Active tectonics in the northwestern outer Himalaya: evidence of large-magnitude palaeoearthquakes in Pinjaur Dun and the Frontal Himalaya

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The Himalayan region has experienced a number of *M*8 and *M*5–*M*7.8 magnitude earthquakes in the present century. Apart from the release of strain builtup due to convergence of the Indian and Tibetan plates by seismic activity and aseismic slip, the tectonic activity in the current tectonic regime has also effected morphotectonic changes due to uplift, tilting of drainage basins, shifting or diversion of rivers and their tributary channels. Seismicity is mainly due to activity along numerous active faults, which trend parallel or transverse to the Himalayan mountain belt. In the outer Himalaya or the foothills, lying between the Himalayan Frontal Thrust (HFT) and the Main Boundary Thrust (MBT), some active faults have generated major earthquakes. The present article illustrates two such faults in the Pinjaur Dun and in the HFT zone at Kala Amb, Himachal Pradesh. Palaeoseismological study carried out at Nalagarh in Pinjaur Dun has revealed Late Pleistocene earthquakes along the Nalagarh Thrust (NT) that separates the Palaeogene rocks from the Neogene Siwaliks. The study shows evidences of at least two large magnitude earthquakes that rocked this region. The repeated reactivation of NT and HFT substantiates high seismic potential of the northwestern outer Himalaya and calls for more extensive study of palaeoearthquakes in this vastly populous mountainous region.

Keywords: Active tectonics, NW Himalaya, palaeoearthquakes, tectonic landforms.

Introduction

UNDERSTANDING active tectonics is considered to be significant as it results in landforms which are the surface manifestation of the past and the ongoing deformation in the current tectonic regime. The tectonic landforms essentially evaluate the nature of such deformation basically in terms of faulting and folding, and use geomorphic markers for delineating active tectonics. The analysis of tectonic landforms also helps in recognizing the relation between the Quaternary tectonic movements and seismic deformation in the present, as well as in the past, that has important societal implications. In an active orogenic belt like the Himalaya, expressions of active tectonics are numerous and are mainly manifested in the form of faults, uplifts and tilt of Quaternary deposits such as alluvial fans and river terraces, besides the preferred stream channel migration, river capture, etc.

In the Himalayan orogenic belt, the continued convergence of the Indian plate has produced linear zones of tectonic deformation, resulting in crustal shortening, particularly along the prominent boundary faults[1–4]. These crustal-scale major faults such as the Indo-Tsangpo Suture Zone (ITSZ), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT) have contributed to the present-day structural and topographic architecture of the Himalayan fold-and-thrust belt. As a result of ongoing convergence along the Himalayan front and its influence in the outer Himalaya, many imbricate structures of MBT have developed. Although MCT and MBT are considered to be the major tectonic features of Cenozoic shortening along the entire extent of the Himalaya, the HFT, bordering the mountain front, is believed to be the most active thrust during the Quaternary period. Seismic hazard evaluation in the tectonically active Himalaya is crucial because earthquakes pose a continued threat to the safety of the people living adjacent to this gigantic mountain system of the world. It is now widely accepted that active faults – faults, which have moved repeatedly in the recent geological time have potential for reactivation in the future. They contribute significantly to seismic activity (> 80% seismic activity). Hence palaeoearthquakes in the Himalaya should be studied as precisely and as far into the geological past as possible. This will be realized only through focused studies on the geology and geomorphology which include, in particular, active faults and tectonic landforms. In the outer Himalaya or the foothills lying between HFT in the south and MBT in the north, numerous active faults[5–14] have generated major and great earthquakes[15]. The present article illustrates two such faults (in Pinjaur Dun and in the HFT zone at Kala Amb) and presents studies associated

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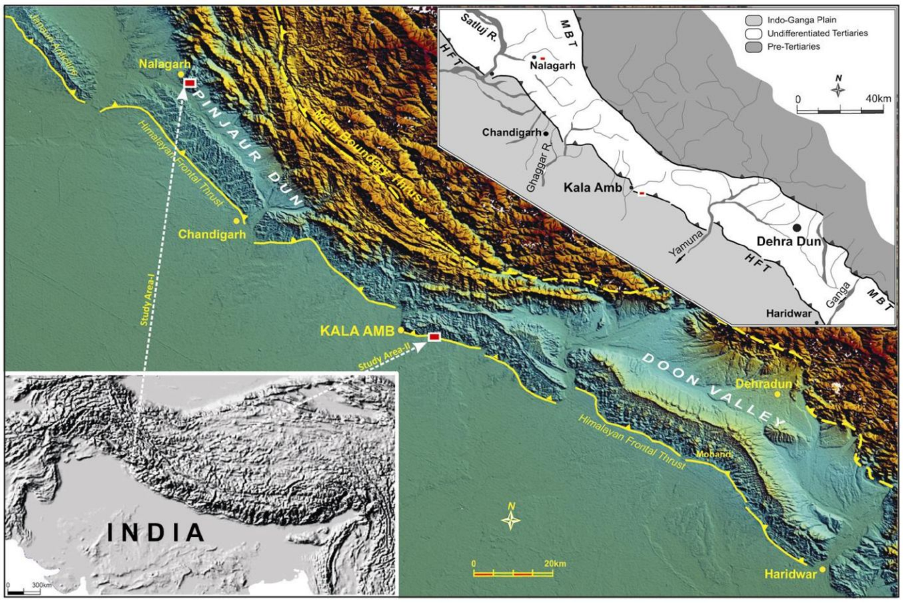

Figure 1. Regional location map (SRTM image) showing major duns in the outer Himalaya and the study area near Nalagarh and Kala Amb, Himachal Pradesh. (Inset) Regional geological set-up of part of the outer Himalaya between the rivers Ganga and Satluj[13].

with tectonic landforms in the northwestern outer Himalaya (Figure 1) as evidence for large-magnitude palaeo-earthquakes.

Study area-I

Reactivation of Nalagarh Thrust in Pinjaur Dun

Pinjaur Dun (Figure 1) is one of the highly populated and rapidly developing industrial belts of the northwestern outer Himalaya, India. The Late Quaternary landforms in this Dun are in the form of alluvial fans (Figure 2) dated between 96 and 20 ka (refs 16, 17) and deposited in front of the Nalagarh Thrust (NT). Subsequently, these deposits have undergone back tilting and warping of fluvial and alluvial fan surfaces and fault scarplets in the Quaternary deposits. This is observed along most of the active faults in the Pinjaur Dun[5,11,18–20]. Active tectonics in the Pinjaur Dun is manifested in the form of dislocation of landforms in Quaternary sediments by major and minor faults. Many active faults have been identified in this Dun[5,11,18]. Among the active faults identified so far, the Pinjaur Garden Fault (PGF) is a prominent fault striking NNW–SSE, exposed near Pinjaur town.

