minimum central pressure at 996 hPa. On the contrary, both WRF-cold and WRF-noVar have minimum central pressure above 1000 hPa and maximum 10 m wind speed below 30 knots. Figure 7 depicts the vertically integrated moisture transport as simulated by the three experiments. It is clear from the figure that the WRF-cyclic has simulated more moisture advection into the storm. Continuous supply of moisture is one of the important factors for storm sustenance. Higher amount of moisture advection serves as an essential feed for storm intensification. This is one of the probable reasons of intensified storm produced by WRF-cyclic compared to the other two analysis.

It is seen that the WRF-noVar and WRF-cold analyses are unable to capture the storm in its full strength. They have not represented the circulation in the form of tropical storm. On the contrary, WRF-cyclic, though more intense, is able to represent the circulation as tropical storm Nisha. According to IMD's record, the minimum central pressure of the cyclonic storm dropped to 996 hPa from 09 UTC of 26 November 2008 to 00 UTC of 27 November 2008. This drop in pressure was better captured by WRF-cyclic and its day 1 forecast (figure not shown). The sea level pressure pattern (figure not shown) also verifies this inference.

Since the analyses for WRF-noVar and WRF-cold mode simulations are available only for the 00 UTC of each day, it is not possible to compare and plot the six-hourly analyses track positions of all the three experiments. Also, the WRF-noVar and WRF-cold analyses have failed to produce the cyclonic circulation at 850 hPa.

WRF-3DVar analyses in cyclic mode have represented the cyclonic system and its circulations very well. It has also produced the cyclonic storm more intense with stronger 850 hPa and surface winds. The genesis, intensification and dissipation of the cyclone are better represented by the cyclic runs. The simulation and advection of higher quantity of moisture by WRF analyses in cyclic mode is one of the probable reasons of over intensification of the storm.

The impact of assimilation is also well highlighted. It is quite evident that the initial conditions prepared through assimilation is superior to the initial conditions directly accepted from the global model forecasts.

1. Barker, D. M., Huang, W., Guo, Y. R. and Xiao, Q. N., A three-dimensional (3DVar) data assimilation system for use with MM5: implementation and initial results. *Mon. Wea. Rev.*, 2004, **132**, 897–914.
2. Skamarock, W., Klemp, J., Dudhia, J., Gill, D., Barker, D., Wang, W. and Powers, J., A description of the advanced research WRF version 2, NCAR Tech. Note NCAR/TN-468 + STR, 2005, p. 100.
3. Qingnong, X. and Sun, J., Multiple-radar data assimilation and short-range quantitative precipitation forecasting of a squall line observed during IHOP_2002. *Mon. Wea. Rev.*, 2007, **135**, 3381–3404.
4. Chen, S.-H., Chen, A., Haase, J., Zhao, Z. and Vandenberghe, F., Study of MODIS retrieved total precipitable water data and their impact on severe weather simulations. *Proc. SPIE*, 2006, **6404**, 640404.
5. Ching-Yuang, H., Kuo, Y.-H., Chen, S.-H. and Vandenberghe, F., Improvements in typhoon forecasts with assimilated GPS occultation refractivity. *Weat. Forecast.*, 2005, **20**, 931–953.
6. Rajagopal, E. N., Das Gupta, M., Mohandas, S., Prasad, V. S., George, J. P., Iyengar, G. R. and Preveen Kumar, D., Implementation of T254L64 global forecast system at NCMRWF, NCMRWF Tech. Rep., 2-42, 2007.

ACKNOWLEDGEMENTS. We thank Dr A. K. Bohra (Head, NCMRWF) for providing the necessary facilities to carry out this work and for his encouragement and support. S.K.D. gratefully acknowledges CSIR, New Delhi for providing the research fellowship. We also thank India Meteorological Department for providing us with the observational details of the cyclonic storm Nisha, and the anonymous referees for their valuable comments, which have helped in improving the quality of the manuscript.

Received 12 October 2009; revised accepted 26 May 2010

Tectonic control on alluvial fans, piedmont streams and Ganga River in western Ganga Plain (India) using satellite remote sensing data

Aniruddh Uniyal[1,]*, K. V. Ravindran[2] and C. Prasad[3]

[1]Remote Sensing Applications Centre-UP, Sector-G, Jankipuram, Lucknow 226 021, India
[2]V.M.C. House, Karamel, P.O. Annur, via Payyanur 670 332, India
[3]489, Uphar, Udhyan 1, Lucknow 226 002, India

The present study pertains to a segment of the western Ganga Plain drained by the River Ganga and its tributaries in the area between Haridwar, Roorkee and Bijnor. Various geomorphic surfaces were identified on the basis of satellite remote sensing data aided by field investigations. The dominant geomorphic surfaces identified are megafan surface (MF), older flood plain (T_1), piedmont fan surfaces, viz. PF_2 (older) and PF_1 (younger), and active flood plain (T_0). The disposition of these geomorphic surfaces and the trends of streams are interrelated and tectonically controlled. Upland terrace surface (T_2), which is the oldest depositional surface of Ganga Plain, is not exposed in this area and it is the reworked MF on which all other surfaces are superposed. The large sized coalescing fans of PF_2 and superposed PF_1 evolved by the deposition of sediments derived from the rising Himalayan and

*For correspondence. (e-mail: aniruddhauniyal@yahoo.com)

Siwalik ranges. The narrow widths of T_1 and T_0 terrace surfaces of the Ganga and its tributaries are the result of deep incision by these rivers owing to their tectonic control. There are evidences of progressive lateral migrations of the Ganga channel to both directions. The study also indicates that presently the processes of deposition are active mainly on T_0 and upper part of the PF_1.

