

Evolution of the Quaternary alluvial fan system in the Himalayan foreland basin: Implications for tectonic and climatic decoupling

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Abstract

The Quaternary evolution of an alluvial fan system in the Himalayan foothills reveals two distinct phases. The Early Quaternary Siwalik system (I) and the Late Quaternary intramontane piggy-back system (II) have been studied in detail in the Subathu sub-basin of NW Himalaya (with system I followed by system II). Sedimentary architecture and facies analysis from chronologically constrained sections (using magnetostratigraphy and TL/OSL) indicate that systems I and II, although developed in similar hinterland-basin settings, indicate contrasting aggradation and entrenchment.

System I is characterised by predominant fan aggradation, in contrast to the variable aggradation—entrenchment response in time and space for system II. System I is time transgressive laterally from east to west with the central part remaining as the uplifted inter-fan domain. Further confinement of system I along the basin margin indicates its syn-orogenic evolution linked to the intra-foreland thrusting. This continued with the formation of the piggy-back basin of system II.

Glacial–interglacial cycles influenced the evolution of both alluvial fan systems. However, greater sediment yield and larger accommodation space favored aggradation during system I. In contrast in System II, insufficient accommodation space relative to sediment yield and ongoing upliftment (and reduced subsidence) resulted in aggradation at the fan head during incessant precipitation, followed by entrenchment during low precipitation. The latest phase, Late Quaternary to Recent, is characterised by two level terraces (at ca. 16 and 5 ka) within the entrenched streams, due to variation in water budget and sediment load governed by glacial–interglacial cycles. This study thus demonstrate the variable importance of accommodation space, base-level change and magnitude of tectonic and climatic forcing as controlling factors on aggradation and entrenchment in Quaternary alluvial fan systems of the Himalayan foreland basin.

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1. Introduction

The Quaternary period is considered as the interval of climatic oscillations (glacial and interglacial) coupled with tectonic episodes. Therefore, tectonics and climate have simultaneously governed the evolution of Quaternary alluvial fans (Ritter et al., 1995; Viseras et al., 2003). Unraveling the tectonic and climatic factors under varied depositional systems is therefore the fundamental issue in understanding the evolution of Quaternary alluvial fans.

Tectonism is considered to be of prime importance in controlling alluvial fan sedimentation in active orogenic belts (e.g. Steel et al., 1977; Heward, 1978; DeCelles et al., 1991; Gupta, 1997; Kumar et al., 2002). On the other hand, the mobility and supply of sediments from catchment to

the basin and the sediment:water ratio are the key factors controlling the process-based mechanism of debris-flow or sheet flood deposition (Wells and Harvey, 1987). Harvey (1984, 1996) reported that major periods of fan aggradation in Spain coincide with Quaternary cold phases, and dissection with periods of lower sediment supply during the warmer phases. Viseras et al. (2003) emphasized the role of base-level change and differential basin subsidence for fan aggradation and entrenchment. Base-level change either in response to tectonics or climate might cause fan incision. However, the tectonically induced base-level changes are temporally independent of climate changes and may show spatial variability (Harvey, 2002).

Quaternary alluvial fan deposits in the Himalayan foreland basin are ideal for understanding the role of tectonics versus climate on alluvial fan sedimentation, as this region has been influenced by both factors to varying degrees (Nakata, 1972; Ruddiman et al., 1989; Valdiya,

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1992, 1993; Singh et al., 2001; Goodbred, 2003; Srivastava et al., 2003; Gibling et al., 2005; Sinha et al., 2005). Major tectonic deformation during the Middle Pleistocene has resulted in the initiation of the Himalayan Frontal Thrust (HFT, Raiverman, 2002). It is the outermost and youngest boundary thrust demarcating the sub-Himalaya from the Indo-Gangetic Plains. The fault-bend folding due to HFT resulted in the cessation of the Siwalik sedimentation (Middle Miocene to Late Pleistocene) creating several intramontane piggy-back basins that received the latest Pleistocene sediments in the Himalayan foothills. The Early Pleistocene deposits of the Siwalik Group have undergone comparatively higher tectonic deformation and are tilted either to the north or south, with varying amounts of dip. Significantly large volumes of sediments have thus been accommodated in the piggy-back basins which have remained largely undeformed since the Late Pleistocene. Thus, the Quaternary sedimentation in the Himalayan foreland basin can be divided into two realms: (I) Early Quaternary Siwalik sediments and (II) Late Quaternary (post-Siwalik) intramontane piggy-back sediments on the folded Siwalik basin floor (with angular unconformity), known as the Dun sediments.

Quaternary deposits, in the form of alluvial fans and other fluvial depositional units, are common in the entire Himalayan foothills, forming in smaller adjunct basins such as Subathu and Dehra Dun (Fig. 1). In the Subathu sub-basin, the Early Quaternary sedimentary succession (Fig. 2(b) and (c)), described here as system I, formed between 1.8 and 0.25 Ma (Tandon et al., 1984; Sangode et al., 1996, Kumaravel et al., 2005). Depositional landscapes of coalescing alluvial fans (bajada or piedmont) formed along the basin margin (Kumar and Tandon, 1985; Kumar et al., 1999). These fans were formed in response to hinterland deformation and basinward thrust migration (Kumar et al., 2002; Raiverman, 2002).

The sheet geometry of the conglomerates and the absence of paleosols (Kumar et al., 1999) indicate that no fan entrenchment occurred during the formation of system I. In contrast, the Late Quaternary post-Siwalik alluvial fans (Fig. 2(a)) show both aggradation and entrenchment related to tectonic and climate variations (Nakata, 1972, 1989; Suresh et al., 2002). Both fan systems have similar source area lithology, hinterland tectonic setting, lithofacies and proximal to distal variation, and similar drainage patterns (from confined to unconfined channel systems).

