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Widespread Geologic Evidence of a large Paleoseismic event near the Meizoseismal Area of the 1993 Latur Earthquake, Deccan Shield, India

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ABSTRACT

The occurrence of large to major earthquakes in Stable Continental Regions (SCR) is a rare phenomenon, generally associated with very long recurrence periods. The deadly seismic event (M-6.3) of 30th September 1993 in Latur district, Maharashtra, and the Jabalpur earthquake of 1999 (M 6.1), central India, challenge the earlier assumptions of the aseismic nature of the Deccan shield of India. Lack of historic seismic records for this region and the recent debate about the reactivation of a pre-existing fault in the basement beneath Deccan traps as the causative source for the 1993 Latur earthquake, led us to investigate the paleoseismicity of Latur, Osmanabad region. We present geological evidences, obtained from three sites, 60 km apart, of a paleoseismic event that took place during 190 BC-410 AD in the meizoseismal area of the 1993 Latur earthquake. The paleoseismic signatures like faults and liquefaction features (such as flame structures) are identified in four trenches made in the alluvial deposits of Tirna and Manjira river valleys. The timing of the paleoseismic signatures is constrained by radiocarbon dating of a number of organic samples from trenches at three sites, as well as through archaeological artifacts found in and around the disturbed horizon in one of the sites. The observed stratigraphic relations and concurrent ^{14}C dates strongly suggest that the observed paleoseismic features resulted from a single prehistoric seismic event, the magnitude of which could be inferred to be greater than that of the 1993 Latur earthquake.

INTRODUCTION

In intra-plate regions, seismicity is commonly localized along pre-existing structures or weak zones. The seismic potential of such weak zones or pre-existing structures is illustrated by 10 historical surface-rupturing earthquakes between 1819 and 1989 [*Johnston*, 1991], prior to the 1993 Latur event [*Gupta*, 1993], in peninsular India. Lack of in-depth observations of the spatio-temporal patterns of large earthquakes in stable continental interiors precludes an estimation of their recurrence interval essential for realistic earthquake hazard assessments. On the other hand, the relative long recurrence intervals of intra-plate earthquakes can be obtained conveniently through paleoseismology [*Tuttle and Schweig*, 1995, 1996].

Paleoseismological studies conducted on some stable continental aseismic faults [*Crone and Luza*, 1990; *Adams et. al.*, 1991; *Crone et al.*, 1992] indicate that potentially hazardous faults can remain quiescent for a long time. Paleoseismological studies around the meizoseismal area of the 1886 Charleston earthquake indicate six paleoseismic events in that area with a recurrence interval of about 500 - 600 years [*Talwani and Cox*, 1985; *Talwani and Schaeffer*, 2001]. Studies of the Meers fault (Oklahoma) suggest two major events in the past 3000 years; and trenching at Tennant creek and Marryat Creek, [*Crone et al.*, 1992; *Machette et al.*, 1993] gives evidence of a recurrence time of more than 100,000 years. Thus, the present state of knowledge on SCR earthquakes indicates very wide differences in the recurrence period of earthquakes in SCRs, which calls for a greater

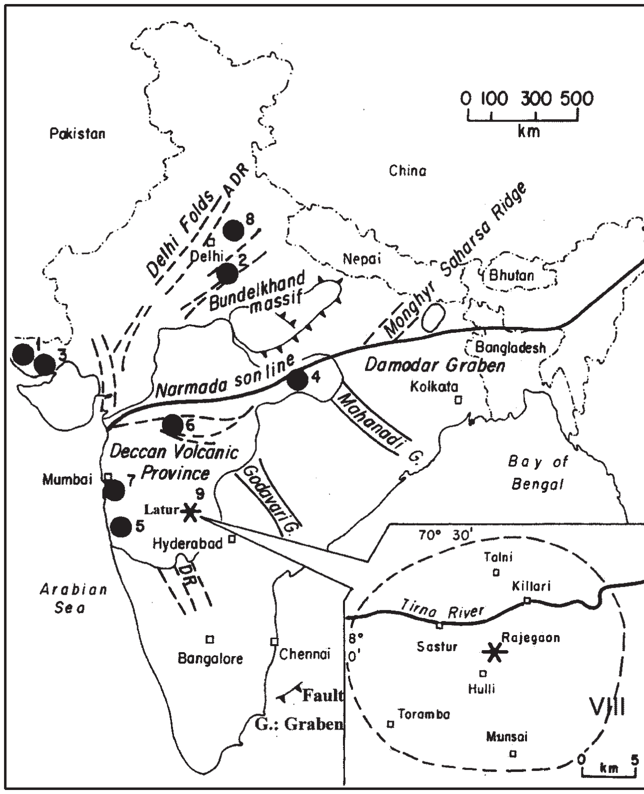

Figure 1. Generalized tectonic map of the stable continental region of India. The star is the epicenter of the Latur earthquake of September 30 1993. Numbered solid circles indicate large earthquakes: 1 - 1618, M=6.24; 2 - 1926, M=6.40; 3 - 1938, M=6.26; 4 - 1967, M=6.3; 5 - 1993, M=6.3; 6 – 1999, M=6.1. Stippled areas denote Mesozoic-Cenozoic volcanism; DR - denotes the Dharvar Rifts and ADR the Aravalli Delhi Rift (Precambrian). (Inset) The meizoseismal area of the 1993 Latur earthquake. Dashed line represents the MMI VIII isoseismal. The surface rupture zone is indicated by dotted line. [Adapted from *Gupta*, 1994a].

understanding of both the long-term and short-term behaviour of seismogenic faults through paleoseismology studies.

Of the 100 SCR earthquakes worldwide with M>6 [*Johnston*, 1993] prior to the 1993 Latur event, eight earthquakes occurred during the period 1618 to 1967 within the stable continental region of India, and all eight are associated with rifts or continent-ocean transition zones [*Gupta*, 1994a]. Earthquake catalogues for peninsular India [*Chandra*, 1977; *Rao and Rao*, 1984] indicate that no significant earthquake (M>6) occurred in the Killari (Latur, Fig.1) region during the last 800 yrs. *Johnston and Kanter* (1990) pointed out that large intra-plate earthquakes are related to stretching in the continental crust associated with rifting. Strangely, the Latur earthquake (M-6.3) occurred in an area having no known rifts, and the nearest postulated Khurdwadi rift [*Gupta*, 1994b] is more than 70 km away. It is included in the list of ten SCR earthquakes [*Johnston and Bullard,* 1990; *Adams et al.,* 1991] associated with known surface faulting. The 1993 Latur earthquake killed approximately 11,000 people in central peninsular India. The earthquake not only raised doubts about aseismic character of the Deccan Shield but also stimulated many researchers to study the origin of the event. The Maximum modified Mercalli intensity of VIII defines an area of about 10 sq. km (Fig.2). The deformation Zone produced by the Latur earthquake extends over a distance of about 3-km in NW-SE direction with a width of 300 m [*Gupta et al.,* 1993]. This deformation is chiefly characterized by surface rupture and is associated with geomorphological changes in the form of relative subsidence and/or uplift and local upheavals of the ground surface on a small scale. However a narrow, linear ridge about 40 m long and 2-8 m wide bounded on either side by subsidence was physically observed close to Killari (in southeastern side) [*Chetty and Rao*, 1994]. Trenches excavated across this ridge show south dipping fault planes with an apparent displacement of ~10 cm. A few isolated, vertically open fractures of different orientations are also present in the deformation zone where the overburden (topsoil) is relatively more

