# Late Quaternary tectonic evolution of Dun in fault bend/propagated fold system, Garhwal Sub-Himalaya

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**Two distinct styles and amplitudes of folding occur in Dun. In the northern part, the overturned Santaurgarh anticline with both limbs dipping steep to moderate was developed as fault propagated fold over the Santaurgarh Thrust (ST). The uplifted hanging wall of the ST constituted the dissected Siwalik, and the down-faulted footwall formed the pedimented Siwalik. To the South in the frontal range, the Siwalik strata were folded into Mohand anticline as fault-bend fold over the Himalayan Frontal Thrust (HFT). The uplifted terraces on the fore-limb of the anticline resulted due to displacement on the HFT in Holocene. The Bhauwala Thrust, Majhaun Fault and Asan Fault were formed as out-of-sequence thrusts within the Main Boundary Thrust-HFT wedge of folded Siwalik and overlying Dun gravels subsequent to ST. Extrapolation of earlier published OSL age data and our observations suggest initiation of HFT between 500 and 100 Ka; the ST was initiated in post-500 Ka and continued to propagate till post-40 Ka. The Bhauwala Thrust was developed between 29 and 20 Ka, and the Asan fault post-dated 10 Ka.**

THE longitudinal intermontane valleys in the Sub-Himalaya are called the Duns. There are number of Duns, e.g. Pinjor-Dun in Punjab, Dehra-Dun in Garhwal and Rapti and Dang Duns in Nepal. The Duns occupy broad synclinal troughs in the evolving fold-thrust system of Sub-Himalaya, which is filled by post-Siwalik fluvial and debris flow deposits in late Quaternary–Holocene. Dehra Dun, also referred to as the Dun valley, lies along the NW–SE regional Himalayan strike in Garhwal Sub-Himalaya[1]. It extends 80 km in length and ~20 km in average width (Figure 1). The Dun valley is bounded in the north by the Mussoorie range with 1800–2800 m elevation. The Mussoorie range, constituting the Proterozoic to Lower Cambrian rocks of the Lesser Himalaya, is separated from the Cainozoic Siwalik Group and the Dun gravels by the Main Boundary Thrust (MBT; Figure 2). The MBT, dipping NE at moderate angle and running at the base of Mussoorie range, brings the Krol group rocks to override the Siwaliks. The Dun in the south is bounded by young topographic relief of the frontal Siwalik range with ~800 m average elevation. The southern boundary of the frontal Siwalik range, characterized by a sudden topographic rise from the alluvial plain, is marked by the Himalayan Frontal Thrust (HFT; Figure 1), locally called the Mohand Thrust. The HFT, dipping NE 30°, separates the middle Siwalik from the underlying Holocene alluvial sediments. The Siwalik range front is faulted along N–S-oriented Yamuna tear fault and NE–SW trending Ganga tear fault. Ganga and Yamuna rivers debouch from mountainous terrain to alluvial plains facilitated along these tear faults (Figures 1 and 2).

Among the early workers, Nossin[2] described the outline of the geomorphology of the Dun, and Nakata[3] identified four levels of geomorphic terraces in the Dun. In search of hydrocarbon, the Oil and Natural Gas Commission of India (ONGC) mapped the Siwalik Group and described the major subsurface structures in the Dun[4]. Philip[5] mapped the fan and active faults and described upliftment and westward tilting of the fan sequence on the basis of analysis of Landsat TM satellites data. According to recent study[6], the Dun gravels were deposited in a piggyback basin during the last ~50 Ka. While reviewing previously published studies, we considered elaborating the understanding of the post-Siwalik tectonics in terms of (a) sequence of fold thrust system in the northern part *vis-à-vis* the southern part of the Dun, (b) constraining the age of fold-thrust events on the basis of available OSL dates[6] and (c) post-Siwalik deformation *vis-à-vis* Dun gravels deposition. We have undertaken several N–S traverses both over the fans and along the entrenched stream sections to understand the relationships of the bed-rock Siwaliks with the cover of the Quaternary Dun gravels.

## Geomorphic divisions

Geomorphically, the Dun valley can be divided into two slope regimes by axial drainage of NW flowing Asan and SE flowing Suswa-Song rivers (Figures 1 and 2) joining the Yamuna and Ganga rivers respectively. The northern slope of the valley is occupied by three main piedmont fans of post-Siwalik Dun gravels, viz. Donga fan, Dun Principal fan and Bhogpur fan (Figures 1 and 2). The dip controlled southern slope of the valley, the dip of Siwalik strata corresponding to fan slope, is covered by piedmont fan gravels

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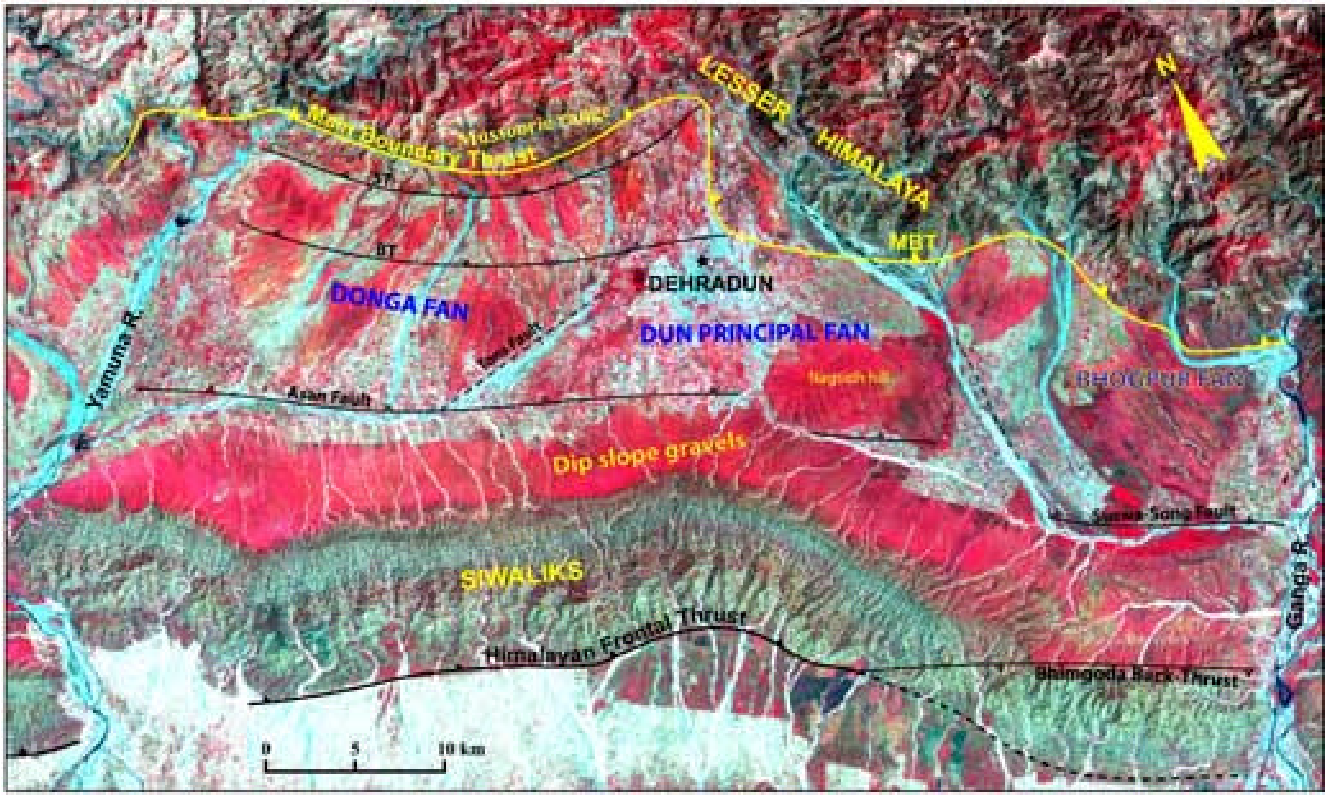


