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Climatic and tectonic controls on the sedimentary processes of an alluvial fan of the western Ganga Plain, India

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Abstract – Detailed facies analysis and morphotectonic investigations of the Malin River's alluvial fan in the western Ganga Plain, India, reveal that the morphology of the fan is largely tectonically controlled whereas the sedimentary processes are mainly climatically controlled. The sedimentation occurred in two distinct evolutionary cycles which are separated by a time gap. The older cycle deposited thick gravelly units up to the distal-fan area, whereas the sediment fill of the younger cycle is gavel-dominated in the proximal-fan area, gravel–sand dominated in the middle-fan area and sand–mud dominated in the distal-fan area. The gravels of the older cycle were emplaced by intense sediment gravity flows during periods of strengthened monsoon and steeper regional gradient. During the younger cycle, the proximal to distal parts of the fan were dominated by different sedimentary processes. This was a time of relatively weaker monsoon and gentler regional slopes, when gravels could travel only up to the middle-fan area. The gravels in the proximal-fan area have mainly been deposited by sediment gravity flows and channel processes; in the middle-fan area channel processes, sheetfloods and sediment gravity flows have been the main sedimentary processes; and in the distal-fan area fluvial processes of channel migration and overbank deposition have been the main sedimentary processes.

Keywords: alluvial fan, facies analysis, geomorphology, Ganga Foreland Basin.

1. Introduction

Alluvial fans and megafans occupy vast areas in the northern and central parts of the Ganga Plain (Geddes, 1960; Singh, 1996). The megafans are dominantly sandy in nature, extend up to the central part of the Ganga Plain, and have a large spatial extent (more than a thousand square kilometres) and low gradient (generally $< 0.5°$) (Geddes, 1960; Gohain & Parkash, 1990; Shukla *et al*. 2001; Chakraborty *et al*. 2010). On the other hand, the alluvial fans are dominantly gravelly in nature, restricted to the piedmont zone of the Ganga Plain, and have small areas (not more than a few hundred square kilometres) and a steeper gradient (up to 3°) (Shukla & Bora, 2003; Shukla, 2009; Goswami, Pant & Pandey, 2009; Goswami & Yhokha, 2010).

The morphological and sedimentological aspects of the megafans of the Ganga Plain have been studied in detail by many workers (see Gohain & Parkash, 1990; Shukla *et al*. 2001; Chakraborty *et al*. 2010 and references therein). But, the alluvial fans of the piedmont zone have not gained much attention from the workers, most likely because of the dense forest cover and limited accessibility over a large part and intense human activities in the remaining part. Detailed geomorphological and morphotectonic studies of a few alluvial fans of the western Ganga Plain have been carried out in recent years (Shukla & Bora, 2003; Goswami, Pant & Pandey, 2009; Goswami & Yhokha, 2010). However, the detailed sedimentology of only one fan, the Gola (also called Gaula) Fan, has been determined so far (Shukla, 2009).

The present study has been carried out to fill the gap-in-knowledge regarding the geomorphology and sedimentology of alluvial fans of the western Ganga Plain. This area is located in the subtropical region and has a humid climate influenced by summer and winter monsoons, and it may be pointed out here that there is still a limited literature available on the geomorphology and sedimentology of alluvial fans within the humid climatic settings of the subtropical–tropical regions (e.g. Kochel & Johnson, 1984; Kochel, 1990; Evans, 1991; Silva *et al*. 1992; Harvey, 2002; Hashimoto *et al*. 2008; Shukla, 2009; Goswami, Pant & Pandey, 2009).

We have mapped the morphotectonic features and carried out detailed facies analysis of the alluvial fan of the Malin River, which is a tributary of the Ganga River. This fan, hereafter called the Malin Fan, is located to the west of Kotdwar town (78° 31′ 25″ E 29° 45′ N) in the Uttarakhand state of India (Fig. 1a, b). The main objective of the study is to understand the climatic and tectonic controls on alluvial fan evolution in the tectonically active piedmont zone of the Ganga Plain (Nakata, 1972; Yeats & Thakur, 2008; Goswami, Pant & Pandey, 2009). We have carried out detailed facies analysis to establish a conceptual depositional model of the fan and understand the role of palaeoclimate and neotectonics on the fan evolution. We hope that this data will be helpful in understanding the sedimentary processes of alluvial fan evolution in the piedmont zone of the Ganga Plain and similar climatic and geotectonic

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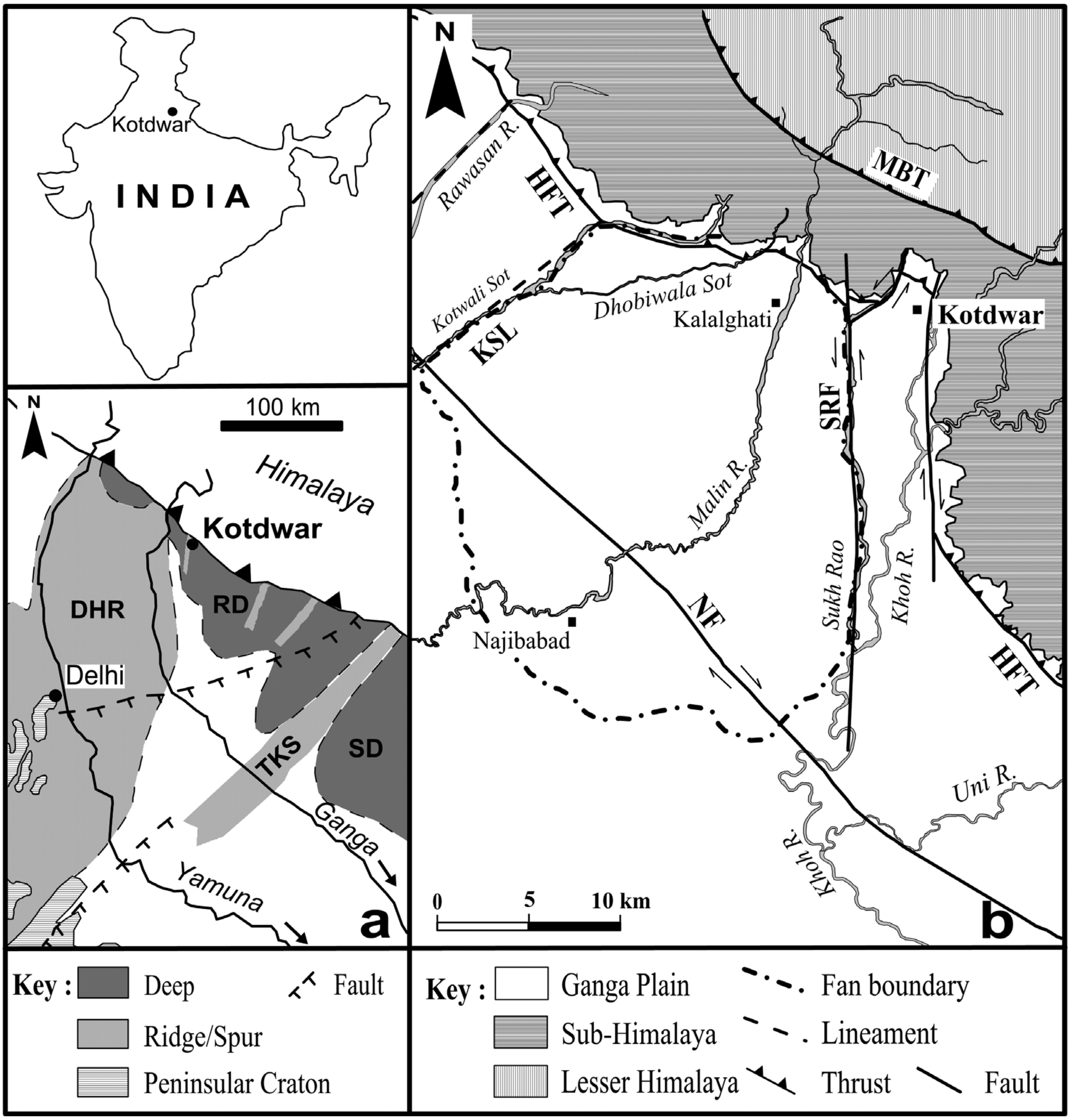

Figure 1. (a) Schematic map showing subsurface structures of the western part of the Ganga Plain (compiled from Karunakaran & Ranga Rao, 1979 and Raiverman, Kunte & Mukherjea, 1983). DHR – Delhi Haridwar Ridge, TKS – Tanakpur Kasganj Spur, RD – Ramganga Deep, SD – Sarda Deep. (b) Geological map showing major lithotectonic units and faults/thrusts of the area. The boundary of the Malin Fan is marked with a dashed line. MBT – Main Boundary Thrust, HFT – Himalayan Frontal Thrust, SRF – Sukh Rao Fault, NF – Najibabad Fault, KSL – Kotwali Sot Lineament, R. – River. Rao and Sot mean stream in the local dialect.

settings in other parts of the world. This can also be helpful in interpreting ancient alluvial fan deposits.

2. Geological setting of the study area

The Ganga Plain is the central part of the alluvium-filled Indo-Gangetic foreland basin system formed on the Indian Plate lithosphere, which was flexed downwards in response to the over-riding of the Himalaya following collision of the Indian and Asian plates (Dewey & Bird, 1970; Lyon-Caen & Molnar, 1985). The sedimentary fill of the basin is of Tertiary (Siwalik Group) and Quaternary ages (Alluvium), which rests unconformably over the Precambrian basement that has a number of ridges/spurs, deeps and faults (Rao, 1973; Raiverman, Kunte & Mukherjea, 1983). The thickness of the sedimentary fill in the basin is highly variable and controlled by the topography of the basement, being a maximum of ~4.5 km in the piedmont zone and decreasing gradually towards the south (Rao, 1973; Raiverman, Kunte & Mukherjea, 1983). The study area corresponds to the western part of the Ramganga frontal deep. There is a nearly N–S-trending spur in the basement of the area (Fig. 1a) (Raiverman, Kunte & Mukherjea, 1983).

