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SEDIMENTOLOGICAL FRAMEWORK OF LATE PLIOCENE AND PLEISTOCENE ALLUVIAL DEPOSITS IN THE BHITTANI RANGE, PAKISTAN[1]

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ABSTRACT

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We measured a section along the southern limb of the Marwat Kundi anticline near the village of Malagan in northwestern Pakistan. Three major depositional systems were differentiated that were based on the sampled data from this section and on some comparisons with their lateral equivalents.

The lower system, the Kargocha Formation, consists of a thick succession of mainly mudstones with intercalations of conglomeratic and sandy sheet- or ribbon-like alluvial bodies. This lower depositional system was characterized by relatively small fluvial systems.

The following Marwat Formation consists mainly of very thickbedded sandstones, followed by thinner bedded sandstones in its upper parts. The thick sandstone beds represent large fluvial channel complexes that were formed by a large sandy braided river, comparable to the present-day Indus river. The thin-bedded succession represents an abandonment of this large river system and a migration of the paleo-Indus towards the east to its present-day position.

Finally, the Malagan Formation is formed by terminal fluvial fans, of which its modern analogue can be found within the present-day intramontane basins.

INTRODUCTION

In 1979 members of the Howard University/Geological Survey of Pakistan team carried out a sedimentological survey in the Bhittanni Range (Bannu area) along the southern limb of the Marwat Kundi anticline (see Fig. 1 for location).

Early geological observations in the Bannu area were carried out by STEWART (1860), OLDHAM (1860) and COSTELLO (1864). The first comprehensive and reliable geological description of the area is given by WYNNE (1880). Detailed mapping of the area and an excellent description of the rock units were carried out by MORRIS (1938). He was also first to describe the much discussed Bain Boulder Bed, which he believed to be of glacial origin. A more recent description of the stratigraphic framework of the Bannu area is given by HEMPHILL & KIDWAI (1973).

Uplift and erosion of the Himalayas during the Neogene has resulted in the deposition of thick and extensive alluvial deposits which belong to the Siwalik Group. Many geological studies of the Siwalik Group have contributed to the reconstruction of the general depositional framework of these Neogene and Early Quaternary deposits (e.g. MORRIS, 1938; WADIA, 1951; GANSSER, 1964; JOHNSON & VONDRA, 1972; HALSTEAD & NANDA, 1973; LE FORT, 1975; JOHNSON, 1978; JOHNSON ET AL., 1979, 1982; BARRY ET AL., 1982).

VISSER &, JOHNSON (1978) presented a general sedimentological analysis of Late Pliocene fluvial deposits in the Jhelum area, some 100 km west of Mianwali, whereas BEHRENSMEYER & TAUXE (1982) discussed the Miocene fluvial systems on the Potwar Plateau north of the Salt Range in detail.

Published data on the sedimentology of the Bannu area are, however, very scarce (NIO & HUSSAIN, 1981; WELLS, 1983) and a more detailed sedimentary facies analysis is practically non-existent. The purpose of the present sedimentological investigation of the Bhittanni Range is primarily to obtain a general picture of the depositional framework of the area, which will support future detailed geological investigations. Furthermore, a tentative model will be given of the relationship between the different fluvial regimes, lithological composition and the neotectonics of the region.

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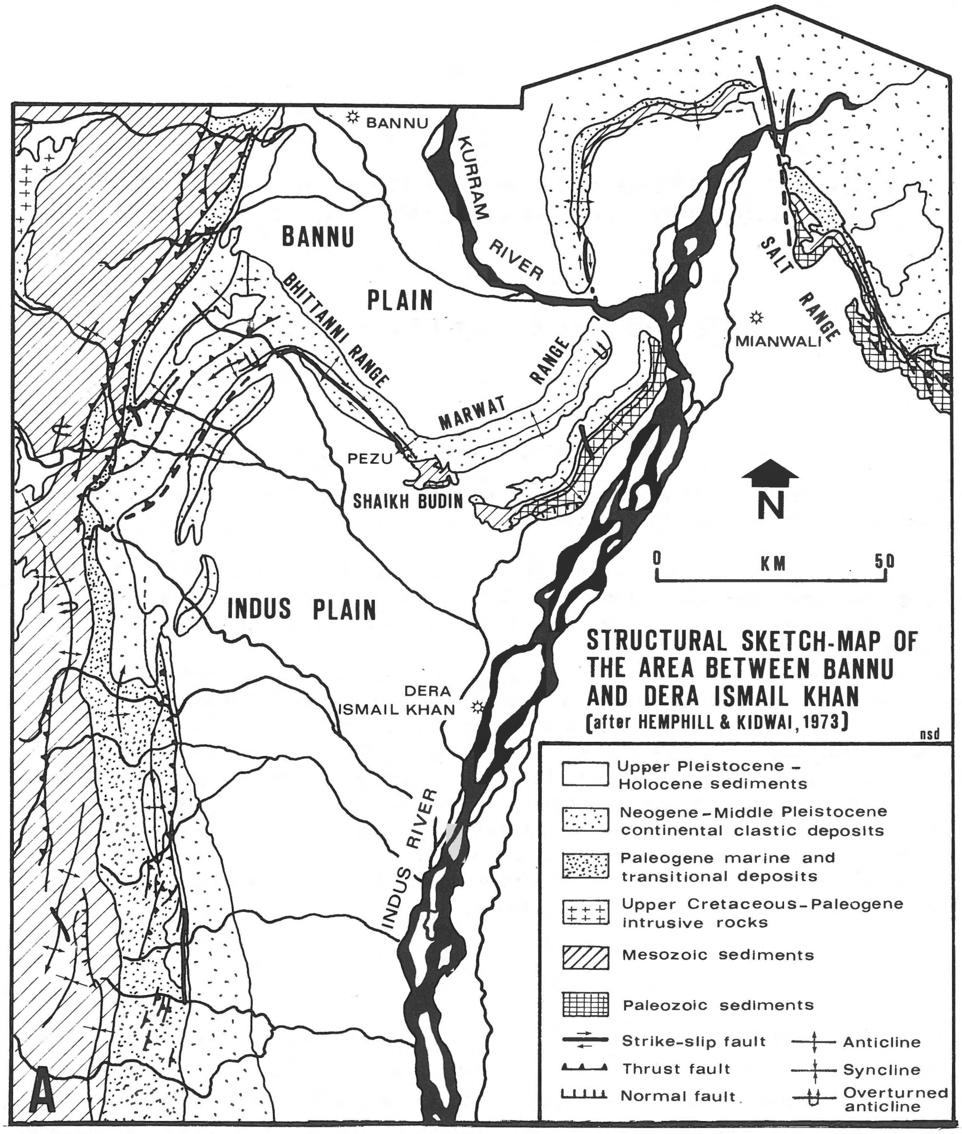

Fig. 1A
Structural sketch map of the area between Bannu and Dera Ismail Khan (after Hemphill and Kidwai, 1973).

GENERAL GEOLOGIC SETTING

The Bhittanni and Marwat Range form the border between the Bannu Plain in the north and the Indus Plain in the south (Fig. 1). The Bannu Plain can be considered as one of the many small intramontane basins which form the northern extension of the present-day Indo-Gangetic molasse basin. Formation of these intramontane basins is related to the folding and faulting of the Bhittanni and Marwat Range during the most recent phase of tectonic activity in the Sulaiman Range, which forms the western boundary of the Indus plain. The base of the Indo-Gangetic molasse sequence consists of Early Eocene shallow-marine carbonates, overlain by a regressive mega-sequence which starts with transitional fluvio-deltaic sediments (Late Paleogene and Early Neogene) and which rapidly passes upwards into the Neogene continental deposits of the Siwalik Group.

The Late Pliocene and Pleistocene deposits of the Bhittanni and Marwat Range derive mainly from the north (the transitional area between the Sulaiman and Kurram Range) and northwest (the Sulaiman Range). The Bhittanni and Marwat Ranges consist of two plunging anticlinal flexures, the Marwat Kundi anticline in the west and the Marwat anticline in the east.