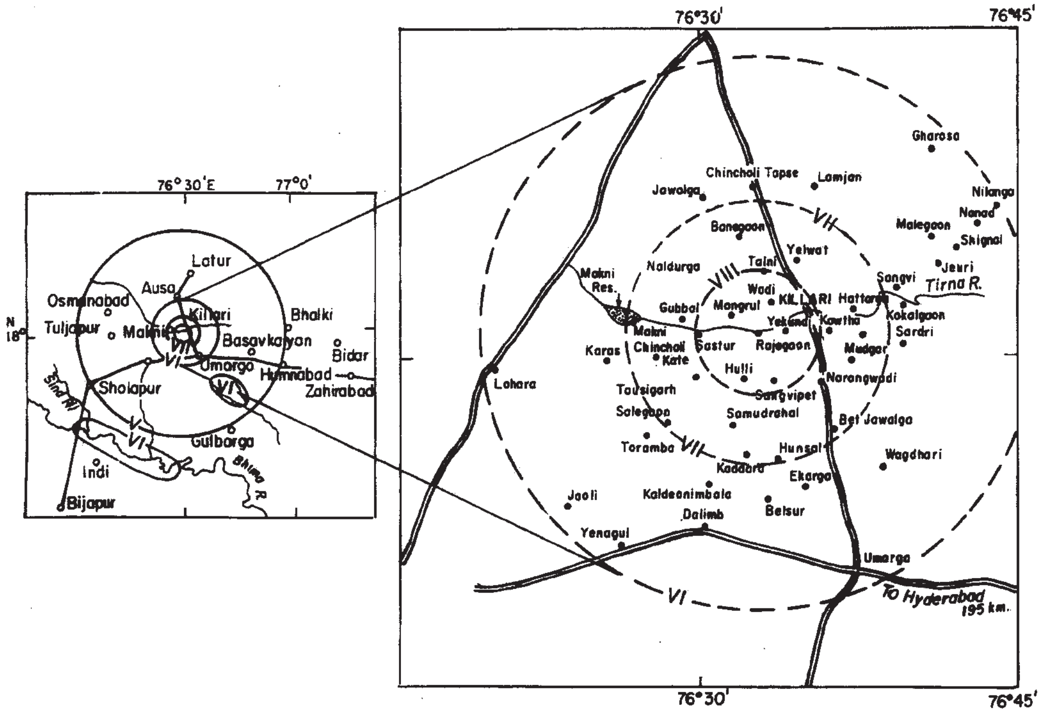

Figure 2. Map Shows the Isoseismals V to VIII of 1993 Latur earthquake. The meizoseismal area (about 10 sq. km) encompassed by isoseismal VIII. Isoseismals V-VIII were drawn based on field surveys and news paper reports, and the meizoseismal area on the basis of field surveys [*Indra Mohan and Rao*, 1994].

compact. Several subsurface faults [Fig.3; *Chetty and Rao*, 1994] along the Tirna river, have been inferred based on anomalous and/or sudden changes in the river's drainage pattern such as sharp bends, linear courses, convergence or divergence, deflected drainage etc. using satellite pictures. These sub-surface faults strike predominantly NW-SE direction. However many lineaments in east- west and north-south directions are also common.

Seeber [1994] suggested that large earthquakes in stable continental areas are produced by many ubiquitous faults with varying frequencies, which show no obvious correlation with historically recorded patterns of seismicity. *Seeber et al.* [1996] in their analysis of a probable source mechanism for the 1993 Killari earthquake did not rule out reactivation of a pre-existing fault. However, other possible source mechanisms advanced include a new fault in the overlying basalts and reservoir-triggered seismicity in Killari (near Latur) [*Seeber et al.*, 1996]. In contrast, *Rajendran et al.* [1996] argue that the 1993 Latur event is part of a series of episodic seismic activity, with long intervals between events, for which they have found geologic evidence in trenches made across the 1993 rupture area. *Rajendran* [1997], and *Rajendran and Rajendran* [1999] studied the river bluffs at Ther and observed flexures, warps, buckle folds and vertical offsets in the sedimentary section. On the basis of limited radiocarbon age data and archaeological evidence they suggested that the area experienced an earthquake around 350-450 A.D.

We present here geological evidence of a prehistoric earthquake, recorded in the alluvial sediments of the Tirna River near Ther (Site 1 and 1A) and of the Manjira River near Halki (Site 2) and Shivoor (Site 3), Osmanabad district, Maharashtra State (Fig. 4). The sites 2 and 3 are located towards east approximately 60 km away from site 1 and 1A, and the distance between sites 2 and 3 is about 15-20 km in N-S direction (Fig.4). Figure 4 also indicates the epicentral area of 1993 earthquake and the rupture zone. The site at Ther village is of archaeological importance, being the site for three civilizations between 3rd century B.C. and 3 rd century A.D. [*Chapekar*, 1969]. Its location at the intersection of prominent lineaments trending NW-SE and ENE-WSW (Fig.3), its proximity to the meizoseismal area of 1993 earthquake, and lack of historical records (though local tradition says that the site had earlier experienced upheavals), together led us to conduct the paleoseismological studies at Ther and two other sites at Halki and Shivoor (Fig. 4).

Table 1. Carbon-14 dates of Organic samples collected from Ther, Halki and Shivoor trenches for paleoseismic studies.

