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Palaeoseismic indicators in the rupture zone of the 1993 Killari (Latur) earthquake

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The 1993 Killari (Latur) earthquake in Maharashtra has provided a rare example of surface rupture in the Precambrian shield. No historic seismic events of comparable magnitude have been recorded in Killari. However, deep trenching in the 1993 rupture zone revealed deformational structures consisting of thrust sheets possibly related to previous faulting. These structures indicate that the 1993 event was indeed preceded by earthquakes in the recent geologic past. Our studies also indicated an obsequent fault-line scarp, aligned with the current rupture zone. The morphological features in the area suggest mass removal of the upper part of the hanging wall, that is on the southwestern side of the rupture, aided by the highly crushed nature of the rock and high rate of weathering. Our observations imply a long recurrence interval of seismic events in the epicentral area of the 1993 earthquake.

THE Killari earthquake ($m_b = 6.3$) of 30 September 1993 occurred in a part of the stable continental shield of peninsular India (Figure 1), and is one of the most damaging and rare midplate earthquakes in history. A common global feature of the intracratonic seismicity is that they do not seem to exhibit well-defined spatial and temporal patterns. Previous studies have not been conclusive enough to understand the recurrence pattern of such earthquakes. For example, field studies in the interior of Australia show that earthquakes in shield areas are generated on suitably oriented discrete faults[1]. Alternatively, another set of data implies activation of new faults as the causative mechanism of some of the earthquakes within the continental crust[2]. In this background, the Killari event is of greater significance in that it provides an opportunity to learn about the rarely occurring cratonic earthquakes. Further, from the point of view of the seismic hazard assessment, a key question addressed here is whether this event had any association with a preexisting fault.

The Killari earthquake occurred in an area, zoned as having the least seismogenic potential, and considered to be devoid of any neotectonic activities and significant historic seismicity. It is located near the eastern margin of the late Cretaceous–Eocene basalt flows (Deccan Traps). The basalt flows in Killari, estimated to be several hundred meters thick (~ 450 m), are presumably underlain by Precambrian granite-gneiss. Although, in general the terrain is flat, the Bouguer anomaly map of the area[3] indicates an uneven basement, marked by bedrock ridges and basins. The flows are of varying thickness and are occasionally separated by layers of red bole. Red boles are believed to be hydrothermally altered basalts, reddened by the succeeding flow. They remain as hard rocks as long as they are not exposed, but rapidly disintegrate to red clay upon exposure. The flows in the area, composed of both compact and amygdaloidal basalts, are highly weathered. The exfoliation and associated 'onion-skin' fractures are most common on the upper part of the flows. Fairly large deposits of alluvium are present along some of the river valleys.

Whether or not Deccan Traps are affected by the basement faults is controversial among the Deccan Trap