LITHOSTRATIGRAPHIC SETTING

MORRIS (1938) made the first lithostratigraphic devision of the Bhittanni Range and distinguished four formations. The oldest one is the Kargocha Formation, which crops out within the core of the Marwat Kundi anticline. This is followed by the Marwat, Sheri Gasha and Malagan Formations. These formations were distinguished on the basis of heavy-mineral

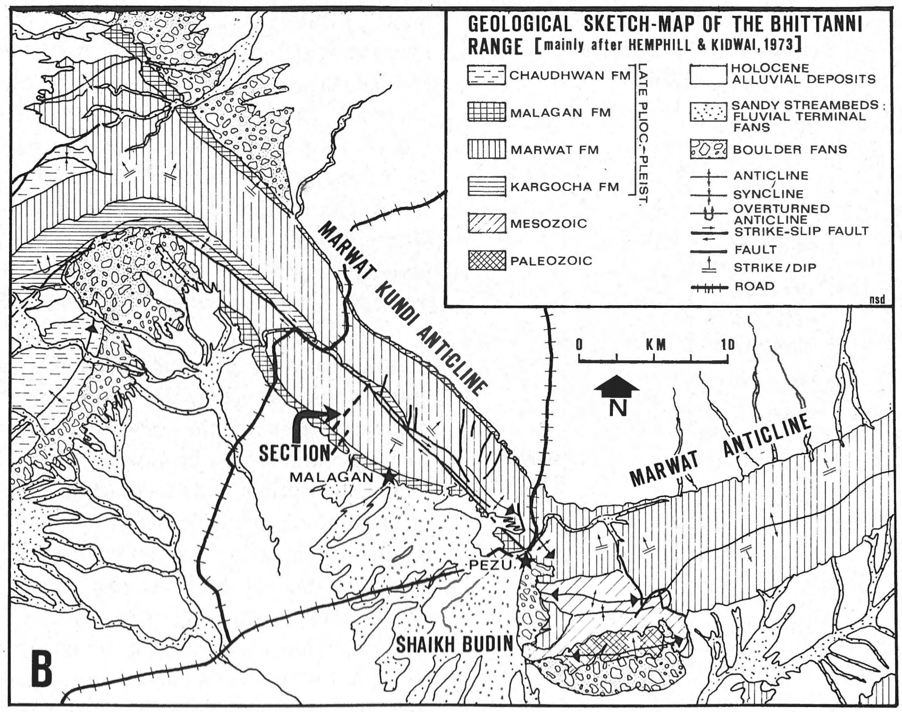

Fig. 1B
Geological sketch-map of the Bhittanni Range (mainly after Hemphill and Kidwai, 1973).

assemblages. MORRIS (1938) also mentioned the similarity of these assemblages with the lithostratigraphic formations of the Potwar Plateau. The same arguments were used by HEMPHILL & KIDWAI (1973) to correlate these formations with those of the Siwalik Group of the Potwar Plateau. In accordance with the Stratigraphic Code, defined by DAY ET AL. (1962), HEMPHILL & KIDWAI recognized the following formations within the Bhittanni and Marwat Range: the Chinji Formation within the core of the Marwat Kundi anticline, followed by the Nagri, Dhok Pathan and Malagan Formations.

At this stage, however, stratigraphic correlations between these formations and those of the Siwalik Group of the Potwar Plateau are not recommended. As long as a better stratigraphic control is still inadequate, a more practical threefold division will be used here. The differentiation into three formations (Table I) is mainly based on MORRIS's original lithostratigraphic division (see also NIO & HUSSAIN, 1981):

Table I

	MORRIS (1938)	this paper
Early/Middle Pleistocene	Malagan Formation	Malagan Formation
	Sheri Gasha Formation	Upper Marwat Fm.
	Marwat Formation	Lower Marwat Fm.
Late Pliocene	Kargocha Formation	Kargocha Formation

THE SEDIMENTARY SEQUENCE AND GEOMETRY OF SEDIMENT BODIES

A sedimentary section has been measured from the core of the Marwat Kundi anticline along its southern limb near the village of Malagan (Fig. 1). The lower part of the section, which consists of the Kargocha Formation, was not measured in detail and only an incomplete survey was carried out. The approximately 2300 m thick succession of the Marwat and Malagan Formations, however, has been measured in detail (Fig. 2). The base as well as the top of the entire sequence are not exposed. The lower part of the Kargocha Formation is concealed within the core of the anticline and the upper part of the Malagan Formation is unconformably overlain by Holocene continental deposits of the Indus Plain.

The entire sequence, with the exception of the upper 500 metres of the Malagan Formation, consists of an alternation of sandstone beds of variable thicknesses and silty mudstones. Most of these sandstone beds have an erosional base and each one of them is characterized by a distinct structural and textural sequence. The thicker sandstone beds along the southern limb of the anticline can be traced laterally for about 15 km and are cut off by a strike-slip fault at the SE-end of the anticline (Fig. 1). Along the undisturbed northern limb, however, the thicker sandstone beds can be followed for as far as 35 km. From aerial photographs one can observe a gradual thinning of these sandstone beds towards the NW and a thickening towards the east. The Marwat anticline consists

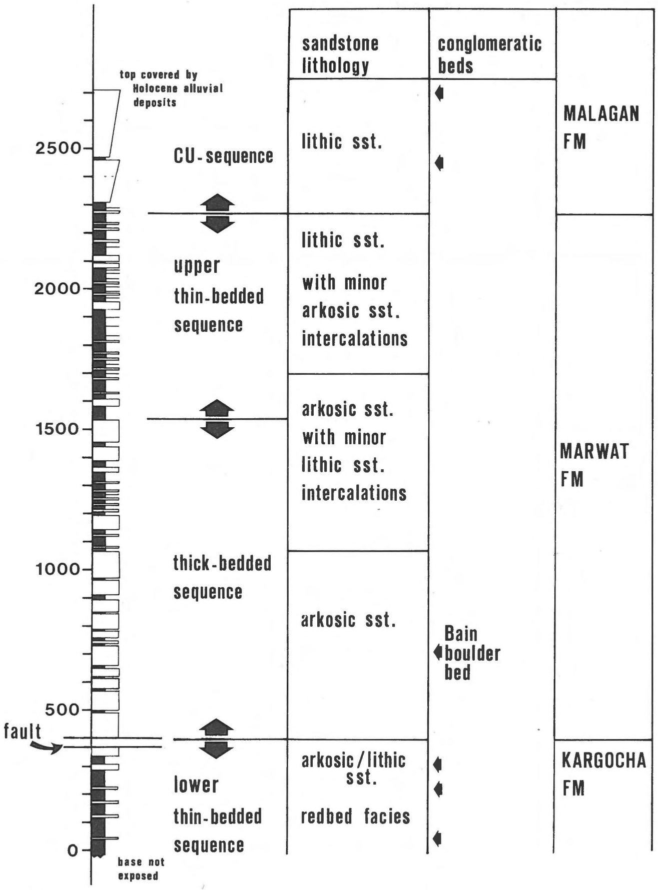

Fig. 2
Schematic section through the southern limb of the Marwat Kundi anticline near the village of Malagan. Black: mudstone intervals, white: sandstone bodies, arrows: conglomeratic intercalations.

mainly of these thick-bedded sandstones, which belong to the Marwat Formation (HEMPHILL & KIDWAI, 1973).

Based on their geometry and sequential development we interpret these sandstone bodies as channel deposits of a very large river system. Because of the excellent outcrop conditions one can reconstruct the entire river complex from the aerial photographs. The bankfull width of the entire ancient river is estimated to be between 15 and 35 km.

The entire section can be divided into 4 major intervals, each of which is characterized by a specific sequence (NIO & HUSSAIN, 1981; Fig. 2):

a. A lower thin-bedded sequence, which consists of alternating thin sandstone beds (maximum thicknesses 15 m), sheet-like conglomeratic layers and thick mudstones. This part of the section belongs to the Kargocha Formation.

b. A thick-bedded sequence, which consists of sandstone beds with maximum thicknesses of 120 m, separated by thin mudstone intervals. This sequence appears within the Lower Marwat Formation.

c. An upper thin-bedded sequence, which consists of sandstone beds thickness ranging between 5 to 15 m, separated by thick mudstone intervals. This sequence is also characterized by thin, laterally persistent fine to medium-grained sandstone beds (thickness less than 1 m). This sequence belongs to the Upper Marwat Formation.

d. A coarsening-upward (CU) mega-sequence, which in itself consists of smaller CU-sequences. Two major intervals, which are separated by a thin mudstone layer, can be differentiated and each interval consists of 7 CU-sequences (average thickness of each sequence is 30-40 m). This part of the section appears within the Malagan Formation.

Lithologically the measured section consists of arkosic and lithic sandstones (Fig. 2). Within the lower thin-bedded sequence most of the sandstone beds are arkosic; the conglomeratic layers, however, consist of pebbles of mainly sedimentary origin and to a much lesser extent of plutonic or metamorphic origin. The sandstones that are related to these conglomeratic beds are generally lithic sandstones. The thick sandstone beds of the Lower Marwat Formation are mainly arkosic. Towards the upper part of this formation a gradual increase in thin lithic sandstone beds is observed. Finally these lithic sandstones become dominant within the Upper Marwat and Malagan Formations. The pebbles within the Malagan Formation are dominantly of sedimentary origin.

An interesting feature is the occurrence of thin bentonite beds within the mudstone intervals of the Marwat Formation. The matrix of the conglomeratic Bain Boulder Beds consists mainly of volcaniclasts.

