Doughnut precursory seismicity pattern and stress conditions for the Killari (Indian shield) earthquake

B. Ramalingeswara Rao

National Geophysical Research Institute, Hyderabad 500 007, India

During the past six decades before the onset of the Killari earthquake of 30 September 1993, widespread occurrence of subterranean sounds accompanied by micro-tremors were reported in Latur–Osmanabad–Parbhani districts of Maharashtra state in the South Indian shield. From 1976 onwards, a doughnut pattern of seismicity (of these clusters) and/or swarms in the vicinity of Killari have been identified, which indicate nucleation of fault ruptures under preparatory area of about 550 km^2 near and around Killari. Within this, a quiescent area or gap of 280 sq km has been identified in the present study. A precursory period of one decade has been indicated by the enhancement of the seismic activity in the region. The occurrence of micro-tremors may be the signature of reactivation of old faults in the upper crust of the Deccan Volcanic Province of the Indian stable continental region. The analysis of stress conditions *vis-à-vis* the Coulomb–Navier criterion of failure indicates the necessity of the reduction of normal stress. This reduction of normal stress due to pore-fluid pressure, differential erosion or a combination of both (and thereby the uplift of the crustal blocks in the area) could be the possible cause of the occurrence of the Killari earthquake.

THE occurrence of the Killari earthquake of 30 September 1993 in the stable continental region of the peninsular India attracted the attention of seismologists all over the world mainly because of its enormous devastation. Immediately after the main shock, several scientists rushed to the affected area to investigate the cause and effects and some of them gave their opinion on the Indian shield seismicity with regard to Killari earthquake of 30 September 1993 (refs 1–6). Although Deccan Volcanic Province (DVP) is covered with the basaltic flows and many aspects about its tectonics remain unknown, several authors had attempted to delineate the old fault patterns by using the seismicity data[7–11]. Before the occurrence of the Killari earthquake, several micro-tremor activities accompanied by subterranean sounds had been taking place in this region, the data of which had been collected and compiled by different authors[12–14]. These authors have reported them as micro-tremor activities in and around Killari region, but no attempt has been made to identify them as precursory pattern for the earthquake of 30 September 1993. The importance of these repeated episodic observations of small earthquakes accompanied by subterranean sounds of natural origin is that they may be precursors to major earthquakes[15]. The shallow devastating earthquake which occurred in the Killari–Latur, Umerga area on 30 September 1993, appears to have been caused by the strong upward moment of the uplifted blocks[3]. Critical gradients of different geophysical parameters such as gravity, temperature and topography near the weak zones indiate nucleation for the earthquake occurrence[16]. It has been observed that DVP had experienced not only low magnitude clusters/swarms but also five significant earthquakes such as: Mahabaleswar, 1764; Son-Valley, 1927; Satpura, 1938; Koyna, 1967 and Killari, 1993 earthquakes of magnitude 6 and above. Identification of the seismicity pattern preceding these large earthquakes is not possible due to lack of observed data. Hence, the study of historical seismicity and its background level in the vicinity of the Killari earthquake of 1993 plays an important role in understanding the occurrence of large earthquakes in the (cratonic) stable Indian shield. In the present study, reported data have been modelled in a systematic seismicity pattern and identified the failure conditions of the Killari earthquake region.

Seismotectonics of the area

The area is covered by Deccan volcanics. The deccan volcanic flows are considered to have been outpoured onto the Dharwarian Peninsular gneissic basement of Precambrian age as fissure type eruptions. The thickness of the volcanic flow in the vicinity of meizoseismal area of the Killari earthquake is 338 km and is mainly of tholeiitic composition[17]. Most of the flows are massive, compact and fine-grained with vesicular and amygdaloidal traps. The vesicles, at places, are filled with crystalline chlorite and calcite and are occasionally rimmed with glass.