Keywords: Alluvial fans, Ganga Plain, geomorphic evolution, piedmont fan surface, river valley terrace, tectonic control.

SEVERAL workers have attributed the evolution of the Ganga Plain to collision of Indian and Asian plates during Tertiary[1–4] and subduction of Indian plate under the Asian plate during the early Miocene. This resulted in the emergence of a narrow, actively subsiding peripheral foreland basin that grew wider and deeper during Middle Miocene and attained its present configuration in Late Pleistocene to Holocene[5–7]. This foreland basin is an over-supplied and under-filled basin with fluvial sedimentation still going on[5–7] and it embodies the riverine deposits of several generations[4]. The present paper pertains to the results of studies on the geomorphological and tectonic set-up of the area around Haridwar, Roorkee, Najibabad and Bijnor using satellite remote sensing data (Figure 1). An attempt has also been made to establish the influence of geomorphic processes and tectonics on the geomorphic evolution and channel modifications of the region. LANDSAT MSS band-7 images, IRS-lA LISS-I false colour composite (FCC), IRS-1B LISS-II FCCs and IRS-lC LISS-III FCCs have been used to delineate the various geomorphic surfaces and fluvial landform, faults and lineaments. Arc GIS 9.3 software has been used for creating compositions of final maps.

The left bank tributaries of the Ganga such as Pili Nadi, Rawasan Nadi, Kotawali Rao, Ratnal Nadi and Malin River are running parallel or subparallel to the master stream. The Solani and the Banganga are the prominent right bank tributaries of the Ganga River whereas streams like Rainpur Rao and Pathri Rao discharge into Banganga (Figure 1).

The geomorphic set-up of the area under study is defined by a number of surfaces of Late Pleistocene–Holocene period[6–8]. Prominent geomorphic surfaces observed in the study area are megafan surface (MF), river valley terrace surface (T_1), piedmont fan surfaces (PF_2 and PF_1) and present day active flood plain (T_0)[9].

The Siwalik range, which occupies the northern fringe of the study area, forms the oldest geomorphic unit of Denudo-structural Hills. This unit is characterized by moderate to high dissection and drainage density. Its undulating formations are distinctly traceable in the satellite images (Figure 2) and are thrusted over the Piedmont Zone along Himalayan Frontal Fault (HFF)[10].

The extensive MF occupies the southern part of the study area. Shukla and Bora[7] explained that MF is resting over the oldest geomorphic surface, the upland terrace surface (T_2) and represents sedimentation under higher sediment-water discharge and higher regional slope than today. It has large dimension, low relief and is dominantly sandy[7,10].

Examination of satellite images and field investigations has shown that MF is characterized by variable slopes which become gentler in the southern part of the study area, around Bijnor. The surface also shows relict features of ancient river system such as palaeochannels and oxbow lakes, etc. Relics of an ancient anastomosing drainage pattern are pronounced in the area to the south of Roorkee township and west of Harinagar and Tughlaqpur villages (Figure 2). These abandoned anastomosing channels are more or less straight and are occupied by the aeolian deposits in the west of Tughlaqpur and Harinagar villages (Figure 3). This is evident by the alignment of these aeolian deposits and their narrow, elongated linear to curvilinear shapes (Figures 3 and 4 *a*). Lakes/ponds of MF get filled by the deposition of sediments from surrounding areas in the form of sheet wash from the PF_2 and PF_1 and also from minor streams during monsoons