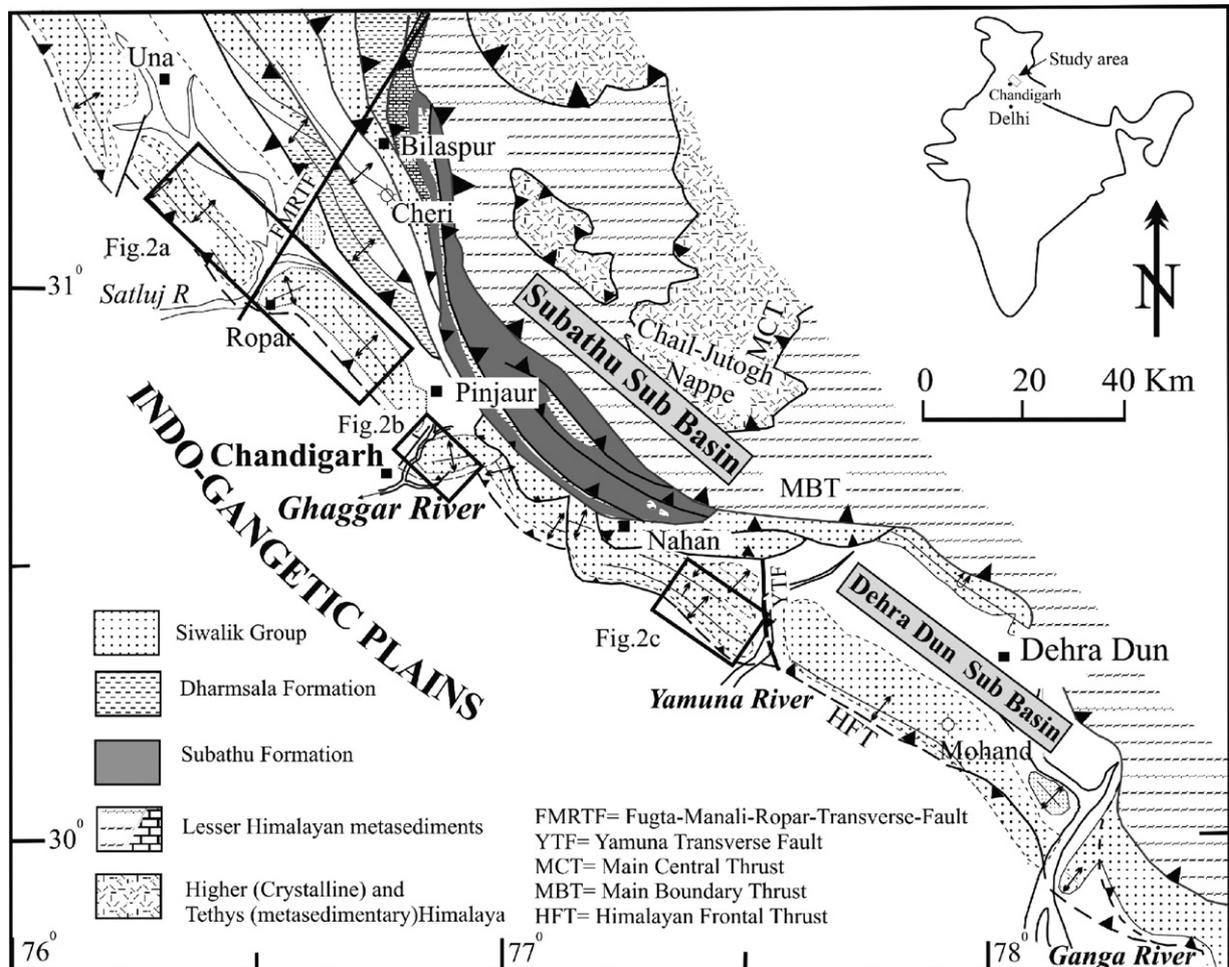


Fig. 1. Simplified Geological map of northwestern part of the Himalayan foreland basin showing different lithostratigraphy and tectonic units (adopted from Kumaravel et al., 2005). Location of studied area is marked by rectangles.

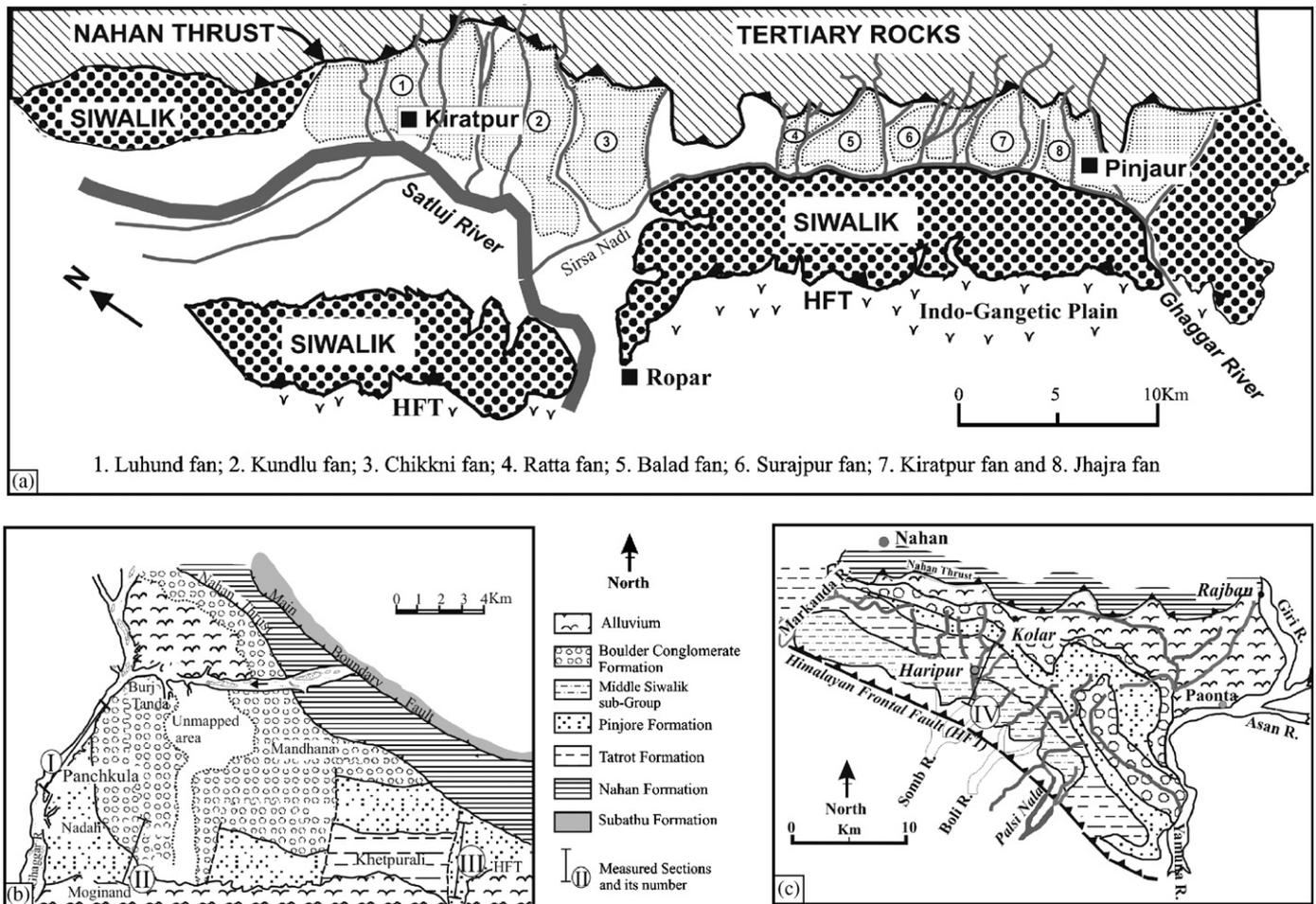


Fig. 2. Detailed geological maps of the studied areas. (a) Pinjaur piggy-back basin (after Suresh et al., 2002); (b) Ghagger area (after Kumar and Tandon, 1985) and (c) Haripur area (after Kumar et al., 1999).

However, the Siwalik fan system is developed in a basin bordered by hinterland thrusting, compared to the system II fans that developed in a basin bounded by both hinterland and frontal thrusting with anticlinal backs.

The Ganga basin south of HFT provides another good example to study the modern response to tectonic/climate activity, although its hinterland is far more extensive. Various time equivalent aggradation and incision phases are reported in this basin, controlled by climate (Shukla et al., 2001; Gibling et al., 2005; Sinha et al., 2005) and tectonics (Aggarwal et al., 2002; Srivastava, et al., 2003). Goodbred (2003) inferred that sediment dispersal in the Ganga plain is chiefly governed by the SW monsoon. The Quaternary records in the Himalayan foothills are little explored in light of the records from the Ganga basin.

Therefore, this paper attempts to document the causative factors of the difference in the evolution between the two Quaternary alluvial fan systems (Siwalik and post-Siwalik) in the Himalayan foothills focusing on responses to tectonics and climate. These studies also provide a link to the modern records of the Ganga basin to south. The Subathu sub-basin was selected for the following reasons: (1) good quality exposures for both Siwalik and post-

Siwalik sediments; (2) both fan systems are well constrained in relation to other basins using magnetostratigraphy (Tandon et al., 1984; Sangode et al., 1996; Kumaravel et al., 2005 and others) and OSL dating (Suresh et al., 2002); (3) availability of detailed groundwork on sedimentation and basin tectonics (Kumar and Tandon, 1985; Nakata, 1989; Kumar et al., 1999, 2003) and (4) tectonically the area is still active (Nakata, 1989; Kumar et al., 2002; Malik and Nakata, 2003).

2. Geological setting and stratigraphy

The study areas are located in the Subathu sub-basin in the central part of the Himalayan foreland basin (HFB) and are marked by the Yamuna Transverse Fault in the east and Fugal–Manali–Ropar transverse fault in the west (Fig. 1). The Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT) demarcate the HFB in the north and south, respectively. The dominant geological units exposed in the HFB are the Early Tertiary Subathu Group, Miocene to Pleistocene Siwalik Group and post-Siwalik Late Quaternary Pinjaur Dun sediments. Along HFT, the Middle Siwalik subgroup (~11–5 Ma) is exposed

Table 1
Stratigraphy and lithofacies in Quaternary deposits of Subathu sub-basin (compiled after, Kumar and Tandon, 1985 and present work)

