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GEOLOGICAL EVOLUTION OF GANGA PLAIN - AN OVERVIEW

INDRA BIR SINGH
DEPARTMENT OF GEOLOGY, LUCKNOW UNIVERSITY, LUCKNOW - 226007.

ABSTRACT

Flexing of the Indian lithosphere in response to the compressive forces due to collision, and thrust-fold loading produced the Ganga Plain foreland basin in the Early Miocene. The basin expanded in the Middle Miocene, and attained its present configuration in the Late Quaternary. The Ganga Plain foreland basin is in a mature stage of evolution, with oversupply of sediment and underfilled condition, building to 300 - 50 m above sea-level, exclusively by fluvial processes. Continuing compressional forces result in distinctive patterns of neotectonic activity in the plain.

The present-day regional geomorphic surfaces of the Ganga Plain, namely Upland Terrace Surface (T_2), Marginal Plain Upland Surface (MP), Megafan Surface (F), River Valley Terrace (T_1), Piedmont Fan Surface (PF), and Active Flood Plain Surface (T_0) are considered the result of changing climate and base-level adjustments (sea-level changes) during the last 120 Ka. Base- level changes and an increased water budget during the Early Holocene (10-8 Ka) led to the formation of large lakes, which silted up during the Middle-Late Holocene due to decreased water budget and increased sediment supply. The river channels show a wide range in variety and geometrical parameters; most of them formed under conditions of higher discharge than today.

Distinctive facies associations of gravelly fan deposits, sandy interfluve deposits, muddy interfluve deposits, and large river channel deposits are discussed. Due to longer residence time of the channels, large rivers produce multistoried sandbodies. The interfluve areas produce a succession of fine- grained sediments which are sometimes classed as flood plain deposit. The Ganga River shows a wide range of geomorphic, grain size, and channel pattern changes along its 2000 km long course.

INTRODUCTION

The Indian subcontinent is subdivided into three major physiographic subdivisions, the Himalaya, Indo-Gangetic Plain and Peninsular India. The Indo-Gangetic Plain is the extensive alluvial Plain of the Ganga, Indus and Brahmaputra rivers and their tributaries, and separates the Himalayan ranges from Peninsular India. Traditionally, geological studies concerned mainly the rock successions; hence the study of this vast alluvial plain was ignored. The extreme flatness of the region and geomorphologically monotonous character also did not attract the geomorphologists to undertake detailed investigations of this region.

In the classical literature, generalized views were expressed as to the nature of this vast alluvial plain, often termed the Indo-Gangetic Trough. It was variously referred to as fore-deep (Suess, 1883), 'Rift' (Burrard, 1915), or even 'Basin', 'Yolked basin', 'Half graben', 'Broad basin shallow' (Rao, 1973). The vast alluvial plain was broadly classified into Older Alluvium (Bhangar) and Newer Alluvium (Khadar), each with different sediments (Pascoe, 1973). Interest in the petroleum exploration led to the geophysical studies in the Indo-Gangetic Plain (Aithal *et al.*, 1964; Datta *et al.*, 1964; Moolchand *et al.*, 1964) that provided insight into the basement structure and the nature of sediment fill.

The Ganga Plain occupies a central position in the Indo-Gangetic Plain (fig. 1), and shows a variety of landforms and drainage system. Some systematic geomorphic studies have been carried out (Geddes, 1960; Mukerji, 1963); and the basement structure and nature of sediment fill was discussed from the point of view of petroleum prospects (Rao, 1973; Sastri *et al.*, 1973).

In the last two decades, because of the links of the Ganga Plain with the evolution of Himalaya, in response to the continent-continent collision; and due to increasing awareness of the value of study of Quaternary sediments in environmental planning and for predicting future changes, the study of the Ganga Plain and its Quaternary history has become very important. Nevertheless, still only a limited data base exists on the Ganga Plain; but certainly a beginning is made.

In this paper an attempt is made to give an overview of the geological evolution of the Ganga Plain, emphasizing its Late Quaternary history in response to events in the Himalaya, and global climatic changes. Although, only Ganga Plain is discussed in this paper, many of the generalizations may be valid and of significance in understanding the other parts of the Indo-Gangetic Plain.

GANGA PLAIN

The Ganga Plain extends from Aravalli-Delhi ridge in the west to the Rajmahal hills in the east; Himalayan foothills (Siwalik hills) in the north to the Bundelkhand-Vindhyan plateau - Hazaribag plateau in the south, occupying an area of about 250,000 Km^2, roughly between long. 77°E, and 88°E, and Lat. 24°N and 30°N. The length of Ganga Plain is about 1000 km; the width is variable, ranging between 450-200 km, being wider in the western part and narrower in the eastern part (fig. 2). The southern margin of Ganga Plain is irregular, and shows at many places outcrops of rocks protruding out of the alluvium. The northern margin of the Ganga plain

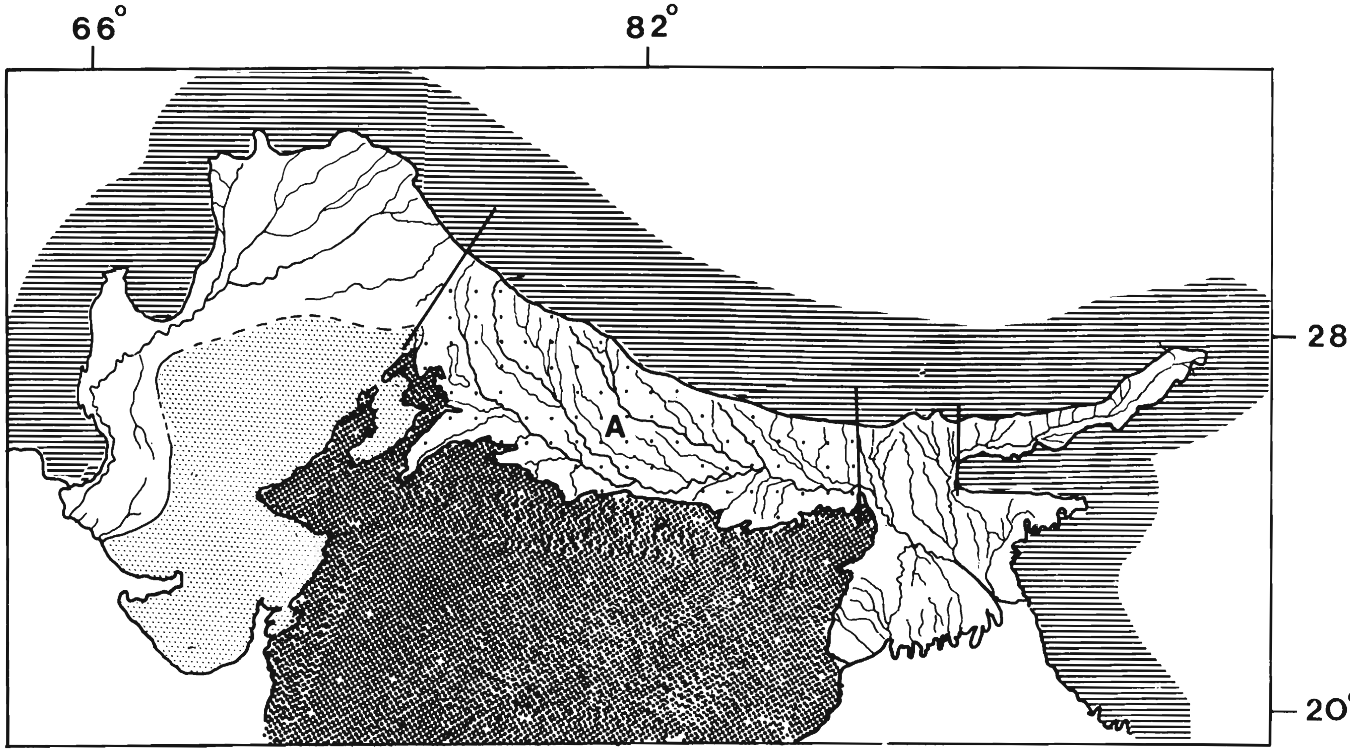


Fig.1. Map showing the Ganga Plain (A) within the Indo-Gangetic Plain.

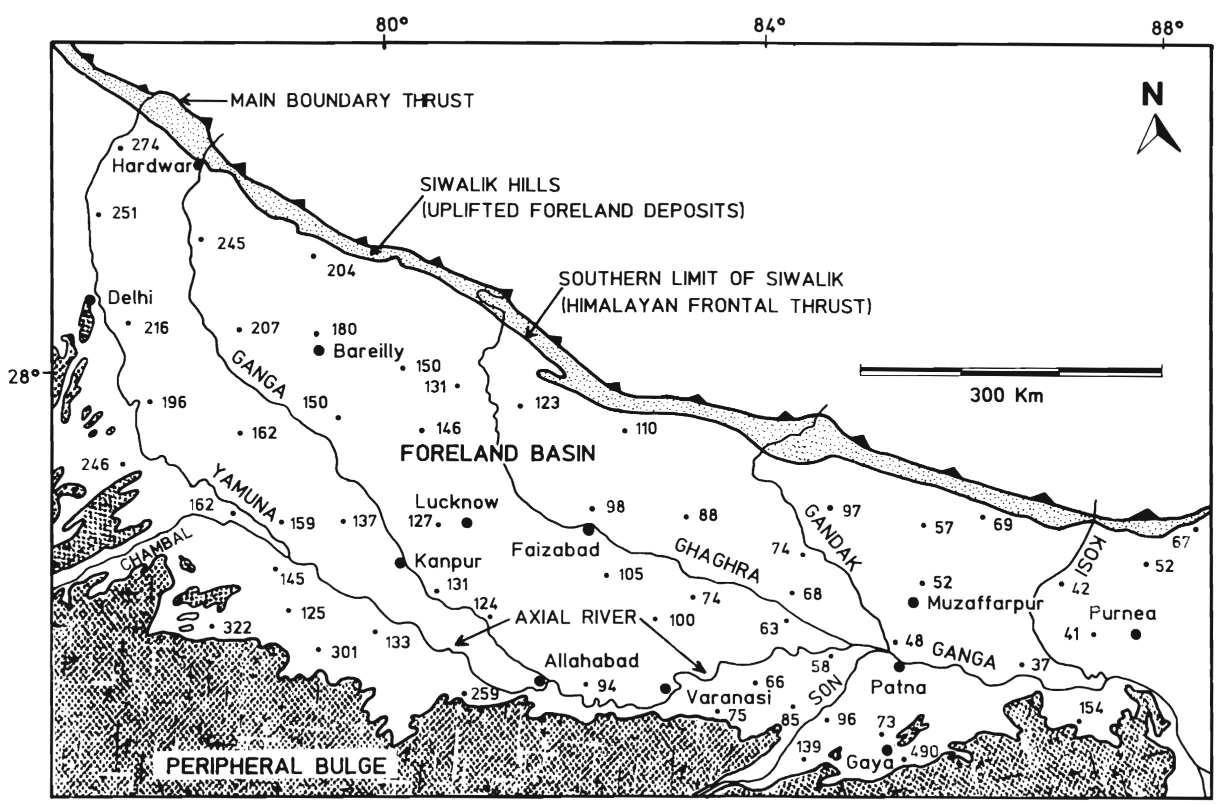


Fig.2. Ganga Plain showing major drainages and spot height (in m) within the alluvial plain.

is marked by the exposure of Siwalik rocks; the contact is often marked by a thrust (HFF) (fig.3).

With low relief and limited height differences over long distances, the surface of the Ganga Plain appears as a rather flat alluvial plain. It is a shallow asymmetrical depression with a gentle easterly gradient; where the northern part shows southward slope, and the southern part shows northward slope. The deepest part of the Ganga Plain Surface in the eastern and western parts is located near the southern margin, occupied by the axial river system in which all the drainages ultimately meet either on the northern or southern side. In the middle part of the Ganga Plain, the lowest altitude zone is occupied by the Ghaghara river; while the Ganga river as axial river is present at a higher surface. An eastward slope of the Ganga Plain surface is very prominent. The altitude change in the axial part is from about 175 m near Mathura in the west to 25 m near Azmabad in the easternmost part. Fig. 2 gives spot heights in different parts of the Ganga Plain surface to emphasize slope patterns. The drainage basin of Ganga River occupies an area of 1,060,000 km^2. More than 60% of water flowing into Ganga plain comes from the Himalayan source; while 40% comes from the Peninsular region.

Most of the rivers in the northern Ganga Plain follow a southeasterly trend; some of the rivers initially flow in the SW direction but then also swing to the southeasterly direction. The rivers of the southern part follow a northeasterly trend; and only those in the axial part follow the easterly slope. The Ganga River is the trunk river of the Ganga Plain into which the large Himalayan rivers join from the north; except for the Yamuna river which meets the Ganga River from the south. Several rivers come from the Peninsular plateau to join the Yamuna or Ganga River. There are also a number of groundwater-fed streams originating within the alluvium which meet the major streams. The rivers of Ganga Plain show a wide range of channel sizes and channel patterns. The Yamuna River is the axial river of Ganga Plain in the western part; while Ganga River becomes the axial river in the eastern part, after Yamuna-Ganga confluence at Allahabad.

The Ganga Plain is sometimes identified into two or three regions (Singh, 1987; Singh and Ghosh, 1992, 1994). The western Ganga Plain (Uttar Pradesh) shows a more rugged terrain and prominent incision of the drainages; while the eastern Ganga Plain (Bihar) shows rather

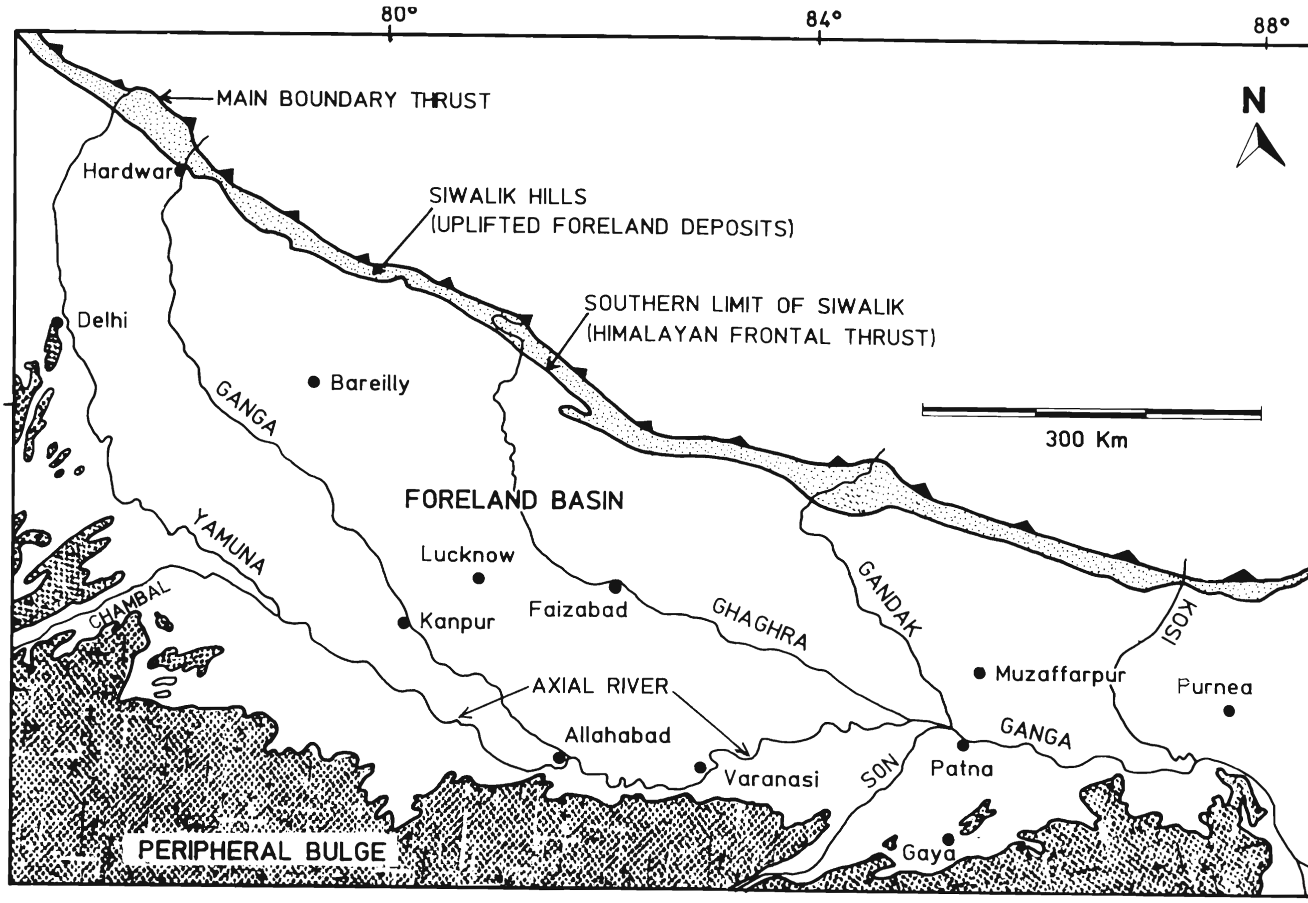


Fig.3. Ganga Plain bounded by Siwalik hills in the north and Peninsular craton (peripheral bulge) in the south.

Fig.4. Four-fold subdivision of Ganga Plain in Uttar Pradesh (modified after Pathak, 1982). The Bhabar and Terai belts together make the Piedmont Plain. Dark stippled part in the south represent the rock outcrops.

uniform relief and very little entrenchment by the drainage.

From north to south, the Ganga Plain can be identified into four distinctive regions (fig. 4) (Pathak, 1982).

Bhabar Belt - This is a 10-30 km wide belt of gravelliferous sediments adjacent to Himalaya with steep slopes and ephemeral streams.

Terai Belt - This is a 10-50 km wide low-lying area adjacent to the Bhabar Belt with extensive development of swamps, ponds, small sandy rivers.

Central Alluvial Plain - This represents the major part of Ganga Plain, located between the Bhabar-Terai Belt and the axial river. The drainage is mostly aligned in a SE direction.

Marginal Alluvial Plain - This is the north-sloping surface, located south of the axial river, and characterized by NE-flowing gravelly to coarse sandy rivers showing entrenched meandering. This area is made up of sediments from Peninsular craton.

However, it is more practical to identify three broad areas in Ganga Plain :

1. *Piedmont Zone* (It includes both Bhabar and Terai zones).
2. *Central Alluvial Plain*
3. *Marginal Alluvial Plain*

These three areas show distinctive landforms, characteristic deposits, and specific tectonic setting. The areas of Bhabar and Terai are closely linked. It appears that in the areas where there is intense fan-building Bhabar is well-developed; while in areas of subdued fan building Terai is well-developed. With changing fan building activity, Bhabar can change to Terai and vice versa. Thus, both are grouped together as Piedmont Zone.

BASEMENT STRUCTURE IN GANGA PLAIN

A number of regional geophysical studies have been carried out over the Ganga Plain, including aeromagnetic, seismic, gravity and magnetic surveys. Moreover, some information about the subsurface is available from deep drilling carried out by Oil and Natural Gas Commission (ONGC) for oil exploration. This information has been utilized by several workers to interpret the basement structure and nature of foreland sediment fill (Rao, 1973; Sastri *et al.*, 1971; Agarwal, 1977; Qureshy *et al.*, 1989; Qureshy and Kumar, 1992; Karunakaran and Ranga Rao, 1979; Narain and Kaila, 1982; Lyon-Caen and Molnar, 1985). In these studies the basement is taken as the metamorphosed rock succession of Precambrian age.

Geophysical information shows that the basement rocks of Ganga Plain exhibit distinctive features (fig. 5). The metamorphic basement exhibits a number of ridges and basins, over which the thickness of sedimentary cover is highly variable. The important basement highs are the Delhi-Hardwar ridge, the Faizabad ridge, the Monghyr-Saharsa ridge, a poorly developed high in the Mirzapur-Ghazipur area; and smaller "highs" of Raxaul, Bahraich and Puranpur. There are two important basins or low areas, namely Gandak and Sarda depressions. There are also a number of basement faults, namely Moradabad fault, Bareilly fault, Lucknow fault, Patna fault, and Malda fault (Sastri *et al.*, 1971; Rao, 1973). The southern part of Ganga Plain in Mirzapur area shows E-W and ENE-WSW trending linear magnetic anomaly zones. Seismic studies in the Ganga Plain indicates that the basins and ridges were also active during deposition of Late Proterozoic sediments. However, the foreland sediments (Siwalik and Alluvium) rest on a rather uniform surface dipping towards north. This surface is made up of different type of rocks in different parts (Karunakaran and Ranga Rao, 1979. The basement fault recorded in geophysical studies have not affected the foreland fill and also do not show any evidence in geomorphic features.

The foreland sediments rest on the metamorphic basement rocks in the west (the Delhi-Hardwar ridge), and on the Faizabad and Monhgyr - Saharsa ridges. In the area between the Delhi - Hardwar ridge and the Faizabad ridge, foreland sediments rest on the Late Proterozoic unmetamorphosed sediments, which are part of Vindhyan basin in the south and part of the Krol basin in the north. Between the Faizabad and Monghyr-Saharsa ridges, foreland sediments again rest on unmetamorphosed Late Proterozoic sediments, related to the Krol basin. East of the Monghyr-Saharsa ridge, the Late Proterozoic sediments are not present; instead a graben structure containing a thick succession of Gondwana rocks forms the base for the foreland sediments. Figs. 6a-e shows the subsurface stratigraphy in different segments of the Ganga Plain, based on geophysical studies with a few borehole control points.

Thus, the foreland basin sediments rest on a gently north-sloping basement which may be made up of metamorphic rocks, Late Proterozoic or Gondwana sediments.

GANGA PLAIN FORELAND BASIN

Following continent-continent collision with development of mountain chain a foreland basin develops in front of the orogen, on the underthrusting flexed lithosphere, and is known as peripheral foreland basin (Dickinson, 1974). The Himalayan mountain chain is a product of continent-continent collision between Indian and Asian plates, where Indian plate is still underthrusting the Asian plate (Sieber *et al.*, 1981; Molnar and Tapponier, 1975; Ni and Barazangi, 1984; Molnar, 1984). One of the most spectacular landscape formed in post-collision time is the Indo-Gangetic Plain, a peripheral foreland basin system, formed on the flexed Indian plate lithosphere (Lyon-Caen and Molnar, 1985; Singh, 1987).

A foreland basin is formed as a result of compressional stresses developed in the underthrusting plate due to collision and by the vertical load of the thrust-fold belt in the orogen. The main reason for the development of a foreland basin in front of an orogen is flexing of the lithosphere. Modelling the flexure of the crust in a foreland basin is done by assuming elastic or viscoelastic nature of the crust (Beaumont, 1981; Lyon-Caen and Molnar, 1985). In the flexed, subsiding area in front of orogen, sediments derived from the orogen as well as from the craton accumulate to produce an asymmetrical

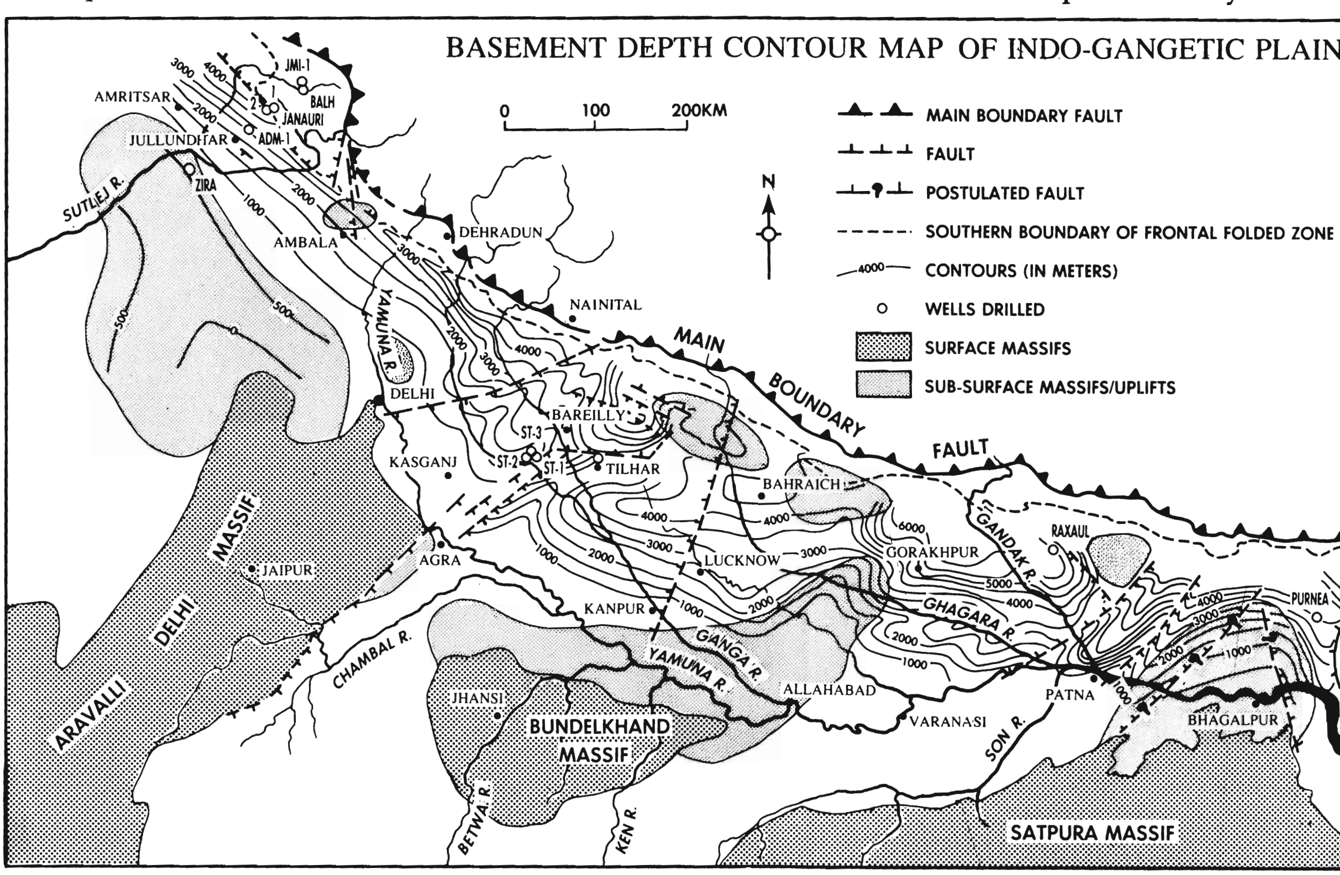


Fig.5. Basement map of Ganga Plain based on the information of O.N.G.C. Redrawn and simplified after Sastri *et al.* (1971), Rao (1973), and Karunakaran and Ranga Rao (1979).

sediment wedge in the foreland basin, thickening towards the orogen.

