A Paleogeographic and Depositional Model for the Neogene Fluvial Succession, Pishin Belt, Northwest Pakistan: Effect of Post Collisional Tectonics on Sedimentation in a Peripheral Foreland Setting

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Abstract: Detailed facies analysis of the Neogene successions of the Pishin Belt (Katawaz Basin) has enabled documentation of successive depositional systems and paleogeographic settings of the basin formed by the collision of the northwestern continental margin of the Indian Plate and the Afghan Block. During the Early Miocene, subaerial sedimentation started after the final closure of the Katawaz Remnant Ocean. Based on detailed field data, twelve facies were recognized in Neogene successions exposed in the Pishin Belt. These facies were further organized into four facies associations i.e. channels, crevasse splay, natural levee and floodplain facies associations. Facies associations and variations provided ample evidence to recognize a number of fluvial architectural components in the succession e.g., low-sinuosity sandy braided river, mixed-load meandering, high-sinuosity meandering channels, single-story sandstone and/or conglomerate channels, lateral accretion surfaces (point bars) and alluvial fans. Neogene sedimentation in the Pishin Belt was mainly controlled by active tectonism and thrusting in response to the oblique collision of the Indian Plate with the Afghan Block of the Eurasian Plate along the Chaman-Nushki Fault. Post Miocene deformation of these formations successively caused them to contribute as an additional source terrain for the younger formations.

Key words: Active tectonics, fluvial system, paleogeography, Pishin belt, Indian-Eurasian collision zone

1 Introduction

Continent-continent collision causes the development of peripheral foreland basins marked by deformation followed by flexure of the inherited passive margin of the foreland plate. Progressive convergence develops a foreland basin from a flysch stage to an overfilled molasse stage (Allen et al., 1991; Sinclair, 1996; XU et al., 2013) and the thick sedimentary successions were fed by the uplifted mountain ranges. Continued deformation and uplift cause erosion of sedimentary units; these eroded sediments were deposited as progressively younger sediments. The Pishin Belt (Fig. 1) is a perfect example of a peripheral foreland basin, which was opened after the initial collision of the Indian Plate with the Afghan Block of the Eurasian Plate between 66 and 55 Ma. The collision closed the northern part of the Neo-Tethys Ocean and opened the Katawaz Remnant Ocean in the southwest (Qayyum et al., 1997). The Katawaz Basin started receiving siliciclastic detritus from the emerging western Himalayas, through major drainage systems, and was deposited on to the forelands of the Himalayas as molasse, and further taken into the delta and submarine fan in the deeper ocean (Graham et al., 1975; Qayyum et al., 1996; Kassi et al., 2011, 2015). Qayyum et al. (1997, 2001) proposed that the Paleo–Indus River eroded and transported the Palaeogene siliciclastic detritus from the western Himalayas to the Katawaz delta and associated submarine fan system (Khojak-Panjgur submarine fan system; Critelli et al., 1990; Kassi et al., 2011; 2015). Continued collision between the Indian Plate and the Afghan Block ultimately closed the Katawaz Remnant Ocean. The uplifted carbonate (Nisai Formation), the siliciclastic marine successions of the Khojak

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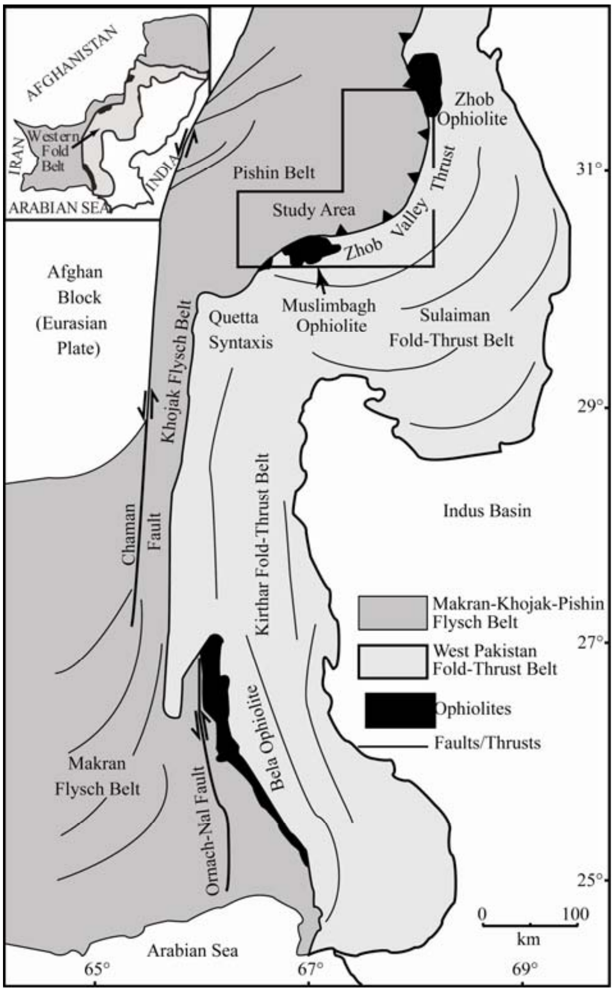

Fig. 1. Generalized geological map of the western part of Pakistan, showing the position of the Pishin Belt and study area (after Bannert et al., 1992).

Formation and the Muslim Bagh Ophiolite started providing detritus to the molasse successions of Miocene through Holocene successions (Dasht Murgha Group, Malthanai Formation, Bostan Formation and Zhob Valley deposits) deposited in the south- and southeast-verging successive thrust-bound foreland basins at the outermost extremity of the Pishin Belt (Kasi et al., 2012,; 2016; Kasi, 2014).

This is the first study of its kind, which describes and interprets facies and facies associations of the Neogene strata of the Pishin Belt. An attempt has been made to conceive tectonically active paleogeography and a depositional model for the Dasht Murgha Group, Malthanai Formation and Bostan Formation.

2 Geological Setting and Stratigraphy

The Pishin Belt is part of the Makran-Khojak-Pishin Flysch Belt, located in northwestern Pakistan (Fig. 1). It is a median basin, having an axial length of more than 700 km and a maximum width of 200 km. The belt was first mapped by Jones (1961) as part of their reconnaissance survey. Qayyum et al., (1997; 2001) subsequently mapped the area using Landsat imaging. Maldonado et al. (2011) further modified the Jones (1961) map. It is a wide, southeast-verging belt comprising several tectonostratigraphic zones (Fig. 2) (Kasi et al., 2012). In the west, it is bounded by the Chaman-Nushki Fault and the Afghan Block and in the east and southeast by the Zhob Valley Thrust, the Muslim Bagh-Zhob Ophiolite and the succession of the Indian Plate (Lawrence et al., 1981; Jadoon and Khurshid, 1996). The Quetta Syntaxis bends the N-S-trending Khojak Flysch segment into the NE-SW-trending Pishin segment (Powell, 1979; Sarwar and DeJong, 1979; Bender and Raza, 1995). The belt has been folded into tight anticlines and broad synclines representing transpressional to compressional deformation styles from its western edge to the eastern edge (Iqbal, 2004). The entire succession of the belt has been tectonically transported to the southeast along the Zhob Valley Thrust over the Muslim Bagh-Zhob Ophiolite, associated mélanges and successions of the Indian Plate (Fig. 2) (Lawrence and Yeats, 1979; Lawrence et al., 1981; Treloar and Izatt, 1993; Bender and Raza, 1995; Jadoon and Khurshid, 1996; Kazmi and Jan, 1997).

The Pishin Belt has been divided into six tectono-stratigraphic zones bounded by major thrusts (Fig. 3); each zone having its distinct lithostratigraphy (Kasi et al., 2012; Kasi, 2014). The Muslim Bagh Ophiolite comprises Zone I, and, believed to be the base of the Pishin Belt, is the remnants of the oceanic lithosphere of the Neo-Tethys. It was obducted onto the western margin of the Indian Plate subsequent to the closure of the Neo-Tethys and the collision of the Indian Plate with the Afghan Block of the Eurasian Plate at the Cretaceous-Tertiary boundary, or later in Paleocene-Early Eocene times (Alleman, 1979; Sarwar, 1992; Mahmood et al., 1995; Ahmed, 1996; Gnos et al., 1996; Qayyum, 1997; Kakar et al., 2012). The Eocene Nisai Formation, which comprises Zone II, non-conformably overlies the Muslim Bagh Ophiolite. The Nisai Formation, which comprises Zone II, is mostly exposed along the Zhob Valley Thrust (Fig. 2). It comprises limestone, marl and shale. Bukhari (2015) proposed a Middle Eocene to Late Oligocene age, based on larger benthic foraminiferal assemblages. The formation has been deposited on a shallow water carbonate platform and deep water slope and basin plane environments (Qayyum, 1997). It is conformably overlain by the Khojak Formation. The Khojak Formation (Zone II) comprises two members; the lower Murgha Faqirzi Member is dominated by shale, and the upper Shaigalu Member is dominated by sandstone (Qayyum, 1997).