The sediments of the study area are derived from the Lesser Himalayan and Sub-Himalayan terranes in the north (Fig. 1b). The Lesser Himalayan terrane is composed of low- and medium-grade metamorphic rocks, granitic quartz-porphyry, sandstones, mudstones and a dolomite-dominated suite of calcareous rocks of Precambrian – Early Cambrian age (Heim & Gansser, 1939; Valdiya, 1995). It is thrust southwards over the Sub-Himalaya along the Main Boundary Thrust (MBT) (Auden, 1934). The Sub-Himalayan range comprises mudstones of the Subathu Formation of Late Paleocene to Eocene age, and mudstones, shales, siltstone and sandstone of the Lower and Middle Siwalik subgroups of Miocene age (Raiverman, 1979; Tandon, 1991; Thakur & Rawat, 1992). The Sub-Himalaya is then thrust southwards over the Ganga Plain alluvium along the Himalaya Frontal Thrust (HFT). The Himalayan rock succession is extensively folded, faulted, fractured and sheared. There are a number of incidences of mass wasting in the Himalaya, most of which are triggered during rains.

3. Morphotectonics of the Malin Fan

The frontal Sub-Himalayan mountain range, adjoining the Malin Fan, rises up to 1056 m amsl (above mean sea level). It has generally planar slope facets. The streams exhibit sub-dendritic, sub-parallel, sub-trellis or semi-rectangular patterns in different parts and debouch into the adjoining piedmont zone through narrow, V-shaped valleys along mountain-front embayments. There are a number of landslides, triangular facets and cliffs developed along different segments of the Siwalik mountain-front. The morphotectonic features of the Malin Fan and surrounding area have been delineated with the help of multispectral imagery from the Indian Remote Sensing satellite, Geographical Information System (GIS) based Digital Terrain Models (DTMs) and field data. The boundaries of the fan were demarcated on the basis of morphological characteristics as proposed by Blair & McPherson (1994). The morphological characters of the fan, like shape, slope angle, slope aspect, longitudinal and transverse profiles, and drainage pattern were examined through DTMs. The measurements of all morphological parameters, like area, length, width, slope angle, etc. were calculated in the GIS. The tectonic features have been demarcated on the basis of their geomorphic expressions, like surface deformations and drainage anomalies.

The Malin Fan and its drainage basin are located in the subtropical region. The mean annual average temperature is around 23 °C, with a maximum of ~40 °C during daytime in summers and a minimum of ~7 °C during winter nights. The rainfall in the area is influenced by the southwest monsoon, the Indian Summer Monsoon, with a maximum rainfall during July and August. Westerlies contribute ~5 to 8 % to the annual rainfall during the months of December to February. During about the last century, the region has been receiving an average of ~1750 mm rainfall during the summer monsoon and an average of ~170 mm precipitation by the westerlies (data source: Indian Institute of Tropical Meteorology, Pune).

The Malin Fan has an area of ~480 km^2 and a radial length of ~27.5 km. It has developed on the footwall of the HFT, but some of its proximal part rests on the hanging wall of the HFT (Figs 1b, 2). The 2-D profiles drawn in the GIS show that the fan is concave-up in longitudinal profile and convex-up in transverse profile. The average radial slope of the fan is ~1.4° in SE to SW directions in the proximal part and ~0.16° in SE to WSW directions in the distal part. The altitudes of the apex and toe of the fan are 518 and 260 m amsl, respectively, and the flow expansion angle beyond the mountain-front embayment is ~114°. The eastern boundary of the fan is defined by the Sukh Rao stream, which flows along the N–S-trending Sukh Rao Fault (SRF) (Fig. 2) (Goswami & Mishra, 2012). The western boundary of the fan is defined by the Kotwali Sot stream, which flows along a distinct NE–SW-trending lineament, hereafter called the Kotwali Sot Lineament (KSL) (Fig. 2). Presently, there is only one prominent channel across the fan that becomes active during the rainy season. It is incised up to ~20 m in the proximal-fan area, with two levels of paired strath terraces developed along its banks. The elevation differences between successive terraces, i.e. river bed (T_0) to first level terrace (T_1) and T_1 to second level terrace (T_2), are ~2 to 4 m and ~9 to 20 m along the right bank and ~2 to 4.5 m and ~9 to 9.5 m along the left bank. However, the elevation difference between successive terraces gradually decreases downstream, and ultimately the terraces terminate at a distance of ~3.4 km downstream of the fan-apex. The channel incision also decreases in the downfan direction to ~5 m in the middle-fan region. In the distal-fan region the channel has a ~2.5 km wide active flood plain. The presence of a major abandoned channel in the west indicates that the stream flow has diverted eastwards into the present-day channel sometime in the Holocene, most likely as a result of the block-tilting caused by the HFT and SRF (Fig. 2).

In the western middle-fan area, and further to the west, a ~7–9 km wide badland zone with up to ~7 m deep gullies is developed almost parallel to the Himalayan trend. This zone represents an upwrap related to the active blind Najibabad Fault trending almost parallel to the Himalayan strike (Parkash *et al.* 2000; Yeats & Thakur, 2008; Goswami & Mishra, 2012). In the east, there are sharp knee-bend turns along the courses of the Khoh and Uni rivers where they cross this fault (Figs 1b, 2).

The Malin Fan receives the bulk of the sediments from the drainage basin of the Malin River, and a subsidiary amount from the drainage basin of the

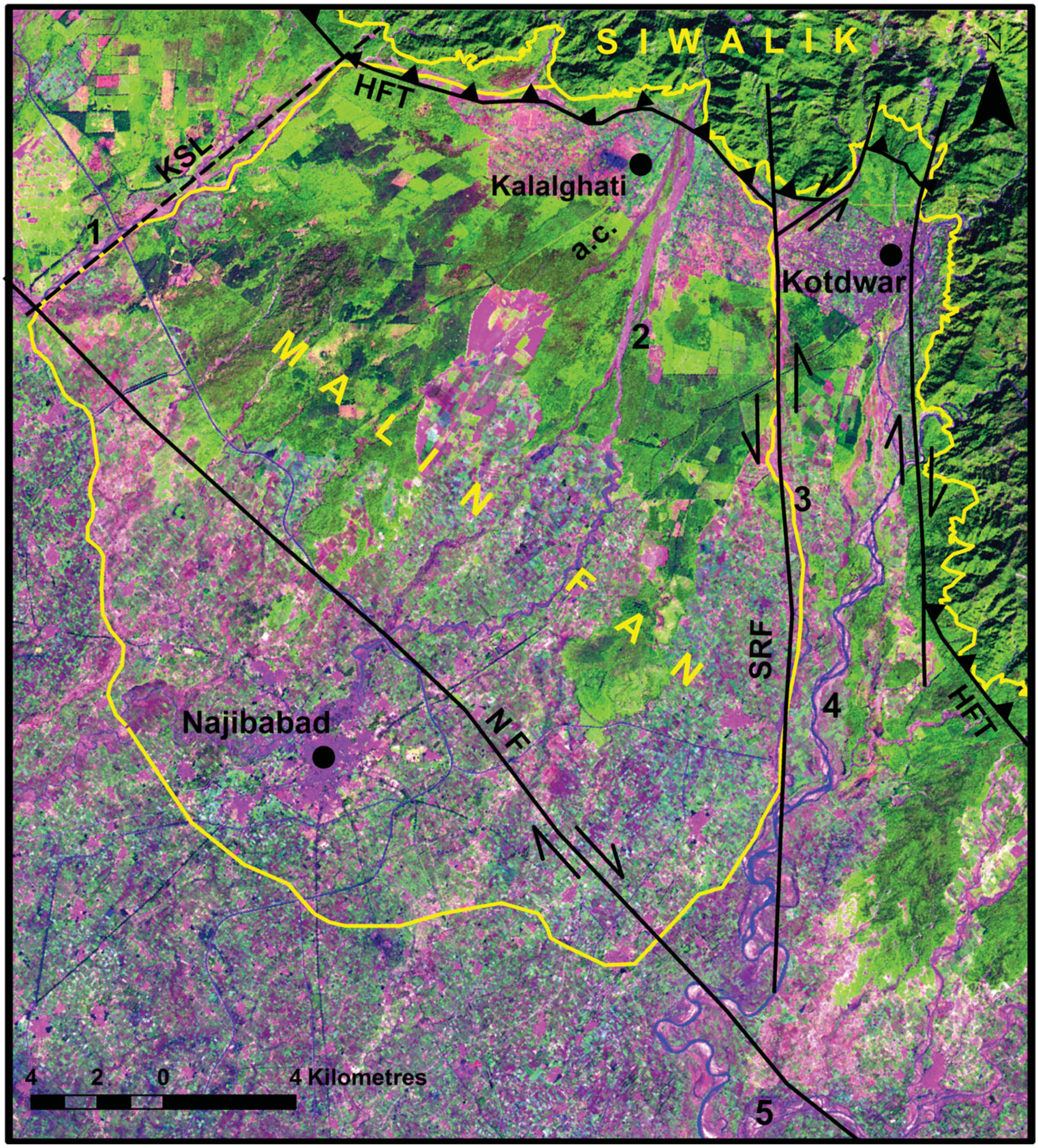

Figure 2. (Colour online) RESOURCESAT-1 LISS III False Colour Composite (Band 3, 4, 5 in Blue, Green, Red channels, respectively) of November 2007 showing the Malin Fan and various tectonic features. 1 – Kotwali Sot stream; 2 – Malin River; 3 – Sukh Rao stream; 4 – Khoh River; 5 – Uni River; a.c. – abandoned channel; KSL – Kotwali Sot Lineament; SRF – Sukh Rao Fault; HFT – Himalayan Frontal Thrust; NF – Najibabad Fault.