**Figure 1.** Digitally processed IRS 1C LiSS image FCC of band 321 (RGB) of the Dun valley showing geomorphic expressions of different tectono-stratigraphic units and faults.

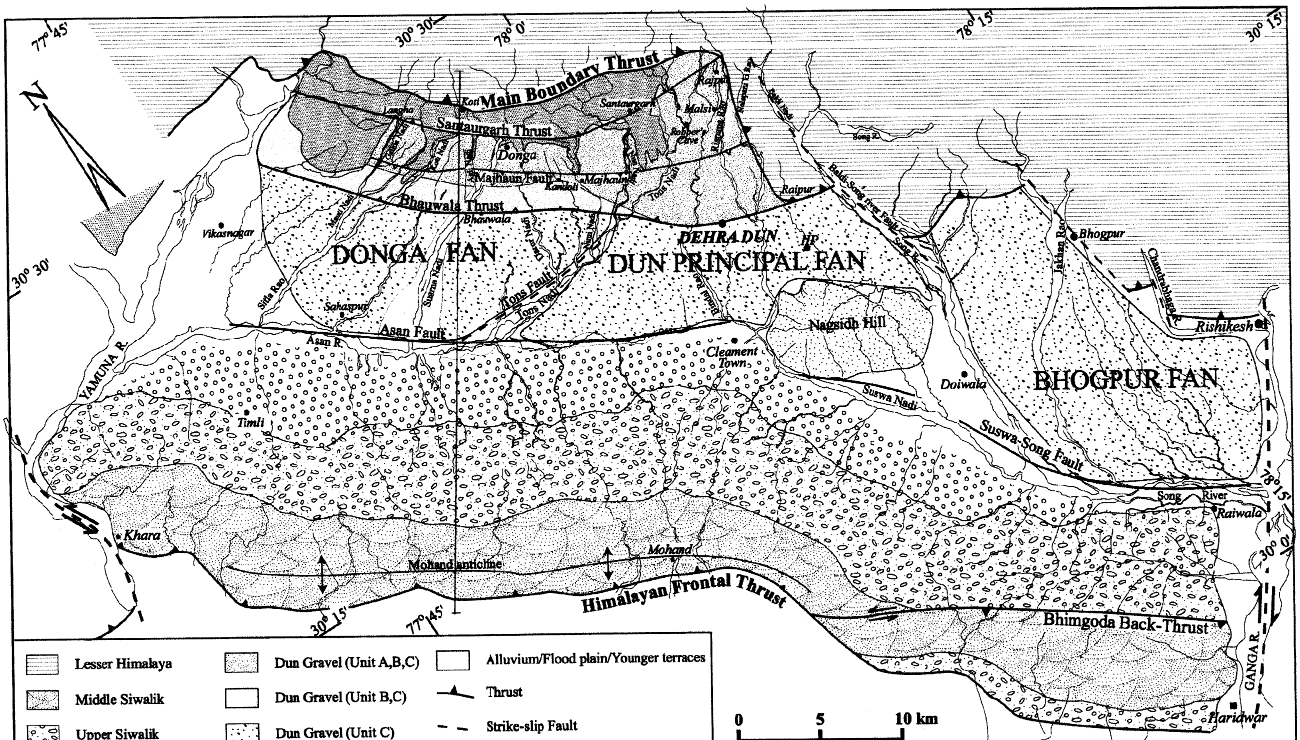


**Figure 2.** Geological land cover map showing distribution of Siwalik and post-Siwalik Dun gravels in the Dun valley, Garhwal Sub-Himalaya.

derived from uplifted topography of the frontal Siwalik range in the south (Figures 1 and 2). The axial ridge, trending NE–SW, of the Dun Principal fan acts as water divide between the Yamuna and Ganga catchments.

In the northern slope of the Dun, the Siwalik Group occurs as uplifted and dissected hills with sparse gravel cover in the footwall of the MBT (Figures 2 and 3 *a*) and further south as pediments with a thick cover of gravel in the deeply incised stream sections (Figures 2 and 3 *c*). The pedimented Siwaliks with a thick cover of Dun gravels also occur as isolated N–S trending ridges above the younger Dun fan surfaces (Figure 3 *b*). The dissected Siwaliks, occurring as uplifted hanging wall, abut against the gravel cover of pedimented Siwaliks in the footwall block of the Santaurgarh Thrust with a sharp topographic break (Figures 1 and 2). The southern tips of N–S trending ridges of pedimented Siwaliks are bounded by the Bhauwala Thrust (Figure 1).

