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Role of extensional tectonics and climatic changes in geomorphological, pedological and sedimentary evolution of the Western Gangetic Plain (Himalayan Foreland Basin), India

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Abstract: The western Gangetic plain shows various geomorphic features such as floodplains, aeolian ridges, terminal fans, palaeochannels, alluvial piedmont plain, plains associated with rivers and interfluve plains. Soil-geomorphic studies of the Ganga-Yamuna Interfluve in the western Gangetic plain, India have enabled the identification of thirty-three soil-geomorphic units. These units are grouped into five morphostratigraphic sequence members viz. QGMS-I to V (Quaternary Geology Morphostratigraphic members). Polymineralic fine grained Luminescence dating bracket these morphostratigraphic members to ages <1.7, 1.8-3.6, 3.7-6.5, 6.6-9.6, >9.6 ka, respectively.

Using the satellite remote sensing, digital elevation model and nature of drainage pattern, seventeen faults (3-longitudinal and 14-transverse) are identified. The longitudinal faults show a southwest curvilinear trend, whereas the transverse faults are steeply dipping and nearly perpendicular to the longitudinal faults. Longitudinal faults are the expression of compression from southwest and the transverse faults are attributed to in an extensional regime. Activities along the transverse normal faults led to the deposition of the terminal fans on the downthrown blocks, on which thin channel deposits capped by soils can be observed.

Climate seems to have become wet and warm after 10 ka, leading to increase in discharge and incision by rivers and development of areally extensive soils, as compared to the adjoining eastern region marked by a wetter climate, where rivers started degrading just after the Last Glacial Maximum. Also, soils developed in two wet periods 1.7 to 3.6 and 6.5 to 9.6 ka, as compared to the rest of the Holocene, are characterized by increased illuviation.

INTRODUCTION

The Indo-Gangetic Plains form an active peripheral foreland basin, which receives the sediments shed by the Himalayan Orogen. These plains include some of the most agriculturally productive lands in India. Srivastava *et al*. (1994) and Thomas *et al*. (2002) classified the Gangetic Plain into three well marked zones viz. Upper, Middle and Lower Gangetic Plains. The Upper Gangetic Plain is marked by uplands (interfluves) with incised rivers and moderately to well-developed soils overlying the interfluves. These plains extend from the Yamuna River in the west to Rapti River in the east over a length of 570 km and constitute about 56% of the whole of the Gangetic plains (Fig. 1).

Several models have been proposed for the style of deposition on the interfluves. Singh *et al*. (1999) designated the thick fine grained muddy overbank deposits of the Siwalik Group as the interfluve deposits, though the depositional processes on the interfluve were not described. Similarly Gibling *et al*. (2005) postulated that the deposition on the interfluves during the Quaternary Period was controlled by attachment and detachment of floodplains of the bounding rivers caused by an increase and decrease in their discharges during climatically wet and dry phases, respectively. However, more recently Singh *et al*. (2006) noted that major sedimentation on the adjoining Deoha/Ganga-Ghaghara interfluve was in the form of terminal fans, initiated by activity of transverse normal faults at different times.

Kumar *et al*. (1996) emphasized that uplift and tilting of different tectonic blocks was the major factor controlling the degree of development of soils in the major parts of the Ganga-Yamuna interfluve. However, their work was based on 1:1 million scale images and the degree of soil development, and dates on soils were too few to provide a detailed idea of geomorphological and pedological evolution of the area.

Keeping all these points in view detailed studies of regional geomorphology, distribution of soils and tectonic features of the western Gangetic Plain between the Ganga and Yamuna Rivers were carried out using satellite data of Linear Self Scanning Sensors (LISS-III; resolution of 23.5 m) and Wide Field Sensors (WiFS; resolution 188.8 m) of Indian Remote Sensing Satellites IA/B (IRS IA/B). Also, field and laboratory study of soils from different geomorphic units to infer the degree of soil development and absolute dating of soils by Optical Luminescence dating technique were carried out and an attempt was made to work out roles of extensional tectonics

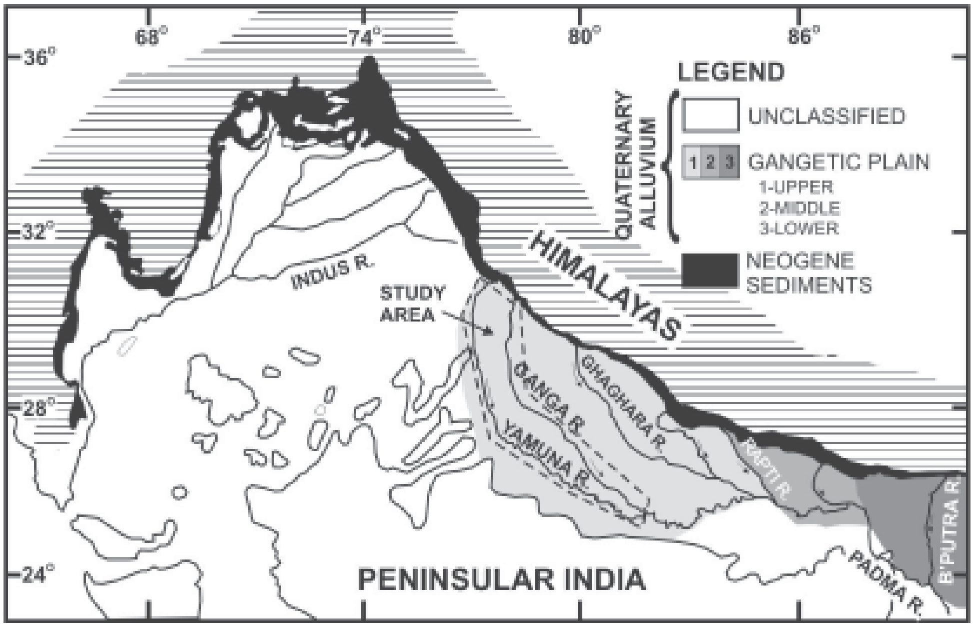


Fig. 1. Location map of the study area pedons.

and climatic changes in development of geomorphology, soils and sedimentation during the Holocene Period.

METHODOLOGY

Remote Sensing analysis of satellite images and geographical information system analysis, which includes preparation of Digital Elevation Models (DEMs), Digital Terrain Models (DTMs) and 2-D topographic profiles across the inferred faults, were undertaken. For this purpose Survey of India topographic maps at a scale of 1:250, 000 and 1:50, 000 and LISS-III and WiFS data of IRS IA/B satellites were used. To process, visualize and interpret the data, ERDAS 8.5 along with Arc-View 3.2a and Surfer 8 softwares were used. All these techniques were employed to map different landforms and geomorphic units with soil characters varying within small ranges (soil-geomorphic units, Mohindra *et al*. 1992).

Detailed field work was carried out for ground-truthing the identified landforms and to check the boundaries of soil-geomorphic units (Fig. 2). Field study of soil morphology, sample collection for laboratory analysis from typical pedons (Fig. 3) and geomorphological features were carried out. Luminescence dating of soil samples using the Infrared Stimulated Luminescence (IRSL) technique was used to ascertain the time of soil forming events. In addition to this, grain size analysis to evaluate the texture of soils of different soil-geomorphic units and chemical studies in terms of Electrical Conductivity (EC) and pH to understand the nature of the soils were undertaken. Also, micromorphological studies of *in situ* soil samples collected during the fieldwork were carried out to evaluate the degree of soil development and pedogenic processes. Ground Penetrating Radar (GPR) investigations on four inferred faults were carried out to ascertain their subsurface nature.

LUMINESCENCE DATING

The luminescence dating method is based on the time-dependent accumulation of radiation energy stored in non-conducting crystalline materials as a result of natural radioactivity. In the laboratory, the stored energy can be released in the form of luminescence by stimulating the crystal either by heat (Thermoluminescence abbreviated as TL) or light (Optically Stimulated Luminescence abbreviated as OSL). Since the luminescence output is a time dependent function of radiation dose, it can be termed as the palaeodose i.e., the dose acquired after the geological luminescence is reset by the sun to the near residual level during the transport of the sediment in fluvial environment. It has been observed that aquous environment tends to attenuate the solar flux due to the turbidity and depth at which sediment was transported. In view of this, the floodplain samples are considered to be an ideal choice for optical dating because a majority of them are transported as suspension load. Age of the sediment is obtained by dividing the palaeodose with the dose received annually (a function of the concentration of radioactivity, which is assumed to be constant with time). Thus the age

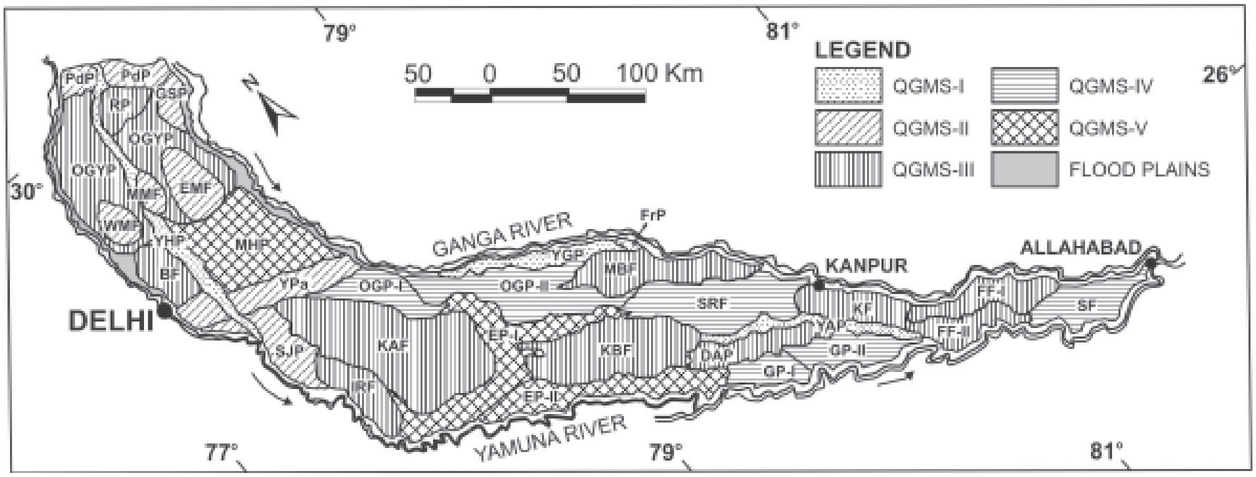


Fig. 2. Soil-geomorphic map of the study area. Symbols for different soil-geomorphic units are explained in Table 1.

equation can be given as

$$(\text{Age}) = \frac{\text{Palaeodose (Gy)}}{\text{Dose per year}}$$

Gy- Gray, unit of radiation dose

Soil samples were collected from the C or BC horizons of the soil profiles from each soil-geomorphic unit (Fig. 2). Care was taken to avoid collection of sediments that show any post-depositional disturbances such as root penetration and bioturbation. Samples were collected in iron or steel pipes (dimensions- 5 cm diameter × 15 cm length), which were driven into the horizon using a sledge hammer. Care was taken to avoid the shattering or collapse of the tube during hammering.

Samples were prepared under subdued red light conditions. About 2 cm of the exposed sample from both ends of the metal cylinder was removed. Details of procedures of the dating are given by Aitken (1985) and Singhvi *et al.* (2001). In the present study, OSL (infrared light source, IRSL) was used on polymineralic fractions of 4-11μ grain size which are likely to remain for long time in suspension hence ensures the sun bleaching of the geological luminescence (Hutt *et al.* 1988). A sequential treatment using 1N HCL, 30% H_2O_2 and 0.01N sodium oxalate was done in order to remove the carbonates, organic matter and to avoid flocculation. The fine-grain fraction (4-11μm) was collected by Stokes' method in acetone medium and it was deposited on 40 aluminum discs.