In the Quaternary sediments deposited in northwestern part of the Pinjaur Dun, we have identified new trace of an active fault which is parallel to NT near Nalagarh in Himachal Pradesh. The area around Nalagarh has three major landform units: the Late Pleistocene alluvial fan, the fluvial terraces and the bedrock hills composed of Tertiary (Siwaliks and Subathu–Dagshai–Kasauli) rocks (Figures 2 and 3). Here NT is expressed by thrusting of Lower Tertiary rocks (comprising olive green and reddish sandstone and shale) over the Late Pleistocene alluvial fan deposits (Location-I in Figure 4 *a*). The alluvial fan deposit, ≈ 10 m thick above the present ground level, is mainly composed of gravel, sand and silty mud units, exposed over a distance of about 150 m at Kirpalpur, a village adjacent to Nalagarh township (Figure 3 *a*). The fan deposit has been folded, and reversely faulted by another younger fault (Location-II in Figures 3 *b* and 5) that is about 100 m south of NT at Kirpalpur in (Location-I in Figure 3). The fault restricted to the fan deposit has subdued surface expression and is discontinuous due to widespread agricultural and ongoing rapid industrial activities in the Pinjaur Dun. The easterly extension of this fault in the Quaternary fan deposit in the Pinjaur Dun has been exposed near the village Kheda (Location-IV in Figure 3), which is about 3500 m SE of Location-II. Here the exposure of Quaternary sediments shows almost similar reverse displacement of Quaternary gravel, as observed in Location-II. About 400 m SE from Location-I, another distinct exposure of the fault is observed at Location-III (Figure 4 *b*). The fault exposure reveals that the lower Tertiary rocks have been thrust with an angle of 26° towards ENE direction over the younger Quaternary fluvial terrace.

Trench excavation: A trench excavation survey was carried out at Location-II (Figures 3 *a* and 4 *a*) across the folded, back-tilted and faulted Quaternary alluvial fan located about 150 m SW of the topographic front at Kirpalpur village (Location-I in Figure 3). The log of the

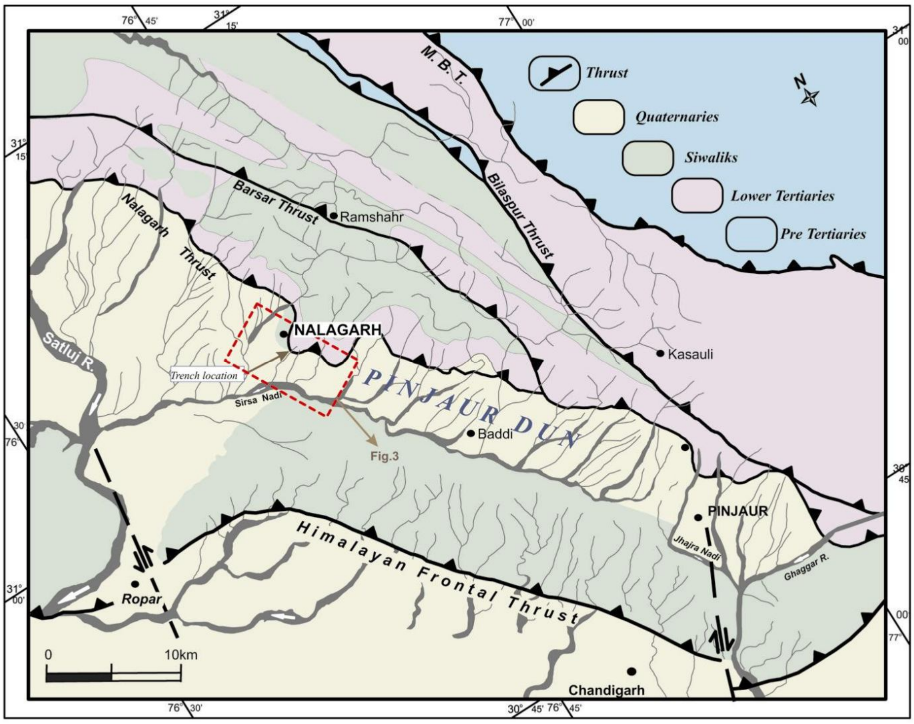

Figure 2. Geological map of Pinjaur Dun and its surrounding and location of the trench site[12].

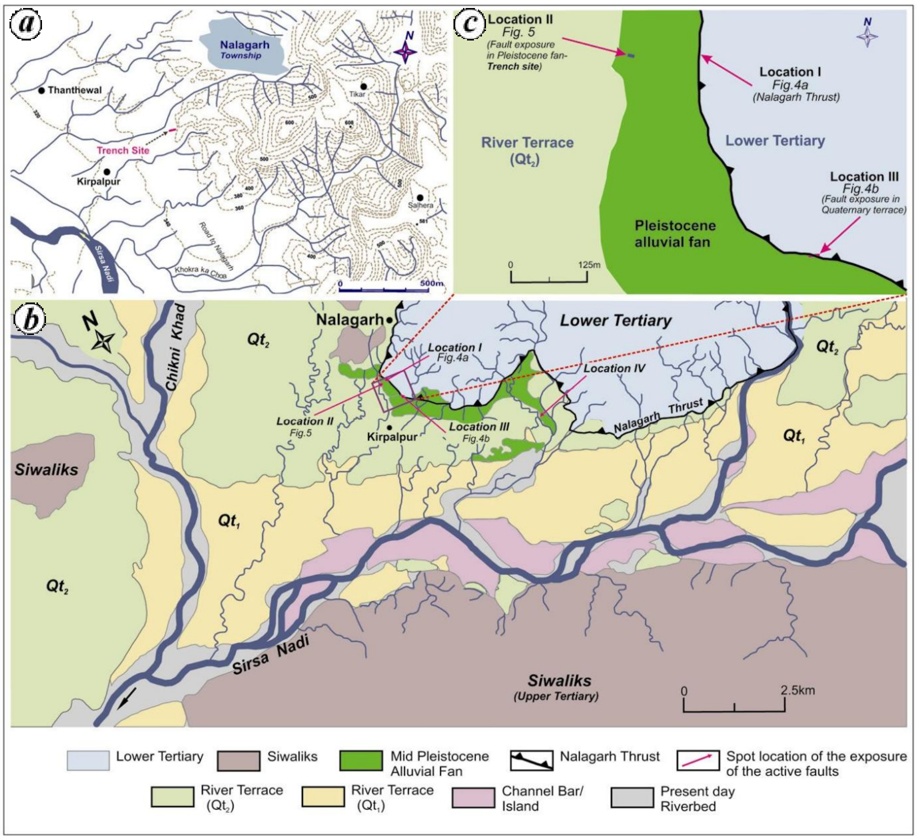

Figure 3. ***a***, Location map of the trench site at Kirpalpur, Nalagarh. ***b***, Landform map of the area around Nalagarh Thrust near Nalagarh showing spot locations of Late Pleistocene faults (prepared using aerial photographs). ***c***, Close-up view showing spatial relationship of the fault in the vicinity of Nalagarh Thrust near Nalagarh[12].