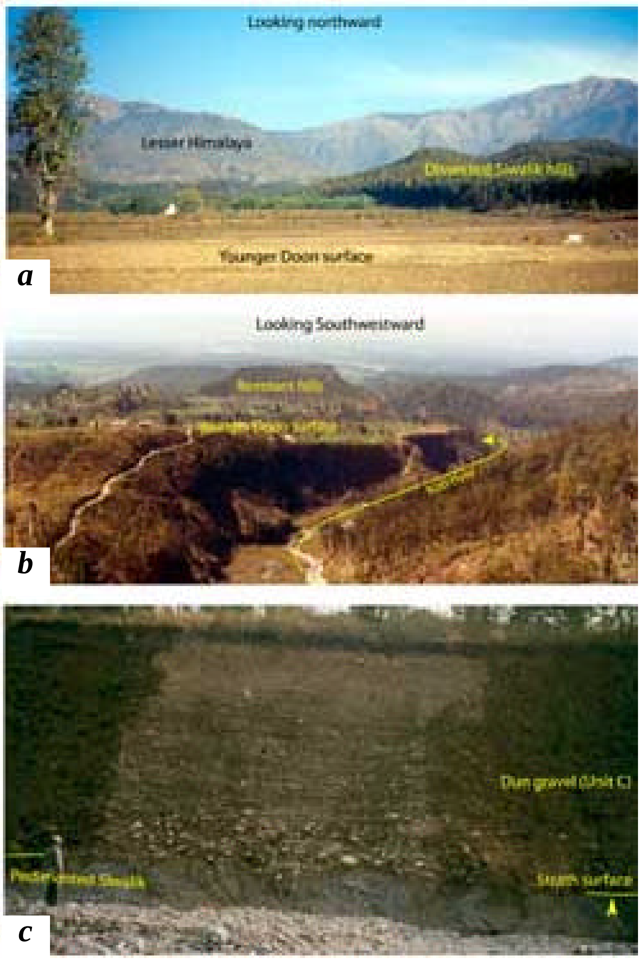


**Figure 3.** Different fault-bound geomorphic units in the northern part of Dun Valley. ***a***, High-rise Mussoorie range constituting the Lesser Himalaya is separated from dissected Siwalik hill by MBT. The dissected Siwalik hill, in the front of Lesser Himalaya, constituted of normal limb of Santaurgarh anticline abuts against the younger Dun fan along Santaurgarh Thrust. ***b***, Isolated hills of pedimented Siwalik with cover of Dun gravels are surrounded by younger Dun fan lying to the south of Santaurgarh thrust. Southern terminus of these hills marks the Bhauwala Thrust. ***c***, Eroded and steeply dipping pedimented Siwalik in the Suarna river section covered by recent gravel deposits. These pediments are inverted limb of the Santaurgarh anticline and lie to the south of Santaurgarh thrust.

## Lithostratigraphy

The Dun valley was formed as an intermontane valley within the Siwalik Group rocks in forelandward propagating fold-thrust system of Garhwal Himalaya. The Siwalik Group and Dun gravels are two principal formations of the Dun valley (Figure 2).

## Siwalik group

The stratigraphy of the Siwalik Group of Dun and adjoining frontal Siwalik range is well described[4,7]. The Middle Siwalik (sandstone dominated) and Upper Siwalik (conglomerate dominated) subgroups form an upward-coarsening succession in an alluvial fan system[7]. The magnetostratigraphic dating of Upper Siwalik gives an age range[8] between 5.3 and 0.5 Ma. The Middle Siwalik, representing a multistory sandstone complex, exhibits vertical facies variation from sandstone–mudstone to sandstone to mudstone-conglomerate. The Upper Siwalik is made of predominately conglomerate with subordinate sandstone and mudstone facies, overlying the Middle Siwalik with transitional contact. There is a marked change in sedimentation pattern around 5.23 Ma from sandstone-dominated to conglomerate-dominated and a rapid increase in sedimentation rate[8] from 0.26 to 0.70 mm/yr.

In the northern slope of Dun valley, Upper and Middle Siwaliks are observed in dissected hills dipping steeply at N/NE 60–70° and showing right-way-up bedding revealed by cross-bedding structures. In the pediments, the Siwaliks, exhibiting inverted bedding recognized on the basis of cross-bedding, dip steeply N/NE 80° and are overlain by thick fan deposits of Dun gravels (Figure 4). In the central part of the Dun, the Siwaliks are not exposed as they are covered by ~300 m thick Dun gravels. In the southern slope of the Dun valley and frontal Siwalik range, the Middle and Upper Siwalik formations are exposed with gentle dips and right-way-up structural setting (Figure 4). The magnetostratigraphic dating has yielded 0.5 Ma age for the top part of the Upper Siwalik conglomerate[8] in the western portion of the Dun valley. This suggests that the post-Siwalik Dun gravels were deposited after 0.5 Ma in the Dun valley.

## Post-Siwalik Dun gravels

There are two slope realms of post-Siwalik deposition in the Dun Valley divided by Asan and Song rivers. The three main piedmont gravel fans (Donga fan, Dun Principal fan and Bhogpur fan) on the northern slope are unconformably

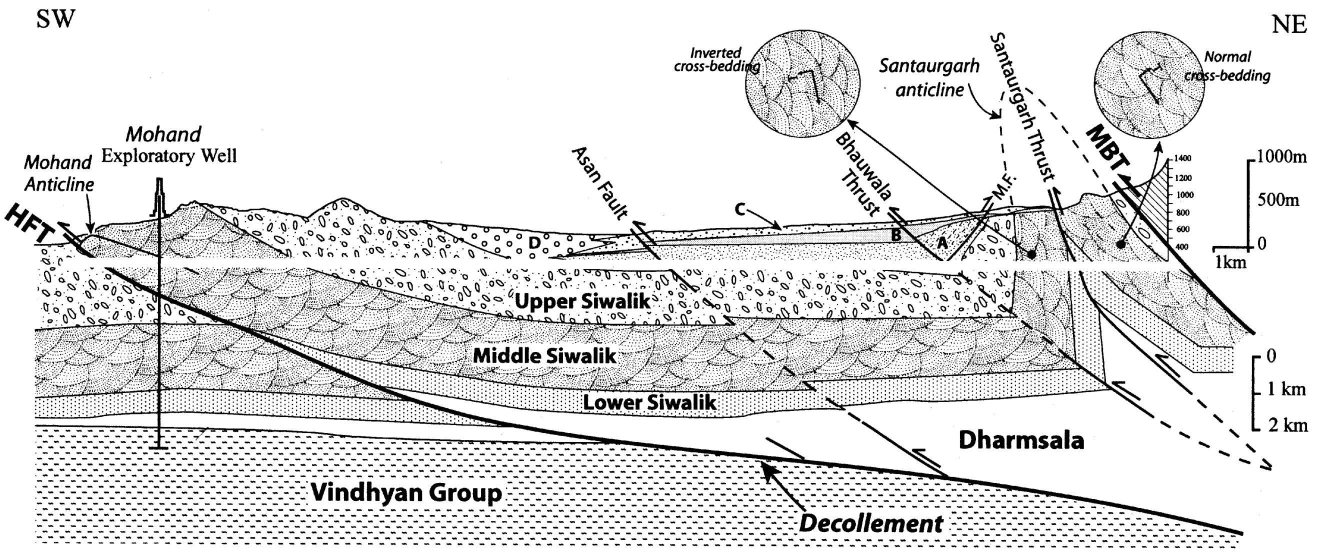


**Figure 4.** Geological cross-section across Dun valley (note the position of cross-section in Figure 2). Upper portion of the cross-section (above white strip) is vertically exaggerated for better depiction of structural disposition of post-Siwalik Dun gravels (Units A, B, C and D). Subsurface structure (below white strip) based on seismic reflection profile of Dun valley by ONGC, India is adopted after Power *et al.*[11]. Vertical scales are separately given; horizontal scale is the same. Note the inverted and normal cross-bedding in the south and north limb of Santaurgarh anticline respectively. Small arrow with 'T' in the inset suggests the top of the cross-bedding. MBT, Main Boundary Thrust; MF, Majhaun back-thrust; HFT, Himalayan Frontal Thrust.