Another important feature which can be observed in the field, is the different geometrical organization of the conglomerate and sandstone bodies. FRIEND ET AL. (1979) described the important relationship between river-flow processes and the geometry of these fluvial sediment bodies. Most of these studies, however, are restricted to relatively small river systems. The lateral and vertical dimension of the sandstone bodies in the Kargocha and especially in the Marwat and Malagan Formations indicates the presence of a very large river system, comparable to the present-day Indus river. Despite this important dimensional difference, however, the classification of fluvial sediment bodies given by FRIEND ET AL. (1979) presents an excellent framework (Fig. 3). More recently, ATKINSON (1983) modified and completed this classification; some of his results are used to interpret the different alluvial sediment bodies in the Bhittanni Range. Geometrically three major types can be observed in the Bhittanni Range (compare Fig. 3):

Type A: Sheet geometry, where locally small channels are present within the sediment body fill (dominant type in the Kargocha and Malagan Formations). The stacking of several sheet units produced the complex build-up of this sediment body (type A2). W/D ratio generally exceeds 30 to 1.

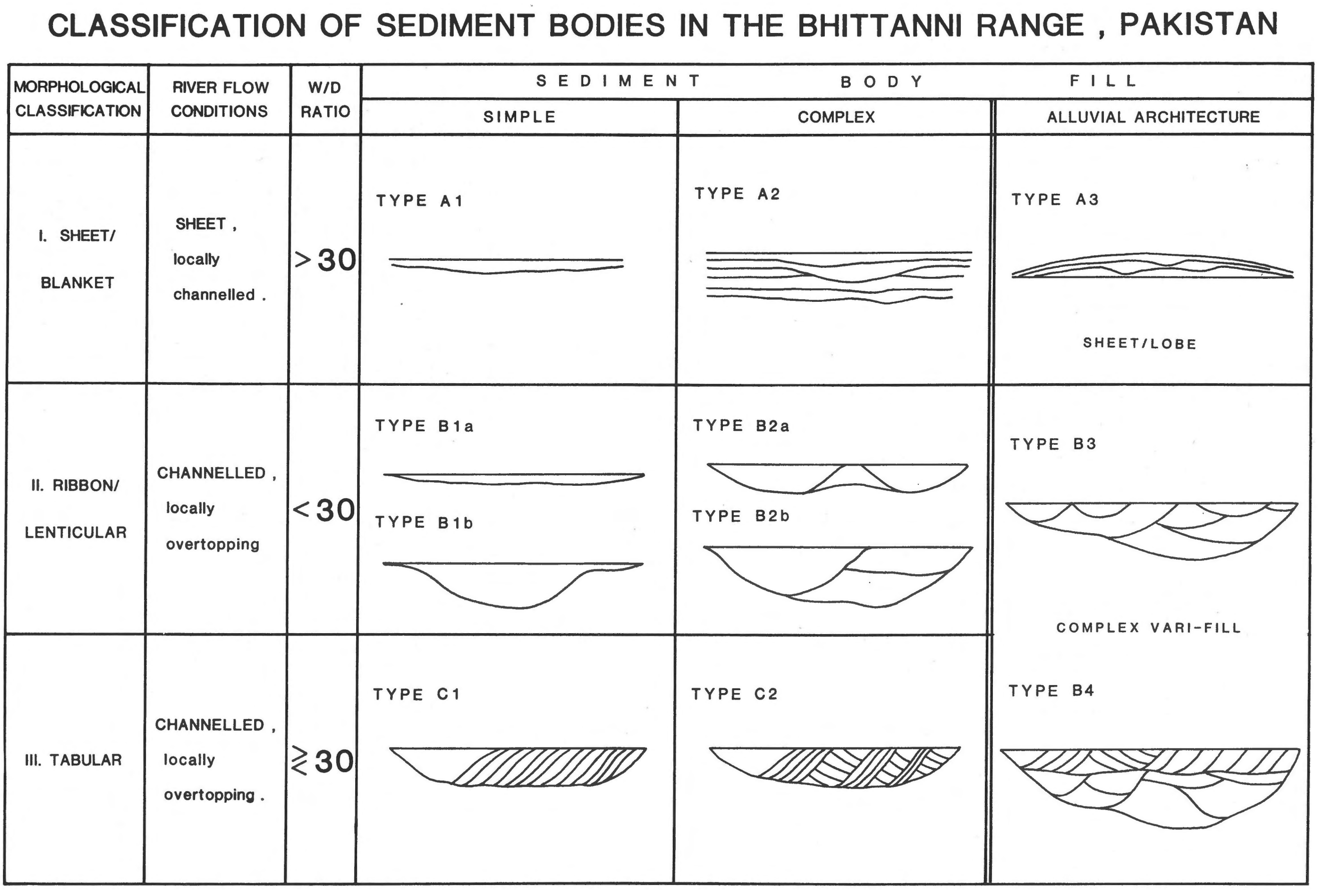

Fig. 3
Classification of sediment bodies in the Bhittanni Range, Pakistan (modified after Friend, 1978 and Atkinson, 1983).

Type B: Elongate geometry (ribbons), where different channel units can be recognized. The channel units, which are separated from each other by scour surfaces, can be arranged laterally (multi-lateral, type B2a) or stacked (multi-storey, type B2b). W/D ratio is smaller than 30 to 1. This type of sediment body geometry is common in the Marwat Formation.

Type C: Tabular geometry, where due to pointbar migration large-scale low angle cross-bedding occurs within the internal fill of the sediment body. This type of geometry is not very common in the Bhittanni Range; usually scattered as small isolated sandstone bodies in the Kargocha and Marwat Formations.

In a more large-scale basinal dimension one can recognize two major types of alluvial architecture (compare Fig. 3):

- Sheet/lobe architecture (type A3), which is common in the Kargocha and Malagan Formations.
- Complex vari-fill architecture (type B3 and B4) which is characteristic for the Marwat Formation.

DESCRIPTION OF THE SEQUENCES

1. *The lower thin-bedded sequence (Kargocha Formation).*

The framework of the sequence consists of channel sandstone bodies (maximum thickness 15 m and numerous sheet-like conglomeratic beds of several metres thickness. A characteristic feature is the presence of thick mudstone intervals (up to 50 m thick). The sand/mud ratio tends to increase towards the upper part of the sequence, which is mainly caused by a thickening of the channel bodies. The main lithofacies within this sequence are:

a. the multi-coloured mudstones
b. the channel sandstone bodies
c. the conglomeratic beds

a. *The multi-coloured mudstones*–A characteristic feature of the mudstone is their vivid brownish-red coloured intervals, mostly associated with thinner yellowish-brown intervals. The brownish-red intervals are generally more calcareous and contain abundant caliche nodules. These nodules generally appear in layers. Whenever these caliche nodules are present, they form small sequences, approximately 1 m thick, in which the density of these nodules increases upward. Vertical mottling structures are also common within these brownish-red intervals.

The thinner yellowish-brown intervals are apparently structureless. Thin and laterally more or less continuous fine sandy to silty layers (thickness in decimetre scale) are intercalated within the mudstone intervals. These more resistant layers, which can easily be recognized in the field, show a pronounced red colouration.

b. *The channel sandstones*–Two main types of sandstone body geometry can be observed within the Kargocha Formation. The tabular sandstone bodies (type C1 in Fig. 3) are more common in the lower part of the sequence. They are embedded within thick mudstone intervals. Towards the higher parts of the sequence, however, elongate or ribbon-like sandstone bodies (type B2a, Fig. 3) become more frequent. At the same time the thickness of the sandstone beds tends to increase.

The tabular sandstone bodies (type C1) are laterally discontinuous (lenght tens of metres). They generally show a distinct FU-sequence with a well developed lateral accretion bedding, which can be traced upon to distances of 30-40 m. The maximum thickness of this pointbar sequence is 3 m. Sedimentary structures within the accretionary units can occasionnally be observed especially in the lower parts and consist mainly of trough crossbedding in decimetre scale. The base of the pointbar sequence consists mostly of coarse sand and may contain some resedimented caliche nodules. The upper parts of the channel are generally homogenized, possibly by rootlets. Fine sandy levees are commonly preserved on top of the pointbar. In addition, the cutbank is also often preserved and the erosional surface is generally obscured by slumped blocks. The bankfull width of the paleochannel is estimated to be approximately 15 m.

The fill of the channel body usually shows a simple pattern (see type C1 in Fig. 3); in some cases, however, complex tabular sandstone bodies occur (type C2 in Fig. 3). Occasionally a cut-off frequency or channel abandonment can be observed (Fig. 4). In that case most of the channel is filled with mud and the thin lateral accretion interval shows an alternation of thin sandy and somewhat thicker mudstone bundles.

The ribbon-like sandstone bodies are laterally continuous (length hundreds of metres), which is caused by the multilateral arrangement of individual channels. The sequence of each channel body can be differentiated as follows:

- an erosional base with a lag deposit consisting of small pebbles, mudstone intraclasts and resedimented caliche nodules. The channel lag is overlain by coarse-grained parallel laminated sands (facies identifier Se2 in Table II);
- a thick interval (average thickness 8-10 m) of coarse to medium-grained parallel laminated sands which may contain some intervals of somewhat coarser resedimented caliche nodule layers (facies identifier Sh in Table II; see also Fig. 5A);
- a thin interval (approximately 1 m), which consists of fine-grained, smallscale cross-bedded sands (facies identifier Sr in Table II; Fig. 5B);
- a mudstone interval, which occasionally shows fine laminations, but is generally homogenized (facies identifier F1 in Table II).

