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Aeromagnetic anomalies, lineaments and seismicity in Koyna-Warna Region

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ABSTRACT
Koyna area, situated near the western margin of India, is well known for its seismic activities for over three decades. In order to understand its seismotectonics, numerous geoscientific investigations in and around this region were conduced, specially after the M = 6.3 disastrous December 10, 1967 earthquake. This included a multi-level aeromagnetic survey around the Koyna-Warna area, which is covered by a suite of thick and randomly magnetized basaltic rocks. Here, we attempt to discern linear magnetic features and prominent lineament patterns from the measured magnetic fields and satellite imagery, and interpret them in the light of available seismological data.

Our study reveals a prominent 300-400 m local Quaternary upliftment over the already uplifting block of western margin. These uplifted regions, situated on either side of the Koyna river faulted/ subsided block, appear to be a block-like structure. They are bounded on either side by two faults, one originating in the NNE-SSW and the other in the NNW-SSE direction. The NNE-SSW trending fault falls in the line of Koyna reservoir. These two faults are intersected in the middle by two parallel E-W trending faults, which correspond well to the course of the Koyna River. These intersecting faults result in the formation of two triple junctions, one situated south of the Koyna dam and the other near Urul-Nisre region lying to the east of Koyna. Between the Koyna-Warna reservoirs, several intersecting lineaments are observed. A good correlation between the lineaments derived from the satellite imagery and from aeromagnetics can be seen. The intersection of the magnetic lineaments along Warna region with NNE-SSW trending fault suggests possible development of a new system of faults between Koyna and Warna reservoirs.

It is surmised that the local stress buildup is caused by Quaternary uplifting which, over a period of time, gave rise to the development of several weak zones within the less dense and highly porous vesicular traps into which the Koyna and Warna reservoir waters seem to be percolating through interconnected fault zones. In such a situation, additional stress over and above the one already being generated by localized Quaternary uplifting is likely to be developed due to pore pressure. Slow accumulation of these cumulative stresses may have culminated in generating the recurring seismic activities in the Koyna and Warna region. We infer that the subsurface tectonic features activated with the impounding of water in the reservoirs may have been largely responsible for the recurring seismicity around the Koyna – Warna region.

INTRODUCTION

The Koyna area of Maharashtra State (Fig.1) has been a focus of attention ever since an earthquake of M = 6.3 occurred there on December 10, 1967. Seismic activity has since then continued though sporadically. In the last about 30 years nearly 17 earthquakes of M ≥ 5.0 and 162 earthquakes of M > 4.0 to 5.0 (Gupta 1992; Talwani, Kumara Swamy & Sawalwade 1996; Talwani 1997; Rastogi & Mandal 1999) have rocked the area (Fig.2). Seismologists all over the globe have been debating about the possible cause for the occurrence of these earthquakes in an area, which was hitherto considered to be aseismic. Many theories about the possible origin of these earthquakes have been put forward. However, seismicity induced by the impounding of water in the Shivaji Sagar Lake remains to be the most quoted one (Rastogi et al. 1997; Gupta & Rastogi 1976; Gupta 1992; Talwani, Kumara Swamy & Sawalwade 1996; Rastogi 2001 etc.).

The Koyna earthquake zone lies near the western margin of Deccan volcanic province of 65 Ma age (Fig.1). The Flood basalts are about 1 to 2 km thick. Numerous geoscientific investigations over and around this region were carried out in the past to understand the subsurface hidden tectonic and structural features, besides the nature of pre-Deccan trap topography. This included a multi-level aeromagnetic survey carried out for the first time over and around highly randomly and heterogeneously magnetized suite of basaltic rocks by the Airborne Surveys Group of the National Geophysical Research Institute, Hyderabad. For this, using a Rubidium vapor magnetometer, 13 E-W oriented short profiles of approximately 100 km in length were recorded at 1220, 1524 and 2134 m above mean sea level. The time variation of the earth's magnetic field was monitored by a proton precession magnetometer and the position location of the aircraft was achieved with the help of accurate Survey of India toposheets on a scale of 1" = 1 mile. The objective of the multi-level survey was to study the systematic variation of the magnetic field with height over a magnetically complex zone besides providing automatic filtering of unwanted noise due to surficial basaltic rocks and enhance the signals from the basement configuration underneath (Negi & Agrawal 1983; Negi, Agrawal & Rao 1983; Agrawal & Negi, 1990). These data were hitherto quantified to determine the thickness variation of the trap rocks (Negi, Agrawal & Rao 1983; Agrawal & Negi 1990). The present study aims to examine the possible magnetic features and lineaments over a part of the surveyed area bounded between latitude 17° 05′N to 17° 35′N and longitude 73° 25′E to 74° 10′E in the light of subsequently available new seismological and satellite imagery data. A 2-D schematic model based on these features is presented which may have significant bearing on the seismicity of the Koyna area.

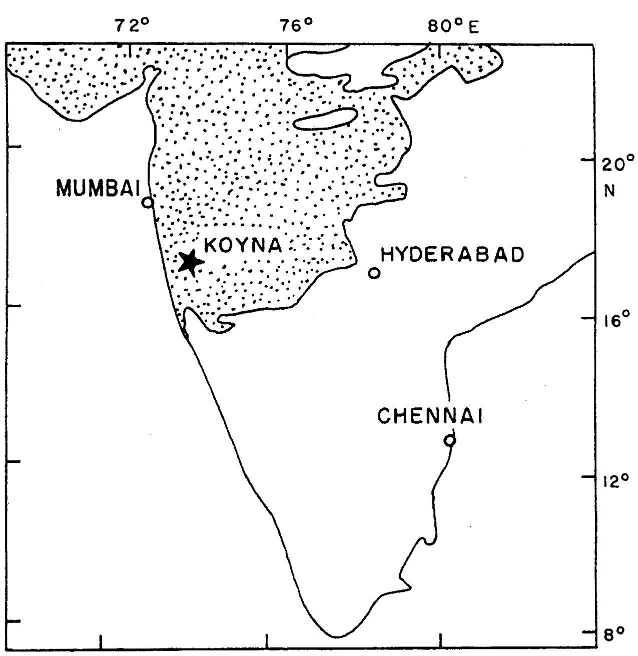

Figure 1. Location map of the Koyna region. Dotted area indicates 65 Ma old Deccan Trap region.

MULTI-LEVEL AEROMAGENTIC MAPS

Figs 2-4 present the residual aeromagnetic maps at 1220 m, 1524 m and 2134 m above mean sea level respectively which were derived from the observed absolute total-intensity field by subtracting a plane mathematical surface which were different for different flight altitudes (Negi, Agrawal & Rao 1983). It may be seen that the maps depict long wavelength character in the western half while the eastern half is characterised by high frequency short wavelength anomalies. However, the 2134 m level map presents matching wavelength characteristics on both sides although some differences do exist. The reason for such a difference in character of the anomalies in the shallow level maps in the eastern half of the area may be attributed to the shallow ground clearance between the highly randomly magnetised basaltic rocks and the aircraft. As can be seen from the regional topography (Fig.5), the topographic heights in the western half is less than 600 m which rises to more than 1000 m in the eastern half. Obviously, the sources being very close to the magnetic sensor in the eastern part produce randomly oriented high frequency magnetic centres particularly at the 1220 m level. The higher level maps however do provide some automatic filtering of the unwanted noise resulting in the longer wavelength nature of the anomalies at 1524 m and 2134 m heights. As expected, the highest altitude map (viz., 2134 m) reveals NW-SE trending broad and smooth wavelength anomalies reflecting the Precambrian basement grain in the area. Relationship between localized Quaternary uplifting and seismic activity is shown in Fig.6.