Formation, thickness and age	Lithologic detail	Contact relationship	Depositional environment
Late Quaternary alluvial fan (20–50 m) ~200–~5 ka	Thickly bedded massive to crudely stratified conglomerate (2–10 m) with pebbles, cobbles and boulders, embedded in sandy to silty matrix and interstratified sandstone and mudstone in the proximal part, and mudstone-sandstone in the distal part	Lower contact: unconformable with Siwalik; upper contact: thrustured (Nahan Thrust).	Proximal to distal alluvial fan setting, transition from unconfined to confined channel deposits.
Upper Boulder Conglomerate (120–330 m) ~1.2–~0.25 Ma	Thickly bedded massive to crudely stratified conglomerate (2–10 m) with pebbles, cobbles and boulders embedded in sandy to silty matrix and interstratified sandstone and mudstone	Lower contact: transitional with Lower Boulder Conglomerate Formation; upper contact: thrust contact with the Nahan Thrust, physically overlying Lower Siwalik Subgroup.	Transition from debris-flow to sheet flood deposits from proximal to medial alluvial fan by unconfined channels.
Lower Boulder Conglomerate (200–250 m) ~1.79–~1.20 Ma	Brown to greyish brown, fine, medium to coarse grained sandstone with pebble and brown mudstone and pedogenic horizons, well imbricated, stratified conglomerate	Upper contact: transitional with Upper Boulder Conglomerate; alternation of conglomerate-sandstone- mudstone gradually passes into thickly bedded massive boulder conglomerate. Lower contact: transitional with Pinjor Formation; pebbly beds gradually increase and sandstone-mudstone bed gradually decrease.	Streamflow deposits with wide floodplains by confined gravelly braided stream on alluvial slope.

locally and is overlain by the Upper Siwalik subgroup (~5–0.25 Ma) towards the north. The Lower Siwalik subgroup (= Nahan Formation) overlies the Upper Siwalik subgroup across the Nahan Thrust (Fig. 2b and c). Further north, the Nahan Formation is overlain by Lower Tertiary sediments (>14 Ma, White et al., 2001) of the Subathu group across the Main Boundary Fault (MBF), followed by the hanging wall of Lesser Himalayan formations (including Crystalline Nappes) along the MBT (Valdiya, 1980). The detailed stratigraphy of Quaternary sediments of the Subathu sub-basin is given in Table 1.

3. Depositional setting

3.1. Early Quaternary sedimentation (System I, between 1.77 and 0.25 Ma)

The Early Quaternary Upper Siwalik sediments in the Subathu sub-basin are dominated by alluvial fan deposits exposed all along the basin margin, more prominently in the eastern part (Fig. 2(b) and (c)). These alluvial fan deposits (>500 m thick), the Boulder Conglomerate Formation of the Upper Siwalik subgroup, were initiated ~1.77 Ma (Table 1) and have a time transgressive lower contact ranging from 1.77 to 1.1 Ma (Fig. 3). The alluvial fan sedimentation was initiated ~1.77 Ma in the easternmost (Haripur section) and western part (Ghaggar River section). It occurs at ~1.16 and 1.1 Ma, respectively in the Khetpurali and Moginand sections (Tandon et al., 1984; Kumaravel et al., 2005; Fig. 3). All the measured sections

show stratigraphic coarsening upward successions with increases in clast-size and bed thickness, and decreasing sandstone-mudstone content.

Description and interpretation of mode of deposition of the lithofacies identified in the Quaternary deposits of the Subathu sub-basin are given in Table 2. The lower stratigraphic interval (Fig. 4) displays alternations of 5–25 m thick conglomerate-sandstone-mudstone cycles. Individual cycles commonly start with conglomerate or sandstone, invariably passing upward into mudstone. The lower contact is erosional with local relief not exceeding 1 m. The conglomerate beds are 1–6 m thick and generally show lenticular geometry, but rarely sheet geometry. These conglomerates are poorly sorted with rounded to sub-rounded clasts, matrix- to clast-supported, stratified and imbricated (Gm) and locally cross-stratified (Gt). The Gm facies passes upward into stratified and/or massive sandstone (St/Sm; Table 2). Average clast-size in these conglomerates is 6 cm at the base, gradually increasing upward to 20 cm.

The sandstone is coarse-medium to fine-grained, fining upward and cross-stratified. Thickness of the sandstone beds varies from 1 to 4 m, and rarely exceeds 11 m. The overlying mudstone is variegated (brown, reddish brown to yellowish brown) and massive (Fm1). In places it shows pedogenic modification with calcretes and iron concretions (Fm2). Thin sheets of fine sandstone and mudstone (Fl) up to 2 m thick are present at places, representing levee deposits. The thickness of mudstone beds varies from 1.5 to 8 m and rarely exceeds 14 m.

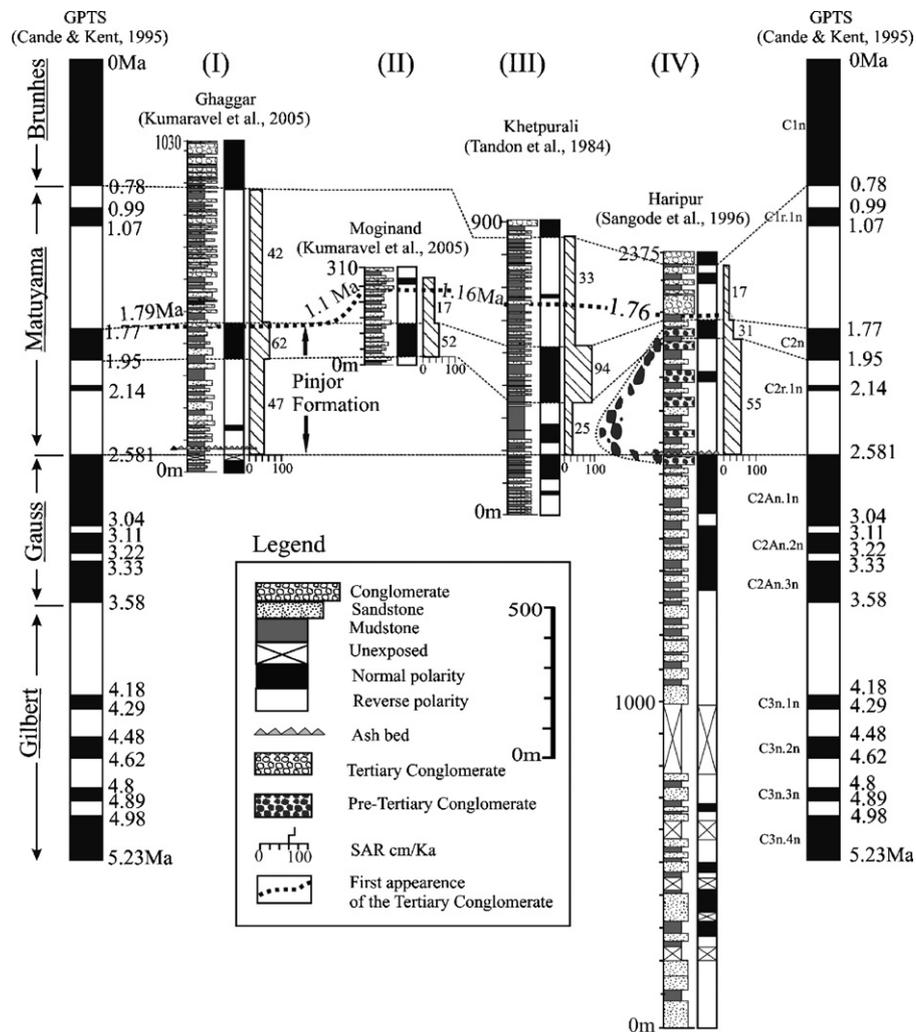


Fig. 3. Correlation of four magnetostratigraphically dated sections of the Upper Siwalik subgroup in the Subathu sub-basin (Tandon et al., 1984; Sangode et al., 1996; Kumaravel et al., 2005; Cande and Kent, 1995). Note the time-transgressive nature of the Boulder Conglomerate Formation marked by solid dotted line at different time intervals. Section position with number shown in Fig. 2(b) and (c).

Thickness and clast-size of conglomerate beds gradually increase up section with corresponding decreases in sandstone–mudstone percentage (Fig. 4). The conglomerates are massive, poorly sorted, matrix- to clast-supported, crudely stratified and imbricated (Gm; Table 2), and have sheet geometry. The thickness of the conglomerate beds varies from 4 to 15 m and rarely exceeds 20 m. Gm is overlain by lenticular St (up to 2 m thick) and Fm1 (up to 2.5 m thick and rarely exceed 8 m). In places massive, poorly sorted, disorganized, ungraded, matrix to clast supported (Gdm) with outside clasts up to 1 m are interbedded with Gm. Gdm beds are 1 to 3 m thick with planar irregular lower contacts. Further up section, thickly bedded (up to 25 m) massive conglomerate is composed of randomly oriented sub-rounded to sub-angular clasts (largest 1 m) embedded in sandy-muddy matrix (Gms). Lenticular, massive and pebbly mudstone (up to 3 m thick) and locally well-stratified conglomerate bodies are also associated with Gms.

