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The Lower and Middle Siwaliks fluvial depositional system of the western Himalayan foreland basin, Kohat, Pakistan

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Abstract

The lower and middle Siwaliks equivalent to the Chinji and Nagri formations in Kohat-Potwar plateau, were deposited in a terrestrial foreland basin that developed in response to the Himalayan orogenic movements. Detailed sedimentologic studies from three different sections reveal that both the Chinji and Nagri formations consists of four lithofacies that are abbreviated as C and N, respectively. These include Cross-bedded Channel Sandstone Facies (C1), Cross-bedded and Cross-laminated Sandstone Facies (C2), Interbedded Mudstone, Siltstone and Sandstone Facies (C3) and Mudstone Facies (C4), and Channel Conglomerates Facies (N1), Cross-bedded Sandstone Facies (N2), Interbedded Sandstone, Siltstone and Mudstone Facies (N3) and Mudstone Facies (N4). C1 facies of the Chinji Formation probably represents deposits of mixed-load channels, from which C2 facies of crevasse splay channels in associated floodplains was produced by frequent crevassing and avulsion. C3 facies is interpreted as overbank deposits produced by the waning flow strength of sandy to muddy sheetfloods through crevasse splays, whereas C4 facies indicates a flood basin origin in a well drained oxygenated environment. N1 facies probably represents the collapse of cohesive bank sediments into nearby channels. N2 facies suggests sand deposition in very wide, shallow channels of a distal, sand-dominant braided fluvial system. N3 facies is interpreted to be a crevasse channel-fill deposit, whereas N4 facies probably represents levee and minor distal splay deposits.

Sandstone of the Chinji Formation was most probably deposited by mixed-load rivers, which transported fine suspended sediment as well as significant bedload, whereas the floodplain deposits of the Chinji Formation seem to be deposited by suspended-load rivers. Presence of calcrete concretions and mottling within the mudstone indicate incipient soil formation and limited subaerial exposure of the mudstone facies. The Nagri Formation was most probably deposited by sandy bedload braided fluvial system.

Furthermore, vertical stacking of the multistorey sandstone complex with varied facies associations, the sheet geometry, and frequent occurrence of erosional surfaces suggests its deposition in a braided river environment. The upward transition from mudstone-dominant facies (Chinji formations) to sandstone facies (Nagri Formation) suggests a systematic shift from distal to proximal fluvial deposits associated either with thrusting and/or uplift of the orogenic belt or a higher rate sedimentation than of subsidence in the basin.

The depositional model for the Miocene fluvial system of the Himalayan Foreland Basin can best be represented by a wide channel belt, internally showing a braided morphology of minor channels, wholly enclosed within finer-grained overbank sediments. The minor differences among the studied outcrops indicate contemporaneous deposition within a single large braided river such as the Brahmaputra where a variety of styles of deposition can be observed within the river at any given moment. Significantly thick floodplain deposits of the Chinji Formation show rapid accommodation generation whereas subordinate amount of floodplain deposits in Nagri Formation show relatively static or slow accommodation generation in the basin.

Keywords: Chinji-Nagri Formations; Depositional system; Kohat; Himalaya; Pakistan

1. Introduction

The Siwalik Hills consisting of sandstones, mudstone and conglomerates, form the sub-Himalayan lithotectonic unit of the Himalayan tectonic system and extend for over 2000 km from Kohat Plateau (northern Pakistan) in the west to the eastern syntaxial bend in India (Fig. 1). The Miocene Siwalik strata of these hills are interpreted as fluvial and lacustrine deposits, accumulated in a foreland basin adjacent to the Himalayan hinterland to the north (Willis, 1993a; Zaleha, 1997a, 1997b; Khan et al., 1997).

The Miocene Siwalik sediments of the Himalayan Foreland Basin are extensively studied in different sub-basins of India (e.g., Kumar and Tandon, 1985; Kumar and Nanda, 1989; Kumar and Ghosh, 1994; Najman et al., 1997, 2000; Kumar et al., 1999, 2004) and Potwar Plateau of Pakistan (e.g., Behrensmeyer and Tauxe, 1982; Johnson et al., 1985; Raynolds and Johnson, 1985; Behrensmeyer, 1987; Willis, 1993a, 1993b; Willis and Behrensmeyer, 1994, 1995; Zaleha, 1997a, 1997b) (Fig. 1). Studies regarding the Miocene to Pliocene Siwalik Group sequence of the Potwar Plateau, Pakistan include lithostratigraphic and biostratigraphic sub-division (e.g., Pilgrim, 1913; Lewis, 1937; Fatmi, 1973; Shah, 1977), palaeomagnetic polarity correlation (e.g., Johnson et al., 1982, 1985), sedimentary characteristics related to tectonism (e.g., Raynolds and Johnson, 1985; Johnson et al., 1985; Cerveny et al., 1989; Burbank and Beck, 1991; Burbank, 1992; Meigs et al., 1995) and detailed sedimentological reviews and studies (e.g., Behrensmeyer and Tauxe, 1982; Behrensmeyer, 1987; Abbasi and Friend, 1989, 2000; Abbasi, 1994, 1998). However, despite of such an impressive body of previous work, a detailed account of Siwalik deposits from the southwestern part of Kohat Plateau and beyond is largely lacking. The present study focuses on the southwestern part of Kohat Plateau and is aimed at a detailed investigation of sedimentary structures in the Lower and Middle Siwalik rocks for deducing their depositional environments.

2. Geological Setting

The Siwalik Group of the Himalayan Foreland Basin is exposed in the southern frontal area of the Himalayas in a WNW to ESE trending belt and is bounded by the Main Boundary Thrust (MBT) to the north and the Salt Range/Surghar Range Thrust to the south (Fig. 2). The Siwalik Group of rocks consists of 5000 to 5500 m thick clastic sediments, which are folded and faulted near the MBT, but grading southward into less deformed beds near the HFT has been reported by Karunakaran and Rao, 1979.

The Siwalik Group clastic sediments are assumed to have been eroded from the metamorphic rocks of the Himalayan orogen (Najman et al., 1997; DeCelles et al., 2001). These thick units of clastic sediment are separated by a major unconformity from the last marine facies of Eocene times (Mathur, 1978; Pivnik and Wells, 1996). In between the Eocene marine sequence and the Siwalik Group sediments are the Late Palaeogene alluvial rocks, named as the Balakot Formation (Hazara-Kashmir syntaxis) (Bossart and Ottiger, 1989) and the Murree Formation in Pakistan (Shah, 1977), and the Dagshai Formation and Dharamsala Formation in India (Table 1) (Bhatia, 1982).

The study area i.e., the Kohat Plateau constitutes the westernmost deformed part of the Himalayan Foreland basin, located between latitude 32° and 34° N, and longitude 70° and 74° E. It is bounded by the MBT in the north, Surghar Range Thrust/ Salt Range Thrust in the south, Kalabagh Fault in the east and Kurram Fault in the west (Fig. 2) (Khan et al., 1986).

3. Stratigraphic units

Medlicott (1864) was the first who introduced the term Siwaliks for the fresh water deposits of Late Tertiary age from Siwalik Hills in the Indian held Kashmir. Later on Wynne (1879) extended it to similar rocks of the Potwar Plateau, North-West Frontier Province, Kashmir, Baluchistan and Sindh areas of Pakistan. The constituent sediments were produced as a result of the high uplift rates of the Himalayan orogenic belt during Miocene time (Zeitler, 1985) that exposed different types of rocks for denudation, and transported by the Himalayan drainage system analogous to the present day river systems of Indus, Ganges and Brahmaputra that started flowing axially through the mentioned belt into their respective basins (Abid et al., 1983; Abbasi and Friend, 2000).

Table 1. The Neogene molasse stratigraphy from selected sections of the Himalayan Foreland Basin (Kazmi and Jan, 1997; Yin, 2006; Najman, 2006).

