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Fluvial architecture and depositional system of the Miocene molasse sediments, Shakardarra formation, southeastern Kohat, Pakistan

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ABSTRACT: *The Neogene molasse sediments in southeastern Kohat area are divided into two groups, the Rawalpindi, and the Siwalik groups. The Siwalik Group in the study area, around Shakardarra town, is a coarsening upward sequence of silt dominated Chinji Formation, sand dominated Shakardarra Formation, and polymictic conglomerate dominated Indus Conglomerate Formation. The Shakardarra Formation is comprised of sandstone-siltstone in the basal part, dominantly sandstone in the middle part and sandstone-conglomerate in the upper part. The major sandstone-bodies, on average, are up to 15m thick and many km in lateral extent in the lower part, whereas, up to 100m thick and tens of kilometres in lateral extent in the middle and upper parts. The sandstone-bodies are multistoried, and are characterized by inchannel lithofacies such as plane-bedding, low angle plane-bedding and trough cross-bedding. A number of bar macroforms and channel features of different hierarchal order have been observed in the sandstone-bodies. An high energy braided river system is suggested for the deposition of the sediments. The paleoriver system was flowing approximately parallel to the present day Indus river, and entered the foreland basin through the study area at least since last 10 ma.*

INTRODUCTION

Post orogenic molasse sediments in the Kohat area (Fig. 1) are grouped into two coarsening upward sequences (Fig. 2). The basal Rawalpindi Group is comprised of silt dominated Murree Formation in the basal part and sand dominated Kamlial Formation in the upper part. The overlying Siwalik Group is comprised of silt and mud dominated Chinji Formation, passing upward into the sand-rich Shakardarra Formation which grades up-section into polymictic conglomerates of the Indus Conglomerate Formation. The Shakardarra Formation in the Kohat area is stratigraphically equivalent to the Nagri Formation in the Potwar area and Trans-Indus Ranges, whereas, the Indus Conglomerate Formation is comparable to the Dhok Pathan Formation of the Potwar and Trans-Indus Ranges. The new names are proposed for this area because these formations are lithologically very different from their stratotype in the Potwar area. The sediments of the Siwalik Group are not only time transgressive (Raynolds & Johnson, 1985), but also exhibit remarkable lithological variations. For example, the Nagri Formation at its stratotype in the Potwar area is comprised of interbedded sandstone and siltstone, while in the study area, the stratigraphically equivalent strata is comprised of conglomerate, sandstone and siltstone. Similarly, the Dhok Pathan Formation at its type-locality is characterized by siltstone interbedded with sandstone and subordinate conglomerate. Stratigraphically equivalent strata in the study area is characterized by thick

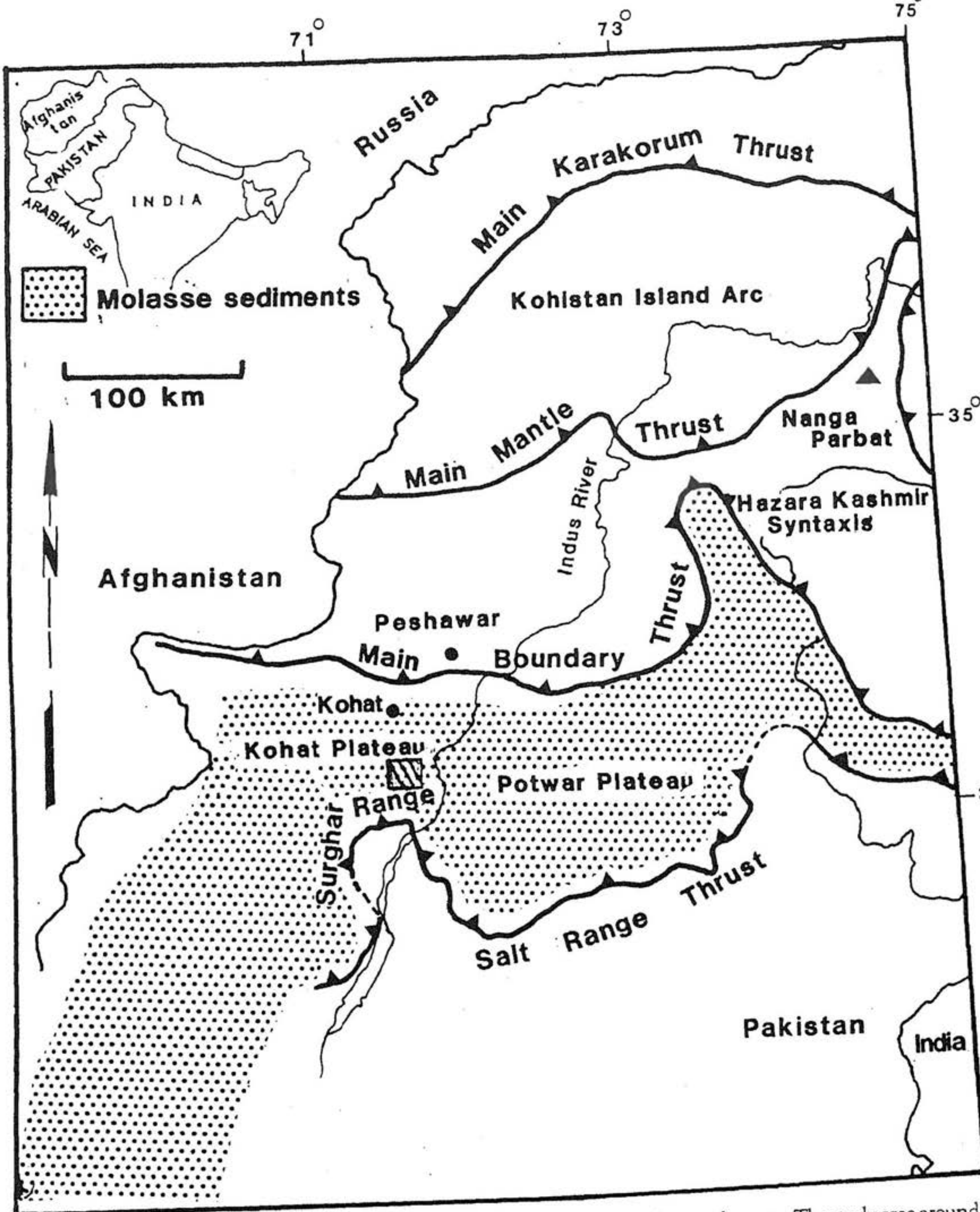


Fig. 1. Sketch map of the Kohat-Potwar area showing distribution of molasse sediments. The study area around Shakardarra town is marked by a square.

