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# Signatures of Late Neoproterozoic Gondwana assembly and Maronian glaciation in Lesser Himalaya: a palaeogeographical and stratigraphical approach

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ABSTRACT:

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Stratigraphical and sedimentological analyses of Late Neoproterozoic successions in Lesser Himalaya are combined herein with palaeogeographical considerations and comparisons with equivalent successions in India and South China. The succession starts with the Hazara Formation, which contains complete and incomplete Bouma sequences suggesting its deposition in deep marine turbidite settings. The overlying Tanawal Formation, rich in massive sandstone, shale and siltstone, was deposited in shallow marine conditions, as indicated by the presence of parallel lamination, large scale tabular, trough cross- and hummocky cross-stratifications. The Tanawal Formation facies shift laterally from proximal (south-southeast) to distal (north-northwest). The glaciogenic Tanaki Boulder Bed, overlying the Tanawal Formation, was deposited during the Maronian glaciation. It is equivalent to the Blaini Formation of India, and to the Sinian diamictites of South China. The Abbottabad Formation of Cambrian age overlies the Tanaki Boulder Bed, and is composed of dolomite, chert nodules and phosphate-rich packages; similar successions are documented in India and South China at the same stratigraphical interval. The similarities of the Neoproterozoic successions of Lesser Himalaya (both in Pakistan and India) and South China suggests their possible proximity during the break-up of Rodinia and the assembly of the Gondwana Supercontinent.

**Key words:** Neoproterozoic; Palaeogeography; Glaciation; Rodinia Break-up; Lesser Himalaya.

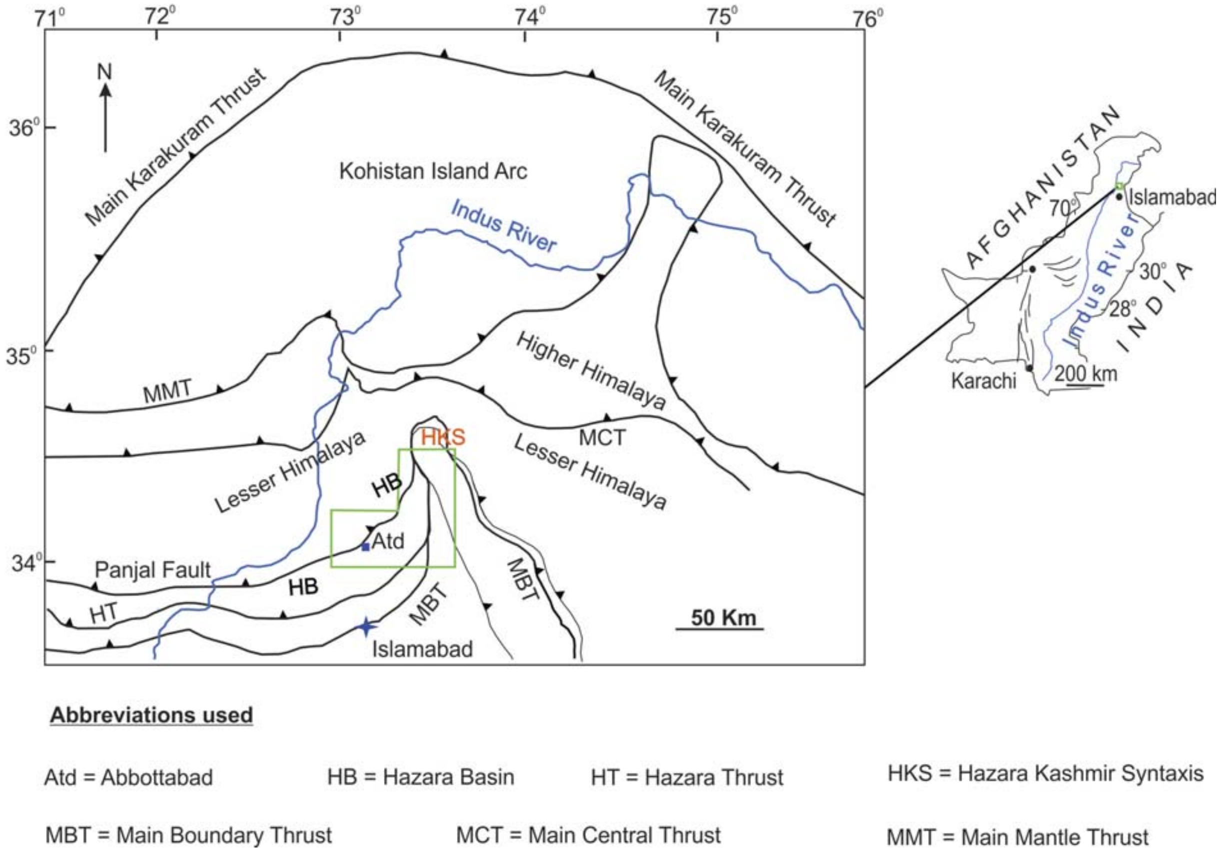
## INTRODUCTION

The Neoproterozoic and its transition into the Early Cambrian was a significant time span in Earth history because it recorded the break-up of the Rodinia supercontinent and the subsequent assembly of Gondwana, coupled with extreme climatic variations (low latitude glaciations), as well as the onset of early Ediacaran multicellular life. This unusual period is extensively recorded in sedimentary basins that are preserved across the planet (Li *et al.* 2008; Meert 2003). In the context of the Rodinia supercontinent, debate remains on the palaeogeographical position of South China (cf. Li *et al*. 2008; Cawood *et al*. 2013). Li *et al*. (2008) preferred South China to have been located between eastern Australia and Laurentia, whereas Kumar (1985) and Cawood *et al*. (2013) placed the Neoproterozoic rift succession of South China proximal to the northern edge of

India. In this paper we present stratigraphical, facies, and palaeogeographical analysis in the Lesser Himalayan region to examine these conflicting interpretations. The study was carried out in a part of the Lesser Himalaya in northern Pakistan (Text-fig. 1) where a complete Neoproterozoic succession of the Hazara Basin is well exposed. Detailed sedimentary features within the basin show its complex evolution throughout the Late Neoproterozoic, with the presence of shallow to deep marine environments, glaciation events and the preservation of condensed successions. The stratigraphical and palaeogeographical analyses of the Hazara Basin succession reveal the break-up of Rodinia, the assembly of Gondwana and the Maronian glaciation, and allow its correlation with other Neoproterozoic successions in the region.

## REGIONAL GEOLOGY

Understanding of the Neoproterozoic to Early Cambrian evolution of the sedimentary succession of the Hazara Basin is hindered by intense tectonic overprint associated with the Cenozoic to recent India–Asia collision. Our study of the Hazara Basin was conducted within the east–west trending Hazara Fold and Thrust Belt (Text-fig. 1), located along the northwestern portion of the main Himalayan Fold and Thrust Belt. The Hazara Fold and Thrust Belt is structurally complex and is characterized by a system of thrust faults bounded by the Panjal Thrust in the north and the Main Boundary Thrust in the south (Text-fig. 1). The Main Karakuram Thrust is the northernmost segment of the thrust system and separates the Kohistan Island Arc Complex in the south from deformed igneous and meta-sedimentary rocks of Asia in the north. A younger suture of the region is the Main Mantle Thrust, which preserves the deformed remnants of the Kohistan Island Arc between Eurasia and India. The Main Mantle Thrust zone juxtaposes the Tethyan Himalayas against the Indian plate (Tahirkheli and Jan 1979). Most of the deformations within the Lesser Himalaya are due to the Main Boundary Thrust, which juxtaposes Neoproterozoic–Cenozoic stratigraphical successions over younger strata (Seeber *et al.* 1981). The Panjal Thrust occurs in the Pir Panjal Range (Kashmir) and extends northward along the eastern flank of the Hazara Kashmir Syntaxis. It lies at the base of Neoproterozoic metamorphic rocks and tectonically separates the Neoproterozoic Hazara Basin from the younger Panjal Imbricate Zone of Palaeozoic

