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GEOLOGY

Soft Sedimentary Deformations Structures (SSDS) in Neoproterozoic Sharaban Formation, Kirana Complex, Pakistan: Regional Tectonic Implications

B. Ahmad[a], S. H. Ali[a,*], A. Wahid[b], Y. Bashir[c], N. Shoukat[d], S. M. T. Qadri[e], A. Ali[f], N. A. Siddiqui[d], M. Abioui[g,h], and A. Yaseen[i]

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Abstract—Soft sedimentary deformation structures (SSDs) are imperative intuition into the paleotectonic history of an active tectonic setting; however, they become arduous when dealing with Neoproterozoic intracratonic regions. A lesser known stratigraphic unit of Neoproterozoic age Sharaban Formation in Pakistan was undocumented for its SSDs and other stratigraphic details. Sharaban Formation was always thought to be a unit of metaquartzites in previous studies. Though, sedimentary and metasedimentary rocks were present. These rocks are associated with primary and secondary sedimentary structures (especially SSDs). This paper aims to identify facies, primary and secondary sedimentary structures, especially SSDs, and later link them to the paleotectonic history of the region. For this purpose, a detailed field study was designed and carried out for more than a decade, with high-resolution field photographs, sketches, and plotting. Our fieldwork reveals that the formation is made up of four rock types, metasandstone, metaconglomeratic sandstone, limestone, and quartz veins. Numerous types of sedimentary structures are found like graded bedding, cross-bedding, imbrication, synsedimentary deformation structures, convolute structure, flame structure, folds and faults, chevron–type folding, ball and pillow structure, chaotic bedding, etc. The Sharaban Formation's depositional environment is represented from low energy coastal environment to possibly a braided river system, while limestone could have deposited in a lagoonal setting. Later the SSDs could have been formed as a result of seismic activity subsequently controlled by the cratonic rifting in the larger Kirana-Malani Basin. Our results reveal that the Neoproterozoic was a time of extreme changes in tectonic conditions in the Kirana Malani Basin. Additionally, the SSDs found in the Sharaban Formation may help to understand the paleo-tectonics, tectono-dynamic reconstructions and structural kinematic studies in the NE Gondwana and other terrains like India (Bilara Formation), China and Siberia.

Keywords: Soft sediment deformational structure (SSDs), Tectonics, Neoproterozoic, Kirana-Malani Basin, Punjab Platform

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[a] *Department of Earth Sciences, University of Sargodha, Sargodha, 40100 Pakistan*
[b] *Institute of Geology, University of Azad Jammu and Kashmir, Muzaffarabad, Pakistan*
[c] *Department of Geophysical Engineering, Faculty of Mines, İstanbul Technical University, İstanbul, Turkey*
[d] *Department of Geosciences, Universiti Teknologi PETRONAS, Perak, Malaysia*
[e] *Faculty of Science, University of Fraser Valley, Abbotsford, Canada*
[f] *School of Earth Sciences, Zhejiang University, Hangzhou, China*
[g] *Geosciences, Environment and Geomatics Laboratory (GEG), Department of Earth Sciences, Faculty of Sciences, Ibnou Zohr University, Agadir, Morocco*
[h] *MARE-Marine and Environmental Sciences Centre—Sedimentary Geology Group, Department of Earth Sciences, Faculty of Sciences and Technology, University of Coimbra, Coimbra, Portugal*
[i] *Pakistan Museum of Natural History, Garden Avenue, Sakarparian, Islamabad*
**e-mail: haroon.ali@uos.edu.pk*

1. INTRODUCTION

Sedimentary structures are the basis for describing early depositional environments [1], the sedimentary structures are products of physical, chemical, or biological processes, either during or after deposition, which are approximately verified in stratigraphic records for these processes. Sedimentary structures are larger scale than textures or sediments arrangements found within a rock. These structures are used to describe the formation of rocks and the depositional environment in which they are formed. They are usually formed through a variety of processes that are compared to modern depositional environments. Sedimentary structures such as graded beds, cross-beds, and mud cracks can be used to determine the actual sequence of sediments and the depositional setting [1]. Soft sedimentary deformation structures or SSDs are formed in the sedimentary succession as a result of liquefaction or fluidization, triggered by an earthquake

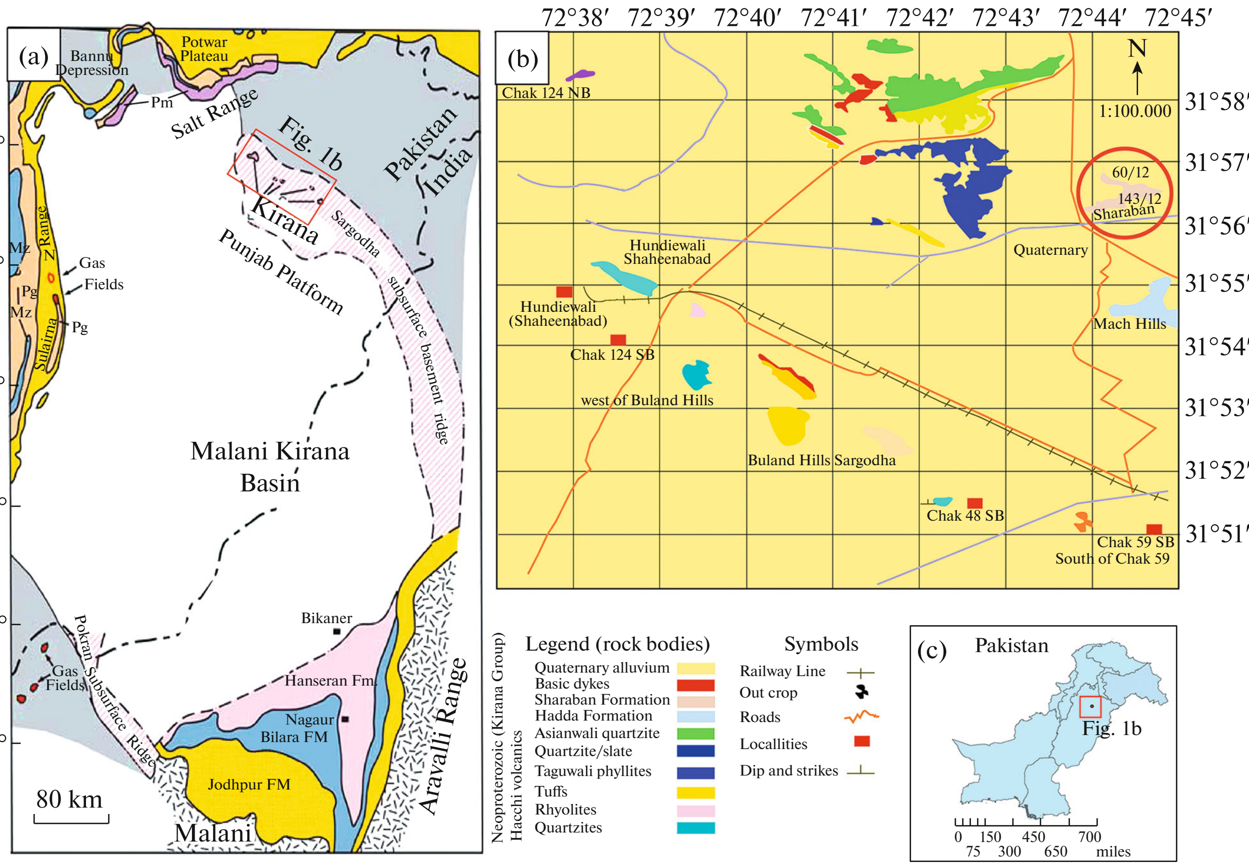


Fig. 1. (a) Geological map of Western India and Pakistan, showing an outline of Kirana – Malani Basin in both countries. The Kirana Hills can be seen in the Northwestern part of the map [8]. (b) Geological map of Kirana Hills with volcanic, metavolcanic, and metasedimentary rocks distribution in the isolated outcrops, The Sharaban Hill is present in the Northeastern part of the map, with a circle outlining it. (c) The location of Fig. 1b in the Map of Pakistan [18].

or paleoseismicity [2]. SSDs are studied from two prospective one is the deformation mechanism and the other is the triggering agent. The SSDs are present from Precambrian to Quaternary sediments [1, 2]. Most of the previous works were on clastic rocks [3, 4], with some limited studies on carbonates as subsequent diagenesis destroys the fabric and field features. Tectonic forces make it possible in the crust to deform rocks and trigger sedimentary processes; new applications of sedimentary structures include the paleo–reconstruction of the depositional setting [3–7]. The cause of these SSDs in tectonically active sedimentary basins can be correlated with deformation features and active faulting [3–5]. But, in intraplate basins or cratonic basins where the data collection itself is a problem due to accessibility in scattered, highly populated, or mined outcrops, recognition and linking it to tectonic settings becomes a huge challenge. Some previous workers like [8–12] have recommended a seismogenic origin of SSDs in cratonic or stable regions of the earth's crust.

