Geomorphology evolution of Dehra Dun, NW Himalaya: Tectonics and climatic coupling

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A B S T R A C T

The Dehra Dun is a good example of a piggyback basin formed from the growth of the Siwalik hills. Two large rivers, the Ganga and the Yamuna, and their tributaries deposit a significant part of their sediment load in the Dun before they enter the Gangetic plains. This work documents the geomorphic complexities and landform evolution of the Dehra Dun through geomorphic mapping and chronostatigraphic investigation of the incised fan sections. Lesser Himalayan hills, inner and outer dissected hills, isolated hills, proximal fan, distal fan, dip slope unit, floodplains, and terraces are the major geomorphic units identified in the area. Isolated hills of fan material (IHF), proximal fan (PF), and distal fan (DF) are identified as fan surfaces from north to south of the valley. The OSL based chronology of the fan sediments suggests that the IHF is the oldest fan consisting of debris flow deposits with a maximum age of ~43 ka coinciding with the precipitation minima. The proximal fan consisting of sheet flow deposits represents the second phase of aggradation between 34 and 21 ka caused by shifting of deposition locus downstream triggered by high sediment supply that exceeded the transport capacity. The distal fan was formed by braided river deposits during 20–11 ka coinciding with the deglacial period. The IHF, PF and DF surfaces were abandoned by distinct incision phases during ~40–35, ~20–17, and ~11–4 ka respectively. A minor phase of terrace deposition in Dehra Dun was documented during 3–2 ka. Our results thus show that the evolutionary history of the alluvial fans in Dehra Dun was primarily controlled by climatic forcing with tectonics playing a minimum role in terms of providing accommodation space and sediment production.

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1. Introduction

Tectonic and climatic processes have interacted through tightly coupled feedbacks at variable spatiotemporal scales to shape mountainous landscapes along the Himalayan belt (Seebach and Gornitz, 1983; Ori and Friend, 1984; Lavé, and Avouac, 2000, 2001; Kirby and Whipple, 2001; Kumar et al., 2007; Suresh et al., 2007; Singh and Tandon, 2007, 2008). Intermontane valleys (Duns) are important elements of mountainous landscapes in the Himalaya that have developed in response to climatic fluctuations and neotectonic activities during the Quaternary period (Kimura, 1999; Singh et al., 2001; Dühnforth et al., 2007; Goswami and Pant, 2007; Kumar et al., 2007; Suresh et al., 2007; Singh and Tandon, 2008; Suresh and Kumar, 2009; Malik et al., 2010; Dutta et al., 2012). Alluvial fans, fluvial terraces and floodplains have been mapped as the main landforms in the Duns (Nossin, 1971; Nakata, 1972; Rao, 1978; Chandel and Singh, 2000; Singh et al., 2001; Suresh et al., 2007; Thakur et al., 2007; Singh and Tandon, 2010; Sinha et al., 2010; Dutta et al., 2012). The alluvial fans in the Duns occur at multiple topographic levels (Nakata, 1972; Suresh et al., 2002, 2007; Philip et al., 2009) and have been described as a piggyback system developed through multiple phases of aggradation and entrenchment during the late Quaternary period (Kumar et al., 2007). The development of these fans is influenced by tectonic and climate factors such as glacial-interglacial cycles, base-level changes, sediment supply from the catchment, availability of accommodation space, and degree of tectonic activity (Harvey, 1990, 2004; Silva et al., 1992; Ritter et al., 1995; Harvey et al., 1999a, 1999b; Harvey and Wells, 2003; Mather and Stokes, 2003; Mather et al., 2009; Viseras et al., 2003; Robustelli et al., 2009). Fluvial terraces also occur widely in Duns, and multiple levels of terraces have been mapped in the frontal parts of the Himalaya, e.g., three to five levels in the Yamuna valley (Singh et al., 2001; Dutta et al., 2012) and four levels in the Ganga valley (Sinha et al., 2010). Most rivers draining the fan surfaces are incised and therefore have developed rather narrow floodplains except in the distal parts (discussed later). In a more recent work, several piggyback basins along the Himalayan front were examined to explore storage and release of sediments from these basins and their downstream influence (Densmore et al., 2015). The suggestion has been made that the Duns have controlled the temporal variations in sediment flux into the Gangetic plains and have therefore influenced the landscape development in the plains (Densmore et al., 2015).

Despite several generations of geomorphic mapping and landform evolution studies in the Duns in the NW Himalaya, we note significant
gaps in terms of terminologies, field validation, and controlling factors. For example, the term ‘piedmont’ was used to describe the depositional surfaces by Singh et al. (2001), Thakur and Pandey (2004) and Thakur et al. (2007) but they do not ascribe the processes that might have shaped them. Generally, the terminology ‘piedmont’ is used for erosional and depositional landforms formed adjacent to a mountain front (Leece, 1990; Goudie, 2004). Chandel and Singh (2000) described the post-Siwalik deposits in Dehra Dun as ‘doon piedmont’ but without much process interpretation of the associated geomorphic elements. Further, a suggestion was made that the geomorphic evolution of the Dun involved a number of depositional and erosional phases superimposed on each other and regulated by climatic changes and tectonics (Nakata, 1972), but very limited information is available in terms of field evidence and chronological data. Age data on different geomorphic surfaces in the Duns has been limited, and therefore a sound chronostratigraphic framework of fans is lacking. In summary, the understanding of the evolution of landforms and their spatial relationships is fragmentary.

