The 1993 Killari Earthquake (m b 6.3)

The September 30, 1993 Killari earthquake (m b 6.3) occurred in the Deccan province of central India, in the Latur district of Maharashtra state. It occurred in the middle of the Stable Continental Region (SCR) of low seismic activity (Fig. 1). The local geology in the area is obscured by the late Cretaceous-Eocene basalt flows, referred to as the Deccan traps. This makes it difficult to recognize the geological surface faults that could be associated with the Killari earthquake. The epicentre was reported at 18.090 N and 76.620 E, and the focal depth at 7 ± 1 km was precisely estimated by waveform inversion (Chen and Kao, 1995). The maximum intensity reached to VIII and it caused a loss of about 10,000 lives and sever damages to properties (GSI, 1996).

An aftershock investigation was carried out by making a temporary microearthquake (MEQ) network by the GSI. About 150 aftershocks were well located; the epicentre map is shown in Fig. 2a. Almost all the epicentres are located within the meizoseismal area, in the high intensity (VIII) zone. A N-S depth section shows that most of the aftershocks (77%) are of shallow origin, depth 0-<6 km, and rest of the events occurred at a depth range 6-15 km; the deeper events lie on a south dipping fault plane that meets the surface rupture (Fig. 2b). Fault- plane solutions show reverse faulting for the main shock and deeper aftershocks (depth 6-15 km), and strike-slip faulting for the shallower aftershocks (0-5 km), (Fig. 2a). A fault interaction model is presented that explains the generating process of the main shock and the aftershocks (Fig. 2c). A detailed discussion on the seismotectonics of the main shock and aftershocks is given by Kayal (2000).

Summary

During the last decade (1993-2004), five devastating earthquakes, the 1993 Killari (m b 6.3), 1997 Jabalpur (M w 6.3), 1999 Chamoli (m b 6.3), 2001 Bhuj (M w 7.7) and the 2004 Sumatra-Andaman earthquake (M w 9.3) caused severe damages and large casualties in various parts of India. These earthquake sequences are well studied by the Geological Survey of India (GSI); the results are briefly highlighted here.

Fig. 1: Geotectonic features and significant earthquakes (M≥5.0) in Peninsular India (after Kayal, 2000).

Using about 2700 seismic arrivals, 1500 P and 1200 S, Kayal and Mukhopadhyay (2002) studied seismic tomography of the earthquake source area by simultaneous inversion (Thruber, 1983). In this method the location errors (rms, epicentre, depth) are much improved, and the lateral heterogeneity of the velocity structure is revealed. The tomography structure at a depth of 6 km, at the main shock source area, is illustrated in Fig. 3. An E-W trending low velocity zone (LVZ) is prominent with a N-S trending LVZ to its south. The main shock occurred at the contact between
The 1997 Jabalpur Earthquake (mb 6.0)

The May 22, 1997 Jabalpur earthquake (mb 6.0), epicentre at 23.08°N and 80.06°E, is a well studied earthquake in the Son-Narmada-Tapti (SONATA) seismic zone (Acharyya et al., 1998; Rajendran and Rajendran, 1998; Kayal, 2000), (Fig. 1).

A notable aspects of this earthquake is that it was the first significant event in India to be recorded by 10 Broadband (BB) seismic stations which were established in 1996 by the India Meteorological Department (IMD). The focal depth was well estimated using the ‘converted phases’ of the BB seismograms. The focal depth was given in the lower crust at a depth of 35 + 1 km (Bhattacharya et al., 1997), similar to the moderate earthquakes reported from the Amazona ancient rift system in SCR of South America.

Maximum intensity of the Jabalpur earthquake reached to VIII in the MSK scale (Fig.4a); and this earthquake killed about 50 people in Jabalpur area.

The 1999 Chamoli Earthquake (mb 6.3)

The main shock (mb 6.3) of 28 March, 1999 occurred in the Chamoli area, which falls in the Garhwal Himalaya tectonic zone of the Main Himalayan Seismic Belt (MHSB) (Fig. 5a). The U.S. Geological Survey (USGS), based on global network data, reported the epicentre at 30.49°N and 79.29°E and the centroid depth at 15 km. The event was well recorded by the permanent national network of the IMD, including the broadband stations, and by the temporary GSI network, that occurred at depth 35-40 km in the lower crust (Fig.4b). Details of the aftershock investigation is given by Kayal (2000). The fault-plane solution of the main shock and aftershocks reveal reverse faulting with left-lateral strike-slip motion; the solutions are comparable (Fig.4a). It was inferred that the south dipping Narmada South Fault, the southern margin fault of the Narmada Rift Basin, was activated by reverse faulting (Kayal, 2000). Seismic tomography study of the source area could not be done due to meagre aftershock phase data for simultaneous inversion.