The Kirana Hills marking the NW boundary of the lesser known Kirana Malani Basin of NE Gondwana [7, 14–17], are well known for their good quality aggregate resource all over the worldwide [7, 14–17]. However, lesser known about the rich geological history they carry.

The Kirana Hills is a mountainous range in Sargodha, Punjab Pakistan [8–11] (Fig. 1). It is located about 40 km from Sargodha and Jhang [11–16]. The Neoproterozoic Kirana Hills signify accessible outcrops of magmatic and metasedimentary rocks distributed in the plain areas of Punjab from Sargodha to Chiniot, Sangla Hill, and Shahkot [9]. They are mainly comprised of igneous rocks that belong to basaltic rhyolite magmatic with metasedimentary rocks [7, 8] (Fig. 2). These rocks are intruded by sills and dykes.

This study is on one of the younger and metasedimentary units in the Kirana stratigraphy called the Sharaban Formation.

The objectives of the paper are: (i) To provide details on the description of facies and rock types in the Sharaban Formation; (ii) To list the sedimentary structures and their types with interpretation; (iii) undocumented and undescribed SSDs from the

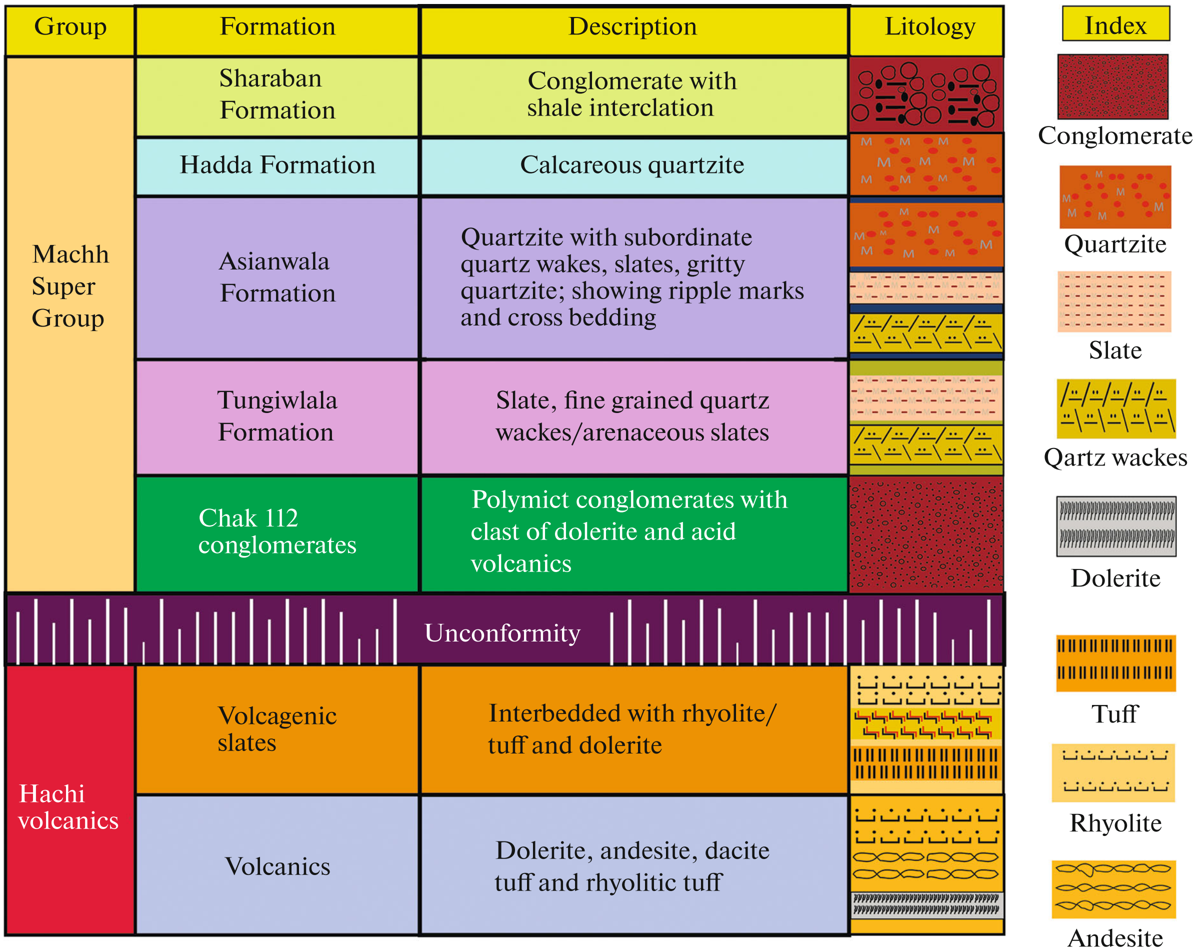


Fig. 2. Stratigraphic classification of the Kirana Complex, into groups and formations [8, 9]. The stratigraphy is divided into two groups, Hachi Volcanics, and Machh Supergroups. The Hachi Volcanics Group is dominated by volcanic, while the latter by metasedimentary and metamorphics.

metasandstones, metaconglomerates, and minor limestones, and (iv) To link the sedimentary structures and sedimentary fabric to the paleodepositional environment and tectonics.

The Sharaban Formation is considered to be a thick sequence of 120 m metaconglomerates (Fig. 3) and metasandstones and minor limestones [18]. The metaconglomerate has a thick bed (5–10 m) and is concentrated in layers (1–10 cm) of quartzite and slate. The metaconglomerate also contains limestone pebbles that are supposed to come from a distant source because there is no limestone outcrop in this area [18]. No fossils have been found in this formation. Nevertheless, some unknown structures similar to trace fossils are seen. The upper contact of the formation is covered with alluvium.

2. GEOLOGICAL SETTING

The Kirana Hills represent exposures of the oldest rocks in Pakistan, west of the Aravalli Ranges of India [3, 18]. Notable orogenies in the region include Aravallis and Delhi (1500 to 1700 Ma) [18]. These Proterozoic orogenic episodes affected the cratonic interiors and the overlying sedimentary cover in larger regions [8, 9]. The release of stresses of Aravalli orogeny resulted in an extension in the western parts of the Indian plate, while an extension in the east [8]. These extensional episodes not only resulted in the formation of plutonic and volcanic rocks but also the subsequent deposition of sedimentary layers in the study area (Fig. 2). The center of hotspot activity during the Neoproterozoic was approximately around 873 + 40 Ma, 870 + 40 Ma in the Kirana area. The rocks of this region include the upper Proterozoic and bimodal cratonic rift assembly volcanoes. These consist mainly of dolerites and rhyolites. Minor lithologies include volcanic slates, dacites, and andesites. In the Kirana area, more than 40 different hills surround the alluvium of the Punjab plains. These rocks are part of a vast volcanic–sedimentary succession known as the Malani Basin [18] and are rediscovered now as Kirana–Mal-

