Sci, 1995, **68**, 631–641.
5. Morgan, S. E. and McCormick, C. L., *Prog. Polym. Sci.*, 1990, **15**, 103.
6. Kullicke, W.-M., Kötter, M. and Gräger, H., *Advances in Polymer Science*, Springer, Berlin, 1989, pp. 1–204.
7. Sellin, R. H. J., Hoyt, J. W. and Scrivener, O., *J. Hydraul. Res.*, 1982, **20**, 29.
8. Sellin, R. H. J., Hoyt, J. W., Pollert, J. and Scrivener, O., *J. Hydraul. Res.*, 1982, **20**, 235.
9. Lee, W. K. Vaselaski, R. C. and Metzner, A. B., *AIChE J.*, 1974, **20**, 128.
10. Deshmukh, S. R. and Singh, R. P., *J. Appl. Polym. Sci.*, 1986, **32**, 6163.
11. Deshmukh, S. R. and Singh, R. P., *J. Appl. Polym. Sci.*, 1987, **33**, 1963.
12. Singh, R. P., Deshmukh, S. R. and Majumdar, S. K., in Proceedings of the X Congress on Rheology, *Sydney*, 1988.
13. Ungeheuer, S. Bewersdorff, H. W and Singh, R. P., *J. Appl. Polym. Sci.*, 1989, **37**, 2933.
14. Deshmukh, S. R, Sudhakar, K. and Singh, R. P., *J. Appl. Polym. Sci.*, 1991, **43**, 1091.
15. *Kowalik, R. M., Duvdelani, I., Piffer, D. G., Lundenberg, R. D.*, Kitano, K. and Shultzs, D. N., *J. Non-Newtonian Fluid Mech.*, 1987, **24**, 1.
16. Reddy, G. V. and Singh, R. P., *Rheol. Acta*, 1985, **24**, 1.
17. Malhotra, J. P., Chaturvedi, P. N. and Singh, R. P., *J. Appl. Polym. Sci.*, 1988, **26**, 837.
18. Paladhi, R. and Singh, R. P., *Eur. Polym. J.*, 1994, **30**, 251; *J. Appl. Polym. Sci.*, 1994, **51**, 1559.
19. Malhotra, J. P., Chaturvedi, P. N. and Singh, R. P., *Rheol. Acta*, 1987, **26**, 31.
20. Hoyt, J. W., in *Turbulent Flow Interaction and Drag Reduction in Polymer-Flow Interaction* (ed. Rahim Y.), AIP Conf. 1985, Proc. No. 137, AIP, New York, p. 95).
21. Singh, R. P., Chand, P., Reddy, G V., Deshmukh, S. R. and Adinarayana, B., in Proceedings of Third International Conference on Drag Reduction (eds Sellin, R. H. J. and Moses, R. T.), Bristol, *1984, Paper D. 4.*
22. Singh, R. P., Malhotra, J P. Deshmukh, S. R., Majumdar, S. K. *and Sudhakar, K., Turbulent drag reduction in water by Graft* copolymer in presence of salts, DTSR 708401/RD-82, May 1986–*Oct.1988*
23. Choi, S. U. S, Cho, Y. I. and Kasza, J., *Non-Newtonian Fluid Mech*, 1992, **41**, 289.
24. Brostow, W., *Polymer*, 1983, **24**, 631.
25. Brostow, W., Ertepinar, H. and Singh, R. P., *Macromolecules, 1990*, **23**, 5109

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Trenching in the Koyna area

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The results of excavating a trench to uncover fissures associated with the 1967 Koyna earthquake suggest that evidence of prehistoric earthquakes can be preserved in fissures. Future paleoseismological investigations can be used to seek evidence of prehistoric earthquakes in the Koyna–Warna area and at other locations.