Generally it is not difficult to derive conspicuous trends or lineaments from the magnetic or gravity data as they invariably bring out well defined signatures of rock dislocations, folding or other structural forms due to appreciable susceptibility or density contrast across them. However, the Deccan flood basalts, magnetically, pose a complex problem due to factors like (i) uncertainty in the number of geomagnetic reversals during their period of extrusion, (ii) large variation in the susceptibility or magnetization values within a short space, (iii) varying thickness of the normally and reversely polarized rocks, and (iv) the unconventional situation of highly magnetized rocks sitting over a relatively less magnetized basement rocks. The aeromagnetic map particularly at 2134 m level was found useful as it reflects, by and large, the basement/tectonic grain below the area. The magnetically derived structural model has been correlated with satellite imagery derived lineaments and available seismicity.

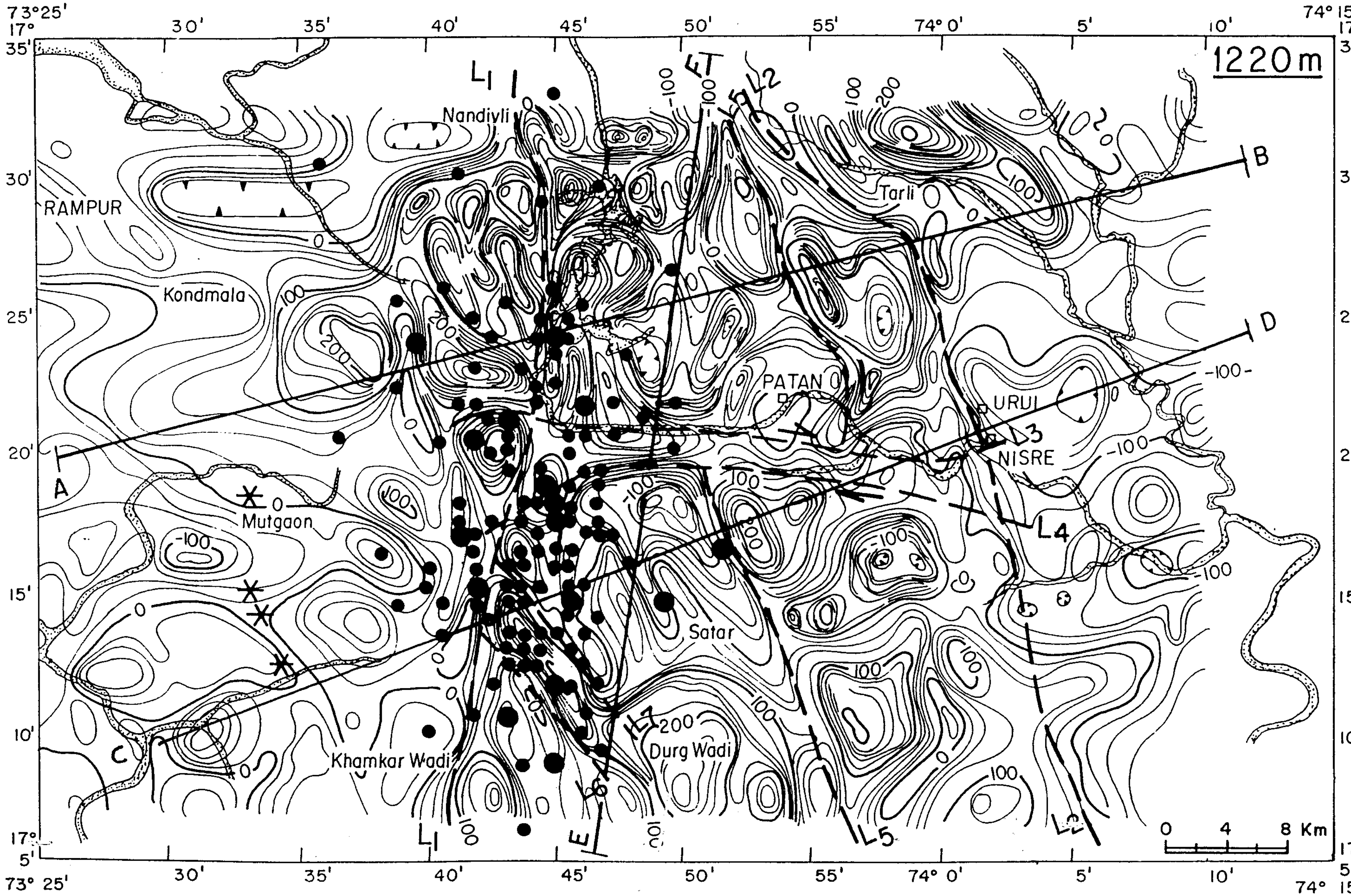

Figure 2. Residual total intensity aeromagnetic anomaly map over and around the Koyna region at a flight height of 1220 m above msl (Negi, Agrawal & Rao 1983). Solid circles indicate earthquake epicentres (bigger dots: ≥ 5.0 and smaller dots: ≥ 4.0 – 4.99). Star denotes location of thermal springs (Ravi Shanker et al. 1991). L1 to L7 indicates derived magnetic lineaments. AB, CD, EF are the locations of long profiles shown in Figs. 8-10. (Earthquake data source: Gupta, 1992; Talwani, Kumara Swamy & Sawalwade1996; Talwani, 1997; Rastogi & Mandal, 1999). Contour interval: 20 nT.