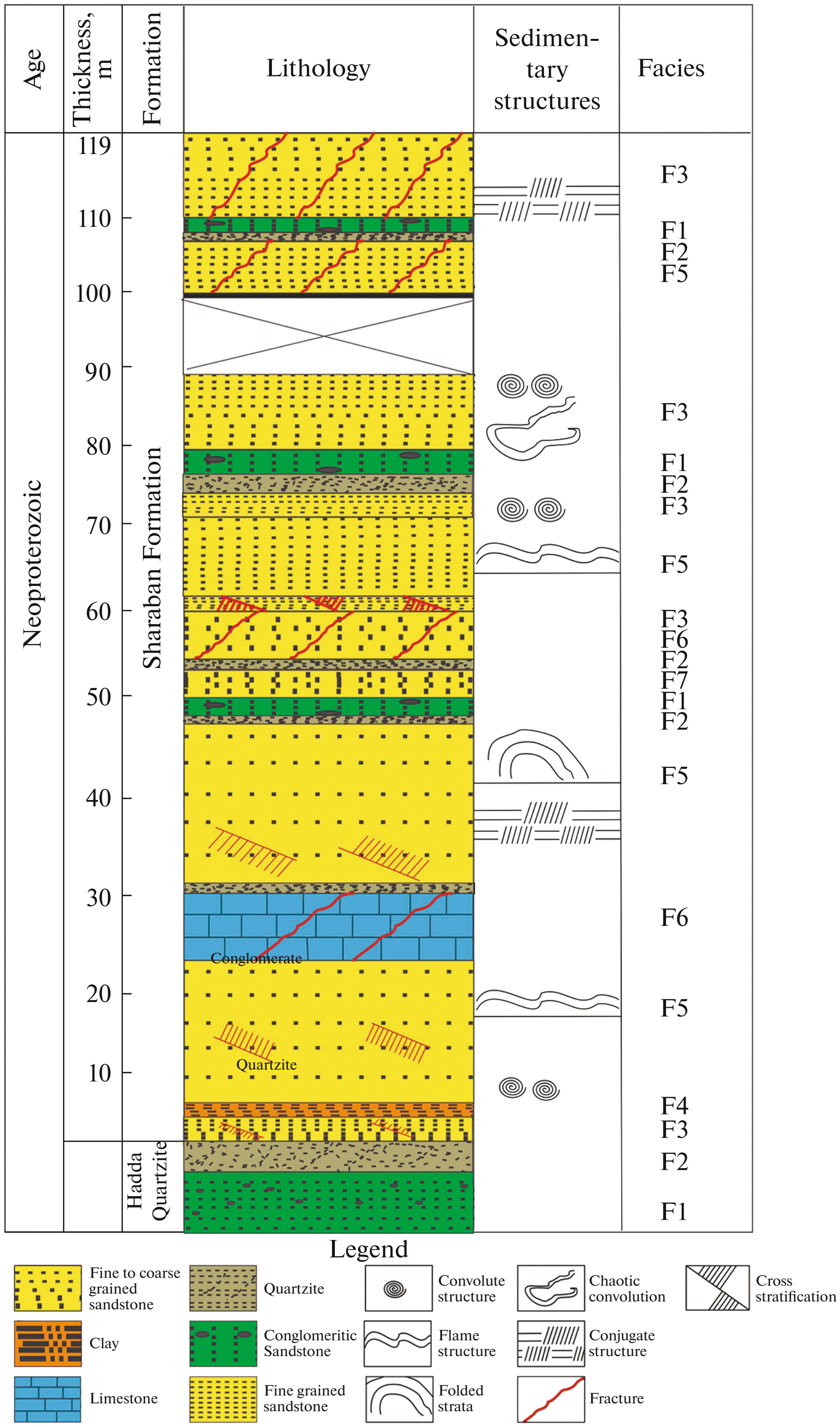


Fig. 3. Lithostratigraphic column of Sharaban Formation, presenting metasandstones, metaconglomeratic sandstone, limestone, and other lithologies, overlying the older Hadda Formation, some sedimentary structures can be seen here, for details on sedimentary structures refer to Table 1.

ani Basin [8]. The geology and stratigraphy of the Kirana Hills have been described by many authors [19]. As [29] improved the stratigraphy of the area and subdivided the rocks into groups and formations. The oldest rocks are the Hachi volcanics, with rhyolites, rhyolitic tuffs, dacite, dacitic tuff, andesite, etc. The base of Hachi volcanic is not exposed. These volcanic are overlain by Chak 112 conglomerates which are polymict in origin. Tuguwali Formation, consisting of phyllites and psammites, overlapping with Asianwala quartzite containing lithic greywacke and quartz wackes, and the Hadda Formation overlain by metaconglomerates with slate intercalation consisting of calcareous quartzites (Fig. 2). The Hadda Formation is overlain by the youngest Sharaban Formation and is composed of metaconglomerates and metasandstones, intruded by dykes and sills. Calcitic and quartz veins are also present. There are a variety of sedimentary structures present in the succession, including both primary and secondary sedimentary structures. The sedimentary structures present a variety of depositional and post-depositional changes within the succession [19, 20]. The sedimentary structures include cross-bedding, flame structures, ball and pillow structures, graded bedding and convolutes structures, etc. [9].

3. MATERIALS AND METHODS

The highly eroded and long exposed rocks of the Kirana Hills pose a challenge for their description. The results presented in this paper are a result of fifteen years of extensive fieldwork in this area. Rock types were differentiated based on their field examination of a hand lens, testing with a 10% dilute solution of HCl for carbonate rocks, as well as the stratigraphic column of the area, was also utilized. Field photographs were taken by Canon EOS 4000D Kit EF–S18–55III. This camera comes with an aluminum flexible tripod camera stand. The field photographs taken were geo-referenced using Picasa software V. 3.9. About 1500 high-resolution field photographs were taken during the field excursion.

The soft sedimentary deformation structures (SSDs) have never been reported from this area, here they are described, plotted, and placed in the lithostratigraphic column of the formation. A field sedimentary log was used for the identification of these SSDs in the data collection stage. Separately from the SSDs, some brittle deformation structures such as joints, and faults were also marked. The later syn–sedimentary movements have greatly modified the sedimentary fabric. Using a uniform classification for the identification of SSDs is very tough. We have named all the structures as SSDs, regardless of the various processes that formed them, like liquefaction, fluidization, and hydroplastic deformation [1]. The sedimentary structures are marked in field photographs and are also sketched, with their evolution in the sedimentary record in the terminal part of the paper.

4. RESULTS

4.1. Sedimentary Facies Analysis

Lithofacies analysis has been based on the lithology/composition of the rock. The Sharaban Formation consists of variable lithofacies including metaconglomerates, metasandstone, minor limestone, and quartzite (Fig. 3). These sediments are slightly metamorphosed; however, the sedimentary fabric is still preserved. Based on lithology Sharaban Formation consists of the following lithofacies:

a. Metasandstone facies. This lithofacies generally consist of metasandstone (Fig. 3). Metasandstone normally consists of quartz, mica, feldspar, and some other minerals. Quartz grains are subangular to angular and some are rounded. Some microfractures are also present at the outcrops. The metasandstone is present from fine to coarse grain textures. A variety of soft sedimentary deformation structures are present in the sandstone facies. Microfractures associated with large–scale fractures are also reported from this facies.

b. Metaconglomerate facies. This lithofacies is the significant facies of the Sharaban Formation, mostly consisting of sandstone with gravel including metaconglomerates and pebbles (Fig. 3). Metaconglomerates are rounded to subrounded and at some places subangular. Metaconglomerates are generally poorly sorted. Metaconglomerates are mostly from sandstone and igneous composition. Some striations are present in this facies. Conglomeratic sandstone is coarse-grained with some accessory minerals. The main sedimentary structure is graded bedding.

c. Limestone facies. This lithofacies mostly comprises carbonate composition (Fig. 3). Microfractures are more common as compared to sandstone. The dissolution phenomenon is also present in limestone facies, so the fractures and dissolution increase the rock porosity and permeability. The percentage of limestone facies is low as compared to conglomeratic sandstone, sandstone, and quartzite lithofacies.

4.2. Sedimentary Structures Analysis

Sedimentary structures are such types of structures that form at the time of deposition and after deposition (Table 1). There are two types of sedimentary structures observed in the Sharaban Formation:

- Primary sedimentary structure (cross bedding, graded bedding, imbrication, trace fossils (unknown), lamination, flute casts, lenticular bedding, turbidity flow (?), clast–induced bedding, etc.).
- Secondary sedimentary structure (convolute, flame structure, sedimentary faults, sedimentary folds, anticline, ball and pillow structures, sedimentary mini–basin, fault slips and folds, chaotic bedding, chevron fold type structure, etc.).
- Brittle deformation structures (e.g. dyke, veins, etc.).

