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Invited review

Five decades of triggered earthquakes in Koyna-Warna Region, western India – A review

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ABSTRACT

We review Reservoir Triggered Seismicity (RTS) in the Koyna-Warna region of India since the impoundment of the Koyna reservoir in 1962 until the year 2015. We include seismicity that occurred farther south in response to the impoundment of Warna reservoir in 1993, about 35 km to the south of Koyna reservoir. The on-going earthquake activity for more than five decades in a small seismic volume of about $30 \times 20 \times 10$ km^3 has characterized the Koyna-Warna region as globally unique and significant. To date, 22 earthquakes of $M \geq 5$, about 200 earthquakes of $M \geq 4$ and several thousand smaller earthquakes have been recorded by a dense network of stations in the region. Various seismological, geophysical and hydrological studies have been carried out to understand the phenomenon of triggered seismicity including source mechanism, fault geometry, crustal structure, earthquake processes, causal relationship with reservoir water level changes and anomalous water level fluctuations in cased bore-wells. The present review takes stock of all such studies undertaken so far to summarise the understanding on various geo-scientific issues and milestone achievements with regard to mechanism of triggered seismicity and source processes, fault plane solutions commensurate with geometry of faulting, source parameters, seismogenic depth, crustal structure and the role of reservoir water level. Two-stage increase in seismic energy release coinciding with peaks of annual filling and draining cycle of reservoir with one month delay vis-à-vis spurt of moderate earthquakes ($M > 5$) due to (i) rapid rise in reservoir level (12 m/week) (ii) reservoir water level exceeding the previous maxima and (iii) duration for which high reservoir level is retained, are characteristic features. Numerical models simulating diffusion of pore fluid pressure fronts during the filling stage of reservoir suggest stress perturbations of the order of 0.75–2.25 bar at hypocentral depth, triggering earthquakes on critically stressed pre-existing faults. In the year 2005, a 13-station digital seismometers network became functional that characterized the distribution of epicentres in the area with increased accuracy, and suggested four major seismic zones with well-defined clusters. Scientific drilling carried out recently provide several new information regarding the subsurface geology and structure in the Koyna region, such as (i) thickness of Deccan Traps (933 in the Koyna area and 1185 m in the Warna area) (ii) presence of granite-gneiss basement directly underlying the Deccan Traps (iii) absence of infratrappean sediments and (iv) temperature not exceeding 150 °C at hypocentral depth. It is planned to establish a deep borehole observatory close to the seismic source zone for direct measurements of physical and mechanical properties of rocks, pore fluid pressure, hydrology, thermal condition and other parameters of an intra-plate active fault zone in the near field of earthquakes before, during, and after their occurrence. Results from such experiment and long term in-situ monitoring of critical parameters would enhance our understanding on the mechanism of triggered earthquakes and the role of reservoir water level fluctuations.

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1. Introduction

The Koyna-Warna region located about 50 km inland from the west coast of India offers a classic example of triggered seismicity that started soon after the impoundment of the Koyna reservoir behind the Koyna dam in 1962 (Narain and Gupta, 1968a; Gupta, 1992). The Koyna dam, situated close to Koynanagar, is a major concrete gravity dam with a height of 103 m built on the Koyna river. Small to moderate tremors continued to occur in the vicinity of the reservoir and eventually culminated into the largest triggered earthquake of M6.3 on 10 December 1967 that devastated the region by claiming more than 200 human lives and causing severe damage to Koynanagar (Gupta and Rastogi, 1976). Another artificial water reservoir, the Warna reservoir started impounding behind the Warna dam in 1985 and was completed in the year 1993. The height of the Warna dam is 80 m. The reservoir, located about 35 km to the south of Koyna dam, further intensified the earthquake activity in the region. Although earthquakes continued to occur in the vicinity of the Koyna dam, a prominent southward migration of seismicity was observed (Rastogi et al., 1997). The on-going earthquake activity for more than five decades in a small seismic volume of about $30 \times 20 \times 10$ km^3, primarily confined between the downstream of Koyna reservoir and upstream of Warna reservoir, has characterized the Koyna-Warna area as a unique natural laboratory to test hypotheses concerning the genesis of reservoir triggered earthquakes.

The triggering phenomenon characterizes initiation or enhancement of seismicity due to impoundment of reservoirs in an area with threshold ambient stresses close to rock failure along pre-existing faults. Carder (1945) for the first time pointed out triggering of earthquakes by artificial water reservoirs at Lake Mead in the United States of America. Thereafter, more than ninety sites have been identified worldwide where earthquakes were triggered on impoundment of artificial water reservoirs (Gupta, 2002).

Various seismological, geophysical, and hydrological studies have been carried out since the late 1960s to understand reservoir triggered earthquakes in the region and also to know the possible triggering mechanism associated with such earthquakes (Guha et al., 1966; Gupta et al., 1972a; Gupta, 1983; Talwani, 1995, 2000; Talwani et al., 1996; Rastogi et al., 1997; Bansal, 1998; Bansal and Gupta, 1998; Rajendran and Harish, 2000; Gupta, 2001, Pandey and Chadha, 2003; Chadha et al., 2003; Gahalaut et al., 2004; Chadha et al., 2008; Durá-Gómez and Talwani, 2010; Gavrilenko et al., 2010; Yadav et al., 2015). The studies until the year 2000 emphasized the dominant role of artificial water reservoirs in a region having ambient stresses close to failure for triggering earthquakes. The later studies focused on understanding the causal relationship between seasonal fluctuations in reservoir water level and continued triggered seismicity using quantitative statistical and numerical approaches. The triggered earthquakes at depths of about 6–8 km in the Koyna region was attributed primarily to the diffusion of excess pore pressure fronts, which lead to small stress perturbations of the order of 0.75–2.25 bar and are sufficient to cause failure on critically stressed pre-existing fault (Pandey and Chadha, 2003).

Gupta (2005) perceived several important features categorically and envisaged the Koyna–Warna region as an ideal site for detailed investigations by establishing a network of boreholes to better comprehend the physics of the triggered earthquakes and possibly to forecast them. A few such features are – (i) earthquakes occur in a small area with focal depths limited to about 10 km and there is no other seismically active zone in the vicinity (ii) the Koyna-Warna seismic zone is accessible for deployment of all kinds of experiments and making observations (iii) earthquakes have been occurring regularly following an increase of water level in the reservoirs during monsoons and later during emptying stage of the reservoir (Rajendran and Harish, 2000; Gupta, 2001; Pandey and Chadha, 2003) (iv) spurt of $M \geq 5$ earthquakes due to reservoir loading rate of 12 m/week (Gupta, 1983) and exceeding the previous maxima of the reservoir water level (Gupta, 2002) (v) an increase in foreshock activity some 15 days before an $M \geq 5$ earthquake (Gupta, 1992; Gupta and Iyer, 1984) (vi) a quasi-dynamic nucleation process found to occur some 100 h before an $M \geq 4$ earthquake (Rastogi and Mandal, 1999) (vii) co-seismic changes in water levels for four earthquakes of $M > 4.3$ along with precursory decrease observed in the bore wells of the Koyna–Warna region (Chadha et al., 2003).

Despite improved knowledge and understanding acquired through the previous studies, many important issues remain unanswered such as geometry of causative faults, physical processes, crustal velocity model representing disconformities sandwiched with low/high velocity layers, focal depths and identification of precursors of seismological, geophysical, geochemical and hydrological origin. To address such relevant issues more efficiently, the Ministry of Earth Sciences (MoES), India has launched a deep scientific drilling experiment in the region with an objective to set up two geo-scientific deep borehole observatories in close proximity to the source zone. The results from the preparatory phase studies, carried out as part of this experiment, are detailed in a later section.

In this paper, we review the findings of various seismological, geophysical and hydrological studies carried out since the late 1960s, and discuss unresolved issues and current initiatives to develop a comprehensive understanding on Reservoir Triggered Seismicity (RTS) in the Koyna-Warna region.

2. Geology and tectonics of Koyna-Warna region

The Koyna–Warna region is situated in the western part of the Deccan Volcanic Province (DVP) (Fig. 1). The flood basalt exposed in the province, also known as the Deccan Traps, comprises a thick succession of lava flows that were erupted during the passage of India over the Reunion hot spot around 65 million years ago (Morgan, 1972; White and McKenzie, 1989; Campbell and Griffiths, 1990). The lava flows have been classified into simple and compound flows (Deshmukh, 1988). The DVP is bounded by the Precambrian Dharwar craton in the south, the Aravalli-Bundelkhand craton in the north and the Bastar craton in the east. Drilling carried out for hydrocarbon exploration confirms the presence of significant volume of Deccan flood basalts in the Arabian Sea (Biswas, 1987). In the Koyna-Warna region, the traps consist of multiple lava flows, with each flow featuring massive, vesicular, and amygdaloidal basalts, with red bole or flow top breccias separating it from the subsequent flow. The thickness of Deccan Traps in the region has been estimated by a number of geophysical studies (Kailasam et al., 1972, 1976; Kaila et al., 1981; Lightfoot, 1985; Patro and Sarma, 2007) and variations have been attributed mainly to pre-trappean topography (Sarma et al., 2004). The topography is found to vary from an average elevation of 600 m on the Western Ghats escarpment to about 100 m within the Konkan Plains.

The Koyna River originates in Mahabaleshwar to the north, flows in north-south direction up to Helwak (a place in the old Koynanagar, close to the epicentre of the 1967 M6.3 Koyna earthquake) and thereafter follows a sharp eastward bend. The tectonic framework of the Koyna-Warna region is shown along with the seismicity in the region in Fig. 2. Langston (1981) analysed LANDSAT imageries of the Koyna region and found dominance of NNE-SSW and NW-SE trending lineaments in the region that corroborated well with the findings by Rastogi and Talwani (1980). Chadha et al. (1997) delineated two NNE-SSW trending faults in the region based on distribution of epicentres; one originating from Koyna parallel to the N-S portion of the Koyna river and extending southward for about 30 km length, and the other with fault length of ~20 km passing through Warna reservoir. Kailasam and Murthy (1971) suggested a possible shear zone (fault) in N-S direction parallel to the Koyna river course and buried within the Deccan Trap possibly extending into the underlying basement rocks. The NNE-SSW trending faults were later designated as the Koyna River Fault Zone (KRFZ) with steep westward dip and the Patan Fault (PF) dipping about 45° to the NW respectively, characterizing the seismicity of the Koyna-Warna region (Talwani, 1997a, 1997b). The existence of KRFZ has been corroborated through various other studies based on aerial photographs, ancient geomorphic surfaces and gravity-magnetic profiles (Deshpande and Jagtap, 1971; Snow, 1982; Kailasam and Murthy, 1971). Talwani (1997b) also inferred a number of NW-SE trending intersecting fractures in the Koyna seismic zone criss-crossing the NNE-SSW trending faults and extending down to hypocentral depths.