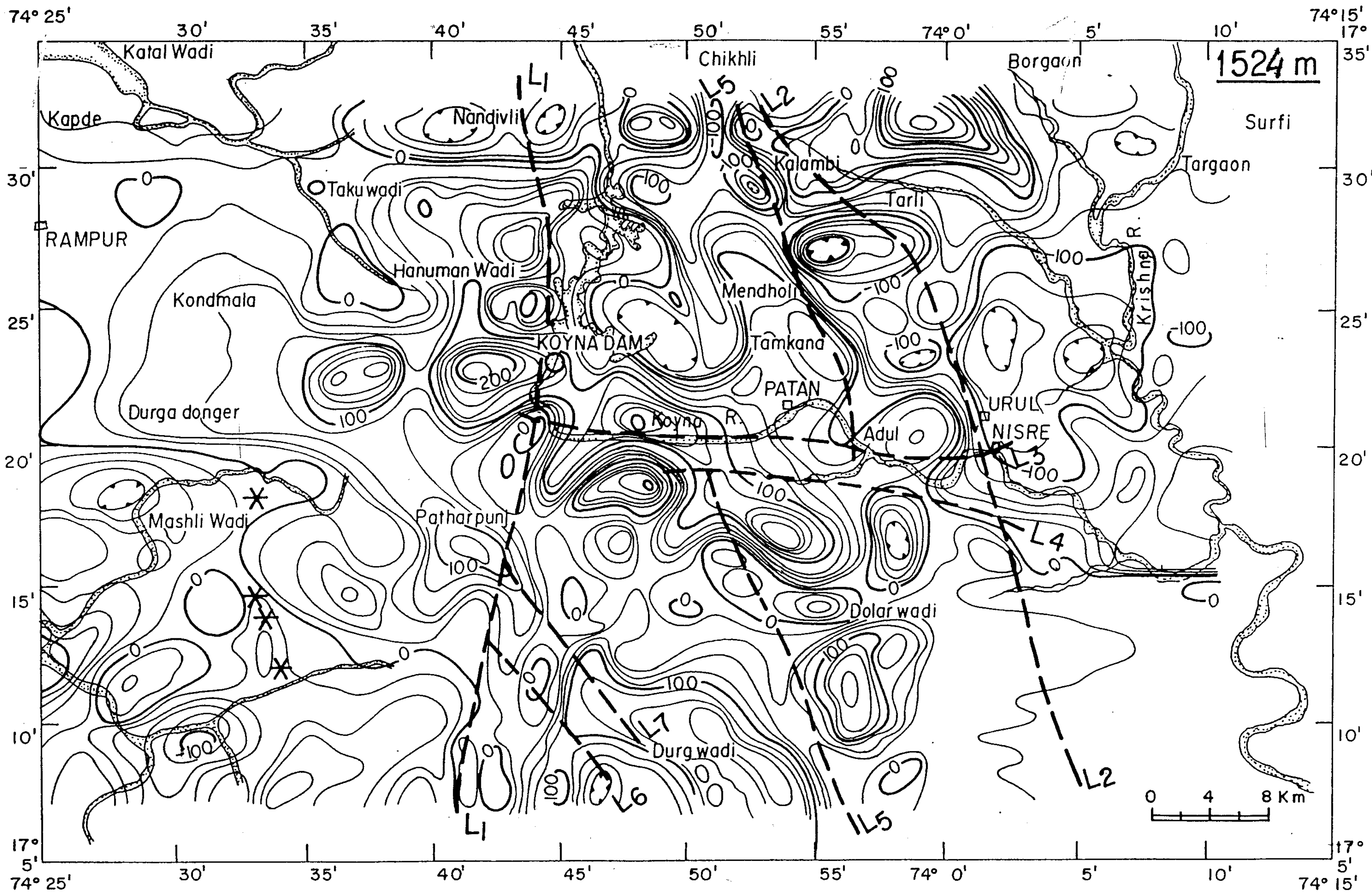

Figure 3. Residual total intensity aeromagnetic anomaly map over and around the Koyna region at a flight height of 1524 m above msl (Negi, Agrawal & Ro 1983). Star denotes location of thermal springs (Ravi Shanker et al. 1991). L1 to L7 indicates derived magnetic lineaments. Contour interval: 20 nT.

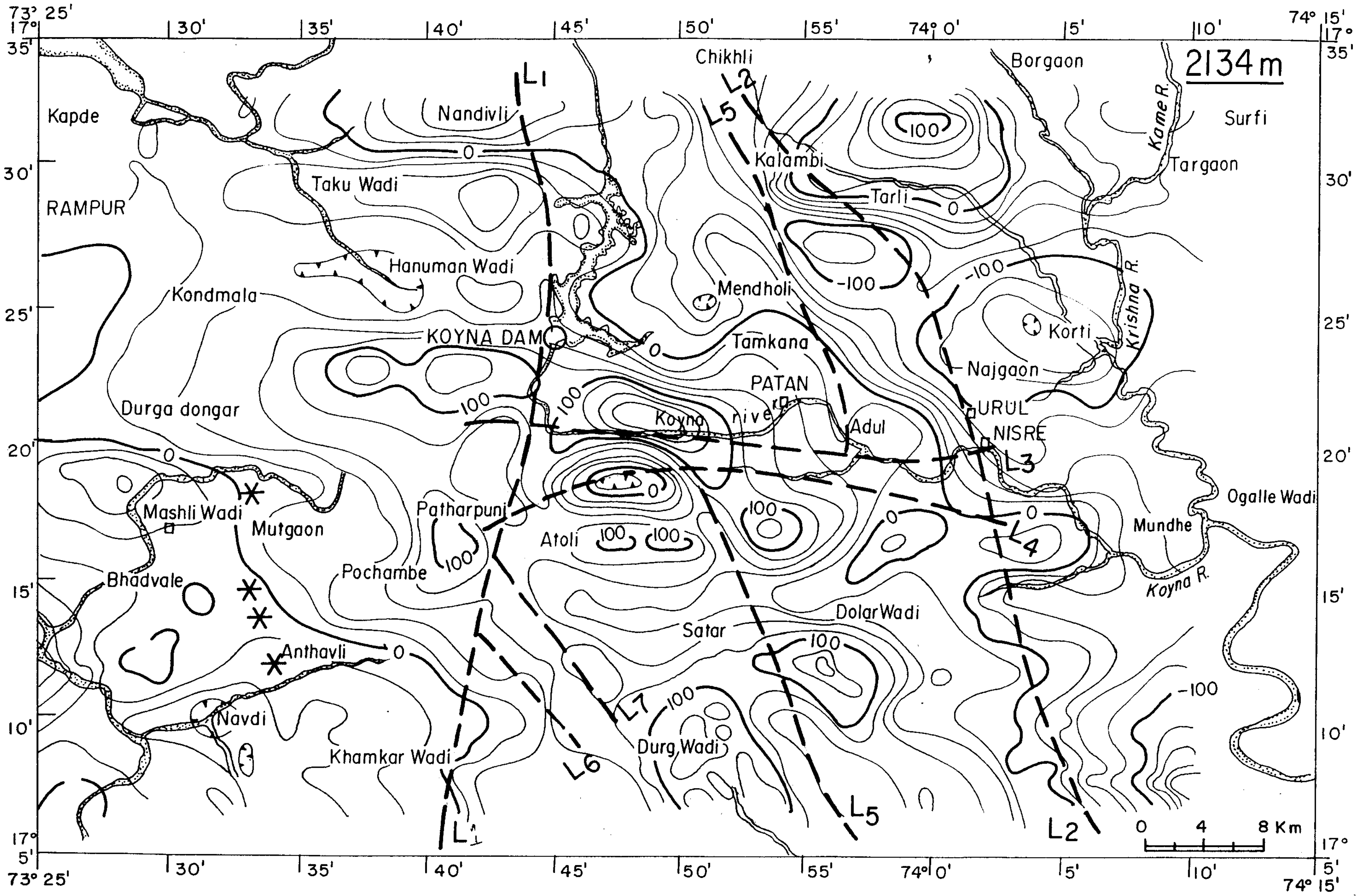

Figure 4. Residual total intensity aeromagnetic anomaly map over and around the Koyna region at a height of 2134 m above msl (Negi, Agrawal & Rao 1983). Star denotes location of thermal springs (Ravi Shanker et al. 1991). L1 to L7 indicates derived magnetic lineaments. Contour interval: 20 nT.