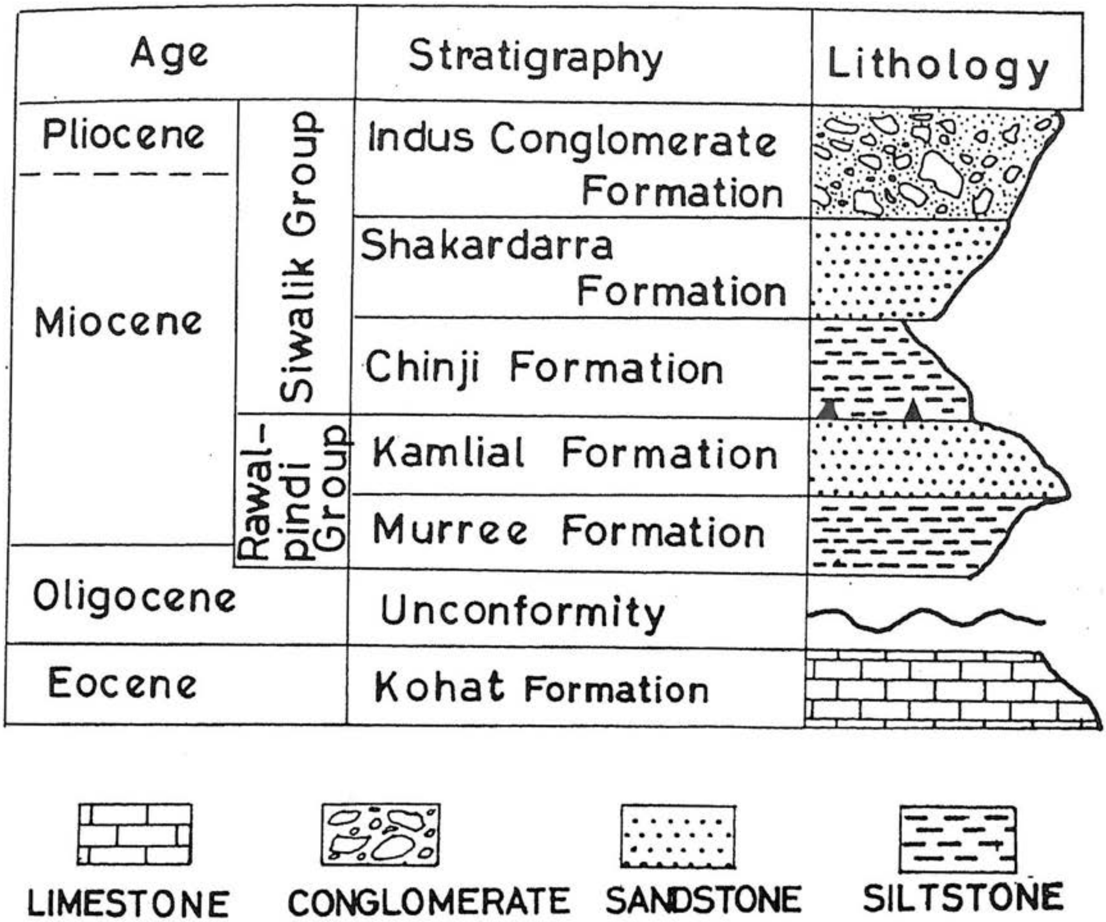
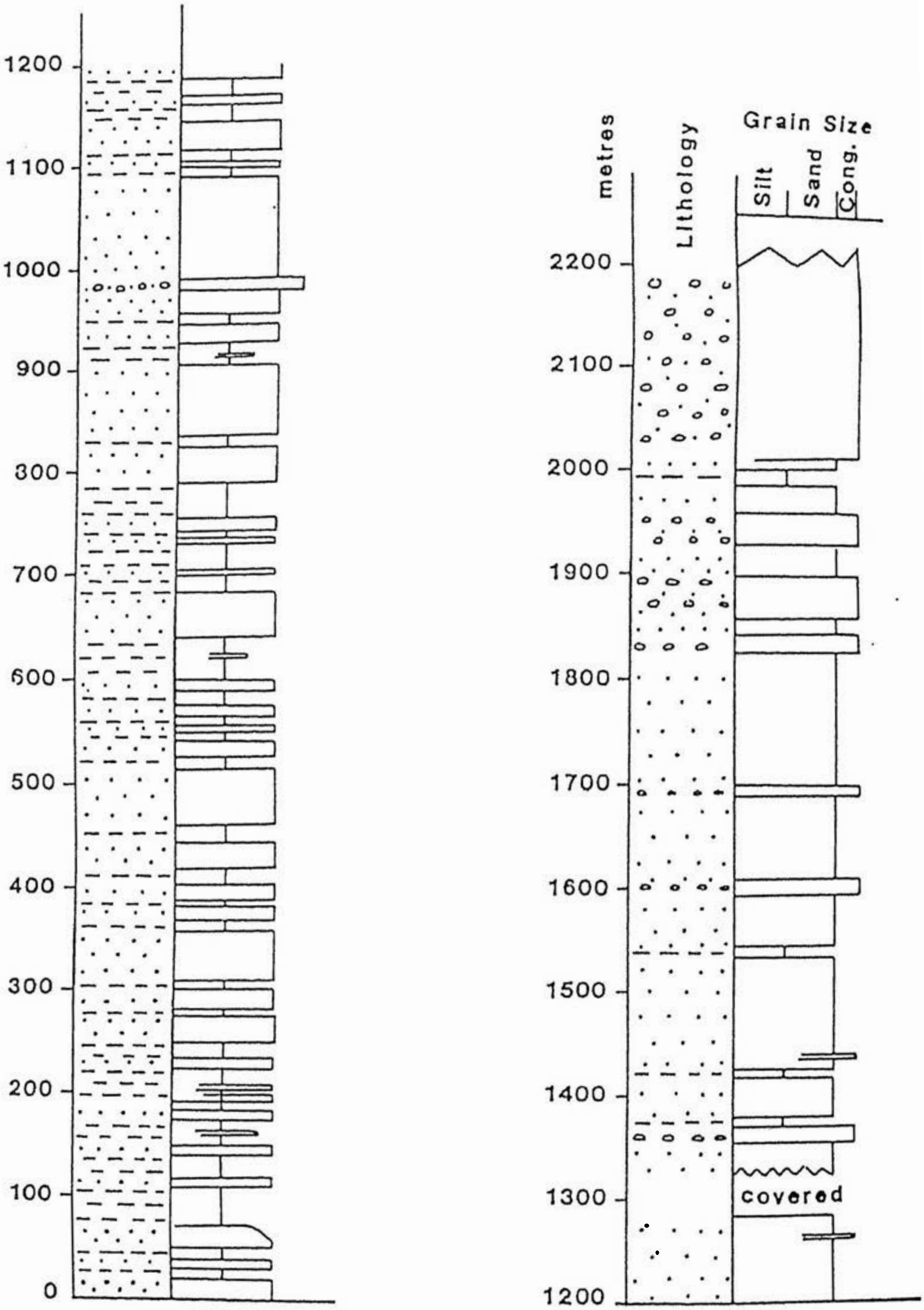


Fig. 2. Neogene stratigraphy of the molasse succession in Shakardarra area.

polymictic conglomerate interbedded with subordinate sandstone.

In the Potwar area, the molasse sediments have been a focus of extensive research in palaeontology (Pilbeam, 1982), magnetostratigraphy (Opdyke et al., 1979; Johnson et al., 1982; 1985; Tauxe & Badgley, 1988) and sedimentology (Visser & Johnson, 1978; Behrensmeyer & Tauxe, 1982; Willis, 1991; Khan, 1994) during past two decades. On the contrary, similar strata in the Trans Indus Ranges and Kohat area lack such studies. Nio and Hussain (1984) presented a general sedimentological analysis in the Marwat Range, south of the study area. McDougal (1989) described the change in course of Paleo-Indus river during past 1 ma, while Abbasi (1991) worked out the depositional system of the Kamlial Formation from the study area.

The Shakardarra Formation (Miocene) in the study area is about 1800m thick and can be divided into three distinct lithological units (Fig. 3 & 4a, b). The basal unit is about 600m thick and is comprised of almost equal proportions of sandstone and brown to yellowish brown colour siltstone. The sandstone units are generally 10-15m thick, interbedded with intraformational and exotic conglomerate. The middle unit is



Shakardarra Formation

Fig. 3. Stratigraphic section of the Shakardarra Formation from the study area.