The measurements were carried out on Daybreak 1100 TL system using Corning 7-58 and BG-39 filters coupled to EMI-9635QA PMT. Figure 4 shows growth, shine down curves and

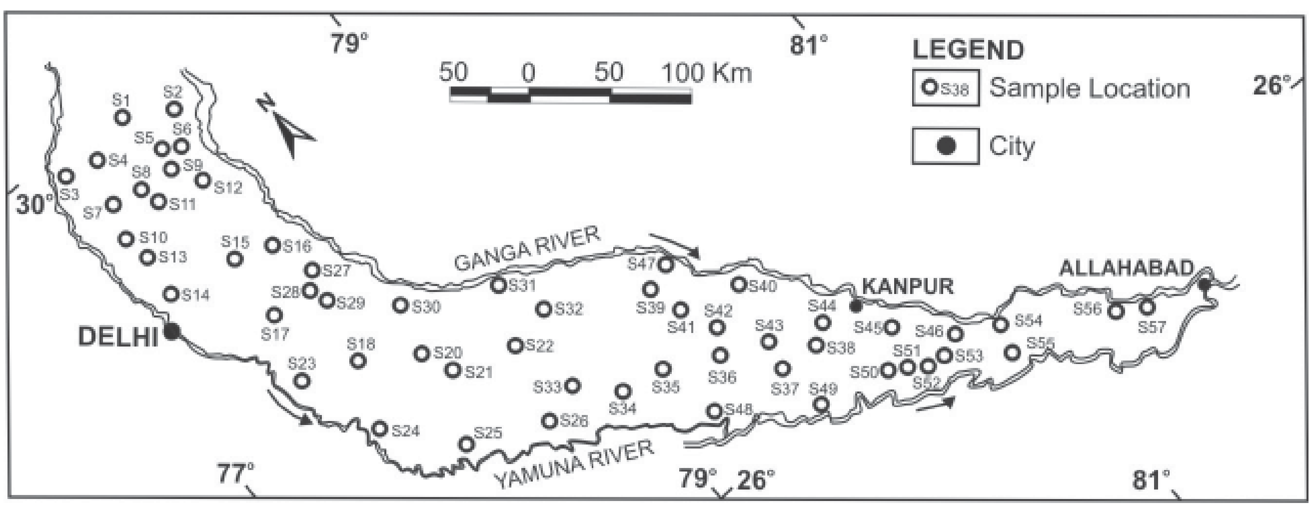


Fig. 3. Location of studied pedons.

Table 1. *Radioactivity values, equivalent dose and absolute ages of dated samples from morphostratigraphic units QGMS-I and V.*

Sample No.	DEPTH(cm)	238U (ppm)	232Th (ppm)	40K (%)	ED (Gy)	AGE (ka)
QGMS-I (< 1.7 ka)						
Young Hindon Plain (YHP)						
S58	31	5.50±1.16	9.90±5.75	1.10±0.06	2.60±0.73	0.6±0.20
Young Arind Plain (YAP)						
S38	70	6.20±0.12	16.77±7.01	1.69±0.08	5.52±1.22	1.05±0.25
Young Ganga Plain (YGP)						
S31	40	6.64±1.31	10.15±5.40	1.23±0.06	4.18±1.95	0.8±0.41
QGMS-II (1.7-3.6 ka)						
Young Piedmont Plane (YPdP)						
S3	106	6.02±1.42	9.90±3.01	2.01±0.10	9.26±0.49	1.7±0.22
Ganga-Solani Plain (GSP)						
S59	68	6.7±0.79	9.75±7.53	1.28±0.06	9.24±1.01	1.8±0.39
East Muzaffarnagar Fan (EMF)						
S9128	13.64±1.09	34.97±4.81	2.28±0.11	40.63±1.99	3.6±0.37	
S12	135	8.36±0.67	25.42±3.50	2.31±0.11	28.80±3.60	3.4±0.53
West Muzaffarnagar Fan (WMF)						
S10	128	10.00±0.80	29.44±4.05	2.28±0.11	26.69±2.86	2.8±0.40
Middle Muzaffarnagar Fan (MMF)						
S11	197	14.08±1.13	30.85±4.24	2.08±0.10	27.76±1.48	2.5±0.27
Yamuna Palaeochannel (YPa)						
S29	117	12.18±1.18	28.95±4.14	2.10±0.10	28.06±1.56	3.1±0.43
S27	125	12.90±1.03	32.00±4.40	1.92±0.10	25.12±2.28	2.4±0.31
S17	103	12.03±0.96	28.52±3.92	1.99±0.10	33.44±3.09	3.4±0.44
Sikandrabad-Jewar Plain (SJP)						
S23	100	2.42±1.41	16.91±4.85	1.75±0.09	4.75±0.56	1.9±0.21
Roorkee Plain (RP)						
S1146	7.86±0.42	21.08±4.23	1.95±0.10	32.16±3.54	2.9±0.78	
QGMS-III (3.6-6.5 ka)						
Iglas-Raya Fan (IRF)						
S24	73	5.20±1.20	22.78±8.14	1.82±0.09	36.54±4.50	5.7±1.17
Muhammadabad-Bhilaur Fan (MBF)						
S39	160	7.61±0.59	11.38±7.30	2.82±0.14	37.60±3.26	5.4±0.82
S40	210	4.72±0.29	22.49±6.94	3.46±0.17	45.20±3.41	5.9±0.76
Kanpur Fan (KF)						
S46	100	5.67±1.44	8.77±4.98	1.58±0.08	19.92±2.00	4.2±0.86
S45	200	8.46±0.29	11.21±6.95	1.09±0.05	34.31±1.80	6.1±1.00
Debiapur-Akbarpur Plain (DAP)						
S37	120	3.61±0.77	18.16±7.24	1.06±0.05	21.25±2.04	5.3±1.16
S4-	5.53±0.56	13.80±6.20	0.53±0.03	19.05±1.48	4.4±0.90	
Karhal-Bidhuna Fan (KBF)						
S33	60	5.22±0.54	11.74±6.73	0.75±0.04	21.89±2.39	5.3±1.20
S34	133	6.35±0.91	8.49±5.69	0.70±0.03	17.47±4.43	4.2±1.31
S36	215	5.98±0.22	14.98±6.97	1.26±0.06	31.70±3.28	6.0±1.15
S35	165	5.10±1.20	13.82±5.69	2.22±0.11	35.60±3.24	6.2±1.03
Fatehpur Fan-I (FF-I)						
S56	160	7.92±0.63	26.88±3.70	3.01±0.15	43.90±2.35	4.9±0.50
Old Ganga-Yamuna Plain (OGYP)						
S13	145	7.00±0.99	7.59±5.54	1.36±0.07	29.49±2.37	6.0±0.98
S7172	8.23±0.38	15.06±6.64	2.02±0.10	38.65±3.12	5.6±0.98	
S5135	6.45±1.09	7.81±5.62	3.17±0.02	38.17±3.74	5.9±0.99	
Baghpat Fan (BF)						
S14	171	5.09±1.37	16.84±5.13	1.98±0.10	9.26±0.49	6.0±0.69
Fatehpur Fan-II (FF-II)						
S55	134	8.36±0.67	25.42±3.5	2.31±0.12	28.08±3.60	3.4±0.52
Khurja-Aligarh (KAF)						
S19	133	4.47±1.12	14.18±5.87	1.57±0.08	27.87±2.37	5.7±1.04
S20	105	7.88±1.30	18.70±8.89	1.83±0.09	35.11±1.38	5.3±0.93

Sample No.	DEPTH(cm)	238U (ppm)	232Th (ppm)	40K (%)	ED (Gy)	AGE (ka)
S18	50	5.04±1.20	11.38±5.67	1.20±0.06	28.73±1.83	6.4±1.22
QGMS-IV (6.5-9.6 ka)						
Old Ganga Plain-I (OGP-I)						
S30	126	7.66±0.46	11.65±7.19	1.75±0.08	42.16±2.08	7.4±1.17
S31	240	4.70±1.37	10.96±5.20	2.46±0.12	37.3±3.74	6.8±1.20
Old Ganga Plain-II (OGP-II)						
S59	140	7.74±0.45	18.10±7.20	1.34±0.07	41.89±2.53	9.4±1.91
Ghatampur Plain-I (GP-I)						
S49	121	3.42±1.28	15.40±4.19	1.36±0.07	32.03±3.84	7.2±1.56
Ghatampur Plain-II (GP-II)						
S52	157	4.79±1.33	9.63±4.51	1.59±0.08	39.82±6.12	8.4±1.97
S50	146	7.45±1.32	19.87±8.35	1.36±0.07	47.70±4.75	7.3±1.49
Saurikh-Rasulabad Fan (SRF)						
S41	108	5.50±0.95	11.81±5.93	0.71±0.04	35.39±2.02	8.3±1.66
S42	90	6.88±1.23	14.14±4.23	2.08±0.10	52.48±4.80	8.3±1.30
S43	77	7.55±0.74	12.07±6.49	0.84±0.04	42.93±5.46	8.3±1.68
S44	290	6.81±1.36	14.70±8.40	1.71±0.08	50.00±3.89	8.3±0.82
S8175	5.37±1.20	10.09±5.67	2.40±0.12	42.10±2.22	7.6±1.15	
Sirathu Fan (SF)						
S57	180	4.16±0.91	15.91±6.29	2.28±0.01	71.20±4.00	9.1±1.08
QGMS-V (>9.6 ka)						
Meerut-Hapur Plain (MHP)						
S15	230	2.62±0.53	23.11±6.79	1.18±0.05	57.30±4.56	11.8±2.27
S16	180	8.06±0.82	13.54±7.56	1.54±0.08	59.80±2.27	9.7±1.59
Etawah Plain-I (EP-I)						
S22	123	6.25±0.85	16.74±6.39	1.03±0.05	61.05±4.17	11.3±1.99
S25	123	4.08±0.88	11.50±3.05	0.38±0.03	36.76±2.41	11.0±1.86
Etawah Plain-II (EP-II)						
S26	140	4.86±1.28	16.40±8.06	0.76±0.03	46.75±3.80	10.3±2.13
S48	165	4.22±1.33	14.03±4.98	0.99±0.05	42.39±1.52	9.9±1.92
Farrukhabad Plain (FrP)						
S47	330	4.05±1.02	16.68±6.09	1.28±0.06	66.10±12.40	13.8±3.57

age plateaus. Table 1 shows the data obtained from luminescence dating.

PHYSIOGRAPHIC FEATURES

The Gangetic plain is a great alluvial crescent stretching from the Yamuna River to the delta of the Ganga River in Bangladesh. Topographically, the plain is homogeneous, with the exception of the floodplain bluffs, features associated with river erosion and changes in river courses forming palaeochannels. The most prominent geomorphic feature of the plain is the presence of piedmont zone (locally called *Bhabhar*), south of the Himalayan ranges. Climate varies from semi-arid in the west-southwest to dry sub-humid towards the eastern and to wet sub-humid continental in the northern areas in the Himalayan foothills. Figure 5 gives the details of the soil moisture regimes of area published by the National Bureau of soils and Land Use Planning Nagpur (1993). The northern part of the study area is dominated by Typic Udic soil moisture regime. Typic Ustic soil moisture regime prevails over central part of the study area and most of the southern part of the study area is covered by Aridic Ustic type of soil moisture regime.

GEOMORPHIC FEATURES

Six major geomorphic features have been recognized in the study area. These are floodplains, plains, aeolian ridges, palaeochannels, terminal fans and interfluve plain.

Floodplains

These are the sites for young sediment deposits. Floodplains are occasionally inundated during the rainy season; hence the soils on these plains are weakly developed. The dimension of the floodplains in the Ganga and Yamuna rivers are considerably wide (0.10-4.15 km). Compared to this the inland river floodplains are quite narrow (10-200 m).

Aeolian Ridges

The study area is studded with localized aeolian ridges along

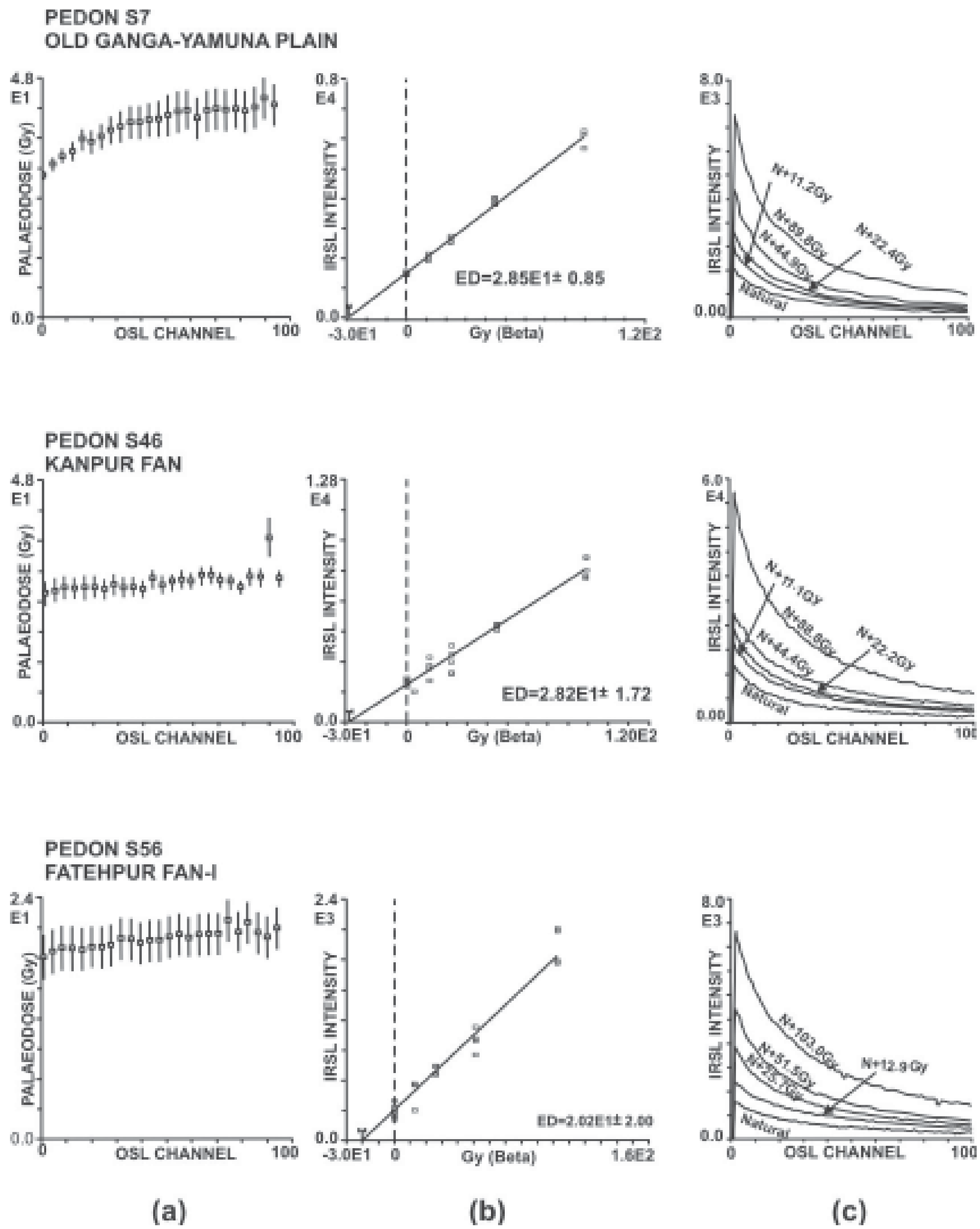


Fig. 4. IRSL shine down, growth curves and equivalent dose plateaus for some typical samples of the study area.