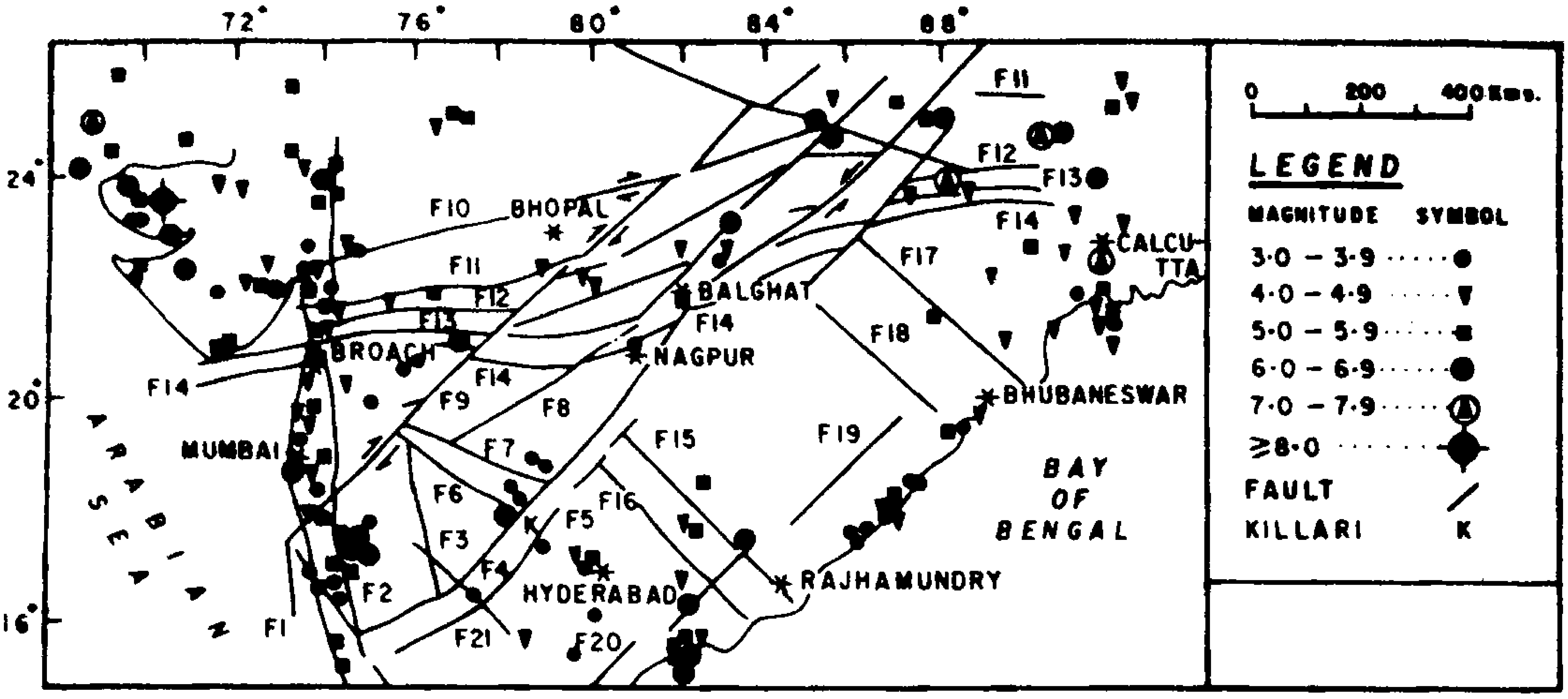

Figure 1. Seismotectonics of the study area with attendant historical seismicity for the period from 1764 to 1996 (after Ramalingeswara Rao and Sitapathi Rao[7] and also inclusive of recent earthquake data up to 1996 and base map after Ravi Shanker[19]).

A multidimensional porous medium, like zeolites, is also present at different depths in the vicinity of Killari earthquake region.

The Latur area was identified in the seismic zoning map of Peninsular India as a future potential zone for moderately large earthquake of intensity V (ref. 18). Several blocks as shown in Figure 1 have been identified in DVP[19], a set of four major NE–SW trending transverse fault systems (F_4, F_5, F_8 and F_9) of regional significance, intersecting the old ENE–WSW trending 'SONATA ZONE', NNW–SSE trending Cambay–west coast rift and NW–SE Godavari and Mahanadi rift system. Further, it has been observed that small earthquakes occurred in the blocks, mild to moderate earthquakes on faults and moderately large earthquakes at the junctions of two or more blocks. The present Killari earthquake occurred at the intersection of two sets of faults NE–SW and NW–SE trending faults system (Figure 1). The background historical seismicity has been given in the figure from the database[7,11].

Database

In the present study, reported subterranean sounds (mostly felt) within the radius of 100 to 200 km from the Killari region are compiled and considered as micro-earthquakes of 1 to 3 magnitudes occurring at the shallowest depth of few hundreds of meters below the surface. These subterranean sounds (swarms) occur even after 3 years of occurrence of the main shock. The subterranean sounds at Bandgarwadi and Jagdalwadi well sites were also observed during 14 August 1995, 21 December 1995 and 22 December 1995 (Indra Mohan, personal communication). Very recently, mysterious sounds resembling a cannon ball thunder, baffled many people in the villages of Parli, Wadgoan, Aswalamba, Dadahari and Bendsur in the district of Beed in the month of September, 1996, which might be construed as a swarm type of activity of low magnitude of 0 to 1.

Reports on historical mild tremors from the villages Halberga, Hamnabad, Ghanpur, Ghandhari, Ujani and other parts of Maharashtra, have also mentioned subterranean sounds[12]. Later, there was a recurrence of micro-tremor activity with subterranean sounds in the year 1983. The subterranean sounds have been studied for the villages of Parbhani, Bhir, Nanded, Osmanabad and Latur Districts of Maharashtra state. Every effort has been made to collect data of the micro-tremors accompanied by subterranean sounds in the area from different sources of earthquake catalogues and newspaper agencies for the present study. These reports were actually confined to very small area, sometime less than a kilometer radius, and were meticulously investigated by local geologists.

Seismicity pattern

The earthquake-affected Latur belt has been exhibiting micro-seismicity for quite some time (1962, 1963, 1967, 1983, 1984 and 1993). Obviously, internal strain has been progressively building up all through the time[1]. Two sites, Salimba and Killari have also experienced subterranean sounds during October–November, 1992 (which are shown as star and big solid circle in Figure 2 *b*). On the basis of background level of seismicity information, we have studied the space–time pattern of