deposited over the Siwaliks. In the northern part they are deposited over eroded and steeply dipping Siwaliks with maximum thickness of ~100 m, whereas in the central part their thickness is >300 m, as estimated on the basis of tube-well boring and field observation. Dun gravels are massive, thickly bedded and poorly consolidated to unconsolidated conglomerates with pebble-to-boulder size clasts in fine-grained matrix. The clasts are sub-angular to sub-rounded and poorly sorted. The gravels were deposited in these fans by fluvial streams and water saturated debris flow at a later stage. In the northern part of the Dun north of the Asan river, the clasts, pebbles and boulders are predominantly of quartzite and phyllite which are similar in lithology to the Chandpur phyllite and Nagthat quartzite of Krol Group exposed immediate to north in the Lesser Himalayan Mussoorie range. A minor amount of sandstone clasts resemble Middle Siwalik sandstone. Sedimentary fabric of imbrication (prolate clasts dipping N10–30°) is observed at most places in the fans, indicating provenance in the north from the uplifted Lesser Himalayan formations and the Siwalik Group. The dip-controlled southern slope of the valley is covered by piedmont fan apron over the hogback of gently dipping NE 30° strata of the frontal Siwalik range (Figures 1 and 2). The composition and roundness of pebbles and boulders of the piedmont gravels are similar to those of the boulder conglomerate of the Upper Siwalik exposed immediate south. On the basis of lithology and structural framework, the Dun gravels are classified into four units, Units A–D. Based on published OSL dates[6], tentative ages are assigned to these units.

### *Unit A*

Unit A is composed of sub-angular to sub-rounded, granule-to-pebble size clasts set in fine-grained matrix. The weakly consolidated gravel beds are inter-layered with sand and mudstone beds. The sandy matrix and mudstone generally have characteristic shade of orange to rusty brown and red colour. The clasts are mainly derived from Lesser Himalayan limestone and shale/slate and Lower Tertiary purple and buff green coloured sandstone. The clasts show pebble imbrication with their long axes dipping NE 15–30°, indicative of fluvial deposit with streams originating from north in the Lesser Himalayan region. Unit A gravels show tilting with variable dips ranging SW 15–65° exposed in different river sections. It is also folded and faulted as well in horizontal disposition in some localities. In the Nun river section, vertical to steeply dipping Middle Siwalik sandstone is overlain with depositional contact by the gravel with interbedded mudstone dipping SW 10–25°. In the Nimmi river section, the Unit A dips SW 35–45° (Figure 5 *a*) and unconformably overlies the NE 80° dipping inverted boulder conglomerate bed of Upper Siwalik. Near village Kandoli in the stream section, Unit A is tilted and folded with limbs dipping SW 20–30° as well as NE 30–40°. At this locality the orange-red coloured Unit A is overlain with irregular depositional contact by the boulder-pebble bearing bed of Unit B. Further north, near village Bidhauli, Unit A unconformably lies over the steeply dipping (NE 80°) sandstone of Middle Siwalik pediments. In Suarna and Agli river sections, Unit A dips SW ~70°

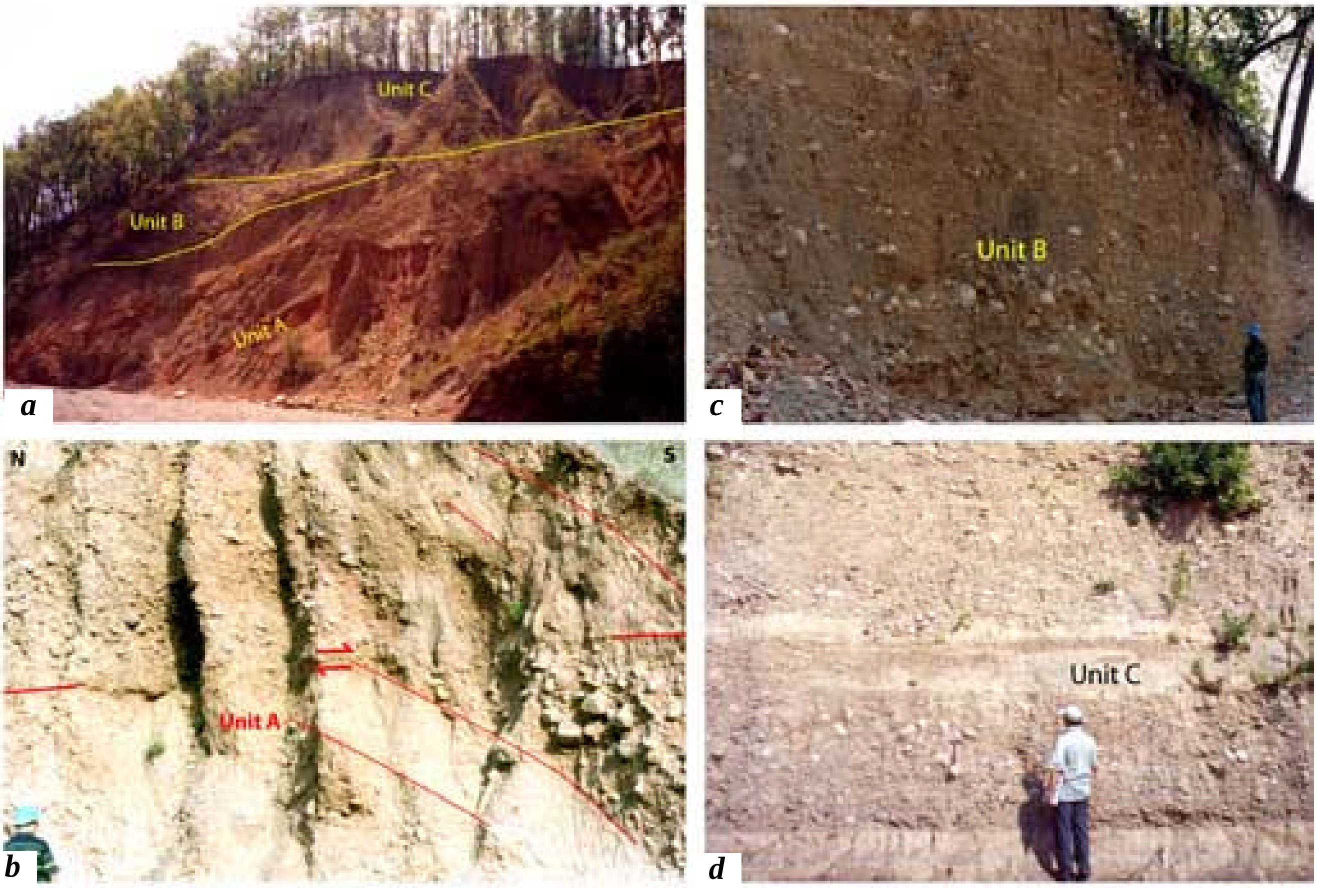


**Figure 5.** Different litho-units of post-Siwalik Dun gravels. ***a***, Section close to village Majhaun showing different Dun gravel units. Unit A is tilted (~35–45° due SW) sequence of alternate gravel with sand and mudstone with typical orange-red colour. The overlying Unit B with horizontal bedding is mainly constituted of reworked quartzite clasts of Upper Siwalik boulder conglomerate. The topmost Unit C with horizontal disposition is constituted of angular to sub-rounded clasts. ***b***, Close view of Unit A gravel in the Agli river section show tilted bedding is faulted by horizontal fault with top to south shear sense. ***c***, Section south of village Kandoli showing horizontally disposed Unit B of Dun gravel. Note the sub-rounded quartzite pebbles in fine-grained matrix. ***d***, Section close to the southern limit of Nimmi river showing horizontally disposed Unit C of Dun gravel. Note the predominantly angular, granule-to-pebble size clasts inter-bedded with sand layers and lenses.

and SW ~40° respectively (Figure 5 *b*) and uncomformably lies over the NE 70–80° dipping boulder conglomerate of Upper Siwalik. A strong tectonic fabric defined by preferably oriented long (*X*) axes of the pebbles and boulders is observed in the Boulder Conglomerate Formation. In the Koti river section, pedimented Upper Siwalik is overlain by Unit A gravel with S 35° dip. In Gauna river, Unit A dips SW 70°, overlying the folded Upper Siwalik boulder conglomerate. To the north of these folded strata lies steeply N-dipping Siwalik conglomerate showing strong preferred orientation of the long (*X*) axes of pebbles.