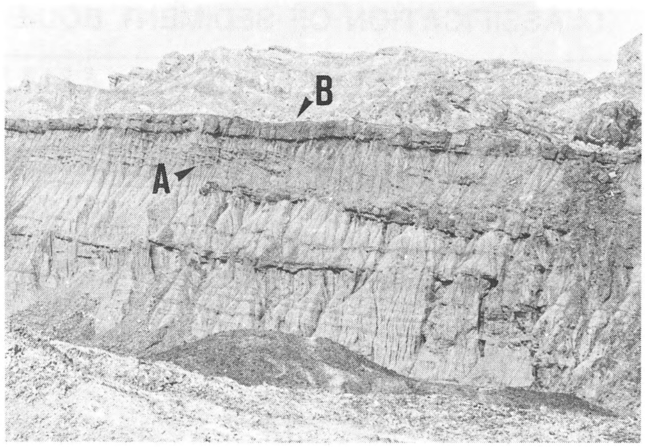

Fig. 4
Mud-filled tabular fluvial body of the Kargocha Formation (type C1). A: initial development of lateral accretion bedding. B: sheet-like conglomeratic layer (type A1).

The fill of these ribbon-like sandstones consists of a multilateral arrangement of individual channels (type B2a); only within the uppermost part of the Kargocha Formation these individual channels (multi-storey arrangement) are stacked.

Most of the channel bodies consist lithologically of greyish-white arkosic sandstones and to a lesser extent of brownish lithic sandstones.

c. *The conglomeratic beds*–Intercalations of conglomeratic beds become more frequent towards the upper part of the Kargocha Formation. These sheet-like conglomeratic bodies (type A1) usually appear together with the ribbon sand bodies. The thicknesses are relatively small (average thickness 1-2 m). The base of these beds is generally flat. The average diameter of the pebbles is 10-15 cm and they are for a larger part of sedimentary and to a lesser extend of plutonic or metamorphic origin. These matrix-supported conglomeratic beds have in general a massive appearance in the field. The matrix consists of a badly sorted coarse-grained lithic sand.

Interpretation–Our observations strongly suggest the existence of extensive floodplains, which were dissected by streams of different fluvial regimes. The mudstones are believed to be deposited in rapidly aggrading floodplains. The occurrence of caliche nodule horizons and the vivid brownish-

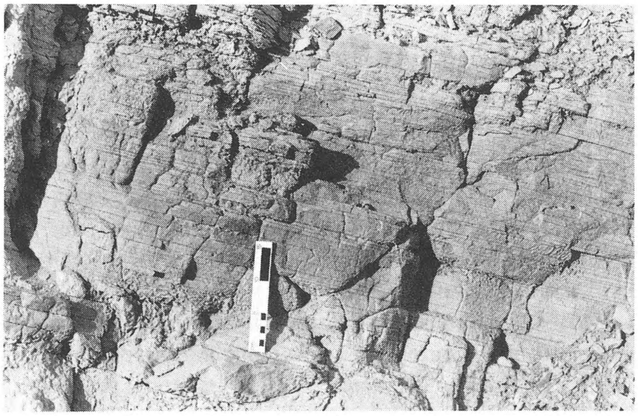

Fig. 5A
Coarse to medium-grained parallel laminated sands of a ribbon-like channel sandstone (type B2a) in the Kargocha Formation. The basal part consists often of small resedimented caliche nodules. Facies identifier Sh in Table II.

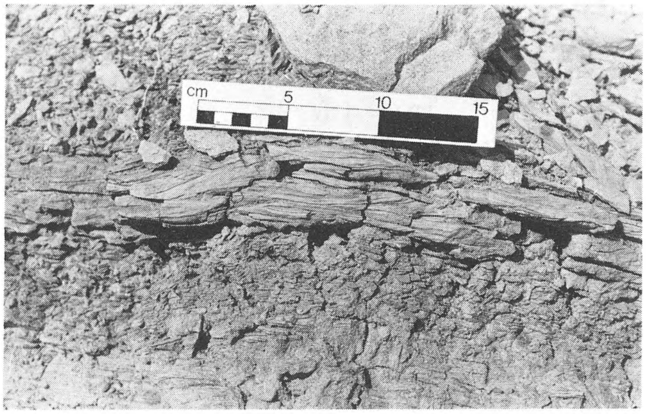

Fig. 5B
Small-scale cross-bedding in the upper parts of ribbon-like channel sandstones in the Kargocha Formation (type B2a). Facies identifier Sr in Table II.

red colours, together with the presence of vertical mottling structures, indicate that these paleosoils were formed under partly hydromorphic conditions in a warm and relatively wet climate, that were interrupted by long hot periods with little precipitation. The brownish-red colours indicate an advanced stage of redbed formation, where iron has been dissolved and oxydized to hematite (WALKER, 1967) through intrastratal alteration of iron-bearing detrital components.

The evolution of the fluvial regime within the Kargocha Formation shows a change from high-suspension meandering river systems (type C1 in Fig. 3) within the lower part of the formation to a coarser-grained and braided system in the upper part (type B2a in Fig. 3). The well-developed lateral accretion bundles, sometimes interrupted by thin mudstone levels within the pointbar sequence, suggest an irregular lateral migration that was caused by periods of high and low water levels (PUIGDEFABREGAS & VAN VLIET, 1978). The occurrence of mud-filled channels also indicates the presence of a cut-off frequency or channel abandonment. The trivial presence of complex tabular channel sandstones (type C2 in Fig. 3) also suggests the initial development of meander belts.

The appearance of a braided river system together with the sheet-like conglomeratic bodies (type A1 in Fig. 3) in the upper part of the Kargocha Formation indicate a change in sediment supply, water discharge and gradient within the basin. The presence of thick intervals of medium to coarse parallel-laminated sands suggests that the depositional processes were dominated by the upper regime flow in relatively shallow channels. These conditions are common in proximal

Table II: Facies identifiers, lithotypes and sedimentary structures (mainly after Miall, 1977, 1978; Rust, 1978)

facies identifier	lithotype	sedimentary structures	interpretation
Gms	massive, matrix-supported gravel	none	debris flow deposits
Gm	massive or crudely bedded gravel	horizontal bedding, imbrication	longitudinal bars, lag deposits
Se1*	erosional scours with intraclasts	trough x-bedding	scour fills
Se2*	erosional scours with intraclasts	horizontal bedding	scour fills
Ss	coarse-medium sands	trough x-bedding	scour fills
Sh	coarse-medium sands	horizontal lamination; parting lineations	planar bed flow (lower/upper) flow regime
S1	coarse-medium sands	low angle bedding ($\leq$ 10 degrees)	scour fills, antidunes
St	medium-fine sands	grouped trough x-bedding	dunes (lower flow regime)
Sp	coarse-medium sands	grouped planar x-bedding	transverse bars, and waves (lower flow regime)
Sr	fine sands	small-scale x-bedding	ripples (lower flow regime)
F1	fine sands, silt/mud interbedded	fine laminations small-scale x-bed-climbing ripples	waning flow deposits

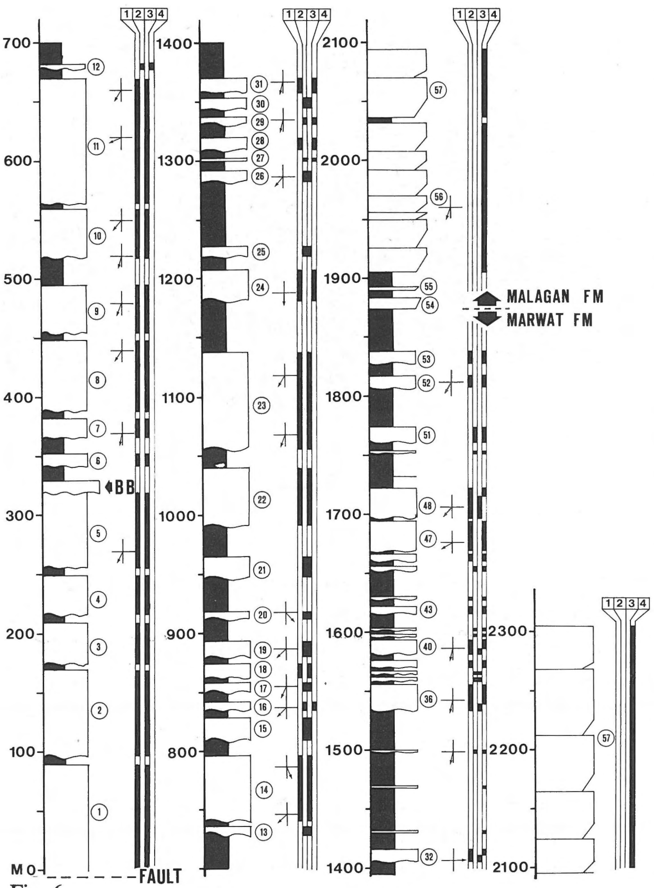

Fig. 6
Schematic section through the southern limb of the Marwat Kundi anticline near the village of Malagan (see Fig. 1B for location). Black: mudstone intervals; white: channel complex sandstones and CU-sequences of the Malagan Formation; BB: Bain Boulder Bed.

