Recent Indian earthquakes

Prantik Mandal*, B. K. Rastogi and Harsh K. Gupta

National Geophysical Research Institute, Uppal Road, Hyderabad 500 007, India

The last decade of the 20th century has seen much progress in comprehending the source processes of Indian earthquakes. It has been possible mainly due to the installation of digital broadband and short period stations as a national network and detailed aftershock studies conducted for several earthquakes of $M \geq 6$. Investigations of the seismogenic faults, including drilling, helium measurements and magneto-telluric surveys over the fault zones for some earthquakes have provided valuable inputs to characterize the seismogenesis of the Indian lithosphere. We discuss the significant results obtained from the seismological, geophysical and geological investigations for five recent moderate earthquake sequences (Uttarkashi 1991 and Chamoli 1999 in Garhwal Himalaya; Koyna 1967–1996, Latur 1993 and Jabalpur 1997 in the peninsular shield region). A better understanding of the causative faults and rupture processes involved in generating Indian earthquakes is obtained. Occurrence of Garhwal Himalayan earthquakes has been attributed to the significant concentration of stresses around the asperity/ramp on the detachment plane due to northward under-thrusting of the Indian lithosphere. The continued seismicity at the Koyna–Warna seismic zone and its triggering by reservoirs has been explained in terms of southward migration of seismicity from Koyna reservoir, high filling rate, duration of loading, Kaiser effect and nucleation process of moderate earthquakes. Seismological observations, geological evidences, drilling results and modelling of intra-plate stresses showed that occurrence of stable continental region earthquakes like Latur (1993) can be explained in terms of sudden movement along the pre-existing faults caused by a coupled force system consisting of topography, density heterogeneity and a NNE compression due to movement of the Indian plate. Further, a highly conductive low-velocity fluid-filled zone at 7–10 km depth beneath the focal zone of the Latur earthquake sequence, as suggested by magneto-tellurics study, low Bouguer gravity and observation of a Pc phase, will enhance stress concentration in the uppermost part of the crust, resulting in mechanical failure. Nevertheless, the nucleation of Jabalpur earthquake (1997) in the lower crust has been attributed to the sudden movement along the south Narmada fault due to the stress concentration around the 'rift pillows'. Progress is made in understanding the source processes, crustal velocity structure and *Q* for some important tectonic regions of the Indian lithosphere and future directions have been identified.

Introduction

The thickness/structure/composition of the Indian lithosphere is a cumulative result of the geodynamic processes from early Precambrian crustal evolution to the Tertiary continent–continent collision over its northern segment. It is bounded by the Himalaya–Burma part of the Alpide Belt in the north, which is seismically very active. During the period 1897–2000, fourteen major earthquakes of magnitude ≥ 7.5, including 5 great earthquakes of magnitude ≥ 8.0 have occurred in the Himalaya–Burma region[1–3]. In the last decade, two earthquakes of magnitude exceeding 6.0 occurred in the Garhwal Himalaya (Uttarkashi, 1991, M_w 6.6; Chamoli, 1999, M_w 6.6; Figure 1). Occurrence of the Himalayan earthquakes is attributed to the movements along thrust planes[4,5] or detachment surfaces due to the underthrusting of the Indian lithosphere[6]. A number of earthquakes (including continued occurrence of earthquakes at Koyna (1967, M 6.3 to 2000, M 5.6) and recent devastating earthquakes at Latur (1993, M_w 6.2) and Jabalpur (1997, M_w 5.8)) have occurred in the Stable Continental Region (SCR) of India, bearing the testimony of ongoing tectonic activity. Thus, during the last four decades, the SCR of India experienced a moderate seismicity. After the occurrence of the 1993 Latur earthquake that killed about 10,000 people[7], the seismic network in the Indian shield was upgraded.

Presently, about twenty broadband stations are being operated in peninsular India by India Meteorological Department (IMD), National Geophysical Research Institute (NGRI) and other research institutes and universities with the initiative of Department of Science and Technology (DST), New Delhi (Figure 1). Prior to this, in Himalaya, several short period and strong motion seismic instruments were added. These new and upgraded stations, aftershock monitoring and studies of causative faults, including drilling, helium measurements and magnetotelluric surveys have led to a better understanding of physical processes responsible for generating Indian earthquakes. The data sets from different organizations have been compiled in the National Report for Uttarkashi earthquake by the Geological Survey of India (GSI)[8] and those for Latur, Jabalpur as well as Chamoli earthquakes published by IMD[9,10].

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*For correspondence. (e-mail: postmast@csngri.ren.nic.in)

In this paper, significant findings of NGRI for five sequences of earthquakes during the 1990s in different important Indian tectonic regions are presented. Important contributions by other organizations are referred. The results from stress modelling and their implications towards the seismogenesis of moderate-sized peninsular Indian earthquakes are discussed.

Uttarkashi and Chamoli earthquakes

Occurrence of Uttarkashi and Chamoli earthquakes in the Garhwal Himalaya, which is in the central seismic gap area for $M \geq 8.0$ earthquakes[1], suggests re-estimation of seismic hazard of the region. Until the present, five earthquakes of $M > 6$ (1803, intensity IX (MSK); 1816, M 6.5; 1945, M 6.5; 1991, M 6.6; 1999, M_w 6.6), twelve earthquakes of M 5.0 to 6.0 and several earthquakes of $M < 5.0$ have occurred in the Garhwal Himalaya extending about 100 km east and west of Uttarkashi and Chamoli epicentres. The data indicate that $M \geq 6$ earthquakes repeat every nine years in the Garhwal Himalaya[5]. The occurrence of these earthquakes has been attributed to movements along the pre-existing thrust planes or detachment surface due to under-thrusting of the Indian lithosphere[4,6,11]. The detachment plane dips at an angle of 2–6° beneath the lesser Himalaya, however, it steepens in the north (≈ 15°) as it dips beneath the Higher Himalaya[12]. Based on the lithospheric flexure or strength of the lithosphere and gravity data, Molnar and Lyon-Caen[13] proposed a crustal scale ramp model beneath the line of Himalayan peaks marking the edges of the Tibetan Plateau. Recently, Thakur and Rohella[14] have tried to explain the occurrence of moderate earthquakes in the Garhwal Himalaya in terms of stress concentration near the ramp, due to NNE under-thrusting of the Indian lithosphere. The fault mechanisms of Kangra (1905), Dharchula (1980) and Uttarkashi (1991) earthquakes show a dominant thrust movement along a preferred north-easterly dipping plane[13–16]. However, strike-slip faulting can also occur in the region along Ganga and Yamuna tear faults[11], indicating strike-slip movements along the boundaries of the Garhwal thrusting block.

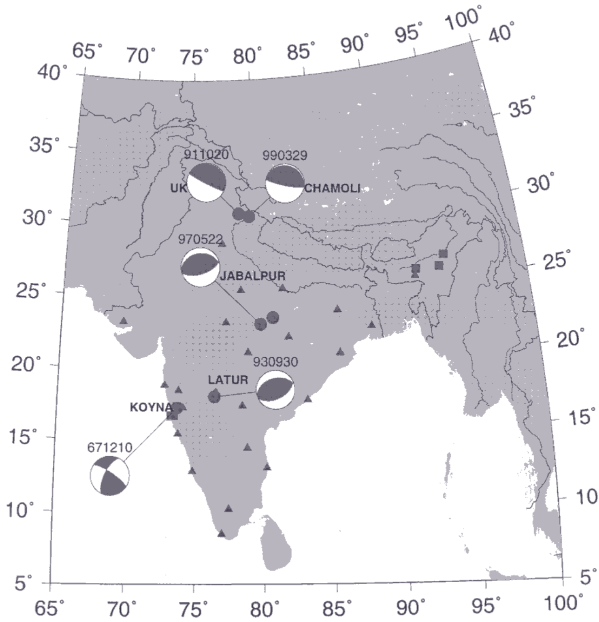

Figure 1. Broadband stations (solid triangle) currently operating in India. Digital short-period local networks of NGRI are shown by filled squares. Epicentres of significant recent earthquakes are shown along with their focal mechanism (dates of occurrences of these earthquakes are mentioned in IST).