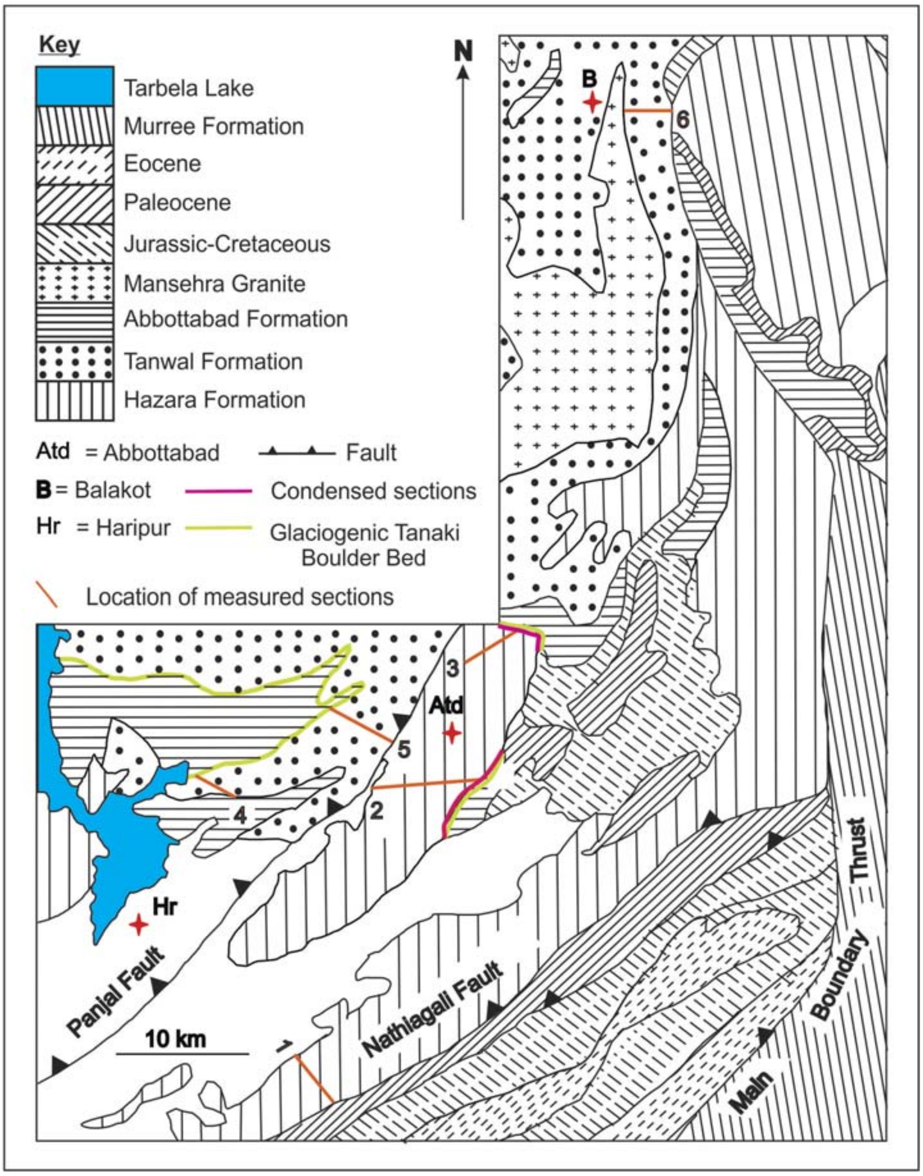



Text-fig. 1. Generalized map of the area indicating location of study area and main tectonic features of the region (modified after Ahsan and Chaudhry 2008) to Mesozoic age (Tahirkheli 1982). The general trends of these major contractional faults are east–west and northeast–southwest and their kinematics indicate south-southeast directed tectonic transport.

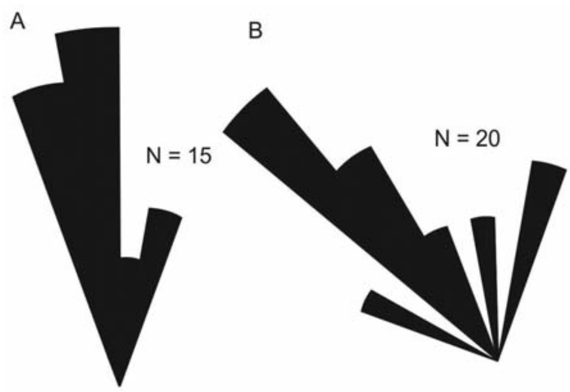
The Hazara Fold and Thrust Belt contains stratigraphical units deposited during the Neoproterozoic to Holocene (Table 1; Umar *et al*. 2014). The oldest of these, the Hazara Formation, dated at 765 ± 20 Ma and 950 ± 20 Ma: using the Rb/Sr method (Crawford and Davies 1975), was deposited in a deep marine environment. The overlying Tanawal Formation is interpreted to have been deposited during the Late Neoproterozoic. It overlies the Hazara Formation unconformably and underlies the Moranian glacial deposits of the Tanaki Boulder Bed.

## METHODOLOGY

Six detailed stratigraphical sections (Text-fig. 2) are selected to illustrate the stratigraphical architecture, the lateral and vertical facies variations of the Neoproterozoic succession of the Hazara Fold and Thrust Belt. The sections are well exposed and demonstrate well the palaeogeographical relationships within the Neoproterozoic Hazara Basin. Palaeocurrents were determined based on flutes, grooves, ripples and cross-bedding. These structures also constrained potential source regions. All of the palaeocurrent data were corrected for tectonic uplift and are presented in Text-fig. 3.




Text-fig. 2. Geological map (after Searle and Khan 1996) of the study area indicating location of measured sections, position of glaciogenic Tanaki Boulder Bed and condensed section of Tanawal Formation in Lesser Himalayan region



Text-fig. 3. Palaeocurrent diagram of (A) Hazara and (B) Tanawal formations

## FACIES DESCRIPTION AND INTERPRETATION

Twelve facies and six facies associations were recognized in the Neoproterozoic succession of the Hazara and Tanawal formations; these are described below.

