Climate footprints in the Late Quaternary–Holocene landforms of Dun Valley, NW Himalaya, India

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The Himalayan mountain front is characterized by front parallel longitudinal valleys called Dun, that occupy the synformal troughs. The perennial glacial-fed rivers Ganga and Yamuna experience first major gradient loss along the valley floor of Dehra Dun and produce characteristic landforms and deposits by the gradational processes of streams that are often controlled by climate fluctuation. In Dun valley, barring an isolated patch of ~26 and 20-ka-old terrace, no strath terrace older than the Holocene is observed along the Ganga and Yamuna rivers. A large stretch of the Dun valley is being filled by piedmont deposits that started aggradation since >40 ka until the beginning of the Holocene and have since been undergoing incision. A similar trend is observed in upper Ganga valley, where multiple Late Quaternary aggradational terraces are observed. We analyse these landforms and associated deposits in the Dun valley to understand the role of Late Quaternary–Holocene climate fluctuations and their effect on associated gradational processes.

Keywords: Climate change, geomorphic landforms and deposits, gradational processes.

Introduction

THE topography of Himalaya originated and evolved as a result of collision and continued underthrusting of the Indian and the Asian plates causing stacking of crustal slabs of northern margin of the Indian plate since Eocene epoch. The Indian crust has exhumed along the south-propagating intra-crustal thrusts, namely the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT) with younging initiation ages from north to south[1,2] (Figure 1, inset). These intracrustal thrusts originating from the Himalayan décollement, divide the region into the following lithotectonic subdivisions, namely Tethyan Himalaya, Higher Himalaya, Lesser Himalaya and Sub Himalaya[1,2]. The Himalayan topography started developing during Miocene by rapid exhumation of Higher Himalaya that led to the growth of monsoon system in the Indian subcontinent[3]. During Late Quaternary period, the towering topography of Higher Himalaya (Figure 1) had witnessed extreme climate fluctuations with recurrent episodes of glaciation and warming, synchronous with the global events that affected the fluvial discharge and thereby the gradational processes, downstream towards south. During this period, the MBT–HFT bound Sub-Himalaya has remained tectonically the most active segment, where a series of front parallel synclinal troughs, defined as Dun, have developed due to the exhumation of frontal Siwalik belt along HFT[4–7]. These Duns with gentler slope in the Himalayan front are the locus of first major drop in stream gradient with wider valley floor and act as a repository to the climatic fluctuation in the form of geomorphic markers and associated deposits.

Dehra Dun in NW Sub-Himalaya is >80 km long NE–SW trending front-parallel intermontane valley (Figure 2) that occupies the synclinal trough[8,9]. The Dehra Dun valley was filled by post-Siwalik piedmont sediments and fluvial strath and fill terraces[8,9] during Late Quaternary–Holocene period. The piedmont sediments in this synclinal depression originate from the Lesser Himalayan range and the frontal Siwalik range, towards the north and the south respectively (Figure 3). The strath and fill terraces are produced by Ganga and Yamuna rivers. These glacial fed rivers drain across the eastern and western margin of the Dun valley. These two distinct sets of landforms and associated deposits provide a unique opportunity to explore the effect of regional fluctuating climate during Late Quaternary period and their imprints in the geomorphic record of the Dun valley in NW Himalaya.

Orographic condition of Ganga–Yamuna catchment region

The Ganga–Yamuna river system originates from an amalgam of glaciers in the Higher Himalayan region of Garhwal in NW Himalaya. Sharma and Owen[10] have

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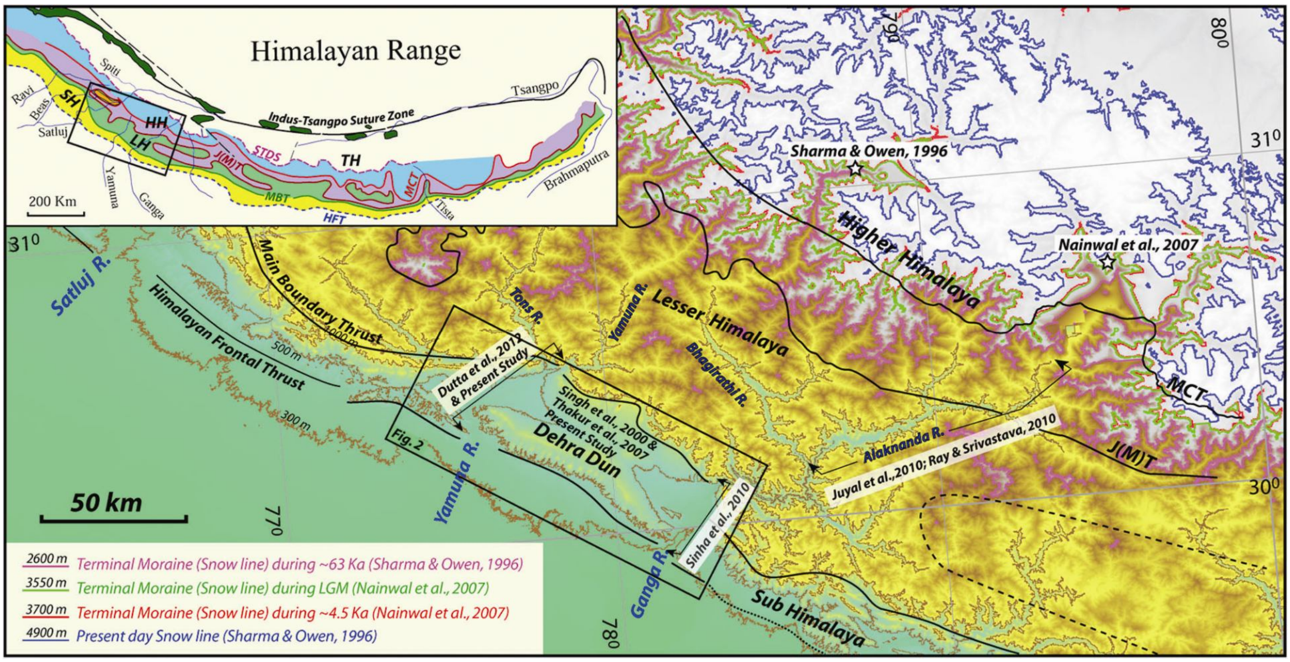