Geol Time	Kohat	Potwar	Sulaiman	Kirthar	Kangra	Subathu
Late Pliocene		Soan Fm	Chaudhwan Fm	Soan Fm	Siwalik Group	Siwalik Group
Middle Pliocene	Dhok Pathan Fm	Dhok Pathan Fm	Litra Fm	Dhok Pathan Fm		
Early Pliocene	Nagri Fm	Nagri Fm				
Late Miocene	Chinji Fm	Chinji Fm	Vihowa Fm	Nagri Fm		
Middle Miocene	Kamlial Fm	Kamlial Fm	Chitarwata/ Gaj Fm	Gaj Fm	Dharamsala Fm	Kasauli Fm
Early Miocene	Murree Fm	Murree Fm				Dagshai Fm

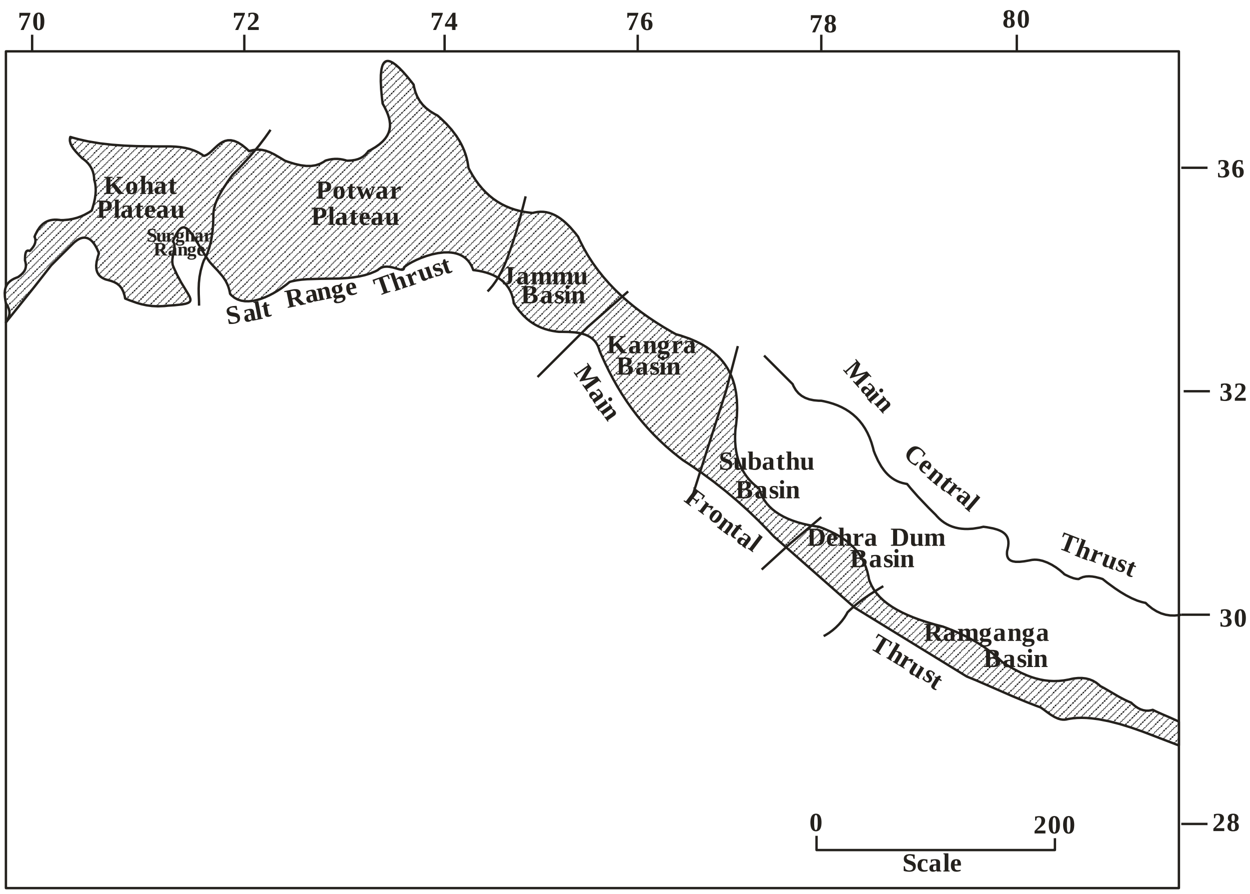

Fig. 1. General and simplified map showing sub-basins of the Himalayan Foreland Basin.

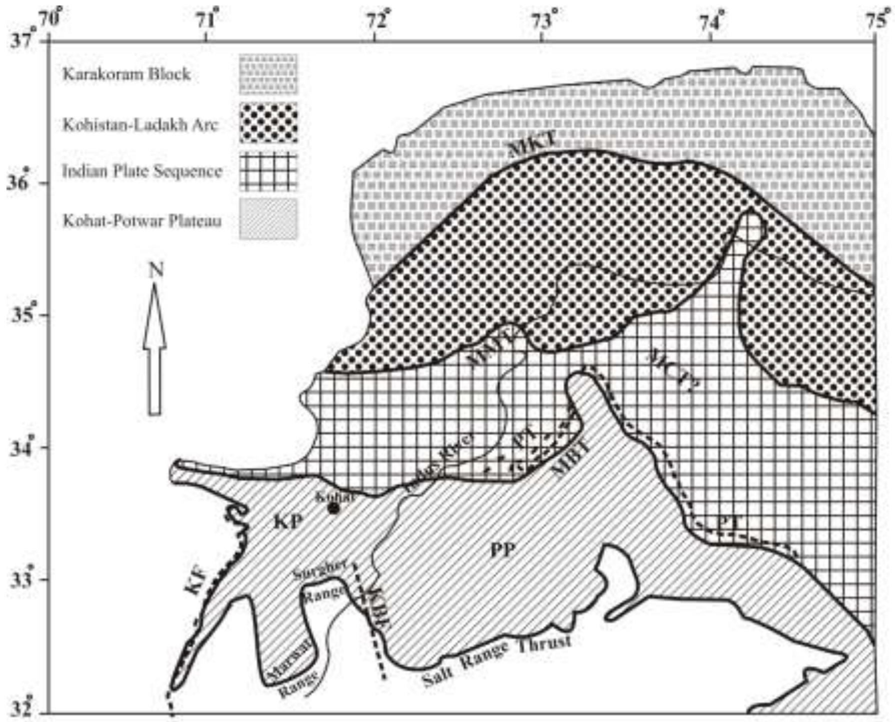

Fig. 1/2. Regional tectonic map of northern Pakistan (modified after Kazmi and Rana, 1982): MKT = Main Karakoram Thrust, MMT = Main Mantle Thrust, PT = Panjal Thrust, MBT = Main Boundary Thrust, KP = Kohat Plateau, PP = Potwar Plateau, KF = Kurram Fault, KBF = Kalabagh Fault.

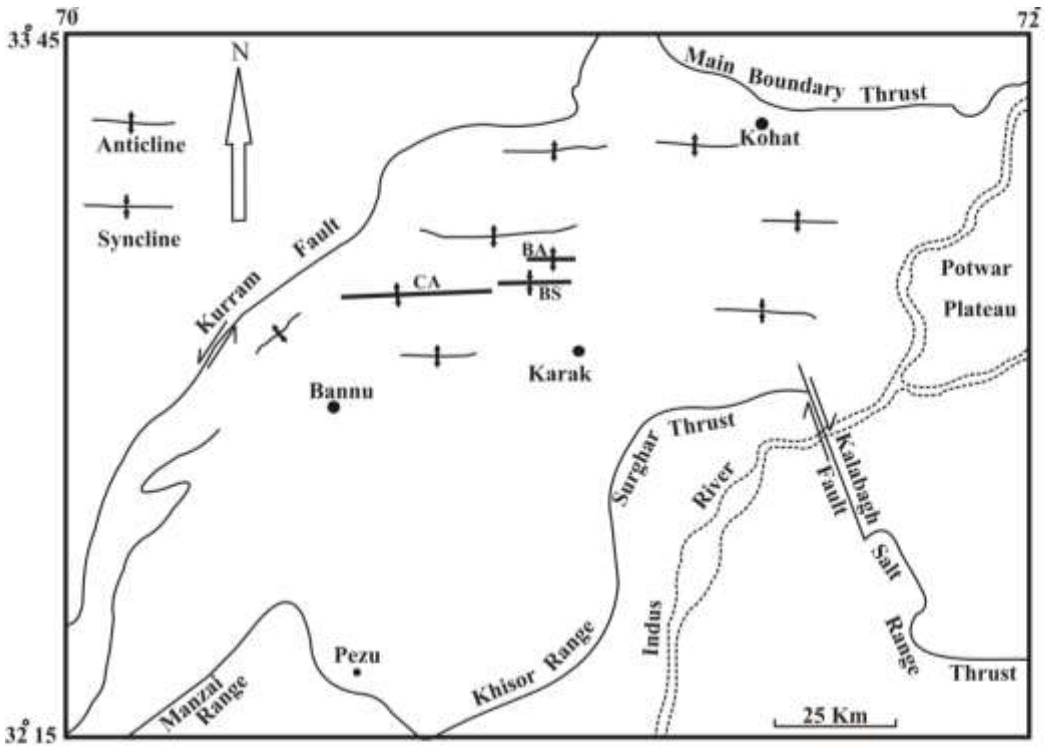

Fig. 2/2. Tectonic map of the Kohat Plateau (after Meissner et al., 1974) showing the location and nature of studied sections. CA = Chashmai anticline, BA = Bahadar Khel anticline, BS = Banda Assar syncline.