3. Seismological studies in the Koyna–Warna region

3.1. Seismicity

The occurrence of 1967 M6.3 Koyna earthquake within about 5 years after the impoundment of Koyna reservoir drew attention of worldwide researchers to understand source mechanism vis-à-vis associated physical processes responsible for genesis of earthquakes in the region. Subsequently, several studies have been carried out in the Koyna-Warna region that has strengthened our understanding of seismotectonic behaviour of the region. For a long time, the Deccan Volcanic Province was considered to be stable. In the Koyna region, there is no historical record of earthquake activity even 100 years prior to the impoundment of the Koyna dam (Verma, 1985). A Benioff seismometer operational since the 1950s at the Poona observatory, located ~115 km north of the Koyna dam, did not report any significant activity in the region (Gupta et al., 1972a). The first noticeable earthquake (M ~ 5) that was

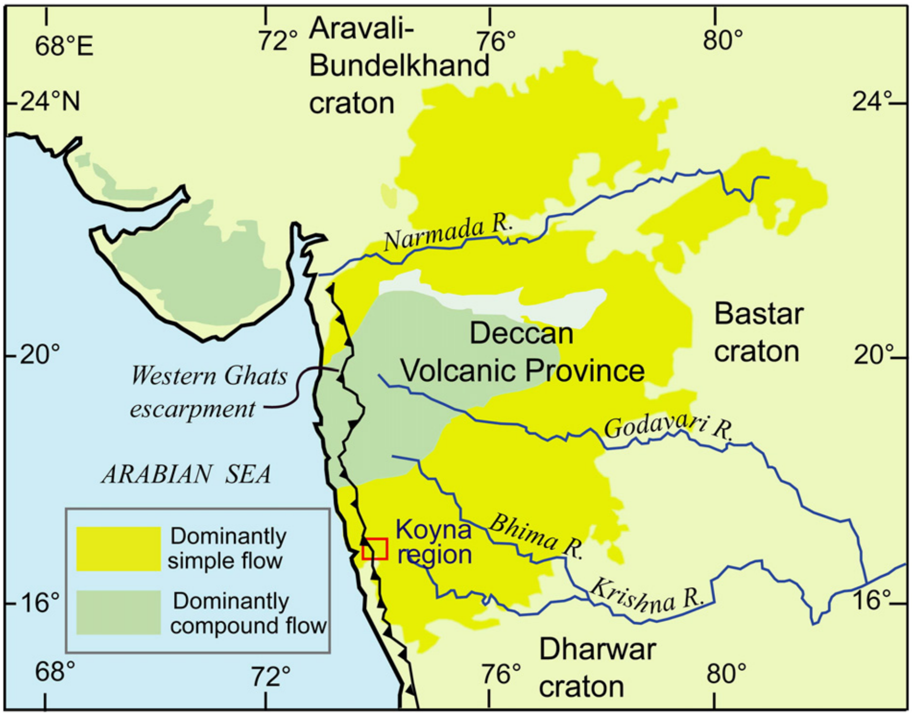

Fig. 1. Geological map of Deccan Volcanic Province showing the Koyna-Warna study region (modified after Kale et al., 2014).

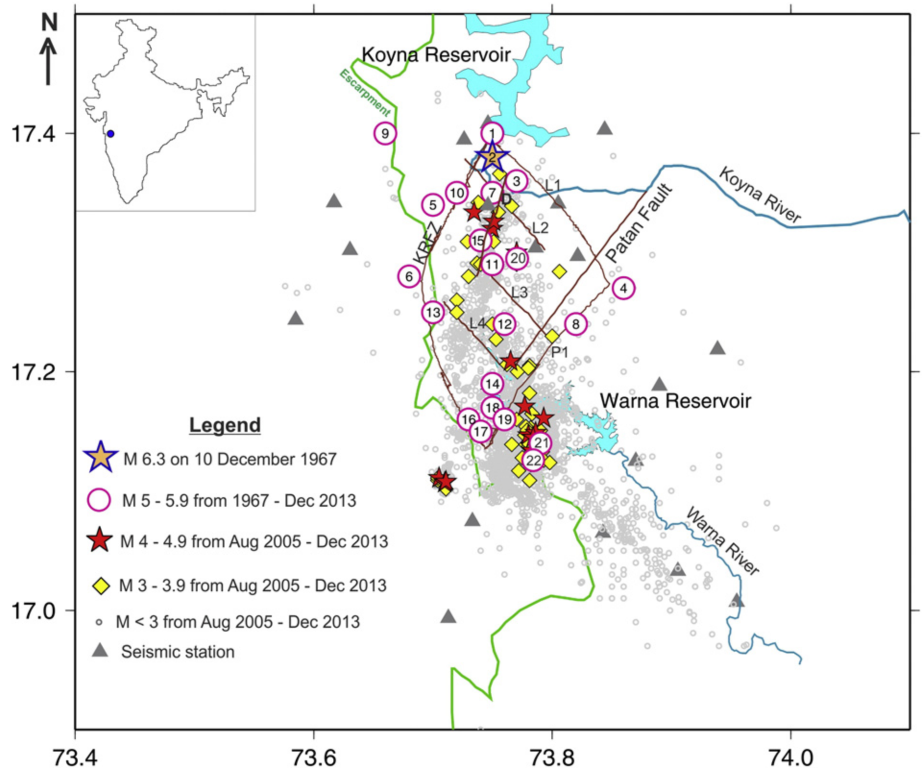

Fig. 2. Inferred fault, lineaments and seismic activity in the Koyna-Warna region. KRFZ: Koyna River Fault Zone; D: Donechiwada Fault; P1: Fault parallel to Patan Fault; L1, L2, L3, and L4: NW-SE trending fractures. Filled triangles show seismic stations in the region. Inset: Location of Koyna on outline map of India (after Gupta et al., 2015).

felt widely in the region and causing minor local damage occurred on 13 September 1967.

Narain and Gupta (1968b) first suggested a possible fault along the Koyna River that was later confirmed along with its NNE-SSW trending orientation on the basis of first motion records and the orientations of epicentres of aftershocks (Tandon and Chaudhury, 1968). Rastogi and Talwani (1980) relocated 300 select earthquakes of magnitude $M_L < 4.0$ in the region and inferred two trends; one NNE oriented near the Koyna dam and the other about 20 km west of the dam in NW direction. A southward shift in seismicity was observed during 1993–94, which was attributed to the newly impounded Warna reservoir constructed about 35 km to the south of the Koyna reservoir (Rastogi et al., 1997). However, data show that the Koyna region continues to remain active even after the impoundment of the Warna reservoir, with two earthquakes of $M > 5$ since 1993 and three earthquakes of $M > 4$ since 2005 besides a few hundred smaller earthquakes.

Later, campaign mode studies carried out in the region either to collect fresh seismic data (Rai et al., 1999) or reprocess the data with double difference technique (Srinagesh and Sarma, 2005) help to delineate different clustering patterns. In the year 1993, five digital seismographs were included in the existing analog network, which was subsequently increased to 13 digital stations in year 2005. As of today, 22 earthquakes of magnitude $M \geq 5.0$, about 200 earthquakes of $M \geq 3.5$, and several thousand smaller earthquakes have occurred in the Koyna-Warna region since the impoundment of the Koyna reservoir in 1962. Data collected so far brings out four well defined clusters of epicentres viz. cluster-A located close to the Koyna dam, oriented NNE-SSW along Koyna River Fault Zone (KRFZ), cluster-B oriented NW and located near the junction of NW trending fissures criss-crossing the NE-SW trending Patan Fault to the south of the Koyna dam, and clusters C and D located adjacent to the Warna dam with both oriented towards NW-SE (Fig. 3). In the years following the impoundment of Warna reservoir, enhanced seismic activity was observed in the clusters B, C and D; however the cluster A witnessed relatively lower activity. Gupta et al. (2011) analysed 29 earthquakes in the magnitude range M 3.5–5.1 recorded by digital seismographs during the period 2005–2010. They found most of the events to be located in the vicinity of the Warna reservoir, with only a few close to the Koyna reservoir, consistent with the earlier observations. Focal depths extend up to about 10 km in cluster-A (Rai et al., 1999; Gupta et al., 2015) compared to about 8 km in the clusters B, C and D (Rai et al., 1999; Dixit et al., 2014; Gupta et al., 2015).

3.2. Characteristic features

3.2.1. Aftershock patterns

Guha et al. (1968) studied the distribution of aftershocks following the 1967 M6.3 Koyna earthquake and found them to be mostly confined along a 20 km long seismic zone extending south of the Koyna Dam. Further, they estimated foreshock and aftershock sequences associated with the main shock as shown in Fig. 4. This specific pattern of foreshocks and aftershocks for the area under the influence of Koyna reservoir was later inferred to be consistent with Mogi's Type-II model (Gupta et al., 1969). This model explains occurrence of smaller number of elastic shocks prior to the main shock and many aftershocks following the main shock; such conspicuous pattern is observed when the breaking material has heterogeneous structure and the applied stress is not uniform (Mogi, 1963).

Tandon and Chaudhury (1968) found that the Koyna main shock was followed by a large number of aftershocks with some of them exceeding magnitude M5.5 that were felt up to Pune and Bombay. Also, they reported a peculiar observation of about 200 aftershocks occurring within short time duration of 24 h after the main shock, which were recorded at Poona Observatory located at a distance of about 130 km from the source. Later, Gupta and Rastogi (1971) attributed the Koyna earthquakes to a complex multiple seismic event and corroborated the aftershock pattern as observed by Tandon and Chaudhury (1968).

3.2.2. b-Value estimation

After the occurrence of the 1967 Koyna main shock, b-value for the Koyna region was estimated to be 1.2 (Gupta et al., 1972a). This value

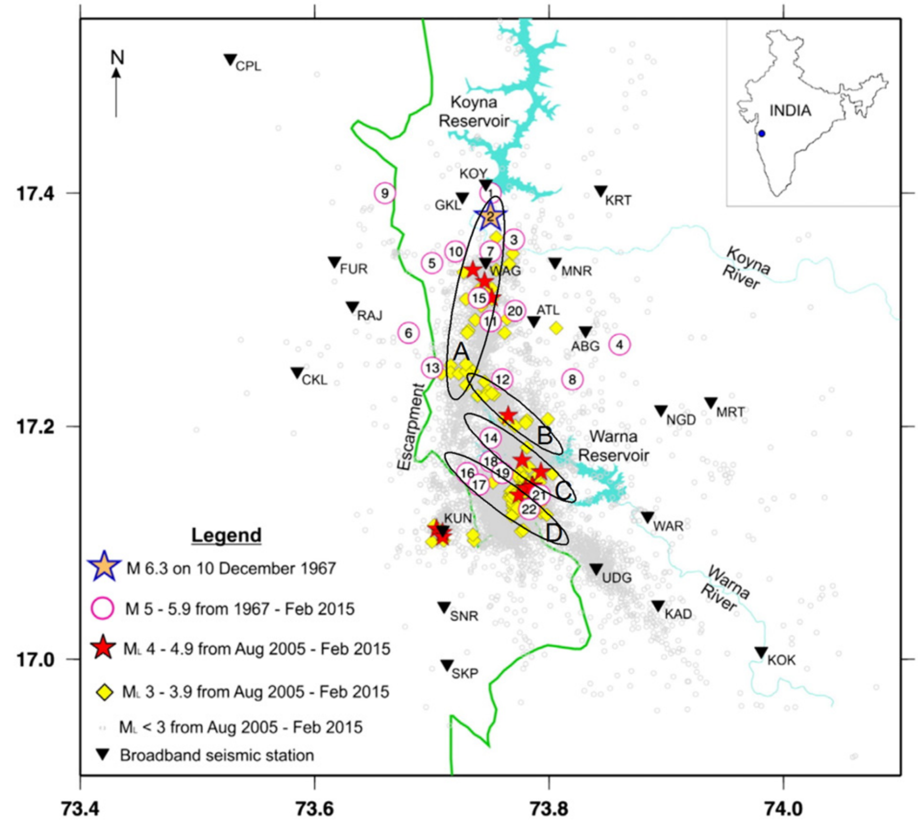

Fig. 3. Seismicity showing four clusters in the Koyna-Warna region; Cluster A (near Koyna dam), Cluster B (south of Koyna dam), Cluster C and Cluster D (Close to Warna dam) (Modified after Rao and Shashidhar, 2016).

has been found to be significantly higher than the average b-value of 0.47 for the peninsular India (Gupta, 1992). Accordingly it was postulated that reservoir triggered earthquakes show typical characteristic of higher b-value in comparison to earthquakes of tectonic origin. In contrary, Sunmonu and Dimri (2000) estimated b-value for the Koyna region in the range 0.48–0.83, which is unequivocally higher than the average b-value of peninsular India but certainly not as high to characterize reservoir triggered seismicity. Recent studies, however, have supported the view of a higher b-value, i.e. >1.0 in the case of triggered seismicity in the Koyna–Warna region (Mandal et al., 2005; Chandrani et al., 2008; Mallika et al., 2012; Smirnov et al., 2014). Consequently, the high b-value for a region showing reservoir triggered seismicity has been accepted as characteristic feature.