Figure 1. Generalized map of Himalaya showing different litho-tectonic subdivisions (inset). SRTM based 2D DEM of part on Garhwal Himalaya covering the Ganga–Yamuna catchment overlaid with broad tectonic boundaries, selected contours (300, 500, 1000 m) and the extent of terminal moraine of valley glaciers during ~63 ka (2600 m), LGM (3500 m), Mid-Holocene (3600 m), and present-day snowline (~4900). (SH, Sub Himalaya; LH, Lesser Himalaya; HH, Higher Himalaya; TH, Tethys Himalaya; HFT, Himalayan Frontal Thrust; MBT, Main Boundary Thrust; J(M)T, Jutogh (Munsiari) Thrust; MCT, Main Central Thrust; STDS, South Tibet Detachment System.)

mapped ~63-ka-old terminal moraine of Gangotri glacier at ~2600 m and a similar glacial advance has been mapped near Badrinath at ~2560 m by Nainwal *et al.*[11], suggesting the maximum glacial advance in the Garhwal region during that period[12]. The glacial advances have been mapped in the region during the Last Glacial Maxima (LGM) at ~3500 m, Mid-Holocene glacial event at ~3600 m and present-day snowline at ~4900 m (refs 10–12), but none reached the previous level of glacial advance ~63 ka ago. Based on the observed terminal moraines, a generalized snowline has been extrapolated giving a schematic view of the possible extent of glacial advance in the Ganga–Yamuna catchment region, during the Late Quaternary–Holocene period (Figure 1). The episodic, climatically controlled melting of these glaciers changed the discharge of the rivers Alaknanda and Bhagirathi that are the dominant tributaries of the Ganga. These perennially glacial-fed rivers descend >4000 m through the Higher Himalaya, Lesser Himalaya and Sub-Himalayan terrain to reach the Gangetic alluvium (Figure 1). These rivers have large catchment areas, fluvial discharge and bed load, which together control the growth and evolution of the landforms[13]. The Ganga system has larger catchment area, high discharge and relatively advanced base level towards north in comparison to the Yamuna system. During their descent from higher topography, they become an ideal gradational agent for producing the characteristic landforms and deposits along their course.

Late Quaternary–Holocene landforms in Dun valley

The front-parallel Dehra Dun is bordered to the north by Late-Proterozoic–Cambrian Lesser Himalaya along MBT and Lower Tertiary sedimentary sequence along MBF with ~2000 m average height of the summit. Towards south, the Dun valley is bordered by frontal Siwalik belt with <1000 m average summit height. The Dun valley is drained by several streams, namely Bata, Asan, Tons, Bindal, Suswa, Song, etc. which originate within the watershed of the valley (Figures 2 and 3); the large, glacier-fed perennial rivers – Ganga and Yamuna – cross Dun valley towards the eastern and western margins (Figures 1 and 2). These two different sets of rivers have different fluvio-dynamics owing to their size, catchment area, water and sediment supply and slope regime of the basin and thereby produce different landforms and deposits. Based on catchment characteristics and provenance, the Dun valley can be divided into two gradational regimes that are responsible for the growth of distinct landforms and associated deposits.

Piedmont deposits in Dun valley

The northern slope of Dun valley is covered with gravels forming large piedmont fans, namely Bhogpur, Principal Dun, Donga and Jamotwa–Amboya fans, from east to west, with radius measuring 10–18 km (Figures 2 and 3).

The crest of Principal Dun fan marks the water divide between Ganga and Yamuna catchment system in the Dun valley. The thickness of the gravels in the central part of the Dun varies from ~100 m in the proximal part to >300 m in the distal part[7,14]. The fans unconformably overlie the steeply dipping Siwalik bedrock and constitute fault-bound geomorphic surfaces, namely, dissected hills (~900 m height) with sparse gravel cover in the footwall of MBT (Figures 2 and 3), pedimented Siwaliks as well as isolated N–S trending hills of ~850 m summit height with thick gravel cover and the Younger Dun surface with height decreasing from ~750 to 450 m towards south[7,15] (Figure 2). The piedmont fans are highly entrenched with 50–200 m relative relief between river floor and surrounding hillocks of the Pedimented hills and Younger Dun surface. Further, the distal part of the fans terminate against axial drainage with ~10–15 m high scarps.