THE Killari earthquake of September 1993 was the most recent reminder that peninsular India is not immune to moderate to large earthquakes. Kutch was the site of a major (M_w 7.8) earthquake in 1819. Mid-plate earthquakes (also called stable continental interior earthquakes) occur much less frequently than their plate boundary counterparts. They account for about 0.5% of the seismic energy release but account for a disproportionate amount of damage and destruction. Besides these two events, the *M* 6.3 Koyna earthquake of 1967 was the most destructive earthquake in peninsular India. Although the temporal and spatial pattern of seismicity near the Koyna Reservoir strongly suggest that it was induced (see e.g. ref. 1 for a comprehensive review), this view is not universally shared.

The objective of the studies reported here was to see if evidence of large prehistoric earthquakes and their rates of recurrence can be documented by identifying the evidence of their occurrence in the shallow sediments. That is, could the nascent science of paleoseismology, the search for prehistoric earthquakes, be a feasible approach in the Koyna–Warna area in particular and other areas in the Deccan Traps in general?

To accomplish this, we decided to trench in the Koyna area to see if ground fissures that were widely observed in 1967 are preserved in the shallow soil and if they could be used to identify the evidence of earlier earthquakes.

Fissures associated with the 1967 earthquake

Following the disastrous magnitude 6.3, 1967 Koyna earthquake, widespread fissuring was observed in the meizoseismal area by Sathe *et al.*[2]. Although some of these fissures were associated with slumping of land forms along hill slopes, several fissures were a direct consequence of the earthquake. Among these was a very well-developed system of fissures about 20 km in length from Nanel and Baje on the SE shore of Shivajisagar (reservoir impounded by Koyna dam), SSW to near Randhiv (Figure 1).

The fissures were mapped in detail by the Geological Survey of India (GSI) and it was thought possible to locate them in the field based on the descriptions in the GSI report.

