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## Active faults and neotectonic activity in the Pinjaur Dun, northwestern Frontal Himalaya

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**Manifestation of ongoing active tectonics in the Himalayan foothill region is evident from a number of major  $M > 7.5$  and great earthquakes ( $M \approx 8$ ) which occurred within the last century or so, besides the recurrent seismic events of moderate magnitude. Active faults of the Himalaya are significant in the study of active tectonics because displacements along them reflect the continued tectonic movements. The present study deals with morpho-structural analysis using remotely sensed data along with selected field investigations in delineating new traces of active faults in the Pinjaur Dun of the northwestern Frontal Himalaya. Fault scarps with heights varying from 5 to 25 m observed along the faults are indicative of long term uplift/deformation in the current tectonic regime and cumulative slip along them. These active faults are signatures of Quaternary tectonics in the zone between the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust.**

**Keywords:** Active faults, Frontal Himalaya, neotectonics, Pinjaur Dun, remote sensing.

ACTIVE faults are widely distributed in different sectors of the Himalaya and are important in that they provide signa-

tures of the recurrent tectonic activity during the Quaternary and in particular the Holocene periods. The activity often resulted in destructive earthquakes, dislocation of old landforms and creation of new ones. Landforms such as river terraces, alluvial fans, fault scarps and other morpho-tectonic features such as triangular facets, knick points, sag ponds, shutter ridges, pressure ridges and pull-apart basins, controlled drainage, and stream piracy are closely related with activity along these active faults<sup>1–10</sup>. Geomorphic and morphotectonic analyses of landforms provide insights into rates, style and pattern of deformation due to active tectonics.

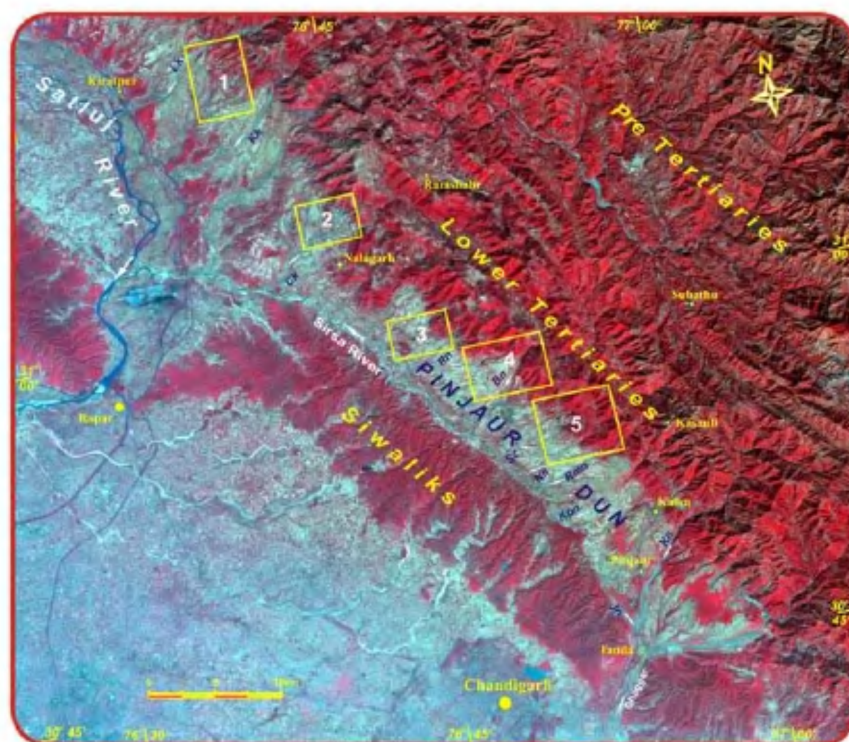
Geodetic, GPS and seismic studies have provided significant understanding of the ongoing crustal deformation in the Current Tectonic Regime (CTR) on a regional scale<sup>11–13</sup> in the Himalaya. However, the site-specific studies are few<sup>3,6,7–9,14–16</sup>. Identification of active faults that have moved within the CTR, i.e. during Holocene, also helps in assessing whether or not tectonic movements are likely to occur and cause seismicity, generally associated with these faults.

In the Outer Himalaya, lying between the Himalayan Frontal Thrust (HFT) and Main Boundary Thrust (MBT) in the north, numerous active faults and neotectonic features have been reported<sup>2,3,15,17–19</sup>, which have generated major and great earthquakes<sup>20–22</sup>. We have carried out a study of these features in an active segment of the Outer Himalaya between the Satluj and Ghaggar rivers and referred to as the Pinjaur Dun (Figure 1), which lies in the meizoseismal zone of the 1905 Kangra earthquake<sup>23</sup>. While the authors and their co-workers have already recorded active faults in the Pinjaur–Kalka area and near Chandigarh<sup>8,9,16</sup>, the present communication reports the discovery of a few more active structures. We have identified ten such faults. However, we discuss here only five major fault systems, since the analysis of other structures is in progress and shall be communicated separately in the near future.