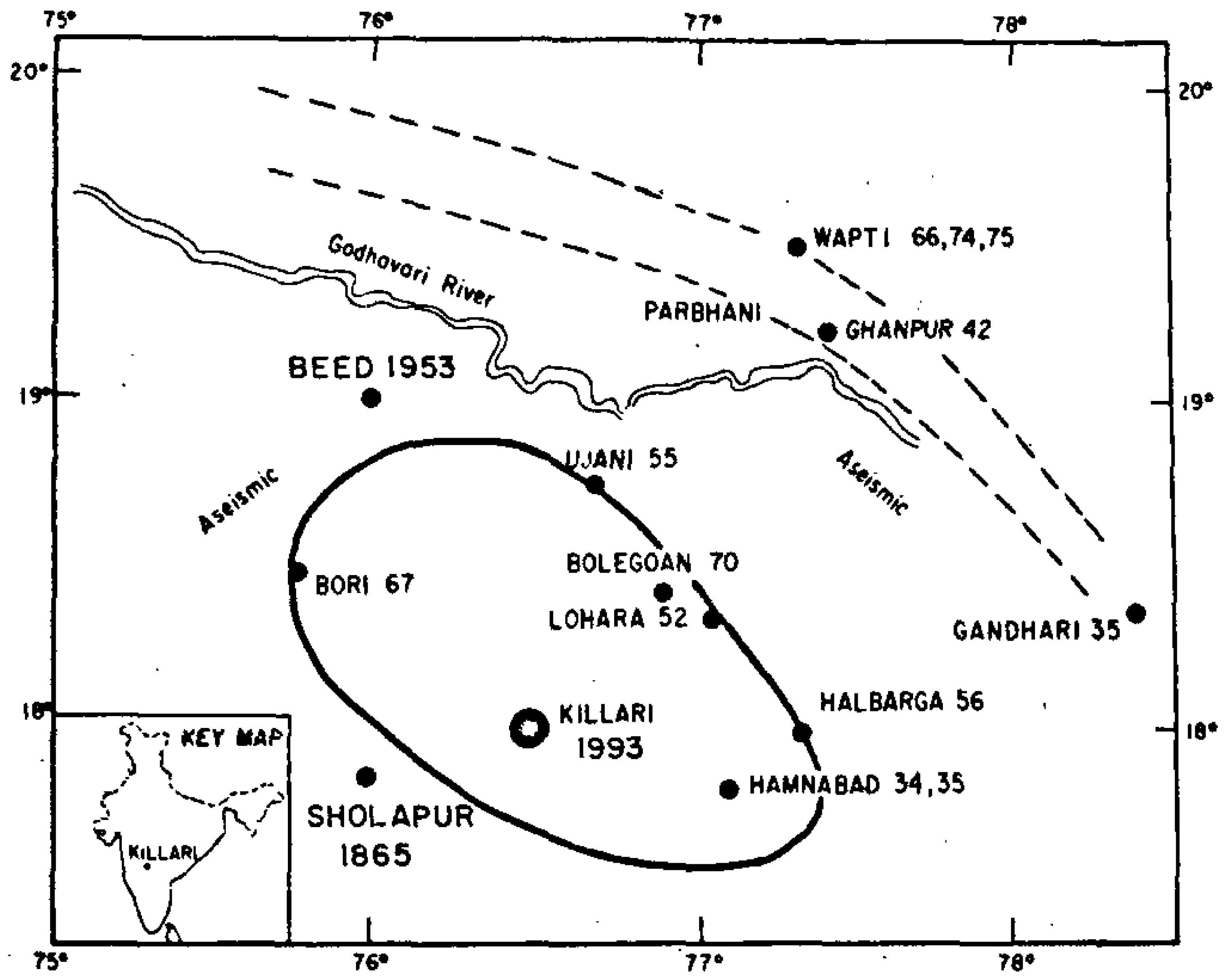

Figure 2 *a*. Micro-tremors shown as solid circle of intensity III to IV M are plotted for a period 1934–1982. A tendency of seismicity pattern may be observed.

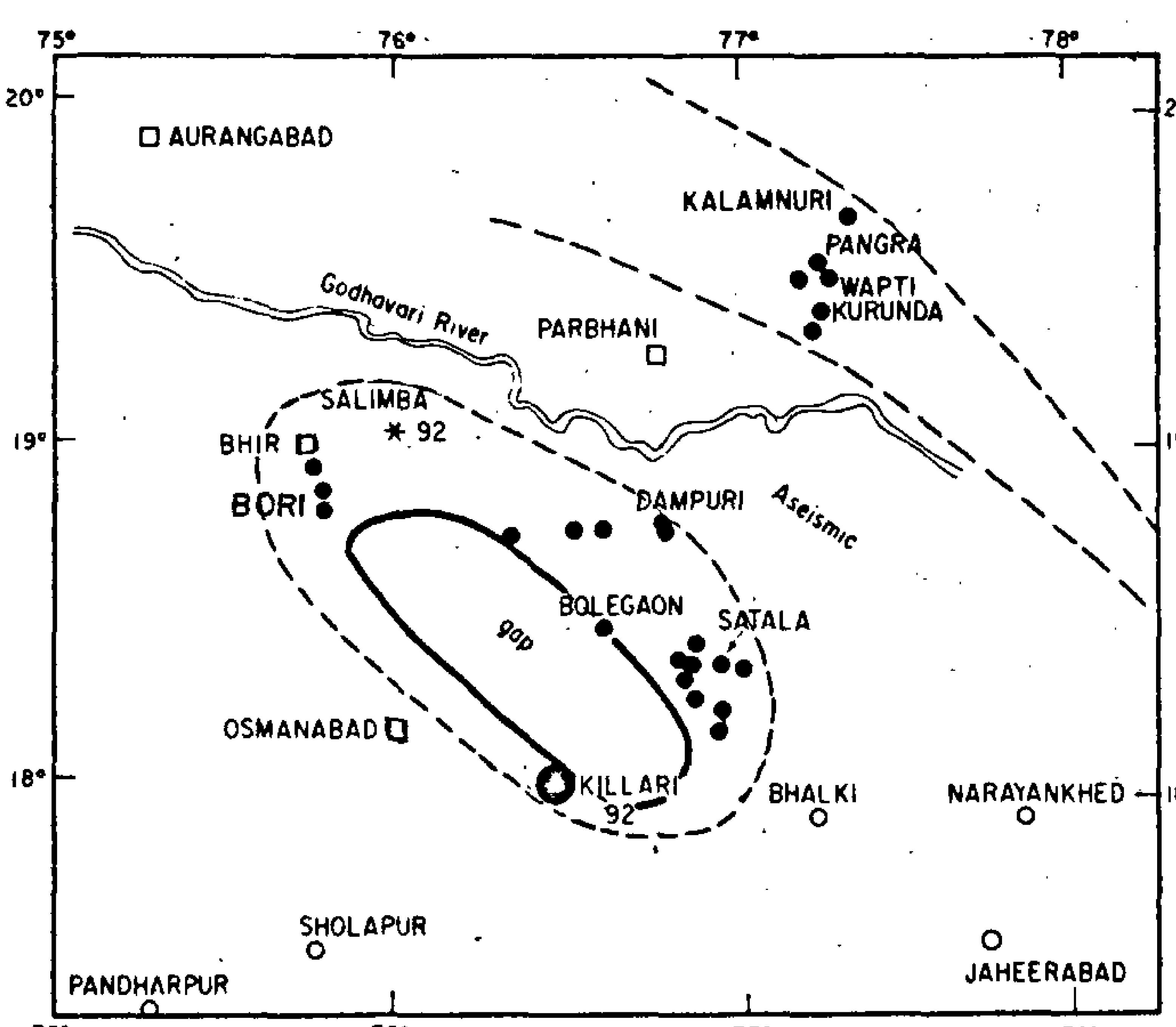

Figure 2 *b*. A doughnut seismicity pattern of earth tremors during 1983–1993 and showing NW–SE direction. Each solid circle indicates number of micro-tremors accompanied by subterranean sounds. Star indicates October '92 to February '93. Micro-tremors occurred before main shock in Salimba and Killari villages.