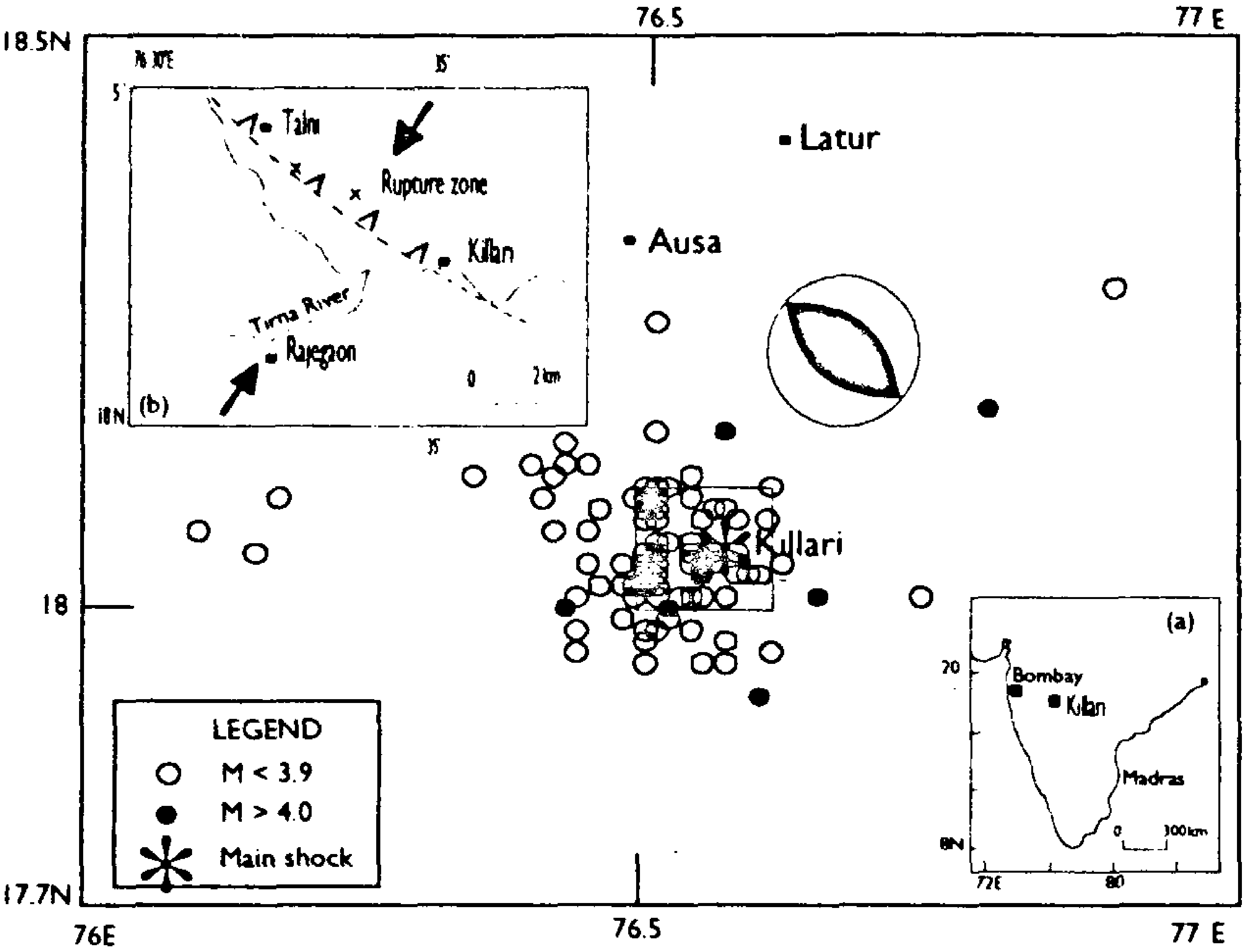

Figure 1. Map showing aftershocks in Killari area (data source: India Meteorological Department). Beachball represents fault plane solution of the main shock. The straight arrows indicate inferred σ_1 direction. Dashed lines with teeth shows the postulated fault. Inset on the top left shows the magnification of the area marked by a square in the middle.

geologists[4]. In some of the reports[5] on the Latur earthquake, the authors are of the view that the Trap rocks in Killari have not been affected by the 1993 earthquake. These workers believe that the basement fault has not propagated through the Trap rocks. Ground check of the lineaments obtained from the remote sensing data in the Killari area by them showed that these lineaments generally conform to the stream courses, and do not seem to have any relation to faulting. These observations, however, need to be amended in the light of our findings, which is the subject matter of this article. Our results show that the trap rocks in the Killari area have indeed been affected by the seismic events and are characterized by a unique pattern of deformation.

The initial attempts at trenching by Seeber *et al.*[6] in the rupture zone (Figure 2) clearly showed the displacement of soil–rock interface with a reverse sense of throw (see Figure 5). This unequivocally proved that the basalt flows have been affected by style of faulting of the 1993 earthquake. Furthermore, the helium degassing observed in the rupture area[8] suggests that the deformation recorded here is related to the processes in the deeper levels of crust. However, the trenches which were dug to a depth of 1 m failed to reveal the palaeoseismic structures[6,7]. Thus, the apparent lack of preexisting structural anomalies and absence of definitive stratigraphic evidence of previous faulting in the epicentral area compelled Seeber *et al.*[6,7] to describe the Killari earthquake as fresh event on a new fault. The question addressed in our investigations was whether there is any evidence of repeated activity in the rupture zone. Here we present our salient observations which suggest previous deformation in the epicentral area of the 1993 earthquake, and discuss its implications.

