HOLOCENE TECTONO-SEDIMENTARY EVOLUTION OF PARTS OF THE MIDDLE GANGETIC PLAIN

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ROORKEE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"HOLOCENE TECTONO-SEDIMENTARY EVOLUTION OF PARTS OF THE MIDDLE GANGETIC PLAIN"** in fulfillment of the requirement for the award of the degree of **DOCTOR OF PHILOSOPHY** and submitted in the **Department of Earth Sciences** of the **Indian Institute of Technology Roorkee, Roorkee** is an authentic record of my own work carried out during the period from July 27 2004 to July 2008 under the supervision of **Dr. B. Parkash** and **Dr. A. K. Awasthi**.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of my (our) knowledge.

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ABSTRACT

Though a fair amount of work on the Quaternary soils/sediments of the Upper Gangetic has been carried out (Srivastava et al., 1994; Kumar et al., 1996; Singh et al., 2006; Bhosle et al., 2008), only limited studies (Mohindra et al., 1992; Gohain et al., 1993) on these aspects of the Middle Gangetic Plains have been undertaken. We have confined our studies to the region between the Ghaghara and Kosi rivers. The region between the Ghaghara and Rapti rivers belongs to the Upper Gangetic plain and the area east of the Rapti forms a major part of the Middle Gangetic plain.

Major geomorphic features identified in the study area are: old piedmont, young piedmont, active piedmont, old plains, terminal fans, megafan (Gandak Megafan), terraces and misfit river (Burhi Gandak River).

Optically stimulated luminescence ages of C-horizons of soils help to categorize soil-geomorphic units into six groups depending upon the major breaks in plot of ages in the form of bars in decreasing order. Based on these breaks, six morpho-stratigraphic members of a Quaternary Ganga Morphostratigraphic Sequence (QGMS-I to QGMS-VI) are recognized with increasing age i.e.<1.4 Ka, 1.4-4.7 Ka, 4.7-6.9 Ka, 6.9-8.4 Ka, 8.4-10 Ka and > 10 Ka, respectively

Using Ground penetrating Radar (GPR), we confirmed the surface expression of two basement faults i.e. West Patna Fault (WPFt) and South Muzaffarpur Fault (SMRFt). The WPFt is a set of normal faults, whereas the SMRFt consist of two sets major normal faults. Also, GPR studies show that due to

activity of normal faults, terminal fans were deposited on the downthrown sides. Three sandy sequences (each 2-3 m), overlying thick sands of a large river (the River Gandak) on the downthrown block of SMRFt were observed, indicating at least three repeated activities of the fault.

GPR studies show that the older Gandak River underlying some terminal fan deposits consist of braid bar deposits formed due migration of dunes or deposition in upper plane bed phase leading to deposition of sigmoidal to trough cross-bedded/flat-bedded sand in deeper anbranches in the lower parts, whereas in upper parts, mainly lateral accretion and upstream/downstream accretions are very common. GPR investigation of terminal fans indicate that these are mainly lateral accretion sand facies overlain by mud facies, deposited in floodplains and/or in abandoned channels.

We have identified three major tectonic features (twenty two faults, two lineaments and three tectonic blocks). The study area is divided into three tectonic blocks namely the Ghaghara-Rapti block, Rapti-Gandak block and Gandak-Kosi block separated by the two major faults i.e. Rapti fault-II and Gandak fault.

The Ghaghara-Rapti Interfluve block is a part of the Upper Gangetic Plains and bounding longitudinal faults like Ghaghara and Rapti Faults are curvilinear with convexity to the SW, like other longitudinal faults in the Upper Gangetic Plains. Here the bounding rivers like Ghaghara and Rapti are incised in nature and the Interfluve is an upland area. The Upland has been a site of deposition since about 10 ka by terminal fans due to the activity of transverse normal faults and longitudinal Rapti Fault-I.

The Gandak megafan block has been marked by northeastward tilting, causing a shift of the Gandak River from west to east over a distance of 80 km during the period 10-8.6 ka. This has led to a higher degree of soil development in the west, which decreases to the east. Since about 4.5 Ka, due to activity of E-W trending faults, four terminal fans have been deposited.

The Gandak-Kosi Interfan Block is marked by a number of E-W trending longitudinal faults. Due to activity of the North Sitamarhi fault, at the base of the Old Piedmont, a 44 km wide younger piedmont has developed, which gives a width of 82 km for the whole piedmont, which is the highest in the Gangetic Plains. Activity of a number of longitudinal faults since 1.3 Ka has led to development of terminal fans, which cover major parts of the plains (mainly swampy in nature).

The curvilinear Ghaghara and Rapti faults (like other such faults in the Upper Gangetic Plains) were earlier explained due to compression from SW (Parkash et al., 2000). However, the development of E-W trending longitudinal faults in the Middle Gangetic Plains suggest a compression from south.

Using Global positioning system Srivedi (2004) found out the Indian plate is showing movements towards NE and N in the Upper and Middle Gangetic Plains, respectively, which are similar to those given by faults inferred by us. However, ages of soils suggest that such deformation patterns have been active at least since ~10 Ka in the Upper and since ~4.5ka in the Middle Gangetic Plains.

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1.1 INTRODUCTION

The Indo-Gangetic foreland basin the largest sedimentary basin in the Indian subcontinent, developed by the collision of the India and China plates during the Paleocene at about 60 Ma (Beck et al., 1995; Klootwijk et al., 1992; Besse and Courtillot, 1988; Patriat and Achache, 1984; Dewey et al., 1970), is one of the extensive fluvial plains of the world. Since about 20 Ma, fluvial sedimentation has been a dominant process. The modern sedimentation processes and the present geographic setting of the basin are essentially a continuation of these processes and set-up, with minor modifications (Parkash et al., 1980). This vast alluvial plain stretches from the Upper Assam in NE of India to the Indus basin in Pakistan in the NW and separates the Peninsular Indian shield in the south from extra Peninsular Himalayan belt in the north. It is essentially made up of terrigenious clastic sediments from the rapidly eroding Himalayas and minor amount of clastic sediment from the Peninsular Shield area of the south. Pankaj Srivastava et al. (1994) and Thomas et al., (2002) classified the Gangetic plains into Upper, Middle and Lower plains. The Upper Gangetic plain is marked by uplands with incised rivers and moderately to well-developed soils with salt efflorescence and calcrete, Middle Gangetic plains marked by relatively high rate of subsidence and by sedimentation in the form of megafans having weakly to moderately developed soils, and the Lower Gangetic plains being characterized by deltaic sedimentation.

Though the major parts of the Upper Gangetic plains have been investigated in fair detail for soil-geomorphic units, location of faults, deformation pattern and times of activity of faults by dating soils by luminescence dating technique by Singh et al. (2006) and Bhosle et al. (2008), the region east of the Ghaghara River, which includes major parts of the Middle Gangetic Plains, needs to be studied in detail.

In the present study, the area between the river Ghaghra and Kosi has been studied for its regional geomorphology, sedimentology, pedology and tectonism. Different faults and soil-geomorphic units were demarked by the help of satellite multi-spectral scanning (MSS) images and digital elevation model (DEM). Soil samples collected from different soil-geomorphic units were studied for their texture and dated using luminescence dating technique. Micromorphology of soils was studied to the pedogenic processes and the degree of soil development. Integration of the above studies has provided rôle of active tectonics in evolution of geomorphology, sedimentology, pedology and deformation pattern during the Holocene period.

1.2 GENERAL DESCRIPTION OF THE STUDY AREA

1.2.1 Location and Extent

The study area lies in the central part of the Indo-Gangetic plain bounded by the river Ghaghra in the west and the Kosi in the east. In south, the River Ganga demarcates its southern boundary and in the north it is bounded by the Himalaya. Geographically it covers the eastern parts of Uttar Pradesh and the northern parts of the Bihar States of India. The northern boundary is shared by the International border with Nepal (Fig. 1.1) .The area between the Ghaghara and Rapti Rivers belongs to the Upper Gangetic Plain and rest of the area east of the Rapti River lies in the Middle Gangetic plain (Thomas et al., 2002).

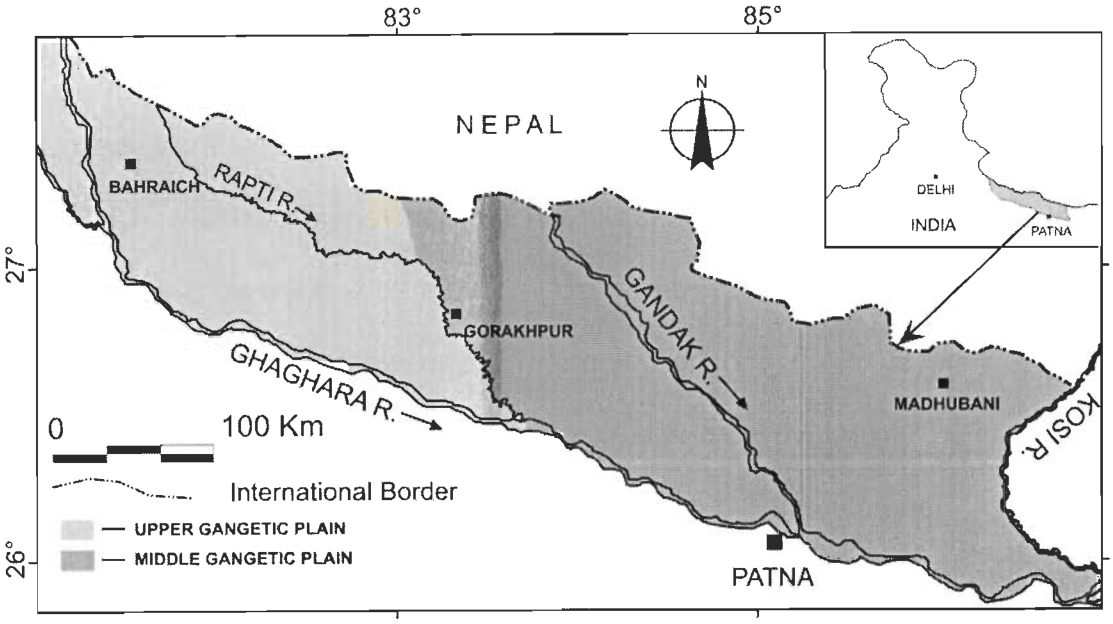


Fig. 1.1 Location and extent of the study area

1.2.2 Physiography

The Gangetic plains of the study area show seemingly featureless flat region lacking topographic prominence. The apparent flatness of the plain made them extremely difficult to map with accuracy (Geddes, 1960). The monotony of the landscape is broadly broken by the geomorphic features like river bluffs, terraces, cliffs, megafans, dead arms of the river channels, levees, oxbow lakes, ponds, paleochannels, ravines and the rivers themselves. However, the marginal inward projection of the Siwaliks in the Champaran districts of Bihar and the fringes of projection of the Peninsular Shield from South (Singh et al., 1971) also influence the monotony of the plain to some extent. The average alluvial-fill decreases from the foothill (8,000 -10,000 m) in the north to the south and thins out as a mere veneer on the Peninsular margin (Singh et al., 1971). The axis of the physiographic Gangetic trough probably lies near the Peninsular block or along the Ganga River. The elevation decreases from NW (160 m) to SE (33 m) of the area.

Major geomorphic zones are: piedmont, Ghaghara-Rapti Interfluve, Gandak megafan, Kosi megafan and Gandak-Kosi interfan region (Geddes, 1960; Pankaj Srivastava et al., 1994). The piedmont zone covers 26% of the study area having an average width of 35 km and has slopes 1.2% in west to 0.9% in the east. The Ghaghara-Rapti Interfluve is an upland overlain by moderately to strongly developed soils. The Gandak-Kosi interfan region is marked by weakly to moderately developed soils and highly avulsing streams. This region represents an aggradational topography with no or little sign of incision (Geddes, 1960). The piedmont zone is marked by southerly slopes and rest of the plains have overall northwest to southerly slopes, which are reflected in drainage patterns of the region.

1.2.3 Climate

The Himalaya in the north controls the movement of the sweeping winds from east and west during the monsoon months (Middle June to end of September) and in turn influences the climate of the region significantly. As monsoon winds from the Bay of Bengal move from east to west, there is a decrease in rainfall from east to west and [illegible] from the Himalaya in North to the southern end of the plains. Major rainfall (85%-88%) is received from middle of June to end of September.

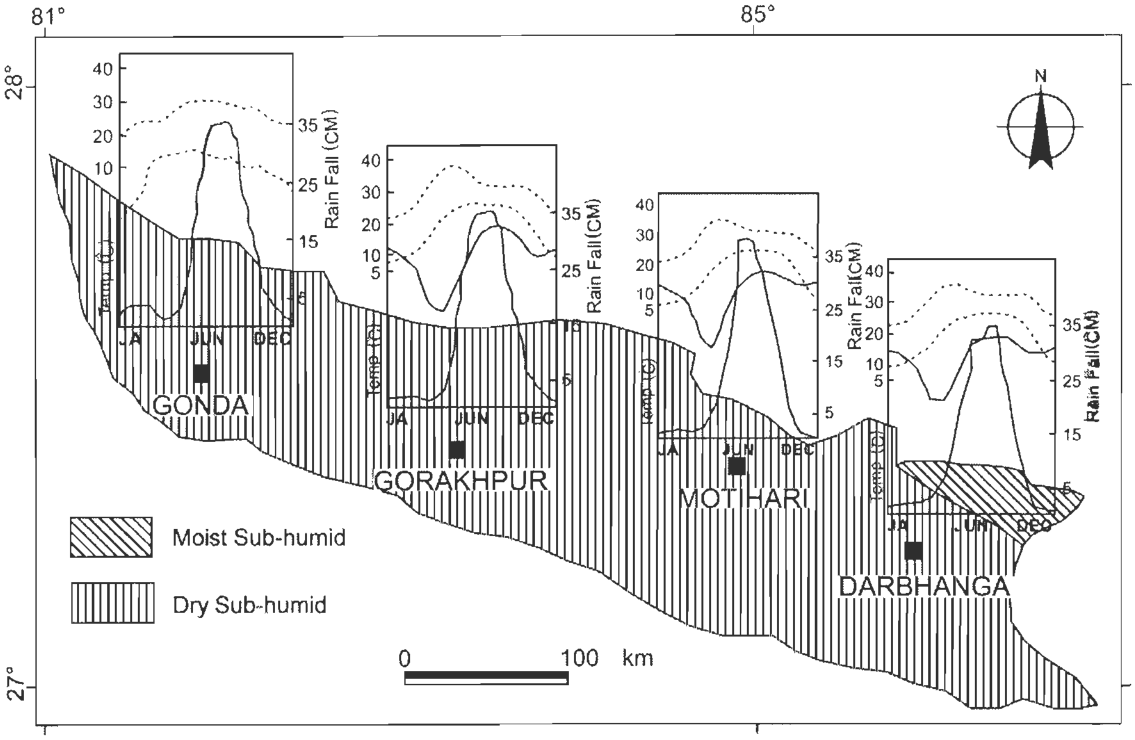


Fig. 1.2 Climate with temperature-rainfall diagram of selected locations of the study area (after Singh et al., 1971)

By November the cold weather sets in, with an appreciable fall in both temperature and relative humidity and the humid Easterly winds are replaced by the dry north-westerly or westerly wind. January is the typical winter month, when the mean temperature ranges between 16.1 to 16.6°C. Due to the cold wave in January, the minimum temperature falls to 4-4.5°C The trend of temperature recording gets a directional reversal from winter to summer: while in winter the temperature decreases from east to west and in summer it increases from east to west (Singh et al., 1971). The area is characterised by moderate to high rainfall i.e.100-150 cm (Singh, 1994; UNESCO, 1984).

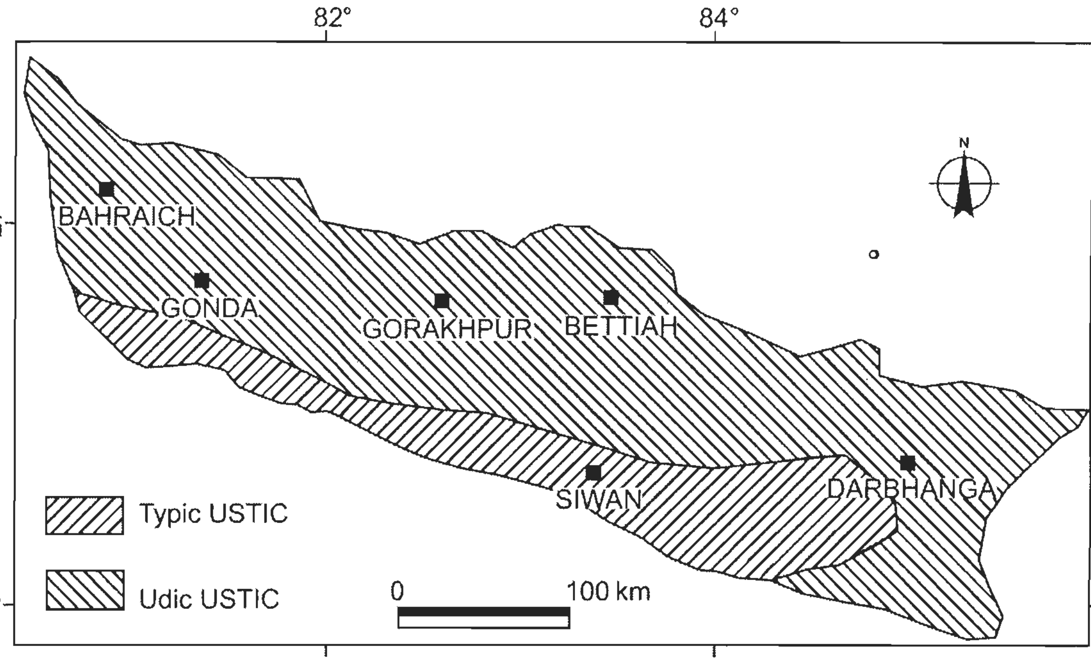


Fig. 1.3 Soil moisture regimes of the study area (after N. B. S. S. & L. U. P., 1993).

Udic-USTIC soil moisture regime prevails in most part of the area, in particular the northern and the central part. However, the Typic-USTIC soil moisture regime prevails in the southern part, as shown by soil-moisture regime map of India (Fig. 1.3) published by National Bureau of Soils Survey and Land Use Planning, Nagpur (N.B.S.S. & L.U.P., 1993).

1.2.4 Drainage

Drainage lines hold particular significance in the region: not only they provide redeeming topographic breaks in the general flatness of the plain and provide sub-regional or even local uniqueness and individuality to the different parcels of the land, but also they govern the human occupance, agriculture and settlements to great extent. The Ghaghra, the Rapti, the Gandak, the Burhi Gandak and the Baghmati are the main rivers which control the drainage system and hydro-geomorphology of the area (Fig. 1.4).

The piedmont zone shows parallel to sub parallel drainage pattern especially in the western part of the study area. The piedmont zone between the Gandak and Kosi rivers exhibits dichotomic pattern characteristics of fans and convergent pattern between the fans (Fig. 1.4). The plains, in general, are marked by southeasterly flowing drainage probably controlled by faults and regional slopes, except for central part of the Ghaghra-Rapti interfluve, where easterly drainage is dominant.

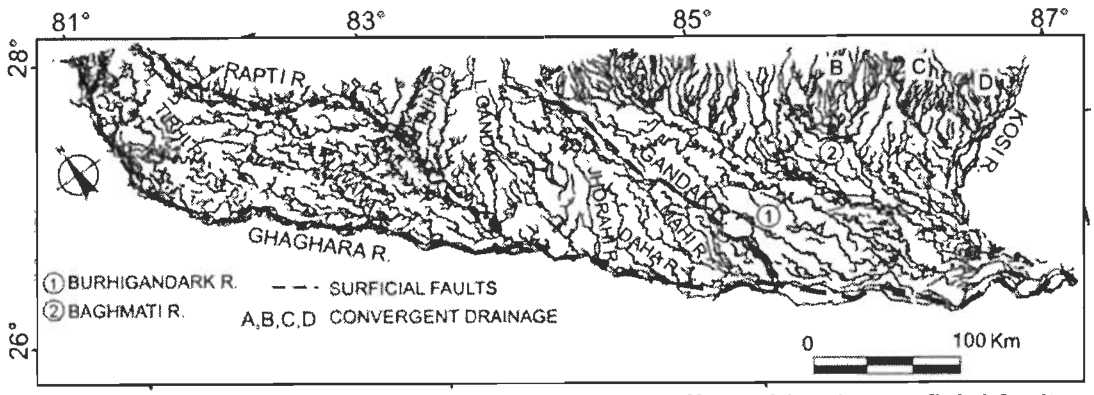


Fig. 1.4 The drainage system of the study area affected by the surficial faults.

In eastern half of the Gandak-Kosi interfan region, the Baghmati River collects waters from all the streams between the Baghmati and Kosi rivers.

Courses of the Rapti (both E-W and NNW-SSE), Ghaghara, Gandak and Kosi are controlled by faults (Gohain and Prakash, 1990; Monhindra et al., 1992; Pankaj Srivastava et al., 1994). The southeastern part of the Gandak megafan is marked by dichotomic drainage pattern due to the presence of terminal fans, as described later.

The preponderance of drainage lines and the resultant medium to fine drainage texture in the region may be partly attributed to the higher amount of rainfall and partly to the proximity of the Himalaya and the incidence of the

Bhabar (Piedmont zone) and Tarai (wet lands at the foot of the Piedmont zone) lands (Singh et al., 1971). All the major rivers of the region are characterised by change of their courses (Tangri, 1986; Chandra, 1993) as evidenced by the presence of paleochannels, swampy areas (Fig.1.5a), oxbow lakes, meander loops, dead arms and ponds (locally called *tal*) in the area.

As the Gandak River shifted from West to East over its megafan, it left behind numerous channels, ponds, lakes and different type of bars in the areas of impeded drainage. With time small ponds, and channels were integrated into a few well defined larger channels and the megafan showed improved drainage (Mohindra et al, 1992).The Gandak megafan is drained by a number of meandering streams originating within the megafan or in the Siwalik ranges, Including the Rohini, the Little Gandak, the Johrahi, the Daha and the Mahi etc. These streams are normally fed by groundwater and also carry considerable surface runoff from the megafan during the monsoon period. They have developed floodplains adjusted to their discharge and are reworking the surface layer of sediments left behind by the shifting Gandak River (Mohindra et al., 1992).

The Gandak-Kosi interfan, due to lower stream power and higher sediment yield, is characterized by the aggrading channels with frequent avulsion and extensive flooding. The variation of stream power is a function of channel slope and sediment yield is attributed to difference in rainfall and rate of uplift in the hinterland (Sinha et al., 2005). The Gandak-Kosi interfluve is drained by a dense network of channels of the Burhi Gandak, Baghmati, Kamla-Balan and numerous smaller channels, which have migrated significantly in recent times (Phillip and Gupta, 1989,

Fig. 1.5 (a) Swampy area in floodplain of the Tirhi River at Dubah village (81°45′42"E, 27°15′16"N) and (b)*Sorea robusta* (sal) jungles in Pandera (83°29′57"E, 26°59′39"N) in Gorakhpur district.

1991; Phillip and Gupta, 1993; Sinha, 1996). The plain-fed rivers cause rigorous and repeated reworking of sediment deposited by the mountain-fed and the foothill-fed rivers in the region. The foothill and plain-fed rivers, however, show high sediment yield, which indicates that the sediments are remobilized vigorously by overbank flooding, bank erosion and channel movements by these rivers. The Burhi Gandak of this area is an exception showing a downstream increase in sediment load, which indicates dominant local bank erosion (Sinha et al., 1994). As the rivers in this area are dynamic in nature, minor channels are known for frequent and extensive flooding (Kale, 2000; Sinha, 1998; Sinha and Jain, 1998; Jain and Sinha, 2003c).

1.2.5 Groundwater

The Middle Ganga plain with adequate rainfall and generally porous alluvial soil cover seems to have adequate storage of ground water. The water table is generally lower in newer sediments, particularly in the river levee zones where the sandy nature of subsoil allows greater sinking of water than the clayey inter fluvial areas of the older alluvium. The water table varies from 3-20 meter. At places artesian condition also occurs at the depth of 60-65 m below the surface (Singh et al, 1971).

1.2.6 Natural Vegetation

An almost unhindered human occupance for over three millennia and centuries of plough and pastoral culture has reduced the natural vegetation in the region except in the northern part of Champaran district, pockets of piedmont zone and some river banks. With a moderate rainfall and fertile soil, this region is a natural habitat of a dense forest cover of sal *(Sorea robusta)* and other facies like Shisham *(Dalbergia sissoo)*, Jamun *(Suzygium cumini)*, Mahua *(Madhuca indica)* and Banyan *(Ficus bengalensis)*. (Fig.14a). Remnants of the ancient *sal (Sorea robusta)* forest are now found in Gorakhpur district. Elsewhere, the vegetation is seen in the form of a savanna with grasses and bush lands dotted with trees of different sizes.

The village wet lands or vacant places are covered with naturally growing trees like Peepal *(Ficus religiosa)*, *Banyan (Ficus bengalensis)*,Tamarind *(Tamarindus indica)*, Mahua *(Madhuca indica)*, Neem *(Azadirachata indica)*, Babul*(Acacia auriculaformis)*, Palmyra*(Borassus flabbelifer)*, Date-Palm*(Phoenix dactylifera)*,and Dhak *(Butea monosperma)*, while grasses of Moonj *(Saccharum bengalensis)*, Kans*(Saccharum spontaneum)* and Jhau *(Tamarix gallica)* are found in low lying areas, and the more omnipotent Dub *(Cynedon dactylon)*, Motha *(Cyperus Rotundus Linn)* and other less pervasive type are found in the cultivated fields and mounds or field boundaries and left-over lands.

1.3 BASEMENT STRUCTURE

The Indo-Gangetic plains, lying between the Peninsular India (Precambrian terrain) and the Extra Peninsular region (Tertiary folded of the Himalayan terrain), constitute a major geologic/geomorphologic unit of the Indian subcontinent. The Precambrian rocks of Delhis, Bundelkhand Gneisses, Aravalis and Vindhyans are well exposed in the South of the plain in the Peninsular region.

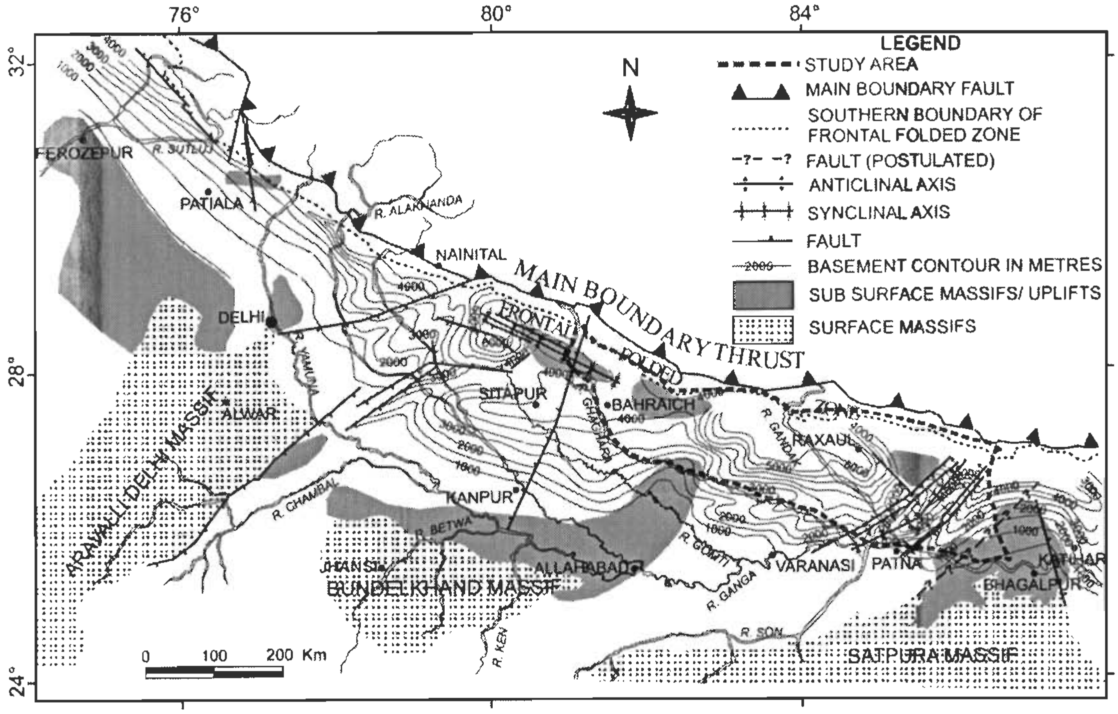


Fig. 1.5 Basement structure of the Indo-Gangetic plain (after Karunakaran and Rangarao, 1976)

Dewey et al., (1970) postulated that the Indo-Gangetic plain was a peripheral foreland basin formed due to the continent-continent collision and has been acting as mainly fluvial basin since Mid Miocene. Northern part of India has flexed down and being under-thrusted along the intra-plate Main Boundary Thrust (MBT). Drilling and geophysical survey by Oil and Natural Gas Corporation (ONGC) (Sastri et al., 1971; Rao, 1973 and Raiverman et al., 1983) indicated that the basement consists of the Delhis, Bundelkhand Gneisses, Aravalis and Vindhyans sloping gently to the north. The basin is a vast asymmetric trough with a maximum (10,000 m) thickness of the Tertiaries and Mesozoic in the North and thinning out to the South (Fig.1.5). The basement underlying the Tertiaries has been divided into many depressions, ridges and shelves (vast areas gently slopping northward) are of two orders: 1st order (>6,000 sq km) and 2nd order (<6,000 sq km) (Eremenko and Negi,1968). In the study area, first order structures are east Uttar Pradesh Shelf, Faizabad Ridge, Munger-Saharsha Ridge and Gandak Depression. The Faizabad ridge in the northward extension of the Bundelkhand massif and marks the boundary between west and east Uttar Pradesh Shelves. The Munger-Saharsha ridge represents NNE projecting basement promontory of the Chotnagpur Plateau and is likely to be composed of rock complexes of the Satpura fold belt. Sedimentary cover over this ridge does not exceed 3,000 m and the Neogene sediments directly overlie the basement. The Gandak depression is the NE-SW elongated trough having sedimentary thickness of more than 6,000 m. The surficial alluvium of the Indo-Gangetic plains was mainly deposited by various rivers emerging from the Himalaya and their tributaries. The alluvium chiefly consists of sand, *kankar* (calcrete) and clay beds. Beds of gravel are also found in the proximity of northern and southern boundaries of the Indo-Gangetic plain.

Many researchers (Agrawal,1977; Sengupta,1977; Tangri et al.,1985; Lyon-Chen et al., 1985; Singh,1987,1992,1996; Bajpai,1989; Singh et al,1989, 1996, 1997, 1999b; Mohindra et al,1992; Srivastava et al,1994; Srivastava and Singh,1998,1999; Kumar et al.1991,1996; Khan,1996; Parkash et al.,2000; Singh, 2004 and Bhosle, 2006b) have suggested influence of basement structure on the evolution of Gangetic plains and Holocene drainage and sedimentation.

1.4 REVIEW OF PREVIOUS WORK

1.4.1 Geomorphology

The vast extent, diverse geomorphology, foreland sedimentation and neotectonic activity of Indo-Gangetic plains have attracted many researchers in diverse fields in the past. Researchers like Oldham (1917), Pascoe (1917) and Pilgrim (1919 *in* Pascoe, 1964) first recognized two major soils/alluvia/surfaces in the Indo-Gangetic plains i.e. the *Khadar* (Newer Alluvium) and the Bhangar (Older Alluvium).The *Bhangar* forms uplands and is overlain by calcareous soils. The *Khadar* region lies close to rivers and may be inundated by floods frequently or rarely. A broad region of alluvial piedmont was called *Bhabar,* followed by *Tarai* in the South marked by groundwater seepage. In addition salt-affected areas (locally called *Usar),* and linear to zig-zag shaped sandy ridges/mounds (locally called Bhur, formed by eolian processes) were identified in alluvial areas.

Geddes (1960) recognized that in the Middle Gangetic Plain, major sedimentation is taking place in the form of megafans by major rivers emerging from the Himalaya. Thomas et al. (2002) suggested that the megafans are marked by coarse sediments and the interfan areas are marked by fine sediments. Both the megafans and the interfan areas together constitute the Lowland Depositional Systems. The Middle Gangetic Plain is characterised by high rate of subsidence. The Gandak-Kosi interfan region is characterised by high rates of channel avulsion, subsidence and aggradations of channels (Jain and Sinha, 2005).

Many researchers have used aerial photographs and satellite images to map small geomorphic features: valley incision by Tandon et al. (2006), channel migration by Jain et al., (2003, 2005), delineation of active faults by Singh (2004) adjacent to the area east of Ghaghara river and mapping of soil-geomorphic units by Pankaj Srivastava et al., (1994) and Mohindra et al., (1992). Tangri (1992) mapped areas inundated by floods using Landsat and IRS satellite data for constructing a bridge near Tanda on the Ghaghra River.

1.4.2 Pedology

Mohindra et al., (1992) studied geomorphology and pedology of Gandak megafan and found eastward tilting of the tectonic block between the Rapti and Gandak Rivers and consequent shifting of the Gandak eastward resulted in an decrease degree of soil development from west to east on the Gandak megafan. Pankaj Srivastava et al. (1994) studied the geomorphology, micromorphology of the soils and pedology of the area between the Ramganga and Rapti Rivers and postulated that uplift of different tectonic blocks at different times determined the degree of soil development on various tectonic blocks, in addition to tilting of large blocks. Pankaj Srivastava et al., (2002) studied micromorphology and inferred polygenetic nature of soils in the region between the rivers Ghaghra and Rapti. Luminescence chronology of sediments in the Central Ganga Plain was studied by Pradeep Srivastava et al. (2003) and the same of Rapti basin by Chandra et al. (1993). Pal et al. (2003a) studied the clay illuviation in calcareous soils in the northwestern part of the area. N.B.S.S. & L.U.P. (1999) brought out soil resource maps of sates of Uttar Pradesh and Bihar. These are useful for agricultural purposes.

1.4.3 Salt Efflorescence

High salinity of the Indo-Gangetic soil was first noted by Medlicot (1863 *in* Bhargava et al., 1982) and Center (1980 *in* Pascoe, 1964). Bhargava and Bhatacharya (1982) reviewed work on salinity and attributed saline nature of soils to shallow water tables, low slope, low rainfall and poor drainage. Soluble bicarbonates and carbonates of alkalis in saline soil are considered to be the product of weathering of alumino-silicate minerals through carbonation (Kapoor et al., 1981).

Pal et al. (2003b) observed that the Indo-Gangetic plain has a large portion of the salt-effected area of the country. Of the 7 million salt-affected hectares of the country, Indo-Gangetic plain contributes 2.32 million hectares of sodic soil (Abrol and Bhumbla, 1971). Formation of sodic soil may involve microbiological reduction of sulphate and ferric iron to form sulfide (FeS), which with CO_2 released by biological oxidation of abundant organic matter forms bicarbonates. Pal et al. (2003b) reported that the non-sodic and moderately sodic soil occurs in micro high and highly sodic soils on micro low positions, respectively, under a semi arid climate. Micro lows are repeatedly flooded with surface water during brief high-intensity showers, so that soils are subjected to cyclic wetting and drying. This provides a steady supply of alkalis by hydrolysis of Feldspars, leading to precipitation of calcium carbonates at high pH and development of subsoil sodicity. The semiarid climate and topography interact to facilitate greater penetration of bicarbonate-rich water in micro low than micro high positions. In the study area, salt affected area is well recognized between the Ghaghara-Rapti interfluve. However, the Gandak-Kosi interfan region does not show efflorescence in the satellite images.

1.4.4 Organic remains

In about 1830, an important discovery of mammalian remains was made in some calcareous shoals of the Yamuna River (Pascoe, 1964). The well foundation of the Ganga River bridge at Allahabad dredged up from depths varying from 80-100 feet below low water mark. Several mammalian bones were identified by Pilgrim (1904, 1905 in Pascoe, 1964) as *Semnopithecus sp., Bos namadicus Falc., Bubalus palaindicus Falc.,Mus sp., Equus sp., Sus sp., Antilope sp.,* and *Eliphas namdicus Falc.* Most of the bones occur in an exceedingly hard calcareous conglomerate overlain by about 120 feet of fine white micaceous sand, intermixed in places with patches of clay and kankar. Beneath the conglomerate band is some yellow sand and then yellow clay with kankar nodules. In most cases the bones are found cemented together with articles of human origin, such as fragments of weapons and boats. According to Pilgrim (1904, 1905 *in* Pascoe, 1964), the Yamuna and Allahabad fossils may be regarded as of the same age.

Recently, Singh et al. (1999a) found vertebrate fossils, namely an elephant tusk (3.54 m long), shoulder blade of elephant, molars of equus, bovids, and bos, along with fragments of bones showing definite evidences of human workmanship in a cliff of the Yamuna River at Kalpi (Ganga-Yamuna Interfluve). Human femurs with unique sharp edges are also found in the calcrete conglomerate horizon and deposit was inferred to be of humid climate around 30

Ka, and is affected by intense seismic events. This is considered as the so far oldest human occupation site of the Gangetic plains.

1.5 RESEARCH OBJECTIVES

The major objectives of the present study are as follows:

1. Recognition and mapping of soil-geomorphic units, structural features like faults using remote sensing, Digital Elevation Models (DEMs) and Digital Terrain Models (DTMs).
2. Inference of the time of activity of major faults from the degree of soil development and dating of soils.
3. Confirmation and working out subsurface nature of inferred faults by using Ground Penetrating Radar (GPR) and study of radar facies of the Gandak megafan and terminal fans of the study area.
4. Field, textural and micromorphological studies of soils to know the degree of development soils on different soil-geomorphic units.
5. To decipher the tectonic processes and the related deformation field responsible for the evolution geomorphology, pedology and sedimentology of the study area.

With the above outlined objectives, different soil- geomorphic units with distinct landforms and soil have been identified and delineated by studying Landsat MSS images, DEMs and DTMs, and transferred to the Survey of India topographic sheets and then checked in field. In the field the soil morphology of typical profiles from all the soil-geomorphological units was noted, loose samples for grain size analysis, undisturbed samples for micromorphological study and pipe samples from C- horizons for dating were collected. In the laboratory, soil samples were analyzed for texture, micromorphology was studied to know the degree of soil development and pipe samples were dated using Infra-red Luminescence Dating technique. In the end, all data were integrated to provide the evolution the area.

1.6 SCOPE OF THE PRESENT STUDY

Remotely sensed derived soil geomorphic maps, field studies, geomorphology, GPR investigation, laboratory studies, dating of soils were used to develop the morphostratigraphy and neotectonic framework of the area. These studies assisted in determining the affects of the incipient activity of some segments of transverse normal faults and helped to understand the pedogenesis, Late Holocene evolutionary history and the sedimentation process in the megafan and inter fan area.

1.7 ORGANISATION OF THE THESIS

The methodology and findings of these studies are presented in six chapters.

Chapter-1 entitled **"INTRODUCTION"** deals with the rationale for selecting the research problem, a general description of the study area including physiography, climate, drainage, ground water, natural vegetation, basement structure. This chapter also includes the review of previous works and objectives of present research.

In chapter-2 entitled **"GEOMORPHOLOGY, PEDOLOGY AND STRUCTURE OF THE STUDY AREA"** is a brief account of the general morphology of the identified soil-geomorphic units and detailed field check of soil properties. This chapter also includes the preparation methods of digital elevation models, digital terrain models, topographic profiles, leading to identification of faults, tectonic blocks and lineaments and morphostratigraphic sequence members of the study area are introduced in this chapter.

Chapter-3 entitled **"OPTICAL STIMULATED LUMINESCENCE DATING OF SEDIMENTS"** includes the protocol of sample preparation and analysis of samples in Infrared stimulated Luminescence method and the ages obtained are discussed briefly.

Chapter-4 entitled **"GROUND PENETRATING RADAR (GPR) STUDIES"** introduces the methodology of the GPR studies used and the results obtained and their interpretation in terms of neotectonic activity and the sedimentation processes.

Chapter-5 entitled **"GRAIN SIZE DISTRIBUTION AND MICROMORPHOLOGICAL STUDIES OF TYPICAL SOIL PROFILES"** elaborates the textural changes in the soil profiles and the micromorphological features on typical pedons in thin-sections.

Chapter-6, the last chapter, entitled **"SUMMARY, SYNTHESIS AND CONCLUSIONS"** briefly summarizes morphology, micromorphology, physical and mineralogical characters, GPR studies and dating of soils in various morphostratigraphic members. Synthesis of all the data in terms of morphostratigraphic sequences and role of tectonic activity and sedimentation were analyzed and the evolutionary history of the area was worked out.

CHAPTER-2

GEOMORPHOLOGY, PEDOLOGY AND STRUCTURE OF THE STUDY AREA

2.1 INTRODUCTION

The study area is a part of the Indo-Gangetic foreland basin. The major rivers that drain the area from west to east are: Ghaghara, Rapti, Gandak and Kosi. The Ghaghara-Rapti Interfluve is a part of the Upper Gangetic Plain and the rest of the study area between the Rivers Rapti and Kosi forms a part of the Middle Gangetic plain (Srivastava et al., 1994; Thomas et al., 2002) (Fig. 2.1). The study area plains are separated from the Siwalik Ranges in the north by the Himalayan Frontal Thrust (HFT).

In the present study, the whole work has been carried out in three stages i.e. desk study, field work and laboratory analysis. Due to negligible relief and apparent flatness it is difficult to map the Gangetic plains (Geddes, 1960). To overcome this problem, in the desk study, different remote sensing techniques and geographic information system (G.I.S.) techniques were used to identify soil-morphologic units (Fig. 2.1) and structural features like faults and lineaments. Fieldwork has been carried out to check boundaries of soil-geomorphic units, record soil morphological characters, collect soil samples (loose and in situ) from various horizons of typical pedons from major soil-geomorphic units. Also, samples from C-horizons of pedons (Fig. 2.2a) were collected for luminescence dating. Confirmation of faults and investigation for the change in sedimentary facies were carried out with the help of GPR (ground penetrating radar) in the field, reported in a later chapter.

The third phase comprises laboratory analysis of grain size, pH and EC

(Appendix-III), luminescence dating, micromorphological description of soils and GPR data interpretation, which are reported in later chapters. In the end an attempt is made to integrate all the data and to work out the role of neotectonism and paleo-climate in evolution of geomorphology, sedimentology and soils of the study area.

2.2 METHODOLOGY

In the present study, different soil-geomorphic units have been mapped on the basis of tone, texture and reflectivity in the LANDSAT MSS imagery using software like ERDAS IMAGINE-8.5, ARC VIEW 3.2a and ARCGIS-9. Point heights were taken from the Survey of India topographic sheets at 1:50,000 scale and DEM was prepared. Later the MSS image was geo-referenced by ERDAS IMAGINE-8.5 to the same coordinate as of the topographic sheets and the image was draped upon the prepared DEM and the DTM was prepared. As the DEM provides the realistic topographic view of the area in the laboratory, the possible geomorphic feathers were identified, transferred to topographic sheets of 1:2, 50,000 scales and were checked in the field. However, for visualisation of topographic expressions of faults and major geomorphic features, DEM with highly exaggerated vertical axis, prepared by using Golden Software SURFER-8 were found to be very useful. The whole work has been described in the flowchart (see page 26).

2.3 IDENTIFICATION OF THE SOIL-GEOMORPHIC UNITS

Landsat MSS image (spatial resolution 82 meters) and Survey of India topographic sheets of 1:2, 50,000 scales were used to identify the regional soil-geomorphic units. Based on the different image elements like tone, texture, association, shape size and pattern twenty-seven soil-geomorphic units were identified. According to Gupta (1991), these image elements reflect surface expressions that include morphology, soil moisture, vegetation cover, and drainage pattern within an area. The location and extent of each unit were checked in the field and soil samples were collected (Fig. 2.2a).

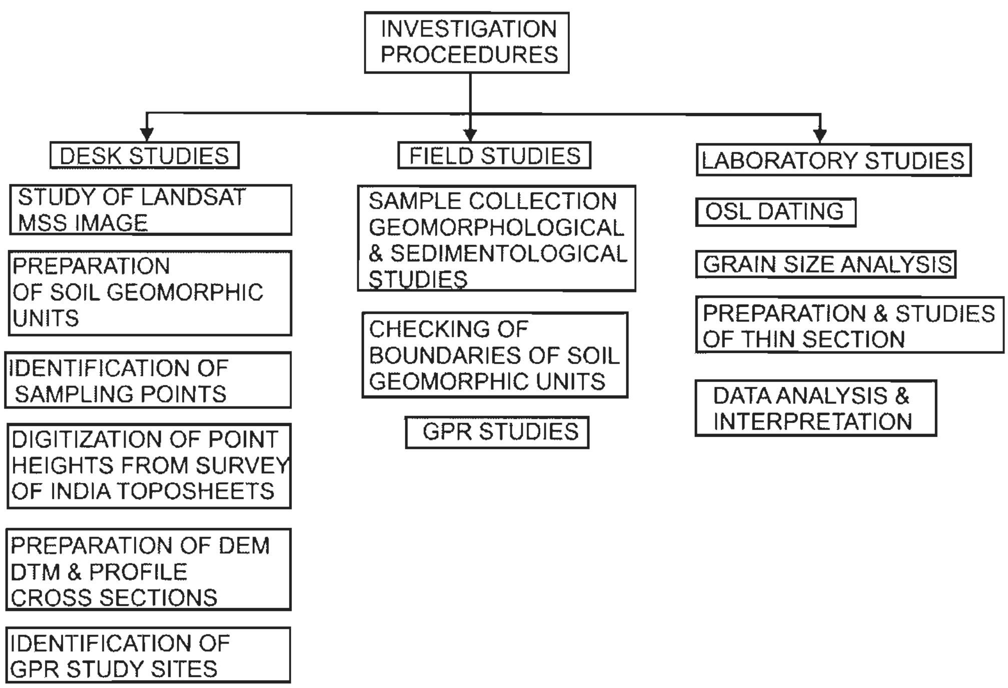
2.4 FIELD INVESTIGATIONS

Fieldwork has been carried out to check the boundaries between different soil-geomorphological units, note soil morphological properties of typical pedons in various soil-geomorphic units and confirm tectonics-related features and possible locations for GPR profiling. Soil profiles were studied in brick kiln excavations, if available, otherwise excavation were made up to C-horizons in individual soil-geomorphic units. Field features of soils were noted (Appendix-I) and samples from various sub-horizons/ horizons of each pedon for laboratory analysis were collected according to United States Department of Agriculture (U.S.D.A., 1966) and Schoeneberger et al. (1998). The soil properties were studied extending through the solum into fresh parent material (C-horizon). Excavations were made in such a way that they had at least one smooth vertical wall and this wall was uniformly illuminated to allow an examination of the soil properties and taking a photograph of the complete profile.

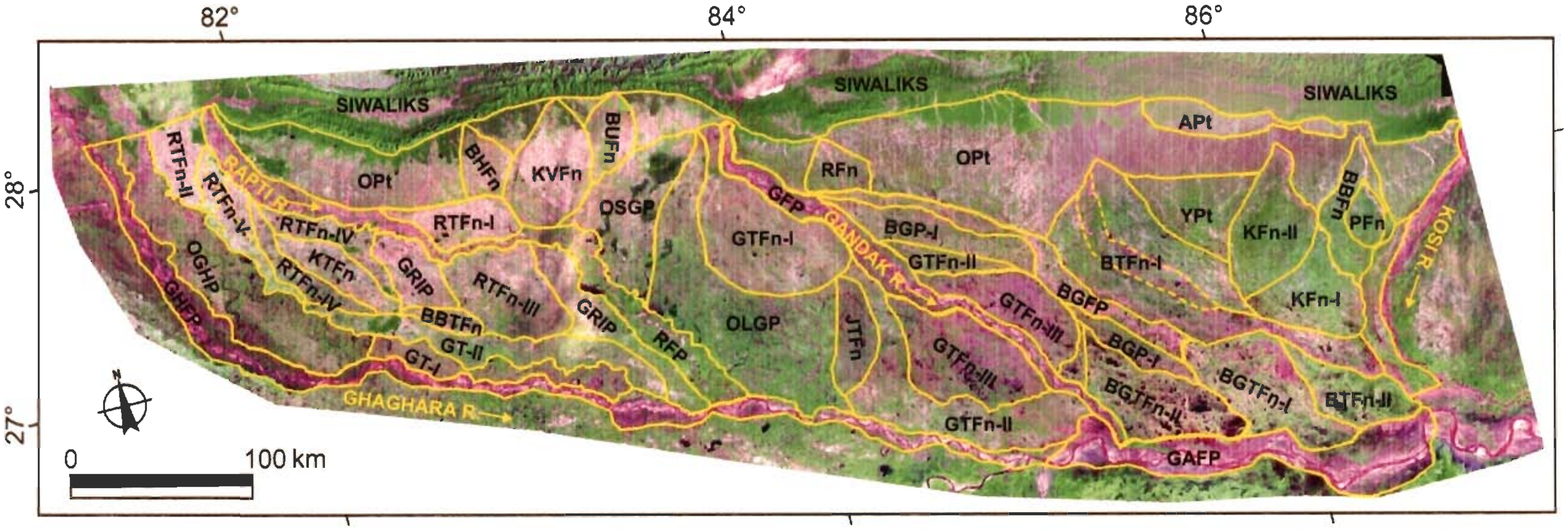
After excavation, different horizons and sub-horizons were marked on the basis of different soil properties. Depth and thickness of each horizon/sub-horizon was recorded and these sub-horizons are designated as A1, Ap, B1, B21, C etc. Also, each sub-horizon was described in the field with special attention to the morphological characteristics of soil like horizon boundary, colour, consistence, texture, structures, carbonate content, pores and roots.

2.4.1 Colour

Soil colours were observed by comparison with Munsell colour chart (Kollmorgen Instruments Corp., 1975). Hue, values and chroma were noted according to Munsell notations and moisture condition was stated. Mottling was described by noting (i) Colour of matrix, (ii) colour of mottles, and (iii) pattern of the mottling. Three aspects like the pattern of mottles, contrast (faint, distinct and prominent), abundance (few - <2% of surface area, common - 2 to <20 % of surface area and many ≥ 20 of surface area) and size (fine - <5 mm, medium - 5 to < 15 mm and coarse - >15 mm were noted.



Flowchart showing the investigation procedures applied in the present study



RTFn-I-V	RAPTI TERMINAL FAN-I-V	OPt	OLD PIEDMONT	BBTFn	BABBAN TERMINAL FAN	RFn	RAMNAGAR FAN
OGHP	OLD GHAGHARA PLAIN	GRIP	GHAGHARA-RAPTI INTERFLUVE PLAIN	BHFn	BAHADURGANJ FAN	APt	ACTIVE PIEDMONT
GHFP	GHAGHARA FLOOD PLAIN	GT-I-II	GHAGHARA TERRACE-I&II	KVFn	KAPILAVASTU FAN	YPt	YOUNG PIEDMONT
KTFn	KHUJURPUR TERMINAL FAN	RFP	RAPTI FLOOD PLAIN	BUFn	BUTUWAL FAN	GTFn-I-III	GANDAK TERMINAL FAN-I-III
JTFn	JHARANI TERMINAL FAN	OSGP	OLDEST GANDAK PLAIN	OLGP	OLD GANDAK PLAIN	BTFn-I-II	BAGHMATI TERMINAL FAN-I&II
BGP-I	BURHIGANDAK PLAIN-I	BGFP	BURHIGANDAK FLOOD PLAIN	GAFP	GANGA FLOOD PLAIN	BGTFn-I-II	BURHIGANDAK TERMINAL FAN-I&II
KFn-I-II	KAMLA FAN-I&II	PFn	PHULPARAS FAN	BBFn	BHATIBALAN FAN	GFP	GANDAK FLOOD PLAIN

Fig.2.1 LANDSAT MSS image (band combination: 1-4-2) of the study area showing the soil-geomorphic units

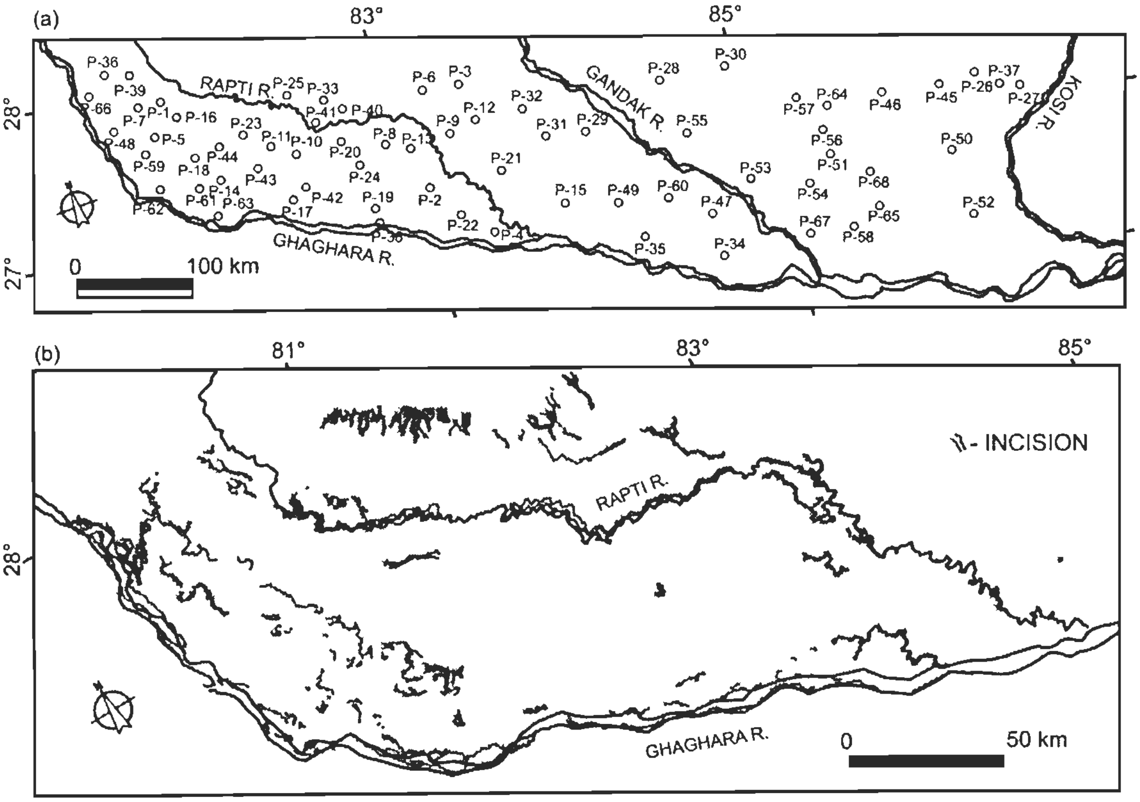


Fig. 2.2 (a) Distribution of sampling locations in the field area for IRSL dating samples, (b) Incision in the Upper Gangetic plain between the Ghaghara and Rapti Rivers.

2.4.2 Consistence

Consistence is a measure of the adherence of soil particles to fingers, the cohesion of soil particles to one another and the resistance of the soil mass to deformation. Because this property varies with moisture content, it was noted whether the soil was dry, moist and wet. The wet consistence (natural wetness or artificial wetness) is useful in determining texture classes in the field and is composed of two quantities-stickiness and plasticity. Stickiness is measured by compressing the soil between thumb and forefinger and noting the adherence of soil to either finger upon release of pressure. The classes recognized are sticky, slightly sticky and non-sticky.

Plasticity is measured by rolling the wet soil between thumb and forefinger in an attempt to form a thin rod. Several classes are recognized: non-plastic - no rod forms; slightly plastic - a weak rod forms, that is easily deformed and broken; plastic - a rod forms, which resists moderate deformation and breakage. Wet consistence helps in determining changes in soil texture.

2.4.3 Texture

Soil texture refers to the relative proportions of various size groups of individual soil grains in a mass of soil. Especially it refers to the proportions of clay, silt and sand below 2 mm in diameter. Textural class is determined by noting the grittiness and wet consistence, and several classes are recognized in the field, but these are determined later more accurately in laboratory by grain size analysis (Sec. 5.2).

2.4.4 Structure

Soil texture refers to the aggregation of primary soil particles into compound particles or clusters of primary particles, which are separated from the adjoining aggregates by surfaces of weakness. Soil structure is the degree of aggregation and expresses the difference between cohesion within aggregates and adhesion between aggregates. In the field, structure is determined by noting the durability of aggregates and the proportions between aggregates and non-aggregated materials those results, when clods of soil material are displaced or gently crushed. The terms for structure are: structure less - without aggregation; weak - a few peds are barely observable and much material is unaggregated; moderate - peds are easily observable and most material is aggregated; strong - peds are distinct in place and separate cleanly when disturbed. Grade, type and size of soil structure are noted and confirmed later with the help of soil micromorphology (Sec. 5.4).

2.4.5 Concretions and Nodules

Concretions and nodules of Fe/Mn and carbonates are noted and their size and volume percentage are estimated (Schoeneberger et al., 1998). Size was noted as: fine - < 2 mm, medium - 2 to < 5 mm, coarse - 5 to < 20 mm, very coarse - 20 to < 76 mm, extremely coarse - ≥ 76 mm and their abundance was recorded as: few - < 2 % area, common - 2 to < 20 % area and many - ≥ 20 % area.

Disseminated fine grained carbonate was determined by indication of reaction with 10% HCl. Classes identified were: non calcareous - acid non reactive; very weakly calcareous - little movement within the acid drop; calcareous - numerous bubbles, but not coalescing to form a froth; strongly calcareous - bubbles forming a white froth, but drop of acid not doming upward; very strongly calcareous - drop vigorously frothing and doming upward **(Retallack, 1988).**

Calcrete development stages (Stages I to IV) as given by Gile et al., (1966) were noted in the field. Stage-I calcretes are marked by thin to thick segregated films and fine to thick thread-like white seams, Stage-II calcretes are observed by irregular-shaped soft to hard nodules. In addition to irregular shaped soft to hard nodules calcareous cement is present in Stage-III calcretes. All pores are completely plugged by calcareous cement in Stage IV calcretes.

2.4.6 Soil Pores

Soil pores were identified by visual examination in the field. Soil pore size (diameter) was noted as: very fine - < 1 mm, fine - 1 to < 2 mm, medium - 2 to < 5 mm, coarse - 5 to < 10 mm, very coarse - ≥ 10 mm and their abundance was recorded as: few - < 1 % area, common - 1 to < 5 % area, many - ≥ 5 % area. Size and abundance were confirmed later with the help of soil micromorphology (Sec. 5.4).

2.4.7 Horizon Boundary

Width of transition zone from the underlying to overlying horizon (distinctness) and topography of the zone are recorded. Distinctness classes are: abrupt - <2 to 2 cm wide; clear - 2 to 5 cm wide; gradual - 5 to 12 cm wide; diffuse - > 12 cm wide. Topography of boundary classes are: smooth (nearly a plane surface), wavy (packets are wider than their depth), irregular (packets are deeper than their width) and broken (boundary is not continuous).

2.4.8 Roots

Size, abundance and penetration of roots are recorded according to Schoeneberger et al. (1998). Different classes of size are: very fine - < 1 mm; fine - 1 to <2 mm; medium - 2 to-<5 mm, and coarse - > 5 mm, and their abundance was recorded as: few (< 1 % of area), common (1 to < 5 % of area) and many (≥ 5 % of area).

2.4.9 Subordinate Descriptors

The subordinate descriptors are used for special property of horizon/s (Retallack, 1988). The main subordinate descriptors used in this thesis are: b-buried soil horizon; c - concretions or nodules; g - evidence of strong gleying, k -

accumulation of carbonates; p - ploughing or other comparable human disturbance; t - accumulation of clay.