4.2.1. Primary or depositional structures. In the study area, there are generally various types of primary sedimentary structures: trough cross-bedding, graded bedding, trace fossils, imbrication, clast-induced bedding, turbidity flow structure, and lenticular bedding formed at the time of deposition.

a. Trough cross bedding. Cross bedding is observed in sandstone and conglomeratic sandstone facies of

Table 1. A summary of primary and SSDs is given with possible controls and tectonic frameworks

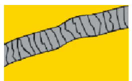
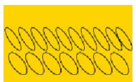
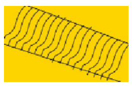
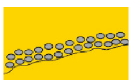
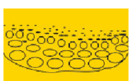
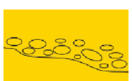
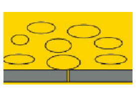
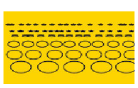
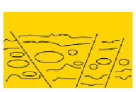
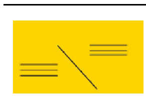
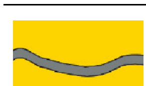
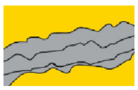
Symbol	Primary/secondary	Name	Description	Interpretation
	Primary	Trace fossils	Track and trail fossils	Activity and behavior of past life
	Primary	Imbrication	Oriented clasts	Found by unidirectional flow
	Primary	Cross bedding	Layers at an angle to the bedding	Formed as a result of current flow direction
	Primary	Clast induced bedding	Larger clast in a finer matrix	Formed due to changing depositional direction
	Primary	lenticular bedding	Lens-shaped geometry between coarse and fine sediments	Formed due to storm-generated conditions
	Primary	Turbidity flow	Liquefied sediment structure	Formed due to downslope movement
	Primary	Lamination	Small scale bedding	Small episode of deposition
	Primary	Ball and pillow structure	Interrupted mud and sand beds	Shaking of sediment by an earthquake
	Primary	Graded bedding	Different clast size	Slumping
	Primary/Secondary	Clast/fractured sandstone	Brittle beds	Rock breakage due to extension
	Secondary	Flame structure	Heavy bed overlay soft bed	Found as a result of rapid deposition
	Secondary	Fault slips	Initiate in brittle beds	Divergent margin structure
	Secondary	Fold/Anticline	Folding of ductile layers	Convergent margin
	Secondary	Convolute bedding	Collapse of sedimentary layers	Fluid plain delta deposits
	Secondary	Synsedimentary fault	Fault that is like a growth fault	Unstable plate margins
	Secondary	Synsedimentary fold	Ductile deformation	Formed during sedimentation as a result of a difference in stress and pore pressure

Table 1. (Contd.)

Symbol	Primary/secondary	Name	Description	Interpretation
	Secondary	Chevron fold type structure	Straight limb sharp hinge	Compressional regime margin
	Secondary	Fault slip/Fold	Fault offset in deformation	Extensional margin
	Secondary	Sedimentary mini—basin and growth faults	Small depression	Exceptional regime
	Secondary	Chaotic bedding	Crumbled beds	Sand deposition on mud/unstable setting

the Sharaban Formation (Fig. 4a). These cross-beds are found in horizontal beds of the Sharaban Formation and are inclined relative to the base.

b. Graded bedding. Graded bedding is a type of sedimentation unit that has different vertical grain size levels. Here, it may comprise from a few centimeters to a few meters in thickness (Fig. 5c). Whereas generally deficient internal strata, which are a part of turbidite strata that can show wavy or tabular strata, were observed in several facies of the Sharaban Formation.

c. Imbrication. Imbrication is a primary deposition fabric in which the clasts have a predominant orientation that continuously overlaps each other, unlike the run of the dominoes at the top (Fig. 4c). Imbrication is observed in some metaconglomerate deposits in the Sharaban formation. Imbrication is an overlapping arrangement of similar parts, similar to roof tiles or fish scales.

d. Trace fossils. Burrows, trails, or tracks of animal activity were found. The trace fossil type is unidentified; this could be one of the earliest traces of life in the region. These structures are present in the form of ridges and small furrows (Fig. 6b, upper part of the photo, indicated by a white arrow here).

e. Lamination. The strata consist of a fine layer (~1 mm thick), also known as lamina, which is common in fine-grained sedimentary rocks here in fine metasandstone facies. The laminated metasandstone sediment bed consists of several laminations or laminae (Fig. 4e).

f. Flute casts. Scoop—shaped structures are found in the field features of the Sharaban Formation (Fig. 6c). They are steep on the upstream sides, and gentle on the downstream.

g. Lenticular bedding. A lens-shaped geometry is found in the metasandstones facies, with coarse sediments overlying relatively finer sediments (Fig. 6d). The coarse sediments inside the lens are cross-bedded. The lens is thicker in the center and pinch outs to the margins. These bodies are much localized and are restricted.

h. Turbidity flow structures. A liquefied sedimentary structure shows geometry and sediments along a sharp surface (Fig. 8b). The mud is greyish green while the sand is pinkish yellow. The grain size in these structures is mud to coarse sands. Some flame structures and load structures are also associated with turbidity flow structures.

i. Clast-induced bedding. It presents larger clasts in the finer matrix (Figs. 4b and 8b). The clasts sometime reach the sizes of a few centimeters. The clast looks highly strained with sizes ranging from granule to pebble. The clasts are made up of clay and mud. The clasts seem to have induced the overlying and underlying sedimentary layers.

4.2.2. Secondary syn—sedimentary structures or Soft sediment deformational structures (SSDs). These secondary soft sedimentary deformation structures (SSDs) are formed after deposition, as a result of loading of wet sediments as burial continues. The most common SSDs are load casts, pseudo—nodules/ball and pillow structures, flame structures, and dikes [1, 2], however, in our case, we found additional SSDs. These include convolute, sedimentary faults, sedimentary folds, anticline, sedimentary mini-basin, fault slips and folds, chaotic bedding, and chevron fold type structure.

a. Convolute structures. Convolute bedding is mostly found in fine sand to silty and their laminae can be traced through folds (Figs. 6b, 7a, and 8c). The beds that contain convolute strata normally range in thickness ranges from 3—25 cm. Convolute structures are such types of structures that are made due to intricate bedding or complex crumpling of strata to uneven, normally small—scale synclinal and anticlinal structures.

b. Flame structures. Some flame crests are overturned or folded; mostly, overturned crests incline all