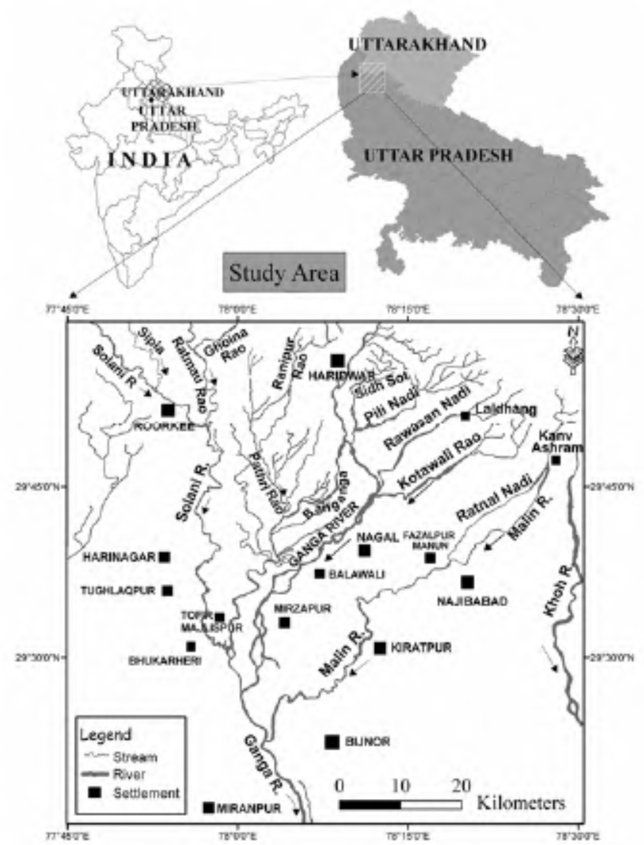

Figure 1. Location map of study area based on Survey of India topographical map sheets and IRS LISS-I, LISS-II and LISS-III images.

and by anthropogenic intervention aimed at reclaiming the wetlands for practising agriculture. The alluvial deposits of this surface are coarser in the northern part, west and northwest of Roorkee, but become finer around Bijnor and Miranpur in the southern part of the study area. Overtopping of the banks of Ganga during floods does not affect this geomorphic surface, as it is at 10–25 m higher elevation compared to the active channel. However, incessant monsoonal rains cause limited flooding of MF.

River valley terrace surface referred as *Khadar* in the literature and by rural folk is entrenched into MF. Singh[6] divided *Khadar* into T_1 and T_0. T_1 appears as an undulating, discontinuous alluvial plain running parallel or subparallel to the present day flood plain (T_0) of Ganga River (Figure 3). T_1 and T_0 together constitute the river valley. However T_1 is entrenched within MF and the boundary between these two is marked by a major break in slope in the form of a cliff line which ranges from 3 to 12 m in height. T_1 is flooded by back flow only and does not witness over bank flow. The high monsoonal discharge due to heavy rainfall in the upstream catchment of Ganga increases its water level. Consequently, the confluences of the tributary streams with the master stream Ganga get choked and cause the back flow of water which ultimately inundates the T_1. The small gullies developed at the boundary between T_1 and MF carry the runoff of MF and discharge into the low lying areas (marshy areas and oxbow lakes) of T_1. These marshy lakes are also inundated during incessant monsoonal rains as they receive the discharge from elevated MF and at the same time their outlets are choked due to the rise in the water level of Ganga River. A number of yazoo streams have developed on the T_1 which flow parallel to Ganga River for many kilometres[9]. Poorly developed soil horizons on the top of T_1 indicate that very little accretion takes place on this surface by yazoo streams and gullies (Figure 4 *d*). The widening of T_1 up to 11 km on the western bank of Ganga in its Harinagar–Tofir Majlispur stretch appears to be the combined effect of intersection of Balawali fault and Ganga Fault Zone and termination of PF_2 in the immediate upstream (Figures 2 and 3). The presence of a number of channel cut-offs, large marshy lakes and oxbow lakes in the Harinagar–Bhukarheri area on the right bank of the Ganga indicates a progressive easterly migration of the channel (Figure 3). Further south (in the NW of Bijnor) the T_1 is wider on the eastern side of the Ganga channel. Channel cut-offs developed on the T_1 near Bijnor indicate westerly migration of the Ganga (Figure 3). All these point towards the existence of

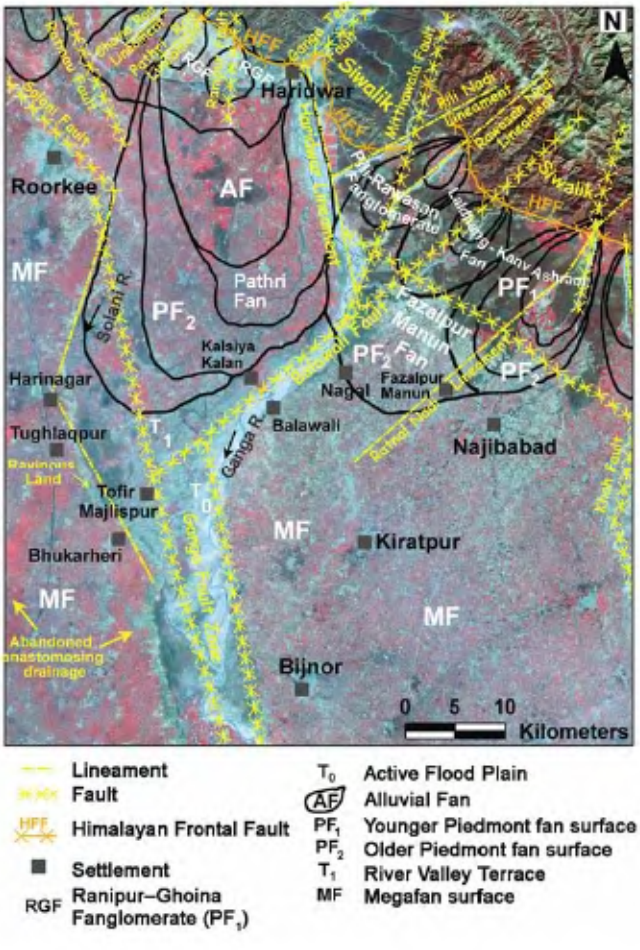

Figure 2. IRS-1C LISS-III False Colour Composite (FCC) showing neotectonic control on drainages and alluvial fans in Roorkee–Haridwar–Najibabad–Bijnor area.