Site	Sample . code	Type of sample	Location of sample in the geol. section	Uncalibrated Carbon-14 ages (Yr. BP)	Weighted mean # (Yr. BP)	Calibrated ages *	UB /LB	Calibrated date of weighted mean
Ther(site 1)	Th- 1	Half burnt wood	Bottom Burnt Bed (BBB)	2030±110		360 BC-235 AD	LB	
"	Th- 2	Burnt grains	"	1980± 90		190 BC-240 AD	"	
"	Th-21	Burnt Paddy grains	"	2050±170		400 BC-380 AD	"	
"	Th-23	"	"	1990±110		345 BC-320 AD	"	
"	Th-27	Charcoal pieces	S. of fault	2270±110	2088 ±40	760 -40 BC	"	
"	Th-28	Burnt wood	Top Burnt Bed	2170±170		760 BC-220 AD	"	
"	Th-29	Burnt grains	Bottom of TBB	2030±170		400 BC-390 AD	"	
"	Th-42	Charcoal pieces	Fault zone area.	2190±260		830 BC-410 AD	"	
"	Th-45	Charcoal pieces	9 m S. of Th-44	2215±170		780 BC-130 AD	"	
"	Th-46	Charcoal post	N. edge of TBB	2330±170		810 BC-20 AD	"	
"	Th-36	Charcoal	10 m S. of Th-21 BBB	2210±170		780 BC-135 AD	"	190 BC-10 AD
"	Th-49	Charcoal pieces	Eqe.to BBB,& N. of fault	2270±175		800 BC-80 AD	"	
"	Th-50	Charcoal post	10 m S. of Th-46, TBB	2390±175		890-40 BC	"	
"	Th-51	Charcoal post	1.5 m S.of Th-50, TBB	2320±155		800 BC-10 AD	"	
"	Th-52	Charcoal pieces	30 cm below Th-51	2140±170		755 BC-240 AD	"	
"	Th-26	Charcoal pieces	N. of fault	1920±160		360 BC-440 AD	UB	340BC-410AD
"	Th-44	Charcoal pieces	S. of 2nd boulder bed	1960±270	1930±137	760 BC-650 AD	"	
Site 1A	Th-56	Charcoal pieces	Southern mound	2200±170		770 BC-140 AD	LB	
Halki (site 2)	LR-3	Charcoal pieces	In deformed peat bed	2160±170		760 BC-230 AD	LB	
"	LR-4	Charcoal pieces	20 cm above LR-3	890±70		1000-1280 AD	UB	
Shivoor(site 3)	LR-7	Shells	10 cm below the flame structure	1990±175		400 BC-420 AD	LB	
"	LR-9	Shells	45 cm above the flame structure	1620±170		65-770 AD	UB	

* Calibrated age: ^{14}C ages in BP are converted to calendar years (with 2σ values) using calibration program of *Stuiver and Reimer* [1993]. Calendar dates are rounded off to nearest 10.

\# Weighted Mean of ^{14}C dates is calculated following *Pantosti et al.* [1996]

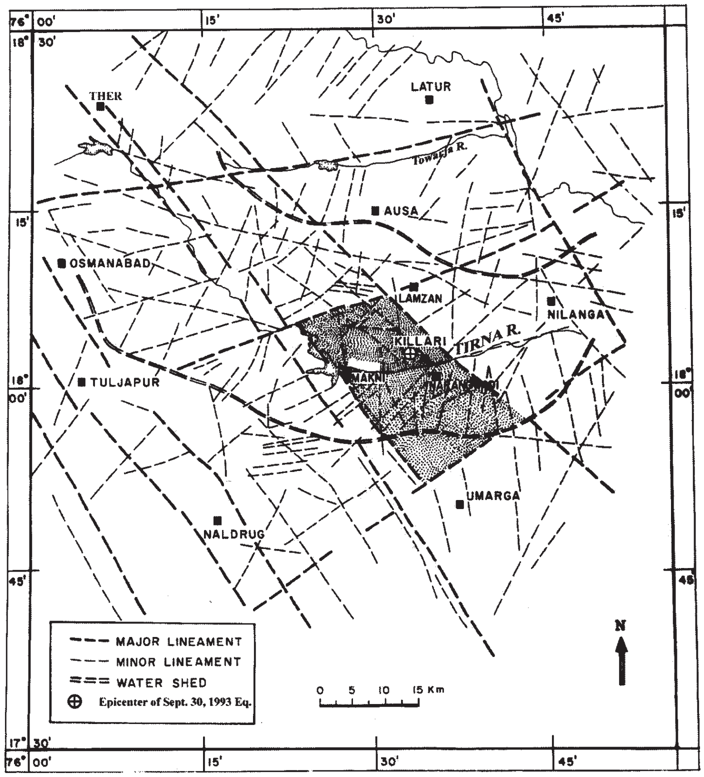

Figure 3. Lineament map of Latur-Osmanabad area [*Chetty and Rao*, 1994]. The directionality of major lineaments is in two ways: one set of lineaments is oriented in ENE-WSW, and the other set is in NW-SE, thereby showing multiple intersections of lineaments. The map also shows the lineament controlled drainage pattern in the Latur-Osmanabad area. The Tawarja and Tirna rivers are following the lineaments oriented in ENE-WSW.

GEOLOGICAL SETTING

The study area is part of the Deccan Plateau and is occupied by basaltic lava flows of Paleocene age covering an area of about 600,000 sq. km in western and central India [*Wadia*, 1964]. The basaltic flows have erupted over a horizontal erosional surface (Peneplain). The flows themselves are horizontal over a large part of the area and the individual flows themselves have usually a great superficial extent. The outcrops are scanty as the area is largely covered by blanket of thin black or lateritic soil. Dykes occasionally intrude the basaltic flows. Drilling at Killari [*Gupta and Dwivedy*, 1996] indicates that the thickness of basaltic layers is about 338 m with about 12-15 flows. The lava flows are underlain by 8 m thick intra-trapean sequence comprising a 1-2 m oxidized shale followed by a conglomeritic grit-sandstone. This layer overlies the Precambrian granitic basement (biotite granitic gneiss to pink granite). Closely spaced gravity survey and modeling along the two profiles [*Mishra et al.*, 1998] across the epicentral area of 1993 Latur earthquake suggest some high and low density bodies of shallow origin indicating highly heterogeneous basement. The extensive brittle fractured rocks are the only evidence of tectonic activity that basalts have undergone. Dating the various sets of fractures is not an easy task, given that they are normally free of associated mineralization. Under these circumstances the most convincing evidence of paleoseismicity as well as tectonic activity, which may have occurred in this region, is most likely to come from the sediments, which have been preserved along the rivers.

The surface topography of the Latur region reach an altitude of 500 to 700 m, has 20 to 40 km wide plateau extending from Ahmednagar in the west and Sangareddy in the east, and carries on it many minor plateaus, ridges and hillocks. The drainage is essentially dendritic becoming trellis because of structural control. River Manjira drains this plateau along with its tributaries like Tirna, Tawarja, etc. The Tirna and Manjira rivers are the places where extensive development of the Quaternary sediments is observed. Along the Tirna and Manjira rivers several pockets of fluvio-colluvial sediments capping the

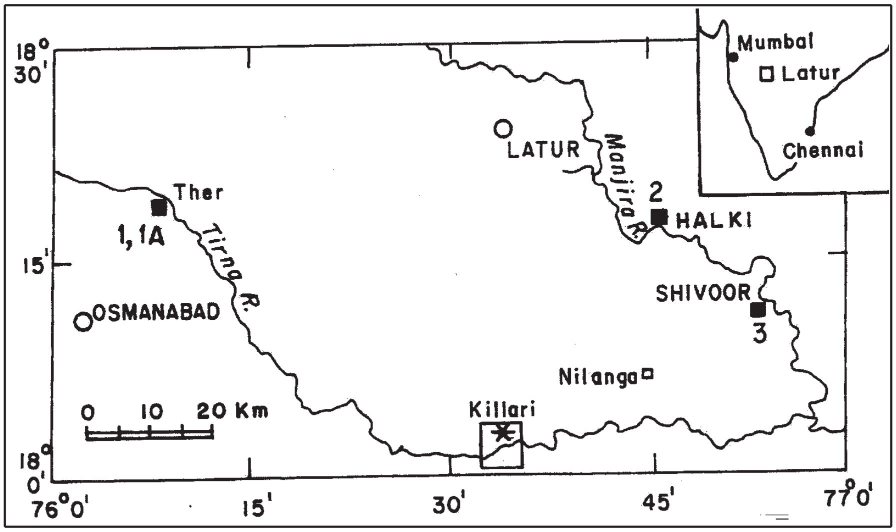

Figure 4. Location of the study area in the Tirna and Manjira river valleys in Latur, Deccan Plateau, Central India. The epicenter of 1993 Latur/Killari earthquakes is denoted by *. Numbers 1,1A, 2, and 3 are the four trench sites for paleoseismic investigations. Site numbers 1&1A are at Ther section on the west bank of Tirna river; site 2 is at Halki village on the eastern bank of the Manjira river, while site 3 is on the west bank of Manjira river at Shivoor.