After recording various soil characteristics systematically, samples from each pedon were collected for laboratory analyses. Loose samples in plastic bags and oriented (undisturbed) samples in tin boxes for micromorphololological studies of soils were collected from each horizon/sub-horizon. Samples from the C-horizons from the typical pedons of the different soil-geomorphic units were collected in one end closed steel tubes. These were dated by Infrared stimulated luminescence (IRSL) dating technique in the laboratory .Out of 108 soil profiles studied in the field, 68 were chosen for detailed laboratory analyses.

Field examination followed by laboratory studies confirmed that the soils in individual geomorphic units are fairly uniform or show variation in a small range. Therefore, these geomorphic units can be referred as soil-geomorphic units.

2.5 GENERAL DESCRIPTION OF VARIOUS SOIL-GEOMORPHIC UNITS

Though the major morphological features identified in the study area include piedmont zone, alluvial fans, braided fluvial fans, terminal fans, terraces, incised vallies, old river plains, megafan, the terraces and the incised vallies are confined to the Upper Gangetic plain (Fig. 2.2b) only and are absent in the Middle Gangetic Plains.

2.5.1 Piedmont Zone

The piedmont zone extends from base of the Siwalik Ranges southwards, covers an area of $20x10^3$ km^2 and constitutes about 26% of the whole study area. The average width of this zone is 35 km in the western region north of the

Ghaghara-Rapti interfluve and is about 60 km in the Gandak-Kosi interfan area in the Middle Gangetic Plains. This geomorphic unit is further subdivided on the basis of the degree of soil development into three soil-geomorphic units as active, young and old piedmonts in the Gandak-Kosi Interfan area, where it has been studied in detail.

2.5.1.1 Active Piedmont (APt)

The active piedmont (APt) lies just south of the Siwalik Ranges and covers an area of 850 km^2 (Fig. 2.1). Lithologically it is mainly composed of gravels and sands and the unit is characterized by light tonal signature in the MSS image. It shows dichotomic as well as parallel drainage patterns. The width of this unit gradually decreases from west about (15 km) to east (6 km).

2.5.1.2 Old Piedmont (OPt)

The Old piedmont lies to the south of the active piedmont or Siwalik Ranges and extends throughout with an average width varying between 44 km in the interfan area to 31 km in the interfluve area. Slope of this unit varies from 1.2% to 0.9% in the interfluve to the interfan area, respectively. This unit is characterised by the convergent, dichotmic and parallel drainage patterns (Fig. 1.4). Most of the streams are incised in this unit. Several small distinct alluvial fans such as Bahadurganj fan, Kapilavastu fan, Butwal fan and Ramnagar fan are identified within this unit (Fig. 2.1) This unit is underlain mainly by sands and gravels and is densely forested.

2.5.1.3 Young Piedmont (YPt)

Due to the activity of Piedmont Fault-II (PtFt-II), at the base of the Old Piedmont, a new 44 km wide young piedmont (YPt) with a number of parallel streams has been deposited. This YPt is mainly restricted in the Gandak-Kosi interfan area, covers an area of 1300 km^2 and is characterised by sandy lithology, lower slope (0.5%), parallel and rarely convergent drainage pattern and weakly developed soils (Fig. 2.1). Some younger fans like the Baghmati fan, the Kamla fans-I & II have developed due to the activity of the Piedmont-II, North Sitamarhi and Madhubani faults, respectively. The OSL ages of these fans are similar to the Young Piedmont.

2.5.2 Terminal Fans

In the plain area, terminal fans occur on the hanging walls of the faults and are formed due to of relief created by their activity (Singh et al., 2006). In the study area, at least two types of terminal fans are recognized:

Table 2.1 Morphological characteristics of the terminal fans on the study area

Terminal fan	Fault	Age (ka)	Area (km^2)	Length (Km)	Slope (%)	Max^m height at proximal end (m)	Max^m Height At Distal end (m)
Rapti-I	Rapti-I	4.2±0.9	1354	47.39	0.03	140	127
Rapti-II	Rapti-I	4.9±0.8	846	30.25	0.04	100	87
Rapti-III	Faizabad-Domariaganj	7.1±1.3	2034	55.07	0.01	92	85
Rapti-IV	Bahraich	7.8±1.1	2339	86.42	0.02	117	100
Rapti-V	Intaha-Parsa	11.2±1.6	1064	86.66	0.01	125	115
Khujurpur	Colnelganj-Balrampur	3.1±0.6	880	66.83	0.01	115	105
Babban	Ayodhya-Dinkarpur	3.4±0.8	358	36.17	0.01	92	87
Gandak-I	Nichlul	4.8±0.6	2537	71.77	0.03	97	77
Gandak-II	South	4.5±0.7	7295	124.27	0.02	80	55

	Motihari						
Gandak-III	South Motihari	1.2±0.2	4553	78.18	0.01	63	55
Jharni	Barhaj-Bettiah	1.4±0.4	912	51.49	0.01	72	65
Baghmati-I	Piedmont-II	1.3±0.2	4208	109.75	0.02	75	47
Baghmati-II	Hathauri-Simariaghat	0.9±0.2	1838	52.44	0.01	40	38
Burhigandak-I	South Muzaffarpur	0.7±0.1	2246	64.34	0.01	50	44
Burhigandak-II	West Patna	0.4±0.09	2268	74.31	0.01	54	50

2.5.2.1 Braided Stream Terminal Fans

The Rapti-II and Baghmati-I are the major examples of braided stream terminal fans. The streams are braided in nature over major parts of these fans (Fig. 2.1). Most of the sediments deposited in these fans are coarse to fine grained sand. However, mud facies occur as overbank deposits as well channel-fills ones, as confirmed by the GPR profiles (Sec. 4.7). Most of these terminal fans are overlain by weakly developed soils (Table 2.1).

The Baghmati terminal fan was created by the activity of the Piedmont Fault-II (PtFt-II) passing through the base of the piedmont. A number of faults traverse through it. The West Patna Fault (WPFt) passes in the middle of this fan. Similarly, Sitamarhi Fault (SFt), South Motihari Fault (SMFt), Madhubani Fault (MFt), and North Muzaffarpur Fault (NMRFt) partially cut this fan. In the distal part of the fan, due to the South Muzaffarpur fault (SMRFt), the channels converge and offset eastward and forms swampy conditions. Due to tectonic instability caused by the repeated activity of these faults, this fan is marked by high rate of sedimentation and hence hyperavulsive nature of streams.

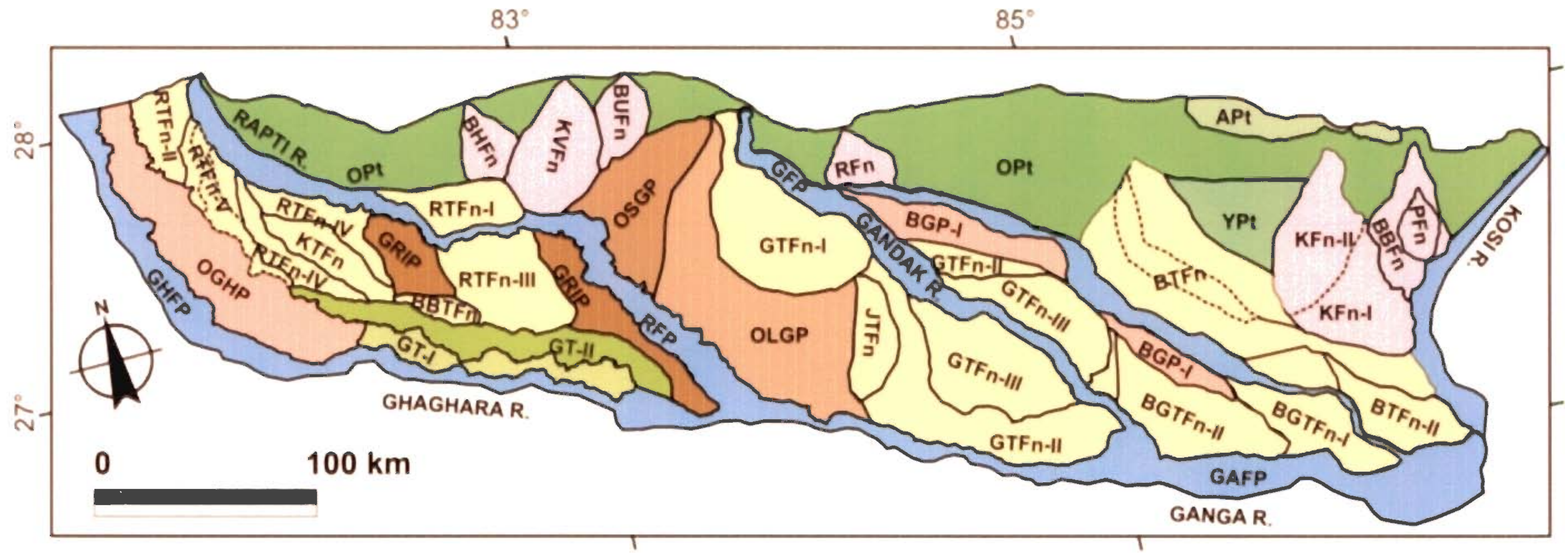


Fig. 2.3 Soil geomorphic units of the study area

Numerous paleo channels across the fan are the signature of the paleo course of Baghmati River.

2.5.5.2 Meandering stream terminal fan:

The Rapti fans-I, III, IV, V, Khujurpur, Babbnan Jharni, Baghmati-II and Burhigandak-I & II terminal fans are the examples of meandering stream terminal fans in the area. The streams on these fans are meandering in nature. Hence most of the areas on these fans are overlain by oxbow lakes and abandoned channels.

The Gandak terminal fan-III shows a number of sandy paleochannels with slightly raised level and low-lying channels with floodplain deposition on a large scale, with widths of 4-5.5 km diverging out from the point, where the Gandak enters the downthrown block of the South Motihari Fault. This indicates frequent splays developing from the Gandak River, leading to the formation of this terminal fan (Fig. 2.6). The low-lying paleochannels are also marked by numerous ponds located in linear fashions. Organic-rich mud is being deposited in these ponds. Also, the Gandak Terminal fans I-II, show such dichotomic pattern of paleochannels, diverging from the points, where associated Gandak River traverses Nichlul fault (fan-I) and South Motihari fault (fans-II), suggesting these have been also formed by splays from the large Gandak river. Here a new term "splay terminal fan" is proposed for such features. The Gandak terminal fans-I and II are 4.5 Ka age and fan-III covers major parts of fan-II and is of 0.9-1.2 Ka age.

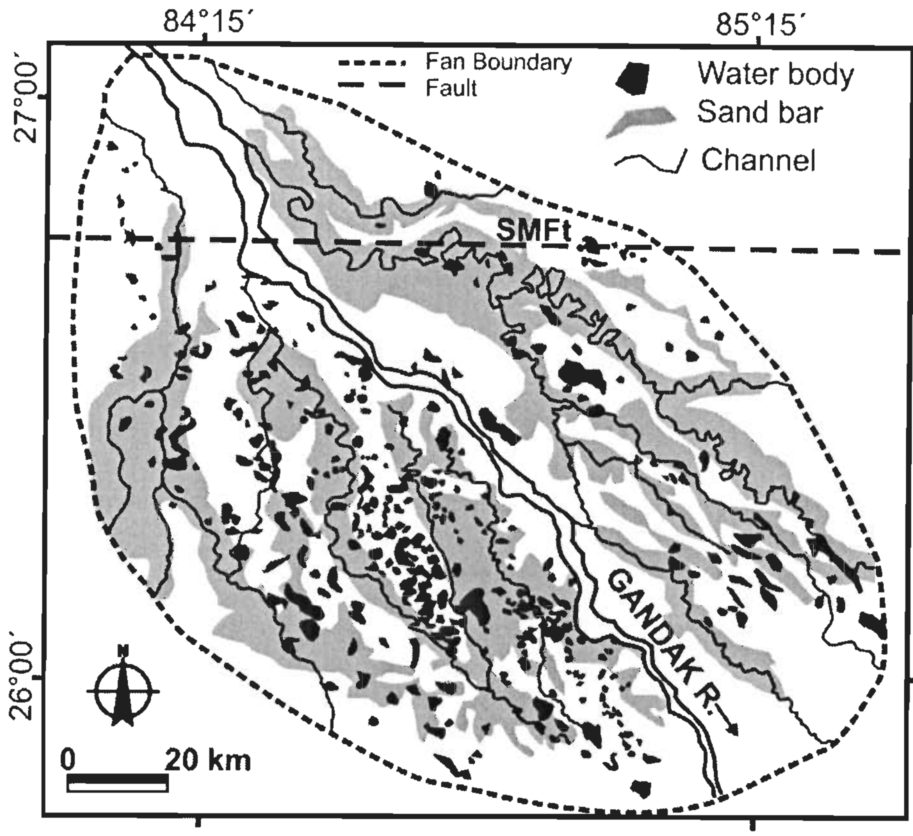


Fig. 2.4 Gandak Terminal Fan-III showing sandy channels formed by the splays of Gandak River and low-lying areas dominated by water bodies.

2.5.3 Megafan

The Gandak megafan (Fig.2.1) lies in the central region of the study area. On this megafan, from west to east, two plains i.e. Oldest and Old Gandak Plains are identified, which formed due to the movement of the Gandak River across the megafan caused by eastward tilting of the Rapti-Gandak tectonic block (Mohindra et al., 1992) (Fig.2.6). The degree of soil development and soil ages decrease and number of abandoned channels and ox-bow lakes increase from the Oldest (>10 ka) Gandak Plain to Old (10-8.6 ka) Gandak Plain (Mohindra et al., 1992).

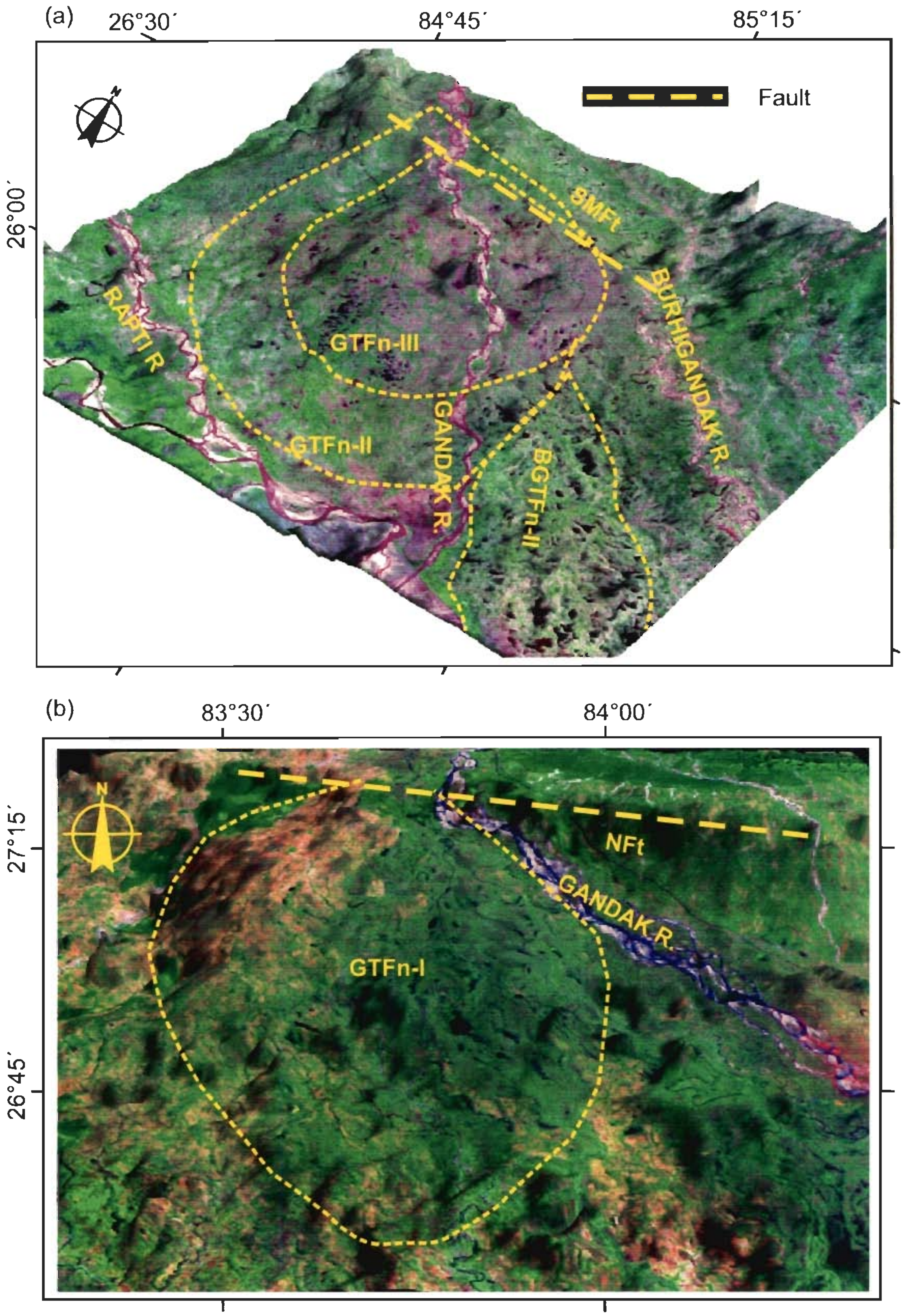


Fig. 2.5 DTM (a) Gandak terminal fan-II& III, (b) Gandak terminal fan-I

Four terminal fans identified from the Gandak megafan area are Gandak terminal fans I-III and Jharni terminal fan, which have been described above.

Earlier the Gandak terminal fan-I and II were considered to form the Young Gandak Plain by Mohindra et al. (1992). They had worked with 1:1 million scales, MSS images and definition of various soil-geomorphic units was on the basis of the degree of soil development. Now with the enhancement of MSS images by use of digital data and use of DEMs, DTMs and dating of soils by IRSL technique, it was possible to recognize the terminal fans. However, we have retained the terms like the Oldest and Old Gandak plains of Mohindra et al. (1992).

The Gandak megafan Block is segmented into three tectonic sub-blocks (Fig.2.6) by the Gorakhpur-Padrauna (GPFt) and Barhaj-Bettiah (BBFt) faults, striking N75°E-S75°W and N50°E-S50°W, respectively. The upper two sub blocks i.e. the Maharajganj sub-block and Captainganj sub-block show unique artifact landscapes like rounded hills (Gandak Terminal fan-I) (Fig. 2.6) and dissected tableland, respectively, in the DTM (Fig. 2.6). In the north this megafan (Oldest Gandak Plain) is separated from the Piedmont zone by the Rohini Fault (Fig. 2.24a, 2.24b).

The Gandak River, though braided in nature, is bringing large amounts of suspended matter, rich in fine clacitic material, which are spread over major parts of the floodplain. Calcitic material gives the top soil in active floodplain a crystic b-fabric. However, in the Old Gandak Plain soils, the calcitic material is being dissolved and leached to C-horizon, which shows development of calcrete nodules. B-horizon is free of calcitic material and shows clay illuviation features. The Oldest Gandak Plain is free of calcitic nodules and exhibits only clay illuviation features on a large scale. These features have been well documented by Mohindra et al. (1992).

2.5.4 Incised Vallies

Incised vallies are mainly confined in the Upper Gangetic plains, mostly along the course of Ghaghara and Rapti Rivers (Fig 2.2b). The Ghaghara shows cliff surfaces of 10-12 m (Srivastava et al., 1994) due to incision. The Rapti is less incised than that of the River Ghaghara. Both of the rivers show more incision in the Basti sub-block. Rivers are incised with the older floodplains as seen in the MSS image, due to upliftment of this sub-block.

2.5.5 Old River Plains

Old river plains are associated both in Upper and Middle Gangetic plains. These plains are recognized by their respective geomorphic features characteristics of the Upper and Middle Gangetic plain.

2.5.5.1 Old Ghaghara plain (OGHP)

The old Ghaghara plain (OGHP) is bounded by the Ghaghara Fault-II in the east and by the Ghaghara flood plain (GHFP) in the west, has an average width of 22 km and covers an area of ~3,200 km^2. Numerous small streams like the Sarju, Terhi and their tributaries rework the plain. It is marked by the presence of numerous paleochannels, oxbow lakes and ponds and dominant sand facies. The oxbow lakes and the abandoned channels become potential sites for the deposition of mud facies. At places, sands have been reworked by

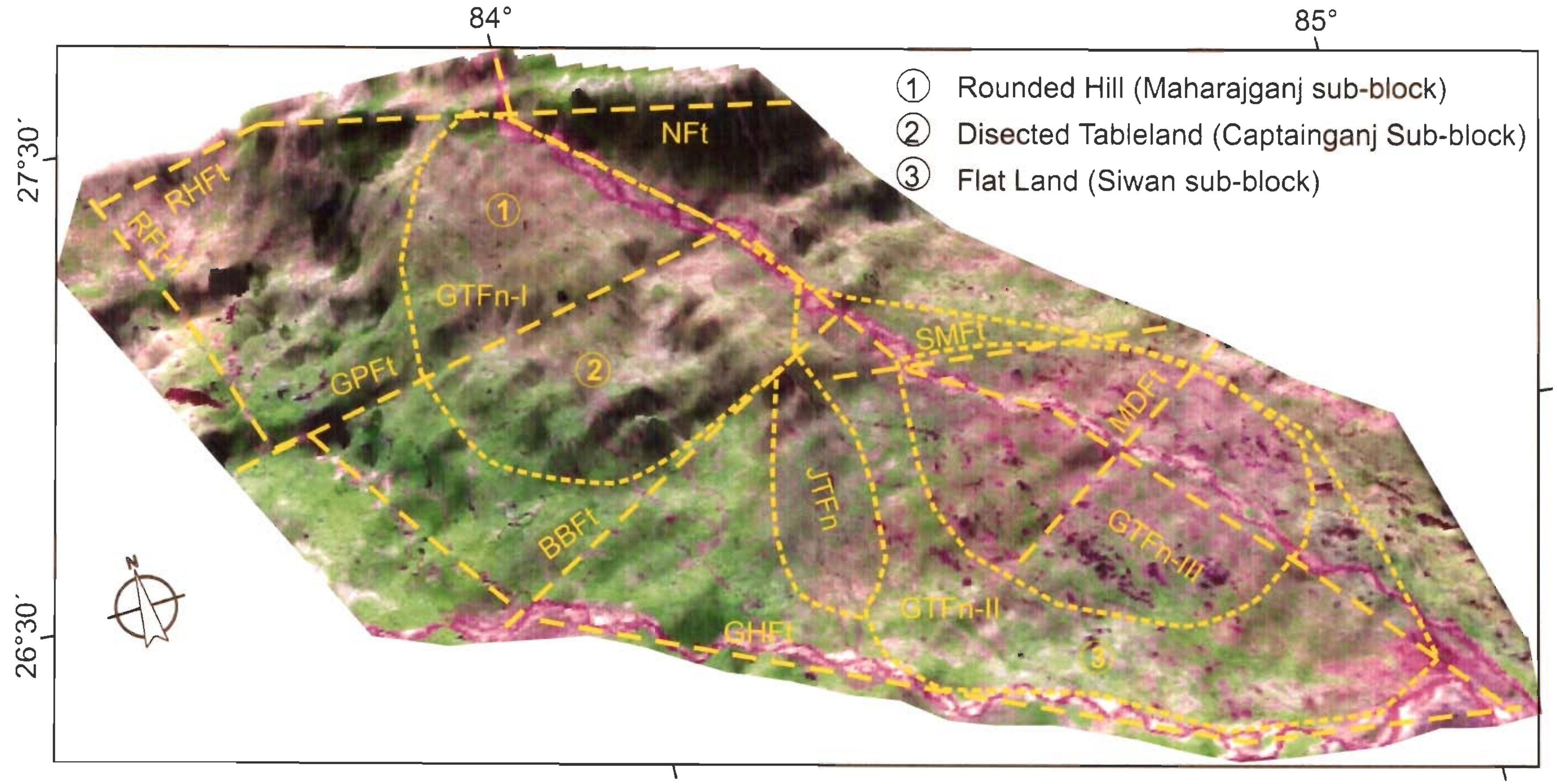


Fig.2.6 DTM of Gandak Megafan Block with associated sub blocks

aeolian activity into dunes and such areas show lighter tone than the rest part of this unit. Weakly developed soil and incised channels are characteristic features of this unit. Because of low relief, some parts of the unit are frequently inundated by the Ghaghara River floods and low relief regions, show darker tone in the MSS image.

2.5.5.2 Burhi Gandak Plain-I (BGP-I)

The plain Bounded by the Burhigandak terminal fan-II and the Gandak River in the west and the Burhi Gandak in the east. As earlier (before 1.2 Ka), the Gandak River was flowing in this plain and since its shift from this area to the present position in the 18th Century, the misfit Burhigandak flows in this plain forming a narrower floodplain. The whole of this plain may be inundated by frequent flooding during rainy season. Because of frequent shifting the Burhigandak River, the plain is marked by numerous abandoned meanders and ponds.

2.5.6 Terraces

Two terraces are associated with the river Ghaghra (Fig. 2.3, 2.7) after it takes the SE turn, namely Ghaghara Terrace-I (GT-I) and Ghaghara Terrace-II (GT-II). The GT-I and GT-II can be traced over distances of 115 km and 154 km and have average width of 10 km and 11 km, respectively. Though both of the terraces are characterised by the oxbow lakes and meanders scars (Fig. 2.7), these are more abundant on terrace GT-I than the older terrace GT-II. The degree of soil development of these two terraces higher in GT-II than GT-I, as evidenced by solum thickness, which is 100 cm and 48 cm on GT-II and GT-I terraces, respectively

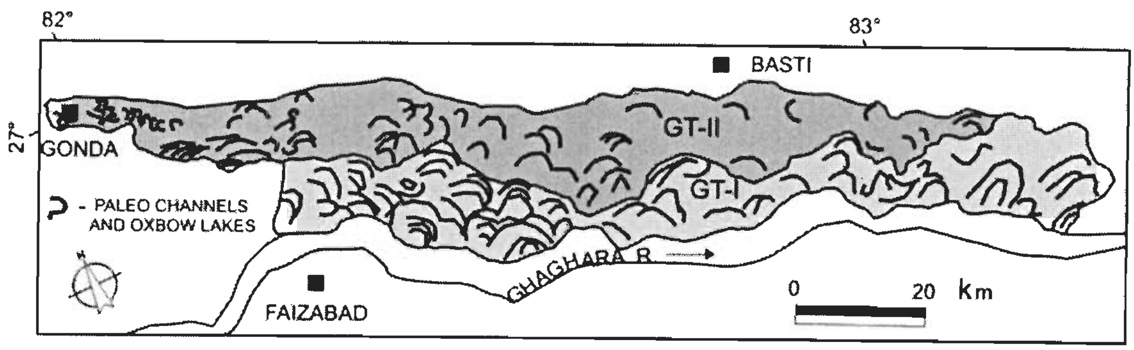


Fig. 2.7 Ghaghara terrace-I & II populated with numerous paleochannels in the study area.

2.5.7 Ghaghara-Rapti Interfluve Plain

Interfluve plain (Fig. 2.1) is a part of the Upper Gangetic plain. This geomorphic unit forms the background for deposition of later terminal fans, consequently occurs in three major isolated patches. This plain covers an area of about 2,990 km^2 and is characterized by moderately to well-developed soils, showing salt efflorescence and development of calcrete at depth.

2.6 MORPHOSTRATIGHAPHY OF THE STUDY AREA

Mohindra et al. (1992), Pankaj Srivastava et al. (1994) and Kumar et al. (1996) used soil-chrono association to rank the soils developed in different broad soil-geomorphic units, based on the degree of soil development. In the present area twenty-eight soil-geomorphic units are recognised (Fig. 2.1). Also, luminescence ages of soils of different soil-geomorphic units were determined (Table 3.1). Broadly relative ages obtained by the degree of soil development are similar to those obtained from Luminescence dating. Based on Luminescence dates of the soil-geomorphic units were grouped into six members of a

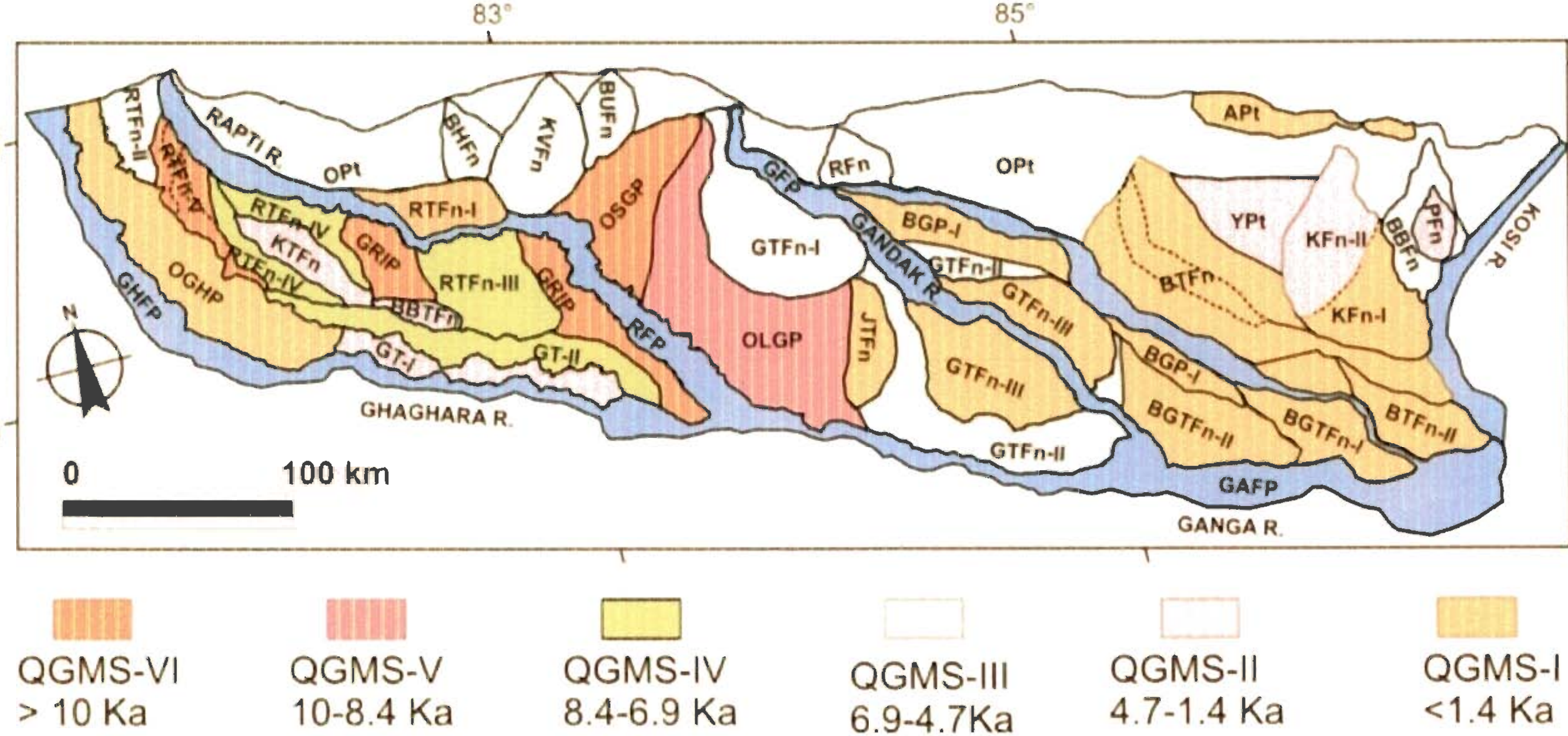


Fig.2.8 Morphostratigraphy of the study area

Morphostratigraphic Sequence (Fig. 2.8): QGMS-I (<1.4 Ka), QGMS-II (1.4-4.7 Ka), QGMS-III (4.7-6.9 Ka), QGMS-IV (6.9-8.4 Ka), QGMS-V (8.4-10 Ka) and QGMS-VI (>10 Ka).

2. 7 GEOMORPHOLOGY AND SOIL MORPHOLOGY OF DIFFERENT SOIL–GEMORPHIC UNITS

2.7.1 Member QGMS-I

Except for the Old Piedmont, Bhatibalan fan and the Phulparas fan and Kamla Fan-II, all other soil-geomorphic units on the Gandak-Kosi interfan area, all active river plains and the Old Ghaghara plain (OGHP) in the Upper Gangetic plain belong to this Member. In all the cases, except for the upper part of the Kamla fan, parent material is usually sand/gravel and A/C type of horizon is observed. In the upper part of the Kamla fan, soil developed on silty parent material is weak with solum and B-horizon thicknesses of 30 cm and 15 cm, respectively (Fig. 2.9).

2.7.2 Member QGMS-II

This member includes seven soil-geomorphic units i e. Rapti terminal fan-I, Young Piedmont, Ghaghara terrace-I, Kamla fan-II, Phulparas fan, Khujurpur and Babban terminal fans. This member is marked by very weakly developed soils with 20 cm thick B-horizons and the solum thickness of 65 cm. The colour of the B horizon varies from 10YR6/4 to 2.5Y5/6. This member shows common, fine and distinct mottles, patchy thin clay cutans in the B-horizon. The texture varies from course to fine sandy to silty loam. Gleying occurs in this member in the Middle Gangetic plains (Fig. 2.10 a, b).

2.7.3 Member QGMS-III

This member of the morphostratigraphic sequence include five soil-geomorphic units i e. Old Piedmont, Bhatiblan Fan, Gandak terminal fans-I & II and the Rapti terminal fan-II.

The solum thickness varies from 45 to 65 cm and that of B-horizon varies from 25-40 cm. The colour of B-horizon ranges from 2.5Y4/2 to 5Y6/4. Moderately thick clay cutans and sub-angular blocky structure, coarse and prominent mottles (10YR3/2 to 10YR5/8) are present in soils of this member. The A-horizon is strongly limy in nature. In the Gandak terminal fans-I & II, the soil grades into silty loam substratum rich in $CaCO_3$ concretions. The B-horizon is silty loam and has common, medium sized, distinct oxidized mottles. Fe-Mn nodules of black to brown colour are found (Fig. 2.10 c, d).

2.7.4. Member QGMS-IV

This morphostratigraphic member comprises three soil-geomorphic units i e. Rapti terminal fans-III & IV and the Ghaghara terrace-II, is characterized by moderate to well developed soils (Fig. 2.11 a, b).

The solum thickness varies from 65 to 85 cm and the B-horizon thickness varies from 50-55 cm. The B-horizon is marked by the colour ranging from 5Y4/2 to 2.5Y6/4. Fine, sub-angular blocky structure and commonly fine to medium mottles are present in the B-horizons. Thin patchy clay cutans are present along the roots channels and soil pores. Soils of this member are marked by fine sandy to sandy loam texture (Sec. 5.2).

2.7.5 Member QGMS-V

The member QGMS-V includes only one soil geomorphic unit i e. the Old Gandak Plain (OLGP), characterized by very well developed soils.

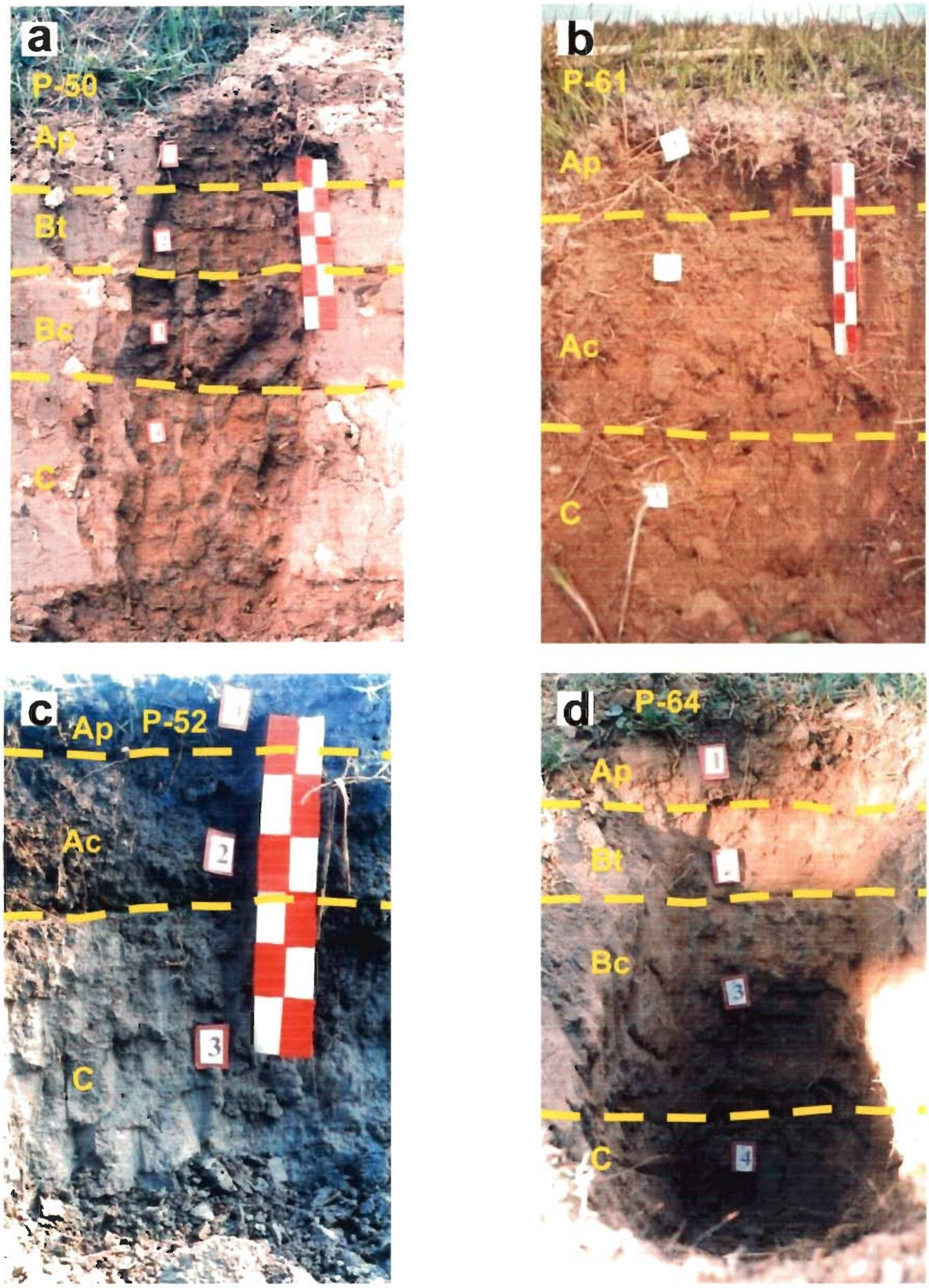


Fig.2.9 Field photographs of QGMS-I soils (a) Pedon P-50 (KFn-I) (b) P-61 (OGHP) (c) P-52 (BTFn-II) and (d) P-64 (BTFn-I).

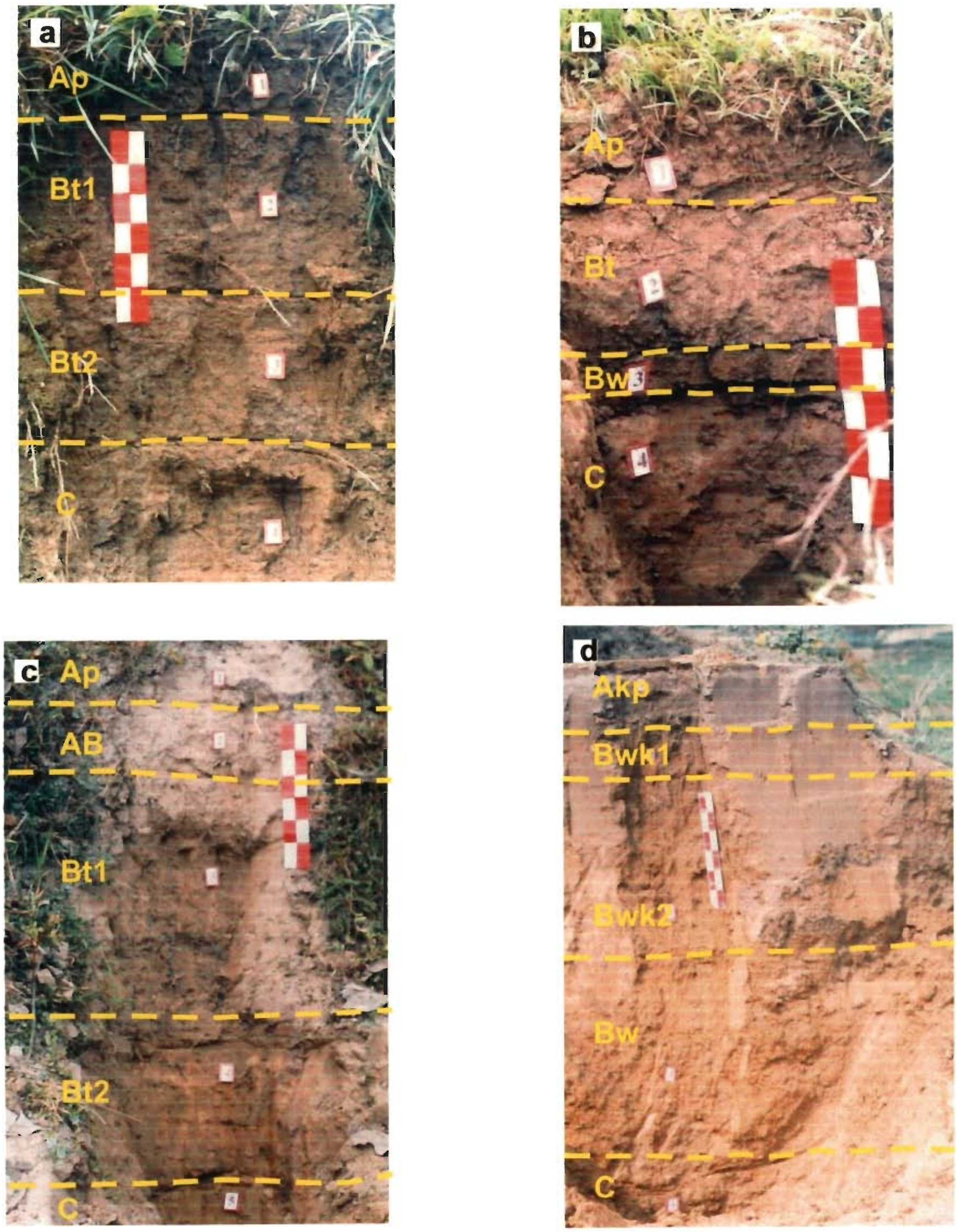


Fig. 2.10 Field photographs of QGMS-II & III soils. (a) Pedon P-45 (KFn-II), (b) Pedon P-46 (YPt), (c) Pedon P-26 (BBFn) and (d) Pedon P-35 (GTFn-II).

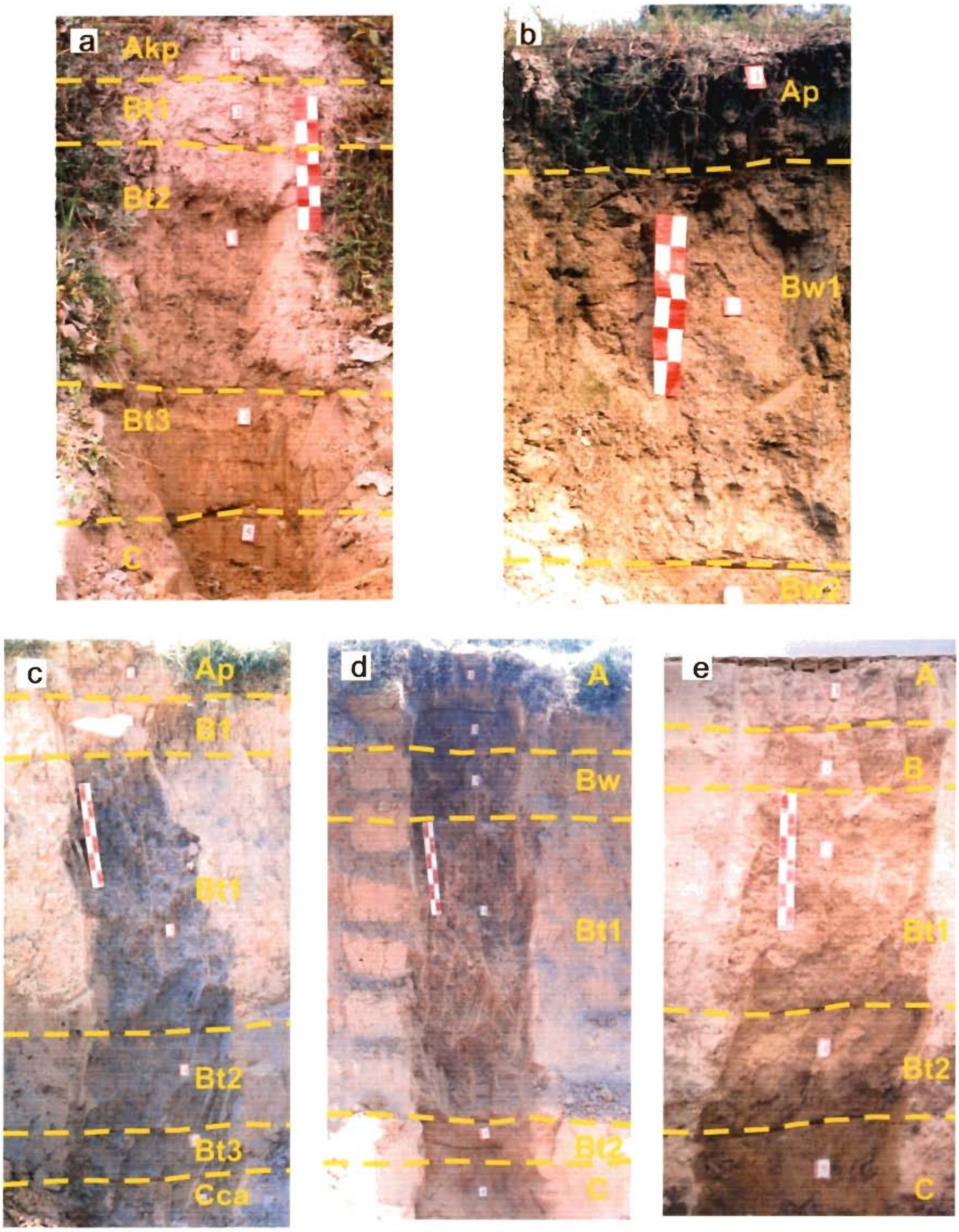


Fig. 2.11 Field photographs of QGMS-IV, V & VI soils. (a) Pedon P-18 (RTFn-IV), (b) Pedon P-20 (RTFn-III), (c) Pedon P-15 (OLGP), (d) Pedon P-9 (OSGP) and (e) Pedon P-2 (GRIP).

A-horizon is 15-25 cm thick, with sandy clay loam in nature, and colour varying from light grayish brown to light brownish gray (2.5Y5/2 to 2.5Y6/4). Soil of this unit is very well developed, with 90-110 cm thick B-horizon showing sub angular blocky structure. It grades downward into calcrete-rich, stratified sandy loamy C- horizon. In B-horizon, the colour varies from dark grayish brown to olive gray (2.5Y4/2 to 2.5Y5/4). Texture varies from heavy silty loam to silty loam with high illuviated clay content in B_2-subhorizon with patchy thick clay cutans in the soil pore and root channels (Fig. 2.11 c).

2.7.6. Member QGMS-VI

The member QGMS-VI includes three soil-geomorphic units, i.e. the Ghaghara Rapti Interfluve Plain (GRIP), Rapti terminal fan-V and the Oldest Gandak Plain (OSGP). Morphological characters of pedons in these units are shown in (Fig 2. 11d, e).

Soil properties in this member vary within a small range. The A-horizon thickness varies from 18 to 30 cm. The colour is light olive brown to olive yellow (2.5Y5/2 to 2.5Y5/4). The strongly developed B-horizon varies in thickness from 70 to 115 cm and shows medium to coarse sub angular blocky structure. Texturally it varies from sandy loam to loam and colour ranges from 2.5Y5/3 to 2.5Y4/3.

In the eastern part of the Ghagara-Rapti Interfluve the soils are salt-affected and salt occur through-out the profile and due to low-lying nature, frequent flooding takes place. Soils colours are 10YR5/4 to 2.5Y5/4.

In the Oldest Gandak plain, the solum thickness and soil properties vary from the distal part to the proximal part. As distal region is finer grained than the

Morpho Stratigraphic sequence	Soil Geomorphic unit	Pedon No	Soil Taxonomic classification	Solum thickness (cm)	B horizon				$CaCO_3$ horizon	Mottles Fe/Mn Concretions In horizon
					Thickness (cm)	Structure	Colour	Texture		
QGMS-I (<1.4 Ka)	KFn-I	P-50	Coarse Loamy Mixed Hyperthermic Typic Haplustalfs	50	35	Weak to moderate	2.5Y5/3, 5/2	Sandy loam	--	Bt, BC & C
	BTFn-I	P-64	Coarse Loamy Mixed Hyperthermic Aquic Haplustalfs	54	39	Weak to moderate	2.5Y5/3	Sandy loam	--	Bt, BC
	BGTFn-II	P-58	Coarse Loamy Mixed Hyperthermic Typic Ustorthents	--	--	Weak to very weak	--	Sandy loam	--	AC, C
	BTFn-II	P-52	Coarse Loamy Mixed Hyperthermic Typic Ustorthents	--	--	Weak to very weak	--	Sandy loam	--	AC, C
	OGHP	P-61	Coarse Loamy Mixed Hyperthermic Typic Ustorthents	--	--	Weak to very weak	--	Sandy loam	--	AC
QGMS-II (4.7 -1.4 Ka)	YPt	P-46	Coarse Loamy Mixed Hyperthermic Typic Haplustalfs	75	65	weak	2.5Y5/3, 5/2	Sandy loam	--	Bt, Bw & C
	KFn-II	P-45	Coarse Loamy Mixed Hyperthermic Typic Haplustalfs	80	70	Moderate to weak	2.5Y5/3, 5/2	Sandy loam	--	Bt1, Bt2 & C
	GT-I	P-38	Coarse Loamy Mixed Hyperthermic Typic Haplustalfs	40	25	weak	2.5Y5/4, 6/2	Sandy loam	--	Ap, Bt & C
	OPt	P-27	Coarse Loamy Mixed Hyperthermic Typic Haplustalfs	85	45	Moderate to weak	5Y5/2,5/3	Sandy loam	--	AB, Bt & C
	BBFn	P-26	Coarse Loamy Mixed Hyperthermic Typic	110	97	Moderate to weak	2.5Y5/3, 5/2	Sandy loam	--	AB,Bt1& Bt2

S-III
7 Ka)

			Haplustalfs							
	GTFn-II	P-35	Coarse Loamy Mixed Hyperthermic Typic Haplustepts	130	105	Moderate to weak	2.5Y4/4, 3/2, 6/2, 4/2	Sandy loam	--	Akp, Bwk1, Bwk2
	GTFn-I	P-29	Coarse Loamy Mixed Hyperthermic Typic Haplustepts	48	30	weak	2.5Y5/2, 5/3, 5/4	loam	Akp, ABk Bk & Ck	Bk
	RTFn-II	P-39	Coarse Loamy Mixed Hyperthermic Typic Ustorthents	55	40	Weak to Moderate	2.5Y5/4, 5/2, 5/5	Sandy loam	Akp,Ak & Ck	--
QGMS-IV (8.4Ka-6.9 Ka)	RTFn-IV	P-18	Coarse Loamy Mixed Hyperthermic Typic Haplustalfs	130	110	moderate	5Y5/2,5/6	loam	Akp & B1tk	B1tk
	RTFn-III	P-20	Coarse Loamy Mixed Hyperthermic Typic Haplustalfs	65	35	moderate	2.5Y5/4, 7.5Y5/6, 4/6	loam	--	Ap,Bw1 & Bw2
	GT-II	P-17	Coarse Loamy Mixed Hyperthermic Typic Haplustalfs	100	70	moderate	2.5Y5/2, 5/4	Sandy loam	A,B&C	B&C
QGMS-V (10 - 8.4 Ka)	OLGP	P-15	Fine Loamy Mixed Hyperthermic Typic Haplustalfs	170	130	moderate to well	2.5Y5/2, 5/4,6/4	Sandy clay loam	--	A&B
QGMS-VI (>10 Ka)	GRIP	P-2	Coarse Loamy Mixed Hyperthermic Typic Haplustalfs	117	105	moderate to well	2.5Y4/3, 4/4	Sandy loam	--	Bt1,Bt2
	OSGP	P-9	Fine Loamy Mixed Hyperthermic Typic Haplustalfs	140	125	moderate to well	5Y5/2,5/4 6/4	Sandy loam	--	C
	RTFn-V	P-7	Coarse Loamy Mixed Hyperthermic Typic Haplustalfs	55	38	moderate to well	2.5Y5/4 2.5Y5/6	Sandy loam	--	Btk1,Btk2& C

Table 2.2: Detailed description of various pedons of the study area.

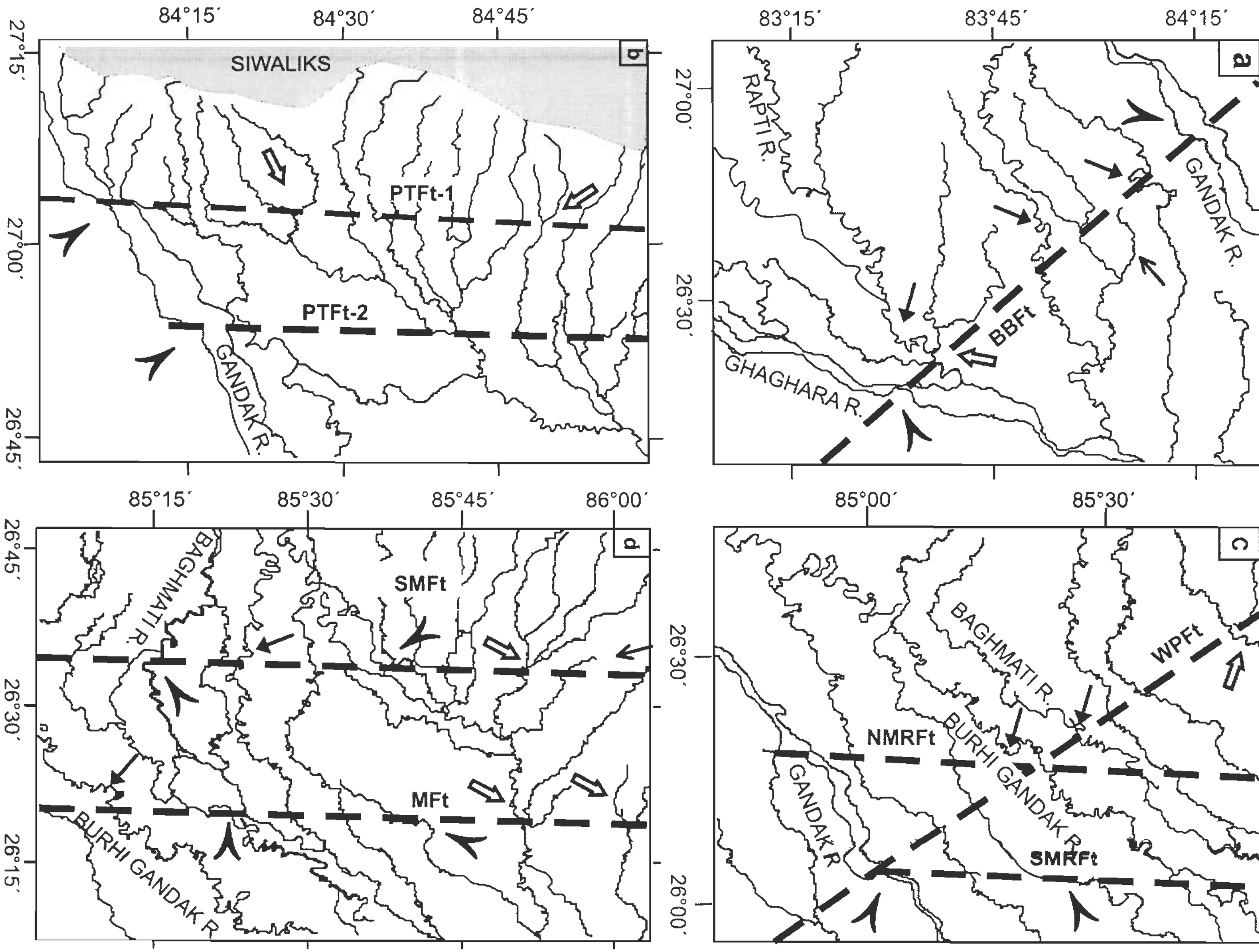
proximal region, soil properties vary from the distal to proximal region. In the proximal part solum and B-horizon thickness varies from 92 to 110 cm and 58 to 65 cm, respectively, but in the distal part these values range from 150 to 162 cm and 95 to 110 cm, respectively. Size of Fe-Mn concretions increases with depth from 3 mm to 5 mm (Fig. 2.11 d, e).

2.8 STRUCTURE AND TECTONIC FEATURES

2.8.1 Methodology Used to Identify Faults and Lineaments

As observed earlier (Bhosle et al. in press) drainage pattern in flat areas is very sensitive to even weak tectonic movements, these drainage patterns reflect closely these tectonic movements. For example, convergent and offset drainage patterns, increase in sinuosity on up thrown block, start of new stream and development of terminal fans on downthrown blocks have been found to closely related to activities of normal faults (Singh et al., 2006, Bhosle et al., in press). These features have used to hypothesize the presence of faults in different area (Fig. 2.12 & 2.13).