Paleoflow directions obtained from clast imbrication and trough cross-stratification in the lower stratigraphic unit

indicate palaeoflow was mainly towards the south with southeast and southwest modes, and an up-section increase in paleoflow variability (Kumar and Tandon, 1985; Kumar et al., 1999, 2003). The conglomerates have nearly oligomictic clast composition, and consist of sandstone clasts derived from sub-Himalayan Tertiary strata lying north of the Nahan Thrust.

The sedimentation pattern in the Early Quaternary deposits displays upward changes in the facies and architectural elements from stratified, lenticular conglomerates with sandstone and pedogenic mudstone to sheet conglomerates with minor sandstones and non-pedogenic mudstones, to massive, thickly bedded disorganized conglomerate. Characteristic features and facies association in the lower stratigraphic interval suggest that their deposition took place in gravelly braided streams with well developed floodplains (Tandon et al., 1984; Kumar et al., 1999). Oligomictic clast composition and paleoflow indicators (Kumar and Tandon, 1985; Kumar et al., 1999, 2003) demonstrate that these deposits were produced by streams flowing southward from the older Tertiary zone

Table 2
Description and interpretation of facies observed in the Quaternary alluvial fans of the Subathu sub-basin, sub-Himalaya

Facies	Sub facies	Description	Interpretation
Conglomerate	Disorganised, matrix supported conglomerate (facies Gms)	Pebble—boulder clasts, chaotic fabric, sub-angular to sub-rounded, very poorly sorted, muddy matrix supported conglomerate, crude stratification observed locally. Beds have sharp, non-erosional basal contact.	Cohesive clast—rich debris flow with minor channel deposits.
	Disorganised, matrix to clast supported conglomerate (facies Gdm)	Pebble—boulder clast, poorly sorted, disorganized, ungraded, matrix to clast supported, out size clasts up to 1 m are common, clasts are sub-rounded to rounded, coarse sand to silty matrix, Beds have irregular, planar basal contact.	Rapid deposition by hyper-concentrated flood flow during catastrophic flood event and/or during interglacial period or heavy rain fall/ cloud burst.
	Crudely stratified conglomerate (facies Gm)	Pebble—boulder clast, poorly to moderately sorted, crude horizontal stratification, well developed transverse clast fabric, matrix to clast supported, clasts are well- to sub-rounded, planar to erosional basal contact. Ungraded to normal grading.	Deposition by persistent steamflows and are common in gravels transported as bed load and deposited under waning flow by accretion of progressively smaller clasts, in channels and on longitudinal bars.
	Cross-stratified conglomerate (facies Gt)	Well-organized, clast- to matrix-supported, pebble—cobble clast. Low angle cross-stratification (range from 100 to 150 but exceed up to 250). Scouring basal contact. Both trough and planar cross-stratifications are present.	Lateral accretion and slip face deposit on longitudinal bar or hollow fill
Sandstone	Pebbly sandstone (facies St1)	Medium-to coarse grained pebbly sand, cross-stratified	Deposited by gravelly braided river
	Stratified to massive sandstone (facies St2)	Medium-to coarse grained grey sand, essentially massive, sometimes cross-stratified, normal grading. Lenticular to sheet geometry. Basal contact is sharp, fining upward	Rapid deposition under waning stage in alluvial channel.
	Massive sandstone (facies Sm)	Fine to very fine reddish to brown sand, massive, lenticular geometry	Rapid deposition by piedmont channel. At place represent bar surface deposits.
Mudstone	Massive mudstone (facies Fm1)	Buff coloured, dominantly silt sized, thickly bedded (<8 m), massive, uniform texture	Fine-grained nature and uniform texture of the beds indicate over bank deposits
	Pedogenic mudstone (facies Fm2)	Variiegated colour, dominantly silt sized, thin to thickly bedded (<3 m), pedogenic, associated with calcareous irregular concretions (< 1 cm), locally iron concretion. Irregular contact with underlying bed.	Overbank deposits; Calcareous concretions indicate pedogenic activity
	Alternation of sandstone and mudstone (facies Fl)	Thin sheets of fine-grained, massive, brownish sandstone and buff mudstone alternatively arranged	Levee deposits

north of the Nahan Thrust (Fig. 2). The presence of channel and floodplain deposits, absence of sheetflood facies and their occurrence in the footwall piedmont zone suggest alluvial slope deposits (e.g. Smith, 2000). Reddish brown mudstone with well-developed calcareous concretions was formed under well-drained hydromorphic conditions in warm, arid to semiarid climates (Gile et al., 1965; Kraus, 1999). Yellowish brown mudstone with iron concretions were developed under reducing, saturated conditions (Birkeland, 1999) in alternating wet and dry seasons (Thomas et al., 2002).

Up-section, the fluvial architecture changes from lenticular to sheet conglomerates with decreases in sandstone–

mudstone content and increased paleoflow variability (SE–SW mode). Mudstones are brown and do not show any evidence of pedogenic alteration except mottling. These features indicate that they were deposited by unconfined sheet floods. Interbedded Gdm facies suggest infrequent interspersed hyper-concentrated flood events. Further up-section, the presence of Gms suggests deposition by debris flow (Kumar and Tandon, 1985; Kumar et al., 1999, 2003). Lenticular pebbly mudstone indicates small feeder channel deposits on the debris flow surfaces.

These features reveal that Early Quaternary deposits of the Subathu sub-basin represent proximal to distal alluvial

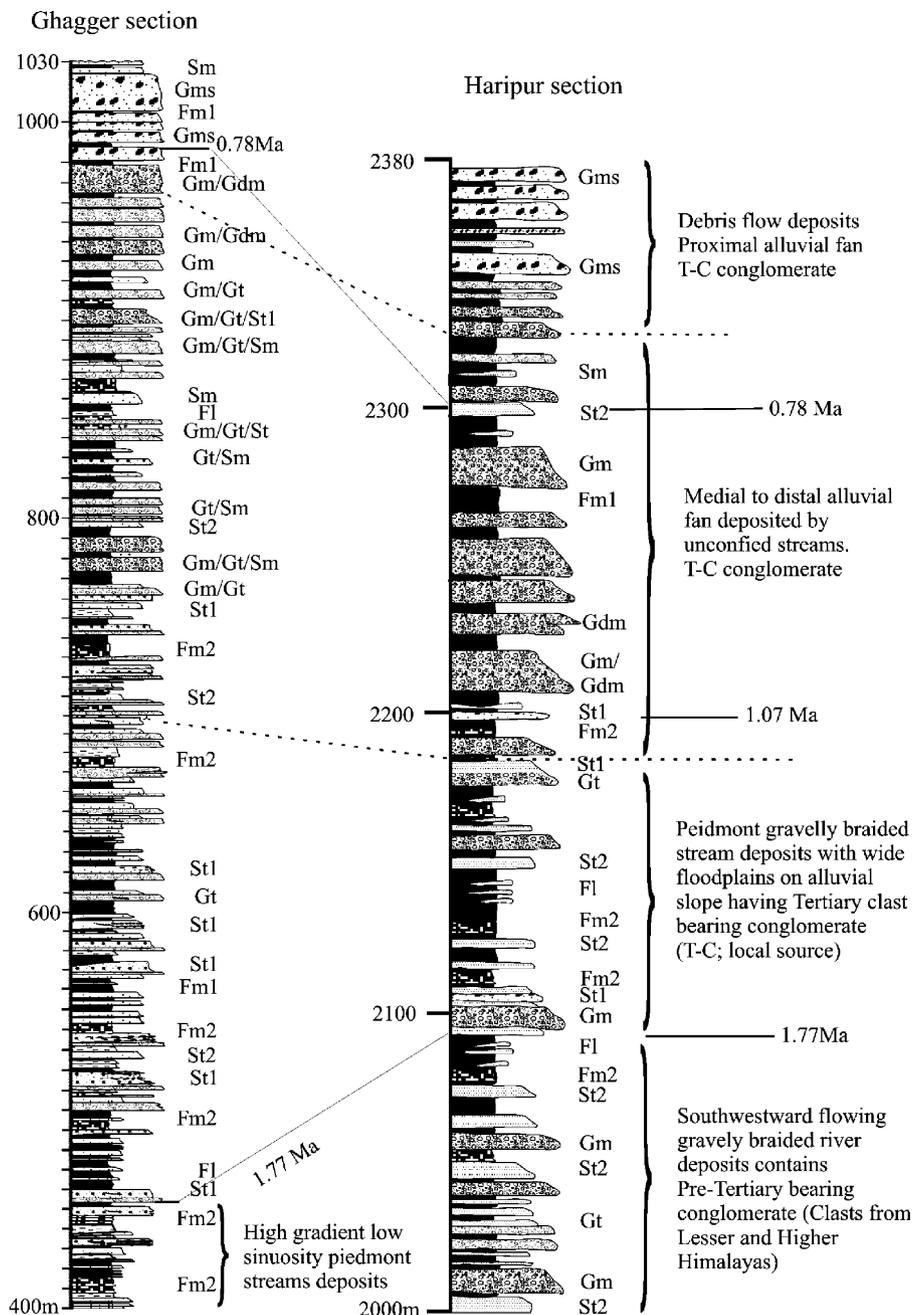


Fig. 4. Measured stratigraphic lithology of Boulder Conglomerate Formation. In both sections, Early Quaternary alluvial fan initiated ~ 1.77 Ma.