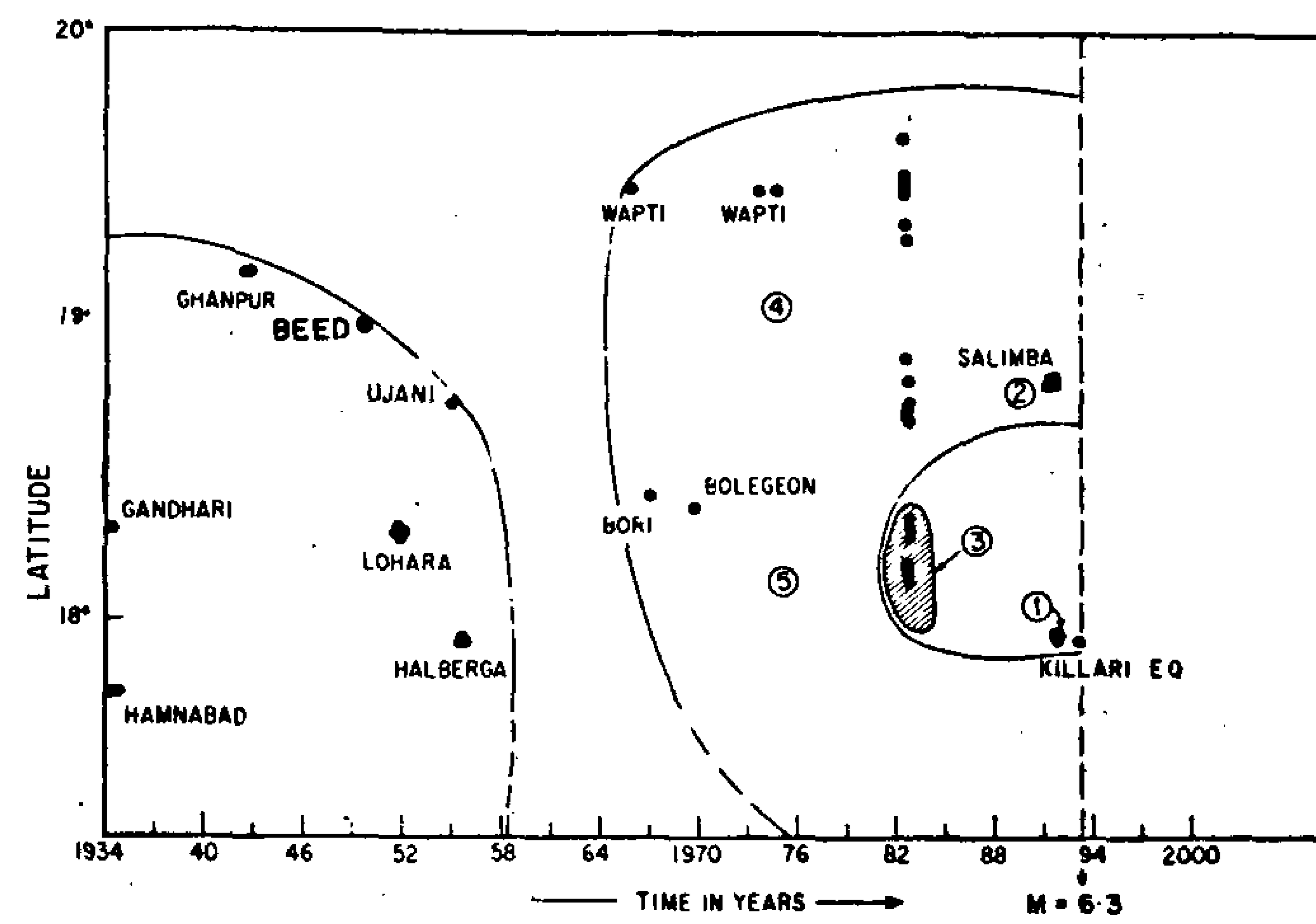

Figure 2 *c*. A temporal variation of swarms/clusters in the vicinity of the Killari earthquake is shown as: Phases 1, 2, 3, 4, and 5.

this micro-tremor activity including subterranean sounds to delineate the possible zones of strain accumulation in the vicinity of Killari. A plot of the microtremor activity, of intensities III and IV for two periods 1934–1982 and 1983–1993 shows an oval-shaped seismicity pattern as shown in Figures 2 *a* and *b* respectively. The recurrence of these tremors accompanied by moderate to high frequency of subterranean sounds in different localities cannot be labelled as local phenomenon. These sounds are manifestations of feeble tremors and are heard locally but the localities in which they have occurred are many and widespread[12]. The micro-earthquakes are aligned in a particular seismic pattern. Although they occur sporadically in seismically active and inactive periods (1934–1993), they show a systematic pattern. It is noted that seismically inactive periods during 1954–1964, 1967–1974 and 1975–1982 are followed by micro-earthquake clusters accompanied by subterranean sounds without any significant earthquakes. Ten years' quiescent period is observed during 1984–1993, which is identified as a precursory period for the large magnitude $Ms = 6.3$ earthquake of Killari on 30 September 1993. The reported sites are all falling in doughnut pattern of seismicity analogous to different authors[20–23]. With appearance of the so-called doughnut pattern, the seismic activity decreases near the focal regions of the great earthquakes termed as seismic gap and at the same time, there as an increase in activity around this quiescent area[21].

Plot of time versus space (latitudes), the micro-tremors/subterranean sounds data have been presented in Figure 2 *c* (each dot represents a large number of small micro-tremors). Five phases of seismic activity in space–time analysis have been inferred from Figure 2 *c*. Phase 1 represents about 200 small magnitude earthquakes that occurred in the vicinity of the epicenter immediately prior to the main earthquake at Killari. Of these, 26 events were recorded at a seismological observatory of the National Geophysical Research Institute during October–November 1992 (ref. 24). Phase 2 also represents the seismic activity occurring at faraway places (near Salimba) immediately prior to the main-shock of Killari and it perhaps represents the earthquake precursory crustal deformation induced activity. Phase 3 is the zone of seismic activity in which earthquake swarms occurred before the appearance of the seismic