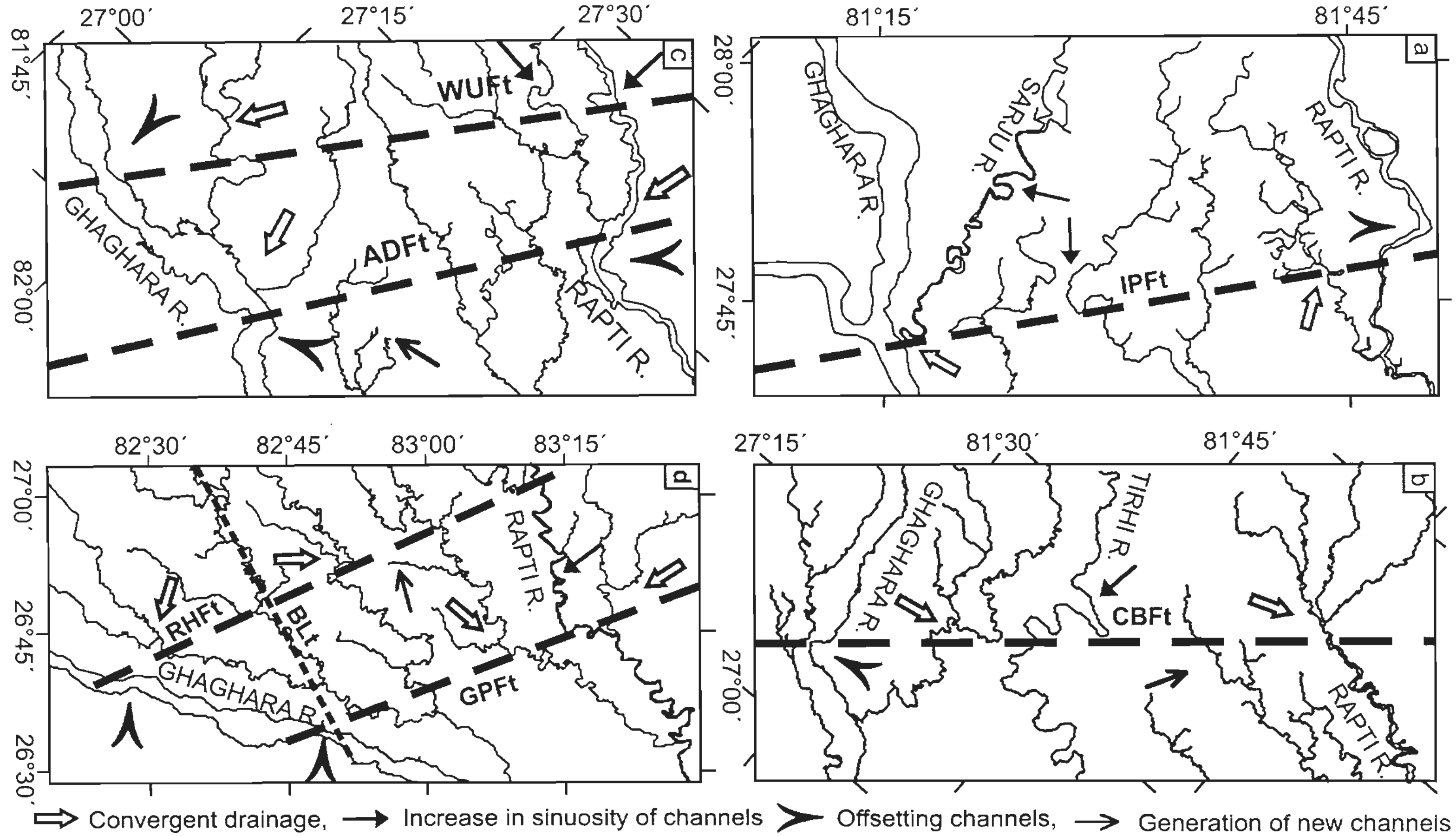
Although SRTM provides high density height data of 90 m grid interval and ±6m resolution, it is not helpful for our study for highlighting the subtle morpho structures because of its low resolution for plain areas (Bhosle et al., in press). Point heights (total no 55,341) with an accuracy of ±2 m were manually digitised from 127 Survey of India topographic sheets of 1:50,000 scales. Spot heights were used to prepare a DEM using linear stretching technique of ERDAS software covering the entire area. Density of spot height is 1-2 points/10km^2, which is good enough for such a regional study (Badura et al., 2005)



⇨ Convergent drainage, ➞ Increase in sinuosity of channels ➤ Offsetting channels, ⟶ Generation of new channels

Fig.2.12 Drainage affected by the faults in the study area

Fig.2.13 Drainage affected by the faults in the study area



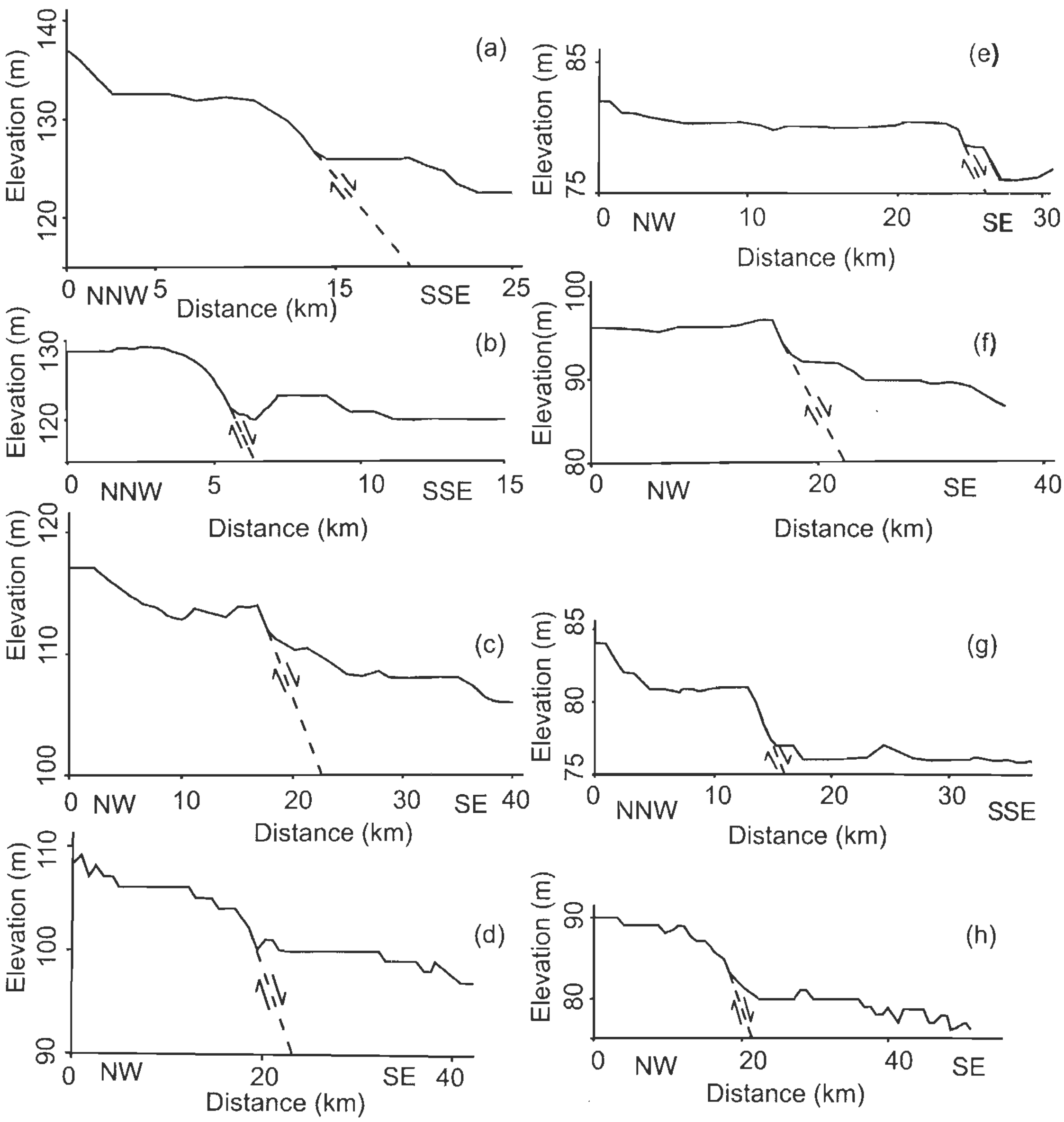


Fig.2.14 Topographic profiles across faults (a) Intaha-Parsa Fault (IPFt), (b) Bahraich Fault (BFt), (c) Colnelganj-Balrampur Fault (CBFt), (d) West Uttraulla Fault (WUFt), (e) Ayodhya-Dinkarpur Fault (ADFt), (f) Faizabad-Domariaganj Fault (FDFt), (g) Gorakhpur-Padrauna Fault (GPFt) and (h) Barhaj- Bettiah Fault (BBFt)

This DEM was also used to find locations of possible faults. 2-D topographic profile (cross-sections) (Fig. 2.14 & 2.15) were across the inferred faults from the DEM and drainage characteristics (Fig. 2.12 & 2.13) to find out the fault throw and the regional as well as the local slope across the faults (Fig.2.14

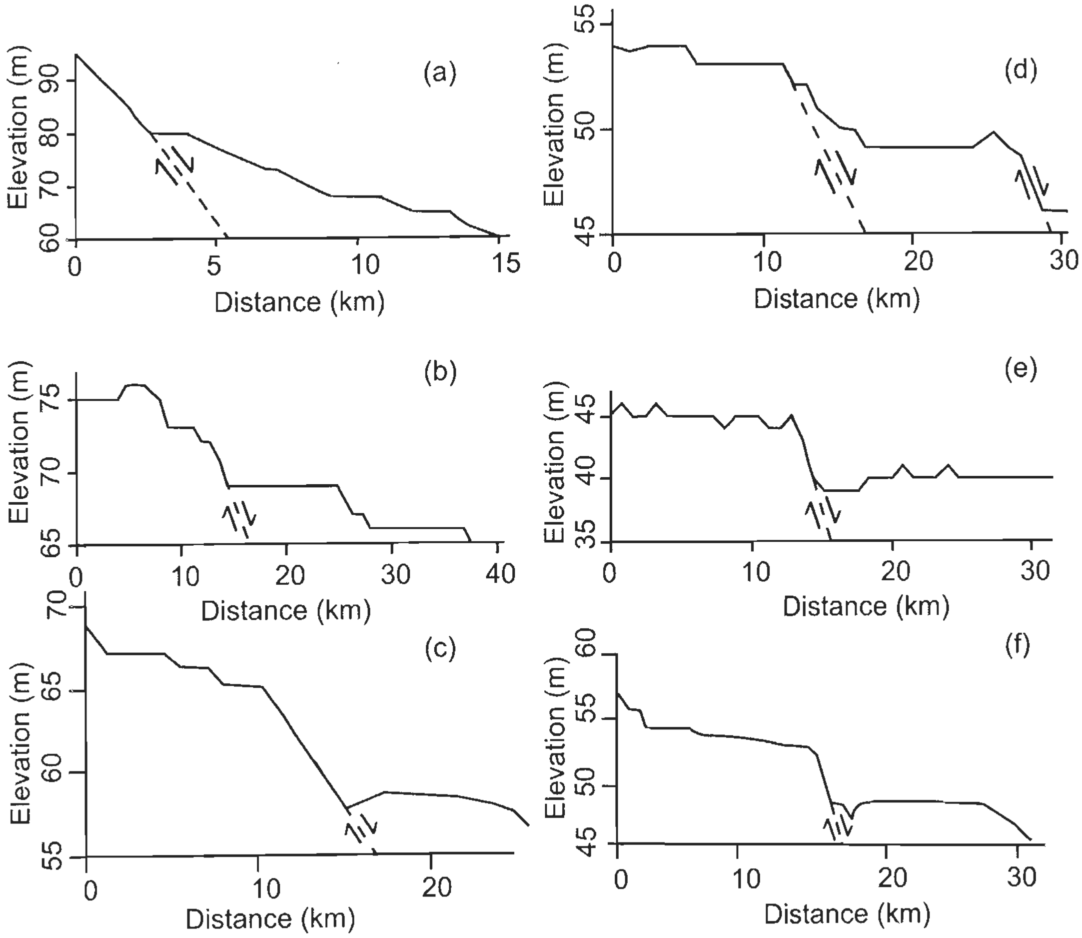


Fig. 2.15 Topographic profiles along the faults. (a) Piedmont Fault -II (PtFt-II), (b) South Motihari Fault (SMFt), (c) North Sitamarhi Fault (NSFt), (d) Madhubani Fault (Mft) and North Muzaffarpur Fault (NMRFt),(e) Hathauri-Simariaghat Fault (HSFt) and (f) West Patna Fault (WPFt).

& 2.15, Table 2.1). Later applying kriging technique and using Surfer-8 program, DEMs of interesting areas measuring 30×25 km around the inferred faults were prepared (Fig. 2.16 - 2.22). Surfer-8 program first generates a grid from the irregularly spaced spot heights and then fits a surface to the gridded data.

DEMs generated above were extremely useful for further confirmation for faults. DEMs show that artefact morph structures like the 'cliff' and 'significant

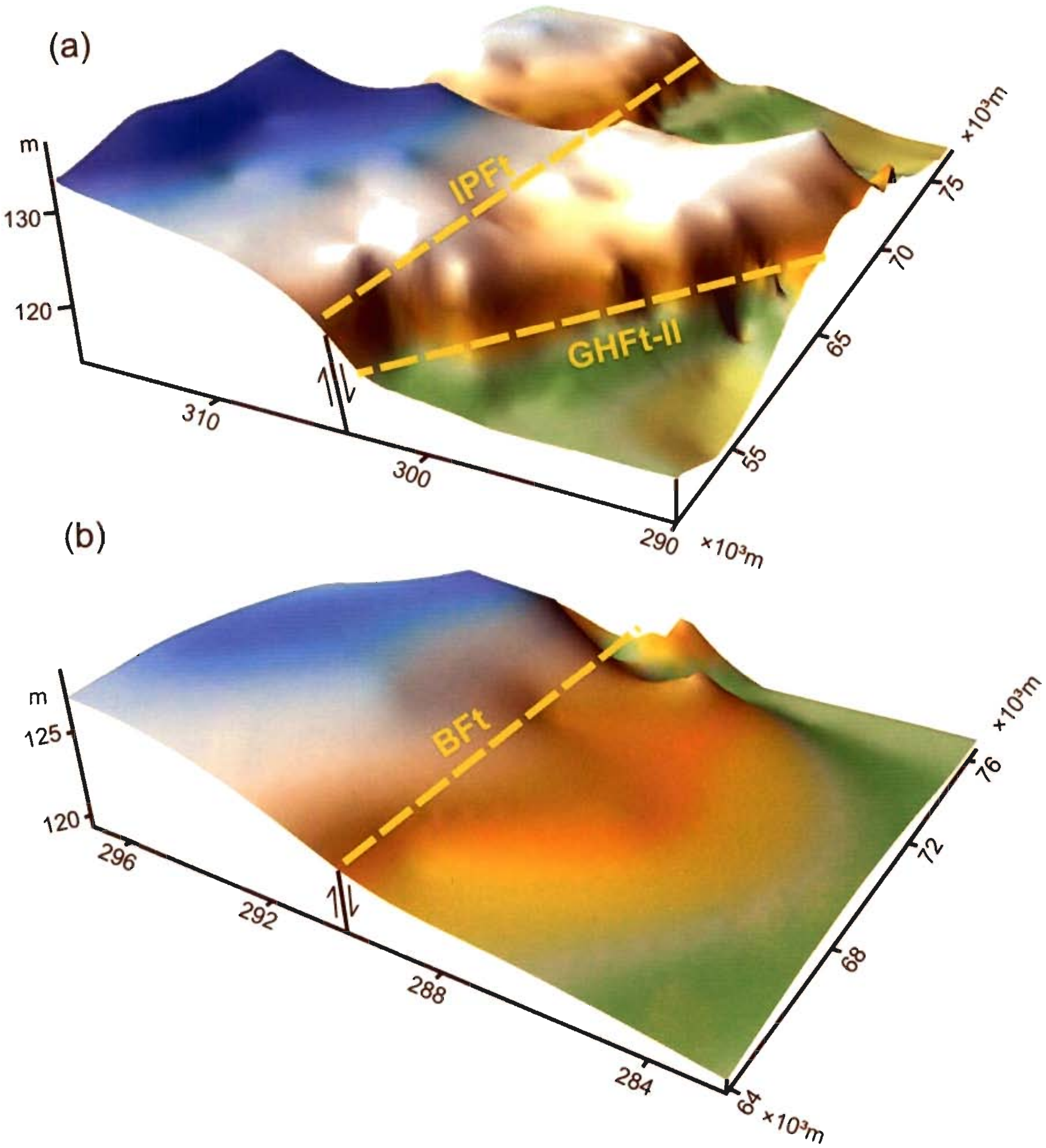


Fig. 2.16 Digital Elevetion Model (DEM) generated by SURFER-8 around (a) Intaha-Parsa Fault (IPFt), Ghaghara Fault-II (GHFt-II) and (b) Bahraich Fault (BFt)

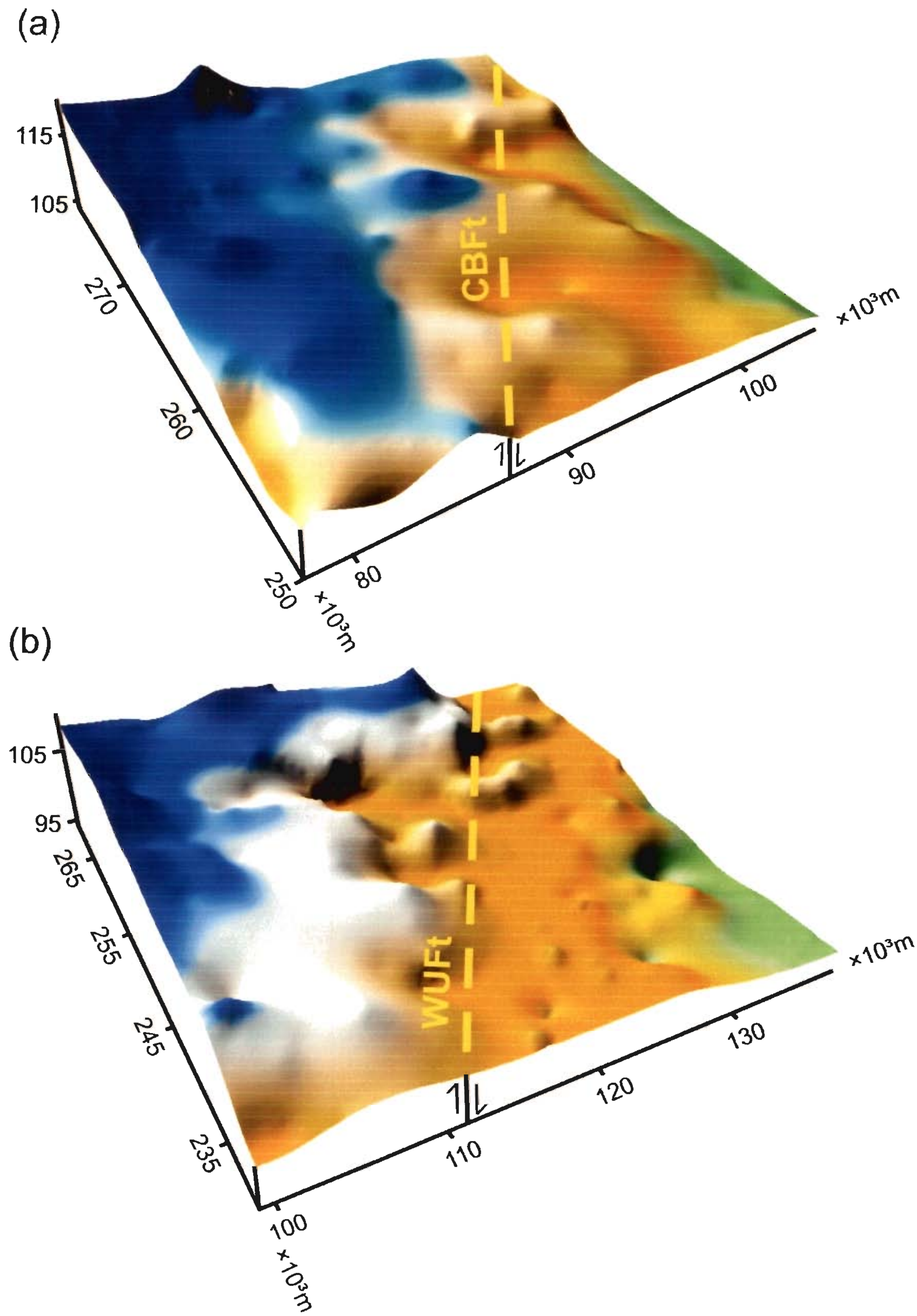


Fig 2.17 DEM around faults (a) Colnelganj-Balrampur Fault (CBFt) and (b) West Uttraulla fault (WUFt).

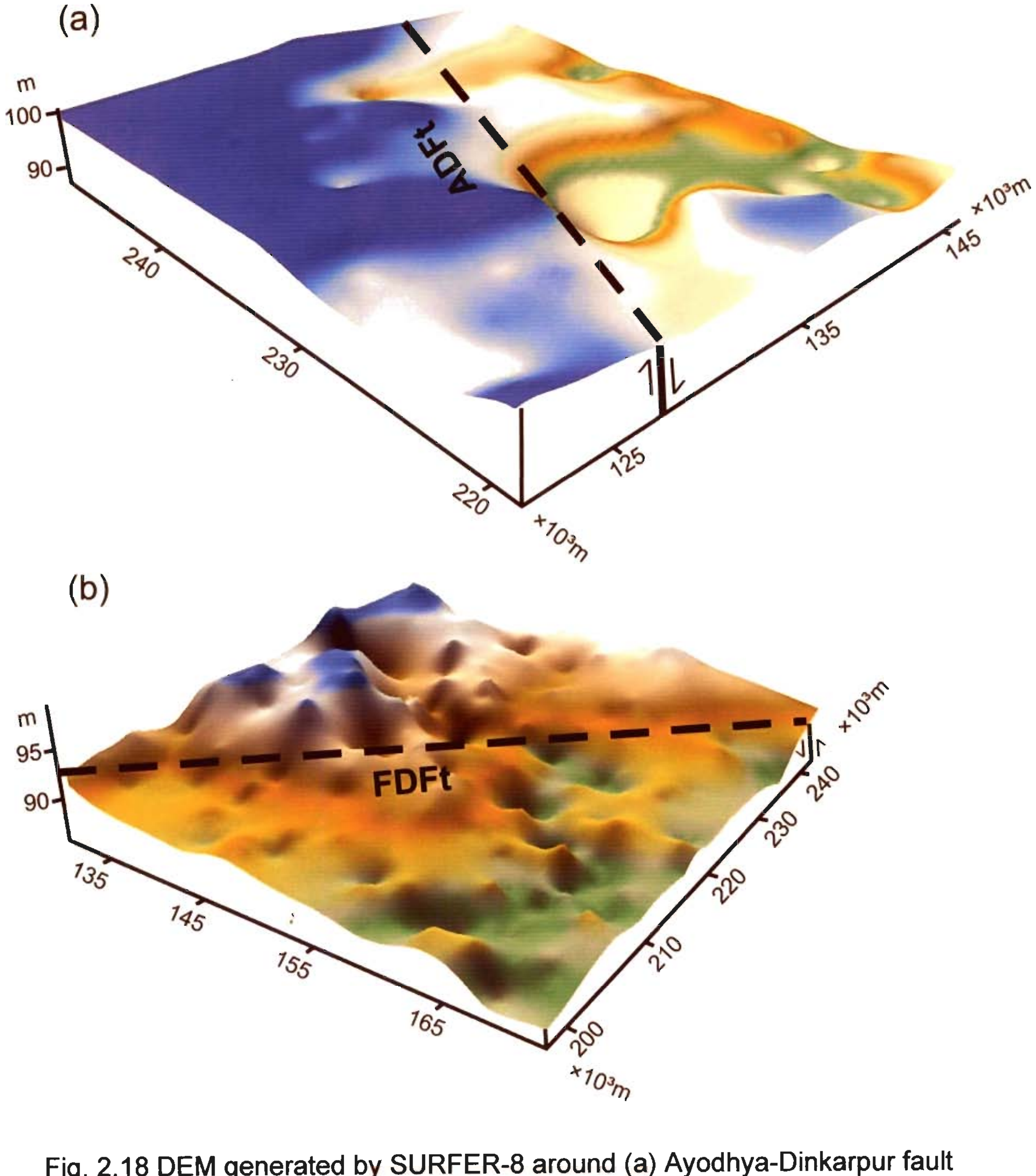


Fig. 2.18 DEM generated by SURFER-8 around (a) Ayodhya-Dinkarpur fault (ADFt) (b Faizabad- Domariaganj Fault (FDFt)

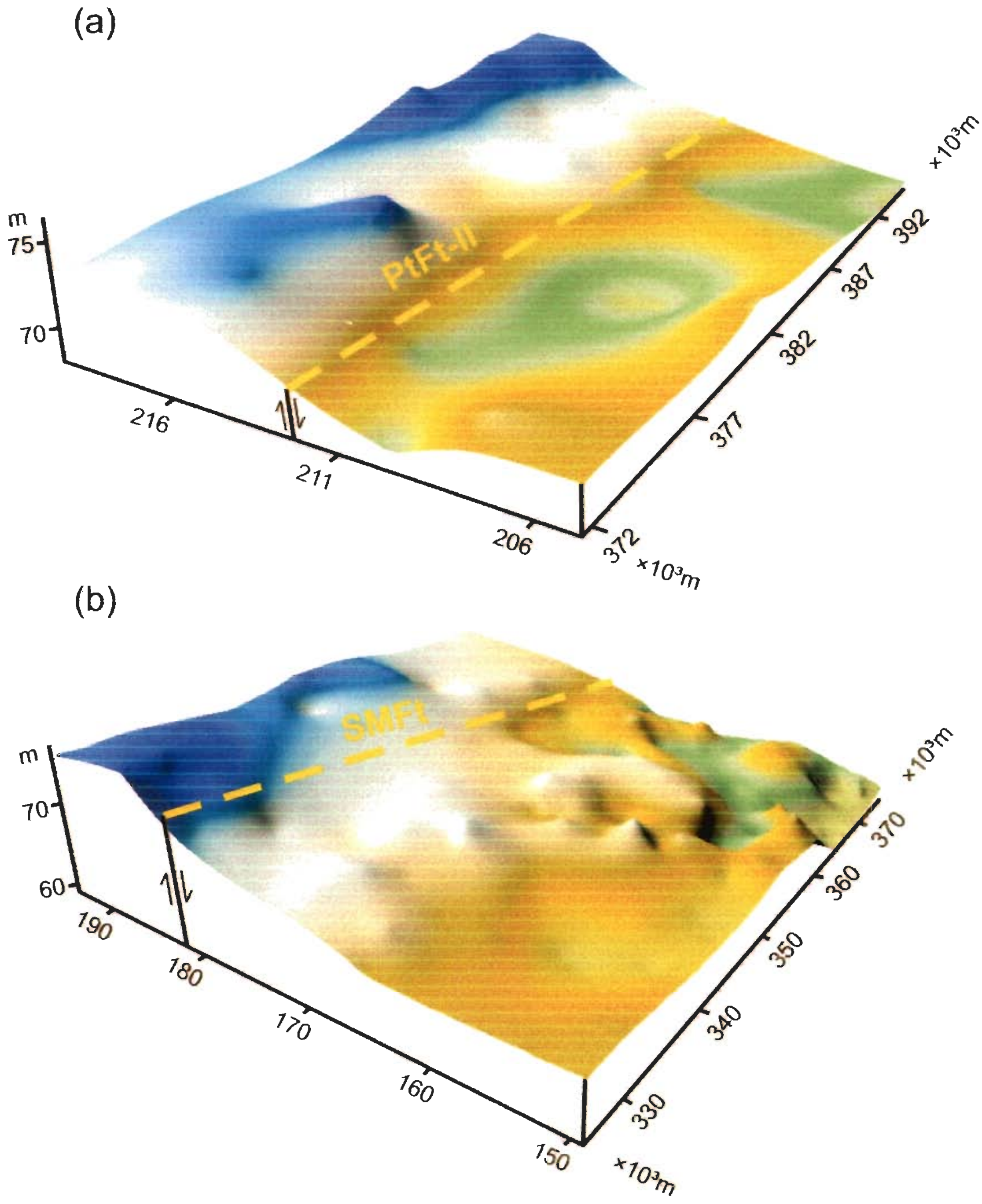


Fig. 2.19 (a) DEM around Piedmont Fault-II (PtFt-II) (b) South Motihari Fault (SMFt)

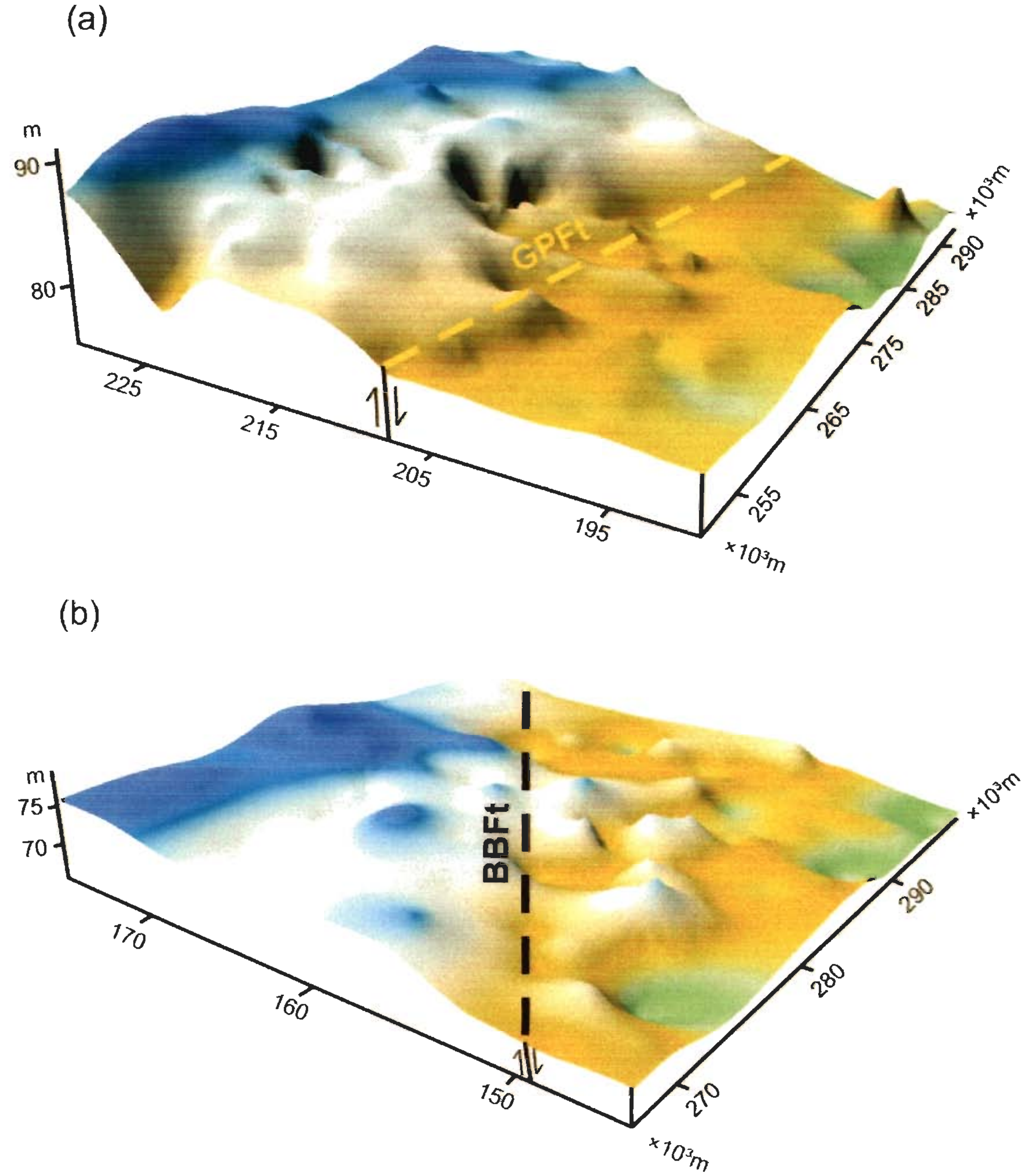


Fig. 2.20 (a) DEM around Gorakhpur-Padrauna Fault (GPFt) (b) Barhaj-Bettiah Fault (BBFt)

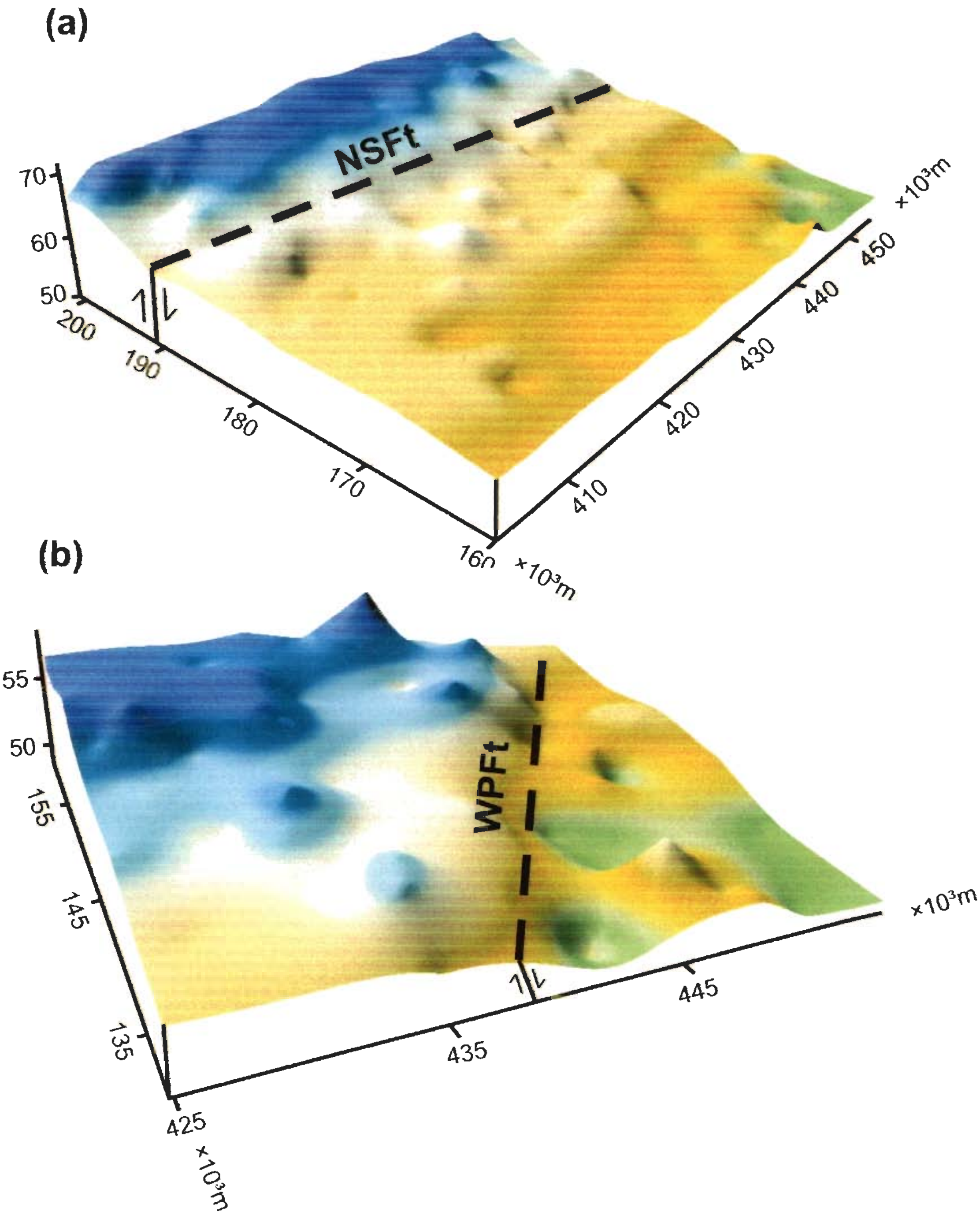


Fig. 2.21 (a) DEM around North Sitamarhi fault (NSFt) (b) DEM around West Patna Fault (WPFt)

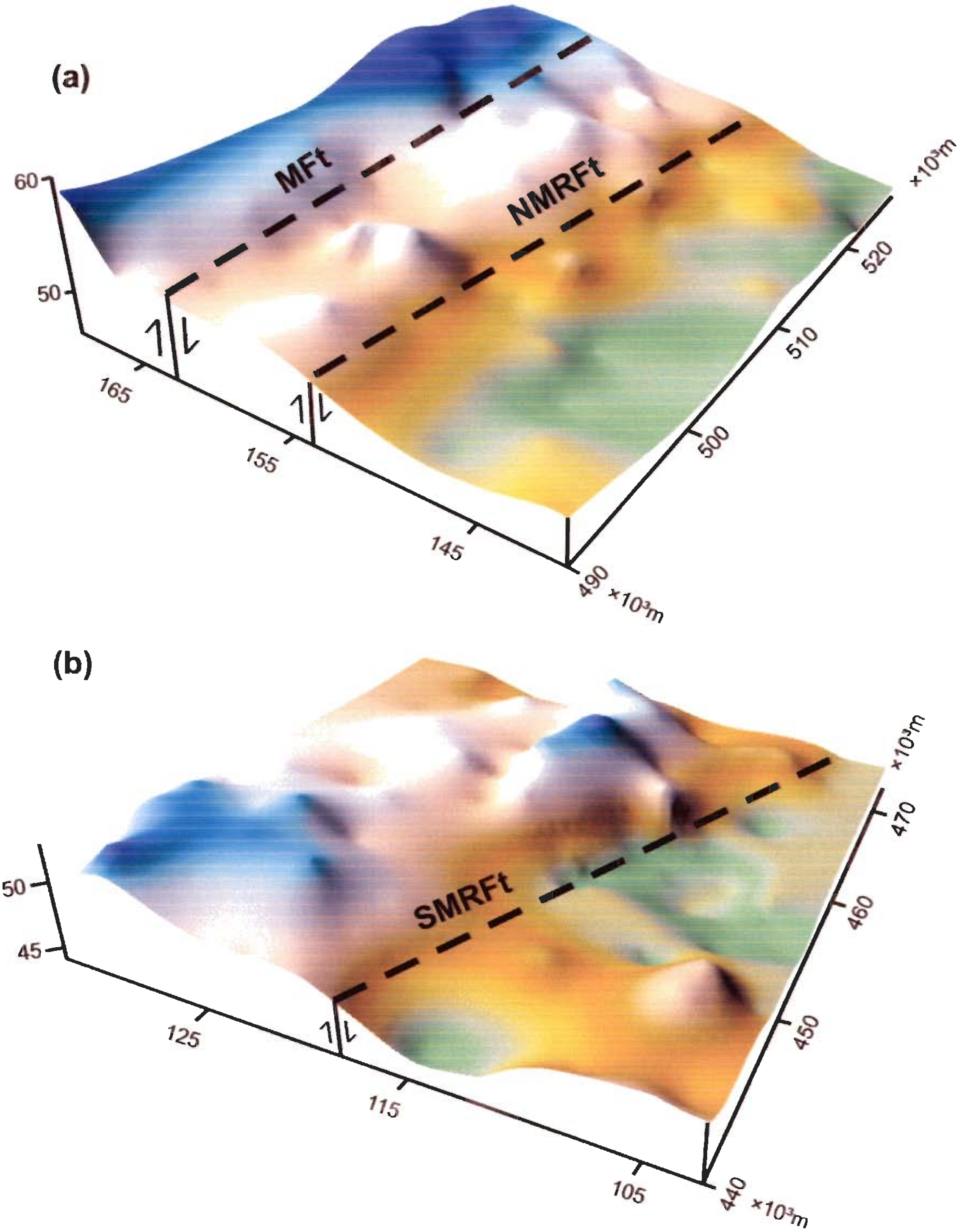


Fig. 2.22 (a) DEM around Madhubani Fault (MFt) and North Muzaffarpur Fault (NMRFt), (b) DEM around South Muzaffarpurb Fault (SMRFt)

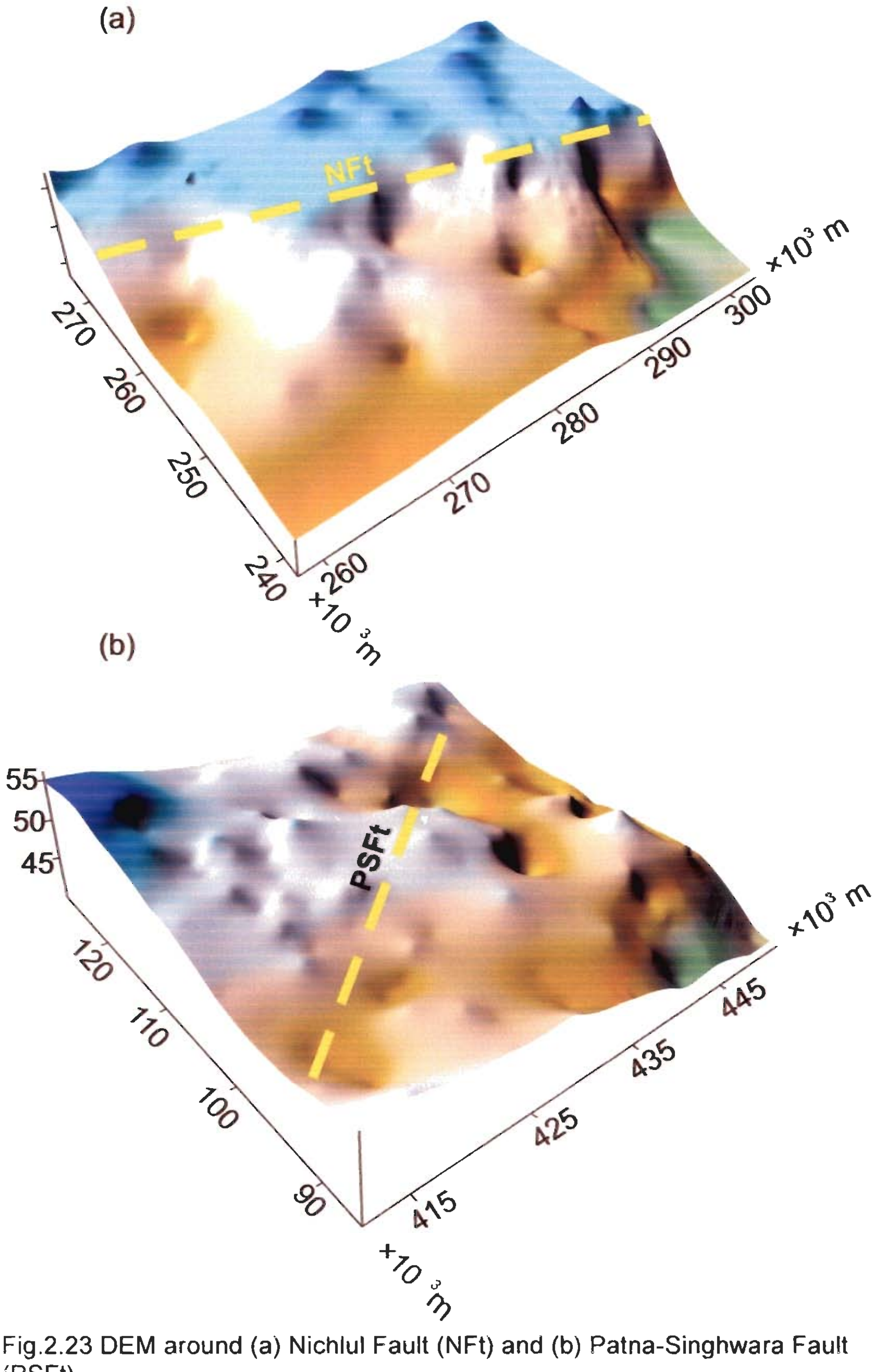


Fig.2.23 DEM around (a) Nichlul Fault (NFt) and (b) Patna-Singhwara Fault (PSFt)

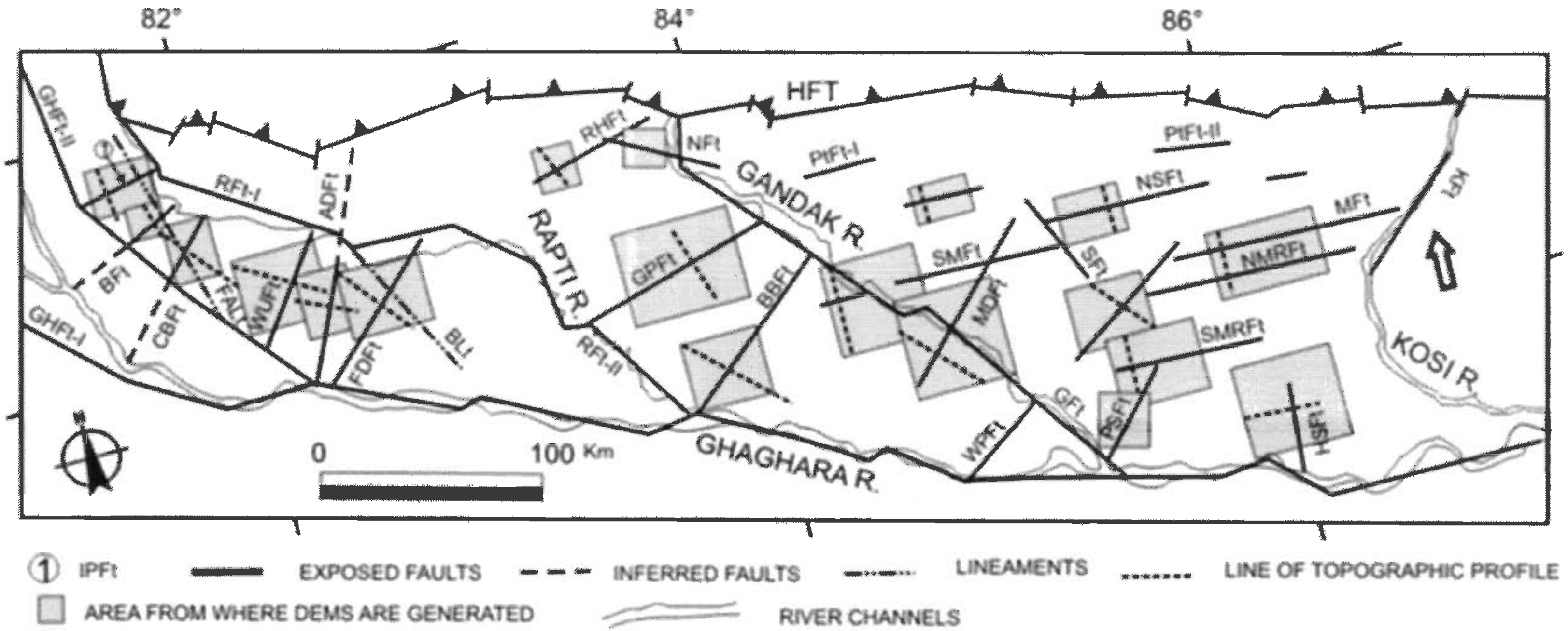
breaks in slopes' (Bhosle et al., in press) were in most commonly associated with faults (Figs. 2.16-2.23). Additionally we found that boundaries of identified artefact morphostructures 'rounded hills, 'dissected tableland' and 'flatland' were marked by faults.

Based on the mapping of soil geomorphic features, degree of soil development, geomorphological signature such as drainage pattern, drainage density, channel sinuosity, and topographic signatures, morph structures, three major tectonic features (twenty-two faults, two lineaments and three tectonic blocks) are identified.

Since Surfuer-8 program has a limitation of number of data points, it can handle, an attempt was made to prepare DEMs for large areas, measuring 300 km x 150 km using ARC-GIS-9 with kriging interpolation technique and then superimposing MSS mosaic on it to get the DTM for the area. These DTMs were able to bring major geomorphological features of the area like terminal fans, piedmont zone and even some faults clearly from the nearly flat plains (Fig. 2.5).

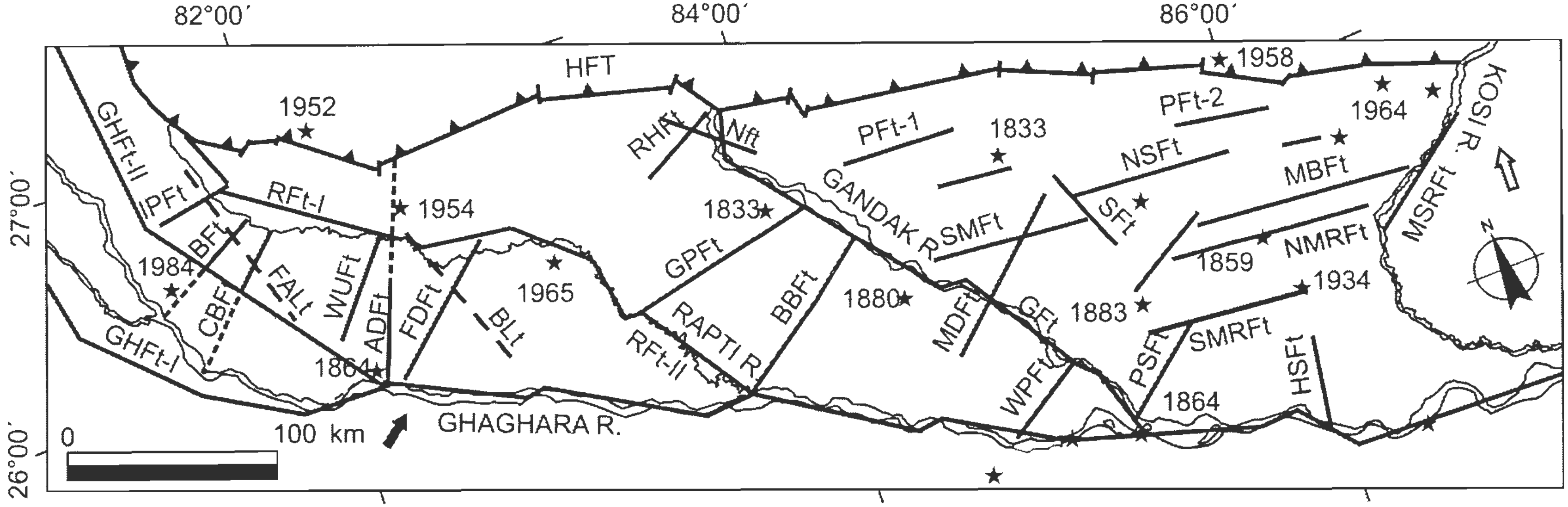
2.9 FAULTS AND LINEAMENTS

Twenty-two major faults are identified in the study area (Fig. 2.24a, 2.24b Table 2.3, 2.4). The Faizabad-Alliganj lineament (a continuation of the Allahabad-Faizabad lineament, Singh at al., 2006) and the Basti lineament (BLt) are the two lineaments in the Upper Gangetic plain of the study area.



GHFt-II : Ghaghara Fault-II GHFt-I : Ghaghara Fault-I RFt-I : Rapti Fault-I IPFt- Intaha-Parsa fault BFt : Bahraich fault
WUFt : West Uttraulla Fault ADFt : Ayodhya-Dinkarpur fault RFt-II : Rapti fault-I FDFt : Faizabad-Domariaganj Fault
GPFt : Gorakhpur Padrauna Fault WPFt : West Patna Fault PSFt : Patna-Singhwara Fault PtFt-I : Piedmont Fault-I
PtFt-II : Piedmont Fault-II SMFt : south Motihari Fault SFt : Sitamarhi Fault NMFt : North Muzaffarpur Fault
SMRFt : South Muzaffarpur Fault HSFt : Hathauri Simariaghat Fault Gft : Gandak Fault KFt : Kosi fault Nft : Nichlul Fault
FALt : Faizabad LineamentBBFt : Barhaj-Bettiah fault NSFt : North Sitamarhi Fault MFt : Madhubani fault RHFt : Rohini Fault
CBFt : Colnelganj-Balrampur Fault Blt : Basti Lineament PSFt : Patna Singhwara Fault HFT : Himalayan Frontal Thrust

Fig.2.24a Faults in the study area. The shaded areas are the boxes from where point heights were taken to prepare DEM in SURFER-8 program



Surficial Faults — Inferred Faults — Lineaments — Ancient Compression Direction

Recent Compression direction — Rivers — 1984★ Earthquake epicenter with year

GHFt-II : Ghaghara Fault-II GHFt-I : Ghaghara Fault-I RFt-I : Rapti Fault-I IPFt- Intaha-Parsa fault BFt : Bahraich fault CBFt : Colnelganj-Balrampur Fault WUFt : West Uttraulla Fault ADFt : Ayodhya-Dinkarpur fault FDFt : Faizabad-Domariaganj Fault RFt-II : Rapti fault-I RHFt : Rohini Fault Nft : Nichlul Fault GPFt : Gorakhpur Padrauna Fault BBFt : Barhaj-Bettiah fault WPFt : West Patna Fault PSFt : Patna-Singhwara Fault PtFt-I : Piedmont Fault-I PtFt-II : Piedmont Fault-II NSFt : North Sitamarhi Fault SMFt : south Motihari Fault SFt : Sitamarhi Fault NMFt : North Muzaffarpur Fault MFt : Madhubani fault SMRFt : South Muzaffarpur Fault PSFt : Patna Singhwara Fault HSFt : Hathauri Simariaghat Fault Gft : Gandak Fault KFt : Kosi fault HFT : Himalayan Frontal Thrust FALt Faizabad Lineament Blt : Basti Lineament

Fig.2.24b Faults with distribution of earthquake epicenters

Table 2.3 description of the faults in the study area

Name of the fault	Nature of the fault	Exposed (km)	Location of topographic profile	Throw of the fault		Drainage Pattern	Time of Last Activity (Ka)	Exaggeration
				Amount (m)	Direction			
Intaha-Parsa (IPFt)	E-W (T)	34	Gokulpur 81°36' E 27°45'N	6.8	South	1,2	6.6	425
Bahraich fault (BHFt)	E-W (T)	22	Paraspur 81°43' E 27°33'N	23	South	1	6.6	500
Colnelganj-Balrampur Fault (PBFt)	NE-SW (T)	28	Waini 81°50' E 27°27'N	6.28	SE	1,2	--	444
West Utraulla (WUFt)	NE-SW (T)	54	Sugapur 81°12'E 27°13'N	6.25	SE	1		577
Faizabad-Domariaganj Fault (FDFt)	NE-SW (T)	73	Nagpur 82°22' E 26°56'N	7.15	SE	1,2	--	810
Ayodhya-Dinkarpur Fault (ADFt)	NE-SW (T)	37	Bhalasand 82°22' E 27°08'N	4	SE	1,2	3.2	1000

1-Converging, 2- New stream, 3-Offset and 4- Damming of streams causing water logging (T)- Transverse fault

Name of the fault	Nature of the fault	Exposed (km)	Location of topographic profile	Throw of the fault		Associated Drainage Pattern	Time Of Last activity (Ka)	Exaggeration
				Amount (m)	Direction			
Rohini Fault (RHFt)	NE-SW & N-S	102	Belhar 81°01'E 26°58'N	6.6	SE	1,2	--	1000
Barhaj-Bettiah Fault (BBFt)	NE-SW	83	Dhuria 83°57'E 26°42'N	7.3	SE	1,2	1.4	1000
Sitamarhi Fault (SFt)	NW-SE		--	--	SW	--	--	--
Madhubani Fault (MFt)	E-W	94	Khairibanka 85°54'E 26°19'N	4	S	1,2,3	--	1000
North Muzaffarpur Fault (NMFt)	E-W	87	Basdeopur 85°54'E 26°11'N	3.6	S	1,3	--	1000
South Muzaffarpur Fault (SMFt)	E-W	61	Fatehpur 85°09'E 26°00'N	3	S	1,2	0.76	1000
Hathauri-Simariaghat fault (HSFt)	N-S	43	Balaha 85°58'E 25°50'N	7	E	1		1000

1-Converging, 2- New stream, 3-Offset and 4- Damming of streams causing water logging (T) - Transverse fault (Continuation of Table 2.3)

2.10 TECTONIC BLOCKS

Based on geomorphology, tectonic behaviour (tilting, subsidence and uplift) and degree of soil development, the study area can be divided into three major tectonic blocks i.e. the Ghaghara-Rapti interfluve Block, Gandak Megafan block and Gandak-Kosi Interfan block, with independent tectonic and sedimentation patterns. These blocks are separated by the NW-SE trending Rapti –II and Gandak faults (Fig. 2.24).

2.10.1 Ghaghara-Rapti Block

This block is bounded by curvilinear the Ghaghara Fault and Rapti Fault-I, with convexity to the SW and Rapti Fault-II in the east. The bounding rivers (Ghaghara and Rapti rivers) have an incised nature with an incision of up to 10-12 m, making the region between these rivers as an upland Interfluve (Srivastava et al., 1994; Kumar et al., 1996). This block is overlain by moderately to well-developed developed soils.

The Ghaghara-Rapti block is divided into three sub-blocks by two major NE-SW trending faults i.e. Colnelganj-Balrampur fault and Ayodhya-Dinkarpur fault: the Bahraich sub-block (northwestern), Gonda sub-block (central region region) and Basti sub-blocks (eastern region) (Fig. 2. 25). The region is cut by a number of NE-SW trending faults Intaha-Parsa fault, Bahraich fault, Colnelganj-Balrampur fault, West Uttraulla fault, Ayodhya-Dinkarpur fault and Faizabad-Domariaganj fault. By analogy with the other parts of the Upper Gangetic Plains (Singh et al., 2006) these faults are extensional, normal in nature. The Bahraich sub-block is marked by exceptional widening of the floodplains of Ghaghara

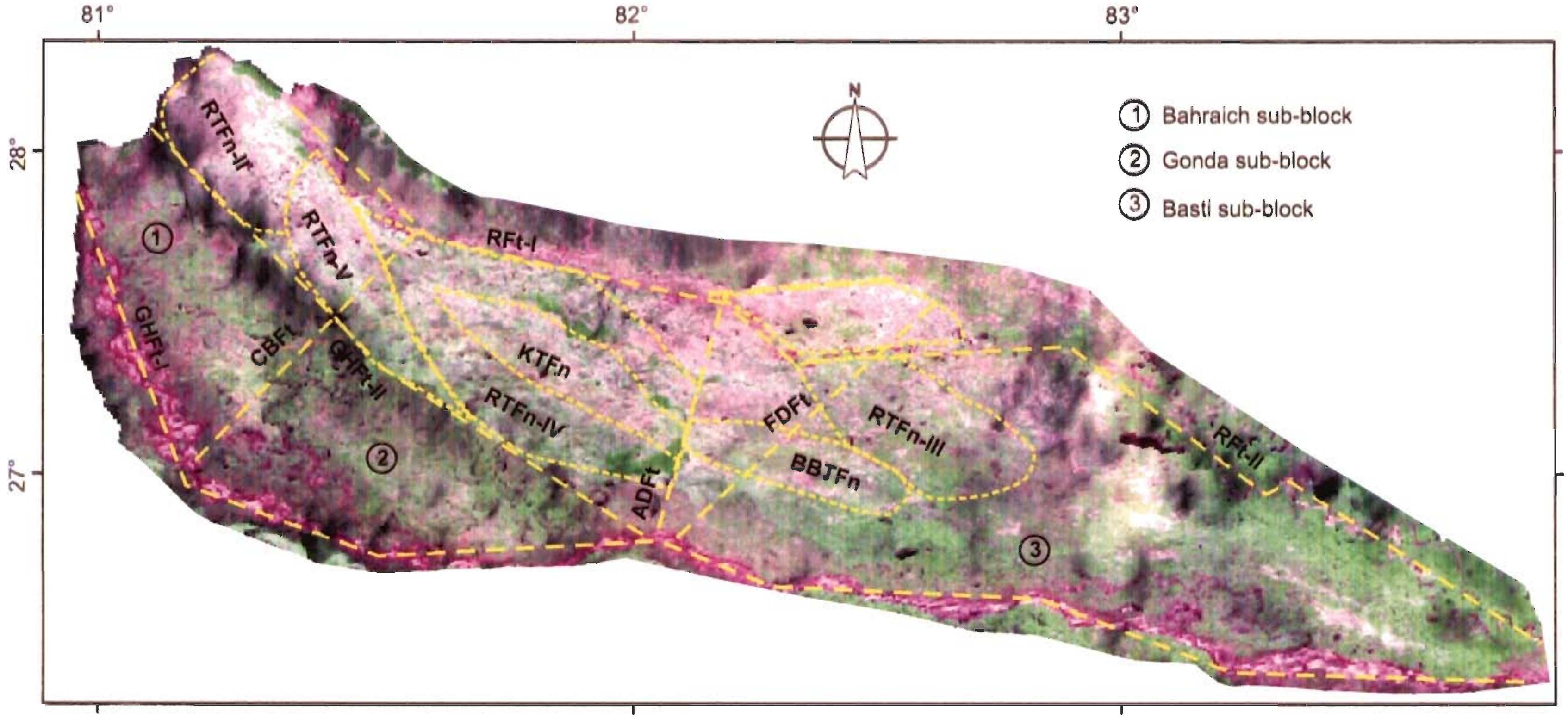


Fig.2.25 DTM of the Ghaghara-Rapti Interfluve block

(30 km) and Rapti (10 km) as compared downstream courses of these rivers. Shifting of these rivers from NE to SW associated with tilting of these sub-blocks which leads to widening of their floodplains. This sub-block sloping 0.3% towards SSE and is at a higher level than the other two sub-blocks, forming a virtual 'table land' (Fig. 2.25).

The most of the Gonda sub-block is covered by Rapti termial fan-IV. The sub-block is marked by the tightness of meanders of the streams and high moisture content due to restricted flow of streams, caused by the presence of the Faizabad ridge at the SE end. The sub-block slopes southeastwards (slope 0.27%).