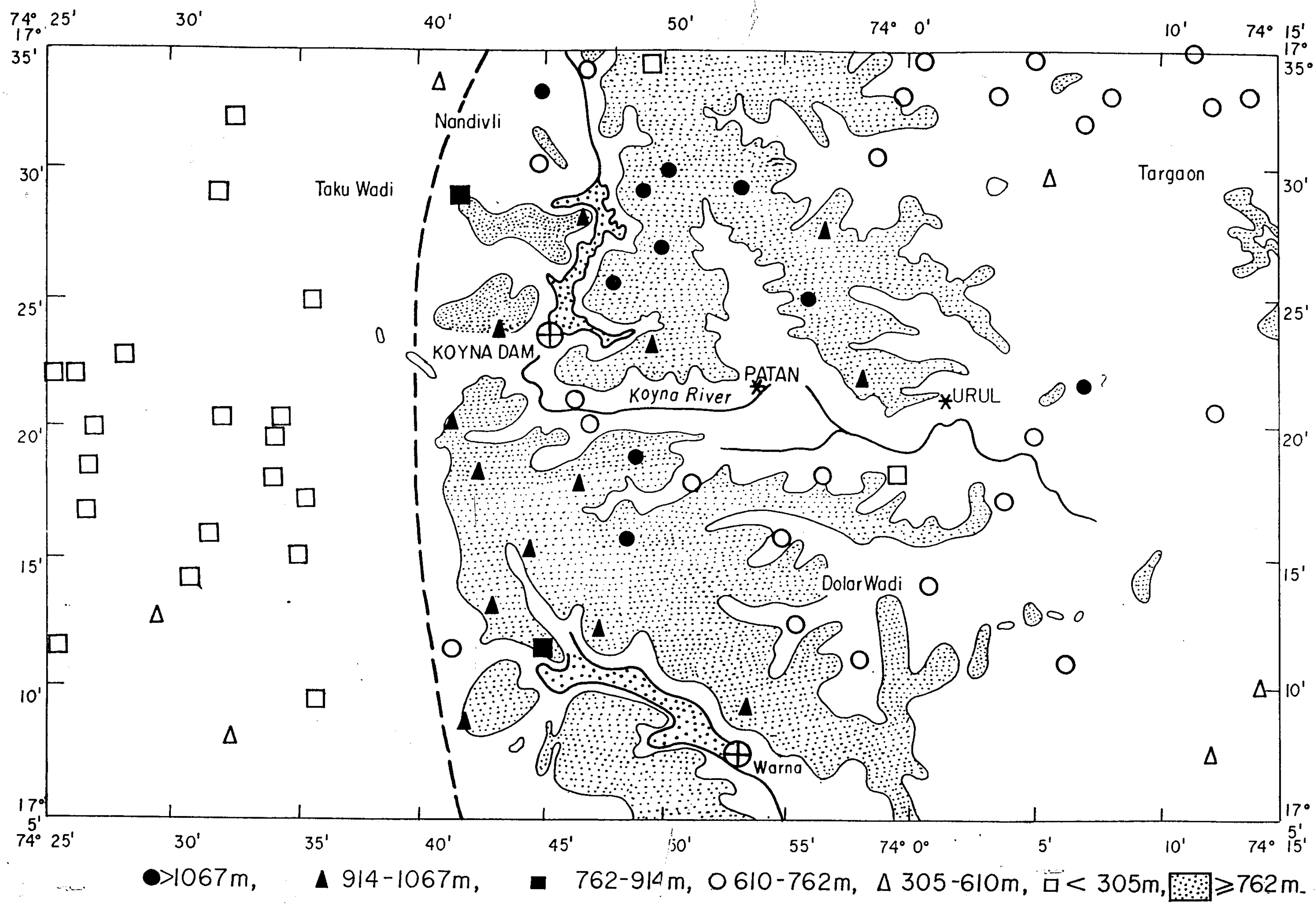

Figure 5. Topographical heights around the Koyna region. Dashed line indicates the location of the place to the east of which topography rises. Circle with plus sign indicates location of dams while star indicates presence of faulted structure.

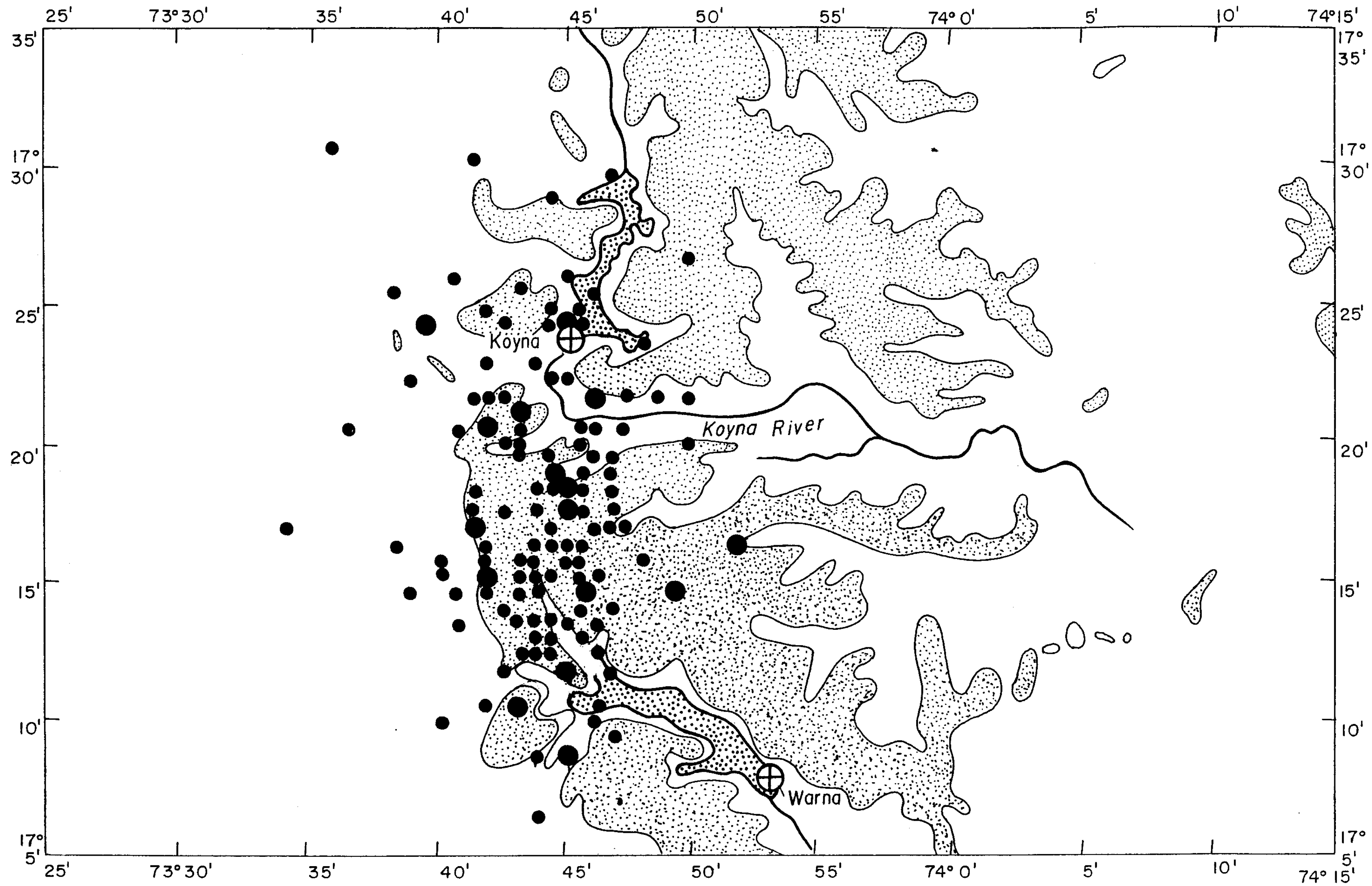

Figure 6. Distribution of earthquake epicenters (bigger dots: ≥ 5.0 and smaller dots: ≥ 4.0 – 4.99) around Koyna region. Dotted areas indicate the topographical heights ≥ 762 m (Earthquake data source, same as Fig.2). Circle with plus sign indicates location of dams.