The Ganga Plain foreland basin shows all the major components of a foreland basin, namely an orogen (the Himalaya), deformed and uplifted foreland basin deposits adjacent to orogen (Siwalik hills), a depositional basin (Ganga Plain), and peripheral cratonic bulge (Bundelkhand-Vindhyan Plateau) (fig. 7). Due to thrust-fold loading in the orogen, there is subsidence beneath the load which diminishes outwards. There is an upward deflection at a distance from load (Beaumont, 1981; Jordan, 1981), called the peripheral bulge or forebulge, which is a gravity high area and may be subaerially exposed as in the case of Ganga Plain. Gravity calculations across Ganga Plain and Himalaya show a deficit of mass below the Ganga Plain and an excess mass below Lesser Himalaya (Lyon-Caen and Molnar, 1985). Fig. 8 shows the Bouguer gravity anomaly map of Ganga Plain indicating a steep northward negative Bouguer anomaly gradient. Fig. 9 shows Airy-Heiskanen isostatic anomaly map of Ganga Plain and adjacent areas, exhibiting negative values over Ganga Plain, and positive values over Himalaya. These studies imply deficit of mass below Ganga Plain.

The wavelength of the tectonic basin (width of the foreland basin) is a function of the strength of the lithosphere, expressed as flexural rigidity (Jordan, 1995). The lithosphere of the Indian plate is very old, cold, rigid, and with many inhomogenities in the form of basement highs and lows. Furthermore, at present, the Ganga Plain foreland basin is located at a considerable distance from the suture zone of Indian-Asian plates. Hence, despite the large-scale thrust-fold loading in Himalaya, the downflexing of the crust in Ganga Plain region is insufficient. The result is formation of a wide but shallow basin with relatively thin sediment wedge. The sediment

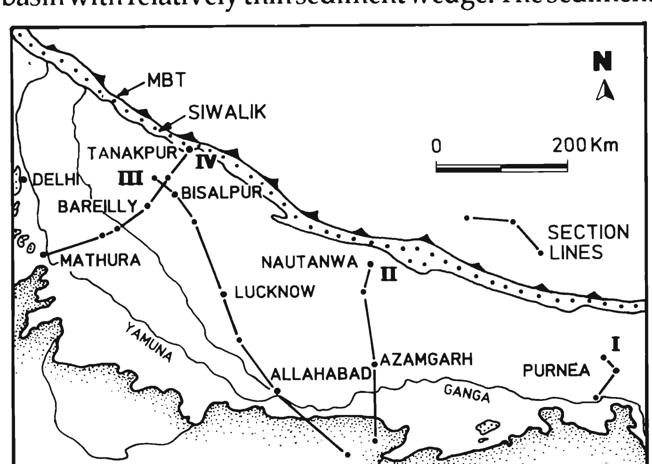


Fig.6a. Location map of Ganga Plain with position of cross-sections of figs 6b-e. Cross-sections are redrawn and modified after Karunakaran and Ranga Rao (1979) and Rao (1973).

input in the Ganga Plain occurs at a rate in excess of the downflexing of the crust; the basin is oversupplied and built above sea-level by 50-300 m in different parts. There is a prominent subaerial peripheral bulge towards the craton, which also contributes sediment to the Ganga Plain foreland basin. Large drainage basins of the craton, beyond the peripheral bulge are also drained into the Ganga Plain. The basement highs in the Ganga Plain resist downflexing, and show a much reduced thickness of foreland sediments, than in the adjacent parts (fig. 11).

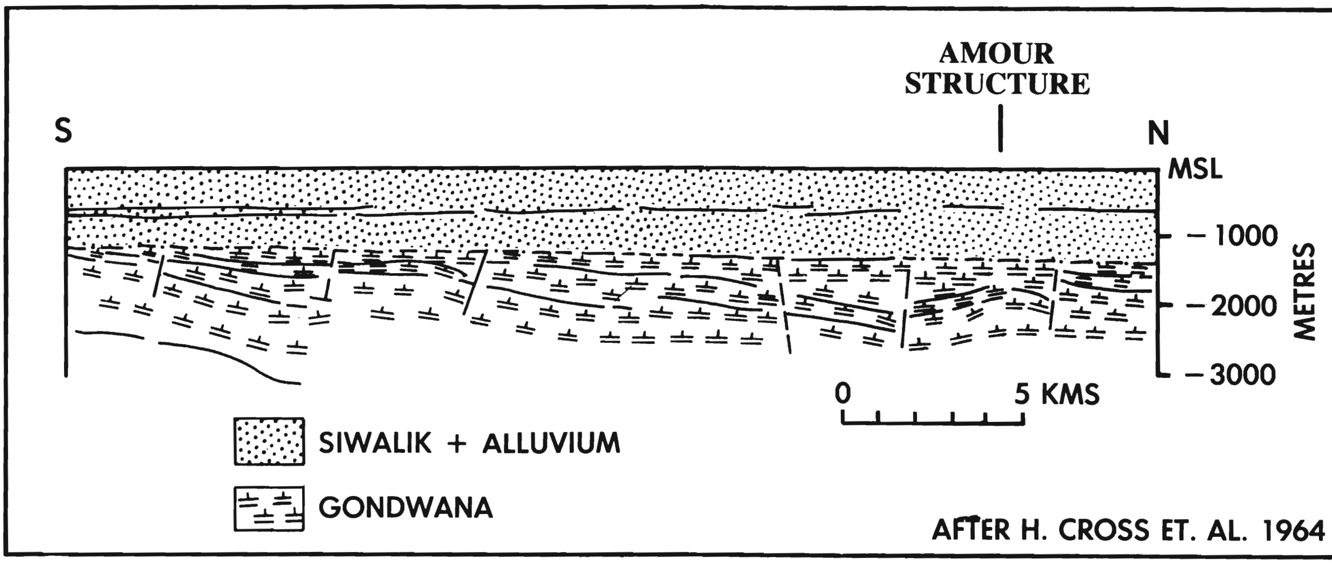
The uplifted orogenward part of the foreland sediments (Siwalik hills) are being extensively eroded and redeposited. This feature suggests that the Ganga Plain foreland basin has reached a mature stage in its evolution when cannibalism of its own deposits has already started. The Ganga Plain foreland basin represents a topographic low between thrust belt (Himalaya) and peripheral bulge (Bundelkhand plateau); hence an underfilled basin (Covey, 1986). However, the underfilled condition of the Ganga Plain foreland basin is not due to little sediment supply; but because of an efficient transport system, which removes bulk of the sediment to be deposited in the Ganga delta and Bengal fan. Thus, Ganga Plain foreland basin is a mature, underfilled basin; though with an oversupply of sediment, where sedimentation is taking place by fluvial processes.

In contrast to the Ganga Plain, the foreland basin of Haryana-Punjab plain is an overfilled basin; where the forebulge is buried under the sediment cover, and there is no topographical expression. Here, sediment supply is only from the Himalaya; there is no contribution from the craton.

Burbank (1992) argued that the Ganga Plain foreland basin has been dominated by transverse river system since Pliocene due to erosionally-driven uplift; and the Indus foreland basin is dominated by the longitudinal river system due to the tectonically-driven uplift. There are certain inconsistencies in the data analysed by Burbank (1992):

(i) Upper Siwalik sediments bave been thrusted and uplifted by about 2000 m vertically in Late Middle Pleistocene, indicating a major thrusting event during Early Late Pleistocene in the Himalaya.

(ii) The geometry of Upper Siwalik sediment wedge as shown in fig. 2b,c is not correct. The Janauri and Jwalamukhi boreholes are located in Siwalik hills and show only an eroded, reduced thickness of upper Siwalik. Adampur and Zira are located in the Punjab alluvial plain, and there is a distinct wedging of the upper Siwalik towards craton. In section 2c also, there is an increase in the thickness of upper Siwalik sediments from Kasganj to Tilhar. Mohand



CPD, CARTO. SECT., LSU

Fig.6b. Cross-section I showing Gondwana rocks above the basement, followed by foreland sediments.

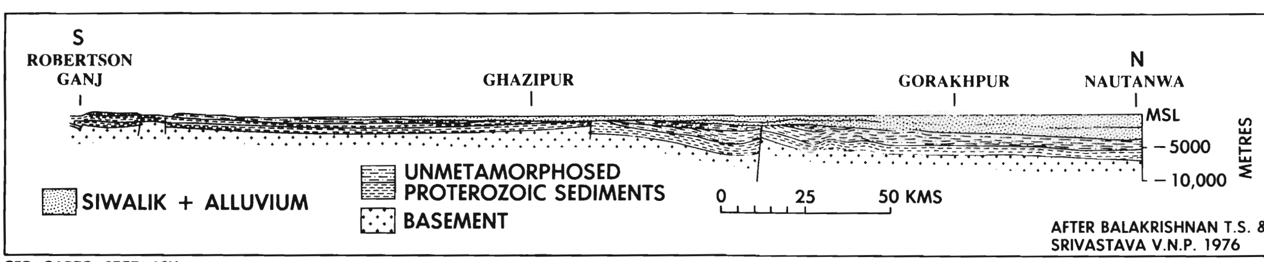


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Fig.6c. Cross-section II. Foreland sediments are present above the unmetamorphosed Late Proterozoic sediments.

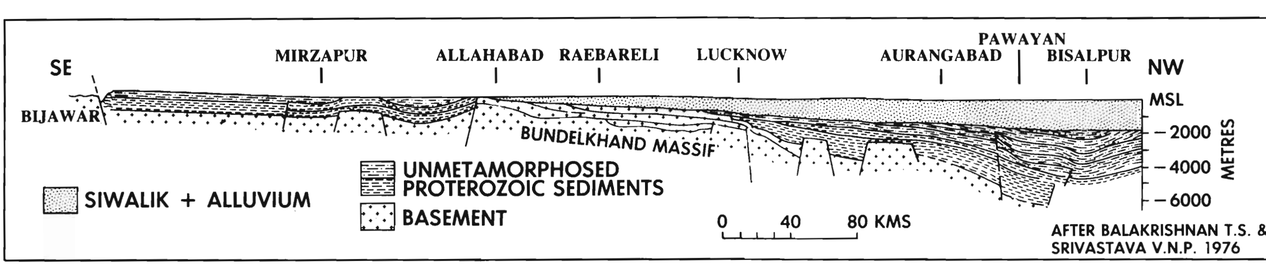

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Fig.6d. Cross-section III. Foreland sediments are partly above the basement, partly above the Late Proterozoic sediments.

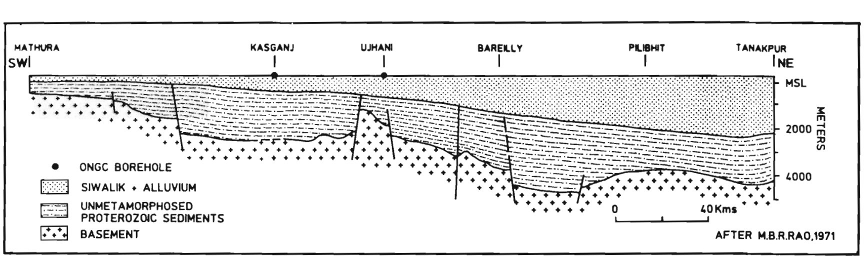

Fig.6e. Cross-section IV. Foreland sediments are present above the Late Proterozoic sediments.

is located in the Siwaliks, and no thickness data of upper Siwalik is available. However, Puranpur well located in the northern margin of Ganga Plain shows an increased thickness of upper Siwalik sediments. Cross-sections drawn by Karunakaran and Ranga Rao (1979) and Biswas (1994) clearly show an increasing thickness of upper Siwalik sediments towards orogen.

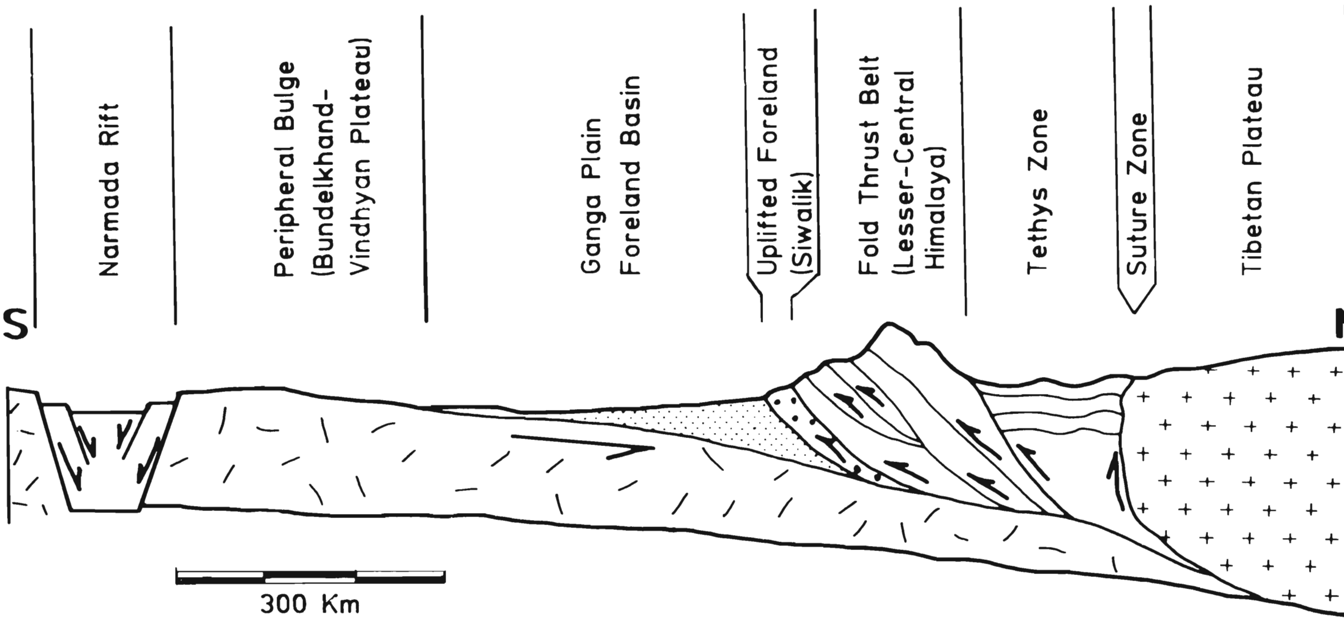

Fig.7. Schematic cross-section of Ganga Plain foreland basin and adjoining area.

(iii) Ganga plain foreland basin shows a prominent peripheral bulge indicating an underfilled basin, which is considered to be related to the thrust-driven uplift by Burbank (1992).

(iv) The Punjab-Harayana foreland basin is an overfilled basin, with no subaerial expression of the peripheral bulge. The sediments and drainage move in the SW direction.

The Indus basin is related to the Himalayan tectonics only in the northern part; downwards it is mainly affected by the Baluchistan orogen or Sulaiman Range (Ghosh and Singh, 1988; Singh and Ghosh, 1994), where

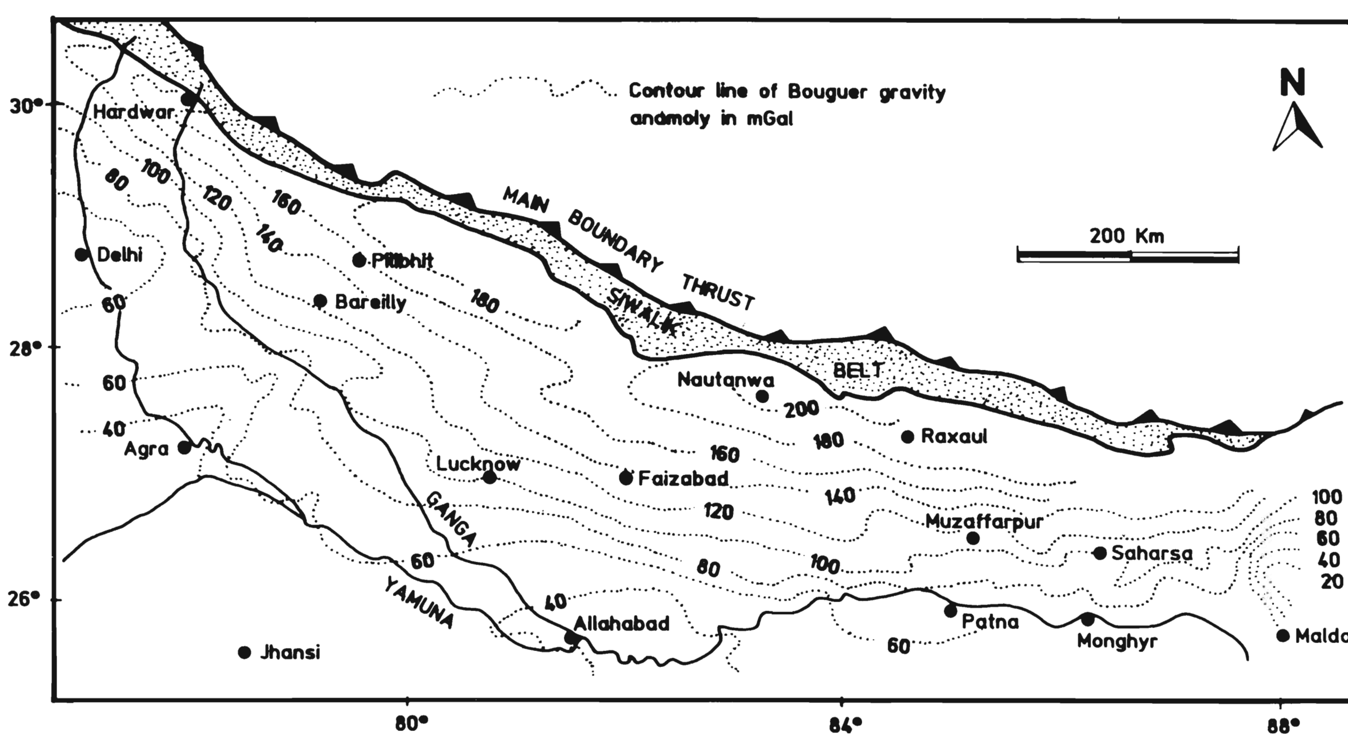

Fig.8. Bouguer gravity anomaly map over Ganga Plain. Values are negative values in m Gal (Modified after Agarwal, 1977; Lyon-Caen and Molnar, 1985).

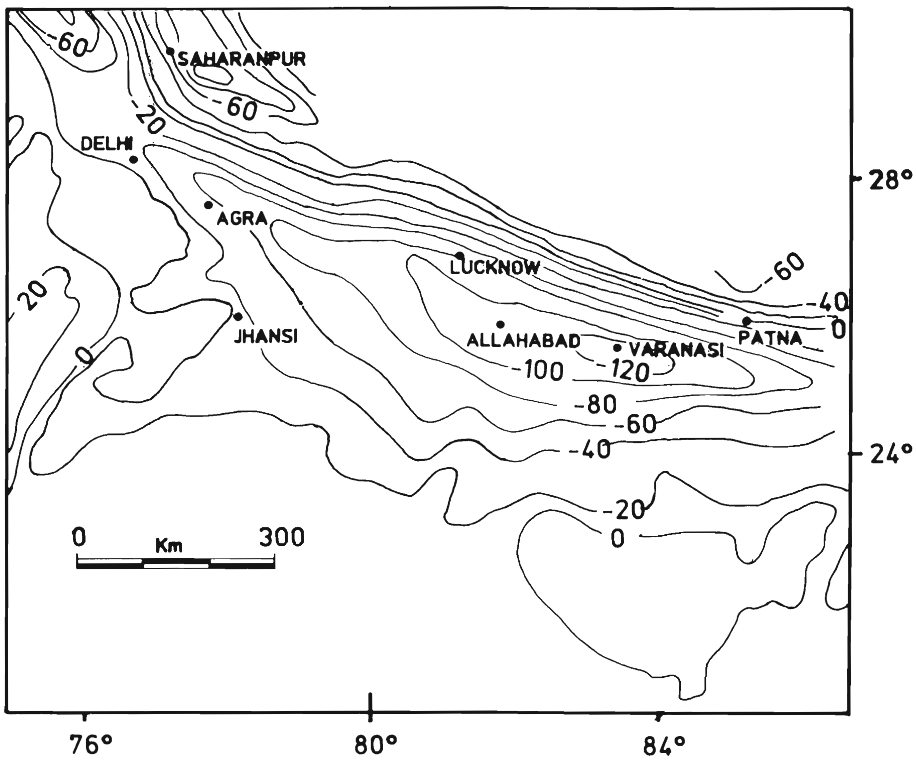

Fig.9. Airy-Heiskanen isostatic anomaly map of Ganga Plain (after Qureshy and Kumar, 1992).

it flows close to the orogen as longitudinal drainage (Burbank, 1992).

During Late Quaternary deposition in both the Punjab-Haryana plain (overfilled basin) and Ganga plain (underfilled basin) has been controlled mainly by expanding and contracting fan systems (transverse drainage) (Ghosh and Singh, 1988; Singh and Ghosh, 1992, 1994).

GEOLOGICAL HISTORY OF THE GANGA PLAIN FORELAND BASIN

Evolution of Indo-Gangetic Plain foreland basin (Parkash and Kumar, 1991) and Siwalik part of foreland basin is recently reviewed (Tandon, 1991). It seems most probable that Early Eocene Subathu sediments were deposited in a rift valley near the present-day southern margin of the Lesser Himalaya, before the initiation of the foreland basin (Singh, 1979, 1981). This presumption is supported by the fact that in none of the boreholes drilled in the Siwalik hills and the Ganga Plain are Subathu sediments encountered (Biswas, 1994).

It appears reasonable to assume that the initiation of Ganga Plain foreland basin took place in the Early Miocene, with a considerable time lag after collision of the Indian-Asian plates during Eocene. In the early phase of this foreland basin, during the Early Miocene, when Murree-Dharmashala sediments were probably deposited, it was very narrow and with little subsidence. In this Early Miocene phase much sediment was provided by the rising and eroding Himalaya; but sediments were mostly carried into Bengal fan (France-Lanord, 1993), as the foreland basin was of very small dimensions, due to subdued flexure of the Indian plate.

Substantial subsidence and flexing of the basin started in Middle Miocene, and a full-grown foreland basin was established. In this stage, the basin was narrow, though deep. However, it received huge quantity of sediment (An oversupply in excess of the subsidence rate). Hence, the basin built up above sea-level and deposition took place by fluvial processes. No marine transgression has affected the Ganga Plain foreland basin throughout its depositional history. It may be pointed out here, that Himalayan orogen supplied huge quantity of sediment, most of which by-passed the foreland basin to be deposited in Ganga delta and Bengal fan. It is reasonable to assume that the supply of sediments from evolving Himalaya was always much more than could be accommodated in the foreland basin.

During the Middle Miocene to Middle Pleistocene (Lower to Upper Siwalik), the orogenward part of the Ganga Plain was uplifted and thrusted basinwards in several discrete steps. The last major thrusting and uplift in orogenward basin margin took place around 500 Ka, when Upper Siwalik sediments were uplifted. During this period of deposition of Siwalik sediments, the Ganga Plain basin shifted cratonwards in response to the

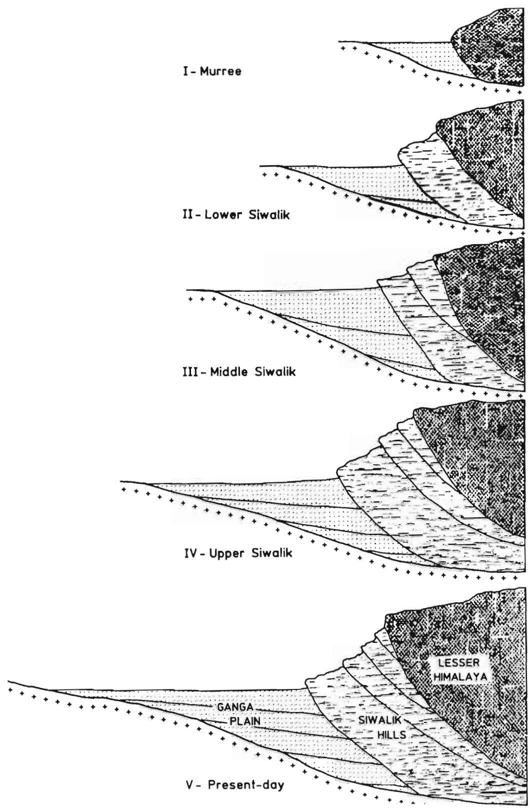

Fig.10. Stagewise evolution of Ganga Plain foreland basin.

thrust-fold loading in the orogen and orogenward foreland basin margin. The stagewise evolution of Ganga Plain foreland basin is depicted in fig. 10.

The thickness of foreland basin sediments (Siwalik + Alluvium) shows a strong asymmetry. The sediment thickness in about 100 km wide belt in cratonward margin is less than 0.5 km. Northwards, the thickness of sediment increases, attaining a maximum value of 3.0-4.0 km near the Siwalik hills (fig. 11). The maximum estimated thickness of sediment in the Siwalik belt is about 6-8 km. It is possible that the rate of subsidence and flexing of crust in Ganga Plain is now reduced, relative to the earlier phase of foreland basin development, when the Siwalik sediments were deposited. It appears that, the width of the foreland basin is greater now, than it was in the earlier phases. It is estimated that Murree-Dharmshala sediments are restricted upto the Piedmont zone, the Lower Siwalik extend to the Ghaghara River, Middle Siwalik may extend to the Sai River in the Central Alluvial Plain, and Upper Siwalik extends to the central part of the Ganga-Yamuna interfluve. There is a cratonward pinching out of the older stratigraphic horizons (fig. 12).

Cratonward migration of Ganga Plain foreland basin during the Late Quaternary (since the Middle Pleistocene) is demonstrated by detailed subsurface information. In the Ganga-Yamuna interfluve, the craton-derived sediments are present above the basement, followed by Himalayan-derived sediments (Singh and Bajpai, 1989) (figs. 13, 14). The southward expansion of the Ganga Plain foreland basin since the Middle Pleistocene is estimated to be about 100 km in the Kanpur-Hamirpur region. It is also argued that since Middle Pleistocene, significant amount of craton-derived sediments are contributed to the Ganga Plain foreland basin.

In the northern (orogenward) part of the Ganga Plain, large thrust sheets of Siwalik sediments moved southwards during the Middle Pleistocene. Some of these thrust sheets show broad synformal depositional areas, making the Duns, corresponding to the piggyback basins (Ori and Friend, 1984). Deposition in these Duns took place by large fans and braided streams, and is contemporary with deposition in the Ganga Plain. A large amount of sediment has been eroded away from the Siwalik thrustsheets (foreland sediments) to be redeposited.

SUBSURFACE SUCCESSION IN ALLUVIAL DEPOSITS

The Ganga Plain is an active area of sedimentation receiving a huge amount of sediments from the Himalaya, and some from the Peninsular craton. Boreholes dug by Central Ground Water Board (CGWB) for water exploration provide insight into the nature of the alluvial succession of the Ganga Plain. The borehole information of about 200 wells (100-750 m deep) of CGWB in different parts of Ganga Plain is summarized. Based on lithological descriptions and electrologs of individual boreholes, vertical lithologs of individual boreholes were prepared, identifying gravel, coarse sand, medium sand, fine sand, mud and mud-kankar. The Ganga Plain was subdivided into the following areas: Doon valley, Bhabar zone, Terai zone, Terai-Ghaghara river, Ghaghara-Gomati interfluve, Gomati-Ganga interfluve, Ganga-Yamuna interfluve and Marginal Alluvial Plain. Lithology of all the boreholes of each area was pooled together and relative percentages of different lithologies were calculated. A 100 m thick idealized profile for each zone was reconstructed in which relative proportion of lithology and their relative position in the profile was considered (see Singh and Wal, *ms.*).