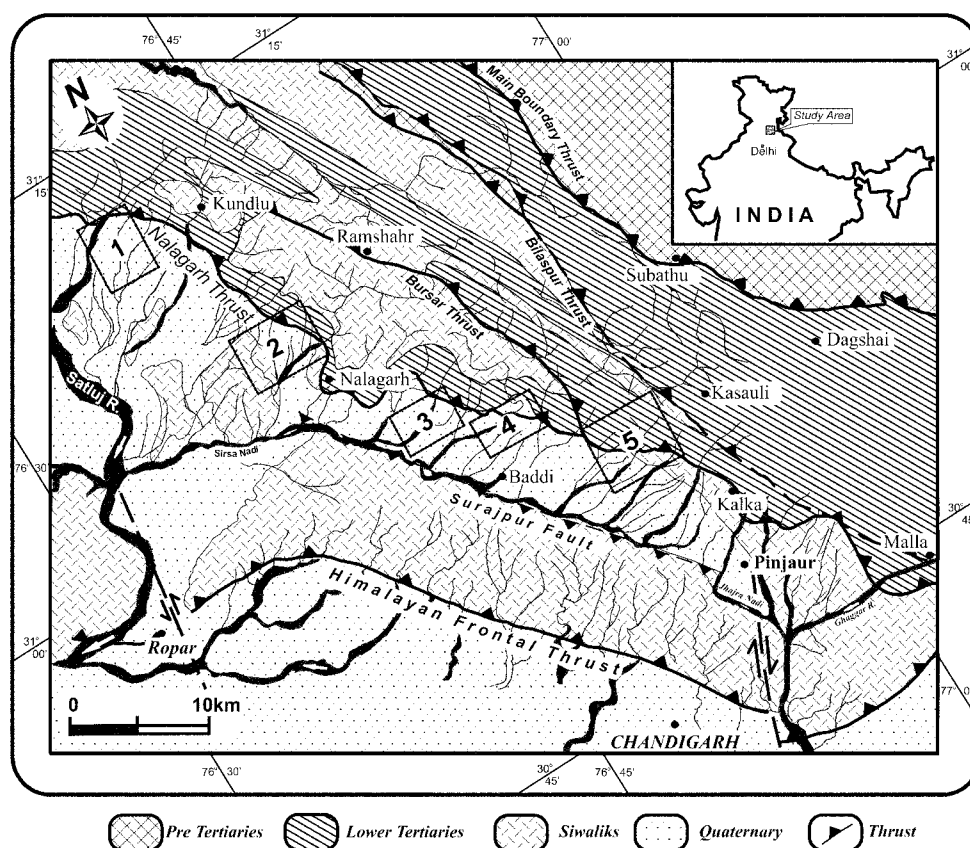
The multi-spectral satellite data of IRS-ID-LISS-III and PAN (date: 04 October 2002) and air photos, supported by the Survey of India Topographic Maps (1:50,000 scale), constituted the main data source for the present study. The satellite data have been digitally enhanced for feature extraction. Selected ground-truth checks have been carried out to re-judge the interpretation.

The Pinjaur Dun is one of the three major Duns in the western Frontal Himalaya, viz. Soan, Pinjaur and Dehra. The Duns are broad synclinal depressions which develop when the growing outer ridges constituted by the Siwalik sediments block and divert the drainage<sup>11,24</sup>. The Pinjaur Dun is NW–SE trending, approximately 55 km long and 12 km at its widest part. It is bound by the Siwalik Hills in the southwest and by the Kasauli–Ramshahr ranges in the northeast. This Dun closes in the east near Malla where the Siwalik and the eastern extension of Kasauli–Ramshahr ranges approach each other. It extends westwards across the River Satluj (Figures 1 and 2). Sirsa is the main axial

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**Figure 1.** IRS-LISS-III + PAN merged image (04 October 2002) showing the regional set-up of the area. Boxes (1–5) show the areas studied around active fault systems 1, Mastanpura; 2, Nangal–Jhandian; 3, Manpura; 4, Bari–Batauli and 5, Majotu. Lk, Luhund Khad; Kk, Kundlu ki Khad; Ck, Chikni Khad; Rn, Ratta Nala; Bn, Balad Nadi; Sc, Surajpur Choa; Nn, Nanakpur Nadi; Rmn, Ramnagar Nadi; Kpn, Kiratpur Nadi; Jn, Jhajra Nadi and Kn, Koshallia Nadi.



**Figure 2.** Regional geological map of the area (modified after Raiverman *et al.*<sup>17</sup>). Boxes (1–5) show areas studied around active fault systems: 1, Mastanpura; 2, Nangal–Jhandian; 3, Manpura; 4, Bari–Batauli and 5, Majotu.