The Basti sub-block exhibits a slope of 0.17% due south. This change from the southeasterly slopes in the Gonda sub-block to southerly direction in this sub-block causes numerous streams with parallel drainage pattern to deflect to the south. Two terraces GT-I and GT-II of the Ghaghara River are developed within this sub-block and the Rapti River shows widening of its floodplain within this sub-block. Both these rivers are incised within their floodplains in this sub-block presently.

2.10.2 Rapti-Gandak Block

The Rapti-Gandak block (Fig. 2.6), bounded by the Rapti fault- II in the west, the Gandak fault in the east and the Himalayan frontal thrust (HFT) in the north. This block is marked by eastward shifting of the Gandak River over 80 km due to the eastward tilting of this block (Mohindra et al. 1992) during the period 10.7-5.4 ka (this study). Tilting of this block at different time interval has left two different soil-geomorphic units (Oldest and Old Gandak Plains) in the region. Consequently soil development decreases from west to east on the Gandak megafan, though on the whole, soil is moderately to very well-developed.

This Rapti-Gandak block is further subdivided by the NE-SW trending Gorakhpur-Padrauna and Barhaj-Bettiah faults into three sub-blocks viz. Maharajganj (northernmost), Captainganj (central) and Siwan sub-blocks. These sub-blocks and bounding faults were identified and mapped on the basis of recognition of artifact geomorphological features (Maharajganj sub-block- low drainage density, rounded hills, Captainganj sub-block- high drainage density and moderate drainage density dissected tableland and Siwan sub-blockand flatland) in DTMs. Slope decreases from 0.3% towards SSW in the Maharaganj sub-block in the northern region to 0.26% in SSE in the Captaingnaj sub-block to 0.24% due south in the Siwan sub-block in the eastern region.

Three NE-SW trending faults i.e. the Rohini fault, Maharajganj-Dhaka fault and West Patna fault and one small fault parallel to the Himalayan trend (Nichlul fault) are also present in this block. The Rohini Fault in northern region separates the piedmont zone from the plains.

2.10.3 Gandak-Kosi Block

Lying in the interfan area between the Gandak and Kosi megafans, this block (Fig.2.26)is bound the HFT in the north, Gandak Fault in the west, Kosi Fault in the east and the Ganga Faults in the south. This block is traversed by numerous sub-parallel nearly east-west trending faults, i.e. starting from the piedmont zone, Piedmont fault-II, North Sitamarhi Fault, South Motihari fault,

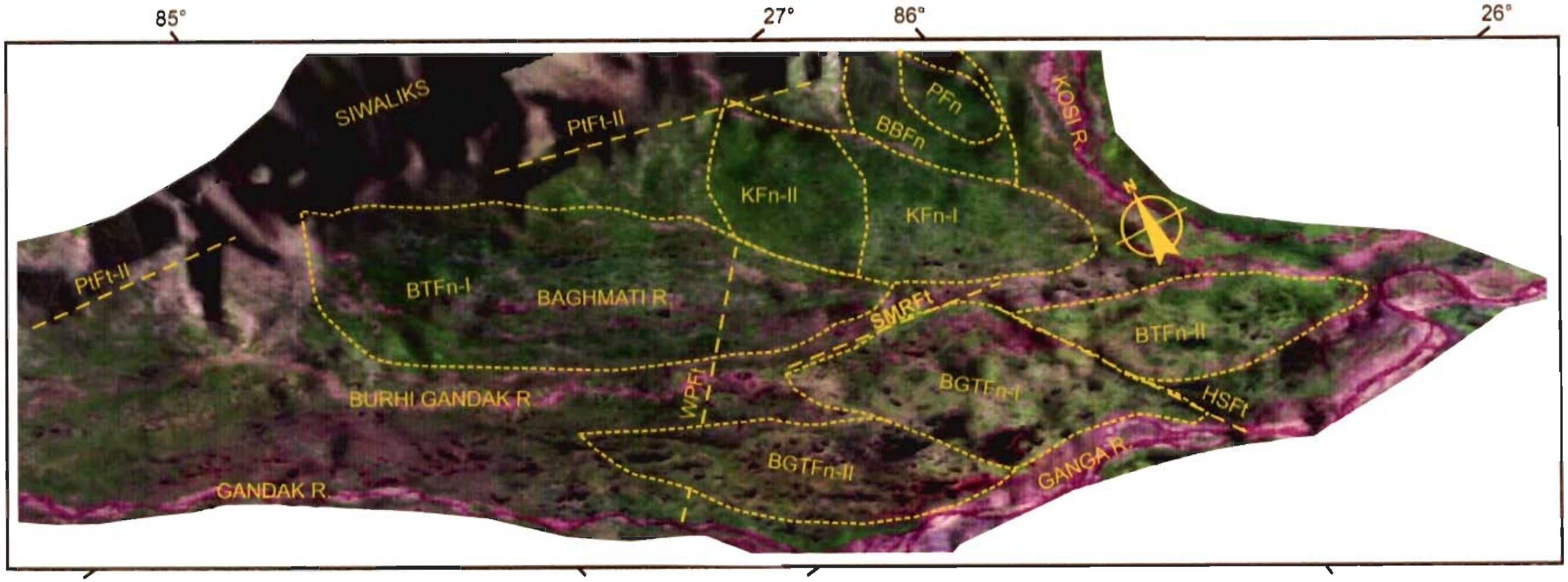


Fig. 2.26 DTM of the Gandak-Kosi interfan area.

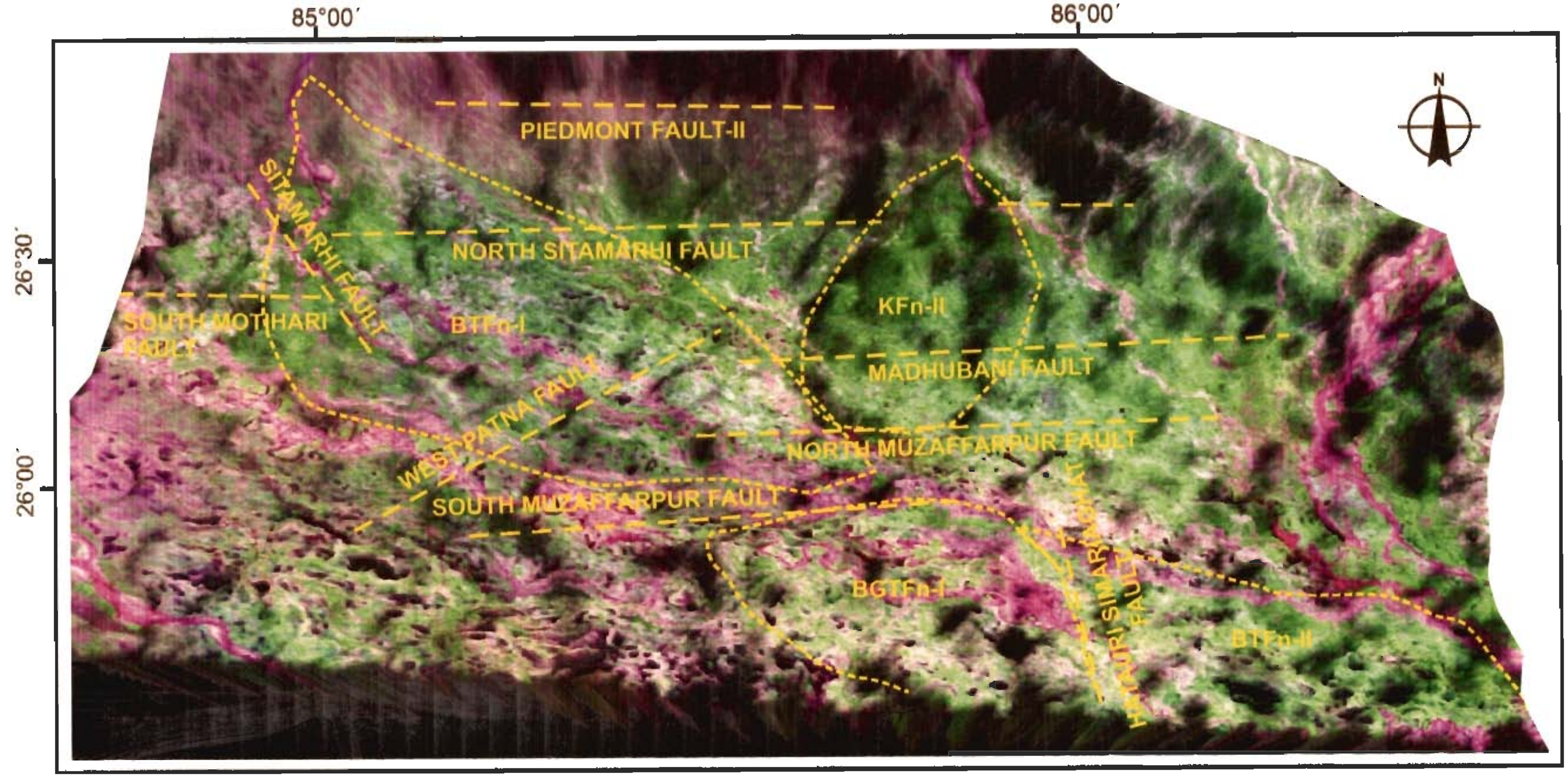


Fig. 2.27 DTM of the Gandak-Kosi Interfan area shows the Faults and the associated terminal fans

Madhubani fault, North Muzaffarpur fault and South Muzaffarpur fault) with throw decreasing from north to south, forming a step-fault system. These are considered as longitudinal faults, as they are sub-parallel to the Himalayan trend.

This block is marked by the hyperavulsive rivers (Sinha et al., 2005), shifting large distances in short periods due to active tectonics and high rates of sedimentation. Very weak to weak development of soil profile, wide and well distinguished piedmont zone (82 km), highly sinuosity tightly meandering streams; widespread swampy and waterlogged river plains are the characteristic features of this block (Fig 2.26). On the whole, the block exhibits southern to southeasterly slope.

The North Sitamrhi Fault divided the Gandak-Kosi Interfan block into Piedmont and Plains sub-blocks. The piedmont is marked by considerable slope (0.6%) and parallel to sub-parallel drainage is found in the north part and dichotomic and convergent drainage (not related to faulting), as indicated by Singh et al. (2006) are prevalent in the lower distal region. Some distinct alluvial fans are recognized in this sub block.

The plain sub-block is characterized by 0.23% of slope. Most of the southern region is marked by swampy lands and is covered by braided (Baghmati-I) as well as meandering (Burhigandak-I&II and Baghmati-II) terminal fans.

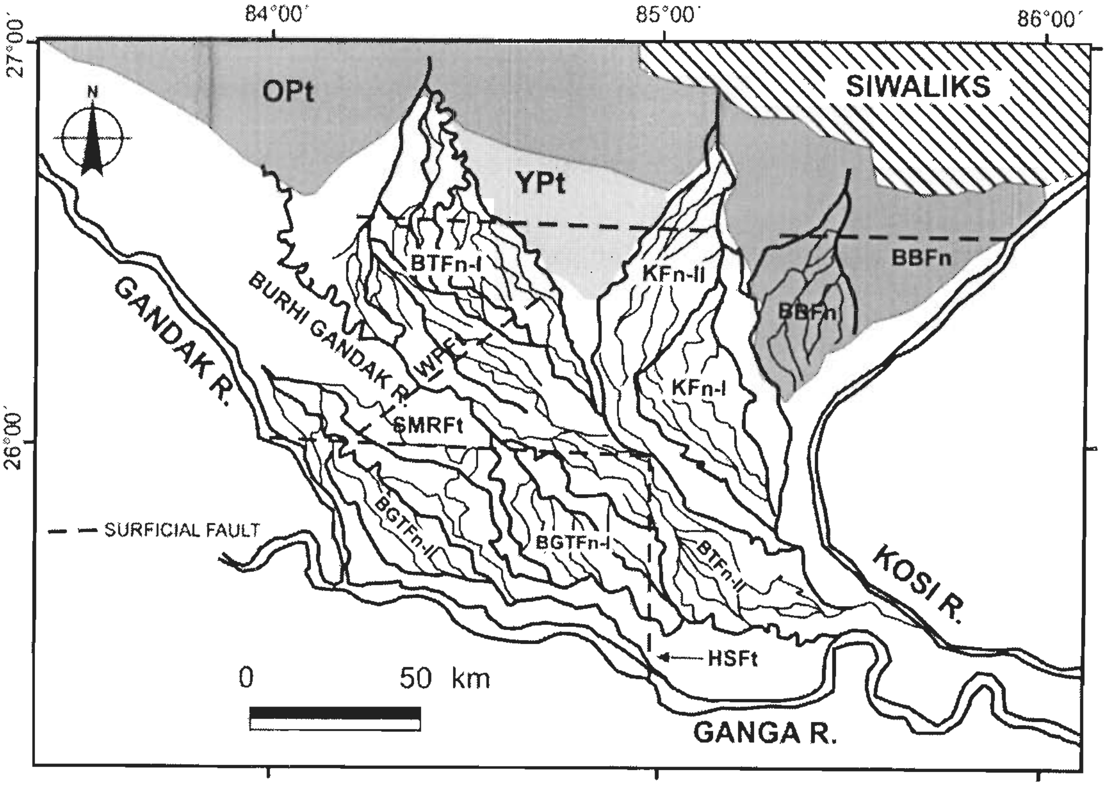


Fig.2.28 Gandak-Kosi interfan area shows the terminal fans created by the activity0f faults

On the Ghaghara-Rapti block the curvilinear Ghaghara and Rapti Faults with convexity to the SW are classified as longitudinal faults, by comparison with similar faults in the rest of the Upper Gangetic Plains, further west (Singh et al., 2006; Bhosle et al., 2008). Other NE-SW trending faults (Intaha-Parsa Fault, Bahraich fault, Colnelganj-Balrampur Fault, West Uttraulla Fault, Ayodhya-Dinkarpur Fault, Faizabad-Domariaganj Fault) almost perpendicular the longitudinal faults are considered as extensional normal faults. The E-W and NE-SW trending faults, roughly parallel to the Himalayan trend on the Rapti Gandak and Gandak-Kosi blocks are classified as longitudinal faults.

Table.2.4 Earthquakes occurred by the faults with year

Year	Date	Latitude	Longitude	Magnitude	Associated Fault	Distance of epicenter from nearest fault (km)
1819	3rd August	26.50	85.50	--	South Motihari	4.6
1880	1st November	26.47	84.43	--	South Motihari	5.6
1833	4th October	27	85	--	Piedmont-II	6.4
1935	21st March	27	85	6.3	Piedmont-II	6.4
1962	11th January	27	85	6.0	Piedmont-II	6.4
1833	18th October	27	84	--	Garakhpur-Padrauna	6.5
1859	7th October	26.17	85.90	--	North Muzaffarpur	2.8
1864	30th August	25.60	85.20	--	Ghaghara-Ganga	0
1898	30th September	25.63	82.05	--	Ghaghara-Ganga	0
1864	30th September	26.80	82.20	--	Ayodhya-Dinkarpur	0
1883	6th October	26.12	85.38	--	West Patna	6.7
1897	30th November	25.30	86.50	--	West Patna	1
1939	11th May	25.30	86.50	--	West Patna	1
1936	13th January	26.50	86.50	--	North Sitamarhi	5.7
1958	25th November	26.50	86.50	--	North Sitamarhi	5.7
1952	8th November	27.90	82.20	6.0	Himalayan Frontal Thrust	2.25
1953	29th August	27.90	82.20	6.0	Himalayan Frontal Thrust	2.25
1958	3rd December	27	86	--	Himalayan Frontal Thrust	2.8
1988	21st August	26.72	86.63	6.4	Himalayan Frontal Thrust	8.8
1988	21st August	26.72	86.63	6.4	Himalayan Frontal Thrust	8.8
1954	20th November	27.50	82.50	--	Rapti Fault-I	14.4
1965	1st June	27	83	5.7	Rapti Fault-II	9.4
1934	15th January	26.60	86.80	8.3	Munghyr Saharsa Ridge	8.6

In most of the Upper Gangetic Plains (Singh et al., 2006, Bhosle et al., 2008) terminal fans have developed has a result of relief created by activity of transverse extensional faults. In the Ghaghra-Rapti Interfluve belonging to the Upper Gangtic plain, three terminal fans (KTFn, BBTFn & RTFn-III) have developed a similar manner as described earlier. However, three terminal fans (RTFn-II, IV & V) have developed due to the activity of the different segments of the longitudinal Rapti Fault-I. In the Gandak megafan and Gandak-Kosi interfan blocks, terminal fans have been developed as a consequence of activity of longitudinal faults.

2.11 RESUME

Major geomorphic units recognized from the study area: piedmont (active, young and old), terminal fans, megafan, incised valley, terraces, and interfluve plain (Singh et al., 2006; Bhosle et al., 2008). Terminal fans can be further classified into three types; braided, meandering and splay terminal fans.

Thirty-eight soil-geomorphic units are identified from the study area. Based on IRSL dates of C-horizons of soils, these units have been grouped six members of a morphostratigraphic sequence: QGMS-I (<1.4 Ka), QGMS-II (1.4-4.7 Ka), QGMS-III (4.7-6.9 Ka), QGMS-IV (6.9-8.4 Ka), QGMS-V (8.4- 10 Ka) and QGMS-VI (>10 Ka). Studies of morphological characters of soils on all the soil-geomorphic units show these characters like the thicknesses of B-horizons and solum and degree of development increase from QGMS-I to QGMS-VI soils,

The whole study area between the River Ghaghara and Kosi is divided into three tectonic blocks namely Ghaghara-Rapti block, Rapti-Gandak block and Gandak-Kosi block separated by the three major faults i.e. by Rapti fault-II and

Gandak fault.

The Ghaghara-Rapti Interfluve block is a part of the Upper Gangetic Plain and bounding longitudinal faults like Ghaghara and Rapti Fault-I are curvilinear with convexity to the SW, similar to other major interfluves in the Upper Gangetic Plains (Singh et al., 2006, Bholse et al., 2007). Here bounding rivers like Ghaghara and Rapti are incised in nature the Interfluve is an upland area. The Upland has been a site of deposition since about 10 Ka in the form terminal fans due to activity of transverse as well longitudinal faults. This block is overlain by moderately to very well developed soils.

The Gandak megafan block bound by NW-SE trending major faults has been marked by eastward tilting, causing a shift of the Gandak River from west to east over a distance of 80 km during the period10.7-5.4 Ka (this study). This has led to higher degree of soil development in the west which decreases to the east. Since 4.5 Ka, four terminal fans have deposited to the activity of Nichlul Fault, South Motihari Fault and Barhaj-Bettiah Faults. The block is marked by mainly moderately to weakly developed soils.

The Gandak-Kosi Interfan Block is marked by a number of longitudinal faults. Because of the North Sitamarhi fault, at the base of the Old Piedmont, a younger piedmont of 44 km long has been developed, which gives a width of 82 km for the whole piedmont, which is highest in the Gangetic Plains. Activity of longitudinal faults leads to development of terminal fans, which cover whole of Plains (mainly swampy in nature) (Fig. 2.28). Here soils are mainly weakly to very weakly developed.

CHAPTER-3

OPTICAL STIMULATED LUMINESCENCE DATING OF SEDIMENTS

3.1 INTRODUCTION

Mohindra et al. (1992), Srivastava et al. (1994), Kumar et al. (1996) and Singh et al. (2007) used soil-chronoassociation to rank the soils developed on different broad soil-geomorphic units, based on the degree of soil development. Also, these workers used soil-chrnoassociation to provide relative times of tectonic activity and climatic changes. In the present case, we have provided absolute ages for C-horizons of typical pedons form the study area, so that these can be used in constraining times of paleoclimatic changes and neotectonic activity.

Though initially the Luminescence method was used mainly for dating aeolian sediments, later developments of the technique allow dating of fluvial sediments. In India, several workers have used this technique to date fluvial sediments (Rao et al., 1997; Kale et al., 2000).

The luminescence dating technique utilizes the microdosimetric property of minerals in dating of sediments. Quartz, feldspar, zircon and calcite are known to be natural dosimeters. These minerals are continuously in receipt of ionising radiations from the ambient radioactive environment and Cosmic Rays (Fig. 3.1a). The presence of defects (Fig. 3.2b) in crystal lattice facilitates retention of small fraction of this ionisation energy, which grows continuously with burial time (Fig. 3.1b). The sediment age i.e. the time elapsed since deposition to retrieval is obtained by calibrating the total energy accumulated in crystal over this period with the rate of acquisition of this energy. An exposure to light causes 'bleaching' of stored energy (Fig. 3.1b). The extent to which zeroing occurs depends upon the duration and the optical spectrum of the light to which the sediment is exposed. Amongst the luminescence dating the Optically Stimulated Luminescence (OSL) including Green

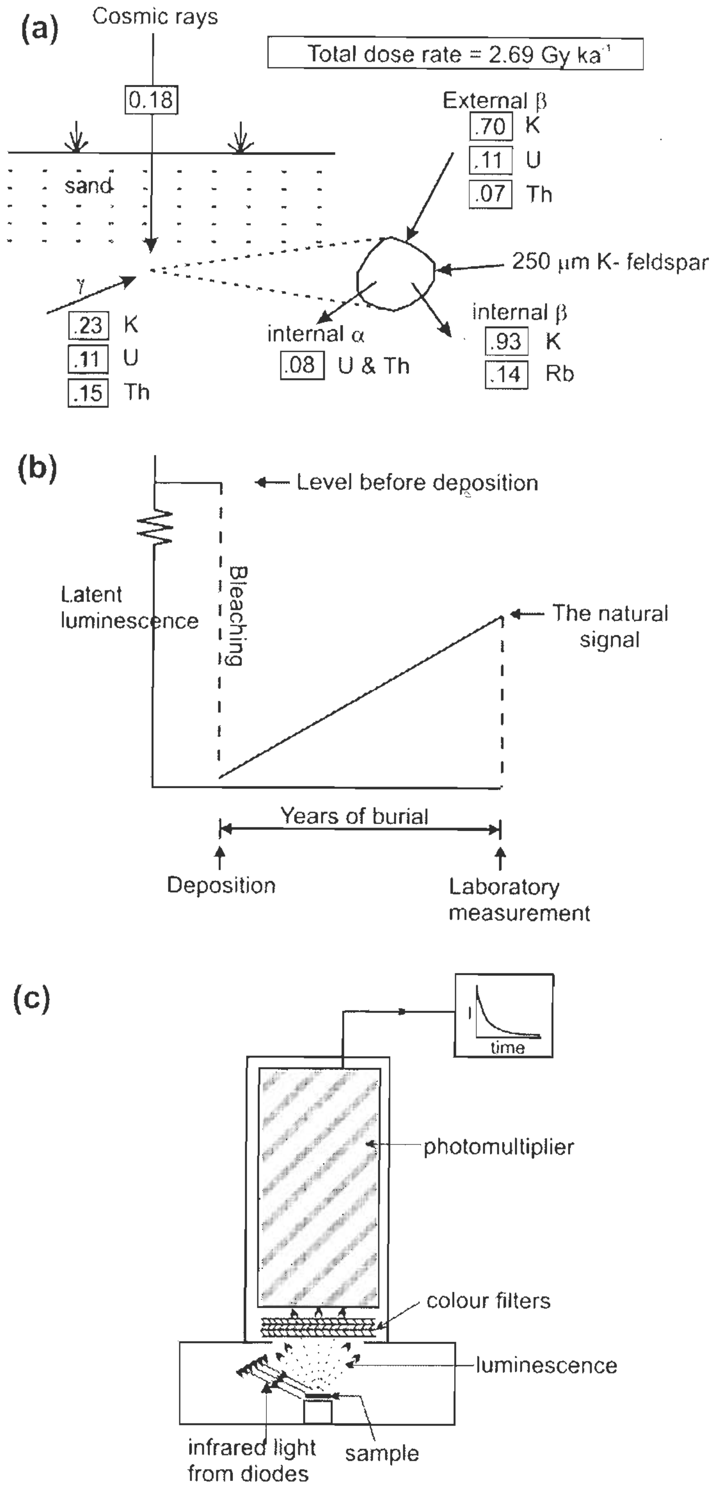


Fig. 3.1(a) Illustration of various contributions to the dose rate for coarse grain K-feldspar (Huntley and Lian, 1999), (b) Resetting of the Luminescence clock (Aitken, 1998) and (c) The Basic experimental arrangements for measurement of the IRSL dating (modified after Aitken, 1998).

Light Stimulated Luminescence (GLSL) and Infrared Stimulated Luminescence (IRSL) techniques are the most recent ones. These techniques can date even those sediments, which are exposed to light equivalent to just a few minutes of clear day-light and thus are considered to be the most suitable for the present study.

3.2 LUMINESCENCE DATING

3.2.1 Mechanism of TL/IRSL/GLSL emission process

Basic principles of TL and OSL (IRSL and GLSL) dating are similar and can be explained using an energy level diagram for ionic crystals (Figs. 3.2a, 3.2c-d). All the rocks contain small amounts of radioactive materials especially ^{238}U, ^{232}Th and ^{40}K (Fig. 3.1a). Radiation from these materials causes ionisation leading to creation of free electrons (Fig. 3.2a). Most of the free charges recombine (Figs. 3.2c-d) instantaneously except for a small fraction, which get attracted and are trapped in the crystal defects sites (Fig. 3.2b), which act as traps during electron diffusion in the crystal.

As the rocks weather and are broken down and transported by streams/wind, due to exposure to the Sun, sediments get 'bleached' i.e. all the free electrons (Fig. 3.1b) trapped in defect sites get detrapped. On deposition, again build up of trapping of electrons takes place. The trapped charges can be made free instantaneously by an appropriate stimulation i.e. thermal heating (TL) or optical excitation (OSL) and it results in luminescence (Fig. 3.1c). The intensity of luminescence (i.e. the number of photons per unit area per unit time) is proportional to the trapped charge concentration, which in turn is proportional to the amount of nuclear radiation to which the crystal has been exposed (and, therefore, to the time that has elapsed since the traps were last emptied) and thus can be used for determining the time of deposition of sediment (Aitken, 1998 p. 6).

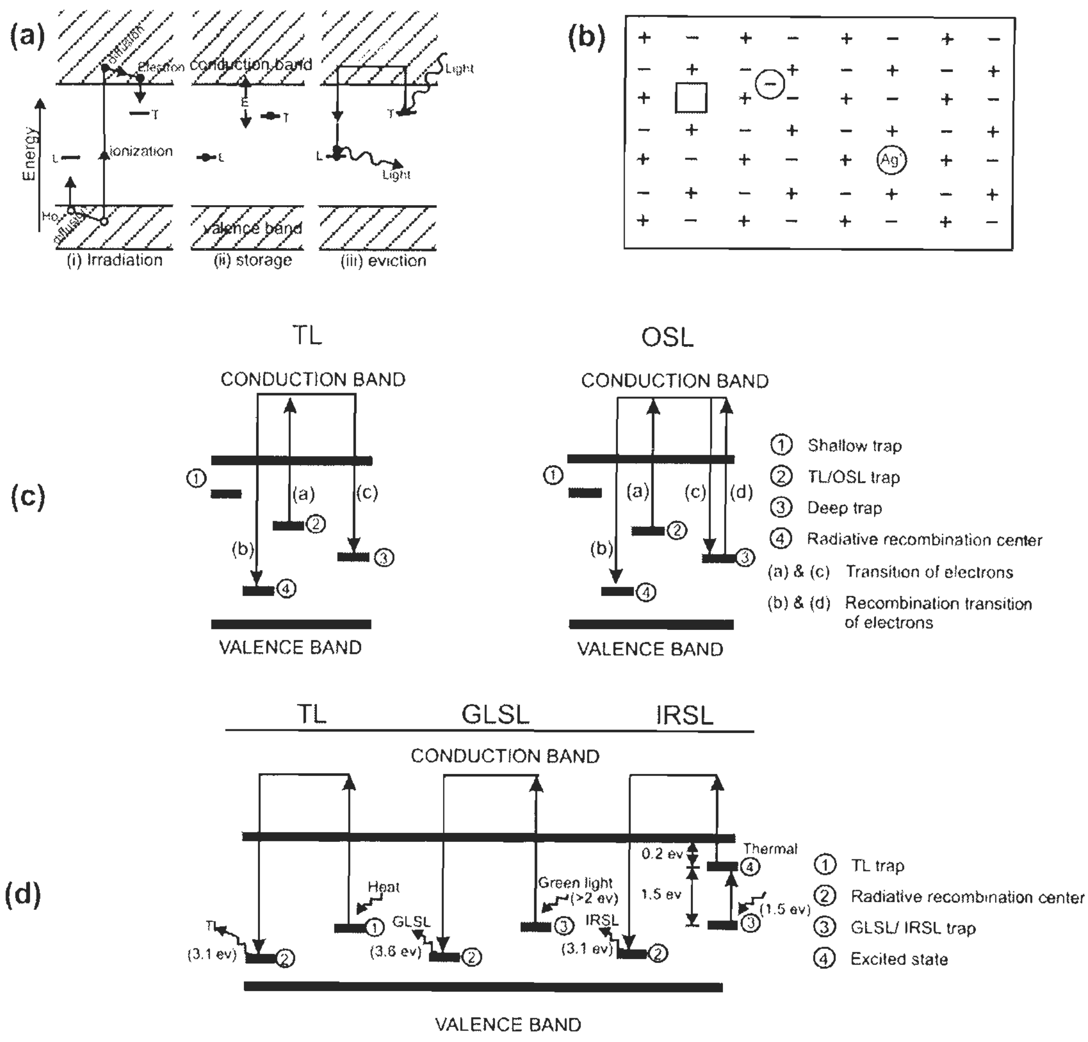


Fig. 3.2 (a) Thermoluminescence process based on band theory of solids (Aitken, 1985), (b) Schematic diagram showing lattice defects in an ionic crystal (Aitken, 1985), (c) Phenomenological energy diagrams describing TL and OSL processes. (Botter-Jensen and McKeever, 1996) and (d) Schematic energy diagrams for TL, GLSL and IRSL (Lars Botter-Jensen, 2000).

3.2.2 Optical/Infra-red stimulated luminescence (IRSL) dating

As the signal stimulated by thermal energy (TL) takes several hours' durations in clear daylight exposure for their detrapment, luminescence dating was initially used for dating aeolian sediments. Later discovery that the OSL signal is being bleached readily and more than 90% of bleaching of optically sensitive signal is accomplished in a few minutes of sun exposure/stimulation, use of OSL has been used extensively with advantage for dating of marginally sun-exposed sediments such as; alluvium, colluvium, glacio-fluvial deposits (Wintle et al., 1993; Perkin and Rhodes, 1994; Mckeever, 1994; Singhvi et al., 1998; Franklin, 1998 and Wallinga et al., 2001). Instrumentally, taking measurements with optical technique is more convenient compared to the conventional TL as it does not make use of sophisticated temperature controllers, control of oven environment and long measurements as needed in TL read-outs.

For OSL dating, sources such as argon ion laser or white light sources such as, Halogen lamp or Metal halide lamps in combination with appropriate optical band pass filters are used (Huntley et al., 1985 and Bøtter-Jenson et al., 1992). Also, infrared (IRSL dating) from infrared light emitting diodes, emitting light at 880 nm is commonly employed for dating (Fig. 3.1c) (Spooner et al., 1990). More recently, Single Aliquot Additive Regeneration (SAARA) method (Duller, 1994) has been introduced, which dates low quantity sample. In dating, measurements are made on multiple aliquots prepared from the same sample. The aliquots are irradiated to increasing radiation dose levels using appropriate laboratory sources. The signal decay on shining with stimulation source at constant source intensity is measured (Figs. 3.4a, d, g, j and m). For aliquots with identical sample amount, intensity of luminescence at any instant is related to the total radiation dose acquired (natural plus artificial dose). Thus a 'growth curve' for signal (normalized to sample amount) vs. laboratory dose is constructed (termed as 'additive growth curve') at various time intervals on shine-down curve. The growth curve is then extrapolated up to a zero dose value. The dose acquired in antiquity (also termed as paleodose, denoted by P) is then read from the extrapolated growth curve by reading the dose required to produce luminescence level equal to that of a natural aliquot (Figs. 3.4b, e, h, k and n). The age (A) is estimated by dividing paleodose (P) with the annual dose (R), which is responsible for the growth of luminescence signal. The radiation dose rate (R) is the sum of the doses due to the α, β and γ radiations received from the various decay modes of ^{238}U, ^{232}Th and ^{40}K present in the ambient environment as impurities and the dose due to Cosmic Ray (CR) exposures (Fig. 3.1a).

Thus the age, A is given by:

$A= P/R= P/ (aD_\alpha+D_\beta+D_\gamma+D_{CR})$

Where, D_α indicates radiation exposure rate due to alpha (measured in the unit of Grays/year abbreviated as Gy/a) similarly for D_β, D_γ and D_{CR}.

Significance of factor 'a' termed as alpha efficiency factor can be understood in the following way. The paleodose in the age expression is determined by constructing growth curve by irradiating sample with α or β source. Luminescence production efficiency (luminescence per unit dose) for β and Cosmic Ray is nearly same, but it is very small for α particles as these are massive charged particles. Due to high mass and charge, interaction of α particle with crystal causes extensive ionisation along their short track length such that the free charges exceed the trap.

Moisture adds complication through attenuation of radiations and can also become means for disequilibrium. Thus, the estimated dose values are incorporated into the equation after correcting for attenuation due to moisture content, radioactive disequilibrium and inhomogeneity in the distribution of radioisotopes.

The fact that pure quartz can not be stimulated by infrared source, the IRSL technique is employed only in feldspar dating or in dating of feldspar inclusions in quartz (Huntley et al., 1993). This property of quartz and feldspars to infrared stimulation is also used in detecting contamination of feldspars in quartz (Mejdahl & Christiansen, 1994; Duller et al., 1995).

Unlike aeolian system, in fluvial sediments, the suspended grains may receive attenuated and restricted sunlight causing incomplete bleaching of the IRSL signal. This may lead to age-overestimation (e.g. Berger, 1990 and Stokes et al., 2001). To some extent, this can be determined by dating modern surface sediment and applying correction to the obtained age (Rao et al., 1997).

3.3 SAMPLE COLLECTION AND PREPARATION

The sampling locations are given in Fig. 2.2a. Material for dating was collected in opaque steel tubes of size 5 cm (dia.) x 20 cm (length) by pushing horizontally into a freshly exposed pedons. The tubes were tightly wrapped in opaque photographic bags and were then transported to the laboratory.

All the samples were analysed by fine grain technique on polymineralic fraction (4-11 μm size fraction). The entire chemical treatment, physical separations and measurements were carried out in subdued red light. Prior to chemical separation, the outer 3 cm thick material from either side of the tube was removed as it might have got bleached by exposure to sunlight during sampling and the removed material was retained for estimation of ^{238}U, ^{232}Th and ^{40}K concentration. The middle core was then sequentially treated with 1N HCl to remove carbonates, sequentially 10%, 20%, 30% and 40% H_2O_2 to dissolve the organic fraction and 0.01N Na-oxalate for deflocculation and each chemical treatment followed by ultrasonic treatment to remove suspended clay fraction. The samples were then washed several times with distilled water. Subsequently, the required grain size (4-11 μm) fraction was separated using Stokes's law (Galehouse, 1971) in acetone medium. The separated 4-11 μm grain size fraction was then dispersed in acetone and equal volumes of this suspension were pipetted into small flat-bottomed glass tubes, each containing an aluminium disc (9.6 mm dia.) at the bottom. After drying the solution in an oven at a temperature of ~45° C, the discs containing monolayer of fine grains were taken out and transferred into sample holders. 50-60 discs from each sample were prepared. Omission of outer edge was found to be convenient in handling discs during irradiations and measurements. Uniformity and monolayer deposition is necessary for transparency and uniformity to irradiation, stimulation and luminescence transmission.

3.4 OSL MEASUREMENTS

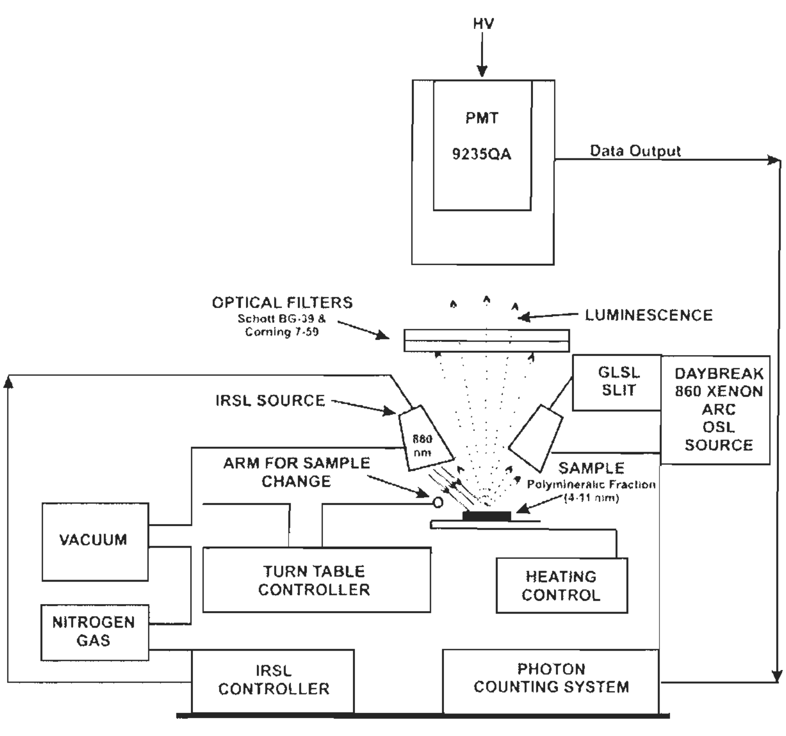


Fig. 3.3TL/OSL system during IRSL measurement.

All the measurements were carried out on TL/OSL reader (Daybreak 1150 Automated TL/OSL System; Bortolot, 1997) (Fig. 3.4). The instrument is equipped with OSL sources for photoluminescence measurement as well as heating arrangement for thermo-luminescence measurement. The samples under consideration were investigated by IRSL technique. The IRSL source is composed of 12 IRLEDs (T-1 GaAlAs diodes) connected in an array emitting light at 880 nm wavelength, delivering ~45 mW/cm^2 power at the sample position. Power supply to optical sources is controlled to stabilize the beam intensity. Source intensity fluctuation at the sample position is less than 1%. Sample position, heating control and optical excitation timings are controlled through inbuilt software interfaced with the instrument.

The sample luminescence is filtered using Schott BG-39 and Corning 7-59 filter combination (detection window: 330-480 nm; Godfrey-Smith et al., 1996, *in* Krbetschek et al., 1997) in order to screen the scattered luminescence, to select the particular spectrum for feldspar and to optimise signal to noise ratio. The filters are used before the photo multiplier tube (Figs. 3.1c and 3.3). The photo multiplier tube (EMI 9235QA) with an associated electronic device for low-level photon counting is used for detection of IRSL emission.

For artificial irradiations, β exposures were given on Daybreak-801, 20 seater beta irradiator using ^{90}Sr source (β-source No.: QC9818; Model No.: SIF. D1; Nuclide: ^{90}Sr; Code No.: SIF 1177; S. N.: 3715 BB; Normal Activity: 100 mci; Activity measurement date: 24th March, 1998) delivering dose at the rate of

5.25 Gy/min for coarse grain quartz and 2.6 Gy/min for fine grained quartz samples (measured on 1st January, 1999) (see sec. 3.8). Alpha of 'a' value (α efficiency factor) was taken 0.08±0.01.

The experimental protocol for fine grain polymineralic aliquots using IRSL technique is designed following published protocols (Bøtter-Jensen et al., 1993; Mejdahl et al., 1994; Bøtter-Jensen, 1997, 2000; Wintle, 1997; Wilkinson et al., 1997; Aitken, 1998; Wintle et al., 1998; Singhvi et. al., 1999; Liritzis, 2000 and Jain et al., 2003). The protocol includes consideration of several factors that affect estimation of paleodose and dose rate (Aitken, 1985, 1990).

3.5 ESTIMATION OF ANNUAL DOSE

Estimation of dose rate or annual dose requires measurement of the individual concentrations of radionuclides, ascertaining the status of their radioactive equilibrium and their alpha efficiency. The ^{238}U and ^{232}Th were measured using thick source Daybreak 583 alpha counter. The sample was crushed to ~10 μm grain size and then evenly spread in a thick layer on a ZnS (Ag) screen placed at the base of a circular perspex container. The system was calibrated using standards of known activity such as sand 109A (Aitken, 1985; p. 306). From this activity, concentrations of ^{238}U and ^{232}Th were evaluated by assuming that half of the measured activity is due to uranium series and other half due to thorium. The uranium and thorium concentrations thus obtained were then converted into dose rates using factors given by Aitken (1985, p. 66) by assuming these radioactive series to be in equilibrium. Background (BG) was measured before measuring each sample and BG counts were subtracted from the signal. For ^{40}K estimation, solution was prepared as suggested by Shapiro (1975). ^{40}K concentrations in the samples were then estimated by Induced Coupled Plasma-Atomic Absorption Spectrometry at the Institute Instrumentation Centre of Indian Institute of Technology Roorkee.

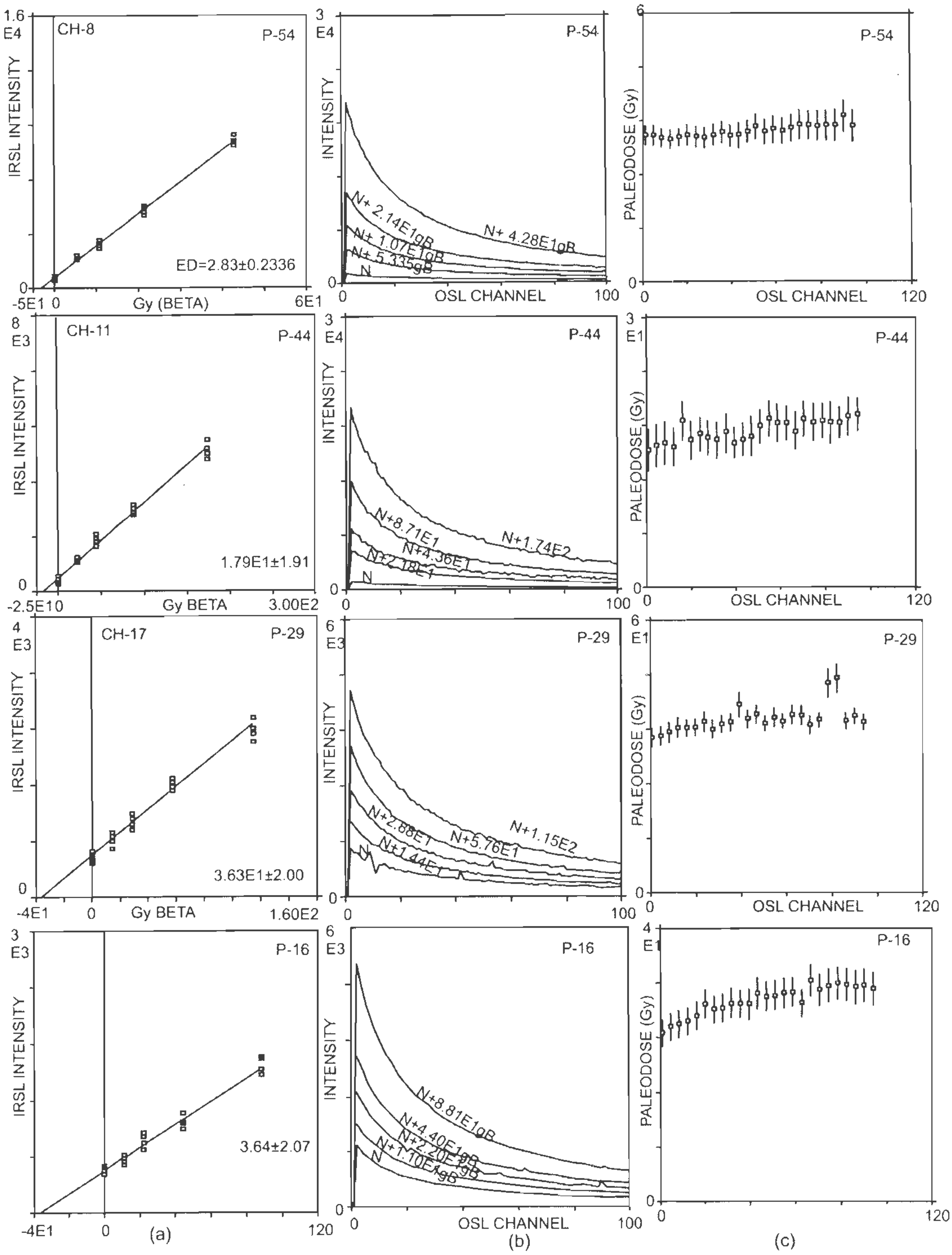


Fig.3.4 (a) growth curve, (b) Shine wodn curve and (c) Equivalent dose plateaus of QGMS-I-IV samples

An average dose rate of 150 µGy/a (at a depth of around 1 meter) was taken as contribution due to Cosmic Rays (Aitkin, 1985; p. 297). Moisture contents for dry and moist samples were taken as 10±5% and 15±5%, respectively.

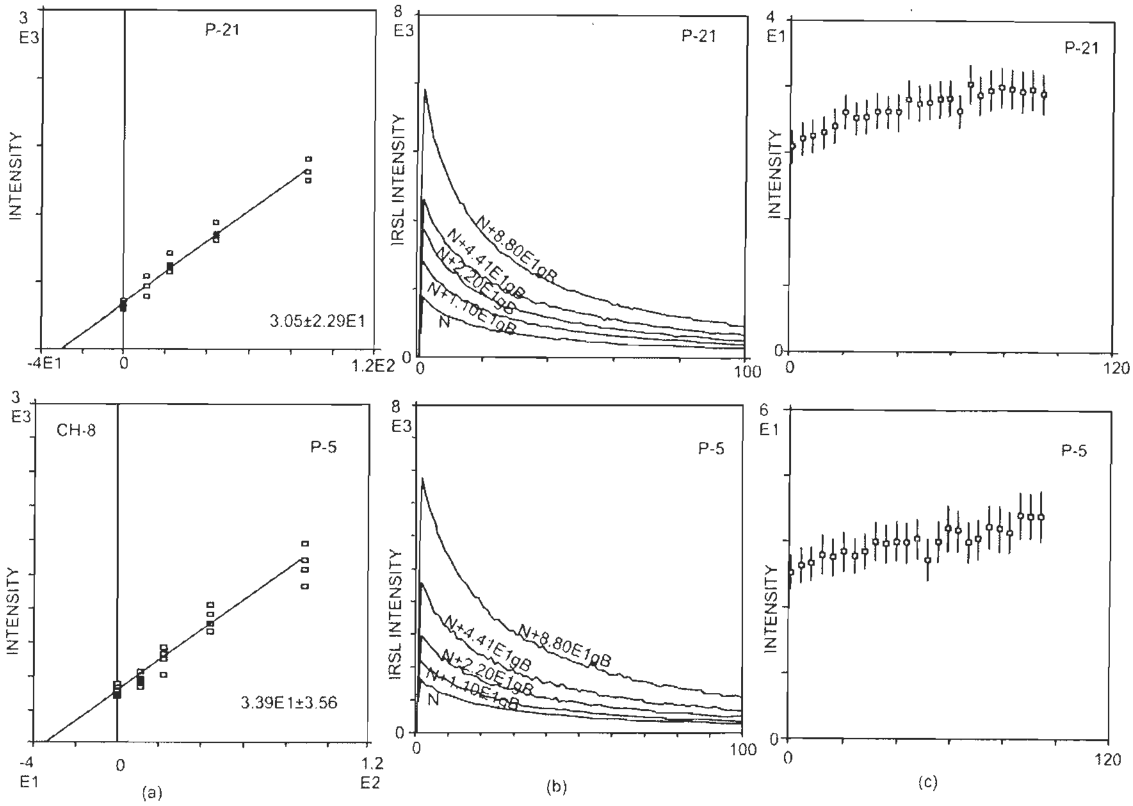


Fig 3.5 (a) Growth curves, (b) Shine down curves and (c) Equivalent dose plateau of QGMS-V-VI samples.

3.6 ESTIMATION OF PALEODOSE/EQUIVALENT DOSE

Prior to any measurement, samples were short shined to determine normalization factor to account for variation in sample amount between discs and to account for variation in luminescence sensitivity between grains. For short shine measurements, samples were exposed to 0.3 sec pulse of ~20 mW of 880 nm IRSL stimulation. The integrated signal output over this period, which is proportional to the number of grains on aliquot, luminescence efficiency of grains is used as a factor for normalization in signal analysis for IRSL. It was also observed that over 0.3 seconds of 880 nm stimulation, the shine down curve remained flat showing no significant depletion of the IRSL

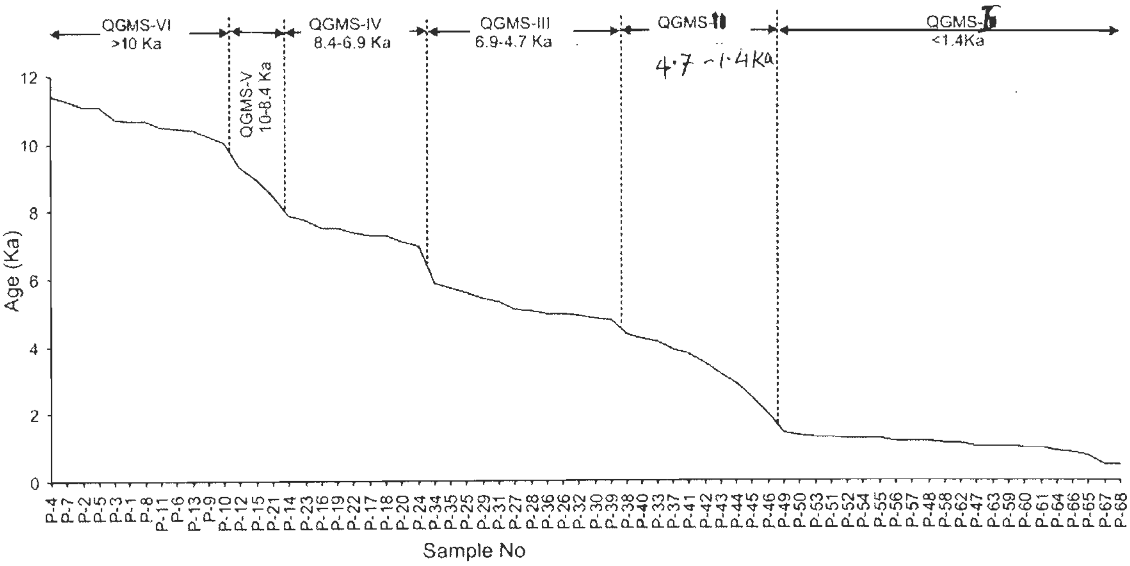


Fig.3.6 Frequency curve for 68 soil samples arranged in descending order.The flat or gently sloping plateau shows the rectonically stable period.

signal. Although initially, attempt was also made by taking sample weight as normalization factor, but due to its poor control on data scatter it was considered unsuitable in final calculations. The poor control over normalization could be due to difference in pre-depositional zeroing level of these grains and differences in their luminescence efficiencies.

The shine down curves for IRSL were measured by stimulating samples with 880 nm lights, pulse of ~40 mW for 99 sec. For IRSL measurement, constructing growth curves and plateau test TLAPPLIC (ver. 3.3) software was used. Typical normalized shine down curves for IRSL measurements are shown in (Fig. 3.4). To obtain equivalent dose, growth curves (luminescence intensities vs. applied beta doses) were constructed using linear fits extrapolated to the residual level. Plot of equivalent dose versus shine down time (exposure energy) were derived to check for the existence of 'shine plateau' (Fig. 3.4). On the growth curve, natural dose point is an average of measurement on six aliquots and beta dosed points on 4 aliquots. The doses were administered to the sample aliquots in such a way that luminescence level of the highest dosed point exceeded more than twice the level of natural (un-dosed) aliquot. In most cases the estimated paleodose values were less than 15% of maximum administered beta dose used in making the growth curves. Thus extrapolation was insignificant to induce any meaningful error in the measured paleodose.

3.7 AGE ESTIMATION

Age estimation requires measurements of paleodose and annual dose-rate. The paleodose were determined from the plateau value (Figs. 3.4). To estimate the annual dose rate, the concentrations of ^{238}U, ^{232}Th, ^{40}K, a-value, cosmic flux and moisture content were calculated. After determining the above factors, the dose-rate estimation and computation of the ages of the samples along with the errors were calculated using protocols described by Aitkin et al. (1972), Aitkin (1985) and Grün et al. (1994).

3.8 RESULT AND DISCUSSION

Sixty-eight samples from all the twenty-seven soil-geomorphic units were dated (Table 3.1). The error in age is the highest due to errors associated with dose rate components and statistical error in luminescence measurements.

The following observations are made from the measured dates:

1. IRSL ages were arranged in a descending order and a frequency curve plotted (Fig. 3.6) from these data suggest that ages for the soils of different

soil-geomorphic units (Table 3.1) fall into six distinct members I to VI of Morphostratigrapic Sequence of the study area with ages as ≤1.4 Ka, 1.4-4.7 Ka, 4.7-6.9 Ka, 6.9-8.4 Ka, 8.4-10 Ka and >10 Ka, respectively. These ages also indicate the period of stability of different surfaces.

2. All the samples show an excellent age plateau with some exceptions of QGMS-I samples. At higher ages of samples, the ED plateau showed marginal increase in trend. This might be because of contribution of IRSL derived from hard to bleach traps, which carry relict IRSL components i.e., the pre-depositional exposure not having been sufficient for completing zeroing of such traps.

In age calculations, almost all samples show error less than 15%. The errors are, in general, higher in QGMS-I samples.

Fig. 3.6 Frequency curve of IRSL ages from different soil-geomorphic units, with ages arranged in a descending order. Breaks in slope of the curve are used o define different members of the Morphostratigraphic Sequence.

Table 5.1 OSL ages of the samples from QGMS-I to QGMS-VI

QGMS	SOIL GEO-MORPHIC UNIT	PEDON NO	^{238}U (ppm)	^{232}Th (ppm)	^{40}K (%)	MOIS-TURE (%)	ED (Gy)	DOSE RATE (µGy/a)	AGE (Year)
QGMS-VI	GRIP	P-4	6.56±1.35	14.53±5.21	1.32±0.06	8±2	70.12±3.7	5899±899	11886±1917
	GRIP	P-2	2.38±1.54	17.6±4.19	1.81±0.09	12±2	51.58±4.65	4732±804	10901±2096
	GRIP	P-1	3.12±1.67	16.23±4.32	1.62±0.08	12±2	50.13±2.45	4702±853	10660±2002
	GRIP	P-8	5.38±2.54	10.13±4.29	1.32±0.06	8±2	51.91±2.54	4874±1202	10651±2822
	GRIP	P-11	1.99±1.40	10.21±3.74	1.62±0.09	12±2	37.38±3.19	3567±717	10479±2288
	GRIP	P-13	4.5±1.50	10.15±5.12	1.27±0.06	8±2	46.43±2.07	4463±908	10402±2166
	GRIP	P-10	3.28±1.81	13.45±4.23	1.62±0.08	12±2	45.42±2.25	4446±887	10217±2100
	RTFn-V	P-7	5.89±1.32	12.43±3.42	1.54±0.07	8±2	65.01±2.67	5576±771	11765±1695
	RTFn-V	P-5	1.21±0.01	5.68±0.52	1.52±0.07	8±2	30.93±3.14	2791±148	11081±1271
	OSGP	P-3	4.31±1.00	11.32±4.98	1.32±0.06	8±2	49.09±2.8	4574±767	10731±1900
	OSGP	P-6	5.83±0.89	12.23±4.50	1.39±0.07	5±2	58.45±2.93	5596±745	10446±1485
	OSGP	P-9	5.78±0.89	10.30±5.79	1.52±0.08	5±2	55.91±1.59	5464±872	10233±1659
QGMS –V	OLGP	P-12	4.13±1.42	11.12±4.12	1.27±0.06	8±2	40.66±1.46	4427±816	9184±1724
	OLGP	P-15	4.56±0.08	11.54±6.59	1.21±0.06	8±2	41.03±1.94	4600±834	8920±1671
	OLGP	P-21	1.82±0.26	8.36±2.50	1.11±0.05	8±2	25.19±1.98	2979±351	8455±1197
QGMS–IV	RTFn-IV	P-14	5.96±1.32	14.89±4.93	1.81±0.09	10±2	47.26±2.50	5988±844	7894`±1188
	RTFn-IV	P-23	3.15±1.01	9.42±2.50	1.11±0.05	8±2	28.34±1.51	3661±547	7742±1228
	RTFn-IV	P-18	6.59±2.38	14.76±4.89	1.62±0.08	8±2	45.32±1.78	6216±1196	7291±1431
	RTFn-IV	P-16	2.61±1.27	15.57±4.54	1.82±0.09	10±2	35.38±2.43	4714±774	7505±1335
	GT-II	P-17	4.37±2.09	14.40±3.79	1.37±0.07	12±2	37.26±5.06	4757±959	7832±1904
	GT-II	P-19	5.63±0.89	12.22±5.20	1.52±0.08	8±2	40.64±2.33	5423±781	7494±1161
	GT-II	P-22	4.83±1.53	10.59±4.21	1.64±0.08	8±2	36.87±1.92	5006±851	7365±1309
	RTFn-III	P-24	5.57±2.14	16.51±3.75	1.73±0.09	12±2	37.85±1.46	5769±968	6962±1130
	RTFn-III	P-20	4.57±2.14	16.54±3.35	1.71±0.09	12±2	39.28±1.49	5379±962	7302±1334
	BBFn	P-26	6.02±1.95	14.32±5.35	1.56±0.08	7±2	29.36±1.93	5958±1133	4928±991

QGMS-III	OPt	P-27	5.31±1.40	12.99±3.61	1.29±0.06	7±2	26.66±1.23	5237±787	5091±800
	OPt	P-28	1.89±0.25	5.22±1.34	1.29±0.06	7±2	14.42±0.64	2866±235	5033±469
	OPt	P-30	5.17±2.06	14.52±4.76	1.39±0.07	7±2	26.28±1.13	5463±1083	4811±976
	GTFn-I	P-29	6.94±1.55	14.75±6.33	1.60±0.08	8±2	34.39±2.28	6351±1052	5415±966
	GTFn-I	P-31	8.15±1.68	17.78±6.39	1.48±0.07	8±3	37.61±2.45	7108±1129	5291±908
	GTFn-I	P-32	7.85±2.35	15.26±3.36	1.67±0.08	12±2	21.89±2.45	4457±655	4912±907
	GTFn-II	P-35	4.79±1.10	10.05±3.45	1.29±0.06	7±2	26.25±1.33	4591±660	5718±871
	GTFn-II	P-36	6.35±1.54	14.89±5.36	1.58±0.08	10±3	20.39±1.98	4121±546	4948±812
	GTFn-II	P-34	5.74±1.10	9.55±4.72	1.38±0.07	12±3	27.77±0.87	4752±728	5846±910
	OPt	P-25	5.56±0.94	14.21±5.13	1.37±0.07	7±2	30.78±2.42	5492±787	5605±916
	RTFn-II	P-39	4.92±1.67	14.27±5.52	1.52±0.08	10±3	24.91±1.22	5234±986	4759±926
QGMS – II	RTFn-I	P-41	5.02±1.85	12.11±3.05	1.60±0.08	10±2	17.71±2.21	5094±868	3778±735
	RTFn-I	P-40	5.32±1.83	14.27±3.22	1.54±0.08	10±2	22.76±3.69	5416±876	4203±962
	RTFn-I	P-33	5.33±1.65	10.29±3.25	1.60±0.08	10±2	20.52±4.28	5004±808	4103±1081
	BBTFn	P-42	5.36±2.31	17.00±4.12	1.73±0.08	12±2	18.38±3.58	5770±1062	3186±853
	KTFn	P-43	1.38±0.53	14.50±4.21	1.8±0.09	12±2	12.56±2.05	3979±569	3158±685
	KTFn	P-44	4.01±1.11	17.51±4.18	1.8±0.09	12±2	15.53±2.44	5389±720	2883±595
	KFn-II	P-45	7.30±1.26	11.84±7.67	1.51±0.07	10±2	14.86±0.95	6020±1129	2469±489
	YPt	P-46	4.57±1.20	7.11±4.10	1.34±0.07	8±2	8.48±0.38	4258±746	1992±360
	PPFn	P-37	4.02±0.83	10.78±3.01	1.38±0.07	7±2	17.55±0.42	4505±558	3896±491
	GT-I	P-38	2.1±1.04	8.40±3.37	1.80±0.09	12±2	15.55±2.68	3565±586	4364±1039
QGMS – I	KFn-I	P-50	5.26±1.51	9.25±4.06	1.34±0.06	10±2	6.28±0.30	4802±846	1309±239
	BTFn-I	P-56	3.61±1.44	15.00±4.95	1.27±0.06	10±3	5.29±0.36	4563±869	1159±234
	BTFn-I	P-51	4.85±1.56	12.56±5.35	1.37±0.07	10±2	6.26±0.23	4886±983	1287±252
	BTFn-I	P-64	5.74±1.61	21.23±5.26	1.28±0.06	10±3	5.33±0.27	6167±975	864±143
	BTFn-II	P-52	4.62±0.87	14.51±0.93	1.36±0.07	10±2	6.29±0.46	5133±460	1227±142
	BTFn-II	P-57	5.64±1.25	14.32±4.65	1.67±0.08	12±2	5.01±1.23	3805±417	1290±347
	BGP-I	P-54	4.61±0.85	9.99±3.64	1.35±0.07	10±3	5.44±0.29	4446±607	1225±180
	BGP-I	P-55	5.50±1.36	15.14±4.36	1.31±0.06	10±3	6.56±0.19	5202±753	1221±189
	GTFn-III	P-53	5.56±1.23	14.05±4.18	1.67±0.08	12±2	5.01±1.23	3805±417	1296±347

	GTFn-III	P-47	9.33±1.17	14.04±5.55	1.51±0.07	12±5	6.08±1.28	4028±1108	1012±134
	GTFn-III	P-60	6.26±1.51	9.22±5.15	1.56±0.08	10±2	5.18±0.26	5399±965	960±178
	BGTFn-II	P-58	4.79±1.12	13.56±3.85	1.31±0.07	10±2	5.44±0.31	4905±690	1110±168
	BGTFn-I	P-65	4.05±0.62	13.83±5.66	1.37±0.07	10±2	3.53±0.32	4693±751	753±139
	OGHP	P-59	2.27±0.51	12.41±4.01	1.54±0.08	10±2	3.94±0.87	3962±524	995±260
	OGHP	P-66	3.69±1.53	11.45±4.61	1.54±0.08	12±2	3.55±0.29	4271±829	831±175
	OGHP	P-48	5.89±2.38	14.00±3.87	1.60±0.08	12±2	6.32±1.31	5516±1071	1146±325
	OGHP	P-61	4.17±2.04	11.90±3.45	1.38±0.07	12±2	4.14±0.46	4400±920	940±223
	OGHP	P-62	5.71±1.66	12.15±4.45	1.54±0.08	12±2	5.76±0.60	5326±895	1082±214
	OGHP	P-63	5.52±2.04	13.9±3.45	1.50±0.08	12±2	5.30±0.16	5269±932	1007±180
	JTFn	P-49	6.58±1.34	9.78±4.09	1.55±0.07	10±2	7.94±0.82	5624±808	1413±249
	GFP	P-67	5.35±1.55	10.25±5.42	1.34±0.07	12±2	2.15±0.17	4639±948	464±102
	BFP	P-68	5.21±1.44	14.42±4.71	1.29±0.06	15±2	2.20±0.13	5017±883	440±81

4.1 INTRODUCTION

Ground Penetrating Radar (GPR) is a well established geophysical technique for high resolution imaging of the geological features in the shallow subsurface (Jol and Bristow, 2003). In sedimentary geology, especially in Quaternary sediments, GPR is primarily used for stratigraphic studies where near-continuous, high-resolution profiles aid in determining: (1) stratigraphic architecture, (2) sand body geometry and (3) correlation and quantification of sedimentary structures. In the last few decades, GPR has been used in numerous sedimentological studies to reconstruct the past depositional environments and the nature of sedimentary processes in a variety of environmental settings with a few to assist in hydrocarbon reservoir analogue investigations (Neal, 2004). One of the more promising applications of GPR is its use in the detection and mapping of subsurface fluids including groundwater and contaminants such as hydrocarbons (Olhoeft, 1984) and can be used for petroleum and hydrogeology reservoir modeling (Thomson et al., 1995; Jol et al., 1996b; Corbeanu et al., 2001). This is because, in the correctly processed radar profiles, at the resolution of survey, primary reflections are parallel to the primary depositional structures. GPR is a non invasive geophysical technique that uses dielectric properties of materials by which it detects electrical discontinuities in the shallow subsurface (typically <50 cm). By generating, transmitting, propagating, reflecting and receiving of discrete pulses of high frequency electromagnetic (EM) wave energy in megahertz (MHz) frequency range and subsequently digitally recording in a manner similar to the seismic process, it maps the subsurface with a high resolution (20-25 cm in our case for 100 MHz antennae).