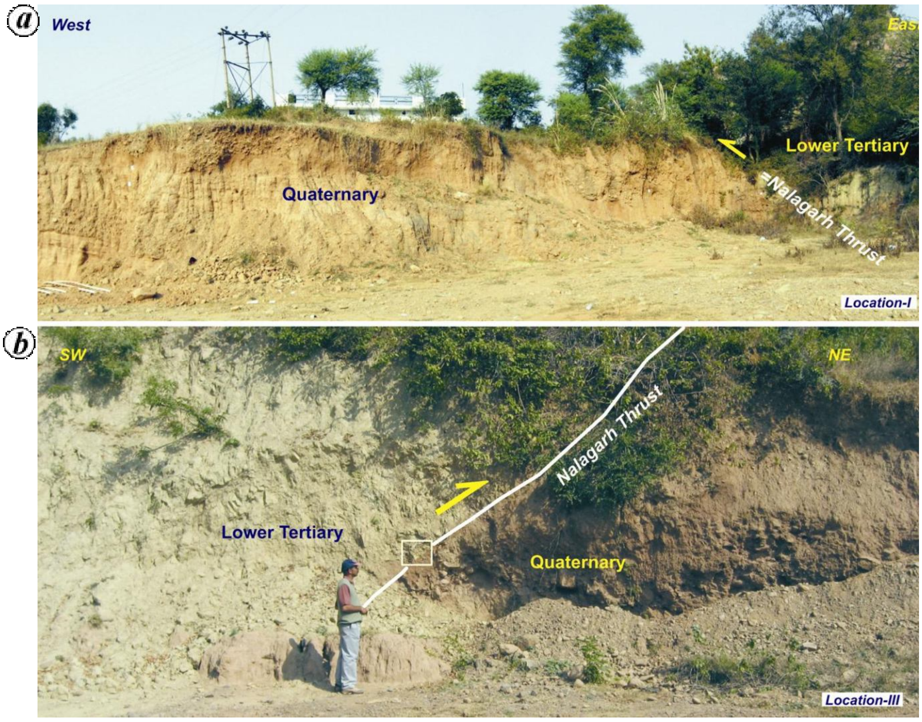

Figure 4. ***a***, Lower Tertiary rocks thrust over the Quaternary fan deposits along Nalagarh Thrust at Kirpalpur (Location-I). ***b***, Lower Tertiary rocks directly thrust over the younger Quaternary (Holocene?) deposit along the fault (≈ Nalagarh Thrust) dipping 26° towards ENE direction (Location-III)[12].

trench wall (Figure 5 *b*) helped in the reconstruction of the stratigraphic succession of the deposit, which consists of well-organized clastic deposits of colluvial and alluvial origin. Lithologically, the units composed of gravel, sand and mud units, are divided into six separate principal sedimentary sub-lithological units, from A (oldest) to F (youngest) (Figure 5 *b*). Compositionally, the clasts consist of grey, olive green and rare pink sandstone, indicating derivation from the inner Tertiary ranges. The geometry and pattern of deformation show tight fold and reverse faulting that clearly displaces the lithologic units exposed in the trench wall (Figure 5 *b*). The external geometry of the units in the hanging wall shows back tilting, whereas the litho-units in the footwall side of the fault show no back tilting but are horizontally bedded with a ~ 5° modified surface slope towards west.

Induced soft-sediment deformation features: Well-defined, diagnostic soft-sediment deformation features are observed in the trench wall at Kirpalpur. These features are irregular in size and shape and are basically developed as muddy sand veins or tube-like dykes. In the hanging wall of the fault, units A, B and C clearly show a number of such features. They are wedge-shaped and are filled with fine sand coming from the underlying strata and are parallel to the micro-fractures. Others are irregular due to liquefaction and vibration originating from earthquakes or the water-escape of sediments. There are cross-cutting dykes which branch irregularly upwards in smaller segments. The unit C sandy mud has made vertical and lateral injections into unit D. The lithology of these fillings is different from the surrounding lithologic unit, and the boundary between them is clear but irregular. The mixture of sand, silt and clasts has a sharply defined contact with the side walls. Some scattered small tubular dikes are also observed in the trench wall.

The sedimentary structures, essentially the water-escape structures, are prominent features observed in the trench (Figure 5). The shapes of gravel layers in Figure 5 *b* indicate the liquefaction process and water-escape structures in unconsolidated sediments with higher water content. The water-escape structures have also altered the thickness of the sedimentary units by upward and lateral injection of fine-grained materials. During heavy shaking, the unit has been broken into small blocks, and the separation between the individual blocks is more than a few centimetres. This is clearly observable in the pebbly layer in unit A and in the broken unit B (Figure 5 *b*). The water-escape structures are formed where strong hydraulic forces of short duration are suddenly applied. This is possible only because of sudden tectonic strain release here in this case due to earthquake-induced liquefaction[21]. The presence of the water-escape structures in the litho-units A and B indicates that the structures are formed consequently during discrete seismic events. The mechanism of folding, deformation, development of liquefaction

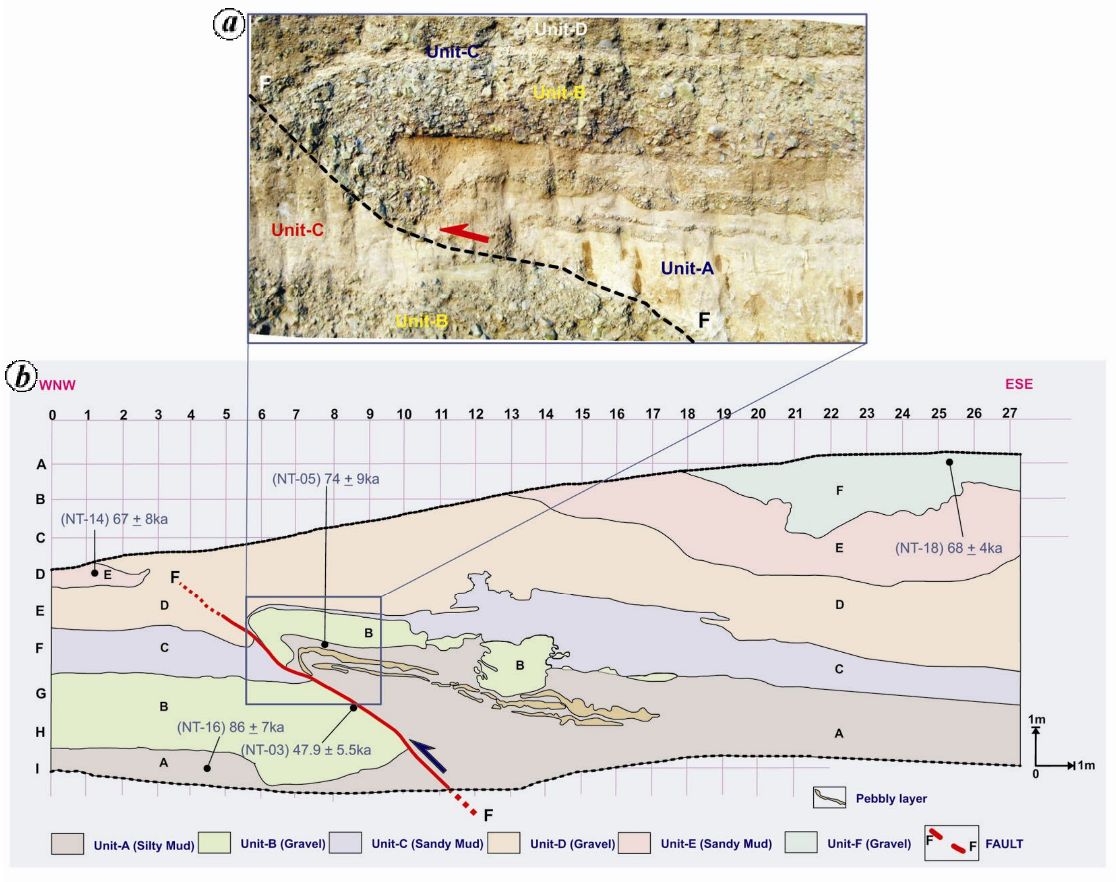

Figure 5. ***a***, Part of the trench wall showing the manifestation of folding and reverse faulting (*F–F*) in the fan deposit at Kirpalpur, Nalagarh (Location-II). ***b***, Trench wall log showing displaced Quaternary units along the active reverse fault (*F–F*). OSL sample locations are marked with their ages[12].

and water-escape structures hence have definite genetic link with occurrence of a large-magnitude earthquake and its aftershocks. Considering the base of unit D as a marker, around 1.2 m vertical and ca. 2.5 m along-fault slip has been suggested in this case. A total displacement of about 2.5 m was measured in the trench, taking into account the marker beds represented by units C and D, which mark the prominent piercing point and contact that has been displaced along the fault.