In the Dun principal fan at several localities in the Ton river section and Robert Cave, a calcareous conglomerate occurs between Unit A and Siwalik sandstone. The cemented, calcareous gravel bed has horizontal disposition and lies over the steeply N 70–80° dipping Middle Siwalik sandstone. A thin layer of calcareous gravel overlying the boulder bed is also observed in the southwestern part of Nagsidh Hill along the Suswa river section, north of Clement town. The tilted Unit A is generally overlain by horizontally disposed Unit B of Dun gravel (Figure 5 *a*), but in some localities Unit A is directly overlain by Unit C, implying the absence of Unit B due to its erosion. The oldest dated gravels in the Dun fan from the northernmost part near Rajpur and from middle part of Dun Principal Fan have yielded OSL age of 38.3 ± 8.4 and 40.3 ± 3.9 Ka respectively[6], suggesting that Unit A is older than 40 Ka.

### *Unit B*

Unit B, with horizontal disposition, unconformably overlies Unit A and in some localities it overlies directly the eroded and vertically disposed Upper and Middle Siwalik formations. This relationship has been observed in all the river sections and around Kandoli, Donga and Langha villages in the Donga fan (Figure 2). The typical lithology of Unit B is unconsolidated massive gravel with predominance of rounded to sub-rounded boulders and pebbles of predominantly quartzite together with sandstone and phyllite (Figure 5 *c*). The gravel is poorly sorted, clast-supported towards north and gradually becomes matrix-supported in the southern part. The pebbles show imbrications with long axes of pebbles dipping NNE 15–30°. The composition of pebbles and imbrication indicates that Unit B was predominantly derived from Upper Siwalik boulder conglomerate along with Middle Siwalik sandstone and Lesser Himalayan phyllite and quartzite. Unit B roughly corresponds to the Langha Boulder Bed, as described by Rao[9]. The boulders and pebbles of Unit B are fractured, with fracture planes oriented at acute angles to the horizontal bedding. The fracturing in pebbles of Unit B is consistently observed near villages Majhaun, Kandoli and west of Langha and in the Suarna river sections. The origin of fracturing of pebbles in Unit B is not resolved at present. It could be tectonic deformation or more likely climatic factor. The predominance and widespread prevalence of orange-red colour in Unit A, indicative of warm humid climate, was probably followed by cold climate reflected in fractured pebbles of Unit B. The 29.4 ± 1.7 Ka OSL age of gravel near Donga village[6] tentatively suggests the youngest age limit of Unit B.

### *Unit C*

The youngest gravel unit constituting the younger fan surface (Figure 3 *a*) has been categorized as Unit C. The horizontally disposed Unit C unconformably overlies Unit A as well as Unit B of Dun gravels and the pedimented Siwalik formations (Figures 2, 4, 5 *a* and *d*). It consists of poorly sorted angular to sub-angular granule and pebbles interspersed with large pebbles and occasional boulders. The clasts are supported by sandy to gritty matrix and large pebbles and boulders are supported by finer clasts. Discontinuous layers and lenses, 1 m thick, of sand and silt occur horizontally disposed within the gravel (Figure 5 *d*). The pebbles show imbrication fabric dipping N 10–15°, suggesting provenance from north and deposition by the fluvial streams. Unit C gravel is widely distributed south of Santaurgarh thrust and spreads right across the distal part of the fan (Figure 2). In the distal part, the clasts size decreases and mud and silt content increases. This has provided an opportunity to use the clay by brick kilns of the Dun valley located in the distal part of the fan gravel of Unit C. The sand layer of Unit C in the distal part has yielded OSL age of[6] ~10 Ka. On the right bank of Suarna Nadi to the west of Donga village, pedimented Middle Siwalik sandstone is unconformably overlain by Unit C gravel. The base and top of this gravel have yielded 22.8 and 10.7 Ka OSL age respectively[6].

### *Unit D*

The gravel deposited on the hogback of the frontal Siwalik range on the southern dip slope of the Dun valley has been categorized as Unit D (Figures 1, 2 and 4). On the back limb of the Mohand anticline, the Upper Siwalik conglomerate passes upward into the Unit D gravels apparently without any break. Unit D is made of unconsolidated pebble bed and gravel. The pebble bed overlying the Upper Siwalik conglomerate consists of sub-rounded to rounded, poorly sorted pebbles and boulders of predominantly (>90%) quartzite in sandy matrix without imbrication fabric. The gravel consists of angular to sub-angular clasts of quartzite, phyllite and sandstone in sandy to silty matrix, poorly sorted and devoid of bedding or fabric.

The geometry of Unit D on the southern slope shows fan surface dipping NE ~30°, corresponding to dip of the underlying Siwalik strata, and becoming horizontal in disposition further north in the central part of the Dun. The present-day streams draining across the fan from south to north appear to represent the modern analogue of the deposition pattern that prevailed during the deposition of Unit D. The composition and nature of clasts and matrix of Unit D are similar to the Upper and Middle Siwaliks exposed immediate south, suggesting that Unit D was deposited from the rising frontal Siwalik range to the South.

### *Nagsidh hill*

An anomalous ~850 m high topography of Nagsidh hill with radial drainage pattern, peculiar in Dun valley, lies in the distal part of Dun Principal fan (Figures 1 and 2). The uplifted Nagsidh hill exhibits a modified escarpment, ~30 m, towards the south along Suswa river and has a gentle north dipping slope along the northern face of the ridge. The well-exposed escarpment section along the Suswa river shows poorly consolidated boulder bed with sub-rounded to sub-angular boulders and pebbles predominantly of quartzite with subordinate sandstone, leucogranite, gneiss and rarely limestone. There are discontinuous bands and lenses of micaceous sand layers within the boulder bed. The boulder beds with sand layers are horizontal to dipping N 15°. The boulder bed with exposed ~30 m thickness is overlain by a thin calcareous cemented gravel bed similar to Unit A of Dun Principal fan. The northern slope of the Nagsidh hill is constituted of poorly sorted and sub-angular, large size boulders. The boulder bed of Nagsidh hill is mapped as Upper Siwalik by ONGC workers[4]. On account of its unconsolidated nature, horizontal bedding and overlain by calcareous cemented gravel of Unit A, we propose the conglomerate of Nagsidh hill as transitional bed between uppermost Upper Siwalik conglomerate and Unit A of Dun gravels. The southern margin defining a scarp and northern gently dipping slope suggests a faulted contact, and uplift of the Nagsidh ridge is due to displacement on the north dipping thrust fault named Suswa-Song fault (Figures 1 and 2).

