Geomorphology and sedimentology of Piedmont zone, Ganga Plain, India

U. K. Shukla* and D. S. Bora

Department of Geology, Kumaun University, Nainital 263 002, India

The Ganga Plain, a part of Indo-Gangetic Foreland basin system, is geomorphologically diverse. The Piedmont zone is the northernmost geomorphic element in the Ganga Plain. Divisible into gravelly Bhabar zone developed adjacent to mountain foot, and distal sandy Terai areas, the Piedmont surface shows uneven topography, a low drainage density and sub-parallel to radiating drainage pattern. The rivers are incised and do not contribute any sediment load to the Piedmont surface. Both clast-and-matrix-supported gravel horizons representing channel fill and debris flow deposits respectively, constitute the bulk of the Piedmont succession. The individual fan expansion cycles (15–56 m thick) forming the Piedmont zone, indicate that with time, the fan-building activity has diminished and successive events became smaller. At present, the Piedmont surface is vertically accreting mainly by mass wasting and sheet flow processes.

THE Indo-Gangetic Plain, the largest alluvial tract in the world, is divisible into three sectors namely, Brahmaputra Plain in the east, Ganga Plain in the middle and Indus Plain in the west. Confined between Delhi–Aravalli ridge in the west to Rajmahal hills in the east, the Ganga Plain is geomorphologically diverse, and drained by numerous southeasterly flowing Himalayan and plains-fed rivers. The Piedmont zone, developed adjacent to the Himalayan foothills, forms the northern limit of the Ganga Plain[1] (Figure 1). The Piedmont surface is considered to have formed around latest Pleistocene–Holocene times[2,3]. Incorporating gravelly Bhabar and sandy Terai areas, the Piedmont zone is made up of discrete coalescing alluvial fans, forming a 10–50 km wide Piedmont Fan Surface (PF)[3,4] (Figure 1). Developed adjacent to Himalaya, the Bhabar belt is 7–15 km wide, and away from the orogen, it grades into a 10–40 km wide belt of Terai. Along the Himalayan front, the PF shows an unequal development from east to west. It is 10–30 km wide in the study area located in Nainital District of Uttaranchal state (Figure 1). Using data collected from (a) long, continuous, surface exposures, (b) deep boreholes distributed over the Piedmont surface between Haldwani and Pantnagar areas and (c) systematic geomorphology, an attempt has been made to understand the evolution of Piedmont zone, and the role of synsedimentary climate and tectonic changes influencing the Piedmont sedimentation.

Geomorphic surfaces of Ganga plain

The Ganga Plain forming a part of Indo-Gangetic Foreland basin system shows a number of geomorphic surfaces of regional extent[5,6] and genetic significance[3,7]. In the Ganga Plain, Singh[3] identified at least six major geomorphic surfaces and based on morphostratigraphy proposed a relative hierarchy and chronological scheme for these geomorphic units. The Upland Terrace Surface (T_2) is considered to be the oldest, acting as the basement of deposition for rest of the geomorphic surfaces[3,8] (Figure 1). Comprising fine-grained material, the T_2 surface deposits show strong mottling, extensive development of calcrete and lack preservation of primary physical structures and organic matter (Figure 2 *a*). The deposits are interpreted to have formed by interfluve (Doab) sedimentation[8]. Located south of axial river Ganga, the Marginal Plain Upland Surface (MP) is considered time-equivalent to T_2 surface[3]. Divisible into mottled silt, interbedded silt and mud, channelized sand, variegated clayey silt and cross-bedded calcrete lithofacies (Figure 2 *b*), the succession represents sedimentation in sloping topographic depressions, small sandy-gravelly ephemeral channels reworking the Marginal Plains.

Considered to have formed during middle Late Pliestocene, the Megafan Surface (F), sitting over the oldest T_2 surface, is largely sandy (Figure 2 *c*) and represents sedimentation under conditions of higher sediment-water discharge and higher regional slopes than today. Developed adjacent to mountain foot, the PF—considered to have formed around latest Pleistocene–Holocene[2,3]—often overlaps the megafan surface and is gravely in nature (Figures 1 and 2 *d*).