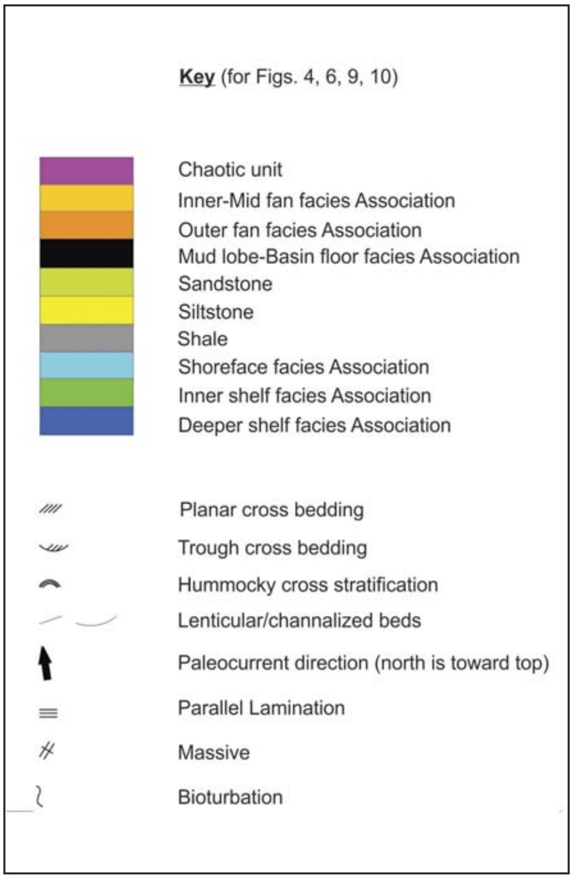
### Graded Sandstone Facies

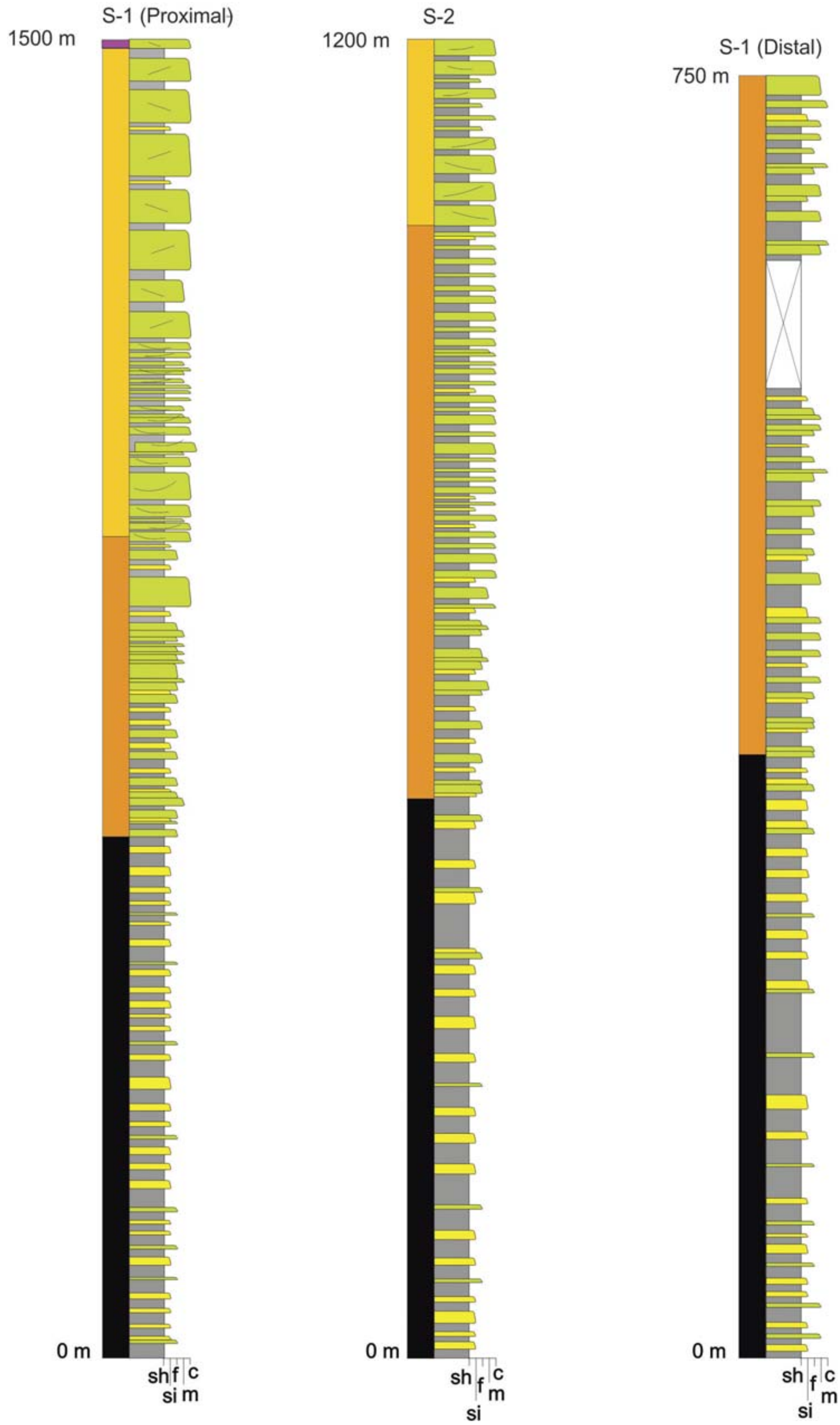
*Thin-bedded graded sandstone*

The thin-bedded graded sandstone sub-facies occurs in the Hazara Formation and is characterized by thin-bedded to occasionally medium-bedded sandstone interbedded with shale and siltstone. The sandstone beds are chiefly fine-grained and infrequently medium-grained. This sub-facies is prevalent in the middle and lower parts of the Hazara Formation (Text-fig. 4). The bedding is tabular, laterally continuous and in general exhibits upward-thickening trends. The beds grade upward into siltstone and shale displaying an overall normal grading and sharp bases. Erosion surfaces and load structures are lacking in this sub-facies. The normal grading, parallel laminated lower parts of the sub-facies and cross-laminated upper parts indicate their deposition under low to moderate turbidity currents during decelerating flows. The interbedded siltstone and shale suggest periods of low energy between turbid events.

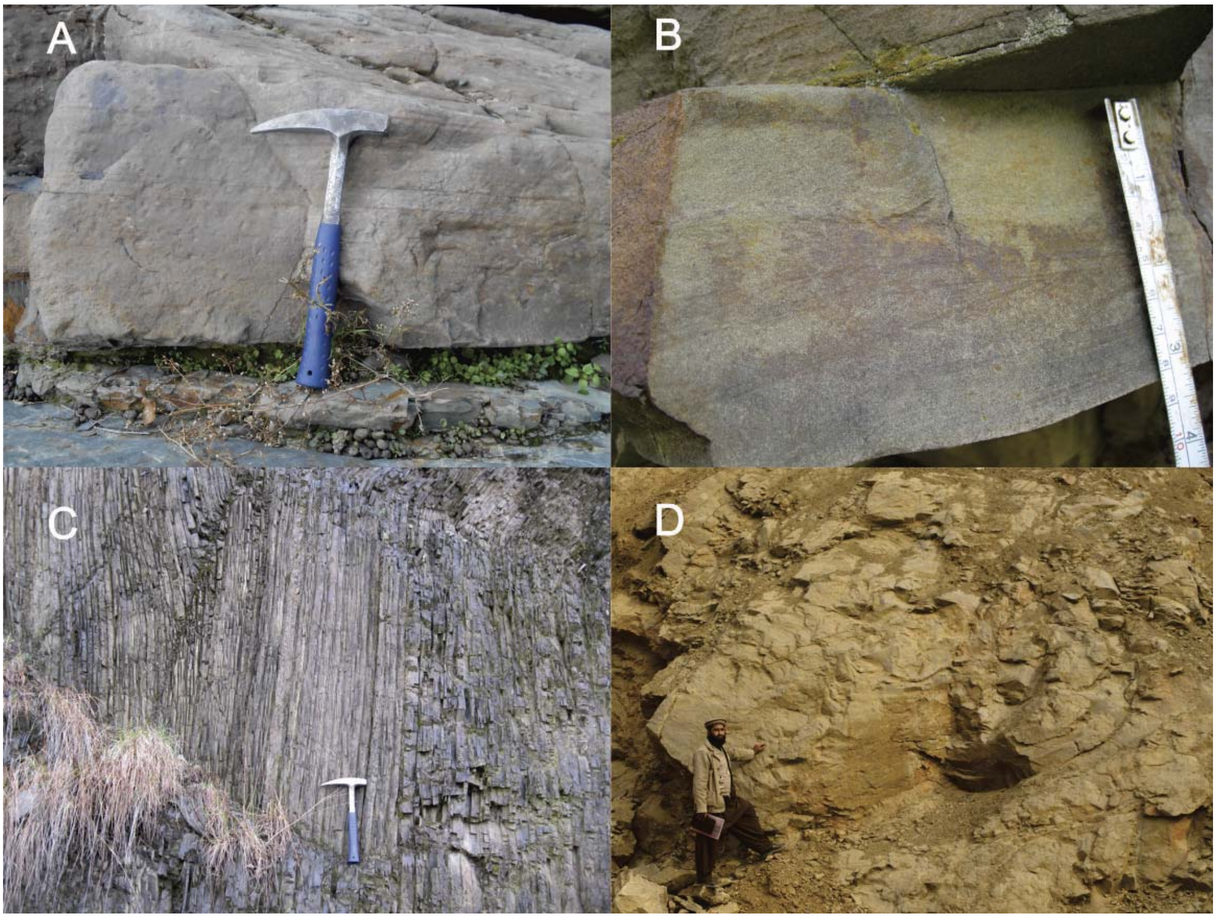
*Medium- to thick-bedded graded sandstone*

The medium- to thick-bedded sub-facies comprises medium- to very thick-bedded sandstone of the Hazara Formation. The sandstone beds are mostly medium- to very coarse-grained, and in places pebbly. The sandstone is interbedded with shale. This sub-facies is common in the middle and upper parts of the Hazara Formation. Parallel and cross-laminations in the vertical succession indicate Bouma Ta and Tab/Tabc sequences (Text-fig. 5A). However, thick to very thick sandstones with massive bedding that lack internal sedimentary structures are also common. These massive-bedded sandstones are highly amalgamated and have sharp eroded bases. Some beds are lenticular, with channel morphology. Evidence of slumping occurs in the topmost part of the Hazara Formation, indicting a proximal setting. Load structures, flute and groove marks occur at the base of some of the sandstone beds. The medium- to thick-bedded sub-facies is interpreted to have been deposited by very dense turbidity currents (Pickering *et al*. 1989), mostly in the proximal part of the submarine fan system (Mutti and Rucci Luchhi 1978). The medium- to thick-bedded graded sandstones that preserve Bouma sequences represent deposition from turbidity currents. The massive sandstones suggest rapid deposition of large volumes of sand from fluidized flows. These massive sandstones probably represent the passing of turbidity currents, which normally maintain their sand load in suspension by fluid turbulence, through a phase of fluidized flow in the final moments of flow immediately preceding deposition (Walker 1978).