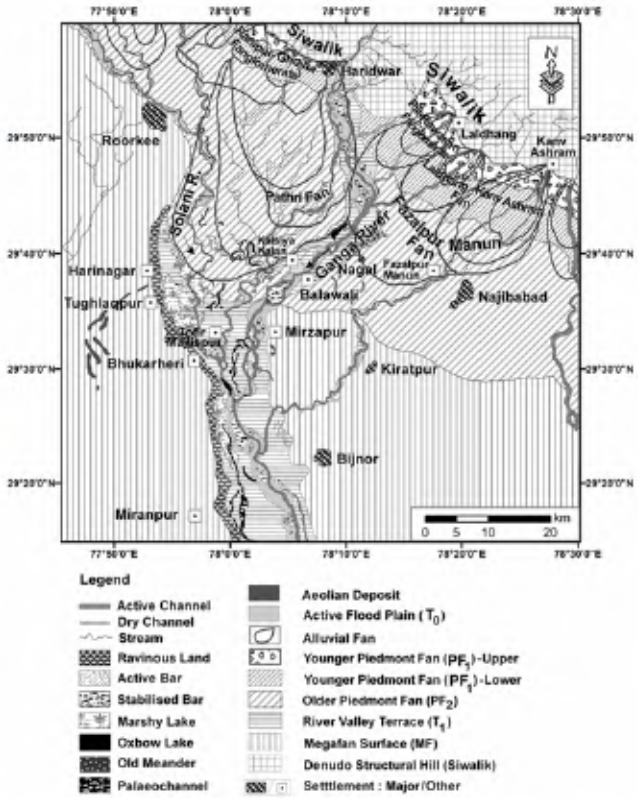

Figure 3. Geomorphological map of Haridwar–Najibabad–Bijnor area.