Developed within the river valleys, and believed to have formed during Late Pliestocene[1,8], under the conditions of high rainfall and sediment input, the Valley Terrace (T_1 surface) is characterized by rippled and cross-bedded silt, sand and lensoid units of silty mud (Figure 2 *e*). The rivers of Ganga Plain (T_0 surface) are flowing

*For correspondence. (e-mail: uksgeo@rediffmail.com)

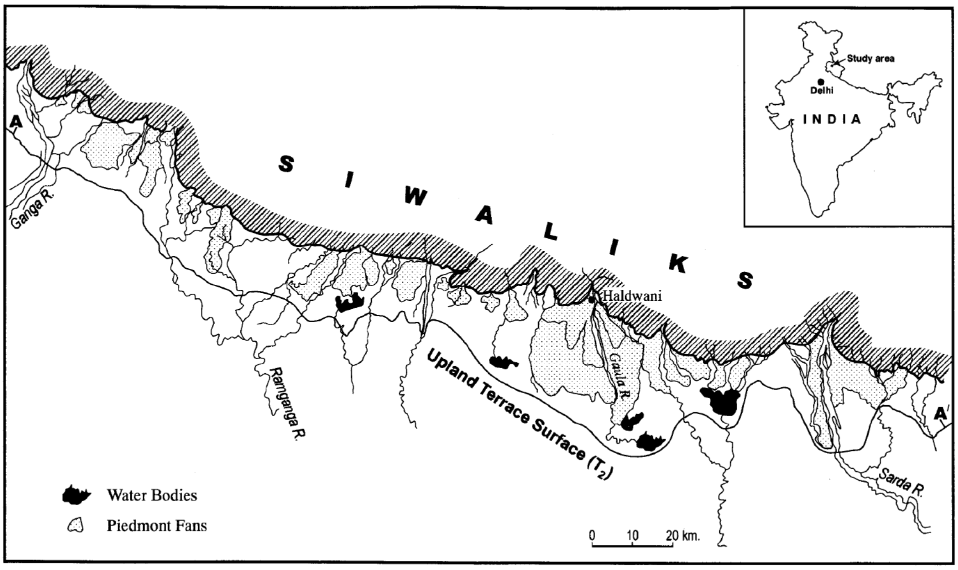

Figure 1. Schematic geomorphic map of the intercone bounded by Sarda River in the east and Ganga River in the west. The line A–A′ marks the limits of the Piedmont zone. Distal Terai belt shows the development of water bodies.

incised into the T_1 surface, and have narrow valleys. The rivers carry mainly silt and fine sand forming huge channel bars and floodplain–levee sequences (Figure 2*f*).

Geomorphology of the Piedmont zone

Using Survey of India toposheets and IRS imageries in 2 : 50,000 scale, a detailed geomorphic map of Piedmont zone of the intercone bounded by Sharda River in the east and Ganga River in the west has been prepared. Based on the extent of the Piedmont fans and the drainage characteristics, the boundary of the Piedmont zone has been marked (Figure 1). The Piedmont area located between latitude 29°15′ and 29°0′ and longitude 79°20′ and 79°0′ has been covered for detailed investigations, and extensive field surveys were made (Figures 1 and 3). The Lower Siwalik succession comprising sandstone-shale alternations are in juxtaposition to Piedmont zone, and overthrust it along the Himalayan Frontal Fault (HFF)[10]. To the north, the Siwalik sequence shows a thrust contact with the Pre-Cambrian Lesser Himalayan rocks along the Main Boundary Fault (MBF). At the contact with the Piedmont zone, the Siwalik rocks show dips of 70–90° and are highly sheared and shattered. Another set of structural features offsetting the Siwalik rocks and controlling the trends of rivers in the Piedmont zone are NNE–SSW and NW–SE trending conjugate system of strike slip faults[11,12], which possibly also influenced the sedimentation processes in the Piedmont zone. The evolution of Piedmont surface seems largely related to neotectonic activities taking place along various faults of Lesser Himalaya–Siwalik belt and HFF. The Piedmont zone is under compressional tectonic regime with a number of blind faults modifying the surface in the form of undulations and surface ridges[13]. The most evident geomorphic features indicating neotectonic activity in the area are displacement of Siwalik rocks in almost N–S direction, alignment of river channels, presence of nick points, sudden change in valley widths, development of unpaired terraces, and tens of meters high cliff lines extending along river channels for several kilometres.