QUALITATIVE INTERPRETATION OF AEROMAGNETIC MAPS

Figs 2-4 clearly demonstrate the nature and character of the anomalies with variation in flight altitudes. It is conspicuous from the lower level maps at 1220 m and 1524 m that longitude 73° 40'E is the line that separates the long and short wavelength contours. This is appropriate as the magnetic topography starts rising from this boundary. Some other prominent trends in each map are described below:

i) 1220 m Map:

Two long linear features, one oriented NNE-SSW (Marked L1) and the other oriented NNW-SSE (Marked L2) are conspicuously discernible on the eastern half of the map (Fig. 2). Interestingly, L1 coincides and is in line with Koyna reservoir. The high gradient contours along both the features suggest fault like structures. Running almost perpendicular and intersecting these two features are another set of E-W trending L3 and L4 lineaments, which form two triple junctions. Significantly, two more NW-SE trending lineaments, L6 and L7, paralleling each other also join the lineament L1 near Warna reservoir. Besides these, another NW-SE trending lineament L5 seems to run across a newly developing fault zone bounded by lineaments L3 and L4 but with a considerable shift. This may possibly be due to lateral movement along the EW faults, which are not unusual features in this region (Ravi Shanker 1995). The strike of this fault zone coincides with the course of the Koyna River. Most of these trends and features are masked in the magnetic anomaly maps possibly due to high random magnetization in the area.

Fig.2 also depicts the location of higher magnitude earthquakes ($M \geq 4.0$), which reveal that the majority of earthquakes are concentrated along the lineament L1 and at its intersection points with lineaments L3, L4, L6 and L7.

ii) 1524 m Map:

In comparison to Fig.2, Fig. 3 depicts automatic filtering of high frequency magnetic anomalies to the east of Longitude 73 40'E. The topography in this area being ~ 300 m higher than the lower level provides almost the matching wavelength anomalies in whole of the area. The lineament L1 seen in the 1220-m map is not prominent at this level indicating that this structure is not deep enough. This is supported by the satellite imagery map (Fig.7) where no such fault signature is traceable. However, lineament L2, L3 and L4 are mildly visible which are seen in the satellite map too. Especially the EW trend is remarkably well brought out in the satellite derived lineament map (Fig.7). Lineament L5 too is feebly seen at this level. Besides these, the basement trends are much better reflected in this map. By and large, the features seen in the 1220-m map are shown up in the 1524 also.

iii) 2134 m Map:

This map (Fig.4) shows smooth and long wavelength characteristics throughout. It appears that at this height, most of the high frequency noise due to the factors mentioned earlier, have been eliminated and the response from the basement is enhanced. At this level, the signature of lineament L1 is absent while L2 is prominently reflected indicating that the latter is deeper than the L1. The signature of L3 and L4, though feeble, is present, and L5 is not reflected. A new feature as pointed out by Talwani, Kumara Swamy & Sawalwade. (1996) is the abutting of the 60 nT contour in the NW-SE direction which is in line with the course of the Warna river. It may be noted that this feature joins the lineament L1. It appears that a new system of fault might be developing between the Koyna and Warna reservoirs.

SATELLITE-DERIVED LINEAMENTS AND SEISMICITY

Satellite derived lineament map of the area under study is presented in Fig.7, which also includes earthquake epicenters associated with Koyna seismic region. It is largely dominated by NW-SE and to some extent NNW-SSE and NE-SW Precambrian basement trends. NNW-SSE trending lineaments of considerable extent parallel the Koyna reservoir. From the lineament pattern, it can be observed that a cluster of lineaments intersect each other near the pronounced seismic zone associated with Koyna –Warna reservoirs which is a point of diversion of satellite derived lineaments. Uplifted parts around the Koyna region seems to be confined to NNW-SSE and NE-SW trending faults. These lineaments broadly correlate well with geomorphic features and with the tectonic trends delineated by multilevel aeromagnetic maps. It may be of significant interest to note that in the satellite imagery, a prominent NW-SE trending lineament passing near the Warna reservoir, change their orientation to NNW-SSE, which passes through Koyna and subparallels the Koyna reservoir. This indicates some sort of movement at depth. Aeromagnetically derived lineaments such as L1 and L2 correlate better with these changed orientations. Further, a zone of