The succession in Doon Valley shows about 18% gravel, 16% sand, 66% clay, with gravel horizons increasing in the lower parts. The Bhabar zone shows 50% gravel, 34% sand, and 16% mud with thicker horizons of gravel in lower part. The Terai zone shows 24% gravel, 36% sand, and 38% mud. The northern part of Central Alluvial Plain (Terai-Ghaghara zone) shows about 5% gravel, 45% sand and 50% mud. The southern part of

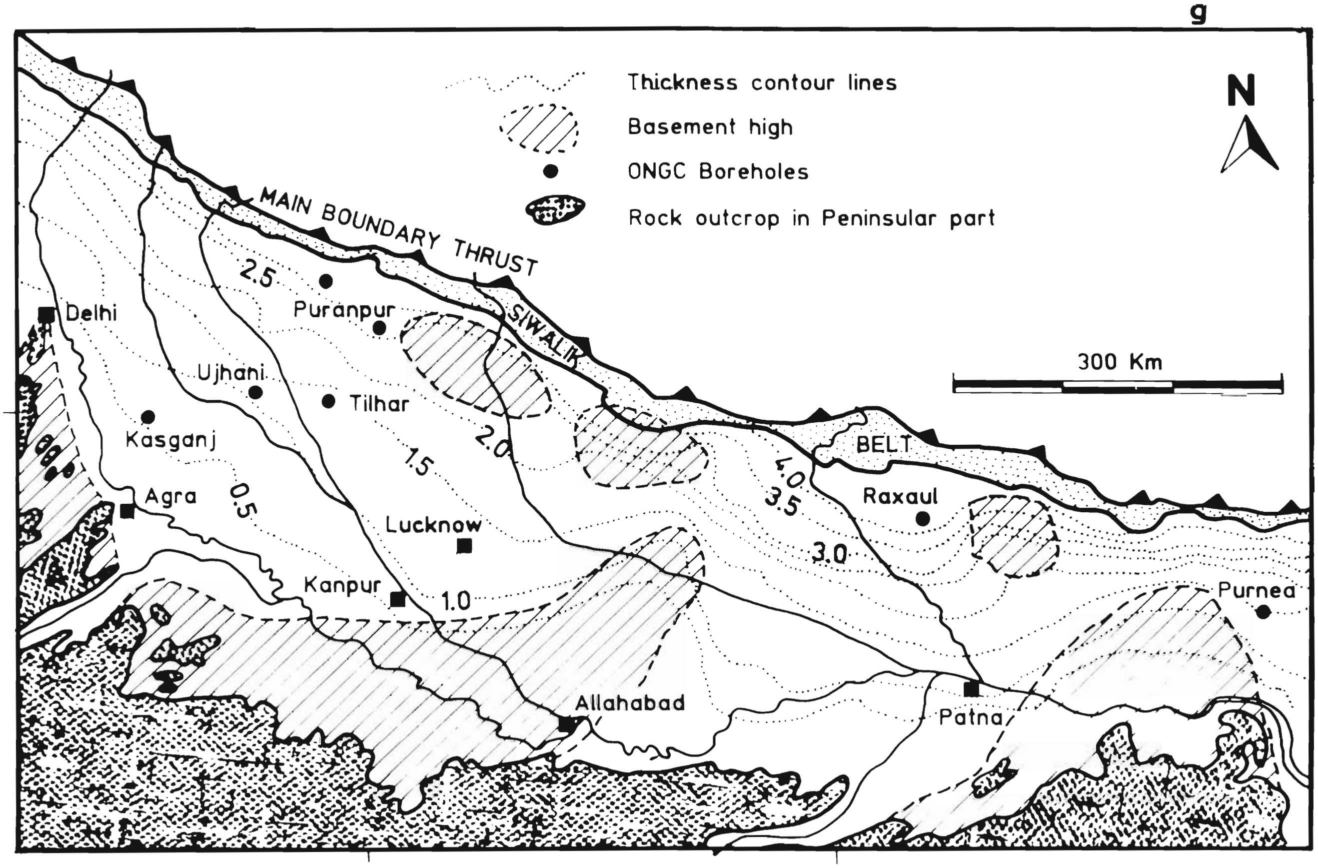

Fig.11. Isopach map for foreland sediments in Ganga Plain. Based on data of CGWB borehole, and seismic data of ONGC, Agarwal (1977), and Karunakaran and Ranga Rao (1979).

Central Alluvial Plain (Ghaghara-Gomati Interfluve) shows 50% mud-kankar, 20% mud, 20% sand and 10% gravel. The Gomati-Ganga interfluve shows 62% mud, 26% gravel, 8% sand, and 4% kankar. The Ganga-Yamuna interfluve shows 45% gravel-coarse sand, 35% medium-to fine sand, 20% mud-kankar. The succession of the lower part is of craton-derived sediments. The Marginal Alluvial Plain shows gravel-coarse sand-65%, fine sand 10%, mud-kankar 25%. The sediments are essentially derived from the Peninsular craton. Idealized vertical alluvial successions in different parts of the Ganga Plain are shown in fig. 15.

It is important to note that throughout the Ganga Plain, the top few metres of the succession show a distinctive fining upward sequence, mostly terminating in mud-rich sediments. The Himalayan-derived gravel beds are present only in the Bhabar and Terai belt. The gravel horizons of Central. Alluvial Plain are reworked kankar and carbonate-cemented sand. The gravel horizons of the southern part of the Ganga Plain are derived from the Peninsular craton. The Central Alluvial Plain shows rare thick sandy successions (50-100 m), most of the sandy horizons are only few meter thick. Kankar development is common in the southern part of Central Alluvial Plain and in Marginal Alluvial Plain.

Khanna (1992) and Chaturvedi *et al.* (1992) have identified five distinct stratigraphic units in the topmost 400 m thick succession, which make distinct aquifers. The stratigraphic units are made up of mud-dominant and sand-dominant succession (fig. 16). The topmost unit is about 20 m thick muddy sediments developed throughout the Ganga Plain, where 1-3 m thick lenses of very fine sand are scattered. This is cut and overlain by sandy sediments in the river valleys and channel belts.

GEOMORPHOLOGY OF THE GANGA PLAIN

The classical literature on Ganga alluvial plain gives a very generalized idea about the geomorphic features of Ganga Plain (Oldham, 1917; Pascoe, 1917; Pilgrim, 1919), defining two morphostratigraphic units, namely **Older Alluvium (Bhangar = Bangar)**, and **Newer Alluvium (Khadar)**. The **Older Alluvium** makes the higher interfluve areas; while the **Newer Alluvium** forms deposits of the major river channels and their valleys. A broad zone of gravelly sediments near foothills is identified as **Bhabar**; the flat marshy areas of northern part as **Terai (Tarai)**. The linear sand ridges of northwestern part are **Bhur**, the salt-effected areas are **Usar**. The southern rivers, namely the Yamuna, Betwa, and Chambal show areas of extensive gulleying, the **Ravines** (Pascoe, 1973).

Cone and inter-cones (Fan and interfan areas) in the northern part of the Ganga Plain are emphasized and incision of major rivers in the Bangar surface is noticed (Geddes, 1960). It is also argued that sea-level changes might have affected the river channels backwards for considerable distance (Geddes, 1960). In a detailed study of the alluvial morphology of upper Ganga-Yamuna Doab, **Bhangar, Khadar, Khola**, and **Bhur** are identified as the major geomorphic features. It is demonstrated that the drainage pattern on the Bhangar, Khadar and Khola surfaces show distinctive characteristics; the Bhur is considered to be formed by deposition of aeolian sand along the abandoned channels. It is also noted that the drainage on the Bangar surface is incised, producing terraces. These Bangar terraces are depositional terraces (Mukerji, 1963). The role of sea-level changes (base-level adjustments) and climatic change in the origin of depositional terraces of the Bhangar surface is discussed (Mukerji, 1963). Das Gupta (1975) give a detailed account of the geomorphology of the Upper Gangetic flood plain, identifying three levels of river valley terraces in the Ganga Khadar (Ganga river valley), and two levels of terraces on the Bangar surface. The Bangar surface towards north is onlapped by the Piedmont surface terraces. Role of changing sea-level during Late Quaternary in the origin of different terrace levels of Gomati River system is emphasized (Kumar and Singh, 1978). Remotely-sensed data offers a synoptic regional view of Ganga Plain, and a number of studies described various geomorphic features (Pal and Bhattacharya, 1979; Saxena *et al.*, 1983; Khan *et al.*, 1988; Philip *et al.*, 1991). Mappable geomorphic units of Ganga Plain are identified and mapped in the Quaternary mapping programme of the Geological Survey of India (see many extended abstracts in Records GSI, volume 122-126, part 3 and 8). In the Ganga Plain of Uttar Pradesh regional upland surfaces are termed as Varanasi Older Alluvium and Banda Older Alluvium, and Piedmont fan deposits are termed Bhat Alluvium (Gopendra Kumar, 1992; Joshi and Bhartiya, 1991; Khan *et al.*, 1987). Regional mapping of Ganga Plain in Bihar also show distinct regional mappable surfaces. However, the height difference between these surfaces in the North Bihar plain is only few meters (Sinha *et al.*, 1989; Om Prakash *et al.*, 1989). Some attempts are also made to give a relative hierarchy and chronology of events of geomorphic units of Ganga Plain (Singh, 1987; Ghosh and Singh, 1988; Singh *et al.*, 1990).

In the following, an account is given of regionally significant geomorphic surfaces, their morphology and relative hierarchy. This is based on a mapping on 1:1 million and 1:500,000 scales using remotely-sensed data and SOI sheets (see also Singh and Ghosh, 1992, 1994). (fig. 17) ig 4

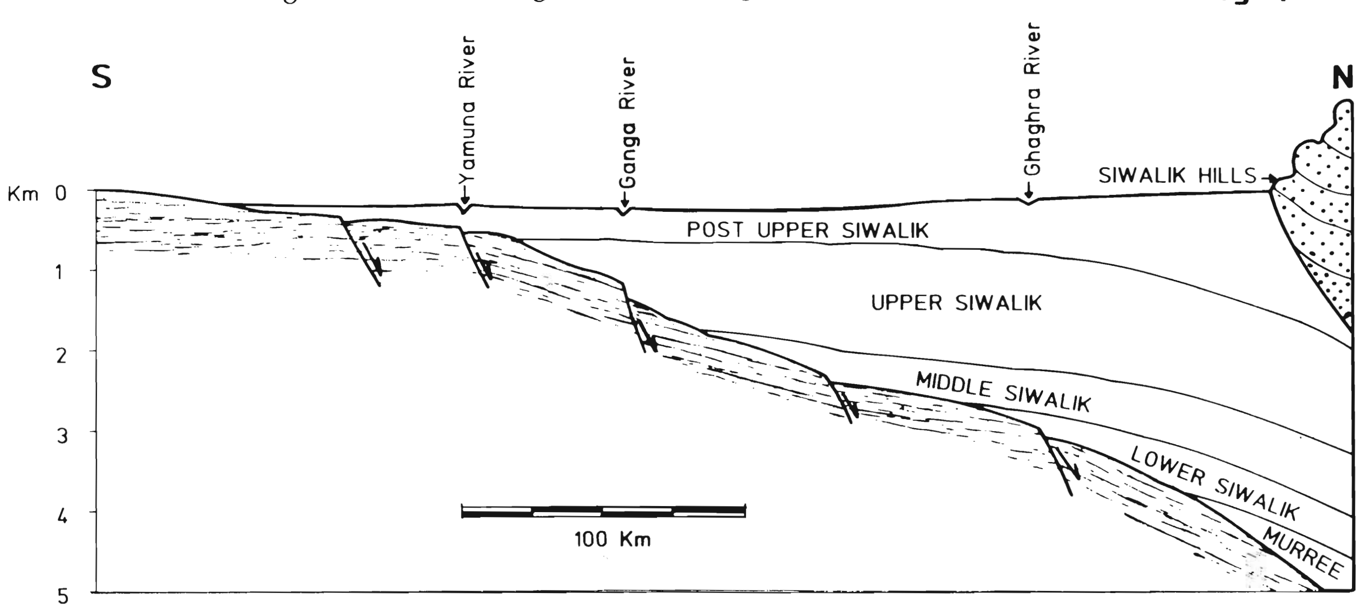

Fig.12. Section across Ganga Plain showing cratonward pinchout of various stratigraphic units of foreland deposits. Based on the ONGC borehole data from Sastri (1971).

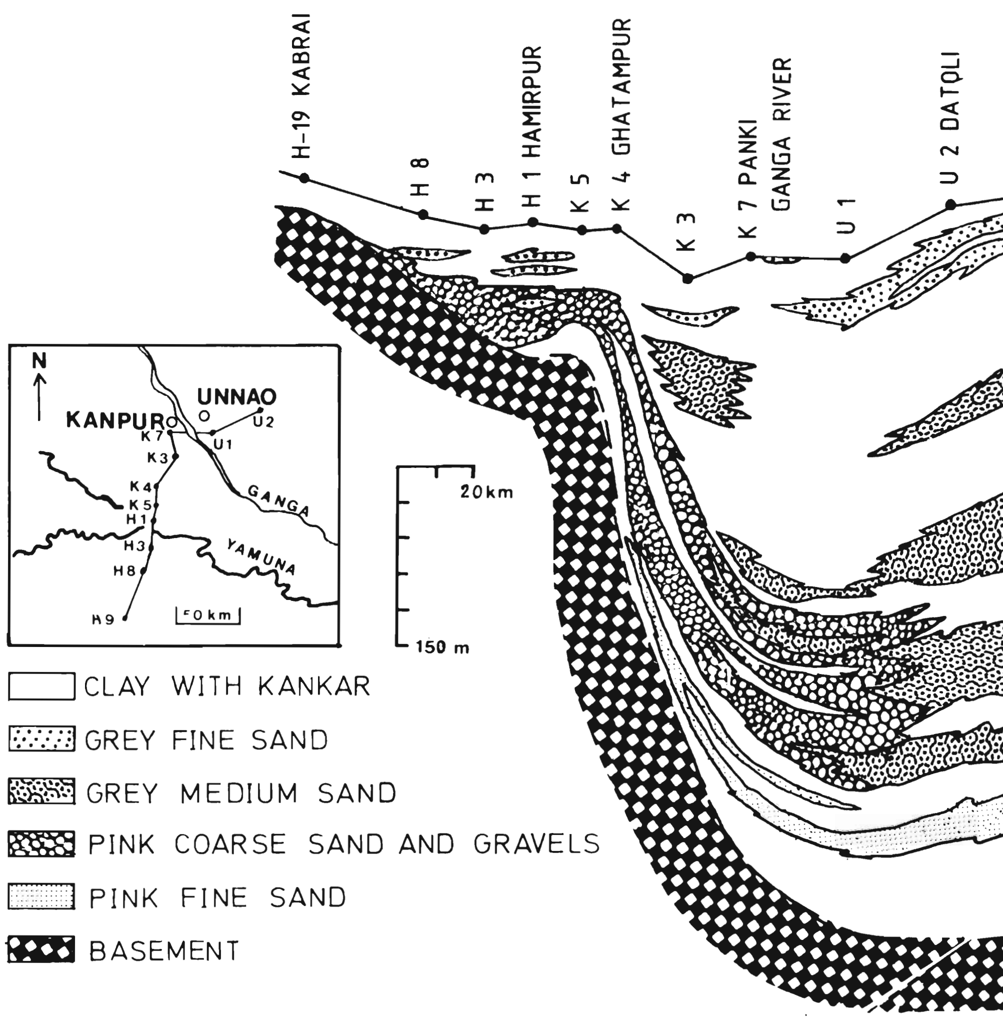

Fig.13. Subsurface stratigraphy of southern part of Ganga Plain showing onlap of Himalayan-derived sediments over craton-derived sediments (After Singh and Bajpai, 1989).

To these regional geomorphic surfaces of the Ganga Plain, the areas of the **Duns** may be added, these being alluvial depositional domain on the folded thrust sheet of Siwalik rocks, separated from the Ganga Plain by a topographical thrust sheet ridge.

All of these geomorphic surfaces of Ganga Plain are essentially depositional surfaces. All of them have a succession of sediment deposited on their top which are younger than the time of the formation of respective surfaces. The topmost few meters of sediment on all the surfaces are of Holocene age; hence dating of these geomorphic surfaces is very difficult. The relative timing of their origin is established on the basis of their morphological interrelationship and order of superposition.

Upland Terrace Surface (T_2)

The major part of the Ganga Plain north of the axial river shows interfluve highland areas (Older Alluvium or Bhangar) making the Upland Terrace Surface with a southern or southeasterly regional slope. Its best development is seen in the southern part of the Central Alluvial Plain. This surface shows a variety of distinct domains, e.g. gentle regional ridges, linear narrow sand ridges (bhur), ponds, lakes, a variety of river channels, and abandoned channel belts. Most commonly, the river channels are incised showing highly sinuous underfit character. The river channels may be carrying sand or mud; or may be highly sinuous decaying channels not transporting any significant sediment.

The sediments of this surface are characteristically fine-grained showing interlayering of fine sand, silt, mud with calcrete horizons. The surface soil shows a wide range in variety and grain size. This is the oldest geomorphic surface of the Ganga Plain, as all the other surfaces are either superimposed or cutting into it.

This surface is beyond the reach of floods by overtopping of the river channels. However, flooding and water stagnation takes place from rain water flowing over this surface.

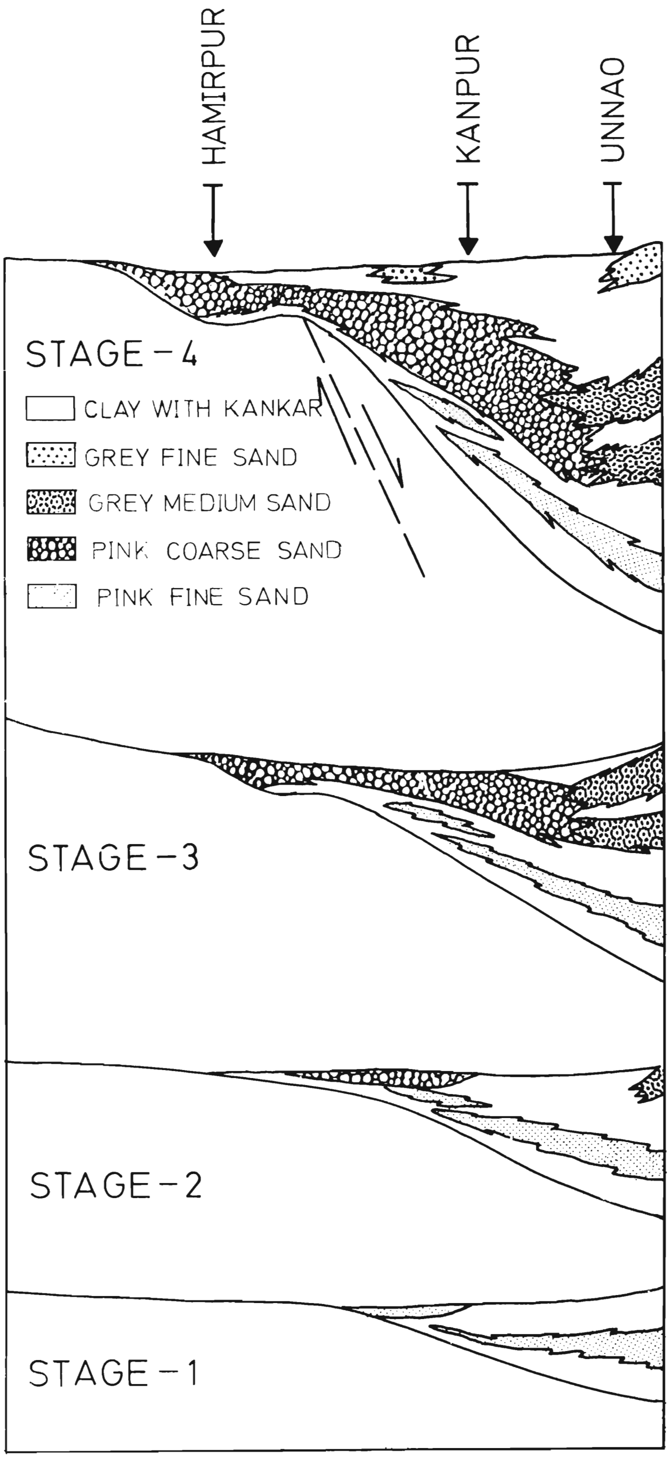

Fig.14. Schematic diagram showing southward expansion of the Ganga Plain (After Singh and Bajpai, 1989).

Marginal Plain Upland Surface (MP)

The north and northeasterly sloping surface of the Marginal Alluvial Plain is designated the MP-surface. This surface is mostly classified with Older Alluvium or Bhangar. This is considered as a separate geomorphic surface, mainly because it is composed of sediments derived from cratonic source, and because of a different regional slope from that of the T_2-surface. The regional gradient of this surface is higher than that of the T_2-surface, and it is made up of slightly coarser sediments.

In the southernmost region, near the cratonic rock outcrops there is a zone of angular gravelly sediments, a few hundred meter wide, which merges downslope into sandy-silt or sandy-clay sediments, representing poorly developed alluvial fans. The surface shows many shallow, meandering ephemeral streams; and a few major rivers showing much entrenchment, where extensive ravine development due to gulleying has taken place. The gulleying and ravine development is more extensive in the western part than in the east. The micromorphology of this surface is less diverse than on the T_2-surface. In the cliff sections of this surface silty sediments with sand lenses, and an abundance of kankar horizons are developed. Locally, clays rich in gypsum are also recorded. This surface is considered to be equivalent to the T_2-surface. Different segments of this surface are also given local names, e.g. the Bundelkhand-Vindhyan (V-surface), Gaya-Mungher (GM-surface), and Bhagalpur surface (B-surface) (Singh and Ghosh, 1992, 1994).

Megafan Surface (F)

The synoptic study of remotely-sensed data has helped in identification of a number of megafan surfaces in the northern and central part of the Ganga Plain, earlier referred as Large alluvial fan surface (Singh and Ghosh, 1992). These megafan surfaces are relict features, now being modified by various fluvial processes. From east to west, the megafans identified are: the Kosi, Gandak, Sarda, and Yamuna-Ganga Megafans. These Megafan Surfaces are about 100 km in length, and 100-150 km in width near their bases, and are superimposed on the T_2-surface. The distal parts of these Megafans merge with the T_2-surface, where it is not easy to distinguish the two. The surface of these abandoned megafan has been alluviated by deposition of mainly muddy sediments, and shows development of immature soils. It appears similar to the T_2-surface. The Gandak and Sarda Megafans are skewed in SE-direction due to active tectonic lineaments. The northern parts of the megafans show sandy nature; while the southern distal part mostly shows muddy, silty sediments with linear belts of fine sand. These Megafans show smaller fans superimposed on the larger ones, indicating diminishing fan- building activity through time.

Kosi Megafan: This Megafan shows a radiating distribution of partly anastomosing stream channels, where one or the other channel becomes the dominant stream (Gole and Chitale, 1966; Wells and Dorr, 1987a; Gohain

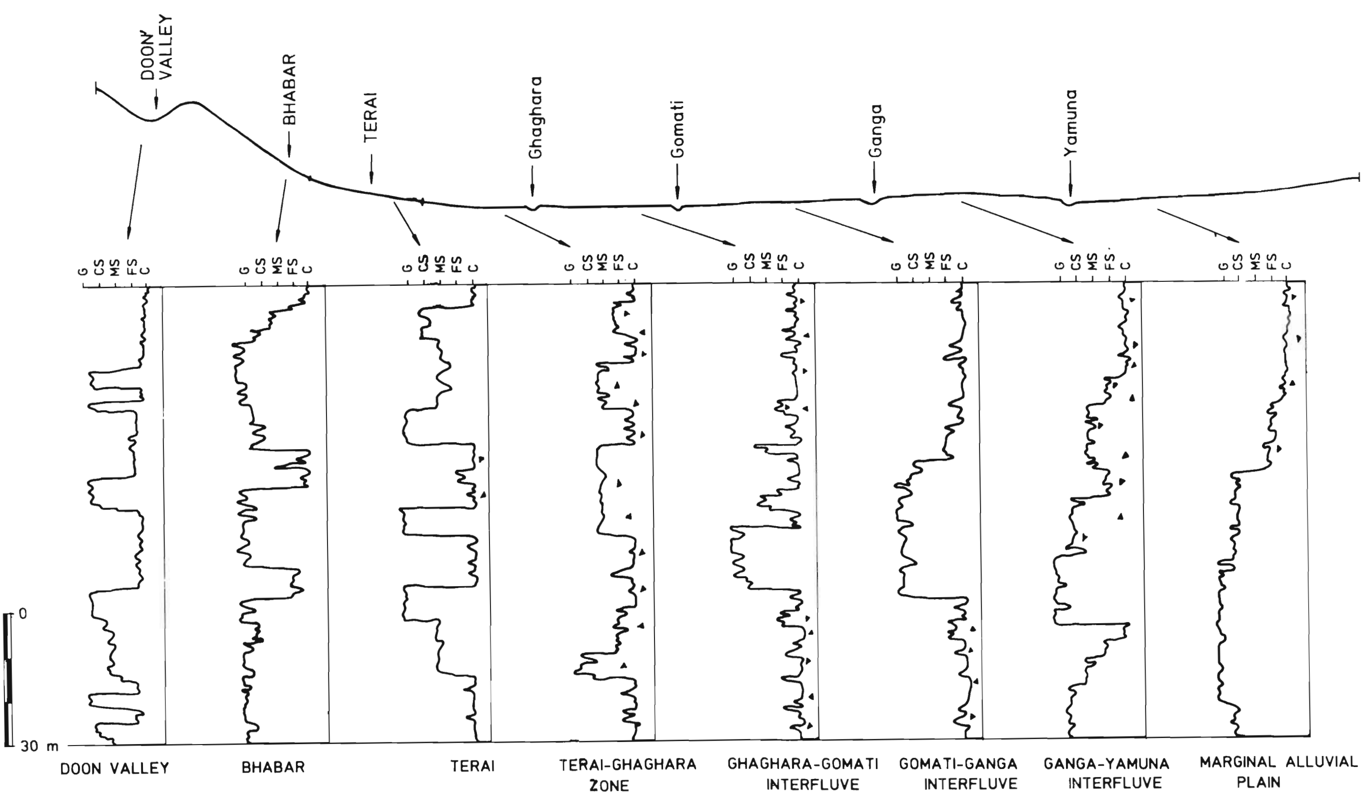

Fig.15. Generalized litholog of subsurface sediments across Ganga Plain, depicted as idealized 100 m thick vertical succession (From Singh and Wal, in press).

and Parkash, 1990). The channels of this Megafan show a wide range of patterns, i.e. braided, meandering, anastomosing; and many of them are groundwater-fed. Some of the channels show prominent natural levees. Present-day active fan deposition is restricted to only 20 km wide belt in the apical part. On the Kosi Megafan mostly muddy sediments are being deposited; many of the abandoned channels are also being silted up. H.