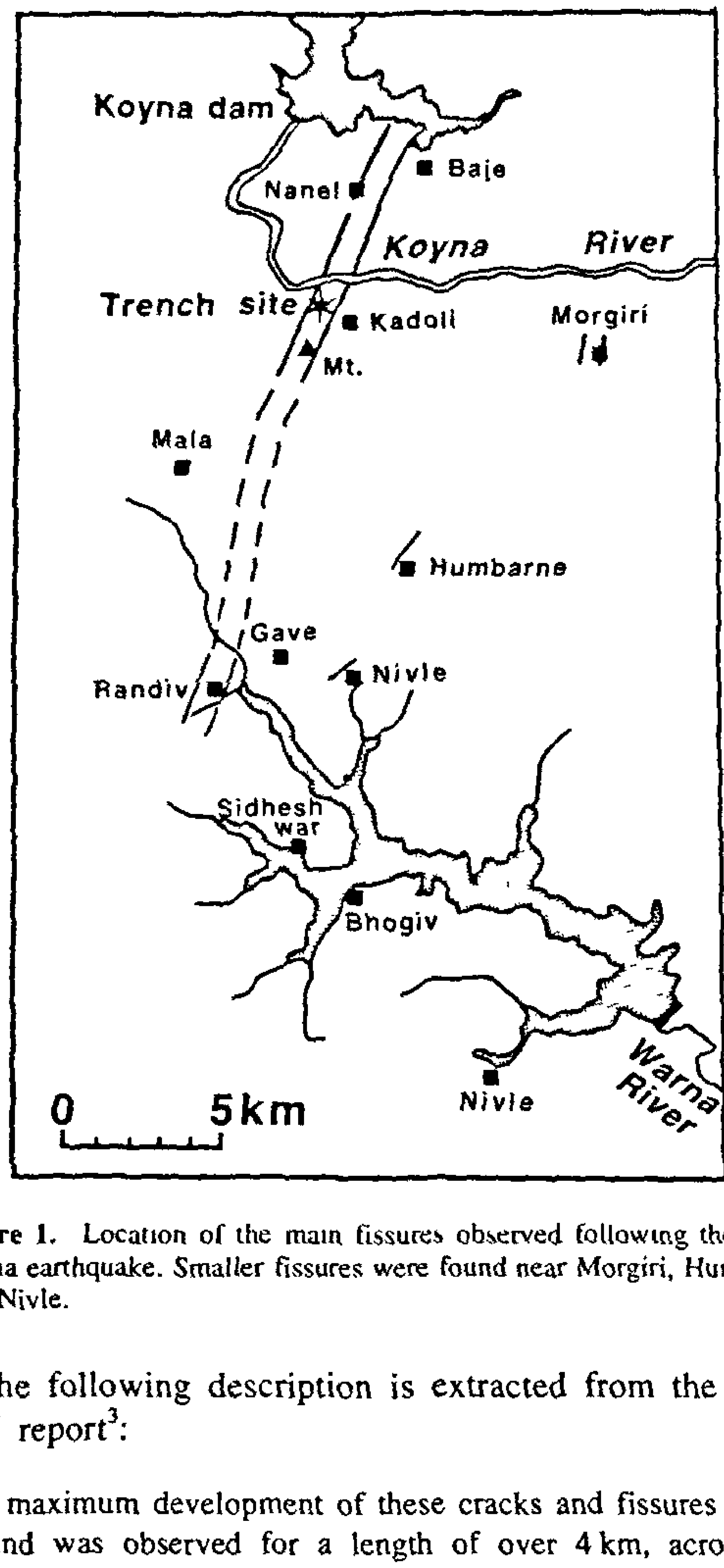

Figure 1. Location of the main fissures observed following the 1967 Koyna earthquake. Smaller fissures were found near Morgiri, Humbarne and Nivle.

The following description is extracted from the 1968 GSI report[3]:

The maximum development of these cracks and fissures in the ground was observed for a length of over 4 km, across the *west-to-east flowing Koyna River between Donechiwada to the* southwest near Kadoli (of which 2.7 km were mapped in detail, the rest were inaccessible). Fissures were also observed both to the south and north of this area but were comparatively inconspicuous and intermittently developed in soil only. Fissures of varying lengths were oriented N–S or N10°E to N25°E and formed a zone nearly 200 m wide. The fissure zone trended NNE–SSW in an *en echelon* pattern. Although this zone of *fissuring is about 200 m wide, the actual distance between the* easternmost fissure in the north and westernmost fissure in the south is about 1 km. Within this zone, these cracks and fissures displayed an easterly shift while proceeding from south to north. The shift interval of these fissures varied from 1 m to as much as 15 m. In addition to this, a number of cracks 3–4 cm wide ran parallel to the main fissures at many places. Individual fissures, which ranged from 10 m to 60 m in length, varied in width from a few centimeters to as much as 40 cm. The maximum observed depth was 2–3 m. A pit opened north of Kadoli to a depth of 2 m on one of these cracks did not reveal its continuity beyond a meter. The fissures showed heaving displacement of 5–10 cm to the west as well as to the east. However, north of Rohini temple, in the thick soil cover, the fissures had been lifted up by 25 cm on the eastern side.

A fine hair crack was observed in basalt outcrop in the nala, 0.8 km WNW of Kadoli, transverse to the trend of the fissures in the soil cover. This is the only place where the basalt has shown failure. On either bank of the Koyna River the fissures lost their continuity in the river gravel, but were picked up again as widely separated thin parallel cracks.

About 12 km SW of Kadoli Village, small fissures or cracks were seen on the lower contours of the western ridge face of Randhiv village trending mostly along a N20°E–S20°W direction. These extended over a distance of 50 m or so and were nowhere more than 1 8 m in depth. The fissure at Randhiv *occurred more or less in the same alignment as those of the* Kadoli–Donechiwada fissures. Detailed examination of the hill slopes of the intervening area between Kadoli and Randhiv did not reveal continuity of these fissures throughout this *intervening tract.*

The 2.7 km long N20°E–S20°W fissure south of Koyna River was chosen for further study because of the excellent descriptions and detailed mapping carried out by the officers of GSI[3].