## Structural framework

The Siwalik Group strata are folded into asymmetric Mohand anticline in the frontal Siwalik range, broad Dun syncline occupying the Dun valley, and the overturned Santaurgarh anticline in northern part of the Dun valley[4]. The Mohand anticline is an upright asymmetric fold in the frontal part of the Siwalik range towards south of the Dun. Its axial trace runs NW–SE between Mohand and Yamuna rivers. The forelimb of the fold dips steeply both N and S, and the back limb dips NE 15–30°. Dun syncline is a broad open syncline which is expressed geomorphologically as the Dun valley. The flat-lying Siwalik strata of synclinal depression are not exposed due to its burial underneath a thick pile of Dun gravels. The seismic profile[10,11] across HFT and Dun shows Mohand anticlinal structure and horizontally layered Siwaliks in the synclinal depression of the Dun (Figure 4).

The MBT, which marks a major tectonic boundary between the pre-Tertiary Lesser Himalayan formations and the Cainozoic sediments of Sub-Himalaya, is geomorphically expressed by a sharp slope break across the thrust (Figures 3 and 4) and a marked difference in erosion pattern of the rocks. The MBT plane generally dips NE 30–50°, but in some places near the surface, the MBT appears to have vertical to steep dip due to later reactivation of the fault by neotectonic events[12]. At Sayaru Khala, ~1 km from Koti, Chandpur phyllite and quartzite, dippping NE 40°, override the Upper Siwalik boulder bed. The boulder bed, stained by orange-red colour in sandy matrix with interbedded sandstone layers, is underlain by grey sandstone (Figure 6 *a*). The boulder bed dips steeply NE 75° and is overlain by Chandpur phyllite of Krol Group dipping NE 40°. This contact relationship suggesting an angular discordance along the MBT between two units probably resulted from passive rotation of the hanging wall of the younger Santaurgarh Thrust in post-Upper Siwalik time. The bedding in the boulder bed is displaced by a set of shear planes striking 260° and dipping due S 60° (Figure 6 *a*, inset). The pebbles are also deformed by a series of fractures parallel to the shears (Figure 6 *a*, inset). These observations suggest southward propagation of MBT and brittle deformation. South of the MBT steeply NE dipping boulder bed is overlain with erosional contact by ~10 m thick gravels, which shows a planar fabric of clasts dipping S30° (Figure 6 *a*). Near Rajpur and Rispana Rao in the Dun valley, the MBT dipping NE 40° brings the Chandpur phyllite of Krol Group to override the Late Quaternary – Holocene Dun gravels, indicating Holocene to Recent tectonic activity along the thrust. Active thrusting along an en-echelon shear of the MBT is described by Sati and Rautela[13]. The tectonic contact between the Chandpur phyllite and the Dun gravels is sharp and characterized by crushing and fault gauge, indicative of brittle deformation.

South of the MBT, the Siwalik strata are folded into Santaurgarh anticline (Figure 4), which is an overturned anticline with NW–SE axial-trend. The southern inverted limb and the northern normal limb are recognized on the basis of cross-bedding criterion observed in the Siwalik sandstone in Nun, Darer, Suarna and Gauna river sections and around villages Donga, Koti and Langha. The Upper Siwalik boulder bed with orange-red matrix dipping NE 65° occurs below the MBT on normal limb near villages Koti and Thangaon. The same lithology in the inverted limb

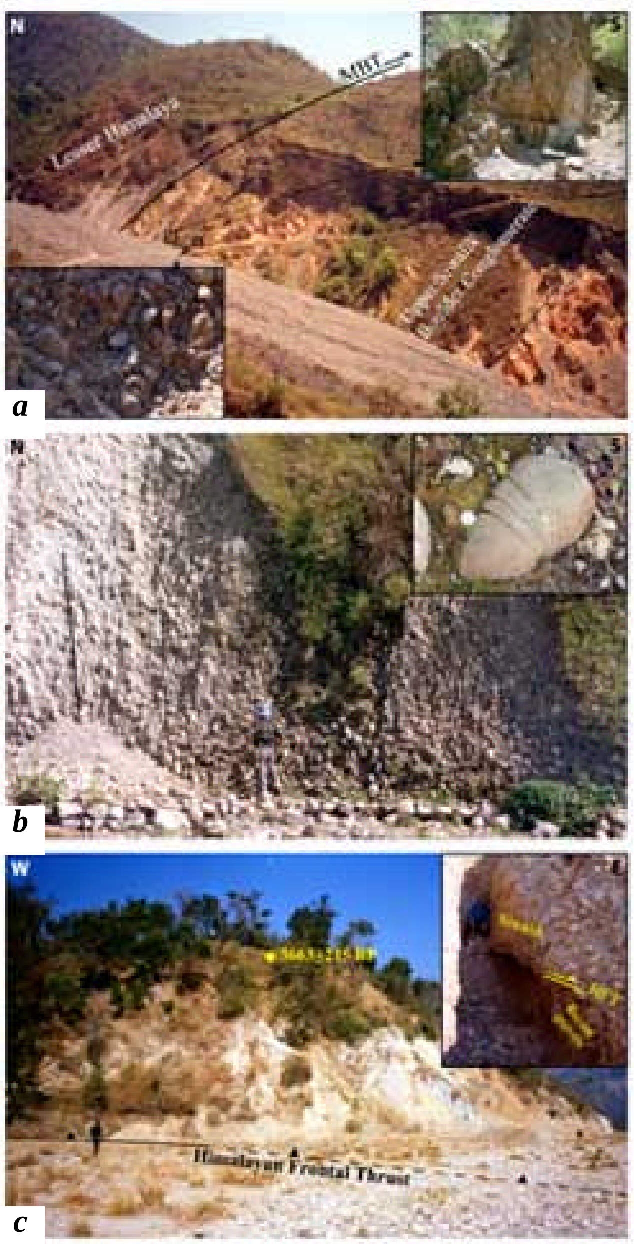


**Figure 6.** Outcrop view of MBT and HFT zones. ***a***, Outcrop view of MBT near village Koti, where the steeply dipping Boulder Conglomerate Formation is tectonically overlain by Lesser Himalayan rocks. (Inset) conjugate set of shear zones with top to south shear sense in the footwall and fractured pebble with similar shear zones. ***b***, Pebbles in Boulder Conglomerate Formation showing preferred alignment of their long axes in the inverted limb of the Santaurgarh anticline. (Inset) Pebbles are fractured, suggesting a brittle–ductile deformation regime. ***c***, View of HFT zone near Mohand marked by the sharp topographic break separating the Siwalik range from the alluvium. (Inset) Middle Siwalik sandstone tectonically overriding the recent stream gravel in an excavated trench.

with vertical to NE 80° dip is observed in Nimmi, Agli and Koti river sections.