Dhobiwala Sot stream. The drainage basin of the Malin River has an area of ~84 km^2 in the Sub-Himalayan and Lesser Himalayan terranes, whereas the drainage basin of the Dhobiwala Sot stream has an area of ~4 km^2 in the Sub-Himalaya. The Malin River is a mainly rain-fed river with its drainage basin extending to a maximum altitude of 1803 m amsl. The river valley is lined with uplifted paired and unpaired terraces, landslides and talus cones in the mountains.

4. Facies analysis

The present facies analysis is based on sedimentological data collected from selected stratigraphic cuts along the complete radial transect of the fan. These cuts are exposed along the banks of the Malin River. Two-dimensional sedimentological profiles/vertical logs were measured and drawn at these stratigraphic cuts. Most of the high stratigraphic cuts in the proximal- and middle-fan regions have collapsed because of the

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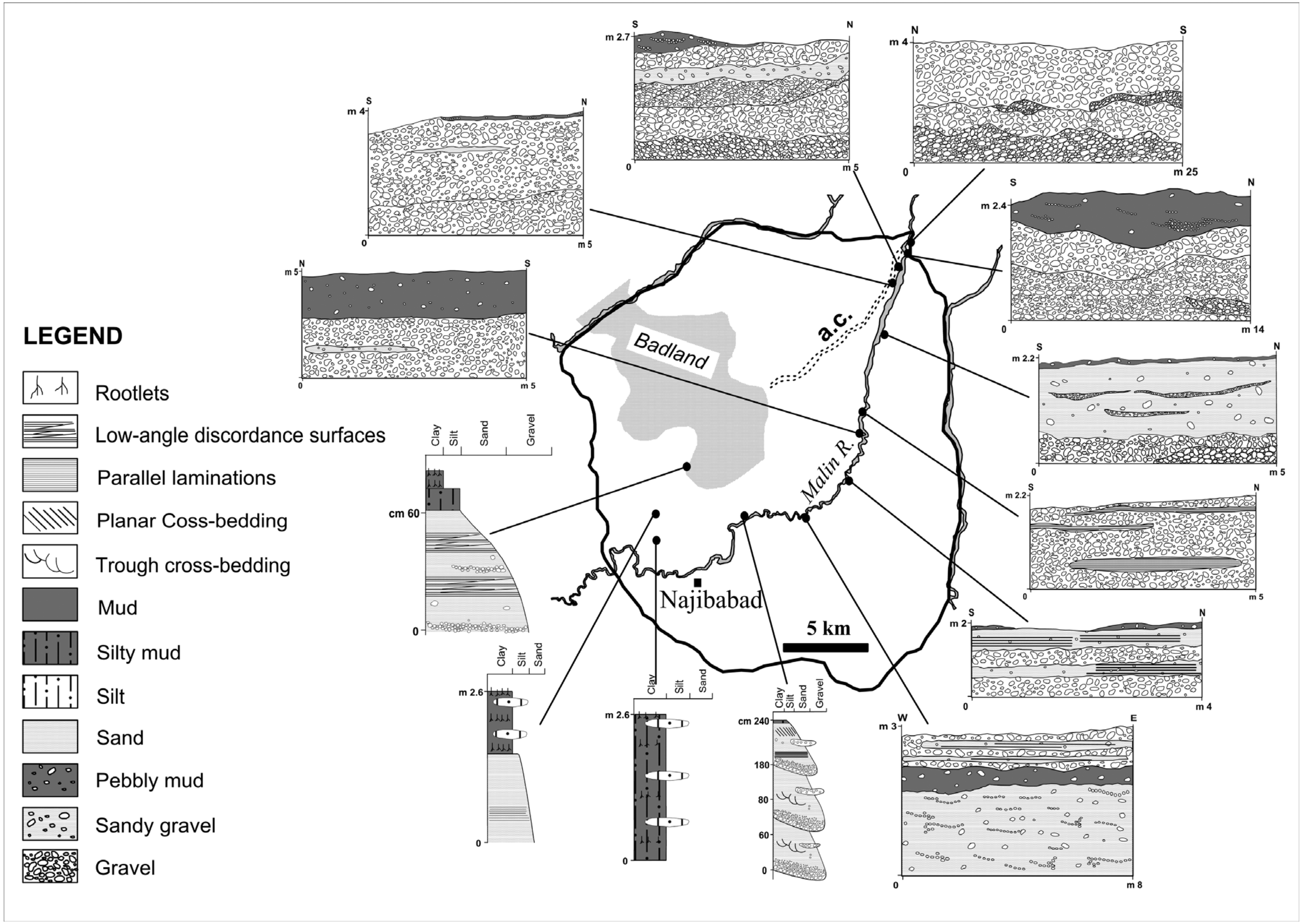

Figure 3. Sedimentological 2-D sections and logs from different parts of the Malin Fan. The badland zone developed in the western part of the fan and an abandoned channel (a.c.) on the fan surface are also shown in the figure.

Figure 4. (Colour online) (a) Matrix-supported gravel (G1 facies) in the proximal part of the fan. Height of the person is 182 cm. (b) Clast-supported gravel (G2 facies) grading upwards into the sand in the middle-fan area. At the top is soil. Length of the hammer is 26 cm. (c) Planar cross-bedded gravel (G3 facies) with basal scour into the underlying matrix-supported gravel (G1) in the middle-fan area. On the top is a sandy gravel unit (G6 facies).

large-scale gravel and sand mining. The collapsed material forms a steep surface along the foot of the cuts and, as such, hinders the sedimentological measurements. Thus, profiles and logs could be drawn only along the stratigraphic cuts of relatively short heights (up to 4 m high). However, sedimentological attributes have been noted at many other cuts as well. Thirteen representative 2-D profiles and logs of the fan are shown in Figure 3. The individual lithofacies have been identified on the basis of bed morphology, mutual contacts with bounding units, clast size, sorting and fabric, and sedimentary structures. In all, nine major facies could be identified from the proximal to distal parts of the fan: six gravel facies, one sand facies and two mud facies. Each of these lithofacies has distinct sedimentological attributes pointing to specific processes of deposition (Table 1; Figs 4–6).

5. Facies associations and distribution

Two distinct stratigraphic packages have been identified in the sedimentary succession of the Malin Fan, hereafter referred to as the lower stratigraphic package (MF_{LS}) and upper stratigraphic package (MF_{US}), respectively. The contact between these two packages is sharp to erosional having undulations of low relief (a few decimetres to ~1 m) and large wavelength (a few metres to a few tens of metres). At a few places along this contact there are intervening, discontinuous, up to a few decimetres thick, fine sand and silty mud layers with some rootlets and faint pedogenesis, and some discontinuous, few millimetre thick ferruginized layers. The vertical and lateral distribution of lithofacies in both the packages shows distinct characters. The unit facies cycles as well as the facies associations are fining upwards (Figs 3, 7). The individual units show a decrease in thickness and clast size and an increase in clast roundness in the downfan direction. In the proximal-fan the MF_{LS} constitutes the tread of the upper level strath terrace. Here the MF_{LS} and MF_{US} do not occur in contact. But, in the far middle-fan and near distal-fan regions both the MF_{LS} and MF_{US} are exposed in normal stratigraphic order. The middle-fan area consists of only gravel facies in the MF_{LS} and dominantly gravel and sand facies in the MF_{US}. The distal-fan area consists of only gravel facies in the MF_{LS} and dominantly sand and mud facies in the MF_{US} surface. At many places in the proximal- and middle-fan areas, the fan surface is covered with an up

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Table 1. Description and interpretation of the lithofacies of the Malin Fan