These geomorphic surfaces are best developed in the Donga Fan, where gravels have been categorized into different litho-units with distinct structural disposition. The Donga fan is bordered in the north by Lesser Himalaya, Lower Tertiary and Siwalik sequences, which act as provenance to the gravel in the fan. Three distinct gravel units, namely unit A, B, and C with increasing order of superposition were observed[14] (Figure 4 *a*). Unit A gravel is poorly sorted and fairly well consolidated conglomerate consisting of granular to pebble-sized clasts set in the fine-grained matrix with inter-layered sand and mudstone beds. The sand–mudstone beds have characteristic orange to rusty brown colour, suggesting multiple episodes of prolonged pedogenesis. The imbrication of clasts suggests fluvial transport from the Lesser Himalayan limestone and shale/slate and the Lower Tertiary purple and buff green sandstone provenance. Unit A shows characteristic tilting (dipping 15–65° due S–SW) with gentler dips towards south and is folded and faulted. Unit A yielded 35.4 ± 7.3 to 33.6 ± 4.7 ka OSL ages in the Donga fan. It unconformably overlies the steeply dipping overturned Siwaliks[7]. The overlying unit B is characterized by unconsolidated, clast-supported conglomerate, which gradually becomes matrix-supported in the distal part. It has predominance of rounded to subrounded boulders and pebbles, largely of quartzite and sandstone (Figure 4 *a*), mainly derived from the Upper Siwalik Boulder Conglomerate Formation in the dissected Siwalik zone. Unit B has yielded 29.4 ± 1.7 to 20.5 ± 1.7 ka OSL ages[7,16]. The youngest unit C is a gravel composed of poorly sorted sub-angular to sub-rounded granules and pebbles with occasional boulders. Thick lenses 0.5–1 m and discontinuous beds of sand and silt are noted in this unit, which increase towards the distal part of the fan. The sand layers of unit C from the Donga fan have yielded OSL ages between 22.8 and 10.7 ka (refs 7 and 16). The top of unit C, constituting the younger fan surface, suggests the last aggradation phase of the piedmont fans and final peneplanation phase of the piedmont fans before Holocene.

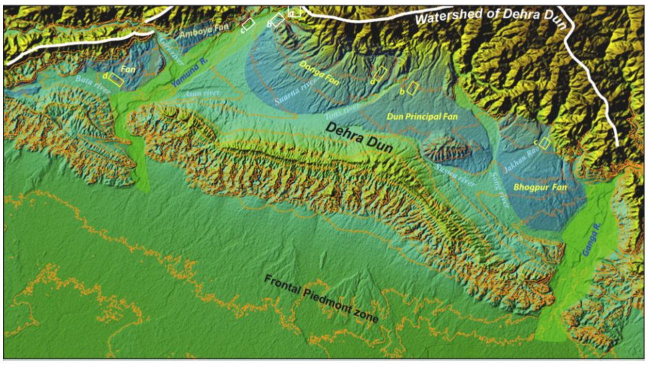

Figure 2. SRTM-based DEM of Dehra Dun valley showing spatial disposition of different Late-Quaternary–Holocene landforms. Note the catchment area for the piedmont fans and the location of field observations (yellow box, Figure 4, Piedmont fans and white box, Figure 5, Strath and fill terrace of Yamuna river).

In the Dun Principal fan, the unit A gravel is underlain by calcareous conglomerate constituted of quartzite, sandstone, shale and limestone clasts in calcareous cement (Figure 4 *b*). The carbonate clasts are derived from the Precambrian limestone of Lesser Himalaya. The thickness of this cemented conglomerate decreases to ~1 m in the Nagsidh hill. The gravel of unit A has yielded 40.3 ± 3.9 ka OSL age[16] in the Dun Principal fan, suggesting >40 ka age for the cemented conglomerate.

The Bhogpur Fan, Jamotwa–Amboya Fan and other trans-Yamuna fans show continuous deposition with little lithological variation (Figure 4 *c* and *d*) and have yielded 30.2 ± 2.5 ka (ref. 16) and 33.93 ± 3.99 to 19.02 ± 2.39 ka (ref. 17) ages for the eastern and western part of the Dun valley respectively. Further, an apron of unconsolidated conglomerate, constituted of unsorted quartzite pebbles derived from Upper Siwalik Boulder Conglomerate is observed over north-dipping hogback of frontal Siwalik range. This has yielded 30.0 ± 2.0 ka OSL age[7]. Similar ages and general characteristics of piedmont gravel, throughout the Dun valley, suggest continuous synchronous fan aggradations events during the Late Quaternary (>40–10 ka) period.

Strath and fill terraces

The River Ganga with a larger catchment, fluvial discharge and bed load, enters the Dun valley at a lower immediate base level of ~350 m; whereas the smaller Yamuna river enters the valley at an immediate base level of ~530 m (Figures 1 and 2). Four levels of unpaired and paired strath terraces (T4–T1), formed during 11–2 ka, are mapped along the Ganga and Yamuna rivers in the Dun valley[16,18,19] (Figures 2, 3 and 5). Two levels of older terraces formed during ~26 and 20 ka are also observed