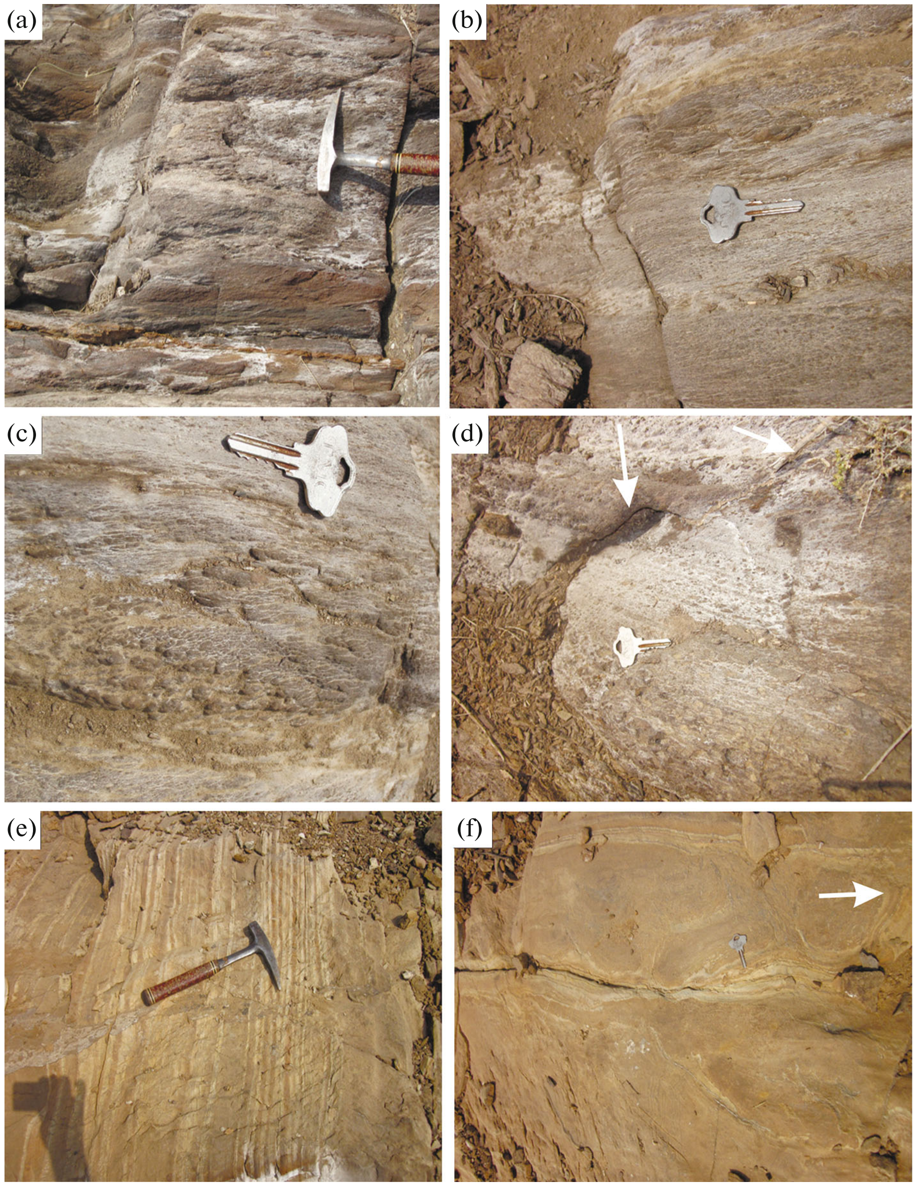


Fig. 4. Field features of the Sharaban Formation: (a) cross-bedding in sandstone, (b) clastinduced bedding, (c) imbrication in conglomeratic sandstone, (d) sedimentary injections like a sedimentary dike indicated by an arrow, (e) sedimentary lamination, (f) sedimentary folding, load casts and a sedimentary dike on the right side.

points in a similar direction, but this is not always uniform (Fig. 5a). Flame structures are such types of structures that are in flame-shaped or wavy tongues of mud. These layers are projected above into superimposing layer that is mostly in metasandstone.

c. Syn-sedimentary faults. These are deformation structures like syn–sedimentary faults which are common in heterolithic lithologies in the studied area (Fig. 5b). Here, the placement of the fault plane is usually less than cm–scale and bound to beds that are unformed indicating syn–sedimentary origin.

d. Sedimentary folds. Mostly the depositional folds are associated with clean metasandstone units, while a few sedimentary folds are related to heterolithic beds (Figs. 5e and 7e). Sedimentary folds have a broad or narrow area of fold axis which is observed in the Sharaban Formation.

e. Anticline. Anticline is a structural feature that is formed by the folding of rock strata into an arch-like shape (Fig. 5c). The rock layers in the anticlinal trap were first laid horizontally and the motion of the earth transformed them into an arch-like shape called the anticline.

f. Ball and Pillow structures or pseudo–nodules. Such types of structures are present in the lower part of metasandstone beds (Fig. 5f). They comprise kidney

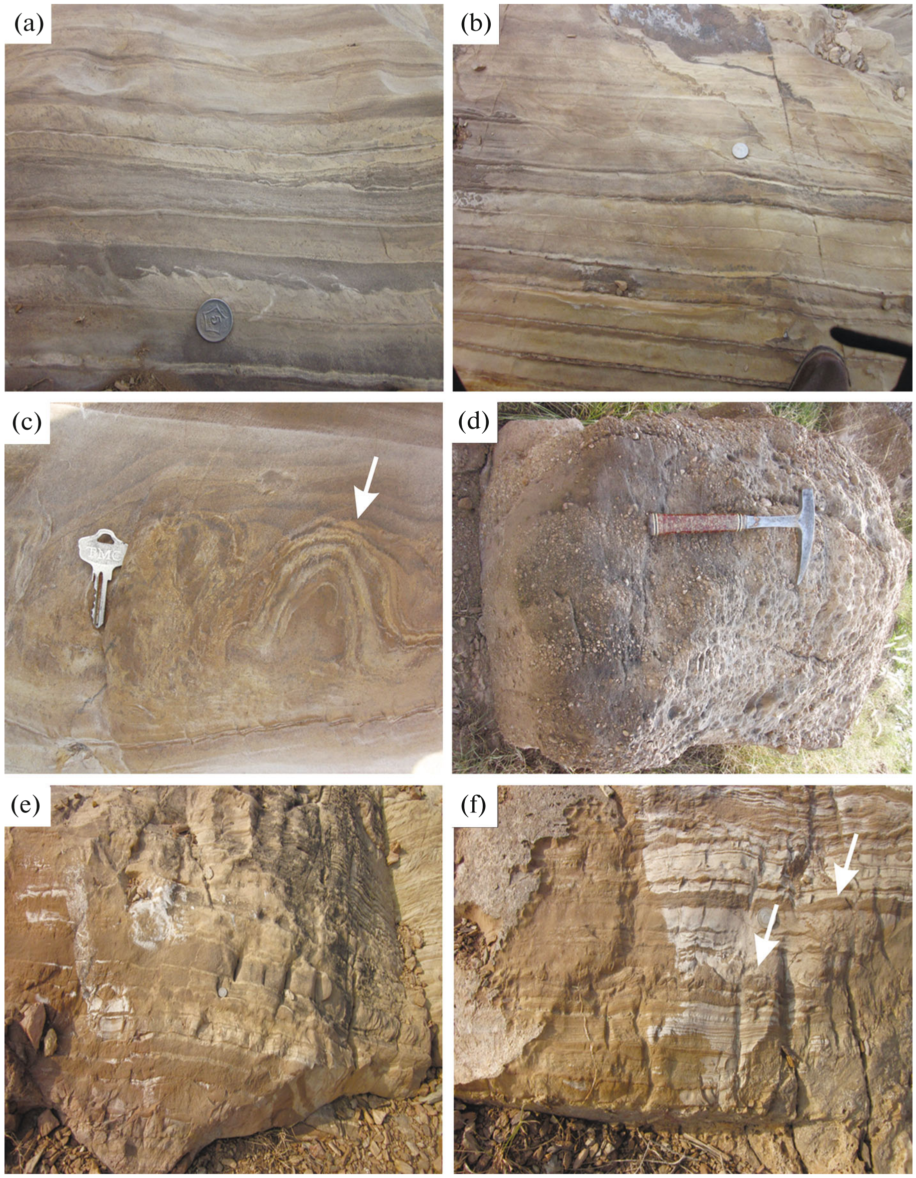


Fig. 5. (a) Flame structures, (b) fault slips and other syn–sedimentary structures, (c) Sedimentary anticlines like structure or convoluted folds and fault slip, (d) graded bedding in sandstone and conglomeratic sandstone intervals, (e) small–scale folding and syn–sedimentary structures, (f) ball and pillow (lower white arrow) and load structures in the sandstone beds.

or hemispherical–shaped masses of metasandstone that show internal laminations. In some parts, the laminae might be deformed or curved, chiefly next to the outside edge of hemispheres, where they tend to obey the shape of the edge.

g. Sedimentary mini–basin type structure. It is a small basin with a size of a few tens of centimeters (Fig. 6a). The layers in the metasandstone appear to be concave upwards.

h. Fault slips and folds. Very small–scale faults are present along with folds (Fig. 5c). Faults show a small offset of 2–3 cm. These faults seem to be creating more accommodation for the upper layers. These faults could be an example of seismities due to their geometry and shape. These are arranged in an echelon pattern or parallel to each other.

i. Chaotic bedding. These beds have crumbled beds, with no sedimentary layering preserved (Fig. 6f). It is found in a metasandstone unit. These structures are present in finer-grained sandstones. They look similar to slump structures. The layers are bended and folded in various directions. The color variations indicate more than one episode of chaotic beds.

j. Chevron folds type structure. Chevron–type folds are characterized by a sharp hinge and straight limbs (Fig. 8a). They represent V-shaped beds stacked together. Very well-developed beds are part of this structure. Interlimb angles between the fold limbs are