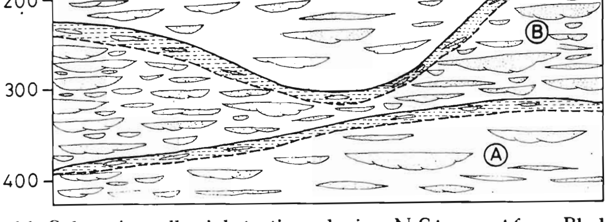

Fig.16. Subsurface alluvial stratigraphy in a N-S transect from Bhabar to Central Alluvial Plain. Five units A-E are identified in the 400 m thick succession (Based on Khanna, 1992 and Chaturvedi *et al.*, 1992).

Singh *et al.* (1993) have developed a facies model of the Kosi Megafan based on the borehole information.

Gandak Megafan: This is a skewed megafan bounded in the west and southwest by the Rapti River, following active lineaments; the eastern boundary is located immediately east of the Burhi Gandak, running parallel to it. The southern margin is demarcated by the Ghaghara and Ganga rivers. It shows many distinctive geomorphic features (Mohindra and Parkash, 1994; Mohindra *et al.*, 1992). The surface is being reworked by several groundwater-fed streams. This Megafan surface shows evidences of reduction in size and orientation of the Megafan through time (fig. 17). The Gandak River is slightly incised in the Megafan surface, and follows an active lineament.

Sarda Megafan : This is the most spectacular megafan of the Ganga Plain. The Ganga River marks its southern limit, while the Ghaghara River marks its northern limit. It shows many NW-SE aligned ground-water fed streams and abandoned channel belts. There is evidence of reduction in size and orientation of this Megafan. Geddes (1960) indicated that the Ghaghara River does not make any cone (Megafan); however, a highly skewed, large Megafan built by Sarda and Ghaghara rivers is identified in this study.

Yamuna-Ganga Megafan: A prominent megafan is developed in the western part of the Ganga Plain; the Yamuna River marks the western limit and the Ramganga River the eastern limit. The northern part of this Megafan shows many N-S aligned drainages, and an eastern tilt of the surface. The Ganga and Yamuna rivers are deeply incised in this Megafan surface. The surface shows evidences of many abandoned channels; many of them of anastomosing type.

River Valley Terrace (T_1)

The major rivers of Ganga Plain show development of broad river valleys in which the present-day active river channels with their flood plains, are entrenched. The broad river valleys are entrenched into the T_2, MP or F Surfaces. The River Valley Terrace Surface is termed the T_1-surface. In the classical studies the T_1-surface along with the active channel flood plain (To) is termed as Khadar or Newer Alluvium. The T_1- surface is sometimes described as Older flood plain, and To- surface as Active flood plain.

The T_1-surface is located several metres higher than the active flood plain, and is normally not flooded by the bank overtopping of the river channel. It can be flooded by rainwaters and backflow phenomena during floods in the main rivers, coupled with the heavy rains in the area. The T_1-surface shows extensive development of relict features of abandoned channels, meander cutoffs, linear water bodies, which are not related to the present-day active channel. Below the few meter thick muddy deposits, thick sand is present, which is coarser-grained than the sand of the present-day active channel. The River Valley Terrace is a depositional terrace formed during an earlier more humid climate, when large river valleys were formed (Singh *et al.*, 1990). Sometimes the T_1-surface shows several levels (fig. 18) (Das Gupta, 1975). The contact between T_2 and T_1 surfaces in Ganga-Yamuna Doab shows extensive gulleying and referred to as Khola (Mukerji, 1963; Das Gupta, 1975). The T_1-surfaces of the Marginal Alluvial Plain are narrow and asymmetrical, showing more than one step. T_1 surface is developed in almost all the rivers of the Ganga Plain, including the Ground-water fed highly sinuous rivers. However, the height difference varies in the different parts of the Ganga Plain.

Piedmont Fan Surface (PF)

Along the Himalayan foot hills, a 10-30 km wide belt of coalescing fan surfaces has developed showing both diverging and converging drainages, and a few prominent gravelly fans with 3^{o}- 4^{o} dips. This surface is characterized by mostly dry shallow channels, which become active during the rainy season. Such areas form the Bhabar zone. Adjacent to the Bhabar are the swampy Terai areas showing sluggish groundwater fed meandering streams. The PF-surface includes both Bhabar and Terai belts, as they are interrelated. Mostly, two levels are identified on the PF-surface. The lower level is rather flat with muddy deposits on the top. the upper level is steeper and exhibits rugged topography,

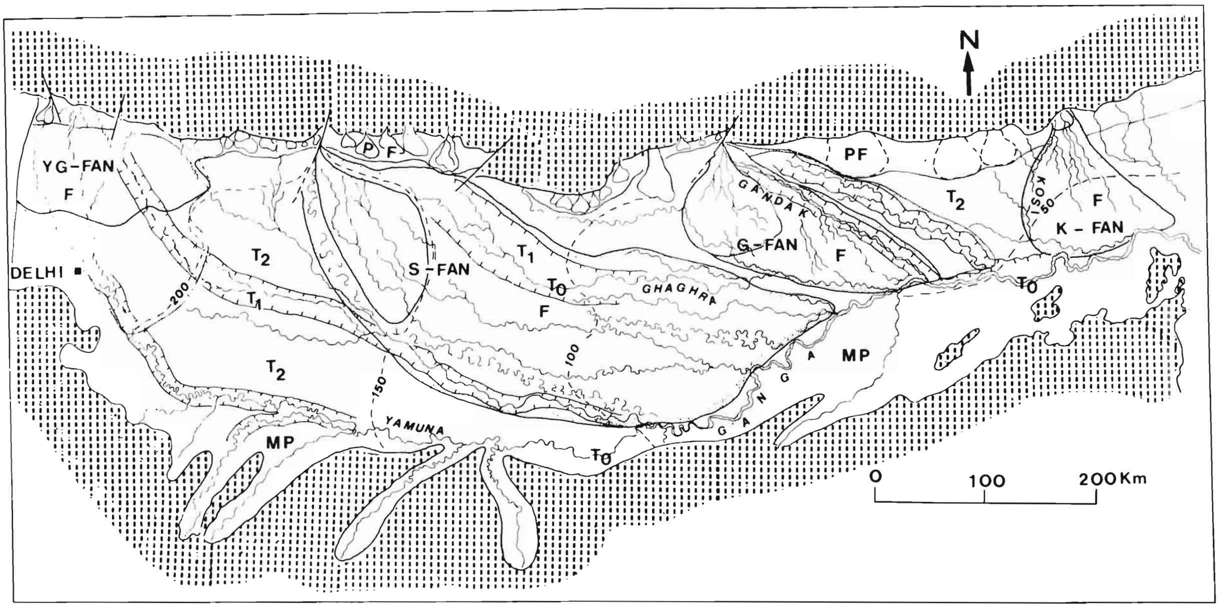

Fig.17. Schematic geomorphic map of Ganga Plain showing regional geomorphic surfaces. T_2-Upland Terrace Surface, MP-Marginal Plain Upland Surface, F-Megafan Surface (YG-FAN-Yamuna-Ganga Megafan, S-FAN-Sarda Megafan, G-FAN- Gandak Megafan, K-FAN-Kosi Megafan), T_1-River Valley Terrace Surface, PF-Piedmont Fan Surface, T_o-Active Flood Plain Surface. On the YG-FAN, S-FAN, G-FAN surfaces several events of reduction of Megafan are identified.

often exposing gravels in the gulleys. On the upper level, often individual fan morphology can be identified. The fans of this surface show evidence of shrinkage in the recent past, as smaller fan are superimposed on the larger fans. This surface is superimposed on the T_2-or F-surface, and is also younger to the T_1-surface.

Active Flood Plain Surface (To)

Active flood plains of most of the rivers of Ganga Plain are rather narrow and entrenched in the river valleys. The flood plains are poorly developed. Even in the case of Ganga River, the active flood plain is only few hundred meters to about 2 km wide. This surface shows a variety of fluvial landforms, including channels, channel bars, levees, meander cutoffs, ox-bow lakes, swamps, crevasse channels, and a wide range of sediment types are deposited in different parts. This surface is subjected to annual flooding. It is the youngest geomorphic surface, and is present within the the older surfaces. Most of the major river channels and their flood plains show a lateral shift of only few km in last few tens of years. Due to entrenchment of the river channels, lateral shift of the channels in the last few thousand years is only a few kilometres. However, in the northern part of Uttar Pradesh and Bihar, many channels show avulsion over a time span of 10^2-10^3 years.

Duns

Duns are small to large spindle-shaped valleys within the Siwalik hills, on the folded thrust sheets and represent piggyback basins. Duns are areas of piedmont sedimentation, separated from the main Ganga Plain due to development of thrust sheet ridges in between (fig. 19). Study of Doon Valley shows that the sedimentation in Duns took place mainly by fan-building activity, followed by braided stream sedimentation (Chandel, 1992) (fig. 20).

LATE QUATERNARY CLIMATIC CHANGES AS CAUSE OF THE GEOMORPHIC SURFACES IN THE GANGA PLAIN

The wide range of geomorphic surfaces and related geomorphic features present in the Ganga Plain, their different altitude and spatial distribution strongly indicate that they represent genesis in different climatic conditions, especially the associated water budget and base-level conditions. Nevertheless, following line of evidence and argument has been used to develop a sequence of events for the geomorphology of the Ganga Plain. The Active Flood Plain Surface (T_o) is Late Holocene in age and it mostly shows aggradation. The T_o-Surface is incised in the T_1- Surface. The grain size of the sand below the muddy cover of the T_1-Surface is coarser-grained than the sand of the T_o-surface. The channel character of the abandoned drainage on the T_1-Surface is much different than that of the T_o-Surface. This suggests that T_1-Surface and its drainage was formed under different set of conditions than those of the present day.

This feature is developed in all the rivers of the Ganga Plain; only the magnitude of incision varies from 1-2 m to 10 m. In the rivers of the Bihar plain incision is very low.

— In the major rivers, e.g., Ganga River, the broad river valley with T_1-and T_o-surfaces extends almost upto the Siwalik hills. In this part, the T_1-surface is covered by the alluvial fans (PF-surface); and T_o-surface has cut this surface. The PF-surface makes a continuous belt along the Siwalik hills and appears to be partly younger than the T_1-surface, but older than the T_0-surface.

— The PF-Surface (10-30 km wide) sits partly on the 100 km wide Megafan (F)-Surface. The F-Surface is also cut by the broad river valleys of the major rivers (T_1+T_o-surfaces). Thus F-Surface is older than the PF, T_1 and T_o-surfaces. Below the topmost few meters of the muddy sediments, the F-Surface is made up of predominantly sandy deposits of grain size which is much coarser-grained than the sand of the T_o-Surface in the vicinity.

— The Megafan (F)-Surface rests on a regional flat upland surface, the T_2-Surface. Thus, the T_2-Surface is the oldest surface of the Ganga Plain.

— In the Marginal Alluvial Plain, the T_1+T_o-Surfaces are incised in a regional surface the MP-Surface.

A regional study of the geomorphic surfaces in other parts of the Indo-Gangetic Plain, namely the Indus Plain, Punjab-Rajasthan Plain, Bengal Plain and Brahmaputra Plain demonstrated that all these areas show remarkable similarity in terms of the geomorphic surfaces and their interrelationship to those developed in the Ganga Plain (Singh and Ghosh, 1994). Thus, it seems reasonable to assume that these geomorphic surfaces are related to the regional or global processes of climatic change and base-level adjustments.

It is already argued that the various regional geomorphic surfaces of the Ganga Plain can probably be related to different climatic and base-level conditions during Late Pleistocene-Holocene (Singh, 1987; Singh and Ghosh, 1992, 1994). The various geomorphic surfaces and related features are of regional character, and needed different climatic conditions for their genesis. It is apparent that all these features can not be produced within Holocene; some of them must have been produced during Late Pleistocene. As already pointed out that all the geomorphic surfaces of the Ganga Plain are depositional areas. The topmost few metres on all the surfaces represent Holocene cover; hence any attempt of dating the topmost few metres would give a Holocene age. This fact makes the dating efforts in the Ganga Plain rather difficult. In the absence of any absolute dates for the origin of various geomorphic surfaces of the Ganga Plain, an attempt was made to correlate the formation of various surfaces to different climatic events of the Late Quaternary. Late Pleistocene-Holocene is a period of several prominent climatic changes.

The beginning of Late Pleistocene is taken at 128 Ka, at the base of oxygen isotope substage 5e. The 128 Ka history (Late Pleistocene-Holocene) is subdivided into several oxygen isotope stages; representing alternating events of ice sheet growth and decay. The glacial-interglacial events, absolute ages, names in U.S.A., relative climatic curve, relative sea-level curve of Late Pleistocene-Holocene is shown in fig. 19. During this time span there are 4 to 5 periods of cold climate (with increased aridity) corresponding to the base-level (sea-level) lowering.

An attempt is made to correlate these Late Quaternary climatic changes to the origin of major geomorphic regional features of Ganga Plain (fig. 21). The basic assumption in this excercise is that the geomorphic surfaces present in Ganga Plain have been produced in Late Quaternary.

The regional plateau surface or Upland Terrace Surface (T_2) and the MP-Surface are high planar landforms and must have their origin in a major period of humid climate of reasonable duration leading to widespread alluviation and planation. It seems probable that this surface was formed during stage 5 (128-74 Ka) with three sea-level high events and a long time of relatively humid climate.

The Megafan Surface (F) was formed during stage 4 and part of the stage 3 (74-35 Ka). This period had an initial humid climate, followed by a long period of arid climate. During this period a huge amount of sediment which was already produced and accumulated in the Himalaya, was transported into the Ganga Plain by diverging drainage. The increased sediment budget from the Himalaya may be related to a period of increased rates of erosion in the orogen. It is also the timing of initiation of large river valleys of major rivers.

The 33-25 Ka was a period of very humid climate, when the large river systems produced the River Valley Terrace Surface (T_1) due to deposition from quickly shifting meandering rivers in broad river valleys.

The stage 2-1 (25-10 Ka) witnessed formation of Piedmont Fan Surface (PF) in a narrow belt near the Himalaya. As the supply of sediment was low due to subdued tectonics in Himalaya, and due to low sediment-water budget, the size of alluvial fans was small. It was also the timing of entrenchment of major drainages into their T_1-surfaces, in response to the base-level lowering.

During the Holocene, deposition in the entrenched river channels of the present-day (T_o) took place with increased rate of aggradation, in response to the rising sea-level. In the present study, the incision and alluviation of the Ganga Plain has been ascribed mainly to the base-level changes caused by the sea-level changes during Late Quaternary. The similarity in the pattern of incision and alluviation, not only in the Ganga Plain, but also in other parts of the Indo-Gangetic Plain requires role of some global or regional events. Himalayas have been tectonically quiescent during the period under consideration; hence base-level changes in the Ganga Plain have been linked with the seal-level changes during Late Quaternary. The high degree of incision in the western and southern part of the Ganga Plain is certainly related to the vertical upliftment of these areas during Late Quaternary. However, this would explain only the magnitude of incision of the drainage, but not the regional pattern of the incision and alluviation.

Drainages which meet the sea, develop a graded longitudinal profile of equilibrium. Any change in the sea-level (the base-level) would lead to the incision or

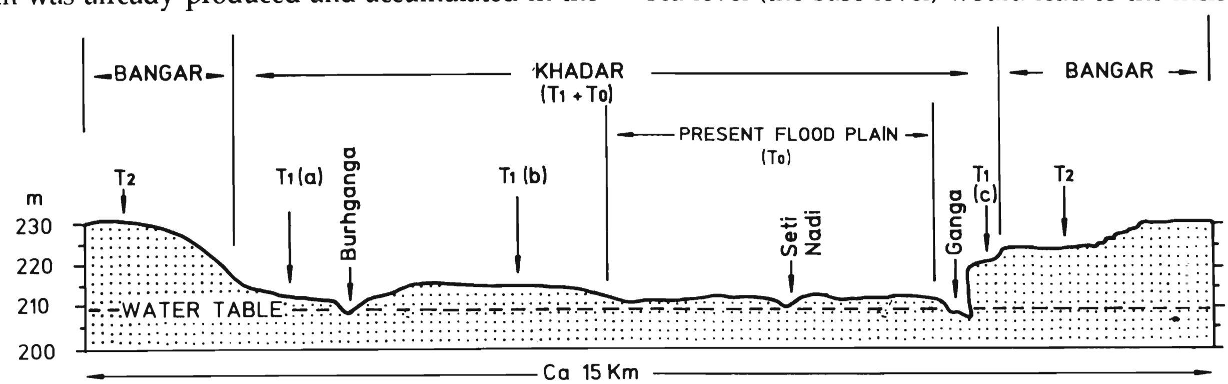

Fig.18. Schematic cross-section across Ganga River near Hastinapur (simplified after Dasgupta, 1975).

aggradation in the channel to restore the profile of equilibrium. Tectonics and climate also effect the profile of equilibrium. Fisk (1944) argued that sea- level changes (base-level change) have effected the alluvial valley deposition of Mississippi River for several hundred kilometres upstreams. The lowering of the sea-level causes steepening of the river profile near its mouth which joins the original profile at a break in slope (Nick point). The nick point migrates upstream by erosion and may effect the entire coarse of the river (Butcher, 1990). However, many of the workers are of the opinion that effect of the sea-level change would be seen only in the deltaic region. Recently, Schumm (1993) and Wescott (1993) demonstrated that rivers are capable of making significant adjustment to changes in the slope by change in sinuosity; but large changes in the slope (base-level changes) are accomodated by incision and aggradation.

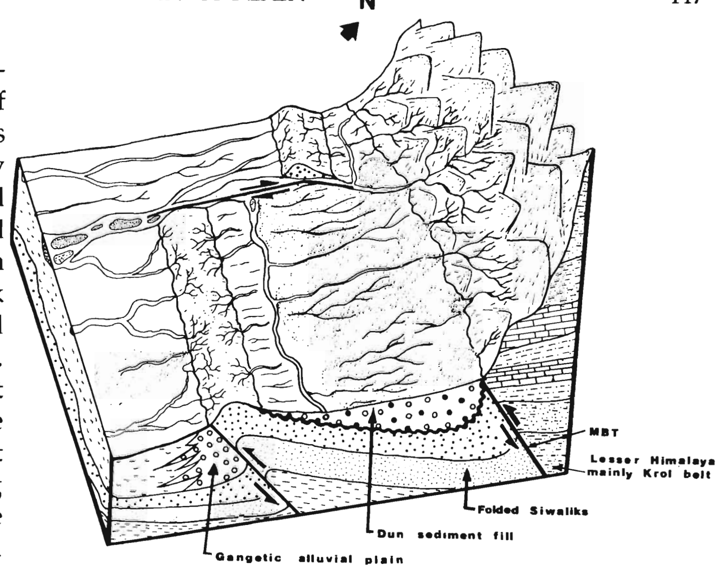

Fig.19. Schematic diagram showing relationship between Duns and Ganga Plain and their sedimentation pattern (After Chandel, 1992).

The Ganga Plain has very low gradient; maximum height of the Ganga Plain in NW corner is about 270 m a.s.l. Within axial zone the height near Mathura is only 175 m a.s.l. in the westernmost part. The length of Ganga Plain and Ganga Delta Plain is about 1500 km; while the length of the Ganga river up to sea coast is about 2100 km. Thus, there is a drop of 275 m over a distance of 2100 km for the Ganga River. In contrast, the slope of the continental shelf in the Ganga Delta region is much steeper. The 150 m depth contour is located about 100 km away from the coast line. During last glacial event (18Ka) the sea-level was lowered by about 150 m. Thus, during sea-level low-stand (18Ka), the river length increased by 100 km; while the gradient dropped by 150 m. Thus, the gradient at sea-level lowstand is 425 m over a distance of 2200 km to compensate steepening of this gradient (fig. 22), the rivers entrenched in their valleys to produce terraces. Similarly, rise in sea-level is responsible for a marked decrease in the gradient, causing alluviation in the river valleys and the Ganga Plain in general. The North Bihar Plain is only 70-30 m a.s.l. It is reasonable to assume that this region has undergone

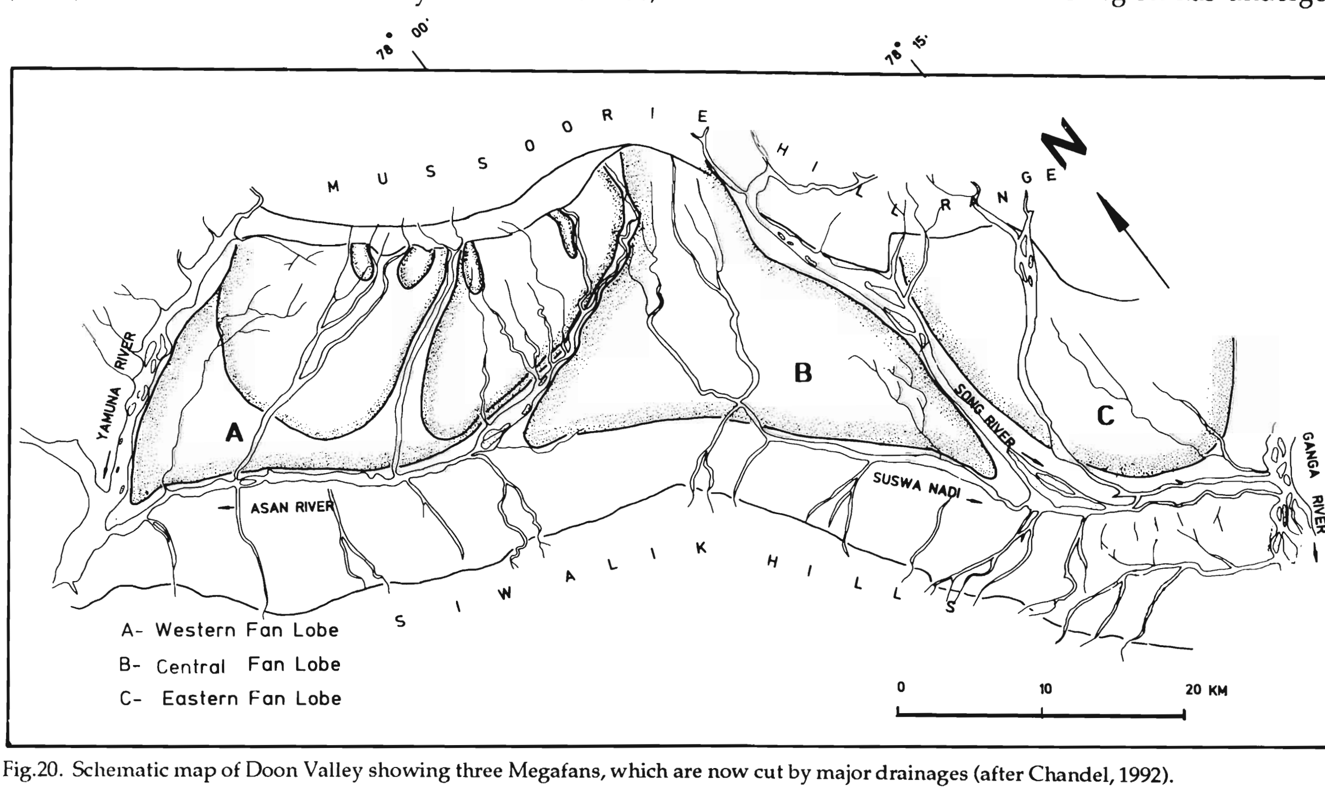

Fig.20. Schematic map of Doon Valley showing three Megafans, which are now cut by major drainages (after Chandel, 1992).

extensive alluviation during Holocene, in response to the decrease in gradient. As the Ganga Plain is located at a very low altitude, changes in the seal-level may effect the base-level of the drainages throughout its extent, causing changes in the channel pattern, incision, and aggradation. These effects have been magnified in certain parts of the Ganga Plain due to vertical movements. Future detailed studies are required to assess the relative role of sea-level changes, tectonics, and climate in controlling the base-level changes in different segments of the Ganga Plain.

HOLOCENE HISTORY OF THE GANGA PLAIN : EVIDENCE FROM CALCRETE AND SHELL LAYERS

It has been earlier emphasized that all the geomorphic surfaces of the Ganga Plain which originated during different climatic conditions of Late Quaternary are depositional surfaces, and the topmost few metres of the sediment represent deposits of Holocene age.

The surface sediments of the Ganga Plain are exposed to various soil forming processes, and the surface shows development of immature soils. Mohindra *et al.* (1992) and Srivastava *et al.* (1994) made extensive study of the surface sediments of the Ganga Plain to document the nature of soils and develop a soil chronostratigraphy. The Ganga Plain was subdivided into a number of geomorphic areas with differing soil characters. These areas were assigned different ages based on the soil characteristics, and were considered to be formed at different times within Holocene. Sinha (1995) argues that muddy sediments of North Bihar Plain do not show any prominent mineralogical and chemical changes related to the soil-forming processes, in contrast to the study of Mohindra *et al.* (1992). Sinha *et al.* (1995) dated shell material by ^{14}C-method, collected from different depths within the topmost 2 m of the muddy sediments in North Bihar Plain, and obtained ages between 2415-756 years. The net accumulation rate is 0.7-1.5 mm/a. This data indicates that it is an area of accumulation; hence cannot have older soils exposed at the surface.

In our view, the Ganga Plain sediments do not show prominent soil profiles; the soils are immature. The vertical and horizontal changes in the grain size and mineralogy are related to the changes in the provenance and the depositional processes. The ages given to different soil-geomorphic units by Mohindra *et al.* (1992) and Srivastava *et al.* (1994) also have little validity. Areas with better drainage usually show formation of calcrete; while muddy sediments with poor drainage show development of ferrugenous nodules. These areas occur adjacent to each other.

The T_2-Surface, though presumed to be formed around 120 Ka, has a cover of few metre thick sediments of Holocene age. In the Central Ganga Plain, T_2-Surface is often incised by the rivers exposing 10-20 m thick muddy sediments which represent the Holocene apron of the T_2-Surface. These sediments often contain calcrete horizons. Moreover, T_2-Surface has a number of water bodies, which contain shell deposits in the subsurface sediments. These calcrete and shell layers have been dated by ^{14}C-method and the associated sediments are studied to develop the Holocene depositional history of this region.

Calcrete Horizons- The Central Alluvial Plain in Uttar Pradesh, and the Marginal Alluvial Plain in both Uttar Pradesh and Bihar shows extensive development of calcrete (kankar) horizons, mostly in the deposits of T_2-and MP-surfaces. In the escarpments along major rivers several horizons of kankar, which may be nodular or bedded, are dispersed in the silty and fine sandy sediments. Areas showing salt encrustations and relatively higher parts on the regional plateau surface are usually rich in kankar deposits, occurring as decimetre thick horizons, about 0.50-1.50 m below the surface. Some of these kankar horizons run in sinuous fashion, and may represent dry beds of shallow channels (Agarwal *et al.*, 1992). In some areas, 1-2 m thick horizons of reworked kankar are developed showing cross-bedding, suggesting that they represent deposition by flowing water in shallow channels. The kankar development is mostly due to precipitation from groundwater. The groundwater of the Ganga Plain is mostly alkaline, capable of precipitating $CaCO_3$.