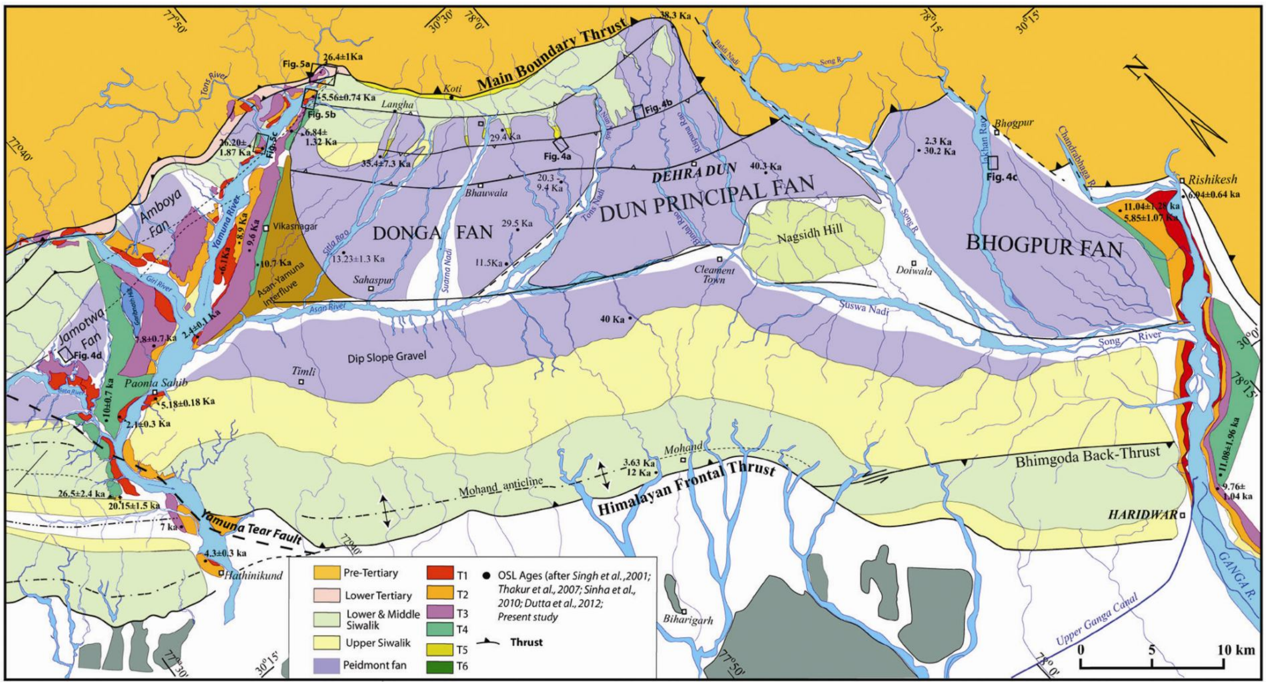

Figure 3. Geological and geomorphic land cover map showing distribution of the Siwaliks and post-Siwalik gravels in the Dehra Dun. Note the location of field observations marked as box.

along Yamuna river[19]. The terraces are mostly constituted of subrounded pebble sized conglomerates, which are matrix to clast supported, poorly stratified with intermittent sand and mud beds suggesting deposition in active channel during waning flow[20]. The strath and fill terraces have developed over bedrock, as well as on the piedmont fans (Figure 5). The piedmont fans at places resemble terrace deposits owing to similar lithology and fabric. Different terrace levels along River Yamuna show spatial variation in age of aggradation, e.g. T4–T1 terraces on the eastern bank of the Yamuna yielded ages ranging from 10.7 ± 2.2 to 6.1 ± 1.2 ka (ref. 16), whereas at other locations these terrace levels correspond to ~10, ~7.8, 5.8–4.3 and ~2 ka (Figure 3). The unpaired terraces on opposite banks of the river indicate channel migration (Figure 5 *a*) and at places the younger terraces occur at a higher relative relief, suggesting unequal uplift/incision of the valley floor along the active structures. In general, the terraces from T4 to T1 show decreasing age, relief and narrowing flood plain from ~5 km during T4 to < 2 km in the Recent (Figures 2, 3 and 5 *a*). This suggests continuous incision in response to the base-level change that may be controlled by fluviodynamics of incising rivers, i.e. carrying capacity, bed load and gradient. The base-level change may be correlated with the climate fluctuation or tectonic uplift of the Dun valley floor or a combination of both.

Fluvial terraces in the upper Ganga valley

Since the landform in Dun valley has resulted in response to the water discharge and bed load from the upstream, it is imperative to understand the Late Quaternary history of Upper Ganga and Yamuna river sections. There is not much data on the Late Quaternary landform evolution along the River Yamuna, but some studies along the Ganga river and glaciers in the catchment region[10–12,21,22] provide reasonable constraints for the correlation with the Dun valley. The mapping and dating of the strath and fill terraces along the Alaknanda river (Figure 6) suggest a series of aggradational phases, that correlate with the fluctuating climate during the Late Quaternary period[21,22]. Juyal *et al.*[21] have identified >45, ~26, 18 and 15–8 ka aggradation events and <18–>15 ka and 8–6 ka incision events; whereas Ray and Srivastava[22] suggested two aggradation phases at 49–25 ka and 18–11 ka followed by rapid incision post 11 ka.

Discussion

Active tectonics

Seismically active Himalaya mountain belt is also affected by Late Quaternary climate cycles causing extreme variation in gradational potential of fluvial regime. The strain rate of Indian plate suggests Himalaya is expected to witnesses great earthquakes every 500–1000 years (ref. 23). These great earthquakes produce surface rupture in Sub-Himalayan belt causing episodic exhumation of the frontal belt along HFT forming Duns in the Sub Himalaya[7]. A very high incision rate of ~9.5 mm/yr is observed in the hanging wall of HFT along Ganga river near Haridwar[18] and ~6.9 mm/yr near Mohand[24], suggesting enhanced localization of tectonic incision. The piedmont