Deccan Traps are observed. Thickness of scattered flood plain deposits varies from a few meters to a few tens of meters. These sediments have been interpreted to manifest the variation in the fluvial dynamics of the parent river systems in response to quaternary climatic variations in the region [*Rajguru et al.*, 1993].

Several alluvial mounds occur along the western bank of the river Tirna near Ther village. These alluvial mounds in general, show evidences of deposition by river surge and/or marked by alternating layers of coarse sands with cobbles and silty clay. The coarser layer may have been deposited during the floods and fine sediments during the lean seasons. Texturally the sediments can be classified as clay loam, sandy clay and silty clay loam. Such types of sediments have been noted for major rivers in Maharastra, and are categorized as flood loams or diluvium. The studies in the uplands of Maharastra show that the four major alluvial formations and one colluvial formation reflect the spectrum of fluvial activity at different discharges of the upland rivers during the Quaternary period [*Rajguru et al.*, 1993]

PALEOSEISMOLOGICAL SITES AND RESULTS

As the 1993-rupture zone is narrow and restricted to only trap region, there is not much scope to investigate the paleoseismicity through this rupture zone as well the study area mainly consists of basalts and has a few occurrences of sediments in the form of mainly flood plain deposits. Hence, the investigation was undertaken along the river courses and where the river deposits exist. Though we investigated quite extensively, we could locate the paleoseismic features at three sites. The sites are located at Ther (35 km northwest of Killari), Shivoor and Halki (latter two sites are about 40 km NE of Killari, Fig.4). Organic samples, associated with the identified seismites at these sites are collected and radiocarbon dated using gas proportional counter at National Geophysical Research Institute, Hyderabad (India) and the ^{14}C dates are converted to calendar dates using calibration program of *Stuiver and Reimer* [1993].

Ther (Site 1)

Ther village is on the west bank of the Tirna river and has an approximately 15-m-thick layer of alluvium topped by anthropogenic dump. The alluvial deposits cover a few km^2 on both sides of the river. The alluvium is highly dissected and now represented by nine irregular mounds. Ther village is spread over these mounds. Basalt outcrops are present in the Tirna riverbed and on the east bank as residual hill of Deccan basalts. Archaeological artifacts provide evidence of sudden floods during periods of subsidence belonging to different civilizations [*Chapekar*, 1969]. The Ther village is located at the intersection of prominent lineaments trending NW-SE and ENE-

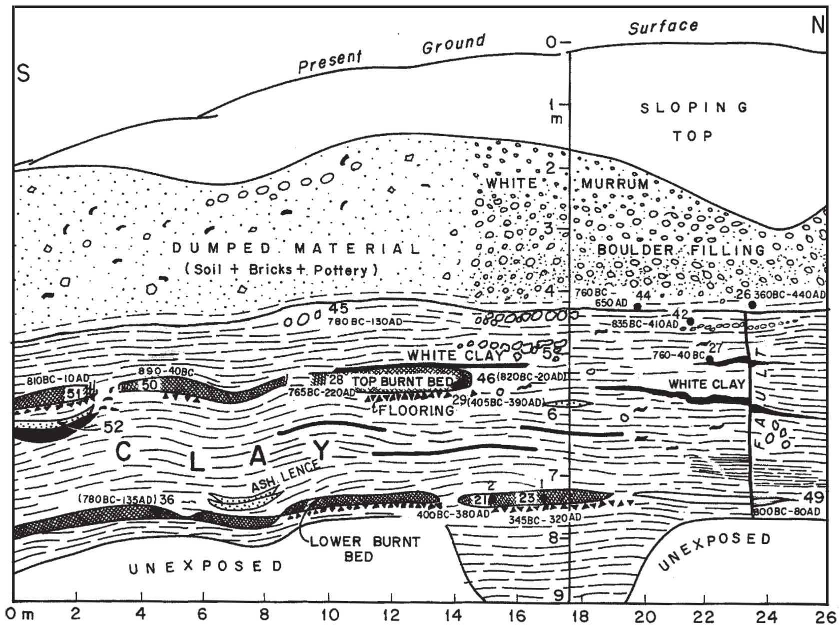

Figure 5. Geological section (site 1) along Tirna river at Ther. The 9-m-thick alluvial section depicts various strata including two burnt beds and a normal fault with a strata displacement of 15-25 cm. The fault is terminated by a thin undisturbed layer. The solid circles with numbers are the sampling locations for ^{14}C dating. The calendar dates of the organic samples are mentioned besides the sampling position. The two burnt beds at about 5.5 and 7.5 m depth contained burnt paddy, millets etc., which are carbon-14 dated. The top 4 m thick overburden is indicative of post-seismic anthropogenic build up. Sample numbers Th-26 and Th-44 which are located just above the fault line indicate upper bound and rest of the samples indicate lower bound for the paleoseismic event. We considered the lower bounds (sample nos. Th-1, Th-2, Th-21, Th-23, Th-27, Th-28, Th-29, Th-42, Th-45, Th-46) which are close to the fault for constraining the paleoseismic event.

WSW [Fig. 3; *Chetty and Rao*, 1994]. This region is crossed by several other lineaments whose pattern agrees with that of surrounding southern Indian Shield. *Chetty and Rao* [1994] interpret the lineaments of the Deccan area as representing the rejuvenation of pre-existing lineaments in the crystalline basement.

A well exposed vertical section of one of the mounds along a road cutting on the west bank of Tirna river, was selected for paleoseismic investigations. This 9 m thick section (Fig. 5) extends in a N-S trending arc measuring about 30 m long with the concave surface facing the road. This section mainly consists of dumped material like broken bricks, pottery, boulders etc. for the top 4 m, followed by dominant black clays inter-bedded with varied mixtures of sand, silt, and ash in the form of either thin layers or elongated lenses and wedges. The bedding is imperfect and is commonly marked by color variations in individual layers. Bedding becomes indistinct in the black clay layers. The fluvial/fluvio-lacustrine nature of the bottom layer at a depth of 7 m, is evidenced by the presence of load casts and scour and fill structures deposited in a high-energy environment. Pebble/stone beddings at different depths (5.5 and 7.5 m etc.) in the section appears like flooring, implying settlements at various stages of building up of the section by fluvial deposition.