Mandal et al. (2005) obtained b-value of 0.97 ± 0.5 for the Koyna-Warna seismic zone and attributed the higher b-value in the region to stress release mainly through smaller magnitude earthquakes and scattered seismicity. Chandrani et al. (2008) estimated b-value for the region as 1.12 from analysis of earthquakes of magnitude $2.5 \leq M \leq 5.5$ during the period 1996–2005, using maximum likelihood approach based on self-similarity of earthquakes. The higher b-value has been attributed to the enhanced seismic activity in the region following impoundment of the Warna reservoir. Later, Mallika et al. (2012) carried out similar analysis for the subsequent time window (2005–2010) and found higher b-values, 1.15 ± 0.04, for the Koyna-Warna region, corroborating the hypothesis of higher b-values in the environment of reservoir triggered earthquakes.

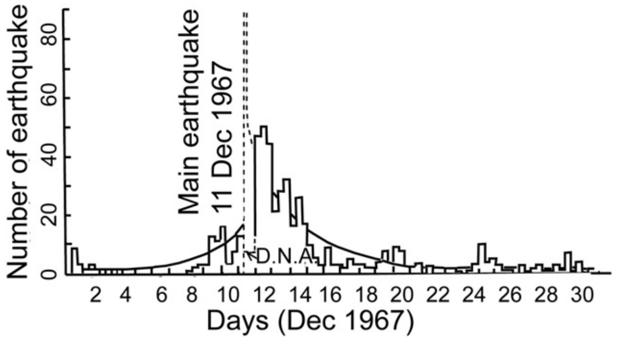

Fig. 4. Temporal distribution of foreshocks and aftershocks for the Koyna earthquake of December 10, 1967. D.N.A.: Data not available (after Guha et al., 1968).

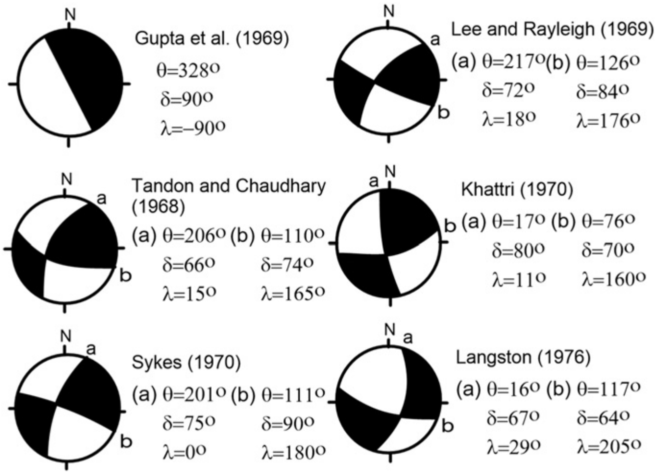

Fig. 5. Focal mechanisms of December 10, 1967 Koyna earthquake M 6.3 obtained by previous researchers (after Langston, 1976).

3.3. Fault plane solutions

Many researchers have attempted to comprehend the source mechanism of the 1967 M6.3 Koyna earthquake (Fig. 5). Tandon and Chaudhury (1968) estimated the fault plane solution using more than 70 records of P waves and suggested almost entirely sinistral strike-slip fault plane striking N 26° E and dipping at an angle of 66° in N296°E direction. Gupta et al. (1972b) later revised their earlier estimates (Gupta et al., 1969) considering the Koyna earthquakes to be an extremely complex multiple event with rupture propagating from south to north, corroborating the finding of Tandon and Chaudhury (1968). Many other researchers (e.g., Lee and Raleigh, 1969; Sykes, 1970; Singh et al., 1975) subsequently carried out focal mechanism study for the same earthquake using data from larger number of stations and with improved computing techniques. The studies led to the general conclusion about left lateral strike slip nature of the Koyna fault with strike direction in the range N10–26°E and dipping westward with dip range 66°–75°. However, Langston (1976) used a generalized inversion technique on WWSSN long period P and SH waveforms and reported left lateral oblique slip fault dipping towards east.

Rastogi and Talwani (1980) analysed data obtained from 5 to 11 seismographs in the Koyna-Warna region during 1967–1973 to generate composite fault plane solution of large earthquakes ($M > 4$). They suggested left lateral strike-slip faulting along a NNE fault close to the Koyna reservoir and normal faulting in the NW direction located about 20 km south of the Koyna reservoir. In another study, earthquakes in the magnitude range M3.7–5.4 that occurred close to the Warna reservoir during 1993–94 were also found associated with normal faults (Talwani, 1997b). Srinagesh and Sarma (2005) later relocated micro-earthquakes that occurred in the Koyna-Warna region during April 1996 to December 1997. They found a strike-slip focal mechanism for the Koyna fault consistent with the findings of earlier workers and normal faulting for the earthquakes located near Warna reservoir, which has been corroborated by the study of Shashidhar et al. (2011).

Synthesis of available information indicates that the Koyna-Warna seismic zone is primarily bounded between two major faults (i) a NNE-SSW trending, nearly vertical fault with left lateral strike slip movement extending from close to Koyna dam to about 30 km south of it, and (ii) a NW-SE trending, moderate dipping fault to the south of the Warna reservoir. Monitoring of earthquakes using a local network of surface and borehole seismometers would improve the accuracy of focal parameters, which may resolve the dip orientations of the inferred faults.

3.4. Source parameter estimation

A study of source parameters for the 1967 M6.3 Koyna earthquake was carried out using Rayleigh wave spectral amplitudes (Singh et al., 1975). Gupta and Rambabu (1993) have estimated the source area, seismic moment and stress drop to be 252 km^2, 8.2×10^{18} Nm and 0.6–2.0 MPa respectively for the Koyna area, using strong motion accelerogram recorded at the foundation gallery of the dam. Mandal et al. (1998) analysed S-wave spectra of 193 selected earthquakes (M1.5–4.7) during October 1994 to June 1995 and estimated larger stress drop, ≥2 MPa for earthquakes $M \geq 3$. They delineated two different depth zones, 0–1 km (shallower) and 5–13 km (deeper), showing high seismic energy release and large stress drops. The large stress drop at the shallower zone was attributed to incremental stress in subhydrostatic conditions due to impoundment of Koyna and Warna reservoirs. However, at the deeper horizon, large stress drops were attributed to the incremental stress of suprahydrostatic nature due to pore fluid pressure diffusion from the reservoirs and the local tectonic settings.

A significant decrease in stress drop prior to the main shock for the Koyna-Warna region has been postulated as an important parameter for precursory studies (Jain et al., 2004). In a recent study to establish empirical relations among various source parameters, spectral analysis of 38 local earthquakes of magnitude range M3.5–5.2 recorded during the period March 2005 to April 2012 have revealed a wide range of stress drops, 3–26 MPa, for the region (Yadav et al., 2013). Increase in stress drop with focal depth has been found as a characteristic feature for the region.

3.5. Crustal velocity structure

The Koyna–Warna region located in the western part of the Deccan Volcanic Province, is covered by a thick pile of ~65 my old flood basalts. As a result, the subsurface structure is largely unknown. With a view to understand earthquake processes and mechanisms responsible for continued seismicity and further to ascertain any causative relation with variations in thickness of Deccan basalt, a large number of studies have been carried out in the past few decades to delineate subsurface crustal structure in the region (Kaila et al., 1979; Negi et al., 1983; Tandon, 1973; Nayak et al., 2006; Patro and Sarma, 2007). The first systematic study to image the crustal velocity structure was the deep seismic sounding survey carried out along two profiles during 1975–1976 (Fig. 6) (Kaila et al., 1979). The first profile (Koyna-I) covering a distance of 220 km from Guhagar on the west coast to Chorochi towards east, and passing through Chiplun, Koyna and Karad was chosen with the objective to find out detailed crustal structure in the Koyna area. The second profile (Koyna-II) starting from Kelsi village on the west coast to Loni village towards east, passing through Mahad, Bhor, Nira and Baramatand, was located about 60–70 km north of the Koyna-I profile to find the alignment of the fault that was considered responsible for the Koyna main earthquake of 10 December 1967. Analysis of seismic data along these two profiles provided the first crustal velocity model for the Koyna region, which has been extensively used by subsequent workers. The study also inferred a deep-seated, east-dipping hidden fault separating two crustal blocks on either side of the fault. A thin layer of 1.2 km thickness corresponding to Deccan trap was also ascertained on top of the crustal blocks (Kailasam et al., 1969; Tandon, 1973; Bhattacharya and Srivastava, 1973). It is to be noted that the east dipping Koyna fault as inferred from the seismic study corroborates the finding of Langston (1976) but contradicts the views of several other researchers suggesting a westward dipping Koyna fault (Tandon and Chaudhury, 1968; Lee and Raleigh, 1969; Sykes, 1970; Singh et al., 1975).

In addition to the active source mapping, the passive seismic data acquired in the region through the years have been processed to further refine the velocity structures beneath the Koyna-Warna region (Dube et al., 1973; Gupta et al., 1980; Rastogi and Talwani, 1980; Bhattacharya, 1981; Langston, 1981; Srivastava et al., 1984; Krishna et al., 1989; Rai et al., 1999; Krishna, 2006; Shashidhar et al., 2011). Fig. 7 shows an up-to-date compilation of 1D crustal velocity models inferred from different studies. The salient results regarding the deep crustal structure of the Koyna-Warna region are summarized below:

(i) The first order Mohorovicic discontinuity occurs at 40 km depth. This discontinuity is sharp and distinctly separates the crust from the mantle, which suggest that there is no mixing of material at the transition of crust-mantle boundary and that it remained undisturbed while passing over Reunion hot spot.

(ii) The velocity models inferred from the deep seismic sounding and the passive experiments suggest 1.2 km thickness of Deccan basalt (Kailasam et al., 1969; Tandon, 1973; Bhattacharya and Srivastava, 1973). Nayak et al. (2006) independently corroborated this result by inversion of aeromagnetic data.

(iii) The velocity structures given by Dube et al. (1973), Bhattacharya (1981) and Srivastava et al. (1984) suggest a two-layer crust with distinct granitic and basaltic layers having thicknesses of 20 km and 18.7 km respectively. Further, these models suggest the presence of the Conrad discontinuity at about 20 km depth

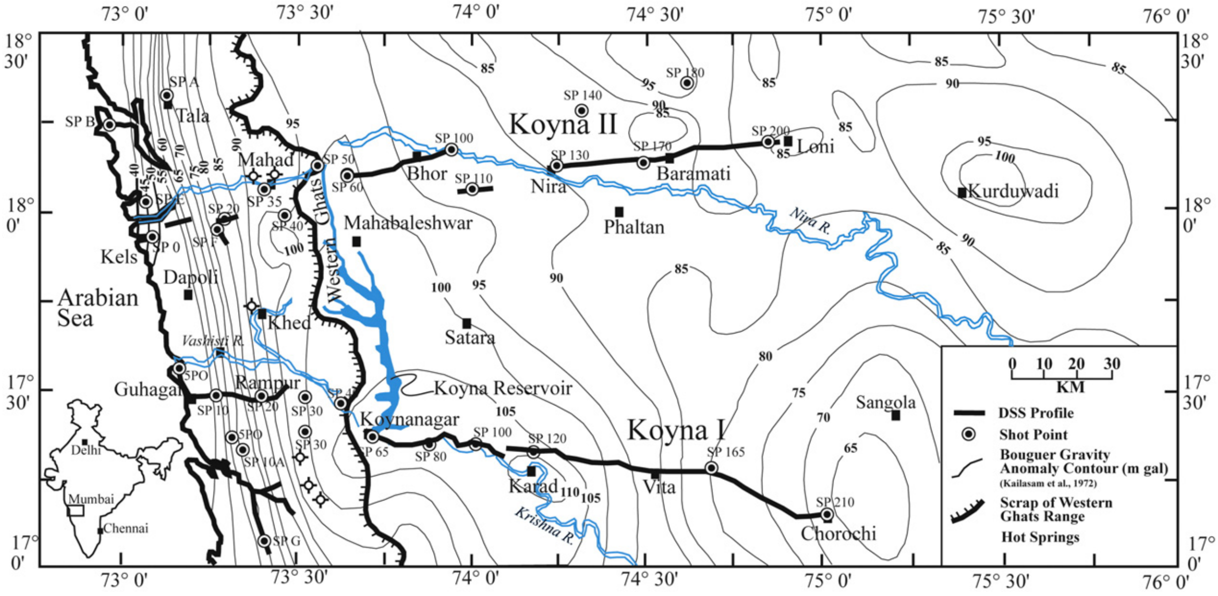

Fig. 6. Deep seismic sounding profiles (Koyna-I & Koyna-II) shown on a gravity map of the Koyna-Warna region (after Kaila et al., 1981).

in the region. However the existence of this discontinuity is not accepted globally and thus the presence of such layer in the study area remains contentious.