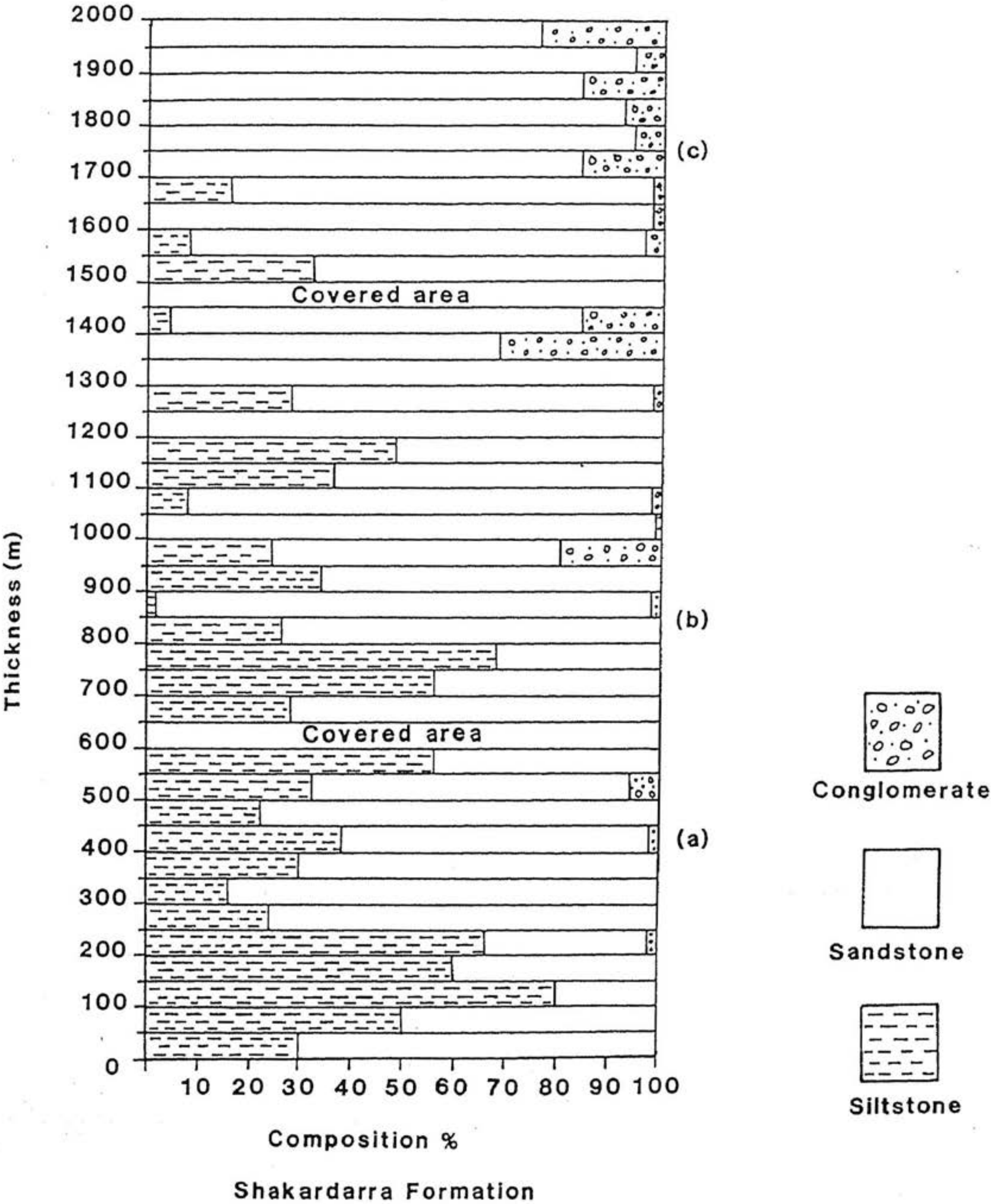


Fig. 4. (a) Lithological plot of the Shakardarra Formation. Note decrease in fine grained sediments upsection. Sandstone is the dominant lithology in the middle part, and sandstone-conglomerate interbeds in the upper part of the formation.

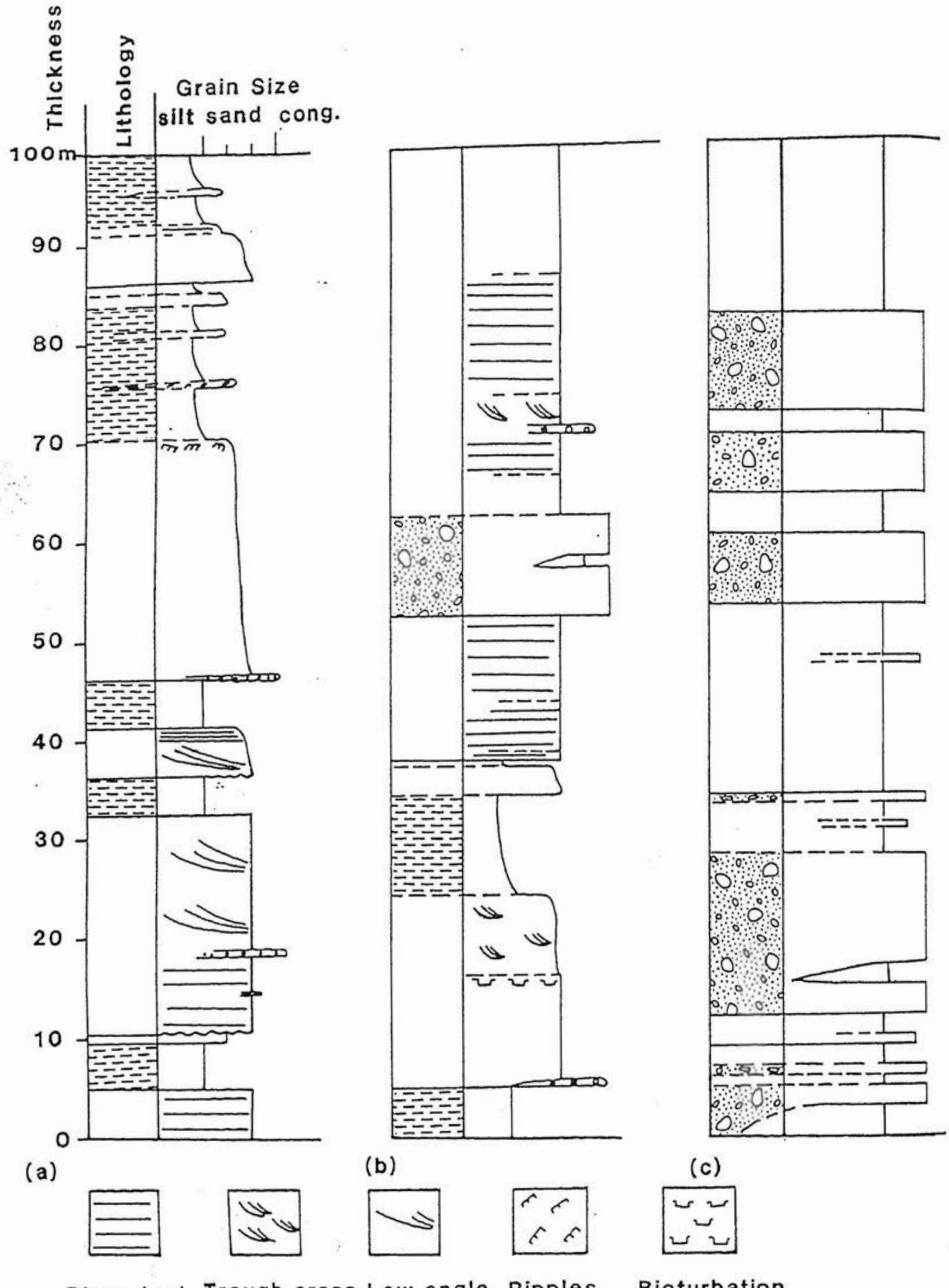


Fig. 4. (b) a, b and c are detailed measured sections in the lower, middle and upper part of the formation marked in Figure 4a.

about 800m thick, sandstone with subordinate clay, silt and conglomerate. The sandstone sequences are multistoried and vary in thickness from 60-80m (Fig. 3). The beds of exotic conglomerate are commonly interbedded with sandstone units. The upper unit of the formation is comprised of sandstone interbedded with polymictic conglomerate. Siltstone is either absent or minor in amount. This unit is about 400m thick and conformably passes up section into the major conglomerate succession of the Indus Conglomerate Formation. The sandstone sequences are on average 50m thick, while conglomerate units are 20m thick, and are composed of igneous and metamorphic clasts of Himalayan affinity (Abbasi & Friend, 1989; Abbasi & Khan, 1990).