Luminescence chronology

Selected samples, representing all the lithologic units in the hanging wall and foot wall of the fault, were dated using the OSL technique to constrain the age of events (Table 1). The Quaternary sediments have also been dated from different locations (Locations III and IV) as shown in Figure 3. These locations are respectively, about 400 and 3500 m to the SE of the trench location. The displacement of all the lithological units in the trench and back tilting of the hanging wall units towards NE direction indicate that the tectonic reactivation along NT commenced after the cessation of alluvial fan deposition. Based on OSL ages from the sedimentary units of the trench, it is inferred that the fan deposition was initiated before 85.8 ± 7.2 ka and terminated after 67.0 ± 8.4 ka. The palaeoseismological studies in this fan across the fault scarp indicate post-depositional deformation. However, in the present case, there are no capping litho-units in the trench which are not displaced by the fault. This is a major limitation in precisely placing the timing of the tectonic activity during which the Quaternary stratified deposit has been reversely displaced. Therefore, we consider that the tectonic activity occurred only after the cessation of alluvial fan younger to 67.0 ± 8.4 ka. However, the observed younger age (47.9 ± 5.5 ka) close to the fault plane (sample NT-03) probably indicates resetting of the luminescence signals subsequent to tectonic movement and associated liquefaction.

Considering the vertical displacement and total displacement of the fault in the trench and by employing the two empirical equations proposed by Matsuda[22] and Wells and Coppersmith[23], we are of the opinion that a palaeoearthquake of magnitude ~ 7 must have occurred in this region. Further, the OSL ages obtained from two different locations (Locations III and IV), show ages of

Table 1. Optically stimulated luminescence ages of samples from the trench and other Quaternary deposits at Nalagarh. Elemental concentration of uranium (U), thorium (Th), potassium (K) and moisture content used for dose rate calculation and equivalent dose (De) are also given[12]

Sample no.	U(ppm)	Th (ppm)	Potassium K (%)	Moisture content (%)	De (Gy)	Dose rate (Gy/ka)	Age (ka)
NT-14	3.6 ± 0.04	7.3 ± 0.07	1.50 ± 0.02	1.03	202.37 ± 25.10	3.02 ± 0.04	67.1 ± 8.4
NT-16	2 ± 0.02	7.7 ± 0.08	1.40 ± 0.01	3.57	215.07 ± 17.77	2.51 ± 0.04	85.8 ± 7.2
NT-18	3 ± 0.03	9.7 ± 0.10	1.49 ± 0.01	4.11	200.72 ± 11.23	2.94 ± 0.04	68.4 ± 3.9
NT-03	4.5 ± 0.05	11.3 ± 0.11	1.59 ± 0.02	5.58	163.95 ± 18.78	3.42 ± 0.05	47.9 ± 5.5
NT-05	2.1 ± 0.02	11.7 ± 0.12	1.65 ± 0.02	6.79	217.12 ± 26.36	2.93 ± 0.05	74.0 ± 9.1
NL-01	3.97 ± 0.04	14.38 ± 0.14	1.70 ± 0.02	1.25	72.71 ± 1.87	3.66 ± 0.04	19.9 ± 0.6
NL-04	2.98 ± 0.03	10.83 ± 0.11	1.45 ± 0.01	0.35	86.46 ± 3.45	2.98 ± 0.04	29.0 ± 1.2

19.9 ± 0.6 ka (NL1 – collected from the top surface) and 29.0 ± 1.2 ka (NL4 – collected 5 m below the top surface) respectively. At Location-III NT is riding over the Quaternary (19.9 ka old) deposit indicating that the tectonic activity occurred after its deposition. The fault observed at Location-IV indicates that these sediments have experienced post-depositional tectonic activity. As OSL age (29.0 ± 1.2 ka) at Location-IV is obtained from 5 m below the surface, the age of the top surface must be still younger. Therefore, we believe that tectonic deformation at locations III and IV may be contemporary. This shows that NT has reactivated after 20 ka. The tectonic activities observed in the trench (Location-II) and at locations III and IV are therefore two time spaced tectonic episodes. The evidence suggests that NT, defining an imbricate structure in the Outer Himalaya, has been repeatedly reactivated during the Quaternary period.

Active tectonics observed in the Pinjaur Dun reflects intermittent tectonic impulses due to large-magnitude earthquakes, which produced prominent fault scarps. As Pinjaur Dun is closely bordered by MBT, NT and the Bursar Thrust in the north and the Surajpur Fault and HFT in the south, reactivation of these faults must have created many fault scarps which are parallel to them. As the Pinjaur Dun falls in the meizoseismal zone of Kangra (1905) earthquake, we cannot rule out the possibility of large-magnitude earthquakes occurring in the area in the future.

Study area-II

Reactivation of HFT in the Frontal Himalaya at Kala Amb

The HFT is manifested in the Quaternary, rather in the younger alluvium, in the form of discontinuous range-front scarps that truncate the Quaternary fluvial terraces and alluvial fans and form the southernmost active tectonic mountain front of the Himalaya. To understand the active tectonics at HFT further, palaeoseismological study has been carried out in its vicinity along the Himalayan Front near Kala Amb, Singhauli village, ~ 10 km southeast of the Kala Amb township (Figure 1). The HFT in the Kala Amb area dips 20–30° towards N to NNE. It brings the Tertiary rocks (here the Middle Siwalik sandstones) over the Quaternary alluvium (here the Indo-Ganga Alluvium) in the piedmont zone (Figure 6). Active deformation along HFT is recognized by the presence of fault scarps (although presently scarps are degraded and modified to some extent), and uplifted and back-tilted Late Pleistocene and Holocene deposits.

Trench excavation: A trench excavation survey was carried out along the left bank of Singhauli Nala, across the faulted and displaced fluvial terrace in the topographic front uplifted along HFT at Singhauli village (Figure 7). The trench log (Figure 8) helped in the reconstruction of the lithostratigraphic succession of the deposits, which consist mainly of Late Pleistocene and Holocene clastic deposits of fluvial origin overlying the Tertiary Middle Siwaliks. Although the lithologic units in the trench wall show stratification, they are further deformed and at places have distinct erosional contacts with the overlying units. Based on variations of colour, matrix, size and distribution of the clasts, individual sedimentary units were distinguished within the excavated section. Besides the oldest Middle Siwalik sandstone (unit A), the Quaternary units are further divided into eight separate principal sedimentary sub-lithological units, from unit B (oldest) to unit I (youngest) (Figure 8). They are comprised of sub-angular to angular, pebble to boulder-sized clasts that exhibit matrix or clasts-supported nature. The boulders vary in size from a few centimetres to > 1.5 m at places. Compositionally, the clasts consist of grey and pink sandstone, indicating its derivation from the hinterland Tertiary mountain ranges.