We present here a detailed geomorphology of the Dehra Dun based on mapping from high-resolution satellite images and digital elevation models (DEM) coupled with field validation. Stratigraphic framework is based on several lithologs from incised fan sections and a sound chronological data that provides an insight to the depositional history of the Dun.

2. Study area and previous work

The Dehra Dun is one of the largest intermontane valleys between the Mussoorie Ranges of the Lesser Himalaya to the north and the Siwalik Ranges to the south (Fig. 1). The Siwalik Ranges are mainly a group of rocks and categorized as lower (mudstone), middle (sandstone), and upper (conglomerate) units. The Dehra Dun is bounded by major faults from all sides; the Main Boundary Thrust (MBT) to its north, the Himalayan Frontal Thrust (HFT) to its south, the Yamuna Frontal Thrust is the major structure that separates the Siwaliks and the Lesser Himalaya. Other major structural features documented in this area include the Santaurgarh thrust (Raiverman et al., 1983), the Bhauwala thrust (Singh, 1998), the Asan and Tons faults (Thakur and Pandey, 2004), and the Majahaun fault (Thakur et al., 2007).

Fan deposits in Dehra Dun mainly consist of boulders, cobbles, and pebbles with a sandy and silty matrix (Nossin, 1971; Thakur, 1995). Previous workers (Singh et al., 2001; Thakur et al., 2007) have suggested four major depositional units in the valley based on OSL ages. Unit A is the oldest with ages varying from 40.3 ± 3.9 to 33.5 ± 4.7 ka and mainly consisting of poorly to fairly consolidated gravels with interlayered mudstone and sand beds (Thakur et al., 2007). Unit B of unconsolidated massive gravels overlies unconformably on Unit A and yields maximum
and minimum OSL ages of 29.4 ± 1.7 ka (Singh et al., 2001) and 20.5 ± 1.8 ka (Thakur et al., 2007), respectively. Unit C has been dated between ~22.8 and ~10.7 ka and is mainly composed of angular to subangular pebbles and gravels. Unit D has been dated as ~30 ka and covers the northern slopes of the outer Siwalik range at the southern part of the valley. The total thickness of fan deposits in the Dun using tube-well depths, is estimated to be ~100 m in the proximal part and N300 m in the distal part (Thakur et al., 2007). The gravel units in fan deposits are massive to thickly bedded, and poorly consolidated to unconsolidated. Clasts are randomly oriented and angular to subrounded (Singh et al., 2001; Thakur et al., 2007).

3. Data and methods

Geomorphic mapping of the Dehra Dun valley was carried out using satellite images, elevation data, and topographic maps. Satellite data consisted of IRS P6 LISS 3, LANDSAT image, Shuttle Radar Topography Model (SRTM) version 4 (spatial resolution 90 m), and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) v. 1 (spatial resolution 30 m). The IRS P6 LISS 3 (spatial resolution 23.5 m) images were provided by NRSC (National Remote Sensing Center, India) and the rest of the data were downloaded from the USGS web site (http://earthexplorer.usgs.gov). The LANDSAT (resolution 30 m) and SPOT (resolution 5 m) images were fused together in order to enhance the spectral and spatial properties. Major geometric features were mapped using the LISS 3 image, fusion image of LANDSAT and SPOT, topographic maps of 1:50,000 scale and the ASTER DEM. The ArcGIS 10 software was used for mapping and geometric analysis. The ERDAS imagine 8.5 software was used for image processing and River Tools v. 2.4, and ‘System for Automated Geo Scientific Analyses’ (SAGA) 1.2 were used for drawing the profiles across the valley to distinguish the geomorphic units on the basis of their relief. Fig. 2 shows the geomorphic map of the study area along with major geological structures. Table 2 provides a summary of different geomorphic units mapped in this work along with corresponding terminologies used by previous workers.

Six lithologs were prepared from the exposed sections across different fan surfaces to describe the stratigraphic framework of fans. To establish the chronology of the fan units, 11 samples were collected from the fan surfaces and terraces in the study area. Samples were collected in iron pipes and immediately sealed to prevent the exposure of light. These samples were processed using optically stimulated luminescence (OSL) dating technique at Wadia Institute of Himalayan Geology, India. The available OSL dates from previous literature (Singh et al., 2001; Thakur et al., 2007; Dutta et al., 2012) were also used, although limited information was available for these samples. Table 3 presents the OSL data generated in this work.

4. Major geomorphic units and fan stratigraphy

4.1. Lesser Himalaya hills (LHH)

Lesser Himalaya hills are situated at the hanging wall of the Main Boundary thrust to the north (Fig. 3A). This unit is mainly composed
of Lesser Himalayan rocks, which include argillites, phyllites, quartzite, carbonate, and slates (Hagen, 1969; Stocklin, 1980; Valdiya, 1980). This area can easily be demarcated on the satellite images because of its rugged and high relief pattern on the DEM. Slope ranges from 10° to 50° and altitude varies from 500 to 3000 m in this unit. The presence of active lineaments makes this area prone to landslides and debris falls (Fig. 3B) and sediments are transported to the Dun through dendritic to subdendritic drainage network.