On the basis of palaeontological data, the Siwalik sediments have been classified into Lower, Middle and Upper Siwaliks (Pilgrim, 1913). These three distinct types of the Siwaliks occur in the Potwar region of Pakistan and in the western Indian Himalayas, and are respectively represented by mainly mudstone facies, significantly sandstone facies and sandstone plus conglomerate facies (Table 1; Najman, 2006).

The Lower Siwalik Subgroup is generally characterized by an alternation of sandstone and mudstone (mudstone >50%). The transition from the Lower to Middle Siwalik succession is marked by a change in sandstone geometry (ribbon type to sheet type) and increase of sandstone abundance by a factor of 2 to 3 at about 11 Ma in the Potwar Plateau (Johnson et al., 1985), 10 Ma in the Kangra Subbasin (Kumar et al., 2003) and 9 Ma in Nepal (Decelles et al., 1998b). The Middle Siwalik succession grades upward into thickly bedded conglomerate of the Upper Siwalik Subgroup, which contains lenticular bodies of sandstone in its lower part at around 5 Ma, though a fine-grained facies (Tatrot and Pinjor Formations) is also observed in the Subathu Sub-basin (Kumar et al., 1999).

In Pakistan, the Siwalik Group consists of the Chinji, Nagri, Dhok Pathan and Soan formations. Of these, the Chinji and Nagri formations broadly represent the Lower and Middle Siwalik units (Table 1). Detailed stratigraphy of the Pakistani Siwaliks has been established through collaborative studies among University of Peshawar, Geological Survey of Pakistan, Darth Mouth College and University of Arizona, USA, Yale University, UK and Lamont-Doherty Earth Observatory.

4. The Chinji and Nagri Formations

The terms “Chinji Zone” (Pilgrim, 1913) and “Chinji Stage” (Pascoe, 1963) for the interbedded sandstone, silty clay and siltstone units were later on reworded as “Chinji Formation”. The type section is exposed near Chinji village (Late. 32° 41′ N, Long. 72° 22′ E). The Chinji Formation is dominantly composed of interbedded bright red and brown orange siltstone and ash-gray sandstone, with siltstone: sandstone ratio of 4:1 in the type section that decreases northward. The interbedded in-channel and overbank siltstone sequences are 10-50 meter thick while the major sand bodies are multistoreyed. The individual storeys are generally 5-10 meter thick and complexly stacked both vertically and laterally (Behrensmeyer, 1987; Willis, 1993a, 1993b; Willis and Behrensmeyer, 1994).

The “Nagri Zone” of Pilgrim (1913) was formalized as “Nagri Formation” by Lewis (1937). The Stratigraphic Committee of Pakistan accepted the term “Nagri Formation” for the middle part of the Siwalik Group. The type section of the formation is the village of Dhok Sethi Nagri (Late. 32° 45′ N, Long. 72° 14′ E).

Ages of the Kamlial-Chinji and Chinji-Nagri boundaries (Table 1) in Potwar Plateau are interpreted as 14.3 Ma and 10.8 Ma, respectively (Johnson et al., 1985) while to the west in the Surghar Range, the base and top of the Chinji Formation are believed to be 11.8 Ma and 8 Ma old, respectively (Khan and Opdyke, 1993). The Nagri Formation is assigned an age from 10.8 to 8.5 Ma on the basis of magnetic stratigraphic studies (Johnson et al., 1982). On the basis of different fauna, the formation is considered to be Late Miocene (Sarmatian) to Early Pliocene (Pohtian) (Fatmi, 1973).

5. Lithofacies of the Chinji Formation

The Chinji Formation has a thickness of 140 m, 133 m and 100 m in Bahadar Khel anticline, Banda Assar syncline and Chashmai anticline, respectively (Fig. 4; Plate 1). The formation is composed of overbank fines and sandstone; and has a sharp upper contact with the overlying Nagri Formation (Plate 1). Overbank fines are reddish-brown to reddish-maroon and include clay beds, shale and siltstone. Sandstone is grayish-brown to yellowish-gray, soft/hard, dominantly fine-grained/fine- to medium-grained and medium-to thick-bedded. Some units of the sandstone are bioturbated. Pedogenic surfaces/calcareous nodules generally associated with overbank fines occur at seven horizons in the formation. Some of these are lens-shaped.

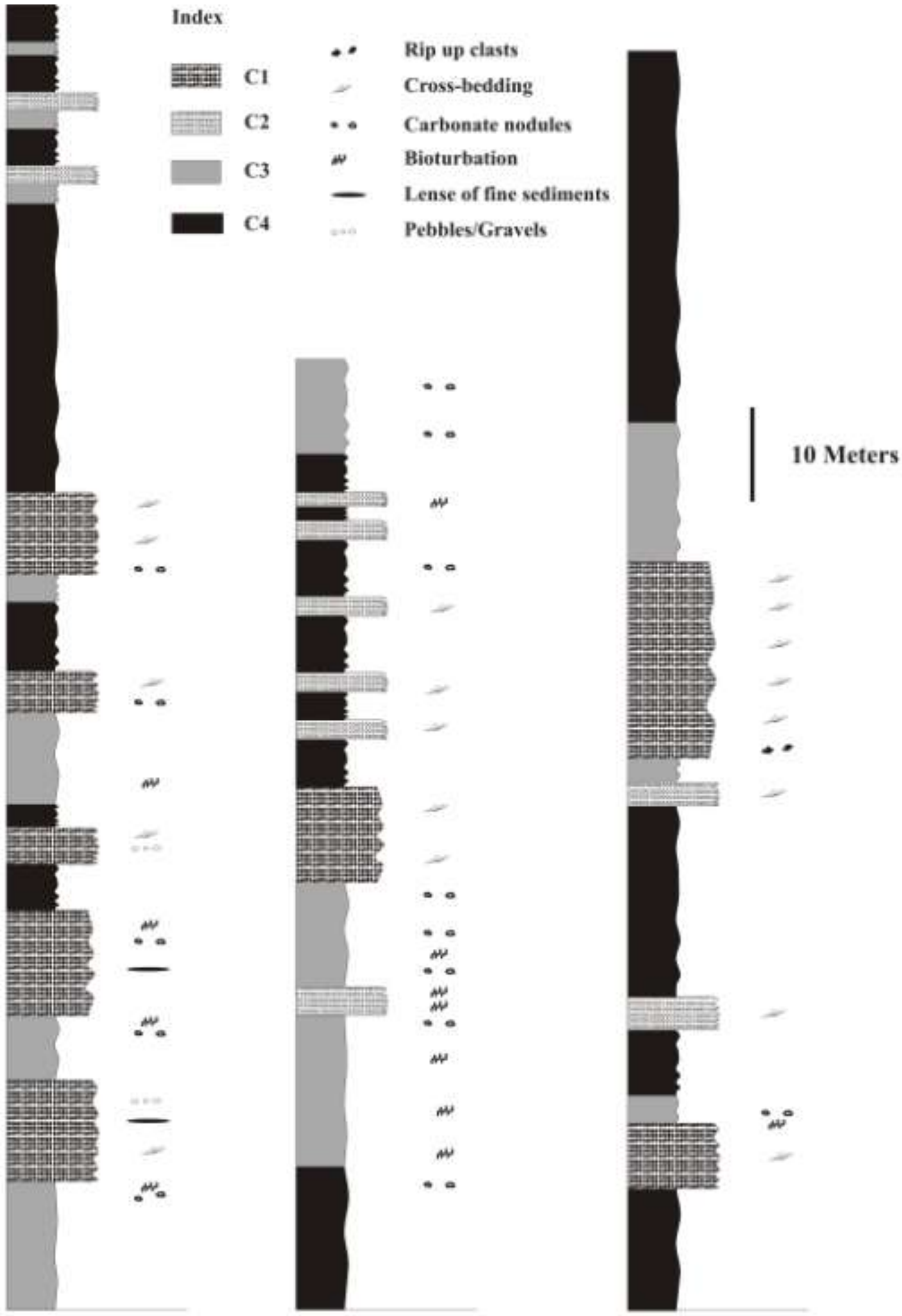

Fig. 3. Measured lithocolumns showing facies association of the Chinji Formation (southwestern Kohat Plateau): Bahadar Khel anticline (left), Chashmai anticline (middle) and Banda Assar syncline (right).