The northern normal limb of Santaurgarh anticline is upfaulted along the Santaurgarh Thrust (ST) which passes through axial plane (Figure 4). It is well delineated in the satellite imagery trending NW–SE (Figures 1 and 2) and is marked by a sharp topographic break between the dissected Siwaliks with higher elevation in the hanging wall abuting against the pedimented Siwaliks with thick Dun gravel cover in the footwall. The underthrusted footwall block of pedimented Siwaliks are exposed at lower elevation in deeply incised stream sections. The Dun gravels cover over the dissected Siwaliks is largely eroded, except a few isolated outcrops. In the hanging wall of ST near Rajpur at an altitude of 1000 m, Dun gravels have yielded ~38.3 Ka OSL age and also 40.3 Ka OSL age near IIP at an altitude 550 m south of Bhauwala Thrust (BT). This suggests that the last phase of faulting along the ST is post-40 Ka; however, initiation of ST may be much earlier in post-Upper Siwalik time (post-0.5 Ma).

The N–S trending isolated ridges of thick Dun gravels with pedimented Siwalik base (Figure 3 *b*) abruptly terminate with a topography break. The southern tips of these ridges are aligned along a prominent lineament with uplifted northern block (Figure 1), which represents the BT. This thrust has also been described by Nossin[2] and Nakata[3] as a tectonic line on the basis of geomorphology. The name Bhauwala has been adopted after the village Bhauwala from where the thrust passes. The BT demarcates the southern boundary of pedimented Siwaliks and tilted units A and B of the Dun gravels in the north against the horizontal bedded Unit C to the south (Figures 2 and 4). The thrust expression has been observed in Gauna, Koti, Suarna, Darer and Nimmi river sections from west to east in the Donga Fan. It continues further eastward into the Dun Principal fan, where a sharp knee-bend turn of streams are also observed.

In Nimmi river section, Unit A of the Dun gravels dipping S/SW 35–45° overlies the inverted NE 70–80° dipping Upper Siwalik conglomerate with well-developed shape-preferred fabric. Similar observation has been made near Majhaun and Kandoli villages as well as in Darer, Suarna, Koti and Gauna river sections, where the pebbles in the Upper Siwalik show fabric (Figure 6 *b*). The fabric was developed as axial–planar during folding of the overturned Santaurgarh anticline. The pebbles are mostly fractured (Figure 6 *b*, inset), suggesting a regime of brittle–ductile deformation. The uneven erosional contact is observed at many places between Unit A and the Middle Siwalik sandstone and Upper Siwalik conglomerate. However, at Majhaun and Nimmi river sections, south-dipping faulted contact is observed between the two, where Unit A overrides the Siwaliks along moderate to south-dipping fault, called the Maghaun fault. The Bhelonwala fault passing through village Bhelonwala to the north of Bhauwala described by Rao[9], may correspond to the Majhaun fault. In our interpretation, the Majhaun fault was developed as back thrust simultaneously during the early stage evolution of the BT.

In western Dun Asan river flows from SE to NW direction joining Yamuna river (Figures 1 and 2). Tons, Nun, Nimmi and Darer rivers initially flowing N–S, curve around to SW as tributaries and join the NW-flowing Asan river. In southern Dun, all the consequent streams originating from the Siwalik water divide flow NE over the dip slope and meet the Asan river. A scarp, ~10–15 m high running NW–SE, is observed on the northern bank of Asan river between Suarna Nadi and Sitla Rao (Figure 1). The scarp is developed between elevated distal part of Donga and Dehradun fans against recent flood plain. The NW–SE-oriented straight course of Asan river, presence of uplifted scarp and drainage pattern on both the northern and southern catchments indicate a fault named Asan Fault. The Asan Fault is inferred as a thrust fault dipping NE (Figure 4). It has uplifted the distal part of the youngest (~10 Ka)[6] Dun gravel of the Donga fan as a result of displacement along the fault, implying the Asan fault is post-10 Ka. The Nagsidh Fault demarcating southern margin of Nagsidh hill and the Suswa-Song Fault lies in the same orientation as that of the Asan Fault.

The HFT is defined by a sharp topographic break between the frontal Siwalik range and the alluvial plains (Figure 6 *c*). Near Mohand at Khajanawar Rao (stream) and further west in other stream sections, steeply dipping, both N and S, middle Siwalik sandstone abuts against the recent alluvium. The trenching done across the range front in Khajanawar Rao near village Mohand exhibits that the surface expression of HFT in the outcrop is an apparent one; for the Siwalik wedge, continuation of the main Siwalik, exposed in 10 m deep trench is observed overlying the older alluvium and overlain by recent stream sediments (Figure 6 *c*, inset). The uplifted strath terrace deposits resting unconformably on the Middle Siwalik sandstone on the forelimb of Mohand anticline are exposed about 20 m above the present stream level along the range front between Mohand and Yamuna river. The terraces have been uplifted as a result of displacement on the HFT. The radiocarbon age of the terrace deposit is $3663 \pm 215$ before present[14]. Constraining the dip of HFT to about 30º and the radiocarbon date, the slip rate on the HFT was estimated[14] to be $13.8 \pm 3.6$ mm/yr.

The 70 km long frontal Siwalik range of the Dun is dissected nearly at right angle on the eastern and western extremities by Ganga and Yamuna rivers respectively. Earlier workers placed tear faults, namely Ganga tear and Yamuna tear on the basis of displacement shown by the Siwaliks on the range front[4,10]. West of River Yamuna, the NW–SE trending HFT takes an inward bend towards the north and joins the HFT east of Yamuna, showing 7–8 km left lateral displacement. However, across the river Ganga HFT shows a right lateral displacement of ~8 km. On the regional scale, the Siwalik belt and HFT segments on both western and eastern margins of the Dun valley (Block) have moved a few kilometres southward relative to the Dun, with opposite sense of movement. This sense of movement is interpreted as representing lateral ramps of HFT, indicative of amount of displacement suffered by the southward transfer of HFT. Assuming the 8 km displacement suffered by HFT during post-0.5 Ma (i.e. post upper Siwalik), the calculated slip rate on the fault comes to 16 mm/yr.

## Tectonic evolution

A secondary isoseismal area of intensity VIII (MM scale) of the 1905 Kangra earthquake was observed between the MBT and HFT in Dun[15]. Evidence of a historic large earthquake was recorded in earthquake-induced soft sediment deformation in the Dun valley[16]. Two large surface rupture earthquakes with total displacement of 8.5 m have occured on the HFT during last 650 years[17] between AD 1349 ± 55 and 1523 ± 99 and after AD 1523 ± 99. These observations indicate an active zone of deformation between the MBT and HFT. Two distinct styles and amplitude of folding on large scale have been observed in the Dun valley: the overturned Santaurgarh anticline with steep to moderate dipping limbs associated with steeply dipping ST, and the upright asymmetric Mohand anticline associated with HFT (Figure 4). The former lies close to the MBT in the northern part and the latter in the frontal part of the Siwalik range, both the structures separated by a broad and open syncline depression of the Dun.