**Table 1.** Litho-tectonic setting of Pinjaur Dun and the surroundings

North	Litho Unit	Lithology	Age
Pre-Tertiary (Undifferentiated)	Krol Group	Clastics and Carbonates	Late Proterozoic
<b>Krol Thrust/Main Boundary Thrust (MBT)</b>			
Siwalik Group (Middle Miocene to Pleistocene)	Lower Siwaliks	Grey coarse grained sandstone and brown mudstones and siltstone	Middle Miocene
<b>Unconformity</b>			
Lower Tertiary (Palaeocene to Early Miocene)	Kasauli Dagshai Subathu	Micaceous sandstone Red/Green sandstone and mudstones Shales with limestone bands and subordinate sandstones	Early Miocene Late Oligocene Paleocene-Eocene
<b>Bursar Thrust</b>			
Siwalik Group (Middle Miocene to Pleistocene)	Middle Siwaliks	Grey fine to coarse grained sandstone with subordinate brown grey mudstones	Late Miocene
	Lower Siwaliks	Grey coarse grained sandstone and brown mudstones and siltstone	Middle Miocene
<b>Unconformity</b>			
Lower Tertiary (Palaeocene to Early Miocene)	Kasauli Dagshai Subathu	Micaceous sandstone Red/Green sandstone and mudstones Shales with limestone bands and subordinate sandstones	Early Miocene Late Oligocene Paleocene-Eocene
<b>Nahan Thrust</b>			
Siwalik Group (Middle Miocene Pleistocene to Pleistocene)	Upper	Sandstone, conglomerate	Pliocene to Middle
	Middle	Grey fine to coarse grained sandstone with subordinate brown grey mudstones	Late Miocene
	Lower	Grey coarse grained sandstone and brown mudstones and siltstone	Middle Miocene
<b>Himalayan Frontal Thrust</b>			
South	<b>Indo-Gangetic Alluvium</b>		

stream which flows NW and joins the Satluj. Numerous major and minor streams, drain into the axial stream both from north and south, while the former being much longer than the latter reflects the asymmetry and tectonic tilting of the basin to the southwest. Major streams like Luhund and Kundlu directly join the Satluj while Chikni, Ratta and Balad Khads, Surajpur Choa, Nanakpur Nadi, Ramnagar Nadi and Kiratpur Nadi drain into the Sirsa (Figure 1).

The Outer Siwalik hills constituted by the Upper Siwalik sandstone and conglomerates are separated from the alluvial plains in the south by the HFT, while to the north these have a fault contact, i.e. Surajpur fault against the Dun fans and the Siwaliks within the Pinjaur Dun. The Quaternary sediments and the Siwaliks in the Dun are thrust over by the Lower Tertiary sediments (Subathu–Dagshai–Kasauli sequence) of Kasauli–Ramshahr ranges along the Nalagarh and the Bursar thrusts<sup>17,25</sup> in the NE (Figure 2 and Table 1). Both the Siwaliks (Upper Tertiary) and the Lower Tertiary sediments (Table 1) are folded into NW–SE trending, broad, open folds with axial traces traceable for many kilometres.

Geomorphic setting of the Pinjaur Dun is controlled by three major features, viz. (a) Outer Siwalik ranges, (b) Kasauli–Ramshahr ranges and (c) Main Dun with alluvial fans and river terraces of Sirsa, Jhajra and their tributaries.

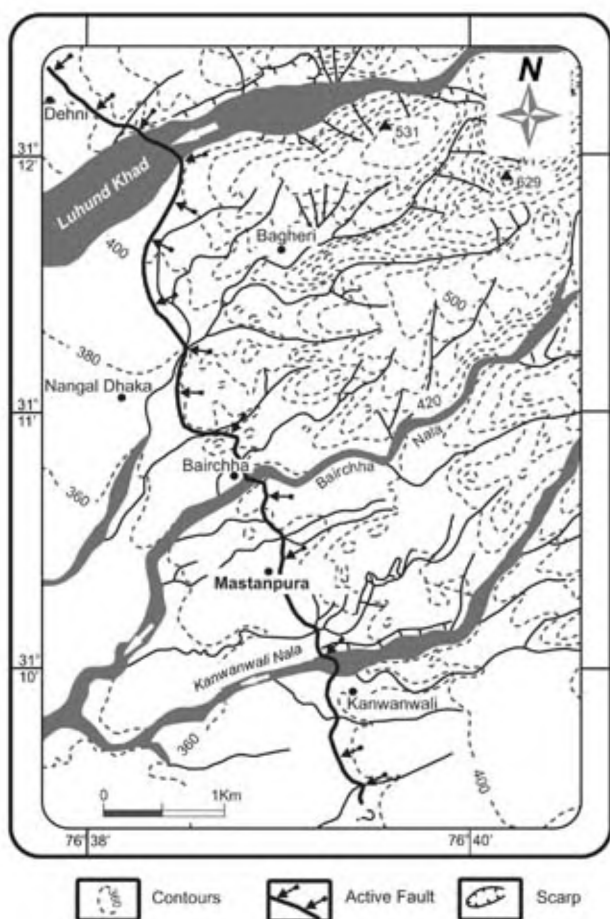
The Outer Siwalik Hills trend NW–SE and have a rugged topography with prominent hogbacks. The Siwaliks dip due southwest and prominent dip slopes are also observed. A characteristic feature of the Siwalik Range is the watershed lying close to its northern limits; thus the streams cutting through and draining south into the plains are long, while those draining northeast into Sirsa or Jhajra are small. The overall asymmetry of drainage is attributed to the uplift of the Outer Siwalik range due to movement along the HFT and the Surajpur Thrust.

The Kasauli–Ramshahr ranges are constituted by Lower Tertiary rocks of the Subathu–Dagshai–Kasauli sequence (Table 1; Figures 1 and 2). The Nalagarh and Bursar thrusts delimit the Pinjaur Dun from the rugged topography of the Kasauli–Ramshahr ranges and control the deposition of alluvial fans in the piedmont zone. The ranges are traversed by a number of major thrusts and tear faults<sup>17,25</sup> and are tectonically still active, undergoing rapid uplift and erosion.

