Optically stimulated luminescence dating of alluvial fan deposits of Pinjaur Dun, NW Sub Himalaya

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The Quaternary deposits of Pinjaur Dun characterized by a series of alluvial fans, are indication of tectonic uplift of the northern part of the Sub Himalaya and variation in climate through the time of their sedimentation. The quartz optically stimulated luminescence ages of the exposed bottom and top of the fan deposits indicate that the sedimentation commenced well before 57 ka BP and continued up to around 20 ka BP. Presently the base of the river is about 30–40 m below the distal fan surface indicating that after the termination of fan sedimentation around 20 ka BP, river incision and subsequent terrace formations occurred probably due to change in climate and tectonism.

QUATERNARY deposits are good repositories of global climate and neotectonics. A persistent problem in Quaternary studies is determining the timing of events (e.g. climatic, tectonic, etc.) as found in sedimentary records. Luminescence dating, an absolute dating technique, which relates to absorption of nuclear energy by natural minerals (quartz, feldspar, etc.) and emission of luminescence on thermal or optical excitation, has aroused the interest of Quaternary scientists. Depending on the type of excitation the phenomenon is termed as thermally stimulated luminescence (generally known as thermoluminescence or TL) or optically stimulated luminescence (OSL). The OSL dating is classified into green light stimulated luminescence (GLSL) and infrared stimulated luminescence (IRSL), depending upon the nature of the stimulation light. The GLSL can be obtained from both quartz and feldspar, whereas IRSL is for feldspar. A detailed account about the luminescence dating method and its application has been given by several workers.1-6 Luminescence dating of sediments requires a proper resetting of the previously acquired luminescence in the natural minerals into a very low level (natural zeroing event), either by exposure to sunlight (optical bleaching during pre-depositional transportation) or by a thermal event. Following the zeroing event and subsequent burial, the natural minerals begin luminescence acquisition afresh from the natural radioactive elements (U, Th and K) present in the sediments. The time elapsed since deposition can be obtained by the ratio of total luminescence acquired to the annual rate of acquisition. Wintle and Huntley3 recognized that in some environments (e.g. fluvial) sediments may not receive long light exposure prior to deposition and are unable to completely reset the thermoluminescence signal. However, introduction of the OSL method3 has reduced the severity of this problem. The OSL signals for quartz and feldspar drop considerably within the first 20 s of sunlight exposure, and the speed of signal deduction enables the technique to be applied to mineral grains which did not receive long light exposure prior to deposition, such as hill wash or fluvial sediments. Among quartz and feldspar, the quartz OSL dating has an added advantage due to its speed of signal reduction.

In view of the fact that OSL dating can provide absolute dates for fluvial sediments, we applied this technique for dating the alluvial fan sediments exposed in the Pinjaur Dun in the Sub Himalaya (Figure 1, after Karunakaran and Rao6). A Dun is a longitudinal tectonic depression in the Sub Himalaya. It is not one continuous depression, but is separated into several individual Duns (e.g. Dehra Dun, Kota Dun, Pinjaur Dun, etc.). Within the Dun-type foot-hills, the Himalayan rivers are accumulating their sediment load as alluvial fans and river terraces. The previous work carried out on the Pinjaur Dun suggested that the depositional phases can be correlated to glacial periods, and erosional phases to inter-glacial periods, in Pleistocene. On the contrary, in the western part of Pinjaur Dun near Kirathpur, the exposed fluvial sediments were mapped as Upper Siwalik11. However, no absolute date was available for these fluvial deposits exposed in the Pinjaur Dun. The present study focuses on establishing the chronologically-controlled stratigraphic framework.

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based on OSL dating technique, for the alluvial fans exposed in the Pinjaur Dun. This study will throw light on the tectonic/climatic control on the formation of alluvial fans and related geomorphic features in the Sub Himalaya.