4.2. Dissected hills (DH)

The dissected hills unit is composed of middle and upper Siwalik rocks that are dominantly sandstone and conglomerate, respectively. This unit has been mapped as ‘inner’ and ‘outer’ dissected hills based on its position in the valley, i.e., north and south of the Dun, respectively. The ‘inner dissected hills’ unit is situated on the footwall of the MBT and on the hanging wall of the Santaurgarh thrust (Fig. 3A). The elevation of ‘inner dissected hills’ ranges from 1000 to 1200 m and slope varies from 10° to 30°. The activity of the Santaurgarh thrust is manifested as deeply incised valley in the inner dissected hills and presence of large boulders upstream of the Koti (Fig. 3C), a very small stream draining the dun surface. The ‘outer dissected hills’ constitute the SW flank of the Mohand anticline. The elevation of the outer dissected hills ranges from 550 to 800 m and slope varies from 5° to 30°. This unit is highly dissected by several small streams like the Suarna, Koti, Mauti, Tons, and many minor ephemeral streams that flow parallel to each other.

4.3. Isolated hills (IH)

Isolated hills are low-elevation, rounded residual hills adjacent to the Himalayan front (inner Siwalik hills, Fig. 3A). The elevation ranges from 620 to 880 m and the slope varies from 5° to 20°. On satellite images, this unit can be identified as disjointed hills separated from each other and at higher elevations compared to the alluvial fans. This unit is covered with thick vegetation (reserved forests) and yields highly positive NDVI values (0.40–0.60, Table 2). Based on their composition, this unit has been further divided into two subunits, namely isolated hills of fan material (IHF) and isolated hills of Siwaliks (IHS). The IHS subunit is mainly composed of sandstones of middle Siwaliks and conglomerate deposits of upper Siwaliks. This unit is mainly exposed at the eastern and western margins of the study area (Fig. 2). The conglomerate deposits are mainly made up of subrounded gravels of quartzite and mudstone derived from the Lesser Himalayan region. The IHS unit is at a higher altitude in comparison to the IHF and shows a radial drainage pattern.

4.4. Proximal fan (PF)

The proximal fan unit occupies the area between the ‘isolated hills’ unit close to the mountain front (Fig. 3D) but extends farther downstream of the Santaurgarh thrust, ~5–10 km. The preserved fan surface has a radius of 4–5 km and surface area of ~54 km². The elevation of this
unit ranges from 500 to 840 m, and slope varies from 2° to 5° southward (Table 1). The NDVI values range between $-0.04$ and $+0.04$, suggesting comparatively less vegetation cover with flat cultivated areas.

The proximal fan unit was identified as depositional unit GD-II (Singh et al., 2001) and unit ‘B’ by Thakur et al. (2007) (Table 2). This unit lies unconformably over the steeply-dipping to overturned middle Siwalik sandstones (Thakur et al., 2007) at the hanging wall of the Santaurgarh thrust but shows no evidence of offset or deformation across the Santaurgarh fault. The exposed thickness of this unit is ~50 m. The proximal fan unit is exposed continuously for ~1.5 km up-stream of the Santaurgarh thrust along several major drainages, including the Koti and the Suarna rivers. At the footwall of the Santaurgarh thrust, this unit appears to overlie the IHF unit (Fig. 3D), and the fan head has been entrenched by later fluvial processes. The proximal fan sediments have clasts ranging from pebbles to gravels and rarely boulders. Clasts are relatively poorly to fairly sorted but fining upward.