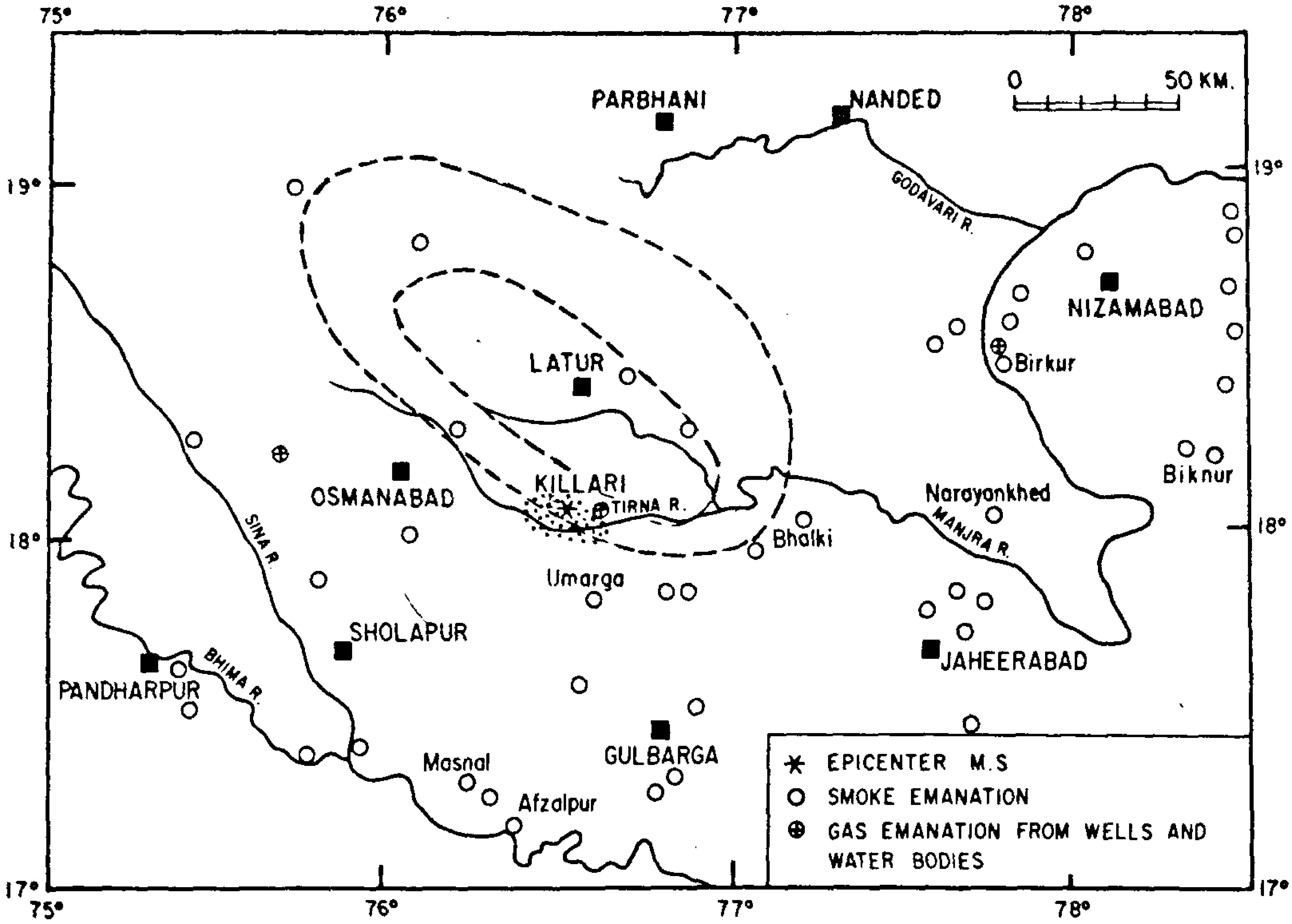

Figure 2 *d*. After mainshock of $Ms = 6.3$, $h = 6.5$ km, the smoke and gas emanation in South and North east of Killari region. (after Rastogi and Rao[14]) are shown as open circles.

gap. Observations revealed no micro-tremor activity for a period of approximately five decades (1934–1982) in this seismic gap (Figure 2 *c* hatched area). Phase 4 represents doughnut pattern seismic activity. Observations in four phases indicate the nucleation of the strong earthquake in the identified gap. Thus, in Phase 5, crustal stress gradually rises and activity over a wider area increases. It is interesting to note that within the doughnut seismicity pattern, there were no reports of occurrence of micro-tremors with subterranean sounds from the region between Bori and Killari (Figure 2 *b*). The micro-tremors reported are shown in figures as solid circles. Absence of micro-tremor activity in Phase 5 is an indicative of stress build up in the area. Similar doughnut seismicity pattern was also observed in Baykal region of Soviet Union. During Phase 5, there will not be widespread incidence of micro-earthquakes in the doughnut area depending upon the nature of the main fault.

Coulomb–Navier failure criterion

Coulomb–Navier criterion of failure may be stated that at the point of failure, the maximum shear resistance of the material (shear strength) equals the shear stress on the plane of failure plus the internal frictional resistance ($\sigma_n\ \mu$). The constant μ is known as the coefficient of internal friction. The shear stress and the normal stress on a failure plane inclined at an angle θ to the minor principal stress σ_V, where the major principal stress is σ_H, are:

$$\sigma_n = \frac{\sigma_H + \sigma_V}{2} - \frac{\sigma_H - \sigma_V}{2} \cos 2\theta, \qquad (1)$$

$$\tau = \frac{\sigma_H - \sigma_V}{2} \sin 2\theta, \qquad (2)$$

where σ_H and σ_V are horizontal principal compressive stress and vertical stress respectively. The case of reactivation of existing faults varies with their orientation in the prevailing stress field. This is illustrated in an analysis of the condition for frictional reactivation of cohesionless faults obeying the simplified criterion[25].

$$\tau = \mu(\sigma_n - P_p^*), \qquad (3)$$

where σ_n and τ are respectively normal and shear stresses to the existing fault; P_p^* is the fluid pressure and

μ is internal friction. If a material has no cohesion it depends entirely upon internal friction of the fault for its stability. The fault zone material may consist of clay gouge or montmorillonite at a depth of 6–8 km. It is tempting to speculate that the comparatively low level of micro-seismic activity generally observed in the top few kilometers may correlate with the depth extent of weak montmorillonite-rich gouge present in the fault zone[26]. At Killari, the clayee and/or tuffy material may be present at this depth, which may have approximately 0.4 frictional coefficient.

In the case of Killari, the cohesive strength will be zero because of the presence of pre-existing fractured fault zone in which volcanic tuffy materials, etc. are filled. σ_n is the normal stress at failure. We tried to analyse the stress conditions in the Killari earthquake meizoseismal area (Figure 3). The vertical stress σ_V can be computed by using the equation:

$$\sigma_V = pgh, \quad (4)$$

where p is the average rock density in g/cc, g is the gravitational acceleration and h is the depth to the focus. The top basaltic layers of different soft and hard rocks are considered as one layer of 500 m average thickness having density 2.9 g/cc. This vertical stress due to basaltic layer is approximately 14.2 MPa loaded on another layer of gneissic basement of 6 km thickness. The vertical stress due to lower peninsular gneissic layer is computed as 162 MPa. The total vertical stress is thus 176.2 MPa for 6.5 km. Three-dimensional intraplate stress distribution induced by topography and crustal density inhomogenities and the average plate tectonic stress beneath Killari region have been computed[27]. The differential stress $\sigma_H - \sigma_V$ on the average is approximately 42 MPa for 2 km depth. Further, they noted that the magnitude of this differential stress decreased with depth other than for 2 km. The corresponding differential stress at 6 km is 11.7 MPa. By using the equations (1) to (4), we have computed σ_H and σ_V at the Coulomb–Navier failure criterion. The Mohr's diagram is drawn for the stresses prevailing at Killari meizoseismal area (Figure 2 *b*). The centre 'C' of the Mohr's solid circle due to tectonic stresses and additional basaltic load is shown as circle with crosses. As evident from the Mohr's diagram, this failure condition required reduction in the normal stress to cause a main fault ruptured by Killari earthquake of 30 September 1993. This reduction must have been brought about by pore-fluid pressure, differential erosion and thereby resulting in crustal uplift in the stress regime. The pore-fluid pressure, differential erosion and the consequent uplift of the crustal blocks in this stress regime, must have brought about this reduction in the normal stress of the order of 67 MPa. The effective normal stress (148.9 MPa), shear stress and the effective principal stresses at failure condition can be represented by driving the Mohr's circle from the centre C to the new centre C′ without changing the differential stress (diameter of the Mohr's circle).