large palaeochannels in the northern parts, suggesting large scale aeolian reworking of sandy materials of the abandoned channels. In view of their proximity to the river channels, they can be considered as the source bordering aeolian ridges. Due to the extensive agricultural activity on the aeolian ridges, a large part of them have been removed and only small parts are left. In southern semi-arid parts of the study area, large sub-circular aeolian ridges measuring up to 1 km in diameter and several meters in height are observed.

Terminal Fans

There are several terminal fans in the study area, out of which some remarkable ones are Muzaffarnagar fans (east, middle and west), Khurja-Aligarh fan, Muhammadabad-Bhilaur fan, Kanpur fan, Fatehpur fan-I, Fatehpur fan-II, Iglas-Raya fan, and Karhal-Bidhuna fan (Fig. 2). All the fans are elongated, convex-upward in nature and gently sloping (10.4% -23.4%), and their distal boundaries are not clearly defined. Geometric

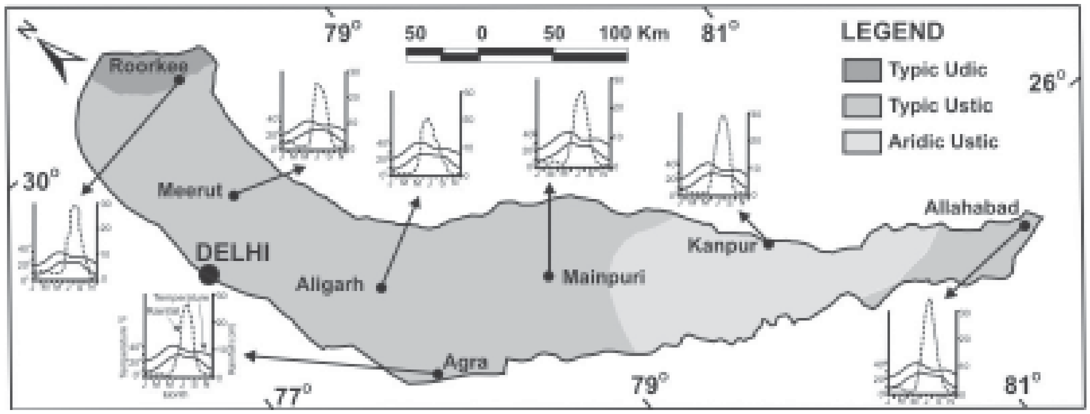


Fig. 5. Soil moisture regimes of the study area (after NBSS LUP, 1993).

aspects like length (34.8-146.7 km), area (340-5127 km^2), associated faults and ages of soils overlying terminal fans are given in table 2. The largest mapped fan is Khurja-Aligarh Fan in the central part of the study area and it shows a well developed distributary system (Fig. 6). Aligarh city is located on the proximal part of the Khurja-Aligarh fan, which gets flooded once in 10-15 years. This would imply that the fan is still subjected to the large scale sheet flows. The top layer of the terminal fans shows high salt efflorescences and moderate to strong pedogenesis. At places soils developed on the terminal fans may laterally pass into or are overlain by aeolian and lacustrine deposits.

Our study of five vertical sections exposing about 15 to 24 m thick sequences along the river banks and analysis of 3 borehole data in the Ganga-Yamuna interfluve by Sinha *et al.* (2005) suggest that major parts of these sequences are

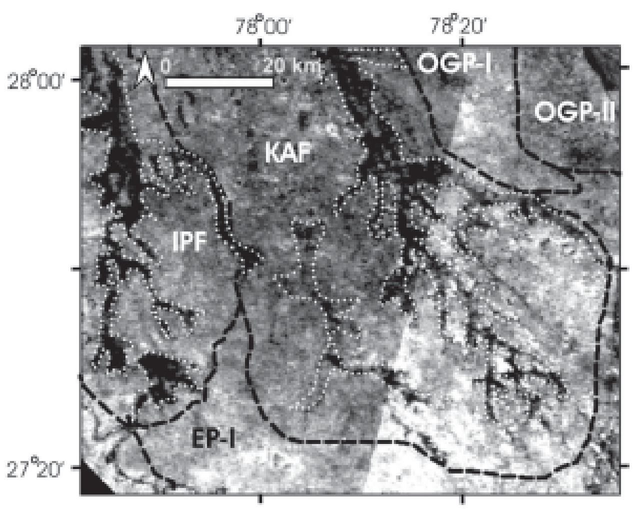


Fig. 6. FCC of WiFS (October 2000, 1 and 2 bands) showing modern distributory patterns of Khurja-Aligarh (KAF) and Iglas-Raya (IRF) terminal fans. Other symbols explained in Table 1.

composed of thin channel deposits overlain by palaeosols, suggesting that the main process of deposition on the interfluve was in the form of terminal fans at least for the last 57.2 ka (age of the Kalpi Section, after Gibling *et al*. 2005).

Palaeochannels

2.5 to 15 km wide palaeochannels are recognized from satellite images from the northern parts of the interfluve and could be traced northward where they meet the main modern channels of the Ganga and Yamuna rivers. The Ganga Palaeochannel near Barla village (Muzaffarnagar Distt.) has been dated as 2.58 ka, and the Yamuna Palaeochannel as 2.40-3.56 ka). Also, numerous small stream palaeochannels can be made out near Fatehpur in the eastern part of the study area.

Piedmont Plain

Northwestern part of the study area is marked by a steeply sloping, elongated piedmont zone, which extends up to the Himalayan foothills (Fig. 2). Parallel to sub-parallel drainage pattern is developed in this zone due to the steep sloping nature of the terrain (Fig. 7).

Kumar *et al*. (1996) divided piedmont zone into two (a) younger piedmont overlain by younger soils (weakly developed) and (b) older piedmont overlain by older soils (well developed), which have been removed by erosion at most places in the eastern half and is present in western half extensively.

Plain associated with the Ganga and Yamuna rivers

This plain lies immediately south of the Piedmont Plain. It is marked by numerous palaeochannels of the Ganga and Yamuna rivers and invariably overlain by moderately to strongly developed soils. Investigations of subsurface lithologies

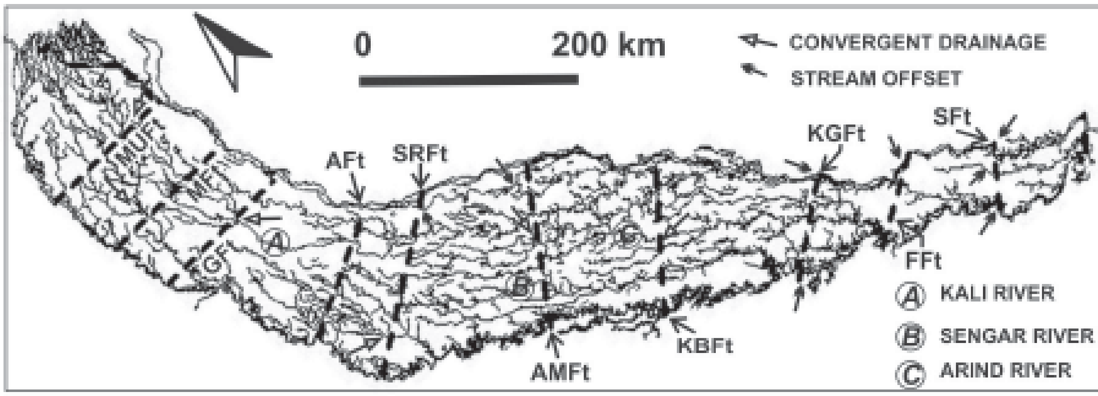


Fig. 7. Drainage map of the study area, showing initiation of new streams, convergent drainage and offset streams caused due to the faults. MuFt- Muffaranagar Fault, MFt- meerut Fault, GFt- Ghaziabad Fault, Aft- Aligarh Fault, SRFt- Sikandra Rao Fault, AMFt- Aliganj-Mianpuri Fault, KBFt- Kannauj-Bidhuna Fault, Kanpur-Ghatampur Fault, FFT-Fatehpur Fault, SFT- Sirathu Fault.

indicate that the plain is underlain by sandy sediments, suggesting presence of large rivers in this region in the past.

Interfluve plain

In the south and east of the Meerut City is a plain, above the reach of modern rivers. It acts as a carpet for terminal fan deposition. Also, in the central part of the study area, Etawah Plain-I and Etawah Plain-II form the base over which younger terminal fans were deposited. These plains are overlain by strongly developed soils.

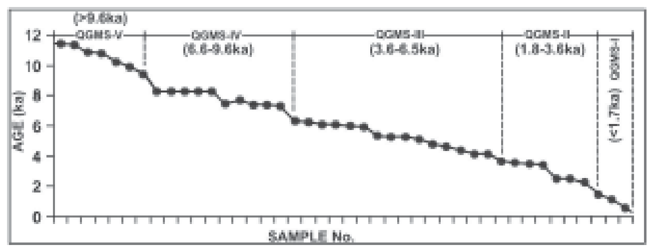


Fig. 8. Frequency curve for 55 IRSL ages from different soil-geomorphic units with ages arranged in a descending order. Tectonically stable periods are marked by the flat or gently sloping portions of the curve. Sharp breaks are used to define different members of the morphostratigraphic sequence.

MORPHOSTRATIGRAPHY

An attempt was made by Kumar *et al*. (1996) to classify the northern part (from Himalayan foot hills to Aligarh) of the study area, where they identify the five soil-chronoassociation members based on the soil development characteristics and visual interpretation of satellite imageries of 1:1 million scale. In the present study using the high resolution satellite images (23.5 m) a total of 33 soil-geomorphic units were identified and mapped (Fig. 2). This was followed by detailed optical dating. The ages thus obtained are shown in the form of a bar diagram, where ages are plotted in ascending order (Fig. 8). Figure 8 shows distinct breaks in age distribution, which are used to construct morphostratigraphy of the study area (Frye & Willman 1962 *in* Fairbridge 1968, p. 915) with five members: QGMS-I (<1.7 ka), QGMS-II (1.8-3.6 ka), QGMS-III (3.7-6.5 ka), QGMS-IV (6.6-9.6 ka) and QGMS-V (>9.6 ka).

VARIATIONS IN SOIL PROPERTIES AMONG DIFFERENT SOIL-GEOMORPHIC UNITS

Changes in characters of B-horizons

Soils belonging to QGMS-I member are very weakly developed with B-horizon thickness varying between 0-17 cm. B-horizons, if present, show very weak development of granular to sub-angular blocky structure. Soils of the QGMS-II are weakly to moderately developed, with small B-horizon thicknesses varying between 41-83 cm. Soils of the QGMS-III member are moderately developed with B-horizon thickness varying from 40 to 87 cm with the exception of pedon S55, which shows a low value (23 cm). The moderately developed soils show sub-angular blocky structure. In QGMS-IV member moderately to well-developed soil can be observed. The B-horizon thickness varies between 40-90 cm with the exception of pedons S43 and S32, which show a low value of 30 cm and pedons S36 and S44 show high values of 110 and 125 cm, respectively. Soils exhibit well developed sub-angular blocky structure. In QGMS-V soils, B-horizon thickness varies between 30 and 80 cm, with the exception of pedon S15, which shows a high value of 140 cm. Soils of this member show well-developed sub-angular blocky structure (Fig. 9). A bar diagram showing solum thickness of various pedons in different morphostratigraphic members (QGMS-I to V) brings out that solum thicknesses in members QGMS-II and –IV are comparatively higher than expected from the general trend (Fig. 10).