The Piedmont zone of the study area is located in subtropical region, where mean annual temperature varies from 20 to 25°C. In the past decade, the average rainfall in the region has been 2076 mm/year. The maximum rainfall occurs during July and August varying between 590 and 600 mm/month, and minimum rainfall is 10–30 mm to nil during April and May.

The average slope of the fan surface is 7.8 m/km, which is fanning out along the radii of the fan. The gravelly proximal part of the Piedmont (Bhabar region) exhibits uneven topography with a surface relief of 1–2 m. The distal Terai belt is sandy and swampy with low-lying waterlogged conditions and extensive development of ponds, lakes and abandoned channel belts. The drainage pattern in the mountain hinterland is dendritic, while the Piedmont surface shows a sub-parallel to radiating drainage pattern with low drainage density (Figure 3).

The Piedmont surface is drained by a number of small to moderate size rivers. Gaula, Sukhigad and Bhakhara are the main rivers draining the area (Figure 3). Flowing towards south, the rivers are entrenched in the fan surface, and expose 5 to 15 m high cliffs paralleling river

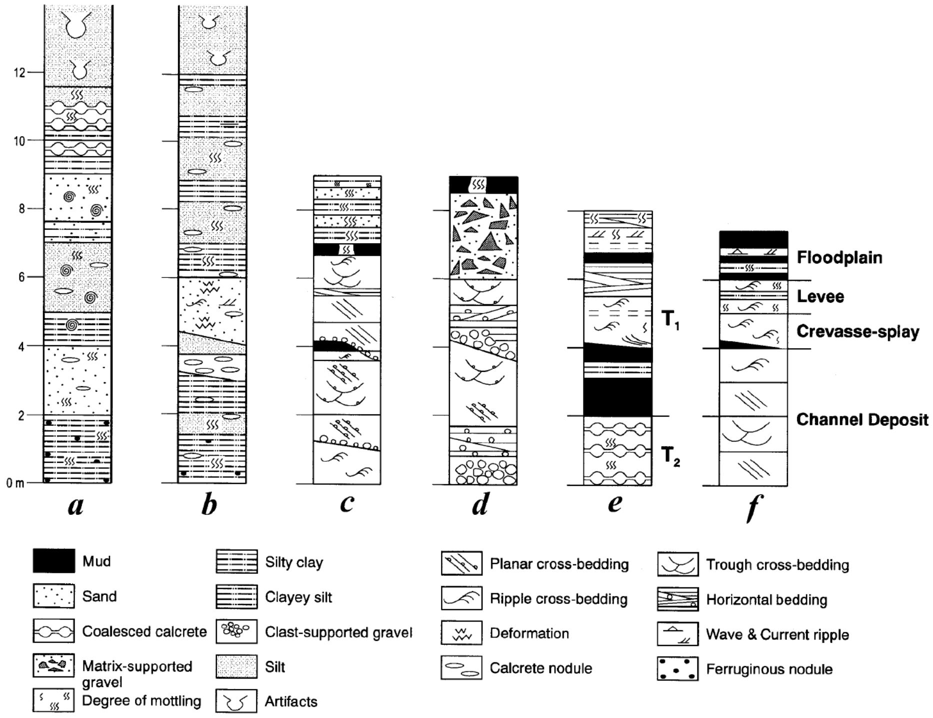

Figure 2. Sedimentological logs of different geomorphic surfaces, ***a***, Upland Interfluve deposit at Bithoor; ***b***, Marginal Plain deposit at Kalpi; ***c***, Megafan deposit at Nagal; ***d***, Piedmont fan deposit at Haldwani; ***e***, Valley terrace deposit at Ganga Ganj; and ***f***, Active river deposit at Paharapurghat.