Dating of kankar by ^{14}C-method has certain inherent problems; but some attempts are made to get an idea of the timing of their formation. A large number of near-surface samples in the Lucknow-Kanpur region of Ganga Plain give ages between 10-4 Ka BP. It seems the Early and Middle Holocene was a period of extensive calcrete formation in this region, in response to the fluctuating groundwater levels. Rajagopalan (1992) dated calcrete samples from boreholes in the Marginal Alluvial Plain, and obtain a rate of accumulation of 20.4 cm/100 yr for the topmost 50 m of the alluvium, representing a time span of 35 Ka.

Shell Deposits- The T_2-surface of the Central Alluvial Plain shows a number of linear lakes, representing cutoff meanders and abandoned channels of highly sinuous river system, which are inactive today. In the subsurface of the sediment fill of such lakes decimetre to metre thick shell layers are present, which are often referred as marl deposits (Nautiyal, 1945).

The shell deposits of Lucknow, Barabanki, Rae-Bareli, and Unnao districts have been extensively

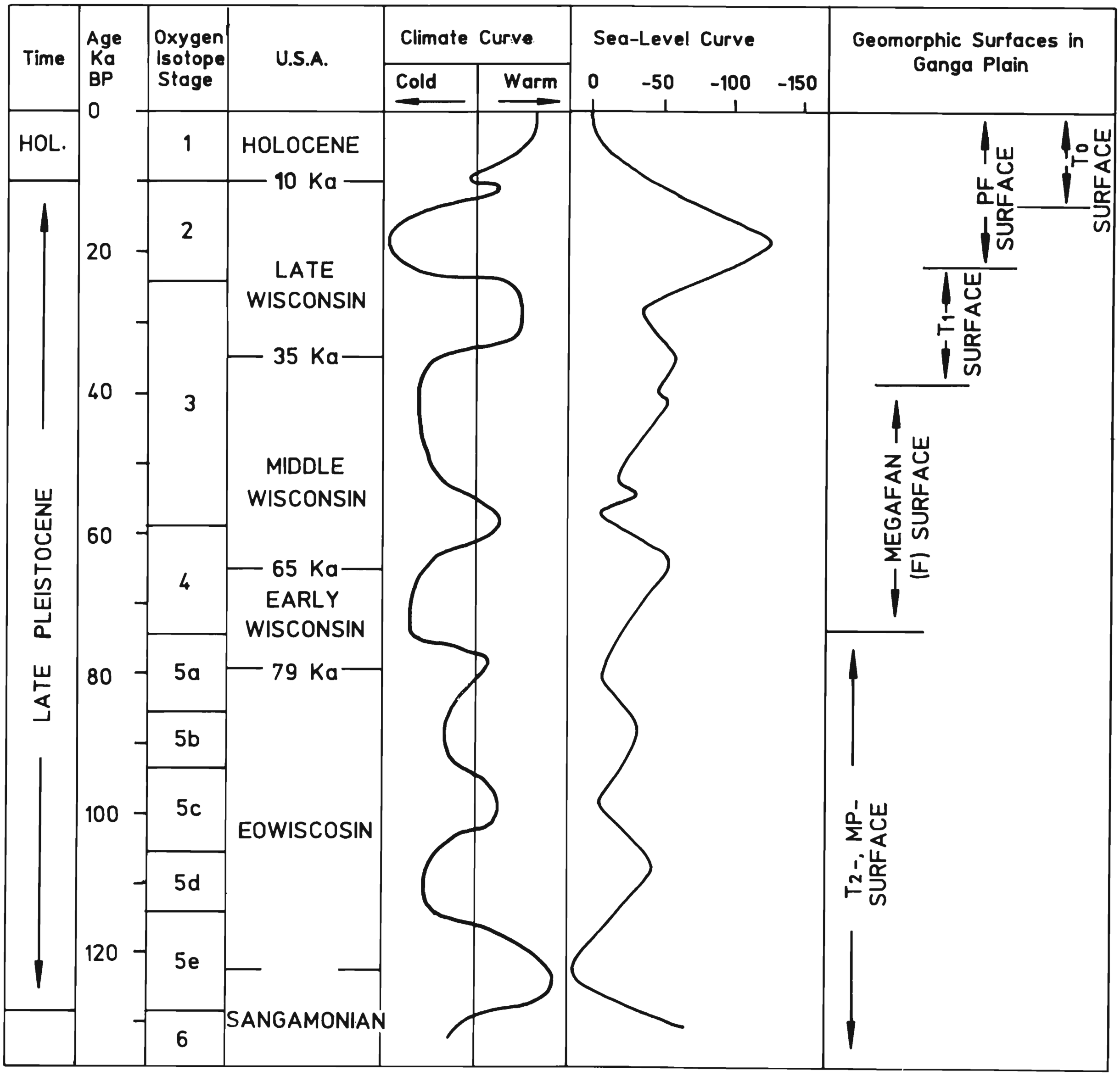

Fig.21. Diagram showing Late Pleistocene-Holocene climatic, sea-level changes and proposed timing of formation of regional geomorphic surfaces in Ganga Plain. The climatic and sea-level changes are compiled from various sources and simplified.

studied, as the material can be used as raw material for mini- cement plants (Agarwal *et al.*, 1986; 1992). These shell layers are suitable for dating by ^{14}C-method, and closely-spaced samples have been dated by Dr. G. Rajagopalan, BSIP, Lucknow. The general stratigraphy of these lake deposits show a sand deposit at the base, followed by lenticular beds of shells. This is followed by black loamy clay and silty subsoil at top (Agarwal *et al.*, 1992). The total thickness of such deposits is 3-4 m, and the base of the shell layer is usually dated at around 8 Ka. Based on the dates available on the shell deposits, nature of sediments of these lakefill sequences, and general geomorphic patterns, an attempt is made to develop a history of climatic changes in the Ganga Plain during Holocene. The lithological succession and ^{14}C-dates in a lakefill deposit of Misa Tal, Lucknow district is given in fig. 23. The net accumulation of the lake fill is about 0.3 mm/a.

12 - 8 Ka - Activation and formation of river channels on T_2-surface due to lowered sea-level and increased water budget but reduced sediment supply. The increased water budget was in response to the melting of Himalayan glaciers and high precipitation in Early Holocene.

8-6 Ka - Abandonment of many channels and channel belts and formation of large linear lakes. The channel abandonment took place mainly in response to base-level adjustment due to rising sea-level.

The large lakes were maintained due to continued high water budget, related to high precipitation rates.

6-4Ka - Lakes started shrinking in size, and there was increased rate in supply of clastic terrigenous sediment due to dry climate, as evidenced by the initiation of the filling of the lakes by clayey sediments which are low in shell content. It is a time of deterioration of climate, increased aridity, reduced water budget.

4-2 Ka - Increased rates of siltation and deposition of organic matter - rich clays in the lakes. The increased sediment supply may be partly related to further increase in dry spells and partly related to the anthropogenic factors, as man started utilizing the land for agricultural purposes. Man started agricultural activity in the Ganga Plain in around 3-2 Ka.

2-0 Ka - Siltation of major part of lakes, which also become ephemeral in character, deposition of oxidized clayey silt as top layer.

Fig. 24 shows evolution of lakefill deposits in the Ganga Plain.

Climatic changes and sea-level changes along with the events in linear lakes of Ganga Plain during Holocene are depicted in fig. 25.

It is a general observation that the Early Holocene witnessed high levels of lakes in Africa, Arabia and India, in response to the return of humid conditions after the arid climate of glacial period. Kutzbach (1981) modelled the orbital parameters of the Earth during Early Holocene, and suggests that the summer monsoon intensified in Northern Hemisphere and led to an estimated increase in precipitation of 20 to 100 percent.

DRAINAGE CHARACTERISTICS OF GANGA PLAIN

The river system of Ganga Plain shows a wide range of channel characteristics, in terms of channel patterns and other geometrical parameters, despite the fact that the slope of the Ganga Plain is very gentle and rather uniform, and the grain size of sediment also varies within a narrow range. The shape of the drainage basins of different rivers within the Ganga Plain is elongated and narrow with low density of drainage network. The water divide within the Ganga Plain are poorly defined.

Singh (1992) classified the rivers of the Ganga Plain into three broad categories : Himalayan-source rivers, Groundwater-fed rivers of the alluvium, and Peninsular-source rivers. Sinha and Friend (1994) classified the rivers of the north Bihar plain into four categories: Mountain-fed rivers, Foothill-fed rivers, Plains-fed rivers and Mixed-fed rivers. They argued that the mountain-fed rivers make Megafans and bring large amount of sediment flux from the Himalaya. The other rivers also carry high sediment discharge, obtained by erosion of the alluvial plain. In this study, the rivers of the Ganga Plain are classified according to their geographic-geomorphic position :

(i) Piedmont Plain rivers

(ii) Central Alluvial Plain rivers

(iii) Marginal Alluvial Plain rivers

The rivers classed under the category of Piedmont Plain rivers are those which have their major extent within the Piedmont zone. These rivers originate in the Higher or Lesser Himalaya, Siwalik hills or within the Piedmont zone. Broadly three type of patterns are recognized, namely rather straight, narrow and shallow channels, shallow braided to meandering channels showing diverging pattern, shallow channels of variable characters converging together near the lower margin of the Piedmont surface or meeting the major drainage.

In the upper part of the Piedmont zone, many of these channels are ephemeral with water flowing only during the monsoonal floods. The channels are mostly shallow and wide, carrying gravels in the upper reaches and sand in the lower reaches. The channel pattern is straight or braided in upper parts, changing to the

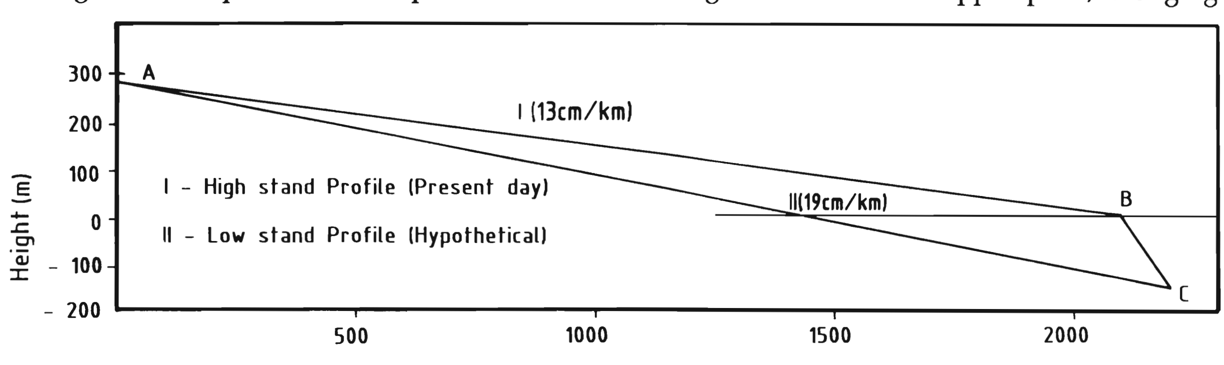

Fig.22. A-B is schematic profile of the Ganga River at present. During last glacial maxima a drop of 150 m of sea-level led to increase in the river length by 100 km due to high gradient of the continental shelf, and development of a much steeper profile (A-C).

meandering pattern in the lower parts. In the lower parts, many of them make distinctive anastomosing pattern. The channels are mostly 30-200 m wide. Many of the channels show deep incision in response to the upliftment of area related to neotectonic activity. Channel cross-section is often asymmetrical.

The rivers of the Central Alluvium Plain originate in Himalaya, Piedmont Plain or within the Central Alluvial Plain. The Himalayan-source river bring initial sediment-water discharge from the Himalaya; but considerable amount of sediment and water is added within the alluvium. Groundwater contributes significantly to the discharge of these rivers. The Alluvial Plain rivers are Groundwater-fed rivers. The Himalayan-source rivers are mostly braided in upper reaches, becoming meandering type in the lower reaches, or they can be braided type throughout e.g. Gandak river. Some of them, e.g. Ganga River may have segments of varying channel patterns along its length (Singh and Singh, 1992). The alluvial plain rivers are of meandering type however with variable sinuosity. The rivers Mostly run in linear fashion for long distances before joining each other at acute angles. The larger rivers mostly show asymmetrical cross-section.

The rivers of the Marginal Alluvial Plain drain vast areas of Peninsular craton, originating mostly in the rocky terrain and entering the alluvium as highly entrenched meandering-type channels. Some of the smaller rivers of this area are ephemeral. They show extensive gulleying of the river banks and development of many small rivulets (fig. 24). The rivers carry moderate amount of sediment and water discharge.

However, this grouping of rivers only provides information on the regional variability of the rivers in the Ganga Plain, but it does not give information on the channel geometry and hydraulic characters.

Channel pattern of a river is primarily controlled by the discharge and slope (Leopold and Wolman, 1957); but other parameters like variation in type and size of river sediment, bank material and vegetation, type and amount of sediment load supplied from upstream are equally important (Ferguson, 1987). Schumm (1977, 1981) emphasized role of nature of sediment in controlling the channel pattern. Based on the channel character and nature of channel bar sediment deposits, some distinctive channel patterns are identified in the rivers of the Ganga Plain (Singh, 1992). These patterns are braided, sinuous-braided, meandering, small sinuous, complex sinuous, highly sinuous-tortuous, narrow sinuous, and abandoned sinuous. This variability in the channel pattern exist despite of the fact that the slope and nature of sediment in all these channels are similar. The most important parameter controlling the channel pattern in the Ganga Plain is the total sediment load and relative proportion of bed load and suspension load which shows wide range of variation from one river to the other or in different reaches of the same river. Friend and Sinha (1993) use a modified system of sinuosity and braiding index for the rivers of the north Bihar plain. There are certain problems in calculating braiding parameter by this method, because of difficulty to differentiate between thalweg channels and low-stage runnels. Moreover, the braid bars in most of the rivers of the Ganga Plain are totally submerged during bankfull discharge producing a single channel river.

The rivers of the Ganga Plain are rather shallow, and increase in the river discharge is mostly accomodated by widening of the river channel. Not discussed here in detail, the bankfull width of the channel is considered to be related to the bankful discharge of the river. Based on the channel width, four categories of rivers are identified within the Ganga Plain. The channel width was measured from 1:50,000 SOI topographical sheets. The minimum measurable width in this study was 30 m.

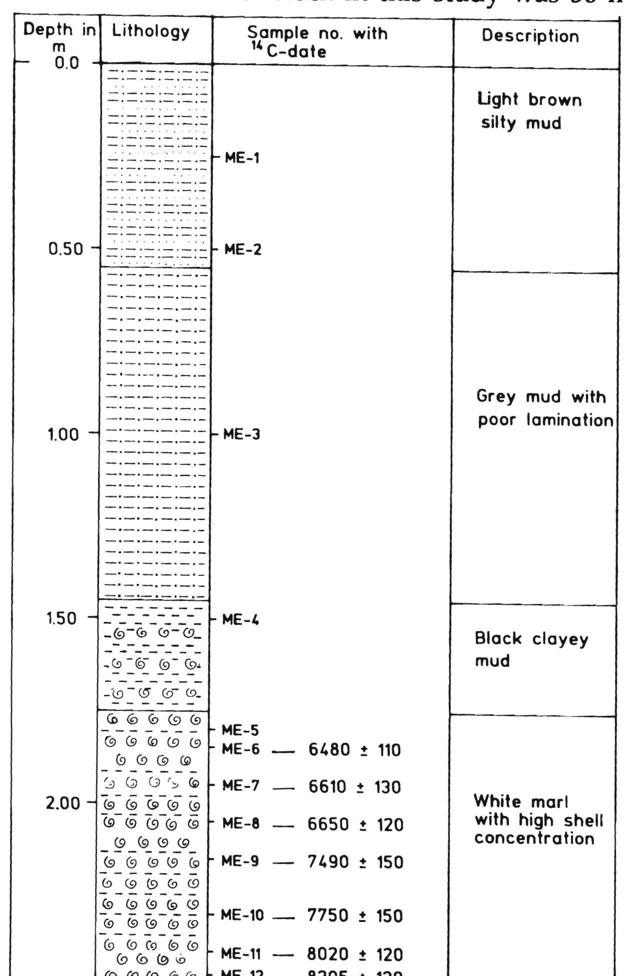

Fig.23. Vertical litholog of lake fill deposit in Misa Tal, Lucknow district, along with ^{14}C-dates.

There are many extremely narrow streams, which are not included in this study. The observations were supplemented by the field checks of many rivers.

(i) *30-50 m wide-* The channels are shallow, making poorly-defined low depressions in the landscape (as observed in the field), and mostly devoid of any point bar deposition. The channels usually show high sinuosity, and are often dry for few months. These channels essentially drain the excess runoff during monsoon time and carry only little fine-grained sediments, locally eroded from adjoining areas. They are often underfit streams with very low discharges.

(ii) *50-200 m wide-* These rivers are of low discharge and also low sediment load. The channels are moderatly to highly sinuous with some straight reaches. The river carries locally derived sediment during monsoonal discharge and often make small point bars. the channels are distinct with low natural levees, and raised river banks, which show gulleying.

(iii) *200-800 m wide-* They are meandering-type rivers of moderate discharge with moderate sediment load. The point bars are moderately to well-developed. The river channels show well-defined, prominent natural levee. The rivers are mostly incised and show, at least, one level of prominent river valley terrace. The channel margins often show gulleying.

(iv) *800-2300 m wide-* They are the major rivers of the Ganga Plain showing high water and sediment discharges. The channels show low to moderate sinuosity, often with mid-channel bars or with prominent point bars. The channels have prominent natural levees. The channel is incised in a wide river valley showing river valley terrace. The river valley is incised in the regional high surface.

The frequency distribution of river channels according to channel width in Ganga Plain is shown in fig. 26, based on the measurement of 221 rivers. The majority of the rivers are 30-50 m wide. The large rivers are only few in number.

Amplitude, meander wavelength, channel width, and sinuosity in different segments of important rivers were calculated to establish emperical relationship between different parameters. These parameters were calculated by carrying out measurements on topographical sheets with 1:50,000 scale, and cross-checked for some parts from satellite imageries and photographs on 1:50,000 scale. One striking point is that in the smaller rivers (low width), meander wavelength shows a wide range of values; while river width shows very little change (figs. 27, 28). The larger rivers show increasing values of river width with increasing values to meander wavelength, indicating some control of discharge on river geometry (figs. 29, 30). The slope of regression line varies from river to river. It is not clear why in many small rivers of the Ganga Plain, there is no increase in the channel width with increasing meander wavelength. It is likely that these rivers are underfit rivers, which formed wide channels earlier when the river was carrying much higher discharge than today. At present, channels of these rivers are carrying only a fraction of the earlier discharge. thus, width of the channel is much larger than the requirement of the present-day discharge. Consequently, there is no downstream increase in the channel width; however, the downstream increase in the discharge has been accomodated by the increase in the meander wavelength. More detailed studies are required on the relationship of geometrical parameters to the discharge in the rivers of the Ganga Plain.

Bivariate correlation has been attempted for the channel width and meander wavelength, and amplitude and meander wavelength for the rivers of the Ganga Plain (figs. 31, 32). In the case of smaller rivers, there is no corresponding increase in channel width with the increase in the meander wavelength. For the larger rivers, there is some increase in channel width with increasing meander wavelength. There is a distinct

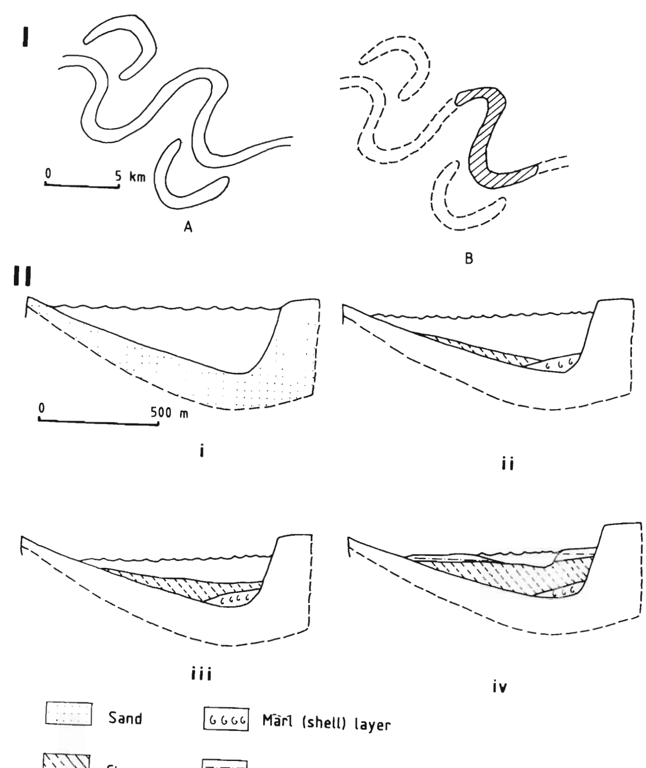

Fig.24. Evolution of lake fill deposits in abandoned channels. I- Plain view of lake formation II- Lake filling history (i) Formation of large lake (ii) Initial stage of deposition (iii) Filling and shallowing of lake (iv) Highly reduced lake with lake fill deposit (After Agarwal *et al.*, 1992).

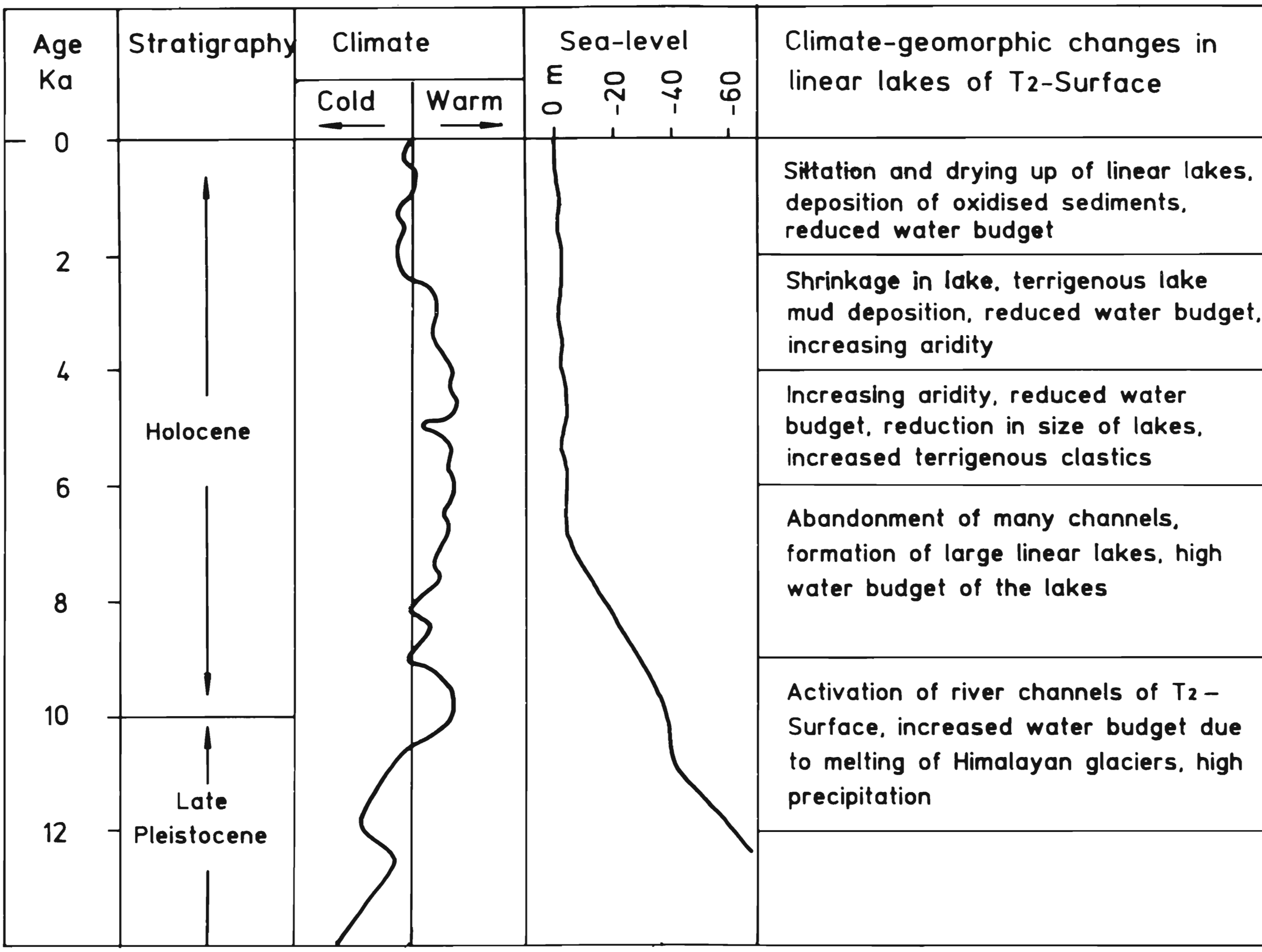

Fig.25. Latest Pleistocene-Holocene climatic and sea-level changes, along with the changes in the linear lakes of Ganga Plain. The climatic and sea-level changes are compiled from different sources and simplified.

linear relationship between amplitude and meander wavelength.

The geometrical parameters of some of the important rivers are given in table 1 showing their range and mean values. Channel width and meander wavelength of individual rivers were determined throughout their course and plotted graphically to see any relationship. Calculation of discharge for many Ganga Plain rivers shows that for small rivers, the calculated bankfull discharge values are much higher than the present-day actual discharges. In these rivers bankfull discharges are almost never achieved. These channels seem to have been formed in the past, when higher discharges were available for these rivers. It appears that many river channels of the Ganga Plain are in different stages of decay due to decreased water budget in the last few hundred to few thousand years.