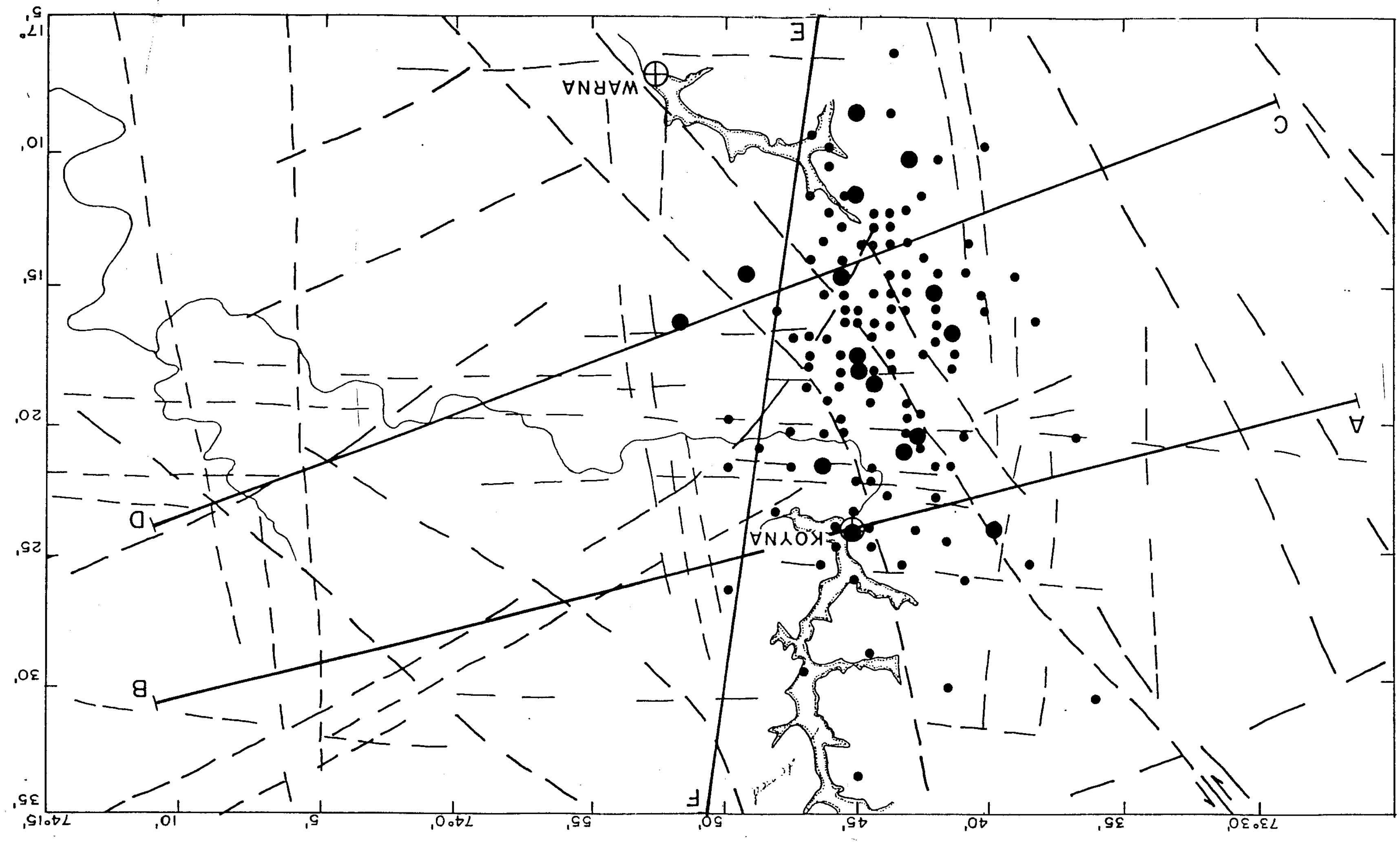

Figure 7. Satellite derived lineament map of the area under study and distribution of earthquake epicenters (bigger dots: ≥ 5.0; smaller dots: ≥ 4.0 – 4.99). AB, CD and EE are the locations of long profiles shown in Figs 8-10 (Earthquake data source, same as Fig.2).Circle with plus sign indicates location of dams.

E-W trending closely spaced lineaments seems to have been developed at the point of diversion, which coincides with the E-W trending course of the Koyna river. These E-W trends match well with aeromagnetically derived L3 and L4 lineaments. Further, the lineaments falling along the course of the Warna River also show some correlation with magnetically derived structure but with a little shift in their pattern.

MAGNETIC RESPONSE OVER LINEAMENTS AND STRUCTURAL FEATURES

In order to better understand the magnetic response over various known lineaments and topographic structural features, we present these characteristics along three profiles AB, CD and EF (Figs 8, 9 and 10). The first two profiles trend ENE-WNW while EF trends NNE-SSW. It is observed from these figures that, by and large, there is an inverse correlation between the magnetic field and topography, the cause of which is not clearly known. Such a correlation, however, is not quite apparent at some places along the profiles possibly due to a nominal shift caused by position location errors in the aeromagnetic surveys in an area of highly rugged topography. Interestingly, there is a distinct inverse correlation over the Koyna and Warna rivers, which is reflected by a prominent magnetic high, the two limbs of which signify the faulted margins. However, the NE-SW oriented Patan fault postulated earlier by Talwani, Kumara Swamy & Sawalwade (1996) is not delineated in any of the three level aeromagnetic maps. Almost the entire region lying along these profiles appears to be severely faulted as reflected by magnetic and topographic characteristics.

In order to better understand the subsurface structural configurations, we present a 2-D modeling results along the profile AB (Fig.11), The structural configuration was derived by using the inversion program developed by Radhakrishna Murthy (1998). In this simple but elegant approach, a series of juxtaposing prisms, one below each anomaly point, is assumed and their thickness is considered with respect to some undisturbed depth Z. The inversion scheme determines the thickness of the prisms above this assumed undisturbed depth Z and then calculates the depth to the top of the prism Z_t that defines the basement topography. The initial values of Z_t are equated to the mean depth and the error in magnetic anomaly is equated to the algebraic sum of products of the anomaly gradients of the prisms and the increments to the initial values of their depth. The increments are determined by solving the error equations, which are linear.

Considering the published paleomagnetic results over and around the Koyna region (Athavale & Indra Mohan 1976), the effective inclination, declination and intensity of magnetisation were calculated for modelling purposes. The calculated parameters along the profile AB with a digitised spacing of 1.64 km are as follows:

Intensity of effective magnetisation = 650 nT
Effective inclination = - 30°
Direction of measurement = 75°

The derived model (Fig.11) brings out clearly the basement magnetic interface along the profile. It also depicts two faults, one close to the Koyna dam and the other about 3-4 km east of Patan (Fig. 2) as also qualitatively determined by the trend of the aeromagnetic anomalies.

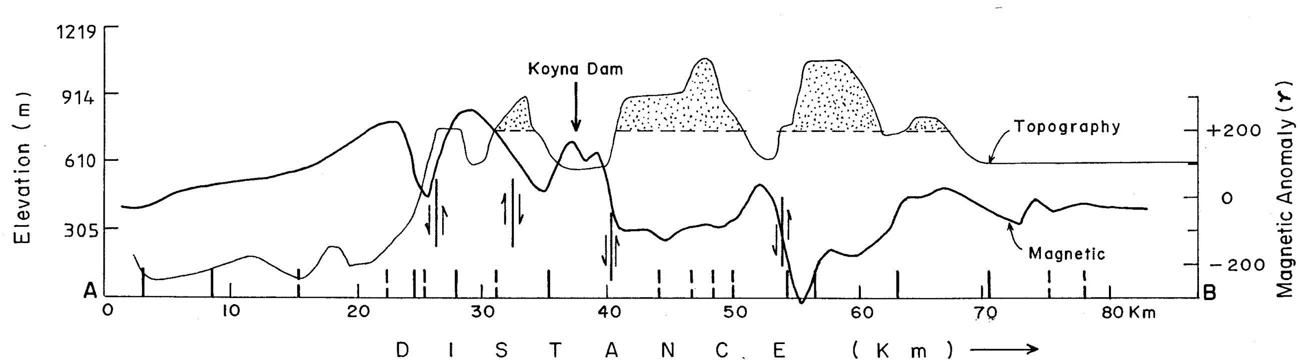

Figure 8: Variation of residual total intensity magnetic field and regional topography along the profile AB (Fig. 2). Locations of satellite derived lineaments along the profile is also shown on the abscissa (solid line: major lineament; broken line: significant lineament). Dashed area indicates topography ≥ 762 km above msl.

2-D Tectonic Model

Based on the inferences drawn from the multilevel aeromagnetic and satellite imagery maps, a 2-D cartoon model is shown in Fig. 12. A block-like structure bounded by two faults, L1 and L2, is observed which are intersected in the middle by E-W trending faults L3 and L4 paralleling the course of the Koyna River. A structural feature in line with the Warna River obliquely traverses the fault L1. Also a NW-SE trending fault-like feature cuts L4. We shall examine this model in the light of available seismicity of the area.