Text-fig. 4. Sedimentary log of the Hazara Formation in measured sections (S1–S3), mainly showing deep marine turbidite environments in transition from proximal to distal settings. An overall shoaling-up sequence in vertical section can be seen from basin floor to upper slope facies associations; for explanations see text-figure on page 4




Text-fig. 5. Field photographs of various facies studied in Hazara Formation. A – Tab/Tabc Bouma divisions; B – Cross-laminated sandstone facies (Tc); C – parallel laminated siltstone facies (Td) and D – slumped facies

**Parallel-laminated sandstone facies**

The parallel-laminated sandstone facies is the most common facies in both the Hazara and Tanawal formations. In the Hazara Formation it is characterized by coarse- to fine-grained sandstone interbedded with shale and siltstone. Bedding is mostly thin- to medium bedded. Laminations are mostly parallel and are interpreted to represent Bouma interval Tb (Bouma, 1962). These beds mostly occur within the graded sandstone and represent complete and/or incomplete Bouma sequences. Bedding is in general planar and laterally continuous; however, some beds are lenticular within this facies. Parallel laminations are also dominant in sandstone beds of the Tanawal Formation that lacking grading and other characteristic features of turbidites. These sandstones contain evidence for shallow marine facies such as large-scale cross-bedding, massive and thick beds. Medium- to very thick-bedded facies are tabular in nature and exhibit an upward-coarsening trend. Parallel laminations are formed by various processes in shallow marine conditions such as storm-induced unidirectional flows, wave oscillatory motion at the sea floor and combined flows (Arnott and Southard 1990). Parallel laminations associated with deep marine facies represent deposition from turbidity currents as a result of decreased turbulence and fluctuation in current velocity in suspension clouds (Reineck and Singh 1980).

**Cross-laminated sandstone facies**

This facies occurs in the Hazara Formation. The cross-laminated sandstone facies constitutes medium- to fine-grained, thin- to medium-bedded sandstone. Low-angle cross-laminations are also present. Fine cross-laminations (Text-fig. 5B) commonly occur at the top of normal graded beds. Beds are characterized by sharp bases. The medium- to thin-bedded sandstones are interpreted to have been deposited by low density turbidity currents in an upper flow regime. Ripple cross-lamination are interpreted to represent Bouma (1962) Tc divisions, which are common in turbidites and were formed during transport and deposition by turbulent flow.

**Parallel-laminated siltstone facies**

The parallel-laminated siltstone facies only occurs in the Hazara Formation. This facies consists of medium- to thin-bedded parallel-laminated siltstone of light to dark grey and green-brown colour (Text-fig 5C). The bedding is mostly thin to very thin and tabular in geometry. The beds are characterized by sharp bases with the underlying sandstone and/or shale. The facies is dominant in the lower and middle parts in stratigraphic sections and is interpreted to represent the low density turbidity currents. The facies reflects calmer depositional conditions, which are common during the late phase of deposition (Strba 2012).

**Dark grey shale facies**

The dark grey shale facies is present in all of the measured sections. This facies consists of thin- to very thin-bedded (5–10 cm), dark grey to black shale and occurs as either a stand-alone package or has an association with Tb, Tc, Td Bouma sequences in the Hazara Formation. In the Tanawal Formation the dark grey shale facies is associated with interbedded shallow marine sandstone. The dark grey shale facies is most prevalent in the lower part of the Hazara Formation. This facies is interpreted to record the more distal parts of the basin, perhaps in response to low energy turbidity flow and/or pelagic, hemipelagic conditions during calm episodes of sedimentation (Stow *et al*. 2001), or alternatively by highly concentrated mudflows, which have the capability to move large amount of material down gradient (Masson *et al*. 1997).

**Chaotic Units**

The chaotic unit facies is exclusively represented in the upper part of the Hazara Formation in proximal settings (section 1). This facies is characterized by sandstone which occurs as rounded irregular blocks (Text-fig. 5D). The sandstone is medium- to coarse-grained and partly comprises pebbly beds. The chaotic unit is interpreted to represent mega-slumping within individual slumped packets up to 5 m thick and 10 m wide. A number of processes may be responsible for slumping at this scale (Lewis 1971). Liquefaction, steep gradient and rapid deposition on slopes can trigger slumping of sediments (Umar *et al*. 2011a, b; Khan *et al*. 2002). The local preservation and complete absence of this facies in most of the measured sections suggest its origin either by slumping along a channel margin or an over steepened part of the slope. The absence of this facies elsewhere in the study area suggests that the slope was relatively gentle in the depositional basin.

**Maroon Shale Facies**

The Maroon shale facies occurs mainly in the lower part of the Tanawal Formation (Text-figs 6, 7A) in all of the measured sections. The shale is thin- to very thin-bedded (generally 5–10 cm thick), parallel laminated and contains occasional, thin (5 cm thick) interbeds of very fine-grained sandstone. This unit is typically 25–50 m thick. The sand ratio increases upward until the facies becomes completely capped by sandstone facies. This facies was formed under low energy conditions with the fine-grained sediments settling by suspension, which is indicated by parallel lamination (Boggs 2011).

**Large-scale cross bedded sandstone facies**

The large-scale cross-bedded sandstone facies predominates in the Tanawal Formation (Text-fig. 6). This sandstone is medium- to very coarse-grained, containing occasional pebbly beds, and is thick- to very thick-bedded (30 cm to 2 m) (Text-fig. 7B). Large-scale cross-bedding and hummocky cross-stratification indicate deposition during strong traction flows under high velocity conditions (Collinson *et al*. 2006), such as those produced by storm- or river-induced currents (Khan *et al.* 2002).

**Massive Sandstone Facies**

The massive sandstone facies occurs in both Hazara and Tanawal formations. In the Hazara Formation, thick-bedded, graded sandstone packages are massive. These are associated with submarine channels and inner fan facies associations formed by high density turbidity currents. This facies is also present in all of the sections of the Tanawal Formation (Text-fig. 7C). Within the Tanawal Formation the facies is characterized by massive sandstone beds that are medium- to very thick-bedded. The grain size varies from medium to very coarse, and in some instances bioturbation is evident. The sandstones of this facies were probably deposited by rapid dumping from high density flows by freezing of very concentrated traction flows. The absence of laminations, which often indicate rapid deposition, is most probably due to current deceleration.


Text-fig. 6. Sedimentary log of Tanawal Formation in measured sections (S4–S6), mainly showing shallow marine environments, indicating lateral transition from proximal (shoreface) to distal (deeper shelf) settings. An overall shoaling-up sequence in vertical section can be seen from deeper shelf to shoreface/inner shelf facies associations; for explanations see text-figure on page 4


Text-fig. 7. Field photographs of facies identified in Tanawal Formation. A – lowermost part containing maroon shale, siltstone with some interbeds of sandstone; B – Large scale cross-stratified sandstone facies (Tc); C – Massive sandstone facies and D – Hummocky cross-stratified sandstone facies

**Bioturbated sandstone facies**

The bioturbated sandstone facies is less prevalent in the Tanawal Formation and is documented in the lower part of section 5. The sandstone is fine- to medium-grained and comprises beds up to 50 cm thick. Bioturbation partly destroyed the primary structures of the sandstone such as parallel and cross-laminations, which are only rarely preserved. Rip-up clasts are also present. The beds are characterized by regular and laterally continuous geometry at outcrop scale. The limited extent of this facies and its occurrence with parallel-laminated and cross-bedded sandstones suggest its origin during alternate calm intervals (Umar *et al*. 2011a; Khan *et al.* 2002).