The study was carried out in the western part of Pinjaur Dun near Kiratpur (Ropar District, Punjab) in the Sub Himalaya (Figure 1). The Sub Himalaya, the southernmost division of the Himalaya, is separated from the Lesser Himalaya by the Main Boundary Thrust (MBT) in the north and the southern boundary is demarcated from the Indo-Gangetic Plain by the Himalayan Frontal Fault (HFF). The northern part of the Sub Himalaya is characterized by a series of intra-basinal thrusts (Nalagarh, Barsar and Bilaspur) which are in general parallel to the MBT. The Pinjaur Dun is developed between the detached anticlinal ridges of Siwalik molasse (mainly Upper Siwalik Formations) in the south and Lower Tertiary (Dagshai, Kasauli and Subathu/Tertiary (Lower and Middle Siwalik) rocks in the north (Figure 1). The Nalagarh Thrust marks the northern boundary of the Dun, which brought the Tertiary/Lower Tertiary rocks over the Quaternary Dun sediments.

The Satluj river and its tributaries (Figure 2) are the major drainage system in the Dun. The Satluj river flows in a longitudinal course from the northwest to the southeast, whereas its tributaries originate from the higher reaches of Sub Himalaya, between Nalagarh Thrust and MBT, and flow in transverse courses in a south-southwest direction. The catchment areas of these piedmont rivers (tributaries of Satluj) are mainly comprised of Lower Tertiary and Tertiary (Lower and Middle Siwaliks) rocks (Figure 1). Mudstones and sandstones are the predominant rock types in the Lower and Middle Siwaliks, respectively.

The important geomorphic features observed within the Dun basin are alluvial fans and river terraces. Alluvial fans are fan- or cone-shaped sedimentary bodies that accumulated at the base of the Sub Himalayan mountain front, south of Nalagarh thrust, downslope from the point where piedmont rivers emerge from the uplands. Extensive road cuttings and river cuts provide
an excellent opportunity to examine nearly continuous exposures (from fan head to toe and transverse view) of these fan sediments. A series of alluvial fans are observed, exposed around present-day rivers, between Kiratpur in the west and Pinjaur in the east. In the present study, two alluvial fans exposed around Luhund Khad and Kundlu Ki Khad rivers in the vicinity of Kiratpur were selected (Figure 2). The Kundlu Ki Khad fan is about 15 km long and 6 km wide, whereas the Luhund Khad fan is about 11 km long and 7 km wide.

Litho-sections representing the proximal, middle and distal parts of Luhund Khad and Kundlu Ki Khad fans were measured and the facies distribution was recorded (Figures 3 and 4). The four litho-sections measured in the Luhund Khad fan are Dehni (proximal fan, near Dehni village), Dabhar (middle fan, near Dabhar village), and Bhatoli and Baba Gurditta (distal fan, near Bhatoli village and Baba Gurditta mandir, respectively near Kiratpur). The Dehni and Dabhar sections are longitudinal sections measured along the Luhund Khad and Misewal Khad rivers, respectively, whereas Bhatoli and Baba Gurditta sections are transverse sections measured along the Nagar Hydel Canal cutting. The three litho-sections representing the Kundlu Ki Khad fan are Baglehr (proximal fan, near Baglehr village), Barun (middle fan, near Barun village) and Alowal (distal fan, near Alowal village). The Baglehr and Barun sections are longitudinal sections measured along the Kundlu Ki Khad river and a road cut (Barun–Palahi village road), respectively. The Alowal section is a transverse section measured along the road cut (Ropar–Kiratpur Highway).

The Dehni and Baglehr sections, representing the proximal part of Luhund Khad and Kundlu Ki Khad fans, respectively are dominated by boulder conglomerates interbedded with mudstones/sandstones facies (Figure 3). The measured sections are about 10 m thick from the river base. The conglomerate beds are 1 to 4 m thick and comprise predominantly of boulder clasts associated with pebble and cobble. They are poorly sorted with chaotic fabric (i.e. scattered distribution of large boulder) and are matrix to loosely framework supported. Matrix consists of coarse silt to clay with scattered angular clast. Content of matrix varied both vertically and laterally. Outsize clasts floating in the

**Figure 2.** Drainage map of a part of Pinjaur Dun area showing Sutlej river and piedmont rivers. The piedmont rivers originate from the elevated regions of the Sub Himalayas, north of Nalagarh thrust, and follow a transverse course. The fan boundaries of Luhund Khad and Kundlu Ki Khad fans are shown as dashed lines. The locations of litho-sections measured are: 1. Dehni; 2. Dabhar; 3. Baba Gurditta; 4. Bhatoli; 5. Baglehr; 6. Barun and 7. Alowal.