This paper describes the fluvial architecture and depositional system of the Shakardarra Formation from southeastern Kohat (Shakardarra area) in order to workout the paleoriver system and orogenic imprints on the foreland basin.

FLUVIAL ARCHITECTURE

A complete sequence of the Shakardarra Formation is exposed in the northern limb of a box shaped syncline near Bori village (Fig. 5a), 1 km east of Shakardarra town. The Shakardarra Formation is nicely exposed, and sandstone-bodies are traceable for several hundreds of metres laterally, particularly in its lower part. In a few cases internal bedforms can also be studied. The uniform grain size (medium sandstone) in the Siwalik sandstones makes the study of sedimentary structures rather difficult. The stratigraphy is younging southward and the strike of the sandstone-bodies trends E-W. A stratigraphic section BB' (Fig. 5b) was measured and studied laterally, and locally described in detail.

The lower part of the Shakardarra Formation is a sequence of interbedded sandstone and siltstone in almost equal proportions. The sandstone-bodies are composed of gray to bluish-gray in colour, medium-grained sandstone. Sandstone-bodies B1 to B23 (Figs. 5b, 6) interbedded with overbank fines were studied in-detail. The sandstone-bodies are on average 8-10m thick, but sandstone-bodies over 15m thick are also present. Thickness varies greatly along strike as the sandstone-bodies pinch and swell laterally. Their basal contact with the underlying siltstone is sharp and erosional, exhibiting sole structures such as flute marks, gutter casts and pedestal structures (Abbasi & Friend, 1993). The sandstone-bodies are internally composed of plane-bedding, low-angle plane-bedding, trough cross-bedding both small and large scale, bar macroforms and channel scour features. Important features observed in the sandstone-bodies are a) vertical and lateral amalgamation, b) bar macroforms, c) Large-scale trough cross-sets and d) channel-fill deposits.

Vertical and lateral amalgamation of sandstone-bodies

The large thicknesses and extensive lateral persistence of the sandstone-bodies is attributed to vertical and lateral amalgamation. The sandstone-body B8 in its western part is the result of amalgamation of two individual sandstone-bodies, each about 4m thick. In the eastern part they are separated by two metres thick overbank fines (Fig. 7b). This indicates at least two metres of erosion in the western part before deposition of the upper part of the sandstone-body. The sandstone-body B23 has been formed as a result of stacking of a major sandstone-body, a minor sandstone-body, and a channel-fill deposit in the eastern part (Fig. 7d). The sandstone-body B13 is about 10m thick and contains a thin clay/silt layer in its upper part. Similarly at least three erosional surfaces are recognized in the sandstone-body B17 which is 15m thick.

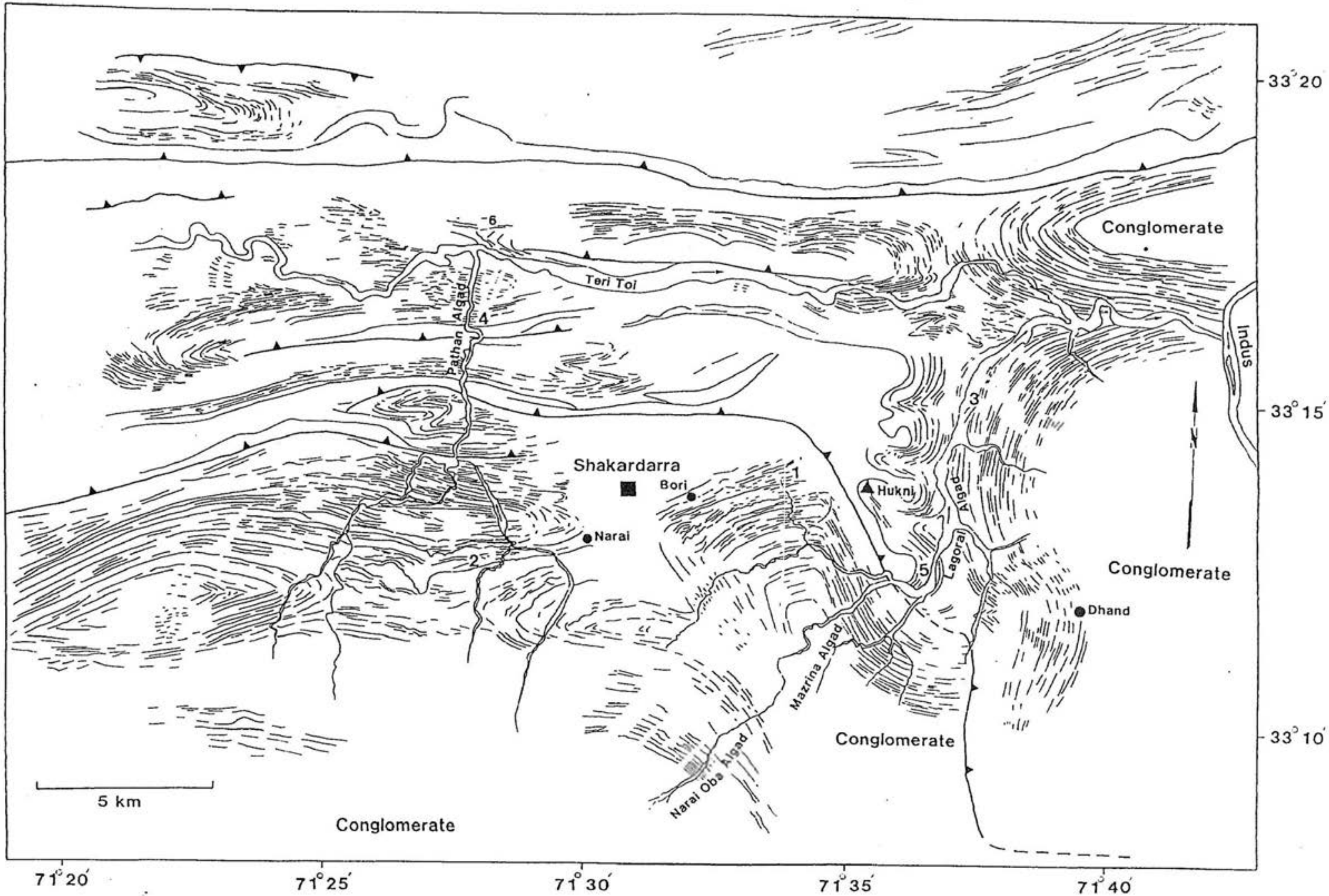


Fig. 5. (a) Line drawing map (from the aerial photographs) of the sandstone-bodies around Shakardarra.