The site has been modified by human activity, and is a well-known archaeological site. Artifacts like pottery, beads, idols and even large objects like earthen pots and a number of in situ wooden posts used for construction of various structures are present in the section. Two burnt beds are clearly discernible in the section: one at a depth of about 7.5 m from the present ground surface and the other at 5.5 m. Within these burnt layers, lumps of paddy, millets, and wheat were located. The grain lumps were more prevalent in the lower burnt bed than in the upper one. However, burning was more intense in the top burnt bed, where we observed a ~30-40 cm thick, highly burnt soil and remnants of wooden posts (now charcoal) used for individual structures. The burnt grain in the lower bed could be due to an ancient natural calamity like fire.

The most important structural feature noticed at

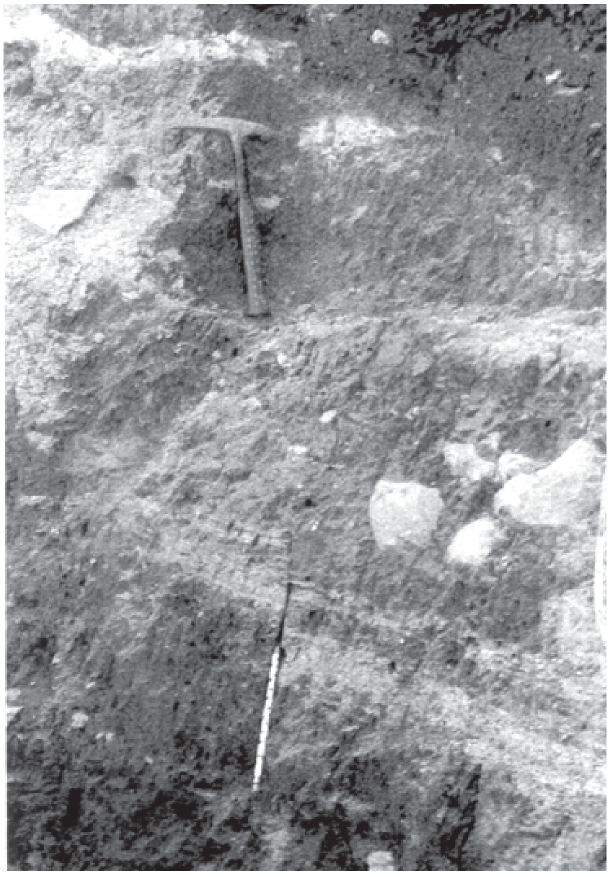

Fig. 6: Photograph shows view of faulted and fractured zone as observed before exposing the section at Ther (site 1). The fracture zone is dissected with many cracks, joints and fissures and also show displacement in subdued form. The movement along the fault is evidenced by dragged boulder along the fault.

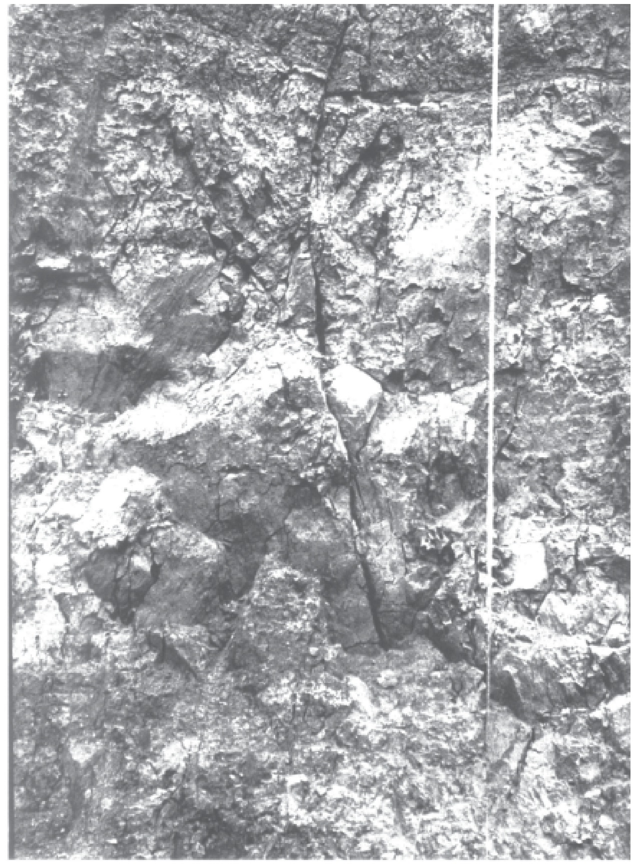

Fig. 7: Photograph shows the view of fault with displacement of beds at the Ther (site 1) after exposing the section. Warped clay bed, which is faulted and has a displacement of 25 cm. The fault extends downwards and the clay layer is also observed to be faulted by 15 cm, as the northern block moved down. Some of the boulders embedded in the strata are also seen.

this section is a north dipping normal fault trending approximately E-W (Fig. 6 and 7). The observed fault appears to be a secondary manifestation of a deep-seated disturbance in the area. Surface faults are not reported in the region. Ancient faults are likely to be present below the Deccan trap volcanic cover and do not have any direct expression on the surface. Therefore, it becomes necessary that geomorphic evidences indicating tectonic activity have to be linked with seismicity via the drainage pattern, soft sediment deformation in alluvial and colluvial sediments [*Chetty and Rao,* 1994].

In the trenches the strata displacements were observed at different levels. The full alluvial sequence could not be trenched due to logistic problems of water table and unstable slopes. Thus in the absence of surface expression of faults and in view of the presence of several inferred faults in the region, it is thought reasonable to conclude that the features observed in the 9 m deep trench could be surface manifestation of a deep seated disturbance in the region.

The observed fault in the section is prominent in the variegated clay/silt beds separated by a featureless clay horizon of about 3 m thick. The fault is about 4 m below the present ground surface, and we observed a displacement of about 15-25 cm of different beds. This separation is prominent in the upper part of the section, where a thin white clay layer in the black clay bed shows maximum displacement (Fig. 6). The top of the fault is truncated by a thin clay layer followed by a thick artificial dump (consisting of boulders, bricks, pottery, white murram (disaggregated basalt), which is totally undisturbed. During our first visit in

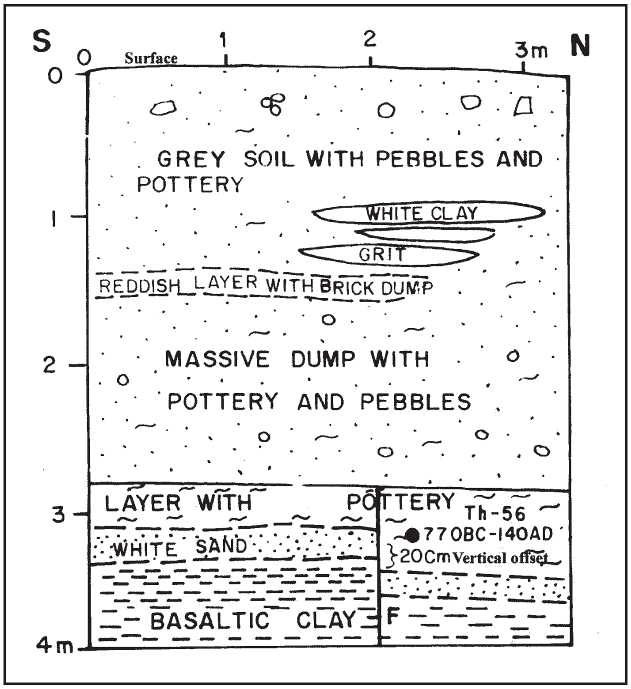

Figure 8. A trench (site 1A) made 200 m away from south of the studied geological section (Fig.5, Site 1) at Ther. It shows clearly the displacement of white sand bed by about 20-cm. The charcoal sample (no. Th-56) provides the lower bound for the seismic event, as the sample is located in the disturbed layer. However no upper bound sample is available for this feature. The top 3 m overburden consists of grey soil with pebbles and pottery, white clay, grit and reddish layer with brick dump.