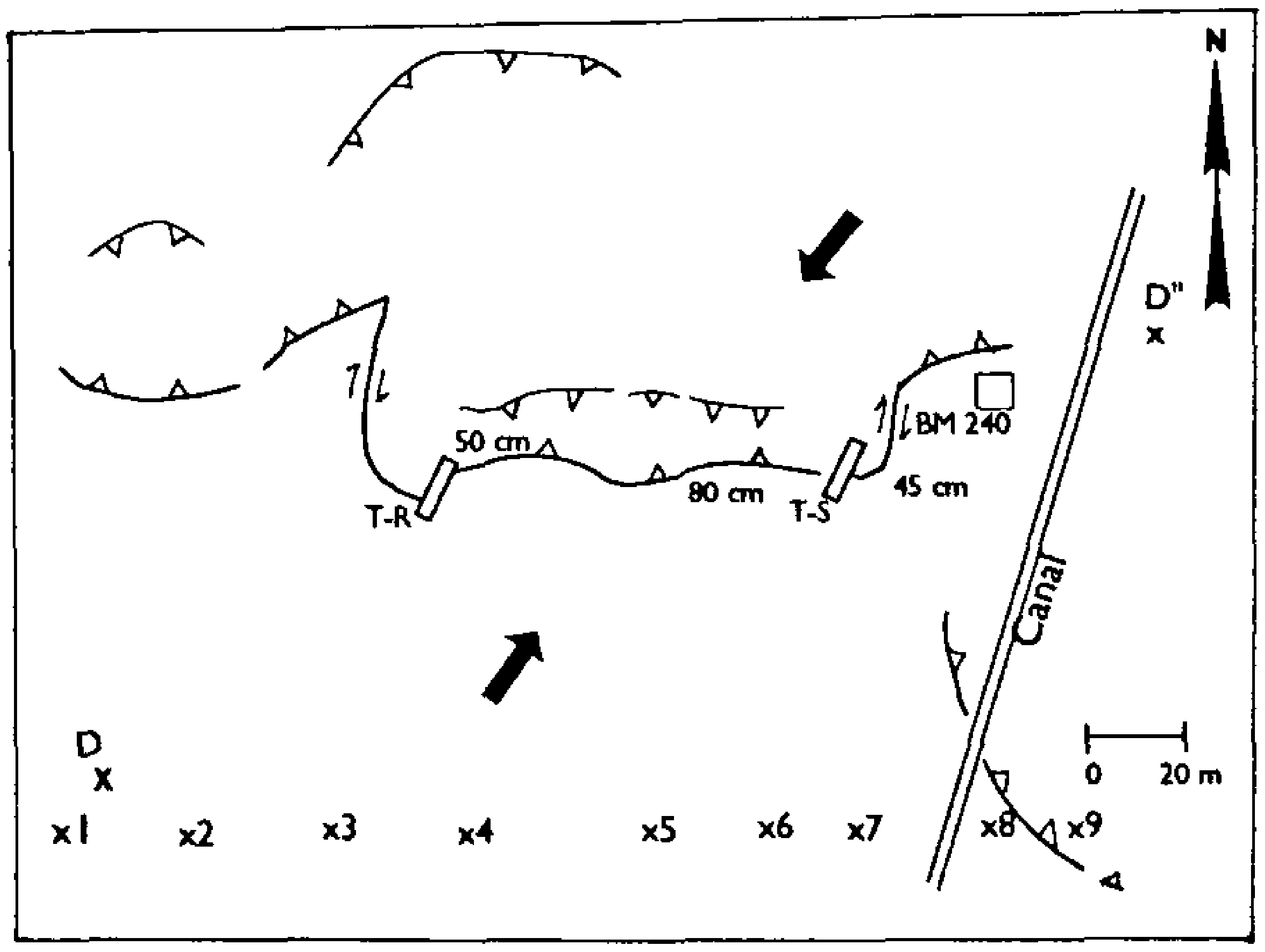

Figure 2. Sketch of the central part of the rupture zone near Talni. Arrows indicate σ_1 direction. 'x' shows location of the profiles. D–D″ shows the direction of the profile taken diagonally, which is shown in Figure 4.

Rupture zone

A 500-m-long, 100-m-wide rupture zone was located near the village Talni, about 4 km north west of Killari (see Figure 1 for location of Talni). The rupture zone consists of discontinuous and opposite vergent scarps (Figure 2). Scarp heights are typically 45–50 cm; the maximum height is ~ 80 cm. This complex rupture pattern has a dominant ENE–WSW trend. The escarpment consists of two parallel scarps and a raised broad ridge between them. Indication of strike-slip motion (maximum horizontal displacement ~ 70 cm) can be discerned on the eastern and western sides of the rupture zone. The rupture zone is also marked by open fissures and ground cracks. The trace of this zone probably extends discontinuously up to Talni in a WNW direction, including an uplifted area associated with the 1993 event[9].