The Pinjaur Dun is covered by sediments deposited over the Siwalik Range, as a series of alluvial fans brought down by tributaries from both sides to join the Sirsa axial stream. The fans deposited by streams draining from Kasauli–Ramshahr ranges are large in comparison to those deposited by streams draining the northern slopes of the

Siwalik Range. In the apex region of the northern fans the tributary streams have cut deep gorges, while in the distal portions these have wide channels with local braiding of streams. The fan surfaces are extensively degraded due to anthropogenic activity and intense precipitation during the monsoons. A series of terraces have been carved out by erosion and deposition by both the Sirsa river and its major tributaries.

Active tectonics in the Pinjaur Dun is reflected by dislocation of landforms by major and minor faults in Quaternary and pre-Quaternary sediments. A number of lineaments and active fault traces have been delineated on aerospace data and also verified in the field. Most of the fault traces and lineaments show a NW–SE trend, which is almost parallel to the regional trend of the MBT, Bursar and the Nalagarh thrusts. Some stream courses are fault-guided and also controlled by lineaments. Uplifted and tilted Quaternary landforms and sediments indicate the activity along these faults. A brief account of five major active fault systems identified in the Pinjaur Dun is given below.



**Figure 3.** Mastanpura active fault system (box 1 in Figures 1 and 2) defining a prominent topographic scarp trending NNW–SSE direction. Arrows show movement of the hanging wall of low-dipping thrust fault.

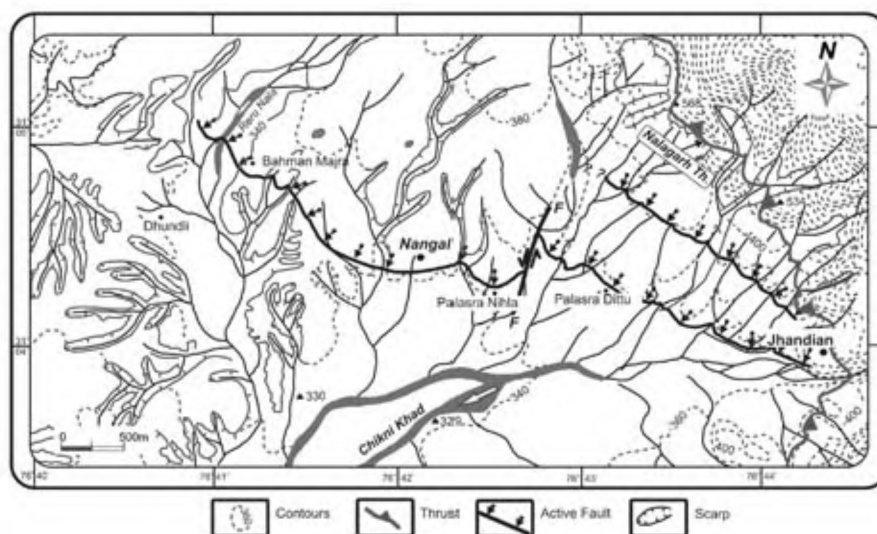
**Mastanpura–Bagheri active fault system:** The fan terrace, exposed at about 400 m amsl, in the inter-fluve of Kundlu ki Khad and Luhund Khad (Figure 1) near Mastanpura and Bagheri, has a NW–SE trending scarp produced by an active fault (Figure 3). The scarp has been intensely modified due to agricultural activity and urbanization. Though its surface exposure is discontinuous, the fault trend is traceable over 4–5 km between Kanwanwali and Bagheri. The back-tilted fan terrace displaced by the fault shows a scarp with height varying from 10 to 15 m. In a section near a culvert over a small stream west of Nangal Dhaka, nearly horizontal sandy layers within the conglomerate show a low-angle reverse fault dipping  $10^\circ$  due NE. The pebbles in the layers are aligned, dragged and shattered. The original surface is gentle with  $2\text{--}3^\circ$  average slope. The fault has also exercised control on drainage and topography. The Kanwanwali Nala in the hanging-wall region also shows a steep cliff due to rapid down-cutting. A series of ponds have been observed aligned almost parallel to the fault trace. It appears that the fault does not die near Bagheri, but may extend further NW across the Luhund Khad towards Dehni (Figure 3).

**Nangal–Jhandian active fault system:** New traces of parallel to sub-parallel active faults have been identified in the Nangal–Jhandian sector to the north of Chikni Khad (Figure 4). Dislocated fan terrace observed near Palasra Nihla village (Figures 5 and 6a) forms a 15 m high scarp and shows back-tilting of about  $10^\circ$  (Figures 6a and b) along the stream draining east of Palasra Nihla. The Nangal–Jhandian Fault is displaced sinistrally by about 300 m along a fault, which runs parallel to the stream (Figure 5). The fault scarp trends WNW–ESE and extends for about 6.5 km from Bahman Majra to Palasra Dittu (Figure 4). A number of parallel to sub-parallel fault scarps are observed to the north of this fault and could be extended for about 2 km up to Jhandian just south of the Nalagarh Thrust. Well-preserved fault scarps are also observed in streams draining between two Palasras, where nearly horizontal fan gravels are thrust over the river deposits and the fan material is tilted to the northeast (Figure 6b). The fault scarps almost perpendicular to the small tributaries of Chikni Khad originating from the Lower Tertiary rocks, appear to be basically due to movement along a thrust fault with northside up, though minor deflection of channels suggests a left lateral strike slip component. The diversion of NE–SW-flowing Reru Nala into a NNW–SSE tributary of Chikni Khad between Dhundli and Bahman Majra is due to movement along this fault (Figure 5). The parallel to sub-parallel active fault systems traceable for a total of 8–9 km appear to be merging at Jhandian. A sag pond located to the northeast of Nangal corroborates the back-tilting of the terraces and formation of a depression (Figure 6c). A small, dried-up pond is also observed east of Bahman Majra.