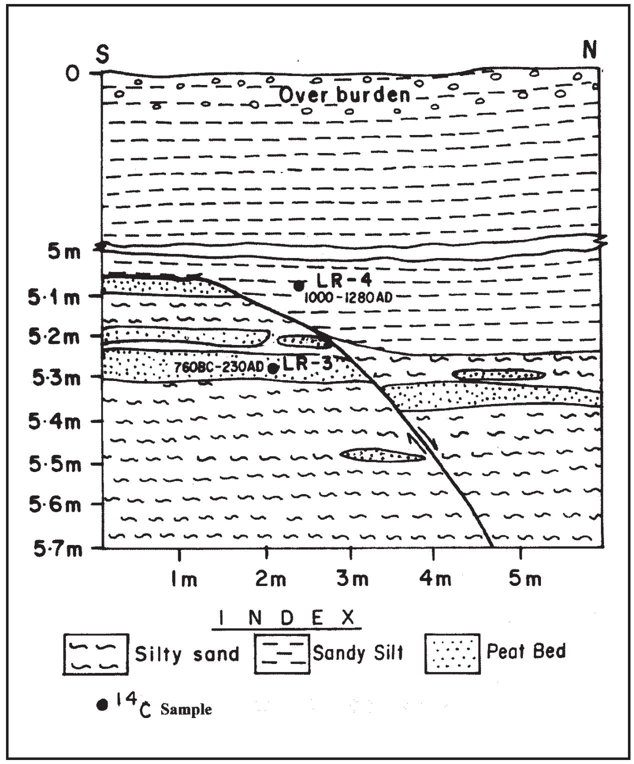

Figure 9. A geologic section (site 2) at east bank of Manjira river near Halki village, shows displacement of peat bed by about 15 cm. LR-3 and LR-4 charcoal samples are collected for radiocarbon dating. The sample (LR-3) embedded in the displaced peat bed provides the lower bound, while sample LR-4 provides the upper bound for the seismic event.

1995, we have observed a listric fault with lesser displacement and bending of different beds towards the fault plane. During faulting a boulder in the fracture trapped may have been dragged down along the fault (Fig. 7). Due to flexuring and movement of one block over the other, the saturated clay (~2 m thick) became compacted, dehydrated and fractured. However, the clay horizon at the lower portion of the fault shows the severity of frictional and compressional forces acting simultaneously on it, whereby it broke into blocks. During subsequent field programs, scraping of the section showed the fault plane clearer, and the displacement of different beds observed to be 15-25 cm (Fig. 6). We attribute the displacement (15-25 cm) of different horizons, rolling/ dragging of boulder along the fault plane and slickensided surfaces of the clay blocks as surface manifestations of tectonic disturbance. To assess the possible time of the faulting a number of charcoal samples were collected around the fault as well as from the rest of the section. Samples were also collected from the burnt beds where lumps of paddy and millets were found. The samples are scattered in different layers in a 4 m column of the section (from 4 to 8 m; Fig. 5).

Radiocarbon dates obtained for samples collected from the section are converted to calendar ages (Table 1). The calendar ages within this segment range from about 900 BC to 650 AD.

Ther (Site 1A)

About 200 m south of the site 1 (main Ther section) another trench was made measuring 3´2´4 m^3 (Fig. 8). At this site, ground level is relatively lower than the ground level at site 1. The top 2.75 m of the section consists of gray soil with pebbles, pottery, lenses of white clay, reddish layer with brick dump and massive dump with pottery and pebbles. Below 2.75 m, a well-marked 20-30 cm thick layer with

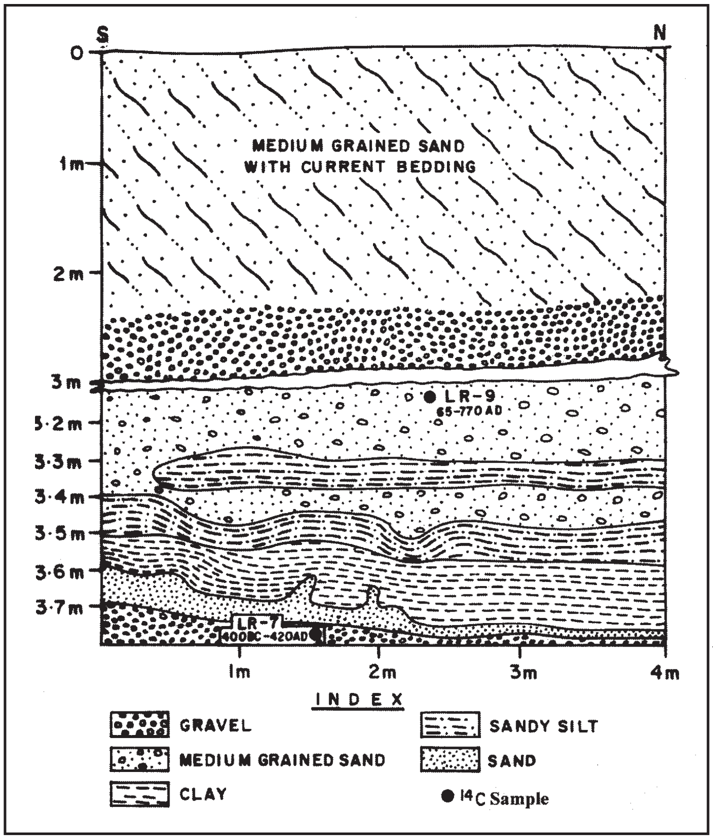

Figure 10. The figure shows liquefied flame structure at a trench (site 3) on the west bank of Manjira river near Shivoor village. The wavy nature of the sandy silt and sand layers reflects the seismic shaking. The liquefaction feature intruded into the overlying clay strata. LR-7 and LR-9 are the samples collected for ^{14}C dating. The sample LR-7 provides the lower bound while the sample LR-9 provides the upper bound for the seismic event that caused deformation and liquefaction.

plenty of pottery indicates unconformity between the two layers. A 15-20 cm thick sand bed sandwiched between top and bottom thick black clay pottery layers may be the indication of flood deposition. At this portion of the section white sand layer, which is almost horizontal, had discontinuity at about 2/3rd of the trench width towards north. After the discontinuity, the level of the strata was lower by ~ 20 cm, thereby indicating displacement of the sand bed. A weak trace of displacement line also extended up to pottery layer thus indicating that the displacement might have occurred during/after the formation of pottery layer. A charcoal sample that is collected from the pottery shall indicate lower bound to the seismic event that caused the sand strata offset. The collected organic sample dated about 770 BC-140 AD.