Trenching in Kadoli area

Shallow trenching was carried out near Kadoli Village located 6.5 km southeast of Koyna Dam (Figure 1). The trenching had two objectives:

1. To see if fissures/cracks observed following the 1967 Koyna earthquake were preserved in the shallow soil.
2. To assess the feasibility of paleoseismic investigations to search for prehistoric earthquakes in the Koyna area in particular and other areas in the Deccan Traps in general.

To select a site for trenching the first step was to locate the fissures in the field below the presently cultivated soil. We had detailed discussions with Dr Sahasrabudhe, formerly of GSI, and a co-author of the report following detailed investigations in 1968. Dr Sahasrabudhe kindly supplied us with a copy of the GSI Report, which included a plate showing the location of the fissures.

In the field, we visited the estimated location of the fissure north of the river near the village Dhonachi Wadi. The new road construction and steep slopes and thick vegetation made it difficult to locate precisely the fissures shown in Figure 1. However, we were able to locate the nala to the south of the Koyna River near Kadoli village where fissures had been mapped by GSI by surveying. We identified two possible locations for cutting shallow trenches in order to encounter the 1967 fissures. These locations were also confirmed by the village elders, who remembered the open fissures from 1967.

Two trenches were cut at the sites identified above. Trench I was hand-cut and is closer to the big bend in the nala. Trench II, located about 130 m to the south of trench I, was cut using a backhoe. Trench I was about 10 m long, 2 m wide at the top and oriented N85°W–S85°E so as to cut the fissures almost orthogonally. It was dug by hand to a depth of about 1 m, and in the area where fissures were encountered it was deepened to a depth of about 2 m. The trench was also widened in the area where fissures were encountered. Trench II was dug by a backhoe to a depth of about 3 m; it was about 2 m wide and 21 m long and was oriented N75°E–S75°W.

Fissures

Fissures were encountered at a depth of about 30 cm on the southern face of trench I. A small fissure was also encountered on the northern face. The northern face contained pebbles and stream cobbles, suggesting that they are paleochannel of the nala, which is now flowing about 30 m to the north. A cursory examination of trench II cut in the late evening did not reveal any obvious fissure.

Most of our descriptions are therefore related to the southern face of trench I. Figure 2 shows the trench log. The bottom of the trench is about 2 m below the surface and is still in the soil. The original soil profile was exposed 20–30 cm below the cultivated soil (labelled plow zone) in Figure 2 and consisted of ochre-coloured to reddish brown clayey soil with high silt content and randomly scattered basalt and reddish lateritic soil pebbles with rounded edges and corners. The predominant soil profile consists of soil with few gravels of laterite. It has been cut by a horizon consisting of limonitic, decomposed granules of basalt. No clear evidence was seen of distinctive soil horizons. The presence of a band of smooth pebbles 5–7 cm wide at a depth of 1.5 m below the surface suggested the presence of a paleochannel cut by the southern face.

In the 2 m width we encountered six fissures on the southern face. The width of these fissures ranged from about 0.5 cm to 5 cm. Except where it had been destroyed during digging, the filled material was loose soil distinguishable from the host material, which was more cohesive and firm. The 'fill' material could be easily pressed with a finger and compacted whereas the host soil was firm. Where loose fill material was removed from the fissure, the inner walls appeared uniform. The fissures tapered downwards (Figure 2) and were traceable to a depth of about > 1 m as they continued to the bottom of the trench. Some of the smaller fissures curved and ended up in the larger fissures. One fine, angular fissure was found terminating into another wider fissure.

The largest fissures were found to continue into the plane of the trench for at least 1 m. A rod inserted in the fissures (horizontally) easily displaced the soil to show that the fissure continued in the plane of the wall. This lateral extent and near-vertical altitude strongly suggested that they were not caused by rodents or abandoned roots.

The depth extent of nearly 2 m (to the bottom of the trench and nearly uniform 2–3 cm width) are strong arguments against these cracks being desiccation cracks. The cracks cut all horizons (soil and pebbly), again suggesting that they are not desiccation cracks. Thus, the occurrence of these fissures in an area where eye witness accounts of the 1967 earthquake had described them, their location where they had been mapped by GSI and the general parallelness of the fractures all favour the conclusion that the fissures encountered in the southern face of trench I were formed by the 1967 earthquake.