The study of the river channels demonstrate that there is a wide range of channel patterns and river types present in the Ganga Plain. These diverse types of rivers must have been formed over a relatively long period of time under varied climatic conditions. These rivers appear to be in different stages of evolution because of their age, or due to avulsion related to the tectonic activity, normal fluvial processes or base-level changes. In general, a river responds to short term changes by changing its sinuosity or by chute or neck cutoff. As a long term change, avulsion of older channels takes place, and the rivers move to the new channels. In the fluvial basins, avulsion of the channel is the most important process for shifting the channels, and producing sandbodies. Avulsion can take place simply by fluvial activity, where deposition on the natural levees and within the channel results in raising the level of the channel. Once a river starts flowing at a raised level it looses its hydraulic advantage; abandonment of such a channel takes place, and the river starts flowing through a pre-existing or new channel of the lower topographical

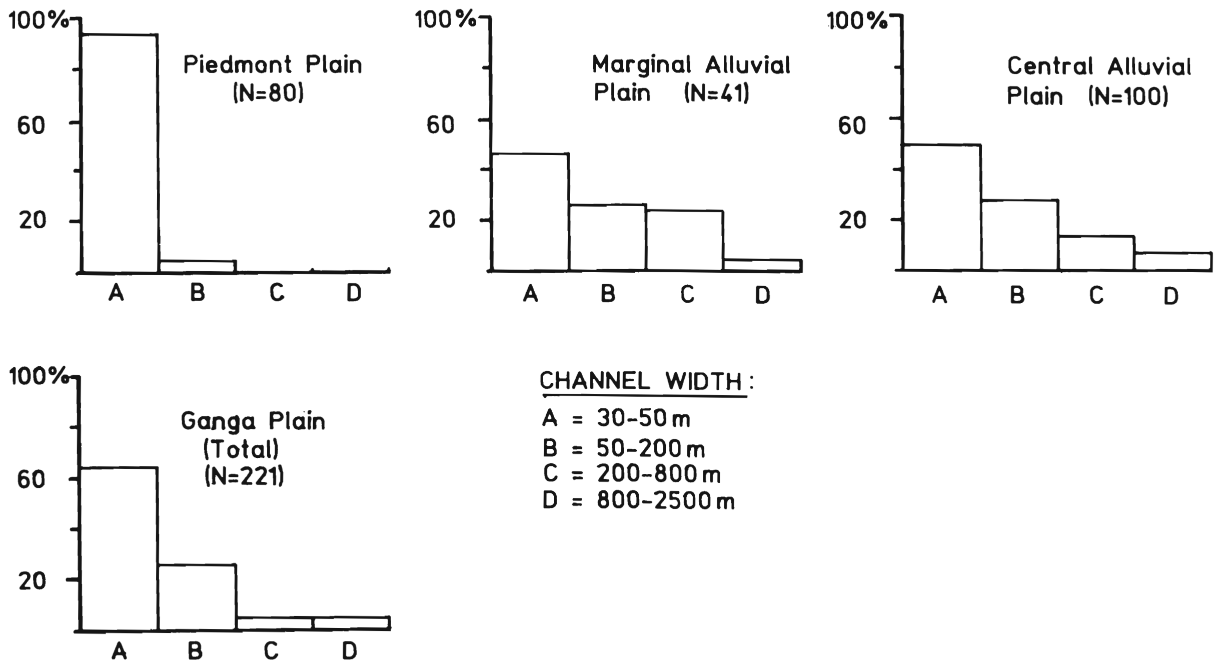

Fig.26. Frequency distribution of river channels in Ganga Plain according to the channel width.

position. The river avulsion is also caused by tectonic movement or base-level changes.

Richards *et al.* (1993) argue that many of the river systems in the Ganga Plain can be considered part of the *avulsive channel system*, where there is exchanges of role over time between 'dominant' and 'secondary' channels, when aggradation encourages avulsion. They state that such systems are common in the northern part of the Ganga Plain and in the Bihar plains, and channel shift takes place rapidly over a period of 10^1-10^2 years.

Avulsion of channels in Kosi Megafan has taken place on the scale of few tens of years, and is often considered to be typical of the Ganga Plain (Gole and Chitale, 1966; Gohain and Parkash, 1990). Gohain and Parkash (1990), H. Singh *et al.* (1993), Mohindra *et al.* (1992), Sinha and Friend (1994), Mohindra and Parkash (1994), Sinha (1995, 1996) argued that in north Bihar plain channel avulsion takes place every few tens of years on Kosi Megafan, Gandak-Kosi interfan and Gandak Megafan. Mohindra and Parkash (1994) and Sinha and Friend (1994) suggest that Gandak River shifted into its present course in the last 60-100 years from the position of Burhi Gandak. Sinha (1996) considers that the shift from Burhi Gandak to present-day Gandak took place in discrete steps within 100 years, implying shift every few tens of years.

On the contrary, Singh *et al.* (1990) argued that the Ganga River shows incision and does not show evidence of avulsion on a time-scale of 10^1-10^3 years. It was emphasized that all the major rivers of the Ganga Plain show a river valley terrace with meander cutoffs and meander scars; though present-day river (T_o- Surface) may be of braided type. Even the smaller rivers show development of river valley terrace, and evidences of river metamorphosis. The present-day rivers are mostly underfit streams (Singh, 1992). A careful look of the rivers of the Ganga Plain shows that all the *active rivers*, whether small or large show some degree of incision; the channels not showing any incision are abandoned drainages, some of which get activated during monsoon period to drain the excess rain water. On a time-scale of 10^2-10^3 there are evidences of development of meander cutoff (neck and chute cutoff) in the meandering channels on the T_o- Surface.

In the light of the studies carried out in the western Ganga Plain (Uttar Pradesh), the studies of the north Bihar plain are reassessed. The Bihar plain shows much similarity in the geomorphology with that of the Uttar Pradesh, than has been earlier emphasized. The major rivers, namely Gandak, Burhi Gandak, Kamla, Balan show some incision and development of a broad river valley with a river valley terrace. However, height difference between T_o-T_1-Surfaces is 2-3 m; and between T_1-T_2-Surfaces is about 2 m. The T_1-Surface in case of Gandak River shows large meander scars and meander cutoffs, although the present-day Gandak River is of braided type. (Similar to the Ganga River, Singh *et al.*, 1990). The Burhi Gandak River occupies a broad river valley, in which it is incised by 2-3 m. The broad river valley shows an abandoned channel belt of large, highly sinuous river. The channel geometry of the older, abandoned channel is much different than that of the present-day Burhi Gandak River. The active Burhi Gandak channel shows many meander cutoffs developed between 1928 and 1986 (Sinha, 1996).

The interpretation that the Gandak River has shifted its position from Burhi Gandak to the present position in the last 60-100 years in discrete steps (Sinha, 1996) would suggest that the present position of Gandak River has been occupied only 30-50 years back. On the contrary, the flood protecting embarkments of the Gandak River were built more than 100 years back. Some of them (Saran embankment) were built in 18th century. The 1922 and 1965 surveys show only minor changes in the channel of the Gandak River (Godbole, 1986) (fig. 33). The old villagers living near the Gandak River provided the information that they have been living there for several generations, and the villages are several hundred years old. This information shows that the Gandak River is occupying this position for, at least, several hundred years (may be few thousand years). Thus, the interpretation of rapid shift of Gandak River within a time span of 10^1-10^2 years is based on some misinformation.

The northern part of the Gandak-Kosi interfluve has a prominent Piedmont zone showing a large number of abandoned channels of an earlier anastomosing system. During monsoon, many of these channels carry water and are prone to overtopping due to poorly developed natural levees. The southern part of the Gandak- Kosi interfluve shows many meandering abandoned channels; many of them part of a relict anastomosing system. These abandoned channels can become active and abandoned on a time scale of tens of years, in response to the monsoon rains.

The avulsion of channels on the Kosi Megafan is well documented. However, one basic question remains whether the present-day Kosi River channel was not existing few hundred years ago? We suspect that the main Kosi River was existing for quite some time (several hundred years), and the other smaller channels on the Kosi Megafan surface were also present. The

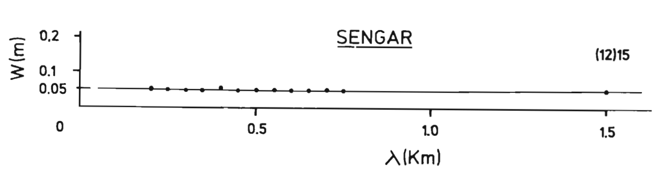

Fig.27. Relationship between meander wavelength and channel width in Sengar River.

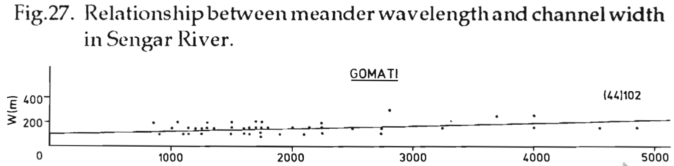

Fig.28. Relationship between meander wavelength and channel width in Gomati River.

smaller channels received only a small part of the discharge of the Kosi River.

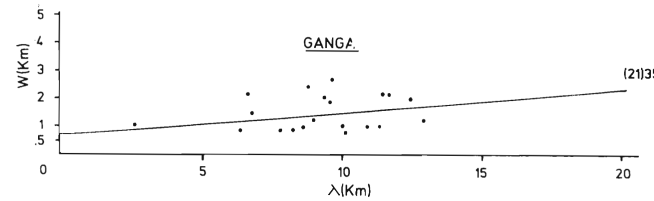

Fig.29. Meander wavelength and channel width plot of Ganga River.

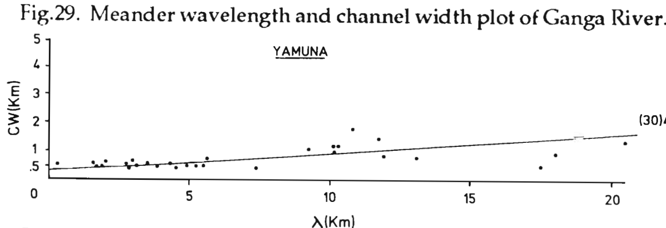

Fig.30. Meander wavelength and channel width plot of Yamuna River.

Thus, the major rivers of the northern Bihar plain are incised and do not show avulsion on a time scale of 10^2 years. The abandoned channels of earlier relict anastomosing system are activated during monsoon, and show avulsion in few years to few tens of years. Due to fast alluviation of Bihar plain during Holocene, the relief differences between various geomorphic surfaces are very little, and difficult to decipher.

NEOTECTONIC ACTIVITY IN GANGA PLAIN

Neotectonic activity are tectonic effects of the recent past, and the present, which have helped in shaping the geomorphic features of the present-day. Foreland basins are tectonically very active areas in continent-continent collision mountain chain systems. The Himalaya along with the Ganga Plain foreland basin experiences strong compressional stress conditions (Zoback, 1992); hence it is logical to assume that in the Ganga Plain a number of tectonically-controlled geomorphic features are formed under new stress conditions, or older tectonic features are reactivated to become active lineaments.

Some morphotectonic studies in the Ganga Plain have been carried out (Singh and Ghosh, 1994; Singh and Bajpai, 1989; Mohindra and Parkash, 1994; Singh and Rastogi, 1973; Bajpai, 1989; Singh *et al.*, 1996; Srivastava

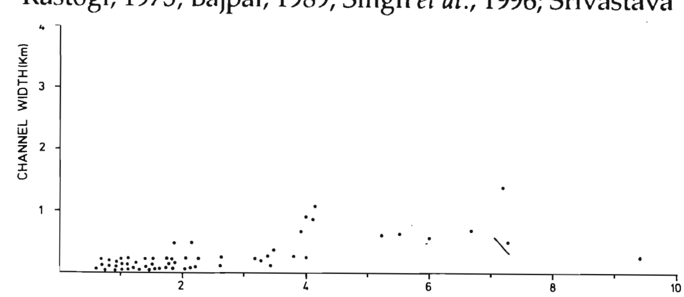

Fig.31. Meander wavelength vs. channel width plot for the rivers of the Ganga Plain.

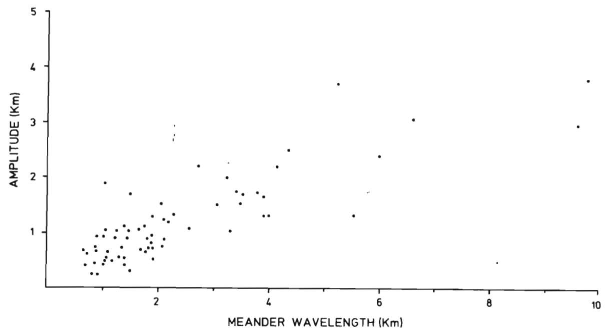

Fig.32. Meander wavelength vs. amplitude plot for the rivers of the Ganga Plain.

et al., 1994). The parameters used in identification of neotectonic activity in Ganga Plain are: displacement of the Siwalik hills; skewness of fan surfaces; preferential alignment of rivers; sudden changes in the direction of river courses; nick points and distorted meanders, straightening of river courses; presence of escarpments and asymmetrical terraces (Singh *et al.*, 1996) (fig. 34).

On the basis of tectonic setting the Ganga Plain foreland basin is subdivided into three domains (Singh, 1992; Singh *et al.*, 1996), which also show specific type of neotectonic activity: the Piedmont Plain, the Central Alluvial Plain, and the Marginal Alluvial Plain.

Piedmont Plain

This zone is located adjacent to the Himalayan mountain belt, where the sediment fill is in direct response to the thrust-fold tectonics, flexed lithosphere and subsidence. The rate of subsidence is high, and the region is also directly effected by the Himalayan tectonics. The most important neotectonic feature of this zone is development of the E-W oriented Himalayan Frontal Fault (HFF), which has moved the Siwalik rocks over the alluvium, and caused upliftment and tilting of Post-Upper Siwalik gravels (Hagen, 1956; Krishnaswamy *et al.*, 1970; Nakata, 1988). Another significant neotectonic feature of this zone is the development of a conjugate system of strike slip faults, causing offsetting of Siwalik rocks and running for considerable distance in the alluvium. The general direction of these strike slip faults is NNE-SSW and NW-SE. The NNE-SSW system seems to be older of the two, where movement is mostly strike slip with a gravity component, making the southeastern part a downthrow block. NW-SE lineaments become important away from the Siwalik hills, and are responsible for the sudden changes of direction of river channels, and skewness of the Megafan surfaces. The river systems of this zone are controlled by NNE-SSW and NW-SE lineaments (Singh *et al.*, 1996). These tectonic movements occurred during Late Pleistocene as multiple events. Some of the faults show activity during Holocene, effecting the very young sediments. Within a few km from the Siwalik hills, the alluvium shows small ridges, which are indication of blind thrusts in the subsurface.

Central Alluvial Plain

This region extends between the Piedmont Plain and the axial river of the Ganga Plain. Basement inhomogenities and newly-formed lineaments control the thickness of sediment fill; while the facies distribution is related to the fluvial processes. This large alluvial tract has several major rivers coming from Himalaya, and many ground water-fed streams beginning within the alluvium, exhibiting a prominent NW-SE orientation.

Analysis of lineament trends of the drainage of this zone shows a dominant NW-SE trend, along with a WNW-ESE trend (Singh *et al.*, 1996). These trends have also controlled the general slope of the surface, and the skewness of the Megafan surfaces. In the southern part of this zone, the trend becomes more WNW-ESE and W-E. The NW-SE lineament is part of the conjugate fault system developed in response to the compressional tectonics of Himalaya.

The major drainages of this zone show prominent entrenchment, development of escarpment often on the southern side and a wide flood plain on the northern side. Some of these lineaments along major rivers acted as gravity faults, showing marked differences in the thickness and facies development on the two sides of the lineament (Singh and Rastogi, 1973; Singh and Bajpai, 1989; Bajpai, 1989).

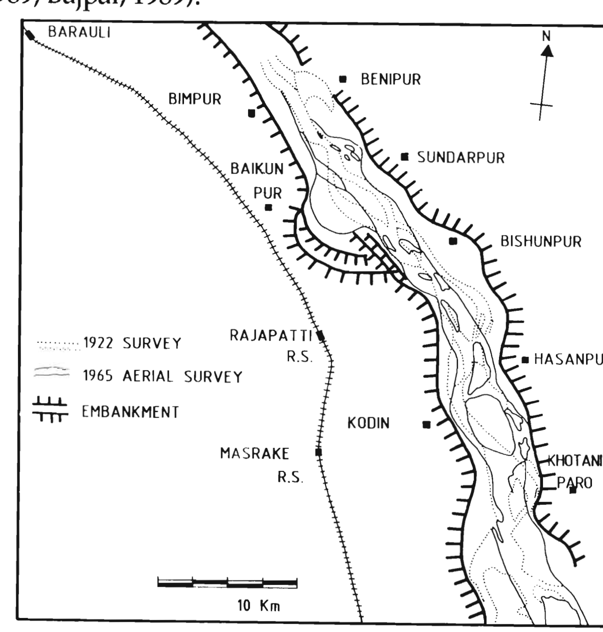

Fig.33. Channel patterns of 1922 and 1965 survey of the Gandak River (After Godbole, 1986).

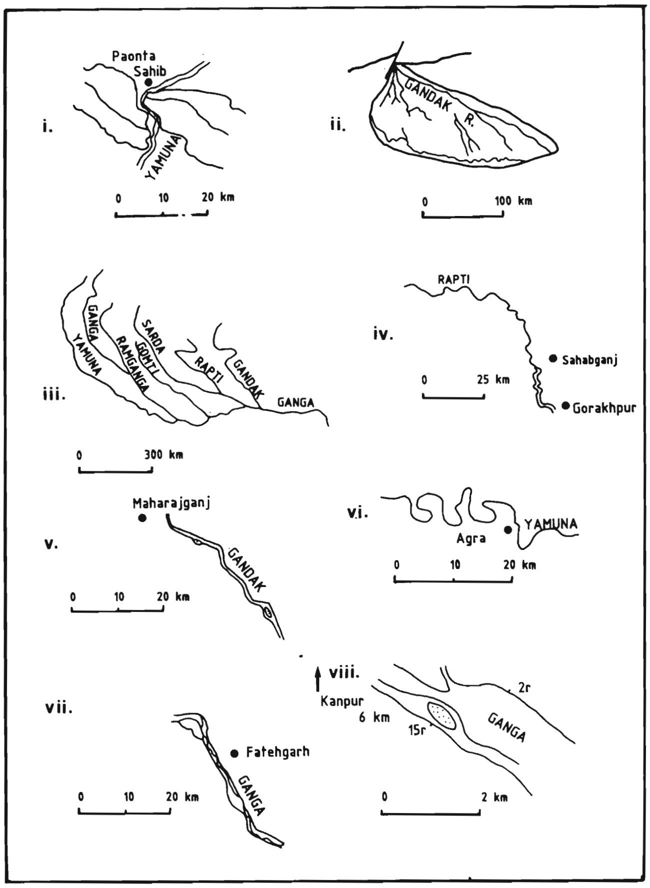

Fig.34. Morphotectonic features used in identification of lineaments in Ganga Plain (i) Dislocation of Siwalik hills (ii) Skewed Megafan (iii) Preferential alignment of river channels (iv) Sudden change in the direction of river alignment (v) Knick points (vi) Distorted meander (vii) Straightening of river course (viii) Asymmetrical terrace (After Singh *et al.*, 1996).

Marginal Alluvial Plain

The Marginal Alluvial Plain forms the southernmost part of the Ganga Plain, where control of basement is very significant on the thickness of sediment fill and also the positioning of fluvial channels. This zone displays a north to northeasterly slope, which is also the lineament direction controlling the drainages (Singh *et al.*, 1996). The SW-NE trend is also a main lineament trend in the basement rocks. The rivers show prominent downcutting, and may be incised by 40-50 m with prominent scarp development (Misra *et al.*, 1994).

Neotectonic activity in this zone is in the form of reactivation of basement lineaments (SW-NE) in response to the Himalayan tectonics; and block vertical uplift on the regional scale. Some of the lineaments show differential movement as gravity faults.

A lineament map prepared by the study of trends in major rivers of different zones shows rather prominently the above discussed trends (fig. 35).

Thickness of alluvium in the Marginal Alluvial Plain is highly variable, showing sudden changes across certain lineaments, indicating movement along these faults. The Ganga river along with its valley shows prominent changes along its course in terms of geomorphology, nature of channel, and valley width. In the area of Bijnor, the river valley terrace of the Ganga river shows stepwise arrangement of the meander cutoff only in one direction, indicating tectonic tilting of the surface during channel migration (fig. 36).

As already discussed, the Ganga Plain has a prominent peripheral bulge of the Peninsular craton in the middle part. This uplift is in response to the thrust-fold loading in the Himalaya due to crustal rebound. The effect of uplift are also apparent in the sediment fill of this zone. In this zone the trunk rivers Ganga and Yamuna are flowing through an area which is topographically high. The lowest point of northward slope is along the Ghaghara river. The Ganga, Yamuna and other rivers in this area have compensated the vertical uplift by making deep valleys. In the cliffs along these rivers, shell-bearing horizons give ages of 15-10 Ka by ^{14}C-method. This indicates that some of the upliftment is of Holocene age.

The western part of the Ganga Plain shows deep incision of Ganga and Yamuna rivers in their Megafan surface making 15-30 m high cliffs, very close to the Piedmont zone. It seems that movement along Delhi-Hardwar ridge caused vertical upliftment of this area, leading to incision of the major drainages. The effect of this vertical upliftment along Delhi-Hardwar ridge gradually diminishes eastwards. the timing of this tectonic movement post dates deposition of Megafan during Middle Late Pleistocene and is before the formation of River Valley Terrace (T_1).

In the eastern part of the Ganga Plain, i.e. Bihar, the effect of vertical uplift and peripheral bulge are rather subdued. However, in this region there are a number of E-W trending gravity faults, running parallel to the Ganga River within a narrow zone. It is likely that in this region, the stresses have been released by making parallel gravity faults, and not making a prominent peripheral bulge. Roy and Ghosh (1979) recognize E-W and ENE-ESW trending active lineaments in this area.

Late Pleistocene-Holocene is a time of tectonic quiescence in the Himalaya and the deposition in the Ganga Plain foreland basin has been mainly controlled by the fluvial processes responding to the climatic and base-level changes. However, there is much evidence that within the depositional basin tectonic has been active causing faulting, vertical uplift and tilting. The positioning of the major drainages is controlled by the active lineaments.

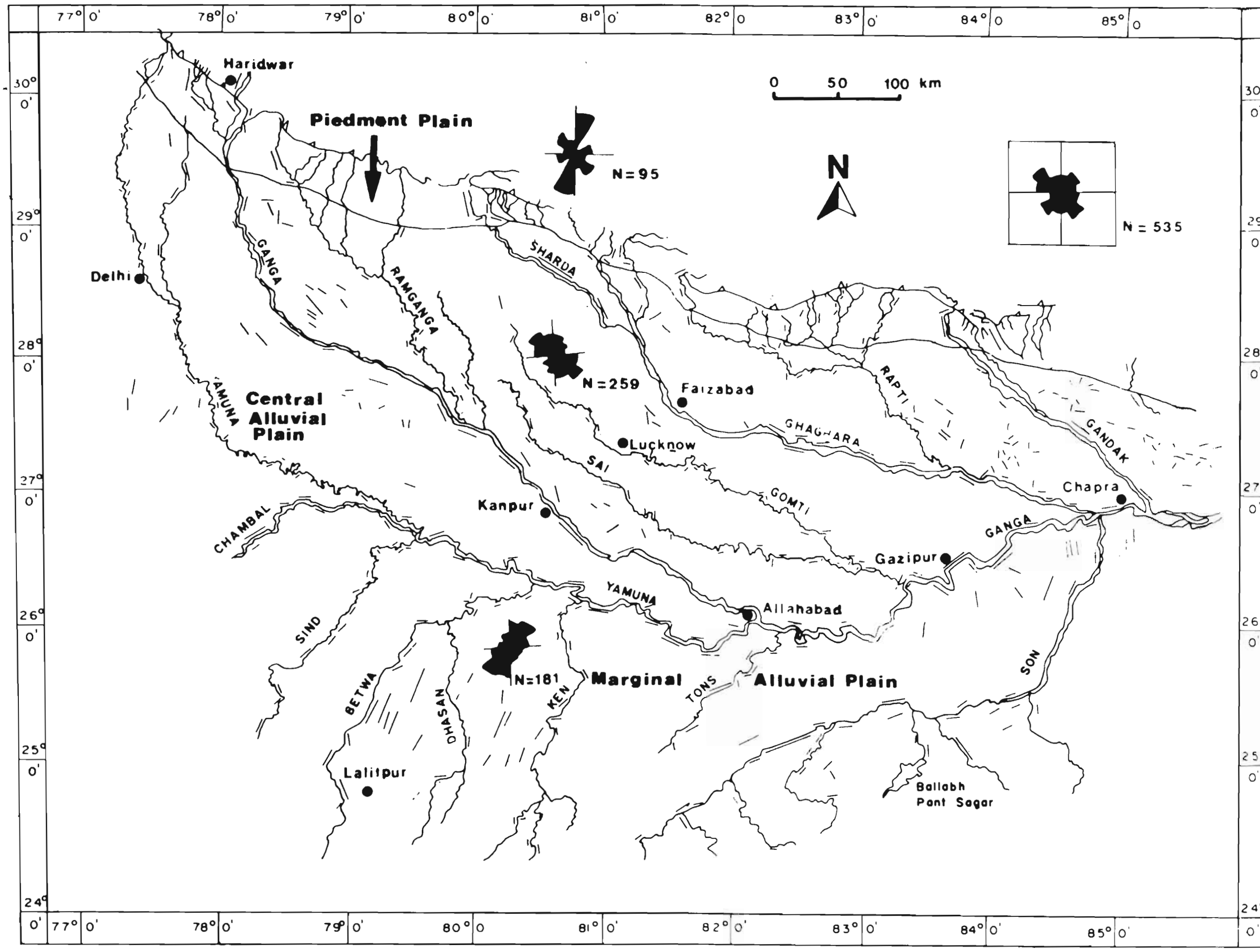

Fig.35. Lineament trends in Ganga Plain of Uttar Pradesh, depicted as rose diagrams for Piedmont Plain, Central Alluvial Plain and Marginal Alluvial Plain. A composite rose diagramm of the lineaments in Ganga Plain of Uttar Pradesh is also shown (After Singh *et al.*, 1996).

FACIES ASSOCIATION MODELS IN GANGA PLAIN

The Ganga Plain shows a wide range of depositional domains in the fluvial system; gravelly alluvial fans, fine-grained megafans, depositional terrace surfaces, large braided streams, large meandering streams, small meandering streams, cut-off meanders, ponds, lakes, gentle sloping surfaces and flat surfaces. Each of these areas produces a specific type of deposit with a characteristic lithology, succession of sedimentary structures, and geometry. Several of these domains may be naturally stacked vertically to produce a characteristic facies-association and vertical cyclicity on a scale of few metres to few tens of metres. In the following, the lithofacies succession of four types of area are described. There are many more areas for which lithofacies model need to be developed.

Gravelly Fan Deposit

The Piedmont fan belt, adjacent to the Siwalik hills, is a relatively steep surface characterized by many shallow but wide channels, carrying gravel and coarse sand. There are also belts of sandy mud and sand deposits, reworked by flowing water during rains. The vertical succession of these deposits shows distinctive features (fig. 37). There are mostly 1-4 m thick gravelly units, where gravels of different sizes are seggregated into distinct layers, showing low-angle cross-bedding, and rarely high-angle cross-bedding. The gravel beds are interbedded with 1-2 m thick muddy units, containing decimetre thick lenses of sand. Sometimes, 1-4 m thick sand units showing mostly low-angle cross-bedding are also present. Rarely, thin sandy horizons may show ripple bedding. This facies association is characteristic of the small alluvial fans, dominated by shallow braided streams with low braid bars.