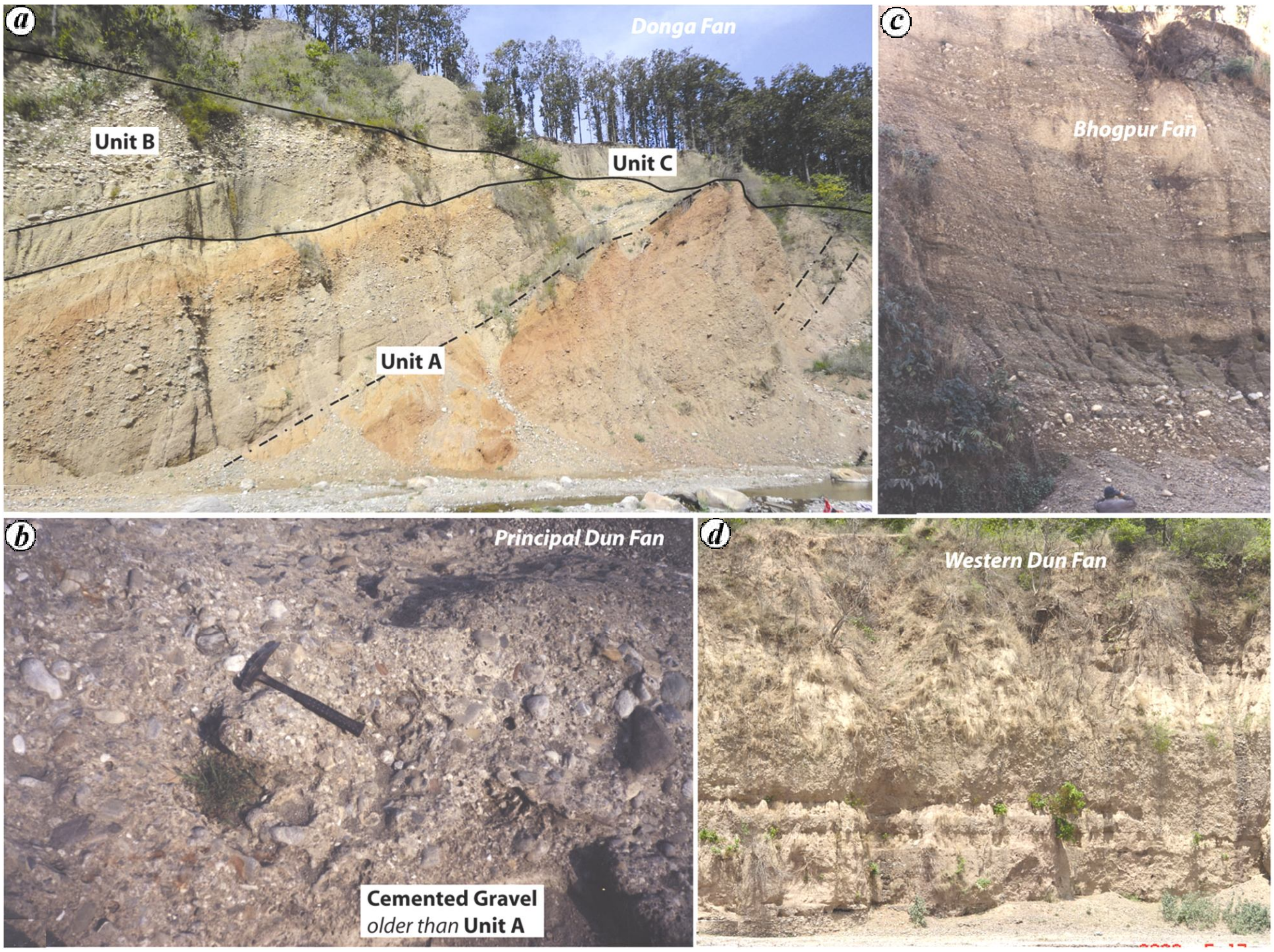

Figure 4. Different litho-units of the piedmont gravels in the Dun valley. ***a***, Stratigraphic disposition of different gravel units A–C in the Donga Fan. ***b***, Cemented gravel in the Principal Dun Fan that lies below unit A of Donga Fan gravel. ***c***, ***d***, Continuous sedimentation in Bhogpur and western fans without significant lithological variation.

fans and Ganga–Yamuna valley floor show continuous incision during Holocene in the Dun valley. The valley floor incision rate along Yamuna river is of the order of ~2 mm/yr (ref. 16). This incision is driven by exhumation of basin floor in response to active tectonics of Dun[7–9,14,15] to maintain the base level. In such an active terrain, the formation of extensive strath and fill terraces requires high fluvial discharge and sediment load in the stream.

Climate response

The fluvial discharge is directly associated to the monsoon intensification and deglaciation, causing variation in erosion and aggradation. It is therefore imperative to understand Late Quaternary–Holocene fluctuation in the summer monsoon intensity and glaciation in the region. In the upper Alaknanda basin of Garhwal Himalaya, three stages of glaciation are identified[11]. The stage I glaciation was the most extensive with glacier advance up to ~2600 m and occurred prior to LGM. A similar glacier advance is observed in Gangotri, where the ~63-ka-old terminal moraine is mapped at ~2650 m elevation[10]. Stages II and III correspond to LGM and Mid Holocene (~4.5 ka) glaciation when the snowline advanced to ~3550 and 3700 m respectively (Figures 1 and 6). The enhanced glacier advance during ~63 ka glaciation in comparison to LGM is possibly related to the far superior monsoon precipitation during Marine Isotope Stage (MIS)-3 in South Asia[12,25]. The weaker monsoon and lower insolation during LGM at around 18 ka are also observed in other independent proxies, including data from paleolake levels[26–28], pollen profiles[29–31] and deep-sea cores[32,33]. Clay mineralogy of the core samples from western Indian margin also observed two discrete humid events at 28 and 22 ka BP interrupting LGM[34]. An early strengthening of summer monsoon is observed between 15.7 and 14.8 ka BP (ref. 34) and during ~16,000 ± 150 calendar yrs BP (refs 35 and 36) as well as an early Holocene monsoon intensification during 11,600–8,600 calibrated yrs BP in the Arabian Sea.

Figure 5. Strath terraces along river Yamuna in Dun valley. ***a***, Panoramic view of River Yamuna showing different levels of strath and fill terraces. Also note the channel migration. ***b***, Four levels of strath terrace developed over the piedmont fan of tributary river. ***c***, Four levels of strath terraces observed in true colour *Google* Image (www.earth.google.com) overlaid with contours generated from SRTM data. Note the varying OSL ages from T2 terrace[19] showing the terrace age in (***b***) and the piedmont fan gravel substrate (***c***).