The Uttarkashi earthquake of 20 October (19 October, 21 h 23 m 15 ± 1.51 s, UTC) 1991 was associated with the Main Central Thrust zone of Himalaya (just south of the Vaikrita thrust) at 30.77 ± 0.023°N, 78.77 ± 0.018°E at a depth of 15 ± 1.5 km (constrained by depth phase pP-P, ISC)[16]. Having claimed about 2000 human lives, it was the most significant earthquake of 1991. With a M_w 6.6, M_s 7.0 (USGS) and intensity VIII, this event is characteristic of the present-day motion on the thrust-fault system. The Uttarkashi earthquake and aftershocks were well recorded at many new seismograph and accelerograph stations established in the Himalayan region under the Himalayan seismicity study programme of DST[16]. These stations were maintained by IMD, Roorkee University and Wadia Institute of Himalayan Geology (WIHG). About 30 local analogue stations were deployed for aftershock studies by these three organizations and GSI as well as NGRI. A detailed intensity survey was carried out by GSI[17]. Study of this earthquake with different data sets yielded better understanding of the faulting process of a major earthquake in the Himalayan frontal arc region[16].

Firstly, modelling of the centroid moment tensor solution with teleseismic data indicated a shallow (between 10 and 15 km) depth, low angle thrust event consistent with the fault plane solution from first motion phase data. Secondly, the forward modelling of the strong motions recorded at six stations helped in confirming the epicentre and showed that the rupture propagated towards the west. Inversion of the accelerograms gave distribution of the slip on the fault plane that is inferred to have a dimension of about 36 km × 48 km (Figure 2). The maximum slip (1.5 m) occurred 10 km west and 15 km south-west of the hypocentre (Figure 3). The slip source–time function obtained with near-field data is similar to the function obtained from teleseismic records and shows a low moment release at the beginning of the rupture and a maximum rate of moment release 4 s after. Most of the seismic moment was released between 2 and 8 s with a total rupture duration of 9 to 11 s (Figure 4). The relation between the slip distribution obtained by inversion, isoseismals, mapped faults and the aftershock locations indicated that the Uttarkashi earthquake probably occurred along the detachment surface which coincides with the upper surface of the subducting Indian lithosphere. This detachment surface is gently dipping under the Lesser

Himalaya and south of the Vaikrita thrust. The Vaikrita thrust marks the line separating the very shallow-dipping detachment (along which earthquakes like the Uttarkashi earthquake could occur) from the steeper-dipping, aseismic basement thrust further north. This observation is important for an appropriate estimate of seismic hazard in the Uttarkashi region.

The 29 March (28 March, 19 h 05 m 11.03 ± 0.15 s, UTC) 1999 Chamoli mainshock (30.512 ± 0.04°N, 79.403 ± 0.024°E) occurred on a 9° north dipping thrust at a depth of 15 km beneath a region about 25 km NNE of Chamoli[18]. The aftershock activity of this earthquake was monitored by NGRI with a dense network of digital stations installed in and around the epicentral area of the earthquake[19]. The aftershock activity of this earthquake was also studied by other organizations like GSI[20], IMD[21] and WIHG[14], but their hypocentral locations showed a relatively diffused pattern. A total of 204 aftershocks of magnitude varying from 1.4 to 4.8 were recorded by NGRI during 4 April 1999 through 20 May 1999 (ref. 19). The estimated hypocentral parameters for these well-located aftershocks delineate three distinct seismic trends corresponding to: (i) a detachment surface dipping at 15° to NNE at depths of 10–16 km; (ii) Munsiari (MCT2) thrust dipping at 45° to NE at depths 2 16 km; and (iii) NE trending transverse fault dipping at 45° to SE extending from a depth of 4 to 10 km (Figure 5). They also revealed that the mainshock occurred near a junction between the detachment surface and MCT2 at a depth of 15 km. Narula *et al.*[22] also suggested, based on aftershock data as well as the seismo-tectonic setting of the area, that this event has nucleated at the intersection of a transverse fault and the rupture propagated towards the west, along the detachment surface. A marked concentration of large stress drop near a junction between the detachment plane and a south-east dipping transverse fault at 10 km depth can be attributed to a large accumulation of strain energy around that asperity/bend/junction. Depth distributions of stress drop as well as seismic moment indicate that the large stress drop events (about 75% of moment release) have occurred along the detachment plane, whereas the transverse fault has liberated about 22% of moment. However, it would be important to note that MCT2 has liberated only 3% of moment. Moment-tensor solutions of aftershocks of M_w exceeding 2.5 decipher that the detachment plane as well as Munsiari thrust are mainly characterized by thrust movement, whereas the transverse fault shows strike-slip movement (Figure 6). The P-axes point on an average toward N–S. Whilst, the T-axes dip on an average toward NNE which is in good agreement with the down dip direction of the underthrusting of the Indian plate.

The studies of Uttarkashi and Chamoli earthquakes have helped to identify the causative thrust in the lesser Himalaya and frontal thrust area of the Himalaya. The earthquakes nucleate near the ramp (at 10–15 km depth) beneath the surface expression of Vaikrita thrust. The ruptures then propagate up-dip and towards E or W.

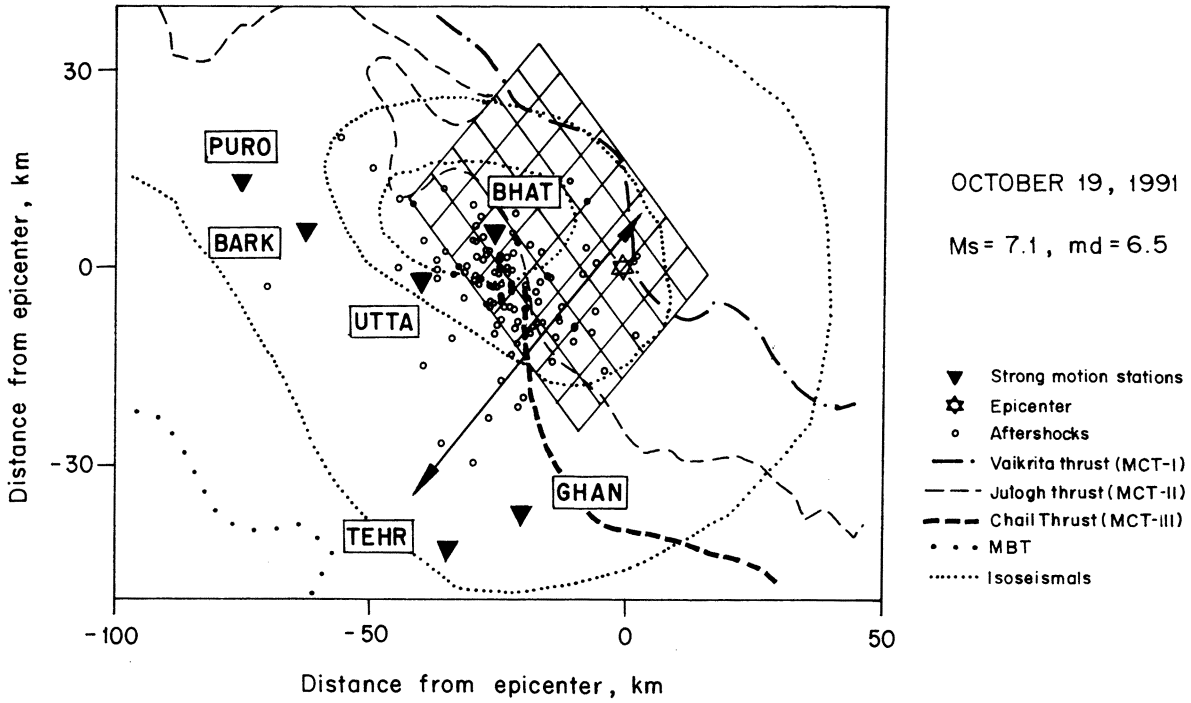

Figure 2. Location map showing the fault plane (divided in 48 sub-faults) used in the strong-motion inversion, isoseismals and the aftershocks of the Uttarkashi earthquake. The double arrow indicates the location of geological section shown in Figure 4 (after Cotton *et al.*[16]).