**Figure 3.** Litho-section showing the distribution of facies in Luhund Khad alluvial fan. The proximal part of the fan is characterized by conglomerates interbedded with sandstones whereas the middle and distal parts are predominantly composed of sandstones and mudstones. However, thick beds of conglomerate were observed towards the upper part of the mid-fan section. The longitudinal profile of the fan shows steep gradient change towards the proximal part, indicating neotectonic activity. Sample positions (BK-T1, BGK-T1, DK-T4, etc.) and quartz GLSI ages are also shown.
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clay matrix are common throughout the bed. Boulders even up to 1 m in diameter (long axis) were observed. Clasts are angular to subrounded and show no preferred orientation. Clast imbrication is absent and internally the conglomerate beds do not show any grading or structure. The composition of clasts indicates that they are predominantly sandstone boulders and are greyish in colour. At a few places, lenticular body of fine-grained sandstone, having irregular lower and upper contact, is observed (Figure 5). These conglomerates are restricted along basin margin and show rapid lateral variation.

Clayey-matrix supported, poorly sorted, disorganized fabric and lack of sedimentary structures suggest debris flow deposits\textsuperscript{12,13}. High percentage of clayey matrix in these debris flows suggests that the high viscosity medium aided the friction resistance on its slope, thus reducing the mobility of debris flow\textsuperscript{14,15}. The presence of thin beds of mudstone may represent levees deposits of debris flow\textsuperscript{12}. Chaotic fabric suggests rapid deposition on the fan head.

The Dabhar and Barun sections, representing the mid-fan area of Luhund Khad and Kundlu Ki Khad fans, respectively, were characterized by 20–27 m thick succession of fine-to medium-grained sandstone-mudstone and sandstone-conglomerate cycles (Figures 3 and 4). The medium-grained sandstones are more or less unconsolidated and have sharp bedding plane contact with underlying and overlying strata. The mud-

![Figure 4. Litho-section showing the distribution of facies in Kundlu Ki Khad alluvial fan. The proximal part is characterized by conglomerates and the middle and distal parts are dominated by sandstones and mudstones. However, thick beds of conglomerate were observed towards the upper part of the mid-fan section. The longitudinal profile of the fan shows gradient change towards the proximal part. Sample positions (LKK-T4, ASN-T1, etc.) and quartz GLSL ages are also shown.](image)

![Figure 5. Proximal fan showing conglomerate beds exposed along the Kundlu Ki Khad river. Lenticular body of fine-grained sandstone having irregular lower and upper contact within the conglomerate is also seen.](image)

![Figure 6. Continuous sequence of fine to medium-grained sandstone and mudstone cycles in the middle and distal fan areas of (a) Luhund Khad (longitudinal view), and (b) Kundlu Ki Khad (transverse view) fans. Also seen are thinly-beded conglomerates in the Luhund Khad fan.](image)
stones and fine sandstones are thin to thickly bedded, massive and compact. The bedding contact varies from sharp to gradational depending upon the underlying and overlying units. The beds are more or less parallel to the fan surface (horizontally bedded) and continue for t 50 metres (Figure 6a). The conglomerate beds are predominantly comprised of either boulder or pebble clasts. Clasts are rounded to subrounded and embedded in coarse-grained sand/clay matrix. The pebbly conglomerates are thin-bedded, whereas the boulder conglomerates are massive. Thick beds of boulder conglomerates were observed towards the upper part of the middle fan (Figures 3 and 4). The conglomerate units are crudely stratified and show well-developed imbrication. Crude stratification and imbrication reveal traction flow deposits in the proximal to distal gravelly-braided river.