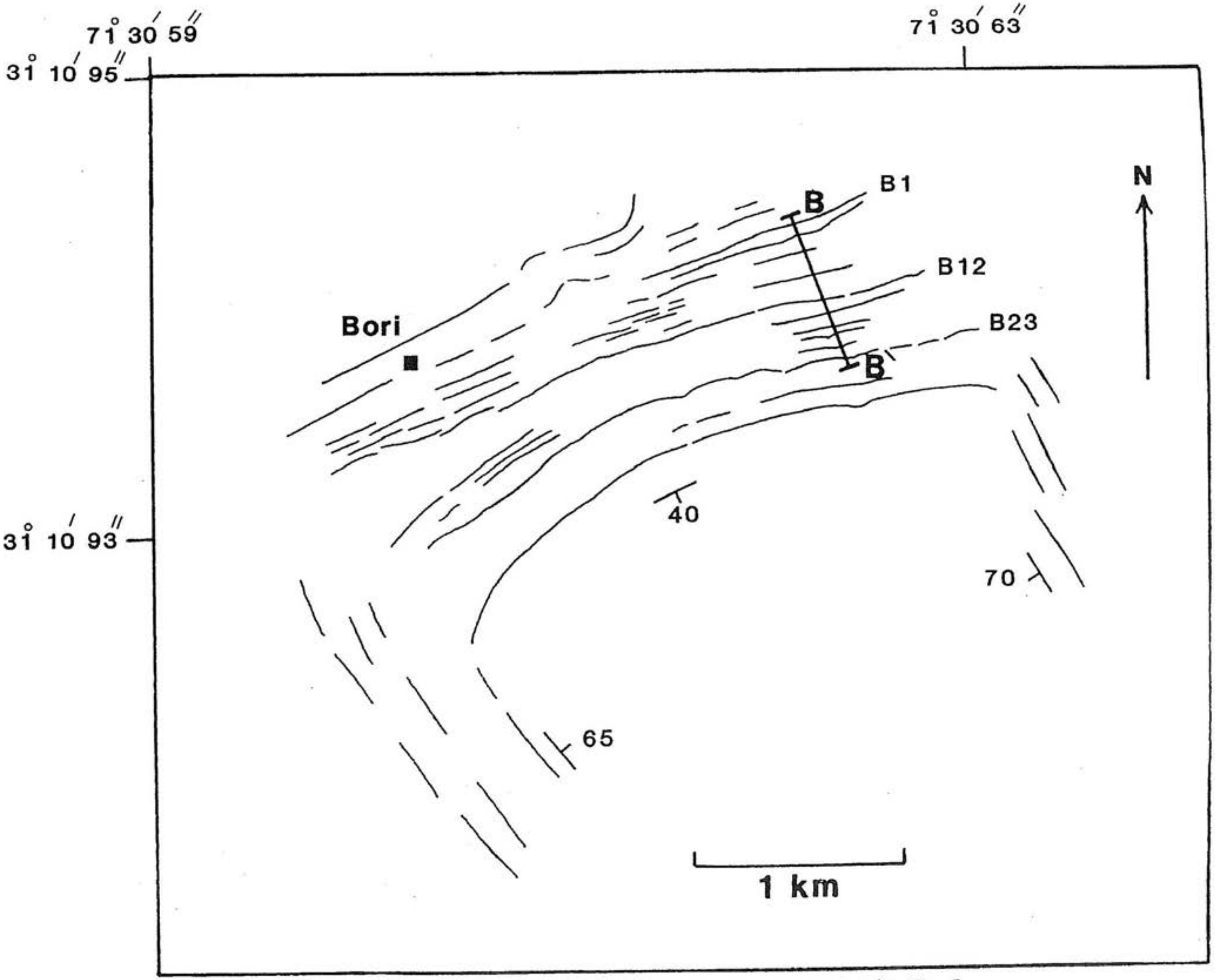


Fig. 5. (b) Sandstone-body map around Bori area across line B-B' in Fig. 5a

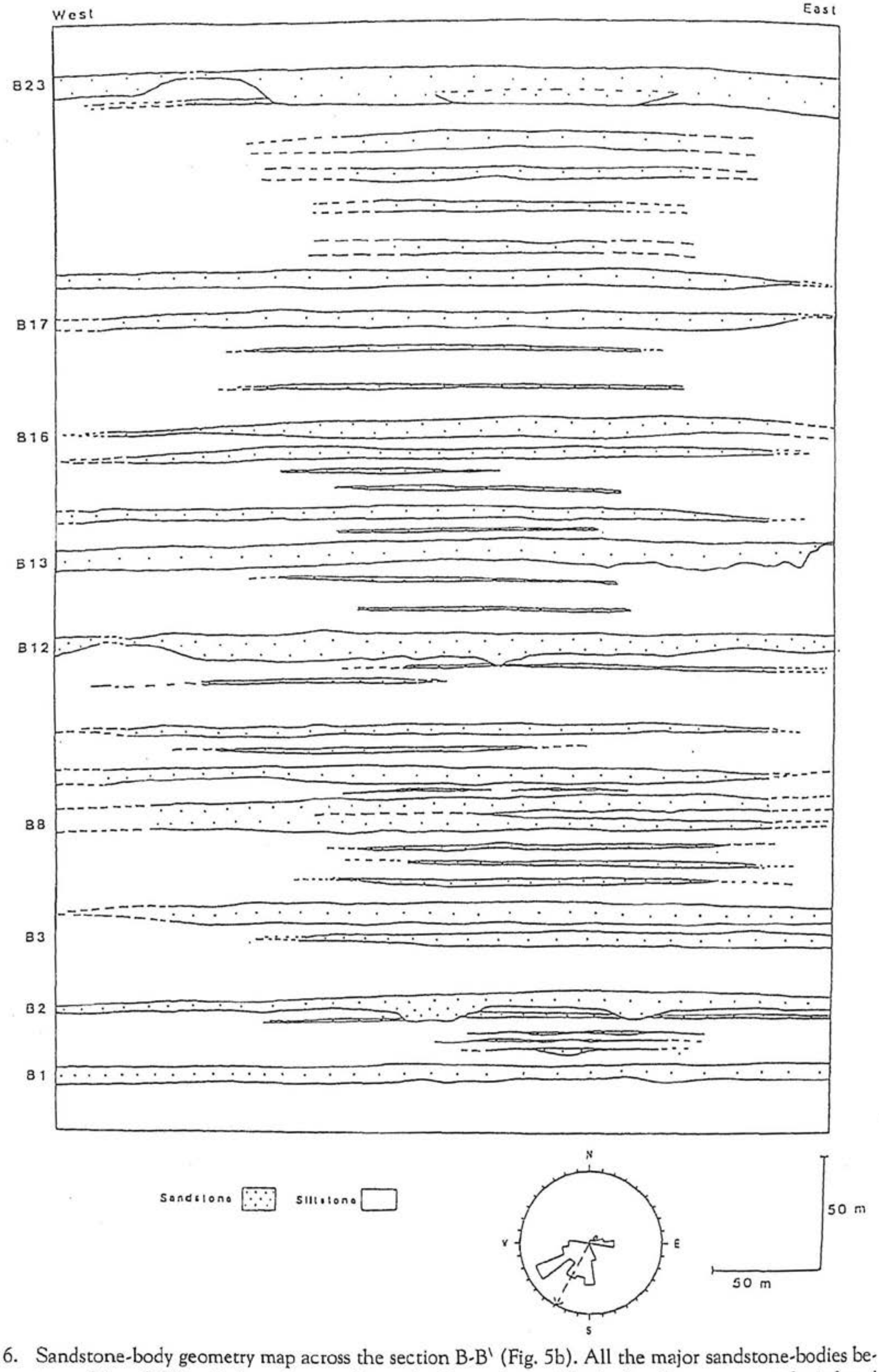


Fig. 6. Sandstone-body geometry map across the section B-B' (Fig. 5b). All the major sandstone-bodies between B1 and B23 and a few minor sandstone-bodies are shown. The broken lines represent the inferred extension of the sand-bodies as they disappear under the fields.