From south to north, the trench wall shows three thrust faults: Fault-0, Fault-I and Fault-II, which are parallel to the HFT thrust plane (Figures 7 and 8). Towards the southernmost part of the trench within the Late Pleistocene fluvial sediments, Fault-0 displaced and deformed the units B–F. Also, ~ 9 m north of Fault-0 another fault, i.e. Fault-I is observed (Figure 8). This fault (Figure 7 *c*) dips 23°N, along which the Middle Siwalik sandstone has thrust over the units B–E. However, the tip of Fault-I has been later eroded and covered (Figure 7 *c*) by a channel-fill deposit (unit I).

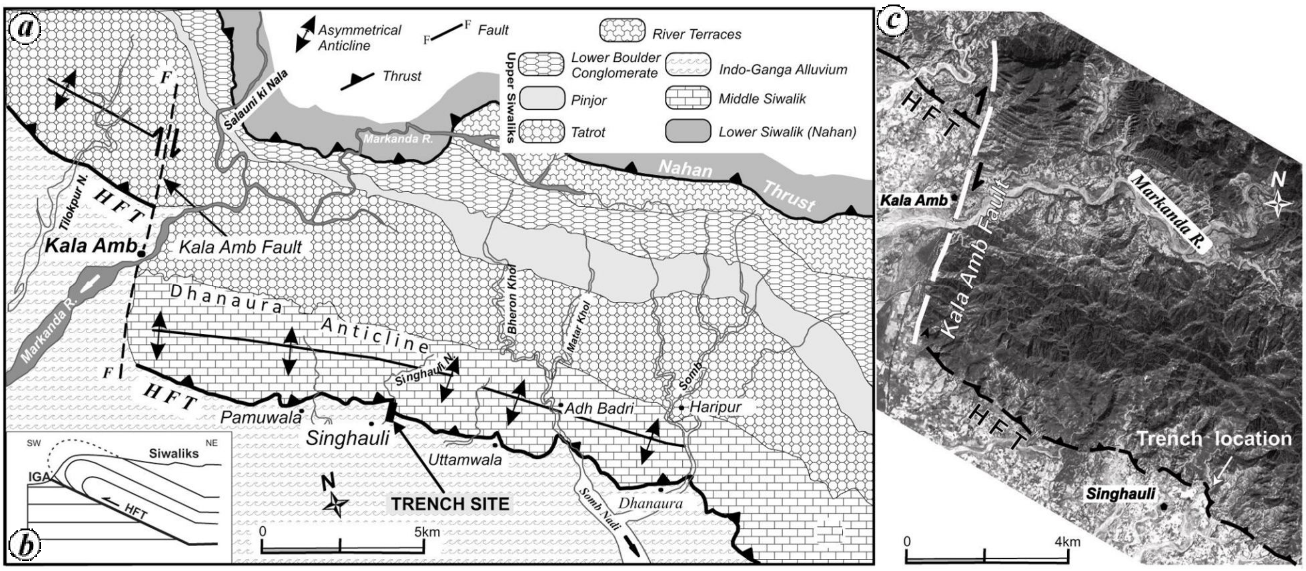

Figure 6. ***a***, Geological map of the area showing major lithological and structural features of the Frontal Himalaya around Kala Amb. The Kala Amb Fault has dextrally displaced the Siwaliks. ***b***, Schematic cross section across HFT in the study area, Kala Amb, showing the Siwaliks thrust over Indo-Ganga Alluvium (IGA). ***c***, Corona satellite photograph showing the Kala Amb Fault and the trench location near Singhauli in the Frontal Himalaya. Location of the strath terrace of the Markanda river is also shown[13].

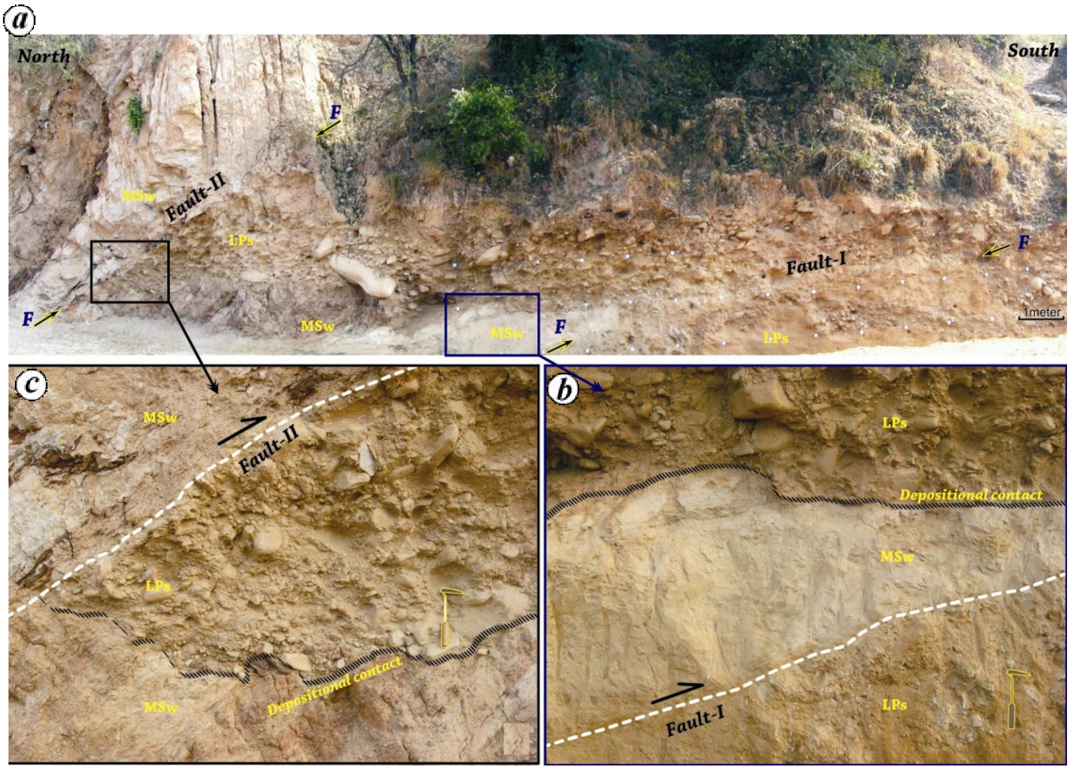

Figure 7. Earthquake faults: ***a***, Panoramic view of the trench wall (with 1 m grid) showing two distinct faults (*F–F* shown with arrows), where the Middle Siwalik sandstone (MSw) thrust over the Late Pleistocene sediments (LPs) along HFT, Kala Amb. ***b***, ***c***, Close-up views of part of the two palaeoearthquake faults (Fault-I, the older and Fault-II, the younger) observed in the trench. Depositional contact of the Quaternary alluvium with the Middle Siwaliks is shown by shaded lines[13].