Juyal *et al.*[21] have attributed the formation of the oldest depositional landforms in the Alaknanda valley to rainfall-induced failure of slopes forming debris flows prior to 45 ka during MIS-3. The subsequent aggradations during 26, 18 and 15–8 ka corresponds to the transition from MIS-3 to MIS-2, the LGM and the younger Dryas (YD) respectively[21]. However, aggradation phases between 49–25 ka and 18–11 ka correspond with the two phases of

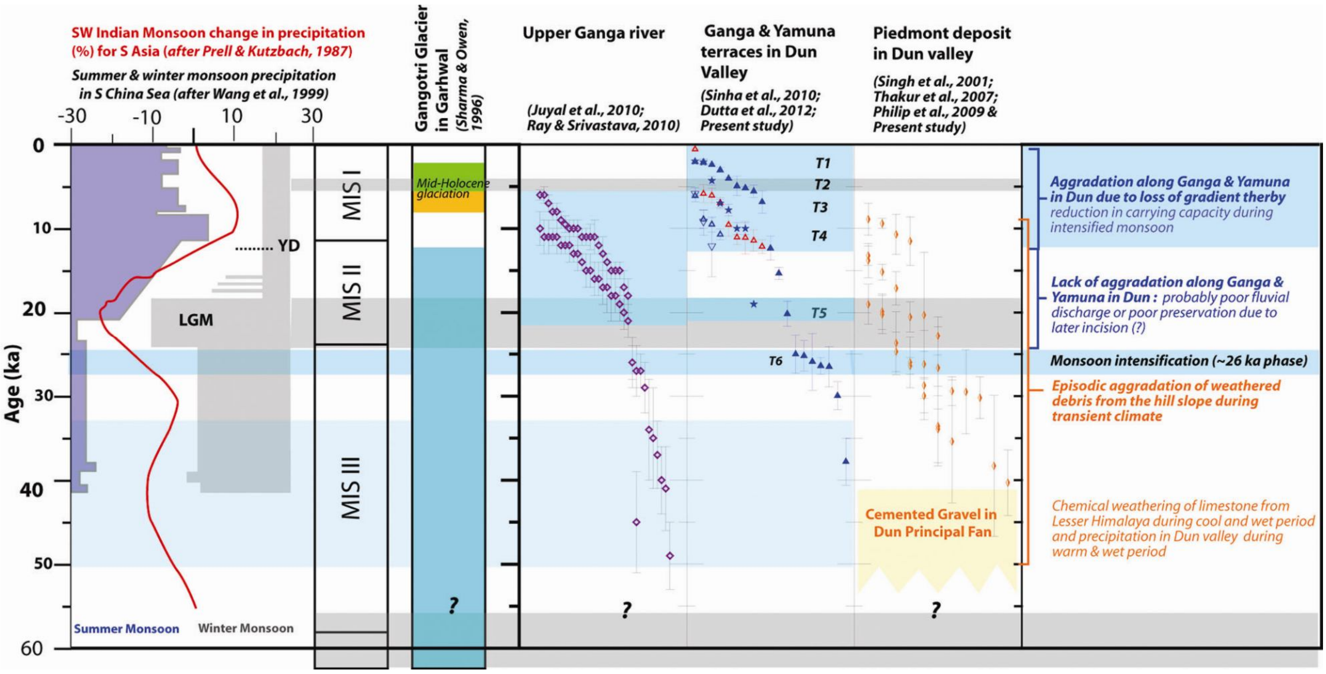

Figure 6. Schematic model showing age distribution of different strath and fill (aggradation) terraces[18,19] and piedmont fans in the Dun valley[7,16,17] of NW Himalaya. The ages of aggradation terraces along the upper Ganga valley[21,22], glaciations phase in Gangotri glacier[10], SW Indian monsoon change in precipitation (%) for South Asia[27], and summer and winter monsoon precipitation in the South China Sea during Late Quaternary[41] are overlaid for correlation with the observed data in the Dun valley.

deglaciation causing increased sediment supply[22]. The incision phases between 18 and 15 ka and 8 and 6 ka (ref. 21) and post-11 ka (ref. 22) are correlated with the strengthened monsoon, increased precipitation and fluvial discharge.

The above analogy may hold good for the upper Ganga valley, which lies close to the source of fluvial discharge that affected the carrying capacity, but none of the aggradation phases up to Holocene is observed in the Dehra Dun valley (Figures 3 and 6), barring the isolated patch of ~26 and ~20 ka terraces in the Yamuna valley[19] (Figure 3). These isolated aggradation phases in Dun valley correspond to the period of unusually high fluvial aggradation at an interval of intensified monsoon phase during 29–24 ka (ref. 37). The sporadic availability of pre-Holocene aggradation phase of Ganga and Yamuna rivers in the Dun valley also suggests that these phases might have been lost due to subsequent erosion. Further, the intensified monsoon during Holocene caused degradation and incision in the upper Ganga and Yamuna valleys due to excess fluvial discharge with higher carrying capacity. The carrying capacity of rivers is reduced in the Dun valley, owing to low gradient and increasing distance from the source of fluvial discharge (Figure 1). This led to the fluvial aggradation along the Ganga and Yamuna rivers in the Dun valley.