**Hummocky cross-stratified sandstone facies**

The hummocky cross-stratified facies occurs in sections 4 and 5 in the Tanawal Formation (Text-fig. 6). Pinch and swell structures in the sandstone beds are common (Text-fig. 7D). Individual beds are between 20 and 100 cm thick. Thick beds are amalgamated in places. The sandstone is medium- to very coarse-grained. This facies exhibits parallel and cross-lamination in some cases. Strong surges of oscillatory flows generated by relative high storm wave (Harm *et al*. 1982) and/or by a combination of unidirectional and oscillatory flow related to storm activity (Cheel and Lackie 1993) were responsible for the formation of hummocky cross-stratification. This facies is interpreted to indicate a shallow marine environment (Boggs 2006).

**Trough cross-bedded sandstone facies**

This facies occurs only in the uppermost part of the measured sections (Text-figs 6, 8A). The sandstone is coarse to very coarse-grained and thick- to very thick-bedded. Individual beds are up to 2.5 m thick and amalgamated. This facies is interpreted to form by migration of trough-shaped dunes under dense unidirectional tractional currents where river-induced flows deliver sediments to shoreface (Boggs 2011).

## FACIES ASSOCIATIONS

The facies defined are grouped into associations to better understand the depositional architecture of the Late Neoproterozoic succession.

### Facies associations of Hazara Formation

#### *Inner-mid fan facies association*

The inner-mid fan facies association occurs mostly in the upper part of the Hazara Formation in section 1 (Text-fig. 6). It comprises mainly graded sandstones generally associated with parallel- and cross-laminated sand facies and occasionally chaotic units. Bouma sequences Tb and Tc are not always fully developed and Ta and Tf facies predominate. These facies characteristic are only well developed in section 1, suggesting a more channelized part of the basin. This interpretation is supported by the lenticular nature of the sand beds and the upward-thinning depositional pattern (Text-fig. 8B). We interpret this part of the formation to represent the inner fan with partly developed submarine channels. In other sections this facies association consists of graded, parallel- and cross-laminated facies showing Bouma Tab, Tabc sequences. These are interpreted to reflect deposition of dense turbidity flows in inner to mid fan environments (Shanmugam and Moiola 1988).

#### *Outer fan facies association*

The outer fan facies association is dominated by parallel- and cross-laminated sandstone with or without thin interbeds of graded sandstone (Text-figs 6, 8C).


Text-fig. 8. Field photographs of A – Trough cross-bedded sandstone facies; B – lenticular/channalized sandstone beds of inner-mid fan facies association in Hazara Formation; C – Thin, parallel and cross-laminated sandstones with or without grading of outer fan setting, Hazara Formation and D – Mud lobe-basin floor facies associations in lower and distal parts of Hazara Formation

The characteristic regular and laterally continuous beds coupled with the lack of lenticular bedding suggest deposition in outer/distal fan lobe settings (Shanmugam and Moiola 1988) (Text-fig. 4). This association is quite common in all of the measured sections.

*Mud lobe-basin floor facies association*

This facies association is well represented in all measured sections of the Hazara Formation and is characterized mainly by dark grey shale and parallel laminated siltstone with interbeds of thin-graded sandstones showing Tde and Tcde Bouma sequences. This unit occurs mainly in the lower parts of all measured sections (Text-figs 6, 8D). Thin interbeds of sandstone occur as thin packages (a few metres thick) intercalated with thicker units of shale and siltstone facies. The predominance of fine-grained clastic (shale) facies, and the thin and tabular nature of beds such as mud lobes, suggest this facies association was deposited in the distal parts of the sedimentary basin. Mud lobes in outer settings provide the space for sandy components of the overlying mid-outer fan facies association of the formation.

**Facies associations of the Tanawal Formation**

*Shoreface facies association*

The shoreface facies association comprises mainly large-scale planar and trough cross-stratified sandstone facies with minor massive, parallel-laminated sandstone facies. Beds are medium to very thick (up to 2.5 m). This facies is common in sections 4 and 5 and is most common in the uppermost part of the Tanawal Formation. The predominance of planar and trough cross-bedding, coupled with the presence of coarse-grained sandstone and the lack of mudstone, is interpreted to represent deposition at surf-breaker zones under very high energy conditions in shoreface settings (Harms *et al*. 1975).

*Inner shelf facies Association*

Hummocky cross-stratification associated with large-scale cross-bedding, parallel-lamination and massive sandstone specifies the inner shelf facies association. This association is prevalent throughout the Tanawal Formation both vertically and laterally (Text-fig. 6). In section 4, this facies association is characterized by coarse to pebbly sandstone with lenticular beds within fine-grained sediments. The presence of hummocky, large and trough cross-stratifications suggests deposition in storm-influenced shallow marine environment (Swift *et al*. 1983; Brenchley 1985). When fine sediments are absent, hummocky cross-stratification represents strong and complex wave activity below fair weather wave base. Frequent high-energy storm pulses followed by oscillating waves most probably caused the deposition of this association (Duke 1990).

*Deeper shelf facies association*

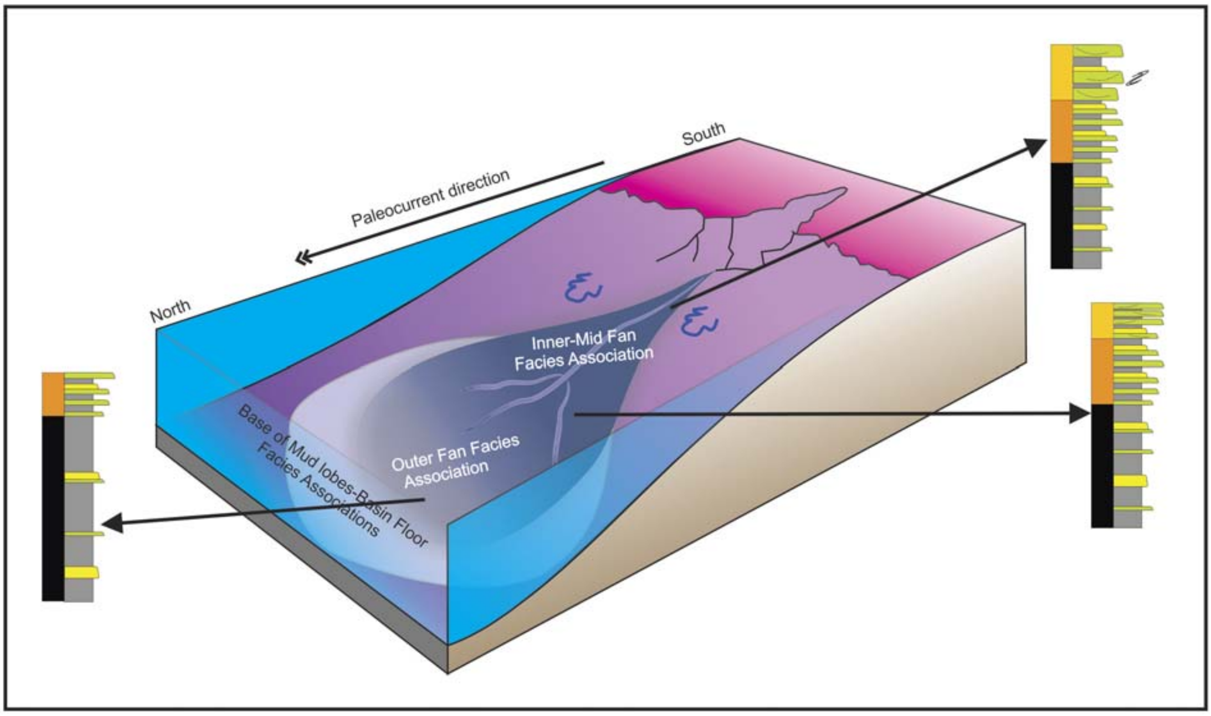
The deeper shelf facies association is dominated by dark grey and maroon shale facies as well as the massive, parallel- to cross-laminated and minor bioturbated sandstone facies. The sandstones are fine- to medium-grained, thin- to medium-bedded and occasionally thick-bedded with tabular bedding forms. The shales are parallel laminated. A high proportion of shale and the absence of grading, cross-lamination, sole marks and other features of turbidites in distal settings are interpreted as deeper shelf. In sections 4 and 5, this facies association is preserved in lower parts of the section, whereas in section 6 it is represents the distal parts of the basin as well.