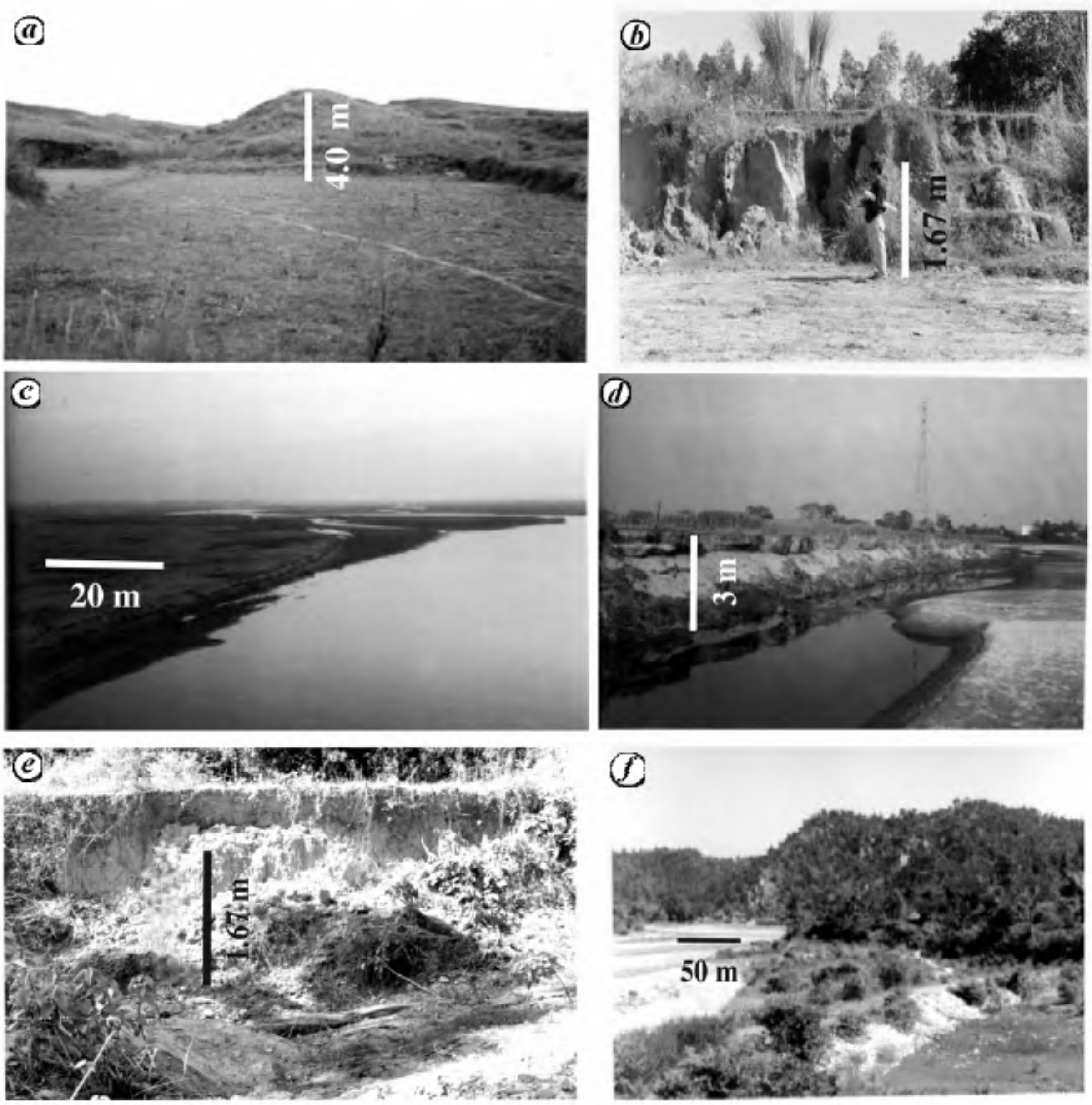

Figure 4. ***a***, A field view of aeolian ridge near Harinagar. ***b***, A field view of 3 m thick sequence of a relict fan at Fazalpur Manun. ***c***, Active flood plain of Ganga with active bar near Balawali. ***d***, An elevation difference of 1–4 m between active flood plain (T_0 surface) and old flood plain (T_1 terrace surface) in the SW of Nagal near Balawali. ***e***, A field view of >2 m high cliff of Mitthawali Fault on the right bank of Rawasan Nadi. ***f***, A field view of the incision of active flood plain of piedmont stream Sidh Sot into the younger piedmont fan surface. Fan cut terraces are also seen in the foreground.

a sinuous and meandering river system on the T_1 in the past that was gradually abandoned.

On the western edge of T_1, along its junction with MF, a narrow linear ravinous zone with varying width of 0.5–1.5 km is developed in the east of Harinagar, Tughlaqpur, Bhukarheri and Miranpur (Figures 2 and 3). Referred locally as *Khola*, this zone is characterized by a network of small incised gullies exhibiting high dissection along 3–12 m high alluvial ridge. The development of gullied land and sudden broadening of T_1 in the immediate north of Nagal may be attributed to the intersection of Haridwar lineament with Balawali and Mitthawali faults (Figures 2 and 3). The continuity of this narrow strip of ravinous land (along prominent alluvial ridge) only along the western side of Ganga in Harinagar–Miranpur stretch and strong incision of T_1 into MF along this ridge are the geomorphic evidences for establishing this western side of Ganga as upthrown block of Ganga Fault Zone (Figure 2).

The coalescing fans forming large piedmont surfaces at the mountain foot are variously referred as *ghar*, *bhabhar* and *kahar* by rural folk. Shukla and Bora[7] explained that piedmont fan surface is gravelly in the upper part and sandy (with gravel) in the lower part and was formed around Late Pleistocene–Holocene.

Table 1. Lithostratigraphy and morphostratigraphy of Haridwar–Roorkee–Najibabad–Bijnor area

Age	Lithostratigraphic unit/morphostratigraphy of geomorphic surfaces	Generalized lithology
Holocene	Ganga/Banganga/Solani/Ratmau/Sidh Sot/Pili/Rawasan/Kotawali/ Ratnal/Malin recent alluvium of active flood plain (T_0 surface)	Boulders, cobbles, pebbles with coarse sand and silt along the piedmont streams and upper stretch of Ganga at Haridwar Fine to medium grained, grey micaceous sand with grey silt in the lower (Nagal–Bijnor) stretch of Ganga
	Bhur sand/aeolian deposits*	Fine to medium grained brown to yellowish oxidized micaceous sand
	Fan cut terrace alluvium of Solani, Ratmau, Ghoina/Ranipur/ Sidhsot/Pili/Rawasan/Kotawali/Ratnal and Malin	Boulder, cobbles, pebbles with sand matrix, pebble bed sand, silt and clays
	Ranipur–Ghoina Fanglomerate – PF_1	Boulders, cobbles, pebbles with grey matrix
	Pili–Rawasan Fanglomerate – PF_1	Boulders, cobbles, pebbles and debris flow conglomerate
	Laldhang–Kanv Ashram Alluvial Fan – PF_1	Boulders, cobbles, pebbles with gritty/sandy matrix
	Pathri/Fazalpur Manun Older Fan – PF_2	Coarser clastics, interbedded debris flow and fluvial conglomerate
	Ganga Younger Alluvium of Older Flood Plain (T_1 surface)	Boulders, cobbles, pebbles with coarse sand and silt along the piedmont streams and upper stretch of Ganga at Haridwar. Gravels with coarse to medium sand and clay in the middle stretch of Ganga and medium sand, silt and poorly developed clay in the lower stretch of Ganga near Bijnor
	Bhur sand/aeolian deposits (occupying relict anastomosing drainage of MF)	Fine to medium grained brown to yellowish oxidized micaceous sand
Late Pleistocene	Doab Banger or Upland Interfluve – MF	Medium to coarse sand with silt and interbeds of clay
Middle to Late Pleistocene	Varanasi Older Alluvium – T_2	Medium to coarse sand with silt and interbeds of clay

*Some Bhur deposits or aeolian ridges are younger to piedmont activity. However majority of them are contemporaneous to megafan.