Micromorphological variations

Micromorphological studies of the soils of different morphostratigraphic sequence members show distinct variations in the features such as grade of pedality, development of cutans, smoothness/roughness of void surfaces, development of b-fabrics and variation in the type, and form of concretions and mottles with increase in age of soils.

Micromorphological investigations show that soils belonging to QGMS-I and II member have weak to moderately developed pedality, whereas in the older members (QGMS-III to V) moderate to well-developed subangular blocky microstructure is observed.

Crystallitic-, reticulate-, parallel-, grano-, poro-striated, stipple- and mosaic-speckled are the major type of b-fabrics in the soils (Fig. 11). In general, the degree of development of b-fabric in the QGMS-I to III soils is significantly stronger than that in the older soils (QGMS-IV to V). The groundmass of B-horizons of most of the soils is light to dark brownish to grayish in colour and the colour is comparatively darker in the older soils. An overall increase in the thickness of argillan and ferriargillan coatings is observed from QGMS-I to V (10-60 μm; 50-250 μm; 50-300 μm; 80-500 μm and 100-550 μm, respectively), except that the argillans and ferriargillans thicknesses are similar in the QGMS-II and III soils and so is true of the QGMS-IV and V soils.

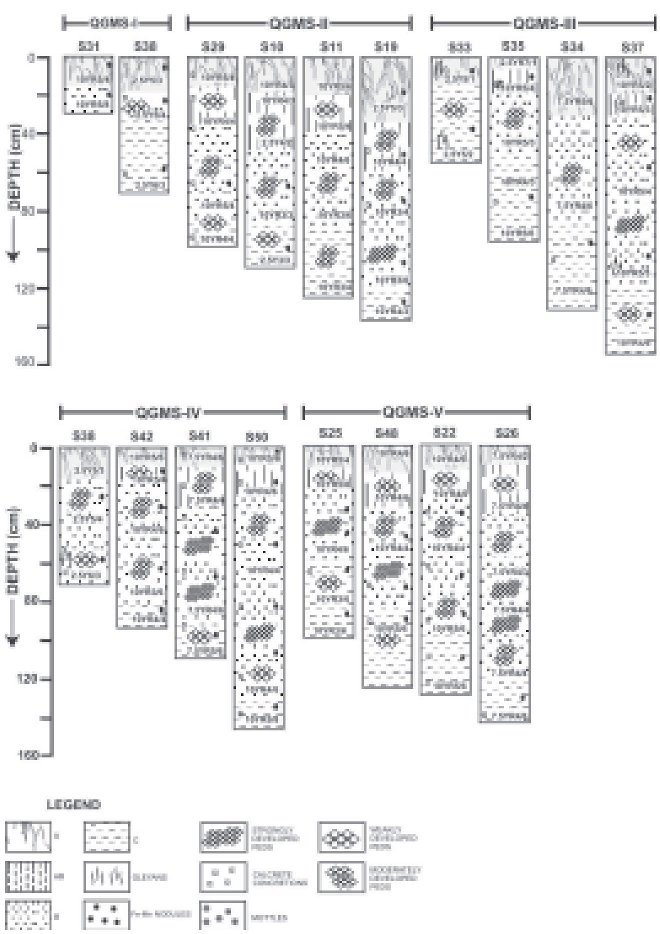


Fig. 9. Soil-morphological characters of typical pedons of soils of different morphostratigraphic members (QGMS-I to V).

The development and occurrences of calcretes does not show any trend however, with the exception that the hard calcium carbonate concretions are usually restricted to the middle part of the study area (south of Meerut to north of Kanpur). The older soils (QGMS-IV-V) viz. Etawah Plain-I and Saurikh-Rasulabad Fans have widespread occurrence of hard calcium carbonate concretions. Compared to this, in the younger soils, calcretes are less abundant and are medium to soft. In the Yamuna Palaeochannel they occur as petrocalcic horizons in the C-horizon.

Ferro-manganese nodules in the QGMS-I soils are soft, few to absent, whereas in QGMS-II soils the nodules are common and soft in some profiles. Fe-Mn nodules are common and soft in some profiles and are moderately hard in the QGMS-III soils. The QGMS-IV soils bear nodules, which are very common to abundant and moderately hard in nature. Table 3 gives the detailed micromorphological characters of different members of morphostratigraphic sequence.

Variations in soil textural and chemical properties

Particle size analysis was carried out for typical soil profiles covering almost all the identified soil-geomorphic units. Textural classes were determined by plotting size data in a combined texture triangle diagram (Schoeneberger *et al*. 1998).

QGMS-I soils are dominated by the clayey soils and were developed in floodplains. However, soils belonging to QGMS-II and QGMS-III show wide textural variability (from sandy loam to sandy clay loam). All the analyzed samples of the QGMS-IV soils fall in the clay class and the oldest soils of QGMS-V fall in the sandy clay to sandy clay loam classes.

Plots of total clay content and pedogenic clay content with depth for typical pedons are given in figure 12a. With increasing ages the pedogenic clays show sigmoidal relations with age, wherein the pedogenic clay content is high in QGMS-

Table 3. *Summary of micromorphological characters of B-horizon soils of different morphostratigraphic members.*

Morphostratigraphic Unit	Pedality	Type of voids/channels and surfaces	C/f ratio, limit and c/f related distribution	Cutans, type and thickness of coating	Development of b-fabric	Degree of alteration of minerals	Concretions and mottles
QGMS-I	Apedal to Weakly developed sub-angular blocky; peds partially to unaccommodated	Irregular, sub-circular, vesicular, oval voids; channel and void walls serrate, mammiliate	30:70 to 40:60; 30 µm; open to double spaced porphyric	Argillan and ferriargillan; typic-, hypo- and rarely quasi-type (10-60 µm)	Moderately to weakly developed crystallitic, parallel-, unistriated, stipple speckled	Weak; pellicular alteration in mica minerals	Weakly impregnated typic-, cross-concentric and compound Fe/Mn (25 µm to 275 µm) nodules with distinct to diffused boundaries
QGMS-II	Weakly developed sub-angular blocky; peds partially to unaccommodated	Irregular, sub-circular, vesicular, vughy voids; channel and void walls serrate, mammiliate	20:80 to 40:60; 20-30 µm; open to double spaced porphyric	Argillan, ferriargillan and calcetan; typic-, hypo- and rarely quasi-type (50-250 µm)	Moderately developed crystallitic, poro-striated, stipple speckled,	Weak to moderate; parallel and pellicular alteration in mica minerals and fracturing in quartz	Moderately to weakly impregnated typic-, aggregate- and compound Fe/Mn (125 µm to 750 µm) nodules with distinct to diffused boundaries
QGMS-III	Weakly to Moderately developed sub-angular blocky; peds partially accommodated	Circular, vesicular, vughy, chamber voids; channel and void walls smooth, undulating	40:60; 20-30 µm; 20-30 µm; open to double spaced porphyric	Argillan and ferriargillan; typic-, hypo- and rarely quasi-type (0-300 µm)	Moderately developed crystallitic, poro-, parallel-, reticulate-striated, stipple-, mosaic-speckled	Weak to moderate; parallel and pellicular alteration in mica minerals and feldspars; fracturing in quartz	Moderately impregnated typic-, aggregate- and compound Fe/Mn (10 µm to 0.37 mm) nodules with distinct to diffused boundaries
QGMS-IV	Moderately developed sub-angular blocky; peds partially accommodated	Rounded, vesicular, vughy, chamber voids; channel and void walls smooth, undulating	60:40 to 40:60; 20-30 µm; double spaced porphyric	Micro laminated argillan and ferriargillan; typic-, hypo-type; (80-500 µm)	Well developed crystallitic, poro-, parallel-, reticulate-, unistriated, stipple-, mosaic-speckled	Moderate to strong; irregular linear and pellicular alteration in mica minerals and feldspars; intense fracturing in quartz	Moderately to strongly impregnated typic-, aggregate- and compound Fe/Mn (25-750 µm) nodules with distinct to diffused boundaries
QGMS-V	Moderately to well developed sub-angular blocky; peds partially accommodated	Rounded, vesicular, vughy, chamber, elongated oval voids; channel and void walls smooth, undulating	30:70; 20-30 µm; double spaced porphyric	Micro laminated argillan and ferriargillan; typic-, hypo- and quasi-type; (100-550 µm)	Moderately to well developed crystallitic, poro-. parallel-, reticulate-, striated, stipple speckled	Moderate to strong; irregular linear alteration in mica minerals; intense fracturing in quartz, fractures filled by secondary fillings	Moderately to strongly impregnated typic-, aggregate-, nucleic- Fe/Mn (25 µm to 500 µm) nodules with distinct boundaries

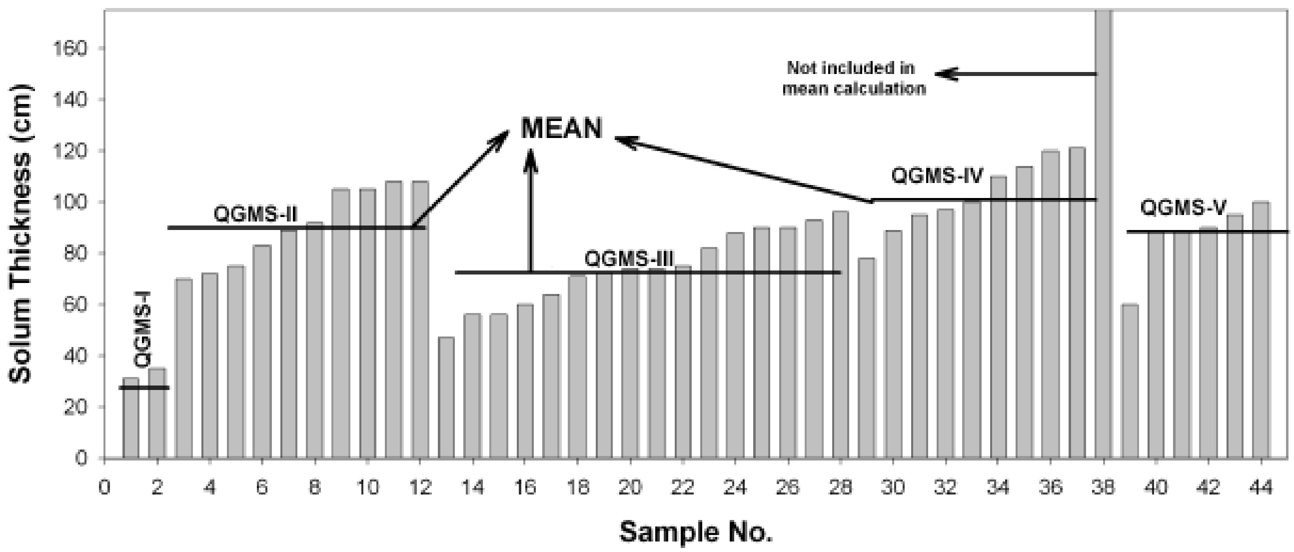


Fig. 10. Bar diagram showing solum thickness of various pedons of different morphostratigraphic members.

II and IV (Fig. 12b). The degree of illuvial translocation has also been assessed by calculating the clay accumulation index (C.A.I.) (Levine & Ciolkosz 1983). The C.A.I in the QGMS-I soil ranges from 154 to 287. The index is significantly higher in the QGMS-II soils (1377–2233). In the QGMS-III soil the index is low (158–604). Again in the QGMS-IV soils the index is higher (837–2010) with exceptional values of 364 and 476 for the Old Ganga Plain-II and Saurikh-Rasulabad Fan soils, respectively. C.A.I. for the QGMS-V soils is lower than QGMS-IV soils and ranges from 212 to 322.

To determine Electrical Conductivity (EC) and pH a mixture of soil and distilled water in the ratio of 1:2 is prepared by shaking it intermittently for an hour (Jackson 1967). This is different from the standard procedure of soil extract measurement instead of conventional EC and pH measurements and are denoted as EC_2 and pH_2 respectively. EC_2 values range from 0.013 to 0.047 mmhos/cm for QGMS-I, it is higher in QGMS-II and varies from 0.083 to 0.646 mmhos/cm. The EC_2 values in QGMS-III soils are lower, which range from 0.012 to 0.036 mmhos/cm with the exceptionally high values in the Karhal Bidhuna Fan, the Old Ganga-Yamuna Plain and Iglas-Raya Fan. The QGMS-IV soils show high values as compared to QGMS-III, which range from 0.089 to 1.21 mmhos/cm. The QGMS-V soils show lower values (0.023 to 0.09 mmhos/cm).