Another prominent fault, Fault-II, ~ 5 m north of Fault-I, has been identified in the trench (Figures 7*c* and 8). The fault plane shows a dip of 30°N where the Middle Siwalik sandstone (Unit A) has thrust over the fluvial terrace deposit (units G and H) along this fault. The Fault-II has uplifted and upwarped the fluvial terrace (T3). The base of T3 terrace is ~ 10 m above the T2 terrace surface in the Singhauli Nala. Pebbles belonging to

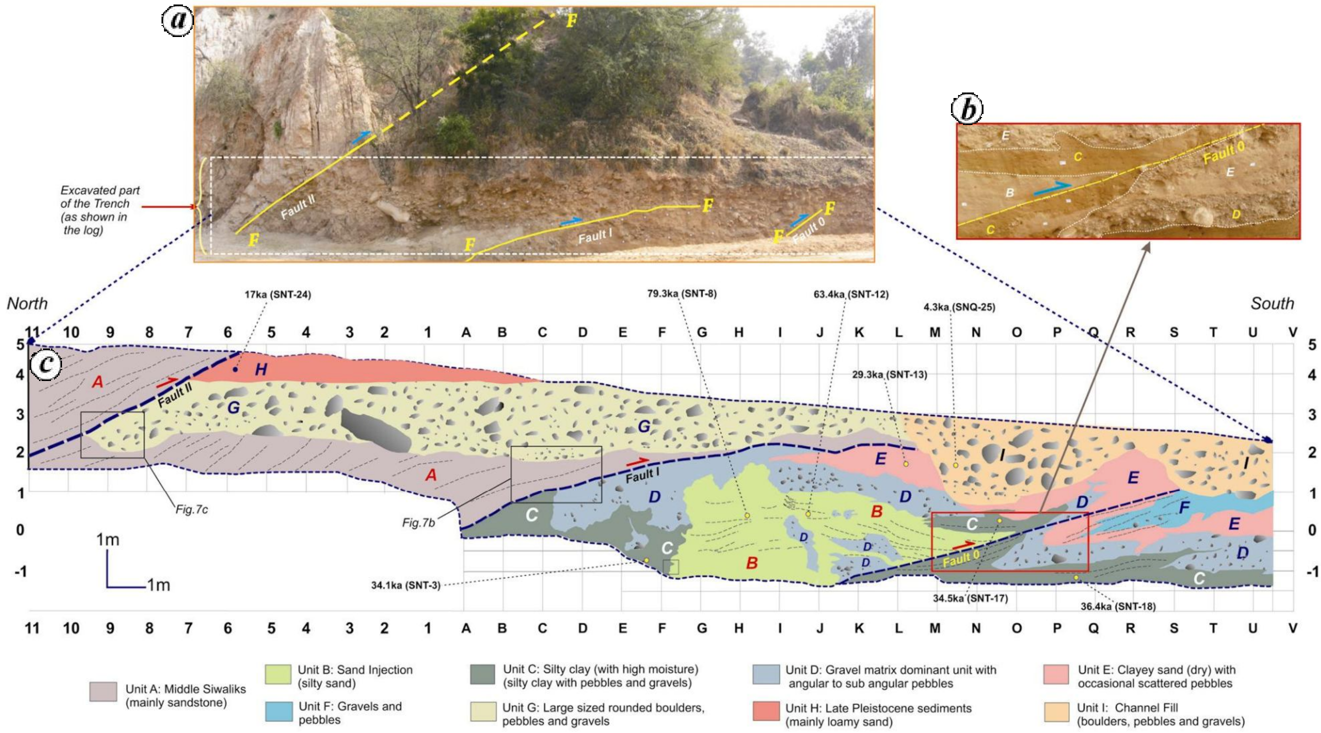

Figure 8. Trench log: ***a***, Field photograph showing the trench excavation site at Singhauli. The rectangle shows the area of trench log prepared. Fault-0, Fault-I, Fault-II are also marked. ***b***, Close-up view of Fault 0 in the trench wall (marked in red box in the trench log). ***c***, The trench log of the left bank of Singhauli Nala near Kala Amb showing repeated reactivation of HFT in the mountain front. The different litho-units (A–I) are individually identified based on the clast and matrix type and distribution. Two distinct faults recognizable in the trench log indicate their activities in the Late Pleistocene and Holocene. The large-sized induced liquefaction feature (unit B) and the deformed and dismembered units are also observable in the trench log. The OSL sample locations (except for two, which are outside the trench) are shown with their ages[13].

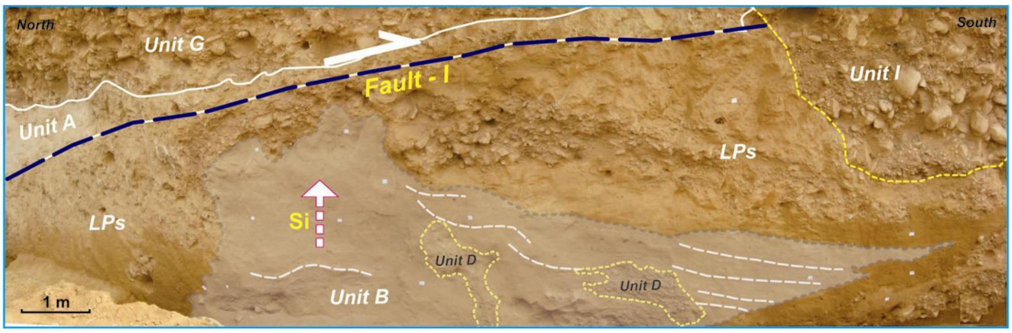

Figure 9. Liquefaction features: Part of the trench wall showing sand injection (Si) features. The arrows show the direction of the movement of sand from the subsurface that has spread laterally also. The dashed white line shows some of the curved stratification preserved within the injection feature. Caught-up chunks of unit D along with the injection features are shown by thin, dashed, yellow lines. The sand injection has not only cut across the Late Pleistocene sediments (LPs) but also uplifted and dismembered other top-lying litho-units as well. The dashed line (in dark blue) shows thrusting of Middle Siwalik sandstone unit A over LPs[13].

the terrace deposits have also got entrained within the highly sheared Middle Siwalik sandstone in this fault zone. The exposed outcrops were left for further degradation by ongoing surface fluvial processes. The external geometry of the litho-units, the Siwaliks and the fluvial terrace (T3) in the hanging wall show upwarping.

Palaeoliquefaction features: Palaeoliquefaction features are recognized in the trench wall. These features are irregular in size and shape, and consist of silty sand as injection features (Figure 9). The large-sized sand injection has not only vertically uplifted and upwarped the overlying litho-units (Figure 8), but has also dismembered some of the units (units C and D). The bowl-shaped liquefied sand in the trench shows a vertical height of ~5 m and has a lateral spread up to ~9 m (Figures 8 and 9). Part of the dismembered units is also found trapped within the large injection feature. The sand injection

Table 2. Optically stimulated luminescence ages of samples from the trench and terrace deposits at Singhauli. Elemental concentration of U, Th, K and moisture content used for dose rate calculation and equivalent dose (De) are also given[13]