(iv) Krishna et al. (1989) modelled the seismic wide-angle reflection/refraction data of the Koyna-Warna region to obtain a velocity model and proposed the presence of alternating low velocity layers at depths of 6–8 km and 11–13 km. In the vicinity of Koyna reservoir, seismicity extends up to about 10 km depth (Rai et al., 1999; Gupta et al., 2015). Dixit et al. (2014) have recently carried out 3D velocity tomography for P and S waves in the area close to Warna reservoir, by deploying a seismic array during January to May 2010. The study indicates a highly complex upper 10 km of the crust. Further, the region appears to be underlain by a zone of relatively high V_p and low V_s, which extends vertically up to a depth of 8 km and laterally northward at least 15 km.

Rai et al. (1999) had inferred a crustal velocity model with rms error < 0.08 and also computed errors in location and depth to <0.5 km and <1.5 km respectively, using quarry blast data used for bauxite mining in the area. Later, Srinagesh and Sarma (2005) reduced the rms error of the analysis to 0.02 using double difference method but they could resolve the velocity model only up to 16 km depth. In a recent study, 658 earthquakes during period 2005–2010 have been analysed and a new crustal velocity model with significantly low travel time residual error 0.09 has been proposed for the Koyna-Warna region using joint inversion approach (Shashidhar et al., 2011). This model has been effectively used in locating earthquakes with minimum errors in location and focal depth of 0.5 km and 1 km respectively (Shashidhar et al., 2013). The improvement in hypocentral locations will contribute directly to study the nucleation processes preceding major earthquakes in the region.

3.6. Attenuation characteristics

The attenuation characteristics of the Koyna-Warna seismic region have been studied by various researchers to understand the anelastic absorption properties of the medium. Mandal and Rastogi (1998) analysed coda seismic waves from 30 local earthquakes having

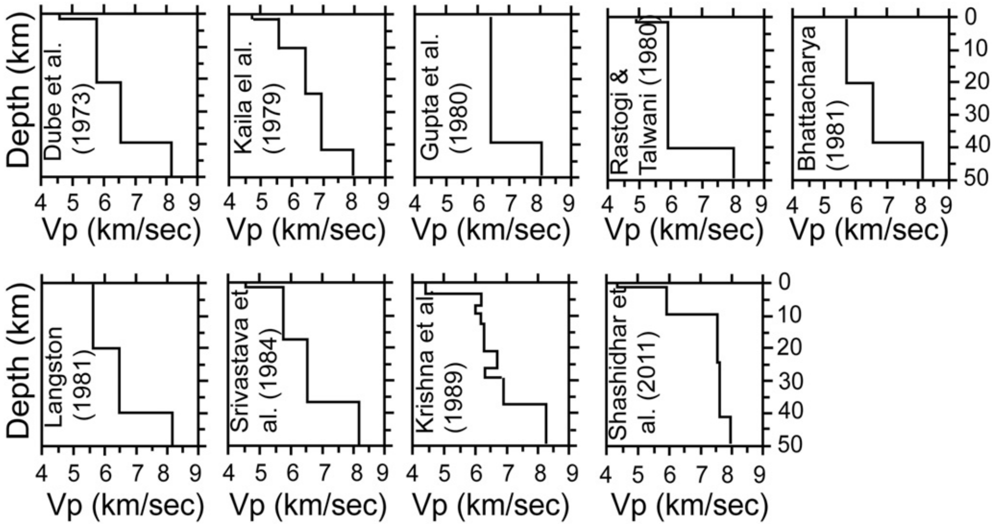

Fig. 7. Crustal P-wave velocity models for the Koyna–Warna region obtained by different workers (after Shashidhar et al., 2011).

magnitude range 1.5–3.8 and estimated a frequency dependent relation for quality factor as $Q_c = 169f^{0.77}$ that characterizes attenuation of the lithosphere around the seismic zone. The obtained Q_c values range between 169 at 1 Hz to 1565 at 18 Hz, and indicates low Q_c for a significant portion of the frequency range, thereby characterizing the region as active compared to stable regions. Low values of Q_c in lower frequency range is attributed to the energy loss due to heterogeneities in lithosphere around the seismic source zone. High Q_c values in higher frequency band is attributed to a relatively homogeneous crust at deeper levels. Gupta et al. (1998) analysed coda waves of 76 seismograms from 13 local earthquakes recorded digitally in a two-month time interval (i.e. Jul–Aug, 1996) using single backscattering approach, and estimated Q_c for the region that corroborates the earlier result suggesting increase in Q_c with increasing depth.

The attenuation properties of crust beneath the Koyna region was later studied using 164 seismograms from 37 local earthquakes, from which quality factors for P wave (Q_α), S wave (Q_β) and coda waves ($Q_{c)}$ were estimated (Sharma et al., 2007). This study reveals $Q_\beta < Q_c$ for low frequency (<4 Hz) and $Q_\beta > Q_c$ for high frequency (>4 Hz) in the region, attributable to multiple scattering effect of the medium. However, Q_β/Q_α ratio > 1 in frequency range 1.5–18 Hz suggests the presence of partially saturated fluid-filled rocks in the region (Abdel-Fattah, 2009).

4. Geophysical studies

4.1. Gravity and magnetic measurements

Regional gravity measurements were carried out using Worden gravimeter by Geological Survey of India during 1964–1970 over the entire Deccan Trap region in Peninsular India (Kailasam et al., 1972). The study reported a negative gravity anomaly of about − 105 mGal around Koyna and Karad areas, suggesting features such as subsidence and flexure. The conspicuous broad closure of − 85 mGal on the Bouger anomaly map was explained as synclinal sag formed due to westward flow of lava erupted through fissures near the coast. Krishna Brahmam and Negi (1973), however, suggested the presence of rift valleys filled with Gondwana sediments below traps. Mishra (1989) attributed the long wavelength Koyna gravity low to 3–4 km depressions in the Moho and Conrad discontinuities. Tiwari et al. (2001) further concluded isostatic compensation as main source for the Koyna gravity low, which is manifested as crustal thickening up to 40 km depth with underlying low density (3.2 g/cm^3) upper mantle. In contrast, a local quaternary upliftment of 300–400 m on either side of the Koyna river was inferred on the basis of aeromagnetic data (Agrawal et al., 2004). This study further attributes stress build-up in the region due to Quaternary upliftment, which facilitates developing weak zones in the highly porous vesicular traps. The models for local stress build-up, proposed by various studies, appear contradictory. Nevertheless, they provide important inputs for developing more realistic models when more data become available.

The thickness of the Deccan Traps in the Koyna region was estimated to be in the range 700–2200 m, using 2D harmonic transformation of aeromagnetic data (Negi et al., 1983). A subsequent study by Nayak et al. (2006) based on 2D and 3D inversion of aeromagnetic data suggested a reduced Trap thickness of about 1500 m. They also analysed gravity data of the region and found the best fit between observed and inverted anomalies corresponding to a trap thickness of 1500 m, considering a low density (2.58 g/cm^3) basaltic column overlying the higher density (2.76 g/cm^3) granite–gneissic basement (Fig. 8). However, as described in a later section, magnetotelluric measurements revealed variable trap thickness, from a few hundred meters to about 1500 m, in the region (Patro and Sarma, 2007).

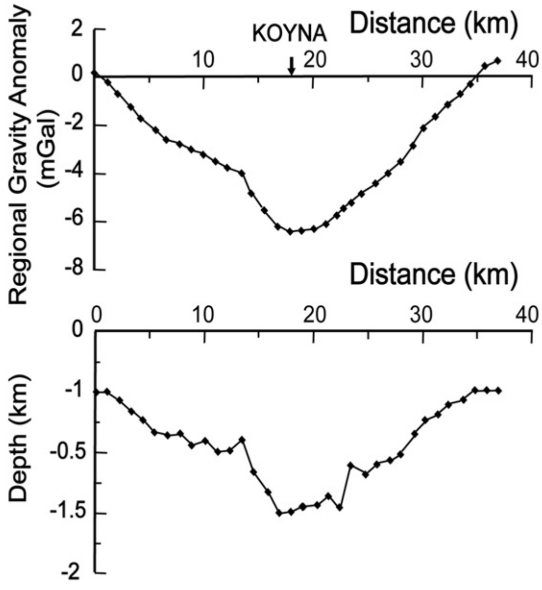

Fig. 8. Residual Bouguer gravity anomaly and thickness of Deccan basalt beneath Koyna region, computed using a density contrast of 0.18 g/cm^3 between trap rocks (2.58 g/cm3) and granitic-gneissic basement (2.76 g/cm^3). Observed anomaly: top, Fitted anomaly: bottom (after Nayak et al., 2006).

The crust-mantle structure for the Koyna-Warna region was inferred through 2-D modelling, combining the results from seismic refraction studies along two profiles with Bouguer gravity anomalies (Singh and Mall, 1998). A 3 km thick and 40 km wide high-density anomalous layer, possibly due to an igneous crustal accretion at the base of the crust, was inferred from the study. The authors further suggested that the underplated layer is an imprint of the magmatism caused by the passage of the Indian plate over the Reunion hotspot. The inferred crust/mantle structure is in good agreement with the later studies carried out using more recent gravity measurements at close spacing of 1–2 km across the Deccan Volcanic Province (Tiwari et al., 2001). The study by Tiwari et al. (2001) further delineated high-density (3.1 g/cm^3) underplated lower crust and low-density (3.2 g/cm^3) upper mantle along the west coast of India, attributable to the interaction of the Reunion hotspot with the Indian lithosphere as well as rifting along the west coast.