### Table 3

<table>
<thead>
<tr>
<th>Litho-stratigraphic unit</th>
<th>Sample no./Log</th>
<th>Depth (m)</th>
<th>$U$ (ppm)</th>
<th>$Th$ (ppm)</th>
<th>$K$ (%)</th>
<th>Moist. cont (%)</th>
<th>Equivalent dose (De) Gy</th>
<th>Dose rate (Gy/ka)</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrace Sitla Rao</td>
<td>ST-1</td>
<td>1</td>
<td>2.17 ± 0.02</td>
<td>10.7 ± 0.11</td>
<td>2.02 ± 0.02</td>
<td>9.44</td>
<td>2.77 ± 0.48</td>
<td>3.05 ± 0.04</td>
<td>0.9 ± 0.2</td>
</tr>
<tr>
<td>Terrace Chor Khala</td>
<td>CKT-1</td>
<td>1</td>
<td>2.34 ± 0.02</td>
<td>15.1 ± 0.15</td>
<td>2.45 ± 0.02</td>
<td>21.48</td>
<td>11.70 ± 0.65</td>
<td>3.32 ± 0.07</td>
<td>3.5 ± 0.2</td>
</tr>
<tr>
<td>Distal fan FS 2.1</td>
<td>4</td>
<td>2.23 ± 0.02</td>
<td>15.3 ± 0.15</td>
<td>2.91 ± 0.03</td>
<td>3.44</td>
<td>59.68 ± 3.96</td>
<td>4.33 ± 0.05</td>
<td>13.8 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>Distal fan FS2.2 (DF1)</td>
<td>5</td>
<td>2.43 ± 0.02</td>
<td>16 ± 0.16</td>
<td>2.46 ± 0.02</td>
<td>13.53</td>
<td>51.46 ± 1.87</td>
<td>3.58 ± 0.06</td>
<td>14.4 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>Distal fan LIS-TOP</td>
<td>2.8</td>
<td>3.3 ± 0.03</td>
<td>18.1 ± 0.18</td>
<td>3.02 ± 0.03</td>
<td>1.27</td>
<td>80.72 ± 6.82</td>
<td>4.99 ± 0.06</td>
<td>16.2 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>Distal fan SU-1</td>
<td>0.9</td>
<td>NA</td>
<td>1.89 ± 0.02</td>
<td>16.4 ± 0.16</td>
<td>2.21 ± 0.02</td>
<td>18.16</td>
<td>65.71 ± 3.62</td>
<td>3.10 ± 0.06</td>
<td>21.2 ± 1.2</td>
</tr>
<tr>
<td>Proximal fan FS3.1 (IH3)</td>
<td>10</td>
<td>4.56 ± 0.05</td>
<td>21.4 ± 0.21</td>
<td>2.65 ± 0.03</td>
<td>14.38</td>
<td>150.87 ± 14.17</td>
<td>4.47 ± 0.08</td>
<td>33.8 ± 3.2</td>
<td></td>
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<tr>
<td>Proximal fan FS1.1 (PF1)</td>
<td>3</td>
<td>NA</td>
<td>NA</td>
<td>2.21 ± 0.02</td>
<td>18.16</td>
<td>65.71 ± 3.62</td>
<td>3.10 ± 0.06</td>
<td>21.2 ± 1.2</td>
<td></td>
</tr>
<tr>
<td>Proximal fan DFS-2 (HF2)</td>
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<td>NA</td>
<td>NA</td>
<td>2.21 ± 0.02</td>
<td>18.16</td>
<td>65.71 ± 3.62</td>
<td>3.10 ± 0.06</td>
<td>21.2 ± 1.2</td>
<td></td>
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<tr>
<td>Isolated hills IFH1</td>
<td>2.8</td>
<td>3.1 ± 0.03</td>
<td>18.4 ± 0.18</td>
<td>3.08 ± 0.03</td>
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<td>207.20 ± 5.47</td>
<td>5.02 ± 0.06</td>
<td>41.3 ± 1.2</td>
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<tr>
<td>Isolated hills DHR-1 (IH2)</td>
<td>9</td>
<td>NA</td>
<td>NA</td>
<td>2.21 ± 0.02</td>
<td>18.16</td>
<td>65.71 ± 3.62</td>
<td>3.10 ± 0.06</td>
<td>21.2 ± 1.2</td>
<td></td>
</tr>
</tbody>
</table>

* Sample depth from surface in m.

![Fig. 3](image-url)
(normal grading), suggesting these to be sheet flow deposits. These sediments were deposited in paleovalleys that were incised by at least 70–75 m into the underlying deposits of the IHF. The axes and orientation of these paleo-valleys are slightly offset from those of the modern drainage system, which means that their width cannot be observed directly (Densmore et al., 2015). The drainages flowing over the fan surface are parallel to subparallel. Large boulders were observed in this unit toward the basin margin (Fig. 5A).

Two lithologs from PF1 and PF2 sections document the stratigraphy of proximal fan sediments. A 6 m high PF1 section is located downstream of Dharer nala, a small tributary of the Tons River. The proximal fan sediments in this section consist of an organized gravel bed (base not exposed) overlain by a 3-m-thick disorganized boulder–gravel layer with randomly oriented clasts and loose matrix (Fig. 4B). A thin sand layer above gave an OSL age of 33.8 ± 3.2 ka (Fig. 4B). An 80-cm-thick paleosol layer separates the lower proximal fan sediments in this section from the upper organized gravel layer, which was interpreted to be a part of distal fan deposits (discussed later). The PF2 section is a reinterpreted section (section D3 of Singh et al., 2001). This section has a massive sand layer (1 m thick) at the base for which an OSL age of 21.2 ± 1.2 ka was obtained by Singh et al. (2001). A major part of this section (10.5 m thick) consists of alternating layers of clast-supported and matrix-supported gravels. A 2-m-thick paleosol above the sand layer represents a major discontinuity and marks the cessation of proximal fan deposition.

The upper part of the IHF2 section (0–8 m) and the middle part of the IHF3 section (6–10 m) have also been interpreted as proximal deposits onlapping the IHF sediments. In the IHF2 section, the proximal fan deposits consist of a massive sand layer overlain by a 3-m-thick layer of pebbly sand and 6-m-thick layer of matrix-supported organized gravels. The upper part of this log consists of another massive sand layer (4 m thick) that was dated as 30.1 ± 3.5 ka (Table 3, Fig. 4B). The sand layer is overlain by a 2-m-thick layer of clast-supported organized gravels, and the section is capped by a 2-m-thick surface soil. In the IHF3 section, the proximal fan deposits are made up of a sand layer (2-m-thick) with a date of 21.2 ± 1.2 ka (Fig. 4B) and a thin layer (1 m) of the imbricated gravels, suggesting a brief period of channelized flow. The overlying paleosol layer (80 cm thick) marks a minor discontinuity in the sequence, and the overlying sediments were interpreted to be a part of distal fan deposits (discussed next).

4.5. Distal fan (DF)

The distal fan has been mapped farther south of the proximal fan. The southern stretch of this unit is bounded by the Asan River. The distal fan unit is a near-planar surface with elevation varying from 480 to 700 m sloping <2° southward. The observed fan radius is ~10–17 km, and the total surface area is ~131 km². This unit consists of poorly sorted, angular to subangular pebbles with rare boulders (depositional unit ‘C’ of Thakur et al., 2007). Singh et al. (2001) identified the same unit as depositional unit GD III and GD IV (Table 2) with pedofacies III. The exposed thickness of this surface varies from ~15 m in the northern part to ~5 m in the southern part. The NDVI values vary from ~0.04 to +0.40 for this unit, suggesting barren lands or settlements with some areas of thick vegetation cover. The topography of this unit is highly undulating owing to dissection by several minor streams.