## DISCUSSION

**Palaeogeography of the basin**

Based on the identified facies, facies associations, lateral and vertical facies variations (Text-figs 4, 6), 3D palaeogeographical models were reconstructed (Text-figs 9 and 10) in order to present the evolution of the Hazara Basin during the Late Neoproterozoic. The facies analysis reveals that the succession of the Neoproterozoic Hazara Formation formed under deep marine conditions (Text-fig. 9). The most proximal sections of the Hazara Formation are characterized by submarine channel facies, as indicated by Ta, Tab Bouma divisions (1962), the medium to thick (50–120 cm) lenticular nature of the beds, small-scale localized slumping and erosive surfaces. This unit is 100 m thick and was developed locally. In general, the slope was gentle as indicated by the absence of channelized and chaotic units in most of the study area. The proximal channelized inner fan and fan lobe components transitionally fall down-gradient to submarine fan-lobes and base of slope (basin floor) turbidites in distal (northward) settings (Text-fig. 9).

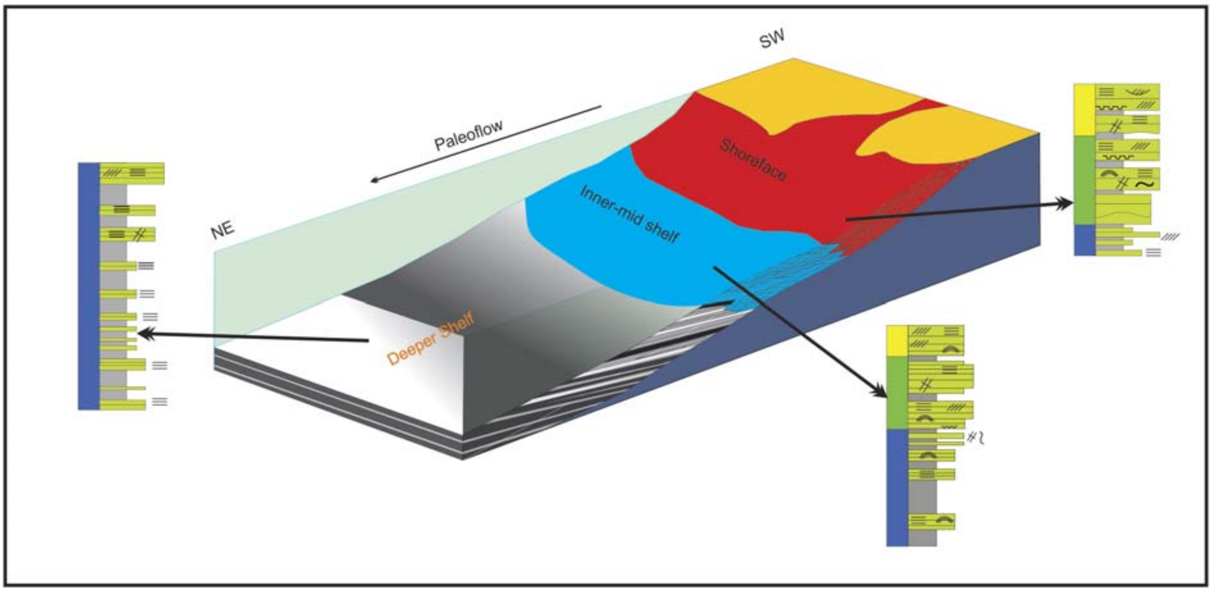
The lower parts of the Hazara Formation show predominantly Tde, Te/Td-rich Bouma sequences, with Te the most frequent. Small intercalated packages of



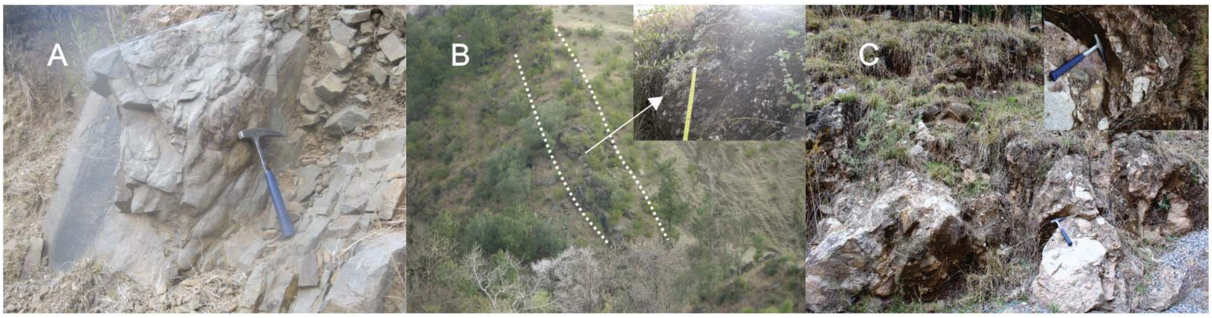

Text-fig. 9. Palaeogeographic model of Hazara Formation formed in deep marine settings. Various components such as inner-mid, outer fan, base of mud lobes-basin floor facies associations and slumping are indicated; for explanations see text-figure on page 4

thin, tabular sandstone beds (commonly 5–20 cm thick) showing characteristics of Ta/Tab/Tabc Bouma sequences also indicate deposition as fine grained turbidites at the base of slope to basin floor settings. Facies vary upsection from basin floor settings to submarine fan lobes and less commonly represent submarine channels. The tabular nature of the beds and the lack of erosive surfaces suggest that these sediments were formed in mid-outer fan settings.

The Tanawal Formation is dominated by sand-rich shallow marine successions composed of deeper shelf to shoreface facies associations. The lower part




Text-fig. 10. Palaeogeographical reconstruction of Tanawal Formation representing the shoreface–deep shelf environments. Various components such as shoreface, inner-mid and deeper shelf are indicated; for explanations see text-figure on page 4




Text-fig. 11. Field photographs of (A) sole marks (flutes), (B) well rounded conglomerate beds (close view in inset) showing unconformity below Tanawal Formation and (C) glaciogenic Tanaki Boulder Bed, close view insets at right side

of the formation was deposited in deeper shelf environments, as suggested by the predominance of maroon shale with massive, bioturbated and laminated sandstone facies present in sections 4 and 5. This unit is overlain by inner shelf to shoreface facies sediments. Grain size and bed thickness increase upwards in this unit showing an upward-coarsening succession. This trend indicates an overall shoaling upwards of the basin fill during the Neoproterozoic. Laterally, from south-southeast to north-northwest, the facies and facies associations within the Tanawal Formation indicate a transition from shoreface to deeper shelf environments. Proximal sections represent shoreface to inner shelf environments whereas the deeper shelf is documented in distal (northwest) sections (Text-fig. 10).