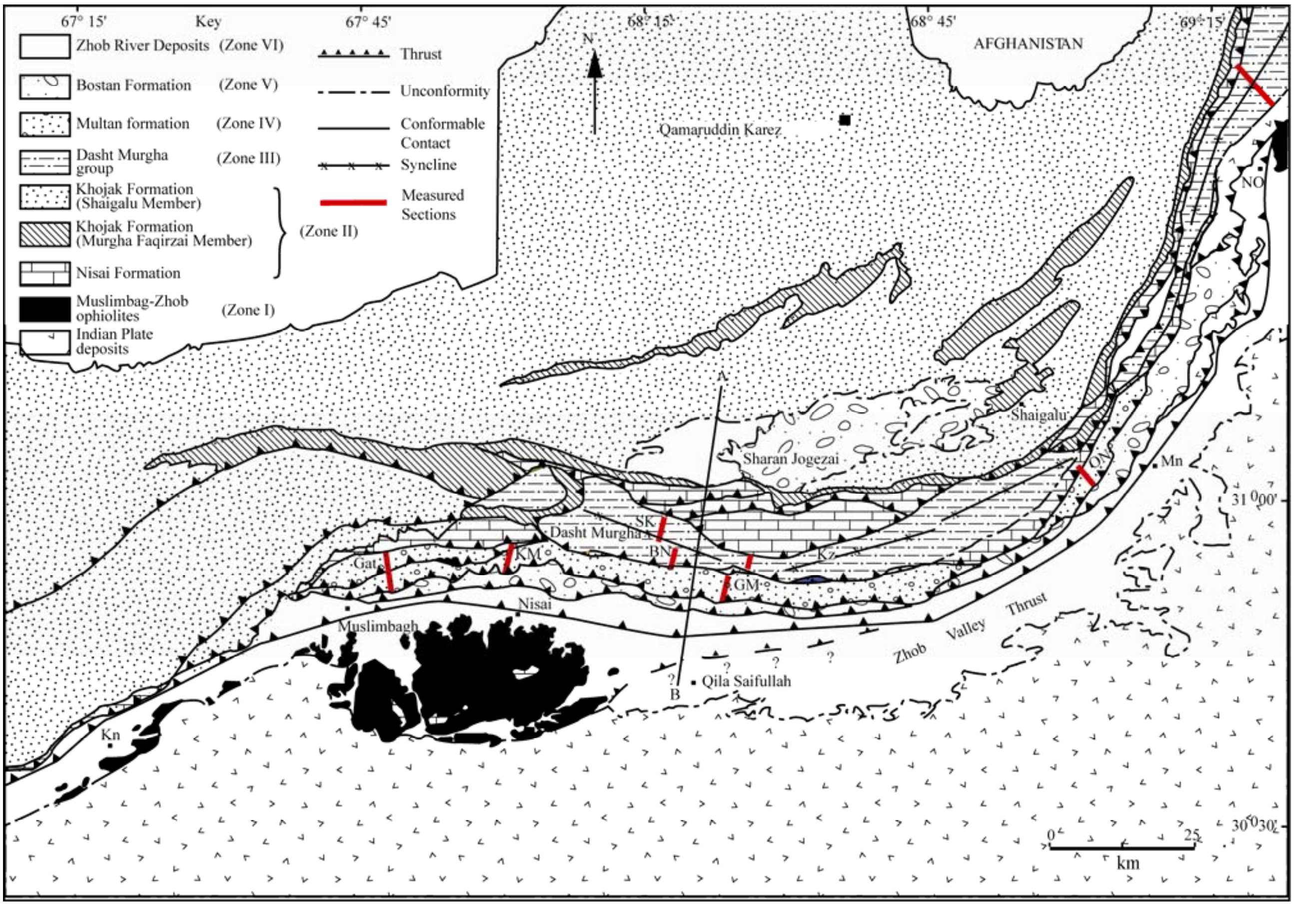

Fig. 2. Geological map showing tectono-stratigraphic zones and lithostratigraphy of the study area (modified from Jones, 1961).
Abbreviations used are: Bn (Bahlol Nika); GM (Gardab Manda); KM (Kazha Mirzai); Kn (Khanozai); Kz (Khozhobai); Mn (Malthanai); No (Naweoba); ON (Oblin Nala) and SK (Sra Khula); AB is the cross-section line.

Jones (1961) assigned an Oligocene age to the formation, while Bukhari (2015) projects the age of the underlying Nisai Formation to the Late Oligocene, which pushes the Khojak Formation towards a Miocene age. The Khojak Formation is deposited in a wave-modified fluvial-dominated delta-submarine fan system (Qayyum et al., 1996; Carter et al., 2010; Kassi et al., 2011; 2015). The Dasht Murgha Group (Zone III) is subdivided into three formations. The lowermost unit, the Khuzhobai Formation, is a cyclic succession of sandstone and mudstone, with mudstone being dominant over sandstone. Its lower contact with the Eocene Nisai Formation is an angular unconformity. The middle unit, the Bahlol Nika Formation, comprises a thick succession of sandstone with subordinate mudstone, siltstone and occasional conglomerate beds. Its upper contact with the Sra Khula Formation is transitional and conformable. The Sra Khula Formation is composed of cyclic alterations of mudstone, siltstone and sandstone, with mudstone exceeding sandstone in proportion. The formation transitionally and conformably overlies the Bahlol Nika Formation. Based on its stratigraphic position we assign an Early to Middle Miocene age to the group. The Malthanai Formation comprises sandstone interbedded with siltstone, mudstone and conglomerate. The proportion of sandstone to mudstone/siltstone is roughly equal. In the type section the formation has thrust contact with the Pleistocene Bostan Formation, whereas its contact with the Nisai Formation is an angular unconformity. Based on its stratigraphic position, we propose that it is younger than the Dasht Murgha Group, and may be of Late Miocene-Pliocene age. The Bostan Formation comprises cyclically interbedded successions of conglomerate, mudstone and sandstone. Conglomerate dominates over sandstone and mudstone. On the basis of its stratigraphic position, Cheema et al. (1977) suggested a Pleistocene age for it.

3 Materials and Methods

Ten stratigraphic sections at outcrop were studied and logged in detail across the Pishin Belt. Twelve distinct lithofacies were identified and grouped into four facies associations (Table 1). The descriptive terminology and facies codes of Miall (1978, 1996) and Arenas and Pardo

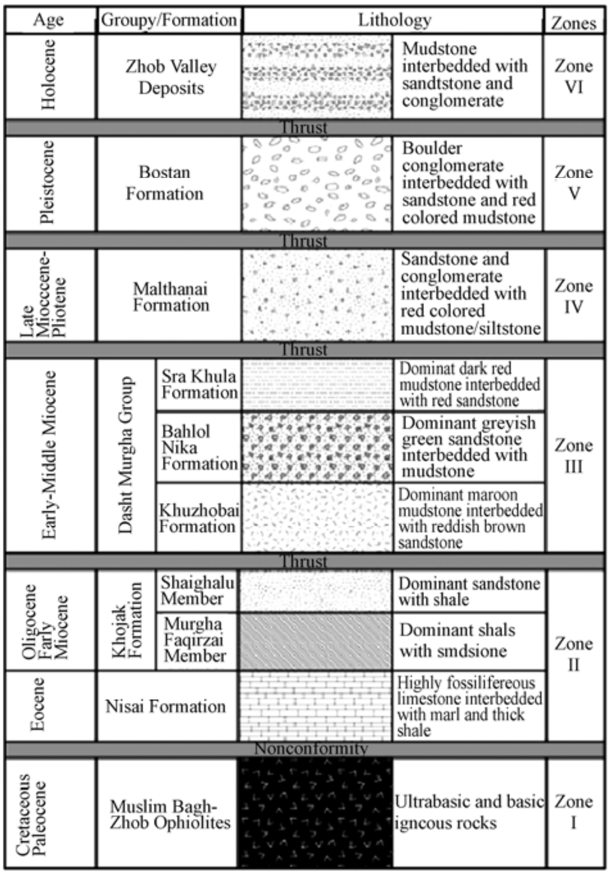

Fig. 3. Lithostratigraphy and tectono-stratigraphic zones of the Pishin Belt (modified from Jones, 1961; Cheema et al., 1977).

(1999) have been used. However, facies and facies associations were defined, classified and interpreted using the classification schemes of Ashley (1990), Bridge (1993), Miall (1978, 1985, 1992, 1996) and Hjellbakk (1997) (Table 2). Bed thickness has been categorized according to the classification scheme of Ingram (1954), and grain size according to the classification scheme of Wentworth (1922).

4 Facies

Facies are the sum total of features that reflect the specific environmental conditions under which sediments were deposited. Twelve distinct facies have been identified and described in the tectonically active fluvial system (Dasht Murgha, Malthanai and Bostan Formations) in the Pishin Belt.

4.1 Clast-supported massive gravel facies (Gcm)

The Gcm facies comprises massive and clast-supported conglomerate (Fig. 4a; Table 1), which comprises extra-formational clasts of various sizes, ranging from 1 cm to 1 m (Fig. 5a). The conglomerate is commonly very poorly sorted and contains well rounded to subrounded clasts of pebble to boulder size. Thin to thick parallel laminated sandstone/siltstone lenses are common within the conglomerate. Bed thickness varies from 30 cm to 10 m. The matrix of the conglomerate is fine to coarse grained sand and silt. The facies is characterized by highly erosive bases (Fig. 5b); huge scours and load casts have been noted at their bases, particularly when overlying mudstone, siltstone or fine grained sandstone (Fig. 5c). Granular debris flows produce Gcm facies (Coussot and Meunier, 1996; Miall, 1996).

4.2 Clast-supported crudely bedded gravel facies (Gh)

Facies Gh commonly shows crude horizontal bedding and clast-supported texture (Fig. 4b). The conglomerate is poorly sorted and contains subrounded extraformational clasts of pebble to boulder size, with maximum clast size of up to 70 cm, showing normal to reverse grading and imbrication (Fig. 5d). Beds have a lenticular morphology, and highly erosive bases (Fig. 5e). Lenticular beds mostly pinch out laterally within a distance of 5 to 30 m. Bed thickness varies from 30 cm to 5 m. The matrix of the conglomerate is fine to coarse grained sand or silt. Gh facies are deposited from migration of low-height bed waves, (e.g. bedload sheets of Bridge, 1993) forming longitudinal bars or sieve deposits (Miall, 1996).