The focal mechanisms indicate reverse faulting on a NW–SE striking nodal planes with one of the nodal planes dipping 40° to the southwest[10]. This suggests that the south-west block (hanging wall) in the rupture zone has been thrusted onto the north-east block (footwall). Accumulated vertical slip in the normal course should have developed a topographic high on the southwestern side. Interestingly, what is present in the area is a topographic high towards the footwall on the north-east, which is opposite to the expected tectonic effect.

In order to constrain the topographical characteristics of the area, a number of elevation profiles were taken across the rupture zone, using digital theodolite and electronic distance meter. The most representative of the eleven profiles is shown in Figure 3. A notable morphological feature of these profiles is that the hanging wall block of this fault occurs at a lower elevation, in spite of it being overthrust onto the footwall block on the northeastern side (Figure 4 *a*). We interpret this to be the result of repeated thrusting from the south, which must have left this block highly crushed and fragmented, facilitating erosion, in contrast to the footwall which is more compact and massive. These processes may have resulted in preserving an obsequent fault-line scarp (Figure 4 *b*). Our observations are also consistent with the features exposed in the deep trench which will be discussed later. Our observations suggest, somewhat tangentially, that during the periods of long interseismic quiescence, most geomorphologic expressions got washed away, leaving little evidence of any previous activity. This aspect of tectonically produced landscape, outstripped by more vigorous erosional processes is a major constraint in the development of geomorphic expression of faults in the intracratonic settings, as also observed in other stable cratons[1,11].

Trenching

Several teams of investigators have attempted trenching in the rupture zone. And, all of these attempts were restricted to a depth of 1 m. These shallow trenches[7] exposed a reverse sense of throw and a south dipping fault (Figure 5); but did not reveal any past offsets[6]. According to Seeber *et al.*[6,7] the mode of faulting observed in these trenches was influenced by the geometry of the preexisting exfoliation fractures. They observed two kinds of fractures: the larger vertical ones in the north–northeast direction in the direction of shortening, which were interpreted by them as extension fractures parallel to the direction of maximum compressive stress and the second group was interpreted by them to be exfoliation fractures related to weathering, and were parallel to the rock–soil interface. The sense and amount of rotation of the fragments from their original position in the exfoliation structure seems to align with the 1993 deformation. Seeber *et al.*[7] however, did not see any evidence of 'pre-1993 deformation along any of the 1993 fault, as in the form of slickensides, concentrated zones of weathering or mineralization'. Thus, they concluded that the 1993 rupture developed on a new fault or a fault with no substantial neotectonic displacement.

A trench measuring 5 m long, 2 m wide and 2 m deep was dug across the rupture zone (N20°E) close to the western end (Figure 6). The trench exposed basalt flows belonging to various generations, fragmented and disturbed by later processes, and presented a highly complex picture[12]. We present here an account of the structures observed in the trench and reconstruct a scenario for their formation. Several structures, including a low angle (~ 15°) south-west dipping thrust fault were exposed on the southern wall. From the disposition of the structures, it was clear that the southwestern block had been thrusted onto the northeastern block (Figure 6). The shear planes and the rock layers showed the same dip angle (~ 15°). In contrast, the northern wall, although highly compressed and buckled, consisted of north-east dipping layers of basalt. Presence of both vertical and south-dipping mineralized veins was observed on the walls. The rock fragments exposed on the northern wall were larger (≥ 8 cm) in comparison to the highly crushed basalt of the southern block. In addition to the multiple thrust sheets, a layer of highly flexured and fragmented reddish basalt, which did not show any offsets, was exposed at the base of the trench (Figure 6). The trench walls also showed a wide impact zone around the thrust sheets, comprising minute fragments embedded in yellowish and whitish clay.