Based on image interpretation, two distinct surfaces of piedmont fans (PF_2 and PF_1) have been delineated in the area. The wider PF_2 is superposed on MF and T_1. The PF_2 surface comprising Pathri Fan and Fazalpur Manun Fan represents one of the several events of fan building activities that western Ganga Plain had witnessed through time due to active deposition in the form of debris flow (Figures 2, 3, 4 *b* and Table 1). Further east of the Haridwar–Najibabad area in Kathgodam–Lalkuan area of Nainital district probably the similar PF_2 of Gaula Fan has been referred by Shukla[10] as fan expansion cycle 'B' that is characterized by matrix supported gravelly debris flows. PF_2 has a general southerly slope and a variable width of about 20 km in the western part (north of Roorkee) and is increasing towards east in Roorkee–Najibabad area. The southern extension of PF_2 is up to the confluence of Banganga with the Ganga River where its width is over 40 km (Figure 3). PF_2 is characterized by superposed fans and braided and incised channels of Ganga, Solani, Rawasan, Ratnal, Malin and Khoh (Figures 1–3). Sub-angular to sub-rounded gravels in the upper part of this surface grade into coarse sand in its middle portion and medium grained sand in the lower part. Satellite data reveals that PF_2 is abruptly terminated against the Solani Fault in northwest and Ganga Fault Zone in the west (Figures 2 and 3). The slope of this surface becomes gentler southward. Old meanders, oxbow lakes and marshy lakes representing the past courses of Solani, Banganga and Ganga are also noticed on the distal part of PF_2. Material of the lower part of this surface has been reworked by rain splashes and subsequent sheet flows and some part of it has been deposited in the active lakes over the T_1. The coarse to medium sand with alternating sequences of clay in the lower part of PF_2 is similar to that of the MF and distal end of PF_2 merges into the MF (Figure 3).

Small coalescing fans (with limited spatial extent) superposed on PF_2 form a narrow zone of PF_1, which is 4–12 km wide zone parallel or subparallel to Siwaliks and is characterized by braided, ephemeral streams[9]. The PF_1 comprising Ranipur–Ghoina, Pili–Rawasan fanglomerates and Laldhang–Kanv Ashram alluvial fans is constituted by clast supported conglomerates with angular to sub-rounded boulders, cobbles and pebbles in the proximal part and gravelly deposits with sandy/gritty matrix in the distal part (Figures 2, 3 and Table 1). PF_1 seems to be similar to the fan expansion cycle 'A' of Gaula Fan in Kathgodam–Lalkuan area of Nainital district, which according to Shukla[10] is characterized by river born clast supported gravelly deposits and overlying the fan expansion cycle 'B'.

PF_1 is further divided into PF_1-upper (Bhabhar zone) and PF_1 lower (Tarai zone). PF_1-upper is drained by seasonal streams and contains generally coarser fragments, angular to sub-rounded boulders, cobbles, pebbles, etc. PF_1-lower appears as a 2–10 km wide belt, characterized by curved and braided perennial streams (Figure 3) and predominantly comprises sub-rounded boulders and fragments embedded in sandy/silty matrix capped by immature soil.

Satellite data of pre-monsoon period indicates that rivers like Kotawali Rao, Ratnal Nadi and Malin witness sudden discharge as soon as they enter the Tarai zone. The sudden appearance of perennial flow (with low discharge during dry season) in Tarai zone (PF_1-lower) may be attributed to the shallowing or emergence of water table along this zone. The PF_1 rests over the proximal part of the gravelly PF_2 that provides avenues for further infiltration of water (Figure 3). The 6°–8° slope of PF_1-upper (recharge zone) facilitates horizontal flow of groundwater towards the gentle PF_1-lower (discharge zone), where it is suddenly obstructed by silty and muddy sediments. The presence of these impermeable sediments in Tarai has led to the formation of some ponds and small lakes.

T_0 is the youngest geomorphic surface running parallel to subparallel to the river channel and is entrenched into the broad T_1 and has a width of few hundred metres to 2 km and an elevation 1–4 m lower as compared to T_1 (Figure 4 *c* and *d*). T_0 is narrower compared to the T_1 (refs 6 and 8). A low natural levee separates T_0 from the active channel and an alluvial ridge of a few metres height marks the outer limit of flood plain or its boundary with the higher valley terrace. The thickness of sediments in the flood plain is 1–5 m and is underlain by sandy channel bar deposits[11] and was formed during Holocene[6,7]. In Haridwar–Bijnor stretch, T_0 of the Ganga River shows strong incision, yet it has broadened at the intersection of Balawali Fault and Ganga Fault Zone near Tofir Majlispur village, with a width of about 2.5 km (Figures 2 and 3). Formed by vertical accretion of muddy sediment with intercalations of sand reworked by the river during its existing regimen, this T_0 is subjected to over-bank flooding of the river and is characterized by numerous old meanders, oxbow lakes and braided dry channels which become active during the high monsoonal discharge of the channel. However, the active and stabilized bars cause the anabranching of the channel (Figures 2 and 3). The active bars are dynamic in nature, devoid of vegetation cover and are prone to inundation by monsoonal floods because of their low elevation (Figure 4 *c*), but the stabilized bars are stable in nature, elevated and covered with scrubs, grasses, etc. The elevation difference between the active and stabilized bars varies from 1 to 4 m. The boundary between T_1 and T_0 is also marked by a 1–4 m difference in height (Figure 4 *d*).