4.3 Cross-stratified conglomerate facies (Gt and Gp)

This facies is characterized by a combination of trough cross-stratified (Gt) and planar cross-stratified (Gp) conglomerates (Fig. 4c; Table 1). Low-angle cross-stratification is also present in some horizons. The conglomerate is clast-supported, moderately sorted and contains subrounded to well-rounded pebble and cobble-size clasts, commonly showing imbrication. Maximum clast sizes in different horizons range from 5 cm to 60 cm. Beds are up to 2 meters thick, showing a lenticular morphology and erosive bases. Matrix comprises fine to very coarse grained (even pebbly) sandstone and siltstone. Rip-up mud clasts are also seen in some horizons. Crudely developed cross-bedding, erosive bases and dominance of extrabasinal clasts indicate that facies Gt was deposited from downstream migration of sinuous-crested dunes in channel fills, whereas Gp was deposited from obliquely migrating straight-crested dunes within transverse bars (Miall, 1996; Paredes et al., 2007).

4.4 Trough cross-stratified sandstones facies (St)

Sandstone of the facies St is fine to very coarse grained, very thin to thick bedded and trough cross-stratified (Fig. 4d). Some cosets of trough cross-bedding may reach up to 4 m in thickness (Fig. 5F). Beds generally have lenticular

Table 1 Summary of the characteristic features of the lithofacies types in the Dasht Murgha Group, Malthanai Formation and Bostan Formation (facies codes after Miall, 1996)

Facies	Gcm	Gh	Gt	Gp	St	Sp
Lithology	Cobble to boulder clast supported conglomerate	Pebble to boulder clast supported conglomerate	Pebble to cobble clast supported conglomerate	Pebble to cobble clast supported conglomerate	Fine to very coarse grained sandstone	Very fine to very coarse grained sandstone
Sedimentary structures	Massive, disorganized	Crudely bedded, normal to reverse grading	Solitary trough cross bedded sets	Solitary planar cross bedded sets	Trough cross bedded, solitary and cosets	Planar cross bedded, solitary and cosets
Geometry	Very thick, tabular to lenticular	Thick, tabular to lenticular	Thick, lenticular	Thick, lenticular	Thick to thin, lenticular	Moderately thick, tabular to lenticular
Contacts	Lower highly erosive, huge load casts	Lower highly erosive, upper sharp to gradational	Lower erosive, upper sharp to gradational	Lower sharp, upper sharp to gradational	Lower erosive, upper gradational	Lower sharp, upper sharp to gradational
Interpreted depositional environment	Debris flow deposits	Longitudinal bars or sieve deposits	Migration of sinuous-crested dunes in gravelly channels	Migration of straight-crested dunes or bars in gravelly channels	Migration of sinuous-crested dunes in sandy channels	Migration of straight-crested dunes or bars in sandy channels
Facies	**Sr**	**Sh**	**Sl**	**Sm**	**Fm**	**P**
Lithology	Fine to coarse grained sandstone	Fine to very coarse grained sandstone	Fine to very coarse grained sandstone	Medium to very coarse grained sandstone	Mudstones, siltstone and very fine grained sandstone	carbonate
Sedimentary structures	Ripple cross laminated	Horizontally bedded/laminated, parting lineation on parting surfaces	Low-angle cross bedded	Massive or faintly laminated	Massive mudstone, parallel or cross laminated siltstone and sandstone	Massive, calcareous and nodular
Geometry	Thin to medium, tabular to lenticular	Thin to thick, tabular	Thin to very thick, tabular	Very thick, lenticular to tabular	Thick, tabular	Medium, tabular
Contacts	Lower gradational, upper sharp	Lower erosive to sharp, upper sharp to gradational	Lower sharp, upper gradational	Lower erosive, upper sharp to gradational	Sharp upper and lower contacts	Lower gradational, upper sharp
Interpreted depositional environment	Migration of ripples on bar tops or minor channels deposits of waning flow	Upper flow regime plane beds	Washed- out dunes or antidunes	Mass flow deposits in channels or crevasse splays	Over bank, floodplain or abandoned channel deposits	Ancient soil deposits

morphology and pinch out laterally. Thickness of the sets range between 15 and 75 cm. Rip-up mud/silt clasts are very common at the basal part of the sets. Sandstone of facies St commonly shows concave-up channel morphology and erosive bases truncating the underlying lithology. Deposition of the facies St resulted from migration of the sinuous-crested dunes or megaripples in the lower flow regime (Cant and Walker, 1976; Miall, 1996; Capuzzo and Wetzel, 2004).

4.5 Planar cross-stratified sandstone facies (Sp)

The facies Sp is characterized by very fine to very coarse grained and thin to thick bedded (range: 10 cm to 1 m) planar cross-stratified sandstone (Figs. 4d and 6a). Beds show lenticular morphology. The lenticular beds have erosive bases with rip-up mud/silt clasts; they generally pinch out laterally within a few meters. Planar cross-bedding is the main feature of this facies, however, they are commonly associated with parallel and cross-lamination of other types. Both solitary and cosets of the planar cross-strata are present, which reach up to an overall thickness of 1.5 m. In places solitary sets of small-scale planar cross-lamination have been observed (Fig. 6b). Facies Sp is interpreted to have been formed by the migration of straight-crested dunes or bars deposited in a lower flow regime (Collinson, 1996; Miall, 1996; Hjellbakk, 1997; Capuzzo and Wetzel, 2004).

4.6 Ripple cross-laminated sandstone facies (Sr)

The facies Sr comprises fine to coarse grained ripple cross-laminated sandstone (Figs. 4e and 6c), which is thin to medium bedded (range: 10 cm to 30 cm) with some thick beds (up to 1 m). Lower surfaces of the beds are mostly straight, except for a few thick-bedded and coarse grained beds, which have erosive bases. Some beds contain ripple cross-lamination in their upper parts, which indicate waning current energy. The presence of asymmetrical current ripples and ripple cross-lamination indicates deposition under a subaqueous traction process (Miall, 1996). Facies Sr shows deposition from migrating asymmetrical current ripples under controlled conditions of sediment supply at a lower flow regime, within largely inactive channels as fill deposits (Allen, 1963; Miall, 1996). It represents temporary abandonment of bar migration as flooding recedes or deposition in areas of sluggish water flow between bars or overbank areas (Kirk, 1983; Bose and Chakraborty, 1994; Collinson, 1996).

4.7 Horizontally stratified sandstone facies (Sh)

This facies is characterized by fine to very coarse grained, horizontally stratified sandstone, possessing pronounced parting lineation on the bedding surfaces (Fig. 4f). Beds are very thin to thick, ranging from 10 cm to over 1 m (Fig. 6d), generally showing tabular geometry and sharp bases. Facies Sh show plane beds of the upper

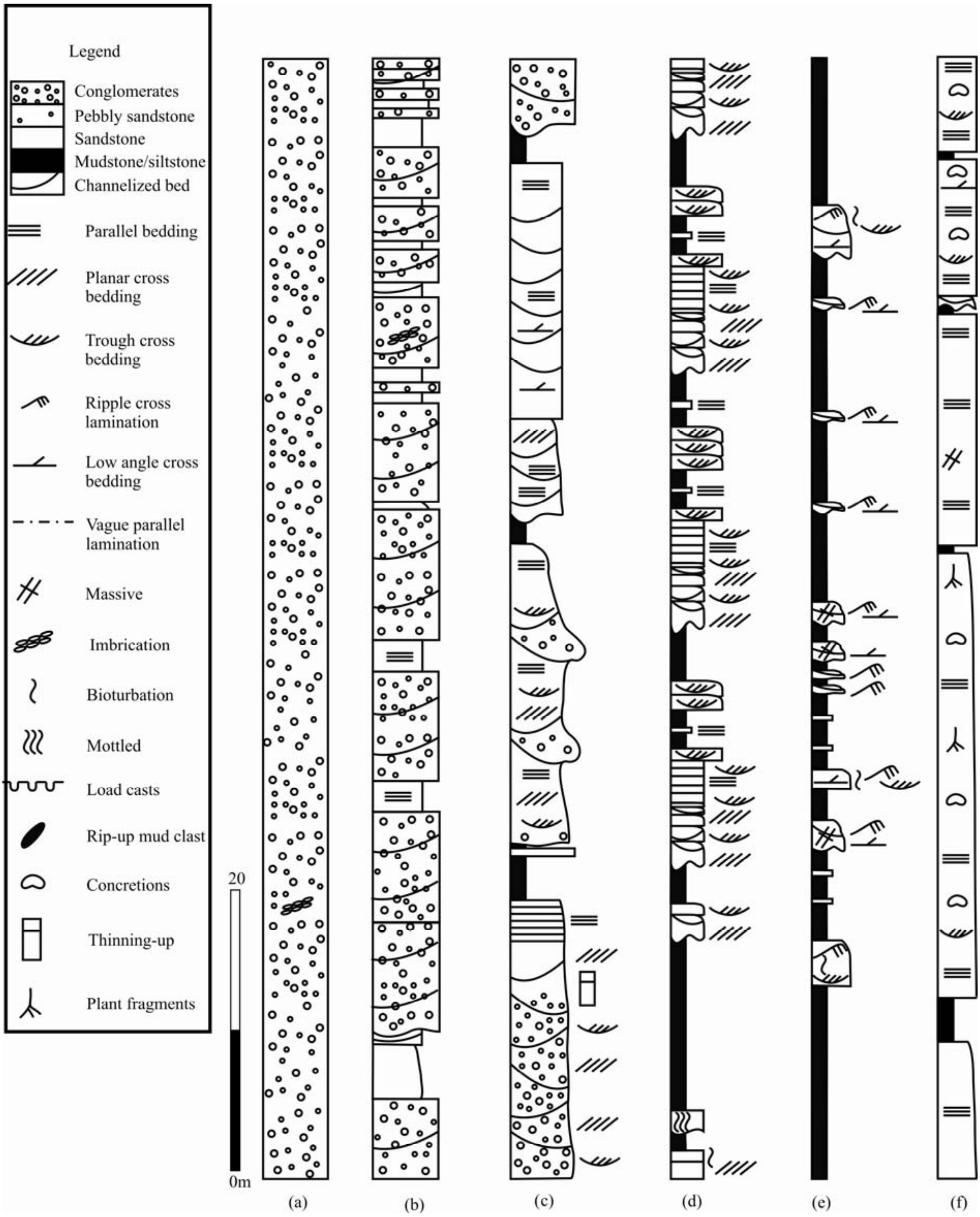

Fig. 4. Columnar profile showing facies in the measured sections (a) clast supported massive gravel facies (Gcm); (b) clast supported crudely bedded gravel facies (Gh); (c) Trough and planar cross-stratified conglomerate facies (Gt and Gp); (d) trough cross stratified sandstone facies (St); planar cross-stratified sandstone facies (Sp); (e) ripple cross laminated sandstone facies (Sr) and (F) horizontally stratified sandstone facies (Sh).