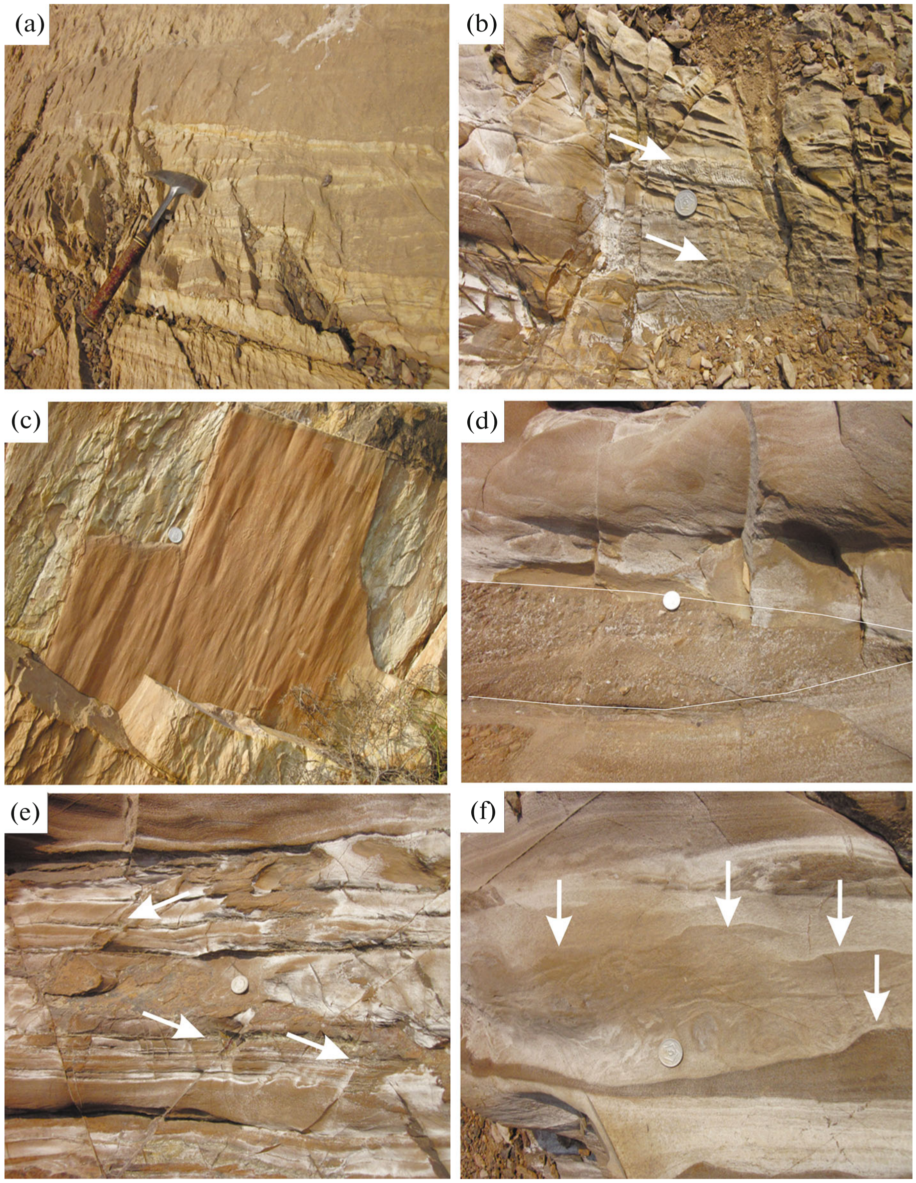


Fig. 6. (a) The geometry of sediments looks similar to the development of Mini–basins, with more accommodation on the right side, with load structures, (b) fractured sandstone with convolute structure or unknown traces, (c) flute casts at the lower bedding surface of sandstone, (d) lens in conglomeratic sandstone, (e) highly fractured sandstone and deformation bands, (f) chaotic bedding with a high degree of turbidite deposition.

less than 60°. Large pebbles of grey color from the termination of the structure on the right side.

4.2.3. Brittle deformation structures. Some features are formed after the primary and secondary sedimentary structures that we call brittle deformation structures. These structures are the result of structural and tectonic deformations in the study area. The following structures have been observed:

a. Fractures. The fractures are present at the outcrop scale to the macroscopic scale (Fig. 6b). There are several fractures sets present in all lithologies, especially metasandstones and limestones. It consists of systematic and nonsystematic joint sets. These could have been formed as a result of continuous deformation phases through the geological evolution of the Sharaban Formation.

b. Sedimentary dyke. A sand flat body of rock in the shape of dyke is cutting horizontal layers. A dyke cuts the metasandstone and metaconglomeratic sandstone beds. It is highly weathered. This dyke is of sandstone composition. Dykes are generally visible because they occur at various angles, and generally have distinct colors and textures as compared to the surrounding rock.

c. Quartz veins. There are quartz veins present in the outcrops (Fig. 3). These range in thickness from

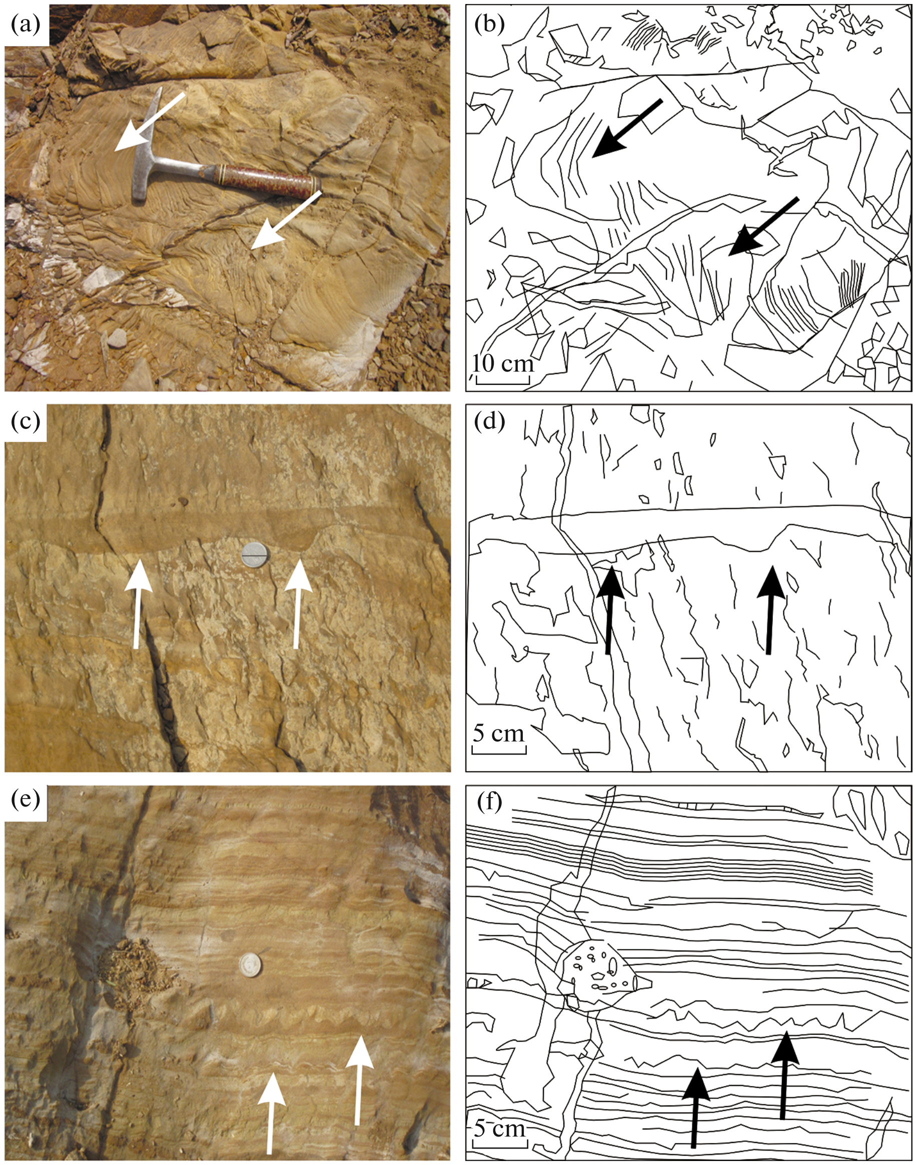


Fig. 7. (a) Convolute bedding in metasandstone. (b) Sketch alongside represents bending, detachment, and fracturing. (c) Load casts overlying conglomeratic metasandstones. (d) The sketch shows a bulbous (arrow) depression formed on the base of the metasandstone bed. (e) Syn–sedimentary folding and load casts. (f) The sketch alongside shows the deformation in the plastic state and detachment of load casts.

10–15 cm. The veins are not extensive and are restricted in the metaconglomeratic and metasandstone lithologies.

5. DISCUSSION

The differentiation of facies and sedimentary structures is important and interlinked to determine the controlling mechanism and triggering events. Facies help in understanding the extent of the SSDs. As sandstone is the dominant facies and is subjected to the growth of SSDs.