4.2. Magnetotelluric measurements

Magnetotelluric (MT) investigations were carried out during 1998–1999 along a profile between Guhaghar to Sangole, passing through the Koyna-Warna region (Sarma et al., 2004). The profile traversed from west to east, crossing the Konkan plains, Western Ghats and the high plateau regions. Data was analysed using a linearized

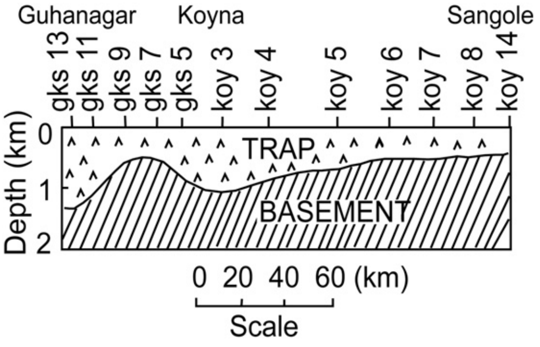

Fig. 9. Shallow geoelectric section showing the variation in thickness of Deccan traps obtained from 1D modelling along Guhaghar–Sangole profile, Western India (after Sarma et al., 2004).

inversion technique and a 1D model for the region was obtained, suggesting varying trap thickness along the profile, from about 0.5 km in the east to about 1.4 km in the west (Fig. 9). The parameters estimated from the 1D model were used for 2D inversion of MT data that resolved the overlying Deccan trap layer with resistivity 40–150 Ωm from the underlying high resistive (5000–20,000 Ωm) granite-gneiss basement with little intervening sediments. Also, layers with variable resistivity located at different depths beneath the Deccan Traps were inferred along different segments of the profile. The study revealed a very high resistive (5000–20,000 Ωm) subsurface layer up to 10–15 km depth in the western half of the profile as compared to a lower resistive layer (5000 Ωm) in the eastern half. However, in the central part of the traverse, below 15 km depth, a resistive (5000 Ωm) crustal block is flanked by relatively low resistive (500–1000 Ωm) blocks on either side suggesting a complex heterogeneous medium in the Koyna-Warna region. It is worth mentioning here that a moderately conductive vertical feature is found to extend up to 8 km depth, resembling the Koyna fault in the region along which most of the seismic activity occurs around that depth. Further, the low resistivity up to the seismogenic depth has been attributed to probable presence of fluids along the fault zone.

A detailed analysis of MT sounding data collected at 139 sites during 1998–1999 along five traverses across the DVP, including the Koyna-Warna region, was later carried out by Patro and Sarma (2007) to better constrain the thickness of the traps and the regional subsurface structure. This study showed a general trend of thinning of the traps from west to east in the DVP, in good agreement with the findings of Sarma et al. (2004). The trap thickness varies from 1.3–1.8 km in the western most part along the Nanasi-Mokhad traverse to 0.2–0.7 km in the east along the Sangole-Partur traverse, possibly attributable to the nature of pre-trappean basement topography (Fig. 10).

However, Patro and Sarma (2007) have found higher resistivity (150–200 Ωm) for thicker traps and relatively lower resistivity (50–100 Ωm) for thinner traps in the east; as contrary to the low resistivity (40–150 Ωm) determined for the traps along Guhaghar-Sangole profile (Sarma et al., 2004). Further, this study has suggested absence of subtrappean sediments along Guhaghar-Sangole profile covering the Koyna region, which is an important finding contrary to the earlier study suggesting intervening sediments (Sarma et al., 2004). Also, along other two profiles, viz. Daulatabad-Koyna and Nanasi-Mokhad, the subtrappean sediments are found absent, with an exception of small thickness of sediment traced along Sangole-Partur traverse. Nevertheless, a thick sediment column of 2 km is delineated in the northern DVP along Edlabad-Khandwa profile.

5. Triggered earthquakes and water level fluctuations in reservoirs and borewells

5.1. Seasonal variations in reservoir water level: characteristic features

A number of studies have been carried out in the past few decades to study the influence of seasonal variations in water levels of the Koyna and Warna reservoirs on the occurrence of triggered earthquakes. The Koyna region, lying in the active monsoon belt, experiences annual rainfall averaging upwards of 5000 mm. Guha et al. (1966, 1968) monitored the earthquakes with a network of 4 stations, equipped with Benioff and Wood-Anderson seismographs, close to the Koyna reservoir. They observed an increase in seismic activity corresponding to rising water levels in the reservoir, albeit with certain time lag. Eventually, thousands of tremors including more than 450 earthquakes of M ≥ 3.0 were located in the region with focal depths confined within 10 km below the surface (Guha et al., 1970). Gupta et al. (1972a) corroborated the results and attributed this conspicuous earthquake activity to a

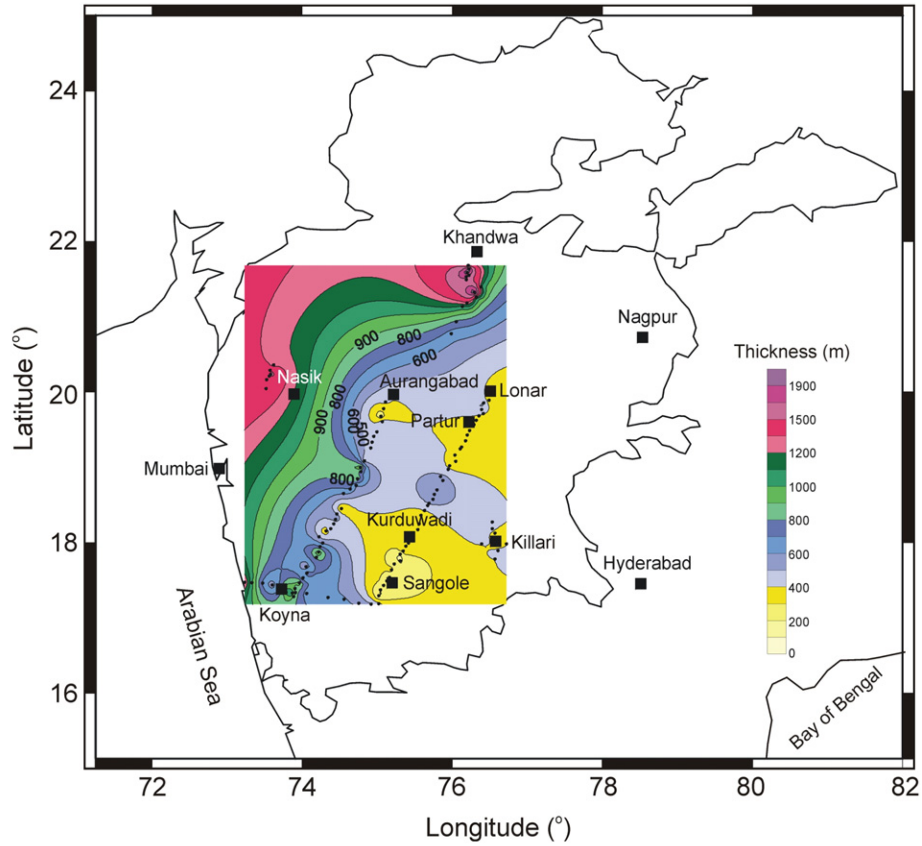

Fig. 10. Contour map of Deccan trap thickness based on the results from the MT models along different traverses in the Deccan Volcanic Province (after Patro and Sarma, 2007).

number of factors including rate of increase of water level, duration of loading, maximum level attained and duration for which the high level is maintained.

Gupta (1983) later analysed Koyna reservoir water levels for the period 1975–1980 to correlate weekly water level changes with occurrence of earthquakes and found three earthquakes of M > 5 that occurred in September 1980 following a rapid increase in the reservoir water level (loading rate > 12 m/week). A similar observation was made in September/December 1967 and again in October 1973. On the basis of those observations, Gupta (1983) proposed loading rate of the reservoir as a necessary, although not sufficient, condition for the occurrence of M ≥ 5 earthquakes in Koyna region. Further, Talwani et al. (1996) found another characteristic feature associated with a burst of seismicity in the region, i.e., the highest reservoir water level exceeding the previous year maxima (Kaiser effect).

In a recent study, Yadav et al. (2015) analysed earthquake and reservoir(s) water level data for the period January 2005–June 2012 and showed enhancement in seismicity in the region with the rise in Warna reservoir water level following monsoon rains (Fig. 11). The increasing trend in seismicity with seasonal rise in Warna reservoir water level is found similar to that characterized for Koyna reservoir, which was constructed in 1960s. Seasonal variations in both the Koyna and Warna reservoirs are found to be typically 35 m (Gupta, 1983).

5.2. Causal relationship between reservoir water level changes and triggered seismicity

A number of researchers have attempted to analyse seasonal changes in reservoir water level and their relationship with occurrence of triggered earthquakes in the region. However, a cause-and-effect relationship between the reservoir water level seasonal changes and the continued seismicity in the region and associated physical processes for the earthquakes remained largely unexplored until the year 2000. Gupta (2001) plotted monthly number of earthquakes (M ≥ 4.0) for the period 1970 through 1999 against the Koyna reservoir monthly water level for three different years and inferred two seismically active phases during a year; one in the month of September following the rapid increase in water level during July due to monsoon rain and other in the month of February during the post-monsoon unloading of the reservoir.

Pandey and Chadha (2003), for the first time, analysed the effect of Koyna and Warna monthly reservoir water level changes on the mean monthly strain factors (Lee and Wolf, 1998) using statistical correlation approach for the earthquakes of magnitude M ≥ 3.0 in the Koyna-Warna region. Four representative time windows covering the period 1963–1999, each window spanning 5–7 years, were chosen for the analysis. The selection of the windows was based on the following considerations: i) First time window, 1963–1967, covering the period since the impoundment of the Koyna reservoir until the Koyna main shock of 10 December 1967 ii) Second and third time windows, 1968–1973 and 1982–1987, covering the period after the 1967 Koyna main shock and before the impoundment of Warna reservoir and iii) Fourth time window, 1993–1999, representing the period following the impoundment of Warna reservoir. This study clearly revealed two-stages hidden periodicities in the time series of seismic energy release coinciding with peaks of annual filling and draining cycle of reservoirs, with one month delay, until 1996 beyond which the systematic pattern was not seen (Fig. 12). The time delay in seismic energy release following the seasonal changes in reservoir water levels is attributed to the diffusion of water from reservoir into the surrounding unsaturated medium through existing fault and fractures, which creates pore pressure changes in the critically stressed medium causing triggering of earthquakes in the region. After 1996, there is a distinct change in the nature of seismic energy release where it is mostly associated with the lower reservoir levels in the Warna dam. This observation is corroborated by Telesca (2010), who carried out correlation study for the subsequent period January 1, 2001 to June 28, 2004 in the region and suggested enhanced reservoir-induced seismic activity mainly during the drawdown phase of the reservoir.

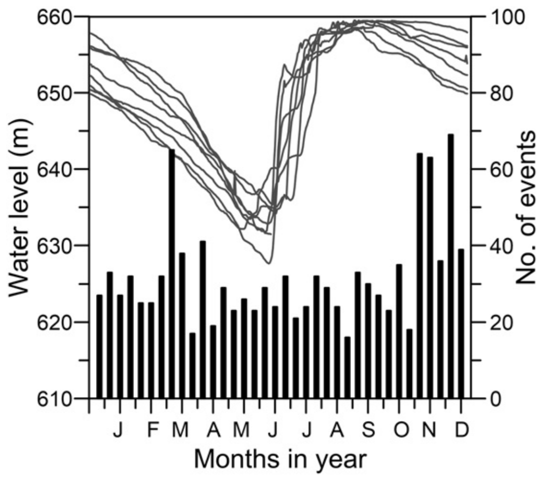

Fig. 11. Plot showing enhancement in seismicity vis-à-vis rise in reservoir water level following monsoon rains (after Yadav et al., 2015).

Yadav et al. (2015) have extended the correlation analysis between seismicity (M > 1.8) and water levels of reservoirs in the region for the period January 2005 to June 2012 (Fig. 13a). Three zones were identified based on spatial distribution of seismicity and pattern, out of which the zone near Warna reservoir showed annual periodicity in the occurrence of earthquakes that suggests a moderate correlation with the Warna reservoir water level fluctuations. For the same zone, a singular spectral analysis was performed to reconstruct the first four components representing the highest Eigen value with most of the variance in the series. The first four reconstructed components and their power spectra for the water level and earthquake time series are shown in Fig. 13b. Power spectra of the first and second reconstructed components (v and vi) show annual periodicity in both the reservoir water level and seismicity series; however the third and fourth reconstructed components (vii and viii) show half-yearly cycles in the water level series and harmonics between yearly to half-yearly cycles in the seismicity series. Further, a cascade effect in the Koyna–Warna region was also suggested due to unknown processes independent of reservoir loading.