braided river systems (MCKEE ET AL., 1967; RUST, 1978). All the sands of the Kargocha Formation were deposited in channeled systems (type B2a); the conglomeratic bodies (type A1) belonged to the distal parts of a large alluvial fan complex. Catastrophic debris flow events during extreme flood periods probably deposited these matrix-supported conglomerates more basinward. The depositional framework within the Kargocha Formation can be summarized as follows:

1. Warm climatic conditions with alternating wet and relatively long dry periods.
2. An evolution of meandering rivers to proximal braided and probably ephemeral river systems associated with distal alluvial fan deposits. The change in fluvial regime was mainly caused by large-scale vertical tectonic movements along the fault system of the Sulaiman Range in the west.

2. *The thick-bedded sequence (Lower Marwat Formation)*

The thick-bedded sequence of the Lower Marwat Formation is approximately 1150 m thick and consists of a succession of 23 sandstone units (Fig. 6). Each sandstone unit consists of a complex of small and large channels, which are laterally as well as vertically stacked. Each unit can therefore be considered as a complex of channels.

The thickest measurable channel complex (nr. 11 in Fig. 6) has a thickness of 105 m. The lowest exposed channel complex probably is more than 120 m thick; its true thickness, however, cannot be measured because of the presence of a fault zone. The smallest channel complex (nr. 12 in Fig. 6) has a thickness of 5 m.

Most of the channel sandstone bodies have an elongate geometry and a complex vari-fill architecture (type B3 and B4 in Fig. 3). The smaller channel complexes consist generally of sandstone bodies with a complex multi-storey sediment body fill (type B2b in Fig. 3) or are of the complex multi-lateral type (type B2a). Within the upper part of the thick-bedded sequence simple channel body fills (type B1b) become more frequent.

The minimum bankfull width of the ancient river can be measured from the aerial photographs and is estimated to be approximately 15 km. The maximum depth of the larger paleo-channels is estimated not to exceed 30 m, which corresponds approximately with the maximum thickness of a more or less complete preserved channel sequence. Therefore, the minimum width/depth ratio is 500. Values exceeding 300 are considered to be braided (LEOPOLD & WOLMAN, 1957; SCHUMM, 1963; MIALL, 1977). The braided character of the large and mostly sandy river of the Marwat Formation is also confirmed by its load type and structural organization.

The channel complexes consist for a large part of coarse to medium-grained sands and numerous conglomeratic intercalations. The presence of many erosional surfaces indicate the unstable behaviour of the different channels.

In an extensive review of braided river deposites MIALL (1977) devised a code system for the different lithotypes. Additions and modifications were made later by MIALL (1978) and RUST (1978). This letter code has been extensively used for describing and classifying the different lithotypes within the measured section (see Table II). Only some minor adaptations have been made. Within the Lower Marwat Formation the following major lithofacies units can be differentiated (see also Fig. 6):
a. the mudstones
b. the channel complexes
c. the conglomeratic bed (Bain Boulder Bed)

a. *The mudstones*–The yellowish-brown mudstone intervals are relatively thin as compared to the thick sandy channel complexes (maximum thickness 52 m). The sand/mud ratio tends to decrease towards the top of the sequence. The mudstones are in general completely homogenized by bioturbation and possibly by rootlets. Occasionally, however, faint laminations of interbedded silty mudstones can be recognized.

Parts of the intervals are calcareous, which is caused by the

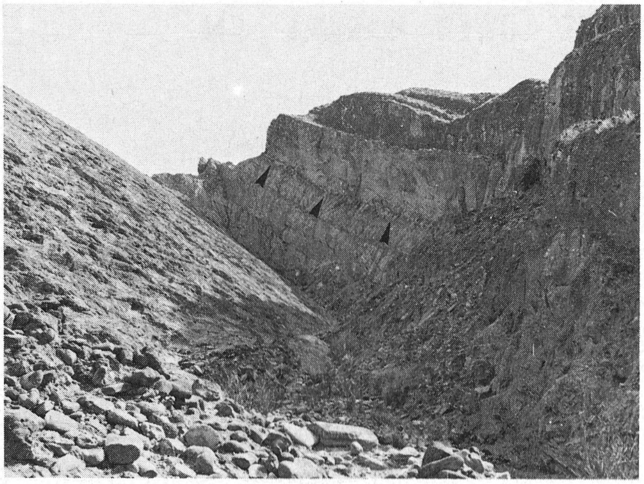

Fig. 7
Base of channel complex 6 (see Fig. 6 for location within the section). Note the relatively flat base of the channel.

presence of several horizons with caliche nodules. Vertical mottling structures are present especially within the thicker mudstone intervals. Several thin white fine-grained beds can be observed within the mudstones. DTA-analysis shows a high content of bentonite, which indicates volcanic activity during the deposition of the Lower Marwat Formation.
The facies identifier of Table II has been used in the sedimentary logs (Fig. 8). The descriptions of the lithotypes and sedimentary structures has been adapted to the field observations and the * marked facies identifiers have been modified.

b. *The channel complexes*–The bases of the sandy channel complexes are in transverse section in general flat and their erosive character can only be seen at large distances (Fig. 7). Several metres of the underlying mudstone intervals are eroded over distances of several hundreds of metres. Local deep erosional scours, however, are present.

Generally two major types of channel complexes can be distinguished in the field:
- Very thick and laterally consistent sandstone units, which form the framework of the Lower Marwat Formation. They display a complex vari-fill fluvial architecture (type B3 and B4). The individual channels have an elongate geometry and are partly vertically stacked (multi-storey arrangement, type B2b) and they also display a multi-lateral arrangement (type B2a).
- Thinner and laterally non-consistent sandstone units, which usually are interbedded within the thicker mudstone intervals. These channel complexes show mostly a multi-lateral arrangement (type B2a) of the individual channels and to a lesser degree a multi-storey succession (type B2b). A few of them, however, have a simple channel fill (type B1b).

The directions of the measured paleocurrents are strikingly stable and are to the SW (each arrow represents 3 or more measurements). Slight variations (within 20 degrees) within one channel sequence, however, are common.

For a more detailed characterization of the channel complexes some examples are here described (Fig. 8):

Channel complex 5: Fluvial architecture type B3. The lower part of this 57.8 m thick channel complex consists of four stacked FU-sequences, interrupted by a 2 m thick conglomeratic bed. The lowest channel unit shows a more or less complete FU-sequence (lithotype succession Se2–Sh–St–Sr). The upper sequence of the two following channel successions was truncated by erosion and is therefore an incomplete FU-sequence. An interesting feature is the presence of a planar cross-bedded interval with set heights up to 2 m. Conglomeratic intercalations occur regularly within this sandstone unit. They mostly have an elongate geometry, probably conformable to the existing channel geometry. The conglomerates are in general poorly sorted and are matrix supported. The pebbles are mostly of sedimentary origin and to a much lesser extent of plutonic origin.

The fine-grained part of the matrix consists for a large part of bentonite, which indicates that the conglomeratic beds within the Lower Marwat Formation were formed in association with volcanic activity. Within the sandy parts we found long vertical burrows (Fig. 9).

Channel complex 8: Fluvial architecture B4. The lower part of the channel complex consists of a complete FU-sequence (Se1–St–Sh–F1). The climbing ripple interval at the top of the sequence shows soft sediment deformation features (Fig. 10).

Channel complex 11: Fluvial architecture B3. The section covers the middle part of the whole sequence. It consists of at least 6 large cross-bedded sets with set heights between 2.5 and 5 m. These large transverse ripples have slightly sinusoidal crests, which can be reconstructed from bedding plane exposures. The base of each set is characterized by more or less deep scours (Fig. 11A) and mostly contains a conglomeratic lag deposit. The dips of the foresets vary between 20 and 25 degrees. Within the foresets a distinct grain size segregation can often be observed, as well as stringers of small pebbles or resedimented caliche nodules (Fig. 11B)

Channel complex 16: Fluvial geometry is elongate with a simple channel body fill (type B1b). The base of the sequence is locally characterized by deep erosional scours and a lag deposit of intraclasts. The sequence consists of a succession of trough cross-bedding and horizontal laminiatons (Se1–St–Sh–St–Sh–Sr–F1). Grains-size and set heights decrease upward, which bring about a distinct FU-sequence (Fig. 12).