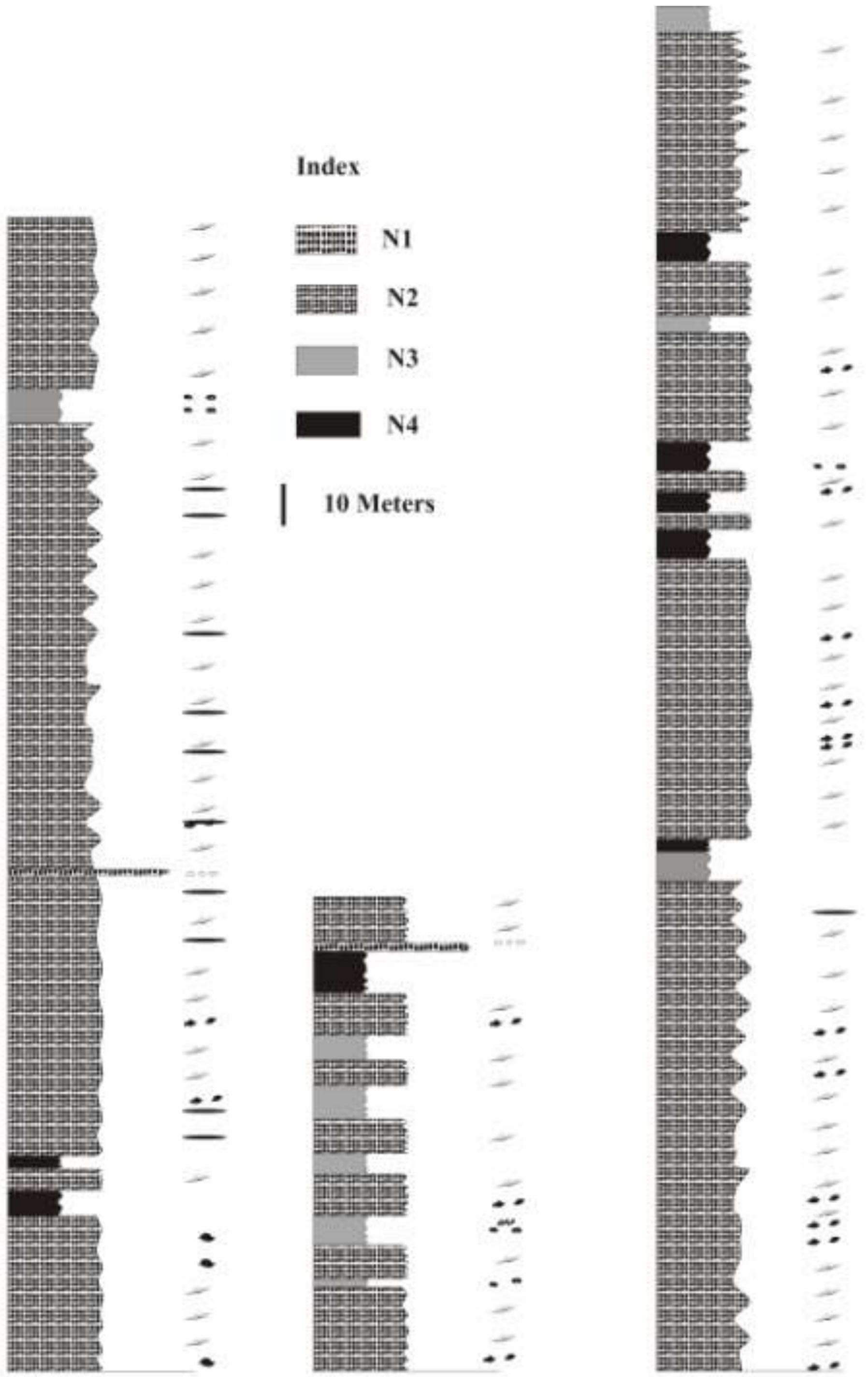

Fig. 4. Measured lithocolumns showing facies association of the Nagri Formation (southwestern Kohat Plateau): Chashmai anticline (left), Banda Assar syncline (middle) and Bahadar Khel anticline (right).For symbols description see Fig. 3.

In addition to abundant overbank fines (silty clay/clay/shale/mudstone), the formation contains subordinate sandstone and siltstone beds at the Banda Assar syncline (Fig. 4; Plate 2). The following lithofacies have been identified in Chinji Formation from southwestern Kohat.

5.1. C1: Cross-bedded Channel Sandstone Facies

Description: The cross-bedded channel sandstone facies consists of laterally persistent sheets of sandstone, dominated by large trough cross-stratification with subordinate small-scale, planar and trough cross-stratification (Plate 3). This facies also contains some sparsely embedded gravel/pebbles at places in some of the units (Fig. 4; Plate 4). Individual beds show very little fining-upward tendencies, possibly due to a lack of the grain size variability.

Interpretation: C1 facies of the Chinji Formation probably represents deposits of mixed-load channels with varying stream competence. The channel base experienced alternating scouring, bed-load transport and deposition, whereas frequent crevassing and avulsion led to the formation of new channels on the floodplain (Smith et al., 1989; Makaske et al., 2002).

5.2. C2: Cross-bedded and Cross-laminated Sandstone Facies

Description: C2 facies is grey, thin to medium bedded/ thick-bedded (Fig. 4; Plate 5), and individual beds grade vertically from cross-bedded sandstone into cross-laminated sandstone and overbank deposits at places (Figs. 4; Plate 6). Some units of the sandstone are bioturbated (Plate 7).

The sandstone beds are broadly lenticular (up to several tens of meters in lateral extent) (Plate 8) and contain pebbles embedded in them at a couple of places. A few 20 to 30 cm thick intraformational and extrabasinal conglomerate units were also noted (Plate 9).

Interpretation: The sandstone is interpreted as the deposit of crevasse splay channels of a distal, sand-dominant braided fluvial system in associated floodplains (DeCelles, 1986). The channel base experienced alternating scouring, bed-load transport, and deposition (Plate 10). The crevasse splay channels were produced by frequent crevassing and avulsion (Plate 11) (Smith et al., 1989; Makaske et al., 2002). Mud clasts at the base are of intraformational origin and are derived locally from the levee and floodplain sediments through which the channel was cut. Textural immaturity implies rapid sedimentation from mixed-load streams and minimum winnowing. Upward increase of shaly lenses, burrows and root traces may be due to progressive crevasse channel abandonment and waning of current energy (Plate 12) (Ghosh, 1987; Smith et al., 1989; Miall, 1996).

5.3. C3: Interbedded Mudstone, Siltstone and Sandstone Facies

Description: C3 facies is dominantly composed of shale, interbedded with thin- to medium-bedded, sandstone and thinly laminated siltstone (Fig. 4). However, at some places, the facies is largely composed of clay beds interbedded with siltstone (Plate 13). Rare, somewhat nodular horizons in this facies indicate weakly developed paleosols.

Interpretation: Strata of the C3 facies are interpreted as overbank deposits produced by the waning flow strength of sandy to muddy sheetfloods through crevasse splays, however, sand bodies of lenticular shape represent levee deposits (Smith et al., 1989; Ferrell, 2001) The red color of mudstone, burrows and calcareous nodules indicate partially emergent floodplains (Retallack, 1997; Mack et al., 2003) and substantial aerial exposure (McCarthy et al., 1997).

5.4. C4: Mudstone Facies

Description: These laterally persistent, 0.5 cm to 2 m in thick and red to purple fine-grained mud bodies consist of massive and laminated mud (Fig. 4). Bioturbation, subordinate small calcareous nodules and minor desiccation cracks are occasionally present.

Interpretation: Features like its geometry, predominant red color and extensive pedogenic horizons suggest a flood basin origin in a well drained oxygenated environment for these mudstones (Wright and Tucker, 1991; Retallack, 1997). The pedogenic caliche horizons presumably

Plate 1

Plate 2

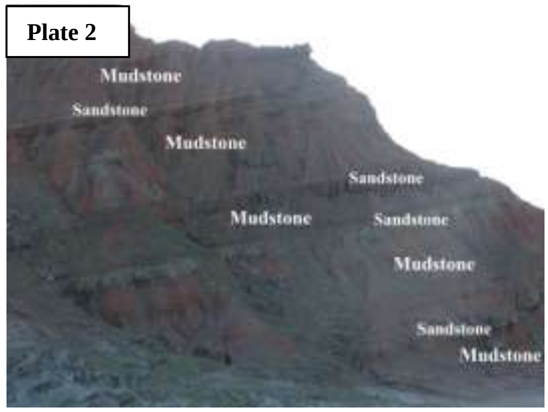

Plate 3

Plate 4

Plate 5

Plate 6

Plate 1. Panoramic view of Bahadar Khel Section (looking north). Contacts of the formations are marked by white lines. The Chinji Formation in the middle is dominantly composed of maroon red mudstone.