A –10-m-thick exposed section (DF1) on the western bank of the Sitala Rao has a 4.5-m-thick layer of disorganized gravels at the base overlain by a 1-m-thick sand layer that was dated as 14.4 ± 0.6 ka (Fig. 5B). The sand layer is overlain by a 1.5-m-thick clast-supported organized gravels, and then by a 1-m-thick matrix-supported organized gravel. In the IHF3 section, the uppermost (0–5.5 m) part of the sequence has been interpreted as distal fan deposits consisting of two layers of matrix-supported organized gravels, each ~1 m thick, separated by a thin sandy layer. The section is capped by sandy soil (1 m thick) that is highly disturbed owing to the presence of thick vegetation. Distal fan deposits are also exposed in the upper part of the PF2 section (0–8 m) consisting of thick alternating layers of clast- and matrix-supported gravels. An intervening sand layer at ~3 m depth in PF2 section was dated to be ~9.4 ka by Singh et al. (2001).

Three additional OSL dates were obtained for distal fan deposits (Table 3). The sample SU-I-1 came from an exposed section on the eastern flank of the Suarna River at a depth of 0.9 m from a location close to the IHF2 section (Fig. 5A) and gave an OSL date of 19.9 ± 2.1 ka (Table 3). The samples LIS-TOP and FS 2.1 were collected from distal fan deposits overlying the IHF/FP deposits (Fig. 5A) and yielded OSL ages of 16.2 ± 1.4 and 13.8 ± 0.9 ka, respectively. Distal fan sediments are onlapping those of the proximal fan as observed in several lithologs (IHF3, PF1, PF2) but not all the way up to the hanging wall of the Sautargarh thrust; this suggests backfilling of this unit over the older fan units.

4.6. Dip slope (DS)

The dip slope unit has been mapped on the northern flank of the Mohand anticline and is mainly controlled by the dip of the Siwalik Ranges (mapped as dip-controlled slope by Thakur et al., 2007). Lithologically, it is mainly composed of unsorted subrounded boulders and pebbles, predominantly of quartzite and sandstone derived from the Siwalik Ranges of the Mohand anticline. The total surface area of this unit is ~115 km², mostly covered by thick vegetation cover characterised by highly positive (0.4–0.6) NDVI values (Table 1). The regional slope of this unit varies from 5° to 10°, and the elevation ranges between 500 and 680 m. Based on TRMM data, Bookhagen and Burbank (2006) interpreted very high annual rainfall (~100–300 cm) along the Mohand stretch because of a significant topographic high. As a result, hillslips failures and landslides are common in this unit (Fig. 5B) and they constitute the dominant sediment transport processes in the area (Barnes et al., 2011). The OSL age of ~30 ka (Thakur et al., 2007) suggests a major unconformity between the underlying Siwalik strata (age ~0.5 Ma; Sangode et al., 1996) and the dip slope unit.

4.7. Channel belt

Channel belts of the major rivers such as the Kosi, Maui, Sitala Rao, and Suarna occupy the lowest elevations in the Dehra Dun. These seasonal rivers dissect the fan surfaces and flow for a length varying from ~20 to 25 km from their point of origin in the Lesser Himalaya to their confluence with the axial river, the Asan (Tons). The Asan (Tons) originates from southern slopes of the Mussoorie hills and drains for ~50 km before meeting the Yamuna. Channel belts of most of the rivers are quite narrow (~0.5 km) in the upstream reaches, but they become wider (1 to 1.5 km) in downstream reaches. Small streams such as the Nimi, Dharer, Ghulata, Umdadi Rao, and Chor khala originate within the valley, mainly from the detached residual hills (IH unit). These are ephemeral streams and most of them are <15 km long. Large boulders were noted in the channel belt of the Kosi and Maui rivers in their upstream reaches. In the downstream reaches, gravels and pebbles constitute a major part of channel sediments.

4.8. Floodplain (FP)

The major rivers draining the study area, the Yamuna, Suarna, Sitala Rao, and Asan, have prominent floodplains. The general slope of the floodplains ranges from 0° to 1° and the elevation ranges from 420 to 660 m. The floodplain unit was demarcated on the satellite images on the basis of image characteristics such as high moisture content and NDVI values (negative to zero; see Table 1). The floodplain along the Asan River is 0.5–2.5 km wide but is much narrower (600–900 m) along the Suarna River (Fig. 5C). The floodplain unit is composed of sand and silt and little mud with some pedogenic modification and intercalated with pebbles. At the western end of the study area, the
Yamuna has a well-developed floodplain, and the width varies from 0.5 km in the upstream to 3 km in downstream reaches.