fan settings. The absence of paleosols in the proximal part of the fan suggests that sedimentation was rapid and fan heads were not trenched (e.g. McCraw, 1968; Wright and Zarza, 1990). This is further indicated by the presence of sheet conglomerate bodies.

3.2. Late Quaternary deposits (System II, $>96\sim 5ka$)

The Late Quaternary deposits (post-Siwalik) are dominated by alluvial fans and fluvial terrace deposits in the intramontane piggy-back basin. This basin, about 140 km in length, elongated in the NE–SW direction and 10–19 km wide, extends between Pinjaur in the east and Una in the

west, and is known as Pinjaur–Soan Dun (Fig. 2(a)). The Nahan (= Nalagarh) thrust separates the northern margin of this basin from the Tertiary mountains.

The Late Quaternary alluvial fans and depositional fluvial terraces are developed on both the northern and southern sides of the Dun and are separated by the Satluj–Sirsa River flowing in the axial part of the basin (Figs. 1 and 2(a)). The alluvial fans are oriented more or less parallel to the present day transversely flowing streams between the Tertiary mountains in the north and the axial rivers (e.g. Satluj and Sirsa rivers) in the south. The fan apices occur at the base of the Tertiary mountains and their toes terminate at the floodplains of axial rivers. The alluvial

Table 3
Description of alluvial fans in the Pinjaur piggy-back basin

Name of alluvial fan	Fan dimension	Drainage basin area (km ²)	Alluvial fan area (km ²)	Remark
Luhund	12 km long and 10 km wide	38	87	Fan is entrenched from apex to toe by streams (Luhund—Misewal khads) debouching from the Tertiary mountains. The fan margins are entrenched by interfan streams.
Kundlu	16 km long and 6 km wide	22	67	Fan is entrenched from apex to toe by a stream (Kundlu ki khad) debouching from the Tertiary mountains. The fan margins are entrenched by interfan streams on the west and streams fedded from Tertiary mountains on the east.
Chikkni	11 km long and 7 km wide	20	44	Western margin of the fan is entrenched by a stream debouching from Tertiary mountain whereas the eastern margin is entrenched by an interfan stream (Chikkni khad). Small patch of relict Lower Siwalik rocks are exposed above the fan surface.
Ratta	5 km long and 3 km wide	25	11	Fan eastern margin is entrenched by a stream debouching from Tertiary mountain (Ratta nadi) whereas the western margin is entrenched by an interfan stream (Phula nala).
Balad	7.25 km long and 3.75 km wide	95	32	Fan margins are entrenched by streams debouching from Tertiary mountain, Balad and Ratta nadis on the east and west respectively.
Surajpur	6.25 km long and 6.1 km wide	42	36	A group of highly coalescing fans, dissected by Nanakpur and Ramnagar nadis and Surajpur choa.
Kiratpur	7.25 km long and 4.8 km wide	17	32	Fan is entrenched from apex to toe by Kiratpur nadi. Western fan margin is entrenched by stream debouching from Tertiary mountain (Ramnagar nadi) whereas the eastern margin is entrenched by an interfan stream (Sirsa nadi).
Jhajra	10 km long and 8 km wide	10	41	Fan is entrenched from apex to toe by Jhajra Nadi (Ghaggar drainage system). Fan eastern margin is entrenched by a Tertiary mountain debouching stream (Koshalla nadi) whereas the western margin is entrenched by an interfan stream (Sirsa nadi).

fans are of varying dimensions (Table 3) and occur as solitary or dissected features with through fan entrenchment. They are entrenched throughout their length by transverse flowing streams debouching from the Tertiary mountains as well as originating within the valleys, presently delivering sediment load directly into the Satluj River (Fig. 2a).

Based on the relative position of the fan surfaces in relation to the modern stream gradient, relative age and areal extent, they are classified into Older (Qf1) and younger (Qf2) fan surfaces. The Qf1 is the highest surface (50–80 m in height from the active stream grade). Qf2 occurs at lower elevations and is more extensive. The depositional slopes of Qf1 vary between 2.1° and 4.2°, and those of the Qf2 vary between 0.7° and 2.1°. The depth of incision is varied, about 8–10 m in the proximal fan areas and 15–35 m at the distal areas of the Qf2 fan surface. Secondary gullies showing parallel patterns are developed on the fan surfaces. Most of these alluvial fans are coalesced.

The second prominent geomorphic features in the system II are fluvial terraces, lying at lower elevations than the fan surfaces on both banks of the incised streams and occurring within the dissected fans as well as at the lateral and terminal margins of the fan deposits (Fig. 5). They are flat, narrow depositional surfaces and consist of gravel and sandy sediments above the eroded remnant fan surface left

by the incised streams. Two levels of terraces were observed below the Qf2 and are deposited as paired surfaces on both banks of the streams. The top terrace below the Qf2 surface is named as T1 and the lower as the T2 terrace. In places, T1 terrace is about 500 m in width and ~6 m thick whereas the T2 terrace is about 50 m in width and ~3 m thick.

The Qf1 fans are dominated by Gms with clast-size varying from pebble to boulder, floating in sandy to silty matrices (Table 2). However, the medial fan regions expose thickly bedded buff sandstones (St1 and Sm) with minor amounts of Gm and Gdm. Distal fan regions have widespread mudstones with calcareous concretions overlain by thick conglomerate of Qf2 with erosional contacts.

The proximal regions of Qf2 (e.g. Dehni and Baglehr sections, Figs. 6 and 7) are dominated by Gm, Gdm and rarely Gt interbedded with Sm or Fm1. The Gdm is massive and disorganised with chaotic fabric in which out-sized clasts are common. Gm is matrix- to clast-supported, massive and crudely stratified with clast imbrication. The palaeocurrent directions obtained in the Gm vary between 170° and 320°. The Gt is well-organized, clast- to matrix-supported and trough cross-stratified. Lenticular bodies (100–120 cm thick) of Sm are observed interbedded with the Gm. In places, thickly bedded Fm1 and Fm2 are present at the top of Qf2 and locally show development of calcrete bearing yellowish mudstone (Fm2). No major depositional phase has occurred on the Qf2 surfaces since

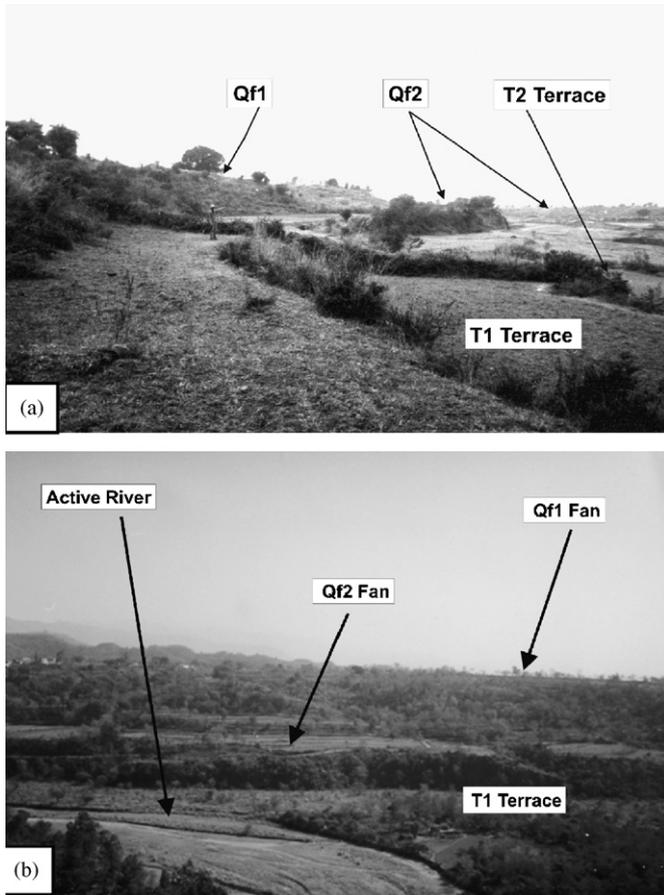


Fig. 5. Photographs showing various geomorphic units in the Pinjaur piggy-back basin. (A) Qf1 and Qf2 fan surfaces with T1 and T2 terrace in the Sirsa Nadi. (B) Modern Luhund stream and various geomorphic surfaces at Tikri, Luhund fan.

the deposition of Fm1 and Fm2, marking the termination of Qf2 sedimentation.