**Palaeocurrent analysis**

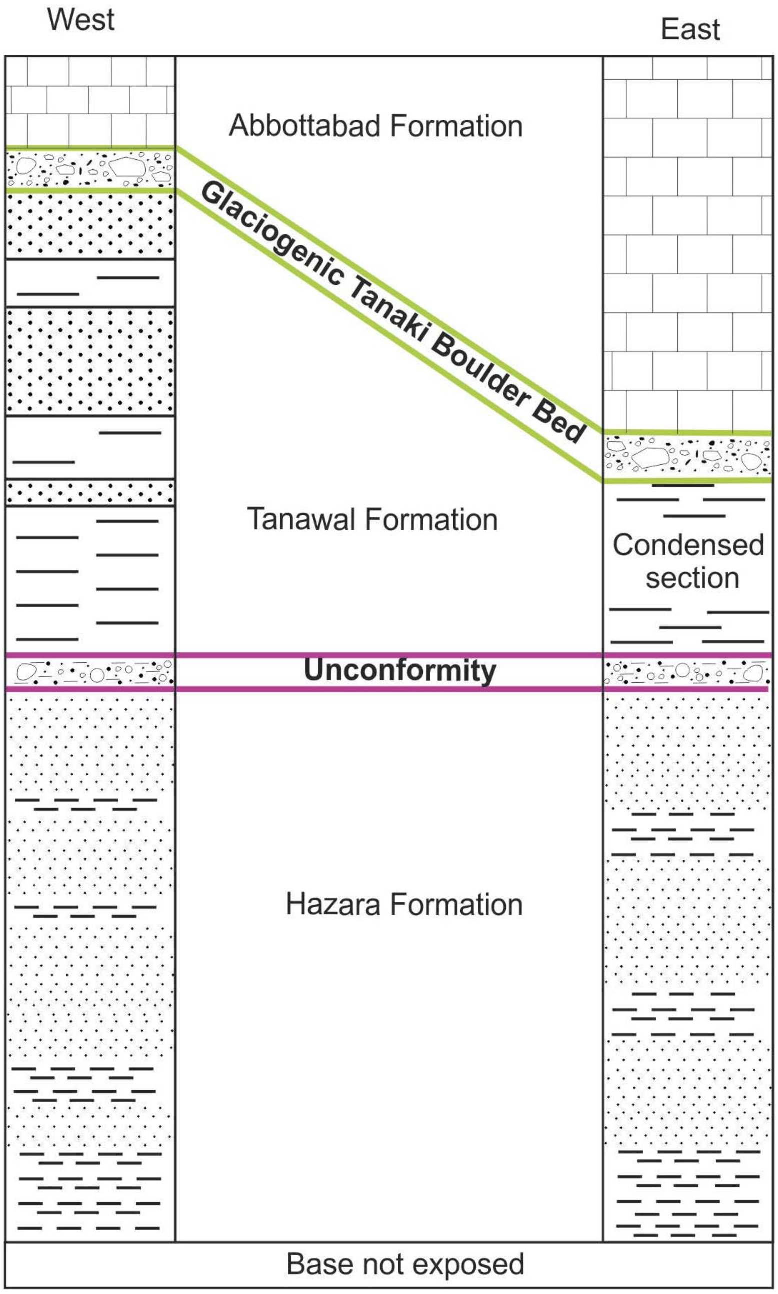
The above interpretation of facies and facies associations is supported by the palaeocurrent data. Palaeocurrent analysis enabled determination of the sediment sources, which provide additional information about the palaeogeographical settings associated with the configuration of Gondwana. Palaeoflow directions were inferred from a variety of sedimentary structures including: abundant sole marks (Text-fig. 11A); groove marks; flute casts; and ripple cross-lamination. Palaeocurrent data show palaeoflows towards north-northwest, indicating sediment supply from the south and southeast. The source areas of the detritus for the Hazara and Tanawal formations are likely to be the 2075–2150 Ma Aravali and Bundlekhand Cratons (Deb and Thorpe 2004).

**Stratigraphic evolution of the basin**

The unconformity between the Hazara Formation and the Tanawal Formation is represented by the 15 m thick conglomeratic bed containing sub-rounded to well-rounded clasts of siltstone and sandstone resembling those of the Hazara Formation (Umar *et al*. 2014; Text-figs 2, 11B, 12; Table 1). This conglomerate suggests episodic uplift and erosion preceding the deposition of the Tanawal Formation, which took place during the latest Neoproterozoic. The Tanawal Formation is very thick in the western part of the study area (sections 4, 5 and 6), where it attained thickness up to 900 m. Conversely it is very thin in the eastern part (sections 2, 3), where it contains maroon shale, siltstone and thin sandstone. Similar lithologies are present in the basal part of the formation in the western part of the study area (sections 4–6), which was included in the Hazara Formation by earlier workers (e.g., Latif 1970). We suggest that this thin succession exposed in the eastern part was formed by condensation (Tex-fig. 12). Earlier workers stated that the Tanawal Formation was eroded during the 80 Ma long period of uplift in the eastern part (sections 1–3) (e.g., Baig 1991). This interpretation raises a number of questions e.g., how can a thick succession be completely eroded without leaving at least some remnants; secondly, where is the thick eroded detritus located as there is no stratigraphic record of this material? We consider the predominantly fine-grained (maroon shale, siltstone and thin sandstone) succession lying just below the Tannaki Boulder Bed in sections 2 and 3 to represent a condensed succession. Condensed successions are common throughout geological history and their development within sedimentary basins can be caused by a number of different processes, including rapid sea level fall or rise (Alberti *et al*. 2012); periods of non-deposition or erosional hiatus; low topographic relief and local-scale subsidence within the depositional basin (Baraboskhin 2009). Condensed sections are also reported from the Hunan-Guangxi and Zhejiang sub-basins during the latest Precambrian and were attributed to rapid sea-level rise as well as localized subsidence (Wang and Li 2001). Condensed sections in South China may correlate with the condensed section identified in our inverstigations and suggest that the condensed succession was probably formed as a result of local-scale subsidence and the reduction of coarse sediment (sand) supply in the eastern part within Hazara Basin during Neoproterozoic time.

## Glaciation in Lesser Himalaya

An excellent example of uplift, sub-aerial erosion and glaciation episodes in the Lesser Himalaya can be deciphered by the presence of the Tanaki Boulder Bed (Latif 1970) (Text-fig. 11C), which consists of very poorly sorted matrix-supported conglomerate containing various sized clasts (3 cm to 50 cm). Clasts include dark grey siltstone, slate and shale, and light grey to brown quartzite, which are similar to the lithologies of the Hazara and Tanawal formations. The clasts are angular to sub-rounded. The conglomerate matrix contains fine pebbles, sand, silt and argillites. We interpret a glacial origin for the Tanaki Boulder Bed because of the preservation of angular fragments, the lack of fluvial features and the preservation of striations. It is suggested here that the Tanaki Boulder Bed represents part of the worldwide Neoproterozoic glaciation.




Text-fig. 12. Stratigraphical column of eastern and western sectors of the study area indicating condensed section of Tanawal Formation

| Rock Units | Lithology | Age |
|---|---|---|
| Havelian Group | Mixture of gravels, pebbles, clay and sand | Holocene/Pleistocene |
| **Unconformity** | | |
| Murree Formation | Interbedded sandstone and shale | Early Miocene |
| **Unconformity** | | |
| Kuldana Formation | Gypsiferrous shale and marl | Eocene |
| Chorgali Formation | Marl and thin bedded limestone | |
| Margala Hill Limestone | Fossiliferrous, nodular limestone | |
| Patala Formation | Shale and siltstone | Paleocene |
| Lockhart Limestone | Nodular limestone | |
| **Unconformity** | | |
| Kawagarh Formation | Grey limestone | Cretaceous |
| Lumshiwal Formation | Massive sandstone | |
| Chichali Formation | Arenaceous shale and marl | |
| **Unconformity** | | |
| Samanasuk Formation | Oolitic limestone | Jurassic |
| Shinawari Formation | Limestone and marl | |
| **Unconformity** | | |
| Abbottabad Formation | Sandstone, dolomite, shale, phosphate and chert nodules | Cambrian |
| Kakul Formation | Sandstone with minor shale | |
| **Unconformity (Glaciogenic Tanaki Boulder Bed)** | | |
| Tanawal Formation | Sandstone/quartzite and shale | Precambrian |
| **Unconformity** | | |
| Hazara Formation | Shale, sandstone, siltstone | Precambrian |
| **Base not exposed** | | |