4.9. Terraces (T)

One set of paired fill terraces were mapped along the Sitala Rao and Suarna rivers. Terraces are cultivated areas with elevation ranging from 480 to 720 m. Terraces are mainly composed of gravels and pebbles in sandy matrix. The NDVI values of these surfaces are nearly zero or slightly positive because of the presence of barren land and cultivated areas. Terraces along the Sitala Rao are ~5 km long and ~0.5–0.8 km wide. We obtained an OSL age of 0.9 ± 0.2 ka from a sample taken from this terrace (Table 3). Terraces along the Suarna River are ~4 to 5 km long and ~0.5 km wide, located ~2 to 3 m above the river bed and are flat with sparse vegetation cover (Fig. 5C). An approximately ~30-km-long and 0.7 to 2.5 km wide asymmetric terrace was identified along the southern bank of the Asan river. This terrace is bordered by the dip slope (DS) unit at the south and is cut by several ephemeral streams flowing from the northern flank of the Mohand anticline that join the Asan River to the south. The formation of this asymmetric terrace along the Asan may be related to the uplift of the Mohand anticline. Another small symmetric depositional terrace surface, ~0.5 km long, ~0.2 km wide, and ~1 m high, was identified along the Chor Khala River (Fig. 5D), a small tributary of the Asan River. An OSL date of 3.5 ± 0.2 ka was obtained for a sample from this terrace (Table 3).

4.10. Undifferentiated gravels (UGF)

This unit, composed mainly of gravels, is flat and occupies a total area of ~200 km² north of the Asan river and east of the Tons river. In the surface profile, there is no major break between distal fan unit and undifferentiated gravels unit. A large part of this unit is dotted with cultivated land and settlements including the city of Dehradun. Although it has been mapped as a fairly continuous unit, it is quite scattered and disjointed owing to human interventions.

Fig. 5. Field photos of different geomorphic units. (A) Location of the sample collected from ‘proximal fan unit’. This ~6-m-high section near Dharer nala has an organized gravel bed at the base that is overlain by disorganized boulder-gravel units. Big boulders were observed in this unit toward the basin margin suggesting high precipitation in catchment. (B) ‘Dip slope’ geomorphic unit, mapped on the NW flank of the Mohand anticline, comprised of unconsolidated gravels, unsorted subrounded pebbles, and boulders of quartzite and sandstone. High rainfall makes this unit vulnerable to slope failures. (C) River terraces along the Suarna River. The terraces are ~4–5 km long and ~0.5 km wide and located ~2–3 m above the river bed. Floodplain width along the river varies from 600 to 900 m. (D) One set of depositional terraces along Chor Khala River. The sample (CKT-1) collected from the right bank of the river, ~1 m below the surface, yielded an OSL age of 3.53 ± 0.21 ka.
5. Discussion

5.1. Tectonogeomorphic evolution and depositional history of the Dehra Dun

The IHF unit is a steeply dipping fan surface and is mainly composed of clast- and matrix-supported boulders to pebble conglomerate. The clasts are poorly sorted and randomly oriented suggesting dominant debris flow deposits (Blair and McPherson, 1994; Singh et al., 2001; Nichols, 2009). The deposition of isolated hills of fan IHF unit occurred during ~43–33 ka coinciding with the precipitation minima around 40 ka (Prell and Kutzbach, 1987). We argue that the availability of sediments in the system was related to reactivation of MBT during 70–55 ka (Banerjee et al., 1999) and 50–35 ka (Singhvi et al., 1994; Singh et al., 2001) that led to the deposition of thick strata of IHF (≥41 ka) in the Dun (Fig. 6). Low transport capacity caused by the precipitation minimum during this period resulted in deposition close to the mountain front.

The proximal fan unit primarily consists of matrix- and clast-supported pebbles to gravels with some boulders having loose contact with matrix that suggests mud flow or sheet flow deposits (Blair and McPherson, 1994; Singh et al., 2001) with minor debris flows. The proximal fan unit is the second phase (34–21 ka) of major aggradation in the Dun that coincides with a period of high sediment production from the Himalaya (Sharma and Owen, 1996; Taylor and Mitchell, 2000; Pant et al., 2006). This is also the period of high precipitation that led to high intensity floods in the foreland induced by high solar insolation at ~31 ka (Goodbred, 2003). High sediment supply (Lecce, 1990) and an increase in water–sediment ratio (Ballance, 1984; Wells and Harvey, 1987; Harvey and Wells, 2003; Densmore et al., 2007; Nichols, 2009) during this period were the primary reasons for transition from debris flow deposits (IHF unit) to sheet flow deposits (PF unit). The elevation difference of ~100 m between the IHF and PF units (Table 2) suggests an incision of the IHF unit prior to the deposition of proximal fan unit.

The onlapping of the proximal fan deposits over the IHF deposits (lithologs IHF2 and IHF3) at the hanging wall of the Santaurgarh thrust suggests widespread deposition of the proximal fan unit during the LGM and eventually backfilling toward and across the Santaurgarh thrust. This backfilling of the proximal fan deposits could have been triggered because of tectonic influences (e.g., increase in slip rate; Bull, 1961, 1964; DeCelles et al., 1991; Gordon and Heller, 1993; Mellere, 1993; Allen and Densmore, 2000). The increase in slip rate provides accommodation space and the younger fan unit can onlap the older units (Densmore et al., 2007). Backfilling can also be influenced by hydraulic conditions such as less water availability or low water-sediment ratio that can lead to the onlapping of the younger unit over the older one close to the mountain front (Goudie, 2004; Densmore et al., 2007; Hamilton et al., 2013). However, as no deformation was observed on the fan surfaces in the Dun and the widespread filling occurred around the LGM time, we argue that climatic factors have had a dominant role in backfilling of the proximal fan unit.