Plate 2. Alternation of thin sheets of sandstone and maroon red mudstone succession of the Chinji Formation. Overbank ratio is more than 50% having characteristic of Chinji Formation. Thin, grey/ brownish-grey beds of sandstone show more resistant to weathering than the associated mudstone.

Plate 3. Cross bedding in Chinji Formation.

Plate 4. Sparsely pedogenic concretions in trough cross-stratified sandstone beds of Chinji Formation, near Bahadar Khel old bridge.

Plate 5. Red/purple mudstone overlain by cross-bedded channel sandstone suggesting amalgamated braided streams.

Plate 6. Thick- to thinly-bedded sandstone with sharp contact of underlying mudstone. The topmost unit of mudstone comprises alternation of thin sheets of fine-grained sandstone and mudstone. Mudstone suggests river overbank episodes in an arid setting whereas sandstone units indicate crevasse splays in river floodplain.

developed during periods of little sedimentation and subsidence. Extensive burrowing near the top of individual sedimentary units made the mudrocks sufficiently porous which facilitated the formation of concretions (see Ghosh, 1987).

6. Lithofacies of the Nagri Formation

The exposed Nagri Formation at the Chashmai anticline is 256 m thick from its lower contact with Chinji Formation (Fig. 4). Upper contact of the formation is not exposed and is covered by recent alluvium. The exposed section of the formation is composed more than 80 % of sandstone, which is gray to brownish gray, dominantly fine to medium-grained and thin- to thick-bedded. Clasts, dominantly of intraformational origin, mostly clay and sand balls occur at places. Pedogenic surfaces/calcareous nodules were also observed at two horizons in the overbank fines, indicating subaerial exposure.

Base of the Nagri Formation at Banda Assar syncline is marked by a thick sequence of sandstone (Fig. 4). The formation has an exposed thickness of 107 m in this section (Fig. 4). The formation is composed dominantly of sandstone interbedded with shale and subordinate clay beds and siltstone (Fig. 4). Sandstone is very fine/fine-grained to medium-grained and medium- to thick-bedded. Floodplain deposits are light red/red in color, and some beds are bioturbated.

The Nagri Formation in Bahadar Khel anticline has an exposure of 326 m and is dominantly composed of sandstone with subordinate siltstone, shale and clay beds (Fig. 4, Plate 14). Sandstone is dominantly grey, fine- to medium-grained and thin- to thick-bedded, and contains lenses of intraformational conglomerate and sparsely embedded gravel/pebbles (Fig. 4).

On the basis of field observations and presence of various sedimentary structures, the following lithofacies have been identified in the Nagri Formation.

6.1. N1: Channel Conglomerate Facies

Description: Channel conglomerate facies is characterized by lenticular beds of massive or crudely stratified conglomerate (Fig. 4; Plate 15). Clasts are typically less than 10 cm in diameter and are dominantly intraformational. Intraformational clasts are mostly clay and sand balls. In the middle of the exposed section, the conglomerate unit is dominantly composed of extrabasinal clasts including quartzite, chert and gneisses. Most of the conglomerate beds are thin, only a few clasts thick. This facies is observed in Chashmai anticline and Banda Assar syncline (Fig. 4).

Interpretation: Classifying as channel floor deposits, they are composed of a coarse fraction, made up of poorly sorted extra- and intra-formational pebbles (Williams and Rust, 1969; Laury, 1971). Coarse channel-floor deposits are essentially lag gravels deposited in the deeper parts of a channel, from which much of the finer material has been winnowed (Beerbower, 1964; Allen, 1965). The subangular fragments and poor sorting show little or no reworking by water. They are probably the result of the collapse of cohesive bank sediments into nearby channels (Laury, 1971).

6.2. N2: Cross-bedded Channel Sandstone Facies

Description: The cross-bedded channel sandstone facies is generally grey in color, fine- to medium-grained and medium to thick bedded. It contains lenses of intraformational conglomerate and sparsely embedded gravel/pebbles at places (Fig. 4, Plate 16). Individual beds show very little fining-upward tendencies, possibly due to the lack of available grain size variability.

The N2 facies is characterized by abundant trough cross-bedded sandstone (Plate 17). Cross-bedded strata most commonly pass upward into ripple laminated sandstone, although in many outcrops they are either erosionally overlain by coarser-grained strata or abruptly overlain by siltstone and mudstone. This facies typically displays multistorey nature, in which bases of individual storeys are delineated by an erosion surface (Plate 18). The thickness of individual bodies in the multistorey complex varies from less than one meter to several meters.

Plate 7. Animal/root trails and some of these are rip up clasts in fine-grained sandstone unit of Chinji Formation.

Plate 8. Sharp, irregular erosional contact of mudstone with overlying channel sandstone shows deep incision of fluvial channel into arid oxidized floodplain.

Plate 9. Thick channel lag deposit consisting of intrabasinal, disorganized pedogenic mud clasts in Chinji Formation, near Bahadar Khel old bridge.

Plate 10. Load marks in sandstone of Chinji Formation suggesting rapid deposition of sand onto semi-liquefied floodplain.

Plate 11. Close-up view of contact relationship of channel and overbank facies. The sandstone unit also shows channels within primary channel. At least three channels in the photograph are marked by white lines.

Plate 12. Mud balls in channel sandstone representing river bank failure.

Plate 13

Plate 14

Plate 15

Plate 16

Plate 17

Plate 18

Plate 13. Thin lenticular fine-grained sandstone encased by thick mudstone representing crevasse splay/levee deposits.

Plate 14. Thick multistoried sandstone of Nagri Formation overlain by red mudstone with sharp contact. The sandstone represents multistoreyed channel deposits and the maroon red mudstone represents floodplain deposits.

Plate 15. Intra-formational conglomerate at base of thick sheet sandstone of the Nagri Formation in Gore Nala, near Bahadar Khel old bridge. Limestone clast of intraformational origin can also be seen in the photograph.

Plate 16. Grey, thick sheet sandstone of Nagri Formation. Infrequent gravel (both extra- and intra-formation) embedded in sandstone, near Kasho Bridge (Ziarat). Scale in the photo is 15 cm (6”).

Plate 17. Thick bed of sandstone with large scale very gentle cross-bedding.

Plate 18. Multistoried sandstone body separated by erosional surface having intraformational conglomerate. Sandstone beds have trough and planar cross-stratification in Nagri Formation, near Bahadar Khel old bridge.

Interpretation: The laterally persistent sheets of sandstone, dominated by large trough cross-stratification with subordinate small scale, planar and trough cross-stratification are interpreted as the deposit of sand-dominant braided fluvial system. Storeys exhibiting large-scale inclined strata are channel bar deposits, formed by the lateral migration and superposition of different bars within the same channel belt, or by the superposition of different channel belts. The multistorey sandstone bodies result from the superposition of channel bars and fill within the large aggrading channel-belt in fluvial environments (Gordon and Bridge, 1987; Bridge and Mackey, 1993). Associated intraformational conglomerates along erosion surfaces of storeys are cut bank material eroded during lateral channel migration.

6.3. N3: Interbedded Sandstone, Siltstone and Mudstone Facies

Description: The N3 facies consists of fine- to very fine-grained, thin- to medium-bedded sandstone interbedded with siltstone and mudstone. Sedimentary structures include small- and large-scale cross-strata, ripple-lamination, parallel-lamination and occasional root marks.

Lateral extents of thin sandstones are in meters to tens of meters. Individual large-scale strata in this facies have erosional bases with scour and load structures. The burrow and root traces exhibit various degrees of bioturbation, leading to almost complete obliteration of primary sedimentary structures. Incipient pedogenic features occur locally, and are typically best developed in the upper few centimeters to decimeters of large-scale strata.

Interpretation: This facies is interpreted to be a crevasse channel-fill deposit (Ghosh, 1987). Mud clasts at the base are of intraformational origin and are derived locally from the levee and floodplain sediments through which the channel was cut. Textural immaturity implies rapid sedimentation from mixed-load streams. Upward increase of shaly lenses, burrows and root traces may be due to progressive crevasse channel abandonment and waning of current energy (Ghosh, 1987).

In theory, each splay sandstone is likely to be associated with a single crevasse channel. Furthermore, current ripple cross-lamination, trough cross-stratification and planar stratification were formed by deposition associated with migrating current ripples, dunes, and upper stage plane beds, respectively (Bridge, 1993). Trace fossils and incipient pedogenic features indicate that many of the overbank sand deposits were sites of insect burrowing, plant growth, and weak soil development.

6.4. N4: Mudstone Facies

Description: Overbank fines of N4 facies are light red/red in color. There is an internal bedding relationship between the mudstone and thin/medium-bedded siltstone. Siltstone units exhibit fine lamination. Some beds of the overbank fines are bioturbated. Pedogenic surfaces/ calcareous nodules occur locally. Sedimentary structures were absent where invertebrate burrows and pedogenic carbonate nodules are common.