**Manpura active fault system:** A NW–SE trending sub-parallel fault scarp has been observed near Chahal Majra



**Figure 4.** IRS-LISS-III + PAN merged image (04 October 2002) showing the Nangal–Jhandian active fault (box 2 in Figures 1 and 2). Arrows show the parallel to sub-parallel active fault traces.



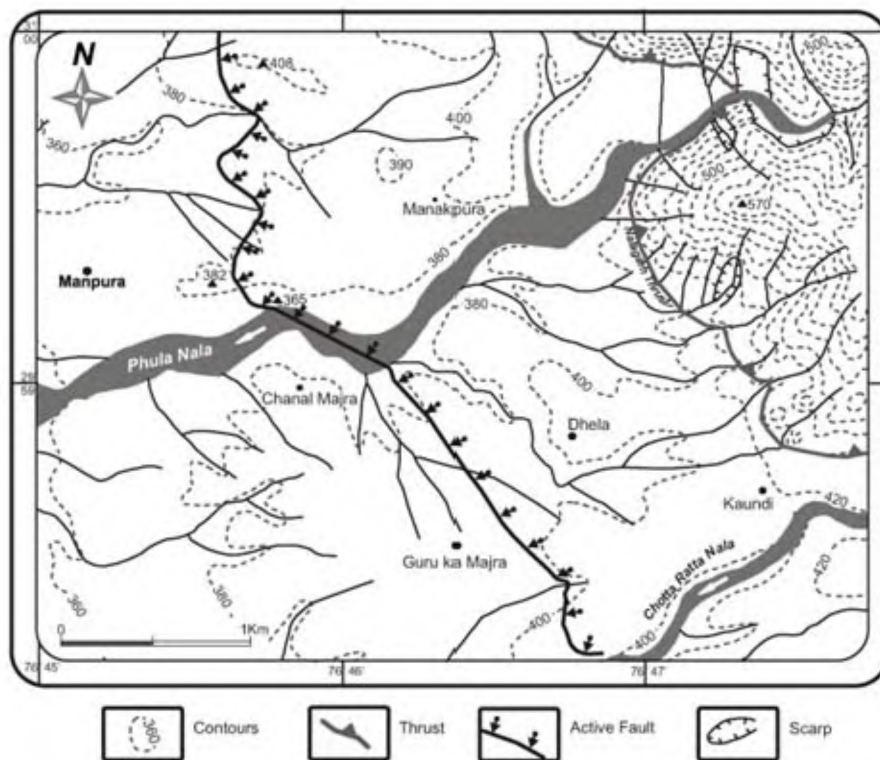
**Figure 5.** Nangal–Jhandian active fault system (box 2 in Figures 1 and 2). Arrows show the upthrown northern block along the low angle thrust. A number of minor faults also occur in the hanging wall.

(Figure 7). This fault appears to be cutting across Phula Nala, a tributary of Sirsa Nadi to the east of Manpura. The surface expression of the scarp is subdued owing to the progressive modification and terracing for agriculture practices. Deflection of Phula Nala east of Chahal Majra helps to extend this fault to the southeast towards Guru ka Majra, where the scarp merges in the fluvial terraces of Chotta Ratta Nala. Along the Phula Nala, a deep cut shows conglomerates of the alluvial fan thrust over the river terrace. Hilltop (390 m) north of Manakpura and riverbed at

365 m show the erosional scarp now to be 20–25 m high. This topographic spur east of the hill (382 m) is almost flat up to Manakpura, east of which the topography steepens across the Nalagarh thrust. A stream draining from Guru ka Majra flows NW along the fault scarp, whereas another stream draining from Kaundi takes a sharp right-angled turn south of Dhela and flows parallel to the fault indicating right lateral slip along the fault. Phula Nala is also shifted by about 600 m dextrally along its trace. A series of springs are also observed along the fault zone.



**Figure 6.** *a*, WNW–ESE trending fault scarp (FS) near Palsara Nihla village with an average height of 15 m. *b*, Backtilting of the Quaternary fan deposit by about 10° (shown by yellow arrows) along the Nangal–Jhandian Fault, exposed along a tributary of Chikni Khad, southeast of the village Palsara Nihla. *c*, One of the sag ponds on the hanging wall, i.e. to the north of the Nangal–Jhandian Fault near Nangal village. View towards north.