Keeping the above aspects in mind, radar profiles were taken across terminal fans and Gandak megafan. Also, traverses were made across the inferred faults to understand their subsurface nature and their development in relation sedimentation.

4.2 PRINCIPLES

The working principle of GPR is given in Fig. 4.1. It consists of two antennas: one transmitter which transmits electrical waves to subsurface and the other is receiver which receives the returned waves. The type of survey depends upon the position of these two antennas and the way in which they interact with the ground. If the position of the source and receiver or just the receiver is varied, the data contains the information on the spatial variation of the subsurface. The visualization of the GPR profile is the time–space representation of the subsurface, but the time is converted to depth by using measured wave velocity.

4.3 METHODOLOGY

GPR survey was carried out after deciding the purpose and selecting the best suitable site for the study. In the study area, both structural discontinuities (faults) as well as facies changes on the Gandak megafan as well as on the terminal fans were studied by GPR. The exact locations of faults, paleochannels and the area of interest on the terminal fans were marked in the digital terrain model (DTM) and on the satellite images (Fig. 4.2) and their locations were transferred to the Survey of India topographic sheets. In the field, GPR studies were carried out on the predetermined locations. On the terminal fans GPR profiles were taken both along, across and oblique to flow direction. In case of faults, GPR profiles were taken across the inferred location of the faults.

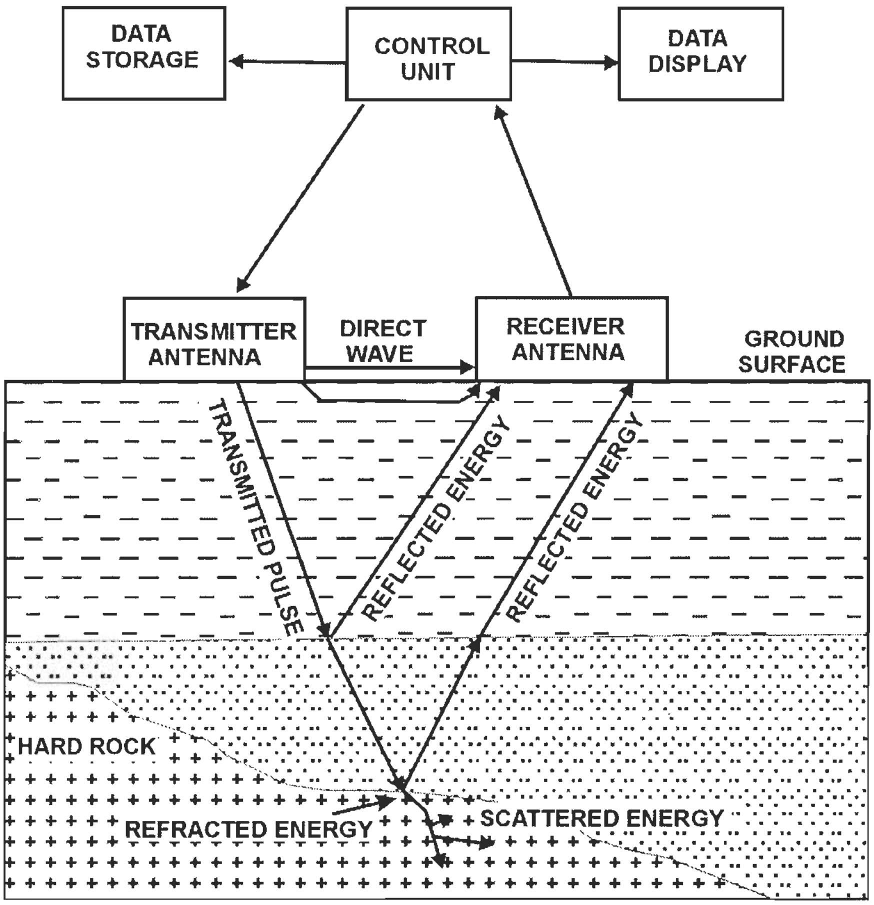


Fig. 4.1 Schematic diagram of working principle of GPR system (After Neal ,2004).

4.4 DATA ACQUISITION METHODOLOGY

Two basic types of data collection i.e. Common Mid-Point method (CMP) for point data and Common Offset Method (CO) for line scan were used. Though a number of the different orientations of the source and receiver antennae can be used, for this study, surveys with perpendicular broad-side position of the antennas (Jol et al., 1996) was used. Also, in most of profiles, we used Common offset method which provides good results for sedimentological studies in the subsurface (Neal, 2004).

The depth to which GPR can image below the surface is dependent upon three main factors: (1) the number of interfaces that generate reflections and the dielectric contrast at each interface, (2) the rate at which the signal is attenuated as it travels through the subsurface. It depends upon the conductivity of the subsurface material, and (3) the centre frequency of the antennas. As the number of interfaces increase, the proportion of energy that propagates to depth is reduced. The conductivity of the materials through which the GPR signal (EM wave) passes controls the depth of penetration. As the conductivity increases, the material acts more like a conductor than a semi conductor. A practical consideration is that, as the frequency decreases, the depth of penetration increases and the resolution decreases, vice versa is also true. As observed by Bristow et al. (2003), 100 MHz antennae provides the best trade off between the two aspects of depth of penetration and resolution, this frequency antennae was used in our investigations. With this antenna, good reflections were obtained up to depths of 12 m.

As the average velocity of profiles varies commonly from 0.0768 to 0.0671 m/ns with 100 MHz, resolution of the GPR survey comes to 25.6 cm to 20.3 cm. assuming the spatial resolution as a quarter of wave length (Reynolds, 1997).

Care was taken while acquiring the data; avoided acquiring data near hyper-tension lines or electrical poles, avoided acquiring data in heavy traffic areas as vibrations from running vehicles can contribute a good amount of noise in the data, mobile phones and other such instruments were switched off as they use electromagnetic energy like GPR, made sure that GPR antennae were moved or towed on the plain ground without any cobbles or pebbles as they add noise to the data.

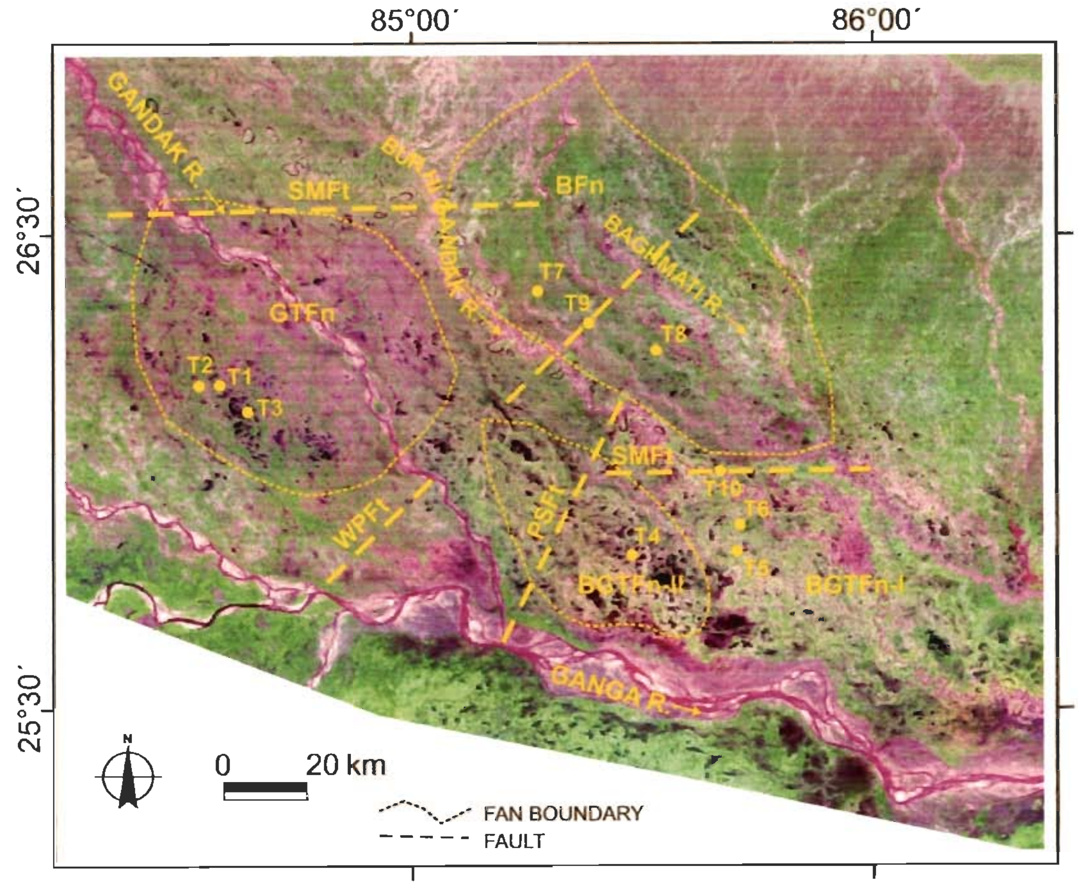


Fig.4.2 Location of the GPR traverse sites in the MSS image

4.5 GPR STUDIES IN THE STUDY AREA

GPR studies were mainly carried out on the terminal fans and Gandak megfan to work out radar facies to understand the fluvial processes. Also, an attempt was made to confirm the faults inferred from remote sensing and G.I.S.

studies and investigate their subsurface nature. The subsurface nature of faults might provide role of their development in contemporaneous sedimentation.

4.5.1 Instrumentation

Subsurface Interface Digital GPR system (SIR-3000) manufactured by Geophysical Survey Systems Inc (GSSI). was used in our investigations. The system comprises five main components (1) control unit, (2) transmitter, (3) receiver, (4) antennae, and (5) interface, data storage, and display module. Shielded antennae were used to avoid ringing inherent in the hardware (Audru et al., 2001). Data were collected in distance mode using a survey wheel (model 620, GSSI) along a profile. Data transfer from the antennae to control unit was through fiber optic cables. Automatic Gain Control (AGC) was applied while collecting the data, as it is the best way of acquiring data in a sedimentary terrain (Neal, 2004). CMP method was used to collect data at places on the terminal fans to find out the velocity of electromagnetic waves in the subsurface to find out the lithology.

4.5.2 GPR data processing and Interpretation

GPR data processing is similar to seismic data processing technique **(Fisher et al., 2000;** Upadhyay, 2004). The GPR data collected from sedimentary terrains do not need much processing (Jol, 2003), as the sediment bed geometries in sedimentary terrain are simple and the layers or beds are almost horizontal in nature. However, collected data were processed and plotted, using GPR Manual Version 5.0 supplied by GSSI, with GSSI computer based RADAN software, which can apply Infinite Impulse Response (IIR), finite Impulse

Response (FIR) filters, 2-D spatial Fast Fourier Transform filters, gain control, distance normalization, surface normalization, deconvolution, band pass filtering and hyperbola migration to the collected GPR data. Filter band width 40/50 and 150/180 MHz were chosen for data processing as suggested by Fisher et al. (2000) for 100 MHz antenna. Velocity measurement was carried out by CMP method and it varies from 0.059 to 0.094 m/ns (wet sand to dry sand) respectively at most places. However, the velocity in the swampy regions of the Gandak terminal fan-III, varies from 0.065 m/ns to 0.086 m/ns, indicting presence of thick mud.

Interpretation of GPR profiles involves the deciphering of interference patterns rather than discrete reflections and diffractions that are characteristic of reflection seismic profiles (Gawthorpe et al., 1993).

In the present study, interpretation was made in the following steps:

(1) Reflections caused by the waves while traveling through the air and the road materials were identified and removed from the main trace.

(2) Origin of the reflections were identified; i.e. whether the interfaces obtained in the traces are real matching the changes expected in the subsurface, since such interfaces can be produced due to the noise and repeated reflections.

(3) Subsurface lithologies in the borehole logs obtained from the Central Ground Water Board (CGWB) were compared and the matched with the GPR profiles.

4.6 FACIES, MACROFORMS, ARCHITECTURAL ELEMENTS AND RADAR FACIES

GPR is not a universal panacea; in all cases. Ground truth is still required because lithological determination is by no means unequivocal. Therefore, bore hole or outcrop data may be required to correlate the result of GPR survey (Bristow et al, 2003). In the study area, the GPR data was interpreted with the help of the borehole log collected from Central Ground Water Board (CGWB), New Delhi and the past geological history interpreted from remote sensing images. After proper processing, GPR profiles were interpreted in terms of the subsurface nature of the area. The GPR profiles were taken along, across and oblique to the depositing stream directions.

At a few places due to the activity of normal faults a small relief is created across the courses of rivers. It leads to deposition of terminal fans on the downthrown blocks, as observed in other parts of the Gangetic plains (Singh et al., 2006, Bhosle et al., 2008). These terminal fans are very common the study area (Fig. 2.28).

4.6.1 Facies

Trough cross bedding

This facies is typically composed of trough cross-beds with foresets tangential or sub parallel to the bounding troughs. The troughs have cross cutting relationship with one another. Individual troughs of >30 m in width and 1.5 to 2 m height are well recognized in the deeper part of some profiles especially in deposits of the Gandak River.

Tabular Cross bedding

This facies is dominant in the fluvial deposits of the area. Low angle (7° to 10°) dipping foresets, varying length from 5 to 10 m in length and 1.5 to 3 m in height are common. The bounding surfaces of the cross-beds dip 7° to 10° in the upstream direction signify the upstream stacking of channel bars.

Horizontal Bedding

These are essentially flat/horizontal beddings in sands deposited both in the lower and upper flow regimes. Due to gross resolution of the GPR reflections, cross-laminated sands are also included in this facies.

Mud Facies

The mud facies is recognized by the parallel or sub parallel continuous reflections (Best et. al., 2003) and lack of any other sedimentary structures. Mud facies are mainly confined to the upper part of the profiles taken in the terminal fans of Gandak, Baghmati and Burhi Gandak Rivers. Two major types are mud facies are identified: mudfacies- I and II. Mudfacies-I represents deposition by vertical accretion in floodplain and are extensive areally. Mudfacies-II is confined to well-defined channels. These are very common in low-lying areas, marked by numerous small lakes formed due to frequent avulsions of small meandering streams. Thickness of mud facies varies from 3 m to 6 m.

4.6.2 Macroforms

Macroforms are large-scale depositional features, products of a long-term component of a depositional system, which accumulate sediments over periods of several to many years and develop an internal consistency of facies and orientation (Jackson, 1976). In general, the most distinctive characteristic feature of the macroform is that it consists of genetically related lithofacies, with sedimentary structures showing orientations and internal minor bounding surfaces that extend from top to the bottom of the element, indicating that it developed by long term lateral, oblique or downstream accretions. A macroform is comparable in height to the depth of the channel in which it formed and in width and length is of similar order of magnitude to the width of channel. Mainly two macroforms of braid bars and channels are recognized from the study area.

Braid bar

Braid bars or mid channel bars are exposed sand or gravel bars that divide flow and cause a braided pattern in the streams (Allen, 1983). These macroforms are characterised by the presence of surfaces of lateral, oblique or down stream accretion, vertical accretion (discussed below), which extend, at a low angle from the top to the bottom of the deposit. In this area the braid bars are well recognized in the profiles across and oblique to the flow direction. These bars are 30-45 m long and 4-5 m height and have a convex up topographic profile. The top of these bars are cut by an erosional surface (fifth order surface, Miall, 1988), on which another sequence is lying. The size of the braid bars of the large rivers is bigger than their small stream counterparts.

Channels

Mainly small channels of 25-30 m width and 3-4 m depth are observed towards the top of radar sequences. These may be filled by mufacies-II, sand or both.

4.6.3 Architectural Elements

An architectural element consists of several or many types of three-dimensional bodies separated and internally subdivided by a hierarchy of bounding surfaces, and are characterised by distinctive litho facies assemblages, external geometries and orientations are termed as architectural elements (Allen, 1983). Major architectural elements observed from this study are different types of accretions.

Accretion is the gradual accumulation of sediments by a stream. In the study area accretions are most common features. Upstream accretion and down stream accretions are best seen in the profile taken along the flow direction of the stream. However, the lateral and oblique accretions are well recognized in the profile taken across and oblique to the flow direction of the stream. Naming of the accretion depends upon the fashion of adding materials. All types of accretions may show internally tabular cross-bedding with set thickness of up to 1 m. Following four types of accretions are recognized in the study area:

Downstream accretion (DA): In downstream accretion beds are added in the downstream direction. These beds are internally composed of planar cross-beds, dipping in the direction dip of accretion surface or flat-bedded sands.

Upstream accretion (UA): It is the adding of material in the upstream direction. Here beds are added one upon another in the upstream. Accretion surfaces dip upstream at angles of 10°-15°.

Lateral accretion (LA): Lateral accretion is the accumulation of material across the stream channel laterally. This is the characteristic feature of the braid bar deposits where the bars frequently migrate laterally such as in the Brahmaputra and Kosi Rivers (Bristow, 1987). Lateral accretion is characterised by cross-bed dip orientations parallel to the strike of the accretion surface (Miall, 1988), typically seen in the later stage of braided stream deposition or in lower part of the fluvial sequence in case of meandering streams

Vertical accretion in Channel (VACH): Within large braided river channels, braid bars are separated by anabranches, which represent deepest parts of channels are accreted by migration of 3-D dunes, giving rise to trough cross-bedded sand, whose cosets may at places be separated by horizontal bounding surfaces. Also, parallel to subparallel (horizontal stratification) sand sheets may be present in the deeper parts of the channels. It can be best seen in the profile across the stream flow direction. Following Best et al. (2003) these are included in the 'vertical accretion in channel' architectural elements.

Vertical accretion on Bar Tops-(VABT)

The braid bar macroform sequences in the topmost part are at places are composed of 1.5-2 m thick accretions mainly consisting of flat-bedded or low angle sands, suggesting their probable deposition in the Upper plane-bed phase (Allen, 1983).

(a)

SYMBOLS AND NOTATIONS USED

(b)

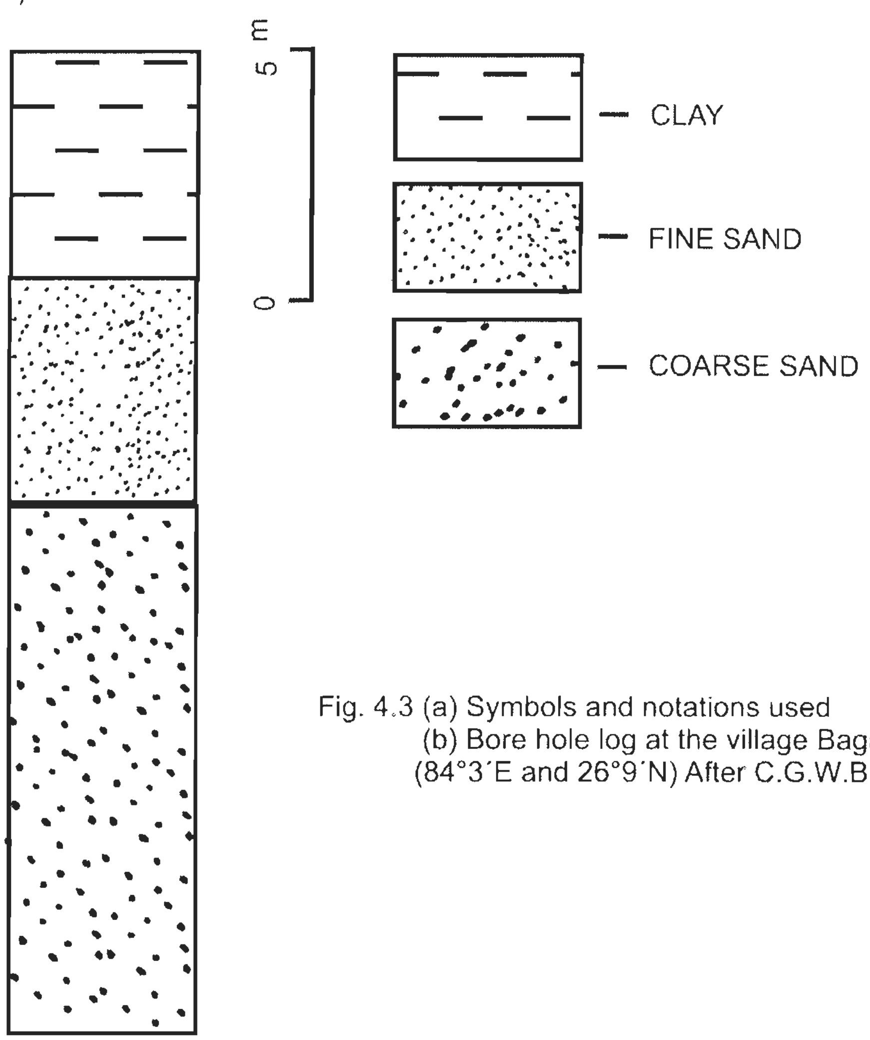
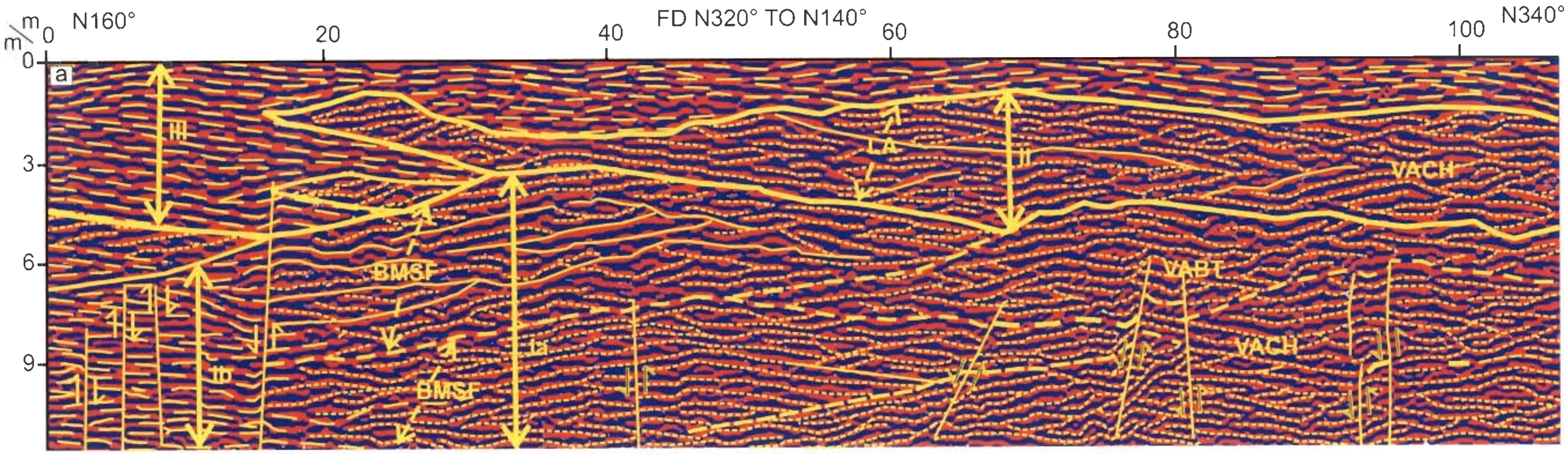


Fig. 4.3 (a) Symbols and notations used
(b) Bore hole log at the village Bagahi
(84°3´E and 26°9´N) After C.G.W.B,2000-2001



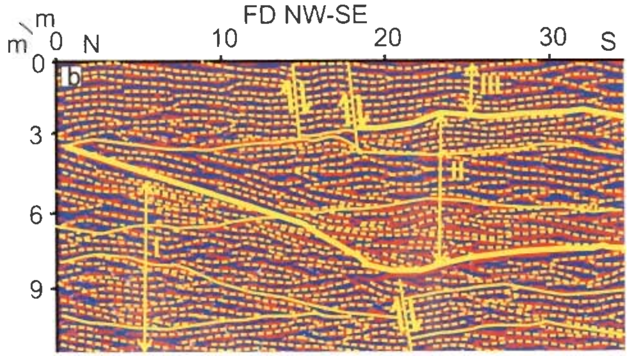


Fig.4.4 GPR profiles across (a) West Patna fault (T-10) and (b) South Muzaffarpur fault (T-9)

4.6.4 Radar sequences

Following Best et al. (2003) radar sequences are identified from the GPR profiles by surfaces, which separate different various radar sequences, provide good reflections and are traceable over the whole length of the profile. In general two or three such sequences are seen from most of the radar profiles.

4.7 OBSERVATIONS

4.7.1 Fault and related terminal fans (T-9 and T-10)

GPR studies of faults in the fluvial sediments of the Upper Gangetic plain was first carried out by **Bhosle et al., (2006b).** Following this study, GPR studies were carried out across the West Patna Fault (WPFt) and South Muzaffarpur Fault (SMRFt) (inferred to be active faults, see Sec.2.9.3.3), and the latter one is responsible for the development of Burhi Gandak terminal fan-II and the Bagmati terminal fan-II (Sec 2.5.2).

West Patna Fault (WPFt)

The West Patna fault is a basement fault trending NE-SW (G.S.I., 2000) and the DEM of the region around this fault and field observations suggest that the fault is an active, and nascent one, with distinct surface displacement of up to 4 m (Fig. 4.4) at places, which die out gradually laterally. In-between active segments lay areas that show no surface displacement. The South Muzaffarpur Fault is not a basement fault, but it also a nascent fault, showing features similar to the West Patna Fault. In the GPR profile T-9 (Fig.4.4) ten faults shows displacement in the lower part of the profile. However, the younger sediments in the upper part of the profile are not disturbed. Segment over which traverse has been taken is marked by a blind fault, whereas at other places, it is characterized by surface displacement in the recent times. Most of the faults show downthrow towards south. However, three faults in the southern part of the profile exhibit downthrow northwards, forming a basin.

Three broad radar sequences are identified in the profile. Thickest unit I (9 m) is marked by development of bar by cessation of dunes, which successively shows bar migration slip face (BMSF) accretion and VABT, leading to increase in height as well width of the bar. This is followed by mud deposition in a pond (grabben) in the southern portion, created due to movements along normal faults. Sequence II is mainly thin (1-2 m) deposit formed by accretion in the channel in north passing into lateral accretion in the south. Sequence III is floodplain mud facies.

Nine meter thick sequence I could have been deposited by a large river like Gandak, whereas the thin sequences II and III have been deposited by the Baghmati River, on whose fan the traverse lays.

Since the profile T9 on the Baghmati Fan is very close to the Burhi Gandak River course, where the Gandak once flowed. The radar profile suggests that the Gandak River flowed in the profile area and later this area was covered by the Baghmati River fan sediments.

South Muzaffarpur Fault (SMRFt)

In T-10, three main radar sequences are identified. Radar sequence-I (3-6 m) is characterized by mainly sigmoidal cross-beds. However, radar sequence

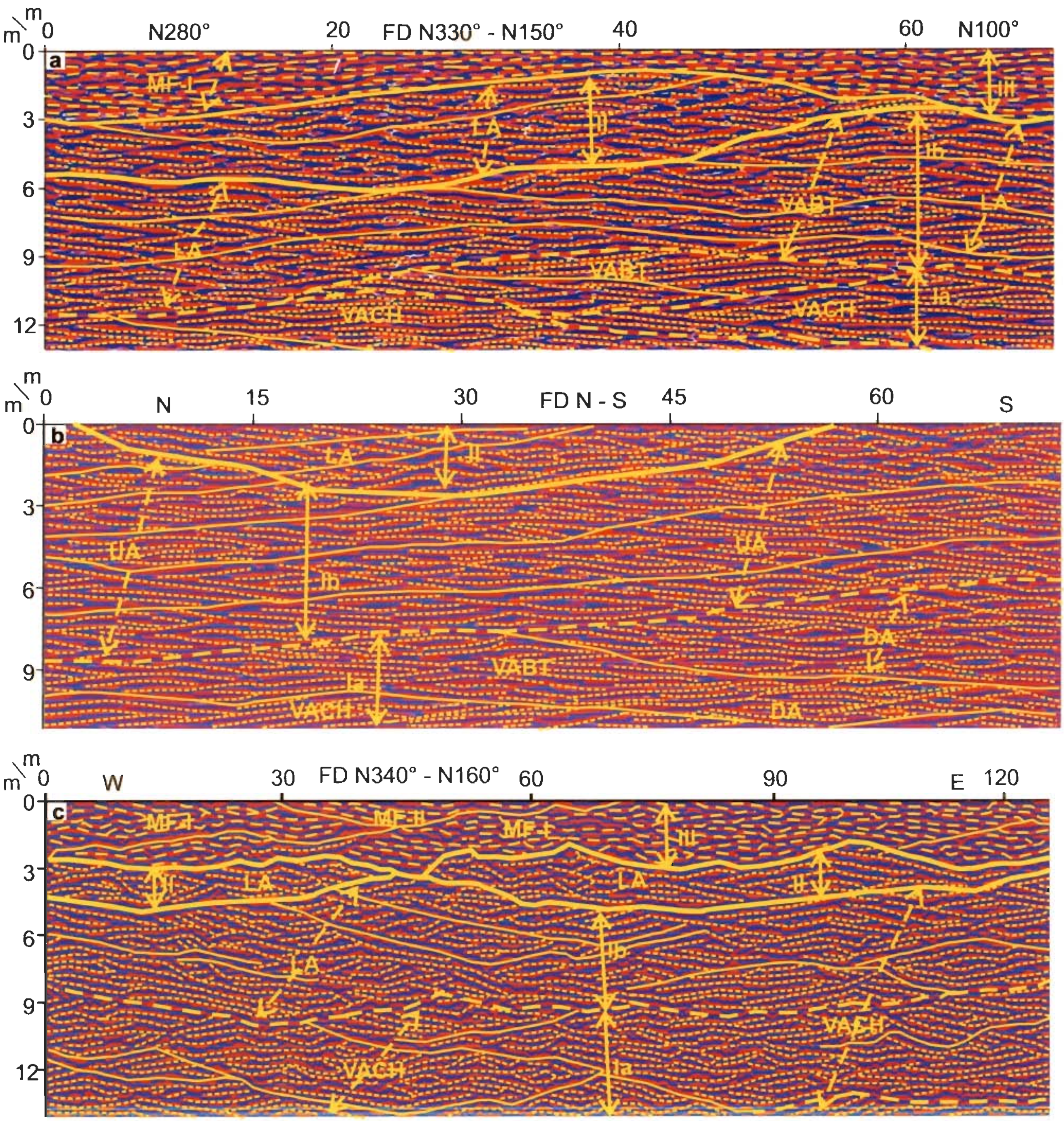


Fig.4.5 GPR profiles taken on the Gandak terminal fan-II & III (a) at Molanpur (T-1). The sequence-Ia shows vertical accretion in channel (VACH) and vertical accretion on bar top (VABT). The sequence-II is deposited by the splays of Gandak and show lateral accretion (LA).Sequence-III is mud depo- sited by the abandonment of channel. (b) at Saidpur (T-2). The sequence-Ia is deposited by Gandak River. The bar top shows vertical accretion (VABT) and downstream accretion (DA) at bar migr ation slip face. Sequence-Ib shows upstream accretion (UA). The sequence-II shows lateral accretion (LA) of sands deposited by small channels and (C) at Bagahi (T-3). The sequence-Ia shows vertical accretionin channel (VACH), Ib shows lateral accretion and sequence-III shows mud deposits.

II consists of three thin fluvial sequences (2-3 m) with upstream and downstream accretions. Radar sequence III is a mud deposit occurring over the whole length of the profile, indicating vertical accretion in a floodplain. Also, South Muzaffarpur Fault (SMRFt) is represented by three subsurface faults, showing displacement of sediments of sequences-I and III.

The area witnesses shifting of the large Gandak River away from this area, Sequence I with sigmoidal cross-beds is attributed to 'vertical accretion in channel' (VACH) of the large Gandak River. Three thin fluvial sequences in sequence II with a lot of upstream and downstream accretions are considered to be deposited by the Burhi Gandak River. These don't continue to North far beyond the inferred faults and thus are interpreted to have been deposited contemporaneously with three phases of the activity of the SMRFt.

4.7.2 GPR Studies of the Gandak Terminal Fans-II & III (Traverses T-1, T-2 and T-3)

As described earlier, first the Gandak River swept across its fan from west to east. Later the Gandak terminal fan-II and III developed on the south-western corner of the Gandak Fan due to the activity of the longitudinal South Motihari Fault (SMFt) (Fig.2.6) at about 4.5 ka and 0.6 ka, respectively. The younger terminal fan-III is smaller than terminal-II and covers only part of the terminal fan-II (Fig. 2.5). The terminal fan-III shows a number of sandy paleochannels and low-lying channels with floodplain deposition on a large scale with widths of 4-5.5 km diverging out from the point, where the Gandak enters the downthrown block of the South Motihari Fault. It indicates frequent splays developed from the

Gandak River, leading to the formations this terminal fan. The low-lying paleochannels are also marked small meandering steams and numerous ponds located in linear fashion along the splays. Organic-rich mud is being deposited in these ponds.

Three traverses T-1, T-2 and T-3 were taken on the Gandak terminal fan-II (GTFn).Traverses T-1 and T-3 are on low-lying the paleochannels. Traverse T-2 is on a sandy paleochannel.

Traverse T-1

A 70 m traverse (T-1) from N280° to N100° direction (Fig. 4.5) was taken on the low-lying paleochannel (flow direction N 330° to N 150°) in the GTFn near village Molanpur (84°34′E and 26°10′N), 28 km east of Siwan. Three radar sequences are identified from the traverse. The lowest part of the profile (sequence Ia), two bars with heights of 4 m are observed, which formed by vertical accretion in the channel (VACH). These get amalgamated by vertical accretion at the top into a large bar with height of about 5.5 m. Later deposits (sequence Ib) apparently form a drape over this bar. As flow directions given by individual accretion on the sides of the large bar are almost in the opposite directions, it seems large bar is marked by lateral accretions on the two sides and vertical accretion on bar top almost simultaneously. Later a smaller meandering stream deposits the sequence II as a lateral accretion, followed by sequence III marked again by lateral accretions with much smaller tabular cross beds, indicating smaller stream.

The geometry and the scale of the architectural elements and the litho facies assemblage suggest that the deposition of the radar sequences I took place by an active phase of the Gandak River, which gave rise to a 4 m high braid bar. Sequences-II and III were deposited by successively smaller streams, representing deposition of the Gandak terminal fans II and III, respectively.

Traverse T-2

A 73 m traverse from South to North was taken along the approximately flow direction of a paleochannel forming a slightly raised ridge within the an overall low-lyinging region, near the village Saidpur (84°31´E and 26°12´N) about 21 km east of Siwan (Fig.4.5).

The profile is composed of three radar sequences I-III. The sequence I (>3 m) is mainly flat bedded or sigmoidal cross-bedded, showing VACH and II is mainly marked by 'upstream accretion' (UA). The thin sequence III (~2.5 m) within a small channel is interpreted as lateral accretion deposit of a small stream.

The sequence-I is considered to have been deposited by the large Gandak River. Sequence II was probably deposited by a small stream, a splay of the Gandak River to form the Gandak terminal fan-II. The sequence III is composed of laterally accretion sand of a small channel during the deposition of the Gandak terminal fan –III.

Traverse T-3

A 70 m long traverse, T-3 (Fig. 4.5) was taken about 35 km east of Siwan at village Bagahi (84°37´E and 26°9´N) within the paleochannel now represented by pond-dominated area. Here three radar sequences are identified. Radar sequence-I consists of sigmoidal cross-bedded sand facies formed by vertical accretion in channel in its lower part (Ia) and the major part of the sequence (Ib) is composed of lateral accretion deposits in the western end, which pass into vertical accretion in channel deposits towards the eastern end of the profile. Sequence-II Is composed of two isolated, thin laterally accreted sand bodies, deposited probably by small streams, Sequence-III consists mud facies of vertical accretion in a floodplain (MF-I) and within abandoned channels (MF-II).

The sequence-I seems to have been deposited by large Gandak River during its sweep across the Gandak Fan from west to east. Later due to the activity of the SMFt, splays from the Gandak River deposited sequence-II. Sequence-III probably represents deposition from splay channels carrying floodwaters of the Gandak River.

Major thick lowermost parts of all the three profiles T1-T3 on the Gandak Terminal fan-III have been deposited by the large Gandak River during its sweep from west to east. The middle thinner parts of these profiles consisting of lateral accretion sands and vertical accretion in small channels seem to represent deposition of the Gandak terminal fan-II. The topmost sequences composed of thin lateral accretion sands (Section T2) and mud facies MF-I and MF-II were deposited by meandering splays from the Gandak River into the downthrown block of the SMFt, forming a low-lying area. This represents deposition of the Gandak terminal Fan-III.

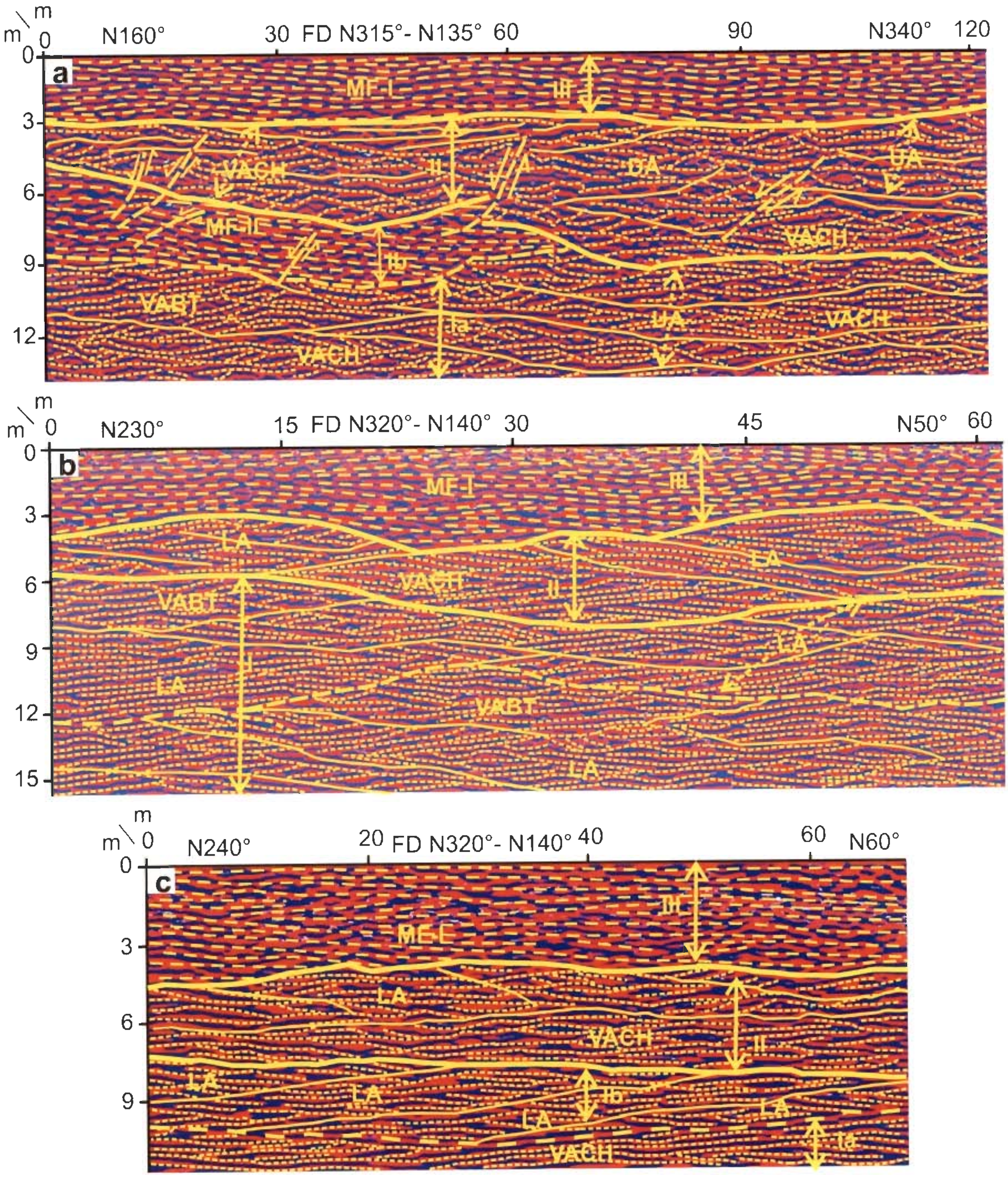


Fig.4.6 GPR profiles taken on (a) Burhigandak terminal fan-II at Abdulpur (T-4). Alternative sand and mud is recognized in this profile.The sequence shows vertical accretion in channel (VACH) and vertical accretion on bar top (VABT). Upstream accretion (UA) and Downstream accretion (DA) are found in this profile. Small scale deformations are marked probably the effect of the Patna-Singwara Fault (PSFt). (b) On Burhigandak terminal fan-I, at Tajpur (T-5).This profile shows vertical accretion on bartop (VABT) and in channel (VACH. Lateral accretion (LA) is dominant in this profile. (C) at Garaura (T-6). The sequence shows vertical accretion in channel filling and shifting of channel shows Lateral accretion (LA).All the three profiles show mud at the top indicating channel abandonment.

4.7.3 GPR Study of the Burhi Gandak Terminal Fan-II (BGTFn-II) (Traverse T-4)

The Burhi Gandak Terminal Fan-II (BGTFn-II) formed (Sec.2.5.2) due to the activity of the West Patna Fault (WPFt). This terminal forms marshy land occupied by numerous ponds and small groundwater-fed streams. One traverse (T-4) was taken along the flow direction.

Traverse T-4

Traverse T-4 was taken at Abdulpur (85°25′E and 25°46′N), 32 km NE of Hajipur along the flow direction. This 120 m long profile (Fig.4.6) is sub-divided into three radar sequences I-III. The radar sequence-I consists of mainly sand deposited by vertical accretion in the downstream end of the profile. Further deposition is by upstream accretion, which passes into VACH towards northwestern end of the profile and the top of the sequence is marked by vertical accretion on the bar top. Later the channel is abandoned, in which mud accumulated. Sequence-II shows accretions in channel, and upstream and downstream accretions. Sequence-III is composed of floodplain mud. Also, five normal faults with throws to the south are observed to affect the sequences-I and II. The lower sequence-I probably continues for a few meters to deeper levels and was deposited by the large Gandak River. After its shifting, the meandering Burhi Gandak deposited the radar sequences-II & III, measuring up to 8 m in thickness on the Burhi Gandak .terminal fan-II. It also indicates that the Burhi Gandak carries considerable charges. The Patna-Singwara Fault is represented by the five small faults. Since these faults don't affect the sequence I, these faults developed during and/or just after deposition sequence II.

4.7.4 GPR Studies of the Burhi Gandak Terminal Fan-I (BGTFn-I) (Traverses T-5 AND T-6)

The Burhi Gandak terminal fan-I was formed by the activity of the South Muzaffarpur fault (SMRFt) (Sec.2.5.2). The terminal is overlain numerous small meandering streams, which avulse frequently. At places small depressions (abandoned channels) contain stagnant water bodies, are sites of the mud deposition on the fan. (Fig. 4.2). Two traverses (T-5 and T-6) were taken along and oblique the flow direction.

Traverse T-5

Traverse T-5 (Fig. 4.6) was taken at Tajpur (85°40′E and 25°51′N) along the flow direction of the channel i.e. N230° to N50° (profile direction). Three Radar sequences are identified here. The bottom sequence-I (>8 m) is composed of two subsequences marked by lateral accretion deposition (Ia) overlain by VABT (Ib). The lower subsequence forms a distinct braid bar. Sequence-II (3 m) represents deposition from VACH followed by lateral accretion. Sequence-III is marked by floodplain deposits.

The lower thick deposit (sequence-I) was deposited by large Gandak River and the sequences-II and III are considered to have been deposited by the Burhi Gandak River as a part of the Burhi Gandak terminal fan-I.

Traverse T-6

Traverse T-6 was taken at Garuara (85°45′E and 25°55′N) 20° oblique to the flow direction (Fig.4.6). Three radar sequences I-III are observed here.

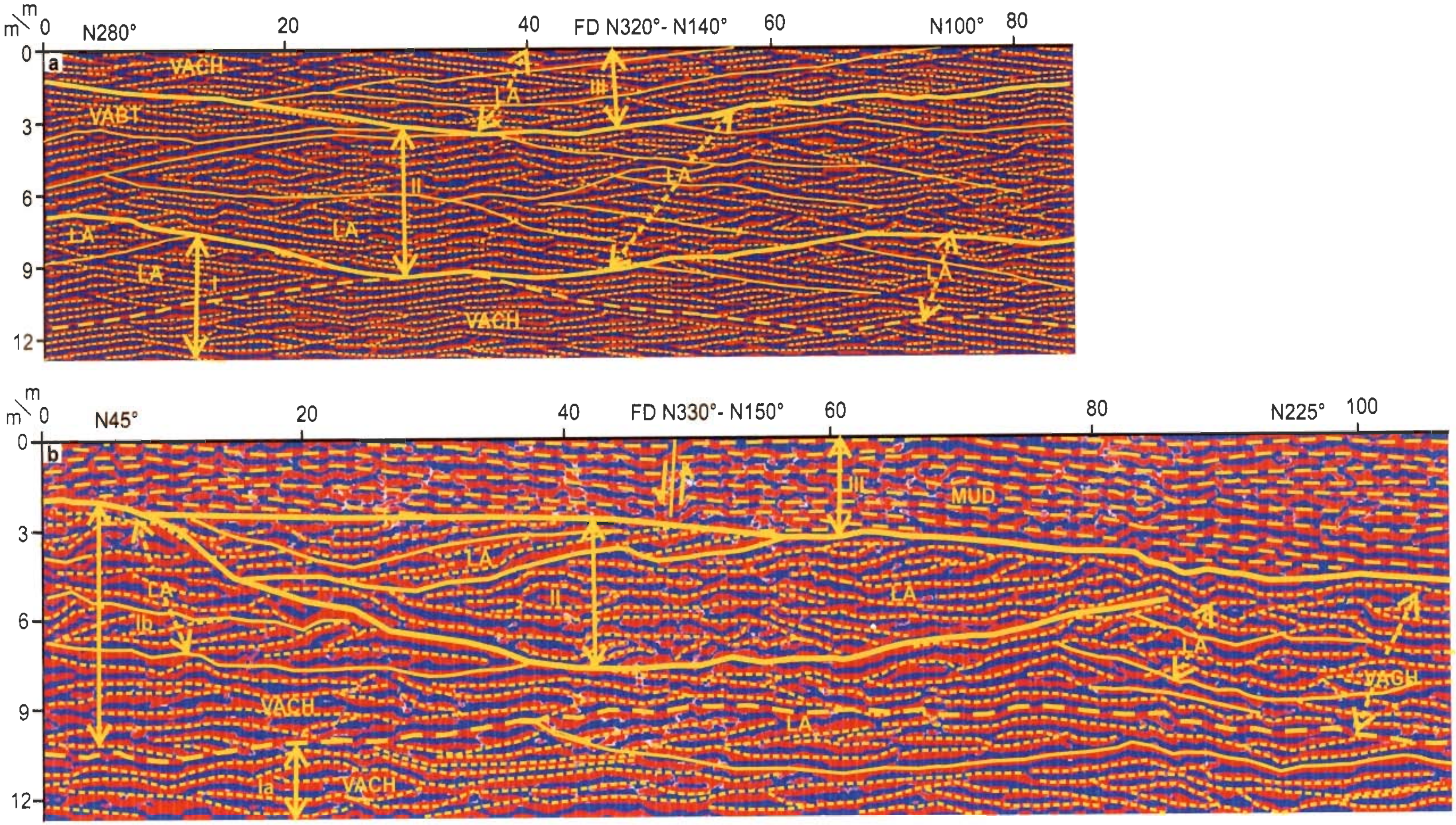


Fig. 4.7 GPR profiles on the Baghmati fan-I (a) at Harkmansahi, Channel is filled by vertical accretion (VACH) and channel shifting is marked by lareral accretion (LA) (b) at Lohsari, Channel is filled by vertical accretion (VACH) and the new channel cuts the older one is filled by lateral accretion. The upper surface is marked by mud deposits due to channel abandonment.

Sequences-I and II are composed of VACH deposits overlain by LA deposits. Sequence-III (4.5 m) is a floodplain deposit of the Burhi Gandak River.

Though sequences-I and II exhibit similar sequences depositional facies and thicknesses, the sequence-I probably continues to a fair depth, is considered to have been deposited by the Gandak River. The Burhi Gandak deposited both the sequences-II and III on the Burhi Gandak terminal fan-I. Thus the Burhi Gandak River has deposited fairly thick sequences in the form of terminal fan-I over the earlier Gandak River deposits.

4.7.5 GPR Studies of the Baghmati Terminal Fan-I (BFn) (Traverses T-7and T-8)

As discussed in Sec. 2.5.2, the Baghmati River has a braided nature over major part of the fan. The river shows extreme migration of its courses, leading Sinha et al. (2005) to call it a hyper-avulsive river. After the shifting away of the Baghmati, still smaller meandering streams take over the area, which leave behind numerous abandoned channels and oxbow lakes. The Bagmati terminal fan is subjected to frequent flooding during rainy season. Two oblique traverses (T-7and T-8) were taken at angles of 30° and 75° to the flow direction, respectively.

Traverse T-7

Traverse T-7 (Fig.4.7) was taken at village Harkmansahi (85°20′E and 26°18′N) 28 km north of Muzaffarpur. The profile shows three radar sequences Sequence-I is composed of sand, deposited by VACH processes and later two ends of the profiles are marked by LA. In sequence-II mainly LA deposits are present, which towards west end pass into VABT deposit. Sequence-III is a channel deposits with mainly lateral accretions.

Sequences I-III have been deposited by the shallow braided Baghmati River, which has deposited mainly lateral accretion sediments, which laterally pass into deeper channel deposits, marked by vertical accretion.

Traverse T-8

Traverse T-8 was taken at the village Lohsari (85°29´E and 26°13´N) (Fig.4.7). The 12 m thick profile is vertically subdivided into three radar sequences I-III. Sequence-I is composed of a large dune with a height of 9 m, formed due to vertical accretion in the channel, which grows by lateral accretion. This is followed up by vertical accretion in major parts of the channel depositing a thin (2 m) flat-bed sand. Later two ends of profile show lateral accretion deposits. Sequence-II shows a large channel with a maximum depth of 5 m. This is marked by lateral accretion leading to development of successively two smaller channels, which are also filled mainly by lateral accretion and minor VACH. Sequence-III with (2-4 m) thick mud represents vertical accretion in a floodplain

Profile T-8 essentially consists of two bottom sandy sequences, which are marked by mainly sand deposited by lateral accretion processes, which pass downwards or laterally into VACH sands of mainly flat-bedded nature. The topmost part is floodplain mud facies.

Though the Baghmati River has braided character in the study area, because of shallow depth, lateral accretion deposits are major deposits in the area. Frequent flooding of the area leads to deposition of thick mud facies.

4.8 RESUME

GPR studies have provided an insight into subsurface nature of faults, their effect on sedimentation and processes involved in deposition of the Gandak Megafan and terminal fans.

1. Faults

a. Using GPR, we confirmed the presence of two faults i.e. West Patna Fault (WPFt) and South Muzaffarpur Fault (SMRFt). The WPFt is a set of normal faults, whereas the SMRFt consist of two major normal faults.

b. GPR studies bring out that due to the activity of normal faults, terminal fans were deposited on the downthrown sides.

c. In one of cases, a grabben was created due to activity of normal faults, which formed a pond, in which mud were deposited.

d. In traverse T-9, we observed three sandy sequences (each 2-3 m), overlying thick sands of a large river (Gandak) on the downthrown block of the South Muzaffarpur Fault (SMRFt), and indicating repeated activity of the fault.

e. Activity of the South Motihari fault at 4.5 ka and 0.6 ka and development of Gandak terminal fans II and & III in almost same area is confirmed by the presence of three GPR sequences in the area (Main Gandak River, Gandak terminal Fan-II and III sequences).

2. Gandak River Sediment Facies

a. The older Gandak River underlying some terminal fan deposits consist of braid bar deposits formed due to stoppage of migration of dunes or deposition in upper plane bed phase and sigmoidal to trough cross-bedded sand in deeper anabranches in the lower parts, where in upper parts, lateral accretion, upstream/downstream accretions are very common. The bars may be marked by vertical accretion on bar top.

.b. Rarely Gandak deposits show bar margin slip face migration, giving rise to large scale cross-beds. Thickness of such deposits increases, as the bar grows in size.

c. Best et al. (2003) observed that upstream accretions on braid bars of the Jamuna River in Bangladesh are thin and occurring only in the upper parts of braid bar sequences. However, in our case upstream accretion deposits are much thicker

3. Terminal fan sediment facies

a. Terminal fan sediments are composed of mainly lateral accretion deposits and minor vertical accretion in channel deposits overlain by mud facies. The overlying mud facies deposited in floodplains and/or in abandoned channels.

b. Well defined channels on the terminal fans in the upper part of their sequences show distinct stages in their filling by lateral accretion.