Koyna earthquakes

Earthquakes have been occurring in the vicinity of Koyna reservoir for the last 39 years, making it the most unique site for reservoir-triggered seismicity (RTS) in the world. Additionally the region has another distinction of having so far the largest and most damaging reservoir triggered earthquake of M 6.3 on 11 December (10 December UTC) 1967 (ref. 23). Until present (June 2000), over 10 earthquakes of magnitude exceeding 5, over 150 earthquakes of magnitude exceeding 4 and over 100,000 earthquakes of magnitude $M \geq 0$ have occurred in the region. The latest burst of seismic activity with M_s 5.6 earthquake in the region occurred on 12 March 2000. During 1962–1992, epicentres of earthquakes were mainly confined to a 20-km long seismic zone extending south of Koyna dam. Nevertheless, seismic activity moved further south during 1993–94, which has been attributed to the filling of the Warna reservoir (filling started in 1985 and the reservoir was filled to a depth of 60 m in 1992), located 35 km SSE of Koyna reservoir. The seismicity during 1993–96 was monitored with a dense network of analogue and digital seismographs enabling better estimates of the hypocentral parameters. This led to the identification of active faults (Figure 7), estimation of source parameters, stress drops at different depths and the identification of nucleation process for moderate size ($M \geq 4.3$) Koyna–Warna earthquakes[24,25]. These studies have led to explanation of continued seismicity for about 4 decades and triggering process of earthquakes due to reservoir filling. The high rates of filling and Kaiser effect (i.e. stress perturbation

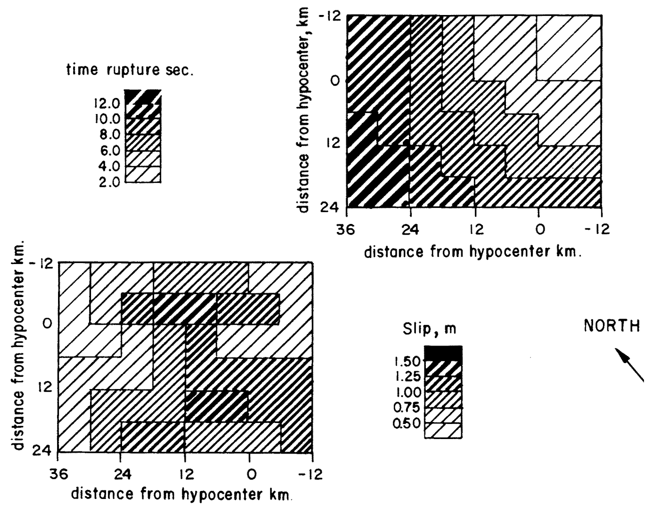

Figure 3. Slip and rupture time distributions on the fault found by strong-motion inversion for Uttarkashi earthquake. The seismic moment for this model is 1.5 × 10^{19} Nm (after Cotton *et al.*[16]).

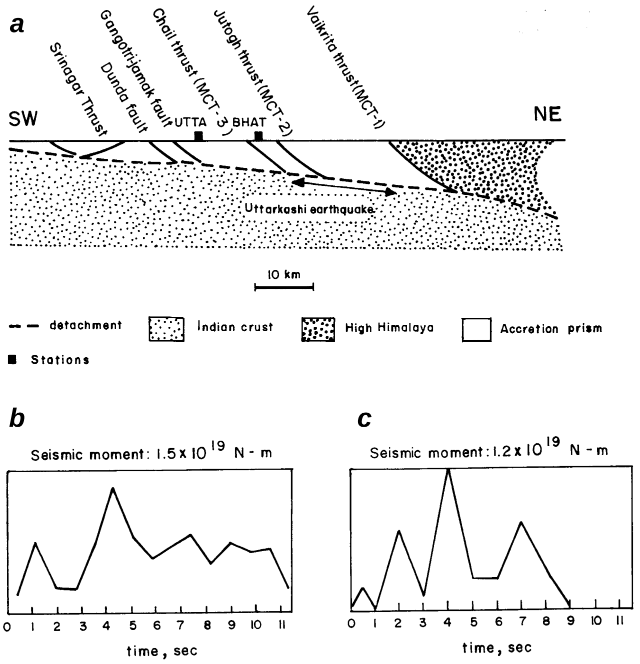

Figure 4. ***a***, Interpretative cross-section showing our tectonic interpretation of the Uttarkashi region and the localization of the earthquake in this tectonic scheme; ***b***, Comparison of source time functions obtained from point source analysis of teleseismic data (bottom); ***c***, Strong-motion inversion (after Cotton *et al.*[16]).

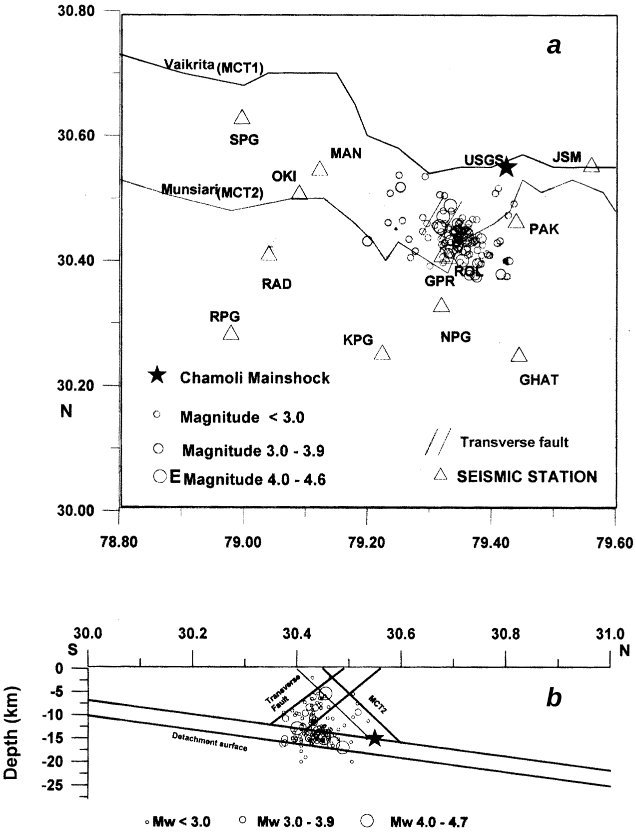

Figure 5. ***a***, Seismic stations (marked by triangles) around Chamoli region in the Garhwal Himalaya. Epicentres of $M \geq 1.0$ during 04 April–20 May 1999; ***b***, Focal depth plots of mainshock and aftershocks on a N-S section.

when previous year's water level maximum is exceeded) are found to be important factors.