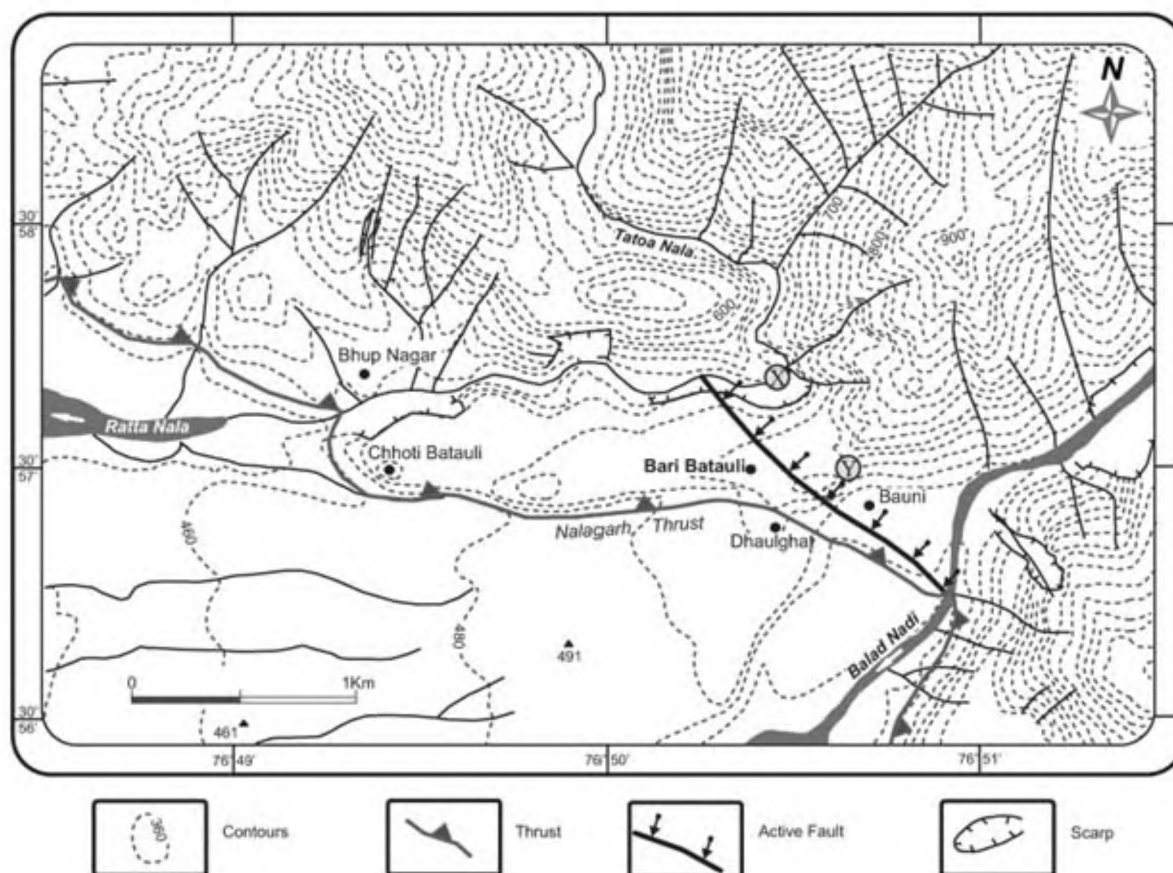
**Figure 7.** Manpura active fault (box 3 in Figures 1 and 2) showing a 15 m high scarp to the east of Manpura village. The fault has dextrally displaced the Phula Nala by about 600 m. Arrows indicate direction of movement of the upthrown block along a low-angle thrust fault.

*Bari Batauli active fault system:* The Balad–Ratta Nala fan system (Figures 8 and 9) in its apex region has been displaced by the NW–SE trending Bari-Batauli active

fault. The fault traceable for about 1.5 km is a high-angle reverse fault dipping towards northeast and is marked by a distinct NW–SE scarp observed near Bauni Village at



**Figure 8.** IRS-LISS-III + PAN merged image (04 October 2002) showing the Bari Batauli active fault system (box 4 in Figures 1 and 2). The pressure ridge (PR) between Chotti Batauli and Dhaulghat rises to over 20 m on the upthrown side of the Nalagarh Thrust, which separates the gently sloping Balad Fan from the rugged terrain constituted by the Lower Tertiary rocks. Arrows show the trace of active fault.



**Figure 9.** Bari Batauli active fault (box 4 in Figures 1 and 2) showing a NW-SE trending fault scarp. Arrows indicate direction of movement of the upthrown block. The Tatao Nala earlier flowing between X and Y was captured by Ratta Nala at X, leaving a wind gap at Y.



**Figure 10.** *a*, Fault scarp of Bari Batauli Fault on the Quaternary fan terrace (Qt) of Balad Nadi. View due south. Arrows indicate NW–SE trace of the fault near the village Bauni. *b*, E–W trending pressure ridge (PR) between Chhoti Batauli and Dhaulghat. Uplifted and tilted terraces of Ratta Nala overlying the Lower Tertiaries are exposed on the hanging wall of north-dipping Nalagarh thrust. View due south.

an elevation of approximately 520 m amsl. The scarp possibly generated by a major seismic event has an average height of 20 m (Figure 10*a*). It extends towards Bari–Batauli to the northwest, where it merges with the upstream terrace deposit of Ratta Nala and dies out near the Balad Nadi in the southeast (Figure 9).

The associated landforms in this region also suggest that a stream (Tatoa Nala) earlier joining the Balad Nadi to the southeast of Bauni was captured due to headward erosion by the Ratta Nala which has cut a deep gorge upstream of Bhup Nagar; it meets the captured stream at right angles at X (Figure 9). The present-day wind gap east of Bari Batauli (Y) supplements this observation<sup>26</sup>. An EW trending ridge between Chhoti Batauli and Dhaulghat represents a pressure ridge (Figure 10*b*) uplifted due to movement along the Nalagarh Thrust, where the Lower Tertiary rocks are thrust over the fan gravels. This ridge

risks to over 20 m with steep cliffs on both sides. Tilted and uplifted terraces are also observed on the northern side along the Ratta Nala (Figure 10*b*).