The large magnitude of sandstone-bodies B12 and B23 is due to lateral interconnection of a number of tabular sandstone-bodies. In sandstone-body B23 (Fig. 7d), the major channel pinches-out to the west with the initiation of a new channel further west. Likewise sandstone-body B12 pinches out towards west of the channel-fill c7, but swells again further west indicating the formation of an active channel (Fig. 7c).

Bar macroforms

Bars are defined as depositional areas adjacent to channel thalweg (Bridge, 1985). The bar dimensions scale with bank-full channel dimensions, but are frequently modified by erosion and deposition, and therefore, experience a complex history of accretion and erosion (Cant, 1978; Cant & Walker, 1978; Church & Jones, 1982). The term macroform was used for bars by Jackson (1975) and Church and Jones (1982). The macroform characteristically consists of genetically related lithofacies and a hierarchy of internal bounding surfaces (Miall, 1985).

A number of bar macroforms were recognized in the sandstone-bodies on the basis of their internal lithofacies bounding surfaces (1st order), and the surfaces lying below and above the bars. Three dimensional exposures in sandstone-body B12 (Fig. 7c) provide a good opportunity to define different bar macroform features. In the eastern part of the sandstone-body, bar B1 is probably the oldest depositional unit. Internally the bar appears massive, and devoid of first order bounding surfaces. The basal contact with the underlying siltstone is erosional and contains a layer of lag deposits. The upper surface is gradational but no cyclicity is present. The sides of the bar were eroded by shallow channels during low-flow, which deposited channel-fill and trough cross-beds. A small channel-fill to the east of the bar shows flow direction to the south. To the west of bar B1, a major channel (probably a 2nd order channel) started scouring and subsequently deposited a channel-fill sequence c1.

During the next flood-season, a new bar B2 was deposited adjacent to and on top of the older bar B1 and channel aggradation deposits. Bar B2 is composed of planar-bedding (Sh) and low-angle plane-bedding (Sl). The plane-bedding dominates the central and upper part of the bar, and low-angle plane-bedding marks the margins of the bar or represents the bar accretion surfaces. These bar accretion surfaces (Sl) show small-scale eastward progradation of the bar. Similar lateral aggradation or lateral accretion surfaces are present in the lower part of the sandstone-body B8, where they laterally pass into the channel-fill deposit c1 (Fig. 7b). This low-angle plane-bedding is also described from the Brahmaputra River (Bristow, 1987) and are regarded as surfaces of downstream and occasionally upstream accretion. Coleman (1969) attributed the low-angle plane bedding to sand-wave migration. Abundant sediment supply and constant shifting of the thalweg results in the preservation of a large percentage of this type of stratification (Coleman, 1969). An important feature of these low-angle surfaces is the formation of scoop-shaped features at their eastern termination (Fig. 7c). A number of prograding surfaces of this type lie parallel to each other. The scoop-shaped features at the margins of lithofacies (Sl) are probably formed due to water-escape structures. These were formed as the water level lowered along a bar, and later lithification forced excess water in the bar to escape along the bedding planes. The bar B2 is capped by a thin layer of lag deposits.

During the following high-flow season, bar B3 started growing adjacent to bar B2. The internal structures are similar to bar B2, and it is delimited in the east by a layer of fine-grained siltstone. Bar B3 contains at least three layers of thin lag deposits suggesting bar aggradation or

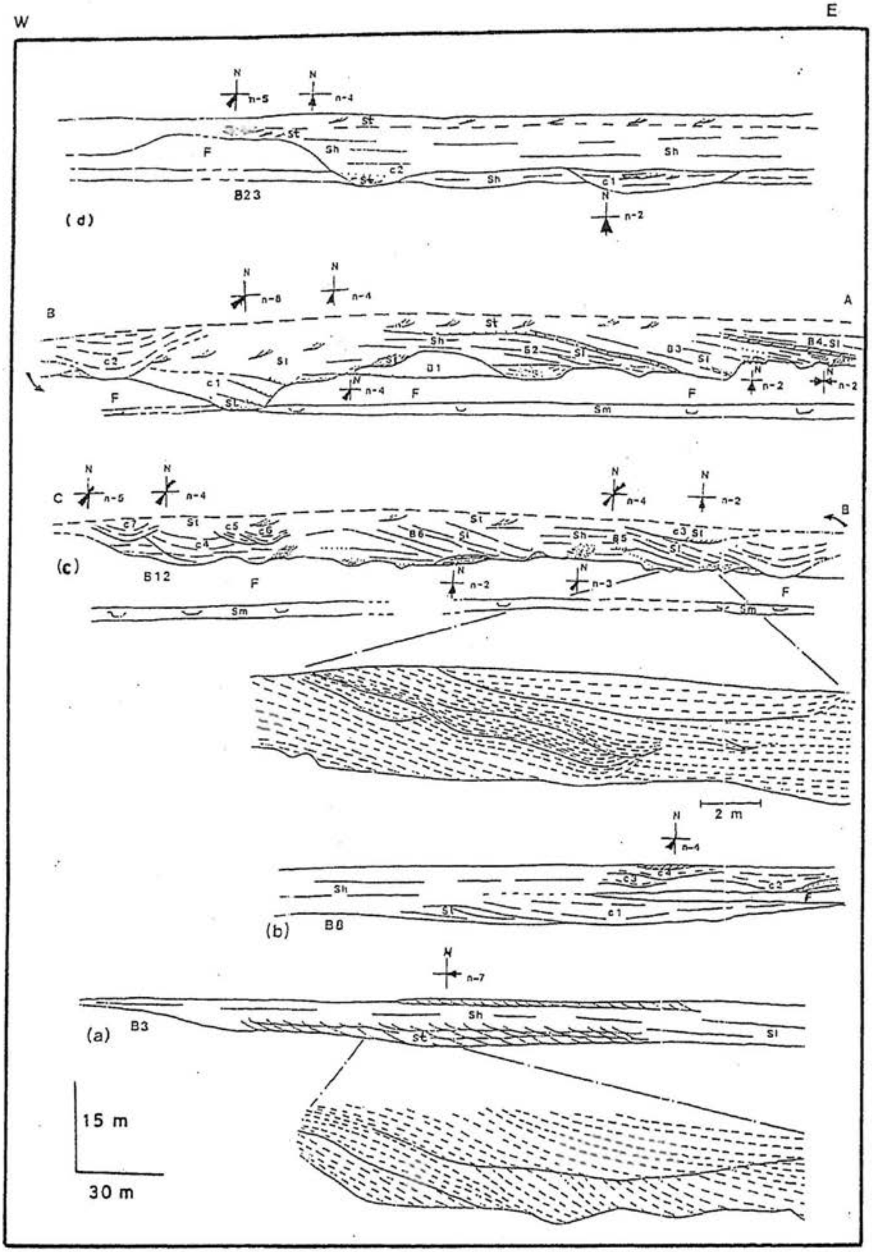


Fig. 7. Detailed internal structures of the sandstone-bodies near Bori village; a) sandstone-body B3, large trough cross-beds showing flow direction to the east; b) sandstone-body B8, a silt-bed about 2m thick occurs between the upper and lower parts of the sandstone-body in the eastern part; c) sandstone-body B12, in which B1-B6 represent bar macroforms, whereas, c1-c7 represent channel-fill features. The lower inset shows waterescape structures along low-angle plane-beds; d) sandstone-body B23, channel c1 scours a minor sandstone-body and is overlained by a major channel deposit c2. Lithofacies St-trough cross-bedding, Sl-low angle plane-bedding, Sh-horizontal bedding, Sm-massive sandstone, F-overbank fines.

macroform growth surfaces. The bar is composed of lithofacies Sl and minor St. The base of the bar is erosional with some erosional cuts more than 1m deep into the underlying siltstone. The erosional surfaces contain sole structures such as flute marks and gutter casts, which indicate a flow direction to the south. The next flood season deposited yet another bar B4 further to the east. Bar B4 is dominantly composed of lithofacies Sh and Sl. Abundant current lineations in facies Sh are orientated E-W. Thus each of these bars represents one season of high flow or flood stage. The upper bounding surfaces of these macroforms parallel the orientation of underlying cross-set (first order) bounding surfaces. This suggests that the bounding surfaces are probably accretionary macroform growth surfaces rather than erosion surfaces.