Inferred rupture history of Koyna Fault from existing focal mechanism solutions

The Koyna–Warna area is situated in the western part of the Deccan Volcanic Province (DVP) of India, characterized by extensive basic lava flows belonging to the upper Cretaceous–Lower Tertiary age, where 1 to 2 km thick flood basalts are probably underlain by Proterozoic sediments or Archean granites and gneisses[26,27]. The basalts are traversed by a number of fractures and tensional joints. Since 1962, the earthquakes are mainly occurring in a 30-km long NNE-SSW trending Koyna zone in a left-lateral strike-slip sense. The fault dips steeply towards the west[28–30]. The 1967 mainshock had ruptured the northern part (10–18 km) of the NNE-SSW trending fault near Koyna reservoir, in a left-lateral strike-slip mode to a depth of about 5 km (refs 28, 31). This part of the rupture zone experienced several aftershocks of the 10 December 1967 M 6.3 earthquake, six of them being of $M \geq 5$. After a lapse of 5 years, an earthquake of M 5.1 occurred on 17 October 1973. Subsequently, the 1980 sequence with two $M \geq 5.0$ earthquakes released the energy from a zone about 20 km south of Koyna along the same fault. Therefore, it can be inferred that until the end of 1980 the seismic activity was mostly confined to the northern part of the main Koyna fault, except occurrence of few earthquakes in the southern part, a zone near to the Warna reservoir. The recent 8 December 1993 event of M 5.0 ruptured a new NNE–SSW trending zone (Bhogiv seismic zone inferred as Bhogiv fault[32]) parallel to the Koyna main fault and also activated the adjacent southern part of the Koyna fault (KRFZ[33]). The Koyna main fault again had an earthquake of M 5.4 on 1 February 1994 that ruptured a zone about 7 km south of Koyna reservoir and at 11-km depth. Further, the simulation of crustal phases of this earthquake shows a left-lateral strike-slip movement at 11-km depth that is very similar to fault plane solution of 1967 main event[34].

The fault plane solutions for a foreshock (13 September 1967) and the main shock (12 December 1967) suggest a left-lateral strike-slip movement, whereas the aftershock on 12 December 1967 and the earthquake on 20 September 1980 were caused by NW-SE trending normal faults[31]. Based on spatial distribution of composite fault plane solutions for Koyna aftershocks of M 4.0 and smaller well-located events for the period up to 1973, it has been suggested that events along a NW striking plane (south of Koyna) are dominated by normal faulting, whereas shocks along a NNE strike plane (same as strike of inferred fault of 1967 mainshock) are characterized by left-lateral strike-slip faulting[35–37]. Talwani[33] obtained fault plane solutions for eight events of magnitude ranging from 3.7 to 5.4 (which have occurred during 1993–94), suggesting normal and strike-slip movement. Through the composite fault plane solutions for Koyna–Warna earthquakes which occurred during January–June 1995, Mandal *et al.*[24] found a NNE-SSW left-lateral strike-slip movement in three clusters of North Koyna, South Koyna and Bhogiv. Further, based on local earthquake moment tensor inversion of P, S_v and S_h amplitudes for Koyna–Warna earthquakes in a

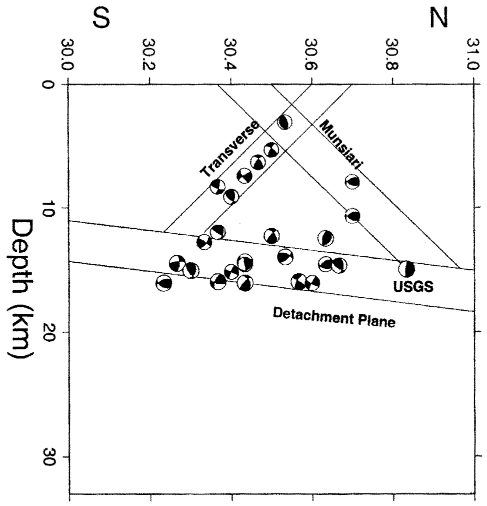

Figure 6. Hypocentral depth plot in N-S direction of focal mechanism solutions of Chamoli aftershocks estimated from local-earthquake moment-tensor inversion of P and S wave amplitudes and polarities. The north-easterly dipping detachment plane as well as Munsiari fault show a dominant thrust mechanism, whereas the south-easterly dipping transverse fault is characterized by strike-slip movement.

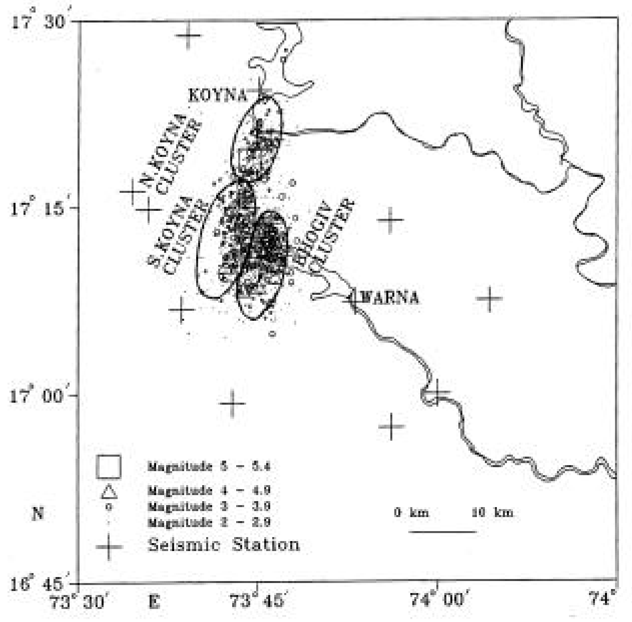

Figure 7. Epicentres of Koyna shocks of $M > 0.5$ during 28 August 1993 to 31 December 1996 (after Rastogi and Mandal[25]).

zone of conjugate faulting near Warna, Mandal and Rastogi[37] showed that the deeper events (focal depth ≥ 5 km) are mainly characterized by a dominant strike-slip component, whereas shallower events (focal depth < 5 km) show a dominant normal component. Therefore, the deformation mode for the region is inferred basically to be a combination of normal and strike-slip faulting.

Drilling and helium study

Based on epicentral distribution and fault plane solution, it was inferred that the 1967 Koyna mainshock was associated with a NNE-SSW striking Donechiwada fault located about 4.5 km SSE of the Koyna reservoir which was further confirmed to be a left-lateral strike-slip fault from surface observations[26,38]. Soil-helium surveys were carried out along 12 traverses at a depth of 1.6 m and 5 m interval in a narrow zone of 20 to 60 m in the fissure zone developed during the 1967 Koyna earthquake near Kadoli village. Gupta *et al.*[38] found that the peak values of the concentration of these traverses vary from 1 to 7 ppm above atmospheric abundance 5.24 ppm. Persistence of helium leakage, even 30 years after the earthquake, provides evidence for active nature of this fault and corroborates seismological observations. From the isotopic composition of helium, they further inferred that the source of soil gas helium is crustal. The results from core drilling at inclined holes in the fissure zone showed that the NNE striking Donechiwada fault dips at an angle of 60° towards WNW. Massive Deccan Trap is brecciated in the fault zone with the breccia fragments cemented by calcite. On steep dipping shear-surfaces, nearly horizontal slickenlines confirm the strike-slip nature of the fault[38].

Earthquakes and water level fluctuations

Gupta[39] pointed out, based on twelve years' (1963 74) water level data of Koyna reservoir and seismic activity, that a rate of loading exceeding 12 m/week is a necessary, but not a sufficient condition for earthquakes of magnitude exceeding 5 to occur in Koyna region. Duration of loading and highest level reached are additional contributing factors[39]. In the Koyna–Warna region, reservoir levels are minimal during May (in summer) and peak in August/September (towards the end of the rainy season). During 1967, the highest reservoir level was reached on 4 October (annual rise 40 m) and the mainshock of M 6.3 occurred on 10 December[33,39]. Similarly, during 1973 the highest water level was reached on 27 September and the main shock of M 5.1 occurred on 17 October[33,39]. In 1980, the highest water level was reached on 2 September and the mainshock of M 5.3 occurred on 20 September[33,39]. In 1985, filling of the Warna reservoir, which is located 30 km south of Koyna, started[32]. In 1992, the maximum water depth exceeded 60 m at Warna. In 1993, the maximum annual-reservoir level fluctuation reached at Warna reservoir was 44.2 m (maximum level on 4 August), whereas at Koyna reservoir it was 30 m (maximum level on 11 September)[32,33]. And, the first earthquake of magnitude exceeding 4.5 of the series (1993–94) occurred on 28 August 1993. It was followed by two larger earthquakes of M 5.0 and M 5.4 on 8 December 1993 and 1 February 1994, respectively. The latest Koyna–Warna earthquake of M_s 5.6 has occurred in a zone about 2 km west of Warna reservoir boundary, which can be attributed to the maximum water level reached (625.2 m, which is 4 m more than the maximum water level reached in previous years) in Warna reservoir during 1998–99. Similar relation between change in water level at Koyna and Warna reservoirs and the occurrences of M 5 earthquakes have been reported by Talwani *et al.*[33]. Further, they inferred that this type of relationship may be explained in terms of Kaiser effect[33,40].