Recently on the basis of luminescence dating of Ganga Plain sediments, Srivastava and Shukla[12] reported the building of MF during > 26 ka up to < 22 ka. They further explained the continued deposition on piedmont fan surface between 8 and 3 ka and activity of yazoo type channels during 3–1.1 ka on T_1 and last phase of active accretion on T_0 after 1.5 ka.

Tectonic set-up of the area is defined by a number of faults and lineaments. A set of NW–SE trending enechelon faults recognized as HFF separates Siwalik Hills and Gangetic plains[13,14]. Between Tofir Majlispur and Bijnor NNW–SSE trending two parallel faults form Ganga Fault Zone and the existence of this fault zone can be attributed to the development of unpaired terraces and prominent cliff line on the west bank wider terrace surface T_1 in the Harinagar–Bijnor segment of Ganga (Figure 3). Ten to 30 m high vertical cliff with deeply dissected ravinous land along the western bank of Ganga at the junction of T_1 and MF is the geomorphic evidence of the western upthrown block of Ganga Fault Zone (Figure 2). NE–SW trending Balawali Fault has an escarpment of about 30 m in the immediate north of Nagal and 20 m near Balawali which decreases to around 2–4 m towards south near Kalsiya Kalan village. Mitthawali Fault trends NNE–SSW and its geomorphic expression on satellite data is observed in the form of anomalous pathway of piedmont streams Pili and Rawasan. The cliff of this fault varies between 2 and 5 m and is observed along the NNE–SSW trending segments of Pili and Rawasan (Figure 4 *e*). The HFF is also offset by this Mitthawali Fault (Figure 2). Steep cliffs varying from 1 to 3 m (in height) along Pili Nadi and Rawasan and their incised channels, prominent niche points (at their entrance from Siwalik to Piedmont Zone) and parallel to subparallel drainage pattern are evidences of Pili and Rawasan Lineaments.

Superposed alluvial fans along piedmont streams with fan disposition resembling the trends of these streams and fan head entrenchment are evidences of the existence of faults along Kotawali Rao, Ranipur Rao and Ratmau Rao and lineaments along Ghoina Rao, Pathri Rao, Pili Nadi, Rawasan and Ratnal Nadi and further indicate a strong neotectonic control on landforms. River course of Ganga in the Piedmont Zone, between Haridwar and Nagal, is controlled by the NNW–SSE trending Haridwar Lineament and in the Nagal–Tofir Majlispur sector, it is controlled by the NE–SW trending Balawali Fault. Further south, Ganga flows along NNW–SSE trending Ganga Fault Zone. The incised channel of the Ganga and its conformity with the trends of Haridwar Lineament, Balawali Fault and Ganga Fault Zone indicate a strong tectonic control of river valley (Figure 2). Disposition of large old Fazalpur Manun Fan and superposed smaller coalescing alluvial fans along the piedmont streams Rawasan, Kotawali and Ratnal are controlled by Rawasan Lineament, Balawali Fault and Ratnal Lineament respectively. This is evident by NE–SW disposition of these superposed fans and their conspicuously incised proximal part (Figures 2 and 3; Table 1). The N–S trending Ranipur Fault and NE–SW trending Ghoina and Pathri Lineaments control the trend of Ranipur Rao, Ghoina Rao and upstream stretch of Pathri Rao respectively and also the disposition of Ranipur–Ghoina Fan developed along these streams (Figures 1 and 2). The Solani River course in the north of

Roorkee is controlled by NW–SE trending Solani Fault, whereas in the south of Roorkee it is controlled by the Ganga Fault Zone (Figure 2). The western extent of PF_2 has been restricted by Solani Fault and Ganga Fault Zone. The distal part of Pathri Fan is skewed in the SSW direction due to the influence of the NE–SW trending Balawali Fault (Figure 2). Ganga Tear Fault, Balawali and Khoh Faults and NNE–SSW trending lineaments control the drainages which are presently incised into fans (Figures 2 and 3). It is clearly evident that the disposition of landform features of this area and their extent were strongly controlled by the neotectonics in the past while the neotectonic effects are also reflected on the present day landforms and have caused the channel incision of the Ganga River and its tributaries. The fan cut terraces of piedmont streams owe their origin to the entrenchment of these streams into the PF_1 and PF_2 during the recent past (Figure 4 *f*).