The loose filled material in the fissures was easily identifiable and distinctly different from the surrounding

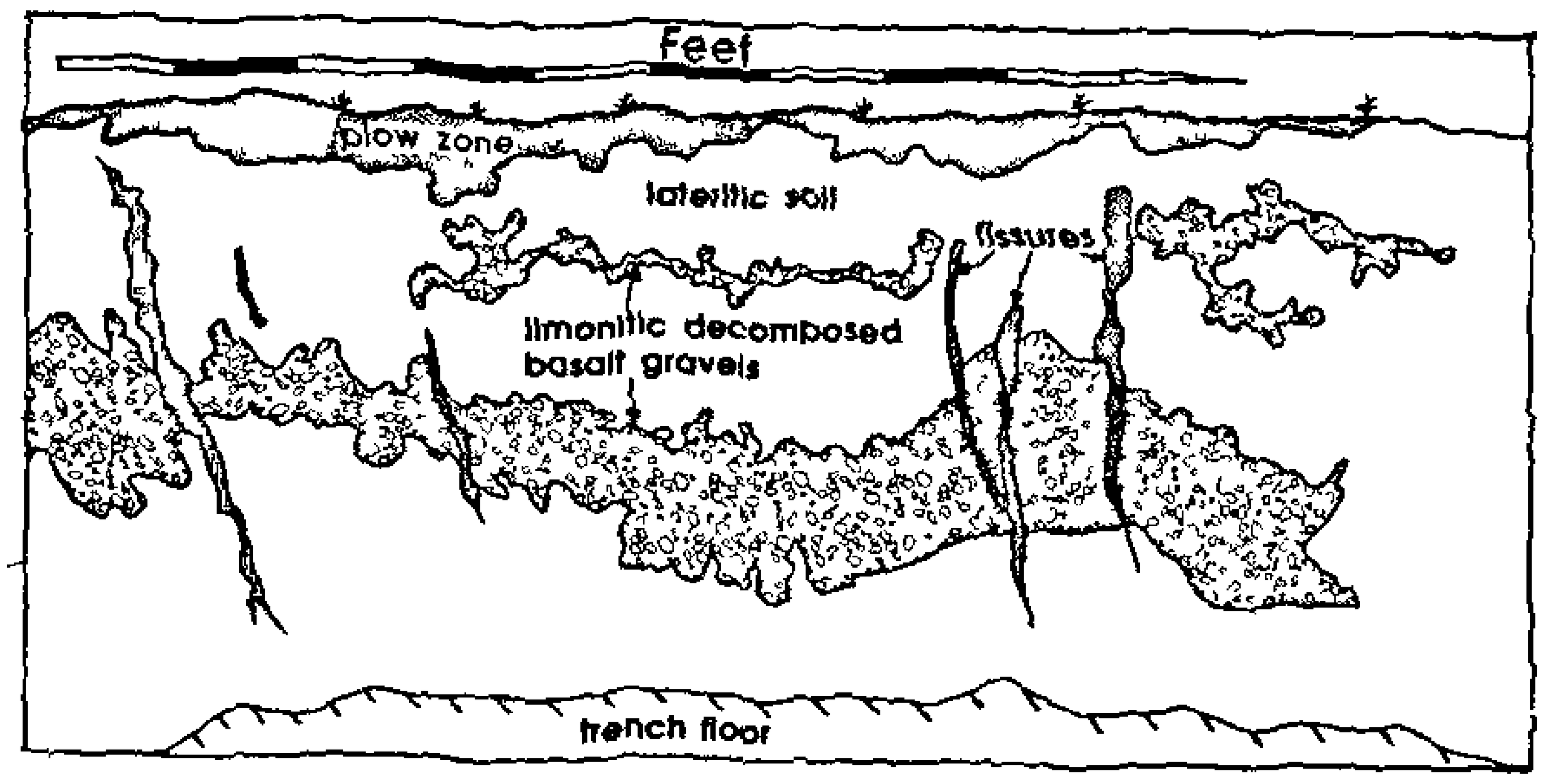

Figure 2. Log of southern face of trench I. Note how the fissures due to the 1967 earthquake cut through the pebbly horizon. (No vertical exaggeration).