flow regime (Miall, 1985). Burst-sweep processes (Bridge, 1978; Cheel and Middleton, 1986) caused by the interaction of sediment transport and turbulence and migration of bedforms of very low-height on flat beds or bar tops are considered to be responsible for deposition of the horizontally stratified sandstone (Allen, 1984; Bridge and Best, 1988; Paola et al., 1989; Santos and Stevaux, 2000). Horizontal stratification is typical of fine- to

Fig. 5. Field photographs.
(a), massive cobble- to boulder-conglomerate (facies Gcm) of the Bostan Formation (Kazha Merzai section); (b), erosive base of massive conglomerate eroding the underlying coarse grained sandstone (Gat section); (c), very large-size load cast at the base of massive and very thick bedded cobble conglomerate in upper part of the Malthanai Formation (Oblin Nala section); (d), imbrication in conglomerate of the Bostan Formation; (Kazha Merzai section); (e), channel-fill conglomerate, embedded in coarse grained to pebbly sandstone, showing lenticular morphology (Gardab Manda section) (f), large scale trough cross-bedding (facies St) in sandstone of the Dasht Murgha Group (Bahlol Nika section).

medium-grained sandstone, associated with parting lineation, resulting from micro-vortices starting under high stream power to sort and deposit sand clasts (Fielding, 2006). Thick successions of the facies Sh form by an interplay of sheet-floods, wash-out dunes and antidunes in the energetic ephemeral streams in arid-semiarid conditions (McKee et al., 1967; Williams, 1971; Frostick and Reid, 1977; Tunbridge, 1981, 1984; Olsen, 1987; Dam and Andreasen, 1990; Best and Bridge, 1992).

4.8 Low-angle cross-stratified sandstone facies (Sl)

Facies Sl is characterized by fine to very coarse grained, thin to very thick bedded low-angle (<15°) cross-bedded sandstone beds (Figs. 6e and 7a) which exhibit tabular geometry. The facies formed from washed-out dunes or antidunes in high energy flow conditions (Miall, 1996).

4.9 Massive sandstones facies (Sm)

Facies Sm comprises medium to very coarse grained to pebbly massive sandstone beds (Figs. 6F and 7B), which

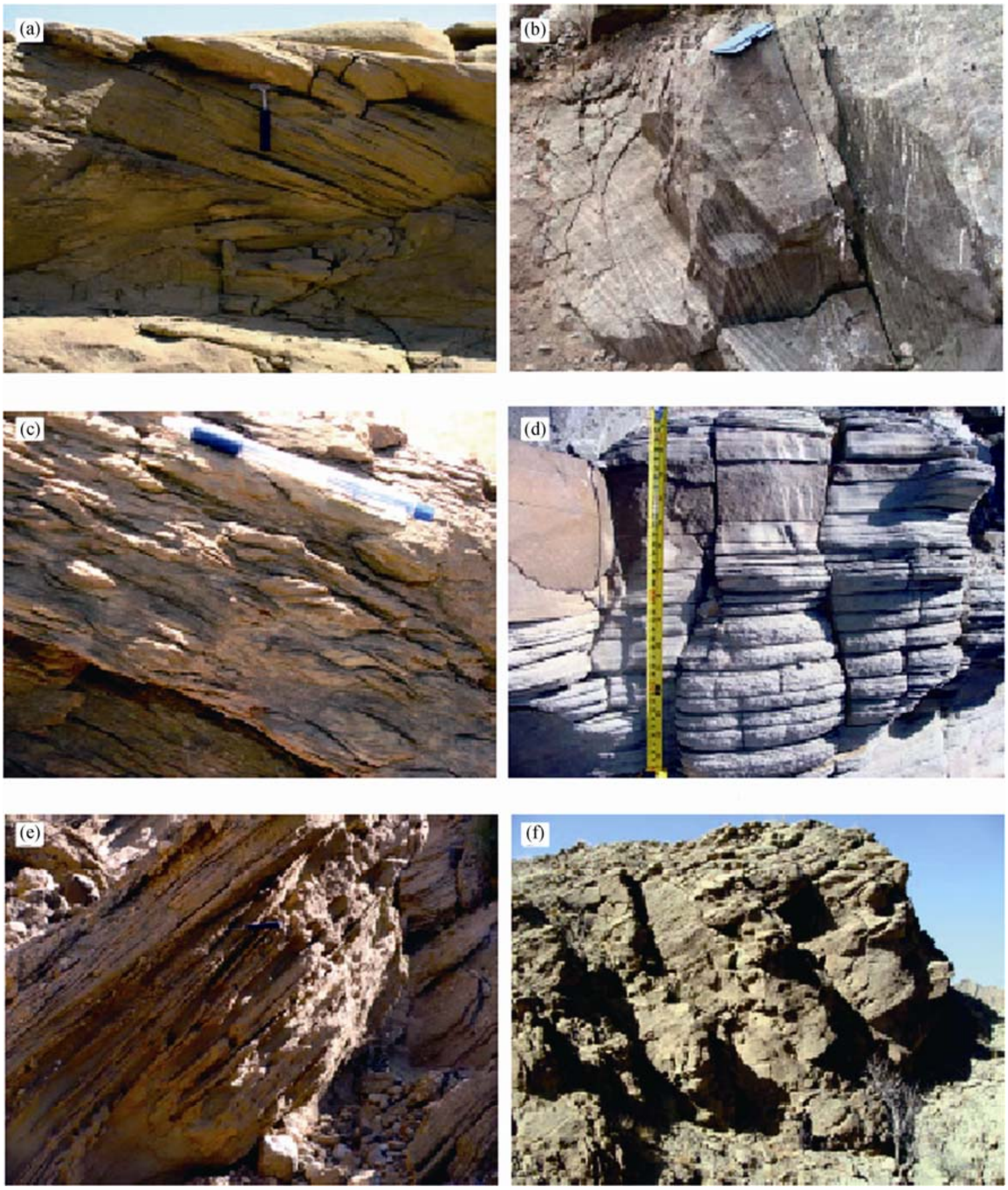

Fig. 6. Field photographs.
(a), a thick set of planar cross-bedding (facies Sp) in sandstone of the Dasht Murgha Group (Khuzhobai section); (b), coset of the planar cross-lamination in sandstone of the Dasht Murgha Group (Naweoba section); (c), ripple cross-lamination (facies Sr) in sandstone of the Dasht Murgha Group (Khuzhobai section); (d), horizontally bedded/laminated sandstone (facies Sh) of the Dasht Murgha Group (Khuzhobai section); (e), a set of low-angle cross-bedded (facies Sl) sandstone of the Bostan Formation (Gardab Manda section); (f), a very thick bedded massive sandstone (facies Sm) of the Dasht Murgha Group (Khuzhobai section).

are mostly thick to very thick, however, some thin beds are also massive. Bed thickness ranges from 30 cm to 15 m and have erosive bases with rip-up mud/silt clasts and iron concretions. Massive beds are generally formed in response to depositional processes such as short-lived mass flows (hyper-concentrated flood-flows of Smith, 1986) followed by sediments dumping at a high-quit rate without allowing for hydraulic sorting mechanisms (Collinson, 1970; McCabe, 1977; Jones and Rust, 1983; Rust and Jones, 1987; Turner and Monro, 1987; Lowe, 1988; Hjellbakk, 1997). During high runoff period the sediments erode from less-compact sand-rich alluvium and its short-lived transportation may be evident from the existence of rip-up mud/silt clasts (Hjellbakk, 1997). Rapid deposition of high sediment load may also be caused by reduction of the turbulence and dispersive