The presence of boulders in the distal part of the fan unit (Fig. 4A) has been debated and alternative hypotheses have been proposed. Kumar et al. (2007) and Giano (2011) interpreted the presence of boulders in fan deposits toward the basin margin because of high precipitation in the catchment. On the contrary, Singh et al. (2001) suggested that the development of the pediments 1 and 2 (IHF in the present work) caused by the activity of the Bhauwala thrust and headward erosion of the streams. They also suggested that the pedimented Siwalik (IHS in the present work) and fan area were uplifted caused by the activity of the Bansiwala thrust (Asan fault according to Thakur et al., 2007). In the hanging wall of the Santaurgarh thrust, fan deposits were observed lying unconformably over the steeply dipping to overturned middle Siwalik sandstones (Thakur et al., 2007), but no evidence was recorded for any deformation in the fan units across the Santaurgarh thrust. We therefore favour the climatic interpretation (high precipitation) for such deposits.

The distal fan unit consisting of poorly sorted, angular to subangular pebbles have been interpreted as braided stream deposits and overbank deposits. The distal fan unit (20–11 ka) represents the third phase of deposition in the Dun. Sheet-like fan deposits indicate high precipitation in the catchment area (Densmore et al., 2007). The timing of distal fan deposition coincides with the post-LGM period that corresponds to high sediment supply from the hinterland because of monsoonal intensification (Overpeck et al., 1996) and to extensive slope failures and hill slope sediment transport (Pratt et al., 2002). The lithologs PF1 and PF2 clearly show that the distal fan sediments onlapped the proximal fan unit.
deposits. This again suggests backfilling of distal fan deposits (Fig. 6) but not up to the hanging wall of the Santaurgarh thrust. We argue that such backfilling is related to water-sediment ratio influencing the transport capacity of the river systems (Goudie, 2004; Densmore et al., 2007; Hamilton et al., 2013).

During the early to mid-Holocene period, minor terrace deposits dating 11 ka (Singh et al., 2001) and 3 ka (present work) have been documented along the rivers in the Dun. This period was the beginning of the incision phase in the Dun because of intense monsoonal activity (Singh et al., 2001). An incision phase started in the Dun at ~12/10 ka and has continued until present (Singh et al., 2001; Suresh and Kumar, 2009). No deposition was recorded after 3 ka except a minor recent aggradational terrace (OSL age 0.9 ka, sample ST-1) along the Sitala Rao (Fig. 4A).

5.2. Conceptual model

Fig. 7 shows the sequential development of the different fan units in the Dehra Dun. The deposition of the IHF unit (Stage I) began at ~43 ka and probably ended around ~33 ka. The reactivation of MBT during 75–65 and 50–35 ka (Singhvi et al., 1994) provided high sediment availability and low precipitation minima (Prell and Kutzbach, 1987), resulting in low transport capacity and deposition of sediments close to the mountain front. The geomorphic expression of this fan is not well preserved because of several cycles of incision. Therefore, the precise timing of deposition and abandonment of this unit could not be ascertained. The proximal fan formed because of continuous deposition from 34 to 21 ka and developed between isolated hills. Field evidences suggest incision of isolated hills and refilling of the valley. The activity of the Santaurgarh thrust before 23 ka (Singh et al., 2001) provided high sediment availability during this period and led to continuous deposition of PF until 21 ka. The distal fan (stage III) formed owing to further southward shift of depositional locus after the abandonment of the proximal fan and fanhead entrenchment. Deposition of the distal fan sediments (~20–11 ka) may have progressed as backfilling over the proximal fan deposits (34–21 ka), but no distal fan deposits are observed over the hanging wall of the Santaurgarh thrust. A minor depositional phase is also documented in the intermontane basin during 3–1 ka (stage IV) that led to thin depositional terraces along the modern rivers.

All four depositional units, namely isolated hills of fan, proximal fan, distal fan, and younger depositional terraces, are separated by strong incision phases (Fig. 7). The timing and duration of the incision phases are not precisely constrained, but these must have occurred after the deposition of fan units, at ~33 ka for IHF, ~20 ka for PF, and ~10 ka for DF. Earlier work (Densmore et al., 2015) estimated that these incision episodes contributed a significant amount of sediment discharge into the plains that were ca. 1–2% of the present-day suspended load of the Ganga and Yamuna rivers that traverse the margin of the Dun.

Fig. 7. Evolutionary model of the Dehra Dun fans. (I) IHF deposits formed during 43–33 ka, and the reactivation of MBT during 75–65 and 50–35 ka provided high sediment availability and low precipitation minima, resulting in low transportation capacity that resulted in sediments deposited close to the mountain front. (II) Proximal fan formed because of continuous deposition from 34 to 21 ka and developed between isolated hills; field evidences suggest incision of IH and refilling of the valley. The activity of the Santaurgarh thrust before 23 ka (Singh et al., 2001) provided high sediment availability during this period and led to continuous deposition of PF until 21 ka. (III) Distal fan (20–11 ka) formed when the depositional locus shifted southward owing to fanhead entrenchment of the proximal fan. (IV) A dominant incision phase (~5 ka) in the Dun with deposition of minor younger terraces during 3–1 ka. (DD—Dehra Dun; PD—Pinjaur Dun, KD—Kiarda Dun, PaD—Parduni basin, CD—Chitwan Dun).
5.3. Comparison with other duns (intermontane valleys) and regional correlation

The OSL ages suggest that the fan development in western Dehradun started at ~43 ka and ceased around 10 ka. Aggradational phase I (~43–33 ka) that corresponds to formation of the IHF unit is comparable to the first aggradation phase in Yamuna valley (~37–24 ka) between the MBT and the HFT (Dutta et al., 2012). An aggradational phase was also documented during ~49–25 ka at various upstream sites in the Ganga basin (Srivastava et al., 2008; Ray and Srivastava, 2010). Fan aggradation in the Pinjaur Dun was also documented from 72 to 24 ka (Kumar et al., 2007; Suresh et al., 2007) but without any incision phase as recorded in Dehra Dun (Fig. 7).