In situ pore pressure monitoring

With a view to understanding the part played by pore fluids in triggering earthquakes, 21 deep borewells (90 to 250 m) were drilled during 1995–98 (ref. 41) and water levels are being monitored. It is observed that the borewells are sensitive to tidal signals, indicating sensitiveness to small strain changes in the connected rock formations. Step-like changes of 2.1 and 6.5 cm amplitudes were noticed at 1.8 and 2.4 km epicentral distances,, respectively, coincident with an M 4.4 earthquake on 25 April 1997. Recently, similar step-like changes in water level were noticed for the M 4.3 event on 11 February 1998 in two borewells. These fluctuations can be explained in terms of poro-elastic response of the earth to small strain changes. Hence, a continuous monitoring of water level in the Koyna–Warna epicentral region would provide important clues to understand the physical processes responsible in generating these earthquakes.

Source parameters of Koyna earthquakes

The installation of digital recorders in September 1994 made it possible to estimate several parameters related to earthquake source as well as medium. Mandal *et al.*[24] estimated source parameters for 193 Koyna–Warna earthquakes of moment magnitude varying from 1.5 to 4.7. They found that the estimated seismic moments for Koyna earthquakes of magnitude varying from 1.5 to 4.7, range from 10^{11} to 10^{16} N-m, the source radii from 94 to 538 m and the stress drops from 0.03 to 19 MPa.

Hypocentres, stress drops and simulated intraplate stresses

Estimated hypocentres of Koyna–Warna earthquakes are mainly shallow and concentrated in the upper crust (down to a depth of 13 km) with concentration of M 5 earthquakes (high stress drops) at a depth of 5–9 km, i.e. within the lower half of the seismogenic layer, while a majority of the small shocks as well as smaller stress drop values are confined to shallower depths[24]. Generally, it is observed that the high pore fluid pressure along upper crustal faults will decrease the material strength of rocks and reduce the frictional resistance to sliding along faults[42]. Thus, high pore fluid pressure can produce large slip, and therefore, large stress drops. A lack of hypocentres is noticed at a depth range of 1–4 km, that can be explained in terms of less stress concentration at that depth range.

The maximum concentration of $M \geq 3.0$ earthquakes and high stress drops within the lower half of the seismogenic layer agree well with maximum magnitude of intraplate stress (90 MPa), induced by topography, crustal interface loading and an assumed ridge push of 30 MPa acting in N30°E direction, inferred at a depth range of 5 10 km (ref. 43). About 40–50 km north-east of Koyna seismic zone, the magnitude of these stresses attains a maximum of 80–90 MPa at a depth range of 5–10 km and then decreases to a value of 55 MPa at 20 km depth. Beneath the Koyna–Warna seismic zone, these stresses show a value of 60 MPa at 5–10 km depth, reducing to a value of 45 MPa at 20-km depth. These stress values are quite high, regionally. It is found that the orientations of these stresses vary from N-S to NW-SE over the DVP[43]. Based on the estimated direction of principal stresses, it is inferred that deformation mode beneath the Koyna region at 10-km depth is dominated by strike-slip movement with a NNE maximum compression. Finally, Mandal and Singh[43] concluded that the seismogenic layer beneath the western part of DVP would lie within 5–10 km depth. This result is in good agreement with the histogram of hypocentres during 1993–95, showing a large concentration of earthquakes at a depth range of 5–10 km (ref. 25).

Foreshocks and nucleation process

The most important finding in recent years is the nucleation process for moderate size Koyna earthquakes[25]. Five small to moderate size Koyna earthquakes of ($M \geq 4.3$, 1993–96) have followed the nucleation model of Ohnaka[44]. The foreshocks of these earthquakes define a detectable zone of pre-seismic slip (5×5 km^2). Space–time clustering patterns of the foreshocks that started 500 h prior to the main shock and within a distance of 5–8 km from the main shock epicentres were studied to decipher the rupture nucleation[25]. The nucleation process is depicted in three phases, viz. quasi-static, quasi-dynamic and dynamic rupturing. The growth rate for foreshock nucleation zone is observed to vary from 0.5 to 10 cm/sec and the nucleation zone finally attains a diameter of about 10 km before the occurrence of the main shock. It is found that the fracture nucleates at shallow depths (< 1 km) and then gradually deepens to cause the main shock near the base of the seismogenic layer, i.e. about 8–11 km in depth[25]. Thus, this nucleation process preceding the main shock can be considered as an immediate earthquake precursor for the Koyna–Warna region. We give the example of the 26 April 1996 main shock to illustrate this important process (Figure 8). For the study of nucleation process, the foreshocks were selected based on the criterion that they cluster within a distance of 8 km from the main shock epicentre starting 100 h prior to the main shock. For the main shock of 26 April 1996, situated along the Koyna seismic zone, foreshocks clustered in an area of 8-km length. The main shock of M 4.4 was preceded by 44 foreshocks of magnitude 1.0 to 3.7 in 100 h. For this case the aftershocks define a nearly N-S rupture zone. The maximum focal depth of foreshocks deepens from 1 to 8.6 km in 60 h. The nucleation zone migrated northward as well as to deeper depths. It is important to note that the growth rate of nucleation zone varied from 0.5 to 10 cm/sec. The nucleation zone ultimately attains a length of about 8.6 km just before the occurrence of the main shock.

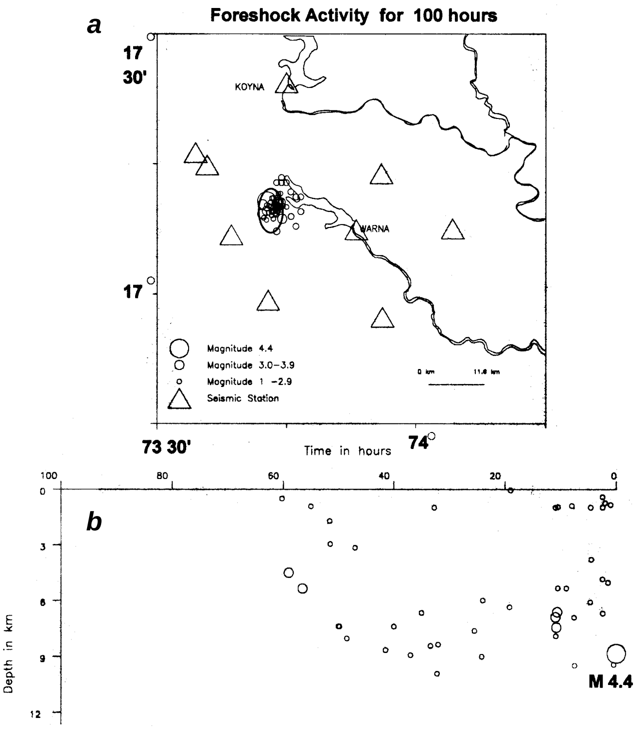

Figure 8. ***a***, Epicentres of foreshocks during 6 to 26 April 1996 for the Koyna mainshock of M 4.4. The foreshocks within an area of 8 km × 6 km are marked by an ellipse; ***b***, Depth variation of foreshocks with time. The mainshock epicentre is shown by the bigger circle, $M = 3$ to 3.9 by medium-sized circles and $M < 3$ by small circle (after Rastogi and Mandal[25]).