Soils of member QGMS-I are slightly acidic to slightly alkaline (pH_2 - 6.7 to 7.3). Acidic soils are exposed in the Young Arind Plain where the drainage system is good. Most of the QGMS-II and III soils, which occur in low-lying areas, are mostly alkaline (pH_2-7.00 to 9.96) in nature except the soils of the Old Ganga-Yamuna Plain and Sikandrabad-Jewar Plain (QGMS-II), which occur at higher levels than the other units and are acidic in nature. The soils of the QGMS-IV and QGMS-V members are mostly acidic in nature with pH_2 varying from 5.9 to 7.0 for most of the soils. A high pH_2 in different pedons is due to the presence of calcrete and probably sodium carbonate or free alkali due to rapid evaporation (Catt 1990). Soil pH_2 is also affected by drainage class as well as rainfall for e.g., pH_2 in a well drained area soils is acidic (Young Arind Plain) and samples taken after monsoon show pH_2 values lower than the normal, as is our case.

Classification of soils

Soils of the study area are classified according to the taxonomic classification of soils given by the United States Department of Agriculture (United States Department of Agriculture 1999). Typical pedons of each morphostratigraphic member were used for detailed studies and classification. The QGMS-I member soils are classified as Fine Mixed Hyperthermic Haplustepts and Coarse loamy fluavaquents. Soils of QGMS-II member are Fine Mixed to Coarse Loamy Hyperthermic Typic Haplustepts. Member QGMS-III soils show a varied nature. They are Fine Loamy to Coarse Loamy Mixed Hyperthermic Haplustalfs and Haplustepts. The QGMS-IV soils are typically Alfisols with some of the soils with Inceptisol character. Inceptisols soils have well-developed subsurface cambic horizons. Member QGMS-V soils are, in general, Fine Mixed Hyperthermic Haplustalfs and some are Haplustepts.. Thus, in general, the degree of soil development increases from Member QGMS-I to V.

Soils of the QGMS-I and II are generally, gleyed, affected

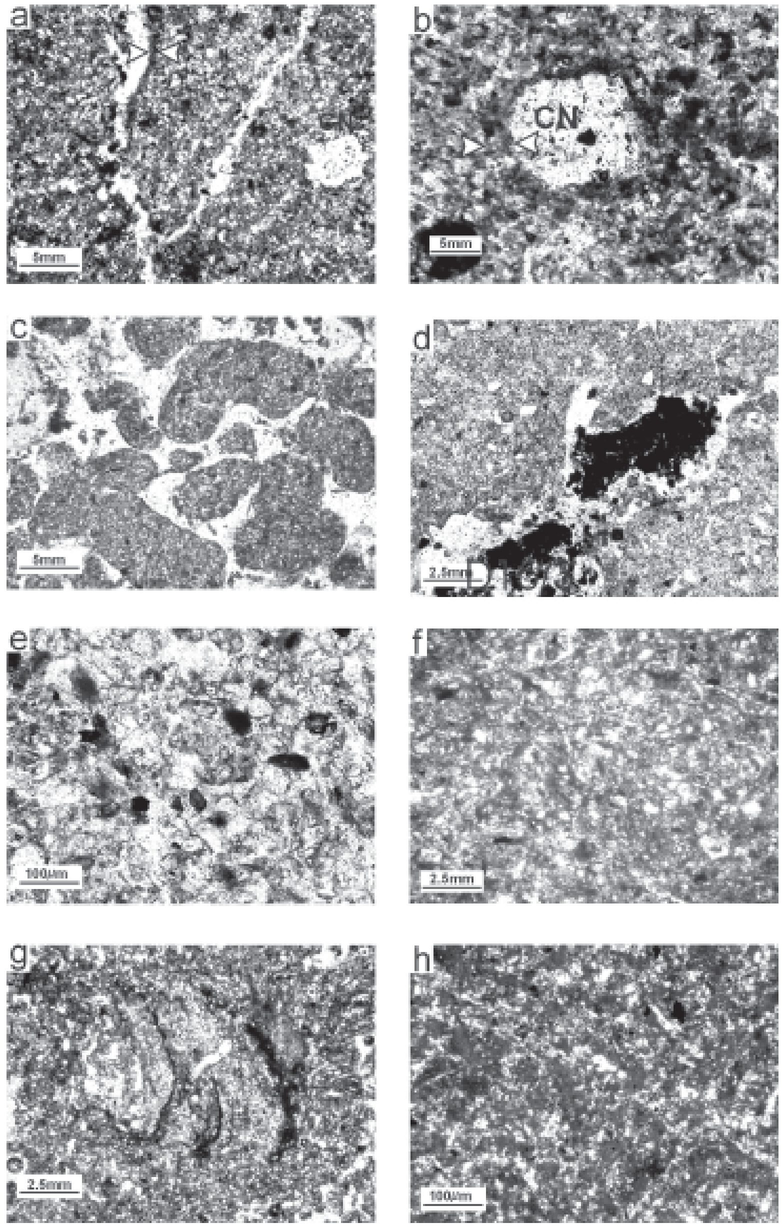


Fig. 11. Micromorphological features of soils (**a**) Well developed subangular blocky peds moderately accommodating to each other, B3w horizon of Pedon S41, Ghatampur Plain-II, QGMS-IV, PPL. (**b**) Section showing compound calcitic pedofeature, note weakly impregnated hypocoating around the void, Pedon S41, Old Ganga Plain-IV, QGMS-IV, PPL. (**c**) Well developed crumb structure. The boundaries of crumbs are extremely smooth and individual crumbs are not accommodating to each other, B2t horizon of Pedon S16, Meerut-Hapur Plain, QGMS-V, PPL. (**d**) Strongly impregnated typic micrite calcitic nodules (CN) with uniform thickness of Fe-Mn hypocoating (arrow), Pedon S20, Khurja-Aligarh Fan, QGMS-III, XPL. (**e**) Compact grain structure with oval to rounded Fe-Mn nodules, Fe-Mn coatings (brownish colour) are present along the boundaries of voids and individual grains, Pedon S18, Khurja-Aligarh Fan, QGMS-III, XPL. (**f**) Moderately to weakly developed mosaic speckled b-fabric, note the preferred orientation of mica minerals, Bt horizon, Pedon S48, Etawah Plain-II, QGMS-V XPL. (**g**) Partially decomposed root nodule replaced by clay and ferric oxide, A horizon, Pedon S57, QGMS-IV, PPL. (**h**) Moderately developed stipple-speckled b-fabric, both ferric and carbonate cements occur together, section shows numerous irregular voids, Bt horizon, Pedon S26, QGMS-V, XPL.

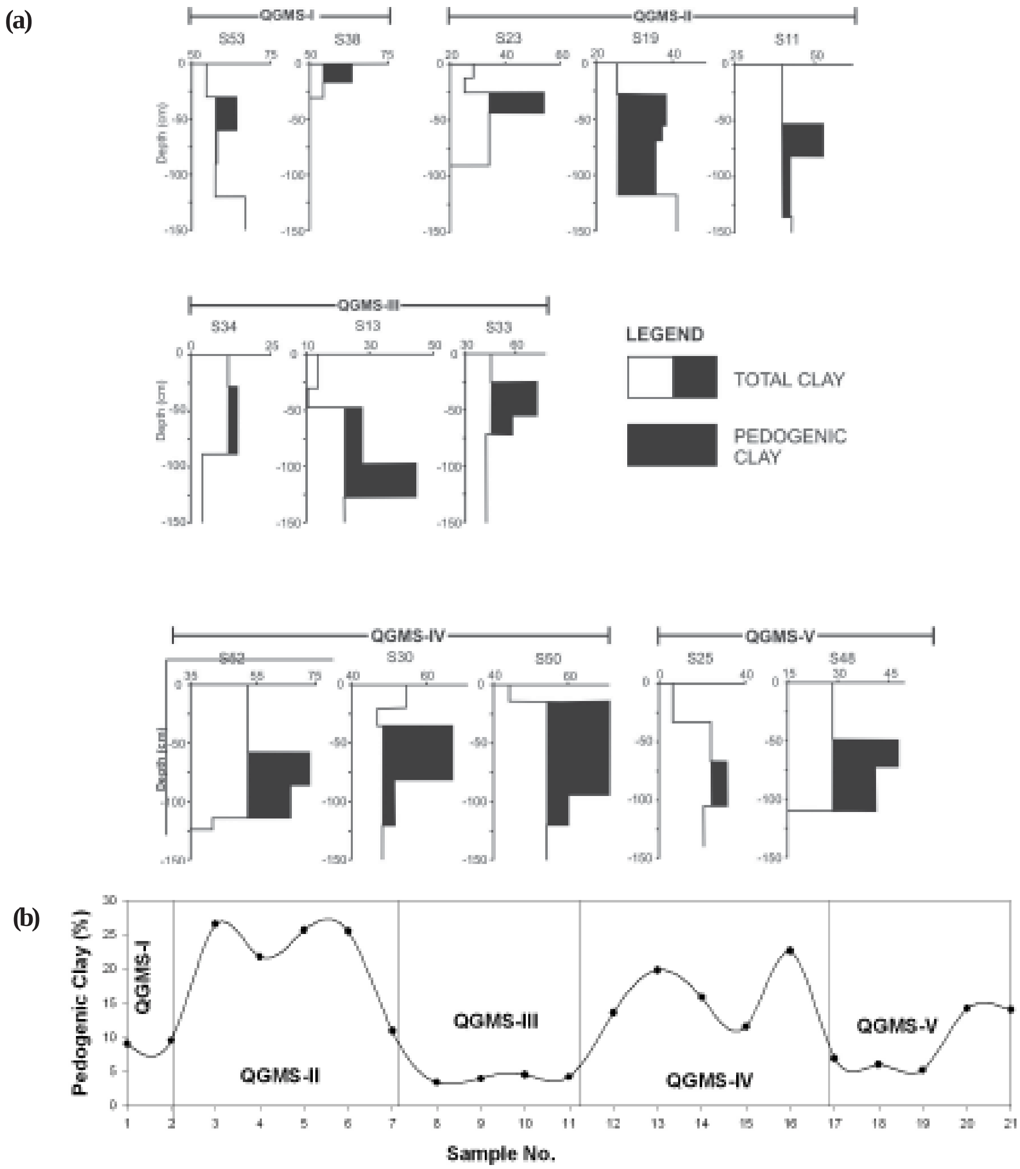


Fig. 12. (**a**) Variation of total clay and pedogenic clay in different members of the morphostratigraphic sequence, (**b**) Plot of pedogenic clay vs age of soils.

by salt efflorescence, non-saline with medium acidic to very strongly alkaline, and non-calcareous. QGMS-III - IV are usually non-saline with slightly acidic to mildly alkaline and calcareous to non-calcareous nature. The QGMS-V soils are non-saline with mildly alkaline and non-calcareous to calcareous nature.

STRUCTURAL FEATURES

Faults

The faults, in the study area, have been identified on the basis of major discontinuities observed in the remotely sensed images and DEMs and characteristics of drainage patterns (Fig. 13). These are discussed in the following sections.

(i) *Convergent drainage pattern and initiation of streams:* In this the sub-parallel streams shows convergent pattern while encountering an obstruction. The combined stream may continue by cross cutting through the obstruction or take a turn and then continue their course after covering some distance (Fig. 7). This is an opposite of dichotomic (divergent) pattern (Howard 1967) observed on the alluvial fans. This pattern was first described by Singh *et al*. (2006) on the upthrown blocks of the transverse normal faults in the adjoining area to the east. This pattern is shown by the Kali River and its tributaries near the Ghaziabad Fault, the Sengar River and its tributaries near Aligarh Fault and small inland streams near the Sikandra Rao, Aliganj-Mainpuri and Kannauj-Bidhuna Faults (Fig. 7).

Most of the transverse faults show initiation of new streams (first order) on the downthrown blocks where, convergent drainage occurs on upthrown blocks. Good examples of this are exhibited by Muzaffarnagar, Meerut and Aligarh faults (Fig. 7).

(ii) *Offsetting of drainage:* The Yamuna Rivers show offsetting along the Kanpur-Ghatampur fault, where the river has shifted moved to the north. The inland Kali River has shifted to the southwest due to the activity of the Aligarh fault. Small inland streams upstream of the Sikandra Rao fault exhibit this feature. Offsetting of the Ganga and Yamuna River courses in the eastern part of the study area is due to activity of the Sirathu fault.

(iii) *Straight courses:* The Ganga and Yamuna Rivers are marked by 15-122 km straight stretches, joined by 6-34 km long cross stretches. Straight river course in an alluvial terrain are attributed to the presence of a subsurface linear features, which in our case are faults.

(iv) *Changes in sinuosity of rivers:* The Yamuna River exhibits higher sinuosity than in the adjoining area just upstream of Aliganj-Mainpuri Fault (Fig. 7). Cause of the same is explained later in discussion section.