Sandy Interfluve Deposit

The term interfluve in Ganga Plain is used to describe slightly elevated areas between two major river channels, not reached by flood waters of the major channels. Such regions are several tens to hundred Km^2 in area, and correspond to the T_2-surface or reworked parts

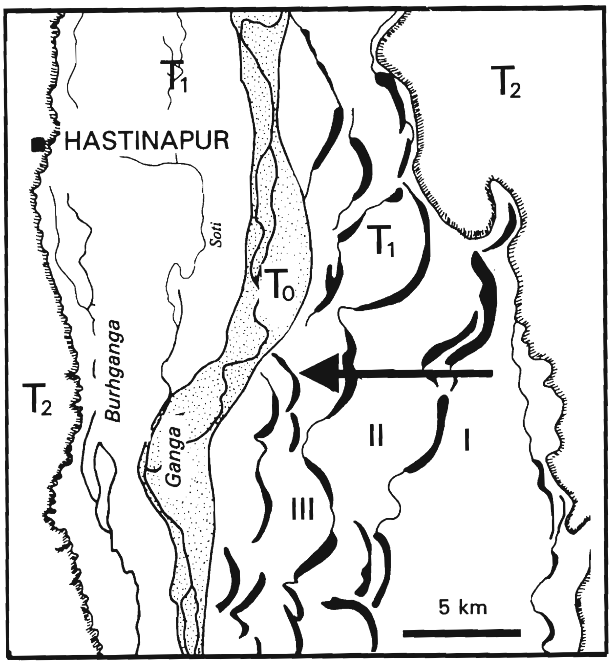

Fig.36. Ganga River Valley near Hastinapur, showing meander cutoffs on the T_1-surface at three-levels. Arrow indicates direction of tectonic tilt and migration of the channel.

of Megafan surface. In the northern part of the Ganga Plain, such areas are common showing many small, shallow, sand-carrying channels, ponds, lakes, and sloping surfaces. The sand-carrying channels are of meandering-type with point bar development. Some of channels are ephemeral with braid bars, but of moderate sinuosity. The deposits show 0.50-2.0 m thick lenticular sand bodies showing a sharp base and top, and representing meandering river deposits. The sand beds are interlayered with 1-2 m thick well-sorted silt and very fine sand, representing sheet flood deposits. Some units of muddy sediments (1-2 m thick) are also present denoting pond-lake deposits (fig. 38). Several discontinuous horizons of calcrete are also present.

Muddy Interfluve Deposit

The southern part of the Central Alluvial Plain is dominated by muddy upland terrace surfaces, located many metres above the main rivers and not reached by their flood waters. The surface shows many meandering channels carrying fine-sand, abandoned channels, small creeks, ponds, lakes, gentle sloping surfaces and flat surfaces. Sedimentation in these areas takes place during the Monsoon period by locally available rainwater (S. Kumar *et al.*, 1992, 1995). The rate of sedimentation is slow; hence sediments are churned by plant and animal activity. The facies association (fig. 39) shows decimetre to 1m thick well-sorted silt, sometimes with extensive calcrete development; 1-2 m thick fine sand deposits, mostly highly mottled, bedded calcrete deposits, and shell-bearing mud. In a casual look this succession looks like a highly mottled muddy deposit. They are very similar to those described as overbank or flood plain deposits. These deposits can make 10-30 m thick successions without any major sandbodies.

Large River Channel Deposit

The main rivers of the Ganga Plain, namely the Ganga, Yamuna, Gomati, Ghaghara, etc show very wide river valleys in which the present-day active channel and its flood plain is entrenched. They are the areas of sand deposition in the Ganga Plain. The residence time of these main rivers in their valleys is on the order of 10^3-10^5 years, during which several climatic and base-level changes have also transformed the character of the river channels, and the nature of the sediment.

These deposits are likely to make tens of kilometre long sheet-like sandbodies, about 300 m-20 km wide, and 10-50 m thick. The sandbodies are multistoried, showing several events stacked vertically (fig. 40). The dominant feature of these deposits is large-scale cross-bedded sand. Single events are 2-10 m thick, showing slight upward reduction in the sand size and average thickness of cross-bedding. The topmost part of a single sequence may show decimetre thick bands showing climbing ripple lamination and ripple bedding, rarely with a decimetre thick discontinuous mud layer. In a single sandbody, each successive event is slightly finer-grained and thinner. The topmost events are only 2-5 m

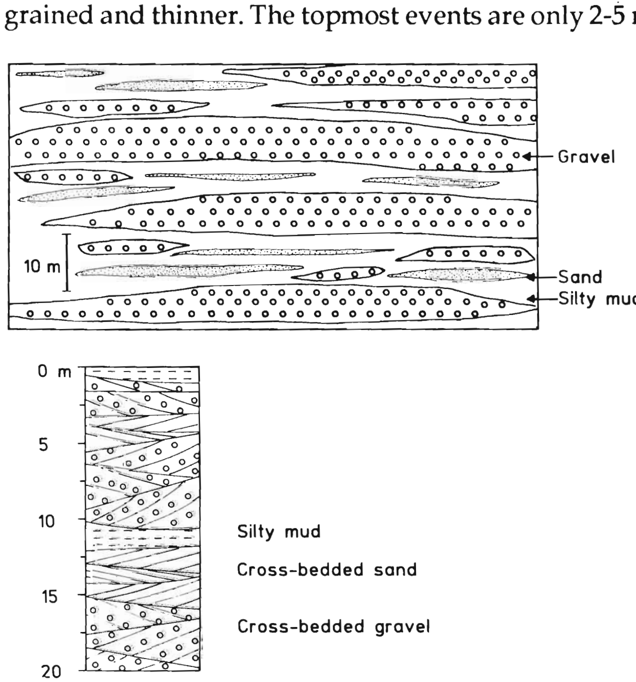

Fig.37. Schematic diagram of gravelly fan deposit showing general lithological association and vertical sequence of sedimentary structures.

thick, usually dominated by ripple bedding and climbing ripple lamination.

The sandbody is overlain by muddy interfluve deposits with a sharp contact. It is emphasized here, that the muddy succession above the sandbody is not the floodplain deposit of the underlying channel; but deposits of another independent muddy interfluve system.

Within a multistoried sandbody, some events may be of braided channels, while others are deposits of meandering channels. In general, the topmost events are of meandering channel of reduced dimensions. Such sand bodies are essentially the valley fill of the large rivers. The initial events are of the large rivers occupying the entire river valley; while the later events are of small rivers, located only in a small part of the river valley.

Palaeocurrent studies carried out in several braid and point bar deposits of the Ganga Plain demonstrate that in the braid bar deposits, the variance is high; while in the point bar deposits variance is lower (fig. 41). This observation is contrary to the existing models, where point bar deposits are considered to show high values of the variance in comparison with the braid bar deposits.

THE GANGA RIVER

Many of the rivers of the Ganga Plain run for long distances and offer an opportunity to study along their length the downcurrent changes in the geomorphic features, channel processes, grain size, mineralogy, geochemistry. Many pollution and environmental changes can also be monitored along the river channels. A systematic study of Gomati River documenting lengthwise changes in grain size, mineralogy of sand has been carried out (Kumar and Singh, 1978).

The Ganga River is the trunk river of the Ganga Plain covering a distance of about 2000 km within the alluvial Plain. The Ganga River is a Himalayan-source river having a large catchment in the mountains. It runs through Piedmont Plain and its Megafan deposits in almost N-S direction; swinging to the NW- SE trend in the Central Alluvial Plain, and acquiring W-E trend when it becomes the axial river. Thus, the Ganga River runs through all the major geomorphic units, and has also responded to the different tectonic setup in the Piedmont Zone, the Central Alluvial Plain and the Marginal Alluvial Plain. The Ganga River flows within its well-defined valley, termed the Ganga River Valley (GRV). Along its lengh the GRV and the Ganga River shows distinctive changes in the geomorphology and channel patterns in response to changes in the discharge, nature of sediment, sediment load, and tectonic setting. The study of the Ganga River has also provided an insight in the response of a river to the Late Quaternary changes in different segments of the Ganga Plain. Some studies on the sedimentology and lithofacies of the Ganga River sediments are available (A. Singh *et al.*, 1993; A. Singh and Bharadwaj, 1991; Singh and Kumar, 1974; Singh, 1977). It has been studied documenting geomorphic and grain size changes (Singh and Singh, 1992). Along the river, samples were collected from 60 stations. At each station 3 samples were collected from the bar deposits, at 15-20 cm below the surface (Singh and Singh, 1992; M. Singh, 1996). In the following, average values of the grain size parameters for each

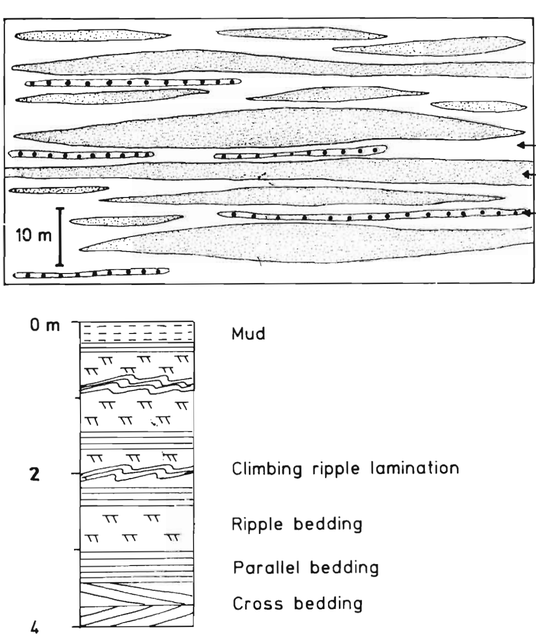

Fig.38. Lithofacies association of sandy interfluve deposit.

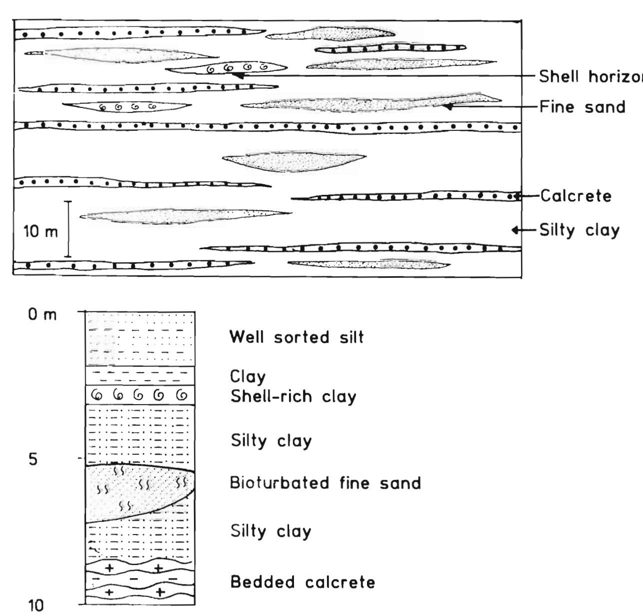

Fig.39. Lithofacies association of muddy interfluve deposit.

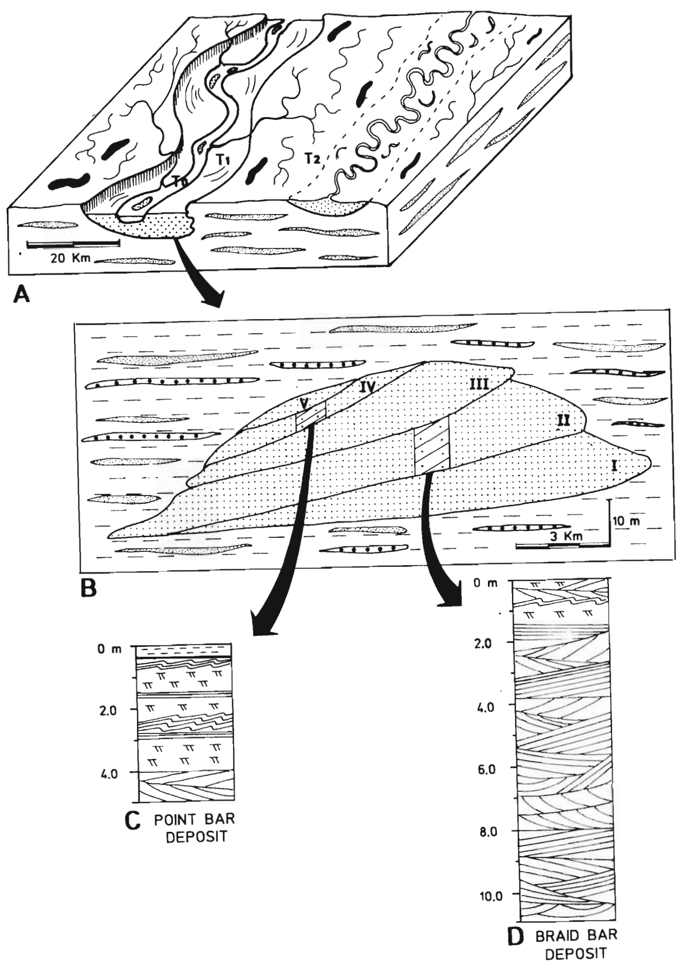

Fig.40. Schematic diagram showing development of multistoried sandbody in large river channel deposit and its lithofacies association.

segment was calculated. The Ganga River Valley (GRV) is divided into six segments from Hardwar to Gangasagar (fig. 42):

GRV-I (Nagal to Hastinapur) - Here the valley is straight and broad following the N-S slope of the Yamuna-Ganga Megafan Surface. The T_1- surface is extensive and shows prominent meander scars, which were formed under the influence of active tectonics. The T_0-surface shows a low sinuosity multichannel braided system with large braid bars. The valley gradient is 142 cm/km, and sinuosity of the channel is 1.14. Sediments contain some gravel, 35% medium sand, 64% fine sand. The grain size parameters are, M_Z-2.18, S_I-0.48, S_{ki}-0.04, K_G-1.23.

GRV - II (Hastinapur to Allahabad) - The valley is broad with cuspate margins, and follows NW-SE orientation. It shows development of an unpaired T_1-surface. Escarpment of 10-25 m are present along the southern margin. The T_1-surface shows extensive development of meander scars, scroll bars. The river channel is mostly a single channel of low sinuosity (1.26). However, at low-water stage-channel bars may be seen. The lower part of this segment shows extremely narrow GRV and a sinuous river channel with prominent point bars, due to presence of a basement high (Faizabad ridge). The valley slope changes from 19 cm/km in upper part to 4 cm/km in lower part of this segment. The lateral shift of active river channel on T_0-surface is 0.5-3.0 km over a time span of about 50 years (fig. 43). This zone shows evidences of active siltation in the last few decades. The sand is made up of about 72% fine sand. The grain size parameters are : M_Z-2.55, S_I- 0.38, S_{KI}-0.12, K_G- 1.24.

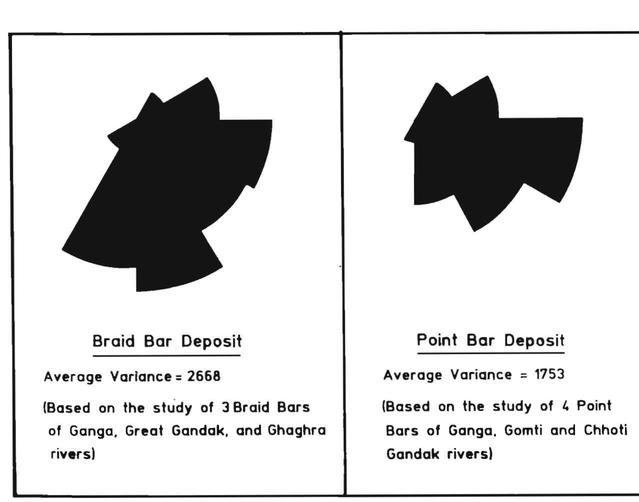

Fig.41. Palaeocurrent patterns in braid and point bar deposits of Ganga Plain.

GRV-III (Allahabad to Buxar) - The river valley is narrow, sinuous, with a poorly developed T_1-surface. The active channel is a single high sinuosity channel with prominent point bars; the maximum sinuosity is 2.2. The valley slope ranges between 13 cm/km to 7 cm/km. The valley orientation is governed by the basement lineament. The geomorphic and channel characteristics of this part are related to the presence of Vindhyan basement high. The sand is made up of 65% fine sand. The grain size parameters are: M_Z -2.33, S_I-0.42, S_{KI}-0.12, K_G-1.35.

GRV-IV (Buxar to Patna) - The valley is rather wide (35 km) with very wide development of T_0-surface (flood plain) of about 10-15 km. The T_0-surface shows many oxbow lakes, meander scars etc. This segment shows confluence of several important rivers, namely, Ghaghara, Gandak, and Son rivers within a short distance. The valley slope is 4 cm/km, and river channel shows moderate sinuosity (1.66). The grain size parameters are: M_Z -2.59, S_I- 0.46, S_{KI}-0.02, K_G-1.50.

GRV-V (Patna-Sakrigali) - The river valley is very wide showing essentially W-E orientation. The southern

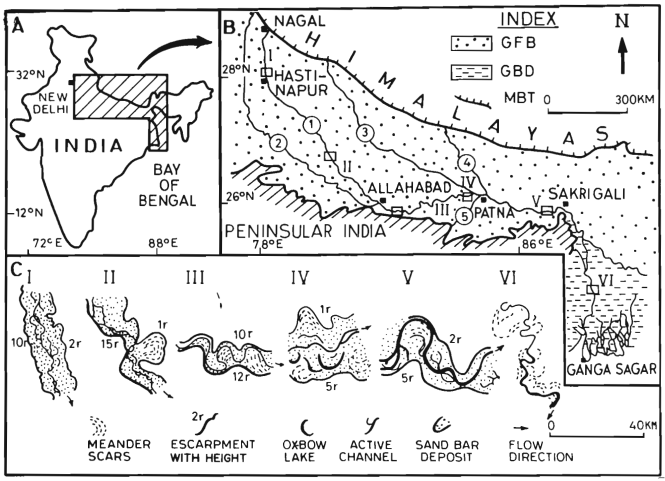

Fig.42. Ganga River showing characteristic features of six segments of Ganga River Valley 1- Ganga River, I-II are GRV segments, 2-Yamuna, 3-Ghaghara, 4-Gandak (After Singh and Singh, 1992).

margin of the valley shows high cliffs, while the northern margin has low cliffs. Basement rocks are sometimes exposed at the southern margin or within the valley. The distributaries of the Ganga River run for tens of km parallel to it, before meeting at acute angles. This zone has a number of W-E trending active lineaments, running parallel to the Ganga River. The T_o-surface is drained by anastomosing channels where one channel remains the major stream. This segment is characterized by a very high sediment load and discharge. The valley slope is 5 cm/km, the river shows multiple channels of moderate sinuosity (1.47). The sand is made up of about 75% fine sand. The grain size parameters are, M_z-2.69, S_I-0.36, S_{KI}-0.27, K_G-1.55.

GRV - VI (Sakrigali to Ganga Sagar) - The valley is located in the delta plain of the Ganga River. The Bhagirathi river is a decaying distributary, carrying only a fraction of discharge of the Ganga River. The valley slope is 5 cm/km, and the channel shows low sinuosity. The river flows southwards and joins the Bay of Bengal. In the lower reaches, the river is influenced by the tidal energy. The silt + clay fraction of the river sand is sometimes almost 30%. The grain size characteristics are: M_z-3.50, S_I-0.41, S_{KI}-0.04, K_G-1.33.

Variation in the proporation of different grain size fractions in downstream direction of Ganga River are shown in fig. 44.

The Ganga River Valley shows at least two cycles of rejuvination in recent geological past (fig. 45). The GRV (T_1- Surface) is incised in the regional upland surface, the T_2- Surface, and mostly shows asymmetrical terrace development, higher cliff on the southern margin and a lower cliff on the northern margin. The T_o-Surface (Active river) is incised into the T_1-Surface. The T_1-Surface shows meander-scars, meander cutoff of much different

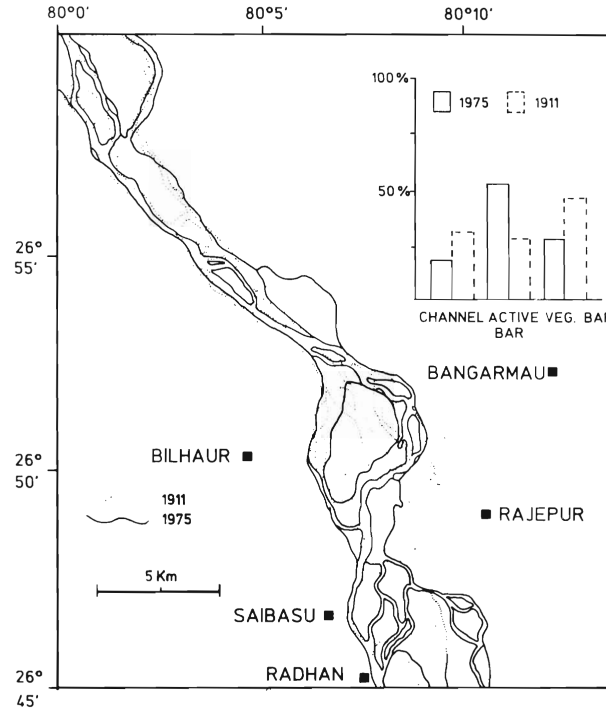

Fig.43. Schematic diagram showing shift and changes in the Ganga River during period of 1911-1975. There is only a nominal lateral shift. The area of active bar has increased, while the channel area has decreased (Based on the SOI topographical sheets).

nature than the active channel of the T_o-Surface. The T_1-Surface is presumed to be formed during humid climate of 25-30 Ka (Singh *et al.*, 1990), when monsoon over India was also stronger than today (Kutzbach, 1981). The active present river channel shows various types of channel patterns due to progressive downstream changes in river gradient, grain size, increase in discharge and sediment load.

Some studies on the heavy metal pollution in the sediments of Ganga River are initiated, indicating reasonable amount of Cr pollution near Kanpur (Kumar, 1992). Sediments of Yamuna River in Delhi region show high level of pollution with respect to Cd, moderate pollution with respect to Cr, Ni, Zn, Cu and Pb (unpublished Ph.D. thesis, M. Singh, Heidelberg University). The sediments of Unnao-Kanpur region, especially the small drains show reasonably high heavy metal pollution with respect to Cr, Pb, Cu and Zn (unpublished data of Mr. A.A. Ansari). It is essential to understand the sediment and water dispersal pattern in the Ganga Plain to monitor the dispersion of heavy metal pollutants. The example of Ganga River, its Valley and adjacent Interfluve upland demonstrate that all the three are independent systems, where sediment and water movement takes place on a large-scale. There is only a limited interaction between these three systems, which

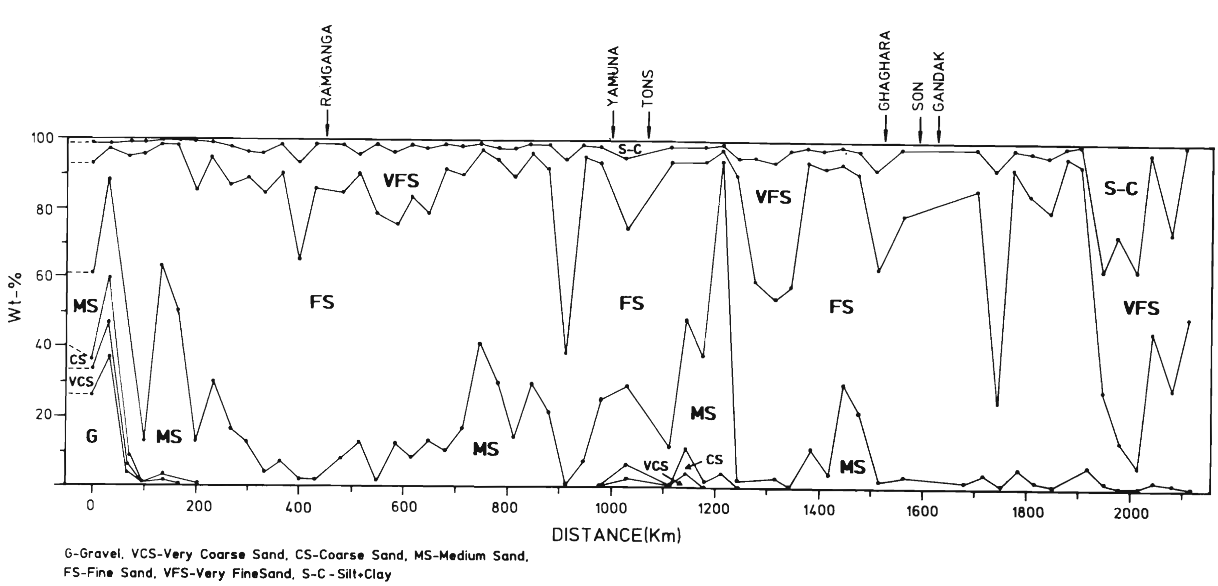

Fig.44. Variation in the grain size fractions along the Ganga River.

varies with the intensity of monsoonal flooding. The study of microgeomorphology and interaction between different geomorphic units must be carried out together with the study of heavy metal pollution.

CONCLUSIONS

The Ganga Plain is a peripheral foreland basin, which came into existence in Early Miocene, expanded in the Middle Miocene, and attained its present form in Late Quaternary. The stagewise evolution of Ganga Plain took place in response to the thrust- fold belt loading events in the Himalaya and consequent southward expansion of the basin.

At present, Ganga Plain foreland basin is in mature stage, with uplifted foreland sediments in the orogenward part, and a prominent cratonic peripheral bulge. The basin is oversupplied with sediments, building above the sea-level by fluvial processes only. At present, there is a significant supply of cratonic sediments in the basin. The Ganga Plain is exposed to compressional tectonics forces, and shows a number of distinctive neotectonic features with changing orientation in different sectors. The Piedmont Plain shows E-W running reverse faults (HFF) and a conjugate system of NNE-SSW and NW-SE running strike faults. The Central Alluvial Plain shows mainly NW-SE lineaments which have also controlled the orientation of river channels. Southwards this direction gradually changes to WNW-ESE to W-E. These are new lineaments formed in response to the Himalayan tectonics. The Marginal Alluvial Plain shows reactivation of SW-NE trending basement lineaments which control the drainages; vertical block uplift of the whole area occurs.

The regional geomorphic surfaces of Ganga Plain are product of Late Quaternary climatic and base-level changes (sea-level changes), and are correlated with different glacial- interglacial events in the last 128 Ka: the T_2-Surface (128-74 Ka), MP-Surface (128-74 Ka), the F-Surface (74-35 Ka), the T_1-Surface (33-25 Ka), the PF-Surface (25-10 Ka), and the T_0- Surface (10 Ka). During the Holocene, abandonment of river channels, formation of large lakes, shrinkage and siltation of lakes occurred in quick succession in response to changes in base-level, water budget, aridity, and supply of sediment.