Latur earthquake of 1993

The devastating Latur earthquake of 30 September 1993 of M_w 6.2, m_b 6.3 and I_{max} of VIII (18°03′N; 76°33′E) occurred in the early morning of 30 September (29 September UTC) 1993 in the southern parts of Latur district in Maharashtra[7]. The earthquake caused widespread damage in 80 villages. In the days that followed, about 10,000 human bodies were extricated from the debris, making the Latur earthquake the deadliest one to strike a stable continental region. The earthquake was caused by an approximately 45° SW dipping thrust at a depth of about 3 km (Figure 9)[45] in the Archean granite-gneiss basement of Dharwar Craton[38]. Nevertheless, Kayal *et al.*[46], based on the composite focal mechanism solutions, showed that the region beneath the epicentral zone of the earthquake is mainly characterized by strike-slip movement at shallow depths ($\leq$ 5 km) and thrust movement at deeper depths ($>$ 5 km). He also drew attention towards the possibility of water percolation from Makni reservoir at shallow depths, which might have caused the Latur earthquake sequence. This idea of RTS near the Killari region was further supported by Seeber *et al.*[47]. Nevertheless, Rastogi[48] showed that the Latur earthquake sequence does not satisfy the necessary conditions for the reservoir-induced/ triggered earthquakes.

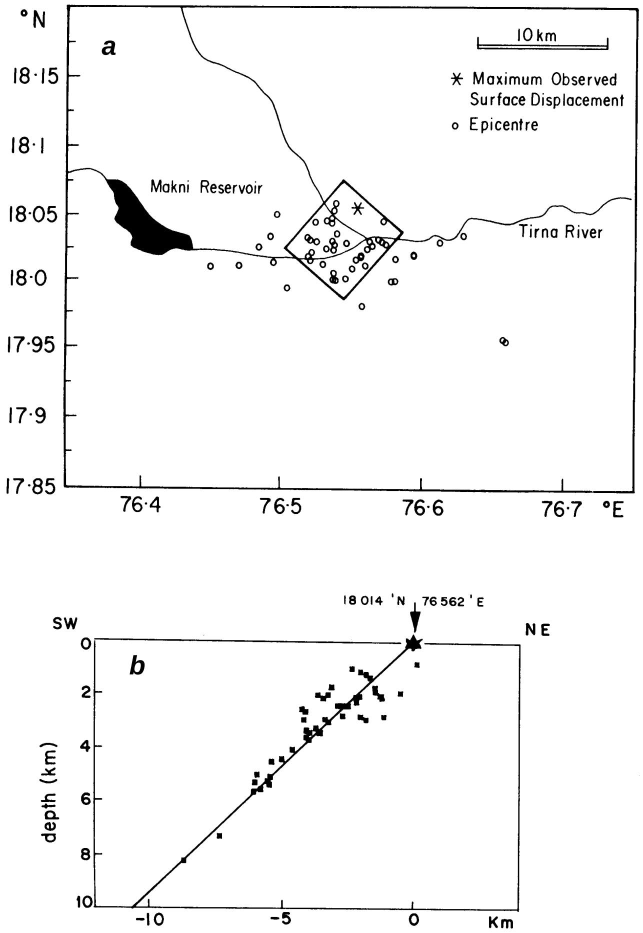

Figure 9. ***a***, Locations of epicentres of Latur aftershocks with the data of a small aperture 3-digital seismographs network; ***b***, Depth section of events in a 5 km × 7 km rectangle, including the epicentre of the main earthquake. The depth section is perpendicular to the strike of the fault plane (135°E). Star indicates the place of observed maximum surface rupture near Killari village (after Gupta *et al.*[45]).

The seismogenic thrust propagated to the surface through the Deccan Trap cover 1.5 km NW of Killari village. On the basis of the location of the aftershocks[49], a plane dipping at an angle of 45° towards the south-west and striking at 135° is inferred to be the fault plane. This plane extends to a depth of 4.5 km and its projection meets the surface in the vicinity of the observed surface rupture[49]. Nevertheless, the aftershock zone of this earthquake obtained by GSI[46] and IMD[50] indicated a relatively diffused pattern in comparison to the above-mentioned aftershock zone. Thus, assuming the aftershock zone of NGRI to be the rupture zone, the stress drop is estimated to be 7 MPa with a maximum displacement of 1.7 m for the main earthquake. A high concentration of helium in the soil in the immediate vicinity of the surface rupture (5 to 38 ppm compared to background value of 0.2 ppm measured far away from the rupture) indicated that a fresh rupture has broken the surface. The ^{3}He/^{4}He ratios ranging from 0.55 to 0.63 suggest that the rupture extends to a depth of a few km[45].

In order to investigate the depth of basement and nature of fault zone, four bore-holes were drilled in the co-seismic rupture zone[38] (Figure 10). The bore-hole results suggest, on an average, a basement depth of the order of 338 m. Further, a comparative study of the corresponding lava flow contacts in the sub-surface indicated movement of 3 to 6 m in thrust mode along the fault plane. However, the 2 to 6 m displacement cannot be accounted for by an earthquake of M_w 6.2. Therefore, it is inferred that this earthquake occurred on a pre-existing fault, which has been involved in movements associated with previous earthquakes. Further, the geological and palaeo-seismological evidences also support the idea of an old pre-existing fault with a recurrence interval of the order of tens of thousands of years for moderate earthquakes, which is in good agreement with low strain rate of the region[51,52]. Nevertheless, Seeber *et al.*[47] proposed an alternative model of a new fault as the causative fault, which had no discernible surface expression prior to the occurrence of the Latur earthquake. Detailed geological and geophysical investigations including study of aftershocks, heat flow, helium, magneto-tellurics, gravity and observation of a Pc phase (lagging behind the Pg phase by about 0.6 to 0.8 s in the seismograms of aftershocks) suggest that a highly conductive low-velocity fluid-filled zone exists at 7–10 km depth beneath the focal zone of the Latur earthquake sequence. Such a zone is likely to enhance stress concentration in the uppermost part of the crust, resulting in mechanical failure[38,53,54].

Results of drilling investigations on the Killari Fault

Three vertical bore-holes (KLR-1, KLR-2, KLR-3), one in the footwall and two on the hanging wall as well as one inclined bore-hole (KLR-4) on the hanging wall, have been drilled in the co-seismic rupture zone about 2 km NW of Killari. Investigations on the drill cores as well as thermal logging in the bore-holes[38] show that:

- 338 m of Deccan Trap lava flows overlying an approximately 8-m thick pre-trappean sediment rest on a granite-gneiss basement.
- The elevation difference for corresponding flow contacts in the footwall and hanging wall indicates 2 to 6 m displacement in the sub-surface. As the slip associated with the 1993 earthquake could be about 1 m, the observed displacement of the fault suggests that the fault has been previously active.
- The observed slickenlines indicate faulting at an angle of 45 to 50° towards NE from the vertical, confirming the dip of the fault inferred from seismological data.
- Palynological studies of the intra-trappean sedimentary rocks show that it might have been deposited during