The structures revealed on the trench walls were dominated by multiple thrust sheets (Figure 6). Even

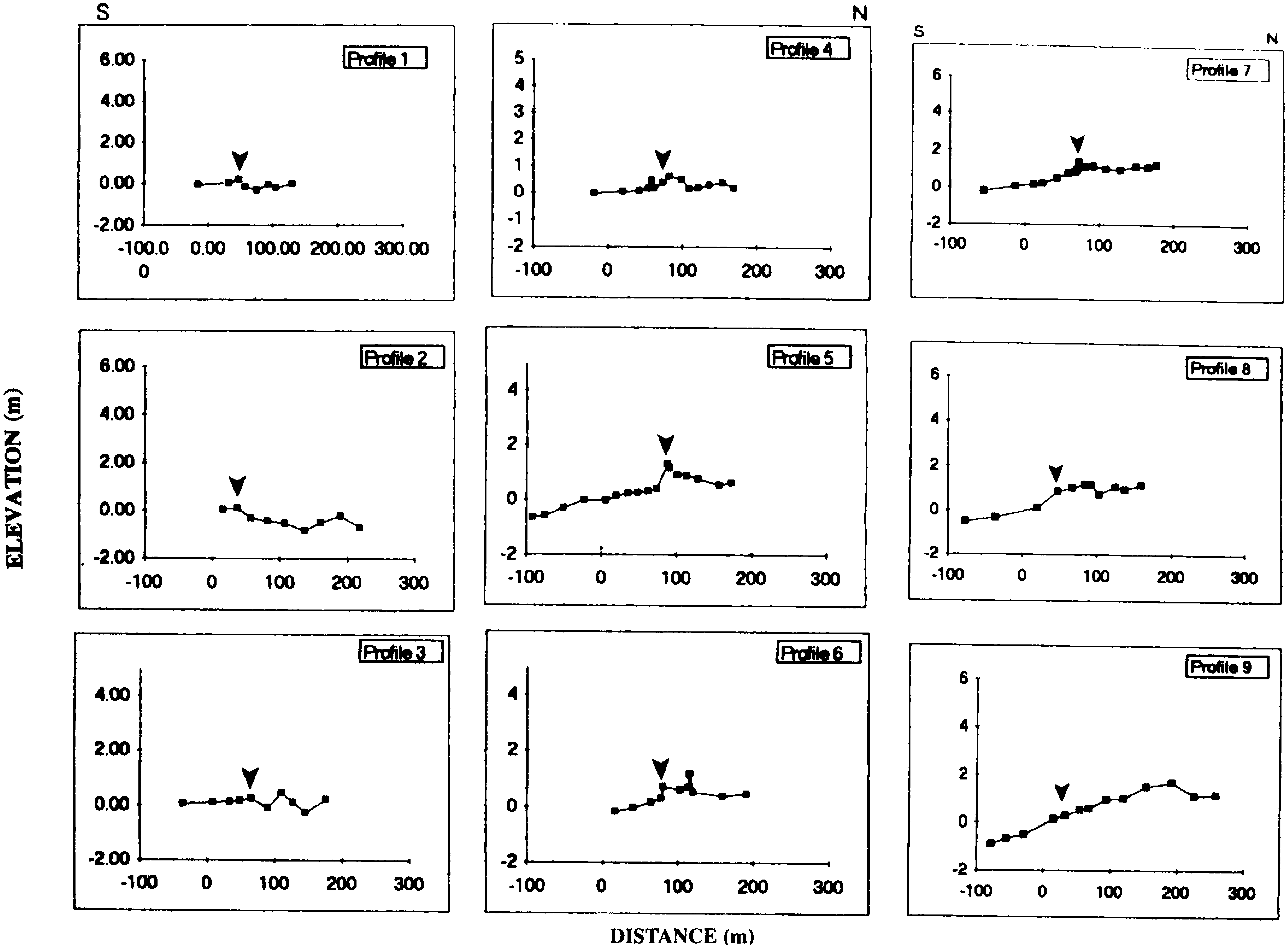

Figure 3. Topographic profiles across the rupture zone. See Figure 2 for the locations. Arrow marks denote the point of increase in elevation.