DISCUSSION AND CONCLUSIONS

Based on the large variation in gravity and other geological and field evidences, peninsular India and particularly the western region covering the Deccan Traps is reported to be severely faulted, fragmented and deformed to varying degrees giving rise to cohesive and disruptive structures (Kailasam, Murthy & Chayanulu 1972; Ravi Shanker 1995). This region is also undergoing Quaternary uplifting at a number of places (Radhakrishna 1993). Satellite imagery and aeromagnetically derived features indeed support this view as a number of major lineaments / faults can be seen intersecting each other just south of the Koyna reservoir. The Koyna region, particularly falling between longitude 73° 40′ – 74° E shows a large variation in topography from 200 m to >1000 m (Fig. 5) implying that either the rate of uplifting in the vicinity of seismic zone has been higher or there has been recent uplifting of about 300-400 m (as indicated in Figs 8 to 10) over and above the already uplifted block of western margin. Uplifting usually results in

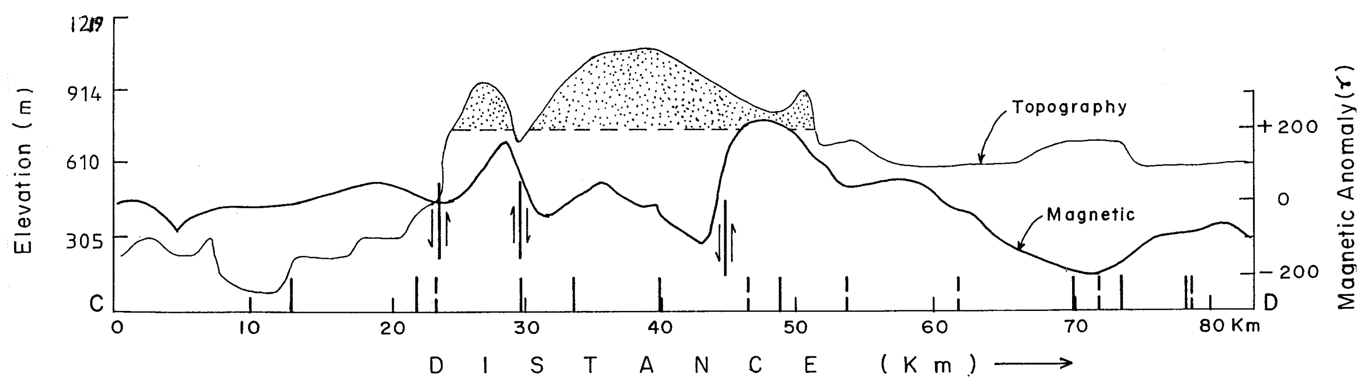

Figure 9: Variation of residual total intensity magnetic field and regional topography along the profile CD (Fig.2). Locations of satellite derived lineaments along the profile is also shown on the abscissa (solid line: major lineament; broken line: significant lineament). Dashed area indicates topography ≥ 762 km above msl.

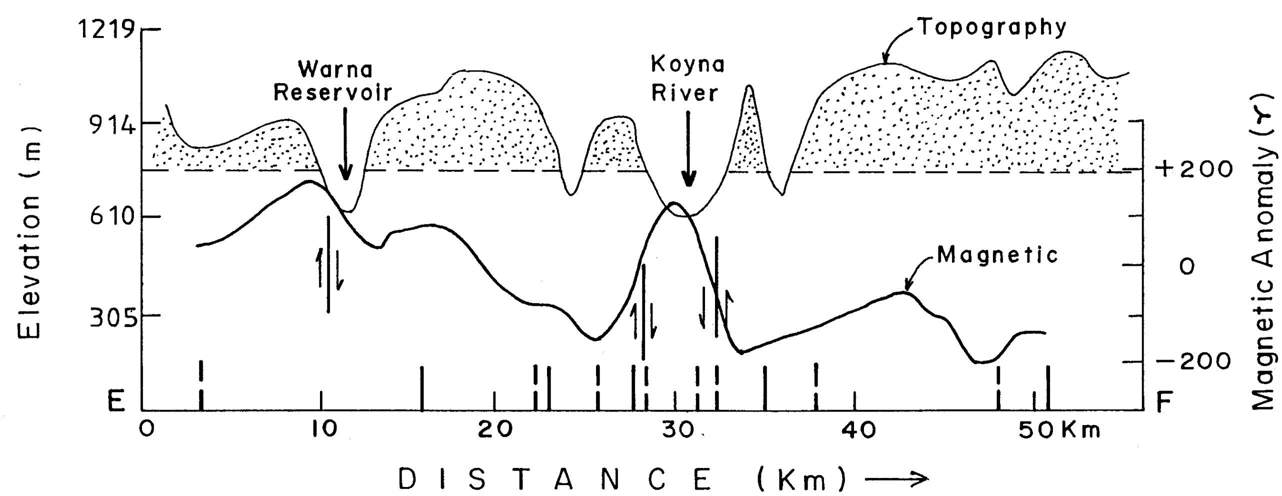

Figure 10: Variation of residual total intensity magnetic field and regional topography along the profile EF (Fig.2). Locations of satellite derived lineaments along the profile is also shown on the abscissa (solid line: major lineament; broken line: significant lineament). Dashed area indicates topography ≥ 762 km above msl.

large-scale differential weathering and erosion as can be seen from the regional topography. It is interesting to note that the Koyna-Warna earthquake zone strikingly coincides with the western margin of the Quaternary uplifted block having elevation of more than 762 m to 1178 m (Figs 5 and 6). The localized Quaternary uplifting could well be due to a possible large size intrusion within the crust. This finds support from the recently concluded teleseismic imaging of this region, where a high velocity anomaly (2% to 5%) in the upper and lower crust has been found to occur, which is flanked on either side by much lower velocities of –2% to –5% (Srinagesh et al. 2000). This contention is also supported by a reinterpreted gravity field, corrected for isostasy and referred in Srinagesh et al. (2000), according to which the Koyna seismic region has a +10 mgal anomaly restricted to Koyna region only compared to –70 mgal in the surrounding region. In such a case, build up of stress over a long period would go on accumulating, resulting