Halki (site 2):

Halki village is situated on right (eastern) bank of Manjira River. Joints trending NNW-SSE and EW are intersecting in this area (Fig. 3). Presently the village is situated over a huge mound overlooking the surrounding area. The mound may be formed because of flood plain deposition. Mostly it is made up of silt with little sand content.

Investigations were carried out around this mound where there are deep excavations for the soil. A paleoseismic feature is observed in a 5.7 m section extending in a N-S direction (Fig.9). This section mainly consists of about 5 m thick sandy silt below the present surface and followed by 1 m thick silty sand with inter-bedded peat layers. These two distinct layers are depicting clear unconformity between them. The structural feature noticed in this section is displacement of peat bed. The peat bed in the northern side moved down by 16 cm in comparison with southern side with a trace of fault line with about 30° dip towards north and approximately with EW strike. This feature is observed at a depth of 5.25 m from the present surface. Top of the fault is truncated by a sandy silt layer indicating unconformity. To assess the

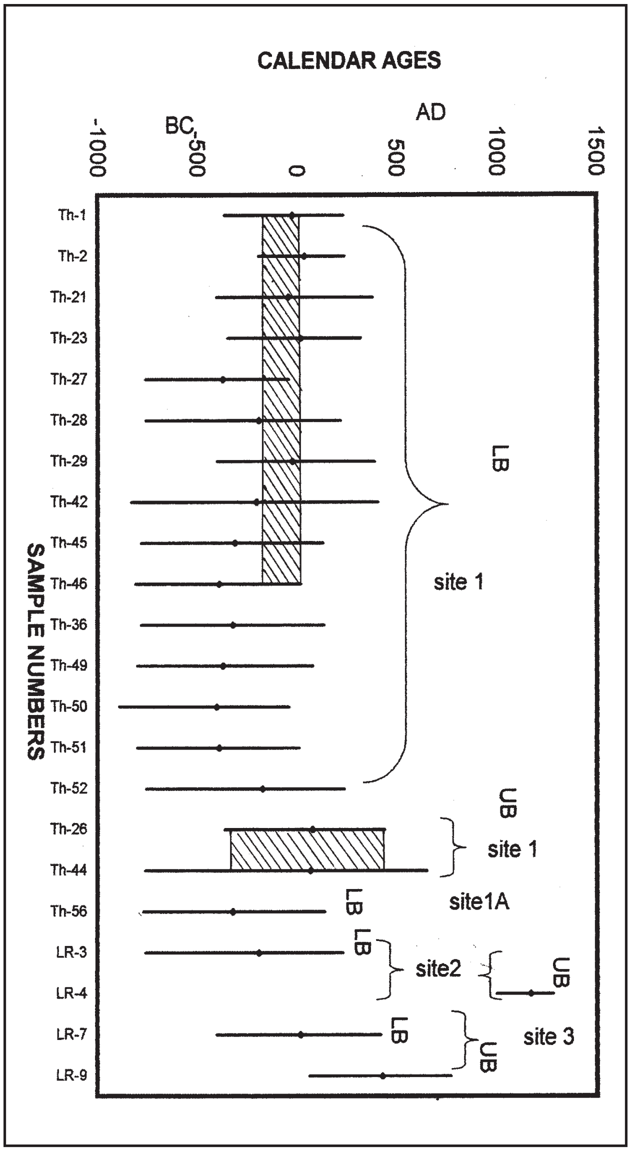

Figure 11. The plot shows the calibrated ^{14}C ages (with 2s error) for different samples collected at three different sites along Tirna and Manjira river banks. The lower bound and upper bound samples are denoted by LB and UB respectively. The lower bound hatched area for site 1 denotes the calibrated age (190 BC-10 AD) of the weighted mean of samples no. Th-1, Th-2, Th-21, Th-23, Th-27, Th-28, Th-29, Th-42, Th-45, Th-46, selected for being close to the fault, while the upper bound hatched area is calculated on the mean value of UB samples nos. Th-26 and Th-44. The lower and upper bounds of sites 1A, 2 and 3 over lap the constrained timing from site 1, which has more samples and more precise chronology. Thus the paleoseismic event is constrained to have occurred between 190 BC and 410 AD.

possible time of deformation, two organic samples were collected representing the lower and upper bound of the faulted zone. One sample is collected from the peat bed and other sample (charcoal pieces) from the top bed. The calendar dates for the two samples (LR-4 and LR-3) collected above and below the deformed feature are 1000-1280 AD and 760 BC-230 AD respectively (Fig. 9).

Shivoor (site 3):

A 3.7 m trench (Fig.10) was made on the river terrace of the Manjira River near Shivoor (Fig.4). The section extends in a N-S direction and is made up of medium grained sand with current bedding in the upper 2.5 m followed by alternate layers of gravel, clay, and sandy silt between 3-3.6 m. At a depth of 3.6 m, a thin sand layer intrudes into the overlying clay layer. This thin sand layer, as well as overlying sandy silt layers shows wavy structure. However, the upper sand strata is undeformed (Fig. 10). Intrusion of sand into clay and wavy nature of clay and sandy silt beds indicate disturbance in these beds attributed to liquefaction caused by an increase in pore water pressure during seismic shaking [*Obermier*, 1996].

The liquefaction feature observed at this site appears to be a flame structure (Fig. 10) at a depth of 3.6 m and is similar to features observed by *Scott and Price* [1988], *Hempton and Dewey* [1983], and *Sims* [1975]. Considering the features are formed because of seismic activity, to constrain the probable time of occurrence of the features, two samples (Shells) were collected from the zones of disturbed and undisturbed beds. The calendar dates of samples (LR-7 and LR-9) collected from the trench are 400 BC-420 AD and 65-770 AD, respectively.

Archaeological excavations [*Chapekar*, 1969] at one of the mounds located on the eastern bank of river Tirna showed evidence pertaining to habitational sequences, found artifacts such as coins, metal ware, potsherds, terracotta articles, glass pieces, beads, shells and even charred grains of wheat, rice, pulses including gram were found. The excavations revealed laying of floorings with cut-stones, undressed stones, pebbles and black clay as cementing material. At some places, postholes were also found. In one of the trenches archaeologists observed two floorings and the first flooring, which is above dark black earth was found heavily disturbed internally. Incidentally this strata corresponds to same strata in our Ther section in which fault is located. In that particular strata, we also have found the same material as observed by the archaeologists mentioned above.