Facies	Characteristics	Interpretation
Matrix-supported gravel (G1)	Dominant facies of the proximal- and near middle-fan areas; poorly sorted to unsorted, sub-angular to sub-rounded, granule to boulder size clasts, chaotic fabric, sandy silt–mud matrix (Fig. 4a). The individual units, having sharp, non-erosional bases are 60 cm to 2.5 m thick, cobble–boulder dominated in the proximal-fan and 27 cm to 1.3 m thick, pebble–cobble dominated in the middle-fan areas. Few widely dispersed outsized clasts. Massive sand lenses, a few decimetres thick, up to 2 m long, often pebbly, are sometimes present within the gravel units.	Cohesive clast-rich debris flow deposits (Postma, 1986; Nemec & Postma, 1993; Blair & McPherson, 1994).
Clast-supported gravel (G2)	Common in proximal- to far middle-fan areas; 20 to 65 cm thick lensoid units, of poorly sorted, sub-angular to sub-rounded, boulder–pebble clast-supported, gravels, showing a downfan increase in roundness and decrease in size. Clast imbrications with a–b planes dipping upfan and aligned transverse to the slope, indicating a SE–SW-directed palaeocurrent with little variance. Interclast spaces are generally void, but sometimes occupied by the sand. Generally erosional basal part. At a few places in the middle-fan area, the facies grades upwards into the sand–silty sand giving rise to a fining upwards sequence (Fig. 4b).	Deposits of incised channel (Blair, 1999).
Cross-bedded gravel (G3)	Common in proximal- to near middle-fan areas; pebbly to cobbly, planar cross-bedded units, mostly with scoured bases, having a relief of up to 10 to 15 cm (Fig. 4c). Coarser clasts fill the scours. The cross-beds are low angled (less than 23°) and have a set thickness of 24 to 64 cm with normally graded, downfan dipping foresets (Fig. 4c). SSE–SW-directed palaeocurrent directions, many reactivation surfaces and small set thicknesses of up to 6 cm in the middle-fan area.	Channel bar deposits formed by high relief bedform migration under sustained flows in confined channels (Teisseyre, 1976; Koster & Steel, 1984; Shukla, 2009).
Horizontal-bedded gravel (G4)	Common in proximal- to near middle-fan areas; 18 to 25 cm thick bedsets of clast-supported gravels (Fig. 5a) generally associated with the G3 facies. Sub-angular to sub-rounded clasts showing vertical as well as lateral size grading, imbricated in many places with a–b planes aligned perpendicular to the slope and dipping upslope. SE–SW directed palaeoflow conditions.	Deposits of persistent steamflows in gravels transported as bed load and deposited under waning flow by accretion of progressively smaller clasts, in channels and on longitudinal bars (Collinson & Thompson, 1982; Suresh *et al*. 2007)
Disorganized gravel and sand couplet (G5)	Developed only in far middle and lower parts of the distal-fan areas; 20 to 48 cm thick, clast to matrix-supported gravel units interstratified in rhythmic alternations with 10 to 35 cm thick, fine- to coarse-grained, sometimes pebbly, generally laminated sand (Figs 5b, c). Clasts in gravels are imbricated in many places with a–b planes dipping upfan and a-axes perpendicular to the slope. The mutual contacts between the gravel and sand units are mostly sharp and uneroded.	Products of alternating phases of transportation and deposition of gravel and sand in sheetfloods (Blair & McPherson, 1994)
Sandy gravel (G6)	Developed only in far middle-fan areas; 62 cm to 2.5 m thick, deposited in proximal- and middle-fan areas, comprising largely sub-rounded to sub-angular pebbles and cobbles set in sandy matrix. The individual units are crudely stratified, up to 65 cm thick, moderately sorted and show a fining up clast size (Fig. 5d); sharp to erosional basal contact. In the downfan direction, the clast roundness increases to rounded, clast size decreases to dominantly pebble, and the clast:matrix ratio also decreases. Occasional outsized clasts fill the scours in the underlying unit.	Vertical accretion of progressively smaller clasts under upper flow regime of persistent, but waning flow in aggrading channels (Teisseyre, 1976; Suresh *et al*. 2007; Shukla, 2009).
Cross-bedded sand (S1)	Developed only in the upper parts of the far middle-fan and distal-fan areas; 90 cm to 4.2 m thick facies, comprising lensoid, fining up, multi-storeyed sand units, generally pebble gravelly at the base and very fine to silty at the top; a few granule–pebbles are also dispersed around; sometimes up to a few decimetres thick pebbly lenses also occur. The sand is planar and trough cross-bedded, and parallel laminated, which sometimes show low-angle discordances (Fig. 6a–c). The trough cross-beds are 4 to 15 cm thick and occur in cosets. The planar cross-beds are 3 to 15 cm thick. The palaeocurrent pattern is SE–SW directed with high variance.	Deposits of point bars, marked with short-lived, intermittent high-energy pulses (Walker & Cant, 1984)

Table 1. Continued

Facies	Characteristics	Interpretation
Pebbly mud (M1)	Developed in proximal- to distal-fan areas; 35 cm to 3 m thick units characterized by massive silty mud containing a few disseminated sub-angular to sub-rounded pebbles; pebbles sometimes occur as few decimetres thick and few metres long irregular pebbly bodies. The a–b planes of the pebbles are mostly aligned parallel to the slope (Fig. 6d). The facies generally has a sharp nonerosional lower contact.	Deposited by clast-deficient mudflows (Coussot & Meunier, 1996; Singh *et al.* 2001)
Massive mud (M2)	Developed only in the upper parts of the distal-fan areas. Highly variable in thickness from 15 cm to 7 m; very common in the distal and middle-fan areas. Yellow and greyish coloured mud containing a few decimetre thick silt layers of the same colour. Pervasive mottling and root traces; uniform texture all though the vertical extent.	Deposited in fluvial overbank environments (Bridge, 1984; Singh *et al.* 2001).

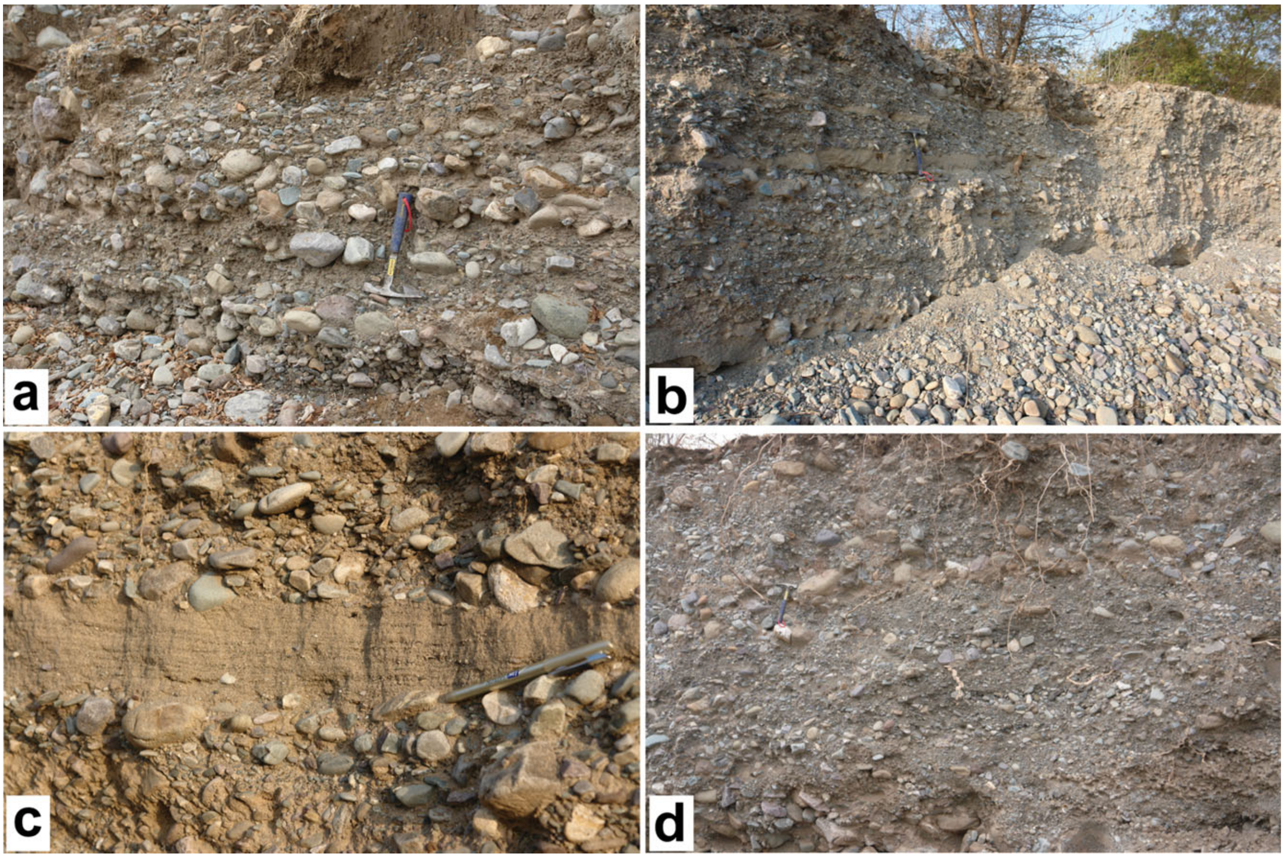

Figure 5. (Colour online) (a) Horizontal-bedded gravel (G4 facies) in the proximal part of the fan. Length of the hammer is 26 cm. (b) Disorganized gravel and sand couplets (G5 facies) in the middle-fan area. (c) Close-up of the sand unit of the G5 facies. The granule–pebble-bearing coarse sand is parallel laminated. Length of the pen is 14.5 cm. (d) Crudely bedded sandy gravel (G6 facies) developed in the middle-fan area.

to a few decimetres thick pedogenic soil. The facies associations observed in different parts of the Malin Fan are shown in Figure 7 and given below:

(1) Matrix-supported gravel (G1), clast-supported gravel (G2), cross-bedded gravel (G3), horizontal-bedded gravel (G4) and pebbly mud (M1) in the proximal part. The G1 facies dominates the succession by constituting ~65 % of the stratigraphic cuts followed by a ~25 % share taken up by the G2, G3 and G4 facies.

(2) Matrix-supported gravel (G1) and pebbly mud (M1) in the MF_{LS} of the middle part with the G1 facies constituting ~80 % of the stratigraphic cuts.

(3) Matrix-supported gravel (G1), clast-supported gravel (G2), cross-bedded gravel (G3), horizontal-bedded gravel (G4) and pebbly mud (M1) in the MF_{US} of the near middle-fan area. The G1, G4 and G3 facies together constitute ~70 % of the stratigraphic cuts.

(4) Disorganized gravel and sand couplet (G5), sandy gravel (G6), cross-bedded sand (S1), clast-supported gravel (G2), pebbly mud (M1) and massive to laminated mud (M2) in the MF_{US} of the far middle-fan area. The G5 facies dominates the succession by constituting ~40 % of the stratigraphic cuts, followed by the S1 facies with a ~30 % share.