The river system of the Ganga Plain shows a wide range of channel characteristics related to the amount of sediment load and relative proportion of the bedload and suspension load, although slope and sediment type are rather uniform. There appears to be a useful emperical relationship between channel width and meander wavelength of the larger rivers. Most of the smaller rivers appear to have formed in the past, when they

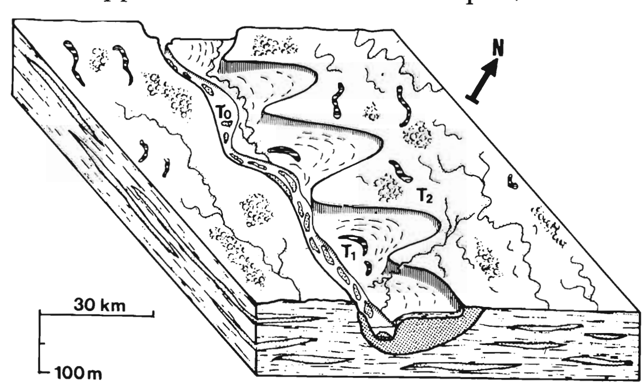

Fig.45. Diagram showing a broad River Valley Terrace Surface (T_1) of Ganga River with prominent meander scars (After Singh *et al.*, 1990).

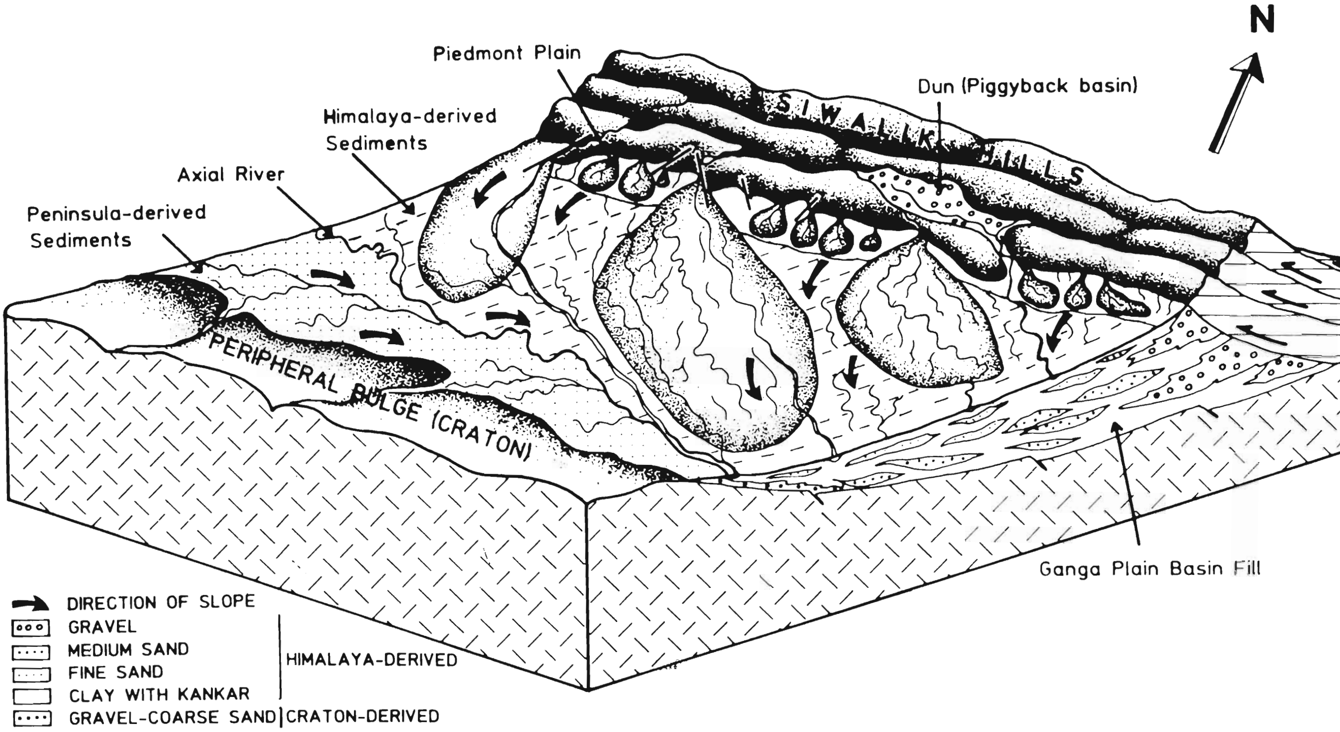

Fig.46. Schematic model for Ganga Plain foreland basin.

carried much higher discharge. At present they carry only a fraction of the former water discharge.

The large river channel deposits produce multi-storied sandbodies due to large residence time of the rivers, and generally show tendency of younger events to be finer-grained, and change from braided type to meandering-type channels. The interfluve areas develop distinctive facies association of fine- grained sediments deposited by sheet flow, small channels, ponds, and extensive calcretization. These deposits are not formed in the flood plain of any active channel, but on the upland surfaces by sediment movement in response to the monsoonal rainfall. The Ganga River shows a wide range of changes in river valley characteristics, river channel patterns, and grain size changes along its 2000 km long river course.

The sediments of Ganga and Yamuna rivers show high degree of heavy metal pollution in the vicinity of industrial areas. In some areas high levels of pollution with respect to Cd, Cr, Ni, Zn, Cu, Pb, are already present, and need to be examined in more detail, keeping in mind the microgeomorphology of different geomorphic surfaces.

GANGA PLAIN FORELAND BASIN MODEL

Integration of geophysical information, subsurface alluvial stratigraphy, geomorphological studies and sedimentological data has helped in developing a model for the Ganga Plain (fig. 46). In the north, the basin shows deformed foreland sediments (Siwalik hills), with some thrust sheets supporting deposition in piggyback basins (Duns). The northern alluvial surface is dominated by Megafans. Drainages channels of various types and dimensions are present, along with extensive muddy interfluve areas. The axial drainage is located near the southern margin of the basin. The main sediment input is from the Himalaya (lihic sand); while sediment from craton (arkosic sand) is also added in small amounts. The deposition is controlled by expansion and contraction of Megafans and avulsion and siltation of river systems; climatic and base-level changes (with changing sea-level); and the changing role of peripheral bulge and thrust-fold loading in Himalaya. The basin shows an asymmetrical sediment fill with few active basement faults, which controlled the sediment fill above.

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REFERENCES

Agarwal, A.K., Rizvi, M.H., Singh, I.B., Kumar, A. and Chandra, S. 1992. Carbonate deposits in Ganga Plain, p. 35-43. In: *Gangetic Plain: Terra Incognita* (Ed. Singh, I.B.), Geology Department, Lucknow University.

Agarwal, A.K., Singh, R.M., Rizvi, M.H. 1986. Status report of marl and kankar deposits for the suitability in mini cement plant. Unpublished Report of Directorate of Geology and Mining, U.P. Lucknow, 14p.

Agarwal, R.K. 1977. Structure and tectonics of Indo-Gangetic Plains. *Geophysical case Histories of India,* AEG, **1**: 29- 46.

Aithal, V.S., Gopalakrishnan, G., Prem, D. 1964. Gravity and magnetic surveys in plains of Punjab. *Proc. sec. 2, 22nd. Int. Geol. Cong., New Delhi:* 179-188.

Bajpai, V.N. 1989. Surface and sub-surface evidences of neotectonic and aquifer disposition in central alluvial terrain of Kanpur-Unnao region in Uttar Pradesh, India. Photonirvachak. *Jour. Ind.Soc. Remote Sensing,* **17**: 47-53.

Beaumont, C. 1981. Foreland basins. *Geophys. Jour. Roy. Astron. Soc.,* **55**: 291-329.

Biswas, S.K. 1994. Status of exploration for hydrocarbons in Siwalik basin of India and future trends. *Him. Geol.,* **15**: 301-320.

Burbank, D. W. 1992. Causes of recent Himalayan uplift deduced from deposited patterns in the Ganga basin. *Nat.,* **357**: 680-683.

Burrard, S.G.C. 1915. Origin of Gangetic trough commonly called the Himalayan foredeep. *Proc. Roy. Soc. London,* **91A**: 220- 238.

Butcher, S.W. 1990. The nickpoint concept and its implications regarding onlap to the stratigraphic record, p. 375-385. In: *Quantitative Dynamic Stratigraphy,* (Ed. Cross, T.A.), Prentice-Hall, Englewood Cliffs.

Chandel, R.S. 1992. Geomorphology of Doon Valley, Uttar Pradesh: Applications of Remote Sensing Techniques. Unpubl. Ph.D. Thesis, Lucknow University. 276 p.

Covey, M. 1986. The evolutin of foreland basin of steady state: the foreland of the Banda Orogen, p. 77-90. In: *Foreland basin* (Eds. Allen, P.A. and Homewood, P.), *Int. Assoc. Sedimentol.* (spec. publ. 8).

Das Gupta, S.P. 1975. The Upper Gangetic Flood Plain : A Regional Survey. *National Atlas Organisation Monograph,* Calcutta, 194 p.

Dickinson, W.R. 1974. Plate Tectonics and Sedimentation, p. 1-27. In: *Tectonic and Sedimentation,* (Ed. Dickinson, W.R.), *Spec. Publ* **22**: SEPM, Tulsa, Okla.

Ferguson, R.I. 1987. Hydraulic and sedimentary controls of channel pattern, p. 125-158. In: *River Channels: environment and process* (Ed., Richards, K.S), Blackwell.

Fisk, H.N. 1944. Geological Investigation of the Alluvial Valley of the Lower Missssippi River. *Mississippi River Commission Vicksburg,* Mississippi.

France-Lanord, C., Derry, L. and Michard, A. 1983. Evolution of Himalaya since Miocene time: isotopic and sedimentological evidence from the Bengal fan, p. 603-621. In: *Himalayan Tectonics,* (Eds. Trelor, P.J. and Searl, M.P.),*Geol. Soc. Spec. Publ.* **74**.

Friend, P.F. and Sinha, R.1993. Braiding and meandering parameters, p. 105-111. In: *Braided Rivers.* (Eds. Best, J.R. and Briston, C.S.)*Geol. Soc. Lond. Spec. Publ.,* **75**.

Geddes, A. 1960. The alluvial morphology of the Indo-Gangetic plain : Its mapping and geographic significance. Trans. *Inst. Brit. Geogr. Publ.,* **28**: p.s. 253-276.

Ghosh, D.K. and Singh, I.B. 1988. Structural and geomorphic evolution of the north-west part of the Indo-Gangetic Palin. *Proc. Nation. Sem. Recent Quaternary Studies in India, Dept. of Geology, M.S. Univesity of Baroda,*: 164-175.

Godbole, M.L. 1986. Training of Ganga River from Mokanch to Mansi. *Seminar on morphology of Ganga River, New Delhi:* 73-90.

Gohain, K. and Parkash, B. 1990. Morphology of the Kosi Megafan, p. 151-177. In: *Alluvial Fan : A Field Approach,* (Eds., Rachocki, A.H. and Clunch, M.) John Wiley & Sons.

Gole, C.V. and Chittale, S.V. 1966. Inland Delta building activity of Kosi River. *Jour. Hydraul. Proc. Ann. Soc. Civ. Eng.,* **92**: 111-126.

Gopendra Kumar 1992. Quaternary event stratigraphy and evolution of Indo-Gangetic plain, U.P. Abstr. Group Discussion on Indo-Gangetic Basin, 9-10 Nov., 1992, Deptt. Geol., Kumaon Univ., Nainital.

Hagen, T. 1956. Über eine Überschiebung der Tertiäre Siwalics ubr das rezente Ganges Alluvium in Ost. Nepal. *Geogr. Helv.,***5**: 217-219.

Jordan, T.E. 1981. Thrust loads and foreland basin evolution, Cretaceous, western United States. *Am. Assoc. Petrol. Geol. Bull.,* **65**: 2506-2520.

Jordan, T.E. 1995. Retroarc foreland and related basins, p. 331- 362. In: *Tectonics of Sedimentary Basins.* (Eds. Busby, C.J. and Ingersoll, R.V.), Blackwell Scientific, Oxford.

Joshi, D.D. and Bhartiya, S.P. 1991. Geomorphic history and lithostratigraphy of eastern Gangetic plain, Uttar Pradesh. *Jour. Geol. Soc. Ind.,* **37**: 569-576

Karunakaran, C. and Ranga Rao, A. 1979. Status of exploration for hydrocarbons in the Himalayan region - contribution to stratigraphy and structure. *Geol. Surv. Ind. Publ.,* **41**: 1-66.

Khan, A.A., Nawani, P.C. and Srivastava, M.C. 1988. Geomorphological evaluation of the area around Varanasi, Uttar Pradesh, with aid of aerial photography and landsat imageries. *Geol. Surv. Ind. Rec.,* **113**(8): 31-39.

Khanna, S.P. 1992. Hydrogeology of Central Ganga Plain, Uttar Pradesh, p. 23-27. In: *Gangetic Plain: Terra Incognita,* (Ed. Singh, I.B.), Geology Department, Lucknow University.

Krishnaswamy, V.S., Jalota, S.P. and Shome, S.K. 1970. Recent crustal movements in northwest Himalaya and the Gangetic foredeep and related patterns of seismicity. *Proc. 4 Symp. Eqk. Roorkee,*: 419-429.

Kumar, S. 1992. Heavy metal pollution in Ganga River sediments, Uttar Pradesh: A Preliminaryy report, p. 59-66. In: *Gangetic Plain: Terra Incognita,* (Ed., Singh, I.B.), Geology Department, Lucknow university.

Kumar, S. and Singh, I.B. 1978. Sedimentological study of Gomti river sediment, Uttar pradesh, India: Example of a river in Alluvial Plain. *Senckenbergiana Marit.*, **10**: 145-221.

Kutzbach, J.E. 1981. Monsoon climate of the Early Holocene : Climate experiment with the earth's orbital parameters for 9000 years ago. *Sci.*, **214**: 59-61.

Leopold, L.B., Wolman, M.G. 1957. River Channel patterns; braided, meandering and straight. *U.S. Geol Survey Prof. paper*, **282**-B: 39-85.

Lyon-Caen, H. and Molnar, P. 1985. Gravity anamolies, flexure of the Indian Plate and the structure, support and evolution of the Himalaya and Ganga basin. *Tectonics*, **4**: 513-538.

Misra, M.N., Srivastava, R.N., Upadhyaya, M.C., Srivastava, M.P. 1994. Quaternary geology and morphotectonic evolution of the Lower Sind Basin, Marginal Gangetic Plain, M.P. and U.P. *Jour. Geol. Soc. Ind.*, **43**: 677-684.

Mohindra, R. and Parkash, B. 1994. Geomorphology and neotectonic activity of the Gandak Megafan and adjoining areas, middle Gangetic Plains. *Jour. Geol. Soc. India*, **43**: 149-157.

Mohindra, R., Parkash, B. and Prasad, J. 1992. Historical geomorphology and pedology of the Gandak Megafan, Middle Gangetic Plains, India. *Earth Surface Processes and Landforms*, **17**: 643-662.

Molnar, P. 1984. Structure and tectonics of the Himalaya: constraints and implications of geophysical data. *Ann. Rev. Earth Planet. Sci.*, **12**: 489-518.

Molnar, P. and Tapponier, P. 1975. Late Cenozoic tectonics of Asia: Effects of a continental collision. *Sci.*, **189**: 419-426.

Moolchand, Datta, A.N., Chellam, R.S., Ghosh, A.P., Awasthi, A.M. Awasthi, D.N. and Garg, V.C. 1964. Seismic surveys in western Uttar Pradesh. *Proc. 22nd. Int. Geol. Cong., New Delhi.* Section 2: 260-276.

Mukerji, A.B. 1963. Alluvial morphology of upper Ganga Yamuna doab. *The Deccan Geographer*, **2**: 1-36.

Nakata, T. 1988. Active faults of the Himalaya of India And Nepal. *Geol. Soc. Am. Spec. Paper*, **218**: 243.

Narain, H. and Kaila, K.L. 1982. Inference about Vindhyan basin from geophysical data, p. 79-192. In: *Geology of Vindhyanchal*, (Eds. Valdiya, K.S., Bhatia, S.B. and Gaur, V.K.), Hindustan Publ. Corp.

Nautiyal, S.P. 1945. Marl deposits in the districts of Barabanki, Lucknow, Rae Bareli and Unnao, Uttar Pradesh (with discussion by J.B. Auden). *Rec. Geol. Surv. Ind.*, **86**: 455- 466.

Ni, J. and Barazangi, M. 1984. Seismotectonies of the Himalayan collision zone: Geometry of the underthrusting Indian plate beneath the Himalaya. *Jour. Geophys.* Res., **89**: 1147-1163.

Oldham, R.D. 1917. The structure of the Himalayas and the Gangetic Plain as elucidated by geodetic observations in India. *Mem. Geol. Surv. Ind.*, **42**(2): 1-153.

Ori, G.G. and Friend, P.F. 1984. Sedimentary basins formed and carried piggyback on active thrust sheets. *Geol.*, **12**: 475-478.

Pal, S.K. and Bhattacharya, A.R. 1979. The role of multispectral imagery in elucidation of recent channel pattern changes in middle Gangetic plain. *Photonirvachak, Jour. Ind. Soc. Photo.-Int.* and *Remote Sensing*, **7**: 11-20.

Pascoe, R.D. 1917. Early history of Indus-Brahmaputra and Ganges. *Quart. Jour. Geol. Soc. Lond.*, **76**: 136.

Pascoe, E.H. 1973. *Manual of geology of India and Burma*-III. Govt. of India Publ., Delhi.

Philip, G., Gupta., R.P. and Bhattacharya, A. 1991. Landsat image enhancement for mapping fluvial paleofeature in parts of Middle Ganga Basin, Bihar. *Jour. Geo. Soc. India*, **37**(1): 63-74.

Pilgrim, G.E. 1919. Suggestions concerning the history of Northern India. *Jour. Asiat. Soc. Bengal* (NS), **15**: 81-89.

Prakash, O., Sinha, K.K., Sinha, R.K., Raju, D.C.L., Haque, M.W. and Reddy, B.S.S. 1989. Quaternary geological and geomorphological mapping of the Kosi-Gandak Interfluve, North Bihar. *Rec. Geol. Surv. Ind.*, **122**(3): 4-5.

Parkash, B. and Kumar, S. 1991. The Indo-gangetic basin, p. 147-170. In: *Sedimentary Basins of India*, (Eds. Tandon, S.K., Pant, C.C., Casshyap, S.M.), Gyanodaya Prakashak.

Qureshy, M.N., Kumar, S. and Gupta, G.D. 1989. The Himalaya megalineament- Its Geophysical characteristics. *Mem. Geol. Soc. India*, **12**: 207-222.

Qureshy, M.N. and Kumar, S. 1992. Isostasy and neotectonic of north west Himalaya and foredeep. *Mem. Geol. Soc. India*, **23** : 201-222.

Rajagopalan, G. 1992. Radiocarbon ages of carbonate materials from Gangetic Alluvium, p. 45-48. In: *Gangetic Plain: Terra Incognita*, (Ed., Singh, I.B.) Geology Department, Lucknow University.

Rao, M.B.R. 1973. The subsurface geology of the Indo-Gangetic Plains. *Jour. Geol. Soc. India*, **14**: 217-242.

Richards, K., Chandra, S., Friend, P.F. 1993. Avulsive channel system: Characteristics and examples, p. 195-203. In: *Braided Rivers*, (Eds. Best, J.L. and Briston, C.S.) *Geol. Soc. Lond., Spec. Publ.*, **75**, London.

Roy R.K. and Ghosh, B.K. 1979. Quaternary morpho-stratigraphy and Neo-tectonic framework of the Southern Ganga Valley, Bihar, India. Neogene/Quaternary Boundary field conference, India, Proc., published 1981: 153-158.

Sastri, V.V., Bhandari, L.L., Raju, A.T.R. and Dutta, A.K. 1971. Tectonic framework and subsurface stratigraphy of the Ganga basin. *Jour. Geol. Soc. India*, **12**: 222-233.

Saxena, P.B., Iyer, H.S., Mahapatra, G. and Saxena, R.K. 1983. The Solani-Ganga interfluve : An application of remote sensing technique on soil resource mapping for agricultural planning. *Photonirvachak Jour. Ind. Soc. Photo. Int. and Remote Sensing*, **11**: 55.

Schumm, S.A. 1981. Evolution and response of the Fluvial system, sedimentological implications, p. 19-29. In: *Recent and Ancient Nonmarine Depositional Environments: Model for Exploration*, (Eds. Ethridge, F.G., and Flores, R.M.) Soc. Econ. Paleontol. Mineral Spec. Publ., **31**.

Schumm, S.A. 1993. River response to baselevel change:implications for sequence stratigraphy. *Jour. Geol.*, **101**: 279-294.

Seeber, L., Armbuster, J.G., and Quittmeyer, R.C. 1981. Seismicity and continental subduction in the Himalayan Arc, p. 215-242. In: *Zagros, Hindukush, Himalaya Geodynamic evolution*, (Eds. Gupta, H.K. and Delany, F.M.), *Am. Geophys. U.*, Washington, Geodynamic Series **3**.

Singh, A. and Bhardwaj, B. D. 1991. Fluvial facies model of the Ganga River sediments, India. *Sed. Geol.*, **72**: 135-146.

Singh, A., Bhardwaj, B.D. and Ahmad, A.H.M. 1993. Tectonic setting and sedimentology of Ganga River sediments, India. *Boreas*, **22**: 38-46

Singh, I.B. 1977. Bedding structures in a channel sand bar of the Ganga river near Allahabad, Uttar Pradesh, India. *Jour. Sed. Pet.*, **47**: 747-752.

Singh, I.B. 1979. Some thoughts on evolution of Himalaya and the northern limits of Indian shield. *Geol. Rdsh.*, **68**: 342-350.

Singh, I.B. 1981. A critical review of the fossil record in the Krol belt succession and its implication on the biostratigraphy and palaeogeography of the lesser Himalaya. *Jour. Pal. Soc. India*, **25**: 148-168.

Singh, I.B. 1987. Sedimentological history of Quaternary deposits in Gangetic Plain. *Indian Jour. Earth Sci.*, **14**: 272-282.

Singh, I.B. 1992. Geological Evolution of Gangetic Plain: Present Status, p. 1-14. In: *Gangetic Plain: Terra Incognita*, (Ed., Singh, I.B), Geology Department, Lucknow University.

Singh, I.B., Ansari, A.A., Chandel, R.S. and Misra, A. 1996. Neotectonic control on Drainage System in Gangetic Plain, Uttar Pradesh. *Jour. Geol. Soc. Ind.*, **47**: 599-609.

Singh, I.B. and Bajpai, V.N. 1989. Significance of syndepositional tectonics in the facies development of the Gangetic Alluvium near Kanpur, Uttar Pradesh. *Jour. Geol. Soc. India*, **34**: 61-66.

Singh, I.B., Bajpai, V.N., Kumar, A. and Singh, M. 1990. Changes in the channel characteristics of Ganga River during Late Pleistocene-Holocene. *Jour. Geol. Soc. India*, **36**: 67-73

Singh, I.B. and Ghosh, D.K. 1992. Interpretation of Late Quaternary geomorphic and tectonic features of Gangetic plain using remote sensing techniques. *Proc. Nat. Symp. on Remote Sensing for Sustainable Development, Lucknow,*: 373-278.

Singh, I.B. and Ghosh, D.K. 1994. Geomorphology and neotectonic features of Indo-Gangetic Plain, p. 270-286. In: *India: Geomorphological diversity*, (Eds. Dikshit, K.R., Kale, V.S. and Kaul, M.N.), Rawat Publications, Jaipur.

Singh, I.B., Kumar, S. 1974. Mega and giant ripples in the Ganga, Yamuna and Son Rivers, Uttar Pradesh, India. *Sed. Geol.*, **12**: 53-66

Singh, I.B. and Rastogi, S.P. 1973. Tectonic framework of Gangetic alluvium, with special reference to Ganga River in Uttar Pradesh. *Curr. Sci.*, **42**: 305-307.

Singh, I.B. and Singh, M. 1992. The Ganga river valley: Alluvial valley in active foreland basin. 29th. *Int. Geol. Cong. Kyoto, Japan*, Abstr., V. II.

Singh, I.B. and Wal, A. 1996. Subsurface alluvial Stratigraphy in the Ganga plain foreland basin of Uttar Pradesh. (Ms.)

Singh, H., Parkash, B., Gohain, K. 1993. Facies analysis of the Kosi megafan deposits. *Sed. Geol.*, **85**: 87-113

Singh, M. 1996. The Ganga River: Fluvial Geomorphology, Sedimentation Processes and Geochemical studies. *Heidelberger Beiträge Zur Umwelt-Geochhemie*, **8**: 1-133.

Sinha, R. 1995. Sedimentology of Quaternary Alluvial Deposits of the Gandak-Kosi interfan, North Bihar Plains. *Jour. Geol. Soc. India*, **46**: 521-532.

Sinha, R. 1996. Channel avulsion and floodplain structure in the Gandak-kosi interfan, North Bihar Plains, India. *Gebruder Borntraeger*, D-14129 Berlin. D- 70176 Stuttgart. 249-268.

Sinha, R. and Friend, P.F. 1994. River systems and their sediment flux, Indo-Gangetic plains, Northern Bihar, India. *Sedimentol.*, **41**: 825-845.

Sinha, R., Friend, P.F., Switsur, V.R. 1995. Radiocarbon dating and sedimentation rates in the Holocene alluvial sediments of the northern Bihar plains, India. *Geol. Mag.*, **133**(1): 85-90

Srivastava, P., Parkash, B., Sehgal, J.L., Kumar, S. 1994. Role of neotectonics and climate in developmant of the Holocene geomorphology and soils of the Gangetic plains between the Ramganga and Rapti Rivers. *Sed. Geol.*, **94**: 129-151.

Suess, 1893-1909. *Das Antlitz der Erde* (4 vols). Prague and Leipzig.

Suyash Kumar, Singh, I.B., Singh, M., Singh, D.D. 1995. Depositional Pattern in Upland surfaces of Central Gangetic Plain near Lucknow. *Jour. Geol. Soc. India*, **46**: 545-555.

Suyash Kumar, Singh, M., Chandel, R.S. and Singh, I.B. 1992. Geomorphic evolution of Lucknow area using Remote Sensing data analysis. *Proc. Nat. Symp. on Rem. Sens. for Sustainable Development, RSAC-U.P.*, Lucknow, 269-272 pp.

Tandon, S.K. 1991. The Himalayan foreland: focus on Siwalik basin, p. 171-201. In : *Sedimentary Basins of India* (Eds. Tandon, S.K., Pant, C.C. and Casshyap, S.M.), Gyanodaya Prakashak.

Wells, N.A. and Don, J.A. 1987a. A reconnaissance of sedimentation on Kosi alluvial fan of India. *Spec. Publ. Soc. Econ. Paleont. Min. Tulsa*, **39**: 51-61.

Wescott, W.A. 1993. Geomorphic thresholds and complex response of fluvial systems - some implications for sequence stratigraphy. *Am. Assoc. Petrol. Geol. Bull.*, **77**: 1208-1218.

Zoback, M.L. 1992. First and second order patterns of stress in the lithosphere : The world stress map project. *Jour. Geophy. Res.*, **97** (b): 11703-11728.