Results from these studies clearly indicate the complex nature of causative factor(s) responsible for on-going seismicity in the region in last two decades; particularly the period 3 years after the impoundment of Warna reservoir in 1993. Nevertheless, the findings from earlier studies may provide required inputs to develop suitable model that would explain the mechanism and process for the seismicity in the region in recent decades.

5.3. Borewell water level changes and triggered earthquakes

In-situ pore pressure monitoring in borewells was started in and around the Koyna-Warna seismic zone to investigate the possible pore pressure fluctuations associated with reservoir triggered earthquakes (Gupta et al., 2000). During the period 1995–1998, for the first time in India, a state-of-the-art 21 borewell network was established to carry out the study. Borewells ranging in depth between 90 m and 250 m were drilled in Deccan basalt at strategic locations covering the seismically active zone. These wells were installed with highly sensitive battery powered pressure transducers with resolution of 1 mm for continuous monitoring of water level fluctuations at 15 min sampling rate (Pandey, 2006). Borewell water levels may change in response to deformation of connected aquifers because of seismic waves (Cooper

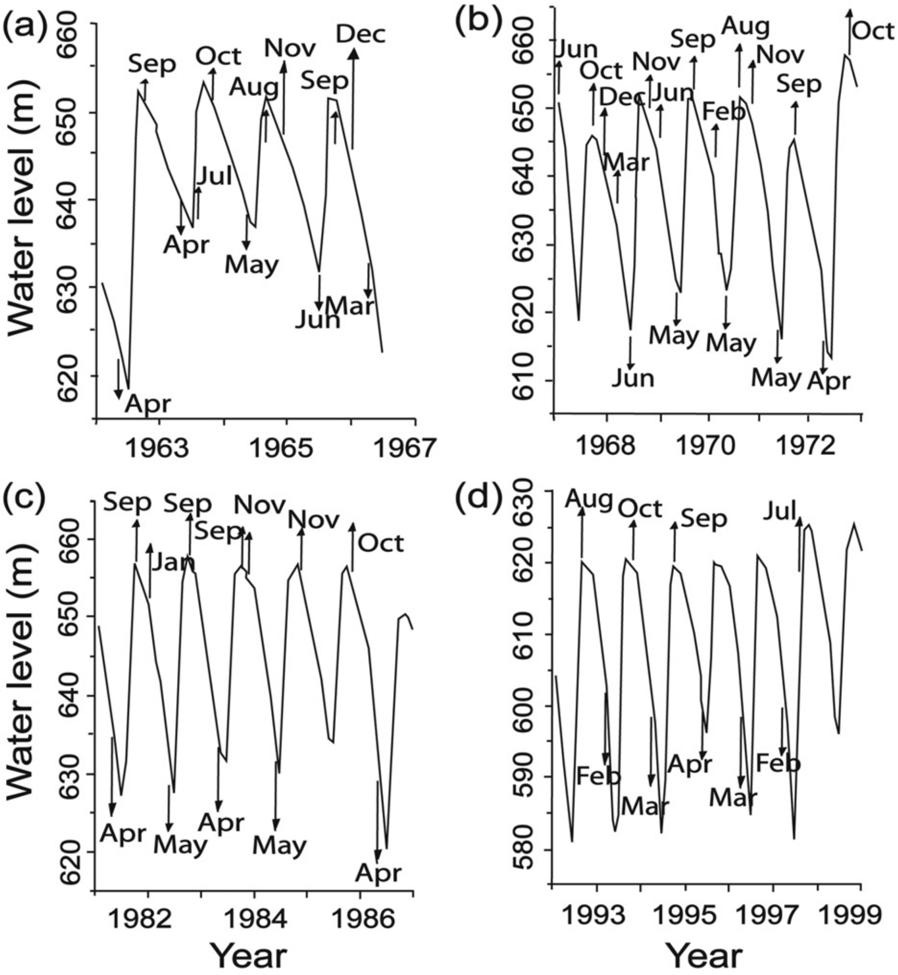

Fig. 12. Plot showing two stages of energy release shown by arrows on the reservoir water level cycle during the periods: (a) January 1963 to June 1967 (b) January 1968 to December 1973 (c) January 1982 to December 1987 (d) January 1993 to December 1999 (after Pandey and Chadha, 2003).

et al., 1965 and Liu et al., 1989), fault creep (Wesson, 1981 and Roeloffs, 1998), tidal strain (Bredehoeft, 1967; Van der Kamp and Gale, 1983) or atmospheric loading (Rojstaczer, 1988). A number of borewells in the Koyna-Warna region revealed signature of tidal signals with varying degrees of sensitivity ranging from 0.06 to 4.15 mm/nanostrain (Janssen, 1998); such wells tapped into confined and fully water-saturated aquifers. Confined aquifers thus appear to be sensitive to small-scale perturbations to rock volume strain caused by redistribution of stress during earthquake cycles, which facilitate the detection of weak pore pressure anomalies due to subsurface crustal stress changes. However, these weak pore pressure anomalies are often masked by tidal fluctuations, atmospheric pressure changes and rainfall. While the effect of the rainfall can be seen visually and correlated, the effects of tides and atmospheric pressure must be filtered out in order to identify anomalous pre-, co- and post-seismic well water level changes in response to the crustal volume strain redistribution (Pandey, 2006).

5.3.1. Co- and pre-seismic well water level changes

On occurrence of an earthquake of magnitude M4.4 on 25 April 1997, step-like co-seismic water level rise of 2.5 cm and 8.8 cm were observed in two nearby borewells located within 2 km from the epicentre. Signals recorded at other sites beyond 2 km, including the nearest one located at 5.2 km distance, appeared to be unaffected by this event. Chadha et al. (2003) have analysed water level data from 19 borewells during 1996–2000 and detected the co-seismic rise or fall of several centimeters in well water level corresponding to four local earthquakes in the region, namely 25 April 1997 (M4.4), 11 February 1998 (M4.3), 6 April 2000 (M4.7) and 5 September 2000 (M5.2) earthquakes. The study showed that the hydrological anomalies in borewells primarily depend on two factors, viz. the magnitude of the earthquake and the distance from the epicentre, and that the local earthquakes of magnitude $M \geq 4.3$ are co-seismically recorded in borewells even at a distance of up to 24 km.

Analysis of six years of water level data from 19 recording wells of Koyna-Warna region during the period 1997–2002 revealed three types of anomalous well water level changes, namely (i) co- and pre-seismic changes (corresponding to 5 local earthquakes of $M > 4.0$), (ii) aseismic changes and (iii) transient changes due to distant seismic waves, e.g., co-seismic change associated with M7.9 Bhuj earthquake of 26 January 2001 (Pandey, 2006). Chadha et al. (2008) later corroborated the results by analysing the well water level data recorded up to the year 2004. Additionally, three of the 19 borewells were able to track transient changes due to the M9.3 Sumatra earthquake of 26 December 2004.

Other than the co-seismic well water level changes, anomalous hydro-chemical changes corresponding to the occurrence of earthquakes having magnitude $M > 4.5$, have also been reported for the region (Reddy et al., 2010). An effort was made to measure concentration of hydro-chemical parameters and oxygen-18 in the groundwater collected from borewells and springs in the region during the period 2005–2007. In case of the M4.9 earthquake of March 5, 2005, significant changes in chemical and isotope values (especially Cl, SO_4, F and $\delta^{18}O$) have been observed in some of the wells and

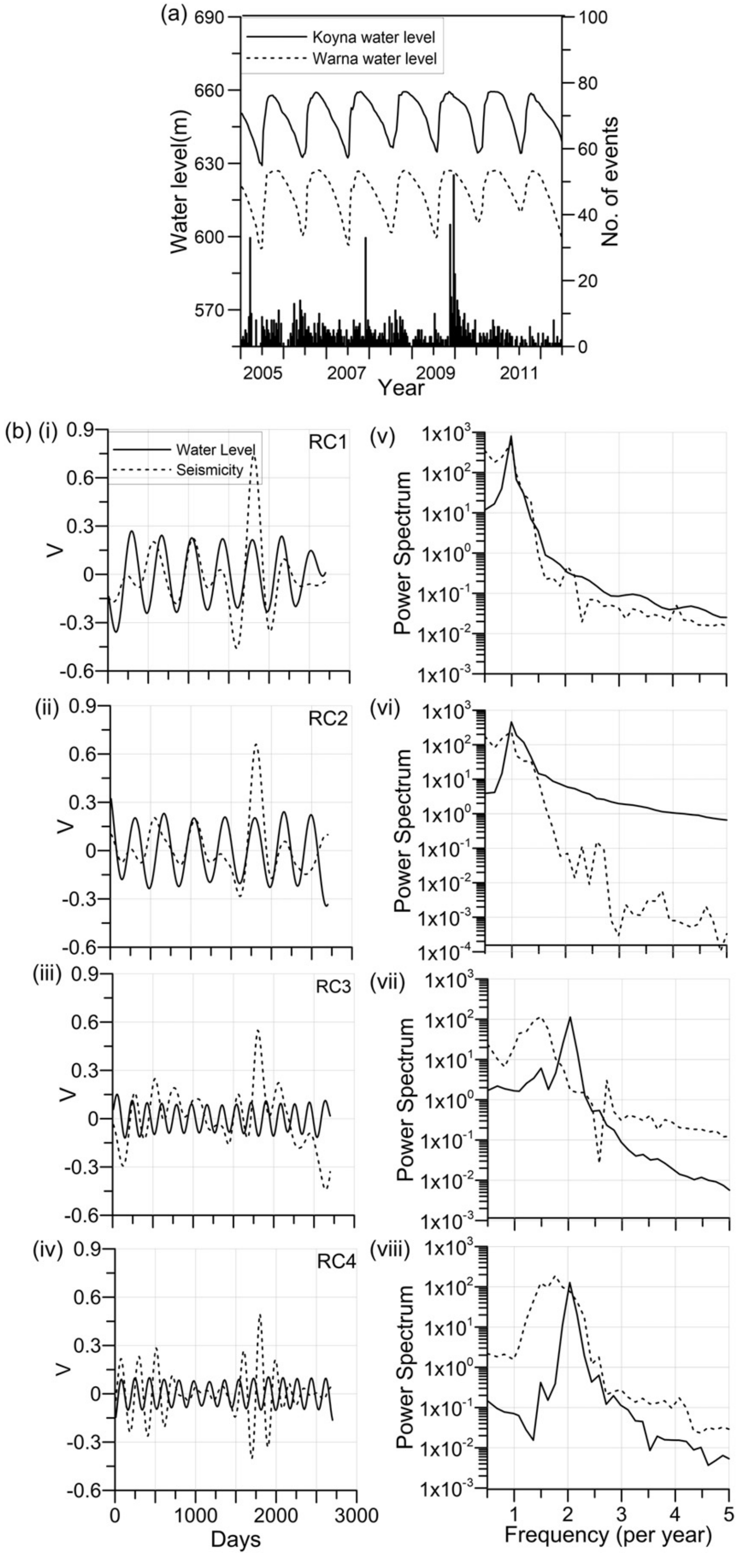

Fig. 13. a. Variation of water levels and frequency of earthquakes for the period January 2005 to June 2012 in the Koyna–Warna region (after Yadav et al., 2015). b. (i, ii, iii, iv): Reconstructed components (RC1, RC2, RC3, and RC4), and (v, vi, vii, viii): corresponding power spectra for the first four components of both the seismicity and water level time series (after Yadav et al., 2015).

the reason for such anomalous changes is attributed to the co-seismic mixing of groundwater from two different aquifers. The observations of near-real time anomalous changes in hydrological signatures vis-à-vis groundwater chemical properties in sensitive borewells for long times may help in identifying earthquake precursors for the region.