However, during the Holocene, the piedmont zone of Dun valley experienced incision (Figure 2), which is caused by intensified rainfall in the catchment area aided by steep gradient and steady tectonic exhumation of the valley floor. The Dun valley experienced piedmont fan growth during >40–10 ka (Figure 6) representing multiple phases of alluvial aggradation during dry to wet transient climate. The transient climate facilitates hill-slope erosion by landslides that accelerate sediment supply to the main streams, leading to the valley floor aggradation with increased precipitation[37–40]. The poorly sorted, subrounded to angular clasts of Dun gravels, with provenance from immediate catchment region (Figure 4), clearly point towards short-distance mass movement. After the short-lived transient period, the valley slope attained equilibrium leading to fine-grained sediment aggradation and soil formation (Figure 4 *a*) with reduced sediment flux from the hill slope. These pedogenic surfaces are not uniformly developed in different fans throughout the valley. Therefore, it is difficult to interpret the effect of climate during aggradational phases of complete piedmont fan sequences. The unconformable contact and superposition pattern of different gravel units (A, B and C in Donga fan) explain changing provenance and aggradation pattern, which is explained by active intra-wedge deformation and thrust–fold growth within Dun[7,14]. Further, the occurrence of cemented gravel beneath unit A in the Dun Principal Fan suggests similar aggradation of gravel during a short episode of transient climate followed by cool and wet period, during which the chemical weathering (dissolution) of calcite occurred in the Lesser Himalayan limestone provenance. Calcite exhibits an unusual characteristic called retrograde solubility in which it becomes less soluble in water as the temperature increases. When conditions are right for precipitation, calcite forms mineral coatings that cement the existing rocks in available pore space and fractures. Calcite precipitated over the gravel sequence in Dun valley at lower elevations with an increase in temperature. Since this happened prior to 40 ka, we speculate it may be synchronous with or immediately followed the ~63 ka cool and wet period, during which the glacial advance was maximum in Garhwal Himalaya[10].

Conclusion

The Dun valley preserves two prominent landforms with distinct fluvio-dynamics responsible for their growth and evolution. The strath and fill terraces developed during Holocene along Ganga and Yamuna rivers along with a couple of isolated ~26 and ~20-ka-old terraces in the Yamuna valley. These aggradation phases correspond to the phase of deglaciation and intensification of summer monsoon when the streams with high discharge lose carrying capacity owing to the low gradient of the basin floor in Dun valley. However, the piedmont fans in the valley experienced incision possibly due to high fluvial discharge and steeper gradient of youngest piedmont fan surfaces. The piedmont fan growth took place due to episodic aggradation of weathered debris from the hill slope during transient climate (from dry to wet) causing increased sediment supply during >40 to ~10 ka. The cemented gravel with calcareous cement in the Principal Dun Fan, possibly the oldest piedmont sediment, indicates that cementing calcium carbonate was derived from Lesser Himalayan limestone during a cool, wet phase and precipitated over the Fan during a warmer phase of the transient climatic episode. The observation clearly suggests an important role of intensified monsoon phase in sediment aggradation and landform evolution aided by increased fluvial discharge, carrying capacity and basin floor gradient of the river.

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1. Valdiya, K. S., *Geology of Kumaun Lesser Himalaya*, Wadia Institute of Himalayan Geology, Dehra Dun, 1980, p. 291.
2. Thakur, V. C., *Geology of Western Himalaya*, Pergamon Press, Oxford, 1992.
3. Molnar, P. and Rajagopalan, B., Late Miocene upward and outward growth of eastern Tibet and decreasing monsoon rainfall over the northwestern Indian subcontinent since 10 Ma. *Geophys. Res. Lett.*, 2012, **39**, L09702, doi: 10.1029/2012GL051305.
4. Valdiya, K. S., The main boundary thrust of Himalaya, India. *Ann. Tecton.*, 1992, **6**, 54–84.
5. Valdiya, K. S., Reactivation of terrain-defining boundary thrusts in central sector of the Himalaya: implications. *Curr. Sci.*, 2001, **81**, 1418–1430.
6. Yeats, R. S., Nakata, T., Farah, A., Fort, M., Mirza, M. A., Pandey, M. R. and Stein, R. S., The Himalayan Frontal Fault system. *Ann. Tecton.*, 1992, **6**, 85–98.
7. Thakur, V. C., Pandey, A. K. and Suresh, N., Late Quaternary–Holocene evolution of Dun structure and Himalayan Frontal Fault zone of Garhwal Sub Himalaya, NW India. *J. Asian Earth Sci.*, 2007, **29**, 305–319.
8. Nossin, J. J., Outline of the geomorphology of the Doon valley, northern UP, India. *Z. Geomorphol.*, 1971, **12**, 18–20.
9. Nakata, T., Geomorphic history and crustal movements of the foothills of the Himalaya. In Report of Tohoku University, Japan, 7th Series (Geography), 1972, vol. 2, pp. 39–177.
10. Sharma, M. C. and Owen, L. A., Quaternary glacial history of the Garhwal Himalaya, India. *Quaternary Sci. Rev.*, 1996, **15**, 335–365.
11. Nainwal, H. C., Chaudhary, M., Rana, N., Negi, B. D. S., Negi, R. S., Juyal, N. and Singhvi, A. K., Chronology of the Late Quaternary glaciations around Badrinath (upper Alaknanda basin): preliminary observations. *Curr. Sci.*, 2007, **93**(1), 90–96.
12. Owen, L. A., Caffee, M. W., Finkel, R. C. and Seong, B. S., Quaternary glaciation of the Himalayan–Tibetan orogen. *J. Quaternary Sci.*, 2008, **23**, 513–532.
13. Bull, W., *Geomorphic Response to Climatic Changes*, Oxford University Press, 1991, p. 326.
14. Thakur, V. C. and Pandey, A. K., Late Quaternary tectonic evolution of Dun in fault bend/propagated fold system, Garhwal Sub-Himalaya. *Curr. Sci.*, 2004, **87**(11), 1567–1576.
15. Thakur, V. C. and Pandey, A. K., Active deformation in Himalayan Frontal Thrust and Piedmont zone south of Dehradun in respect of seismotectonics of Garhwal Himalaya. *Himalayan Geol.*, 2004, **25**(1), 23–31.
16. Singh, A. K., Prakash, B., Mohindra, R., Thomas, J. V. and Singhvi, A. K., Quaternary alluvial fan sedimentation in the Dehradun valley piggyback basin, NW Himalaya: tectonic and paleoclimatic implications. *Basin Res.*, 2001, **13**, 449–471.
17. Philip, G., Virdi, N. S. and Suresh, N., Morphotectonic evolution of Parduni basin: an intra dun piggyback basin in western Doon Valley, NW Outer Himalaya. *J. Geol. Soc. India*, 2009, **74**, 189–199.
18. Sinha, S., Suresh, N., Kumar, R., Dutta, S. and Arora, B. R., Sedimentologic and geomorphic studies on the Quaternary alluvial fan and terrace deposits along the Ganga exit. *Quaternary Int.*, 2010, **227**, 87–113.
19. Dutta, S., Suresh, N. and Kumar, R., Climatically controlled Late Quaternary terrace staircase development in the fold- and -thrust belt of the Sub Himalaya. *Palaeogeogr.*, *Palaeoclimatol.*, *Palaeoecol.*, 2012, **356–357**, 16–26.
20. Collinson, J. D., Alluvial sediments. In *Sedimentary Environments and Facies* (ed. Reading, H. G.), Blackwell Scientific, Oxford, 1986, pp. 20–62.
21. Juyal, N., Sundriyal, Y. P., Rana, N., Chaudhary, S. and Singhvi, A. K., Late Quaternary fluvial aggradation and incision in the monsoon-dominated Alaknanda valley, Central Himalaya, Uttarakhand, India. *J. Quaternary Sci.*, 2010, **25**, 1293–1304.
22. Ray, Y. and Srivastava, P., Widespread aggradation in the mountainous catchment of the Alaknanda–Ganga River System: timescales and implications to hinterland–foreland relationships. *Quaternary Sci. Rev.*, 2010, **29**(17), 2238–2260.
23. Bilham, R., Gaur, V. K. and Molnar, P., Himalayan seismic hazard. *Science*, 2001, **293**, 1442–1444.
24. Wesnousky, S. G., Kumar, S., Mohindra, R. and Thakur, V. C., Uplift and convergence along the Himalayan Frontal Thrust of India. *Tectonics*, 1999, **18**, 967–976.
25. Prell, W. L. and Kutzbach, J. E., Monsoon variability over the past 150,000 years. *J. Geophys. Res.*, 1987, **92**, 8411–8425.
26. Street, F. A. and Grove, A. T., Global maps of lake-level fluctuations since 30,000 yr BP. *Quaternary Res. N.Y.*, 1979, **12**, 83–118.
27. Street-Perrott, F. A. and Roberts, N., Fluctuations in closed-basin lakes as an indicator of past atmospheric circulation patterns. In *Variations in the Global Water Budget* (eds Street-Perrott, F. A., Beran, M. A. and Ratcliffe, R. A. S.), 1983, pp. 331–345.