(iv) *The presence of lakes and flooded areas:* Lakes are mostly confined to the middle and southeastern areas and that too along the inferred fault zones. Lakes commonly occur on the downthrown blocks of the Aligarh, Aliganj-Mainpuri and Fatehgarh-Etawah faults. Most of the lakes, if joined together, appear like past courses of the modern drainages. Oxbow lakes occur on the upthrown blocks of Fatehpur-Etawah fault. Large tracts on the northwestern block and western blocks on the up-thrown sides of the Sikandra Rao and Kannauj-Bidhuna faults, respectively, get waterlogged during rainy season.

(v) *Terminal fans:* All the major identified faults show the presence of terminal fans on the downthrown blocks. The Muzaffarnagar fault has developed three terminal fans (Bhosle *et al.* 2006a), whereas all other faults are marked by the presence of one terminal fan. Topographic profiles across the Muzaffarnagar fault at three places derived from the DEM, suggest that there is a significant break in slope across the fault and the southern side of the fault has gone down relative to the northern side by 6-9 m (Fig. 14a-c). A topographic profile parallel to the downthrown sides of Muzaffarnagar Fault suggests the presence of three small fans (WMF, MMF, and EMF), which are deeply incised (Fig. 14d). Most of the terminal

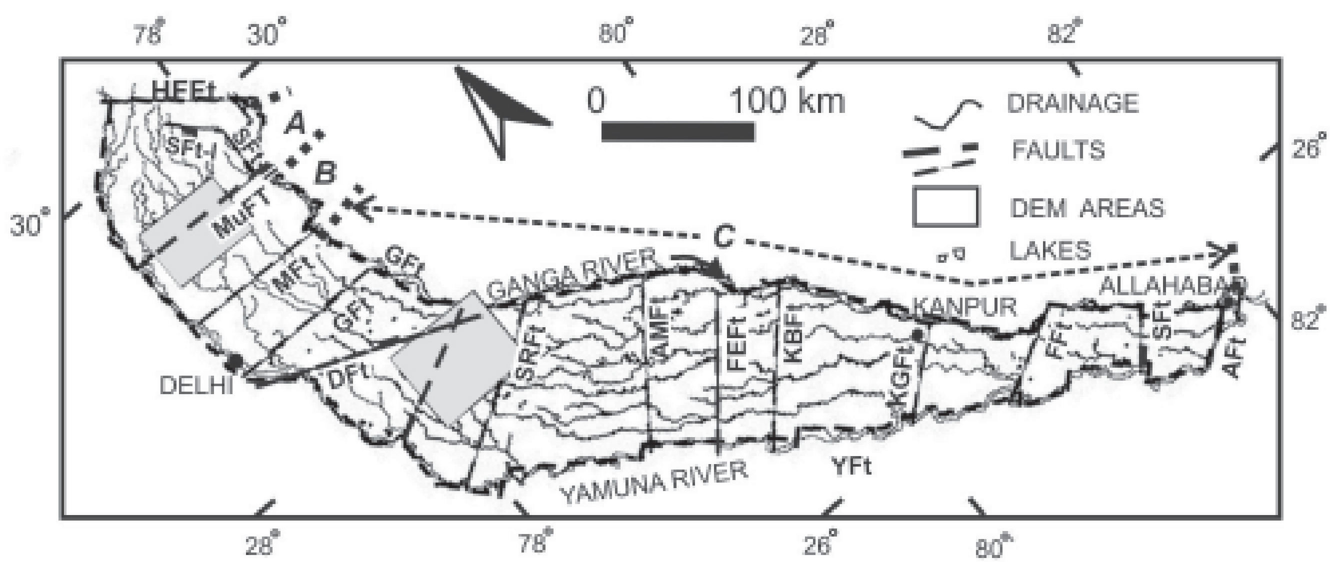


Fig. 13. Structural map of the study area showing faults, drainage and lakes, gray patches in the background are the locations of the digital elevation models. DFt- Delhi Fault, Fatehgarh-Etawah Fault, ALFt- Allahabad Fault. Symbols for other faults explained in figure 6. A- Piedmont block B- Muzaffarnagar block,and C-Mainpuri block. 'a', 'b'and 'c' lines refer to profiles a, b and c in Fig. 14.

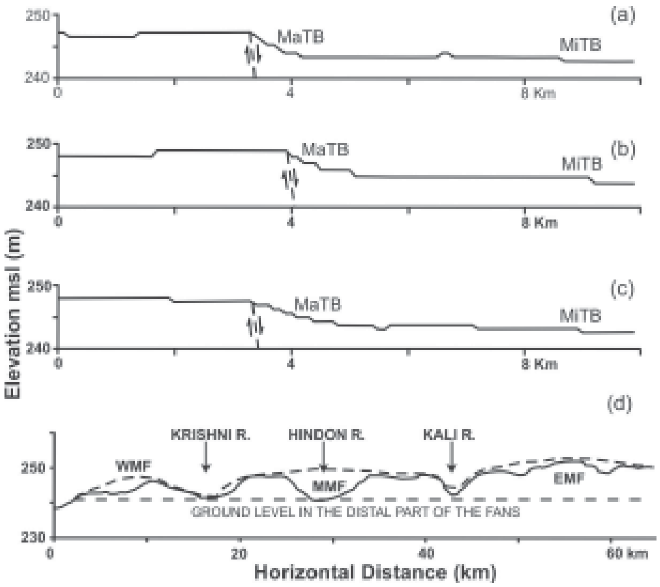


Fig. 14. Topographic profiles across the Muzaffarnagar fault taken along the line shown in figure 13. A clear-cut break in topography related to major faults (MaTB) is visible in profiles (**a-b**) and a minor topographic break (MiTB) at a distance of about 4 km south of the major cliff is present in profiles (**a-c**) indicating probably a small fault. Topographic profile d is parallel to the Muzaffarnagar fault and at a distance of 2 km from the fault on the downthrown block. Three small fans WMF, MMF and EMF can be made out from the profile (**d**).

fans continue on the upthrown blocks in the form of triangular regions forming pediments, formed by the headward erosion by the streams.

(vi) *Scarps and breaks in slope in DEMs:* The faults in the northern regions (Muzaffarnagar, Meerut, Ghaziabad faults, Solani-II), show well developed 'scarps' and streams are significantly incised into the upthrown blocks (Fig. 15a), whereas the Aligarh, Aliganj-Mainpuri and Kanpur-Ghatampur faults show significant breaks in regional slopes in the digital elevation models (Fig. 15b).

The Delhi transverse fault lies in continuation with a segment of the Ganga Faults and its activity seems to have confined the course of the Yamuna River since about 10 ka to about 2.40 ka and is affecting its course near Delhi even presently, Here the Yamuna takes a southwesterly course along the Delhi Fault for ~ 25 km from a southerly course in the upstream region, before continuing in southerly direction.

Based on the above geomorphic expressions, seventeen faults have been recognized in the study area (Fig. 13), which Parkash *et al.* (2000) classified them as longitudinal and transverse faults. Longitudinal faults running along the major bounding rivers– Ganga and Yamuna and are curvilinear in nature (Fig. 13). These trends N-S in the northern part, take NW-SE strike in the middle portion and turn E-W in the distal portion of the study area. The transverse faults are approximately perpendicular to the longitudinal faults (Fig. 13). Major trend of the transverse faults in the northern portion of the study area is E-W and changing to NE-SW in the southern part of the study area (Parkash *et al*. 2000).

Tectonic Blocks

Three major tectonic blocks i.e. Piedmont, Muzaffarnagar and Mainpuri blocks are identified in the study area (Fig. 13). These tectonic blocks are bounded by transverse and longitudinal faults. Mohindra *et al.* (1992) and Kumar *et al.* (1996) explained the influence of block movement on the degree of soil development in different blocks. The Muzaffarnagar and Mainpuri blocks are identified from on the basis that the Muzaffarnagar block has been region of deposition from major rivers i.e. the Ganga and Yamuna , whereas on the Mainapuri block, activities of the large rivers on such a large scale were absent during the Holocene Period.

Piedmont Block: The Himalayan Frontal fault in the north and Solani-I fault in the south forms the boundaries of this block (Fig. 13). The block is marked by the presence of old and young piedmont plain, which are characterized by well developed and weakly developed soils, respectively. In the eastern half, the old piedmont plain is exposed in small isolated hillocks.

Muzaffarnagar Block: This block is bounded by Meerut fault in the south and Solani-I Fault in the north (Fig. 13). Major parts of this block are covered by soils of 5.6-6.0 ka ages. However, the southern parts are covered by terminal fans of ages 2.3-3.6 ka and northernmost parts are overlain by soils of similar age, forming a narrow patch extending in E-W direction, suggesting it as a distal part of the Younger Piedmont.

Mainpuri Block: This is the largest tectonic block of the study area, which is bounded by Meerut fault in the north and Allahabad fault in the east (Fig. 13). In this block the northern and central parts are overlain by large patches of the oldest soils (QGMS-V) (>9.6 ka). In the northern parts of the central region, a wide Old Ganga Plain (QGMS-IV) is present. All these exposures are overlain by terminals fan deposits of different ages (4.2 ka – 8.34 ka).

Earthquakes in the study area

Seven major earthquakes (magnitude 4.3-6.7) and several minor earthquakes (magnitude<4) were recorded in the study area between 1720 A.D. and 1992 A.D. (U.S.G.S., http://neic.usgs.gov/neis/e hpic/epic_circ.html). All of the major earthquakes occurred along the Ghaziabad, Aligarh, Allahabad and Yamuna faults. Although no record of earthquakes is available along the Muzaffarnagar fault, but syn-depositional deformation sedimentary structures caused by earthquake tremors are inferred in the GPR profiles taken across this fault. Thus it seems that seismic activity in the historical past and even earlier in the Holocene was due to activity of the inferred faults.

DISCUSSION

Soils and soil forming processes

Major pedogenic processes observed in the study area are: gleying, alkalinization, salinization, clay illuviation and degraded pedogenesis. Gleying was inferred by the presence of abundant Fe-Mn nodules and low chroma soils (<2). This phenomenon is seen in the Yamuna Palaeochannel, Etawah Plain-I, Saurikh-Rasulabad Fan, Muhammadabad-Bhilaur Fan, Karhal-Bidhuna Fan and distal parts of Khurja-Aligarh Fan.

We attribute the salinization in the study area to the climatic, hydrological and geological factors. These are:

i. In most part of the study area, a semi-arid climatic condition prevails. A rainfall gradient from ~110 cm/year in the north to ~40 cm/year in the south is observed. Similarly, the temperature increases from <40°C in the north to 47°C in the south (Fig. 5).

ii. Water table is deep in piedmont zone and water logging conditions prevail over the central part of the study area. Waterlogged areas are the sites of high evaporation which eventually lead to higher concentration of dissolved salts.

iii. Micro-depressions and micro-highs (especially in the Khurja-Aligarh fan area, are favorable sites for salt precipitation (Pal *et al.* 2003).

Older soils in the study area, especially fan areas (Saurikh-Rasulabad (QGMS-IV), Karhal-Bidhuna (QGMS-III), Mummadabad-Bhilaur Fan (QGMS-III) south of Meerut, marked by arid-semiarid climate, are more saline as compared to the younger QGMS-I and II members. It is due to the fact, these fans have still active streams, which are bringing dissolved salts from the drainage basins, which are precipitated on the fans due to hot, dry climate. This process has been going on since the development of these fans. The younger units (QGMS-I and II) mostly occur in the northern part, south of piedmont zone, with very good drainage and dry sub-humid climate, hence they are mostly non-saline.

The pedogenic clay content varies in a sigmoidal way. The pedogenic clay content for members QGMS-I to V is 9.1 to 9.6, 21.8 to 26.6, 3.4 to 13.6, 12.1 to 31.2 and 6.0 to 14.2 % of the total clay content, respectively. Clayey soils are the characteristics of QGMS-I soils. Soils of the other members are mainly coarse loamy and become heavier with increase in soil development, especially in the B-horizon.

Plots of total clay content and pedogenic clay content with depth for typical pedons are given in Fig. 12. With increasing ages the pedogenic clays are increasing from QGMS-I to QGMS-IV and decreasing in QGMS-V. The degree of illuvial translocation was assessed by calculating the clay accumulation index (C.A.I.) (Levine & Ciolkosz 1983). C.A.I. for members QGMS-I, II, III, IV and V varies from 154-287, 1377-2234, 158-604 837-2010 and 364-476 respectively. The C.A.I. varies in a sigmoidal way, where the C.A.I. of QGMS-II and QGMS-IV show high values in comparison to the other members. Clay illuviation, especially in member QGMS-II to IV soils is indicated by the presence of thick argillan and ferriargillan coatings with thicknesses of 50-250 μm and 80-500 μm, respectively, along the voids, channels, coarse particles and mineral aggregates (Fig. 11).