Sample no.	U (ppm)	Th (ppm)	Potassium K (%)	Moisture content (%)	Equivalent dose (De) Gy	Dose rate (Gy/ka)	Age (ka)
SNQ-4	1.42 ± 0.01	5.4 ± 0.05	0.94 ± 0.01	1.00	2.20 ± 0.35	1.8 ± 0.02	1.2 ± 0.0
SNQ-3	3.54 ± 0.04	13.5 ± 0.14	0.94 ± 0.01	0.63	5.79 ± 0.50	2.81 ± 0.04	2.1 ± 0.2
SNQ-41	4.1 ± 0.04	10.4 ± 0.10	1.54 ± 0.02	4.46	18.39 ± 1.01	3.17 ± 0.04	5.8 ± 0.3
SNQ-25	3.07 ± 0.03	10.2 ± 0.10	1.08 ± 0.01	0.51	11.12 ± 1.58	2.61 ± 0.03	4.3 ± 0.6
SNT-24	3.28 ± 0.03	15 ± 0.15	1.47 ± 0.01	0.80	56.37 ± 6.46	3.31 ± 0.04	17.0 ± 1.9
SNT-13	4.15 ± 0.4	10.7 ± 0.11	1.67 ± 0.02	0.46	100.90 ± 6.50	3.45 ± 0.04	29.3 ± 1.9
SNT-17	3.28 ± 0.03	14.3 ± 0.14	2.16 ± 0.02	5.68	128.39 ± 13.41	3.72 ± 0.05	34.5 ± 3.6
SNT-3	2.8 ± 0.03	17 ± 0.17	1.46 ± 0.01	8.32	106.06 ± 13.88	3.11 ± 0.05	34.1 ± 4.5
SNT-18	0.93 ± 0.01	16.2 ± 0.16	2.26 ± 0.02	4.74	125.15 ± 8.18	3.44 ± 0.04	36.4 ± 2.4
SNT-12	1.47 ± 0.01	9 ± 0.09	1.00 ± 0.01	1.75	128.09 ± 15.02	2.02 ± 0.02	63.4 ± 7.5
SNT-8	1.42 ± 0.01	4.6 ± 0.05	0.95 ± 0.01	1.09	133.38 ± 16.11	1.68 ± 0.02	79.3 ± 9.6

feature is truncated by Fault-I and has neither dismembered nor deformed the overlying litho-units.

The palaeoliquefaction feature in the trench suggests secondary effects of a large-magnitude palaeoearthquake that must have occurred in the area. The OSL samples (SNT-8 and SNT-12 in Table 2) collected from two different spots within the induced sand injection structure (unit B) show ages of 79.3 and 63.4 ka respectively. The sand injection structure has cut across unit C, suggesting that the injection phenomenon occurred after the deposition of unit C (SNT-3, 34.1 ka). The sand injection has also uplifted and pierced into the younger litho-units (units D and E) in the trench. Unit E (SNT-13) shows an younger age of 29.3 ka, which implies that the actual sand injection has happened only after the deposition of unit E. The dismembered units suggest that during heavy shaking, the water-escape structures have also altered the thickness of the sedimentary units by upward and lateral injection of fine-grained materials (Figure 8). The size of the injection feature and the caught-up chunks (unit D) of the Late Pleistocene gravel (Figure 8) corroborate its coseismic occurrence with a large-magnitude earthquake.

Topographic profiling

To comprehend the surface manifestation and related ground surface elevation changes in close vicinity of the faults, using Total Station Survey, topographical cross-profiles were prepared along and across the fault zone, including the fluvial and strath terraces (Figure 10). The topographic profiles have also defined the elevation of important geomorphic marker surfaces with reference to the present-day river-bed elevation (~345 m) of the Singhauli Nala. The top surface of the T3 terrace has been marked at 365 m and the T2 terrace surface at 350 m elevation, although the thickness of the terraces marginally varies. The topographical profiles in the present site suggest that the distribution of T2 terrace (2.1 ka) along the river is not affected by the movement or offset by HFT. This suggests that after 2 ka, no tectonic activity is observed or identified in this locality.

Luminescence chronology

Eleven selected samples from the trench, both from the hanging wall and footwall of the HFT as well as from the adjoining fluvial terraces were dated by the OSL technique (Table 2). This includes (SNQ-41) from the topmost strath T3 terrace (Figure 10 *b*) that gives an age of 5.8 ± 0.3 ka. SNQ-3 from the T2 terrace towards south adjoining the trench (Figure 10 *b*), yields a younger age of 2.06 ± 0.2 ka for the topmost litho-unit.

Fault-I demonstrates the activity of HFT by thrusting of the Siwalik rocks over the Late Pleistocene alluvium (units C–F). After the rupture, the scarp associated with Fault-I and the Middle Siwaliks in the hanging wall remained under sub-aerial weathering and fluvial erosion. Subsequently, units G and H were deposited by the then active Singhauli Nala. Hence the tip of this fault was eroded-off and subsequently covered by unit I, a channel fill-deposit (Figure 8). A parallel fault, Fault-0, is observed in the footwall of Fault-I which has affected units C–F (Figure 8). Based on the OSL ages and the disposition of the lithological units, we believe that the timing of generation of the Fault-0 is equivalent to that of Fault-I. Hence by considering these two ages of the units E (29.3 ka) and H (17 ka), we believe that the reactivation of HFT has generated a large-magnitude earthquake resulting in the development of Fault-I, which occurred after 29.3 ka but before 17 ka. The hanging wall of Fault-I, comprising Middle Siwaliks and units G and H, is again thrust over by the Middle Siwaliks (unit A) along another parallel fault, Fault-II. The fault plane dips 30°N, which is also parallel to average dip of HFT in this region, suggesting this to be yet another reactivation event of HFT. Fault-II has uplifted the Holocene terrace (T3) in the hanging wall that was truncated by HFT. In the present study no counterparts of the respective litho-units on