The Bhatoli and Baba Giridhri sections of Luhund Khad fan and the Alowal section of Kundlu Ki Khad fan, representing the distal fan areas, are characterized by about 0.5—34 m thick exposure of fine-to-medium-grained sandstone-mudstone cycle (Figures 3 and 4). The mudstones and fine sandstones are the dominant facies and are thin to thickly bedded and compact. The beds are horizontally bedded and continue laterally for few metres (Figure 6b). The medium-grained sandstones are loose, with sharp contact with underlying and overlying strata. Although the distal fan is mainly comprised of fine-grained facies, occasional occurrences of pebbly conglomerate (predominantly comprising pebble clast) are also observed. Conglomerate facies are well stratified and at places show cross-stratification.

The distribution of facies from proximal to distal alluvial fan indicates that the alluvial fans are oriented in the direction of the present-day piedmont rivers. Presence of sandstone boulders in the conglomerate indicates their derivation from the Lower Tertiary and Tertiary rocks exposed in the catchment area of the piedmont rivers. This suggests that the alluvial fans were deposited in the piedmont zone due to the activity of the Naragarh thrust.

Longitudinal profiles of the fans indicate steeper relief in the proximal part (Figures 3 and 4). A major gradient change was noticed around 400 m contour and above this, the contours are closely spaced. Uplifted fan sediments, in the form of boulder conglomerates, are observed in a road cut (Kiratpur—Bilaspur highway), which are unconformably underlain by Tertiary formations.

Presently the base of the rivers is about 30—40 m below the distal fan surface and are confined within the incised fan deposits. The fan sediments on both banks of the piedmont rivers are getting eroded and no sedimentation is taking place on them. Three levels of terraces were observed in the confined river channel (Figure 7). Among these, the topmost terrace is more developed with a width of about 500 m near the proximal part of the alluvial fans, followed by the middle terrace. The basal terrace is about 1 m above the active river base.

The samples for luminescence dating were collected from sandstones exposed at different stratigraphic levels, representing the middle and distal parts of Luhund Khad and Kundlu Ki Khad fans (Figures 3 and 4). The samples were collected by forcing a metallic pipe, suitably designed for easy penetration, in the cleaned sediment face. The pipe was withdrawn, and the open end capped.

The samples were later extracted in the laboratory under subdued red light conditions after removing possible exposed surface on both ends of the pipes. All the samples were prepared for quartz inclusion technique. The samples were treated with 1 N HCl and 30% H2O2 for removing carbonate and organic matter, respectively. The treated samples were repeatedly washed with distilled water, dried and sieved for obtaining required size fraction (90—125 μm). Quartz grains were later extracted by heavy liquid separation (sodium polytungstate solution, density = 2.65 g/cm3). They were then etched in hydrofluoric acid for about 40 min to remove the outer 15 μm layer and washed with HCl and distilled water. The dried quartz was re-sieved to remove any grains which have been made significantly smaller.