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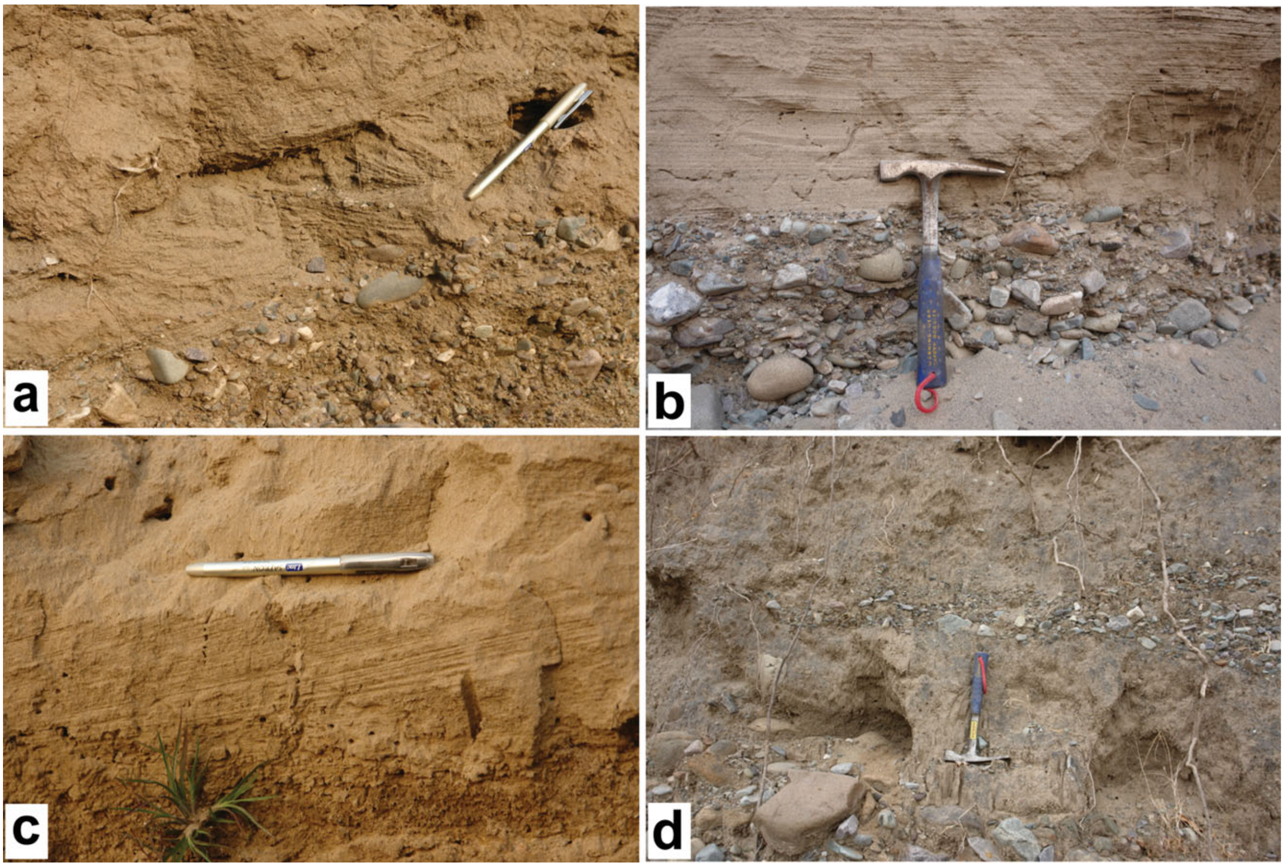

Figure 6. (Colour online) (a) Trough cross-bedding in cosets overlying the pebble gravels (facies S1) in the middle-fan area. Length of the pen is 14.5 cm. (b) Parallel laminated sand (S1 facies) overlying the clast-supported pebble gravel (G2 facies) in the middle-fan area. (c) Planar cross-bedding in the sand (facies S1) in the distal-fan area. Length of the hammer is 26 cm. (d) Pebbly mud (M1 facies) in the proximal part of the fan.

(5) Disorganized gravel and sand couplet (G5) and pebbly mud (M1) in the MF_{LS} of the distal-fan, with the G5 facies constituting ~80 % of the stratigraphic cuts.

(6) Cross-bedded sand (S1) and massive to laminated mud (M2) in the MF_{US} of the distal-fan with variable proportions at different locations.

6. Depositional model

In the piedmont zone of the western Ganga Plain, between Yamuna River in the west and Sarda River in the east, the Malin Fan is the second largest alluvial fan, next to the Gola Fan, which formed ~120 km southeast of the Malin Fan (cf. Goswami, Pant & Pandey, 2009, Goswami & Yhokha, 2010).

The facies associations and distribution indicate that the MF_{LS} and MF_{US} are related to two distinct, most recent cycles of the Malin Fan evolution, the MF_{LS} representing the older and MF_{US} representing the younger evolutionary cycle. These cycles are separated by a time gap, during which there was insignificant sediment supply to the basin and occasional sheet flows redistributed the sediments of the MF_{LS} unit to deposit a veneer of fine sediments in shallow depressions on the fan surface. The absence of any mature soil profile in between the MF_{LS} and MF_{US} units indicates that this time gap was of a short duration. Interestingly, Shukla (2009) also identified two distinct evolutionary cycles, separated by a hiatus, in the exposed fill of the Gola Fan. The older evolutionary cycle of the Gola Fan is characterized by fluvial processes in continuously changing channel patterns, from gravelly braided in the proximal part to sandy braided in the middle part and meandering in the distal part of the fan, whereas the younger cycle is characterized by multiple debris flow events (Shukla, 2009).

In contrast to the Gola Fan, the older evolutionary cycle of the Malin Fan is characterized by sediment gravity flows in the upper reaches and sheetfloods in the lower reaches of the fan, whereas the younger cycle is dominated by sediment gravity flows and channel processes in the proximal-fan, sheetfloods and fluvial processes in the middle-fan, and fluvial processes in the distal-fan regions.

The fan building activities of the MF_{LS} cycle were intense, capable of transporting gravelly sediments down to long distances from the mountain-front (Fig. 8). During this period, a high volume of water flushed out a huge quantity of sediments from the source to the basin, under steeper regional gradients. The sediments were emplaced as sheetfloods caused by flash floods during catastrophic events and as sediment

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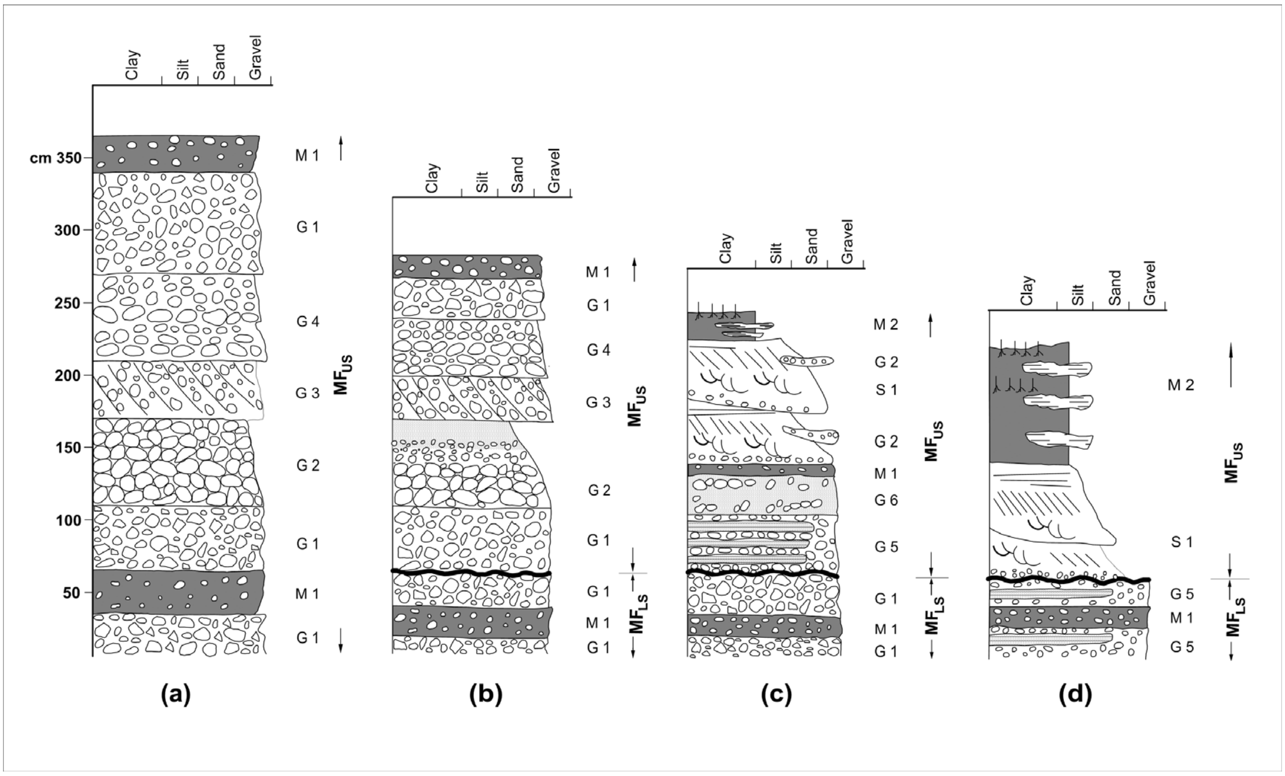

Figure 7. Sedimentological logs showing generalized facies associations in the (a) proximal part of the fan, which is dominated by the matrix-supported gravel (G1) facies, (b) near the middle-fan area, in which the dominance of the matrix-supported gravel (G1) facies decreases in the MF_{US} unit as compared with the MF_{LS} unit, (c) far middle-fan area, in which the matrix-supported gravel (G1) facies is deposited only in the MF_{LS} unit and the disorganized gravel and sand couplet (G5) facies and sandy gravel (S1) facies dominate the $MF_{US,}$ and (d) distal-fan area, in which the MF_{LS} unit is dominated by the disorganized gravel and sand couplet (G5) facies and the MF_{US} unit is exclusively sandy and muddy with no gravels. Legend is the same as in Figure 3.

gravity flows during non-catastrophic events (Fig. 9). The sheetfloods deposited gravel–sand couplets of the G5 facies, whereas the debris flows and mud flows deposited matrix-supported gravels of the G1 facies and pebbly mud of the M1 facies, respectively (cf. Blair & McPherson, 1994).