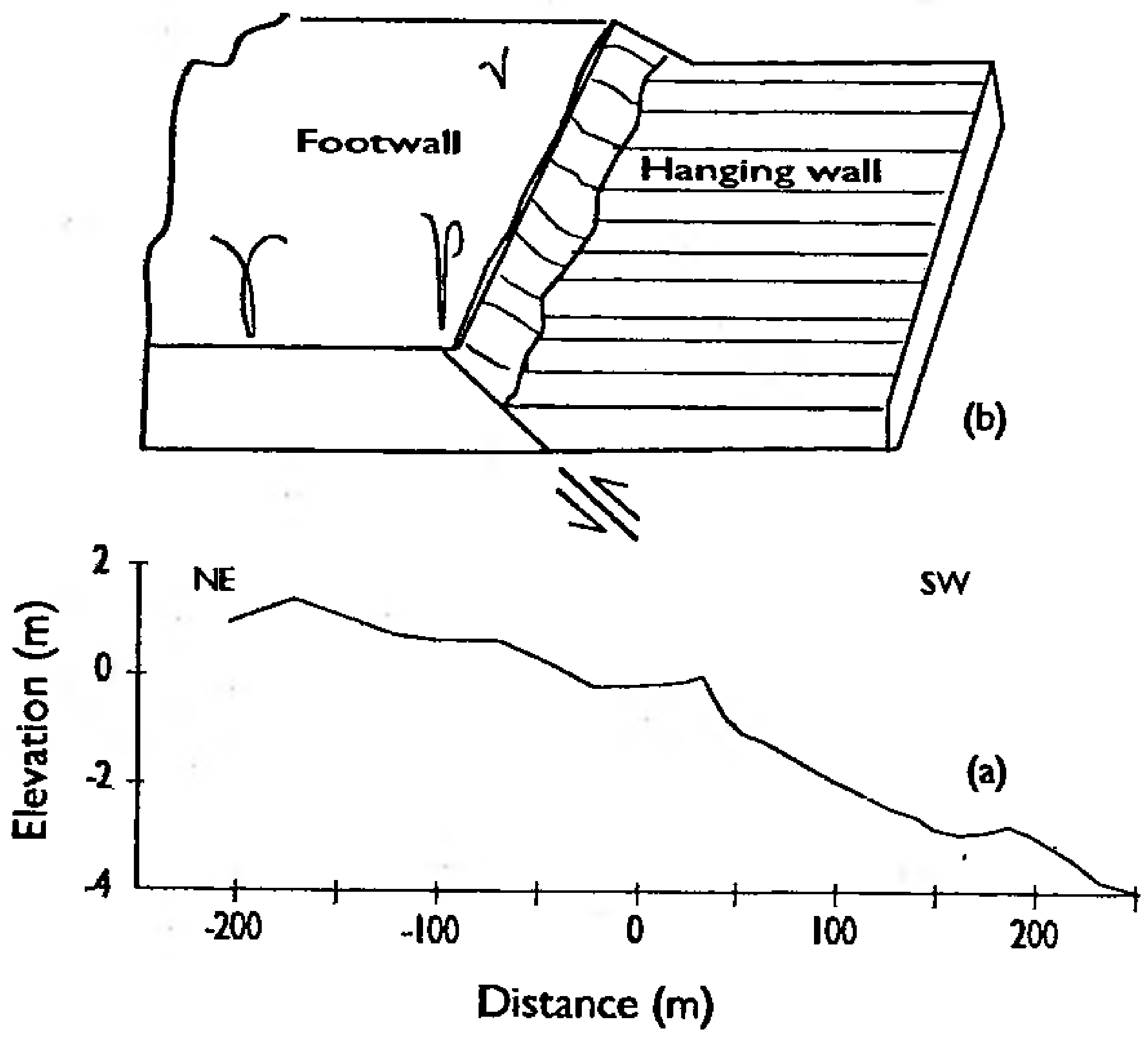

Figure 4 ***a*****,** ***b*****.** ***a***, Topographic profile taken diagonally across the rupture zone. Profile taken along D – D″. See Figure 2 for profile location. ***b***, A schematic diagram of the fault-line scarp. Note the topographic low on the southwestern side.