Interpretation: The sandy silt and mud-clay units probably represent levee and minor distal splay deposits, as indicated by the abundant burrows and calcareous concretions (Coleman, 1969; Ethridge et al., 1981; Sutter et al., 1985). Extensive burrows and rootlets acted as pathways for movement of lime solutions (Ethridge et al., 1981). The pedogenic surfaces and red coloration probably resulted from subaerial exposure and oxidation of iron-rich compounds in overbank areas (DeCelles, 1986).

7. Discussion

7.1. Depositional System of the Chinji Formation

Sandstone of the Chinji Formation was probably deposited by mixed-load rivers, whereas the floodplain deposits seem to be deposited by suspended-load rivers. Mixed-load rivers transport fine suspended sediment as well as significant bedload and the former accumulate occasionally thick enough overbank fines to enhance bank stability (Bluck, 1971; Collinson, 1996). During floods, channel banks are breached and a new channel courses are established on the floodplain, taking place intermittently after several years (Collinson, 1996). On the other hand, suspended rivers carry a very high proportion of their load in suspension, and deposit fine-grained sediment both on the floodplain and to some degree within the channels (Collinson, 1996). The trough cross-stratification and planar stratification in sandstone units are formed by deposition associated with migrating sinuous-crested and straight-crested dunes, respectively. Current and wave ripple cross-lamination record deposition by migrating current ripples and wind action in relatively slow moving water, respectively. Fining upward sequences represent decreasing flow velocities associated with waning flood stages. Desiccation cracks, common in the upper part of the mudstone units, indicate periods of subaerial exposures.

Considering the fluvial lithofacies assemblages, the sequences are typical of a braided river system (Miall, 1977, 1978) and may be related to S. Saskatchewan type. Variability in grain size reflects differences in provenance and/or water stage fluctuations. The deposition can thus be described as a distal braided system in which siltstones represent over 80 % of the sediment thickness (Cojan, 1993). Low lateral and vertical connectivity of the sandstone bodies in Chinji Formation is probably due to high subsidence rates, which lead to high preservation of overbank fines (Allen, 1978; Kraus and Middleton, 1987).

In the central and eastern Potwar Plateau (Fig. 1), the Nagri Formation consists of tens of meters thick multistoreyed sandstone bodies which are normal to paleoflow and extend laterally for kilometers. The thick-bedded sandstone units of the Chinji Formation from Potwar area are interpreted to be river-channel deposits (Zaleha, 1997a). Bankfull channel depths and single channel widths were generally ≤ 15 m and 320-710 m, respectively (Zaleha, 1997a). Similarly, sedimentologic reconstruction of the Chinji Formation in Chinji village shows braided rivers with typical maximum depth of 4-13 m and channel widths of 80-200 m (Willis, 1993b).

The thin-bedded sandstones facies of the Chinji Formation extend laterally for hundreds of meters (Zaleha, 1997a). These thin-bedded sandstone units are interpreted as crevasse channels and levee and splay floodplain deposits, whereas the thick mudstone sequence is interpreted as floodplain (mostly flood basin) and lacustrine deposits (Zaleha, 1997a).

The multistoreyed channel type sandstone-bodies of the Chinji Formation in eastern Kohat area consist of a simple lithofacies association of plane bedding, low angle plane bedding and trough cross-bedding sandstone, however, relationship among these lithofacies is complex and does not follow any trend. Trough cross-beds across the formation suggest a consistent flow direction to the SSE (Abbasi, 1998).

7.2. Depositional System of the Nagri Formation

The Nagri Formation was most probably deposited by sandy bedload rivers, which dominantly carry sand, but gravel may be present dispersed in sand. Highly erodible banks of such rivers give rise to high width/depth ratios and to lateral movement both of the whole channel tract and of bars and island within the tract. Thus sinuosity is rather low and braiding is well developed (Collinson, 1996). The availability of sand is a major control on braided patterns (Smith and Smith, 1984).

The thick sandstone units of the Nagri Formation from eastern Potwar are interpreted as deposits of sinuous, braided channel and the stacking pattern is believed to represent the movement of channels within single or multiple channel belts, whereas individual storeys are thought to be channel-bar deposits of a single flood (Khan et al., 1997). Planar stratification formed under conditions of relatively higher flow velocities associated with upper stage plane beds. Current and wave ripple cross-lamination record deposition by migrating current ripples and wind action in ponded water, respectively. Fining upward sequences represent decreasing flow velocities associated with waning flood stages. Single channel bankfull depths and widths were generally 33 m and 320-1050 m, respectively in Khaur area, Potwar (Zaleha, 1997a).

The thin sandstone units represent deposition from crevasse channels and levee and splay floodplain deposits (Zaleha, 1997a). In the eastern Potwar, Khan et al. (1997) interpreted the mudstones to be floodbasin and lacustrine deposits while thin sandstone bodies represent crevasse splays, levees and floodplain channels (individual channel rivers typically 5 m deep and 100 m wide). Non-calcareous upper horizons of paleosols resulted from non-precipitation or leaching of carbonates (Khan et al., 1997).

The tens of meters thick sandstones alternating with mud dominated strata of the Nagri Formation suggests small-scale variations, whereas one hundred to a few hundreds meters, and formation-scale changes over one km thickness indicate medium-scale and large-scale variations, respectively. Such variations are thought to be associated with autucyclic and/or mountain-front tectonism (e.g., faulting and earthquakes) (Zaleha, 1997b).

In Shakardara area of Kohat Plateau, the 1800 m thick Shakardara Formation (Miocene) is believed to be equivalent to the Nagri Formation elsewhere in the Kohat-Potwar Plateau (Abbasi, 1994, 1998). The major sand bodies of the Shakardara Formation are 10-15 m thick with a lateral extent of a few hundreds meters indicating their extensive multistoreyed and multilateral nature. The well preserved bar macroforms defined on the basis of their internal lithofacies bounding surfaces in these sandstone bodies, are dominantly of mid-channel origin indicating upper flow regime plane-bed conditions, which are common in rivers that undergo high seasonal discharge (Abbasi, 1994, 1998). The internal setting of the bars probably suggests deposition by rivers with a moderate to high flow rate in 10-15 meters deep braided channels with a dominant paleoflow direction to the SSW, which is fairly similar to the present day Indus River system (Abbasi, 1994, 1998).

The low proportion of mudstone-siltstone facies in Nagri Formation might reflect one or more factors including: (1) low subsidence rates promoting regular erosive removal of flood-basin deposits, (2) an arid climatic regime and limited vegetation allowing lesser potential for trapping of fine clastic particles and (3) a strong seasonal discharge resulting in flash flooding and reworking of unconsolidated or semi-consolidated flood-basin deposits as intraclasts.

7.3. Proposed Depositional Model

The sedimentary succession in the Chinji and Nagri formations of the Kohat Plateau (see sections 5 and 6) shows multistorey sandstone complex with sheet geometry, and suggest deposition during sheet floods in braided stream environments (Figs. 5, 6) (Miall, 1978; Rust, 1978a; Gordon and Bridge, 1987). Sedimentological studies of the Siwalik sandstone of the Himalayan Foreland Basin from other sections of the subcontinent also reveal that this complex sandstone was deposited on a fluvial megafan (Kumar and Ghosh, 1994) by a large river system (e.g., Schlunegger et al., 1997, 1998; Horton and DeCelles, 1999), similar to the modern fluvial megafans occurring where modern large Himalayan rivers enter from confined to unconfined areas (e.g., Geddes, 1960; Mohindra et al., 1992; Sinha and Friend, 1994; Gupta, 1997).

The vertical stacking of the sandstone complex (multistorey) with varied facies associations, the sheet geometry, the frequent occurrence of erosional surfaces and palaeoflow consistency at individual locations define its deposition in a braided river environment (Miall, 1978; Rust, 1978a; Gordon and Bridge, 1987; Kumar and Nanda, 1989). Vertical stacking of sandstones is the signature of channel bar and channel fill deposits of aggrading low sinuosity streams which migrate laterally across an alluvial plain (Gordon and Bridge, 1987). The base of each storey is marked by a major erosional surface perpendicular to the palaeoflow direction. The large amount of intra-formational breccia in the form of large mudstone blocks along the erosional surface represents cut-bank material due to bank failure, suggesting high current velocity. Lateral and vertical stacking of the sandstone bodies suggests that several channels with high channel density and braided parameter were active during deposition (Rust, 1978b).