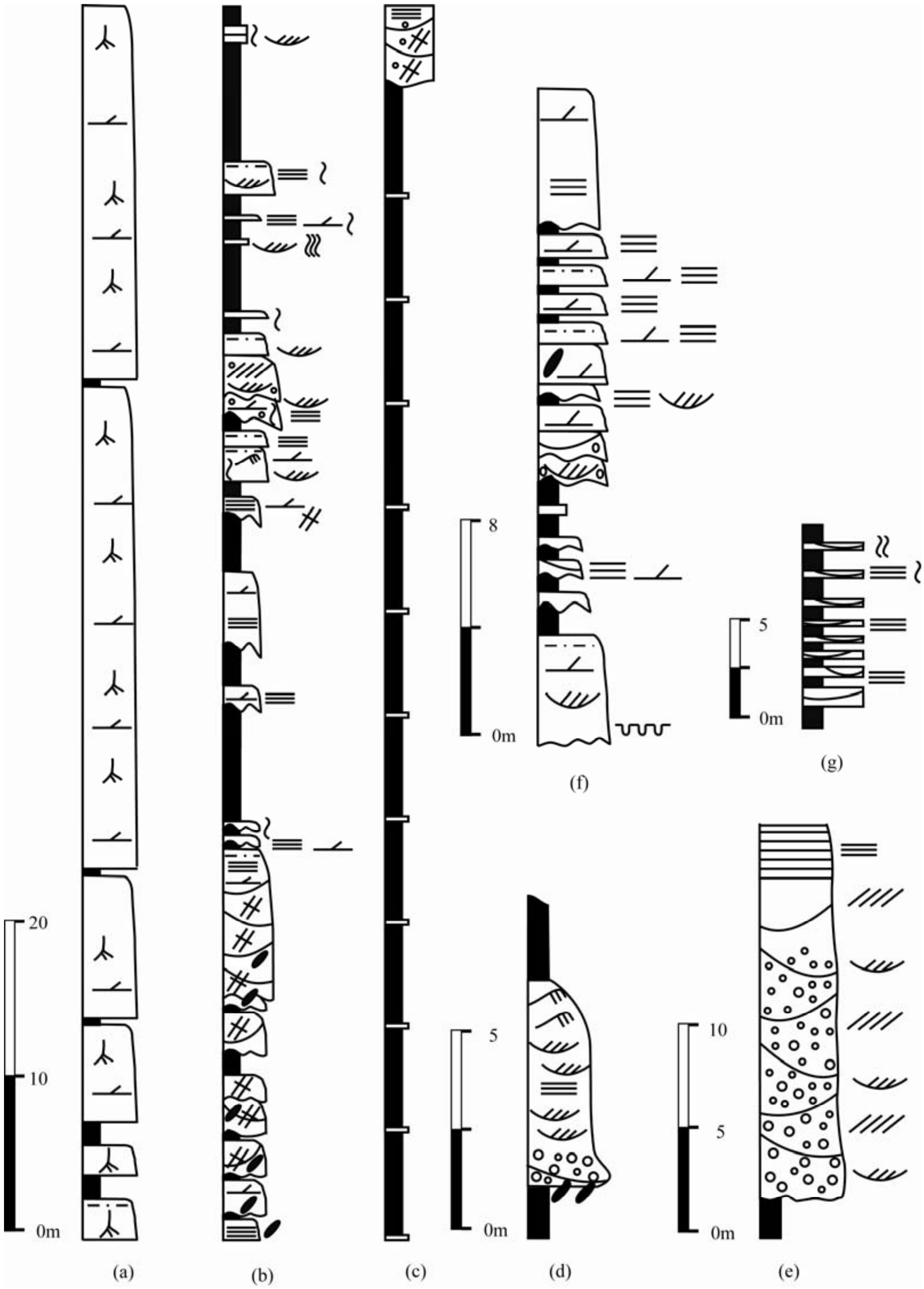

Fig. 7. Columnar profiles showing facies and facies associations in the measured sections.
(a), low angle cross stratified sandstone facies (Sl); (b), massive sandstone facies (Sm); (c), massive mudstone and siltstone facies (Fm) and flood plain facies association (FPA); (d and e), channel facies associations (CHA); (f), crevasse splay facies association (CSA) and natural levee facies association (LVA).

pressure during dense flows, which keeps the coarse grained sediments in suspension (Lowe, 1982; 1988; Smith, 1986).

4.10 Massive mudstone and siltstone facies (Fm)

These facies are characterized by massive brownish-red to maroon, reddish grey, greenish grey mudstones and fine grained sandstone/siltstones (Fig. 7c; Table 1). It is a mud-dominant facies interspersed with thin bedded (5 to 25 cm), very fine to fine grained, parallel laminated to low-angle cross-laminated or massive and bioturbated sandstone and siltstone beds (Fig. 8a), which show tabular and lenticular morphology. Lenticular beds laterally pinch out mostly within a distance of 5 to 15 m. Carbonaceous matter, plant remains and rootlet horizons are also present. The facies is interpreted to have formed from suspension by waning flood conditions in overbank, floodplains and abandoned channels, where fine-grained sediments drape underlying deposits (Miall, 1996; Bahrami, 2007). The presence of the heterolithic deposits of thin bedded sandstone/siltstone interbedded with mudstone is more likely to represent levee and flood-basin deposits that flanked the major channel. Thin sandstone beds represent crevasse channel deposits adjacent to major sandy sinuous river channels (Bridge, 2006). Red mudstone and siltstone units are prominent features of many floodplain deposits

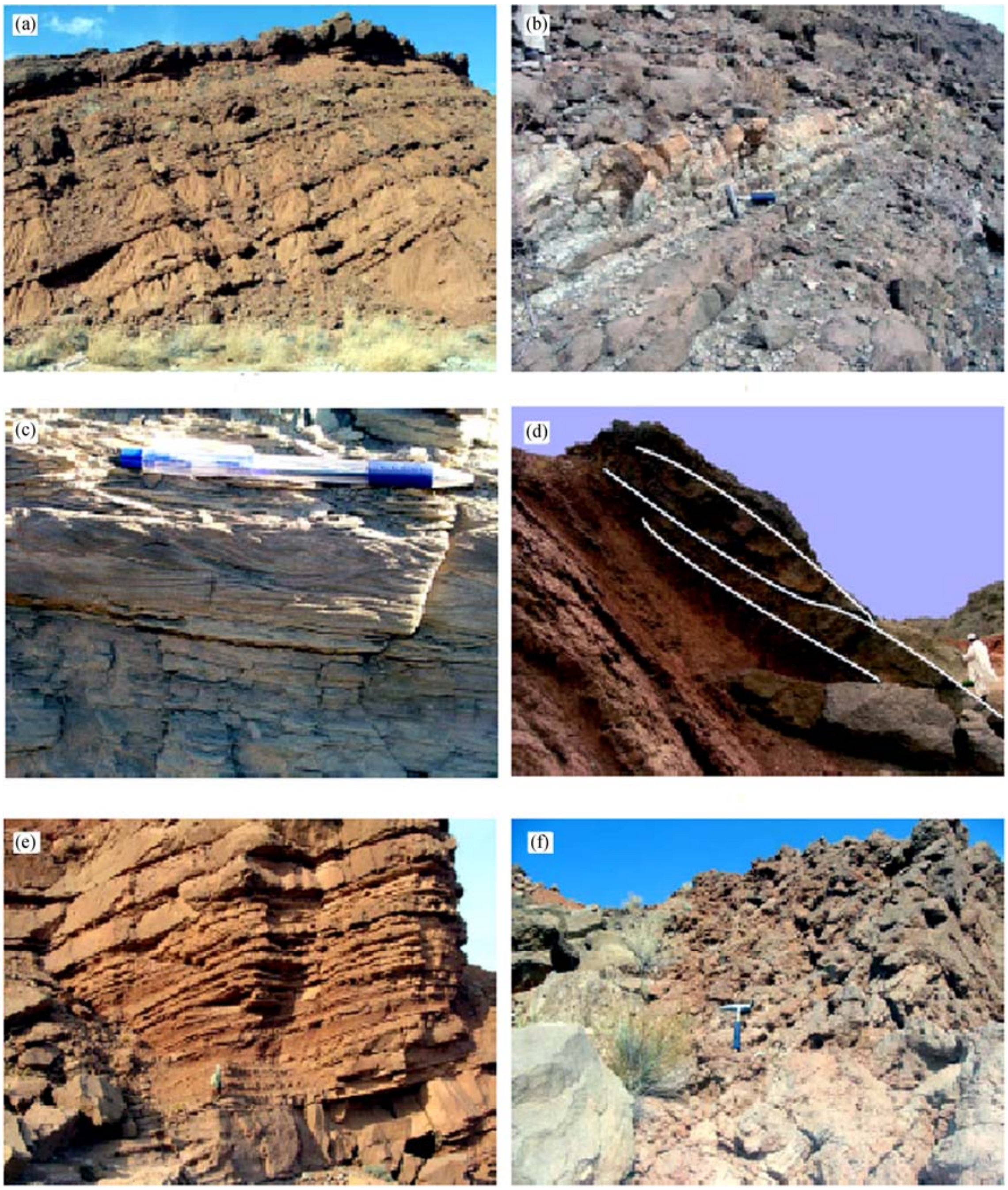

Fig. 8. Field photographs.

(a), a package of the succession dominantly comprising mudstone interbedded with thin to thick bedded fine grained sandstone/siltstone (facies Fm) (Oblin Nala section); (b), a layer of paleosol carbonate facies P, within the sandstone succession of the Dasht Murgha Group (Oblin Nala section); (c), thin bedded parallel laminated facies (Sh) and trough cross-laminated sandstone (facies St) of the Dasht Murgha Group (Khuzhobai section); (d), laterally accreted point bar developed in the Dasht Murgha Group (Bahlol Nika section); (e), a package of the thickening-up sandstone succession of the Malthanai Formation (Oblin Nala section); (f), mottled sandstone in the levee deposits of the Malthanai Formation (Oblin Nala section).

developed in semi-arid to arid settings (Bridge, 2006; Cain and Mountney, 2009).

4.11 Paleosol carbonate (P)

Facies P is characterized by variegated to whitish grey, nodular and calcareous mudstone or calcrete layers within red or grey mudstone or sandstone cycles (Fig. 8b). Calcareous nodules are common on the surfaces of these horizons. Their thickness varies from 80 cm to 260 cm. Facies P forms in response to the pedogenic processes, which show the formation of soil in alluvial plains in semi-arid to arid conditions during a hiatus (Nadon and Middleton, 1985; Retallack, 2001; Thomas et al., 2002).

5 Facies Associations

Facies associations are considered to represent various depositional environments. For a better understanding of the depositional architecture, the Dasht Murgha Group, Malthanai Formation and Bostan Formation have been grouped into the following four facies associations:

5.1 Channel facies association (CHA)

The CHA comprises a combination of the sandstones/ pebbly or gritty sandstones characterized by trough cross-bedding (St), planar cross-bedding (Sp) and horizontally bedded (Sh) facies (Fig. 7d). The association also includes trough cross-bedded and planar cross-bedded conglomerate (Gt and Gp) facies (Fig. 7e). CHA represents sandstone and gravel filled channels. Lenticular concave-up morphology and erosive bases (Fig. 5b) with rip-up mud/silt clasts, pebbly lag of thin to thick, imbricated, extraformational conglomerate and water-logged plants are the characteristic features of channels. The coarser channel facies normally grades into finer trough cross-laminated (Fig. 8c) and/or ripple cross-laminated sandstone (Sr) and mudstone facies (Fm). The low angle cross-stratified facies (Sl) frequently overlies the channel fill facies, which indicates washed out dunes under high energy conditions or at special channel locations, such as the base of longitudinal bars or at the intersection areas of the channels (Mcloughlin and Drinnan, 1997). Thicknesses of the CHA range from less than a meter to over 20 meters.