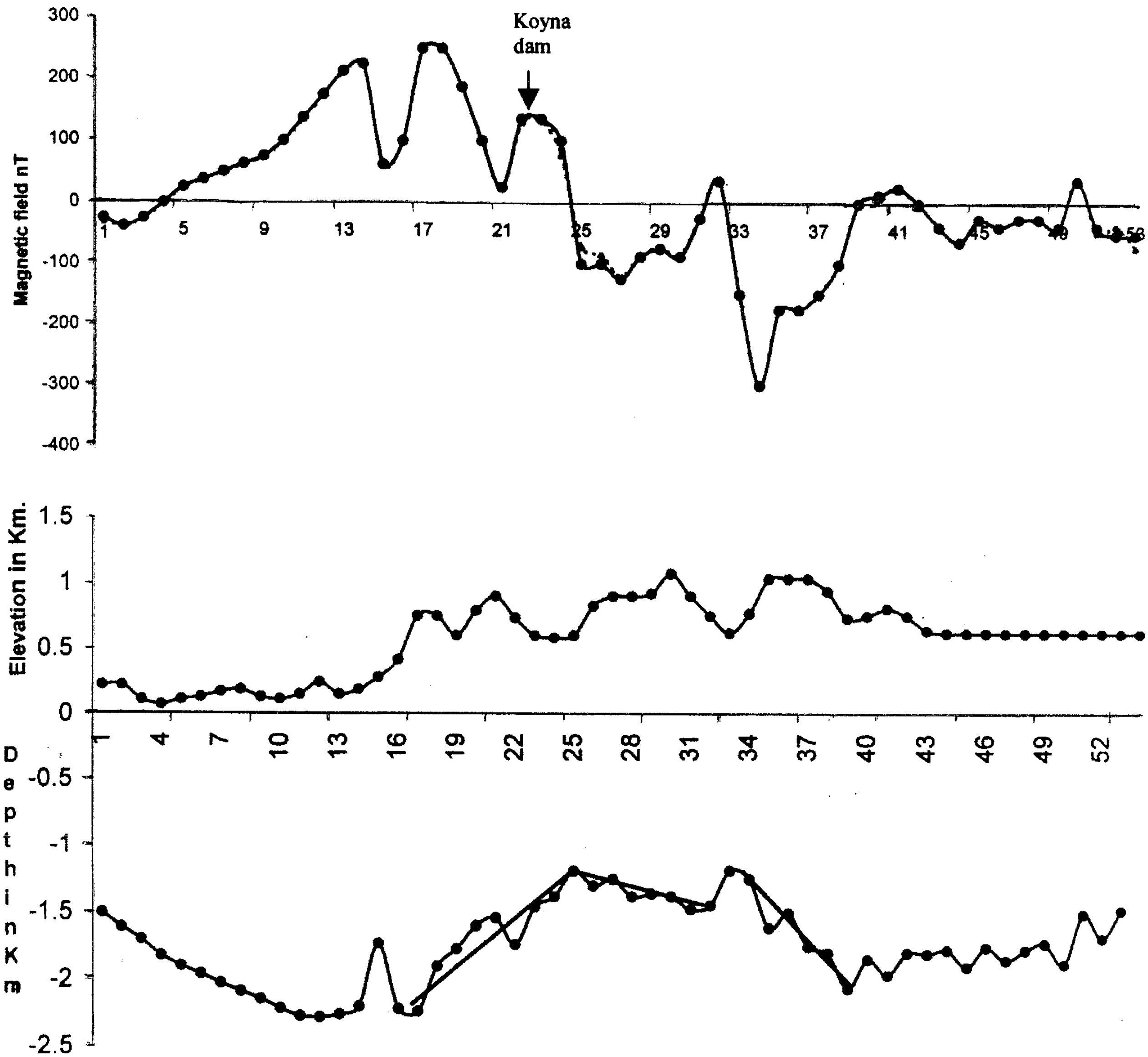

Figure 11. Interface between basement and Deccan volcanic layer as obtained from 2-D inversion of aeromagnetic data along profile AB (Fig.2). Basement faults are shown by straight line. Horizontal distance is in scale unit (1 unit = 1.64 km).

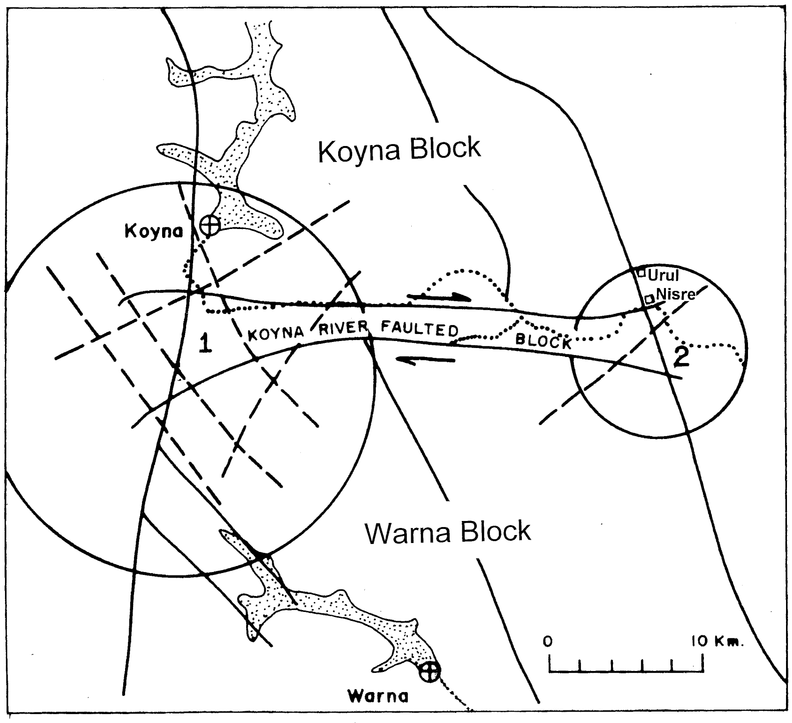

Figure 12. Tectonic structural features around the Koyna region derived from the multilevel aeromagnetic (solid line) and satellite imagery maps (broken line). Circle 1 encompasses seismically active region of Koyna – Warna and circle 2 to aseismic Urul – Nisre region. Circle with plus sign indicates location of dams.

in the development of several weak zones within the traps or even in the basement as evidenced by the magnetic lineaments. Thus it is hardly surprising that a cluster of magnetic and satellite derived lineaments are seen intersecting each other along the path joining the Koyna and Warna reservoirs (Fig.12). These lineaments may connect the two water bodies at depths in some way or the other.

Further, the Deep Seismic Sounding studies below the Koyna area have delineated three low velocity layers (LVL) at different depths of which two of them lie within the crust itself (Krishna, Kaila & Reddy 1991). They are most likely related to the extrusion of substantially fractionated/differentiated Deccan basaltic magma (Pandey & Negi 1987), which are vesicular in nature with much lower density. In fact, the density measurements from a 338 m deep bore hole in Latur earthquake region, which pierced through the Deccan Trap and reached the Precambrian basement, revealed that 47% of the Deccan flood basalts are comprised of non-massive vesicular and amygdaloidal type with a much lower average density of only 2.36 g/cm^3 (Reddy, Rao & Rao 1998). Even the basalt density for the entire column is of the order of 2.65 g/cm^3, which is much lower than 2.9 g/cm^3 usually assumed for Deccan basalts. Thus almost 50% of the erupted low density Deccan magma possesses a reasonably high porosity. The water stored in Koyna and Warna reservoirs must then be percolating to these porous zones through interconnected lineament/fault zones over a long period of time resulting them to be saturated with water. Such a phenomenon will create additional stress due to pore pressure in the rock. The stress created by the pore pressure will add to the already ongoing slow accumulation of stresses caused by regional as well as local Quaternary uplifting over this area.

It may be of interest to note that Urul-Nisre region situated east of Koyna (Fig.12) also lies at the junction of three faults similar to the one found at south of Koyna dam. While most of the faults in the vicinity of Koyna are not traceable at the surface. A faulted structure has been found near Urul-Nisre region (Geol. Surv. Ind. Officials, Poona: Personal Communication). However, this region being quite away from Quaternary uplifting and devoid of a water body could not develop as a potential seismic risk zone. Therefore, we surmise that the recurring seismic activity around the Koyna – Warna region could be largely due to subsurface tectonic features, besides impounding of water in the reservoirs.

ACKNOWLEDGEMENTS

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