Thickness of argillan/ferriargillan coatings in general increases from Member QGMS-I to IV soils, and then decreases in the Member QGMS-V soils, though grain size analysis indicates an overall increase in the pedogenic clay from the Member QGMS-I to V soils. Thus, some degrading pedogenesis is also taking place in the study area, especially in the older soils, causing disaggregation of coatings as earlier observed by Singh *et al.* (2006) and Srivastava & Prakash (2002) in the adjacent Deoha/Ganga-Ghaghara interfluve.

Nature of Faults

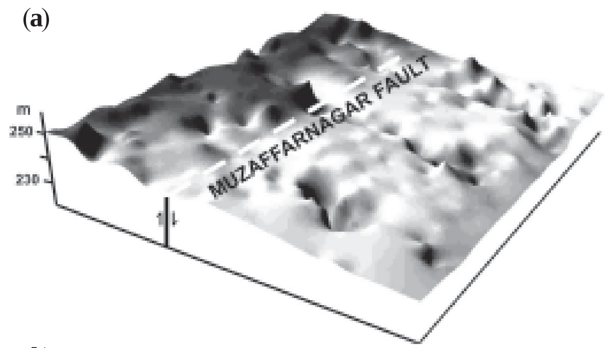
Compression from southwest and west, respectively, was inferred from tilting of large tectonic blocks based on the distribution of soils (Srivastava *et al.* 1994; Kumar *et al.* 1996). Parkash *et al*. (2000) modeled these faults using finite element approach. They used compression from the west and southwest and restraining effects of the shield region in the south and subsurface N-S trending Delhi-Aravalli Ridge occurring just west of the Yamuna River and obtained a pattern very similar to those of the major faults (Ganga Faults, Yamuna Faults and Solani-II Fault). These faults have been recognized as longitudinal faults (in a compressional regime) and other faults (like Solani-I, Muzaffarnagar, Meerut, Ghaziabad, Delhi, Aligarh, Sikandra Rao, Aliganj-Mainpuri, Fatehpur-Etawah, Kannauj-Bidhuna, Kanpur-Ghatampur, Sirathu Fatehpur and Allahabad faults) occurring at large angles to these faults as transverse normal faults occurring in an extensional regime. Normally transverse faults seem to have developed randomly; however, if a basement fault occurs approximately in the direction of the expected transverse faults, reactivation of basement fault has taken place as in case of Muzaffarnagar, Ghaziabad, Fatehpur-Etawah and Kanpur-Ghatampur faults.

Only three major interfluves i.e., Ganga-Yamuna, Deoha/ Ganga-Ghaghara and Ghaghara-Rapti are present in the Upper Gangetic Plain. In case of the later two, there is tectonic continuity from the piedmont zone to the eastern end of the interfluves. However, in the case of the Ganga-Yamuna interfluve, a large Muzaffarnagar block in its northern parts has been a low-lying block, where the two major rivers (Ganga and Yamuna) have been active for a long time. This can be explained with reference to vector stress diagrams of Parkash *et al.* (2000), which shows extremely high Gauss P-stress (Fig. 16) in the north-western part than the rest of the Upper Gangetic Plain and that is perhaps responsible for its acting as low-lying block in the past.

Visualization of DEMs in showing 'scarps' (Fig. 15a) and breaks in slopes (Fig. 15b), the deposition of the terminal fans, incisions and changes in sinuosity of meandering streams suggests that the downthrown sides of the faults are towards south and east in the northern and southern regions of the interfluve in case of all the transverse faults, except for the Solani-I and Delhi Fault. The Solani Fault has a throw of 18 m towards north, as observed earlier by Kumar *et al.* (1996). The Delhi Fault most probably has a throw to the NE, as is true of the Ganga Fault segment lying in continuity with its SE end, as discussed below.

The nature of longitudinal faults like the Ganga Fault have been shown as normal by Rao (1973). Parkash *et al.* (2000) had suggested that as they formed in a compressional regime, they could possibly be thrust/reverse faults. It must be emphasized that basement is bending downwards towards north and ultimately being underthrusted along with the overlying Cenozoic sediments, below the Himalayan Frontal Fault. Bending of the basement will give rise to normal faults, which will propagate through the overlying sediments to the surface and seen as the Ganga and Yamuna faults. Our GPR studies (Bhosle *et al.* 2006b) indicating normal nature of the Solani-II Fault, sub-parallel to the Ganga longitudinal fault, also supports this view.

(**a**)



(**b**)

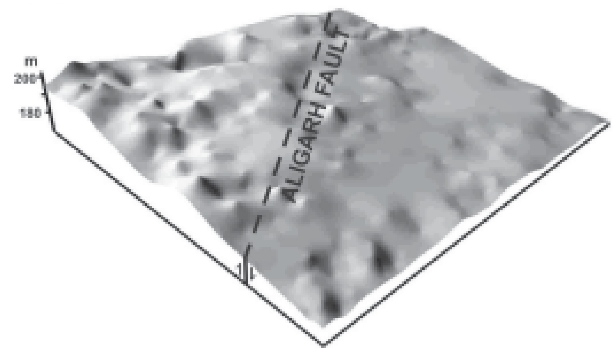


Fig. 15. (**a**) Digital Elevation Model of the area around Muzaffarnagar Fault with 'scarp' like feature, (**b**) DEM of the area around Aligarh Fault, marked by a significant change in slope.

A subsurface basement ridge (Aravalli Ridge) plunging NNE was identified based on geophysical studies and this feature dies out before Deoband is reached. It suggests the presence of a probable fault with a throw of several 100's of meters to the north. Our Muzaffarnagar Fault overlies this basement fault. However, in the present case, the throw is just in the opposite direction i.e. as the northern part is the upthrown block and the southern block is the downthrown block.

Studies of normal fault arrays, their development and nature associated with extensional tectonic regime had been investigated by several workers (Gawthorpe & Leeder 2000; dePolo *et al.* 1991; Machette *et al.* 1991; Schlische 1995). These studies have provided some interesting ideas regarding the incipient development of faults and their extension with time. They have divided the development of faults into three stages. In the first stage (fault initiation), numerous small displacement faults and growth folds define isolated depocenters (dePolo *et al.* 1991; Machette *et al.* 1991). Isolated anticlines and synclines on the upthrown and downthrown blocks, respectively are observed. In the second stage (interaction and linkage), normal faults are segmented along the strike and these segments join to form a major fault zone and transverse anticline (upthrown block), which defines the displacement maxima and syncline (downthrown block), which defines displacement minima. In the third stage (through-going), rupturing takes place and increase in the displacement rate on the central part of the fault. Movements produced by the activity of growing faults affect the topography and modify the drainage (Jackson & Leeder 1994; Fig. 17). These stages are visible in the study area, as discussed below.

Small inland streams normally form a sub-parallel drainage pattern and follow regional slopes. However, on encountering some obstructions like isolated anticlines, associated with upthrown blocks of faults (striking almost perpendicular to the stream course as in first stage of fault development, Fig. 17a) turn by 90° and cross the fault along the synclinal axis, forming an offset stream pattern. This is shown by the Sengar River, which was flowing east, turned to south to meet the Yamuna River, when the Kanpur-Ghatampur fault is encountered and similar is the case for the Arind River due to the Fatehpur-Etawah Fault and small inland streams crossing the Sikandra Rao Fault (Fig. 7). However, as different fault segments extend laterally as in case of stages 2 and 3 of fault development, the streams may join to form a convergent pattern (Figs. 16b-c). Close to the Sikandra Rao and Aliganj-Mainpuri faults, both convergent drainage and offsetting of streams are observed, suggesting an intermediate stage between first and second stages of fault development. The combined convergent stream may continue and cross the anticline or take a turn by 90° and cross the fault at some other point. Development of convergent drainage pattern was earlier described by Singh *et al*. (2006).

Blocking of the river courses due to the development of an anticline on the upthrown block leads to an increase in sinuosity of streams on the that block as shown by the Yamuna River on the upstream side of the Aliganj-Mainpuri Fault. This increase in sinuosity is due to a decrease in land surface slope because of blocking. Partial blocking of streams due to development of anticlinal ridges on the upthrown blocks may cause large scale water-logging on the upthrown blocks during rainy season, as in case of the Sikandra Rao and Kannauj-Bidhuna faults.

The modern drainage is being affected by the recent activity of different transverse faults as discussed above and thus drainage characteristics helped to decipher these faults.

The DEMs of regions around the Aligarh, Aliganj-Mainpuri and Kanpur-Ghtampur faults show significant breaks in slopes along theses faults (Fig. 15b) and do not bring out isolated anticlines, because of low density of available spot

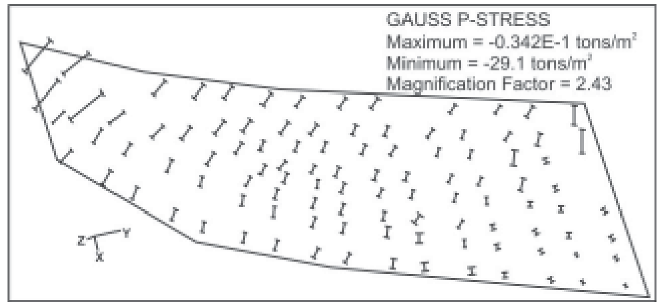


Fig. 16. Vector stress diagram showing principal compressive stress for north-eastward movement.

heights used for preparing the DEMs. However, isolated anticlines are indicated by offsetting of a number small/large streams. Thus these are in first stage of fault development. (Gawthorpe & Leeder 2000).

The DEMs of regions around the Muzaffarnagar, Meerut and Ghaziabad faults show ‘scarps’ along these faults and significant incision of streams into the upthrown blocks, thus breaking the ‘scarps’ into a number of segments, giving the impression of a number of anticlines formed on upthrown blocks, by various fault segments and streams occupying the synclines. These probably are in stage 2 of fault development (Gawthorpe & Leeder 2000).

Third stage of fault development (Gawthorpe & Leeder 2000) is exhibited by the DEMs of the faults, which show linked segments of the faults with maximum displacement at the centre and displacement reduces away from the centre. In most of the cases, inland stream occupy the depression formed in synclines in second stage and continue to do so even in the third stage, forming undulating ridges, similar to the second stage. That makes the third stage of fault development difficult to recognize from the topography.

All the faults observed in the study area affect soils/ sediments younger than 10 ka, so they are active faults (Nakata 1989).

Terminal fans and their origin

Mukerji (1975, 1976) described first the Markanda terminal fan from the region just west of the present area and named it so. The fan was considered to have been deposited due to loss of stream discharge due to seepage downwards and evapo-transpiration under arid to semiarid climate. Later Parkash *et al*. (1983) and Abdullatif (1989) described sedimentary structures of different terminal fans. Possible terminal fan deposits have been described from the ancient rocks from different parts of the world by many workers e.g. Friend (1978),

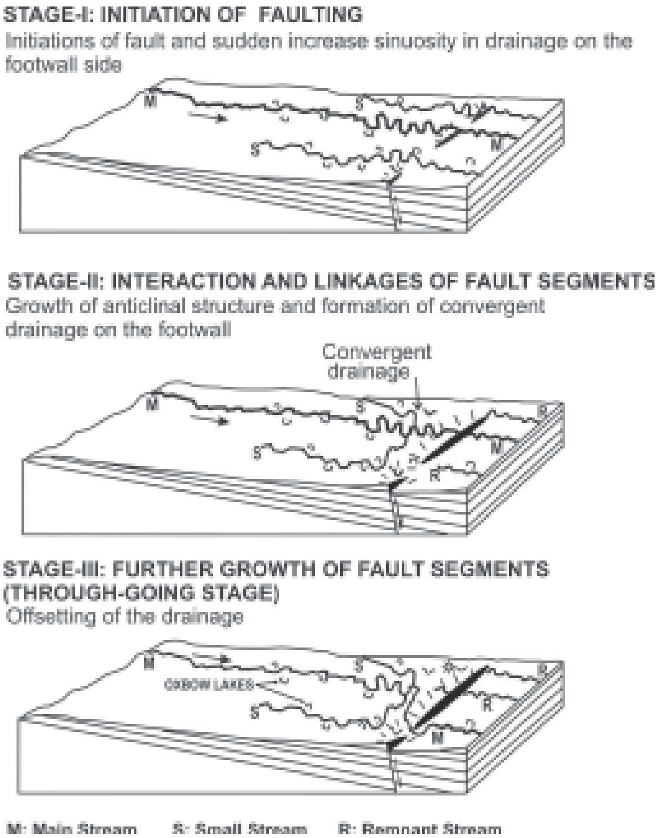


Fig. 17. Schematic model showing development of offset and convergent and offset drainage in the study area due to the activity of the transverse normal faults.

Turnbridge (1984), Olsen (1987), Sadler & Kelly (1993) and Kelly & Olsen (1993). Gradual terminations of streams under semi-arid climatic region of Australia have been described as 'floodouts' (Tooth, 1999, 2000a, b). In the absence of any additional recent terminal fans being recognized, their existence has been doubted (North & Warwick 2007).