Interpretation: An abundance of trough cross-bedding (Fig. 5f) suggests deposition within major channels as large migrating dunes (Ashely, 1990). The dominance and large size of extraformational clasts suggests that deposition occurred close to sediment source area. Some sections show multistory stacking channel geometry characterizing braid channel fill and bar deposits. Large bedforms producing planar cross-bedding in modern rivers include both linguoid and straight-crested transverse bars (Smith, 1971; 1972). However, some sections show meandering channel fill and laterally accreted point bar deposits (Fig. 8d).

The CHA is very common in all measured sections of the Dasht Murgha Group, Malthanai and Bostan formations. Thick conglomerate channel fills, however, are particularly present in the Bostan Formation.

5.2 Crevasse splay facies association (CSA)

The crevasse splay facies association (CSA) is generally characterized by thin- to thick-bedded, coarse grained sandstone interfingering with siltstone and mudstone facies (Fm). The proximal part of the association is characterized by a thickening-up succession (Figs. 7f and 8e) (Morozova and Smith, 2000), comprising lenticular to planar trough cross-stratified sandstone (St), massive sandstone facies (Sm) and horizontally stratified sandstone (Sh). Beds have scoured bases and are commonly amalgamated. In the distal parts, cross-laminated sandstone and siltstone fines upwards and grades into mudstone, in which bioturbation is common.

Interpretation: Deposition of CSA occurs when flows extend across the channels (splays) towards the floodplains, off-stepping aggradation, as traction and suspension (Tooth, 2005). Frequent amalgamation, massive sandstone (Sm) and climbing ripples indicate chaotic flows and rapid deposition after the breach of levees of the meandering channels (Smith et al., 1989; Ferrell, 2001; Makaske et al., 2002).

5.3 Natural levee facies association (LVA)

The natural levees facies association (LVA) is characterized by thin to thick packages of interbedded mudstone, siltstone and fine grained sandstone (Fm facies) (Fig. 7g). Sandstone and siltstone are thin to thick bedded (<2 m), commonly ripple cross-laminated (Sr), planar cross-laminated (Sp) and horizontally laminated (Sl); mudstone is massive and parallel laminated. Sandstone and siltstone are highly bioturbated or even mottled (Fig. 8f); also contains ferruginous concretions and carbonaceous material.

Interpretation: LVA is interpreted to represent vertical accretion deposits of the channel levees and proximal flood basin environments (Mack et al., 2003). Deposition of fine grained sediments, such as mudstone with subordinate siltstone and fine grained sandstone, occur by suspension and decelerating flows along channel margins, when suspended-load-rich water spills over the river banks. Such overflows become unconfined and spread out, causing appreciable reduction in flow velocity, so that sediment is deposited quickly (Brierley and Ferguson, 1997). Presence of the ferruginous concretions and carbonaceous material indicate intermittent aerial exposure of the sediments (McCarthy et al., 1997).

5.4 Floodplain facies association (FPA)

The FPA is characterized by dominantly massive mudstone rarely interbedded with siltstone and very fine grained sandstone facies (Fm) (Fig. 7c). Mudstone packages, belonging to Fm facies, range from 50 cm to 160 m. Sandstone and siltstone are bioturbated, thin, massive to parallel laminated (Sl) and ripple cross-laminated (Sr). Paleosol carbonate facies (P) may also occur intermittently within these mudstone packages showing the development of thin layers of soil.

Interpretation: The FPA represents flood plain deposits formed by suspension as well as by low energy flows (Fisher et al., 2007). The red colour of the mudstones indicates an oxidizing environment. Infrequent rootlets and carbonaceous material show moderate vegetation cover. The formation of paleosol or calcrete layers attest to dry conditions (Mcloughlin and Drinnan, 1997). Massive and cross-laminated sandstones within the FPA may represent distal crevasse splay deposits within the low-energy, distal flood plain environments. Extensively thick packages of this facies in some sections indicate a high sinuosity (meandering) river system with an extensive floodplain area.

6 Description of the Logged Sections

6.1 Gat section

This section comprises over 3.55 km of logged succession exposed 8 km northeast of the town of Muslim Bagh (Fig. 2). The formations exposed in this section are the Dasht Murgha Group (1.56 km thick), Malthanai Formation (1.25 km thick) and Bostan Formation (750 m thick). In this section, the lower 560 m part of the Dasht Murgha Group is sandstone dominant with subordinate mudstone (range: 0.5 m to 3 m) between the sandstone cycles. However, a 24 m thick mudstone package is present in the basal part of the section. The upper 1 km part is mudstone-dominant with thick to very thick, medium to coarse grained sandstone and thin siltstone intervals (>14 m). One of the mudstone intervals in the upper part reaches up to 80 m. The Dasht Murgha Group dominantly comprises of facies St, Sh, Sl and Fm, and subordinately facies Sm and Sr. The lower part of the group shows multistory stacked channels separated by thin mudstone. This part dominantly comprises channel facies association (CHA) with minor floodplain facies association (FPA). However, the upper 1 km part of the Dasht Murgha Group is characterized by solitary channel bodies separated by very thick mudstone horizons. Laterally accreted sandstone channels are also present. This part is characterized by channel facies association (CHA), crevasse splay facies association (CSA), natural levee facies association (LVA) and floodplain facies association (FPA).

The Malthanai Formation in the Gat section is 1.2 km thick; its lower 700 m part is mudstone dominated with thick to very thick coarse grained to pebbly sandstone and thin siltstone intervals (>12 m). One of the mudstone intervals reaches up to 50 m. In the upper 250 m part the lithology grades into pebbly-conglomerate. The uppermost 250 m part comprises very thick pebble to cobble conglomerate with siltstone lenses and interbedded mudstone. The Malthanai Formation predominantly consists of facies Fm, Gcm, Gh, St, Sp and Sh, and subordinately of facies Sl and Sr. The lower part is mostly characterized by solitary channel bodies, which are separated by very thick mudstone packages. This part is characterized by channel facies association (CHA), crevasse splay facies association (CSA), natural levee facies association (LVA) and floodplain facies association (FPA). Laterally accreted sandstone channels are composed of pebbly sandstone, which fine upwards. Crevasse splay deposits are characterized by massive sandstone (Sm), which may show a sudden breach in the levees of the channel. The upper part of the section grades from thick multistory channelized massive sandstone and pebble conglomerate (CHA) packages to massive clast-supported very thick-bedded cobble conglomerate.

The 750 m thick succession of the Bostan Formation is dominantly pebble to cobble conglomerate with subordinate mudstone, minor siltstone and very coarse sandstone. The frequency of the mudstone beds increases towards the upper part of the succession. In the lower part (320 m) the conglomerate is massive, multistory and disorganized, while in the upper part (430 m) it becomes channelized, comparatively thin, imbricated and interbedded with moderately thick mudstone packages. In the Bostan Formation facies Gcm, Gh and Fm are dominant, whereas St, Sh, Sr and Sm are in subordinate proportions.

6.2 Kazha Merzai section

This section comprises 1.15 km of logged succession, exposed 6 km north of the town of Nisai (Fig. 2). The Malthanai Formation (350 m thick) and Bostan Formation (800 m thick) are exposed in this section.

The Malthanai Formation is 350 m thick in the Kazha Merzai section, which comprises a mudstone-dominant succession interbedded with thin to very thick coarse grained sandstone intervals (>19 m). A single mudstone interval reaches up to 108 m in thickness at its basal part. The formation dominantly comprises of facies St, Sp, Sh, Sl and Fm, with minor proportions of Gt and Sm. The middle part is characterized by closely packed channel bodies (range 1m to 5 m) separated by thin mudstone intervals. The upper part of the formation comprises a 19 m thick sandstone succession of stacked channels. A single conglomerate channel is also present. This section is characterized by channel facies association (CHA), crevasse splay facies association (CSA) and floodplain facies association (FPA).

The Bostan Formation is a 800 m thick succession comprising dominantly a pebble to boulder conglomerate with subordinate mudstone, siltstone and very coarse to pebbly sandstone. In the lower parts, the conglomerate is mostly a multistory channelized succession, separated by lenses of siltstone/sandstone or interbedded with sandstone having sharp erosive bases. The frequency of the mudstone increases upwards. There is a 80 m thick mudstone interval in the middle part of the succession. The upper 130 m part is mostly a massive and disorganized cobble-boulder conglomerate. Gcm, Gh and Fm are the dominant facies, whereas, Sp, Sh and Sl are subordinate.

6.3 Dasht Murgha section

The Dasht Murgha section comprises a 1.68 km thick succession of the Dasht Murgha Group only, which is exposed 7 km north of the Bahlol Nika section (Fig. 2). The succession is sandstone-dominant with subordinate mudstone and conglomerate. The lower 400 m part of the section comprises very thick (up to 20 m) mudstone packages; however, the frequency and thickness of the mudstone decrease upwards. The sandstone is medium to very coarse grained to pebbly and very thick bedded (up to 15 m), showing pronounced fining-up trends. The conglomerate is channelized, mostly pebbly and medium to thick bedded, forming either the base of the sandstone channels, or is interbedded with sandstone. The frequency of the conglomerate increases in the middle part of the section, where it is 40 m thick. The main facies of the Dasht Murgha Group are St, Sp, Sh, Sl, Sr, Sm and Fm, however, facies Gcm, Gt and Gp are also present. The Dasht Murgha Group in this section mostly consists of multistory stacking sandstone and conglomerate channel fills. Solitary sandstone and conglomerate channels are also present in the lower part. Wood fragments are common at the base of sandstone channels. The lower part of the section mainly comprises the channel and floodplain facies associations (CHA and FPA) and subordinately crevasse splay and natural levee facies associations (CSA and LVA), while the middle and upper parts are characterized by CHA and subordinately by FPA and LVA.