A build up in the earth stress is generally relieved by frictional slip before $\sigma_H - \sigma_V$ becomes high enough to shear intact rock[28]. In the case of Killari region, we have this situation of moderate differential stress of 67 MPa and high effective normal stress of about 150 MPa which favoured unstable stick-slip motion of different four faults. The computed values σ_V and σ_H are in agreement with *in situ* stress measurements using hydraulic fracturing for 176 m deep bore hole at NGRI, Hyderabad[29]. The ratio of $\sigma_V/\sigma_H = 0.55$ at Hyderabad by *in situ* stress experiment, compares well with Killari presumed value of 0.48 by theoretical computation for 6.5 km depth (Table 1).

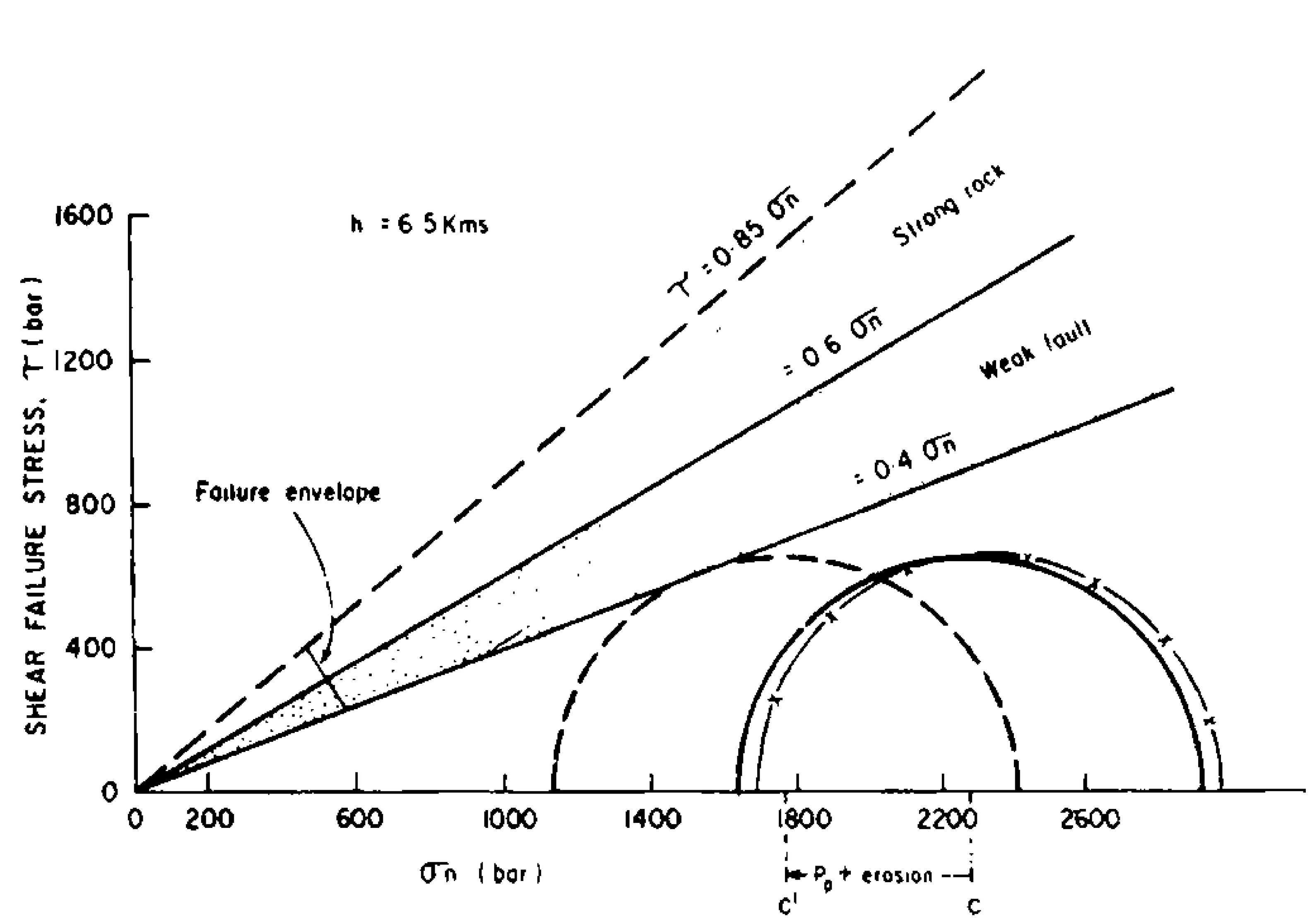

Figure 3. Mohr's diagram indicating the Coulomb–Navier failure criterion. Pore-fluid pressure, differential erosion and gradual crustal block upliftment have reduced the normal stress by 67 MPa.

Table 1. The principal stresses at $h = 6.5$ km have been computed by using Coulomb–Navier failure criterion for the Killari region and hydro-fracturing measurements made at Hyderabad, NGRI[28]

Parameters	At Killari (theoretical computation)	At Hyderabad (Hydrofracture experiment, NGRI)
h Depth	6.5 km	6.5 km (extrapolated)
Density of basalt	2.9 g/cc	–
Granite density	2.7 g/cc	–
Static frictional coefficient	0.4	–
Normal stress	148.9 MPa*	–
Max. principal stress	226.9MPa*	295.2 MPa
Min. principal stress	107.8MPa*	162.5MPa
Ratio = σ_V/σ_H	0.48	0.55
Radius of Mohr's circle	58.5MPa	–
Pore-fluid pressure	67.0 MPa	–
Failure shear stress	56.6 MPa	–

* Effective stresses during Coulomb–Navier failure condition only.