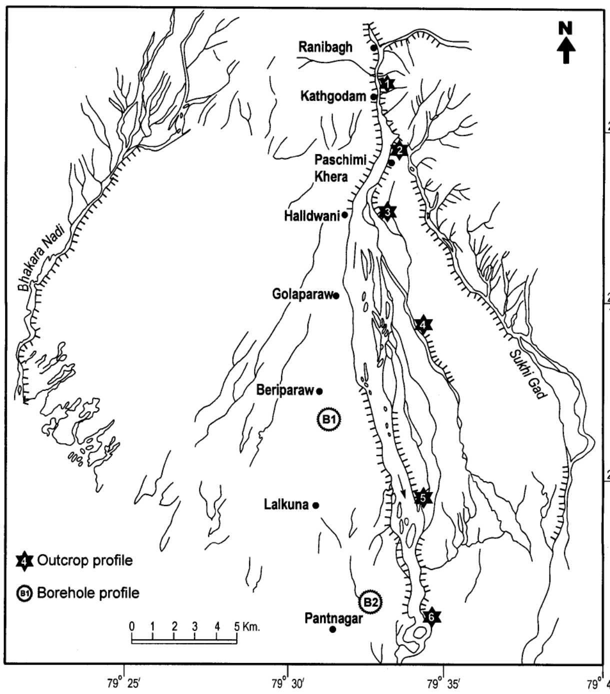

Figure 3. Schematic geomorphic map of Piedmont zone of the study area. The Piedmont surface shows low drainage density and the rivers are entrenched.

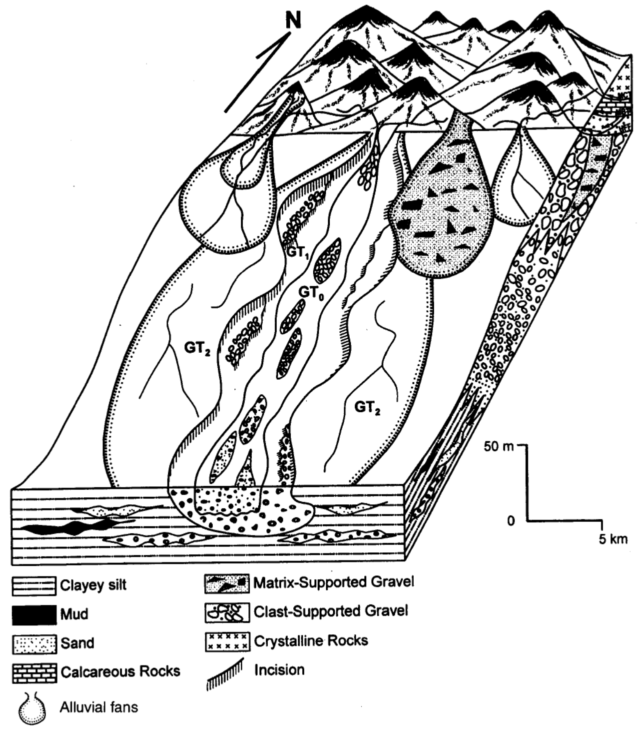

Figure 4. Geomorphic setting of Piedmont zone, showing development of terraces and incision of active river channel. Within the Piedmont zone clast-size decreases progressively away from the mountain front.

channels for several kilometres. Near the mountain front, incision is prominent and progressively diminishes away from it.