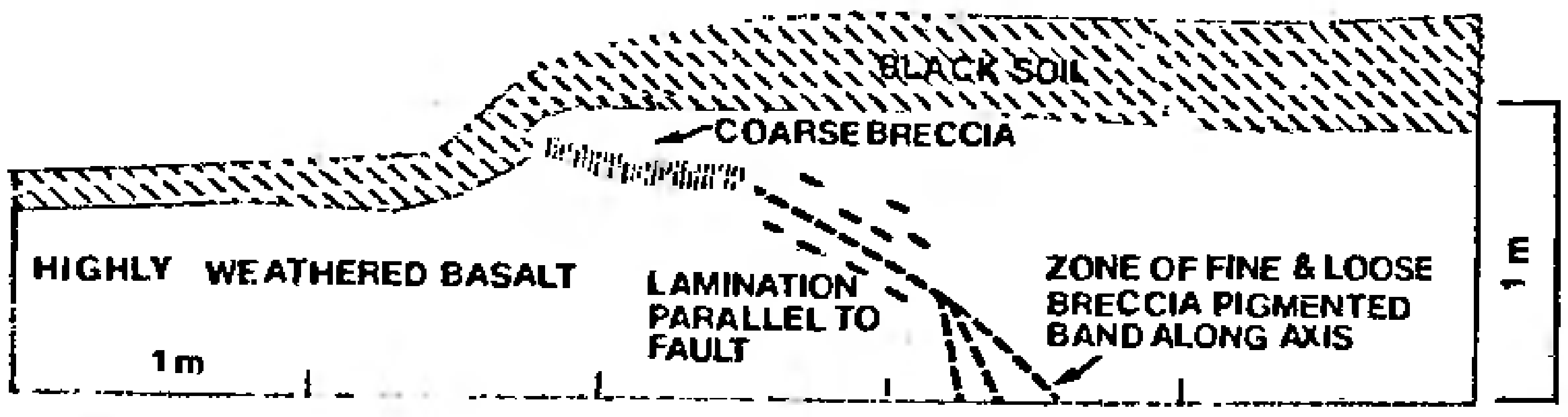

Figure 5. Shallow trench showing the 1993 fault (Seeber *et al.*[6]). See Figure 2 for the location, denoted as TS.