Channel complex 20: Fluvial geometry is tabular with a simple channel body fill (type C1). The base of the channel is erosive and consists of coarse-medium sand. The whole succession shows a more or less complete pointbar sequence, consisting

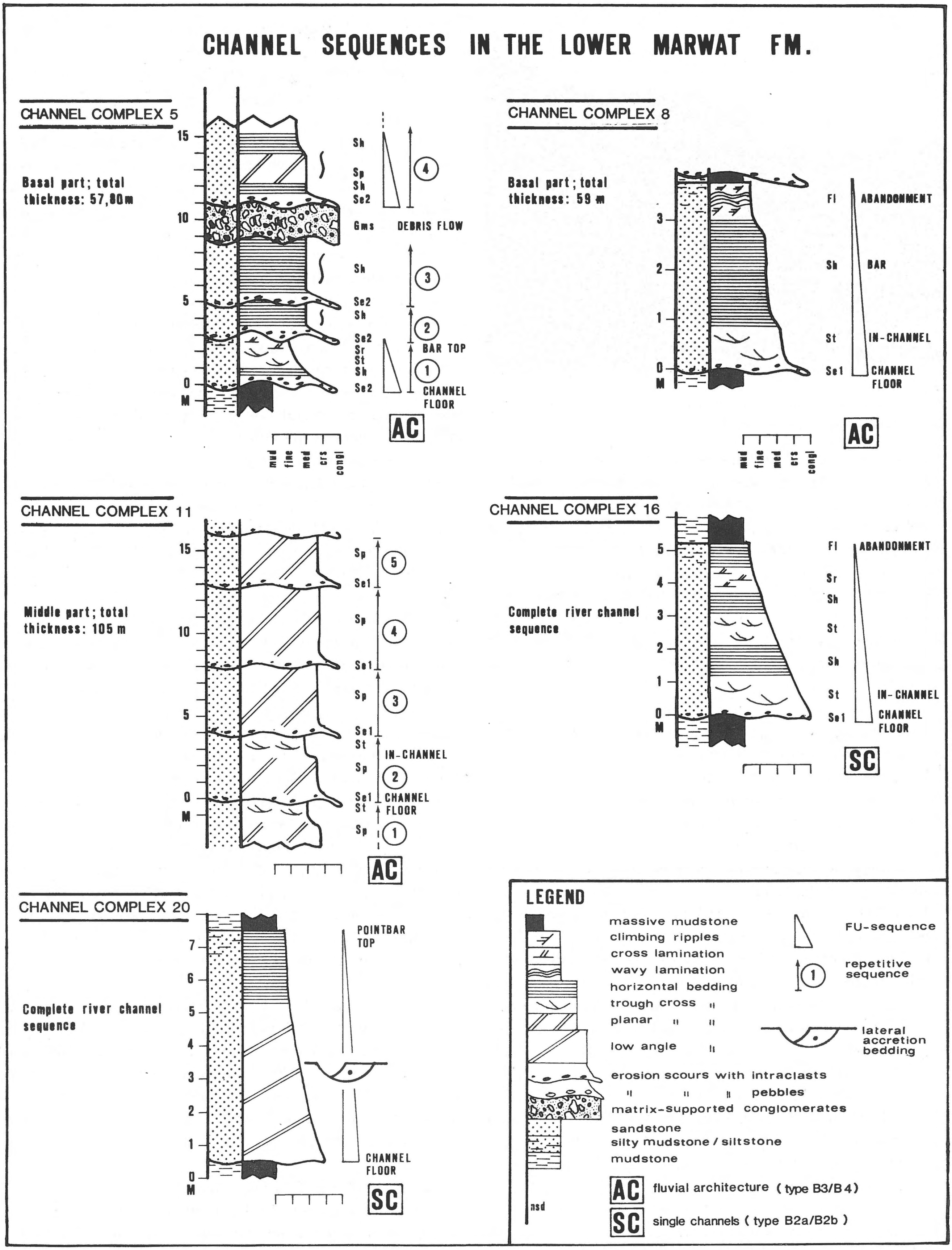

Fig. 8
Some characteristic channel sequences in the Lower Marwat Formation. See text for explanation.

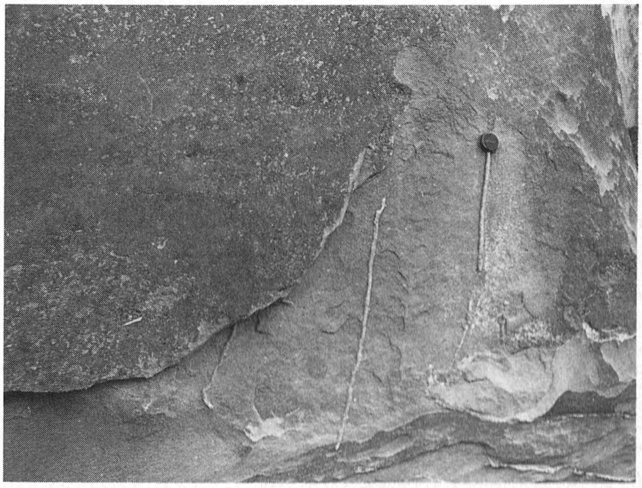

Fig. 9
Long vertical 'escape' burrows within a parallel laminated interval of channel complex 5. See also Fig. 8.

of a lateral accretion interval in its lower part and a medium to fine sandy horizontal bedded upper part (Fig. 13). The fine-grained uppermost part is homogenized by bioturbation.

The channel complexes within the Lower Marwat Formation are mostly arkosic, except for the units 12 and 16 (see Fig. 6), which are lithic. A remarkable diagenetic feature is the abundance of concretions within the sandstones. The larger concretions are found in the more conglomeratic or coarse sandy parts (Fig. 14). Smaller concretions appear partly conformable within the cross-bedded or horizontally bedded layers. Others show no relationship to bedding and appear randomly across bedding planes.

c. *The conglomeratic bed (Bain Boulder Bed)*–MORRIS (1938) first discovered the Bain Boulder Bed in the Bhittani Range. A striking feature of the boulder bed is its lateral consistency. Its thickness varies between 10 and 20 m within a lateral distance of at least 15 km. The boulder bed seems to be

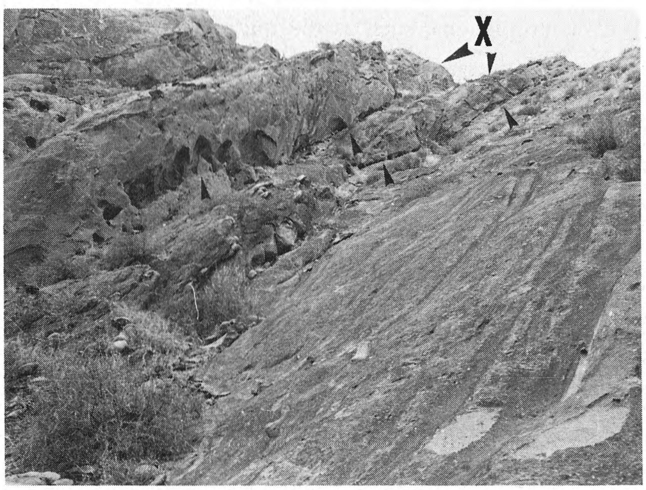

Fig. 11
Giant cross-bedded cosets (X) of channel complex 11. Set heights are 6.5 m. Note the erosional base of the sets (arrows).

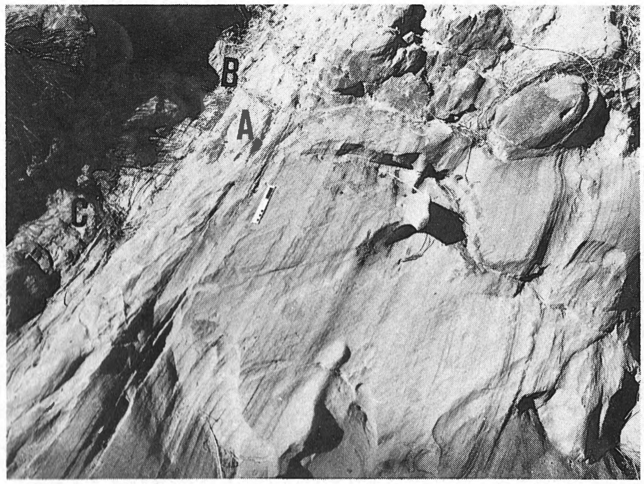

Fig. 10
Basal part of channel complex B (compare also with Fig. 8). Top of the sequence is to the left. The sequence consists of a horizontal laminated interval (scale); a climbing ripple interval (A) a wavy-bedded interval (B) and a contorted cross-bedded interval (C).

thinner in the SE-part of the Bhittanni Range. Its base is generally flat and its weak erosive character is only detectable at large distances (Fig. 15).