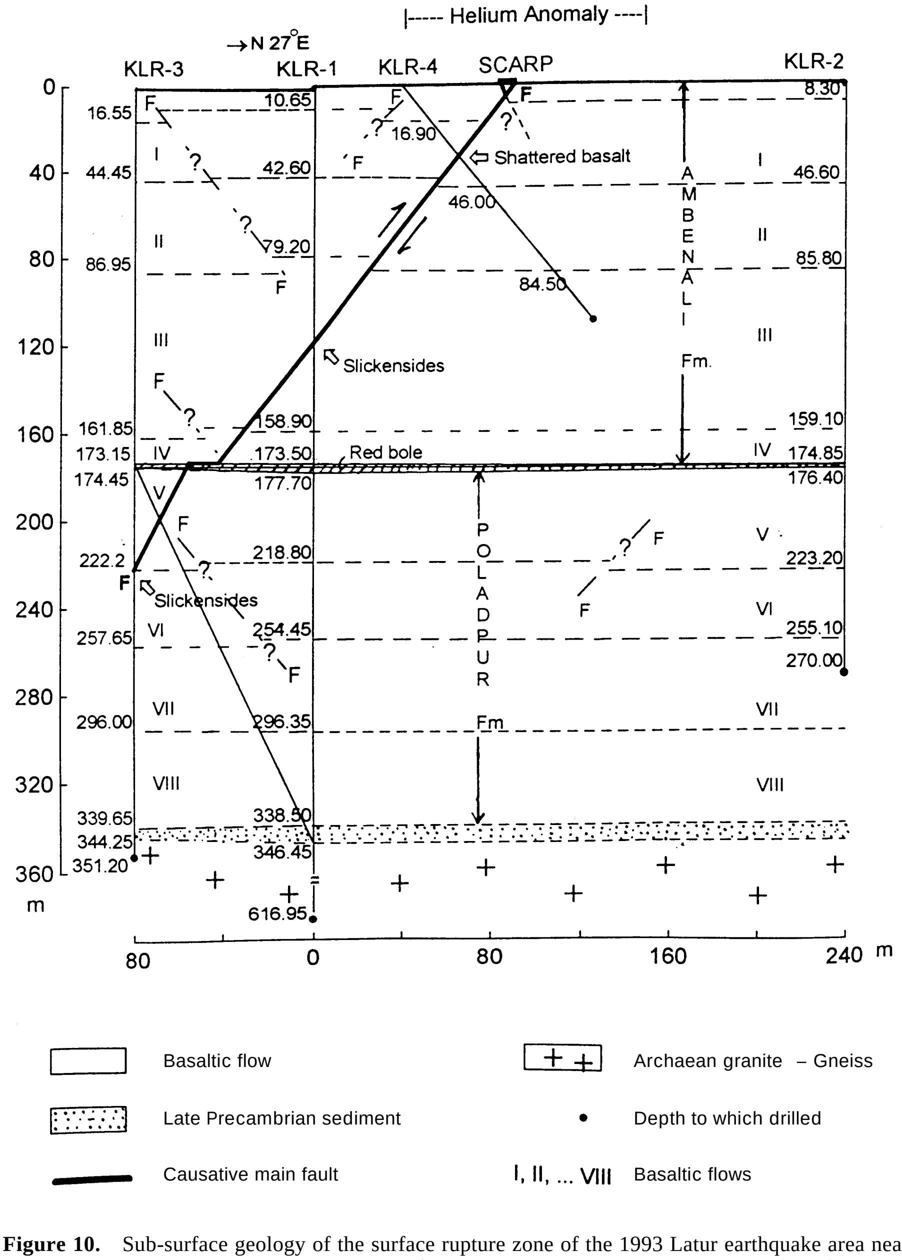

Figure 10. Sub-surface geology of the surface rupture zone of the 1993 Latur earthquake area near Killari, deciphered by drilling. The individual flows are labeled I to VIII. The depths of the flow contacts shown are with reference to the collar of KLR-I. The causative main fault has been traced up to a depth of about 220 m (thick line). The subsidiary faults in the hanging and footwalls have no independent constraints on location and nature (dashed lines with question marks). They have been shown as part of a conjugate thrust system in relation to the main thrust fault following Seeber *et al.*[12] (after Gupta *et al.*[38]).

Precambrian–Cambrian transition time, conforming to Bhima Supergroup. Pb-Pb dating of the basement porphyritic granite collected from KLR-1 shows it to be 2574 ± 61 Ma (ref. 38).

Modelling of three-dimensional intraplate stresses

The occurrence of this earthquake is attributed to the perturbations in the state of stress by local causes along with plate-wide regional forces[53]. It is well known that the heterogeneous nature of the continental crust and topographic load redistribute the stress concentration, resulting in zones of different stress concentrations. Mandal *et al*.[53] showed that the estimated intraplate stresses due to topography and sub-surface mass heterogeneities contribute significantly to the total stress regime of the Killari region. Depth distribution of these stresses beneath the epicentral area suggests a maximum value of 38 MPa at 2 km depth which reduces to 33 MPa at 10 km depth. A regional compression of 30 MPa trending N10°E, when superimposed on these local stresses, shows a NW-SE elongated concentration of stresses beneath the region near Killari, which is correlated with the orientation of the nodal planes of the Latur main shock, as suggested by the fault plane solution of this earthquake. Total stresses suggest the dominance of strike-slip motion with a NE trending maximum compression. These stresses, when resolved along the fault plane of the Latur main shock, however, suggest thrust movement. Hence, a large concentration of deviatoric stresses (≈ 38 MPa) beneath the epicentral area at shallow depth (2-4 km) in the presence of a pre-existing fault could be a probable mechanism for the generation of the 29 September 1993 Latur earthquake[38,53].

Jabalpur earthquake of 22 May 1997

On 22 May (21 May at 21:55:31 UTC) 1997, a moderate size destructive earthquake of M_w 5.8, with a focal depth of 35 km (constrained by two depth phases pPPnp and sPPnp) occurred along the south Narmada fault near the Jabalpur city of central India[55,58]. This southerly-dipping south Narmada fault had also experienced the 1927 Son Valley earthquake of M_w 6.4 (ref. 57) whose return period was estimated to be 35 ± 5 years[51]. Nevertheless, the mean interval between moderate earthquakes in the Narmada-Son lineament (NSL) is estimated to be 16 ± 6 years[51]. A study of depth phases (pPPnp and sPPnp) and the moment-tensor inversion of filtered (20–50 s) broad-band data of IMD seismic stations for the Jabalpur main shock suggest a focal depth of 35 km and a thrust fault with a strike 61°, dip 64° and rake 74° (ref. 58). The ENE trending NSL, about 100 km wide, runs across peninsular India for a length of about 2000 km.

The region has so far experienced two earthquakes of magnitude exceeding 6.0 during the 20th century. These earthquakes occurred in 1927 at Son valley region and in 1938 at Satpura region. The M_w estimates for these two earthquakes are 6.4 and 6.3, respectively[57]. The focal depth of the Satpura earthquake was reported to be 40 km (ref. 59). The focal depth of Son valley earthquake is inferred to be around 35 km (Rastogi, manuscript under preparation). Another significant earthquake of magnitude 5.4 occurred on 23 March 1970 at the western end of NSL near Broach[60]. The focal depth was estimated to be 3.0 km and focal mechanism solution indicated thrust-dominated strike-slip with E-W oriented fault plane[60,61]. On 15 April 1964 an earthquake of magnitude 5.5 occurred at 36-km depth beneath the eastern end of NSL near Midnapore; the fault plane solution showed a thrust mechanism along a preferred EW plane[61]. Another significant earthquake of M 4.5 occurred in 1986, at 10 km depth beneath Valsad, with a predominantly thrust mechanism and a minor strike-slip component[62].

Thus, the favourable deformation mode in NSL, based on the above observations, seems to be thrust-dominated strike-slip along a ENE-WSW fault plane, indicating a dominant compressive stress regime for the area. Nevertheless, it is important to note that, generally, focal depths of NSL earthquakes are of the order of 35–40 km, with the exception of Broach and Valsad earthquakes that occurred on the western end of the NSL. The earthquake nucleation in the lower crust beneath the NSL has been tried to be explained in terms of strain localization around the ‘rift pillows’[63]. This idea is further supported by the small return period for moderate earthquakes in the region, disposition of heat flow values and deep seismic sounding as well as gravity modelling results for the region[63].

Focal depth and rupture propagation

Modelling of low-pass filtered ($f \leq 1$ Hz) displacement seismograms at the two nearest stations (i.e. Bhopal and Bilaspur) suggested a source duration of 1.4 s and a focal depth of 35 km for the 1997 Jabalpur mainshock[58]. A close examination of broad-band seismograms for different IMD stations[58] revealed two depth phases (pPPnp and sPPnp) at 8 and 12.5 s after the arrival of Pn, corresponding to a focal depth of 36 km. Further, a close study of first P-pulse suggested a source consisting of two sub-events separated by 0.65 s. Thus, the rupture nucleated with a first event at a depth of 36 km and then propagated upward with a second event at a depth of 34 km (ref. 58).