The fan building activities during the MF_{US} cycle were reduced, during which gravelly sediments could not be transported far from the source (Fig. 8). During this cycle, the fan aggraded through deposition in the channels as well as on the fan surface (Fig. 9). In the proximal-fan and near middle-fan areas, sediment gravity flows deposited G1 and M1 facies, whereas under high water-to-sediment ratio conditions sediments of the G2 facies were deposited in the shallow depressions of the channels, and sediments of the G3 facies formed channel bars (cf. Teisseyre, 1976; Blair & McPherson, 1994; Blair, 1999; Shukla, 2009). The gravels of the G4 facies were deposited as channel lags or on longitudinal bars under persistent flows of waning floods (cf. Collinson & Thompson, 1982; Suresh *et al.* 2007). During the flash flooding events, sheetfloods were generated which deposited gravels up to the lower reaches of the middle-fan region. The gravel–sand couplets of the G5 facies were deposited on the fan surface, and sandy gravels of the G6 facies were deposited in shallow channels during waning flood conditions (cf. Blair & McPherson, 1994; Teisseyre, 1976). The downfan region was formed by the fluvial processes of smaller sandy channels, which developed due to effective grain-size sorting by consistent flow conditions for a considerable period of time (cf. Brozovic & Burbank, 2000) under a high water-to-sediment ratio and a gentler channel gradient. In this region, sand of the S1 facies deposited in point bars and mud–silt of the M1 facies deposited in overbank areas following floods (cf. Bridge, 1984; Walker & Cant, 1984). The infrequent pulses of high water discharge caused scouring and deposition of pebbles in the channels.

7. Discussion and conclusion

The sedimentation in the piedmont zone of the Ganga Plain started at about 25 ka BP and continued until as late as 3 ka BP (Singh, 1996; Srivastava *et al.* 2003). During this period of time the Ganga Plain and adjoining Himalaya of this region witnessed distinct climatic oscillations (e.g. Barnard *et al.* 2004; Kotlia *et al.* 2010; Ray & Srivastava, 2010). Furthermore, there have been distinct phases of monsoon intensification and weakening during late Pleistocene–Holocene times (see Kale, 2007 and references therein). The Quaternary period was also the time of intense tectonic activities in the region (Nakata, 1989; Valdiya, 2001). In conceptual models, these climatic and tectonic

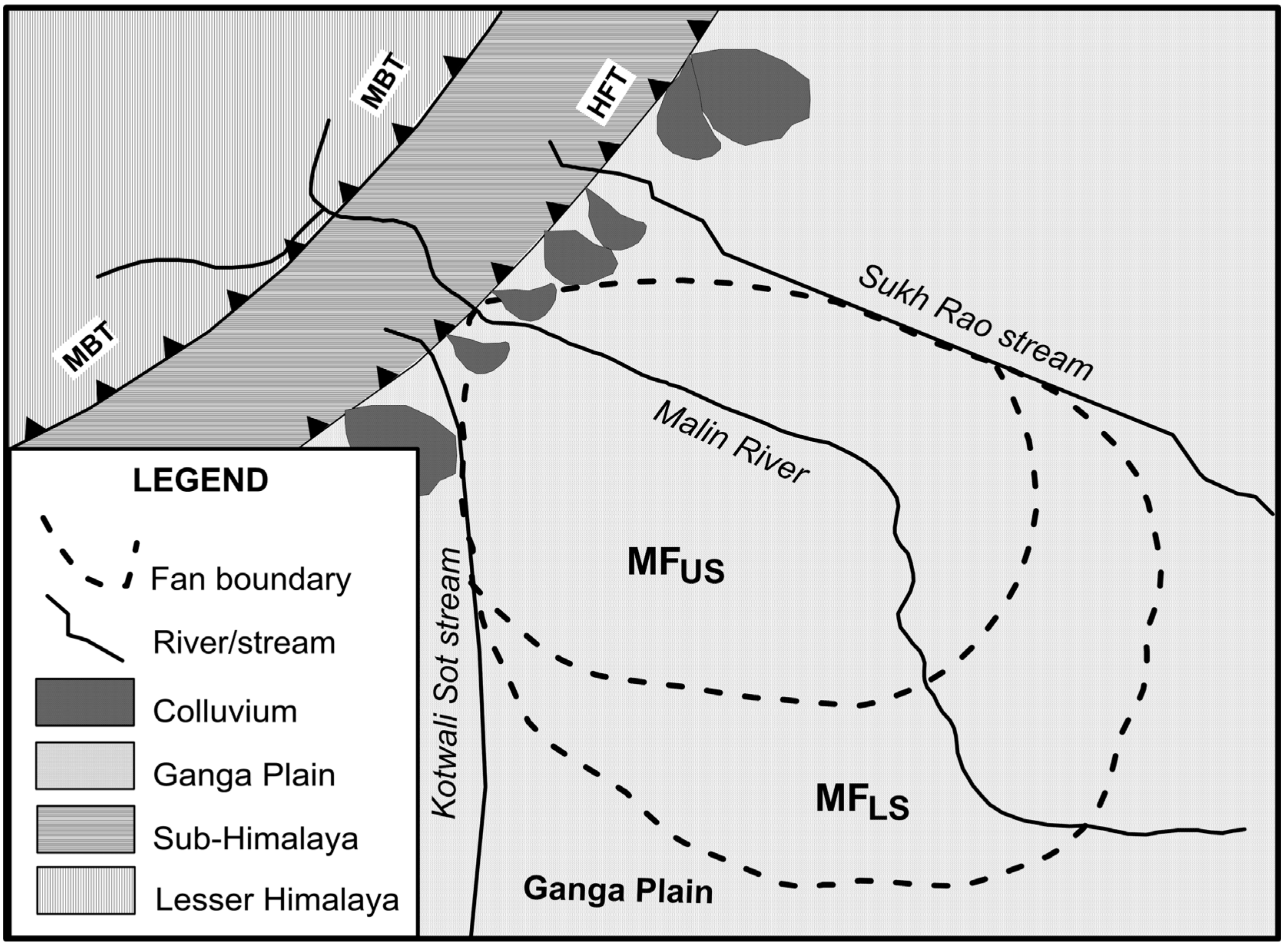

Figure 8. Diagrammatic sketch showing spatial extent of the latest two evolutionary cycles of the Malin Fan. MF_{LS} represents the older cycle and MF_{US} represents the younger evolutionary cycle.

phenomena are considered to be the primary variables of alluvial fan evolution (Ritter *et al*. 1995; Calvache, Viseras & Fernandez, 1997; Harvey, 2003; Viseras *et al*. 2003; Harvey, Mather & Stokes, 2005). The alluvial fans developed ∼100 to 150 km southeast of the present area conform to such models: the morphologies of the Nihal, Gola, Nandhaur and Kalonia fans are tectonically controlled (Goswami, Pant & Pandey, 2009), whereas the sedimentary processes of the Gola Fan have been climatically controlled (Shukla, 2009).

The evolution of the Malin Fan is also tectonically and climatically controlled. The transverse expansion of the fan is tectonically controlled by the SRF in the east and KSL in the west (Fig. 2). The SRF is related to a basement spur that actively pushes and indents the mountain-front (Fig. 1b) (Goswami & Mishra, 2012). Moreover, in the north the HFT has controlled and deflected the streams southwestwards or southeastwards, preventing them from forming their own fans or contributing sediments to the Malin Fan, e.g. the Kotwali Sot stream (Fig. 2). Movements along the HFT have also facilitated further incision of the channel in the proximal-fan and thus controlled the sedimentary processes by confining the flows within the channel itself.

Shukla (2009) identified five mesocycles of gravel emplacement in the Gola Fan: three in the borehole data and two in the exposed sections. The lower four of these cycles deposited gravels up to the distal-fan area, whereas the youngest one deposited gravels only up to the middle-fan area. Similarly, the MF_{LS} and MF_{US} cycles of the Malin Fan deposited gravels up to the distal- and middle-fan areas, respectively. These observations clearly indicate that the fan building activities in the piedmont zone have reduced with time (Figs 8, 9). This reduction could be a result of (i) a decrease in the sediment supply from the source, (ii) a decrease in the water-to-sediment ratio, and (iii) a decrease in the regional gradient, or (iv) a combination of any two, or all, of these climate and tectonics related factors.