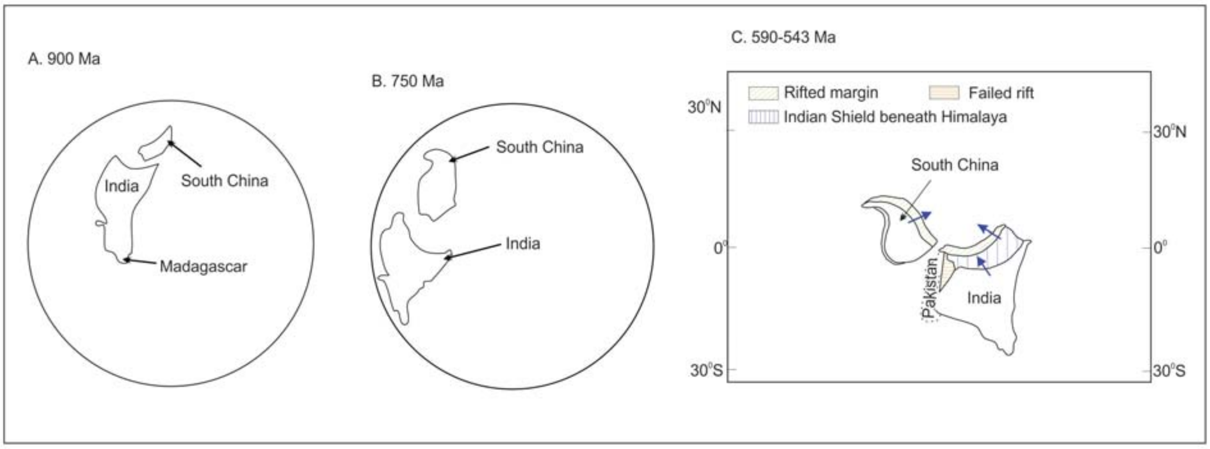
Table 1. Stratigraphy of Hazara Basin lesser Himalaya (after Umar *et al*. 2014)

## Comparison with India and South China

A stratigraphical comparison of the Hazara Basin, India and South China is presented in Table 2. The shale, siltstone, slate and sandstone-dominant Hazara Formation compares well with the Chandpur and Shimla formations (India) and the Madiyi and Hetong formations of South China. These lithostratigraphic units are of the same age, exhibit similar depositional environments and are fine-grained deep marine successions. Correlation of these three regions is indicated by the presence of the regional unconformity above the Hazara Formation and its correlatives in India and South China. The Tanawal Formation correlates with the Nanghtat Formation in India and with the Wuqiangxi and Gong Dong formations in South China. All these units display similar depositional conditions (shallow to deep marine) and are overlain by glaciogenic sediments: the Tanaki Boulder Bed in the study area, the Blaini Formation in India, and the Sinian diamictites of South China. All these glaciogenic units might be formed as part(s) of the globally correlative Marinoan glaciation (at ca 605–595 Ma; Macouin *et al*. 2004).

The unconformity at the base of the Abbottabad Formation can also be correlated. An equivalent unconformity occurs beneath the Krol Group in India and beneath the Doushantou Formation in South China. The Abbottabad Formation, Krol Group and the Doushantou Formation are composed of similar lithofacies (mudstone, sandstone, dolomite, phosphate) and chert nodules. The Neoproterozoic–Cambrian biota record (Krol Group Lesser Himalaya, India and Doushtantuo, Dengying formations, China) suggests that palaeogeographically South China was located near India (Evans, 2009).

Palaeogeography of the Hazara Basin exhibits most of the characteristics of the globally recognized phenomena associated with the break-up of the Rodinia supercontinent and the snowball Earth. The stratigraphical evidence supports a palaeogeographical connection of the Hazara Basin with similar basins in the Indian Lesser Himalayan regions and in South China during the Late Neoproterozoic−Cambrian, perhaps a series of linked sedimentary basins as also suggested by Tewari (2012). The correlation of Lesser Himalaya (both in Pakistan and India) and the South China Block based on the facies, stratigraphy and glaciations in the late Neoproterozoic and Cambrian suggest that South China was located proximal to the northwestern margin of the Indian subcontinent during Rodinia break-up (Text-fig. 13; Jiang *et al*. 2003). Rodinia break-up is dated at 750 Ma (Powell *et al*. 1993) and that major event may be associated with instability of the Lesser Himalayan




Text-fig. 13. Palaeogeographical reconstruction of South China and India during: A – 900 Ma (modified after Cawood and Buchan, 2007); B – 750 Ma (modified after Li *et al.* 2004), and C – 590–543 Ma – early Cambrian; blue arrows in C indicate palaeoflows from shelf to basin (modified after Lin and Fuller 1990)

| **Lithostratigraphic units** | | | **Lithology** | **Depositional Environments** | **Age** |
|---|---|---|---|---|---|
| Lesser Himalaya* | India | South China | | | |
| Abbottabad Formation | Krol Group | Doushtantou formations | Shale, mudstone, dolomite, sandstone and Phosphate, chert nodules and bands | Shallow marine | Cambrian |
| Tanaki Boulder Bed | Blaini Formation | Changan, Fulu and Silikou formations | Boulders, Conglomerates, breecia, sandstone and argillites | Glaciogenic | late Proterozoic |
| Tanawal Fm | Nanghtat Formation | Wuqiangxi/GongDong formations | Mudstone, siltstone and sandstone | Fluvial/Shelf to deep marine | late Proterozoic |
| Hazara Fm | Chandpur Formation/Shimla Group | Madiyi/Hetong formations | Shale, siltstone, slate and sandstone | Deep marine | late Proterozoic |

* Present investigations

Table 2. Regional stratigraphical correlation of the study area with India and South China counterparts (modified after Jiang *et al*. 2003; Wang and Li 2003; Tewari and Sial 2007)

and South China basins causing the development of an unconformity between the Hazara and Tanawal formations. The Tanawal Formation may represent passive margin development in the region.

Furthermore, the similarities (stratigraphical, glaciations, unconformities etc) of the Hazara Basin, Indian lesser Himalaya and the South China Block indicate that these basins underwent the same rifting (800–700 Ma), uplifting (650–500 Ma) and Marinoan glaciation (ca. 595–605 Ma; Macouin *et al*. 2004) episodes and their probable proximity during Neoproterozoic–Early Cambrian time. Our study constrains the positions of Lesser Himalaya (both India and Pakistan) and south China within Rodinia. Li *et al.* (2008) nestled South China between eastern Australia and Laurentia during Rodinia times, whereas Yang (2004) preferred South China to have been located outside Rodinia. These configurations were recently challenged by Cawood *et al*. (2013), who preferred South China to have been located to the north of Greater India and adjacent to Western Australia from Rodinia times through to the amalgamation of Gondwana. Our stratigraphical findings from northern Pakistan provide additional support for the Cawood *et al.* (2013) Rodinia configuration.

## CONCLUSIONS

Based on our findings the following conclusions are made:

Palaeogeographic reconstruction and stratigraphical analysis reveals that the Hazara Formation, consisting of shale, siltstone and sandstone, shows different sets of features related to deep marine environments. The lower part of the formation suggests base of slope to basin floor settings, capped by outer and inner-mid fan components. A proximal inner fan and submarine channels prevailed in the south, whereas an outer fan and basin floor occurred in the north. This notion is consistent with palaeocurrent analysis which indicates sediment supply from the south-southeast. Palaeocurrent data recorded in the field from sole marks (mostly flutes) and cross-bedding support the lateral variations in late Neoproterozoic succession (both the Hazara and Tanawal formations) from south-southeast to north-northwest.

The Tanawal Formation overlies the Hazara Formation unconformably and records shoreface to deeper shelf depositional environments. The lower part of the formation is predominantly composed of lithofacies indicative of deeper shelf settings, whereas the upper parts of the formation are characterized by lithofacies indicative of a shoreface environment.

A condensed section in the Tanawal Formation to the east (sections 2 and 3) is interpreted as the product of sediment supply starvation due to local subsidence within the basin.

The glaciogenic Tanaki Boulder Bed above the Tanawal Formation marks an excellent marker horizon formed in the terminal Proterozoic and is comparable with horizons known from South China and the Indian Lesser Himalaya. The Cambrian Abbottabad Formation constitutes a siliciclastic-carbonate-rich sedimentary succession. The lithostratigraphic units of Neoproterozoic–Cambrian age exposed in the Pakistani lesser Himalaya (Hazara, Tanawal, Tanaki Boulder bed and Abbottabad formations) are compared with successions in India and South China and their probable same origin and close proximity during the Neoproterozoic to Early Cambrian time span are suggested. This comparison is also an indication that these basins passed through similar geological episodes during the break-up of Rodinia and the assembling of Gondwana.

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