Discussion

The drop in shear stress by about 15–20 bars is a necessary and sufficient condition to attain an unstable condition of faults in the cratonic regions and to meet the Coulomb–Navier failure criterion (Arch Johnston, pers. commun.). Thus, the above criterion might be one of the proper physical processes of earthquake preparation which have taken place for several thousands of years in the cratons in the shield areas. The leakages and/or percolation of the terrestrial water through the volcanic flows around the nucleation of the expected faults/lineaments culminating at one zone near Killari, might be one of the factors for the occurrence of this large magnitude earthquake. A well-defined crustal conductor in the epicentral region of the Killari earthquake is present at an estimated depth of 6–10 km (refs 30, 31). The conductor has been interpreted to be a fluid-enriched rock matrix. Further, it has been observed that the low velocity and high conductivity fluid-filled layer will enhance stress concentration in the uppermost brittle part of the crust, causing mechanical failure[31]. The suppression of the seismicity in Antarctica and Greenland may be due to the load of the ice sheet which is attributed to the low level of differential stress of about 11 MPa and ice sheet may not be allowing the flow of fluids into the underlying faults[32]. The situation is quite opposite in the case of DVP of the Indian shield, resulting in enhancement of seismicity where the flow of fluids in the underlying faults is expected.

A landscape block diagram is prepared for the failure conditions of the different soft and hard basalts in the studied area prior to and during the earthquake of 30 September 1993. The cluster and/or swarm occurrences in different villages (as shown in Figure 2 *a* and *b*) may be due to a failure of small fluid-saturated faults in due course of time. The doughnut pattern of a seismic activity with subterranean sounds is also shown in Figure 4. Identification of the reactivation of three more fault segments due to impact of the main fault near Killari, a place at which these segments culminate in 10–15 km radius[33], is also shown in Figure 4. They are reverse (R), strike-slip (SS1), strike-slip (SS2) and normal (N) faults. The fault plane solutions of the aftershocks also indicate strike-slip faults (for shocks ≤ 5 km) and reverse fault for relatively deeper shocks (≥ 5–15 km) (ref. 34). Older thrust sheets and fault gauge formed during previous episodes near the Killari deformed zone are also reported[35,36]. The above studies by different authors partly corroborate with the faulting mechanism, which is shown in the block diagram (Figure 4). Thus, the above four faults such as reverse, strike-slip1, strike-slip2 and normal faults (collapse of top soil in the Killari earthquake area) had occurred in the area with respect to time[33].

Conclusions

The Killari earthquake occurrence might be due to reactivation of old faults in the vicinity and showed definite precursory elliptical shape of NW–SE direction of doughnut seismicity pattern of micro-tremors. The intraplate stress conditions have been studied by using the Coulomb–Navier failure criterion. The effects of pore-fluid pressure, differential erosion and thereby crustal uplift in the vicinity of Killari have been studied. A precursory period of 10 years is significant before the occurrence of the main shock of the Killari earthquake

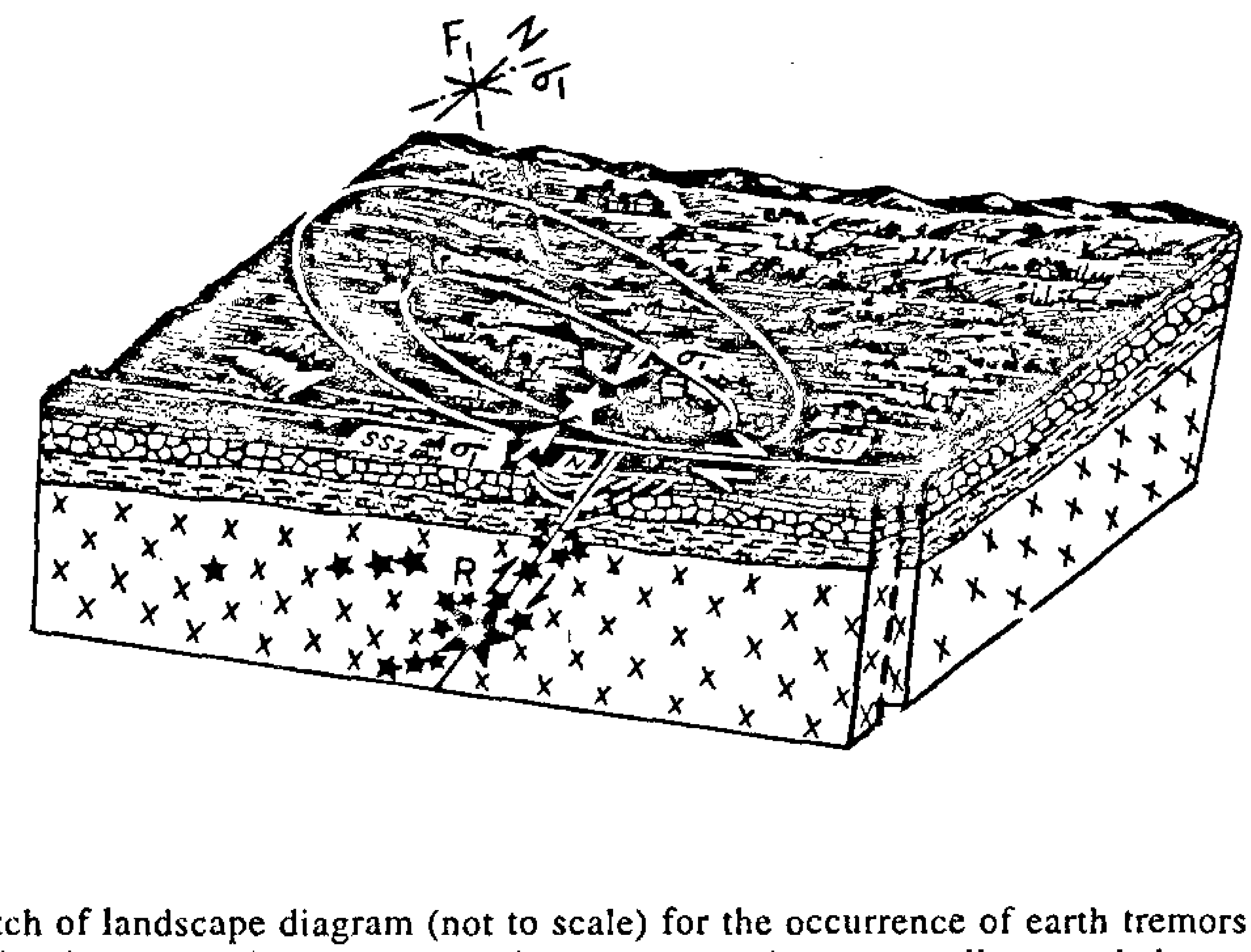

Figure 4. A sketch of landscape diagram (not to scale) for the occurrence of earth tremors with subterranean sounds around Killari mainshock and are also shown as stars (instrumentally recorded events) after-shock sequence in depth section (Baumbach *et al.*[24]). R, Reverse; SS1, strike; SS2, strike-slip and N, normal faults with reactivation angle are indicated (After Ramalingeswara Rao[33]).