The medial fan regions (Figs. 6 and 7) are dominated by medium to fine-grained sandstone and mudstone cycles overlain by sandstone–conglomerate couplets up-section. St2 is the dominant facies whereas St1 occur rarely with low angle cross-stratification. The Fm1 and Fm2 contain hard layers of carbonates (a few centimeters thick) parallel to the bedding planes.

The distal fan regions of Qf2 are dominated by Fm1 and St2 overlain by rare lenticular bodies of thinly bedded Gm. In places, the Gm (maximum clast-size is 50 cm) is channelled (about 2 m thick, 20 m wide). Thick units of Fm1 were deposited towards up section, but at place thick units of Gm separated by sandstone were also observed. Locally exotic white to drab white, medium grained sandstone facies (43 cm–1.21 m thick) occur with mica (muscovite and biotite), armored mud balls coated with mica, and pebbles towards fan toes. This sandstone has thinly bedded (2 cm) pebbly beds and internally shows trough cross-stratification with irregular and erosional base. It extends laterally (about 2 km) up to the Satluj River. The sandstone unit is overlain by rhythmic reddish,

greyish and yellowish mudstones representing lacustrine facies. The lacustrine facies are thinly bedded (1–10 mm layers), although a few thickly bedded (up to 40 cm) gray mudstones are also observed. This is overlain by reddish mudstone (Fm1) and reddish to yellowish-brown sandstone (Sm), similar to other parts of the fan areas.

The sedimentation pattern of the oldest and proximal Qf1 facies is characterized by poorly sorted, disorganised and clayey matrix-supported Gms without any sedimentary structures, indicating its deposition by debris flow process (e.g. Blair and McPherson, 1994). Laterally, Gms passes into Gdm, Gm and Sm representing gradual transitions from debris flow to stream flow deposits in the medial region. Further down-fan, Fm1 and Fm2 are dominant facies in the distal part of Qf1, representing widespread lacustrine environments.

The dominance of Gm facies associated with Gdm and Gt and lenticular Sm and Fm1 in the proximal regions of the Qf2 indicate that they were deposited by unconfined sheet floods with intervening hyper-concentrated flood events (e.g. Smith, 1986; Maizels, 1988; Wells and Harvey, 1987). Chaotic fabrics suggest rapid deposition on the fan head. The minor presence of Gms facies indicates debris flow in the proximal fan regions with low slopes. High percentages of clayey matrix in the debris flow are in agreement with source lithology, and suggest that the high viscosity aided the frictional resistance on its slope, thus reducing the mobility of debris flows (e.g. Rodine and Johnson, 1976; Pierson, 1981). The medial and distal regions of Qf2 are dominated by stream flow process, as is evident from thickly bedded, stratified to massive sheet sandstones and mudstone facies. The presence of white to drab white sandstone with abundant mica in the toe of Qf2 suggests deposition by the Satluj River through toe cutting of the distal Qf2.

The Late Quaternary alluvial fans in the Pinjaur Dun are oriented northeast–southwest, suggesting their deposition by transverse flowing streams similar to the present day streams debouching from the Tertiary mountains. The radial paleoflow pattern, low depositional slopes (0.7–3.98°), absence of fauna and rapid decrease in clast size in the down fan direction are characteristic features of these alluvial fan deposits. The dominance of sandstone clasts in the conglomerate facies and buff sandstone and mudstone facies indicate their derivation from sandstones and mudstones belonging to Dharamsala/Murrees (lower tertiary) and Lower Siwalik (Upper Tertiary) formations exposed in the hanging wall of the Nahan Thrust (Fig. 2(a)).

4. Chronology of events

Based on magneto-stratigraphic data, the depositional phase of system I was initiated ~1.77 Ma in the Haripur and Ghaggar River section and ~1.1 Ma in between (Khetpurali and Moginand Section, Fig. 3). In the absence of any evidence of entrenchment, this time lag indicates

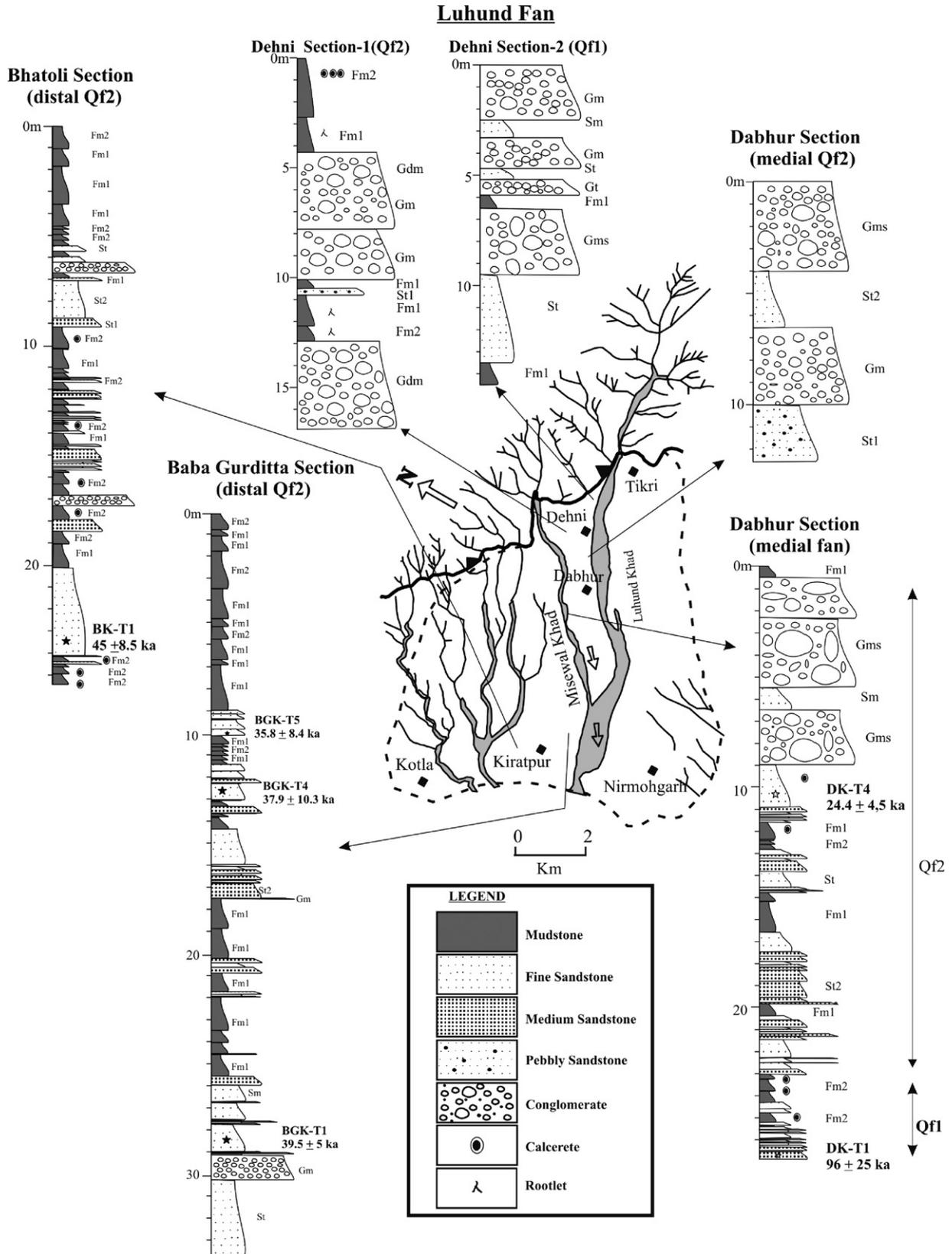


Fig. 6. Luhund fan (Fig. 2(a)) in the Pinjaur piggy-back basin. Stratigraphic columns for proximal to distal parts of the fan with OSL ages. Facies distribution shows dominance of conglomerate in the proximal part, to mudstone and sandstone in the distal part.