28. Street-Perrott, F. A. and Harrison, S. P., Temporal variations in lake levels since 30,000 yr BP – an index of the global hydrological cycle. In *Climate Processes and Climate Sensitivity*, *Geophysical Monograph, 29* (eds Hansen, J. E. and Takahashi, T.), American Geophysical Union, Washington, DC, 1984, pp. 118–129.
29. van Campo, E., Duplessy, J. C. and Rossignol-Strick, M., Climatic conditions deduced from a 150-kyr oxygen isotope–pollen record from the Arabian Sea. *Nature*, 1982, **296**, 56–59.
30. Bryson, R. A. and Swain, A. M., Holocene variations of monsoon rainfall in Rajasthan. *Quaternary Res. N.Y.*, 1981, **16**, 135–145.
31. Swain, A. M., Kutzbach, J. E. and Hastenrath, S., Monsoon climate of Rajasthan for the Holocene; Estimates of precipitation based on pollen and lake levels. *Quaternary Res. N.Y.*, 1983, **19**, 1–17.
32. Prell, W. L., Variation of monsoonal upwelling; a response to changing solar radiation. In *Climate Processes and Climate Sensitivity*, AGU, Geophys. Monogr. Set., 29, Washington, DC, 1984.
33. Prell, W. L., Monsoonal climate of the Arabian Sea during the late Quaternary; a response to changing solar radiation. In *Milankovitch and Climate* (eds Berger, A. *et al.*), 1984, pp. 349–366.
34. Thamban, M., Rao, V. P. and Schneider, R. R., Reconstruction of late Quaternary monsoon oscillations based on clay mineral proxies using sediment cores from the western margin of India. *Mar. Geol.*, 2002, **186**, 527–539.
35. Sirocko, F., Sarnthein, M., Erlenkeuser, H., Lange, H., Arnold, M. and Duplessy, J. C., Century-scale events in monsoonal climate over the past 24,000 years. *Nature*, 1993, **364**, 322–324.
36. Sirocko, F. *et al.*, Teleconnections between the subtropical monsoons and high latitude climates during the last deglaciation. *Nature*, 1996, **272**, 526–529.
37. Bookhagen, B., Thiede, R. C. and Strecker, M. R., Late Quaternary intensified monsoon phases control landscape evolution in the NW Himalaya. *Geology*, 2005, **33**, 149–152.
38. Schmidt, K. M. and Montgomery, D. R., Limits to relief. *Science*, 1995, **270**, 617–620.
39. Pratt, B., Burbank, D. W., Heimsath, A. and Ojha, T., Impulsive alleviation during early Holocene strengthened monsoon, central Nepal Himalaya. *Geology*, 2002, **30**, 911–914.
40. Pratt-Sitaula, B., Burbank, D. W., Heimsath, A. and Ojha, T., Landscape disequilibrium on 1000–10,000 year scales Marsyandi River, Nepal, Central Himalaya. *Geomorphology*, 2004, **58**, 223–241.
41. Wang, L. *et al.*, East Asian monsoon climate during the Late Pleistocene: high-resolution sediment records from the South China Sea. *Mar. Geol.*, 1999, **156**, 245–284.

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