6.4 Sra Khula section

The Sra Khula section comprises a 720 m thick succession of the Dasht Murgha Group only, which is exposed 1 km south of the Dasht Murgha section (Fig. 2). It comprises a mudstone-dominant succession with minor thick to very thick and coarse grained to pebbly sandstone intervals (range: 1 to 5 m). A single mudstone interval reaches up to 180 m, having minor thin fine grained sandstone/siltstone intervals. The facies include St, Sh, Sm and Gt. Sandstone channels are mostly solitary; the most common facies associations are CHA, CSA and FPA.

6.5 Bahlol Nika section

The Bahlol Nika section comprises a 1.14 km thick succession of the Dasht Murgha Group only, exposed in the Dasht Murgha Syncline, 18 km north of the town of Qila Saifullah, and 8 km northwest of the Gardab Manda section (Fig. 2). It is mudstone-dominant, separated by thin to very thick, medium to very coarse grained sandstone/siltstone and conglomerate successions. There is a 35 m thick thin-to-thick pebbly conglomerate unit in the lower part, which is present at the base of the sandstone units in the form of separate, very thick bedded units, separated by thin mudstone. In the middle part of the section, a 320 m thick unit comprises exclusively of mudstone with rare thin siltstone packages. There is a 50 m, very thick bedded multistory sandstone cycle in the uppermost part of the section. The Dasht Murgha Group in this section comprises of facies Gt, Gp, St, Sp, Sh, Sl, Sr, Sm and Fm; and channel, crevasse splay, natural levee and floodplain facies associations (CHA, CSA, LVA and FPA).

6.6 Gardab Manda section

This section is 1.17 km thick, exposed 15 km north of the town of Qila Saifullah (Fig. 2). The Malthanai and Bostan formations are exposed in this section. In this section the Malthanai Formation is 450 m thick and comprises a mudstone-dominant succession with thin to very thick medium to coarse grained sandstone (>2 m), thin siltstone, and medium to very thick conglomeratic intervals. A single mudstone interval reaches up to 90 m. In the middle part, there is a 50 m thick succession of massive sandstone (Sm). Upwards the pebbly-conglomerate becomes frequent. The formation dominantly comprises of facies such as Sp, Sh, Sl, Fm and Gp and subordinately of facies St and Sm. It is characterized by single-story sandstone channel bodies in the lower part and conglomerate channel bodies in the upper part, which are separated by thick to very thick mudstone packages. Facies associations include CHA, CSA, LVA and FPA. Laterally accreted sandstone channels are also present. The Bostan Formation, which is 720 m thick in this section, dominantly comprises of a pebble to boulder conglomerate succession with subordinate mudstone and siltstone, and very coarse to pebbly sandstone. The mudstone becomes very thick in the middle part of the section, reaching up to 50 m. However, mudstone diminishes substantially in the upper part. The conglomerate is massive, multistory and disorganized (boulder conglomerate), channelized and imbricated, having erosive contact with underlying sandstone and pebble-cobble conglomerate, generally showing a coarsening-up trend. Sandstone channels are characterized by thick basal conglomerate lags. Gcm, Gh, Gt and Fm are the dominant facies, whereas Gp, St, Sp, Sh, Sl and Sm are subordinate.

6.7 Khuzhobai section

This section comprises a 650 m thick succession of the Dasht Murgha Group only, exposed 2 km north of the Gardab Manda section (Fig. 2). Its lower part (180 m) is mudstone dominant with subordinate medium to thick bedded and medium to coarse grained sandstone (range: 0.5 m to 2 m). Mudstone is up to 34 m thick in this part. An 80 cm thick paleosol carbonate (P) layer is present in the lower part of the section. The upper part of the section is sandstone dominant with thick to thin intervals of mudstone. The succession dominantly comprises of facies St, Sp, Sh, and Fm, and subordinately of facies Sm, Sl and P. Overall, it shows multistory stacked channel bodies, which are separated by medium to thick mudstone, however, there are a few isolated channels within the mudstone. This section is mainly characterized by CHA, comprising sandy braided channels and bars, and subordinately FPA.

6.8 Kili Sheikhan section

This section comprises an 800 km thick succession of the Bostan Formation only, which is exposed 10 km west of the Malthanai village. It is a pebble to cobble conglomerate-dominant succession with subordinate mudstone and very coarse grained sandstone. Some mudstone packages are up to 70 m thick. In the lower part, the conglomerate is channelized, comparatively thin, imbricated and interbedded with thick, mostly parallel laminated sandstone. The conglomerate becomes very thick, massive and disorganized in the upper part. Facies Gcm, Gh, Gt and Fm are dominant, whereas facies Sh is subordinate.

6.9 Oblin Nala section

The Oblin Nala section comprises an over 2.3 km thick succession of the Malthanai Formation only, exposed adjacent to and north of the Kili Sheikhan section. It comprises a mudstone-dominant succession with thick to very thick (up to 5 m), coarse grained to pebbly sandstone and conglomerate and thin to medium siltstone intervals. Some mudstone-dominant packages are very thick and may reach up to 135 m in thickness. In the lower part (300 m) the sandstone is more frequent and comprises multistory stacked channels (range: 1 m to 10 m). Isolated thick to very thick, pebble to cobble conglomerate beds are present in the middle and upper parts of the section. The succession dominantly comprises of facies St, Sh, Sl and Fm and subordinately Gh, Gt, Sp and Sr. The lower part of the succession is composed of channel fills, however, the rest of the section shows single-story sandstone and conglomerate channels, separated by thick to very thick mudstone packages. The succession is characterized by CHA, CSA, LVA and FPA. Laterally accreted channel bodies are composed of coarse grained sandstone, which fines upwards. Crevasse splay deposits are characterized by channelized facies Sm and St.

6.10 Naweoba section

This section comprises of an over 4.32 km thick succession of the Dasht Murgha Group only, exposed 30 km northeast of the town of Zhob. This is a mudstone-dominant succession with thick to very thick coarse grained sandstone and pebble conglomerate cycles. The lower part (250 m) is sandstone dominant followed by an ~500 m thick mudstone-dominant interval, punctuated by sporadic sandstone channels. This part also contains a 260 cm thick paleosol carbonate layer (P). The mudstone-dominant succession continues upward with thick sandstone cycles appearing at regular intervals of 30 to 40 m until a second ~500 m thick mudstone-dominant interval appears. The second mudstone interval is followed by a 360 m thick multistory stacking conglomerate, and sandstone cycles separated by 3 to 5 m thick mudstone partings. A third 550 m thick mudstone-dominant interval appears in the upper part of the measured section. The Dasht Murgha Group dominantly comprises of facies Fm, St, Gt, and Sl, and subordinately facies Sp, Sm, Sr and P. Its lower part is characterized by multistory stacked channel bodies (range: 1 m to 10 m), however, the rest of the section shows single-story sandstone and conglomerate channels separated by thick to very thick mudstone packages. The succession is characterized by facies associations CHA, CSA and FPA. Lateral accretion surfaces (point bars of Miall, 1985) are present in coarse sandstone and pebble conglomerate.

7 Discussion

7.1 Depositional environments

The Dasht Murgha Group, Malthanai Formation and Bostan Formation belong to three different tectono-stratigraphic zones (Kasi et al., 2012; Kasi, 2014). Therefore, their sedimentology and sedimentary basin evolution will be discussed separately. The Dasht Murgha Group comprises tectono-stratigraphic zone III, separated from the underlying Nisai Formation (Zone II) and the overlying Malthanai Formation (Zone IV) by major thrusts (Table 1) (Kasi et al., 2012; Kasi, 2014). Vertical profiles and facies associations of the Dasht Murgha Group suggest that deposition started with a low-sinuosity, sandy braided river system characterized by stacks of sandstone (and conglomerate) channels and bars with minor proportions of mudstone/siltstone, showing no lateral accretion surfaces. High energy conditions are indicated by the abundance of low-angle cross-stratified units on top of the channel facies association. This type of fluvial style is seen in the lower parts of the Gat, Khuzhobai, Dasht Murgha and Naweoba sections. Upwards, the fluvial style changes from sandy braided system to mixed-load meandering system, characterized by single-story sandstone channels, separated by thick mudstone/siltstone intervals, and the presence of lateral accretion surfaces (point bar deposits), which are noted in the upper parts of the Gat, Dasht Murgha, Sra Khula, Bahlol Nika and Naweoba sections. The Naweoba section is the thickest, most sinuous and distal succession of the Dasht Murgha Group. However, local variations do occur; e.g. the uppermost part of the Naweoba section shows a gravelly braided succession.

The Malthanai Formation comprises tectono-stratigraphic zone IV, which has been separated from the Dasht Murgha Group (Zone III) to the NW and the Bostan Formation (Zone V) to the SE, by major thrusts. We propose that the Malthanai Formation evolved within a distinct fluvial basin. Facies associations of the Malthanai Formation suggest that it was deposited by a high-sinuosity, mixed-load meandering channel system, characterized by single-story sandstone and conglomerate channels (CHA), thick mudstone/siltstone intervals (FPA) and the presence of large-scale lateral accretion surfaces (point bars). The upper reaches of the formation generally become conglomeratic, showing gravelly meandering channels. The uppermost part of the Gat section consists of very thick pebble to boulder conglomerate, which indicates sporadic alluvial fan (debris flow/sheet flood) deposits.

The Bostan Formation also evolved in a separate fluvial regime within a separate tectono-stratigraphic zone (Zone V), bounded by major thrusts. Vertical and lateral variations of facies associations of the succession suggest that it was deposited by a low-sinuosity, gravel-dominated braided channel system in an alluvial fan setting, characterized by thick, superimposing gravel (and minor sandstone) channels and bars, generally with a low proportion of mudstone and an absence of lateral accretion surfaces. The formation is punctuated by very thick bedded, disorganized, poorly sorted, well rounded and clast supported, cobble-boulder conglomerate of either debris flow or steep channel deposits at a fan apex. In the Kazha Merzai section, the abundance of imbricated conglomerate and parallel laminated sandstone demonstrates sheet flood deposits. Thick mudstone intervals in the Kazha Merzai, Gardab Manda and Kili Sheikhan sections show an increased sinuosity of distributary channels at fan terminal areas.