LINE DIAGRAM OF GPR PROFILES

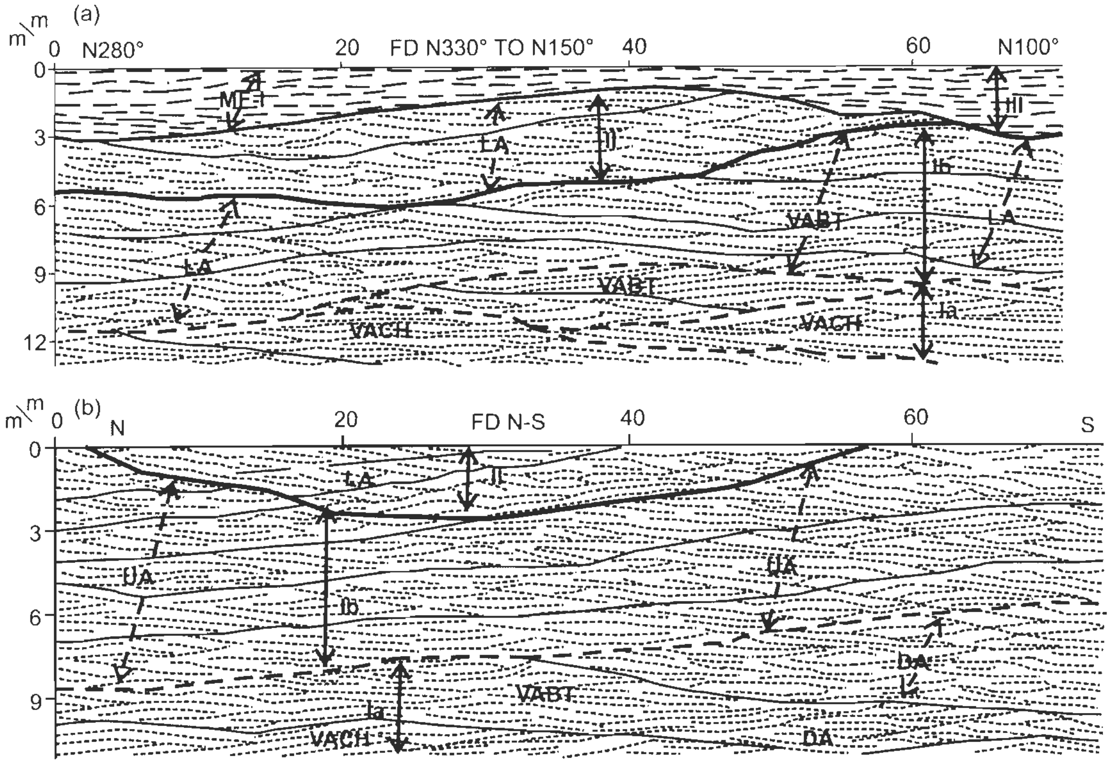
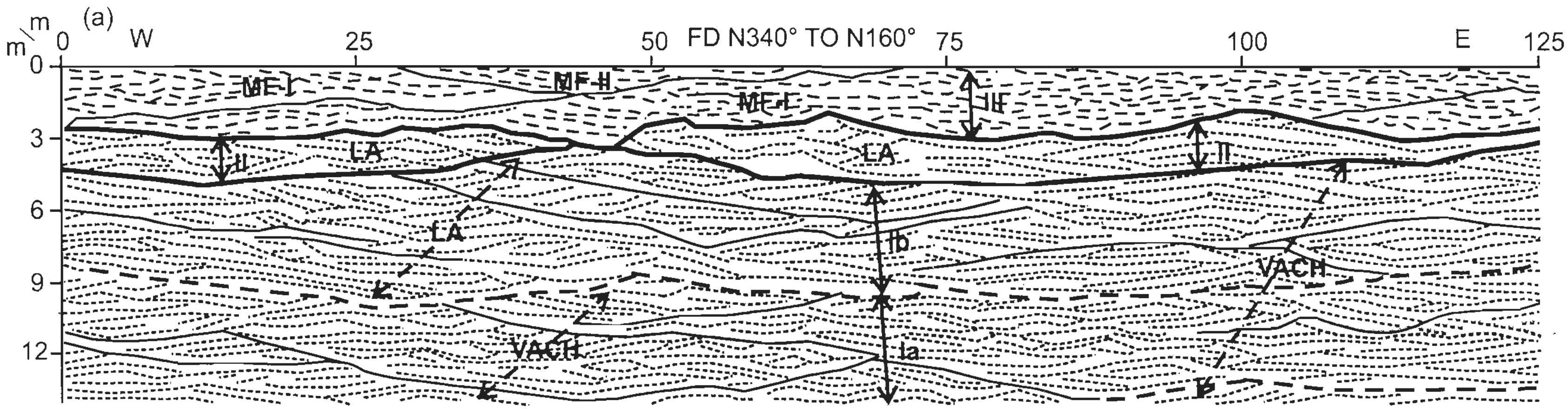


Fig. 4.8 Interpretation of GPR profiles on the Gandak terminal fans II & III (a) at Molanpur (T1) (b) at Saidpur (T2)



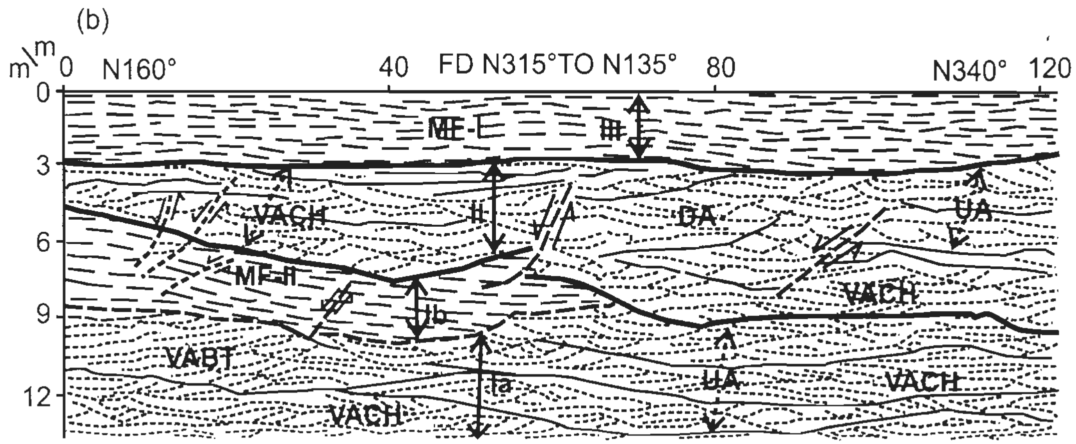


Fig.4.9 Line diagram of GPR profiles (a) on the Gandak terminal fan II & III at Bagahi (T-3) (b) on Burhigandak terminal fan-II at Abdulpur (T-4)

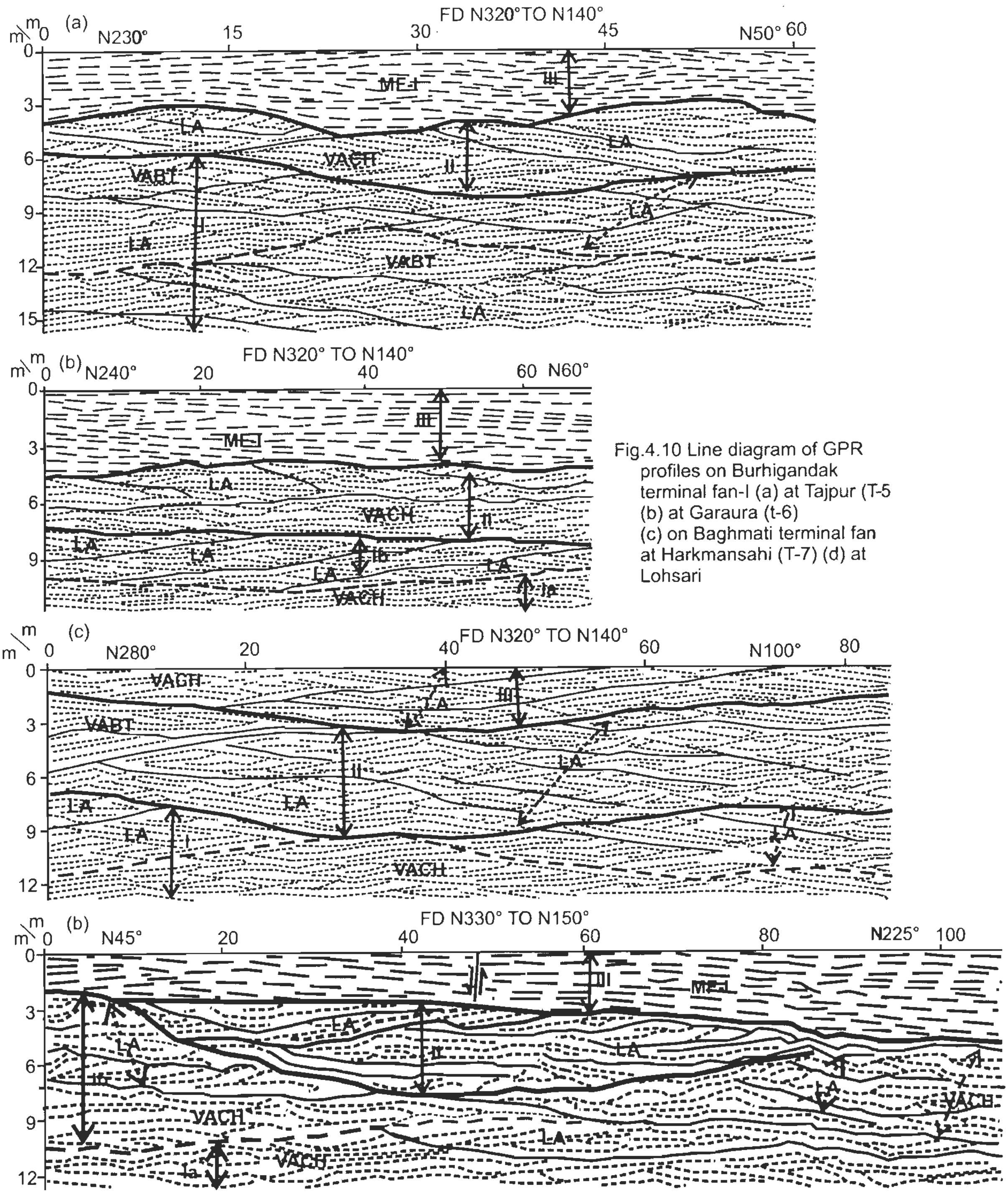


Fig.4.10 Line diagram of GPR profiles on Burhigandak terminal fan-I (a) at Tajpur (T-5 (b) at Garaura (t-6) (c) on Baghmati terminal fan at Harkmansahi (T-7) (d) at Lohsari

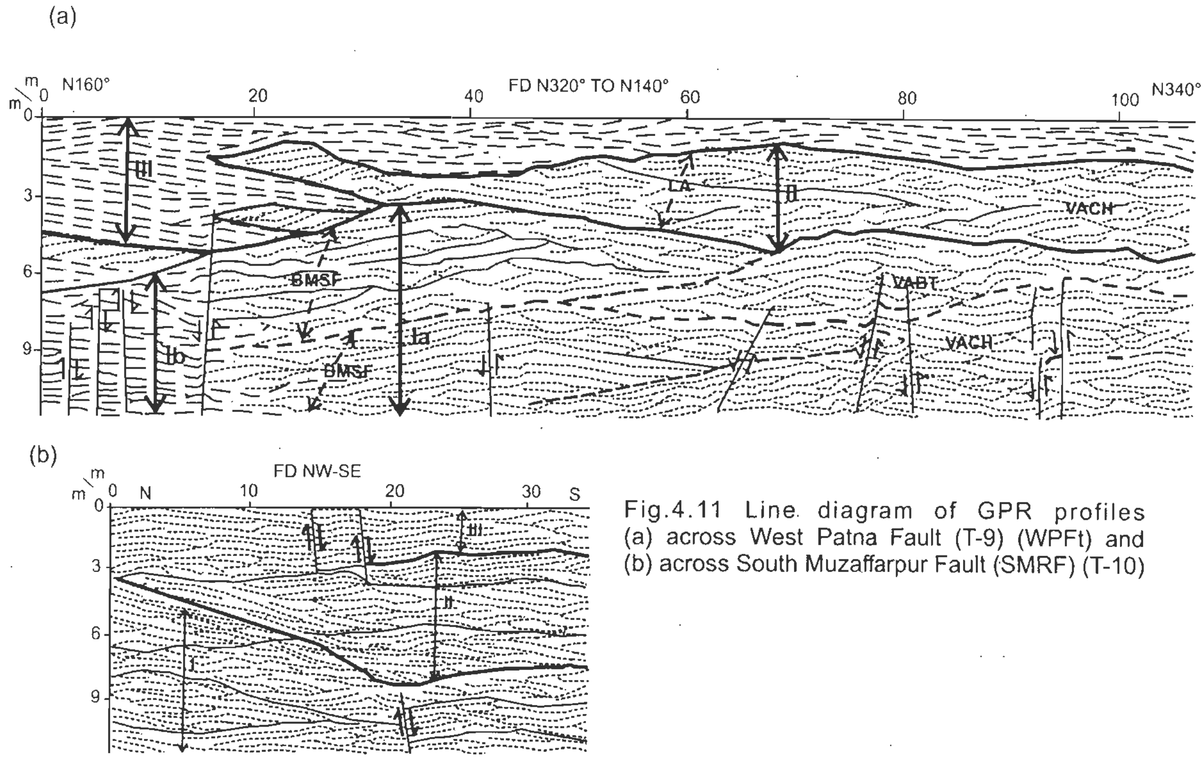


Fig.4.11 Line diagram of GPR profiles (a) across West Patna Fault (T-9) (WPFt) and (b) across South Muzaffarpur Fault (SMRF) (T-10)

CHAPTER-5

GRAIN SIZE DISTRIBUTION AND MICROMORPHOLOGICAL STUDIES OF TYPICAL SOIL PROFILES

5.1 INTRODUCTION

During field investigation, it is not possible to identify all the properties of soils accurately. Hence certain properties like grain size distribution, clay content, PH and electrical conductivity micromorphological studies of soil thin-sections studies were carried out in laboratory. Laboratory analyses of soil are used for several purposes: to quantify some properties more precisely estimated during field investigation like particle size distribution and to understand various soil forming processes (salinity, clay illuviation etc), to identify the parent materials of each horizons and classification of profiles inferred from field observations (Catt, 1986, 1990). In the present study, grain size distribution especially clay contents, and micromorphological study were carried out on typical soil profiles to understand the soil development process and the role of climate if any in their development in the study area.

5.2 PARTICLE SIZE DISTRIBUTION

A total of 100 soil samples from typical soil profiles of different soil-geomorphic units (Fig. 2.2) were investigated for particle size distribution. Particle size analyses were carried out to determine the soil texture (Figs. 5.2 and 5.3) and the amount of clay present in the soil. Soil texture (Catt, 1986, 1990) has been used to workout the nomenclature of soil horizons and classification of soil profiles (Appendix-I).

5.2.1 Methodology

To determine the grain size distribution of soil profiles, the loose samples collected during field work were air-dried and disaggregated. The lumps and clods were thoroughly broken by a wooden pastel. Then the samples were thoroughly mixed and were split into quarters. The opposite quarters were taken for further analyses.

Generally soil particles are bounded by carbonates, organic materials and iron oxides. So at first these materials were removed from the soils to get the grains separated from each others. The removals of the binding materials were carried out by the methods described by Galehouse (1971). The carbonates were removed by the treatment of the samples with 1N HCl. Organic matters were removed by treating the samples by 6-30% H_2O_2 gradually. Iron oxides were removed by putting an aluminum foil and 15 gm of oxalic acid in the soil solution and by boiling it gently. Soluble salts were removed by repeated washing with distilled water. After removing all the binding materials, Sodium hexametaphosphate [Na $(PO_3)_6$] was used as dispersing agent for complete dispersion. Then different size fractions were separated by sieving and pipetting methods.

Sand fraction was separated from the dispersed sample by wet sieving with 230-mesh (>62.5 μm) sieve. Silt and clay fractions were separated by pipette method (Galehouse 1971). Sand, silt and clay percentages (Appendix-II) were calculated according to the size classification used by U. S. D. A. soil survey Manual (1966) (i.e. sand = 2 to 0.05 mm, Silt = 0.05 to 0.002 mm and clay = < 0.002 mm size fraction).

5.2.2 Textural variation and pedogenic clays in soils of the different soil-geomorphic units.

Textural classes were determined from the particle size data according to Schoeneberger et al. (1998) by plotting the sand, silt and clay percentages in a combined texture triangular diagram (Fig. 5.1). The result of the particle size distribution is given in the Appendix-II.

Particle size distribution shows that texture of soils vary in a wide range from sandy loam to silty loam (Fig. 5.2 and 5.3). Most of the soils are grouped in to coarse loamy soil texture family. However, QGMS-IV shows a transition from coarse loamy to fine loamy texture. Soils of the area are mainly coarse loamy and become heavier especially in B-horizon with increase in soil development.

Loamy sand to sandy loam soil occurs in the QGMS-I and they do not show any significant change in the sand, silt and clay content (Fig. 5.4) with depth, which suggests no significant change of the fluvial depositional processes in the area or clay illuviation. The young soils (QGMS-I and QGMS-II) have varied soil texture from sandy loam to sandy clay loam classes, where as the QGMS-III, QGMS-IV QGMS-V and QGMS-VI soils are categorized under loam to silty loam classes.

Plots of the total clay content with pedogenic clay content are shown in the (Fig. 5.6) and the degree of illuvial translocation has been assessed by calculating clay accumulation index (C.A.I) of Levine and Ciolkosz (1983). The clay accumulation index (C.A.I) varies from 0-186 in QGMS-I, 175-630 in QGMS-II, 200-985 in GQMS-III, 690-1270 in QGMS-IV, 1155-1205 in QGMS-V and 1525-1580 in QGMS-VI 5.3.

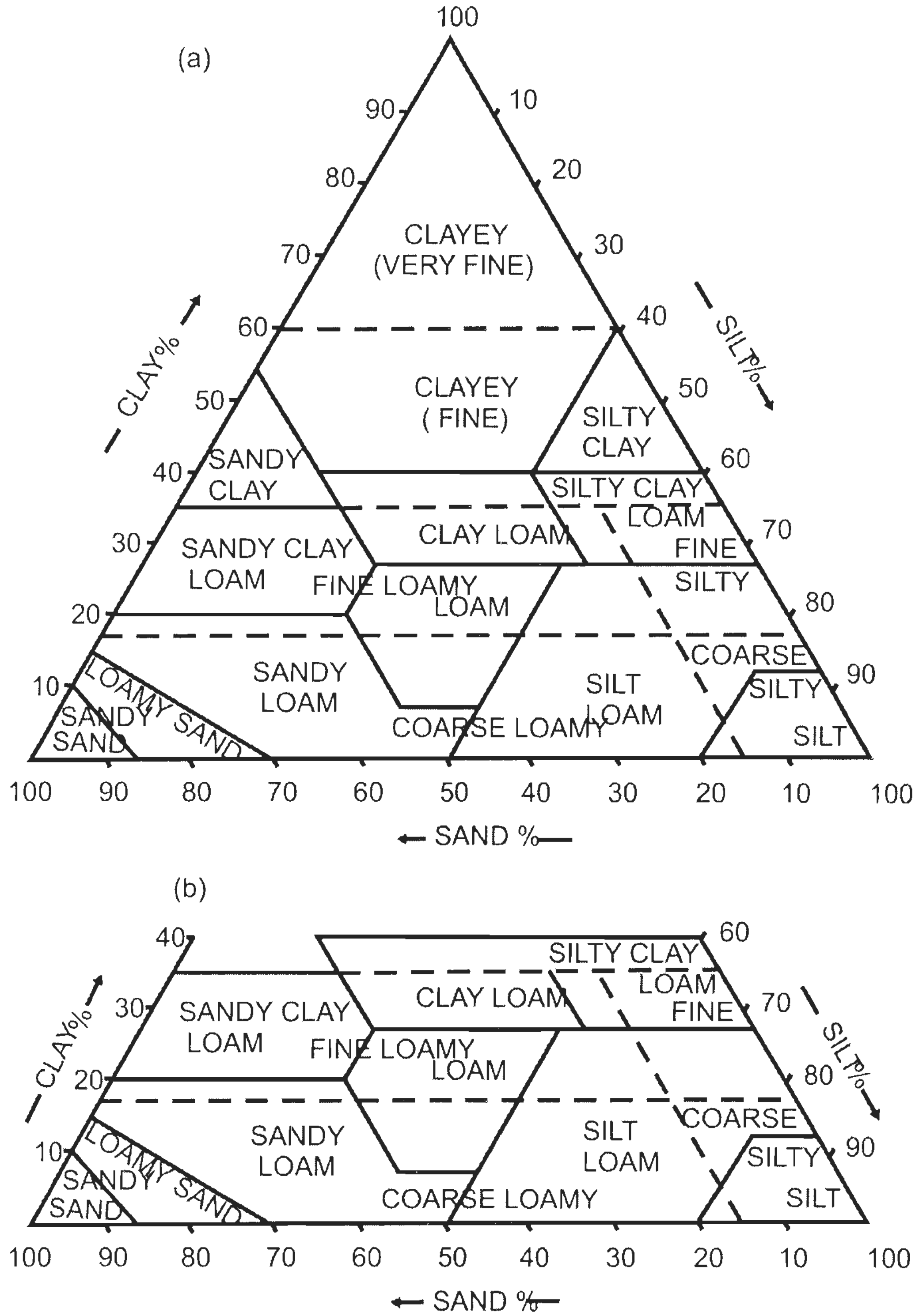


Fig. 5.1 (a) Combine texture triangles (Schoenberger et al.,1998). Solid lines represent fine earth textures and dotted lines represent soil texture family classes.

(b) Portion of the triangle used for plotting the soil texture.

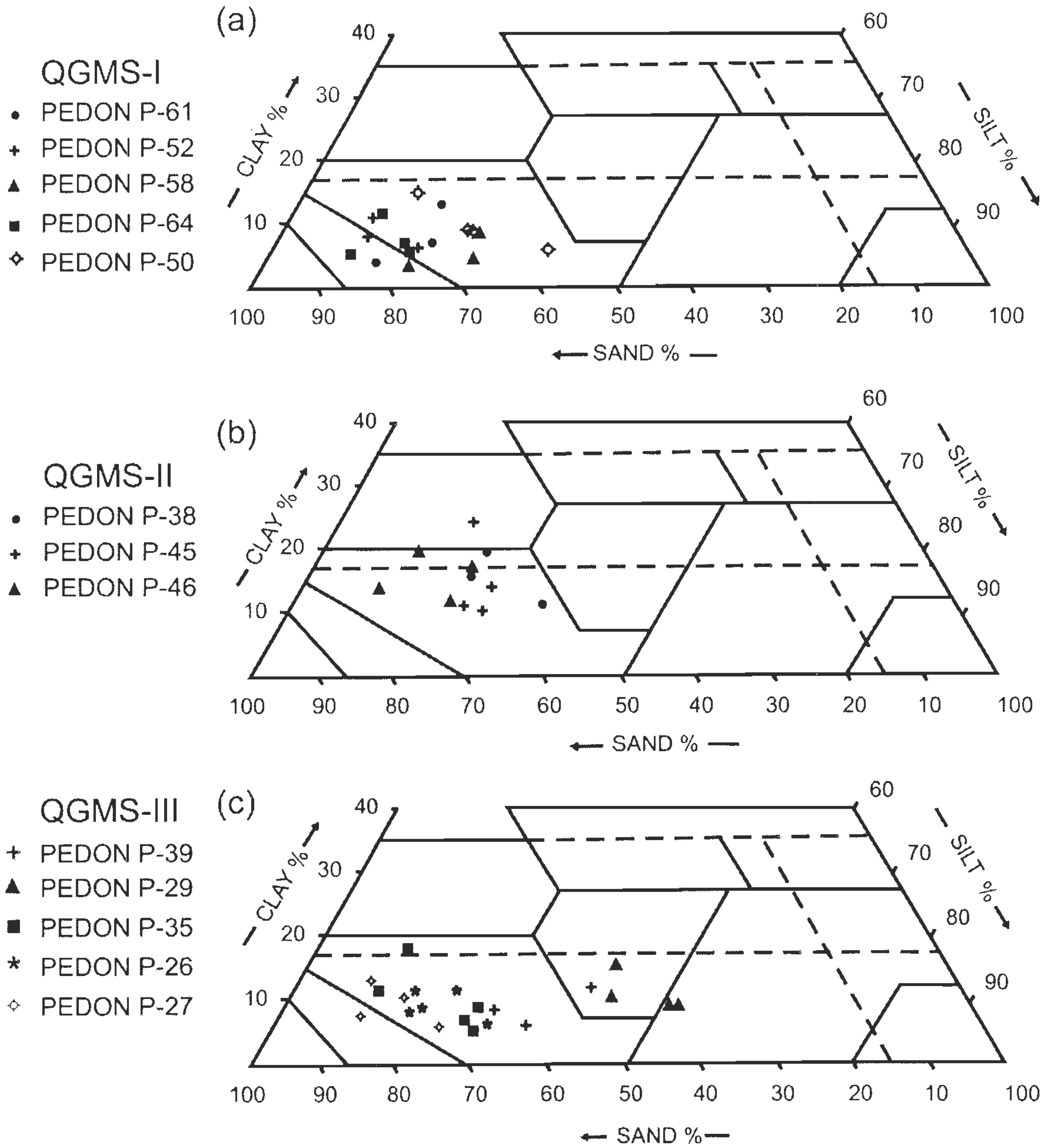


Figure 5.2 a-c Triangular plots of soil texture of typical pedons of QGMS-I,II and III

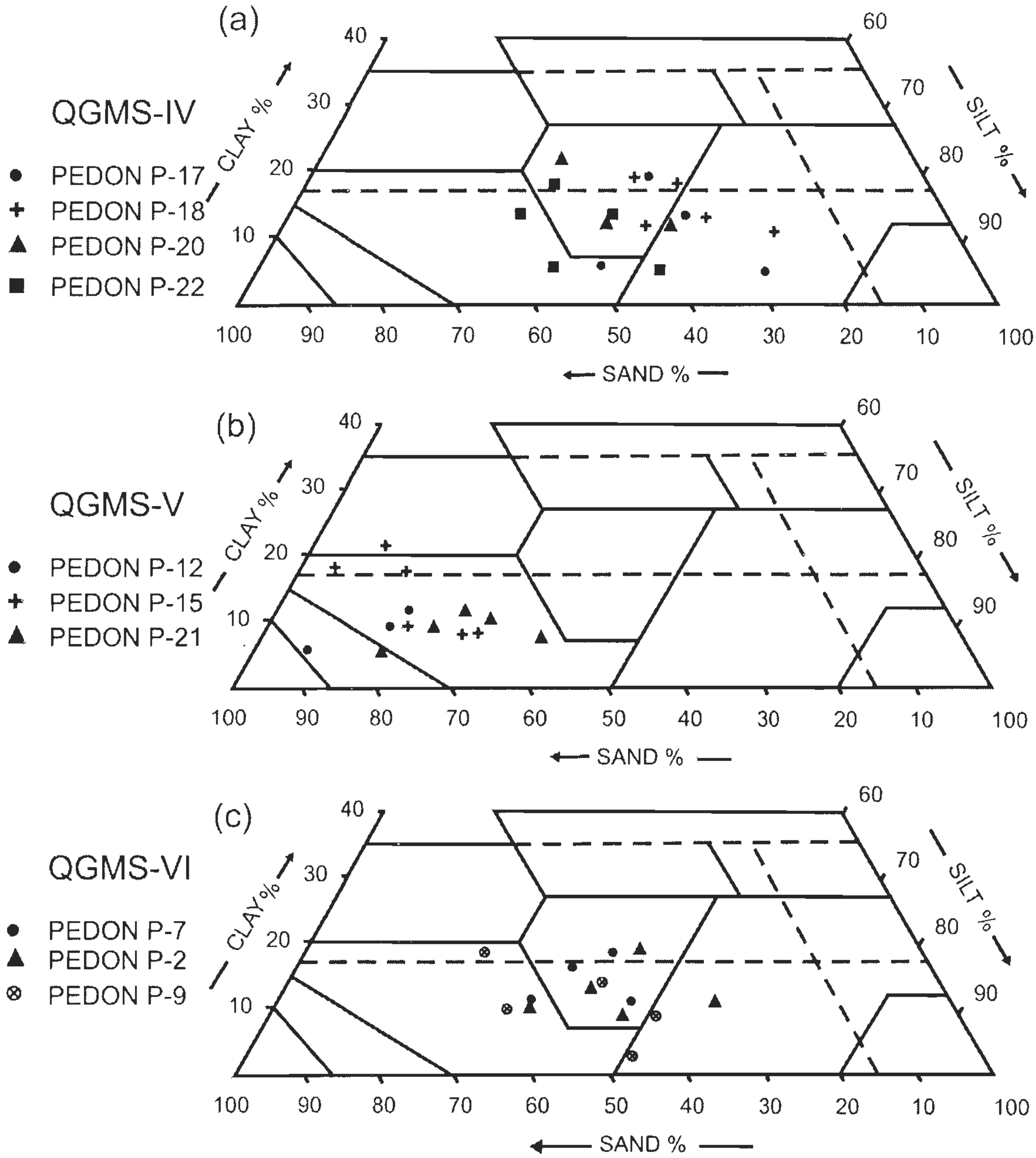


Figure 5.3 a-c Tringular plots of soil texture of typical pedons of QGMS-IV, V and VI

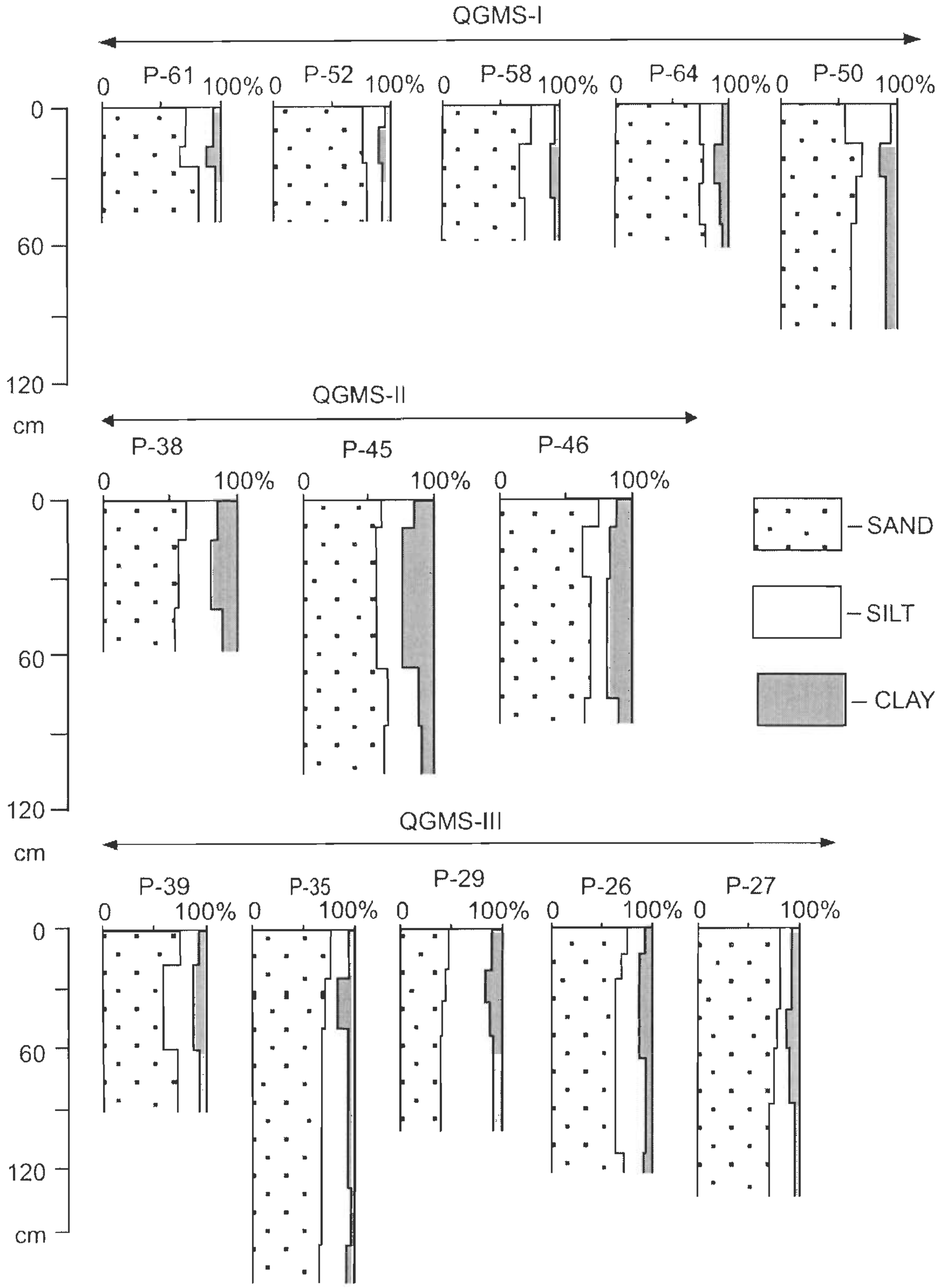


Fig. 5.4 Depthwise grain-size variations in typical pedons from different soil-geomorphic units

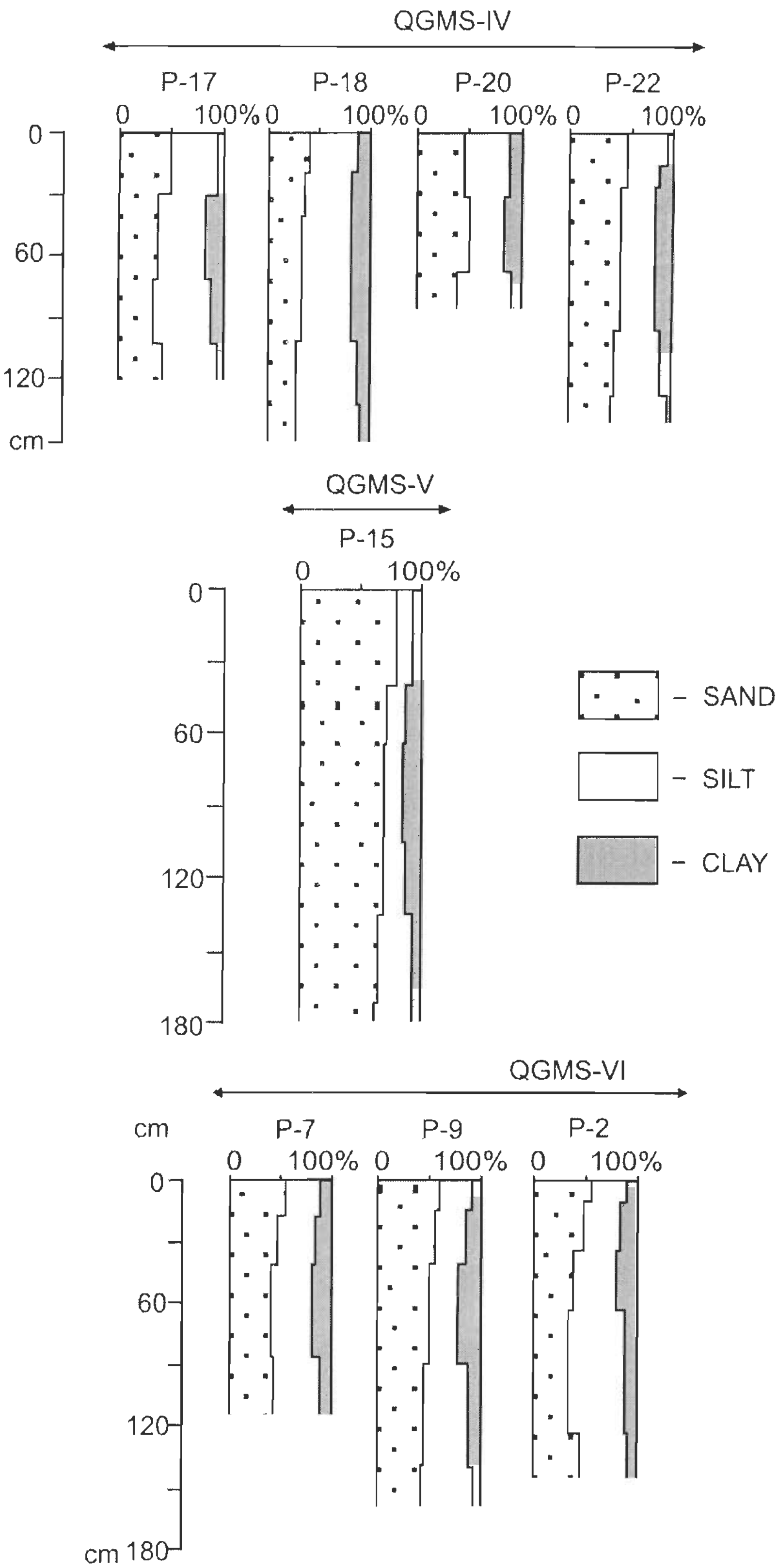


Fig.5.5 Depthwise grain-size variations in typical pedons from different soil-geomorphic units.

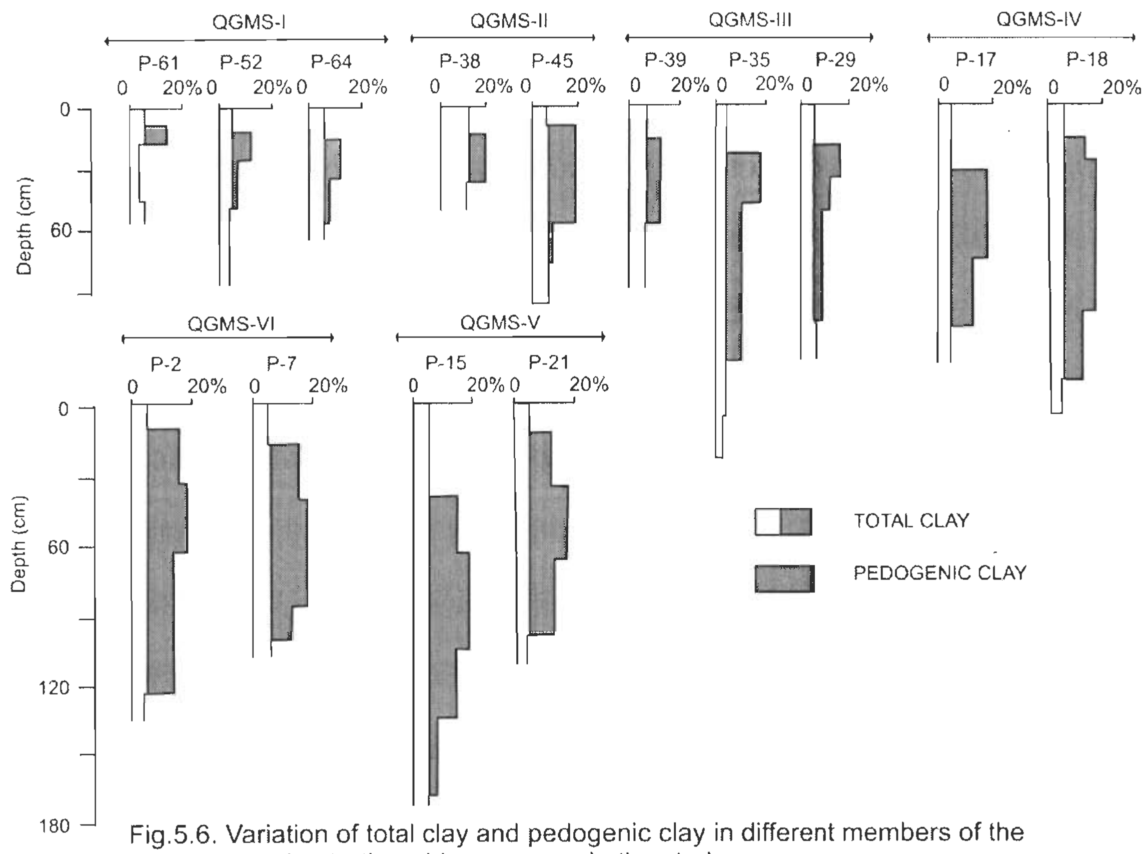


Fig.5.6. Variation of total clay and pedogenic clay in different members of the morphostratigraphic sequence in the study area

5.3 CHEMICAL ANALYSIS

A total of 100 samples from 24 profiles were analyses in the laboratory for determination of pH and EC (Table 5.1) Classification of various soils in terms of acidity and alkalinity was carried out according to U.S.D.A. (1966).

5.3.1 Soil Reaction (pH)

The numerical designation of soil chemical reaction is expressed as pH (U.S.D.A., 1966). To determine pH, a mixture of soil and distilled water in the ratio of 1:2 is prepared and shaking it intermittently for one hour (U.S.S.L.S., 1968) pH reading for the mixture was taken by Lutron PH-201 digital pH meter.

5.3.2 pH variation in soils of different soil-geomorphic units

Variation of pH is given in the table 5.1. In individual pedons, there is no definite order of increase or decrease of the pH value with depth. Members of the QGMS-I soils show acidic to neutral in nature with varying pH from 5.58 in Baghmati Terminal Fan-I to 6.67 of Old Ghaghara Plain. It is seen that the soil geomorphic units present in the low lying area and the piedmont zones are acidic in nature. However, the soil units of the low lying area are more acidic than the other members of the morphostratigraphic unit. The other members of the morphostratigraphic units show neutral to alkaline in nature. Soils of the Ghaghara-Rapti Interfluve are strongly alkaline in nature varying pH value from 7.85 to 8.36.

Increasing alkalinity with depth is mainly observed in the Old Gandak Plain and the Gandak terminal Fan-I & II which also show increasing of calcitic material with depth (Table 5.1). But the pH of the oldest Gandak Plain decreases with depth as compared with other soil geomorphic units of the Gandak megafan. This results decalcification of the parent materials of the Oldest Gandak Plain (Mohindra et al., 1992).

5.3.3 Electrical conductivity (EC)

The EC is related with the dissolved salts, more soluble than gypsum in the soil, but it may include a small contribution (up to 2 dS/m) from dissolved gypsum (U.S.D.A., 1966). The EC (EC_e =EC of 1:2 soil: water extracts, U.S.S.L.S., 1968) of a saturation extract method is the standard measure of salinity. Soil: water (1:2) extracts are prepared by filtering the above suspension and electrical conductivity is determined by digital conductivity meter (R-314, Raina Instrument, Delhi). Appropriate temperature correction for 25°C is made for electrical conductivity (EC) data on soil extracts to the standard temperature as described by U.S.S.L.S.(1968, table 15). Results of the EC values of individual pedons are given in the table 5.1 and appendix-III. It is seen that soils of all the morphostratigraphic units sequence members are non-saline in nature.

5.4 SOIL MICROMORPHOLOGY OF THE STUDY AREA

Micromorphology is the study of the arrangement of the skeletal grains and ground mass. Different pedofeatures which are not seen in the field and the process involved in the pedogenesis and soil profile development can be better understood by the study of thin-sections of soils. A total of 65 thin-sections from 24 typical soil profiles were prepared and studied under microscope. The details of the observations are given in Appendix-IV. The objective of the present study is to enhance the understanding of the genetic background of the soils and find out the relationship of different micromorphological features with increase in ages of soils.

5.4.1 Preparation of Thin-Sections

In-situ soil samples were collected from field during field work as discussed in Sec 2.1 in metal boxes (7.5×5×5.5 cm) of the major horizons of typical pedons from different soil geomorphic units. Thin-sections of the soil samples were prepared following the method proposed by Miedema et al. (1974) and Jongerious and Heintzberger (1975). The collected samples were first saturated with acetone and placed on vacuum desiccator for a couple of hours. Then the samples were impregnated with the mixture of crystic resin, thinner, catalyst and hardener in the following proportions: **a)** crystic resin (Synolite 544) 750 ml, **b)** thinner (Isopropyl Alcohol) 250 ml, **c)** catalyst (Cyclonox LNC) 6-7 ml and **d)** hardener (Co-octoate) 3-4 drops. The mixture was stirred thoroughly and left for 30 minutes, until the air bubbles were removed. The mixture was poured into the metal boxes containing the undisturbed soil samples and then the samples were evacuated for 30 minutes each for complete impregnation of the materials into the pore spaces. The samples were left in the vacuum chamber for about 10-12 hours and cured for at least 5-6 weeks at room temperature to allow them to be hardened.

The hard blocks of the impregnated soil were used for preparation of thin sections. Thin sections (9×6 cm) are prepared according to the procedure described by Jongerious and Heintzberger (1975). In order to prevent buckling and swelling of samples during cutting, kerosene oil was used as lubricant.

The slides were first ground on a lapping wheel and than by hand on a glass plate using silicon carbide and aluminum oxide powders. After obtaining a thickness of about 50-60 µm they were studied for microstructures. Again these slides were ground on a glass plate to a final thickness of 30 µm. and studied for pedo-features.

5.5 MICROMORPHOLOGICAL DESCRIPTIONS OF THE SOILS IN THE STUDY AREA

5.5.1 Methodology

Soil thin-sections have been described mainly according to the system proposed by Bullock et al. (1985) under the main headings as microstructure, basic mineral components, basic organic components, ground mass and pedofeatures. Some features are described according to Brewer's (1964) terminologies. This

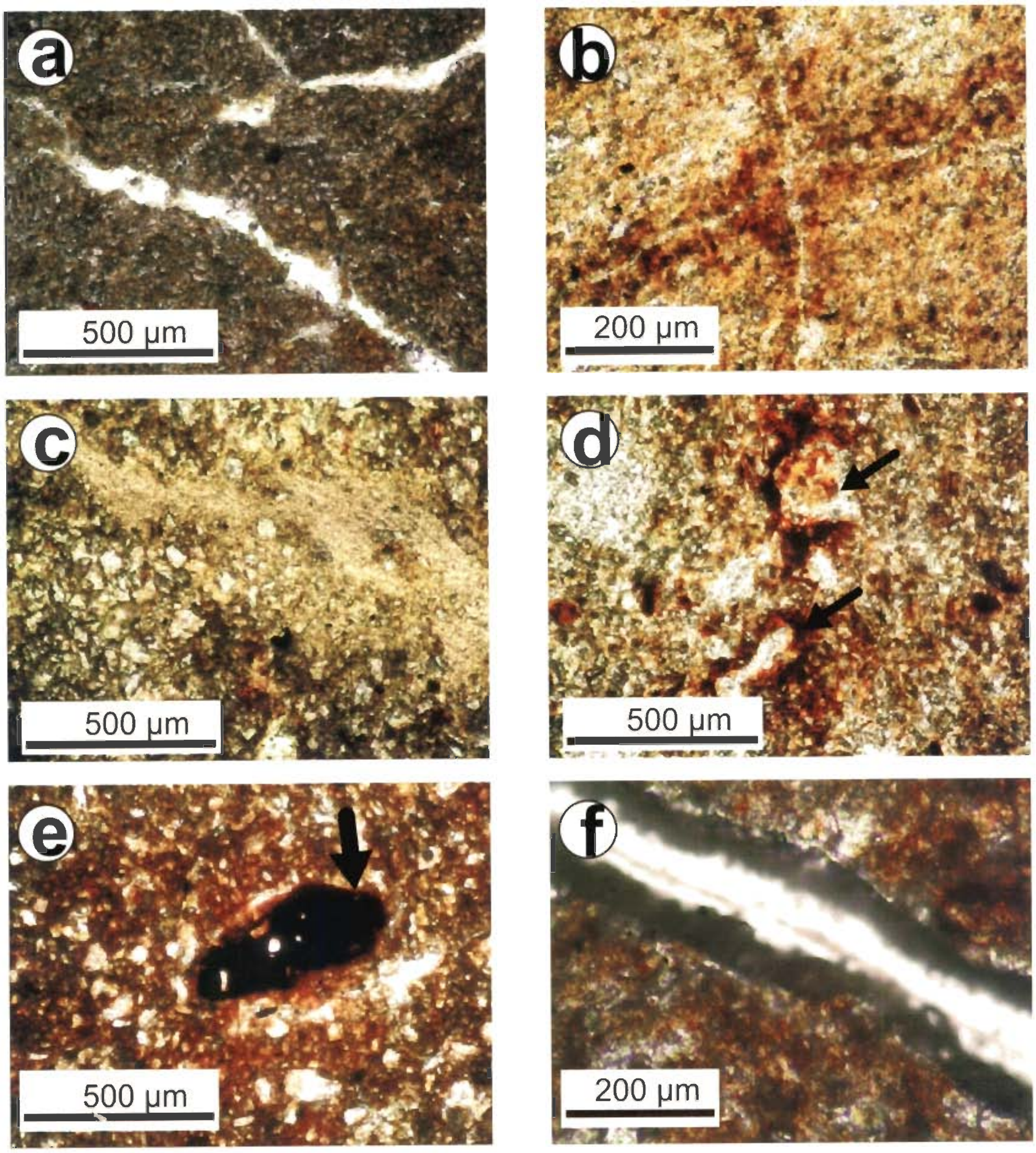


Figure 5.7(a) Apedal,Fe-Mn impregnated dense ground mass, rootlets filled with silica, B2 horizon, pedon P-64, QGMS-I, XPL, (b) Stipple-specled b-fabric,cross cutting typic voids ,B horizon, pedon P-50, QGMS-I, XPL, (c) Illuviation of clay along the voids within the coarse grained ground mass, Bt horizon, pedon P-64, QGMS-I, PPL, (d)Typic void developement, pedon P-50, QGMS-I, PPL,(e) Chitonic to gefuric coarse grain distribution arround feriargilan coated Fe-Mn noudle,Bt2 horizon, pedon P-45, QGMS-II, XPL and (f) Partially decomposed rootlets, core filled with silica, C horizon, pedon P-45,QGMS-II,XPL.

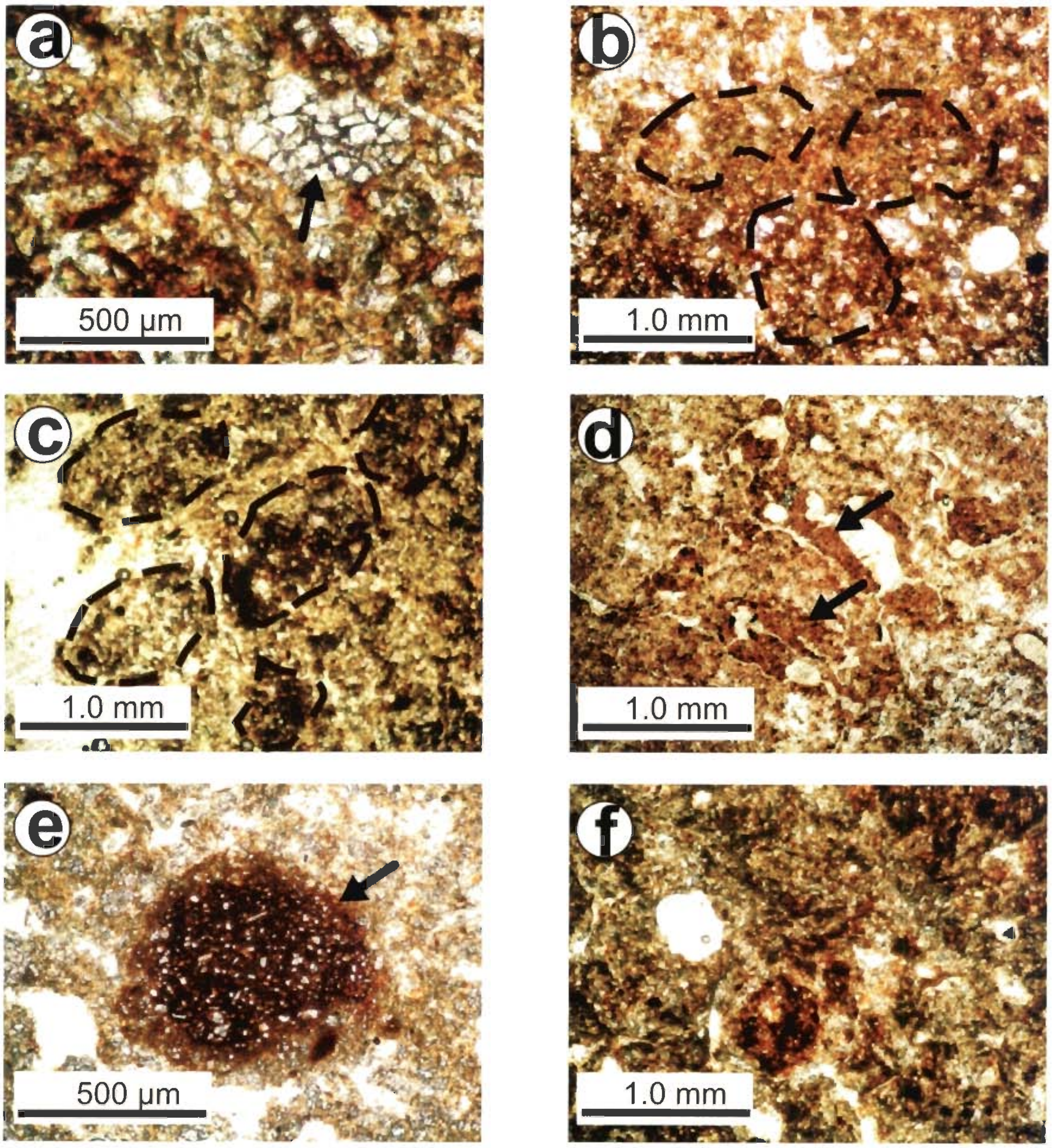


Figure 5.8 (a) Fractured Quartz grain(QZ) and accumulation of Fe-Mn rich materials at B-horizon,pedonP-46,QGMS-II,XPL,(b)Weakly developed sub angular blocky structure in Bt2 horizon,pedon P-45,QGMS-II,PPL,(c)Moderately developed sub angular blocky structure in Bt2 horizon,pedon P-26,QGMS-III,XPL,(d)Porous micro aggregates composed of humified excrement features,C-horizon,pedon P-35,QGMS-III,XPL,(e) Poly nucleotide Fe-Mn noudle within fine grained ground mass in B-horizon,pedon P-27 QGMS-III,PPL and (f) Moderately developed reticulate striated b-fabric,B horizon, pedon P-26,QGMS-III,XPL.

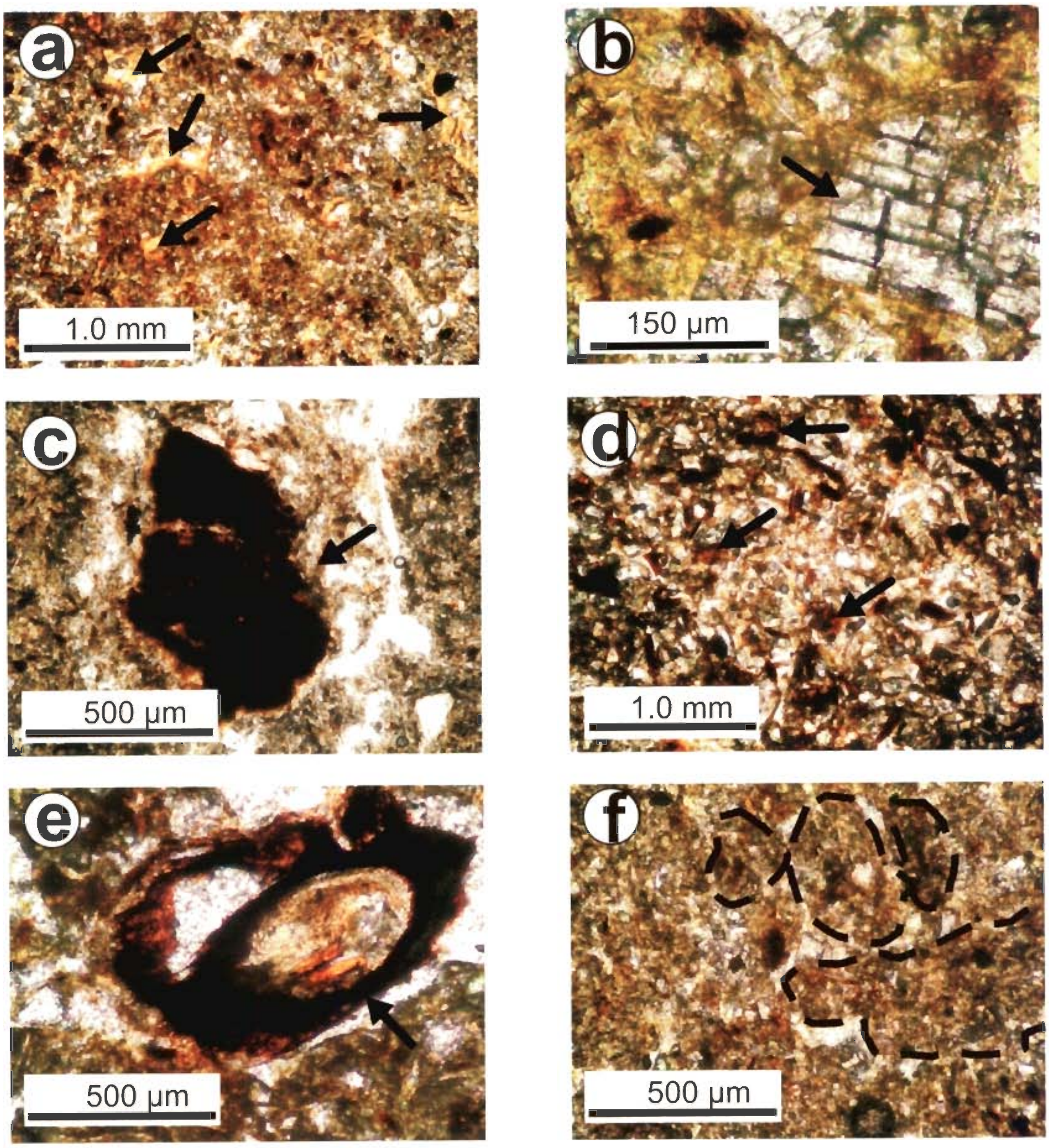


Figure 5.9 (a) Ground mass impregnated with Lepidochrosite, Bt2 horizon, pedon P-18, QGMS-IV, XPL, (b) Cross linear alteration of Felspar, BC horizon, Pedon P-20, QGMS-IV,PPL, (c) Well impregnated Fe-Mn noudle with circular striated b-fabric in ground mass, B horizon,pedon P-17, QGMS-IV, XPL, (d) Chitonic to gefuric coarse grain distribution with alterationof Boitite, B2t horizon, pedon P-18, QGMS-IV, XPL, (e) Fe-Mn features along the margin of the plant root, B1 horizon, pedon P-15, QGMS-V, PPL and (f) Moderately developed sub angular blocky peds with Channels filled with secondary materials,B horizon, pedon P-21, QGMS-V, PPL.