Siltstone and mudstone units of the studied formations were deposited from suspension, representing slack flood water regime (Figs. 5, 6). The alternate beds of fine sandstone and mudstones probably represent levee deposits in the proximal part of the overbank (Allen, 1965; Kumar and Tandon, 1985). Presence of calcrete concretions and mottling within the mudstone indicate incipient soil formation and limited subaerial exposure of the mudstone facies. Evidences for biological activity including vertical, unlined burrows (skolithos) and surface traces (sinusites) are reported locally from the overbank facies (Kumar et al., 2004).

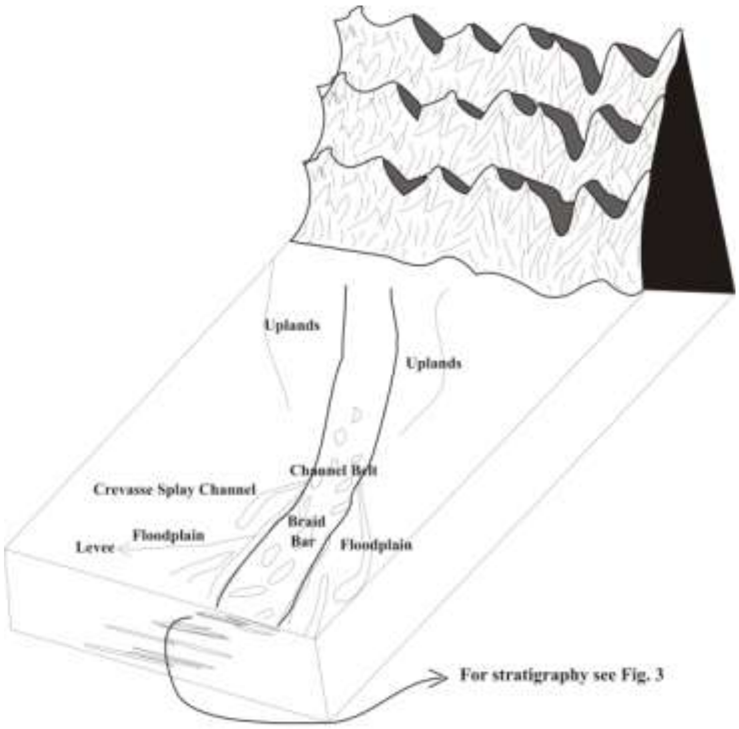

Fig. 5. A schematic block diagram illustrating Chinji Formation, dominantly composed of overbank fine sediments from southwestern Kohat. Deposition of the mud-dominated Chinji Formation was possibly resulted increased tectonic subsidence within the basin.

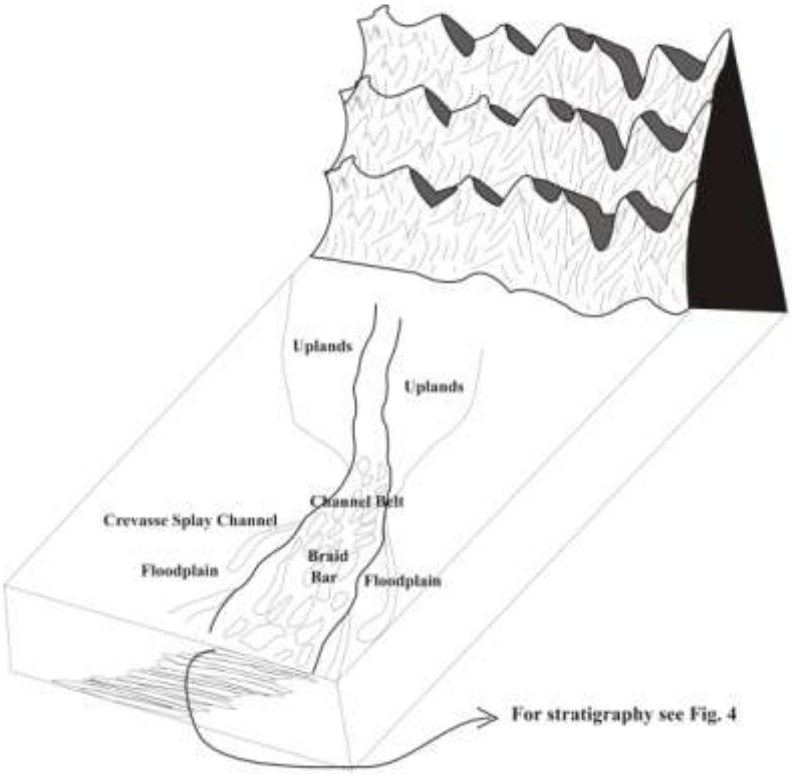

Fig. 6. A schematic block diagram of depositional environments and alluvial architectures of the multistorey sandbodies and associated sandstone splays of the Nagri Formation from southwestern Kohat.

The study by Smith et al. (1989) also offers a possible explanation for the apparent partitioning and subsequent preservation of fine-grained material out of the braided channels into the interfluve setting as the case with the Chinji Formation. The short lived splay systems of the avulsed South Saskatchewan River rapidly deposited large volumes of fine-grained material across its floodplain (Smith et al., 1989). Similarly, the Escamilla splay lithofacies associations represent a large volume of the total fluvial sequences preserved, and are interpreted to have been rapidly deposited during episodic avulsion or overbank flooding (Bentham et al., 1993). Thus, in rapidly subsiding sedimentary basins, streams of braided character can produce deposits that may have many characteristics of higher sinuosity river deposition (Bentham et al., 1993).

According to Gohain and Parkash (1990), multistorey channel bodies can result from climate change, neotectonic activity, differential discharge and sedimentation rates. In the present case, it is inferred that the change in fluvial architecture and channel body proportion is due either to source area uplift (which resulted in an increase in catchment area and high relief, producing more detritus) or altered climatic conditions. In either case, sedimentation patterns suggest a high discharge in large river systems (Kumar et al., 2004).

The depositional model of the Miocene fluvial system of the Himalayan Foreland Basin can best be represented by a wide channel belt, internally showing a braided morphology of minor channels, wholly enclosed within finer-grained overbank sediments (Figs. 5, 6). Within the surrounding interfluve regions, aggradation was accomplished episodically in response to overbank sheets, channelized splay and flood-derived fines deposition (Smith et al., 1989).

The minor differences among the studied outcrops could be explained by the presence of short lived sub-parallel fluvial systems flowing across the alluvial plain at the same time. An alternative possibility is that the different sequences were deposited contemporaneously within a single large braided river such as the Brahmaputra where a variety of styles of deposition can be observed within the river at any given moment in time (Bristow, 1987).

7.4. Fluvial Response to Basin Tectonics

Sedimentation in the Kohat area started after the Eocene continent-continent collision (Dewey et al., 1989; Treloar and Coward, 1991) with slow subsidence rate (Jordan et al., 1988), supported with high degree of interconnectedness of sandstone bodies in the Kamlial Formation. The palaeoflow direction at the time of deposition of Chinji Formation significantly changed because of uplift along the western ranges (Abbasi, 1998). Later on, the high uplift rates of the Kohistan Island Arc and Nanga Parbat Massif (Zeitler, 1985) increased the subsidence rates and hence sedimentation in the foreland basin (Johnson et al., 1985) with abundant sediment supply due to enhanced erosion (Behernsmeyer and Tauxe, 1982; Johnson et al., 1985).

In case of present study, the formation-scale variations exhibited by the Miocene Siwalik Group sequence clearly record different river systems within the Indo-Gangetic foreland basin at that time. Models which attempt to evaluate the response of alluvial deposition to tectonism generally correlate changes in grain size, sediment accumulation rate, slope and facies migration with periods of tectonic uplift and quiescence (stability). Formation level changes in the Siwalik Group were caused by tectonism, increase in channel size and bankfull discharge, with mean channel bed slopes remaining generally constant (Willis, 1993b). The Chinji-Nagri transition seems to represent the establishment of a larger river system in the area (Willis, 1993b). Two likely explanations for this change are discussed below.

a) The development of deformational structures at frontal thrust zones, such as faults and antiforms can cause significant river diversion (DeCelles, 1988; Gupta, 1993). Such structures were present in the Miocene Himalayas (Coward et al., 1987; Treloar et al., 1991a, 1991b, 1992).
b) Differential uplift could have caused river piracy within the mountain belt thereby increasing the discharge of rivers flowing into the foreland.

In either case, the result would be an increase in channel size and bankfull discharge, rise in sediment accumulation rate (and presumably subsidence rate), and increase in grain size without necessarily causing a change in the direction or magnitude of channel bed slopes. The abundance of blue-green hornblende in thick sandstones dramatically increases across the Chinji-Nagri boundary in the western and central Potwar Plateau. It may be a manifestation of river diversion within the mountain belt, however, such a trend is not observed from the eastern Potwar Plateau (Johnson et al., 1985; Cerveny et al., 1989).