7.2 Palaeogeography

Emplacement of the Muslim Bagh Ophiolite changed the configuration of the western passive margin of the Indian Plate and created structural highs and lows in otherwise deeper marine conditions (Qayyum, 1997). The shallow water carbonate platform facies and deep water (slope and basin plane) facies of the Nisai Formation were deposited in these basins (Qayyum, 1997). Continued oblique collision at the northwestern margin of the Indian Plate with the Afghan Block of the Eurasian Plate, gave rise to the Katawaz Remnant Ocean, which was the western extension of the Neo-Tethys (Beck et al., 1995). The Oligocene-Early Miocene Khojak Formation comprises the upper part of Zone II, which conformably overlies the Nisai Formation. The siliciclastic succession of the Murgha Faqirzai and Shaigalu members of the Khojak Formation were deposited in a wave-modified fluvially-dominated delta (Katawaz Delta) and part of the delta-submarine fan (Khojak-Panjgur Submarine Fan) continuum in the Katawaz Remnant Ocean. The system was fed by the proto-Indus River, which derived its material from the nascent Himalayas to the northeast (Qayyum et al., 1996; Carter et al., 2010; Kassi et al., 2011; Kassi et al., 2015).

Continued collision ultimately caused the closure of the Katawaz Basin and deformation of the Nisai and Khojak Formations, and created topographic highs, which served as a major source terrain for the Miocene-Pleistocene molasse succession of the Pishin Belt. The tectono-stratigraphic zones, and their bounding thrusts within the Pishin Belt, are progressively younger towards the south and southeast (Kasi et al., 2012; Kasi, 2014). We propose that tectonic uplift and east-southeastward transport of the hanging walls of the major thrusts caused subsidence of the footwalls, which provided accommodation for the development of successively younger fluvial systems, in which the Dasht Murgha Group, Malthanai Formation, Bostan Formation and the flat-laying Holocene deposits of the Zhob Valley were deposited, respectively.

7.3 Basin evolution

The palaeocurrent pattern and facies associations of the Dasht Murgha Group suggest a river system flowing generally from west to the east and northeast, following the southeast-bulging trend of the belt (Fig. 9a). Proximal parts in the west became braided, and gradually became meandering towards the distal parts in the east and northeast. The Eocene-Oligocene Nisai and Khojak Formations in the north, and the Muslim Bagh Ophiolite in the south, were the main source terrains for the detritus of the Dasht Murgha Group. Continued deformation uplifted the Dasht Murgha Group while another major thrust gave birth to a younger fluvial system, in a foreland fold-thrust belt setting, during the Late Miocene-Pliocene, which we refer to as the Malthanai Formation (Multana Formation of Jones, 1962); it also has an angular unconformable and/or thrust contact with the Nisai Formation. Facies associations of the Malthanai Formation indicate a meandering river system flowing from the west to east-northeast following the arcuate outline of the belt (Fig. 9b). The Nisai and Khojak Formations, as well as the newly uplifted Dasht Murgha Group, were the main source terrains for the detritus of the Malthanai system. Continued deformation once more uplifted the Malthanai Formation along another (younger) thrust. The Pleistocene Bostan Formation postdates the Malthanai Formation; having thrust or angular unconformable contact with the older succession. The Bostan Formation shows radial palaeocurrent directions and deposition within a gravelly braided stream-dominated system by large coalescing fans (Fig. 9c). Clasts of the Khojak, Nisai, Dasht Murgha Group and the Malthanai Formation are commonly present in the Bostan succession, whereas those of the Muslim Bagh Ophiolite are also found in subordinate proportions. Thrust contact between the deformed Pleistocene succession of the Bostan Formation and the nearly flat-

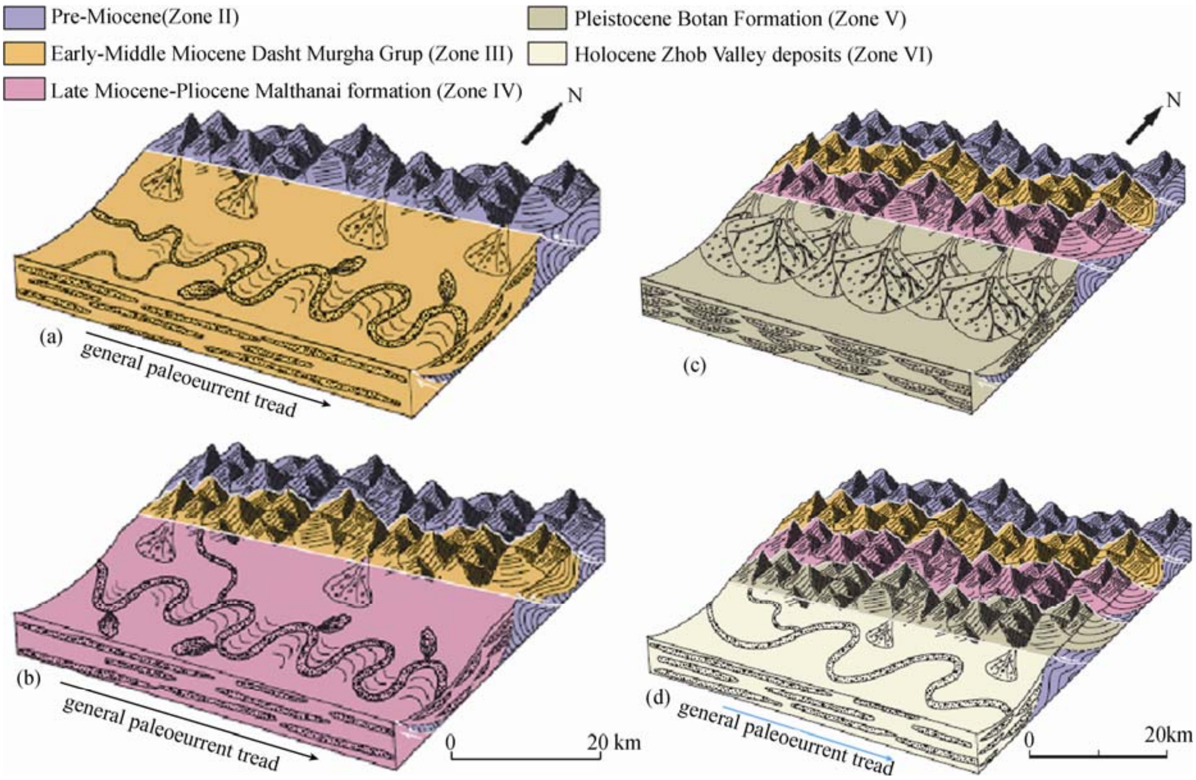

Fig. 9. Conceptual palaeogeographic models showing the successive depositional stages of the Dasht Murgha Group, Malthanai Formation, Bostan Formation and Zhob Valley deposits in the successive foreland basins of the Pishin Belt during Miocene through Recent times.

(a), model showing uplift and deformation of the Pre-Miocene succession (Nisai and Khojak formations) and deposition of the Dasht Murgha Group in a braided to meandering fluvial system during the Middle Miocene; (b), model showing uplift and deformation of the Dasht Murgha Group and the older succession, formation of younger valley to the south-southeast and deposition of the Malthanai Formation in a meandering fluvial system during the Pliocene; (c), model showing uplift and deformation of the Malthanai Formation, formation of yet another younger valley further south-southeastwards and deposition of the Bostan Formation in a gravelly braided coalescing fan system during the Pleistocene; (d), model showing uplift of the Bostan Formation, formation of another valley further southwards, and deposition of the Zhob Valley deposits in a meandering fluvial system from Holocene to recent.

lying fluvial succession of the Holocene-Recent alluvial deposits of the Zhob Valley (Fig. 9d) suggests that deformation continued through the Pleistocene age and may be ongoing. The Active Chaman-Nushki Fault in the west of the Belt and associated neotectonic features in its south also attests to the active deformation of the belt (Szeliga, 2012).

8 Conclusions

The Dasht Murgha Group is a sandstone dominant succession. The main facies of the Dasht Murgha Group include St, Sp, Sh, Sl, Fm, Sm and Sr., however facies Gcm, Gt and Gp are also present. CHA, CSA, LVA and FPA are the facies associations. The Dasht Murgha Group normally grades from multistory stacked sandstone and conglomerate channel fills to solitary sandstone and conglomerate channels. Comparison of vertical profiles and facies associations suggest that the Dasht Murgha Group was deposited by a sandy braided to mixed-load high-sinuosity fluvial system.

The Malthanai Formation is a mud dominant succession. The succession dominantly comprises of facies St, Sh, Sl and Fm and subordinately Gh, Gt, Sp and Sr. The facies associations include CHA, CSA, LVA and FPA. Solitary sandstone and conglomerate channels bounded by mudstones represents the general character. The Malthanai Formation was deposited by a mixed-load high-sinuosity meandering fluvial system.

The Bostan Formation is a conglomerate dominant succession. The clast size ranges from pebble to boulder. In the Bostan Formation facies, Gcm, Gh, Gt and Fm are dominant, whereas St, Sh, Sr and Sm are present in subordinate proportions. The conglomerate is massive, multistory and disorganized to channelized, thin bedded, imbricated and interbedded with moderately thick mudstone packages. It was formed by gravelly braided streams in a coalescing alluvial fan system.

Continued collision of the Indian Plate with the Afghan Block closed the Katawaz Remnant Ocean and uplifted the Eocene-Oligocene succession of the Nisai and Khojak formations, which served as a main source terrain for the deposition of Miocene through Holocene continental molasse successions in tectonic foreland basins.

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