DISCUSSION

Though Peninsular Shield of India was considered as seismically stable, the 1993 Latur earthquake indicated seismic vulnerability of the area. Deep drilling through horizontal flood basalt flows, on both the sides of 1993 rupture zone provided the evidence of a fault and displacement of about 6 m, at a depth of 220 m [*Gupta et al.*, 1998]. Down dip slickenlines on steep dipping slikenside surfaces in the drill cores confirm dip slip nature of the fault. However the observed displacement is too much to account for a single earthquake of Mw 6.1, hence they suggested repeated seismicity in this area. *Rajendran and Rajendran* [1999] also suggests reactivation of the pre-existing fault, and evidence of earlier seismicity in the area by trenching in the rupture zone of 1993 earthquake near Killari. However *Seeber et al.* [1996], though do not rule out the reactivation but offer as well other possibility of reservoir induced seismicity.

The present study is based on the observation of faulting of beds in alluvial formation in three trenches at site 1 (Ther), site 1A (200 m from Site 1), and site 2 (Halki), as well as liquefaction features in the form of flame/torch structures at site 3 (Shivoor). A critical examination of all the four trenches shows that the top 3-5 m is undisturbed followed by the disturbed section and do not have the 1993 faulting, though the investigated area is close to the miezoseismal area of the 1993 earthquake. During 1993, several ground cracks, partial damage to the buildings and gas emanation was reported in these areas [*Rastogi and Rao*, 1994]. However, the studied sections at different sites does reveal that the lower strata were subjected to shaking during a prehistoric seismic event because of which the beds show gentle warping, minor discontinuities and strata displacement of 15-25 cm at different levels and liquefaction at one site.

The paleoseismic sites Ther and Halki/Shivoor are at least separated by a distance of 60 km. An important observation from all the three sites is that the strike of the displacement at all the sites is approximately in EW direction and the northern block appears to have moved down, indicating normal faulting (figs 6, 8 & 9). The two sites, Ther and Halki are located about 50 and 35 km in NW and NE of 1993 earthquake epicenter respectively, and situated in the isoseismal V and VI. The observed strata offsets and liquefaction features in the colluvial formation can be generated during a prehistoric seismic event with the inferred magnitude greater than that of the Latur earthquake. However, we are not able to associate the observed faults, deformation and liquefaction features in four trenches to any particular seismogenic fault though it can be speculated that the faulting could be linked with any of the EW lineaments. As the Latur/Killari earthquake is linked to NW-SE faulting, this seems to be logical in view of the two prominent sets of lineaments (NW-SE and EW).

The chronology of the paleoseismic event was established using associated radiocarbon ages. Though the paleoseismic evidences are found at three sites, the timing of the event/events is constrained on the basis of lower and upper bounds from ^{14}C dates of samples from Ther section which is studied extensively. As site 1 is characterised by a well demarcated fault plane, as well as surface boundary of the fault line, and a large number of lower, and upper bound dates very close to the surface boundary of the fault plane, we prefer to constrain the timing of the paleoseismic event on the basis of the site 1 (Ther section). The dates from other sections are overlapping these dates and thus supplement the data.

Figure 11 shows that, ten samples from the Ther section (numbers: Th-1, Th-2, Th-21, Th-23, Th-27, Th-28, Th-29, Th-42, Th-45, Th-46) collected around the fault zone are considered as lower bound and a weighted mean radiocarbon age is calculated [*Pantosti et al.*, 1996] for which the calendar date is 190 BC to 10 AD. Similarly two samples from the top undisturbed bed provided a calendar date of 340 BC-410 AD representing upper bound. The age obtained for one sample from site 1A representing lower bound is 770 BC-140 AD. For the other two sites Halki (Site 2) and Shivoor (Site 3) each one sample representing lower bound provided calendar dates of 760 BC-230 AD and 400 BC-420 AD respectively. However, a large variation in upper bound is found (Halki: 1000-1280 AD, and Shivoor: 65-770 AD) at these two sites. The younger upper bound date of the Halki may indicate longer non-depositional period. The lower bound and upper bound dates of the features observed at four sites are plotted in Fig.11. Thus using the weighted mean calibrated dates of upper and lower bounds (340 BC-410 AD; 190 BC-10 AD respectively), at Ther section (site 1), we constrain the paleoseismic event occurrence to be 190 BC – 410 AD.

The magnitude of the paleoearthquake can also be estimated by the intensity of the deformed features. The flame like intrusion of sand observed at Shivoor is due to the liquefaction resulted due to increase in pore water pressure due to upward propagation of cyclic shear stress during seismic shaking, which commonly occur at magnitudes of Ms^{3}5.5-6 [*Ambraseys*, 1988; *Scott and Price*, 1988; *McCalpin*, 1996, *Obermeier*, 1996, *Yeats et al.*, 1997]. Further, Comparing the 1993 earthquake magnitude (M 6.3) and displacement in the soil profile on the primary fault at rupture zone [~ 10 cm, *Chetty and Rao*, 1994], we infer the magnitude of pre-historic event to be greater than that of 1993 to justify the occurrence of secondary features like strata displacements at three sites (site 1, 20 cm; site 1A, 20 cm; and site 2, 16 cm; average 18.6 cm) and the fact that the Halki (site 2) and Shivoor (site 3) sites are at about 60 km from site 1 and 1A.

Another supportive evidence for existence of paleoseismicity in the study region comes from archaeological records [*Cousens*, 1903], which lend credence to our identified paleoseismic event. The records show that several historical monuments including temples in Ther village were rebuilt over the old basements indicating natural disaster in the area [*Chapekar*, 1969]. Reported existence of disturbed layers of soil as well as flooring in one of the archaeological excavations carried out at one of the mounds on the left bank of river Tirna at Ther is also an indication of earlier seismicity. In fact the artifacts, which we found in our geologic section are similar to those found in the trenches by archaeologists [*Chapekar*, 1969], which are dated archeologically belong to Satavahana period (about 2nd century BC). Thus the archaeological findings and the carbon-14 dating of the organic samples together support the occurrence of a paleoseismic event in the region around 190 BC - 410 AD

CONCLUSIONS

Paleoseismological investigations carried out near the meizoseismal area of the 1993 Latur earthquake revealed the occurrence of a prehistoric seismic event at about 190 BC - 410 AD. Studies were conducted at three locations (four trenches), maximum 60 km apart, out of which one location (Site1, 1A) has archaeological importance. By comparison of the 1993 earthquake features and observed deformation features at the study sites, it is inferred a large magnitude earthquake occurred in the investigated area. Though we did not observe any rupture of 1993 earthquake in the trenches and also could not identify the causative source fault for the prehistoric earthquake, all the trenches showed movement of northern block by 15 – 25 cm and fault orientation to be EW, and the dates are suggestive of a single prehistoric seismic event. Despite the fact that there exists no known rift in the Latur region, the occurrence of 1993 event and the prehistoric seismic event dated around 190 BC – 410 AD necessitates extensive paleoseismological studies. Such studies would enable a better understanding of the seismic character of the region by developing a chronology of the prehistoric seismic events and evaluation of their recurrence period in the Deccan volcanic province.

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