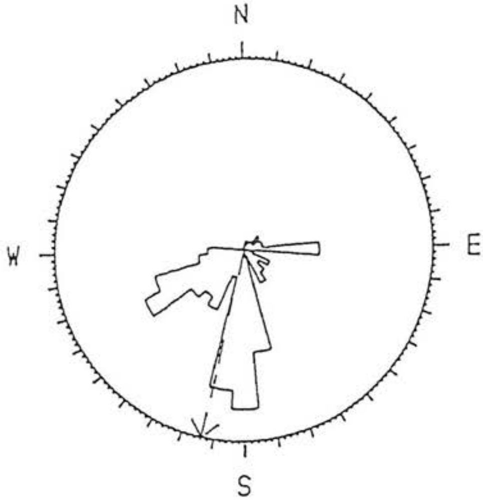
In the western part of the sandstone-body (west of channel-fills c1 and c2) bar B5 and bar B6 were deposited in almost an identical manner as bars B2 and B3. Bar B5 is fairly complex due to the presence of scattered layers of lag deposits and unclear inter-relationships between lithofacies Sl, Sh and St. Lithofacies Sh probably constitutes the top or centre of the bar with facies St at the base. Facies Sl marks the margins of the bar with minor eastward progradation, finally passing into the second order channel c2. The bar top was dissected during falling stage by minor channel c3 flowing to the south. The base of the bar is irregular and erosional, containing sole structures such as flute marks and gutter casts, indicating flow direction to the SSW. Sole structures at the base of bar B6 show flow direction to the south. These bars laterally coalesce to form large sand-flats.

The other sandstone-bodies are mainly composed of lithofacies Sh, Sl and St. The sandstone-body B13 is composed almost entirely of plane-bedding (Sh). It was probably deposited as plane-bedded simple bars (Allen, 1983). Plane-bedded sand is wide-spread in modern low-sinuosity river deposits (Coleman, 1969; Williams, 1970; Cant & Walker, 1978; Bristow, 1987), but the facies Sh is generally uncommon and not known to typify any particular type of bar (Allen, 1983). The common occurrence of lithofacies Sh and Sl in the sandstone-bodies shows that plane-bedded bars were commonly associated with the palaeoriver system. Plane-bedded bars also constitute a major part of sandstone-body B23 (Fig. 7d).

The sandstone-body B3 (Fig. 7a) is anomalous compared to others as it contains exceptionally well developed trough cross-beds which show flow direction to the east (N90°) in contrast to other sandstone-bodies which show flow direction to the SSW (N 200° av.). The maximum thickness of individual cross-beds is about 2m. The cross-set sequence is more than 100m long and passes laterally into plane-bedding and low-angle plane-bedding. The sandstone-body was probably deposited by a tributary channel flowing to the east.

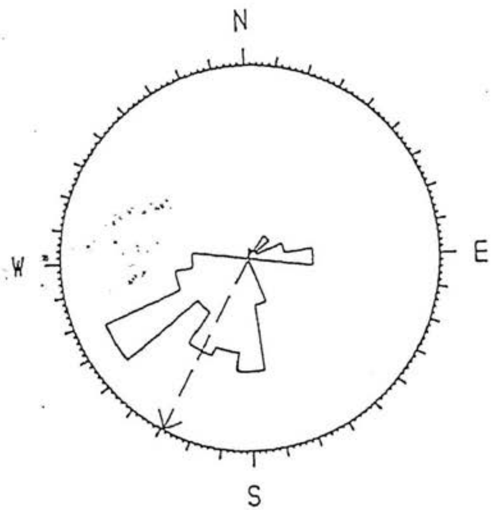
Large-scale trough cross-sets

The uppermost surfaces of the laterally extensive sandstone-bodies (B1, B2, B12 and B23) are covered by large scale trough cross-bedding due to dune migration on top of the sand-bars. In these sandstone-bodies, the cross-sets in the lower-part are generally 10-20cm in thickness and show evidence of in-channel deposition. These cross-beds indicate flow direction dominantly to the SSW (Fig. 8). The top of the sandstone-bodies is almost completely covered by large-scale trough cross-beds, some of which show rib-and-furrow structures. These troughs are up to 1m thick and 3m across. The large-scale trough sets commonly show flow direction to the WSW, which differs from that shown by small-scale in-channel troughs and sole structures at the base of the sandstone-body. The variations in the flow direction of different directional



DIRECTED DATA
N = 127

(a)



DIRECTED DATA
N = 92

(b)

Fig. 8. (a) Palaeocurrent data from the Shakardarra Formation. (b) Bori section.

structures, i.e, sole structures and three dimensional troughs on top of the sandstone-body, might be due to several causes; 1) ridge and swale topography on top of the bar surfaces; 2) sedimentary structures on top of the sandstone-body modified by local streams active in the area, and 3) shallow and wide-spread late stage flow.

Channel-fill deposits

The channel-fill deposits are the largest depositional features in the fluvial system, containing a wide variety of minor channels and bar complexes (Miall, 1985). In some of the sandstone-bodies at least one channel margin can be recognized, such as along the western margin of the sandstone-body B23 (Fig. 7d), and the eastern margin of sandstone-body B13. These are probably high order (first or second order) channels containing bars and minor channels. A number of lower order channel-fills can be recognized in various sandstone-bodies. The channel-fill c1 in sandstone-body B12 (Fig. 7c) has an erosional base scouring into the underlying minor sandstone-body. The channel-fill contains small scale trough cross-bedding at the base and displays three erosional surfaces, suggesting vertical aggradation of the channel-fill. The channel-fill in its upper part shows large-scale trough cross-beds. The channel-fill c2 scours the western margin of c1 and shows flow direction to south. Channel-fills c3-c7 in sandstone-body B12 (Fig. 7c) are minor channels which dissected the bar tops at low-stage flow. The channel-fill c1 in sandstone-body B23 (Fig. 7d) scours the underlying minor sandstone-body and has grown by vertical aggradation.

DEPOSITIONAL SYSTEM

The Shakardarra Formation is composed of sandstone-siltstone (1:1) in the lower part, dominantly sandstone in the middle part, and sandstone-conglomerate in the upper part. The major sandstone-bodies are on average 10m thick, and a lateral extent of a few hundred metres to many kilometres. The magnitude of these major sandstone-bodies is due to their extensive multistoried and multilateral nature. The internal geometry of the sandstone sheets is fairly complex, and includes macroform bar complexes, channel-fills, minor channel scours on top of the bar surfaces, local shale lenses, and thin lag deposits.