5.1. Facies and Sedimentary Setting

There are three facies present, including metasandstones, metaconglomeratic sandstone, and limestones. The sandstone lithofacies were deposited in a variety of depositional settings from low to medium–energy coastal environments to possibly braided river systems [19, 20]. The presence of cross-bedding and a variety of soft sedimentary deformational structures represent its deposition in an unstable sedimentary basin that could have been displaced or reactivated by some mega–scale earthquake or landslide. The conglomeratic sandstone could have been deposited in a braided river system [20]. The main sedimentary

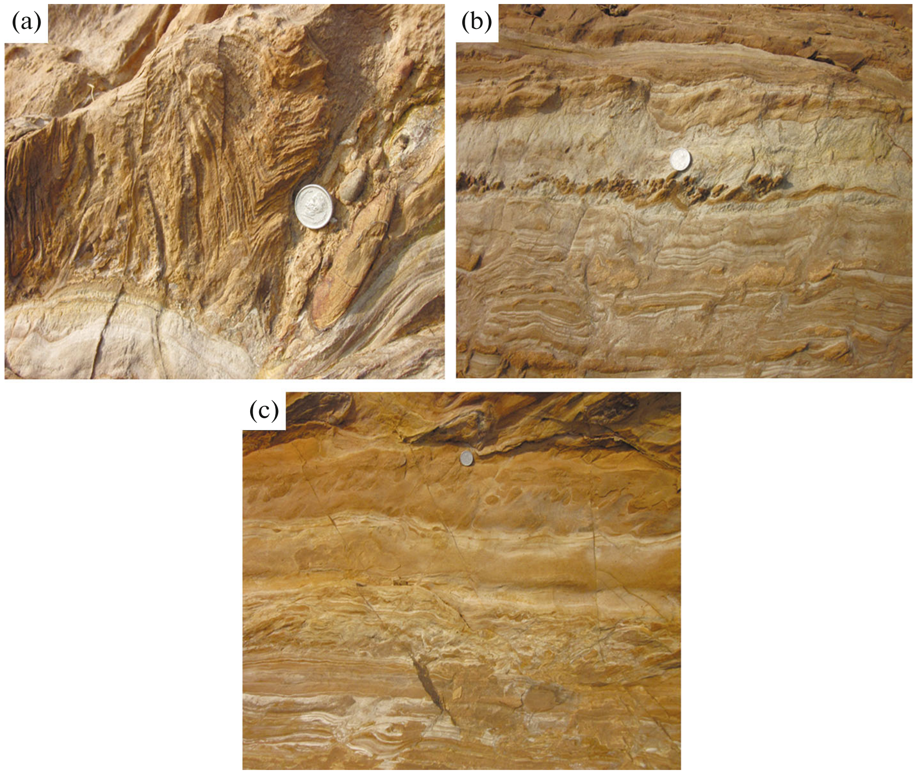


Fig. 8. (a) Chevron–type folding of metasandstone beds, with the head pointing to water escape, (b) clast-induced bedding, (c) convolute and chaotic bedding along with load casts.

structure is graded bedding. There is also the possibility of a turbidity system as the sediments could have settled based on their detritus densities. The limestone could have been deposited in the lagoonal setting [19]. The absence of any fossils could indicate the closed depositional setting. The slightly metamorphosed dolomite crystals could be a product of a mixing zone or burial-related phenomenon as presented by the isotopic data as well. There are two main types of sedimentary structures (Table 1). Primary and secondary sedimentary structures show various depositional and tectonic conditions [1].

5.2. Primary Sedimentary Structures

The primary sedimentary structures include cross-bedding, graded bedding, imbrication, clast-induced bedding, lenticular bedding, and trace fossils. The primary sedimentary structures show flow conditions and depositional conditions resulting from deposition in fluvial to turbidity flow conditions. The primary sedimentary structures are also deformed by later episodes of compression and extension in the basin.

In cross bedding most of the grains are coarser to be transported in suspension, avalanching the bed load sediment down to the lee side of the ripple that will cause the formation of laminae that are steep and straight [1, 2]. Cross bedding origins of many types of cross–beds occur [1] defined a very descriptive classification of cross strata. It depends upon characteristics such as a combination of cross strata sets, scale, kind of bedding plane of beds, angular relation of cross-bedding in a cross set or to the bedding plane, and grain size sorting [1, 2].

In graded bedding, strata indicate that the fining upward sequence shows normal gradation [1–3]. Whereas the coarser particles at the top grading downward to finer particles is known as reverse grading [5]. A graded bed commonly has sharp basal contact [3, 4]. In normal graded bedding most graded beds have been attributed to turbidity current [2–5]. Whereas, in some sedimentary rocks, we observe the reverse size grading is less common than normal grading. In imbrication, there are flat to platyclasts and are usually aligned by strong currents, such that the ‘plates’ dip upstream [5]. These structures are commonly present in gravelly fluvial deposits. Trace fossils here; give evidence of some animal activity [4] at the time of deposition of the Sharaban Formation. These could be associated with rare trilobites (?) as reported from similar age rocks in Nagaur Sandstone of the same basin. Lamination is usually formed in a coastal environment, where wave energy causes a splitting between different sizes of grains [5]. Flute casts are the most common mechanism of their formation in turbidity currents [4]. Lenticular bedding is found as a result of erosion in the channel, as a result of a change in velocity of a stream or channel due to storm conditions [4–6]. Turbidity flow structure is found commonly in the turbidity deposit and is formed as a fast downslope movement of sediments due to sedimentary load [4]. They could be a result of slope faults, land sliding, earthquakes, or geological events [6]. Clast-induced bedding could have resulted from the changing depositional conditions or a small debris flow at the time of deposition [5].

5.3. Soft Sedimentary Deformation Structures

The primary formation of SSDs mechanism (liquefaction, fluidization) of these processes indicates the mechanism and triggering agent (earthquake) [5; (Fig. 8)]. The SSDs are restricted to certain layers especially metasandstone which presents that the liquefaction and fluidization process took place around the time of the Aravalli and Delhi Orogenic episodes [1]. The load and flame are the results of unequal densities across the bedding surface and lead to differential liquefaction of sediments. However, multiple layers having ball and pillow or pseudo–nodules show deformation of unconsolidated sediments and squeezing of sands in the muddy substrate (Table1; [5]). Load structures are also present and suggest the density contrast between different sedimentary layers and disturbance in the sedimentary basin. Ball and pillow structures may remain connected to the overlying bed or may be separated from the bed and closed in the underlying mud [3]. These structures are supposed to be a result of the foundering and breakup of deconsolidated sand, due to fractional liquefaction of underlying mud. It might be instigated by shocking, liquefaction of mud above sand beds or limy sediment to deform into hemispherical masses, which strength the latter to break apart from the bed and sink into the mud [1].

The flame, load structures, folds, faults, chaotic, chevron structures, and fault slips are post-depositional structures [4]. Flame structures and other water escape structures are a result of water–laden sediment movement along with voids or cracks. Flame structures and the overturned crests' rotation suggest that loading might be conveyed due to some horizontal drag or drive among the sand bed and mud. These structures are mostly related to the other SSDs that are due to sediment loading [5]. These are mostly caused due to a load of water-flooded mud layers that have less density than overlying sands and therefore enfolded above into the sand layers.

The development of chevron fold type structure could also be linked to the formation of escape of water–laden sediment at a local scale [11] (Table 1). Chevron fold-type structures could have been developed as a result of local or regional compressional stress regimes [6].

The association of fault slips or microfaults suggests the restriction of such events at a local scale, as the overlying and underlying beds are undeformed [11]. Syn-sedimentary faults indicate irregular dip–slip movements associated with extensional stress. They are associated with the state of collision and subduction regime in the study area. Although, the normal syn–sedimentary faults are occurring occasionally present in the studied sections indicating a local extensional event [2].

There is also the presence of sedimentary folds that indicate an influence of compressive tectonic forces in its development. They indicate episodes in the sedimentary record. Sedimentary folds, the overlying and underlying stratigraphic units are not deformed which shows seismic activities that are responsible for these deformation structures [4]. Sedimentary anticlines result from the compressional forces after the deposition of these layers [3]. A sedimentary mini basin type structure sinks as it receives sediments [4]. It could have been formed by an extensional regime. Similarly, fault slips and folds indicate the presence of extensional forces [2].