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a total of 373 seismic phases from the worldwide and Indian stations, the IMD located the epicentre at 30.410N and 79.420E and the focal depth at 21 km (IMD, 2000). The USGS and the IMD locations of the main shock are shown in Figure 5a. The maximum intensity VIII was reported in the Chamoli town area, and about 100 people were killed.

More than 1000 events were recorded by the temporary stations during 9 April - 29 June, 1999; about 300 aftershocks magnitude > 2.0 were located (Kayal et al., 2003). A north-south depth section of the main shock and the aftershocks (M > 2.5) is illustrated in Figure 5b, incorporating the steady-state tectonic model of the Himalaya envisaged by Seeber et al. (1981). In this model, the plane of detachment, a shallow and low dipping (~30 toward north) plane separates the Himalayan sedimentary wedge from the Indian shield basement, and the Basement Thrust Front which juxtaposes the basement of the Indian shield and the Tethyan slab, dips ~150 toward north beneath the greater Himalaya. The depth of the plane of detachment is about 20-25 km below the surface trace of the Main Central Thrust (MCT) in the Himalaya. The depth section of the earthquakes clearly indicates that the main shock occurred on the Basement Thrust, to the south of the MCT, and the aftershocks, on the other hand, are generated by activation of the Alokandna fault (ANF) to the south of the MCT. All the earthquakes occurred above the plane of detachment (Fig.5b).
Seismic tomography study clearly reveals the MCT and the ANF zones as LVZs (Fig. 5c). The main shock and deeper aftershocks occurred within a HVZ at the ‘fault end’ of the ANF. The S-wave velocity structures resemble that of the P-wave. The earthquake source area is characterized by higher Vp/Vs or higher Poisson’s ratio at the fault end.

The 2001 Bhuj Earthquake (MW 7.7)

The devastating Bhuj earthquake (MW 7.7) of January 26, 2001 in the Gujarat state, in northwestern part of peninsular India, rocked the whole country, and killed about 20,000 people. The maximum intensity reached to X. The epicentre of the earthquake is reported at 23.400N and 70.280E, and the well estimated focal depth at 25 km (IMD, 2002). A total of about 3000 aftershocks (M > 1.0) were recorded till mid April, 2001 (Kayal et al., 2002a). About 500 aftershocks (M>2.0) are well located; the epicentre map shows an aftershock cluster area, about 60 km x 30 km, between 70.0-70.60E and 23.3-23.60N; almost all the aftershocks occurred within the high intensity (IX) zone (Fig. 6a). The source area of the main shock and most of the aftershocks is at a depth range 20-25 km. A detailed report on the seismotectonics of the Bhuj earthquake sequence is given by Kayal et al. (2002a).

The fault-plane solutions suggest that the main shock originated at the base of the paleo-rift zone by a south dipping hidden reverse fault; the rupture propagated along NE as well as along NW. The aftershocks occurred by left-lateral strike-slip motion along the NE trending fault, compatible with the main shock solution, and by pure reverse to right-lateral strike-slip motion along the NW trending conjugate fault Fig. 6b). A seismotectonic model is suggested in Fig. 6c.

Out of 500 aftershocks, 331 best located events were selected for the tomography study (Fig. 6d). A total of 3813 seismic phases, 1948 P and 1865 S arrivals, are used (Kayal et al., 2002b). The tomography images at the
main shock source area, depth 20-25 km, reveal interesting structures. It depicts two LVZs, and in between a HVZ at a depth of 20 km (Fig. 6d). The main shock and the aftershocks are bounded by the HVZ and by the LVZ to its east. The tomography images at a depth of 25 km show that the HVZ is prominent in the source area (Fig. 6d). It implies that the tectonic stress accumulated within the HVZ, and the main shock nucleated at the 'fault end' within the HVZ. The source area at 25 km depth further indicates a lower Vs and higher Vp/Vs (or s), Fig. 6d), which implies that the rock matrix in the source area is partially saturated with fluid (Kayal et al., 2002b).