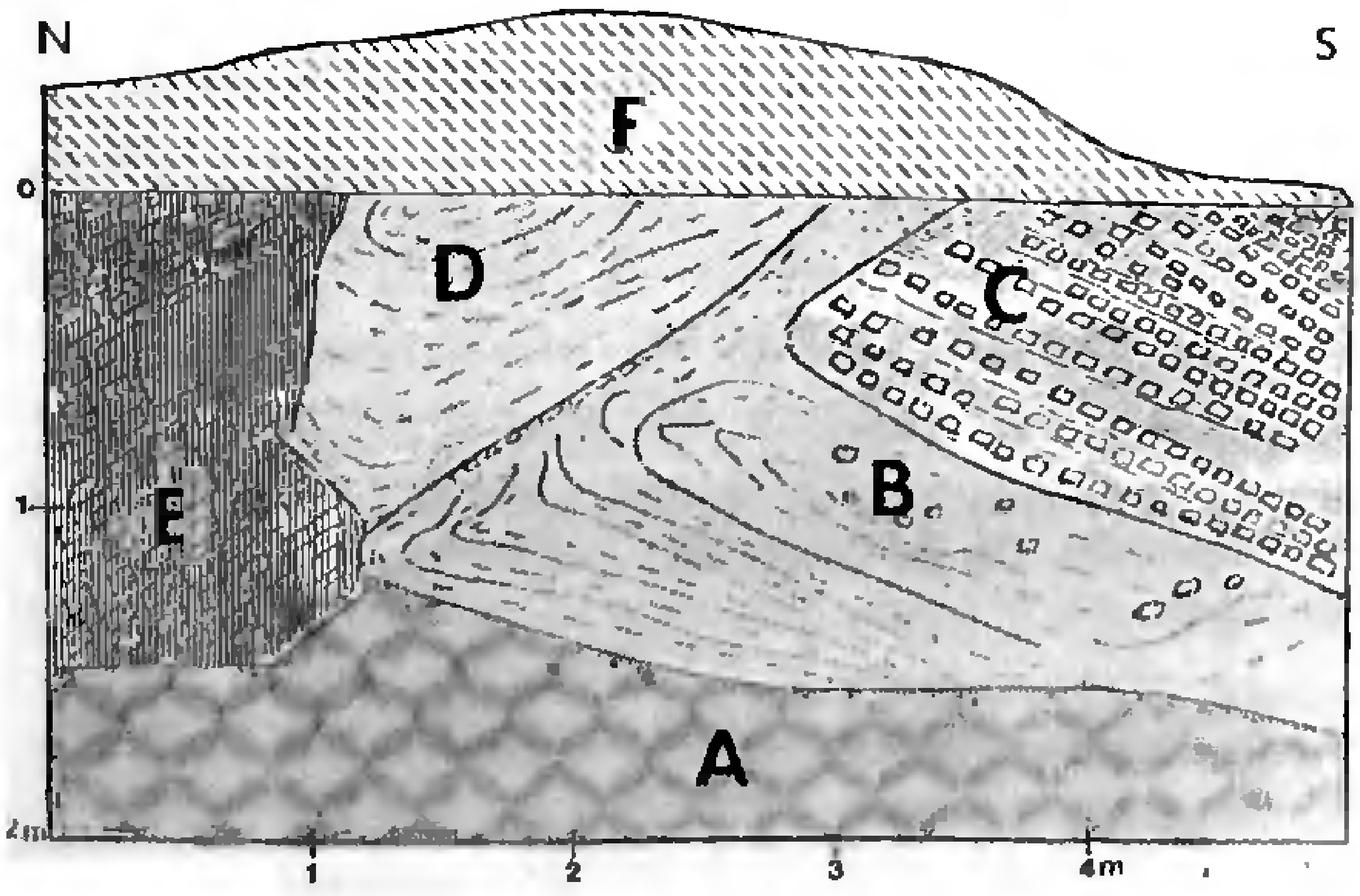

Figure 6. Eastern wall of the deep trench across the rupture. See Figure 2 for the location, denoted as TR. A, reddish basalt; B, older thrust sheet; C, recent thrust sheet; D, yellowish-coloured fault gouge; E, foot wall; F, soil.

though the older structures were highly weathered, the outline of at least one older thrust sheet was clear. The topmost thrust sheet which appears fresh and less weathered may be associated with the 1993 event, and those just below may be related to previous earthquakes. Around the folded nozzle, highly weathered, and crushed rock, probably representing the fault gouge of an older event was found. Freshly formed fault gouge was also observed, along with the older yellowish and reddish coloured gouge. Some of the shearing planes were filled with the crushed rock material. The recent movement had crushed the rocks further and accentuated shear planes that must have formed during the previous events. The thrust sheets had obviously propagated along the layer of underlying reddish basalt, which probably acted as a detachment surface (décollement). An analogy may be made here to fault-bend or fault propagation folds where the thrust sheets move over the weaker rock layers[13]. These thrusts generally propagate along the detachment surfaces which define bedding planes, and are also called as bedding thrusts.

The presence of thrust sheets from earlier deformation below the 1993 event horizon suggests repeated activity on a preexisting fault. The minimum age of the penultimate faulting cannot be estimated by direct methods, as no organic materials were present in the trenches. The subdued topography and the erosional scarp in the rupture zone are suggestive of erosion of the previously formed fault ramp and long recurrence interval (of the order of hundreds of thousands of years) of slip events.

Discussion

Our analyses suggest that the Killari earthquake occurred in a region of previous seismic activity. The structures exposed on the trench walls indicate repeated thrusting related to previous faulting. If pattern of deformation observed in the trench is of any indication, then much of the near-surface deformation in the Killari area will be in the form of a parallel folding which is typical of contractile regions[14,15]. In this type of deformation, stack of competent beds, interlayered with incompetent layers (e.g. red bole layers) is end loaded and the competent beds buckle by slip on mechanically weaker bedding surfaces separating stiffer beds[16]. The challenge in these areas, that are characterized by very long interseismic period, is to differentiate original deformational structures on the rocks from other extraneous features superimposed by the weathering and erosional processes. As there are no aseismic mechanisms that can explain the generation of these type of structures, the folds and flexural bends and the associated structures may provide clues to the underlying fault that might otherwise remain unobserved[17]. Most importantly, identification of similar structures in the region will be helpful in the recognition of seismic source zones.

The subdued topography in the rupture zone area is suggestive of erosion of the previously formed fault scarp, which indirectly points to a long recurrence interval of slip events. Our study confirms that the Killari event is a typical case of reactivation of a segment of an ancient fault zone, where repeated activities with long intervals have occurred.

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MEETINGS/SYMPOSIA/SEMINARS

National Symposium on Technological Advancement in Rice Production

This symposium is being organised by the co-sponsorship of Indian Council of Agricultural Research and Kerala Agricultural University during the 2nd week of May 1996 at Pattambi. All rice workers of international and national level are requested to participate in the deliberations.

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National Conference on Radiation Shielding and Protection (RASP-96)

Date: 26–28 June 1996
Place: Kalpakkam

Topics include: Basic nuclear data and validation; Analytical and computational methods; Reactor physics and radiation transport; Physics and engineering of shield design; Shielding experiments and analysis; Dosimetry and radiation measurements; Radiation effects and radiation damage; Spent fuel active sources, handling and transport.

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The Sixth User Interaction Workshop (with specia on IRS-1C)

Date: 14 March 1996
Place: Hyderabad

The objective of the Workshop is to discuss the produc procedure, data utility, user services and other relevant is to data products and its supply and exciting possibilit applications.

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