**Majotu active fault system:** Near village Majotu, along a tributary of the Surajpur Choa, highly deformed Lower Tertiary sandstones ride over the terrace deposits along a north-dipping thrust (Figures 11 and 12*a*), which developed parallel to and is due to reactivation of the Bursar Thrust. The fault scarp thus produced extends towards SE and is traceable for over 15 km between Palakhwala and Raru, though the best expressions are between Majotu and Koti (Figure 11). The fault trace is also expressed as a series of prominent triangular facets (Figure 12*b*) and a number of ponds aligned parallel to it. An EW-trending fault has also displaced the trace of Majotu fault north of Mandhala. Along a number of stream sections across the fault zone (Figure 12*a*) pebbles in the terrace deposit are aligned

along the fault and many of them are shattered (Figure 12 c). Sandy horizon has also produced sand dykes which cut through the conglomerate.

Many conspicuous tectono-geomorphic features such as warping and back-tilting of fluvial and alluvial fan surfaces and fault scarplets in the Quaternary deposits are observed along most of the active faults in the Pinjaur Dun. The faults show a thrust movement with the north-east side up. Traces of active faults running parallel to each other traverse through Late Pleistocene to Holocene alluvial-fan sediments. Wherever the faults show strike-slip movement, lateral offsets of streams and terraces are observed.

Among the faults we have identified and those known earlier<sup>8</sup>, the Majotu fault system appears to be related to movement along the Bursar thrust. Other faults are confined to the Quaternary fans and terraces within the Dun. Most of the active faults observed are low-angle thrust faults, except the Bari Batauli fault, which is a high-angle reverse fault. These faults could have developed due to ongoing convergence along the Himalayan Front and its influence in the Outer Himalaya. The past seismic events recorded along the Himalayan Front were generated due to convergence and resulting shortening along major thrust planes. The foreland basin bound by MBT and HFT is traversed by numerous thrusts and has undergone a total shortening of nearly 25 km since Miocene<sup>17,27</sup>. As the convergence is an ongoing process, the intervening zone in the Duns will be subjected to shortening along various

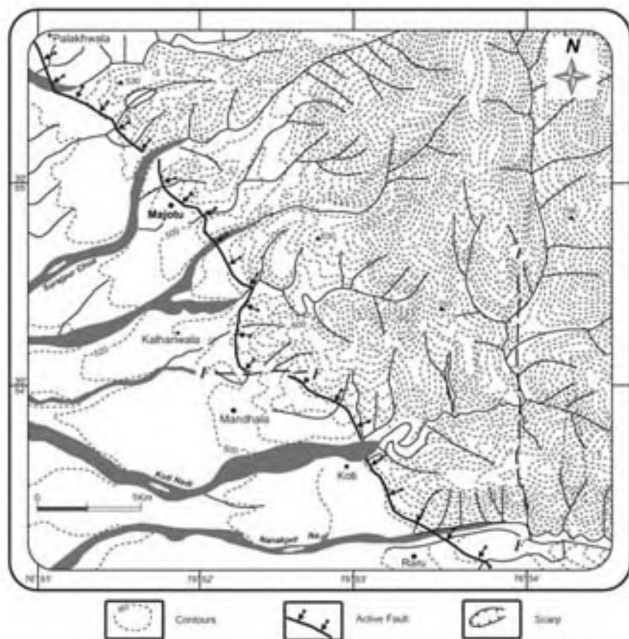
thrusts and active faults and may generate major earthquakes in the near future.

Though the observed extent of the active faults mapped by us has been indicated on maps (Figures 3, 5, 7, 10 and 11), the actual fault trace could extend on both sides since the fault scarps visible on the satellite images are being degraded and modified due to extensive agricultural and urbanization activities. Rapid erosion and poor preservation of the coarse-grained alluvial deposits being subjected to strong monsoon also results into subdued fault expressions.