The river valleys are 80 m to 2 km wide, and show development of distinct terrace surfaces (Figures 3 and 4). Representing the Piedmont surface, the GT_2 terrace, occurs about 5–15 m high above the river-bed (Figure 4). This surface is made up of semi-consolidated to friable clast- and mud-supported gravels, sand and mud (Figure 2 *d*). The GT_1 terrace is present within the river valleys, and shows a level difference of 2–4 m from the active river channels (Figure 4). It comprises friable clast-supported gravels and decimeter thick lenses of sand and mud. The clasts are derived from Lesser Himalayan and Siwalik sequences. The GT_0 represents the active river channel flowing incised into GT_1 surface (Figure 4). Because of incision, these rivers are not presently contributing sediments to the Piedmont surface; rather, they are filling up their valleys. The rivers are ephemeral, braided, gravel bed-rivers forming mid-channel bars and narrow floodplain–levee sequences. Characteristically, most of these rivers carry gravel up to distance of 13–15 km from the mountain front, and then become sandy. Some of them meet with water bodies in Terai area and lose their identity (Figure 1).

Sedimentology of Piedmont zone

Outcrop and bore hole data (from Irrigation department) reveal that the Piedmont deposits are constituted of gravels with quartzite, mica schist, gneiss, spilitic basalt, dolomite, silty shale and fine to medium-grained sandstone belonging to Lesser Himalayan and Siwalik succession. Systematic spatial as well as temporal changes in clast-size, lithology and depositional sedimentary cycles within the Piedmont zone are noted.

The surface outcrops show that the Piedmont zone near the mountain foot (between 0 and 7 km, Bhabar area) is gravelly (98% gravel), where cross-bedded gravels (55%) dominate the succession (Figure 2 *d*). The gravelly sequences are both clast-and-matrix-supported. The clast-supported sequences exhibiting lensoid geometry and erosional lower contacts are 8 to 15 m thick. Gravels constituting such sequences are of varied composition and belong to Lesser Himalaya and Siwalik terrains. They are rounded to well rounded, and most of them vary in size from 10 to 15 cm. Fringing the mountain front and overlying the clast-supported gravel sequence with an erosional transition of regional extent, the matrix-supported horizons are 4–12 m thick, show angular, unsorted gravels floating in muddy matrix (Figure 2 *d*). Characteristically, the silt–sandstone clasts constituting the matrix-supported succession belong to Lower Siwaliks sub-Group. Therefore, within this part of the Piedmont two fan expansion cycles separated by marked erosional contact are superimposed. The Piedmont surface also has 1–2 m thick drape of fine-grained clayey silty-sand covering the underlying gravelly sequences as an apron. Between 7 and 20 km from the mountain front, thick sandy horizons (20–40% sand) associated with gravels are present. In this zone, clast size drastically decreases to pebble to granule size, and only a few clasts of more than 5 cm size can be noticed. Beyond this distance in Terai area where the Piedmont zone merges with central alluvial plains, the sand–mud ratio is almost 50 : 50. The gravels are thin or totally missing. Fluvial channel fills consist of clast-supported and cross-bedded deposits are composed of 1.75–3 m thick fining up cycles, and mud-supported gravels having angular clasts and unsorted texture represent debris flow deposits[1,14,15]. High relief at the mountain front along HFF, and thick silt-clay horizons (2–40 m thick) of the Siwalik sequence, could have provided enough mud content to facilitate the debris flows under gravity, preferably under reduced water budget conditions. The fine-grained sediment cover present on the surface is unrelated to underlying gravelly deposits, and represents vertical accretion by sheet flow processes, operating on the Piedmont surface during rains.