Immediately south of the MBT, the overturned and southward facing Santaurgarh anticline was developed as a fault-propagated fold of the ST[11]. During initial growth of the fault-propagated anticline, the thrust remained blind, but produced uplift (Figure 7 *a*). The uplifted topography was gradually eroded and its sediments were deposited to the south in frontal depression (Figure 7 *b*). With further propagation of the ST to the surface, the upthrown hanging wall became the uplifted, dissected Siwalik and the downfaulted footwall formed the pedimented Siwaliks (Figure 7 *c*). The ST was developed during post-500 Ka, but faulting continued with growth of anticlinal fold till post-40 Ka.

The Mohand anticline has short and steep forelimb and long and gentle to horizontal back limb. Exploratory oil well drilled near Mohand by ONGC[4] revealed the existence of HFT. The seismic profile[10,11] across the frontal Siwalik range and the Dun shows HFT dipping NE 30° in the front and becoming shallow to near horizontal as decollement in the north (Figure 4). The geometry of Mohand anticline and HFT suggests that the anticlinal fold is developed as a fault-bend fold (Figure 7 *c* and *d*) in the manner described by Suppe[18].

In the Tons and Nun river sections, Unit A occurs with depositional contact overlying the eroded, steeply dipping Siwaliks. Unit A is tilted, dipping in varying degree NE 15–45° as well as horizontal in few localities. The horizontal to tilted nature of Unit A is explained due to its synorogenic deposition over the growing Santaurgarh anticline. The horizontally bedded Unit A, overlying the SW 30–40° dipping Siwalik beds, became tilted dipping SW as a result of rotation of underlying Siwalik beds to steeper attitude dipping NE 70–80° (Figure 7 *b*). The horizontally layered Unit B and Unit C, overlying the tilted Unit A, suggest cessation in growth of Santaurgarh fold system with the begining of deposition of Unit B. In other river sections, the steeply dipping Siwalik has a faulted contact with the Unit A along the Majhaun Fault, which is a back thrust (Figure 7 *d*).

The BT was developed subsequent to the ST. The ~29 Ka OSL dated Dun gravels occur at higher elevation (850 m) on the hanging wall as well as at lower elevation (700 m) on the footwall of the BT, suggesting that the BT was ini-

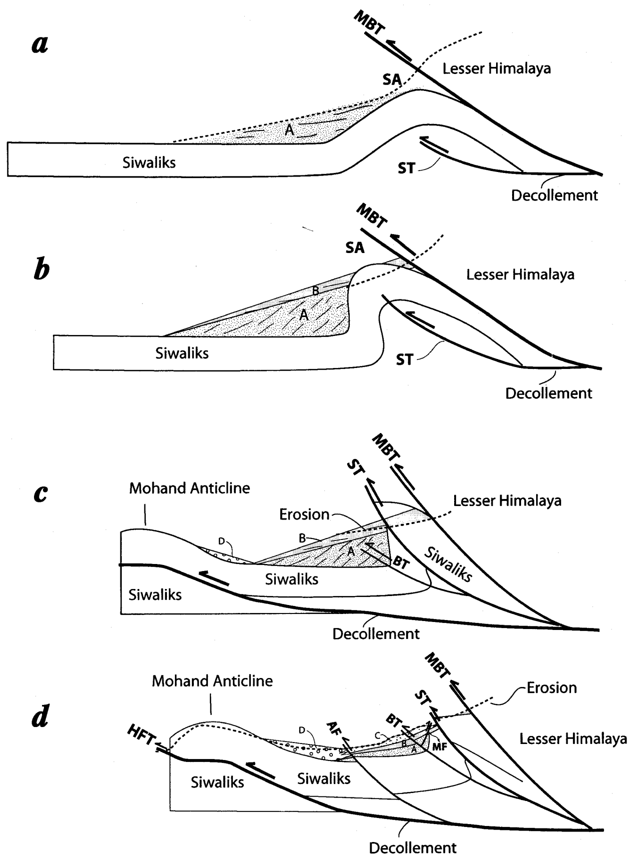


**Figure 7.** Schematic diagram showing Late-Quaternary evolution of structure of Dun valley. ***a***, Initiation of the growth of Santaurgarh anticline (SA) as fault propagated fold over the blind Santaurgarh Thrust (ST) and synchronous deposition of Unit A of Dun gravel. ***b***, Further growth of SA and accompanied steepening of limbs led to the tilting of Unit A gravel. Strath erosion of the crest of growing SA and deposition of horizontally disposed Unit B. ***c***, Steepening of MBT and ST causes locking of thrust that resulted in southward propagation of decollement fault from MBT to HFT. This led to the growth of Mohand anticline and corresponding Dun syncline as fault-bend fold on the decollement. ***d***, Formation of Bhauwala Thrust (BT), coeval Majhaun Fault/back thrust (MF) and Asan Fault (AF) as out-of-sequence thrusts resulting due to further shortening of strata in the Dun.

tiated post-29 Ka. The BT is overlapped on adjoining HW and FW by Dun gravels dated 20 Ka, implying cessation of its activity. The sand and mud of Unit C in the distal part of the fan occurring in the frontal scarp of the Asan fault have yielded ~10 Ka OSL age indicating Asan Fault is post-dated 10 Ka. The assigned ages of these faults *vis-à-vis* the initiation ages of ST and HFT, suggest that the BT, Majhaun Fault and Asan Fault were developed as out-of-sequence fault systems, resulting due to deformation in a wedge of Siwaliks and overlying gravels with decollment between the HFT and the MBT (Figure 7).

The top of the Upper Siwalik conglomerate in the Dun is assigned an age of 0.5 Ma (500 Ka)[8]. Based on rock uplift rate[14] calculated 6 mm/yr, it would take ~100 Ka to uplift 600 m relative relief of frontal Siwalik range. Based on assumption in this time frame, the initiation age of HFT is constrained between 500 and 100 Ka. Another approach in constraining the age of HFT may be based on the premise that Mohand anticline growth is related to the displacement on the HFT. Mohand anticline has accommodated ~5 km of shortening, calculated on the basis of balanced cross-section of Dun valley[11]. The horizontal shortening rate[14] estimated across the HFT in Dun is 11.9 ± 3.1 mm/yr. Assuming a consistent shortening rate for the growth of Mohand anticline, it will take 300–400 Ka to accommodate ~5 km of shortening and that will be the initiation age of the HFT.

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ACKNOWLEDGEMENTS. We acknowledge financial support from CSIR, New Delhi to V.C.T. under Emeritus Scientist scheme and thank Wadia Institute of Himalayan Geology, Dehradun for providing facilities. The manuscript has benefited from constructive comments and suggestions by the anonymous reviewer.

Received 25 August 2003; revised accepted 16 August 2004