The OSL measurements were carried out in an automated Riso TL/OSL reader (model TL-DA-15, Denmark) equipped with an excitation filter pack for green stimulation light from a halogen bulb and an infrared diode array for infrared stimulation. The excitation filter pack consisting of a 0.6 mm thick GG-420 long-wave-pass filter (schott) combined with a short-wave-pass interference filter provides broad-band green wavelength (in the range of 420—550 nm) stimulation light at the sample. The detection filter pack consisted of a 0.5 mm thick U-340 filter (Hoya) with a peak trans-
mission at 340 nm. Before the GLSL measurement of quartz, the purity of the etched quartz grains was checked for any feldspar contamination using IRSL measurement\(^{18}\). For GLSL measurements, the extracted quartz grains are mounted on a stainless steel disc of 1 cm diameter with silikospray™ as binding material. Multiple aliquots were prepared for each sample for obtaining equivalent dose (\(D_e\)) by additive dose method. Each aliquot is exposed to short duration (0.3 s) green light stimulation for obtaining values for short-shine natural normalization\(^{17}\). The aliquots were divided into groups and required ranges of additive beta doses from a calibrated Sr\(^{90}/\)Na\(^{90}\) beta source (source strength = 0.07 Gy/s), attached to Riso reader, were applied. The aliquots were then preheated to 220°C for 5 min to remove the signal from the unstable shallow traps and both natural as well as additional beta irradiated luminescence was measured for 20 s stimulation time. The obtained natural and laboratory-irradiated luminescence intensities were short-shine normalized and plotted against applied laboratory dose to obtain the additive growth curve. \(D_e\) is then obtained by extrapolating the luminescence value to zero. The growth curve construction and equivalent dose measurement are carried out using Grun software. The \(D_e\) value used for age determination is calculated using short-shine normalized integrated counts within the first 20 s of OSL measurement.

The annual dose rate was calculated for each sample by estimating the elemental concentration of uranium, thorium and potassium in the sediments. Thick-source alpha counting\(^{1}\) was carried out for uranium and thorium estimation by an alpha counter (model 538 series, Day Break, USA). The potassium concentration was estimated by XRF method. The cosmic dose contribution was not calculated and average value (150 μGy/a) was used.

The additive growth curve and shine plateau (equivalent dose as a function of OSL measurement time) for samples BK-T1 and LKK-T4 are shown in Figure 8. The disc-to-disc scatter (5–10%) is typical of that observed in quartz OSL measurement\(^{18}\). A flat shine plateau is observed for LKK-T4 (Figure 8). Similar type of shine plateau is also observed for samples ASN-T4, DK-T4, BGK-T5, BGK-T4 and BGK-T1. However, decreasing shine plateau is observed for samples BK-T1 (Figure 8) and ASN-T1. A flat shine plateau indicates complete bleaching at deposition, whereas an increasing shine plateau is considered as a poorly-bleached sample\(^{8}\). A decreasing equivalent dose with time and an initial falling shine plateau are also reported in the literature\(^{18,19}\). The processes responsible for the different behaviours of shine plateau described above are still not fully understood. The equivalent dose, dose rate and the calculated ages for Luhund Khad and Kundlu Ki Khad fan deposits are given in Table 1.

The OSL ages obtained for the basal part of Baba Guruditta and Batoli sections, distal part of Luhund Khad fan, is 39.5 ± 5.1 ka BP (sample no. BGK-T1) and 45 ± 8.5 ka BP (BK-T1), respectively. The other dates obtained for Baba Guruditta section are 37.9 ± 10.3 ka BP (BGK-T4) and 35.8 ± 8.4 ka BP (BGK-T5) at about 21.4 m and 23.8 m from the base respectively. In the Dhabhar section, middle part of Luhund Khad fan, the top of the section just below the boulder conglomerate facies gives an age of 24.4 ± 4.5 ka BP (DK-T4).

The OSL dating of quartz from Kundlu Ki Khad fan, representing Alowal and Barun sections, also gives similar ages. In the Alowal section, the exposed base gives an age of 49.3 ± 7.7 ka BP (ASN-T1), whereas the top of the section gives an age of 24.6 ± 4.9 ka BP (ASN-T4). In the Barun section, the top gives an age of 27.5 ± 2.6 ka BP (LKK-T4). The obtained OSL ages of the Luhund Khad and Kundlu Ki Khad fans suggest that the fan sedimentation initiated well before 57 ka BP and continued at least up to 20 ka BP.

The validity of the obtained OSL age is also confirmed by palaeomagnetic analysis\(^{20}\) carried out in the Baba Guruditta section. An aborted reversal (geomagnetic excursion) was discovered in this section at around 40 ka BP corresponding to globally-reported Laschamp excursion (details are found in Sangode et al\(^{20}\)).