Phase II (~34–21 ka) of proximal fan deposition correlates with depositional phases in the Soan Dun in NW Himalaya during ~36–29 ka (Suresh and Kumar 2009) and falls within the fan aggradation phase (~72–24 ka) in the Pinjaur Dun in NW Himalaya (Kumar et al., 2007; Suresh et al., 2007). Fan aggradation phases in the Kiarda and the Parduni basins in NW Himalaya –recorded from ~34 to 19 ka and from ~27 to 20 ka, respectively (Philip et al., 2009) – are also correlatable to this phase (Fig. 7). In Chitwan Dun in the Narayani basin, southern Nepal, no absolute ages of the fill deposits are available, but Kimura (1995) suggested ages of the depositional units as ~26–16 and <10 ka separated by an incision event.

Aggradational phase III (20–11 ka) represented by distal fan deposition in Dehra Dun, correlates with the second aggradation phase (15–12 ka) in the Yamuna valley between the MBT and the HFT (Dutta et al., 2012). Aggradation in the Ganga valley between MBT and HFT was also documented at ~11 ka followed by incision during 11–9.7 ka (Sinha et al., 2010). A phase of aggradation was documented at several upstream sites in the Ganga basin during 18–11 ka (Srivastava et al., 2008; Ray and Srivastava, 2010). A minor depositional phase was also observed in the Pinjaur Dun during 16 ka (Suresh et al., 2007). Minor terrace deposits during 3–1 ka in the Dehra Dun (aggradational phase IV) correlates with a brief depositional event in the Yamuna valley during (~5-1 ka) (Dutta et al., 2012) and the Pinjaur Dun during 4.5 ka (Fig. 7) (Suresh et al., 2007). Fan aggradation ceased –11 ka ago in the Dehra Dun (Singh et al., 2001) and so did the second phase of fan deposition in the Kangra region around 10 ka (Suresh and Kumar, 2009).

It has been observed that major fan aggradational and incision phases in the Duns along the Himalayan arc (Kumar et al., 2007; Suresh et al., 2007; Philip et al., 2009; Suresh and Kumar, 2009; Sinha et al., 2010; Dutta et al., 2012) correlate reasonably well, but spatial variation in timing of individual events is noted. We therefore suggest that these Duns have gone through similar cycles of sedimentation/evacuation under the influence of climatic variation with interruptions from tectonic activity and sediment supply from the mountainous area. Major aggradational phases are related to the Quaternary glacial period, whereas the degradational phases are related to interglacial periods (Harvey, 1990). We suggest that the role of tectonic activities has been limited to creation of accommodation space in the Dehra Dun region and has not influenced the fan development process in a major way.

Our observations are in line with landscape development in different parts of the Himalaya documented on the basis of sedimentological, geomorphic and chronostратigraphic analysis using OSL and terrestrial cosmogenic nuclide (TCN). These studies have suggested that erosional and depositional processes throughout the Himalaya and Tibet have been mainly controlled by climatic changes, specifically the transition between glacial to deglacial periods (Barnard et al., 2004, 2006a, 2006b; Dortch et al., 2009; Seong et al., 2009; Ray and Srivastava, 2010). In the Central Karakoram region, glacier geochronology and outburst flood deposits have indicated that landform development was dominantly influenced by glaciation to paraglaciation during the late Quaternary (Seong et al., 2009). Paleoclimatic records from the Alaknanda-Ganga system in the Lesser Himalaya indicate that aggradation and incision phases between 63 and 11 ka resulted primarily because of glaciation–deglaciation processes (Ray and Srivastava, 2010). Mass wasting (landslides) and sheet flow processes during the transition between glacial and nonglacial periods (Barnard et al., 2006a, 2006b; Dortch et al., 2009; Seong et al., 2009) also contributed to the sediment input in the Duns (Chandel and Singh, 2000; Singh et al., 2001). However, it has been suggested that tectonic activities along longitudinal as well as transverse faults have continuously modified the landforms in the Duns (Kimura, 1994, 1999; Chandel and Singh, 2000; Singh et al., 2001; Virdi et al., 2006; Philip and Virdi, 2007; Singh and Tandon, 2008; Philip et al., 2009).

6. Conclusions

Geomorphic and stratigraphic investigations in the Dehra Dun in NW Himalaya have suggested that at least three phases of fan sedimentation occurred during the late Quaternary period (I) 43–33 ka, (II) 34–21 ka, and (III) 20–11 ka followed by minor terrace formation during 3–1 ka. Each depositional phase was followed by fanhead incision, abandonment of the active depositional locus and shifting of the depocenter toward the basin margin. Climate change (high precipitation) was the primary reason for the transition from debris flow deposits to sheet flow and stream flow deposits in the Dun. While the evolutionary history of the alluvial fans in the Dun was influenced by tectonic activities, particularly in terms of providing accommodation space, the aggradation and entrenchment of fans were controlled by climatic perturbations.

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