All terminal fans described earlier from the region just east of the study area (Singh *et al*. 2006) and the present area are associated with the activity of the transverse normal faults in their proximal regions, as is true of the Markanda Terminal Fan also (Singhai *et al*. 1991). Relief of a few meters caused by activity of these faults (Bhosle *et al*. 2006a) is sufficient to induce the small ephemeral inland streams to deposit their loads on the downthrown blocks and form terminals fans, Also, as the streams loose their discharge due to evapo-transpiration, precipitation of salt takes place causing large scale salt efflorescence, especially in the distal parts of the fans like the Khurja-Aligarh, Karhal-Bidhuna, Muhammadabad-Bhilaur and Saurikh-Rasulabad fans. The streams attain quasi-equilibrium profiles fairly quickly and then pedogenesis starts on the terminals fans. At places, these fans are reworked by aeolian activity and also some small lakes are present. The soils on these fans give approximate time of deposition of fans. Terminal fan distribution of different ages suggests that different segments of the identified transverse faults were active during different periods in the past (Table 2; Fig. 18).

Repeated activity of transverse normal faults followed by quiescence period leading to the formation of soils may give rise to a sequence of terminal fan deposits consisting of thin channel deposits topped by mainly by soils, and lacustrine and aeolian deposits on a smaller scale.

Role of climate and large bounding rivers on pedogenesis and deposition on the interfluve

The Gangetic Plains witnessed a very cool and dry climate with reduced river discharges and decreased monsoonal activity during the Last Glacial Maximum (LGM) and after the LGM the climate turned cool and slightly wetter (Cullen 1981; Wiedicke *et al*. 1999; Goodbread 2003). Climate ameliorated significantly by 10 ka and turned warm and wet (Overpeck *et al*. 1996; Prell & Kutzbach 1987,1992). During the Holocene, the period 1.7 to 3.6 ka (equivalent to QGMS-II) (Sharma *et al*. 2004; Andrews 1998; Singh *et al*. 1974) and 6.5 to 9.6 ka (equivalent to QGMS-IV) (Sharma *et al*. 2004) are marked by wet periods, relative to the rest of the Holocene Period.

Gibling *et al*. (2005) have suggested that the bounding rivers of the interfluves get attached due to increase in discharge during climatically wet periods and detached during dry periods in the Gangetic plains. However, in the present case the wet period around 10 ka, the bounding rivers got incised due to increase in discharge; the interfluves were exposed paving the way for pedogenesis. So the extensive, oldest (>9.6 ka) soils covering major part of the interfluve and probably forming base of later terminal fan deposits are the major signatures of the climatic amelioration at the beginning of the Holocene. The following pedological and geomorphologic evidences suggest that periods 1.8-3.6 ka and 6,6-9,6 ka corresponding to soils of QGMS-II and QGMS-IV members, respectively, witnessed wet climatic condition;

(i) Clay Accumulation Index (C.A.I.) during the above periods was high (837-2234) in comparison to the other members (154 to 476).
(ii) Pedogenic clay content for QGMS-II (22 to 27%) and QGMS-IV (12 to 31%) is comparatively higher than the other members (QGMS-I, 9 to 9.6; QGMS-III, 3.4 to 13.6; QGMS-V, 6.0 to 14.2 % of the total clay, Fig.12b).

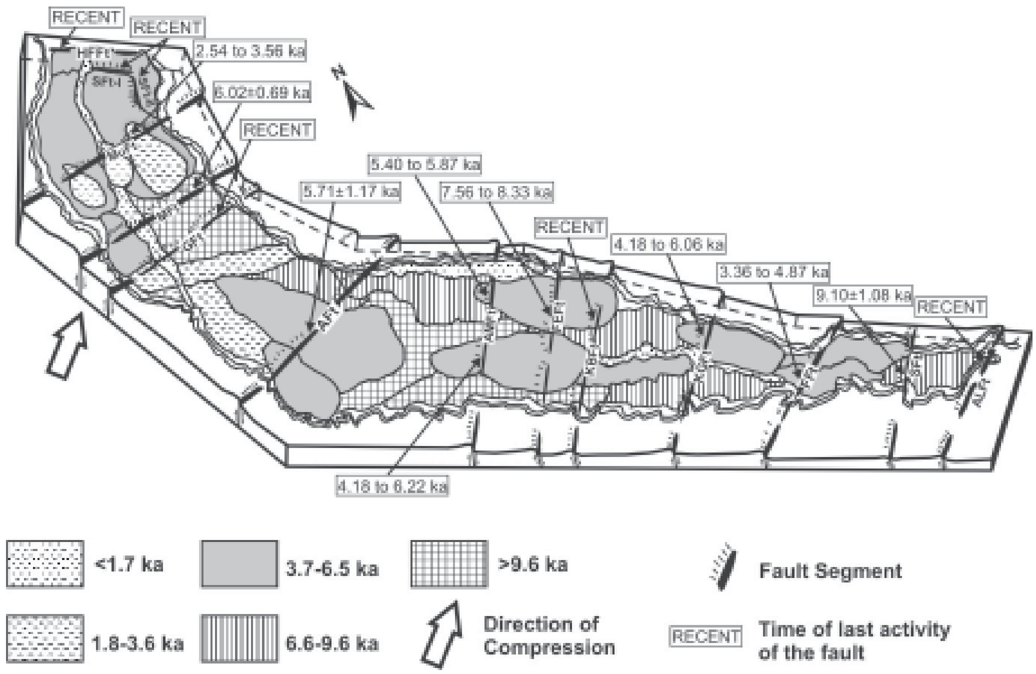


Fig. 18. Schematic models of the study area showing activity of the different transverse faults and the distribution of soil-geomorphic units.

Table 2. *Morphological characteristics of the observed terminal fans.*

Terminal Fan	Age (ka)	Fault	Area (km^2)	Length (km)	Slope (%)	Max. Height at the proximal End (m)	Max. Height at the distal End (m)
East Muzaffarnagar	2.5	Muzaffarnagar	1411	56.8	20.53	255	230
West Muzaffarnagar	3.6	Muzaffarnagar	1098	52.0	22.94	253	231
Middle Muzaffarnagar	2.8	Muzaffarnagar	340	34.8	20.51	248	235
Bagpat Fan	5.6	Meerut	970	46.1	14.59	230	218
Khurja-Aligarh	5.3	Aliagrh	5127	146.7	16.34	205	162
Iglas-Raya	5.7	Aligarh	1427	73.1	16.74	195	173
Muhamadabad-Bhilaur	5.6	Aliganj-Mainpuri	1822	113.9	13.34	158	131
Saurikh-Rasulabad	8.3	Fatehgarh-Etawah	2824	57.7	23.42	150	125
Karhal-Bidhuna	5.4	Aliganj-Mainpuri	3056	106.3	11.69	165	143
Kanpur	5.1	Kanpur-Ghatampur	1442	70.2	10.49	132	119
Fatehpur-I	4.8	Fatehpur-Etawah	1486	94.9	12.47	120	99
Fatehpur-II	3.4	Fatehpur-Etawah	1010	74.9	12.05	119	103

(iii) During 2.4-3.6 ka the Yamuna River overcame the effect of the Delhi fault (continuation of a segment of the Ganga Faults into the Interfluve) and took its present course probably due to increased discharge in addition to the block movements.

At the present time the interfluve is well above (about 10 - 15 m) above the major bounding rivers. So the processes acting in the interfluve are independent of the processes acting in the bounding rivers except in some plains (Old Ganga Plain-I and II, 9.6 ka) close to the bounding rivers and in the northern part of the interfluve (Yamuna Palaeochannel). These plains constitute only 14% of the total interfluve and the rest of the interfluve has been marked by deposition in the form of terminal fans due to the activities of transverse normal faults.

The Gangetic Plain is marked by a climatic gradient from west to east, with semiarid climate prevailing in the present area in the western part and it becomes moist sub-humid to per-humid in the eastern part (Bangladesh), controlled by Indian southwest monsoon (Rao *et al*. 1972). In the adjoining eastern Ganga/Deoha-Ghaghara interfluve with a wetter climate, the streams had low discharge and were aggrading during the LGM. Streams started degrading after the Last Glacial Maximum with climate turning cool and slightly wet, exposing large areas and laterally extensive soils developed on which terminal fans were deposited (Singh *et al*. 2006). However, in the present area with a drier climate, our observations suggest that incision began after 10 ka, under wet and warm conditions, suggesting a delayed geomorphic response of the streams.

Role of Tectonics

Apart from the activities of the transverse faults described above, there are ample other evidences of activities of the faults. The activity of Solani-II fault at about 5.50 ka resulted in shifting of the Ganga and Solani Rivers towards east, which started pedogenesis on the Ganga-Yamuna Plain.

Activity along Solani-I fault at about 2.7 ka resulted in high rates of erosion on the piedmont block so that small patches of the older piedmont (Kumar *et al*. 1996) are left on the northern part of the eastern half of the Piedmont Plain. Also, a part of the Piedmont deposits were left south of the Solani-I Fault on the Muzaffarnagar Block.

At some time earlier than 6.4 ka the Delhi fault got activated and confined the course of the Yamuna River. This continued till about 2.4 ka, when the Yamuna River took its present course. Also, the River Yamuna shows increased sinuosity just upstream of the traverse Mainpuri fault, due to movement along this fault and development of anticlines on the upthrown block in recent time.

SUMMARY

Active tectonics and climate to some extent seem to have played a major role in the development of different soils and landscape in the present interfluve. Significant events and phenomena caused by active tectonics and climatic change are as follows:

Period >9.6 ka

At about 10 ka, start of the warm and wet climatic condition led to significant increase in discharge and incision by the Ganga and Yamuna Rivers. This uncovered major parts of the interfluve, on which soils started forming (QGMS-V; 13.0 - 9.6 ka).

Period 9.6-6.6 ka

Between 9.6 to 6.6 ka, the faults of the Mainpuri block got activated. The movements along the Fatehgarh-Etawah Fault gave rise to the development of Saurikh-Rasulabad Fan, which covered even Ghatampur Plain-I and II. Later the two units got separated from the main fan due to deposition of younger units over the fan. With further increase in discharge of the Yamuna and Ganga Rivers, these rivers shifted away from the interfluve. The Ganga River shifted northwards from the Old Ganga Plain-I and II. The Sirathu Fan deposition took place due to the activity of the Sirathu Fault. Activity of the Delhi Fault confined the course of the Yamuana River, forming the Old Yamuna Plain.

Period 6.5-3.7 ka

This period is marked by the deposition of maximum number of terminal fans. Within the Mainpuri Tectonic Block, movements along the Aligarh, Aliganj-Mainpuri, Kanpur-Ghtamapur and Fatehpur-Etawah faults initiated the deposition of Khurja-Aligarh plus Iglas-Raya, Karhal-Bidhuna plus Muhammadabad-Bhilaur, Kanpur and Fatehpur-I plus II fans, respectively. Due to the activity of the Kanpur fault the Sengar and Arind inland rivers were partially blocked, which led to the deposition of the Debiapur-Akbarpur Plain, The western segment of the Meerut fault got activated and it led to the deposition of the Baghpat fan.

In the northern part of the study area the Ganga and Yamuna were depositing Old Ganga-Yamuna Plain. This plain was slightly uplifted due to the activity along the Solani-II and Yamuna Faults at about 5.8 ka. This caused the migration of the Ganga and Yamuna Rivers towards east and west, respectively leaving behind a wide Old Ganga-Yamuna plain with a number of palaeochannels.

Period 3.6-1.8 ka

During this period, the block defined by the Solani-I Fault in the north and Muzaffarnagar Fault in the south was uplifted by movements along these faults. Movement along the Muzaffarnagar Fault gave rise to the deposition of the three fans (East, West and Middle Muzaffarnagar Fans). The Solani-I Fault caused the Solani River to flow eastwards instead of continuing its southward course. Meanwhile the Yamuna River, which was flowing through the Yamuna Palaeochannel, shifted to the present course through the Sikandrabad-Jewar Plain.

Period ≤1.7 ka

In the Mainpuri block, the Arind River gave rise to the Young Arind Plain, which is now well above the reaches of the river, due to entrenchment of the river. Similarly the north of this block the Young Ganga Plain got deposited. Increase in sinuosity of the Yamuna River upstream of the Aliganj-Mainpuri Fault seems to be due to recent activity of this fault.

Also, offsetting and convergent drainage observed for the small ephemeral and inland streams are caused by recent activity of faults by processes explained earlier. Flooding of large tracts on the upthrown blocks of the Sikandra Rao and Kannauj-Bidhuna Faults during rainy season is due to recent activity of these faults, causing partial blocking of small stream draining these areas.

In summary, tectonic activity of the traverse faults, leading to deposition of terminal fans remains the major process on the Interfluve region. Climate plays a secondary role by inundation of small marginal regions by large rivers during dry climatic intervals and affecting pedogenetic processes like increased clay illuviation during wet climatic intervals.

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