The Bain Boulder Bed lies partly on top of channel complex 5 (see Fig. 6). Laterally towards the SE it covers progressively a mudstone interval below channel complex 5. Also remarkable is the unique appearance of the boulder bed within the more than 2100 m thick succession of the Marwat and Malagan Formations. The boulder bed is distinctly matrix-supported and it pebbles originated mainly from sedimentary and metamorphic rocks (Fig. 15B). Pebbles from granitic or other crystalline rock origin do occur, but to a much lesser extent.

Another striking feature is its greyish-white unsorted matrix. DTA-analysis indicates, that a large part of the matrix consists of bentonite, whereas a minor part consists of kaolinite. In both cases we have to assume, that wheathering of volcanic as well as granitic rocks must have taken place in

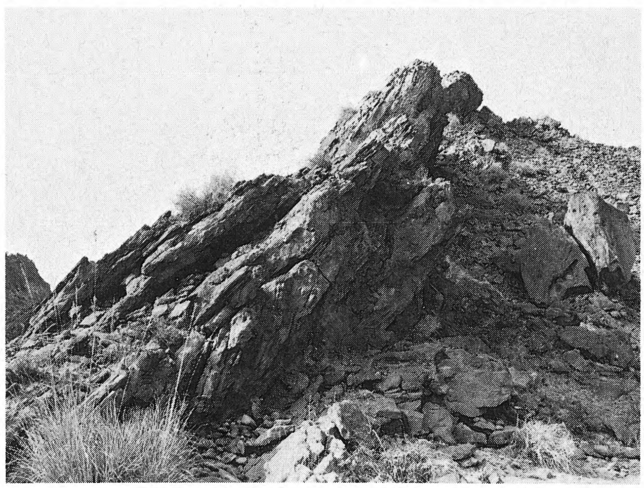

Fig. 12
Complete single channel sequence (channel complex 16, see Fig. 8 for position within the section; type B1a). Top is to the left.

Fig. 13
Tabular fluvial channel body (channel complex 20, see Fig. 8 for position within the section; type C1). Top is to the right; the sequence consists of a lower low-angle lateral accretion bedding (A) and an upper fine sandy-silty parallel laminated part (B).

Fig. 14
Concretions at the base of channel complex 5 in the Lower Marwat Formation. Note the undisturbed parallel laminations.

the provenance area of the Bain Boulder Bed. The coarser fraction of the matrix consists of biotite, feldspar and quartz minerals.

3. *The upper thin-bedded sequence (the Upper Marwat Formation)*

The Upper Marwat Formation is approximately 720 m thick (Fig. 6; from 1150 m up to the lower boundary of the Malagan Formation at 1875 m; see also Fig. 16). The transition from the thick-bedded to the thin-bedded sequence is rather abrupt. The major differences are the much thinner sandstone units or channel complexes, which are separated by thick mudstone intervals. The sandy channel complexes appear within two distinct intervals; a lower grouping of channel complexes appears at 1300-1350 m (see Fig. 6) and an upper grouping within the 1550-1700 m interval. The two groupings of channel complexes are separated by a thick mudstone interval. Within this mudstone interval there are intercalations of thin laterally inconsistent sandstone units. Their structural organization consists of mainly parallel laminations.

The sequential development of the individual channels and the build-up of the channel complexes are similar to those of the thick-bedded Lower Marwat Formation. Bioturbation seems to be more common, especially within the uppermost parts of the individual channel sequences. The lithological development within the Upper Marwat Formation consists of a gradual transition from arkosic sandstones in the lower part to lithic sandstones in the upper part.

4. *Interpretation of the Lower and Upper Marwat Formations*

Despite the small differences between the Lower and Upper Marwat Formations, such as the thicknesses of the sandy

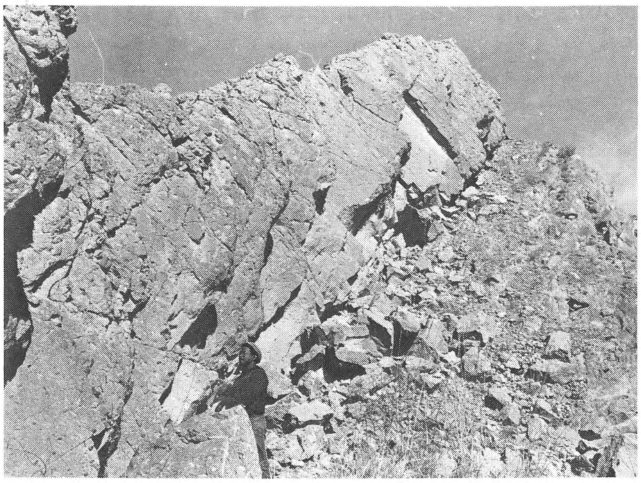

Fig. 15A
The base of the Bsain Boulder Bed. The underlying mudstone interval belongs to the fine-grained part of channel complex 5.

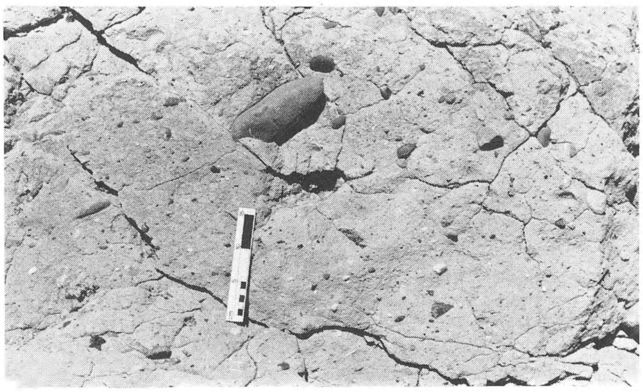

Fig. 15B
Badly sorted and matrix-supported conglomerates of the Bain Boulder Bed. The fines within the matrix consist mainly of bentonite.

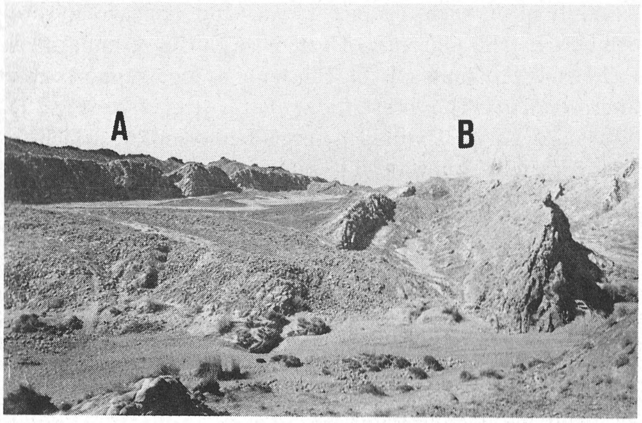

Fig. 16
The base of the Upper Marwat Formation. Note the transition from the thick-bedded sequence (A) into the thin-bedded sequence (B). See Fig. 6 for position within the section at 1150 m.

channel complexes and the lithology, a more or less uniform sedimentation pattern can be assumed. The similar sequential development within the individual channel bodies and the build-up of the channel complexes suggest a continuation of the river regime from the Lower into the Upper Marwat Formation. The differences were mainly the intensity and magnitude of the fluvial processes.

The decrease in magnitude of the channel complexes from the Lower into the Upper Marwat Formation can be explained by a lateral shifting of the main channels in time. The build-up of the different channel complexes also shows a complex picture of an active and less active stacking of individual channels. Within the individual channel bodies itself one can recognize complete as well as incomplete fluvial sequences.

Additional features like width/depth ratio and sediment load type strongly suggest a braided character of the river regime. The magnitude of the channel complexes within the Lower Marwat Formation also suggests the presence of a very large sandy braided river complex, comparable with the present-day Indus river.

Comparisons between the sediments of the Siwalik Group and those of the modern Indo-Gangetic basin are not new, but have been described as early as 1919 by PILGRIM, in 1920 by PASCOE and later by GANSSER (1964); HALSTEAD & NANDA (1973); LE FORT (1975); VISSER & JOHNSON (1978) and BEHRENSMEYER & TAUXE (1982). The multi-channel complex of the present-day Indus river and its flow regime, which is characterized by periods of high-water during the wet seasons and low water during the dry seasons, provides a good depositional model for the Marwat Formation.

The present-day Indus river near Dera Ismail Khan (see Fig. 1) consists of two large main active channels. The secondary channels, which are confined to the sand flats along the river banks and on the large stable islands are only active during the high water periods. The flood channels, which are active at the beginning of the high water period, usually have straight channels. The drainage channels, which are active after the highest flood peak, have a meandering pattern.