Depositional cycles

In the subsurface, gravelly horizons are separated by thick mud units (2–12 m) (Figures 5 and 6). In the borehole data, mud, silt-sand and gravelly units are clearly recognized, but the exact clast-size is not determined. Therefore, relative grain size has been used to prepare the lithologs. The borehole sections have been interpreted in the light of data collected from Piedmont sequence exposed at the surface. In the absence of clast-size distribution, the fining and coarsening upwards trends of sequences represented in the boreholes have been correlated to thickness of the gravel bodies. It has been presumed that thicker gravel sequences occurring as 'gravels' or 'gravel with sand' are deposited by larger magnitude flows, which in turn may imply increased water budget conditions. On the other hand, 'mud with gravel' horizons have been interpreted to represent reduced water budget conditions. During such periods, enough water was not available for effective sorting of the sediments, and they were emplaced as debris flows.

The borehole data of Bhabar and Terai areas reveal that internally the Piedmont zone is made up of sedimentary cycles of three different magnitudes developed in response to auto- and allocyclic processes. The small-scale sequences (minor cycles) constituted of multistoried gravel units overlain by sand or silt-clay are 3–10 m thick and fining upwards (FU) (Figure 5), and probably related to the shifting of the channels over the Piedmont surface.

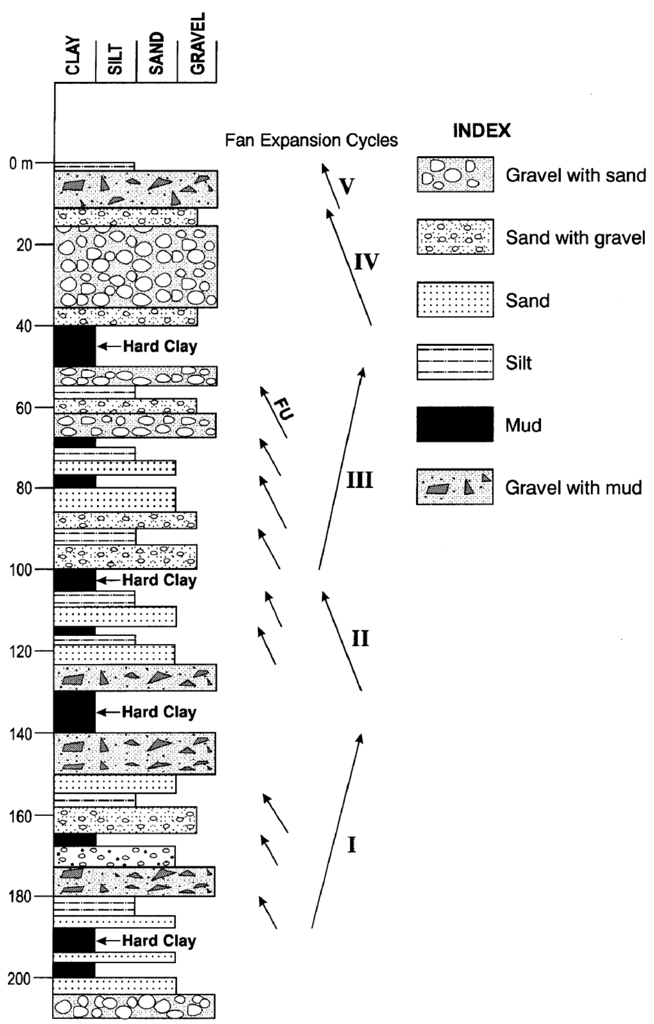

Figure 5. Litholog showing bore hole information of gravely Bhabar zone. The upward coarsening Mega sequence is constituted of five tens of metres thick mesocycles, which in turn are made up fining upwards minor cycles.