Based on our discussions, the following conclusions can be arrived at:

- MF is extensively developed in the western Ganga Plain and superposed over T_2. T_1 is entrenched into the MF. Superposed on the geomorphic surfaces MF and T_1 are older and younger piedmont fans surfaces (PF_2 and PF_1) with the smaller fans superposed over larger ones. This represents various events of fan building activity in the past. T_0 is incised into T_1 (Figures 2, 3 and 4 *d*; Table 1).
- The size of fans forming PF_1 had progressively reduced during Holocene due to decrease in the discharge of rivers and streams but their preferential trends and strong incision in the proximal part remained the same as those of the underlying large fans of PF_2. This can be attributed to their tectonic control (Figure 2).
- It is most likely that the climatic changes during the recent past, coupled with the entrenchment of all the major drainages of the area have gradually reduced the rate of deposition on the PF_2 and PF_1. Consequently, the subdued fan building activity is presently confined to the narrow proximal part of the PF_1 (Figures 2 and 3) and the processes of deposition are presently active only in T_0 and upper part of the PF_1.
- The geomorphic set-up of western Ganga Plain was controlled by active tectonics and climatic changes during Pleistocene–Holocene. The high degree of incision, broader flood plains and preferred trends of Ganga River valley and those of other drainages and the disposition of superposed alluvial fans of PF_2 and PF_1 coincide with the NE–SW, NNW–SSE and N–S trends of major faults and lineaments are some of the evidences of neotectonic activities, complementary to the rise of Himalaya and Siwalik.

The results of this study could prove to be important inputs for further studies aimed at establishing the detailed seismotectonic set-up of this area and seismic hazard assessment along HFF and also for ground water targeting and Holocene geomorphology studies in the western part of Ganga Plains.

1. Burchfiel, B. C. and Royden, L. H., Tectonics of Asia 50 years after the death of Emile Argand. *Eclog. Geol. Helv.*, 1991, **84**, 599–629.
2. Molnar, P., England, P. and Martinod, J., Mantle dynamics, uplift of the Tibetan plateau, and the Indian monsoon. *Rev. Geophys.*, 1993, **31**, 357–396.
3. Brookfield, M. E., The evolution of the great river systems of southern Asia during the Cenozoic India–Asia collision: rivers draining southwards. *Geomorphology*, 1998, **22**, 285–312.
4. Valdiya, K. S., *Himalaya: Emergence and Evolution*, Universities Press (India) Limited, Hyderabad, 2001, p. 93.
5. Singh, I. B., Late Quaternary sedimentation of Ganga Plain foreland basin. Proceeding of Symposium on NW Himalaya and foredeep. *Geol. Surv. India. Spec. Publ.*, 1996, **21**, 161–172.
6. Singh, I. B., Geological evolution of Ganga Plain – an overview. *J. Palaeontol. Soc. India*, 1996, **41**, 99–137.
7. Shukla, U. K. and Bora, D. S., Geomorphology and sedimentology of Piedmont Zone, Ganga Plain, India. *Curr. Sci.*, 2003, **84**, 1034–1040.
8. Shukla, U. K., Singh, I. B., Sharma, M. and Sharma, B., A model of alluvial megafan sedimentation: Ganga Megafan. *Sedim. Geol.*, 2001, **144**, 243–262.
9. Uniyal, A., Unpublished D Phil thesis submitted to H.N.B. Garhwal University, Srinagar Garhwal, 2002.
10. Shukla, U. K., Sedimentation model of gravel dominated alluvial piedmont fan, Ganga Plain, India. *Int. J. Earth Sci.*, 2009, **98**, 443–459.
11. Singh, I. B., Srivastava, P., Shukla, U. K., Sharma, S., Sharma, M., Singh, D. S. and Rajagopalan, G., Upland interfluve (Doab) deposition: alternative model to muddy overbank deposits. *Facies*, 1999, **40**, 197–210.
12. Srivastava, P. and Shukla, U. K., Quaternary evolution of Ganga River system: New Quartz Ages and a review of luminescence chronology. *Him. Geol.*, 2009, **30**, 85–94.
13. Nakata, T., *Geomorphic History and Crustal Movements of Foot Hills of the Himalaya*, Institute of Geography, Tohuku University, Sendai, 1972, p. 77.
14. Kumar, S., Prakash, B., Manchanda, M. L., Singhvi, A. K. and Srivastava, P., Holocene landform and soil evolution of western Gangetic Plain: implications of neotectonics and climate. *Z. Geomorph. NF*, 1996, **103**, 283–312.

ACKNOWLEDGEMENTS. This study is a part of A.U.'s D Phil work. A.U. thanks Director, RSAC-UP for encouragement. Prof. I. B. Singh of University of Lucknow, Mr P. N. Shah and Mr S. Rao of RSAC-UP and Dr M. L. Manchanda, Dr L. I. M. Rao and Mr Piyush Kathuria are also thanked. A.U. also thanks Nidhi, Prabuddha, Pranayak and Vaishnavi. We gratefully acknowledge anonymous reviewers for valuable comments and suggestions.

Received 16 September 2009; revised accepted 19 May 2010