Comparisons with the structural and sequential organization of the channel complexes of the Marwat Formation show striking similarities with the processes in the modern Indus river (see also RAYNOLDS, 1981). The sequential development and the build-up of channel complex nr. 5 and 11 can be interpreted as depositional processes within a main active channel. The sequential development of part of channel complex 5 (see Fig. 8) shows several flood periods, as indicated by the numerous superimposed erosional surfaces. During such periods the channel will widen and the sediment load and flow energy will increase considerably. The presence of several beds with horizontal lamination represents such periods, when depositional processes were dominated by the planar-bed phase of the upper flow regime. The aggradational stage, which consists of a sequence of St–Sr–(eventually F1 when preserved) or Sp-Sh, occurred during the falling stage or post-flood period. The fine-sandy parallel-laminated part at the top of the sequence in channel complex 5 (see Fig. 8) was formed by weak currents, probably during the abandonment stage of part of the channel. Similar processes have been described extensively by COLEMAN (1969) from the Brahmaputra river.

Another characteristic feature of large rivers is the presence of very large bedforms (see e.g. COLEMAN, 1969). Channel complex 11 consists for a large part of cosets of large tabular cross-bedded units (set heights up to 5 m). These very large bedforms are commonly formed during the peak flood period and are confined to the deeper parts of the main channels. Channel complexes 8, 16 and 20 (see Fig. 8) are comparable to the secondary channels of the present-day Indus river. A further conspicuous feature, which abundantly occurs in all the sequences of the channel complexes of the Marwat Formation is contorted stratification. Cross-bedded units are often overturned in a downcurrent direction. According to COLEMAN (1969), such structures are extremely common within the Brahmaputra river deposits. They are formed by a rapid rise and fall of the river level and also by heavily sediment-loaden currents.

The interpretation of the Bain Boulder Bed, a unique conglomeratic bed within the Marwat Formation, has always been a problem. The most common interpretation suggests a glacial origin. Based on the faunas above and below the Bain Boulder Bed, correlations have been made with the Alpine Günz glacial period MORRIS, 1938; GANSSER, 1964). Its glacial origin, however, has been questioned by other investigators (COULSON, 1938; GANSSER, 1964).

The geometry and its textural/structural organization strongly suggest a deposition by debris flow. Channeled debris flow deposits are especially common within the distal parts of an alluvial fan complex (BULL, 1964; RUST, 1978). The lithology of the boulder bed, however, indicates a partly volcanic origin. Catastrophic flood events probably eroded volcanic deposits in the provenance area and transported an unsorted mass as a debris flow basinward. Part of the material has been transported through the existing channels.

The depositional framework within the Marwat Formation can be summarized as follows:

1. Sequences of the individual channels and the build-up of the channel complexes strongly suggest the existence of a large, sandy, braided river system, comparable with the present-day Indus river. We assume, that the sediments of the Marwat Formation belong to the Early Pleistocene Indus river system. An eastward shift to its present-day position must have occurred since the Middle Pleistocene.
2. The Bain Boulder Bed can be interpreted as a channeled debris flow deposit that was triggered by a single catastrophic flood event. Eroded volcanic tuff acted as matrix in which pebbles of sedimentary as well as metamorphic rocks were transported basinward, through the existing fluvial channel system.

5. *The coarsening-upward sequence (Malagan Formation)*

The Malagan Formation consists of three major intervals, which in itself consist of several smaller CU-upward intervals (see Fig. 6). The lowermost interval (sandstone unit 54 and 55) consists of two thin CU-upward sequences, separated by a relatively thin mudstone interval. The two overlying sandstone units (nrs. 56 and 57), however, are more massive and each interval consists of at least 7 CU-sequences. The top of the highest sandstone unit is unconformably covered by recent alluvial sediments of the Indus plain.

A major feature within the Malagan Formation is the absence of channels. The CU-sequences start with a flat and non-erosive base and generally consist of medium sands. The top of such a sequence consists of coarse sand with numerous intercalations of conglomeratic stringers. Locally small-scale scour surfaces may appear within the uppermost part of a CU-sequence. The CU-sequences are structurally organized in parallel beds. The occasionnal appearance of crude cross-bedding is confined to the more conglomeratic beds within the uppermost part of each CU-sequence.

The Malagan Formation lithologically consists of lithic sandstones. Most of the pebbles are also of sedimentary origin.

Interpretation–Interpretation of the Malagan Formation proved to be difficult, as descriptions of modern analogues are still scarce. The lobe-like geometry and the CU-sequences are important features which help the interpretion of the genesis of these deposits. The smaller CU-sequences are related to the smaller lobe-like geometries. The different superposition of the lobes characterizes the progradation of the whole system basinward. The Malagan Formation is probably comparable to fluvial terminal fans. Modern analogues were described by GEDDES (1960) and MUKHERJI (1976) from the Indo-Gangetic plain. FRIEND (1978) gave a more detailed description of such distinct lobate and concave-upward complexes. The presence of extenvise fluvial terminal fans within the proximity of the Bhittanni Range supports this interpretation. The present-day Pezu river (see Fig. 1) discharges its load within a large fan complex, which is approximately 5 km wide at its outer margin and has a length of about 6-7 km. It is obvious that such complexes are formed preferably in large intramontane basins, which function as a kind of catchment basin of the fluvial system. A number of factors may cause a decrease in discharge of such rivers (FRIEND, 1978):

1. Loss of water into permeable alluvium and/or
2. evapo-transpiration coupled with a lower precipitation on the plain and its hinterland.

CONCLUSIONS

The following preliminary conclusions concerning the development of the fluvial regime, basin configuration, provenance area and the related large-scale tectonic movements from the Late Pliocene to the Middle Pleistocene in the Bhittanni Range can be made (see also Table III):

1. Fluvial development

The changes of the fluvial regime from Late Pliocene to Middle Pleistocene are intimately related to changes in channel body geometry and fluvial architecture. The gradual change of the fluvial regime in the Kargocha Formation from high-suspended and high-sinuosity streams into straight and braided streams was probably caused by the shift of the paleo-Indus river system into the Bhittanni Range. The Lower Marwat Formation consists mainly of deposits of the paleo-Indus river system. During a later stage this large river system shifted eastward. The thin-bedded sequence of the Upper Marwat Formation reflects this eastward migration and secondary channels, which were only active during the flood periods, came into existence. A further decrease of the water supply caused a degradation of the fluvial system and also of the basin conditions forming extensive fluvial terminal fans (the Malagan Formation).

The Bain Boulder Bed, finally, represents an exceptional catastrophic event, during which volcanic tuffs were eroded in the provenance area and transported basinward through the existing fluvial channel system. Thin bentonic beds within the mudstone intervals indicate volcanic activity during the deposition of the Marwat Formation.

2. Basin configuration

Sediments of the Kargocha Formation were deposited within large, more or less flat and extensive alluvial plains. The appearance of conglomeratic beds in the upper part of the Kargoche Formation indicates an uplift in the provenance areas and an gradual increase of relief within the basin. At a later stage the basin floor was gradually tilted eastward, which

Table III: Relationship between fluvial development, basin configuration and large-scale tectonic movements in the Bhittanni Range, Pakistan

		Sediment body geometry	Fluvial regime	Basin configuration	Provenance area	Tectonic movements
Malagan Fm		complex type A2 sheet/lobe type A3	fluvial terminal fans	intramontane basins/ large inland basins	sedimentary rocks/ Cretaceous-Tertiary	vertical movements along the Main Boundary Fault
Marwat Fm	Upper	ribbon-simple type B1 and tabular type C1 or complex type B2a	secondary drainage channels abandonment of main active channels	large flat floodplains	mixed sedimentary and rystalline rocks	vertical movements along the Main Boundary Fault
	Lower	ribbon-complex type B2a/B2b; complex vari-fill type B3/B4	large, braided river/ paleo-Indus	large flat floodplain, mainly covered by river bed	mainly crystalline rocks	strong basin subsidence
Kargocha Fm		sheet-simple/complex type A1/A2 sheet/ lobe type A3	straight braided channels and high-sinuosity channels/ alluvial fans	large flat floodplains	mixed sedimentary and crystalline rocks	moderate basin subsidence

probably can be related to vertical tectonic movements within the Sulaiman Range in the west and northwest of the Bhitanni Range.

3. Tectonic activities

Major tectonic movements took place in the source areas in the northwest and west of the Bhittanni Range. Most of the movements probably took place within the Sulaiman Range, west of the Indus plain.

An initial erosion of the sedimentary cover of the crystalline massifs in the north and northwest was accomplished during the deposition of the Kargocha Formation. At a later stage, the crystalline massives itself were eroded and this was associated with volcanic activity during the deposition of the Marwat Formation. New vertical movements along the Main Boundary Fault system brought about a renewed erosion of Cretaceous and Early Tertiary sedimentary rocks. Evidence of considerable basin subsidence during the deposition of the Marwat Formation is manifested by the huge accumulation of fluvial sediments. More recent tectonic movements, finally, caused an intense erosion of the sedimentary rock complexes along the Main Boundary Fault zone, adjacent to the molasse basin of the Bhittanni Range.

The model here presented is still incomplete and some aspects will need further study. Further detailed studies of especially the lateral relationships of the lithotypes within the channel complexes will eventually contribute to a further and better understanding of the depositional framework of ancient large, sandy braided river systems.

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