Chaotic and convolute bedding are also important field features and are a result of disrupting depositional conditions in certain layers [9–11]. The convolute structure is mostly restricted to a single lithological unit or strata, and the upper and lower strata of the bed might show a minor indication of deformation [3]. In convolute bedding, the faulting is generally absent, but the convolution might be merged by eroded beds that might be convoluted [1]. The convolute bedding provenance is not still absolutely unstated, but it looks that caused due to plastic distortion of moderately liquefied sediments later on in the deposition. The convolution increases in intricacy and amplitude above disturbed strata in the lower part of the strata [3, 4]. Convolute bedding is most important in turbidite sequences (85–90). Chaotic bedding has been formed as a result of the deposition of metasandstone on a muddy substrate with unstable tectonic conditions [2].

5.4. Brittle Deformation Structures

Fractures are cracks that are formed due to the different fundamental differential forces i.e., compression, extension, or shear forces within the extension regime [8–10]. Fractures are those surfaces along where rocks have broken; they are therefore surfaces across where the material lost cohesion [1]. They are differentiated due to relative motion that occurs across the fracture surface at the time of formation [3]. These fractures can increase the permeability of rock because various types of fluid can pass through these fractures. So, they can act as fluid migration pathways in tight rocks. Dykes are rocks that intrude the open spaces in rocks like open fractures. The magma creates the fracture or disrupts an existing fracture. The fluidized flow of material might have filled the fissure, pushing the

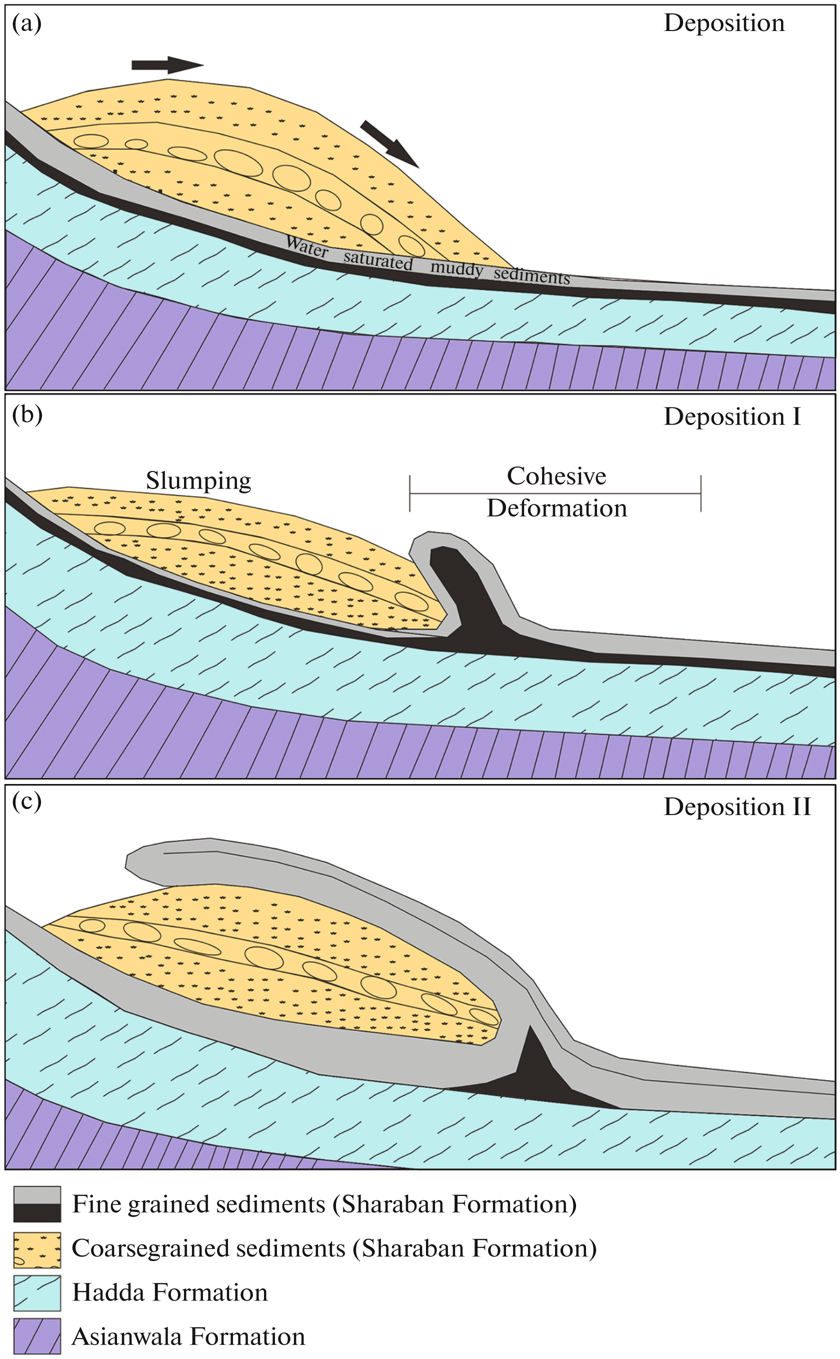


Fig. 9. A conceptual depositional model proposed for the development of SSDSs in the Sharaban Formation. The first stage represents the deposition of the Sharaban Sequence, the later stages represent deformation, and the first stage starts the movement of non-cohesive coarse-grained sediments overlying the cohesive muddy sediments. The indicators of downslope movement are chaotic and convolute bedding, syn-sedimentary folding, and syn-sedimentary fault slips.

rocks aside. The veins could have been formed as a result of the opening of fracture due to exhumation and later filling of quartz minerals. Veins are late injections in the pre-existing rocks of igneous origin. They could be a good prospect for gold and other precious metals exploration.

5.5. Conceptual Model

The Kirana Hills in Pakistan are the extension of the Malani Volcanic Basin of India [19]. A unique set of sedimentary structures are recognized in the Neoproterozoic Sharaban Formation, Kirana Hills. These

SSDs apart from the primary sedimentary structures need some extraordinary conditions to develop. These could be linked to the tectonic and subsequent seismic activities in the region. As suggested by previous works [19] the release of stresses of Aravalli orogeny resulted in an extension in the western parts of the Indian plate, while extension in the east [19]. The syn-rift faulting and formations of the mini–basins indicate the creation of accommodations space in the basins. The SSDs can also be linked to seismic activities [8] with a sudden release of stresses in the region of Kirana Malani Basin. As caused by earthquake waves as one of the triggering mechanisms of SSDs [8–19]. The authors [8] while working on sediments of similar age in the same Kirana Malani Basin has suggested that these structures require an earthquake of ≥5 based on studies by to produce involving folds and faults associated with liquefaction and fluidization of the sediments.

The following stages are proposed for the development of SSDs in the Sharaban Formation (Fig. 9):

• Stage 1 – Deposition – It involves the deposition of coarse-grained non-cohesive sediments on cohesive fine-grained sediments.

• Stage 2 – Deformation I – It represents the stage of downslope movement of sediments due to some tectonic activity or sudden seismic event. It results in the convolution of sediments and the creation of synsedimentary deformation structures like fault slips and sedimentary folding.

• Stage 3 – Deformation II – The terminal stage involves the enveloping of coarse-grained sediments in the fine-grained more cohesive sediments.

As the SSDs occur in the metasandstone layers, hence the layers need strong energy like earthquakes or seismic waves to produce at such stratigraphic levels. This study and model could aid in understanding the basin evolution of the Pakistan part of the Kirana Malani Basin. As these Neoproterozoic rocks (including Sharaban Formation) are basement and underlie the Petroliferous Indus Basin [8–10].

6. CONCLUSIONS

A very distinct set of sedimentary structures are preserved and recognized in a misunderstood metamorphic formation of the Kirana Group. Sedimentary structures are present in all lithologies and indicate a complete set of interesting phenomena happening throughout their deposition. Primary sedimentary structures indicate depositional conditions from fluvial braided to turbidity conditions. However, the SSDs indicate the presence of liquefaction and fluidized cohesive sediment flow and the formation of various sedimentary structures like load cast and flame structures. The triggering mechanism of these SSDs could be the tectonic processes and the seismic waves or seismities. The restriction of these SSDs to specific layers indicates sudden tectonic movements and earthquakes which can be dated and linked to regional tectonics. Other than the SSDs and primary sedimentary structures the brittle deformation structures like fractures, veins and dykes are also present and indicate multiple stress directions and the presence of active volcanic /magmatic activity during the evolution of the Sharaban Formation. This could further enhance our understanding of the sparsely studied larger Kirana–Malani volcanic province and basin. This paper could help in understanding the SSDs in lesser explored Neoproterozoic successions.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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