The chronologically-based stratigraphic record provides an opportunity to reconstruct the evolution of flu-
vial deposits in Pinjaur Dun. The piedmont rivers characterized by sediment storage in the form of alluvial fans, incision and terrace construction, are in response to the prevailing climatic conditions and tectonics. In general, alluvial fans occur commonly at the base of uplifted mountain blocks. This suggests that the deposition of a series of alluvial fans in the Pinjaur Dun is an expression of tectonic uplift within the Sub Himalaya. The Nalagarh, Barsar and Bilaspur thrusts are within the Sub Himalaya, which probably controlled the deposition of alluvial fans in the piedmont zone with different facies.

The oldest OSL date (49.3 ± 7.7 ka BP) obtained from the exposed basal part of the Alowal litho-section indicates that the fan sedimentation probably started well before 57 ka BP (maximum age for the exposed section). It is envisaged that the sedimentation within the Dun valley probably started after the latest orogenic folding of frontal Himalaya and subsequent closing of sedimentation in the Siwalik basin in the Pleistocene (~200 ka). As the basal contact of the fan sediments with bedrock (Siwalik Group) was not encountered, a more thick succession of Quaternary Dun sediments may probably be concealed at present. The youngest date (24.4 ± 4.5 ka BP) obtained from the top of the alluvial fans indicates that the fan sedimentation started well before 57 ka BP and continued at least up to 20 ka BP. This indicates that deposition on alluvial fan has terminated before the global Last Glacial Maximum (20–16 ka BP). However, this is against Nakata’s assumption that the depositional and erosional phases occurred during glacial and interglacial periods, respectively.

Development of alluvial fans requires intense but infrequent precipitation to create flash-flood discharge needed for transporting sediments from the drainage basin to the fan site. The orientation of alluvial fans in the direction of modern piedmont rivers indicates that the piedmont rivers are the sole architecture of fan formation in the Pinjaur Dun. These piedmont rivers are mainly fed by rainwater and the water discharge is high, particularly during the monsoon period. The Himalaya is influenced by the SW monsoon in summer and the mid-latitude westerly in winter. During the rainy season, the enormous detritus material accumulated in the mountain canyon resulting from infrequent times of flow and long dry intervals, will be carried to the mountain front and its immediate deposition due to gradient change and unconfined of flow occurs. The deposition of fan sediments between 57 and 20 ka BP indicates intense precipitation, probably due to the SW monsoon, in the drainage basin of the Pinjaur Dun. Benn and Owen suggested that the observed glacial advances around 60–50 ka BP in the high-altitude western Himalaya reflect strong SW monsoon during this period. Conversely, glaciers in this region were less extensive during global glacial maxima due to weak SW monsoon. However, in some parts of Himalaya, glacial advances were in agreement with global glacial maximum.