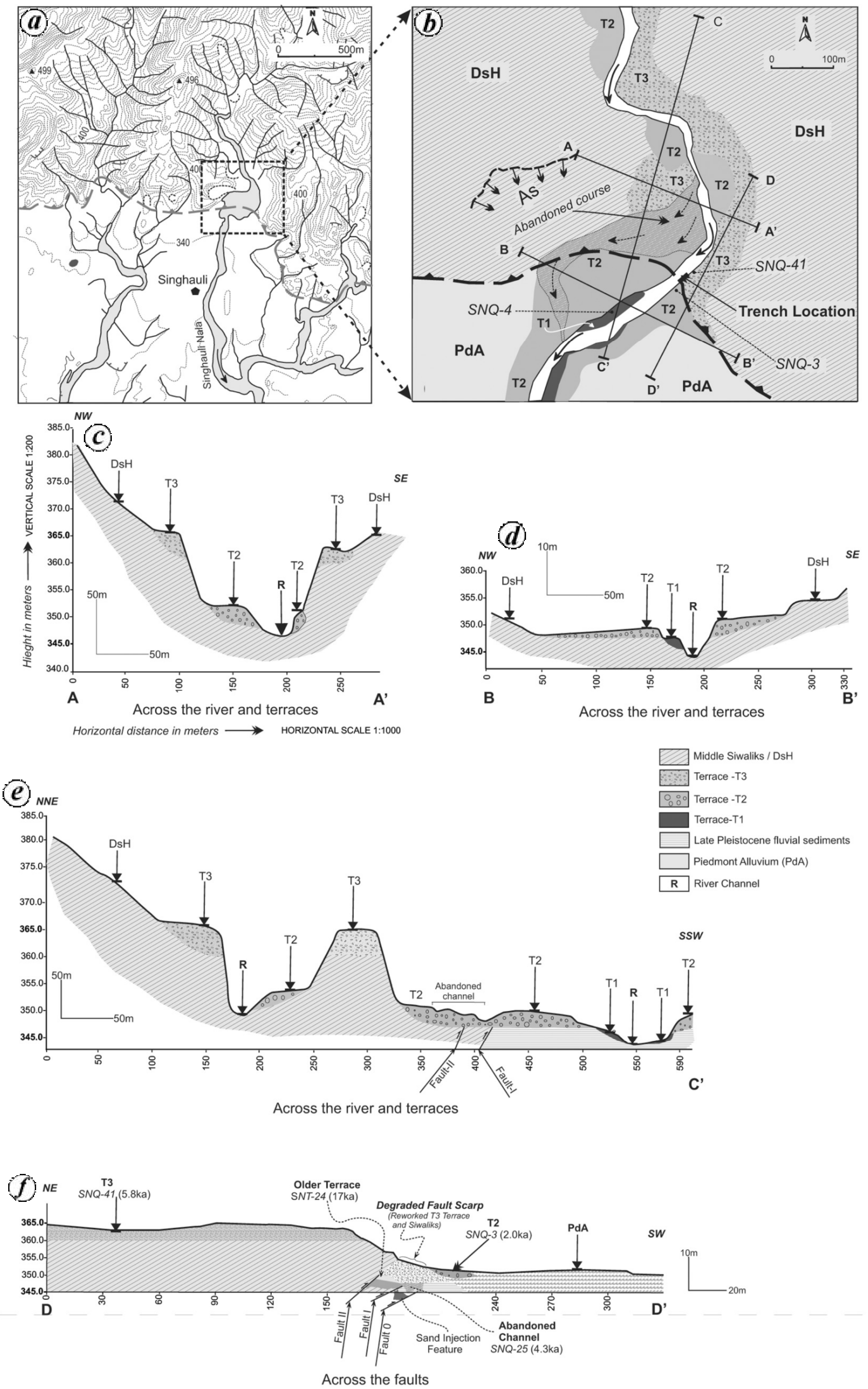

Figure 10. Topographical profiles: ***a***, Topographic map of the area around Singhauli near Kala Amb. ***b***, Close-up of the box in (***a***) showing the landform map of the area around the trench site at Singhauli. Different levels of terraces (T1–T3), abandoned course of Singhauli Nala (shown by dotted arrows), active landslide (As), denudostructural hills (DsH) of the Middle Siwaliks and the piedmont alluvium (PdA) are shown. ***c–f***, Topographic cross profiles showing variation in ground surface due to faulting, disposition of the fluvial terraces and degraded fault scarp in the trench location. The sections, except the profiles, are approximate and not to the scale[13].

the downthrown side for Fault-I are observed on the upthrown side. However, the measured slip of Siwalik rocks along the fault plane in the trench is ~ 12 m. This fault must have caused a minimum vertical displacement of 4.7 m along the 23° dipping fault plane. On the other hand, for Fault-0, (contemporaneous with Fault-I) based on boundaries of the corresponding litho-units, we measured ~4 m slip along the 23° dipping Fault-I resulting to 1.6 m vertical displacement. We therefore believe that a large earthquake with ~ 12–16 m slip suggesting a magnitude 7.5 or greater has occurred in this region in the period between 29 and 17 ka.

With regard to Fault-II, considering the OSL ages of the T3 terrace and unit H besides comparative elevation of the base of unit H and upper part of the T3 terrace, two possibilities of vertical displacement have been taken into account for estimating the earthquake magnitude. Hence for the minimum vertical offset of 10 m, the magnitude will be 7.6, whereas for 11 m offset the magnitude is estimated to be ~7.7. We therefore believe that a large earthquake of magnitude ~7.7 or greater must have occurred in this region with a maximum surface rupture length (SRL) of about 150 km. However, the observable SRL might vary depending on lithology and rate of erosion. In the present study the observed length of the subdued fault scarp is limited owing to fast modification of the landform for agricultural and industrial development. The faults observed at Singhauli suggest that there must have been large-magnitude multiple palaeoearthquakes along HFT during Late Pleistocene and Holocene.

The two faults recognized in the trench wall at Singhauli, where the Middle Siwaliks has thrust over the Quaternary alluvium are significant as far as the repeated reactivation of HFT in the Frontal Himalaya is concerned. The trenches excavated across HFT for palaeoseismological studies[14,10,24] have also substantiated that HFT along the mountain front between Chandigarh and Kala Amb and at Hajipur ruptured during the last 2000 years and generated two or three major earthquakes ($M \cong 7$ or 8).

In the present study, the bottom of uplifted T3 strath terrace (OSL age 5.8 ka) is uplifted almost to a height of 15 m from the present-day river bed. The distribution of the fluvial terraces in these areas and their near similar age of deposition suggest long-term uplift along HFT. The elevation of the fluvial strath terraces is used to calculate the slip and the uplift rates along HFT at Singhauli. The T3 terrace, 3–5 m thick resting over the 15 m high eroded surface of inclined Siwalik rocks, shows a long-term uplift rate of 3.4 mm/year and a slip of 6.8 mm/year along the 30° dipping Fault-II. The large slip of 20–22 m along Fault-II might also be due to past multiple reactivation events along the fault.

The major historical earthquakes in the Himalaya have originated underneath the Higher Himalaya and have ruptured the decollement southward up to HFT[2]. The two faults (Fault-I and Fault-II) observed in the trench wall at Singhauli (Figures 7 and 8), where the Middle Siwaliks has thrust over the Quaternary alluvium, are significant as far as the repeated reactivation of HFT in the Frontal Himalaya is concerned. These two faults have not only uplifted the younger fluvial terraces, but have also induced secondary features and soft-sediment deformation structures, mainly the sand injection and water-escape structures. The present study and many new exposures observed along new water-storage structures constructed for irrigation purpose along HFT, clearly reveal that the Siwaliks (Mio-Pleistocene) is riding over the Quaternary fans and terraces indicating active nature of HFT, and that the seismic slip has taken place along HFT with the rupture propagating to the surface.

Conclusions

Palaeoseismological study carried out at Nalagarh in Pinjaur Dun has revealed the Late Pleistocene earthquakes along NT. The 2.5 m slip observed in the NT and > 1.5 m slip along PGF suggest that active faults in the Pinjaur Dun were capable of generating large-magnitude earthquakes. The two tectonic episodes separated in time observed along NT have shown repeated reactivation in the Quaternary. Trench excavation survey carried out in the vicinity of HFT along the Himalayan mountain front near Kala Amb shows unambiguous evidences of at least two large-magnitude earthquakes that rocked this region. An earthquake with 12 m or larger fault slip with magnitude 7.5 or greater hit this region between 29.3 and 17 ka during the Late Pleistocene. Another great earthquake occurred with 20–22 m or more surface displacement and magnitude of 7.7 or greater between 5.8 and 2 ka in the Holocene. The topographical profiles in correlation with the OSL ages suggest that after 2 ka no tectonic activity is observed in this locality. Repeated reactivation of HFT substantiates high seismic potential of the Frontal Himalaya and indicates that HFT has the potential to produce large-magnitude earthquakes. According to Bilham *et al.*[25], the Central Seismic Gap[26] between 1905 Kangra and 1934 Bihar–Nepal earthquakes has a high probability for one or more $M > 8$ Himalayan earthquakes during this century. The losses in terms of life and property would be much higher compared to the four great earthquakes in the past, because of the explosive growth of population in the outer Himalaya and the adjoining Indo-Ganga plains in the last half a century. As the recurrence interval of large-magnitude earthquakes is presently not well established, this highly populous and fast-developing industrial belt of the outer Himalaya calls for detailed field mapping of active faults and their palaeoseismological studies for a probabilistic earthquake hazard assessment.

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