The upward transition from mudstone-dominant facies (Chinji Formations) to sandstone facies (Nagri Formation) of the Miocene Siwalik Group of the Kohat Plateau suggests a systematic shift from distal to proximal fluvial deposits. The vertical and lateral stacking of the multistorey sandstone bodies in relation to overbank deposits indicates periodic avulsion of the channel belt (Allen, 1965, 1978; Bridge and Leeder, 1979), which suggests an increase in the drainage network in the source area (Kumar et al., 2004). An increase in drainage areas and high relief thus supplied more sediments than small catchment areas having low relief (Pinet and Souridu, 1988). In the Himalayan Foreland Basin, the basin-ward progradation of coarser facies is correlated with either thrusting and/or uplift of the orogenic belt (Burbank and Raynolds, 1988) or a higher rate of sedimentation than of subsidence in the basin (Blair and Bilodeau, 1988; Heller et al., 1988). Similarly, sedimentary basins close to high relief of active orogenic belts receive large volume of sediment, e.g., rivers draining the orogenic belts of southern Asia supply more than 70% of the sediment load entering the oceans (Milliman and Meade, 1983).

Catuneanu et al. (1997, 2000) have described a succession of basin-scale loading/unloading cycles. In a tectonic loading cycle, the foreland basin system is similar to that of the DeCelles and Giles model (1996) and consists of the four depozones i.e., the wedgetop depozone, the foredeep depozone, the forebulge depozone and the backbulge depozone. In a tectonic unloading cycle, the foreland basin system is made up of two depozones (the foresag and the foreslope depozones separated by the flexural hinge line) and the forebulge is missing (Catuneanu et al., 1997). In case of the Himalayan Foreland Basin, the Sargodha High is a basement structure which likely represents the forebulge of the Miocene Ganges basin. Its trend is generally parallel to the trend of the modern Ganges basin. Thickness of the Siwalik rocks dramatically decreases toward this forebulge, but do pass over it. Extensive age-equivalent deposits in both the Indus and Bengal submarine fans and in the Indus and Ganges-Brahmaputra deltas indicate that deposition kept pace with or exceeded subsidence (e.g., Kazmi, 1984; Lindsay et al., 1991).

High exhumation rates in orogens are generally driven by both tectonic convergence and climatically controlled erosion (Whipple and Tucker, 1999; Willett, 1999). Continuous sediment supply needs positive feedback between erosion and exhumation over geologic time and thus requires (a) high regional erosion, and (b) coeval replacement of mass by tectonic influx of material (Thiede et al., 2004). However, the nature of this interaction between the distribution of precipitation, regional erosion rates and patterns of rock uplift is still a matter of controversy (Burbank et al., 2003;. For example, in central Nepal, Burbank et al. (2003) suggest that tectonically forced removal of crustal material is the most important factor affecting erosion across a region, supported by the complete removal of approximately 10-15 km of the Greater Himalayan crystalline rocks along the Sutlej Valley since the MCT was active (Thiede et al., 2004) and the decreasing erosion rates since 8 Ma, immediately following the commonly accepted age of monsoonal strengthening (Burbank et al., 1993). In contrast, measured erosion rates in the modern Himalaya are faster in regions where the monsoon is heavier (Galy and France-Lanord, 2001), supported by ~3 times higher modern erosion rates in the northernmost parts of the Lesser Himalaya than in the adjacent Greater Himalaya (higher rock uplift rates north of the MCT) (Amidon et al., 2005). The asymmetrical nature of the Neogene strata of the Himalayan Foreland Basin as well as the Indo-Ganga plain, thick in the hinterland and thin in the distal regions, indicate tectonically induced uplift in the source area for the studied area.

7.5. Comparison with the Modern Indus Fluvial Basin

It has been long noted that the current Himalayan drainage system is asymmetric, with the Indus River system covering about one-fifth of the Himalayan range and by the Ganges and Brahmaputra River systems the rest. DeCelles et al. (1998a) has proposed that the east-west trending Himalayan drainage system in the foreland had reversed its flow direction from the west to the east in the Pliocene after the deposition of the older part of the Siwalik Group. Another model proposed for the evolution of the Indus and Ganges systems considers the current Himalayan drainage systems to have remained approximately the same configuration since the start of the Indo-Eurasian collision (Brookfield, 1998). Lithofacies of the Chinji and Nagri formations are also thought to represent deposits of either the paleo-Indus river or a similar axial fluvial system (Johnson et al., 1982; Najman et al., 2003). The multistoreyed channel type sandstone-bodies of the Chinji Formation in southeastern Kohat suggest a consistent flow direction to the SSE (Abbasi, 1998). The sedimentary structures in the overlying Nagri Formation suggest a dominant paleoflow direction to the SSW (Abbasi, 1998). Broad similarities between the Siwalik rivers and modern fluvial system of the Indo-Gangetic basin are also noteworthy (Zaleha, 1997b). For example, river systems of modern Indo-Gangetic basin are relatively large, mainly consisting of braided rivers (e.g., the Indus, Jhelum, Chenab, Yamuna, Ganges) and spaced on the alluvial plain at intervals of ~60-200 km (Zaleha, 1997b). These rivers merge 300-600 km downstream from the mountain front, and being generally transverse to the basin axis near the mountain front but becoming largely parallel to the basin axis further down. Alike, similarities in channel geometries, discharges and sedimentary characters of Siwalik rivers and modern Indus river system including emergence from a mountain belt, generally parallel flow to the basin axis, slopes range from 0.000085 to 0.00018, and bankfull discharges in the order of 10^2-$10^3 m^3 s^{-1}$ (Mackey and Bridge, 1995) advocate the same idea.

The Miocene Indo-Gangetic foreland seems to be a composite of two distinct basins that are parallel to the Himalayan mountain belt (Zaleha, 1997b). The ancient Ganges and Indus basins were ~ 2000 km and 1000 km long, respectively. Basin widths were ~ 200-300 km along most of their lengths but may have varied from 100 to 500 km (Zaleha, 1997b).

Furthermore, the large volumes of Siwalik-age-equivalent sediments in the Indus and Bengal submarine fans and in the Indus and Ganges-Brahmaputra deltas (Kazmi, 1984; Lindsay et al., 1991; Weedon and McCave, 1991) indicate the coeval existence of significant drainage systems in both the Indus and Ganges Miocene forelands. The dominantly south to south-west palaeocurrents in Siwalik rocks in the Trans-Indus area (Cerveny et al., 1989) further support the existence of an active drainage system there, which flowed toward the Indus submarine fan during that time.

8. Conclusions

Detailed sedimentologic studies of both the Chinji and Nagri formations from three different sections of the southwestern Kohat Plateau reveal that they consist of four lithofacies, each namely, C1, C2, C3 and C4 (Chinji Formation), and N1, N2, N3 and N4 (Nagri Formation). C1 and N2 facies represent deposition in very wide, shallow channels of a distal, sand-dominant braided fluvial system. C2 and N3 facies contain deposits of crevasse splay channels in associated floodplains. C3 and N4 facies indicate levee and minor distal splay deposits, whereas the mud/clay rocks in C4 facies imply a flood basin origin in a well drained oxygenated environment.

Sandstone of the Chinji Formation was most probably deposited by mixed-load rivers, and the floodplain deposits by suspended-load rivers, whereas the Nagri Formation was possibly deposited by sandy bedload river. Vertical stacking of the multistorey sandstone complex with varied facies associations, the sheet geometry, and frequent occurrence of erosional surfaces define its deposition in a braided river environment. The depositional model for the Miocene fluvial system of the Himalayan Foreland Basin can best be represented by a wide channel belt, internally showing a braided morphology of minor channels, wholly enclosed within finer-grained overbank sediments. The minor differences among the studied outcrops probably reflect contemporaneous deposition within a single large braided river such as the Brahmaputra with a variety of styles at a given moment.

The Chinji-Nagri transition from mudstone-dominant facies of Chinji formations to sandstone facies of Nagri Formation records the diversion or establishment of a larger river system attributed to an increase and spatially variable mountain belt uplift rates in the hinterland areas or drastic change in climate. The low proportion of mudstone-siltstone facies in Nagri Formation might also be due to: (1) an arid climatic regime and limited vegetation allowing greater potential for lateral migration of channels and (2) strongly seasonal discharge resulting in flash flooding and reworking of unconsolidated or semi-consolidated flood-basin deposits as intraclasts. The asymmetrical basin fill in the Ganga Plain foreland basin and Miocene Siwalik sequence suggests tectonically induced uplift in the Himalayan orogen.

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