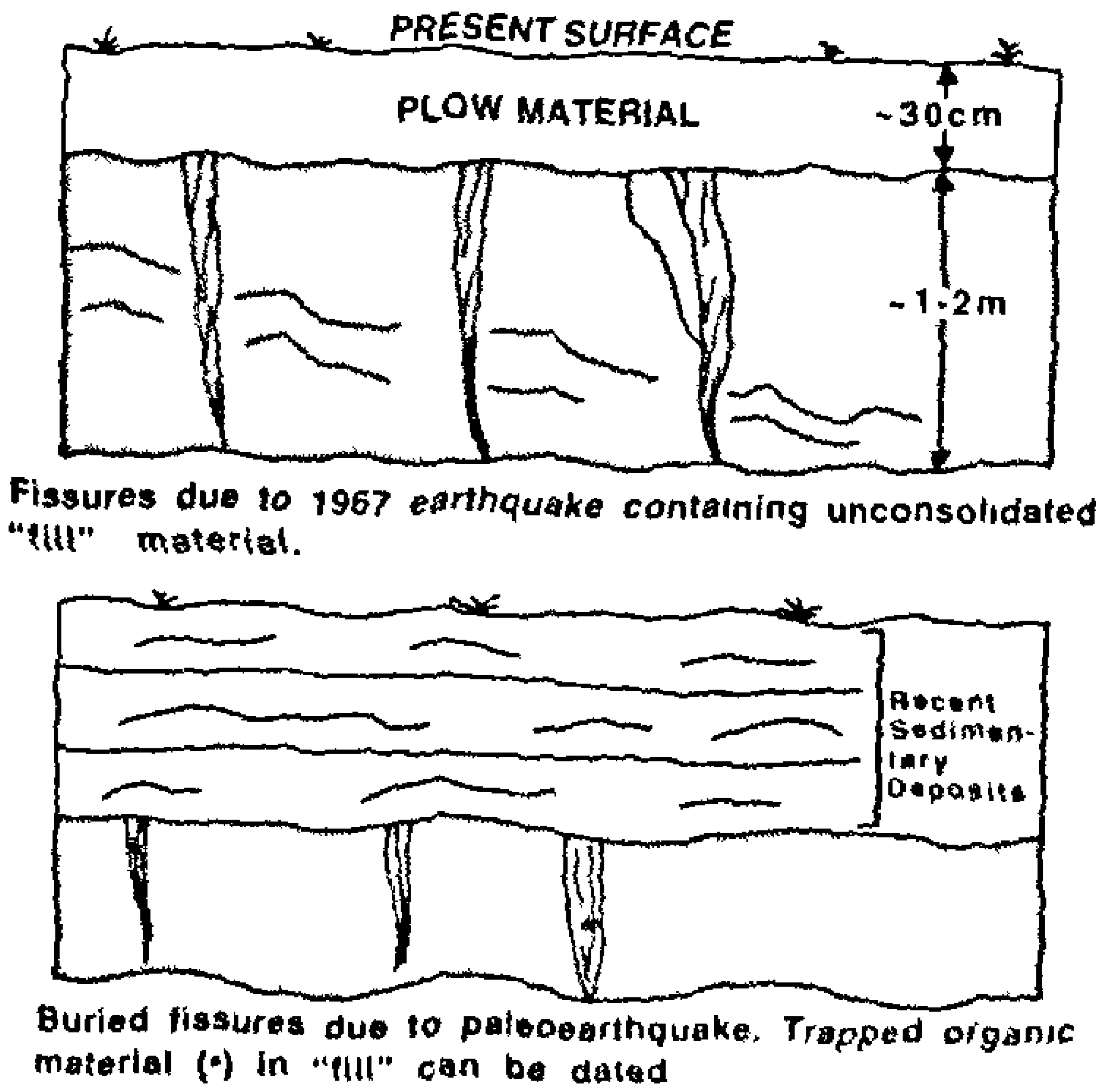

Figure 3. Schematic diagram showing a conceptual view of paleo fissures.

firm, cohesive soil. It was soft and easily removable. It was free from any pebbles and was similar to the loose plow soil.