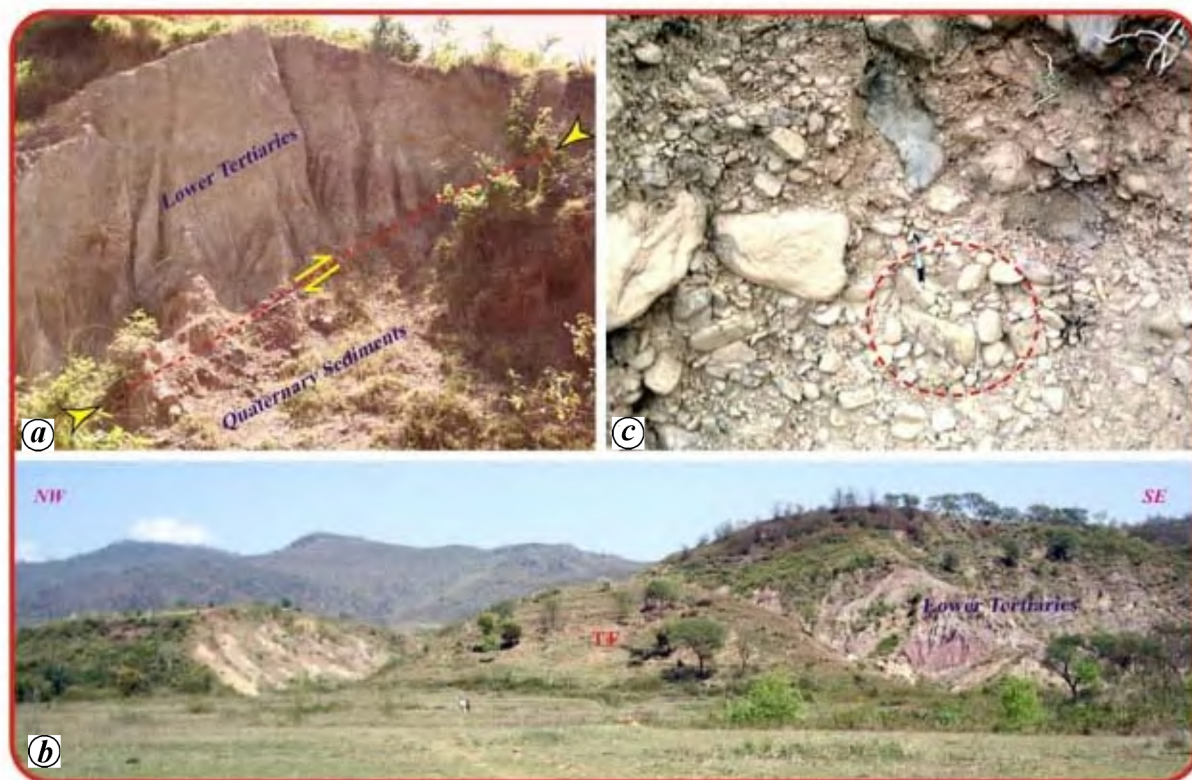
The Pinjaur Dun has been described as a typical piggy-back basin<sup>8</sup> and a fault graben<sup>28</sup>. It has been postulated that such basins or depressions were formed as the thrust fronts propagated southward towards the foreland causing numerous structural and depositional changes and leading to subsequent development of new piggyback basins behind the thrusts<sup>29</sup>. The OSL dates of the exposed bottom and top of the fan deposits indicate that the fan sedimentation commenced well before 80 ka BP and continued up to around 20 ka BP. After termination of fan sedimentation around 20 ka BP, river incision and subsequent terrace formation occurred<sup>30</sup>.

Change in the palaeohydrological regime along with uplift of the Kasauli–Ramshahr ranges led to fast down-cutting by the rivers through gorges both upstream of the mountain front and fans further downstream. Southward push of thrust front over the Siwaliks and Quaternary deposits produced active faults in the prevailing stress regime in the Pinjaur Dun. Total length of the faults traces extends for over 40 km and the fault movement could have generated  $M$  6.5 or  $M$  7 earthquakes in the past. As the area lies in the southeastern part of the meizoseismal zone<sup>23</sup> of 1905 Kangra earthquake  $M$  8, past activity needs to be studied for its chronology and recurrence. The Basdevpura fault<sup>8</sup> near Kalka (Figures 1 and 2) traceable for about 10 km, has displacement of 2 m during a possible  $M \approx 7$  earthquake, while an active fault<sup>9</sup> along the HFT northeast of Chandigarh ruptured during a  $M$  7–7.5 event around AD 1500.

The active faults observed in the Pinjaur Dun reflect the intermittent tectonic impulses due to large earthquakes, which produced prominent fault scarps. Since the Dun is confined between MBT, Nalagarh and the Bursar thrusts in the north and the Surajpur Fault and HFT in the south, reactivation of these faults must have created fault scarps which are almost parallel to them. The above observations further corroborate and support Malik *et al.*<sup>9,16</sup> and report about a large magnitude earthquake around AD 1500. The geodetic measurements carried out by Bilham *et al.*<sup>31</sup> suggest that the Frontal Himalaya with a recurrence interval of 500 years for great ( $M$  8) earthquakes is ready for a major event, since no great ( $M$  8) earthquake has struck the region in the recorded history. According to some authors<sup>21,22</sup> the Kangra earthquake of 1905 was not a great event, but had  $M$  7.8.



**Figure 11.** Majotu active fault system (box 5 in Figures 1 and 2) showing a prominent topographic scarp trending NW–SE direction. Arrows show the movement of the hanging wall of low-dipping thrust fault, which also coincides with the Nalagarh Thrust in this segment.



**Figure 12.** *a*, Field photograph showing the Majotu (Nalagarh Thrust reactivated) active fault near the east of Kalhariwala village. Highly crushed Lower Tertiary sandstones ride over the Quaternary fan gravels; view due southeast. *b*, Triangular facets (TF) along the Majotu fault to the north of Kalhariwala; view due northeast. The flat ground in the foreground represents top surface of the alluvial fan. Hills in the background expose the Lower Tertiary sediments. *c*, Angular to sub-angular pebbles in the Quaternary fan conglomerate showing shattering due to southward movement along the footwall of the Majotu fault.

Active faults and seismic hazard evaluation in the tectonically active Outer Himalaya are crucial because of the increasing urbanization and population growth in the foothills and in the adjacent plains. As the Pinjaur Dun falls in the meizoseismal zone of Kangra (1905) and Chandigarh (1500) earthquakes, with the availability of new datasets and our own observations we cannot rule out the possibility of large magnitude earthquakes visiting the area in the near future.

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