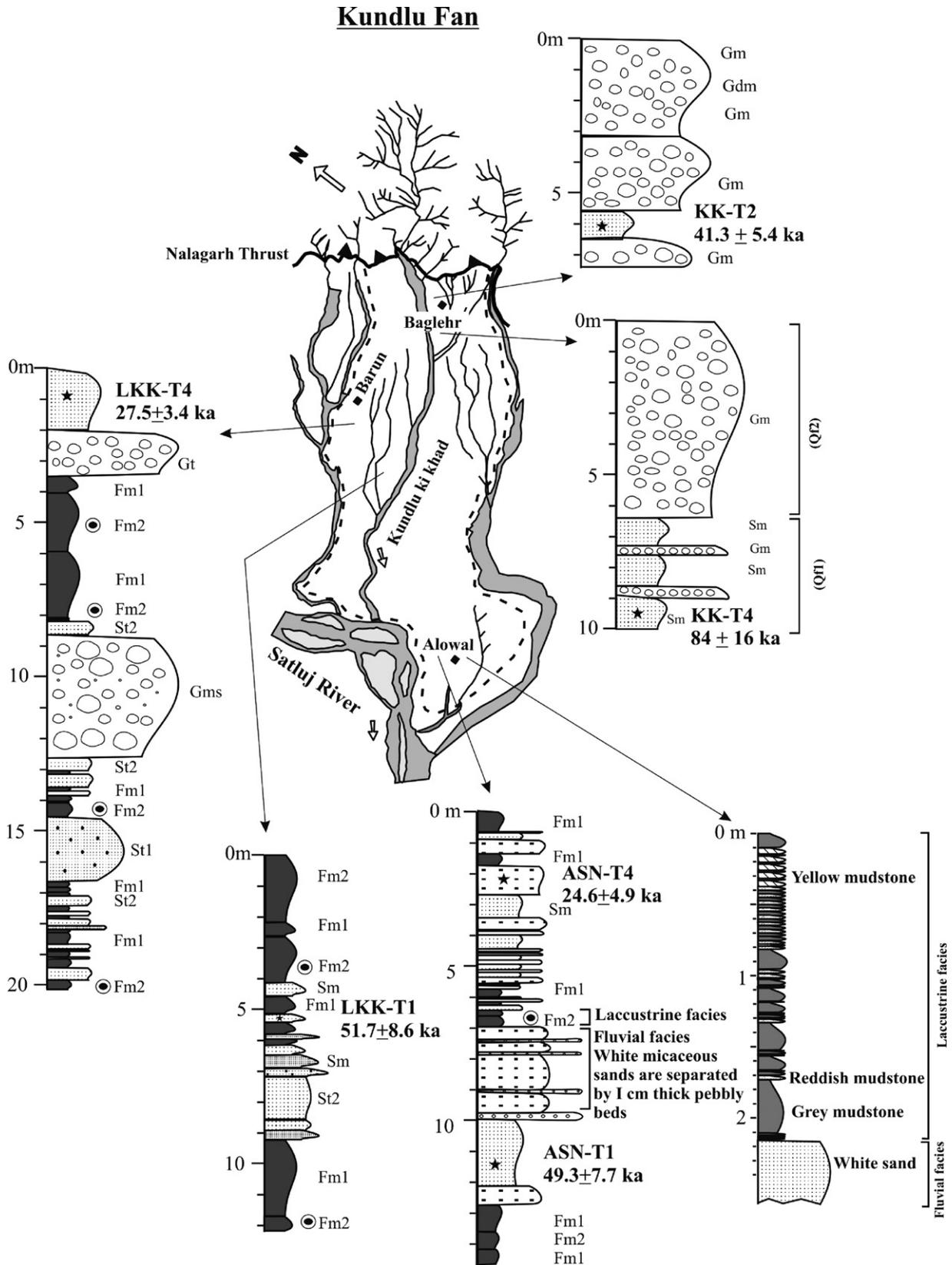


Fig. 7. Facies distribution and OSL ages of the Kundlu fan (Fig. 2(a)). Legend as in Fig. 6.

that the central part of the basin represents an inter-fan area in which alternations of sandstone–mudstone were deposited on alluvial slopes and coalesced with side fans after ~1.1 Ma. These fans are restricted along the basin margin and show rapid lateral variation in clast size from proximal to distal fans. The facies architecture of these fans indicates their syn-tectonic origin in a rapidly subsiding basin due to the intense tectonic activity along the Nahan Thrust (Kumar and Tandon, 1985; Kumar et al., 1999, 2003). This favored vertical aggradation with restricted lateral progradation, resulting in small fans. Similarly, system II fans were developed in front of the Nahan Thrust after the cessation of sedimentation in system I fans at ~0.25 Ma and formation of a piggy-back basin in response to HFT activity. The absence of through-fan entrenchment in the Early Quaternary fans indicates the continuous creation of accommodation space as well as ongoing sediment supply throughout deposition (between 1.77 and 0.25 Ma).

The chronology of the Late Quaternary system II fans is known in more detail through numerous OSL dates (Suresh et al., 2002). System II has four depositional surfaces, with Qf1 at the highest elevation and the younger terrace (T2) at the lowest elevation, indicating that the depositional phases were separated by incision phases. The Qf1 depositional phase was initiated after the formation of the piggy-back basin before ~96 ka and continued up to 83.7 ± 16.3 ka. The Qf1 surface has been entrenched during the subsequent incision phase since 83.7 ± 16.3 ka but before the initiation of the Qf2 at 72.4 ± 13.4 ka. The Qf2 depositional phase stopped at 24.5 ± 4.5 ka with minor toe-cutting event by axial rivers at ~40 ka. The subsequent stream incision, between 24.5 ± 4.5 and 16 ± 2.07 ka, entrenched the Qf2 surfaces from fan head to toe. This incision phase was followed by a short depositional phase, forming T1 terrace sediments at 16.28 ± 2.07 ka. The deposition of T1 terrace sediments in the interfan streams originating within the valley suggests that these streams initiated after cessation of the sedimentation of Qf2, but before the deposition of T1 terrace sediments. The next depositional phase, i.e. T2 terrace sediments, at ~4.5 ka (4.89 ± 1.13 ka and 3.99 ± 0.77 ka) is also a short event at a lower elevation. This suggests that a non-depositional phase occurred between 16 and 5 ka. The ongoing stream incision since 4 ka has resulted in the coupling between mountain streams and the valley axial river. As a result, the sediment load is presently delivered directly into the axial rivers, and no more deposition has taken place in the valley.

5. Discussion and conclusion

Both fan systems (I and II) described above are developed in front of the Nahan Thrust and have similar clast composition and depositional setting from proximal to distal alluvial fans. The main difference between these two systems is that system I represents only aggradation

with minor distal fan entrenchment, while the younger fans (system II) indicate synchronous periods of aggradation and through-fan entrenchment between the fans.

The terminal phase of the evolution of the Himalayan foreland basin is marked by the inversion of the Siwalik system (I) during Late Quaternary (~0.25 Ma) followed by basin-wide folding and formation of a piggy-back basin (system II). Based on sedimentation pattern and OSL and magnetostratigraphic ages, the difference in the evolutionary mechanism of the two systems can be distinguished. Sediments of system I were deposited mainly under Pleistocene climates (both glacial and interglacial events). System I sedimentation was characterized by larger accommodation spaces and higher sediment fluxes with higher sediment:water ratio on a relatively lower depositional slope. Deposition of system I was significantly governed by growing tectonic surges as is evident from the significant coarsening upward pattern without any major entrenchment. A major change in sedimentation pattern from sandstone-mudstone to conglomerate-sandstone–mudstone occurred around 1.7 Ma, that reflects the intensification of intra-foreland thrust activity (Kumar et al., 1999, 2003). Activation and reactivation of this intra-foreland thrust (Nahan Thrust) acted as a major source of sediment supply in the study area and is the main cause of fan reactivation during the depositional regime of system I. However, the role of climate in sediment mobilization cannot be ruled out.