5.3.2. Co-seismic well water levels and poroelastic deformation models

5.3.2.1. Co-seismic changes vis-à-vis static volume strain

Co-seismic strain imposed by an earthquake is expected to result in a step-like change in well water level, which may be seen clearly after other effects are removed. Co-seismic fall and rise in well water level have been attributed to expansion and contraction of connected aquifers due to seismogenic redistribution of the regional strain field (Wakita, 1975). In the Koyna-Warna seismic zone, many step-like changes have been observed corresponding to several earthquakes during the period 1997–2005, and those changes have been modelled to understand the associated mechanism (Pandey, 2006; Chadha et al., 2008; Gahalaut et al., 2010).

Pandey (2006) calculated the static volume strain for a point source model for four separate cases of co-seismic step-like changes observed in several borewells in the near field of epicentres corresponding to earthquakes of magnitude $M > 4.3$. Two events (M4.4 April 25, 1997 and M5.0 March 12, 2000) are associated with left lateral strike slip faulting and the other two (M4.7 April 26, 2000 and M5.2 September 5, 2000) with normal faulting. The study has shown a good agreement between the observed co-seismic rise and fall of water level in borewells and the computed static volume strain in case of all the four events. Gahalaut et al. (2010) later corroborated this finding from analysis carried out on six events, including those of M4.3 February 11, 1998 and M4.9 March 14, 2005 and the previous four events analysed by Pandey (2006), using a poroelastic deformation model. They found that 17 cases of co-seismic water level changes observed in ten bore-wells to be consistent with the signature of simulated co-seismic volumetric strain. The studies provide confidence that well water level fluctuations reflect co-seismic volume strain changes in the near field of epicentres for the Koyna-Warna region.

5.3.2.2. Recovery of co-seismic changes and hydraulic parameters

Borewells tapping confined aquifers in the region have shown co-seismic step-like rise or fall with certain amplitude and subsequent recovery to their normal levels. This process of recovery of co-seismic changes in wells takes anywhere between a few hours to a few days depending upon the hydraulic characteristics of the aquifers in the region and also varies from one well to another in a network of borewells. Changes in well water levels owing to the pore pressure induced by steadily moving distributions of plain strain dislocation slip in fluid saturated linear elastic solid, under undrained condition, have been analysed in some studies (e.g., Wesson, 1981; Lippineott et al., 1985). Roeloft s and Rudnicki (1984) examined the effects of coupled deformation and fluid mass diffusion on pore pressure changes and found that the persistence of water level change in borewells could be related to the slip distribution, its propagation speed and hydraulic diffusivity of the ambient rock. These studies suggest that the modelling of recovery rates in bore-wells could reveal the hydraulic parameters of respective aquifers.

Pandey (2006) modelled the recovery rates associated with co-seismic water level rise in two nearby strain sensitive borewells of the Koyna-Warna region, corresponding to the M4.4 earthquake of 25 April 1997 that occurred on the NNE-SSW trending Koyna fault by left lateral strike slip motion, using the plain strain dislocation approach of Rudnicki et al. (1993). Both the borewells, namely Govare and Taloshi are located in close proximity of the causative fault at perpendicular distances 1708 m and 1836 m respectively. Various hydraulic parameters of the medium have been estimated, namely Skempton's coefficients 0.14 and 0.59, hydraulic diffusivity, 1.5 m^2/s and 14 m^2/s and storativity of the order of 10^{-5} and 10^{-6} for the respective borewells. Talwani et al. (2007) estimated hydraulic diffusivity in the range 0.1 m^2/s to 10 m^2/s and seismogenic permeability in the range $5 \cdot 10^{-16}$ to $5 \cdot 10^{-14}$ m^2 for fractures associated with seismicity. Gavrilenko et al. (2010) suggest low diffusivity, 0.2 m^2/s, for the Koyna region prior to the M6.3 mainshock of 10 December 1967, which is found increased to 2.5 m^2/s after the mainshock. This significant increase in diffusivity could be attributed to enhancement in fractures and fissures owing to the mainshock. The authors have also obtained Skempton's coefficient as 0.31 that corroborates well with the results of Pandey (2006).

These studies show large variability in estimated hydraulic parameters, even between nearby sites, for the Koyna-Warna region. It is necessary to make measurements in deeper borewells, possibly reaching the hypocentral depths, in order to obtain representative hydraulic parameters.

5.4. Mechanism of earthquakes in the Koyna-Warna region: models

Talwani (1995) proposed an intersection model to explain the continued seismicity at Koyna, which contains two essential parts: (i) the intersections of two or more NW-SE trending faults with the major NNE-SSW to N-S feature, facilitating stress build-up in response to plate tectonic forces and (ii) perturbation in this stress build-up by annual loading cycle of the Koyna and Warna reservoirs through the influx of pore pressure in a fluid infiltrated medium. It was also postulated that the diffusion is the prime mechanism for the increase in pore pressure and has a time-delay with respect to the loading cycle. This enhances the seismicity in the region and the delay of 6–8 weeks is consistent with inferred permeability of the fractured rocks. Rajendran and Harish (2000) later proposed a conceptual model suggesting the Koyna fault as a mature fault that can be affected by small changes in stress (Fig. 14). It is hypothesized that the annual loading of the reservoir continues to weaken this fault and with time, the failure occurs at lower value of stress changes under high fluid pressure. Talwani (2000), however, showed that even small changes in strength may trigger large earthquakes in the Koyna-Warna region as the rocks are critically stressed and close to failure.

Pandey and Chadha (2003) carried out simulation study involving 2-D diffusion of pore fluid pressure in an inhomogeneous medium for the Koyna region using a numerical approach, to test the hypothesis that the Koyna-Warna seismicity is mainly controlled by the diffusion process. They examined the propagation and distribution of excess head, i.e., fraction of surface loading in an inhomogeneous medium, by introducing a conductive vertical fault having vertical hydraulic conductivity 2.0 m per day (Fig. 15a). They found that the conductive vertical fault facilitates the diffusion process significantly and that the excess pore pressure front, equivalent to 5–15% of the initial head, reaches up to the hypocentral depths of 6–8 km. Such small stress perturbations of the order of 0.75–2.25 bar at hypocentral depths are sufficient to cause failure on critically stressed pre-existing faults in the Koyna-Warna region. The depth distribution of earthquakes in the Koyna region, shown in Fig. 15b, is consistent with the model.

Durá-Gómez and Talwani (2010) later corroborated these models by relating the seismicity in Koyna-Warna region with the increase in pore pressure beyond the threshold values, causing slippage along the fractures and faults. Also, they attributed the increase in pore pressures at hypocentral depths along a saturated, critically stressed network of NE and NW trending faults/fractures to the reservoir level fluctuations in the region. Although several studies involving both observations and modelling have explained the continued seismicity in the Koyna-Warna region by reservoir trigger mechanisms, alternative views have been expressed by other workers suggesting that the continued seismicity is of tectonic origin and attributing the activity to the fault system geometry, orientation of the fault zones and the effective stress in the region (Gahalaut et al., 2004; Srinagesh and Sarma, 2005).

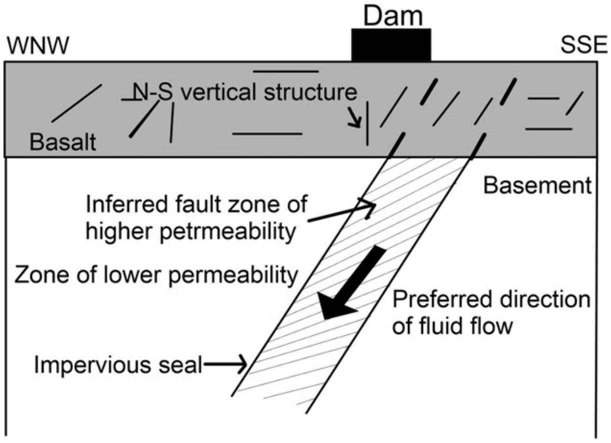

Fig. 14. Schematic diagram for geological and hydrological conditions in a conceptual model for triggered seismicity in the Koyna region (after Rajendran and Harish, 2000).

6. Medium term forecasting

Earthquakes started occurring in the Koyna-Warna region more than five decades ago, since the impoundment of the Koyna reservoir. As described in the previous sections, several studies have been undertaken on various seismological issues including understanding the earthquake mechanism and associated causative source processes. However, work relating to earthquake forecast could be initiated in the late 1990s only (Chadha et al., 1997; Rastogi and Mandal, 1999; Gupta, 2001). Studies carried out by Guha et al. (1968), Gupta et al. (1969) and Gupta et al. (1972b), based on aftershocks distribution, show that the mainshock of 10 December 1967 as well as other earthquakes with magnitude M > 4 were clearly preceded by foreshock activities of Mogi's type-II pattern. Chadha et al. (1997) later examined foreshocks of some earthquakes of M > 4 during August 1993–December 1995 and showed temporal migration in foreshocks, possibly indicating a nucleation process where the fracture initiates at shallow depths and then propagates to hypocentral depth of the main shock.

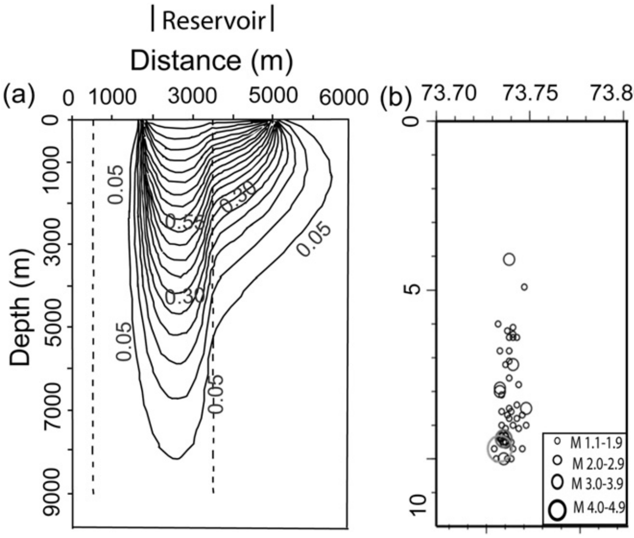

Fig. 15. (a) Contours showing excess pore pressure distribution in an inhomogeneous field with a vertical conducting fault zone, as fraction of hydrologic loading at the surface. The extent of propagation is shown as contours after 5 days of surficial loading. Numbers denote the percent change in the pore pressure of the initial loading (Pandey and Chadha, 2003). (b) Plot showing the depth section of the earthquakes (1.0 ≤ M ≤ 4.9) occurred in the vicinity of Koyna Reservoir during period 2009-April 2014 (Gupta et al., 2015).

Rastogi and Mandal (1999) analysed foreshock nucleation associated with five mainshocks having magnitude range M4.3–5.4 during 1993–1996 and found nucleation lasting for 50 to 110 h, corroborating the observation by Chadha et al. (1997). The foreshock nucleation zone is observed to grow at a rate of 0.5 to 10 cm/s until it attains a diameter of about 10 km before the occurrence of the mainshock. Further, the fracture nucleation starts at shallow depths (<1 km) and gradually deepens up to a depth between 6 and 8 km causing the mainshock. The authors also suggested a quasi-static (slow increase of foreshock frequency) and quasi-dynamic (rapid increase of foreshock frequency) nucleation process before the dynamic rupture of the mainshock, which could be considered as an immediate earthquake precursor for small to moderate sized earthquakes in the Koyna region.