**The 2004 Sumatra-Tsunami Earthquake (MW 9.3)**

The December 26, 2004 Sumatra-Andaman earthquake (MW 9.3) is the fourth largest event (M>9.0) in the world during the last 100 years (Fig.7). It occurred by thrust faulting on the interplate thrust of the subducting India plate and overriding Burma platelet. The main shock rupture, 1200 km long and 200 km wide, propagated from north of Sumatra to Andaman - Nicobar Islands; the slow rupture generated Tsunami which killed about 300,000 people. The epicentre of the earthquake is located at 3.90N and 94.260E with a focal depth at 28 km (USGS). The past significant earthquakes in this zone are the 31 December, 1881 (M 7.9), 26 June, 1941 (M 7.7), 20 January, 1982 (M 6.3) and 14 September, 2002 (M 6.0).

The mega seismic event of 2004 triggered giant tsunamis that devastated the coastal regions of Indonesia, Malaysia, Thailand, Sri Lanka, India, Maldives and even the east coast of Africa. The impact of the tsunami was quite severe in the coasts of Andaman and Nicobar group of Islands, Tamil Nadu, Andhra Pradesh, Pondicherry and Kerala. The Air-base in the Car-Nicobar island was totally devastated by the Tsunami (Fig.8a) and killed about 200 people. Macroseismic survey was carried out by different teams of GSI in North Andaman, Middle Andaman, South Andaman, Havelock Hut Bay and also in the Nicobar group of Islands. A maximum intensity VIII was recorded in the Andaman Islands (Fig. 8b and c).

The mega thrust event was followed by an intense aftershock activity spreading over an area extending between 30-140N along the Andaman - Nicobar - Sumatra Island arc region. The aftershocks are distributed northwards from the epicentre of the main shock suggesting unilateral rupture propagation. The aftershock area covers a length of about 1200 km and a width of about 200 km, in a 'banana' shape (Fig.7). The national network (IMD) recorded almost all aftershocks M>5.0; about 350 were recorded till 31.01.2005. The US Geological Survey located about 500 aftershocks M>4.5 till January 31, 2005 (Fig. 9a). The GSI deployed six temporary seismograph stations in the Andaman and Nicobar Islands and also in Havelok and Narkunda (volcanic) islands. About 20,000 aftershocks (M>3.0) were recorded till end of March, 2005. About 1000 aftershocks (M>3.0) located by the GSI network till January 31, 2005 is shown in Fig.9b.

The aftershocks are still continuing, frequency of occurrences is, however, reduced now. Fault plane solutions suggest predominant thrust faulting in the fore arc region, and normal/strike slip in the back arc region, consistent with the regional tectonics (Fig. 10).

The oblique subduction of the Indian plate beneath the Burmese plate is partitioned into thrust faulting along
(a) Total damage of the Airbase, Car Nicobar.

(b) Ground movement splitting the tree trunk

(c) Mud volcano in Middle Andaman

Fig. 8: Damages due to the 2004 Tsunami earthquake (GSI).

Fig. 9: Aftershocks of the 2004 Sumatra - Andaman mega thrust event till Jan 31, 2005.
the plate-interface involving slip directed perpendicular to the trench, and strike-slip faulting much east of the trench with slip directed parallel to the trench axis.

Crustal deformation study was carried out by various organizations including Survey of India, National Geophysical Research Institute and GSI. Pre- and post earthquake vectors clearly show that islands have moved 2 to 6 meters in horizontal position towards mainland (Fig. 11), and also there is anti-clockwise rotation. The Ground Positioning System (GPS) stations move southwesterly, 2 to 3 m in the Andaman Islands and 5 to 6 m in the Nicobar islands. Tidal observations indicate that there is a rise in local mean sea level of an order of 1.05 m at the Port Blair observatory. This observation is conformable with the GPS/levelling measurements that show a subsidence of the observatory to an extent of 1.1 m. Campaignd mode GPS survey by NGRI at eight stations indicated subsidence in Port Blair and upliftment in N-Sentinel island. The uplift and subsidence are explained by the thrust faulting involving reverse slip; uplift at the updip edge and subsidence at the downdip on the co-seismic rupture (Fig. 12).

Pre- and Post-earthquake marine geophysics surveys are carried out by the GSI. Significant changes in magnetic (100 - 150 nT) as well as in bathymetry (15-25 m) of the ocean floor are recorded.

Study of seismic tomography using the large aftershock data set is in progress.
References


GSI 1996 Killari Earthquake, 30 September 1993, Geol. Surv. of India sp. pub. 37, 282P.