Discussion and conclusions

Improvements in the seismological instrumentation of the country during the 1990s have provided a boost to the seismological studies in India. Deployment of digital seismographs at national network stations and also for aftershock study during the 1990s has enabled important contributions like demarcation of the causative faults and their mechanism. The two earthquakes in the Garhwal Himalaya were recorded on several strong motion accelerographs through which the rupturing process has been modelled. In the SCR of India, the epicentral zone of two earthquakes evidenced surface ruptures. Detailed investigations on these active faults like drilling through the active faults as well as helium measurements over the fault zones, could delineate the orientation and extent of the active faults. The magneto-telluric measurements have provided the knowledge of the anomalous crustal structure beneath the fault zones that have offered favourable locales for accumulation of stresses causing seismicity.

The Himalayan seismicity has been mainly explained in terms of movement along the detachment plane in a compressive stress regime due to the under-thrusting of the Indian plate. Ruptures modelled for Uttarkashi (1991) and Chamoli (1999) earthquakes have been inferred in terms of movements along the detachment plane resulting from the under-thrusting of the Indian plate. For both the earthquakes, rupture propagated up dip along the NE dipping detachment plane. This detachment surface is gently dipping under the Lesser Himalaya and south of the Vaikrita thrust along which major earthquakes could occur. Further north is the steeper-dipping aseismic basement thrust. It would be important to note that the Chamoli earthquake occurred in a zone where Munsiari thrust (MCT2) shows a bend. This bend can be interpreted as an asperity on the detachment plane that would accumulate significant amount of strain energy caused by the NNE compression, due to the movement of the Indian plate prevailing over the whole area.

The above observation is important for an appropriate estimation of seismic hazard in the Garhwal region. The focal mechanism solutions of aftershocks obtained from moment-tensor inversion, waveform inversion and first motion studies suggest that the region be mainly characterized by thrust faulting along the detachment plane as well as MCT2. However, a strike-slip regime is seen along the SE dipping and NE trending transverse features at 4–10 km depths. The P-axes point on an average towards SSW. Whilst the T-axes dip, on an average, towards NNE, which is in good agreement with the down dip direction of the underthrusting of the Indian plate. It would be important to mention that the MCT1 (Vaikrita) thrust seems to be seismically less active compared to the region south of MCT1 and MCT2 (Munsiari). Further studies concerning the source processes responsible for generating the significant Himalayan earthquakes through waveform modelling, empirical Green function study and velocity as well as Q tomographic experiments would be able to provide a much better understanding of the role played by the detachment plane in generating earthquakes in the Himalaya.

Generation of Indian SCR earthquakes is mainly caused by the continual accumulation of strain energy by a coupled force system, consisting of NNE compression due to the movement of the Indian plate and local tectonic forces (e.g. topography, isostatic forces, etc.). This stress is sometimes perturbed by reservoir-induced forces or presence of fluids at the hypocentral depths (which enhances/modifies the crustal stress regime, and therefore, nucleation of the earthquake). Further, erosion of the basalt cover in the Deccan Plateau may add to compressive stress in the region. The earthquake focal mechanism solutions and moment-tensor solutions point to a dominant compressive stress regime over the Indian continental lithosphere which agrees well with the results obtained from the modelling of intraplate stresses induced by topography, crustal density heterogeneities and an assumed ridge compression. These stresses are obtained to be as high as 90 MPa. Artificial water reservoir generated pore fluid fluctuations at the hypocentral depths can significantly modify/enhance the upper crustal stresses, thereby nucleating the earthquake rupture.

Results obtained from controlled source seismic sounding, the observation of Pc phase, broadband MT sounding and several other related investigations showed a highly conductive low-velocity fluid-filled zone in the lower part of the upper crust (at 6–11 km) beneath the focal zone of the Latur earthquake[45,54], which can be attributed to the presence of trapped fluids in that layer. This will enhance stress concentration in the uppermost part of the crust resulting in mechanical failure[45]. It would be important to mention that from controlled source seismic sounding results, a low velocity layer at 6.5–11.5 km depth has also been inferred beneath the focal zone of Koyna earthquakes, where maximum occurrence of earthquakes of $M \geq 3$ is also noticed[24,25]. This combination of LVL and generation of earthquakes can be explained in terms of a fluid-filled low strength fracture zone[33], which might have resulted from the presence of reservoirs along with a pre-existing permeable fault zone.

The extent of the causative faults for 1967 Koyna and 1993 Latur earthquake has been confirmed by soil helium surveys. Further, core drilling has confirmed dip of the causative thrusts/faults. At Killari the rupture zone extends downward from the surface with an approximate dip of 45° towards SSW. It is found to be an old fault as 1 to 6 m displacement of the marker beds is observed. Drilling established a WNW dip of 60° for the left-lateral strike-slip Koyna fault, resolving a long-standing debate. Further, Kaiser effect has been observed for the Koyna–Warna seismicity[33]. A unique experiment has been launched to monitor *in situ* pore pressure at Koyna–Warna seismic zone with twenty-one bore-wells (90 to 250 m deep). The results from a few years of observation will help in comprehending the effect of reservoir level variation on pore pressure. Till date, step-like changes of the order of 6 cm have been noticed for two events of

$M \geq 4.3$, which confirms poro-elastic response of the wells to small strain changes.

Studies in the Koyna–Warna seismic zone revealed two contiguous NNE-SSW trending left-lateral strike-slip faults, which along with an inferred NW-SE normal fault near Warna reservoir, could provide significant concentration of strain energy in response to northward movement of the Indian plate. The periodic water level fluctuation in the reservoir(s) causes the nucleation of fracturing process at shallow depths. It has been inferred, based on study of foreshocks for five moderate Koyna–Warna earthquakes of $M \geq 4.3$, that the nucleation zone is originating at a shallow depth (≤ 1 km) and then propagates to the base of the seismogenic layer (8–10 km) through the critically stressed, relatively porous and permeable Koyna–Warna fault zones.

The 1997 Jabalpur earthquake is unique because of the fact that this event nucleated in the lower crust (i.e. at 35 km depth). Modelling of low-pass filtered ($f \leq 1$ Hz) displacement seismograms suggests a source duration of 1.4 s and a focal depth of 35 km for the 1997 Jabalpur main shock. Further, a close study of first *P*-pulse suggests a source consisting of two sub-events separated by 0.65 s. Thus, the first event nucleated at a depth of 36 km and then propagated upward with a second event at a depth of 34 km (ref. 58). It would be worth mentioning here that nucleation of earthquakes in the lower crust with dominant reverse movement are noticed only in NSL in peninsular India.

In a nutshell, the causative faults of recent Indian earthquakes could be well demarcated by excellent quality hypocentral locations of main earthquakes and aftershocks through digital monitoring. The rupture processes involved in generating these earthquakes could be well understood by source mechanism study and waveform modelling. The operation of digital stations in the peninsular shield during the 1990s has generated a substantial amount of local, regional and teleseismic data of excellent quality. A beginning has been made to use these for source and structure studies. The source of the Jabalpur earthquake has been modeled and also a one-dimensional regional shear-wave velocity model has been obtained using Jabalpur earthquake recordings. Vast amount of data of other regional and strong teleseismic earthquakes need to be modelled for source and structure studies. Inadequate seismic networks in the Himalayan region indicate the need for a better coverage of digital seismographs and accelerographs for better and accurate estimation of source parameters. Expertise needs to be developed in India regarding the modelling of earthquake source (e.g. rupture modelling, dynamic source analysis) as well as the earth's structure (waveform inversion, shear-wave tomography and *Q* tomography).

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