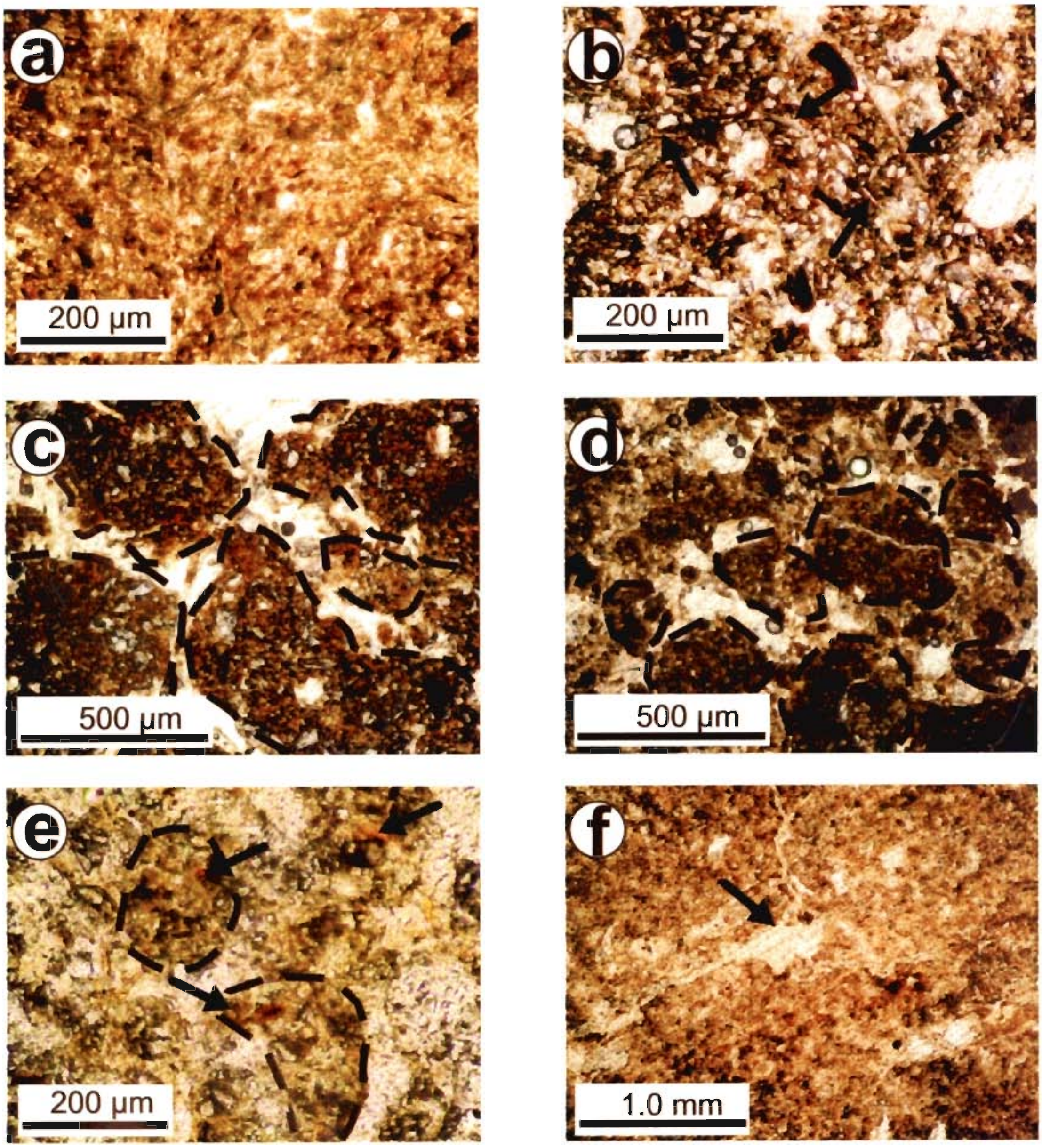


Figure 5.10 (a) Deformed reticulate striated b-fabric,Bt2 horizon,pedon P-21, QGMS-V, XPL, (b) Muscovite laths and Fe-Mn impregnated dense ground mass, C-horizon, pedon P-21, QGMS-V, XPL, (c) Strongly developed spheroidal blocky peds in B-horizon, pedon P-2, QGMS-VI, XPL, (d) Very strongly developed spheroidal blocky peds in Bt2 horizon, pedon P-7, QGMS-VI, XPL, (e) Strongly developed peds with altered Biotites,Bt2 horizon, pedon P-9, QGMS-VI, XPL and (f) Chamber structure with Fe-Mn impregnatedground mass,Bt1 horizon, pedon P-8, QGMS-VI, PPL.

study was carried out mainly on the features described here: (a) *Pedality*: explains the type of peds and the grade of pedality. Types of peds are defined by the shape of the peds as angular blocky, sub angular blocky, prisms, plates etc. The grade of pedality is described by terms as apedal, weakly, moderately and strongly developed depending upon the degree of separation of peds by voids. (b) *Voids*: Description of voids includes type of voids, their shape, size, abundance and roughness/smoothness of void surfaces. (c) *C/f ratio and c/f related distribution*: Coarse/fine component's ratio were measured approximately and the c/f related distributions were expressed mostly as open, single or double spaced porphyric, chitonic and gefuric. (d) *Cutans*: Cutans have been described according to Brewer's (1964) terminology to explain the composition as: argilan for clay, ferriargilan for clay with iron oxides, calcetan for clay with calcium carbonates; and terms describing coatings as typic-, hypo- and quasi-coating from Bullock et al. (1985) have also been used to explain the morphological relation of coatings/cutans to the pores/grains. (e) *Development of b-fabrics*: The orientation and distribution patterns of interference colours of the soil micromass are the birefringence fabric or b-fabric. The b-fabrics are described as unistrial-, crystallitic-, cross-, reticulate-, poro-, grano-, circular-sriated, stippled-. The degree of development of b-fabric has been described as weakly, moderately and strongly developed. (f) *Degree of alteration of minerals*: Alteration of minerals includes alteration of quartz, feldspars and biotites. The alteration patters are describes as pellicular, linear (irregular, parallel and cross) and dotted alterations. The degree of alteration of these minerals has been expressed as weakly, moderately and strongly altered. (g) *Concretions and nodules*: The different forms and degrees of sesquioxidic (Fe/Mn) concretions, mottles and calcite nodules have been described as weakly, moderately and strongly impregnated nodules

5.5.2 Microstructure

Micromorphological investigations show that Member QGMS-I and II soils (Appendix-IV) are weakly developed, where as soils of other members i. e. from QGMS-III to VI have moderate to strongly developed subangular blocky microstructure in B-horizons (Figs. 5.7-5.10). In the upper A and lower C horizons, the soils are apedal or show weak ped development.

Partially accommodated ped faces are separated by channels (Fig.5.10f). Average ped diameter, void diameter, channel width and porosity ranges between 200 μm-3.5 mm, 50 μm-3 mm, 50 μm-1.5 mm and 5-20% respectively. Channel, vugh and chamber are the dominant voids in the soils. The roughness of the voids decreases from QGMS-I to QGMS-VI.

5.5.3 Mineral components

The coarse fraction content is highly variable within the soil profiles as well as among the various soil-geomorphic units. The coarse to fine (c/f) limit ranges 25-40 μm for all the soils, but the range of c/f ratio is 5:95 to 50:50, 5:95 to 40:60, 10:90 to 40:60, 5:95 to 40:60 and 10:90 to 40:60 for QGMS-I to QGMS-VI soils, respectively. Member QGMS-I and QGMS-II soils show open to double spaced porphyric, Member QGMS-III to VI show single space porphyric to chitonic and gefuric distribution. Coarse fraction comprises dominantly quartz (30-60 %) and feldspar (10-50 %) along with muscovite (5-10%) and boitite (10-20%)

Strong pellicular alteration of biotites and feldspar along with irregular linear alteration of feldspars and fracturing of quartz are observed (Fig.5.8, 5.9) in the older soils i.e. Member QGMS-IV-VI soils and the degree of alteration increases from the Member QGMS-I to QGMS-VI.

Fine fraction comprises fine silt sized quartz and feldspars, clay aggregates and micaceous particles. The active Gandak plain shows well distribution of calcitic materials through out the profiles. However, the Gandak terminal fans II & III show partially leached A- horizon and accumulation of calcite in B-horizon. The remnant of calcite in the upper horizon and semihard concretion beds in the lower horizon is noticed in this plain. In the Old Gandak plain, no calcite is found in the upper horizon but a bed of hard concretion in the lower horizon is found. The Oldest Gandak Plain (OSGP) does not show calcitic materials all through the profile.

5.5.4 Groundmass

The groundmass is commonly yellowish brown, yellowish red to reddish brown and in some thin sections it is yellowish brown to gray. The groundmass in a few thin sections of Member QGMS-I to IV show linear accumulation of yellowish to orange colour of lepidochrosite (Bullock et al., 1985; p.51) and dark brown colour of siderite (Fig. 5.9). Reddish brown colour is due to the presence of Fe_2O_3 formed in the oxidizing environment of well drained soils. The sesquioxides released by weathering of boitite gets precipitated close to these grains and biotite exhibits discolouration on weathering (Fig. 5.9).

Micromass of soils in different morphostratigraphic Members exhibit random-, circular-, reticulate striated and mosaic speckled b-fabrics (Fig. 5.9). In general the degree of development of b-fabric in Member QGMS-I to IV soils is significantly stronger than the older member soils.

5.5.5 Pedofeatures

Major pedofeatures observed are coatings like argillans, ferriargilans,Fe-Mn coatings, mottles and Fe-Mn noudles.

5.5.5.1 Coating

Ferriargilan and argilan occurring as typic and hypo (Fig. 5.7) coatings are present in all soils. The thickness of cutans shows a gradual increment from QGMS-I to IV and than decreases in QGMS-VI (0-75 µm for QGMS-I&II, 50-100 µm for QGMS-III, 50-150 µm for QGMS-IV &V and 70-110 µm for QGMS-VI). Like Mohindra et al. (1992) we found Fe-Mn coatings in soils in the younger Members. Ghaghara-Rapti interfluve shows preferred orientation of clay cutans, accumulation of sesquoxides in dense fine fraction in some zones forming fabric pedofeatures and complex argilans. Translocation of clay, silt and organic matters , preferred oriented clay cutans in advanced stage of leaching of pre existing of Fe-Mn concretions are seen in the Oldest Gandak plain (OSGP).

5.5.5.2 Infillings

Few channels and 100 µm-2 mm thick rootlets with large voids filling with loose to dense silicious and calcareous materials (Fig. 5.7) are found in all the soils. Decomposed rootlets and stems (Fig. 5.10) partially filled with Fe-Mn rich materials are seen in all the soils.

5.5.5.3 Ferruginous, Manganiferrous and calcitic pedofeatures.

Micromorphologically sesquioxides are observed as dense groundmass (Fig. 5.9) and as coating with variable thickness along ped, void and channels. Moderately to strongly impregnated typic-, aggregate-, nucleic-Fe/Mn sub rounded to elliptical nodules with sharp boundaries (Fig. 5.9). Fe/Mn features are more common in the wetlands irrespective of the age of the soils. The Old Gandak plain (OGP) shows concretions of both Fe-Mn (4-6 mm diameter) and calcite <10 mm diameter. Fe-Mn may form up to 20% of thr soils in the distal part of the megafan (Mohindra et al., 1992).

5.6 RESUME

According to the soil texture classification of Schoeneberger et al. (1998) most of the soils in the study area are classified as sandy loam. The C.I.A increases systematically from QGMS-I to QGMS-VI suggesting the increase of pedogenic clays with the increasing age of soils. Also, the younger soils have varied textures from sandy loam to silty loam classes and with increase in age soils tend to change their textures to loam probably due to break down of rock fragments and weathering of some minerals.

Micromorphological studies and grain size analysis of soils from different Members of the morphostratigraphic sequence show distinct variation of features such as variation of grade, pedality, degree of alteration of minerals, development of cutans, smoothness/roughness of void surfaces, development of b-fabric and mottles with the increase of age of soils.

Micromorphological investigation show that the Member QGMS-I and II show weak pedality development, QGMS-III shows moderately pedality development and the QGMS-IV to VI show strong pedality development.

Major b-fabrics observed are poro-striated, stipple-speckled and reticulate. In general the degree of development of b-fabric in the Member QGMS-I to IV are stronger than their older soils. The groundmass of a few soil thin sections of Member QGMS-I to IV show yellowish to arrange linear accumulation of lepidocrocite and the waterlogged soil shows accumulation of dark brown colour due to the presence of siderite.

Ped size and porosity % decreases from Member QGMS-III to VI soils. Deformed reticulate-striated b-fabric features are observed in Member QGMS-III.

In wetlands of the study area low chroma soils are observed (Sec 2.7). Micromorphological investigations suggest that Fe/Mn oxide features are observed in all the horizons of such soil. Thus in wetland, most soils are gleyed in nature and the presence of siderite and lepidocrocite supports the inference.

The degree of alteration of minerals increases from the Member QGMS-I to QGMS-VI soils. Moderately to strongly altered feldspar grains are observed in Member QGMS-IV to VI soils.

Table 5.1 Ec and pH of samples

QGMS	SOIL GEO-MORPHC UNIT	PEDON NO	DEPTH (cm)	Ec mmhos/cm	pH
Q G MS-I	Baghmati Terminal fan-II (BTFn-II)	P-52	0-10 10-25 25-50 50-90	0.593 0.613 0.618 0.627	5.91 5.85 6.13 6.09
	Burhigandak Terminal fan-II (BGTFn-II)	P-58	0-15 15-40 40-60	0.548 0.49 0.482	5.45 5.46 5.58
	Baghmati Terminal fan-I (BTFn-I)	P-64	0-15 15-33 33-54 54-66	0.661 0.616 0.586 0.598	6.08 6.01 6.49 5.86
Q G MS-II	Kamla Terminal fan-I (KTFn-I)	P-50	0-15 15-30 30-50 50-100 100-120	0.626 0.592 0.576 0.567 0.601	6.52 6.47 6.35 6.57 6.25
	Kamla Terminal Fan-II (KTFn-II)	P-45	0-8 8-58 58-78	0.471 0.433 0.421	6.73 6.72 6.89
	Young Piedmont (YPt)	P-46	0-10 10-30 30-75 75-90	0.597 0.582 0.601 0.611	6.17 6.22 6.53 6.49
	Ghaghara Terrace-I (GT-I)	P-38	0-16 16-56 56-91	0.559 0.668 0.687	7.16 7.16 7.19
	Old Piedmont (OPt)	P-37	0-40 40-60 60-85 85-135	0.573 0.54 0.563 0.547	6.89 6.86 6.94 6.90
Q G M S - III	Gandak Terminal fan-I (GTFn-I)	P-29	0-18 18-33 33-48 48-98 98-118	0.667 0.601 6.638 0.588 0.472	7.07 7.23 7.23 7.02 7.26
	Gandak Terminal fan-I (GTFn-I)	P-31	0-13 13-25 25-65 65-110 110-125	0.545 0.489 0.492 0.609 0.446	7.63 7.78 7.79 7.82 7.87
	Gandak Terminal fan-II (GTFn-II)	P-35	0-25 25-50 50-130 130-155 155-175	0.601 0.64 0.585 0.606 0.602	7.04 7.18 7.17 7.01 7.24

QGMS	SOIL GEO-MORPHC UNIT	PEDON NO	DEPTH (cm)	Ec mmhos/cm	pH
	Old Piedmont (OPt)	P-25	0-15 15-25 25-95 95-125 125-140	0.706 0.628 0.644 0.642 0.633	6.55 6.64 6.47 6.58 6.52
	Ghaghara Terrace-II (GT-II)	P-17	0-30 30-70 70-100 100-120	0.49 0.462 0.46 0.491	7.68 7.65 7.74 7.63
	Old Gandak Plain (OLGP)	P-21	0-20 20-40 40-100 100-130 130-150	0.677 0.704 0.716 0.712 0.704	7.36 7.51 7.61 7.63 7.66
	Rapti Terminal Fan-III (RTFn-III)	P-20	0-30 30-65 65-85	0.677 0.658 0.674	6.98 7.08 7.06
	Rapti Terminal Fan-IV (RTFn-IV)	P-16	0-40 40-65 65-105 105-135 135-170 170-180	0.56 0.521 0.508 0.5 0.51 0.514	6.81 6.71 6.74 6.85 6.80 6.89
QGMS-V	Old Gandak Plain (OLGP)	P-15	0-10 10-35 35-65 65-95 95-115	0.642 0.627 0.628 0.612 0.597	7.34 7.79 7.8 7.8 7.81
QGMS-VI	Rapti Terminal Fan-V (RTFn-V))	P-1	0-17 17-40 40-85 85-115	0.469 0.435 0.459 0.458	8.36 8.17 7.99 8.06
	Rapti Terminal Fan-V (RTFn-V)	P-7	0-40 40-75 75-100	0.473 0.475 0.49	7.88 7.85 7.98
	Oldest Gandak Plain (OSGP)	P-9	0-15 15-40 40-90 90-140 140-160	0.445 0.432 0.410 0.392 0.443	5.91 5.95 6.17 6.06 6.39
	Ghaghara-Rapti Interfluve Plain (GRIP)	P-2	0-12 12-27 27-57 57-117 117-137	0.614 0.620 0.612 0.620 0.622	7.04 7.26 7.46 7.36 7.34

6.1 INTRODUCTION

The Indo-Gangetic foreland basin, the most extensive (~8, 50,000 km^2) fluvial basin in the Indian subcontinent, came to existence by the collision of the India and the China plates during the Paleocene (Dewey et al., 1970). Pankaj Srivastava et al. (1994) and Thomas et al. (2002) classified the Gangetic plain into Upper, Middle and Lower plains depending upon the degree of soil development and the associated geomorphology. The Upper Gangetic plain is marked by the uplands (interfluves) with incised river valleys and moderate to strongly developed soils. Middle Gangetic plain is marked by relatively high rate of subsidence and sedimentation in the form of megafans and with weakly to moderately developed soils, and the Lower Gangetic plain is characterized by deltaic sedimentation.

Our studies have been confined to the region between the Ghaghara and Kosi rivers. The region between the Ghaghara and Rapti rivers belongs to the Upper Gangetic plain and the area east of the Rapti forms a major part of the Middle Gangetic plain. Parts of the present area have been investigated earlier. For example, the Gandak megafan was investigated by Mohindra et al. (1992) for its pedology and geomorphology and the Gandak-Kosi Interfan region was studied by Sinha et al. (2005) and Jain et al. (2004, 2005) for its geomorphology. However, sedimentary and pedological processes and tectonic framework for the whole study area have not been worked out. Keeping this in mind, the present study was carried with the following objectives:

i. To prepare morphostratigraphy of the study area

ii. To find out the role of neotectonics in the evolution of the Holocene geomorphology, pedology and sedimentation in the basin.

iii. To work out the tectonic framework and the Holocene deformation field/stress field of the study area, and

iv. To understand the sedimentation processes of the terminal fans and Gandak megafan using Ground Penetrating Radar (GPR).

To achieve the objectives, the area between the Rivers Ghaghara and Kosi has been studied in detail for its geomorphology, pedology, sedimentology and tectonics, using remote sensing and geographic information system (GIS) techniques, Luminescence dating, ground penetrating radar, soil micromorphology and grain size analysis.

6.2 INVESTIGATION PROCEEDURES

Identification and mapping of the various geomorphic units in the study area was carried out by using LANDSAT-MSS images in combination with study of the Survey of India topographic sheets of 1:2, 50,000 scales. Digital elevation model (DEM), digital terrain model (DTM), and profile sections were prepared to identify the geomorphological units and faults in the study area. Elevation data was extracted from the Survey of India topographic sheets on scale 1:50,000 by manual digitizing spot heights and contours covering the entire study area by using ARC VIEW 3.2a, GIS software. DEMs for regions around suspected /inferred faults (Figs 2.16-23) were generated by using SURFER-8 softwares using kriging interpolation method, which provides excellent results for plain areas and brings out artifact morphostructures like 'cliffs' and 'significant break in slopes', which are indicative of faults (Bhosle et al. in press). DTMs were also prepared for the study area (Fig. 2.6, 2.25, 2.26) for near realistic visualization of fault-related geomorphic features like terminal fans. Profile sections were prepared across the faults by using ERDAS IMAGINE-8.5 (Figs 2.14-15) to estimate throw of the faults.

Detailed fieldworks were carried out to check the ground truth of boundaries of the soil geomorphic units, to study the soil properties like thickness of soil horizons and sub-horizons, colour, texture, structure, mottling, lime content, consistency and nodules from typical profiles, as suggested by U.S.D.A (1966) and Schoenberger et al.(1998) (Appendix-I) and to collect samples from individual soil units for further laboratory analysis for grain size distribution and micromorphological studies . Also, samples from C-horizons of soils were collected for luminescence dating. In the last phase GPR studies were carried out to confirm faults, find out their subsurface nature and role of their activity in sedimentation and to study the radar facies of the terminal fans.

Sixty-eight samples were dated using Infra-Red Stimulated Luminescence (IRSL) dating method, using fine grain (4-11 μm size) polymineralic fraction. Sample preparation was carried out following the method described by Wintle (1997). The additive dose analytical procedure described by Aitken (1998) was adopted for further IRSL analysis.

Grain size analysis (Sec 5.2) was carried out following Galehouse (1971) mainly to know the percentage of sand, silt and clay in the bulk soil samples.

Clay accumulation index (C.A.I) (Fig.5.6) of Levine and Ciolkosz (1983) for determining the degree of soil development in each soil profiles was calculated from grain size distribution data.

For micromorphological investigations, 88 oriented blocks of undisturbed soils were impregnated with crystic resin by the method described by Jongerius and Heintzberger (1975) and Miedema et al. (1974). Large thin-sections of 9×6 cm size were prepared from resin-impregnated and hardened samples. Thin-sections were described according to terminology given by Brewer (1964) and Bullock et al. (1985).

6.3 GENERAL FEATURES OF THE STUDY AREA

The study area between the River Ghaghara in the west to the Kosi in the east comprises both the Upper and the Middle Gangetic plains (Thomas et al., 2002). The Himalaya in the north and the River Ghaghara and the Ganga in south, demarcate the northern and southern boundaries of the study area, respectively (Fig. 2.1). The area falls in parts of Uttar Pradesh and of Bihar states of India and in north it shares the international border with Nepal (Fig.1.1). Except the northern piedmont zone, the area is a featureless plain with lack of topographic prominence. The elevation from mean sea level gradually decreases from the southern slopes. However, the most of the plains show NW-SE slope, which is well reflected by the behaviour of the drainage pattern (Fig.1.4) and the associated geomorphic units. The main rivers like the Ghaghara, Rapti, Gandak, Burhigandak, Baghmati and Kosi, are characterized by frequent change in their courses, as evidenced by the paleochannels and oxbow lakes in nearby areas (Figs. 2.1, 2.6 & 2.26).

Dichotomic drainage pattern is common in the Piedmont zones both in the Upper and middle Gangetic plains. However, the piedmont zone of the Gandak-Kosi Interfan area shows convergent drainage (Singh et al., 2006) alternating with dichotomic pattern on the piedmont alluvial fans, without any relation to faults, as described earlier by Singh et al. (2006) and Bhosle et al. (2008). Piedmont zone north of the Ghaghara-Rapti Interfluve, exhibits sub-parallel drainage (Fig. 1.4). The Rapti flowing parallel to the mountain front show high sinuosity and the sinuosity decreases as it takes southern turn (Fig. 2.1). Most of the tributaries meet their main rivers at acute angles (Fig. 1.4).

The Ghaghara and Rapti rivers flow southwards after debouching into the plains, from the Himalaya and later take an easterly turn, with convexity of their courses to the southwest. These rivers are following major longitudinal faults described later (Fig. 1.4). Local uniqueness of drainage pattern is controlled by the behaviour of the tectonic blocks, they occupy, as discussed later. The Ghaghara-Rapti Interfluve on the whole is well drained.

The southern part of the Gandak megafan and the Gandak-Kosi Interfan region are poorly drained due to the low-lying nature and hence show frequent flooding throughout the year and are overlain by numerous abandoned channels and ponds locally called *tals.*

The climate of the area is largely controlled by the Himalaya and the SE monsoon. Most of the area falls under the dry sub-humid climate. However, in the northeastern part, close to the piedmont zone, moist sub-humid climate prevails (Fig.1.2). There is a trend of decrease of rainfall from the east (40 cm at Darbhanga) to west (35 cm at Gonda) and from the foot of the Himalaya to the south (Fig.1.2) (Singh et al., 1971). The area comes under USTIC soil moisture regime (Fig.1.3) (N.B.S.S. & L.U.P., 1993).

6.4 MORPHOLOGY AND DEPOSITIONAL CHARACTERISTICS OF VARIOUS GEOMORPHIC UNITS

Major geomorphological features observed in the area are, piedmont zone, terminal fans, megafans, river terraces, incised vallies, old river plains, interfluve plains, misfit river plains and active floodplains.

6.4.1 Piedmont Zone

The piedmont zone (Fig. 2.1) covering 26% of the whole study area gradually becomes wider from interfluve region in west to interfan area in the east, and is longitudinally segmented by three normal faults in the Gandak-Kosi interfan area (Piedmont fault-I, II and North Sitamarhi fault). The average widths of the piedmont zone in the Upper and Middle Gangetic plains are 35 km and 60 km, respectively. Depending upon the OSL ages and the degree of soil development, the piedmont is classified into old, young and active piedmonts (Sec. 2.5.1) with decreasing of OSL ages. The Old Piedmont (OPt) consists of mainly coarse sands and gravels, where loose gravels are exposed at places along the stream courses in the upper part of the piedmont zone. The Young Piedmont (YPt) consists of mainly by sands. The Active Piedmont lies close to the base of the Siwaliks, has been deposited due to the recent activity of the Himalayan Frontal Thrust and is mainly composed of gravels and coarse sands.

6.4.2 Terminal Fans

Two types of terminal fans i.e. the braided and meandering stream terminal fans are recognized in the study area. All the terminal fans of the study area form on the downthrown blocks of normal faults due to relief created by the activity of the associated faults (Table 2.1), as observed earlier (Singh et al., 2006; Bhosle et al., 2008).

The meandering stream terminal fans (Burhigandak terminal fan-I &II, Baghmati terminal fan-II, all Rapti terminal fans except RTFn-II, Khujurpur, Babban and Jharni terminal fans) are mainly composed of medium to coarse grained sands. The abandoned channels in the interfluve area across the terminal fans exhibit salt efflorescence on the surface and development of calcrete nodules at depth. However, there is no calcrete development in the terminal fans in the interfan area; instead this area shows intercalations of organic-rich mud and sand.

Three braided stream terminal fans (Rapti-II, Baghmati-I and Kamla terminal fan) are recognized in the study area. GPR traverses across these fans and borehole logs suggest sequences deposited in these fans consist of fining-up sequence of coarse sand at depth passing gradually into thin overbank mud facies at the top.

The Gandak terminal fan-III (Fig.2.4, 2.5) shows a number of sandy paleochannels with slightly raised level and low-lying channels with floodplain deposition on a large scale, with widths of 4-5.5 km diverging out from the point, where the Gandak enters the downthrown block of the South Motihari Fault (SMFt). This indicates frequent splays developing from the Gandak River, leading to the formation of this terminal fan. The low-lying paleochannels are also marked by numerous ponds located in linear fashions (Fig. 2.4). Organic-rich mud is being deposited in these ponds. Also, the Gandak Terminal fans I-II, show such dichotomic pattern of paleochannels, diverging from the points, where associated Gandak River traverses Nichlul fault (fan-I) and South Motihari fault (fans-II), suggesting these have been also formed by splays from the large Gandak river. Here a new term "splay terminal" fan is proposed for such features. The Gandak terminal fans-I and II are 4.5 ka age and fan-III covers major parts of fan II and is of 0.9-1.2 ka in age.

6.4.3 Megafan

The Gandak megafan (Fig. 2.1, 2.6) lies in the central region of the study area. On this megafan, from west to east, two plains i.e. Oldest and Old Gandak Plains are identified, which formed due to the movement of the Gandak River across the megafan caused by eastward tilting of the Rapti-Gandak tectonic block (Mohindra et al., 1992). The degree of soil development and soil ages decrease and number of abandoned channels and ox-bow lakes increase from the Oldest (>10 ka) Gandak Plain to Old (10-8.4 Ka) Gandak Plain (Mohindra et al., 1992).

Four terminal fans identified from the Gandak megafan area are Gandak terminal fans I-III and Jharni terminal fan (Fig. 2.6), which have been described above.

Earlier the Gandak terminal fan-I and II were considered to form the Young Gandak Plain by Mohindra et al. (1992). They had worked with 1:1 million scale MSS images and definition of various soil-geomorphic units was on the basis of the degree of soil development. Now with the enhancement of MSS images by use of digital data and use of DEMs, DTMs and dating of soils by IRSL technique, it was possible to recognize the terminal fans. However, we have retained the terms like the Oldest and Old Gandak plains of Mohindra et al. (1992).

The Gandak megafan Block is segmented into three tectonic sub-blocks by the Gorakhpur-Padrauna (GPFt) and Barhaj-Bettiah (BBFt) faults, striking N75°E-S75°W and N50°E-S50°W, respectively. The upper two sub blocks i.e. the Maharajganj sub-block and Captainganj sub-block show unique artifact landscapes like rounded hills (Gandak Terminal fan-I) (Fig. 2.5) and dissected tableland, respectively, in the DTM. In the north this megafan (Oldest Gandak Plain) is separated from the Piedmont zone by the Rohini Fault (Fig.2.24a, b).

The Gandak River, though braided in nature, is bringing large amounts of suspended matter, rich in fine clacitic materials, which are spread over major parts of the floodplain. Calcitic material gives the top soil in active floodplain a crystic b-fabric. However, in the Old Gandak Plain soils, the calcitic material is being dissolved and leached to C-horizon, which shows development of calcrete nodules. B-horizon is free of calcitic material and shows clay illuviation features. The Oldest Gandak Plain is free of calcitic nodules and exhibits only clay illuviation features on a large scale. These features have been well documented by Mohindra et al. (1992).

6.4.4 River Terraces

Two river terraces, GT-I (4.1 ka) and GT-II (7.6 to 7.5 ka) in eastern part of the study area, associated with the River Ghaghara, are characterised by the abandoned channels and oxbow lakes (Fig. 2.7). However, the density of these features decreases is higher on the younger terrace as compared to the older one. Both of the terraces are characterised by coarse sands deposited by the Ghaghara. Mud deposits are confined to the oxbow lakes and abandoned channels. The degree of soil development also increases from GT-I to GT-II. Partially decomposed organic materials are found in these terraces.

6.4.5 Incised vallys

The Ghaghara and Rapti rivers form wide incised valleys (Fig.2.2). As compared to their upstream courses, these two rivers show incision within their floodplains, after they cross the Ayodhya-Dinkarpur fault, which coincides with western boundary of the Faizabad Ridge as seen in the MSS image. Incisions also occurred along the recent channels active in the Old Ghaghara Plain (OGP) and the Old Piedmont in Gandak-Kosi Interfan region. Most of the small ephemeral streams on the Ghagara-Rapti Interfluve like the Sarju, Bisuhi and Kuwana are incised.

6.4.6 Old River Plains

The Old Ghaghara plain with a maximum width of 28 km is overlain by very weakly developed soils, due to sandy parent materials. At places, the sandy materials have been reworked by wind into large dunes. This plain is bounded by Ghaghara-I and II faults in the west and east. This plain is formed as result of tilting of the Bahraich and Gonda sub-blocks westward (Mohindra et al., 1992). The Burhi Gandak plain-I has developed due to migration of the Burhi Gandak eastward by 9-11 km and is marked by very weakly developed sandy soil.

6.4.7 Interfluve Plain

The Ghagahra-Rapti Interlfuve Plains forms an upland, overlain by moderately to strongly developed soil (>10 ka) with calcrete development at a few places. This unit forms the background for deposition of later terminal fans, consequently occurs in three major isolated patches. The terminal fans have been deposited by the bounding stream i.e. Rapti River or interfluve streams.

6.4.8 Misfit River Plain

The Gandak River was earlier flowing through the course now occupied by the Burhi Gandak River in the Interfan area in 1.2 ka and it shifted back to the present position in the 18th century (Geddes, 1960). The Burhi Gandak, much smaller than the main Gandak River, occupies a smaller part of the older course at any time and keeps shifting drastically and thus forms a misfit river.

6.5 MORPHOSTRATIGRAPHY OF THE STUDY AREA

Mohindra et al. (1992), Pankaj Srivastava et al. (1994), Kumar et al. (1996) and Singh et al. (2004) used soil-chronoassociation to rank soil development in different broad soil-geomorphic units, based on degree of soil development. In the present study, twenty-eight soil-geomorphic units are grouped into six Morphostratigraphic Sequence Members QGMS-I to QGMS-VI with increasing OSL ages: QGMS-I- <1.4 Ka, QGMS-II- 1.4-4.7 Ka, QGMS-III- 4.7-6.9 Ka, QGMS-IV- 6.9-8.4 Ka, QGMS-V 8.4-10 Ka and QGMS-VI > 10 Ka (Fig. 3.6), (Frye and Willman, 1962 in Fairbridge, 1968). The relative ages of the geomorphic units based on the degree of soil development were compared with the OSL ages obtained for each member and were found to be well matched.

6.6 SYSTEMATIC VARIATION OF SOIL CHARACTERS AMONG THE DIFFERENT MORPHO STRATIGRAPHIC MEMBERS

The six morphostratigraphic sequence members from QGMS-I to QGMS-VI are well distinguished by their soil morphology characters like texture, salinity and alkalinity, and micromorphology

6.6.1.Textural Variation

Particle size distribution studies show that sandy loam to sandy clay loam soil soccurs in the QGMS-I and II soils (Fig. 5.2). These studies do not show any significant change in the sand, silt and clay contents (Fig 5.4) with depth in QGMS-I soils, which suggests no significant change of the fluvial depositional processes in the area or clay illuviation. The QGMS-III-VI soils are categorized as loam to silty loam. Soils of the area are mainly in coarse loamy class.

Variation of the total clay and pedogenic clay contents are shown in the (Fig. 5.6) and the degree of illuvial translocation has been assessed by calculating clay accumulation index (C.A.I) of Levine and Ciolkosz (1983). In general, the C.A.I. value increases with the increase in age of the soil (0-186 in QGMS-I, 175-630 in QGMS-II, 200-985 in GQMS-III, 690-1270 in QGMS-IV, 1155-1205 in QGMS-V and 1525-1580 in QGMS-VI soils).

6.6.2 EC and pH2

Drainage and topography seem to control the soil pH (pH2 = pH of 1:2 soil: water, U.S.S.L.S., 1968) and soil ECe (electrical conductivity of 1: 2 soil: water extracts, U.S.S.L.S., 1968). Depthwise variation of ECe and pH2 for different pedons are given in Table 5.1. Soil- geomorphic units in the piedmont zone and in the northern part of the Upper Gangetic Plains, showing good drainage are slightly acidic in nature. However, soils in the low-lying, swampy areas show high acidic in nature. Soils in the central part of the Ghaghara-Rapti Interfluve are strongly alkaline in nature. Similarly soil units close to the active streams are also show low alkalinity probably due to washing effect. All areas show neutral to slightly alkaline soils. Results of ECe (Table 5.1) show lower salinity in surface soils of the study area than those reported by N.B.S.S. & L.U.P. (1999) and all the soils are classified as non-saline (ECe <1.0 mhos/cm).

6.6.3 Variation of Thickness of B-horizons and Solum

The soils in the study area show systematic variation in the soil morphology from the least developed soils in Member QGMS-I to most developed in Member QGMS-VI soils. Thickness of B-horizons gradually increases from Member QGMS-I (0-30 cm) to Member QGMS-VI (70-115 cm) (Table 5.1 and Appendix-II & III). In Member QGMS-I soils often A/C type soil horizons are observed or a very weekly developed B-horizon is encountered. The solum thickness of various morphostratigraphic members is given in the Fig.6.1. The solum thickness also increases with age from QGMS-I to QGMS-III soils (QGMS-I- 30-62cm, QGMS-II- 40-87cm and QGMS-III- 85-155 cm). Then there is a little decrease in the QGMS-IV soils (65-135 cm) and it again increases with age up to QGMS-VI soils (QGMS-V- 70-140 cm, QGMS-VI- 85-160 cm). The reason for a decrease in solum thickness from QGMS-III to QGMS-IV is not clear.

6.6.4 Soil micromorphology

Micromorphological studies show distinct variations in features such as the grade of pedality, degree of alteration of minerals, thickness of argillans, b-fabric developments, smoothness/roughness of void surfaces, concretions and mottles with increase in age.

Micromorphological investigation shows that the QGMS-I and QGMS-II soils have weak pedality, whereas soils in other Members show moderate to well developed sub-angular blocky microstructures. Stipple-speckled (Fig. 5.7b), circular-striated (Fig. 5.9c, 5.10a), and reticulate- (Fig. 5.8f) b-fabrics are developed in the older members of morphostratigraphic sequence. The degree of development of b-fabric is stronger in QGMS-I to IV and decreases in QGMS-V & VI member soils. Weathering of biotite and feldspars increases from QGMS-I to QGMS-VI soils. The void surfaces are extremely rough in QGMS-I & II, whereas they are rough to smooth in QGMS-III & IV due to clay coatings, but in QGMS- & VI they are dominantly smooth due to thick hypo- and quasi- clay coatings. Multi nucleated Fe-Mn nodules with sharp boundaries are seen in the soils of the study area. Calcrete nodules of <10 mm diameters are found in the Old Gandak Plain. The Gandak terminal fan-I shows calcitans in the upper horizons, suggesting dissolution and precipitation of calcitic material..

6.7 STRUCTURAL FEATURES OF THE STUDY AREA

Structurally the area has been subdivided into three major tectonic blocks such as Ghaghara-Rapti, Rapti-Gandak and Gandak-Kosi blocks, separated by Rapti fault-II and Gandak fault, respectively. These blocks are further subdivided into sub-blocks separated by normal faults within these blocks. Each block behaved independently during the Holocene period.

6.7.1 Ghaghara-Rapti Block

The Ghaghara-Rapti block is bound by curvilinear Ghaghara and Rapti-I &II faults, with convexity to the SW (Fig. 2.25). Both the bounding rivers are incised in nature, forming this block an upland interfluve. Most part of the block is covered by the terminal fans of the Rapti River, which changed its course frequently. The oldest soil in this block has >10 Ka age and forms the base for the deposition of most of younger terminal fans. This block is further subdivided by two major NE-SW trending faults (Colnelganj-Balrampur fault and Ayodhya-Dinkarpur fault, (Fig.2.25) into three sub-blocks i.e. the Bahraich (northwestern) and Gonda (central region) and Basti (eastern region) sub-blocks. A number of smaller NE-SW trending faults like Intaha-Parsa fault, Bahraich fault, West Uttraulla faul and Faizabad-Domariaganj fault are also identified from this block.

The Bahraich and Gonda sub-blocks are marked by exceptional widening of the floodplains of Ghaghara and Rapti as compared to downstream courses of these rivers, caused by shifting of these rivers from NE to SW due to tilting of theses sub-blocks towards SW (Srivastava et al., 1994). This Bahariach sub-block forms a virtual 'table land' as compared to the other sub-blocks (Fig. 2.25).

Due to the presence of Faizabad Ridge in the southeastern region of the Gonda sub-block, leading to probably blocking of drainage results in high moisture content of soils in area west of it, as reflected in MSS images. Also, southward tilting of this sub-block caused widening of the Rapti and Ghaghara river floodplains.

The Basti sub-block is bounded by the Ayodhya-Dinkarpur Fault in the west and the Rapti-II Fault in the east. This block is marked by parallel to sub-parallel drainage patterns parallel to the Basti lineament (BLt). This sub-block in its southern part is marked by two terraces of Ghaghara (Fig. 2.7) and the rivers are more incised in this block as compared to the other sub-blocks.

Two NW-SE trending lineaments (Faizabad-Alliganj lineament and Basti lineament) are observed in the Ghaghra-Rapti Block (Fig. 2.1).

The Rapti terminal fan-I was deposited within the 22.5 km wide floodplain of Rapti in the northern part at the base of the piedmont by the activity of Rapti Fault-I. Other meandering terminal fans of Rapti (RTFn-III-V) were deposited by the activity of Faizabad-Domariaganj Fault, Barhaich Fault and Rapti Fault-I, respectively. In all these Rapti terminal fans, Rapti shows gradual shifting across these fans leaving old plains as in case the Gandak River on the Gandak megafan (Sec. 2.5). The Khujurpur terminal fan is an elongated one having an average width of 13 km and was formed over the Rapti terminal fan-IV, due to the activity of the Colnelganj-Balrampur Fault. The Babban terminal fan was created on the Basti sub-block by the activity of Ayodhya-Dinkarpur Fault.

6.7.2 Rapti-Gandak Block

The Rapti-Gandak block is marked by eastward shifting of the Gandak River over 80 km due to the eastward tilting of this block (Mohindra et al. 1992) during the period 10.3-5.4 Ka (this study), as a result, soil development decreases from west to east on the Gandak megafan, though on the whole, soil is moderately to strongly developed. This block is further subdivided by the NE-

SW tending Gorakhpur-Padrauna and Barhaj-Bettiah faults (longitudinal faults) into three sub-blocks viz. Maharajganj (northernmost), Captainganj (central) and Siwan sub-blocks (Fig. 2.6). These sub-blocks and bounding faults were mapped on the basis of recognition of artifact geomorphological features (rounded hills, dissected tableland and flatland) in DTMs. The Maharaganj sub-block is marked by low drainage density and 'rounded hill', the Captainganj sub-block by high drainage density and 'dissected tableland' and the Siwan sub-block is a 'flatland' with moderate drainage density (Fig. 2.6). The slope of these sub-blocks gradually decreases from NW to SE.

Four additional faults i.e. the Rohini fault, Maharajganj-Dhaka and Nichlul fault and West Patna fault are also present on this block. The Rohini Fault in northern region separates the piedmont zone from the plains and the downthrown block is towards north. The Maharajganj-Dhaka Fault divides the Gandak terminal fan-III into two halves, which continues eastward into the Gandak-Kosi block, where it offsets the active Burhi Gandak to SW by 9 km. These faults trend NE-SW direction. The Nichlul Fault, in the northern region, trends NW-SE, parallel to the nearby Siwalik Ranges, and thus is a longitudinal fault.

Four terminal fans are observed on the Rapti-Gandak Block. Three Gandak terminal fans -I-III are described above. The fourth small Jharni terminal fan formed due to the activity of the Barhaj-Bettiah Fault at ~1.4 Ka.

6.7.3 Gandak-Kosi Block

This block is traversed by seven subparallel nearly east-west trending faults with downthrown sides to the south, with decreasing throw (7 m-3 m) from north to south. These form a step-fault system (Fig. 6.2). These are considered as longitudinal faults, as they are sub-parallel to the Himalayan trend. Most of these faults are traceable for distances of >85 km, whereas others can be traced only in short stretches and in-between these stretches, these are probably covered due to a high rate of sedimentation in the area. One longitudinal fault (Piedmont faults-I) is present in the Old Piedmont zone, one (Piedmont-II) at the boundary of the Old and Young piedmont zones, one in the Young Piedmont zone (North Sitamarhi), four such faults (South Motihari, Madhubani, North Muzaffarpur and South Muzaffarpur faults) are present in the plains.

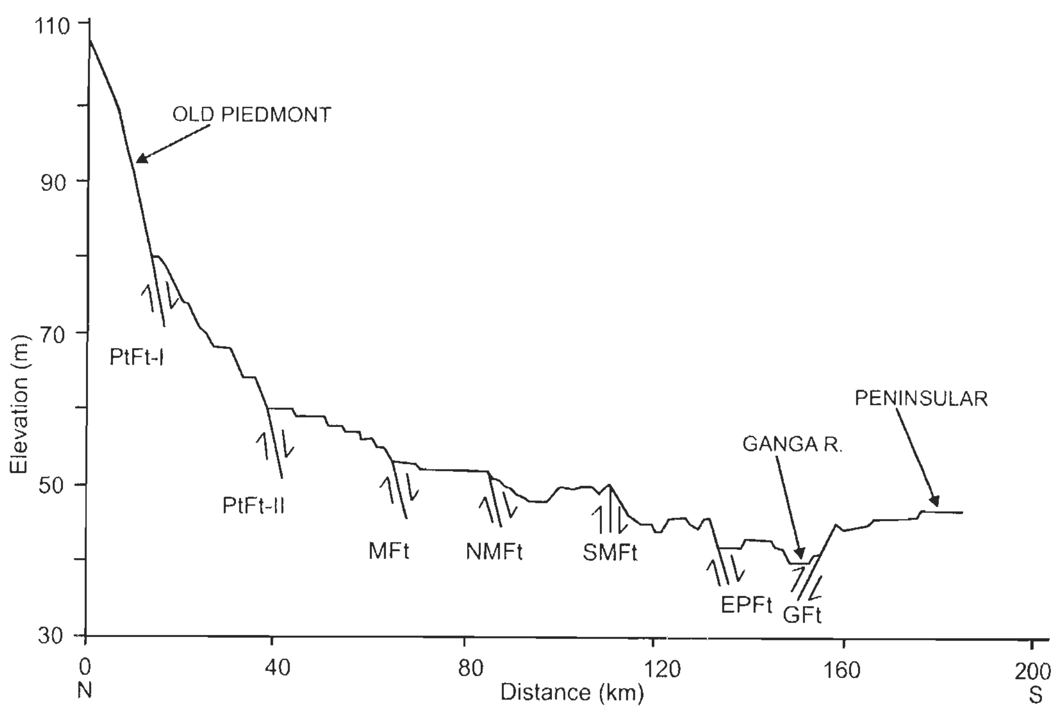


Fig. 6.2 Profile section of the Gandak-Kosi interfan area from piedmont zone to Peninsular boundary shows step like appearence due to activity of normal faults in the region

Very weakly to weakly developed soil profiles, the widest piedmont zone (82 km), widespread swampy and waterlogged plains are the characteristic features of this block (Fig 2.26). On the whole, the block exhibits southerly to southeasterly slopes.

The Baghmati terminal fan-II and Burhigandak terminal fan-I were deposited due to activity of the South Muzaffarpur Fault during the period 1.2-0.7 Ka. These two fans are separated by the N-S trending Hathauri-Simariaghat Fault. The Bagmati-I and Kamla-II terminal fans were deposited due to the activity of the Piedmont Fault-II at 0.8-1.3 Ka and 2.4 Ka, respectively. Activity of the Madhubani and West Patna Faults at about 1.3 Ka and 1.1 ka, gave rise the Kamla –I and Burhi Gandak-II terminal fans, respectively.

6.7.4 Faults and Occurrence of Earthquakes

Twenty-three earthquakes have been recorded in this region from 1833 A.D to 1984 A.D (Fig.2.24b) and are related to inferred faults .Two or more earthquakes are associated with the South Motihari, Piedmont Fault-II, Ghaghara-Ganga, East Patna, North Sitamarhi, Himalayan Frontal and Rapti-II Faults. Three earthquakes of 1833, 1864 and 1865 are close to intersection of two or more faults.

Only two basement faults i.e. West Patna Fault and East Patna Fault have surface manifestation (Fig.2.24b). Other faults located in this study area, unrelated to any known basement faults, seem to have given rise to 19 earthquakes and thus present attempt to locate and map active faults is a useful exercise in understanding occurrence of earthquakes.

It may be noted that the basement East Patna Fault does not show any surficial expression, but movement along this fault has caused 1959 and 1964 earthquakes.

6.8 GPR STUDIES

Using GPR, we confirmed the inferred faults and found out their subsurface nature, the effect of their activity on contemporaneous sedimentation and worked out radar facies of the Gandak megafan and five terminal fans.

We confirmed the surficial expression of the West Patna Fault (WPFt), which is a basement fault (G.S.I., 2000) and South Muzaffarpur fault. The WPFt is a set of normal faults, whereas the SMRFt consist of two major normal faults. Also, GPR studies show that terminal fans were deposited on the downthrown sides due to the activity of normal faults. Three sandy sequences (each 2-3 m thick) were observed overlying thick sands of a large river (Gandak River) on the downthrown block of the South Muzaffarpur Fault (SMRFt) in GPR profiles, indicating repeated activity of the fault. In a similar way, activity of the South Motihari fault inferred at 4.8 Ka and 1.4 Ka leading to the development of Gandak terminal fans II and III in almost same area was confirmed by the presence of three GPR sequences in the area (Main Gandak River, Gandak terminal Fan-II and III sequences).

The older Gandak River sediments underlying some terminal fan deposits consist of braid bar deposits formed due to stoppage of migration of dunes or deposition in upper plane bed phase and sigmoidal to trough cross-bedded sand in deeper anabranches in the lower parts, whereas in upper parts, lateral accretion and upstream/downstream accretions are very common in GPR profiles. Upstream accretion deposits are much thicker (8 m) than those observed by Best et al. (2003) in the Jamuna River deposits in Bangladesh. The bars may be marked by vertical accretion on bar top. Rarely the Gandak River deposits show bar margin slip face migration (BMSF) giving rise to large scale cross-stratification. Thickness of BMSF deposits increases, as the bar grows in size.

GPR profiles on terminal fans bring out that these are mainly lateral accretion deposits overlain by mud facies. The overlying mud facies deposited in floodplains and/or in abandoned channels. Well-defined nested channels in the upper part of terminal fan sequences show distinct stages in their filling by lateral accretion.

6.9 DISCUSSION

6.9.1 Nature of Faults

The Ghaghara-Rapti Interfluve, a part of the Upper Gangetic Plain, is bound by curvilinear Ghaghara and Rapti faults with a convexity to the SW and a number of transverse faults. Similar curvilinear faults like the Ganga fault, Ghaghara fault, Yamuna fault and Deoha Fault are reported in major parts of the Upper Gangetic plains further west (Singh et al., 2006; Bhosle et al., 2008). Deformation pattern in the Upper Gangetic Plain was simulated by finite element modeling technique, using a compression from the southwest (Fig. 6.3), inferred from tilting of large blocks in Upper Gangetic Plain and obtained similar deformation pattern . Curvilinear nature of the major faults (longitudinal) was

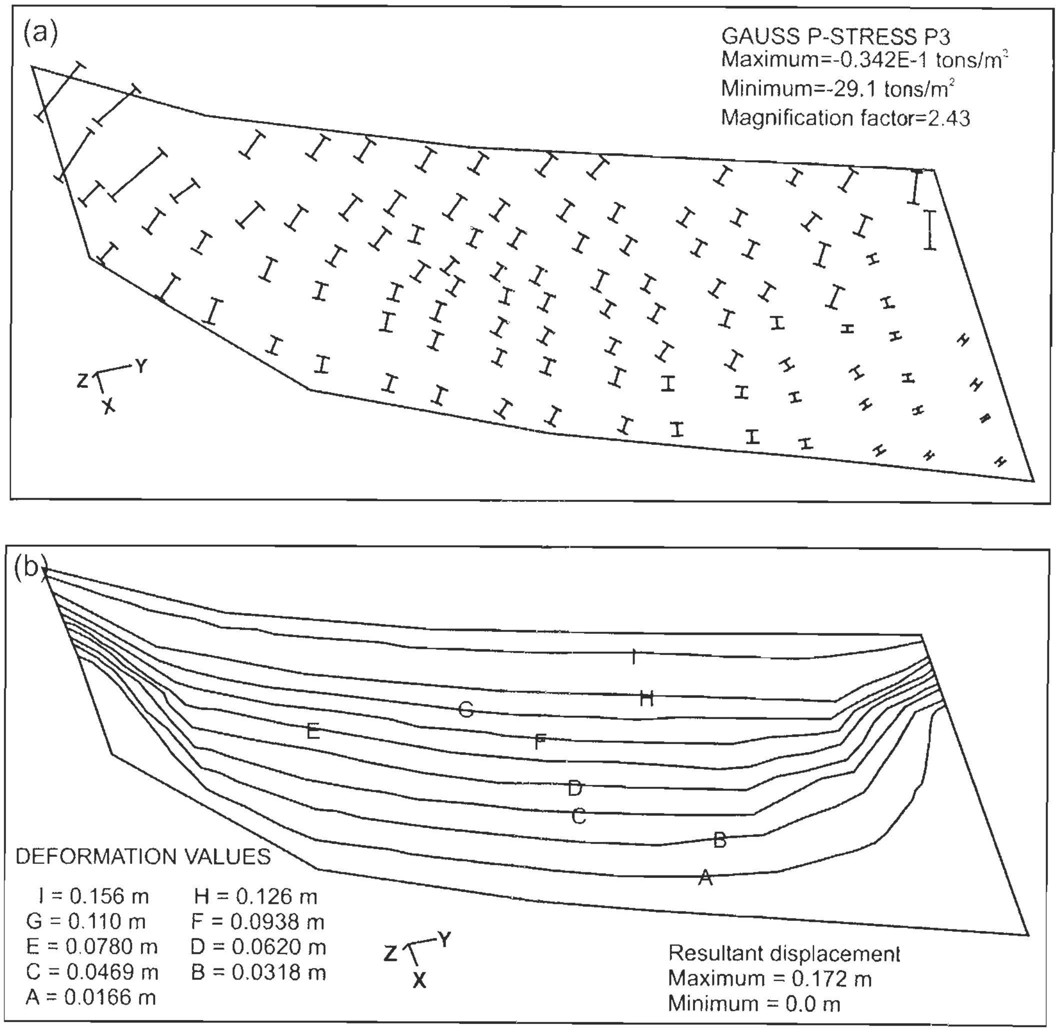


Fig.6.3 (b) Deformation contours for north-east ward movement (after Parkash et al., 2000).
(a) Vector stress diagram showing principal compressive stress for north-east ward movement

attributed to confining nature of the N-S striking, subsurface Delhi-Hardwar Ridge at the western boundary and E-W trending southern boundary of the Gangetic Plain with the South Indian Shield. Faults striking at large angles to the longitudinal faults are called transverse faults and considered as normal type, as they developed in an extensional setup. By comparison with these areas, the curvilinear Ghaghara and Rapti faults are longitudinal faults and NE-SW trending faults in our area also transverse normal faults.

The presence of numerous E-W striking faults sub-parallel the Himalayan trend in the Rapti-Gandak and Gandak-Kosi Blocks suggests a compression from the south.

The E-W trending faults on the Gandak-Kosi Block could be imbricates of the HFT, with near vertical nature near the surface, giving impression of normal faults, as observed in the GPR profiles up to depths of 12 m. Thus these faults should be thrusts in nature. However, another explanation is preferred here. Due to a high rate of convergence on the Himalayan Frontal Thrust opposite the Middle Gangetic Plain, the highest rates of uplift leading to the highest peaks in the Himalaya north of the this plain and very high rate of subsidence in this block suggests a unique situation (Fig. 6.6), where because of high rates of uplift even in area close to the HFT, parts of this block cannot cope with such an uplift and consequently numerous normal faults develop in this area (Fig. 6.2).

Using Global positioning system Sridevi (2004) found that the India plate is showing movements towards NE and N in the Upper and Middle Gangetic Plains (Fig. 6.4), respectively, which are similar to those given by faults inferred by us. However, such deformation patterns have been active at least since ~10 ka in the Upper and since ~4.5 ka in the Middle Gangetic Plain, as suggested by ages of soils in the area.

6.9.2 Sedimentation and Tectonics

The Gandak-Kosi Block is marked by a number of E-W trending longitudinal faults. Due to activity of the Piedmont Fault-II, at the base of the Old Piedmont, a 44 km wide Young Piedmont has developed, which gives a width of 82 km for the whole piedmont, is the widest in the Gangetic Plains. A high subsidence rate in the area (Thomas et al., 2002) and the presence of a step-fault system with throws to south observed in the present study have caused such a large progradation of the piedmont zone towards south.

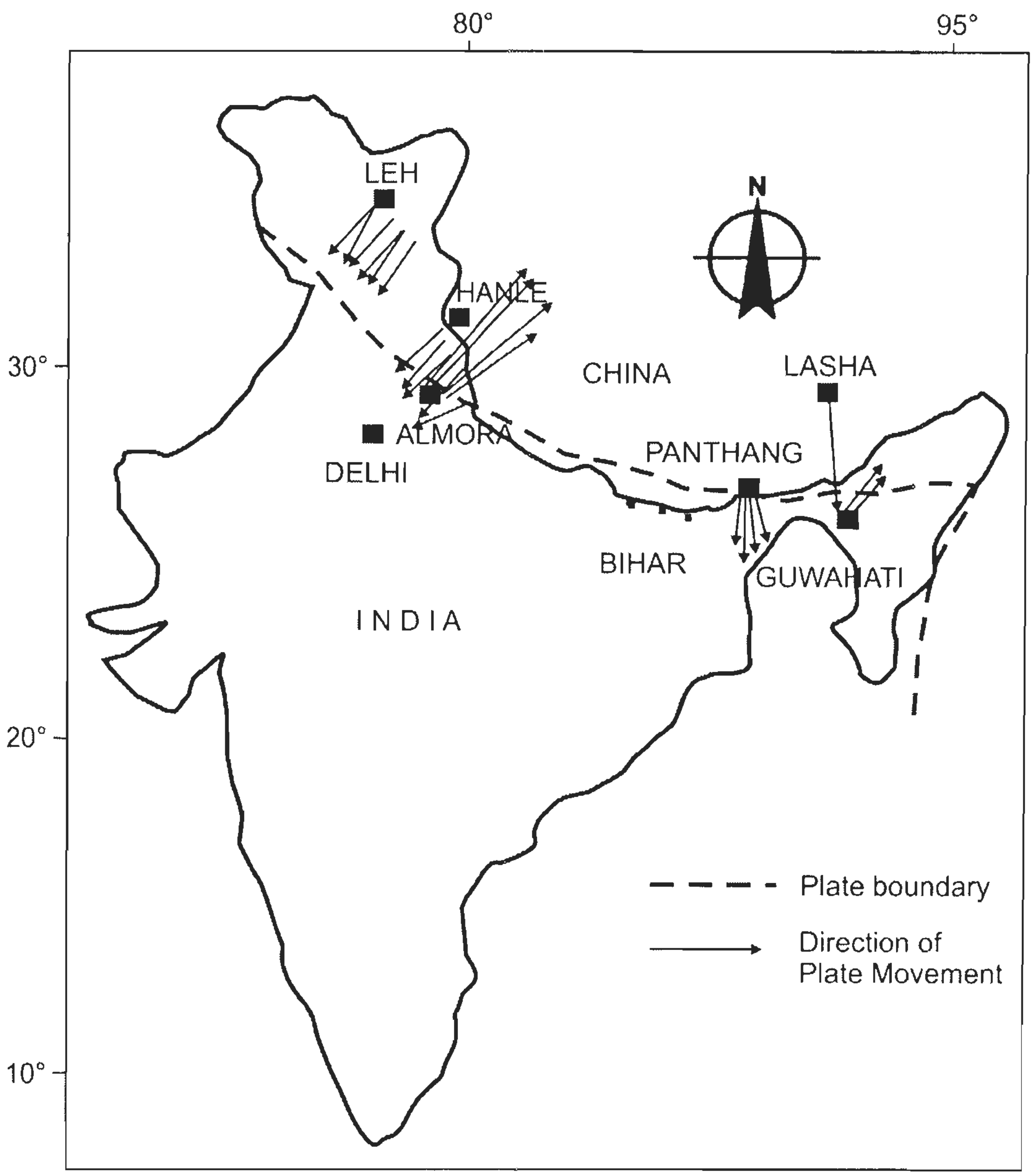


Fig.6.4 Plate movement direction shown GPS stations
(after Sridevi, 2004)

This is the zone of almost parallel streams with overlapping fans (Young Piedmont). As the Piedmont Fault-II also leads to formation of individual fans (included in the terminal fan category in the present study) like the Baghmati-I and Kamla fan, which extend individually up to 96 km into the plains. Inclusion of such fans into the Young Piedmont, will give a width of 107.5 km to the piedmont, leaving only a 60 km wide Interfan plain. Thus transitions do exist from terminal fans to piedmont zone in the Gandak-Kosi Interfan area.

Earlier terminal fans were shown to have been deposited in the Upper Gangetic Plains due to transverse normal faults on the downthrown blocks. In the Middle Gangetic Plain, terminal fans were deposited due to activity of the longitudinal faults. In the Ghaghara-Rapti Interfluve, easternmost part of the Upper Gangetic Plain, activity of the both longitudinal and transverse faults seems to have led to deposition of terminal fans.

Within the Upper Gangetic Plains, earlier Singh et al. (2006) and Bhosle et al. (2008) observed that bounding river of the interfluves deposited sediments over only small parts of the interfluve, marginal to the bounding river. However, in the Ghaghara-Rapti Interfluve, we find a small bounding Rapti River has deposited five terminal fans.

As observed earlier (Singh et al., 2006; Bholse et al., 2008), terminal fans form due to an abrupt slope change caused by faults, across the courses of small streams. However, depending upon the nature of streams, these can be meandering or braided terminal fans, as observed from the present study area. When the large the Gandak River crosses a fault at large angle to its strike, with a small throw, it continues its courses, without any regard for the slope of downthrown blocks. However, small spays keep flowing from the main river along the slope of the downthrown block, forming splay terminal fans like Gandak splay terminal fans-I-III.

6.9.3 Role of Climate

The Gangetic Plains witnessed a very cool and dry climate with reduced river discharges and decreased monsoonal activity during the Last Glacial Maximum (LGM) (18-22 Ka) 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 and Kutzbach 1987, 1992). The periods of 1.7 to 3.6 ka and 6.5 to 9.6 ka (Sharma et al. 2004; Pradeep Srivastava et al. 2003) are marked by wetter periods, relative to the rest of the Holocene Period.

Bhosle et al. (2008) observed a significant decrease in pedogenic activity during the period 3.3-6.5 ka and attributed its to reduced monsoonal activity inferred by Sharma et al. (2004) in the semiarid Ganga-Yamuna Interfluve. In our study area, we find the following evidence of climatic influence:

i. As in most of the Upper Gangetic plain, the Ghaghar-Rapti interfluve upland formed due to incision of the bounding rivers at about 10 Ka. This was caused by an increase in monsoonal activity leading to higher discharges of these rivers. Later different terminal fans were deposited on this interfluve.

ii. In general, solum thickness of soils increases with age up to 10 Ka (Fig. 6.5). However, there is a decrease in solum thickness in older soils (> 10

Ka) than younger ones (10-8 ka), supporting a cool and drier climate during the period >10ka.