Supply of a large amount of coarse clasts from a distant source through a river channel requires a high water budget. In the case of the rivers in the study area, the variations in water budget are directly related to variations in the rainfall because these have been mainly rain-fed rivers. The high rainfall not only flushes out the already generated sediment from the basin but also generates a huge sediment quantity by triggering mass wasting (cf. Bookhagen, Thiede & Strecker, 2005), although the role of tectonic

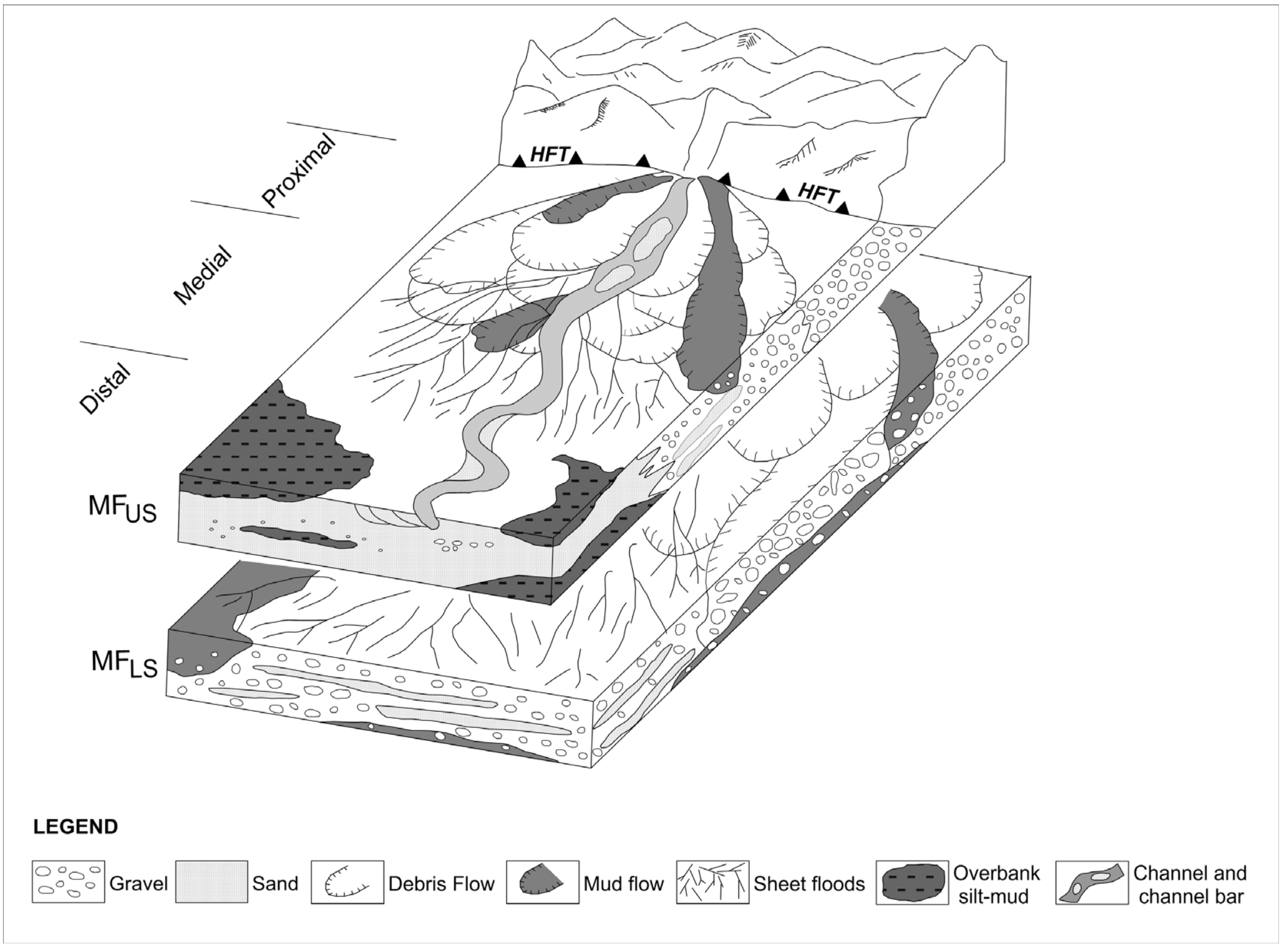

Figure 9. Schematic depositional model of the Malin Fan. During the older MF_{LS} cycle, debris flows, mud flows and sheetfloods deposited gravels at long distances from the mountain-front. During the younger MF_{US} cycle, sediment gravity flows deposited sediments up to the near middle-fan area and sheetfloods deposited sediments in the distal-fan area. Sediments have also been deposited in shallow channel hollows and channel bars in the proximal part of the fan and near middle-fan areas. Down in the far middle-fan and distal-fan areas sediments have been deposited in point bars and overbank areas.

activities in triggering mass wasting and generating sediments in the basin should not be underestimated (e.g. Keefer, 1994). The MF_{LS} cycle of the Malin Fan indicates deposition in a wetter climatic phase of strengthened monsoon when powerful sediment gravity flows and sheetfloods carried coarser clasts down to long radial distances, under steeper regional gradients. This was followed by dry climatic conditions of a weak monsoon, during which occasional sheet flows only redistributed the sediment on the fan surface. The fan building activities were renewed during the MF_{US} cycle due to strengthening of the monsoon, which was, however, not as powerful as had been during the MF_{LS} cycle. Consequently, the fan building activities were comparatively less powerful and generally unable to transport gravelly sediments beyond the middle-fan area. This cycle of the Malin Fan evolution shows clear clast size grading from gravels in the proximal part to gravel–sand in the middle part and sand–silt–mud in the distal part. Such downfan clast size grading has been noticed in most of the fans deposited by fluid gravity processes (e.g. Boothroyd & Nummedal, 1978; Harvey, 1984).

Presently, the Malin River is deeply incised to the north of the Najibabad Fault, in the proximal- and middle-fan regions, and the sediments are deposited within the channel only. Here, the fan surface is only very slowly accreting in some areas by sheet flows, mainly through redistribution of the small colluvial slides. But, to the south of the Najibabad Fault, the distal-fan areas are flooded during heavy monsoonal rains and accrete through overbank sedimentation. In this part of the fan, point bars are also developed along the Malin River. It has been observed in laboratory experiments that the channel entrenchment and terrace formation in the fanhead area, and channel avulsion and migration in the distal-fan area, are commonly associated with the late stages of fan evolution due to intrinsic factors (Hooke, 1968; Clarke, Quine & Nicholas, 2010). Nevertheless, keeping in view the tectonic setting of the region, the role of activities along the Najibabad Fault, HFT and SRF cannot be completely ruled out in influencing the channel entrenchment on the fan. Anthropogenic activities in the form of extensive gravel and sand mining from the river bed and channel walls are also playing their role

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in affecting the channel processes, whether to a little or large extent.

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References

AUDEN, J. B. 1934. The geology of the Krol belt. *Records of the Geological Survey of India* **67**, 357–454.

BARNARD, P., OWEN, L. A., SHARMA, M. C. & FINKEL, R. C. 2004. Late Quaternary (Holocene) landscape evolution of a monsoon influenced high Himalayan valley, Gori Ganga, Nanda Devi, NE Garhwal. *Geomorphology* **61**, 91–110.

BLAIR, T. C. 1999. Sedimentology of gravelly Lake Lahontan highstand shoreline deposits, Churchill Butte, Nevada, USA. *Sedimentary Geology* **123**, 199–218.

BLAIR, T. C. & MCPHERSON, J. G. 1994. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes and facies assemblages. *Journal of Sedimentary Research* **3**, 433–89.

BOOKHAGEN, B., THIEDE, R. C. & STRECKER, M. R. 2005. Late Quaternary intensified monsoon phases control landscape evolution in the northwest Himalaya. *Geology* **33**, 149–52.

BOOTHROYD, J. C. & NUMMEDAL, D. 1978. Proglacial braided outwash: a model for humid alluvial fan deposits. In *Fluvial Sedimentology*. (ed. A. D. Miall), pp. 641–68. Canadian Society of Petroleum Geologists Memoir 5.

BRIDGE, J. S. 1984. Large-scale facies sequences in alluvial overbank environments. *Journal of Sedimentary Petrology* **54**, 583–8.

BROZOVIC, N. & BURBANK, D. W. 2000. Dynamic fluvial systems and gravel progradation in the Himalayan foreland. *Geological Society of America Bulletin* **112**, 394–412.

CALVACHE, M. L., VISERAS, C. & FERNANDEZ, J. 1997. Controls on fan development – evidence from fan morphometry and sedimentology; Sierra Nevada, SE Spain. *Geomorphology* **21**, 60–84.

CHAKRABORTY, T., KAR, R., GHOSH, P. & BASU, S. 2010. Kosi megafan: historical records, geomorphology and the recent avulsion of the Kosi River. *Quaternary International* **227**, 143–60.

CLARKE, L., QUINE, T. A. & NICHOLAS, A. 2010. An experimental investigation of autogenic behaviour during alluvial fan evolution. *Geomorphology* **115**, 278–85.

COLLINSON, J. D. & THOMPSON, D. B. 1982. *Sedimentary Structures*. London: Allen and Unwin.

COUSSOT, P. & MEUNIER, N. 1996. Recognition, classification and mechanical description of debris flows. *Earth-Science Reviews* **40**, 206–27.

DEWEY, J. F. & BIRD, J. M. 1970. Mountain belts and new global tectonics. *Journal of Geophysical Research* **40**, 695–707.

EVANS, J. E. 1991. Facies relationships, alluvial architecture, and paleohydrology of a paleogene, humid-tropical alluvial-fan system: Chumstick Formation, Washington State, U.S.A. *Journal of Sedimentary Petrology* **61**, 732–55.

GEDDES, A. 1960. The alluvial morphology of the Indo-Gangetic Plains: its mapping and geographical significance. *Transactions of the Institute of British Geographers Publications* **28**, 253–77.

GOHAIN, K. & PARKASH, B. 1990. Morphology of the Kosi Megafan. In *Alluvial Fans: A Field Approach* (eds A. Rachoki & M. Church). Chichester: John Wiley and Sons Ltd.

GOSWAMI, P. K. & MISHRA, J. K. 2012. Integrated remote sensing-, GIS- and field-based morphotectonic investigations in the piedmont zone of the western Ganga Plain, India. In *Abstract Volume of the National Seminar on Geology and Georesources of Himalaya and Cratonic regions of India, Department of Geology, Kumaun University, Nainital, India,* 73–4.

GOSWAMI, P. K., PANT, C. C. & PANDEY, S. 2009. Tectonic controls on the geomorphic evolution of alluvial fans in the Piedmont Zone of the Ganga Plain, Uttarakhand, India. *Journal of Earth System Science* **118**, 245–59.