However, the termination of fan deposition at around 20 ka BP indicates that the long-term development of alluvial fans almost ceased in this thrust belt-controlled Dun valley. The abrupt termination of fan deposition and the subsequent river incision and terrace formations may be related to fluviatile response to change in climate and/or tectonism. Some workers believe that tectonic disturbance is the most important reason for changes in alluvial fans, whereas others emphasize the importance of climatic control on the fan entrenchedment. Moreover, alluvial fans are deposited close to the source area along uplifted mountain ranges, they are particularly sensitive to tectonic activity, and their thickness is strongly influenced by tectonism. The tectonic disturbance can affect the fan deposition in two ways. In the first case, the rejuvenation of a marginal fault with a higher rate of river down-cutting can result in the fan head dissection and shifting of the locus of deposition. In the second case, the uplift of the drainage basin with a lesser degree of down-cutting can result in renewed aggradation and the deposition of younger segments close to the fan head. Until graded conditions are reached, erosion predominates along a mountain canyon and deposition on an alluvial fan can take place.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>$^{10}T_{1}$ (ppm)</th>
<th>$^{20}Th$ (ppm)</th>
<th>K (%)</th>
<th>Water content (%)</th>
<th>Dose rate (Gy/ka)</th>
<th>Equivalent dose (Gy)</th>
<th>Age (ka BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASN-T1</td>
<td>1.59 ± 0.77</td>
<td>12.05 ± 2.64</td>
<td>1.35</td>
<td>3.0</td>
<td>2.77 ± 0.27</td>
<td>136.4 ± 16.6</td>
<td>49.30 ± 7.7</td>
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<tr>
<td>ASN-T4</td>
<td>2.70 ± 0.70</td>
<td>6.47 ± 2.39</td>
<td>1.18</td>
<td>0.72</td>
<td>2.51 ± 0.26</td>
<td>61.6 ± 10.5</td>
<td>24.55 ± 4.9</td>
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<tr>
<td>LKK-T4</td>
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<td>11.70 ± 2.02</td>
<td>1.55</td>
<td>0.24</td>
<td>3.61 ± 0.29</td>
<td>99.3 ± 9.5</td>
<td>27.51 ± 3.43</td>
</tr>
<tr>
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<td>13.53 ± 3.43</td>
<td>1.68</td>
<td>0.62</td>
<td>3.62 ± 0.37</td>
<td>162.6 ± 25.7</td>
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</tr>
<tr>
<td>BGK-T1</td>
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<td>8.06 ± 3.65</td>
<td>1.75</td>
<td>3.97</td>
<td>3.26 ± 0.36</td>
<td>128.7 ± 8.9</td>
<td>39.51 ± 5.1</td>
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<tr>
<td>BGK-T5</td>
<td>2.05 ± 0.89</td>
<td>12.23 ± 3.06</td>
<td>1.43</td>
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<td>3.0 ± 0.32</td>
<td>113.7 ± 28.4</td>
<td>37.91 ± 10.3</td>
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<tr>
<td>DK-T4</td>
<td>2.42 ± 0.93</td>
<td>11.45 ± 3.18</td>
<td>1.48</td>
<td>1.52</td>
<td>3.10 ± 0.34</td>
<td>110.8 ± 22.9</td>
<td>35.78 ± 8.4</td>
</tr>
</tbody>
</table>

Table 1. Quartz GLSL ages for samples from the Lahund Khad and Kundlu Khad alluvial fans. $^{10}T_{1}$, $^{20}Th$, potassium and water content used for dose rate calculations and the obtained equivalent dose values are also given.
The steeper relief and uplifted sediments observed at the proximal part of the fans indicate neotectonic activity after the deposition of these fans. However, the absence of superimposed fans suggests that river downcutting is more than the uplift of the drainage basin. Moreover, the three levels of terrace formation within the incised fans, having oldest at the top and youngest at the bottom, and narrowing down of the river channels indicate that the river base is lowering with time. The river incision can be caused by rejuvenation of tec tonic activity along the HFF, south of the detached Siwalik Hills. No data are available regarding the upliftment of HFF, near Pinjaur Dun, but Steven et al. 31, based on uplifted terrace deposit along HFF near Mohand, Dehra Dun have indicated that the uplift rate along HFF is about 6.9 mm/yr.

The absence of a new active lobe in the downfan area indicates that the eroded fan sediments are passing into the Satluj river. However, the deposition of sediments in the terrace has occurred periodically. The non-deposition of sediments between 20 ka BP and the oldest terrace formation within the incised river valley may indicate decreased river discharge during this period. The available data on the variations of SW monsoon from the Arabian Sea and Bay of Bengal 32-35 indicate that during the Last Glacial Maximum (20–16 ka BP) the SW monsoon was weak, resulting in less sediment discharge from the Himalayan rivers. A weak SW monsoon indicates less sediment load and water discharge in the piedmont rivers. Prolonged fan entrenchment may result from decreasing sediment supply. This condition may have caused the non-deposition of fan materials. Although the SW monsoon reactivated after the glacial maximum, the confinement of the rivers coupled with the probable uplift and base level changes prevented any fan formations after 20 ka, and only terraces were formed. The dating of the terrace deposit can give valuable information regarding the uplift history as well as climatic fluctuations experienced in this basin.


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