We are not able to detect the effect of a drier period (3.6-6.5 Ka) of

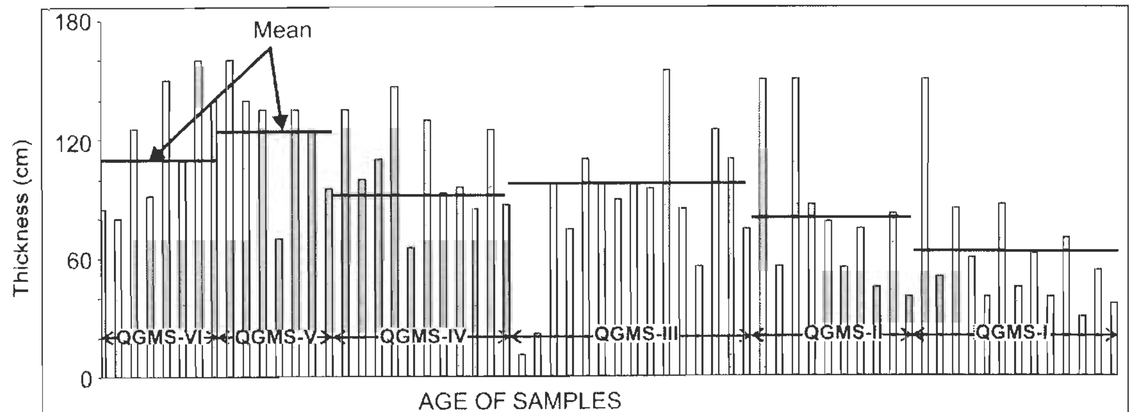


Fig.6.5 Solum thickness verses ages of Morphostratigraphic Members

Sharma et al. (2004) in our soils. However, instead of an increase in solum thickness in QGMS-IV (8.4-6.9 Ka) from QGMS III (6.9-4.7 Ka) as usually expected, there is a slight decrease/no change in solum thickness as compared to QGMS-III, suggesting the period 8.4-6.9 Ka may have been slightly drier than the rest of the Holocene. However, this hypothesis needs to be checked from other criteria.

6.9.4 Evolution of Landforms, Pedology and Sedimentology

Active tectonics seems to have played a major role in the evolution of geomorphology, pedology and the depositional process in the area. Significant events and related phenomenon caused by tectonics are described below:

The Ghaghara-Rapti Interfluve was a region of sedimentation till about 11-10 Ka by the Rapti River and other interfluve region streams. Due to climate becoming warm and wet at 11/10 Ka, bounding rivers got incised due to an increase in discharge. Since then due to activity of transverse faults, major sedimentation in the form terminal fans on the interfluve took place between 8.4-6.9 ka. More recently minor sedimentation in form of terminal fans has been taking place since about 3.5 Ka due to activity of Colnelganj-Balrampur fault and Ayodhya-Dinkarpur Fault. This block was divided from the proximal to distal are into three sub-blocks: Bahraich, Gonda and Basti sub-blocks. The Bahraich and Gonda sub-blocks have shown tilting towards west at about 1.2 Ka causing widening of the Rapti and Ghaghara floodplains up to 10 km and 30 km, respectively. Also, the Basti sub-block tilted southward slighted at about 7.5 Ka and 4-3 Ka to form terraces of the Ghaghra and widening of the Rapti Floodplain.

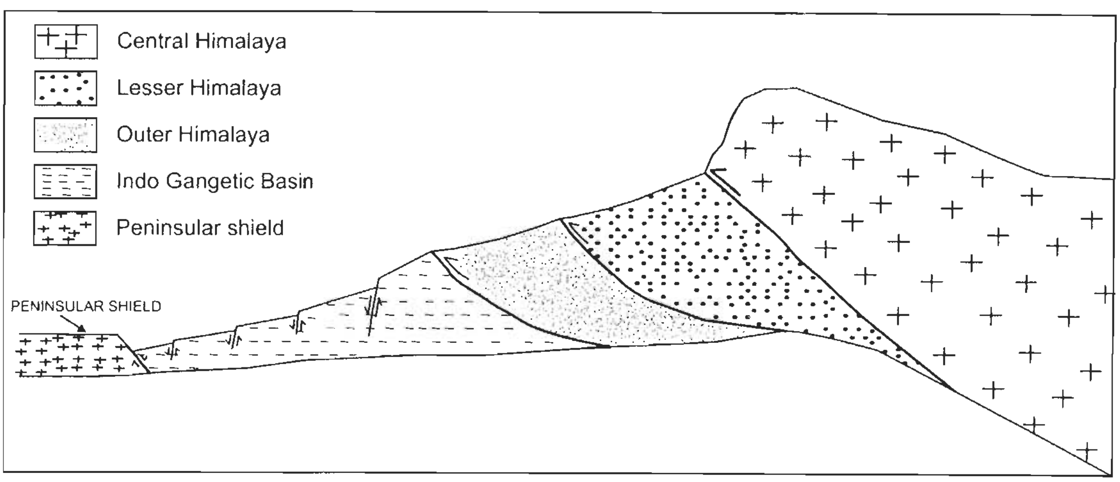


Fig.6.6 Schematic diagram of the Middle Gangetic plain

Sedimentation on the Gandak megafan block, bound by the NW-SE trending Rapti and Gandak faults was controlled by two types of tectonic movements. Firstly this block tilted northeastward, causing a shift of the Gandak River from west to east over a distance of 80 km during the period 10-8.6 ka. This led to the highest degree of soil development in the west which decreases to the east. Secondly since about 4.5 ka, activity of E-W to NW-SE trending longitudinal faults caused deposition of four terminal fans; three of (named as 'splay terminal fans') which formed as a results of splays from the Gandak River on the downthrow blocks of two faults. More recently activities of NE-SW trending faults have divided the megafan into three blocks, with decreasing topographic levels towards southeast in two distinct steps.

The Gandak-Kosi Block was a site of deposition till about 4.5 Ka. Since then the Old Piedmont zone was slightly uplifted and pedogenesis started on this zone and Young Piedmont formed south of it, making piedmont in this block as the widest on in the whole of Gangetic plains. However, most of the plains have been a zone of sedimentation in form of terminal fans due to activity of longitudinal faults. The present surface of the plains bears signatures of two movements along faults at about 1.1 Ka and 0.7 Ka, when recent phase of terminal fans started. Thus the Middle Gangetic plain (the Rapti-Gandak and Gandak-Kosi blocks) have been tectonically highly active in recent times.

The Middle Gangetic plain has been more active tectonically than the Upper Gangetic Plain and was tectonically most active during the period 4.5 Ka to recent period. This is also supported by the recording of a large number of devastating earthquakes from this area.

6.10 CONCLUSIONS

From the systematic mapping of soil-geomorphic units and tectonic features by using remote sensing and GIS tools, field work, GPR traverses, OSL dating, grain size analysis and soil micromorphology studies, the following conclusions are obtained:

(1) Studies of the digital elevation models, the digital terrain models, the MSS images combined with the topographic maps and field checks were very useful in identification of soil-geomorphic units and tectonic elements (tectonic blocks, faults and lineaments).

(2) The identified twenty-seven soil-geomorphic units are grouped into six morphostratigraphic sequence members based on the IRSL ages and the degree of soil development as QGMS-I (<1.4 Ka), QGMS-II (1.4-4.7 Ka), QGMS-III (4.7-6.9 Ka), QGMS-IV (6.9-8.4 Ka), QGMS-V (8.4-10 Ka) and QGMS-VI (>10 Ka).

(3) The soils in the Upper Gangetic plains are moderately to well-developed, whereas soils in the Middle Gangetic plains weakly to moderately developed.

(5) The Ghaghara-Rapti Interfluve, a part of the Upper Gangetic Plain, is bound by curvilinear Ghaghara and Rapti faults with a convexity to the SW and a number of transverse, normal faults. The interfluve is an upland due to incision by the bounding rivers and overlain by 10 Ka soils. Later due to activity of transverse normal faults and the Rapti Longitudinal Fault at different times, a number of younger terminal fans were deposited over the oldest soils.

(6) Sedimentation on the Gandak megafan block, bound by the NW-SE trending Rapti and Gandak faults, was controlled by two types of tectonic movements. Firstly this block tilted northeastward, causing a shift of the Gandak River

from west to east over a distance of 80 km during the period 10-8.6 ka. This led to the highest degree of soil development in the west, which decreases to the east. Secondly since about 4.5 ka, activity of E-W and NE-SW trending longitudinal faults and the locally developed Nichlul Fault caused deposition of four terminal fans.

(7) The Gandak-Kosi Interfan block is marked by a high rate of subsidence and step-fault system with throws to the south, which has caused significant progradation of the piedmont zone southwards, forming the widest piedmont zone (82 km) in the Gangetic plains. This Interfan region is traversed by a number of longitudinal faults, whose activity during the period 4.5-1.3 Ka has led to development of terminal fans, which cover major parts of the plains, marked by low-lying swampy lands.

(8) The terminal fans formed mainly due to activity of transverse normal faults in the Upper Gangetic plains. However, in the Middle Gangetic plains, activity of the E-W trending longitudinal faults (normal type) gives rise to terminal fans under dry and moist sub-humid climates.

(9) Two types of terminal fans (meandering and braided) in the study area have been recognized. However, the Gandak terminal fans-I and II- III formed by the splays of the Gandak River as it crossed the Nichlul and South Motihari faults, respectively. Thus these terminal fans are different from the earlier described ones, where whole discharge of small rivers are involved in their formation. These Gandak terminal fans are named as “splay terminal fans”.

(10) Soils in the upland Interfluve regions of the Upper Gangetic plains show calcrete development at depths and salt efflorescence on the surface. However, the Middle Gangetic plains are extensively marked by swampy water-logged regions and weakly to moderately developed soil.

(11) The curvilinear Ghaghara and Rapti faults (like other such faults in the Upper Gangetic Plains) were earlier explained due to compression from SW and confining effect of the N-S striking (subsurface) Aravalli Ridge forming the western boundary of the Gangetic plains and E-W trending southern boundary of the plains with the South Indian Shield (Parkash et al., 2000). However, the development of E-W trending longitudinal faults in the Middle Gangetic Plains suggest a compression from south.

(11) Using Global positioning system Sridevi (2004) found that the Indian plate is moving towards NE and N in the Upper and Middle Gangetic Plains, respectively, and similar compression directions are given by faults inferred by us. However, ages of soils suggest that such deformation patterns have been active at least since ~10 Ka in the Upper and since ~4.5 Ka in the Middle Gangetic Plains.

(12) Tectonics has influenced significantly the geomorphology, pedology and sedimentation in the area. Due to activity of the faults, terminal fans get deposited on the downthrown blocks and quickly streams start getting entrenched slightly, leading to initiation of pedogenesis. Thus soils on the terminal fan provide time of activity of faults. Also, wide piedmont zone in the

Gandak-Kosi interfan region is a result of activity of a set of normal faults in this zone.

13. Paleoclimate has played subtle roles in the area. In the Ghaghata-Rapti Interfluve region, the bounding rivers got incised at about 10 Ka due to change from dry and cold to warm and wet climate, leading to an increase in discharge. Also, solum thickness of soils shows an increase with age up to 10 Ka and the older soils exhibit a decrease in solum thickness.

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APPENDIX-I

FIELD DESCRIPTION OF TYPICAL PEDONS

A-I.1 QGMS-I

A-I.1.1 Old Ghaghara Plain

Pedon : P-61

Classification : Coarse Loamy Mixed Hyperthermic Typic Ustorthents

Location : Balpur Bazar

Geographic Position : 81° 51′ 19" E, 27° 7′ 74" N

Parent Material : Alluvium

Erosion : Minor aeolian activities are found

Slope : Gentle towards southeast

Drainage Class : Moderately drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivation

Typifying Pedon

Ap 0-16 cm : 5Y8/2 moist, coarse sandy loam; no structure; many fine pores, weakly cemented, cutans absent; many coarse roots; organic activity high

AC 16-26 cm : 5Y7/4 moist; coarse sandy loam; many fine pores, very weakly cemented; few fine-moderate roots; clay cutans absent; few soft Fe-Mn nodules 1-2 mm.

C 26-50+ cm : 10YR5/8; moist; sandy loam; pores fine, many, very weakly cemented, cutans absent; clay cutans absent; few fine-moderate roots; Fe-Mn nodules, very few, soft, 0.5-1 mm.

A-I.1.2 Baghmati Terminal Fan-II

Pedon : P-52

Classification : Coarse Loamy Mixed Hyperthermic Aquic Ustorthents

Location : Lakhanpati

Geographic Position : 86°07′59" E, 25° 43′ 41" N

Parent Material : Alluvium

Erosion : No erosion

Slope : Gentle towards southeast

Drainage Class : Poorly drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivation

Water Table : 20 feet

Typifying Pedon

Ap 0-10 cm : 2.5Y5/3, moist; sandy loam; no structure; many fine pores, weakly cemented, cutans absent; many coarse roots; organic activity high.

AC 10-25 cm : 10YR5/4 moist; sandy loam; many fine pores, very weakly cemented; cutans absent; many coarse to fine roots; few soft Fe-Mn nodules 2-3 mm.

C 25-50+ cm : 10YR6/3, moist; loamy sand; pores fine, many, very weakly cemented, cutans absent; few fine roots; Fe-Mn nodules, dark grayish, spherical numerous, hard, 0.2-0.3 cm.

A-I.1.3 Burhigandak Terminal Fan-II

Pedon : P-58

Classification : Coarse Loamy Mixed Hyperthermic Typic Ustorthents

Location : Salempur

Geographic Position : 85°26′29" E, 25° 50′ 32" N

Parent Material : Alluvium

Erosion : No erosion

Slope : Gentle towards southeast

Drainage Class : Poorly drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivation

Water Table : 20 feet

Typifying Pedon

Ap 0-15 cm : 2.5Y5/3, moist; loamy sand; no structure; many fine pores, weakly cemented, cutans absent; many coarse roots; organic activity high.

AC 15-40 cm : 10YR5/4 moist; sandy loam; many fine pores, very weakly cemented; cutans absent; many coarse to fine roots; few soft Fe-Mn nodules 2-3 mm.

C 40-60+ cm : 10YR6/3, moist; sandy loam; pores fine, many, very weakly cemented, cutans absent; few fine roots; Fe-Mn nodules, dark grayish, spherical numerous, hard, 0.2-0.3 cm.

A-I.1.4 Baghmati Terminal Fan-I

Pedon : P-64

Classification : Coarse Loamy Mixed Hyperthermic Aquic Haplustalfs

Location : Dumra

Geographic Position : 85°29´46" E, 26° 33´ 34" N

Parent Material : Alluvium

Erosion : No erosion

Slope : Gentle towards southeast

Drainage Class : Poorly drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivation

Water Table : 25 feet

Typifying Pedon

Ap 0-15 cm : 2.5Y5/3, moist; loamy sand; no structure; many fine pores, weakly cemented, cutans absent; many coarse roots; organic activity high.

Bt 15-33 cm : 2.5Y5/3 moist; sandy loam; many fine pores, very weakly cemented; patchy thin clay cutans; weakly developed sub angular blocky structure, many coarse to fine roots; few soft Fe-Mn nodules 2-3 mm.

BC 33-54 cm : 10YR5/3, moist; sandy loam; pores fine, many, very weakly cemented, cutans absent; few fine roots; Fe-Mn nodules, dark grayish, spherical numerous, hard, 0.2-0.3 cm.

C 54-66+ cm : 10YR5/2, moist; sandy loam; pores fine, many, very weakly cemented, cutans absent; few fine roots; Fe-Mn nodules, dark grayish, spherical numerous, hard, 0.2-0.3 cm.

A-I.1.5 Kamla Fan-I

Pedon : P-50

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Kotbandh

Geographic Position : 86°06′51" E, 26° 06′ 59" N

Parent Material : Alluvium

Erosion : No erosion

Slope : Gentle towards south

Drainage Class : Poorly drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivation

Water Table : 25 feet

Typifying Pedon

Ap 0-15 cm : 2.5Y5/3, moist; sandy loam; no structure; many fine pores, weakly cemented, cutans absent; many coarse roots; organic activity high.

Bt 15-30 cm : 2.5Y5/3 moist; sandy loam; many fine pores, very weakly cemented; patchy thin clay cutans; weakly developed sub angular blocky structure, many coarse to fine roots; few soft Fe-Mn nodules 2-2.5 mm.

BC 30-50 cm : 2.5Y5/3, moist; sandy loam; pores fine, many, very weakly cemented, cutans absent; few fine roots; Fe-Mn nodules, dark grayish, spherical numerous, hard, 0.2-0.3 cm.

C 50-100+ cm : 2.5Y5/2, moist; loamy sand; pores fine, many, very weakly cemented, cutans absent; few fine roots; Fe-Mn nodules, dark grayish, spherical numerous, hard, 0.2-0.3 cm.

A-I.2 QGMS-II

A-I.2.1 Ghaghara Terrace-I

Pedon : P-38

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Gaighat

Geographic Position : 82°48′57" E, 26° 38′ 13" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Well drained

Moisture Condition : Moist (~15%)

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivated Land

Water table : 20/25 feet

Typifying Pedon

Ap 0-15 cm : 2.5Y6/2, moist; sandy loam; no structure; many fine pores, common medium distinct mottles (10YR6/8), weakly cemented, cutans absent; many coarse roots; organic activity high.

Bt 15-40 cm : 2.5Y5/4 moist; sandy loam; many fine pores, very weakly cemented; patchy thin clay cutans; common medium distinct mottles (10YR6/8), many coarse to fine roots; few soft Fe-Mn nodules 2-3 mm.

C 40-60+ cm : 2.5Y5/4, moist; sandy loam; pores fine, many, very weakly cemented, cutans absent; common medium distinct mottles (10YR6/8) few fine roots; Fe-Mn nodules, dark grayish, spherical numerous, hard, 0.3-0.5 cm.

A-I.2.2 Kamla Fan-II

Pedon : P-45

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Maniarawa

Geographic Position : 86°08′48" E, 26° 30′ 03" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Moderately Drained

Moisture Condition : Moist (~10%)

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivated Land

Ground Water : 40 Feet

Typifying Pedon

Ap 0-10 cm : 2.5Y5/3, moist; sandy loam; no structure; many fine pores, weakly cemented, cutans absent; many coarse roots; organic activity high.

Bt1 10-60 cm : 2.5Y5/3 moist; sandy clay loam; granular structure; pores, many, coarse; weakly cemented, thick clay cutans, common, fine roots; Fe-Mn nodules of 0.2-0.3 mm diameter, organic activity commonly found.

Bt2 60-80 cm : 2.5Y5/3, moist; sandy loam; pores fine, many, very weakly cemented, patchy thin clay cutans; few fine roots; Fe-Mn nodules, dark grayish, spherical numerous, hard, 0.2-0.3 cm.

C 80-100+ cm : 2.5Y5/2, moist; sandy loam; pores fine, many, very weakly cemented, cutans absent; few fine roots; Fe-Mn nodules, dark grayish, spherical numerous, hard, 0.2-0.3 cm.

A-I.2.3 Young Piedmont

Pedon : P-46

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Balwa Village

Geographic Position : 85°48′40" E, 26° 33′ 07" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Well Drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivated Land

Ground Water : 50 Feet

Typifying Pedon

Ap 0-10 cm : 2.5Y5/3, moist; sandy loam; no structure; many fine pores, weakly cemented, cutans absent; many coarse roots; organic activity high.

Bt 10-30 cm : 2.5Y5/3 moist; sandy loam; granular structure; pores, many, coarse; weakly cemented, patchy thin clay cutans, common, fine roots; Fe-Mn nodules of 0.2-0.3 mm diameter, organic activity commonly found.

Bw 30-75 cm : 2.5Y5/3, moist; sandy loam; pores fine, many, very weakly cemented, clay cutans absent; few fine roots; Fe-Mn nodules, reddish, spherical numerous, hard, 0.2-0.3 cm.

C 75-90+ cm : 2.5Y5/2, moist; sandy loam; pores fine, many, very weakly cemented, cutans absent; few fine roots, Fe-Mn nodules absent.

A-I.3 QGMS-III

A-I.3.1 Rapti Terminal Fan-II

Pedon : P-39

Classification : Coarse Loamy Mixed Hyperthermic Typic Ustorthents

Location : Ramnagar.

Geographic Position : 81°38′01" E, 27° 52′ 59" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Moderately Drained

Moisture Condition : Dry

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivated Land

Typifying Pedon

Akp 0-15 cm : 2.5Y5/5, dry; sandy loam; no structure; many fine pores, weakly cemented, cutans absent; many coarse roots; organic activity high.

Ak 15-55 cm : 2.5Y5/4, dry; sandy loam; many fine pores, very weakly cemented; cutans absent; many coarse to fine roots; Fe-Mn nodules absent, calcitic nodules of 2-3 mm are common.

Ck 55-90+ cm : 2.5Y5/2, dry; sandy loam; pores fine, many, structure less, cutans absent; few fine roots; Fe-Mn nodules absent, hard calcitic nodules of 0.1-0.2 mm diameter are common.

A-I.3.2 Gandak Terminal fan-I

Pedon : P-29

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustepts

Location : Charakha Village

Geographic Position : 84°06′43" E, 26° 48′ 32" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Well drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivated Land

Ground Water : 20 feet

Typifying Pedon

Akp 0-18 cm : 2.5Y5/2 moist; loam; structure less; single grain friable (moist); non sticky and non plastic (wet); few fine soil pores; few fine fibrous roots; very strongly calcareous; clear smooth boundary.

ABk 18-33 cm : 5Y5/3, moist; loam; structure less, massive; friable (moist) ; non sticky and non plastic (wet);common fine soil pores; few very fine fibrous roots; very strongly calcareous; clear smooth boundary.

Bk 33-48 cm : 2.5Y5/4, moist; silty loam; weak fine sub angular blocky structure; friable (moist); non sticky and slightly plastic (wet); few, fine, soil pores; very weakly cemented, roots absent; few Fe-Mn nodules.

Ck 48-100+ cm : 2.5Y5/4 moist; silty loam; structure less single grain; friable (moist); non sticky and non plastic (wet); no roots; irregular shape, bigger in size calcium carbonate concretions (4-5 mm diameter); moderately calcareous.

A-I.3.3 Gandak Terminal Fan-II

Pedon : P-35

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustepts

Location : Village Sajanpur

Geographic Position : 84°15´37" E, 26° 07´ 55" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Poorly drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivated land

Ground Water : 30-40 Feet

Typifying Pedon

Akp 0-25 cm : 2.5Y6/2; sandy loam; moist; structure less, single grain; slightly hard (dry), friable (moist), non sticky and non plastic (wet); common fine soil pores; very few and very fine fibrous roots; weakly calcareous and clear smooth boundary.

Bwk1 25-50 cm : 2.5Y3/2, moist; sandy loam; weak fine sub angular blocky structure; firm (moist), slightly sticky and slightly plastic (wet); common fine soil pores; few very fine fibrous roots; moderately calcareous and gradual smooth boundary.

Bwk2 50-130 cm : 5Y4/2, moist; sandy loam; weak fine sub angular blocky structure; concretions; firm (moist), slightly sticky and slightly plastic (wet); common fine soil pores; few very fine roots; moderately calcareous and gradual smooth boundary.

Bw 130-155 cm : 2.5Y4/4, moist; sandy loam; weak fine sub angular blocky structure; no clay cutans; friable (moist), slightly sticky and slightly plastic (wet); few fine soil pores; no roots; moderate to strongly calcareous and gradual smooth boundary

C 155-175+ cm: 2.5Y4/4, moist; sandy loam; structure less; massive loose (moist); slightly sticky and slightly plastic (wet); few fine soil pores; no roots; moderate to strongly calcareous.

A-I.3.4 Bhatibalan Fan (Old Piedmont)

Pedon : P-26

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Village Sonmati

Geographic Position : 86°21´41" E, 26° 31´ 03" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : moderately drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Moist sub-humid

Natural Vegetation : Cultivated land

Ground Water : 60-70 Feet

Typifying Pedon

Ap 0-13 cm : 2.5Y5/3, dry; sandy loam; no structure; many fine pores, weakly cemented, cutans absent; many coarse roots; organic activity high.

AB 13-25 cm : 2.5Y5/3, dry; sandy loam; no structure; many fine pores, weakly cemented, cutans absent; few fine faint mottles; many medium roots; low organic activities.

Bt1 25-65 cm : 2.5Y5/3 moist; sandy loam; sub angular blocky structure; fine pores, many, coarse; weakly cemented, thick clay cutans, common medium distinct mottles (10YR6/3); common, fine roots; Fe-Mn nodules of 0.2-0.3 mm diameter, organic activity commonly found.

Bt2 65-110 cm : 2.5Y5/3, moist; sandy loam; pores fine, many, very weakly cemented, patchy thin clay cutans; few fine roots; common medium distinct mottles, (10YR6/3); gradual smooth boundary.

C 110-125+ cm: 2.5Y5/2, moist; coarse sand; pores fine, many, very weakly cemented, cutans absent; few fine roots, Fe-Mn nodules absent.

A-I.3.4 Old Piedmont

Pedon : P-27

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Village Kakardob

Geographic Position : 86°34′54" E, 26° 22′ 56" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : moderately drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub humid

Natural Vegetation : Cultivated land

Ground Water : 60-70 Feet

Typifying Pedon

Ap 0-40 cm : 2.5Y5/3, dry; loamy sand; no structure; many fine pores, weakly cemented, cutans absent; many coarse roots; organic activity high.

AB 40-60 cm : 2.5Y5/3, dry; sandy loam; no structure; many fine pores, weakly cemented, cutans absent; few fine faint mottles; many medium roots; low organic activities.

Bt 60-85 cm : 2.5Y5/3 moist; sandy loam; sub angular blocky structure; fine pores, many, coarse; weakly cemented; thick clay cutans, common medium distinct mottles (10YR6/3); common, fine roots; Fe-Mn nodules of 0.2-0.3 mm diameter, organic activity commonly found.

C 85-135+ cm : 2.5Y5/2, moist; sandy loam; pores fine, many, very weakly cemented, cutans absent; few fine roots, Fe-Mn nodules absentcommon medium distinct mottles (10YR3/1).

A-I.4 QGMS-IV

A-I.4.1 Ghaghara Terrace-II

Pedon : P-17

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Village Gopinathpur

Geographic Position : 82°21′51" E, 26° 54′ 25" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Moderately drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivated land

Ground Water : 20 Feet

Typifying Pedon

Akp 0-30 cm : 2.5Y5/4, moist; sandy loam; no structure; many fine pores, weakly cemented, cutans absent; many coarse roots; organic activity moderate; calcitic materials found all along the horizon.

Ak 30-70 cm : 2.5Y5/4, moist; sandy loam; no structure; many fine pores, weakly cemented, cutans absent; few fine faint mottles; many medium roots; low organic activities; calcitic materials found all along the horizon.

Bt 70-100 cm : 2.5Y5/4 moist; sandy loam; sub angular blocky structure; fine pores, many, coarse; weakly cemented; bold medium thick clay cutans, common medium distinct mottles (10YR6/3); common, fine roots; Fe-Mn nodules of 0.2-0.3 mm diameter, organic activity not found.

C 100-120+ cm: 2.5Y5/2, moist; coarse sand; pores fine, many, very weakly cemented, cutans absent; roots absent, Fe-Mn nodules present.

A-I.4.2 Rapti Terminal Fan-IV

Pedon : P-18

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Village Kanbawa

Geographic Position : 81°53′00" E, 27° 18′ 22" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Well drained

Moisture Condition : Dry top soil and moist sub surface

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivated land

Ground Water : 50 Feet

Typifying Pedon

Akp 0-20 cm : 2.5Y5/4, dry; silty loam; structure less; friable (dry); no clay cutans; no ped faces; weakly cemented; common fine pores; slightly calcareous; clear smooth boundary.

Bt1 20-40 cm : 10YR5/4, moist; loam; moderately developed sub angular blocky structure; friable (moist); slightly plastic; common fine fibrous roots; patchy thin clay cutans; few fine faint mottles; many fine roots; slightly calcareous; gradual smooth boundary.

Bt2 40-100 cm : 10YR4.5/4, few medium faint mottles; loam; moderately developed sub angular blocky structure; friable (moist); slightly plastic; few fine fibrous roots; clay cutans along pores; common fine medium pores; non calcareous; gradual smooth boundary.

Bt3 100-130 : 2.5Y5/4, common medium distinct mottles (10YR3/1); silty loam; moderately developed sub angular blocky structure; friable (moist); slightly plastic; few fine roots; few clay cutans along pores; common fine medium pores; non calcareous; gradual smooth boundary

C 130-150+ cm: 2.5Y5/6, common medium distinct mottles (10YR3/1); silty loam; massive; friable (moist); pores fine; roots absent; non calcareous.

A-I.4.3 Rapti Terminal Fan-III

Pedon : P-20

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Village Kushumi

Geographic Position : 82°43′27" E, 27° 08′ 58" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Well Drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivated Land

Ground Water : 15 Feet

Typifying Pedon

Ap 0-30 cm : 5Y5/4, moist; loam; no structure; many fine pores, weakly cemented, cutans absent; few fine faint mottles; many medium roots; low organic activities.

Bw1 30-65 cm : 7.5YR4/6, moist; fine loam; moderately developed sub angular blocky structure; pores, very few, very fine; well cemented; clay cutans absent; roots, few, fine; Fe-Mn nodules, common, hard, 1-2 mm; organic activity, uncommon.

Bw2 65-85+ cm : 7.5YR5/6, moist; silty loam; weak sub angular blocky structure; pores, few, fine; very weakly cemented, clay cutans absent; roots, few, fine; Fe-Mn nodules, absent; calcium carbonate nodules absent; organic activity, common; yellowish colour patches were observed.

A-I.5 QGMS-V

A-I.5.1 Old Gandak Plain

Pedon : P-15

Classification : Fine Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Village Khukunda

Geographic Position : 83°52′21" E, 26° 23′ 31" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Well Drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivated Land

Ground Water : 40 Feet

Typifying Pedon

Ap 0-40 cm : 2.5Y5/2, moist; sandy clay loam; few fine distinct mottles of yellowish brown (10YR5/4) colour; structure less; friable (moist); non sticky and non plastic (wet); common fine soil pores; many fine roots; non calcareous; clear smooth boundary.

B1 40-65 cm : 2.5Y5/2, moist; sandy loam; common fine distinct mottles of yellowish brown (10YR5/4) colour and dark yellowish brown (10YR5/4) colour; sub angular blocky soil structure; no clay cutans; friable (moist); non sticky and non plastic (wet); common very fine soil pores; roots, few, medium; Fe-Mn nodules, common; clear smooth boundary.

Bt1 65-105 cm : 2.5Y5/2, moist; sandy loam; abundant medium prominent mottles of yellowish brown (10YR5/6) colour; moderate medium sub angular blocky soil structure; patchy thin clay cutans; firm (moist) pores; non sticky and non plastic (wet); common very fine soil pores; very few very fine fibrous roots; gradual smooth boundary.

Bt2 105-135 cm : 2.5Y5/4, moist; sandy loam; many fine distinct oxidation Fe-Mn mottles (10YR4/4) colour; moderate medium sub angular blocky soil structure; very firm (moist) plastic and sticky (wet); common fine soil pores; very few fine roots; rounded Fe-Mn concretions (4-5 mm diameter); gradual smooth boundary

Bt3 135-170 cm : 2.5Y5/4 moist; sandy loam; common fine distinct mottles (10YR4/4) colour; moderate medium sub angular blocky soil structure; very few patchy thin clay cutans; firm (moist), slightly sticky and slightly plastic (wet); common fine soil pores; no roots; Fe-Mn concretions of 4-5 mm diameter; non calcareous; clear smooth boundary.

CCa 170-180+ cm: 2.5Y6/4, moist; sandy loam; structure less; friable (moist); non sticky and non plastic (wet); few fine soil pores; no roots; irregular chape big size (>10 mm diameter) $CaCO_3$ concretions occupy > 50-60% in volume.

A-I.6 QGMS-VI

A-I.6.1 Oldest Gandak Plain

Pedon : P-9

Classification : Fine Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Village Rajpur

Geographic Position : 83°20´06" E, 27° 01´ 37" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Well Drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : dry sub-humid

Natural Vegetation : Reserve Forest

Ground Water : 40 Feet

Typifying Pedon

A 0-15 cm : 10YR5/3, moist; sandy loam; structure less; friable (moist); slightly sticky and non plastic (wet); common fine soil pores; many coarse roots; rich in organic matters, decomposed roots and animal activities; non calcareous; clear smooth boundary.

Bw 15-40 cm : 10YR5/4, dry and brown to dark brown when moist; sandy loam; weak fine sub angular blocky soil structure; firm (moist); non sticky and non plastic (wet); common fine soil pores; common medium to coarse roots; decomposed roots and animal activities; non calcareous; defused smooth boundary.

Bt1 40-90 cm : 2.5Y5/2, moist; sandy clay loam; abundant medium prominent mottles of yellowish brown (10YR5/6) colour; moderate medium sub angular blocky soil structure; patchy thin clay cutans; firm (moist) pores; non sticky and non plastic (wet); common very fine soil pores; very few very fine fibrous roots; gradual smooth boundary.

Bt2 90-140 cm : 10YR6/4, moist; loam; few fine distinct oxidation Fe-Mn mottles (10YR3/2) colour; moderate medium sub angular blocky soil structure; patchy thin clay cutans; very firm (moist); slightly sticky and plastic (wet); many fine soil pores; common medium and coarse roots; angular and rounded Fe-Mn concretions (4-5 mm diameter); no calcareous; gradual smooth boundary.

C 140-160+ cm: 2.5Y6/4, moist; silty loam; structure less; friable (moist); non sticky and non plastic (wet); few fine soil pores; no roots; irregular chape big size (>10 mm diameter) $CaCO_3$ concretions occupy > 50-60% in volume.

A-I.6.2 Ghaghara-Rapti Interfluve Plain

Pedon : P-2

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Village Maghar

Geographic Position : 83°08´48" E, 26° 44´ 58" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Well Drained

Moisture Condition : Moist

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivation land

Ground Water : 40 Feet

Typifying Pedon

Ap 0-12 cm : Light yellowish brown (2.5Y6/4); sandy loam; structure less; friable (moist); non plastic non sticky (wet); common fine medium fibrous roots; common fine medium pores; non calcareous; clear smooth boundary.

B 12-27 cm : Light olive brown (2.5Y5/4); loam; strongly developed sub angular blocky soil structure; firm (moist); non sticky and non plastic (wet); common fine medium soil pores; few fine fibrous roots; decomposed roots and animal activities; non calcareous; clear smooth boundary.

Bt1 27-57 cm : Light olive brown (2.5Y5/4); moist; loam; abundant medium prominent mottles of yellowish brown (10YR5/6) colour; moderate medium sub angular blocky soil structure; bold thick clay cutans; firm (moist); common fine medium pores; non sticky and non plastic (wet); common very fine soil pores; very few very fine fibrous roots; non calcareous; clear smooth boundary.

Bt2 57-117 cm : Light olive brown (2.5Y5/4); silty loam; common medium distinct mottles of yellowish red (5YR5/8); well developed sub angular blocky soil structure; patchy thin clay cutans; firm (moist); non sticky and non plastic (wet); many fine soil pores; many fine fibrous roots; no calcareous; clear smooth boundary.

C 117-137+ cm: Light olive brown (2.5Y5/4); few medium distinct mottles; Fe-Mn concretions; loam; structure less; friable (moist); non sticky and non plastic (wet); few fine soil pores; no roots; non calcareous.

A-I.6.3 Rapti Terminal Fan-V

Pedon : P-7

Classification : Coarse Loamy Mixed Hyperthermic Typic Haplustalfs

Location : Village Kamlajot

Geographic Position : 81°38′51" E, 27° 40′ 41" N

Parent Material : Alluvium

Erosion : No Erosion

Slope : Gentle

Drainage Class : Well drained

Moisture Condition : Dry top soil and moist sub surface

Soil moisture regime : USTIC

Climate : Dry sub-humid

Natural Vegetation : Cultivated land

Ground Water : 50 Feet

Typifying Pedon

Apk 0-17 cm : 2.5Y5/4, dry; sandy loam; structure less; friable (dry); no clay cutans; no ped faces; weakly cemented; common fine pores; slightly calcareous; clear smooth boundary.

Btk1 17-40 cm : 10YR5/4, moist; loam; moderately developed sub angular blocky structure; friable (moist); slightly plastic; common fine fibrous roots; patchy thin clay cutans; few fine faint mottles; many fine roots; slightly calcareous; gradual smooth boundary.

Btk2 40-85 cm : 10YR4.5/4, few medium faint mottles; loam; moderately developed sub angular blocky structure; friable (moist); slightly plastic; few fine fibrous roots; clay cutans along pores; common fine medium pores; non calcareous; gradual smooth boundary.

C 85-115+ cm : 2.5Y5/6, common medium distinct mottles (10YR3/1); silty loam; massive; friable (moist); pores fine; roots absent; non calcareous.

APPENDIX-II

PARTICLE SIZE DISTRIBUTION IN SOIL PROFILES OF DIFFERENT MEMBERS OF MORPHOSTRATIGRAPHIC SEQUENCE

HORIZON	DEPTH (cm)	SAND (%)	SILT (%)	CLAY (%)	TEXTURE
QGMS-I					
OLD GHAGHARA PLAIN					
PEDON P-61					
Ap	0-16	71	23	6	Loamy sand
AC	16-26	67	20	13	Sandy loam
C	26-50+	80	16	4	Sandy loam
BAGHMATI TERMINAL FAN-II					
PEDON P-52					
Ap	0-10	77	18	5	Sandy loam
AC	10-25	77	12	11	Sandy loam
C	25-50+	79	13	8	Loamy sand
BURHIGANDAK TERMINAL FAN-II					
PEDON P-58					
Ap	0-15	75	22	3	Loamy sand
AC	15-40	64	28	8	Sandy loam
C	40-60+	67	29	4	Sandy loam
BAGHMATI TERMINAL FAN-I					
PEDON P-64					
Ap	0-15	84	12	4	Loamy sand
Bt	15-33	75	13	12	Sandy loam
BC	33-54	75	19	6	Sandy loam
C	54-66+	75	21	4	Sandy loam
KAMLA FAN-I					
PEDON P-50					
Ap	0-15	56	38	6	Sandy loam
Bt	15-30	69	16	15	Sandy loam
BC	30-50	65	26	9	Sandy loam
C	50-100+	62	29	9	Sandy loam
QGMS-II					
GHAGHARA TERRACE-I					
PEDON P-38					
Ap	0-15	62	23	15	Sandy loam
Bt	15-40	58	22	20	Sandy loam
C	40-60+	55	34	11	Sandy loam
KAMLA FAN-II					
PEDON P-45					
Ap	0-10	60	26	14	Sandy loam
Bt1	10-60	57	19	24	Sandy clay loam
Bt2	60-80	65	24	11	Sandy loam

C	80-100+	63	27	10	Sandy loam
YOUNG PIEDMONT					
PEDON P-46					
Ap	0-10	75	12	13	Sandy loam
Bt	10-30	61	22	17	Sandy loam
Bw	30-75	67	13	20	Sandy loam
C	75-90	66	22	12	Sandy loam
QGMS-III					
RAPTI TERMINAL FAN-II					
PEDON P-39					
Apk	0-15	63	29	8	Sandy loam
Ak	15-55	49	39	12	Loam
Ck	55-90	60	34	6	Sandy loam
GANDAK TERMINAL FAN-I					
PEDON P-29					
Akp	0-18	47	42	11	Loam
ABk	18-33	44	40	16	Loam
Bk	33-48	42	51	7	Silty loam
Ck	48-100+	40	51	9	Silty loam
GANDAK TERMINAL FAN-II					
PEDON P-35					
Akp	0-25	76	18	6	Sandy loam
Bwk1	25-50	69	13	18	Sandy loam
Bkw2	50-130	67	21	12	Sandy loam
Bw	130-155	67	29	4	Sandy loam
C2	155-175+	65	26	9	Sandy loam
BHATIBALAN FAN (OLD PIEDMONT)					
PEDON P-26					
A	0-13	74	18	8	Sandy loam
AB	13-25	71	18	11	Sandy loam
Bt1	25-65	66	23	11	Sandy loam
B22	65-110	65	29	6	Sandy loam
C	110-125+	72	20	8	Sandy loam
OLD PIEDMONT					
PEDON P-27					
Ap	0-40	81	11	8	Loamy sand
AB	40-60	77	10	13	Sandy loam
Bt	60-85	74	16	10	Sandy loam
C	85-135+	72	23	5	Sandy loam
QGMS-IV					
GHAGHARA TERRACE-II					
PEDON P-17					
Akp	0-30	49	45	6	Sandy-loam
BK	30-70	37	45	18	Loam
Bt	70-100	35	52	13	Silty loam
C	100-120+	28	66	6	Silty loam
RAPTI TERMINAL FAN-IV					

PEDON P-18					
Apk	0-20	40	48	12	Silty loam
Bt1	20-40	38	44	18	Loam
Bt2	40-100	33	50	17	Loam
Bt3	100-130	32	55	13	Silty loam
C	130-150	24	65	11	Loam
RAPTI TERMINAL FAN-III					
PEDON P-20					
Ap	0-30	46	42	12	Loam
Bw1	30-65	50	28	22	Loam
Bw2	65-85+	37	52	11	Silty loam
QGMS-V					
OLD GANDAK PLAIN					
PEDONP-15					
Ap	0-40	80	13	7	Sandy clay loam
B1	40-65	72	10	18	Sandy loam
Bt1	65-105	69	10	21	Sandy loam
Bt2	105-135	69	13	18	Sandy loam
Bt3	135-170	63	29	8	Sandy loam
CCa	170-180+	60	32	8	Sandy loam
QGMS-VI					
OLDEST GANDAK PLAIN					
PEDON P-9					
A	0-15	60	30	10	Sandy loam
Bw	15-40	58	24	18	Sandy loam
Bt1	40-90	51	24	25	Sandy clay loam
B2t	90-140	46	39	15	Loam
C	140-160+	44	48	8	Silty loam
GHAGHARA-RAPTI INTERFLUVE PLAIN					
PEDON P-2					
Ap	0-12	55	35	10	Sandy loam
B1	12-27	47	38	15	Loam
Bt1	27-57	37	42	21	Loam
Bt2	57-117	32	58	10	Silty loam
C	117-137	44	48	8	Loam
RAPTI TERMINAL FAN-V					
PEDON P-7					
Apk	0-17	55	34	11	Sandy loam
Btk1	17-40	47	37	16	Loam
Btk2	40-55	41	41	18	Loam
C	85-115	42	47	11	Loam

APPENDIX-III

PEDON NO	DEPTH (cm)	Ec (mmhos/cm)	pH	NATURE OF SOIL (SALINE/ALKALINE)
			QGMS-I	
P-61 OGHP	0-16	0.46	6.35	Non saline slightly acidic
	16-26	0.465	6.64	Non saline neutral
	25-50	0.431	6.67	Non saline neutral
	50-70+	0.557	6.59	Non saline medium acidic
P-52 BTFn-II	0-10	0.593	5.91	Non saline medium acidic
	10-25	0.613	5.85	Non saline medium acidic
	25-50	0.618	6.13	Non saline slightly acidic
	50-90+	0.627	6.09	Non saline medium acidic
P-58 BGTFn-II	0-15	0.548	5.45	Non saline strongly acidic
	15-40	0.49	5.46	Non saline strongly acidic
	40-60+	0.482	5.58	Non saline medium acidic
P-64 BTFn-I	0-15	0.661	6.08	Non saline medium acidic
	15-33	0.616	6.01	Non saline medium acidic
	33-54	0.586	6.49	Non saline slightly acidic
	54-66+	0.598	5.86	Non saline medium acidic
P-50 KFn-I	0-15	0.626	6.52	Non saline slightly acidic
	15-30	0.592	6.47	Non saline slightly acidic
	30-50	0.576	6.35	Non saline slightly acidic
	50-100	0.567	6.57	Non saline slightly acidic
	100-120+	0.601	6.25	Non saline slightly acidic
			QGMS-II	
P-45 KFn-II	0-8	0.471	6.73	Non saline neutral
	8-58	0.433	6.72	Non saline neutral
	58-78+	0.421	6.89	Non saline neutral
P-46 YPT	0-10	0.597	6.17	Non saline slightly acidic
	10-30	0.582	6.22	Non saline slightly acidic
	30-75	0.601	6.53	Non saline slightly acidic
	75-90+	0.611	6.49	Non saline slightly acidic
P-38 GT-I	0-16	0.559	7.16	Non saline neutral
	16-56	0.668	7.16	Non saline neutral
	56-91+	0.687	7.19	Non saline neutral
P-37 PPFn	0-40	0.573	6.89	Non saline neutral
	40-60	0.54	6.86	Non saline neutral
	60-85	0.563	6.94	Non saline neutral
	85-135+	0.547	6.9	Non saline neutral
			QGMS-III	
P-29 GTFn-I	0-18	0.667	7.07	Non saline neutral
	18-33	0.601	7.23	Non saline neutral
	33-48	6.638	7.23	Non saline neutral
	48-98	0.588	7.02	Non saline neutral

	98-118+	0.472	7.26	Non saline neutral
P-31 GTFn-I	0-13	0.545	7.63	Non saline mildly alkaline
	13-25	0.489	7.78	Non saline mildly alkaline
	25-65	0.492	7.79	Non saline mildly alkaline
	65-110	0.609	7.82	Non saline mildly alkaline
	110-125+	0.446	7.87	Non saline mildly alkaline
P-35 GTFn-II	0-25	0.601	7.04	Non saline neutral
	25-50	0.64	7.18	Non saline neutral
	50-130	0.585	7.17	Non saline neutral
	130-155	0.606	7.01	Non saline neutral
	155-175+	0.602	7.24	Non saline neutral
P-26 BBFn	0-13	0.545	7.93	Non saline moderately alkaline
	13-25	0.492	7.79	Non saline mildly alkaline
	25-65	0.446	7.77	Non saline mildly alkaline
	65-110	0.489	7.88	Non saline mildly alkaline
	110-125+	0.604	7.80	Non saline mildly alkaline
P-27 OPT	0-40	0.573	7.89	Non saline mildly alkaline
	40-60	0.540	7.86	Non saline mildly alkaline
	60-85	0.563	7.94	Non saline moderately alkaline
	85-135+	0.547	7.90	Non saline moderately alkaline
P-25 OPT	0-15	0.706	6.55	Non saline slightly acidic
	15-25	0.628	6.64	Non saline neutral
	25-95	0.644	6.47	Non saline slightly acidic
	95-125	0.642	6.58	Non saline slightly acidic
	125-140+	0.633	6.52	Non saline slightly acidic
			QGMS-IV	
P-17 GT-II	0-30	0.49	7.68	Non saline mildly alkaline
	30-70	0.462	7.65	Non saline mildly alkaline
	70-100	0.46	7.74	Non saline mildly alkaline
	100-120+	0.491	7.63	Non saline mildly alkaline
P-18 RTFn-IV	0-20	0.677	7.36	Non saline mildly alkaline
	20-40	0.704	7.51	Non saline mildly alkaline
	40-100	0.716	7.61	Non saline mildly alkaline
	100-130	0.712	7.63	Non saline mildly alkaline
	130-150+	0.704	7.66	Non saline mildly alkaline
P-20 RTFn-III	0-30	0.677	6.98	Non saline neutral
	30-65	0.658	7.08	Non saline neutral
	65-85	0.674	7.06	Non saline neutral
			QGMS-V	
P-15 OLGP	0-40	0.56	6.81	Non saline neutral
	40-65	0.521	6.71	Non saline neutral
	65-105	0.508	6.74	Non saline neutral
	105-135	0.5	6.85	Non saline neutral
	135-170	0.51	6.8	Non saline neutral
	170-180+	0.514	6.89	Non saline neutral
P-21 OLGP	0-10	0.642	7.34	Non saline mildly alkaline
	10-35	0.627	7.79	Non saline mildly alkaline
	35-65	0.628	7.8	Non saline mildly alkaline

	65-95	0.612	7.8	Non saline mildly alkaline
	95-115+	0.597	7.81	Non saline mildly alkaline
			QGMS-VI	
P-1 RTFn-V	0-17	0.469	8.36	Non saline moderately alkaline
	17-40	0.435	8.17	Non saline moderately alkaline
	40-85	0.459	7.99	Non saline moderately alkaline
	85-115+	0.458	8.06	Non saline moderately alkaline
P-3 OSGP	0-40	0.473	7.88	Non saline moderately alkaline
	40-75	0.475	7.85	Non saline moderately alkaline
	75-100+	0.49	7.98	Non saline moderately alkaline
P-9 OSGP	0-15	0.445	5.91	Non saline medium acidic
	15-40	0.432	5.95	Non saline medium acidic
	40-90	0.41	6.17	Non saline slightly acidic
	90-140	0.392	6.06	Non saline slightly acidic
	140-160+	0.443	6.39	Non saline slightly acidic
P-2 GRIP	0-12	0.614	7.04	Non saline neutral
	12-27	0.620	7.26	Non saline neutral
	27-57	0.612	7.46	Non saline mildly alkaline
	57-117	0.620	7.36	Non saline mildly alkaline
	117-137	0.622	7.34	Non saline mildly alkaline

APPENDIX-IV

DESCRIPTION OF TYPICAL THIN SECTIONS

A-IV.1 QGMS-I

A-IV. 1.1 Sample No. P-64/2

Microstructures

Weakly developed subangular blocky structures. Peds were separated by channels and voids. Ped faces were unaccommodated to each other. Voids were irregular. Microstructures were intergrain channel, compact grain and vughy type. Channel width varying from 50 to 300 µm. Void and channel walls serrated coated with ferric oxide residue. Estimated porosity was 10-20%.

Basic Mineral Components

c/f ratio at 20 µm; ratio was 20:80.

(a) Coarse Fraction

Coarse fraction consists of anhedral quartz (12%); feldspars weathered broken, weathered muscovite and biotite (4%) were present. Quartz grains varying in size from 50-500 µm, fractured surrounded by ferric oxide residues.

(b) Fine Fraction

Fine fraction constitutes fractured quartz, weathered feldspars, mica, biotite flakes sparitic calcite and other unidentifiable clay minerals.

Groundmass

The c/f related distribution was open to double spaced porphyric, crystallitic, stippled speckled, poro-striated b-fabric. Micromass was brownish in colour uniform throughout the section.

Pedofeatures

Ferriargillan, argillan hypocoating along the void and channel surfaces. Fe-Mn nodules with distinct boundaries varying in size from 200-300 µm. Rootlets were also observed in the section.

A-IV. 1.2 Sample No. P-64/3

Microstructures

Weakly developed subangular blocky structures. Peds separated by channels and voids. Ped faces were unaccommodated to each other. Voids were irregular to subcircular in shape. Microstructures were intergrain channel, channel type. Channel width varying from 125 to 250 µm. Void and channel walls serrated coated with fine ferric oxide residue. Estimated porosity was 15-20%.

Basic Mineral Components

c/f ratio at 20 µm; ratio was 40:60.

(a) Coarse Fraction

Coarse fraction consists of anhedral quartz (10%); weathered feldspars, highly weathered muscovite and biotite (4%) were present. Quartz grains were 625-875 µm, fractured surrounded by ferric oxide residues.

(b) Fine Fraction

Fine fraction constitutes fractured quartz, weathered feldspars, mica, biotite flakes, calcite and other unidentifiable clay minerals.

Groundmass

The c/f related distribution was open to double spaced porphyric, crystallitic, stippled speckled, poro-striated b-fabric. Micromass was brownish colour uniform throughout the section.

Pedofeatures

Ferriargillan argillan hypocoating along the void and channel surfaces. Fabric pedofeatures were observed. Channels were partially filled with nodules. Fe-Mn nodules with distinct boundaries varying size 125-750 µm.

A-IV. 1.3 Sample No. P-50/2

Microstructures

Weakly developed subangular blocky structures. Peds were separated by channels and voids. Ped faces were partially accommodated to each other. Voids were irregular to subcircular in shape. Microstructures were spongy, vughy type. Channel width varying from 10 to 50 µm. Void and channel walls rough, serrated. Estimated porosity was 5-8%.

Basic Mineral Components

c/f ratio at 30 µm; ratio was 50:50.

(a) Coarse Fraction

Coarse fraction consists of anhedral quartz (8%); feldspars absent, muscovite and biotite grains subhedral elongated (10%) were seen. Quartz grains were 25-125 µm, fractured surrounded by ferric oxide residues.

(b) Fine Fraction

Fine fraction constitutes fractured quartz, micaceous and other unidentifiable clay minerals.

Groundmass

The c/f related distribution was open to double spaced porphyric, crystallitic, stippled speckled, parallel striated b-fabric. Micromass was dark brownish.

Pedofeatures

Ferriargillan hypocoating along the void and channel surfaces. Channels were filled with secondary argillan coating. Fe-Mn nodules with distinct boundaries varying in size from 25-50 µm. Excrement pedofeatures common. Rootlets replaced by secondary minerals. Animal activities in the form of burrows were common in the section.

A-IV. 1.4 Sample No. P-50/3

Microstructures

Moderately to weakly developed subangular blocky structures. Peds were separated by channels and voids. Ped faces were partially accommodated to each other. Voids were irregular to subcircular. Microstructures were intergrain channel and spongy type. Channel width varying from 25 to 500 µm. Void and channel walls were rough. Estimated porosity was 10-15%.

Basic Mineral Components

c/f ratio at 30 µm; ratio was 40:60.

(a) Coarse Fraction

Coarse fraction consists of anhedral quartz (10-15%); weathered feldspars, laths of muscovite (5-10%) were present. Quartz grains were 25-625 µm, fractured surrounded by ferric oxide rings.

(b) Fine Fraction

Fine fraction constitutes quartz, weathered feldspars, mica flakes and other unidentifiable clay minerals.

Groundmass

The c/f related distribution was open to double spaced porphyric, crystallitic, stippled speckled, parallel unistriated b-fabric. Micromass was brownish to light brownish in colour. Ferric oxide fillings along the channel walls.

Pedofeatures

Ferriargillan and argillan hypocoating along the void and vesicle surfaces. Excrement pedofeatures present in scattered forms. Fe-Mn nodules with distinct boundaries varying in size from 25-750 μm.

A-IV.2 QGMS-II

A-IV. 2.1 Sample No. P-37/2

Microstructures

Weakly developed crumb structures. Peds separated by channels and voids. Ped faces were unaccommodated to each other. Voids were irregular to subcircular. Microstructure was intergrain channel type. Channel width varying from 50 to 150 μm. Void and channel walls were rough. Estimated porosity was 5-10%.

Basic Mineral Components

c/f ratio at 30 μm; ratio was 40:60.

(a) Coarse Fraction

Coarse fraction consists of anhedral quartz (8%); weathered feldspars, laths of muscovite (4%) were observed. Quartz grains varying in size from 25-625 μm, fractured surrounded by ferric oxide rings.

(b) Fine Fraction

Fine fraction constitutes quartz, mica flakes and other unidentifiable clay minerals.

Groundmass

The c/f related distribution was open to double spaced porphyric, crystallitic, stippled speckled, porostriated b-fabric. Micromass was brownish to yellowish brown in colour, distributed randomly throughout the section.

Pedofeatures

Ferriargillan and argillan hypocoating along the aggregate surfaces. Fabric pedofeatures common. Excrement pedofeatures present in scattered

A-IV.3 QGMS-III

A-IV. 3.1 Sample No. P-26/2

Microstructures

Peds were absent. Voids were irregular to subcircular in shape. Microstructures were intergrain channel, vughy type. Void and channel walls serrated coated with fine ferric oxide residue. Estimated porosity was 10-15%.

Basic Mineral Components

c/f ratio at 20 µm; ratio was 60:40.

(a) Coarse Fraction

Coarse fraction consists of anhedral quartz (10%); weathered feldspars, weathered muscovite and biotite (6%) were present. Quartz grains varying in size from 650-850 µm, fractured surrounded by ferric oxide residues.

(b) Fine Fraction

Fine fraction constitutes fractured quartz, weathered feldspars, biotite and other unidentifiable clay minerals.

Groundmass

The c/f related distribution was open to double spaced porphyric, crystallitic, stippled speckled, parallel striated b-fabric. Micromass was light brownish to grayish in colour varying throughout the section.

Pedofeatures

Ferriargillan and argillan typic hypocoating along the void and channel surfaces. Fabric pedofeatures were observed. Channels were filled by nodules. Fe-Mn nodules with distinct boundaries, corroded and recrystallized material embedded within the nodules forming a sieve like structure.

A-IV. 3.2 Sample No. P-26/3

Microstructures

Moderately developed subangular blocky structures. Peds were separated by channels and voids. Ped faces were partially accommodated to each other. Voids were elongated to irregular in shape. Microstructures were intergrain channel, vughy type. Channel width varying from 125 to 250 µm. Void and channel walls serrated coated with fine ferric oxide residue. Estimated porosity was 5-10%.

Basic Mineral Components

c/f ratio at 20 µm; ratio was 40:60.

(a) Coarse Fraction

Coarse fraction consists of anhedral quartz (4%); weathered feldspars, highly weathered muscovite and biotite (6%) were present. Quartz grains were 125-1375 µm, fractured surrounded by ferric oxide residues.

(b) Fine Fraction

Fine fraction constitutes fractured quartz, weathered feldspars, mica, biotite flakes, calcite and other unidentifiable clay minerals.

Groundmass

The c/f related distribution was open to double spaced porphyric, crystallitic, mosaic speckled, porostriated and parallel striated b-fabric. Micromass was brownish in colour, uniform throughout the section.

Pedofeatures

Ferriargillan argillan hypocoating along the void and aggregate surfaces. Fabric pedofeatures were seen. Fe-Mn nodules with distinct boundaries, rounded to elongate varying in size 625 µm to 0.375 mm. Rootlets were replaced by calcitic material.

A-IV. 3.3 Sample No. P-26/4

Microstructures

Moderately developed subangular blocky structures. Peds were separated by channels. Ped faces were unaccommodated to each other. Voids were irregular to subcircular in shape. Microstructures were intergrain channel and vughy type. Channel width varying from 20 to 90 µm. Void and channel walls rough. Estimated porosity was 5-8%.

Basic Mineral Components

c/f ratio at 30 µm; ratio was 50:50.

(a) Coarse Fraction

Coarse fraction consists of anhedral quartz (6%) with diffused boundaries; weathered feldspars with rims of alterations, muscovite and biotite grains subhedral elongated (9%) were seen. Quartz grains were 30-60 μm, fractured surrounded by ferric oxide residues.

(b) Fine Fraction

Fine fraction constitutes fractured quartz, mica minerals, calcite, weathered feldspars and other unidentifiable clay minerals.

Groundmass

The c/f related distribution was open to double spaced porphyric, crystallitic, mosaic speckled striated b-fabric. Micromass was dark brownish.

Pedofeatures

Ferriargillan and argillan hypocoating along the void and channel surfaces. Some channels were filled with secondary argillan coating. Fe-Mn nodules with diffused boundaries varying in size from 10-50 μm. Fine strands of rootlets were also seen.

A-IV. 3.4 Sample No. P-35/2

Microstructures

Moderately to weakly developed subangular blocky structures. Peds were separated by channels and voids. Ped faces were partially accommodated to each other. Voids were irregular to subcircular. Microstructure was intergrain channel and spongy type. Channel width varying from 25 to 400 μm. Void and channel walls were rough, serrated. Estimated porosity was 5-7%.

Basic Mineral Components

c/f ratio at 30 μm; ratio was 40:60.

(a) Coarse Fraction

Coarse fraction consists of anhedral quartz (5%); feldspars were absent, highly weathered laths of muscovite and biotite (5%) were present. Quartz grains were 20-625 μm, fractured surrounded by ferric oxide residues.

(b) Fine Fraction

Fine fraction constitutes quartz, weathered mica and biotite flakes and other unidentifiable clay minerals.

Groundmass

The c/f related distribution was open to double spaced porphyric, crystallitic, stippled speckled, random striated b-fabric. Micromass was brownish in colour. Thin ferric oxide fillings along the channel walls.