GOSWAMI, P. K. & YHOKHA, A. 2010. Geomorphic evolution of the Piedmont Zone of the Ganga Plain, India: a study based on remote sensing, GIS and field investigation. *International Journal of Remote Sensing* **31**, 5349–64.

HARVEY, A. M. 1984. Debris flows and fluvial deposits in Spanish Quaternary alluvial fans: implications for morphology. In *Sedimentology of Gravel and Conglomerate* (eds E. H. Koster & R. J. Steel), pp. 123–32. Canadian Society of Petroleum Geologists Memoir 10.

HARVEY, A. M. 2002. The role of base level change in the dissection of alluvial fans: case studies from southeast Spain and Nevada. *Geomorphology* **45**, 67–87.

HARVEY, A. M. 2003. The response of dry-region alluvial fans to late Quaternary climate change. In *Desertification in the Third Millennium* (eds A. S. Alsharhan, W. W. Wood, A. S. Goudie, A. Fowler & E. M. Abdellatif), pp. 83–98. Rotterdam: Balkenia.

HARVEY, A. M., MATHER, A. E. & STOKES, M. 2005. Alluvial fans: geomorphology, sedimentology, dynamics – introduction. A review of alluvial-fan research. In *Alluvial Fans: Geomorphology, Sedimentology, Dynamics* (eds A. M. Harvey, A. E. Mather & M. Stokes), pp. 1–7. Geological Society London, Special Publication no. 251.

HASHIMOTO, A., OGUCHI, T., HAYAKAWA, Y., LIN, Z., SAITO, K. & WASKLEWICZ, T. A. 2008. GIS analysis of depositional slope change at alluvial-fan toes in Japan and the American Southwest. *Geomorphology* **100**, 120–30.

HEIM, A. & GANSSER, A. 1939. Central Himalaya: geological observations of the Swiss Expedition 1936. *Memoirs Helvetique des Sciences Naturelles* **73**, 1–245.

HOOKE, R. L. 1968. Model geology: prototype and laboratory streams: discussion. *Geological Society of America Bulletin* **79**, 391–4.

KALE, V. S. 2007. Fluvio-sedimentary response of the monsoon-fed Indian rivers to Late Pleistocene-Holocene changes in monsoon strength: reconstruction based on existing ^{14}C dates. *Quaternary Science Reviews* **26**, 1610–20.

KARUNAKARAN, C. & RANGA RAO, A. 1979. Status of exploration for hydrocarbons in the Himalayan region – contribution to stratigraphy and structure. *Geological Survey of India Miscellaneous Publications* **41**, 1–66.

KEEFER, D. K. 1994. The importance of earthquake-induced landslides to longterm slope erosion and slope-failure

hazards in seismically active regions. *Geomorphology* **10**, 265–84.
KOCHEL, R. C. 1990. Humid alluvial fans of the Appalachian Mountains. In *Alluvial Fans: A Field Approach* (eds A. H. Rachocki & M. Church), pp. 109–29. Chichester: John Wiley and Sons Ltd.
KOCHEL, R. C. & JOHNSON, R. A. 1984. Geomorphology and sedimentology of humid-temperate alluvial fans, central Virginia. In *Sedimentology of Gravel and Conglomerate* (eds E. H. Koster & R. J. Steel), pp. 109–22. Canadian Society of Petroleum Geologists Memoir 10.
KOSTER, E. H. & STEEL, R. J. 1984. Sedimentology of gravels and conglomerates. *Memoir of the Canadian Society of Petroleum Geologists* **10**, 1–441.
KOTLIA, B. S., SANWAL, J., PHARTIYAL, B., JOSHI, L. M., TRIVEDI, A. & SHARMA, C. 2010. Late Quaternary climatic changes in the eastern Kumaun Himalaya, India, as deduced from multi-proxy studies. *Quaternary International* **213**, 44–55.
LYON-CAEN, H. & MOLNAR, P. 1985. Gravity anomalies, flexure of the Indian Plate and the structure, support and evolution of the Himalaya and Ganga basin. *Tectonics* **4**, 513–38.
NAKATA, T. 1972. Geomorphic history and crustal movements of the foothills of the Himalaya. *Tohoku University Science Reports, 7th Series, Japan* **22**, 39–177.
NAKATA, T. 1989. Actives faults of the Himalaya of India and Nepal. *Geological Society of America Special Paper* **232**, 243–64.
NEMEC, W. & POSTMA, G. 1993. Quaternary alluvial fans in southern Crete: sedimentation process and geomorphic evolution. In *Alluvial Sedimentation* (eds M. Marzo & C. Puigdefabregas), pp. 235–76. Special Publication of the International Association of Sedimentologists 17.
PARKASH, B., KUMAR, S., SOMESHWAR RAO, M., GIRI, S. C., SURESH KUMAR, C., GUPTA, S. & SRIVASTAVA, P. 2000. Holocene tectonic movements and stress field in the western Gangetic plains. *Current Science* **79**, 438–49.
POSTMA, G. 1986. Classification for sediment gravity-flow deposits based on flow conditions during sedimentation. *Geology* **14**, 291–4.
RAIVERMAN, V. 1979. Stratigraphy and facies distribution of Subathu sediments, Simla Hills, northwest Himalaya. *Geological Survey of India Miscellaneous Publications* **41**, 111–26.
RAIVERMAN, V., KUNTE, S. V. & MUKHERJEA, A. 1983. Basin geometry, Cenozoic sedimentation and hydrocarbon in north western Himalaya and Indo-Gangetic plains. *Petroleum Asia Journal* **6**, 67–92.
RAO, M. B. R. 1973. The subsurface geology of the Indo-Gangetic Plains. *Journal of the Geological Society of India* **14**, 217–42.
RAY, Y. & SRIVASTAVA, P. 2010. Widespread aggradation in the mountainous catchment of the Alaknanda-Ganga River. *Quaternary Science Reviews* **29**, 2238–60.
RITTER, J. B., MILLER, J. R., ENZEL, Y. & WELLS, S. G. 1995. Reconciling the roles of tectonism and climate in Quaternary alluvial fan evolution. *Geology* **23**, 245–8.
SHUKLA, U. K. 2009. Sedimentation model of gravel-dominated alluvial piedmont fan, Ganga Plain, India. *International Journal of Earth Sciences* **98**, 443–59.
SHUKLA, U. K. & BORA, D. S. 2003. Geomorphology and sedimentology of Piedmont zone, Ganga plain, India. *Current Science* **84**, 1034–40.
SHUKLA, U. K., SINGH, I. B., SHARMA, M. & SHARMA, S. 2001. A model of alluvial megafan sedimentation: Ganga Megafan. *Sedimentary Geology* **40**, 105–29.
SILVA, P. G., HARVEY, A. M., ZAZO, C. & GOY, J. L. 1992. Geomorphology, depositional style and morphometric relationships of Quaternary alluvial fans in the Guadalentin Depression (Murcia, Southeast Spain). *Zeitschrift für Geomorphologie N.F.* **36**, 325–41.
SINGH, I. B. 1996. Geological evolution of the Ganga Plain – an overview. *Journal of the Palaeontological Society of India* **41**, 90–137.
SINGH, A. K., PARKASH, B., MOHINDRA, R., THOMAS, J. V. & SINGHVI, A. K. 2001. Quaternary alluvial fan sedimentation in the Dehradun valley piggyback basin, NW Himalaya: tectonic and palaeoclimatic implications. *Basin Research* **13**, 449–71.
SRIVASTAVA, P., SINGH, I. B., SHARMA, M. & SINGHVI, A. K. 2003. Luminescence chronometry and late Quaternary geomorphic history of the Ganga Plain, India. *Palaeogeography, Palaeoclimate, Palaeoclimate* **197**, 15–41.
SURESH, N., BAGATI, T. N., KUMAR, R. & THAKUR, V. C. 2007. Evolution of Quaternary alluvial fans and terraces in the intramontane Pinjaur Dun, Sub-Himalaya, NW India: interaction between tectonics and climate change. *Sedimentology* **54**, 809–33.
TANDON, S. K. 1991, The Himalayan foreland: focus on Siwalik Basin. In *Sedimentary Basins of India: Tectonic Context* (eds S. K. Tandon, C. C. Pant & S. M. Casshyap), pp. 71–201. Nainital: Gyanodaya Prakashan.
TEISSEYRE, A. K. 1976. Pebble fabric in braided stream deposits with examples from Recent and ‘frozen’ Carboniferous channels (Intrasudetic Basin, Central Sudetes). *Geologia Sudetica* **X**, 7–47.
THAKUR, V. C. & RAWAT, B. S. 1992. *Geological Map of Western Himalaya*. Dehradun, India: Wadia Institute of Himalayan Geology, 22 pp.
VALDIYA, K. S. 1995. Proterozoic sedimentation and Pan-African geodynamic development in the Himalaya. *Precambrian Research* **74**, 35–55.
VALDIYA, K. S. 2001. Reactivation of terrane-defining boundary thrusts in central sector of the Himalaya: implications. *Current Science* **81**, 1418–31.
VISERAS, C., CALVACHE, M. L., SORIA, J. M. & FERNANDEZ, J. 2003. Differential features of alluvial fans controlled by tectonic or eustatic accommodation space. Examples from the Betic Cordillera, Spain. *Geomorphology* **50**, 181–202.
WALKER, R. G. & CANT, D. J. 1984. Sandy fluvial systems. In *Facies Models* 2nd Ed. (ed. R. G. Walker), pp. 71–90. Geological Association of Canada, Newfoundland.
YEATS, R. S. & THAKUR, V. C. 2008. Active faulting south of the Himalayan Front: establishing a new plate boundary. *Tectonophysics* **453**, 63–73.