of 30 September 1993. In the present study, all the reported micro-tremor data were used for the analysis. In the vicinity of Latur area, there were no seismic stations/observatories for the study of micro-tremor activity to represent them in a more authentic way. Hence, it is strongly felt that any outburst of micro-tremor or swarms in the Indian shield, should be considered seriously to record those events in time by deploying a number of seismic stations in the target area. In the present study, we have considered only authentic reports.

1. Valdiya, K. S., *Curr. Sci.*, 1993, **65**, 515–517.
2. Gaur, V. K., *Curr. Sci.*, 1993, **65**, 509.
3. Kailasam, L. N., *Curr. Sci.*, 1993, **65**, 736–739.
4. Radhakrishna, B. P., *J. Geol. Soc. India*, 1993, **42**, 523–526.
5. Gupta., H. K., *Mem. Geol. Soc. India*, 1994, **35**, 1–5.
6. Seeber, L., Ekstrom, G., Jain, S. K., Murty, C. V. R., Chandak, N. and Ambruster, *J. Geophys. Res.*, 1993, **101**, 8543–8560.
7. Ramalingeswara Rao, B. and Sitapathi Rao, P., *Bull. Seismol. Soc. Am.*, 1984, **74**, 2519–2533.
8. Lagwankar, V. G., Kumaraswamy, S. V. and Ghatpande, M. A., (Extended abstract), Workshop on Indian Shield Seismicity and Latur Earthquake of September 30, 1993, NGRI, 1995, p. 57.
9. Ramalingeswara Rao, B. and Divakara Rao, V., (Extended abstract), Workshop on Indian Shield Seismicity and Latur Earthquake of September 30, 1993, NGRI, 1995, pp. 76–77.
10. Rastogi, B. K., (Extended abstract), Workshop on Indian Shield Seismicity and Latur Earthquake of September 30, 1993, NGRI, 1995, pp. 43–45.
11. Deshmukh, D. S., *Indian J. Power River Valley Dev.* (special issue), 1968, pp. 67, 68 and 76.
12. Asolkar, M. R., unpublished report, Directorate of Geology and Mining, Govt. of Maharashtra, Aurangabad, 1983, pp. 1–37.
13. Mohan, I. and Rao, M. N., *Mem. Geol. Soc. India*, 1994, **35**, 7–32.
14. Rastogi, B. K. and Rao, M. N., *Mem. Geol. Soc. India*, 1994, **35**, 139–149.
15. Gold, T. and Sorter, S., *Science*, 1979, **204**, 371–375.
16. Raval, U., Extended abstract, Workshop on Indian Shield Seismicity and Latur Earthquake of September 30, 1993, NGRI, 1995, p. 55.
17. Gupta, H. K. and Dwivedy, K. K., *J. Geol. Soc. India*, 1996, **47**, 129–131.
18. Gubin, I. E., *Bull. Int. Inst. Seismol. Earthq. Eng.*, 1968, **8**, 109–139.
19. Ravi Shanker., *Geol. Surv. India*, 1995, Pub. No.27, 41–48.
20. Mogi, K., *Pure Appl. Geophys*, 1979, **117**, 1172–1186.
21. Mogi, K., *Bull. Reg. Comm. Coord. Earthq. Predict.*, 1980, **2**, 20–21 (in Japanese).
22. Mogi, K., in *Earthquake Prediction*, Academic Press, New York, 1985, p. 355
23. Yamashina, K. and Inoue, Y., *Nature*, 1979, **278**, 48–50.
24. Baumbach, M., Grosser, H., Schmidt, H. G., Paulat, A., Rielebrock, A., Rao, C. V. R. K., Raju, S. P., Sarkar, D. and Mohan, I., *Mem. Geol. Soc. India*, 1994, **35**, 33–65.
25. Sibson, R. H., *J. Struct. Geol.*, 1985, **7**, 751–754.
26. Bakun, N. H., Stewart, C. G. and Marks, S. M., *Bull. Seismol. Soc. Am.*, 1980, **70**, 185–201.
27. Mandal, P., Manglik, A. and Singh, R. N., *J. Geophys. Res.*, 1997, **102**, 11,719–11,729.
28. Engelder, T., in *Stress Regimes in the Lithosphere*, Princeton University Press, Princeton, 1993, p. 449.
29. Gowd, T. N., Rama Rao, S. V. S., Chary, K. B. and Rummel, F., *Proc. Indian Acad. Sci.*, 1986, **95**, 311–319.
30. Sarma, S. V. S., Virupakshi, G., Harinarayana, T., Murthy, D. N., Prabhakar, E., Rao, S., Veeraswamy, K., Madhusudhan Rao, Sarma,. M. V. C. and Gupta, K. R. B., *Mem. Geol. Soc. India*, 1994, **35**, 101–118.
31. Gupta, H. K., Sarma, S. V. S., Harinarayana, T. and Virupakshi, G., *Geophys. Res. Lett.*, 1996, **23**, 1569–1572.
32. Johnston, A. C., *Nature*, 1987, **330**, 467–469.
33. Ramalingeswara Rao, B., 1997, under preparation.
34. Kayal, J. R., *Indian J. Geol.*, 1995, **67**, 151–157.
35. Rajendran, C. P., Rajendran, K. and John, B., *Geology*, 1996, **24**, 651–654.
36. Narula, P. L. and Pande, P., *Geol. Soc. India Spl. Publ.* (eds Narula, P. L., Shome, S. K. and Murty, B. S. R.), 1996, **37**, 237–244.

ACKNOWLEDGEMENTS. I thank Dr Harsh K. Gupta, Director, National Geophysical Research Institute, Hyderabad for giving permission to publish this work; S. C. Bhatia, Shri Indra Mohan and Dr Ch. Rama Rao for their valuable suggestions during this work; and P. J. Vijayanandam for drafting the block diagram.

Received 2 November 1996; revised accepted 2 June 1997.