The sandstone-bodies exhibit well preserved bar macroforms and channel-fill features, such as in sandstone-body B12. However, there is no obvious cyclicity in the bar macroforms. The bars are capped by lag deposits (bar B2, Fig. 7c) or thin beds of siltstone (bar B3, Fig. 7c). The sandstone in the most part remains medium-grained and its contact with the intraformational conglomerate or fine-grained overbank sediments on bar tops is sharp. The parallel orientation of bar bounding surfaces and the underlying cross-sets suggests that the bar bounding surfaces were probably accretionary growth surfaces rather than erosional surfaces. The bar macroforms in the sandstone-bodies are dominantly composed of lithofacies Sh and Sl, comprising cosets several metres thick. These lithofacies indicate upper flow-regime plane-bed conditions, and are common in rivers that undergo high seasonal discharge; for example the Brahmaputra River (Bristow, 1987). The low-angle plane-beds show certain amounts of lateral accretion (Fig. 7c). Palaeocurrents in the Bori area show flow direction to the SSW (Fig. 8), and bar progradation to the east. Bars laterally coalesce to form large sand-flats. The major bar macroforms recognizable on outcrop scale are dominantly mid-channel, with subordinate bank attached bars. According to Bluck (1980), in large alluvial fans, mid-channel bars tend to accrete towards one bank, while the channel itself migrates in the opposite direction. The internal setting of the bars probably suggests deposition by intermediate to high-flow braid channels and bars (Fig. 9). The internal stratification of bars in the sandstone-bodies is fairly similar to the bars of the Brahmaputra River (Bristow, 1987), and to some extent with those of the Platte River (Smith, 1971; Blodgett & Stanley, 1980). A major component of deposition in large braided river systems could be incorporated in lateral bars as seen in the present day Indus River and Brahmaputra River (Coleman, 1969; Bristow, 1987). In these rivers, the movement of the second-order channel is generally by lateral migration (lateral accretion), and is independent of first-order channel movement (Bristow, 1987). The lateral accretion surfaces are difficult to recognize when deposited at very low-angles and under extreme width/depth conditions. The bars are modified by erosion and deposition associated with third order channels occurring during falling-stage flow conditions. A braided river system (Fig. 9) is therefore suggested for the deposition of these sediments.

The minimum channel depth can be estimated from the maximum constructional relief of the bars. The relief of bars B2 and B3 in sandstone-body B12 (Fig. 7c) ranges from 4-6 metres. It is estimated (Bristow, 1987) that bar height is between one half and just less than total bank-full depth in the modern Brahmaputra River. Therefore, the river system which deposited sandstone-body B12 was approximately 8-12 metres deep.

High proportions of coarse-grained facies and increased sediment accumulation rates at the time of deposition of the Shakardarra and stratigraphically equivalent Nagri formations (Johnson et al., 1985) correspond to accelerated foreland basin subsidence in response to high uplift rates along a thick-skinned fault (MMT) at that time (Zeitler, 1985). With high uplift and

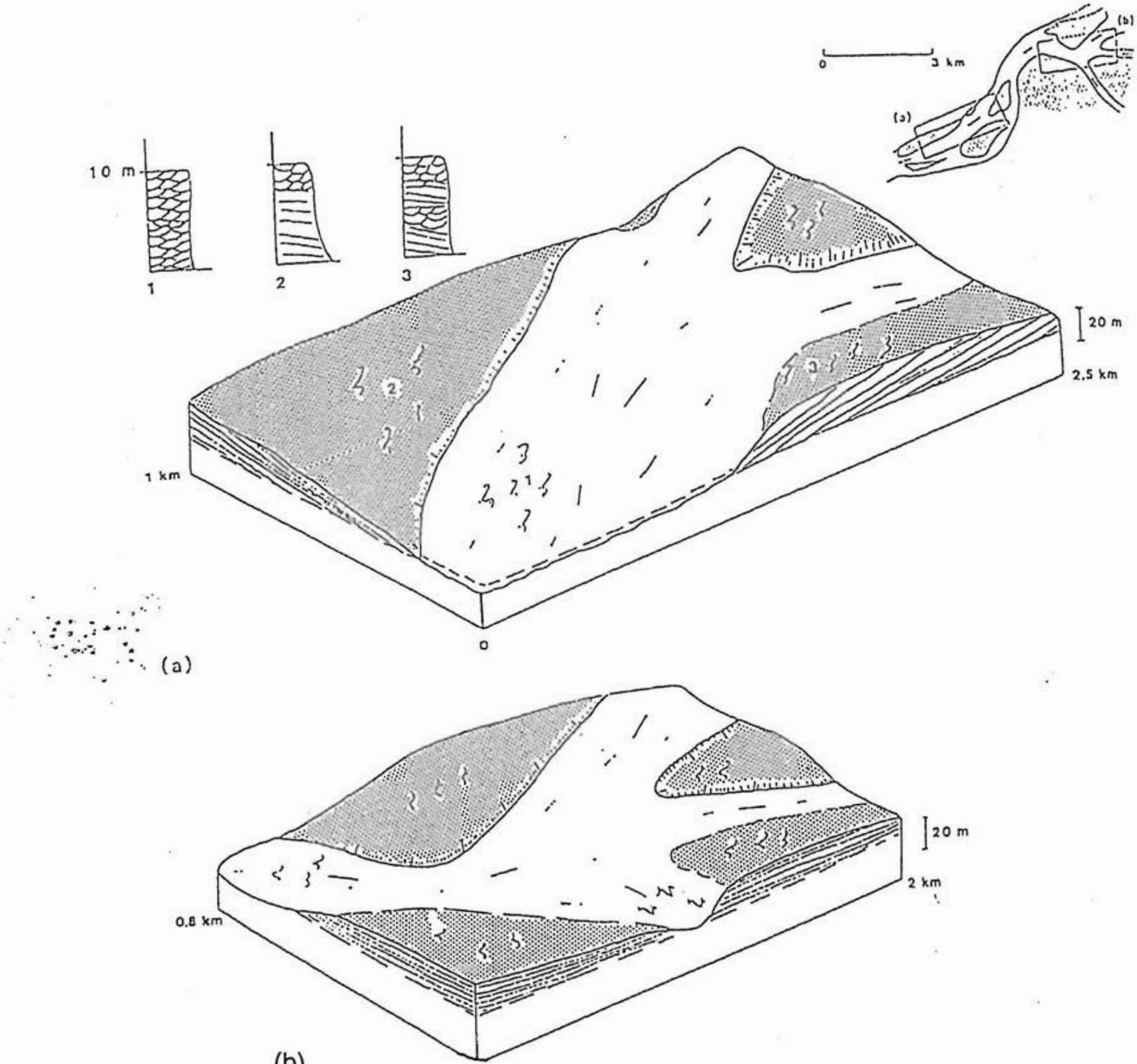


Fig. 9. Hypothetical proposed fluvial depositional model of the Shakardarra Formation.

erosion rates, the palaeoriver system has cut deep into the source terrains and poured enormous amounts of detritus into the actively subsiding foreland-basin. High subsidence rates coupled with abundant sediment supply gave rise to large scale vertical and lateral sandstone-body amalgamation. In the upper part of the formation, thick conglomerates appeared indicating that the river system became a typical sandy to gravelly braided during that time. Occasional over-bank fines were deposited interbedded with sandstone, but these had low preservation potential because of increased channel instability.

The provenance study (Abbasi & Friend, 1989) of the Shakardarra Formation suggests that the paleoriver system which deposited the sediments had a drainage area fairly similar to the present-day Indus River. The palaeocurrent data from the sediments is also comparable with the flow direction of the present-day Indus River system (SSW). Abundance of coarser facies in the study area as compared to that of the Potwar area and Trans Indus Ranges indicates that the major river system probably entered the foreland basin through the Kohat area, at least during past 10 ma.

CONCLUSION

1. In the study area, the Shakardarra Formation is a coarsening upward sequence of siltstone and sandstone in the lower part, sandstone in the middle part and sandstone and conglomerate in the upper part.
2. Abundant upper flow regime lithofacies in the Shakardarra Formation suggests deposition from high energy flow conditions, commonly associated with low sinuosity river systems.
3. The paleoriver system during the time of deposition of the Shakardarra Formation entered the foreland basin through the Kohat area, and had a drainage system similar to the present day Indus river.

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