The medium scale sequences (mesocycle), comprising a number of minor cycles are both fining and coarsening upwards in nature (Figure 5). Such medium scale sequences represented by gravels, gravel with sand or gravels with mud, are separated by thick mud horizons marked as 'hard clay' in the borehole data. The clay deposition may represent abandonment of a channel-belt, or termination of a debris flow, and deposition of fine-grained sediments mainly by sheet flows. Such cycles may represent a fan-building event (fan expansion cycles), which may have an allocyclic control. A borehole section falling in the gravelly Bhabar area comprises at least four 24–56 m thick well-developed medium scale sequences (numbered I to IV in Figure 5) separated by thick mud horizons. The sequence I is dominated by 'gravels with mud', and thin sand-mud couplets. The sequence II having mainly sand and silt and subordinate gravel, is 24 m thick and fining upwards. The sequence III is thickest (about 56 m thick), contains 10–15 m thick 'gravels with coarse sand' occurring near the top of the succession (Figure 5). The topmost sequence IV is about 40 m thick and is exclusively made up of gravel, except the top 5 m constituted of 'mud and gravel' (sequence V, Figure 5). The mud-supported gravel may be the continuation of the latest debris flow event, which is encountered in the proximal part (Figure 2 *d*). The large-scale sequence (megacycle) – a 205 m thick Piedmont succession is coarsening upwards. The coarsening up trend is seen in the increased thickness of gravel units towards the upper levels in the borehole section (Figure 5).

A second borehole drilled in the Terai belt near Pantnagar, characterizes the distal fan setting (Figure 6). The sequence is made up of mainly sand and 2–12 m thick mud horizons; the gravel fraction is subordinate and it occurs in the upper levels of the succession only with fine to coarse sand represented in the borehole data as 'hard yellow clay with kankar', the mud horizons are thicker at deeper levels (below 20 m level) (Figure 6). The mud horizons occurring in the upper levels in the profile with gravelly horizons are black in colour, sticky in nature and only 2–4 m in thickness.

The abundance of 'gravels with mud', and reduced thickness of medium scale sequences (mesocycles I, II) in the lower levels of the Bhabar zone (Figure 5); and presence of calcrete-bearing mud at the lower levels in Terai area (Figure 6), may imply reduced water budget conditions, and a low moisture content in the sediments respectively in the beginning. This was followed by a phase of increased waters in channels to deposit thicker gravel sequences (mesocycles III, IV in Figure 5), and to transport the gravels up to Terai (Figure 6) in the later phases of Piedmont sedimentation. The latest event of fan building represented by debris flow deposits occurring at the surface (Figure 2 *d*), and in borehole profile of Bhabar zone (sequence V, Figure 5), again indicates a phase of reduced water budget. The coarsening up character of borehole sections also indicates an effective role of syn-sedimentary tectonism releasing coarse clastics at the provenance.

Discussion

The Piedmont surface shows gentle slope gradient decreasing away from the mountain front, low drainage density and an uneven topography. The surface processes are continuously modifying the Piedmont surface. During the rains, sheet flows become operative and redistribute the fine-grained sediments across the surface. All the active river channels draining the Piedmont zone are incised into the fan surface (Figures 3 and 4). They are gravel- bed rivers and braided in character. The rivers bring the sediments from Lesser Himalayan terrain, Siwalik hills and also cannibalize the Piedmont surface.

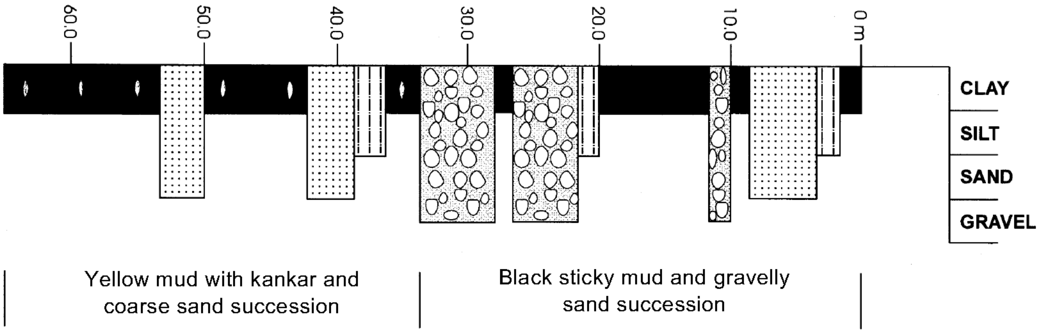

Figure 6. Litholog showing bore hole data of sandy Terai area near Pantnagar. The lower part of the succession is dominated by mud with kankar development, while the upper part becomes gravely sand succession (index as in Figure 5).