Quaternary glaciations resulted in enhanced weathering over a sizeable part of the hinterland releasing greater sediment yield to the foreland and favoring fan aggradation. The glacial advance with limited interglacial conditions between 2 and 1 Ma (Moran et al., 1997) might have altered the hinterland weathering pattern. As well, activation and reactivation of the Nahan Thrust during this time appears to have accelerated the tectonically derived sedimentation as well as relief in the proximal part of the basin. The subsequent interglacial conditions after 1 Ma might have facilitated sediment transport and mobility in the basin. This supply of sediment derived from both climatic and tectonic rejuvenations might have been responsible for the higher aggradation of 0.2–0.4 mm/yr in the succeeding intervals in the study area (Sangode et al., 1996; Kumaravel et al., 2005). Furthermore, limited southward extent of these fans also indicates availability of larger accommodation space due to thrust loading. High sedimentation is also reported from the Bay of Bengal during the same time interval as a result of gradual Himalayan upheaval and the southward advancement of the thrust sheets (Schumm and Rea, 1995; Einsele et al., 1996; Métiévier et al., 1999). This is evident from the increase in depositional slope and lateral time transgressiveness of the Early Quaternary alluvial fan system. The facies architecture of these fans (especially rapid lateral variation and coalescence) indicates their syn-tectonic origin (Kumar and Tandon, 1985; Kumar et al., 1999, 2003). Thus the Early Quaternary alluvial fans of system I were controlled

by tectonic activity but the climate appears to have played a key role in basinward sediment transfer.

The Late Quaternary (post-Siwalik) intramontane piggy-back sedimentation (system II) is subdivided into Qf1: the older, small size piedmont fans (>96–84 ka); Qf2: the younger fans with larger basinward extent (~72–20 ka); and the T1 and T2 terraces (<16 ka). The sedimentation on the Qf1 fan surfaces continued until 83.7 ± 16.3 ka followed by fan-head entrenchment and subsequent initiation of the Qf2 fan active lobe at 72.4 ± 13.4 ka, below the intersection point. The restricted occurrence of Qf1 along the basin margin, and the lateral and down fan facies variation with steep slopes, indicate syn-tectonic origin.

Qf1 was initiated after the formation of the piggy-back basin in response to HFT that caused basin tilting and migration of axial river towards the basin margin. The entrenchment of Qf1 surface could either have resulted from rejuvenation of a marginal fault with a higher rate of river downcutting (e.g. Bull, 1964, 1977) or climatic fluctuation. Evidence of tectonic upheaval is not documented for the Nahan Thrust between 84 and 72 ka. Prell and Kutzbach (1987) reported about 30% fluctuation in precipitation from the present value over the past 150 ka. A major change in the precipitation at ~74 ka was also reported, based on ice-core oxygen isotope record from the Guliya ice cap in far western Qinghai (Tibetan plateau), reflecting the strong influence of the summer monsoon (Thompson et al., 1997). The piedmont streams, the sole feeders to the alluvial fans, are largely influenced by the SW monsoon. Variable precipitation would also cause fluctuations in discharge in the piedmont streams and may be responsible for a change in the balance between sediment load and stream power, resulting in fan entrenchment of Qf1 between 84 and 72 ka.

Later, the basinward progradation of the newer Qf2 fan lobe indicates that erosional unloading continued after the Nahan Thrust activity (e.g. Heller et al., 1988; Paola, 1988; Flemings and Jordan, 1990; Burbank, 1992). This resulted in migration of axial river away from the basin margin (e.g. Burbank, 1992). The streamflow dominated facies and basinward migration of large boulders in the Qf2 fans can be explained by high precipitation in the catchment. In semi-arid to arid regions, precipitation between 300 and 400 mm can be sufficient to mobilize boulders (Ohmori, 1983). Present day average annual precipitation in the study area is about 500 mm with the majority of precipitation occurring during the summer monsoon between June and September. Hence the characteristic streamflow dominated facies during the deposition of Qf2 indicates the availability of ample water in the drainage area. Benn and Owen (1998) reported extensive glaciations in the higher reaches of western Himalaya during 60–30 ka reflecting increased summer monsoon precipitation. The presence of axial river sediments, lacustrine facies and subsequent toe cutting of Qf2 in the distal zone at around 40 ka indicate that the axial river gradually migrated towards the basin margin. This shifting of axial river

without any incision during high precipitation conditions (Prell and Kutzbach, 1987) indicates basin tilting (e.g. Leeder and Mack, 2001) in response to renewed activity along the Nahan thrust at ~40 ka. The subsequent progradation of Qf2 and southward shifting of the axial river again suggests a quiescent phase of thrusting, which is supported by the appearance of conglomerate facies and its predominance over sandstone–mudstone cycles in the medial to distal fan region.

The cessation of the Qf2 fan at $\sim 24.5 \pm 4.5$ ka and prolonged stream incision between 20–16 ka and 14–5 ka, vis-à-vis terrace formation below the Qf2 surface at ~16–14 and ~4.5 ka, appears to result from either base-level changes or an increase in stream power. These terraces terminated abruptly along HFT, suggesting that terrace deposition was controlled by modification of stream gradient due to the activity of HFT. Major tectonic activity during late Pleistocene to Holocene along HFT is reported by several workers (Nakata, 1972, 1989; Wesnousky et al., 1999; Lavé and Avouac, 2000; Malik and Nakata, 2003). This appears to have initiated a base-level change in the Himalayan foreland basin. During this time major oscillations in global glacial–interglacial cycles with strong monsoonal fluctuations are also documented (Cullen, 1981; Duplessy, 1982; van Campo et al., 1982; Prell and Kutzbach, 1987; Sirocko et al., 1991; Thompson et al., 1997). The available data on the variations in the SW monsoon from the Arabian Sea and the Bay of Bengal (Cullen, 1981; Duplessy, 1982; van Campo et al., 1982; Sirocko et al., 1991) indicate that the SW monsoon was weak during the Last Glacial Maxima (20–16 ka), resulting in less sediment discharge from the Himalayan rivers, whereas humid conditions prevail during the present interglacial period. The prolonged stream incision since 20 ka in this basin, with minor depositional phases at 16–14 ka and 4.5 ka, indicate relatively higher stream power but reduced sediment supply as interglacial conditions increased precipitation and vegetation cover. The terrace deposits did not form a new active fan lobe under the present interglacial humid phase, and the position of the axial river was close to the toe of the Qf2. Therefore it is inferred that a coupling between the mountain catchments and downstream drainage under a more humid interglacial climate resulted in the through-fan entrenchment of Qf2 and the absence of any fan lobe since the Late Pleistocene–Early Holocene.

Various time equivalent aggradation and incision phases are reported south of HFT in the Indo-Gangetic plains (Shukla et al., 2001; Srivastava et al., 2003; Gibling et al., 2005; Sinha et al., 2005). Prominent geomorphic surfaces in the Ganga plain (Ganga dispersal system) include, the upland terrace surface and marginal plain upland surface (128–74 ka), megafan surface (74–35 ka), river valley terrace surface (35–25 ka), piedmont fan surface (25–10 ka), and active flood plain surface (Holocene). These are interpreted as responses to Late Quaternary climatic variations (Shukla et al., 2001; Gibling et al., 2005; Sinha et al., 2005). Active tectonic-induced deep incision by

river systems is also reported in the Ganga basin during Late Pleistocene–Holocene (Aggarwal et al., 2002; Srivastava et al., 2003). However, Goodbred (2003) holds the view that the Ganges dispersal system shows little apparent attenuation of sedimentary signals between Ganga plain and downstream basins in the Ganga delta and Bay of Bengal. He inferred that sediment dispersal in the Ganga Basin is in response to hydrological variation from the southwest monsoon.

These observations reveal that evolution of Quaternary fans in the Himalayan foreland basin was affected both by tectonic and climate fluctuations. The Early Quaternary fan was dominated by prolonged tectonic activity which produced and maintained the relief and accommodation space. Late Quaternary fans were governed both by tectonic and climatic perturbation. Therefore, the evolutionary history of alluvial fans in the Himalayan foreland basin reveals their initiation as a result of tectonic movements, with climate playing a major role in their facies assemblage as well as overall aggradation and entrenchment.

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