Gupta (2001) later proposed to monitor the enhanced seismic activity with improved seismic network in the Koyna-Warna region, facilitating precise detection of nucleation processes such that the earthquakes of magnitude M4–5 could be forecasted with a lead time of about 2 days. Based on data collected from existing seismic stations operating in the region, Gupta et al. (2006) were able to forecast earthquakes in the region. An initiation of nucleation was detected on 12 May 2006 and accordingly an earthquake of M ~ 4 was forecasted to occur within 15 days from the day of initiation of the nucleation, with epicentre within a radius of 10 km from the location 17.1°N, 73.8°E. This forecast was validated by the occurrence of an earthquake of magnitude 4.2 on 21 May 2006 with its epicentre located at 17.171°N, 73.777°E. Following a similar approach, another nucleation was detected starting on 8 October 2007 and accordingly an earthquake of M ~ 4 was forecasted to occur in a 10 km radius from the location 17.150°N, 73.780°E, within 15 days from the day of initiation of nucleation. This forecast was also validated, albeit with a smaller earthquake of M3.4, which occurred on 14 October 2007 with its epicentre located at 17.137°N, 73.780°E. Despite a few successful attempts, Gupta et al. (2011) opined that such forecasts, even in the relatively small Koyna-Warna region, is difficult due to the complexity in earthquake generation processes. Nevertheless, they could observe that earthquakes in the zone near Warna reservoir are clearly preceded with foreshocks and nucleation (Fig. 16).

7. Scientific deep drilling

During the past few decades, various seismological and geophysical studies have been undertaken by several researchers to understand ongoing seismicity, earthquake mechanism, associated physical processes, and role of reservoirs in the region. Nevertheless, many relevant issues remain unanswered such as geometry of causative faults, earthquake physical processes, crustal velocity model representing disconformities sandwiched with low/high velocity layers, accurate focal parameters, and identification of precursors of seismological, geophysical, geochemical and geo-hydrological origin. To address such issues, a scientific deep drilling programme has been launched to facilitate measurements at hypocentral depths. Major objectives of the deep drilling programme is to study certain critical parameters such as seismicity, source mechanism, rock properties, temperature, fluid/gas, heat flow, in-situ pore pressure fluctuations, formation properties through well logging, pore fluid chemistry, and in-situ stress-strain changes in the 'near-field' of earthquakes before, during, and after their occurrence. The information acquired in this study would help in comprehending the mechanism of earthquakes and the role of reservoirs in triggering earthquakes. The proposed deep borehole observatory in the active seismic zone of the Koyna-Warna region will permit continuous monitoring of an intraplate seismic zone at depth, leading to better understanding of mechanics of faulting, physics of reservoir triggered earthquakes and would also contribute to earthquake hazard assessment and forecasting.

As a prelude to setting up a deep borehole observatory, exploratory boreholes have been drilled at 9 sites surrounding the Koyna-Warna seismic zone with an aim to obtain critical inputs to identify locations

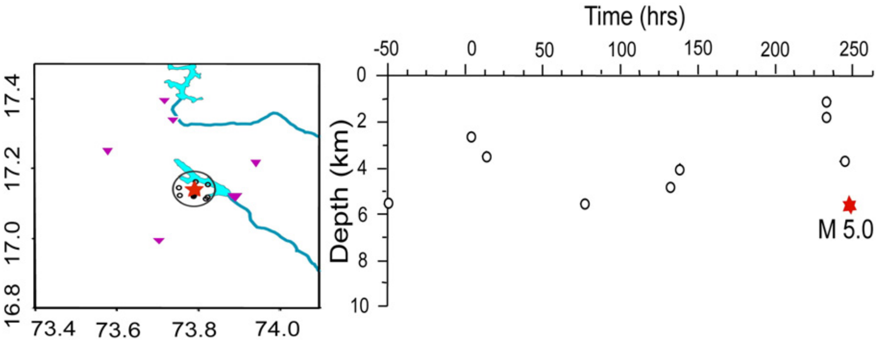

Fig. 16. Seismic activity for the period 50 h before the start of nucleation till the occurrence of M5.0 earthquake on 14 November 2009; nucleation lasted for about 250 h (after Gupta et al., 2011).

for the proposed deep boreholes. These boreholes penetrated through Deccan basalt pile to the underlying basement rock and have reached up to 1500 m depth. Six boreholes have been instrumented with seismometers. The deployment plan of exploratory boreholes is shown in Fig. 17, which also shows two sites for pilot boreholes, to be drilled up to 3 km depth for further detailed investigations. Significant information from these pilot boreholes are expected to provide required inputs for locating the sites of deep boreholes and their design up to the depths comparable to the seismogenic depth in the region.

Analyses of core samples from two boreholes, one near Koyna dam drilled up to 1522 m depth and other located south of Warna dam drilled up to 1196 m depth, revealed the following information (Roy et al., 2013; Gupta et al., 2015): (i) the thickness of the Deccan traps is 933 m in the Koyna area and 1185 m near the Warna area, (ii) absence of sediments between the thick lava pile and the underlying granite-gneiss basement, (iii) highly fractured and crushed basement granitoids at different depths attributed to the shear movements, (iv) almost flat basement topography across the Western Ghats escarpment, and (v) moderate temperature regime in the upper few kilometers of the crust with temperature estimates ranging between 130° and 150 °C at 6 km depth.

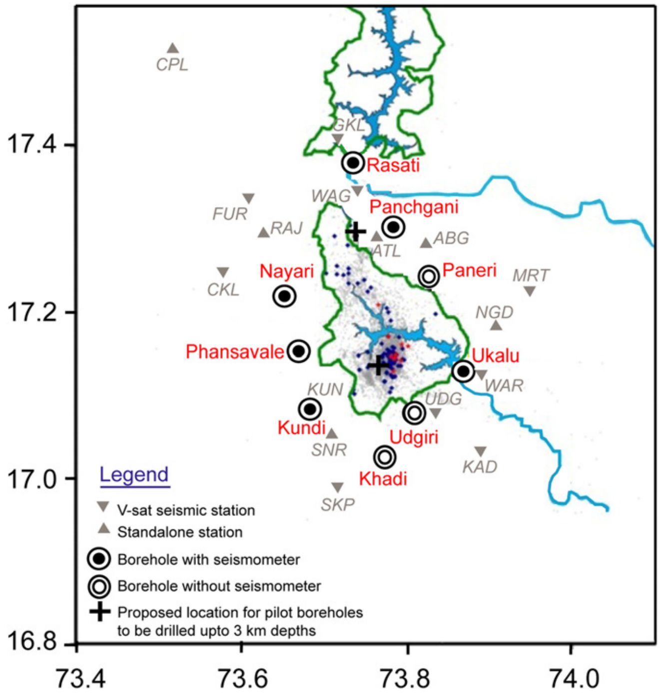

Fig. 17. Deployment plan of exploratory boreholes in the scientific deep drilling programme, shown on a seismicity map of the Koyna-Warna region. Six of the nine boreholes are instrumented with seismometers in the granitic basement underlying Deccan Traps. The network of surface seismic stations is also shown (Modified after Gupta et al., 2014).

8. Summary and conclusion

Reservoir triggered earthquakes have been occurring in the Koyna-Warna region, western India since the impoundment of the Koyna artificial water reservoir in 1962. The activity was enhanced after the impoundment of the nearby Warna reservoir started in 1985, about 35 km to the south of the Koyna reservoir. Also, a substantial southward migration of seismic activity with time was observed, although the capacity and hydraulic head of the newly impounded reservoir is significantly smaller than the Koyna reservoir. Besides the largest triggered earthquake, the 1967 M ~ 6.3 Koyna earthquake, 22 earthquakes of M ≥ 5, 200 earthquakes of M ≥ 4 and several thousand smaller earthquakes have occurred in a restricted area of 20 km × 30 km during the past five decades. The hypocentral depth distribution obtained from a dense network of seismographs operational during the past decade indicates a clear-cut distinction between the northern and southern parts of the Koyna-Warna region, with a shallower confinement of events within 8 km around Warna reservoir and a relatively deeper confinement of events up to about 10 km in the Koyna area. A suite of seismological, geophysical and hydrological studies have been carried out to understand the seismicity and hypocentral depth distribution, and their causal relationship with reservoir water level fluctuations and subsurface pore pressure changes. However, development of an earthquake model to explain the ongoing seismic activity confined within about 10 km depth and the causes for stress accentuation to the threshold levels along existing fault system(s) continues to be a challenge for the scientific community.

Studies pertaining to hypocentral depth distribution and waveform inversion based focal mechanisms for configuring fault geometries depend critically on a precise velocity model representative of the crustal properties up to seismogenic depth in the region. Various velocity models have been proposed by several workers with varied accuracy since the analog recording era. Digital monitoring capability developed in late 1990s, followed by a digital network of stations set up in the Koyna-Warna seismic region in the year 2005, have improved the sub-surface velocity models significantly. Nevertheless, a representative velocity model(s) for the Koyna-Warna seismic zone remains to be elusive. Resolution of contradicting fault geometries, particularly with regard to the dip and its direction for developing causative models, also depend on the availability of reliable velocity model. The scientific drilling in the Koyna-Warna seismic zone provide new information regarding the thickness of Deccan Traps (~1 km) and the nature of the underlying basement rock in the region. The Deccan Traps are underlain directly by granite-gneiss basement, without intervening sediments. These observations do not support the presence of low-velocity zones at the Trap-basement interface. Also, the earthquakes recorded through borehole seismometers installed in the granitic basement allow monitoring seismicity at substantially reduced noise conditions with high signal-to-noise ratio, leading to improved accuracy of hypocentral parameters. The experiment will therefore help to identify precise onset of nucleation process associated with a major earthquake, which may strengthen forecasting capability for the region.

The role of artificial water reservoir in triggering earthquakes is generally envisaged in two ways: (i) instantaneous effect due to the elastic and undrained response to the loading of reservoir, and (ii) delayed effect due to the drained response and pore pressure changes by diffusion at hypocentral depths. Impoundment of a water reservoir would exert load that would trigger seismicity at shallow levels. A few consecutive seasonal cycles of filling and emptying of reservoir could lead to the consolidation of the medium underneath and may abate the necessary load transfer down to the seismogenic depth. However, pore pressure diffusion through permeable fractures and faults would continue with the annual/seasonal cycle of reservoir water level fluctuations. This diffusion would allow the critically stressed medium to continue triggering earthquakes at seismogenic depths, which may be the case in the Koyna-Warna region. There is a general consensus that pore fluid pressure diffusion through the fractures and permeable faults could be largely responsible for causing triggered earthquakes. Modelling studies indicate that even small perturbations in pore pressure may cause failure on critically stressed faults in the Koyna-Warna region.

In-situ pore pressure changes in the subsurface have been monitored in 21 shallow borewells with depth ranging between 90 and 250 m, in and around the Koyna-Warna seismic zone to look for precursors associated with crustal deformation prior to the occurrence of earthquakes. Although significant co-seismic step-like water level changes in borewells have been observed, the pre-seismic anomalous water level changes prior to co-seismic crustal deformation are insignificant and unclear. The amplitudes of anomalous well water level fluctuations are found to depend on such hydraulic parameters as Skempton's coefficient, storativity of the aquifers, fluid viscosity and diffusivity of the medium vis-a-vis degree of confinement of the aquifers. Such parameters contribute significantly to well water level fluctuations; for example, larger Skempton's coefficient would allow higher amplitude fluctuation in well water level corresponding to even weak pre- and co-seismic crustal deformations. Two confined borewells, Taloshi and Govare, located close to the NNE-SSW trending Koyna fault but separated by about 3 km, show significant variation in Skempton's property for the medium – 0.59 for the Taloshi well and 0.14 for the Govare well. Clearly, preliminary information has been acquired through such studies but a detailed assessment of hydraulic parameters at strategic sites across the seismic zone and up to the seismogenic depths is yet to be achieved. Further concerted monitoring over a substantial period is needed to identify precursory signatures, i.e., pre-seismic anomalous signals with reasonable degree of confidence.

In conclusion, we envisage that the ongoing scientific deep drilling experiment in the Koyna-Warna region and continued monitoring of critical physical parameters in near real time would provide key inputs in terms of crustal models, fault geometry, hydraulic characteristics and precursory changes to address unresolved issues. Developing an earthquake model for the reservoir triggered seismicity in the Koyna-Warna region is a pre-requisite for forecasting earthquakes and minimizing hazards in the region.

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