The observation of the easily distinguishable loose fill material devoid of any pebbles clearly suggested that the fissures had once been open and later filled up from the top with loose soil. Thus, it may be possible to distinguish earthquake-generated fissures by examining the nature of the filled material. Also, the presence of organic material in the filled material can be used to get a minimum age for the earthquake. A cursory search for organic material (pieces of wood, grass, leaves, shells, etc.) within the fill material was unsuccessful.

Figure 3 is a schematic diagram showing a conceptual view of how the fissures associated with the 1967 Koyna earthquake would compare with those for a prehistoric earthquake. The fissures for a prehistoric earthquake would be buried beneath recent sedimentary deposits.

Thus, by identifying paleo fissures in road cuts and other exposures evidence can be sought for prehistoric earthquakes. C-14 dating of trapped organic material in these fissures can be used to possibly determine the dates of prehistoric earthquakes (Figure 3).

Conclusions

From an examination of the features in the trench near Kadoli we conclude that:

1. Fissures formed during ground shaking during a large earthquake are preserved in a sedimentary column.
2. The fissures encountered in the trench near Kadoli were associated with the 1967 earthquake. This conclusion is in concordance with the location and description in the GSI report and eyewitness accounts.
3. These fissures could be traced to at least 2 m below the surface to the rocks below.
4. The fill material in the fissures was distinctly different from the host material and can be used to identify other fissures formed by earthquakes and hence used to search for prehistoric earthquakes.
5. The date of the earthquake can be obtained by dating any organic remains within the fill material using ^{14}C method or by other techniques.

1. Gupta, H. K., in *Reservoir-Induced Earthquakes*, Elsevier, Amsterdam, 1992, pp. 33 86.
2. Sathe, R. V., Phadke A. V., Peshwa V. V. and Sukhatankar R. K., *J. Univ. Poona, Science and Technology Section*, 1968, 34, 15–19.
3. Officers of the Geological Survey of India, in *A Geological Report on the Koyna Earthquake of 11th December, 1967, Satara District, Maharashtra State*, Geological Society of India, 1968, p. 242.

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Tree water relations along the vegetational gradient in the Himalayas

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Natural vegetation of the central Himalayas reflects a strong, extensive environmental gradient. The importance of environment, in particular drought, in controlling species distribution and performance is poorly understood. Indirect evidence and a few measurements, however, suggest that tree distribution is strongly related to drought. A study of water relations of trees in native forests along the environmental gradient up the face of the outer Himalayas near Nainital should make clear the role of water in controlling forest properties, and help test generalizations about tree water relations that were developed in other climates.

TREES in the Himalayas are subject to drought for several months each year. Study of their response to drought can contribute to the understanding of the local patterns of species distribution and performance, as well as to plant water relations in general. Data about water relations are available for many taxa related to species in the Himalayas; this information, however, may not be useful in the Himalayas, where trees grow with a different seasonality of rainfall, and many have different leaf and wood properties compared to related species elsewhere. A study of the responses of Himalayan trees to drought will provide a critical test of generalities developed in other climates. Many aspects of ecology of some Himalayan trees are already well known, allowing the significance of their water relations characteristics to be interpreted effectively.

Vegetation–environment relationships

Ecologists study the control of plant distribution by relating the vegetational changes along environmental gradients to associated changes in the environment. The Himalayas present, perhaps, the premier vegetational gradient on the Earth, ranging from tropical forests at the base to alpine meadows within a map distance of

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