At present, these rivers, however, are not contributing any sediment load to the Piedmont surface, but rather, are filling up their valleys. Most of the rivers are ephemeral, and get activated during rainy season. Away from the mountain front, in Terai, they meet with the water bodies and disappear (Figure 1). In this way, these rivers transfer huge sediment loads to alluvial plains, which is being further redistributed by sheet flow processes and supplied to central alluvial plains to form interfluve (Doab) deposits, which show chronological younging[1,8,12]. At present in Terai only fine-grained sand-mud sedimentation is taking place and the gravelly deposits are negligible (Figure 4).

According to Singh[3], the PF is younger than the Megafan (MF) surface and the former is superimposed over the latter. It is emphasized that when the sedimentation of megafans (cones[5]) started by major snow-fed Himalayan rivers, the smaller rivers produced small Piedmont fans within the inter-cone areas. However, the climate became more arid with time, resulting in decreased water budget in the rivers. With the reduced water budget and probably coupled with decreased tectonic activity in the Himalaya, the megafan building activity came to an end, and since then, only Piedmont sedimentation has occurred[1]. As a result, the Piedmont Fan Surface (PF) overlaps over the Megafan Surface (MF) also. In the areas, where Megafan building did not take place, the Piedmont fans overlap the oldest Upland terrace surface (T_2), which acts as the basement of deposition for rest of the geomorphic surfaces of Ganga Plain (Figure 1).

Presence of thick gravel horizons in the sub-surface of the present-day Terai belt experiencing sand and mud sedimentation, implies enhanced fan-building activity in the past (Figure 6). It appears that in the beginning, smaller rivers with a rather low water budget contributed the sediments to the Piedmont surface. Rivers carried mainly sand and silt and produced smaller fan expansion cycles (mesocycles I, II). Sediments accumulated in mountain hinterland were also emplaced as debris flows. Gradually, the water budget increased, rivers became larger, they carried gravels up to Terai areas and deposited thicker gravelly sequences (mesocycles III & IV in Figures 5 and 6). The topmost debris flow deposits occurring at the surface covering the underlying clast-supported gravel deposits (Figure 2 *d*, 5), indicate that the Piedmont fan building activity has receded to form smaller alluvial fans.

The matrix-supported gravels occurring at the surface (Figure 2 *d*) comprise clasts derived from Siwalik sequence only, and hence may also imply a tectonic upheaval in the Siwalik hills juxtaposing the Piedmont zone along HFF. This tectonic event may also have resulted in incision of the present-day rivers into the Piedmont surface. After the incision, the rivers started depositing GT_1 sequence developed within the present day river valleys. Gaula River and other channels are at present flowing entrenched into GT_1 surface depositing narrow linear gravel-sand succession alternating with muddy inter-channel areas (Figure 4). The fan-building activity is highly subdued, and the Piedmont surface is receiving sediment only by mass wasting and sheet flow processes.

Conclusions

The Piedmont zone is characterized by multiple events of fan-building processes forming 15–56 m thick discrete Piedmont fan expansion cycles. The fan-building cycles evolved under the effective role of syndepositional tectonic and climatic events, influencing sediment supply and water budget conditions respectively. Initially, the individual fan-building events (mesocycles) forming Piedmont zone were larger in dimensions reaching farther away from the mountain front, and with time, the fan expansion events receded to form smaller fans. The Piedmont fan sequences are composed of both fluvial and debris flow deposits. However, domination of gravelly facies over fine-grained sand-mud facies, and appreciable representation of debris flow deposits distinguish them from Megafan deposits, which are largely sandy in nature and devoid of debris flows[1].

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