Sedimentological and provenance analysis of the Cambrian succession in the Saiduwali Section, Trans Indus ranges, Pakistan

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ABSTRACT

The Cambrian Khewra, Kussak, and Jutana Formations from the Saiduwali section, Chashma, Dera Ismael Khan, have been studied in detail in order to investigate the sedimentology including lithofacies changes and provenance analysis to predict the depositional environment and source area of the Cambrian sequence. Based on field investigation, total 15 lithofacies were identified based on the lithological variation in the Cambrian Succession. For the purpose of comprehensive petrographic and provenance studies, field samples were also collected from the Saiduwali section. The studied formations are 190–210 metres thick and consist mainly of fine to coarse-grained sandstone, with minor siltstone, mudstone (claystone, shale), and dolomite. The uppermost beds of the Khewra Sandstone also consist of glauconitic sandstone. The sedimentological investigation shows that the depositional environment for the Khewra sandstone was a tidal environment (inter to shallow/subtidal), for the Kussak Formation restricted to marine, and for the Jutana formation supratidal to the intertidal depositional environment are suggested. Sandstone's petrographic composition reveals the existence of mono- and poly-crystalline quartz, less feldspar, heavy minerals including hematite and magnetite, and glauconite in trace proportions. The model classification of the Khewra Sandstone shows that, the Quartz percentage ranges from 85 to 93%, Feldspar 1 to 5%, and the percentage of lithic ranges from 0.5 to 3%. Based on these classifications the Khewra Sandstone falls in the Quartz Arenite Category. The model classification of the Kussak Formation shows that, the Quartz percentage ranges from 80 to 90%, Feldspar 2 to 5%, and the percentage of lithic ranges from 0.5 to 5%. Which shows that the Kussak Formation fall in the Quartz Arenite Category. The source area for Khewra Sandstone, and Kussak

Formation was cratonic interior of Indian shield. In the Jutana Formation, the clastic sedimentation has come from the foreign basin (mostly igneous, and sedimentary rocks). These sediments may be derived from the Cambrian Sea, which was near to the source. In conclusion, the palaeogeographic context reveals that the Aravalli and Malani ranges were the source area for the Khewra Sandstone and Kussak Formation.

Keywords: Lithofacies, Cambrian sequence, provenance, Trans Indus Range, Pakistan.

1. INTRODUCTION

Reconstructing the old sedimentary environments requires evaluating sedimentary facies, facies associations, sedimentary structures, and different types of trace fossil assemblages. However, this can be accomplished. It is possible to determine the depositional environment based on the lithofacies. When attempting to characterised and describe formations, it is necessary to conduct research into the physical, chemical, and biological properties that are responsible for the formation of sedimentary facies (Boggs, 2006). These properties include specific textural and compositional properties, for example. The many types of sedimentary structures that have been identified within the Khewra, Kussak, and Jutana Formations, which range in size from very large (in metres) to very small (in metres), can be broken down as follows: (centimeters). It is possible to evaluate the various types of depositional conditions based on the structures of the sedimentary rocks that have been laid down. The interpretation of palaeocurrents can benefit greatly from the presence of these structures. With the aid of these sedimentary formations (Ghazi, 2009; Ghazi and Mountney, 2011), it is possible to reconstruct the paleoenvironmental conditions that prevailed during the creation of the formation. But if the depositional environment was very specific or not clear (Khan et al., 2021) it is important to look at many different parts of the formation, not just the facies.

The Khewra Sandstone, Kussak Formation, and Jutana Formation are all parts of the Cambrian strata that can be found in Pakistan's Salt Range and Khisor Range. The greatest exposures of these rocks can be found in the eastern half of the country (Noetling, 1894; Ghazi & Mountney, 2011; Hughes et al., 2019). The depositional pattern of the Cambrian sequence could have been caused by significant tectonic movement(s) linked to a massive tectonic upheaval that affected the entire Indian subcontinent (Valdiya, 1995).The Tethyan Ocean's arm that ran along the northern edge of the Indian Plate was where the Palaeozoic period's sedimentation processes got underway. The Salt Range region was located in an area of the Tethys Sea that had a marginal marine environment (Searle, 1986; Ghazi et al., 2020). The Khewra Sandstone, the Kussak Formation, the Jutana Formation, and the Baghanwala Formation are the several parts of the Cambrian sequence that may be found in the Salt Range.

Glauconite is a piece of evidence that points to a maritime environment, and the Khewra, Kussak, and Jutana Formations that have been researched all contain it. Khewra is an example of an open environment that is oxygenating and has a dry climate, in contrast to the organic-rich Kussak Formation, which exhibits a reducing and humid environment. This shift in the environment also demonstrates transgression during the period of time when the Kussak Formation was being deposited and regression during the period when the Khewra Formation was being deposited (Ahmad et al., 2013; Ghazi et al., 2020). Dolomites of the Jutana Formation are typically medium to fine-grained and have the highest ability to preserve the formation's original characteristics. These dolomites originate in semi-arid locations on high intratidal to supratidal flats (Lindholm, 2012; Ahmad et al., 2013; Ghazi et al., 2020). Dolomite of the Jutana Formation is thought to have originated from a primary source due to the very fine to medium grain size of the dolomite crystals and syndepositional sedimentary features such as herringbone-, trough-, and hummocky cross beds (Boggs, 2012; Ahmad et al., 2013). Furthermore, there are few research on the sedimentology and depositional environment of the Formations. So, in this work, we examine the sedimentology, composition, and

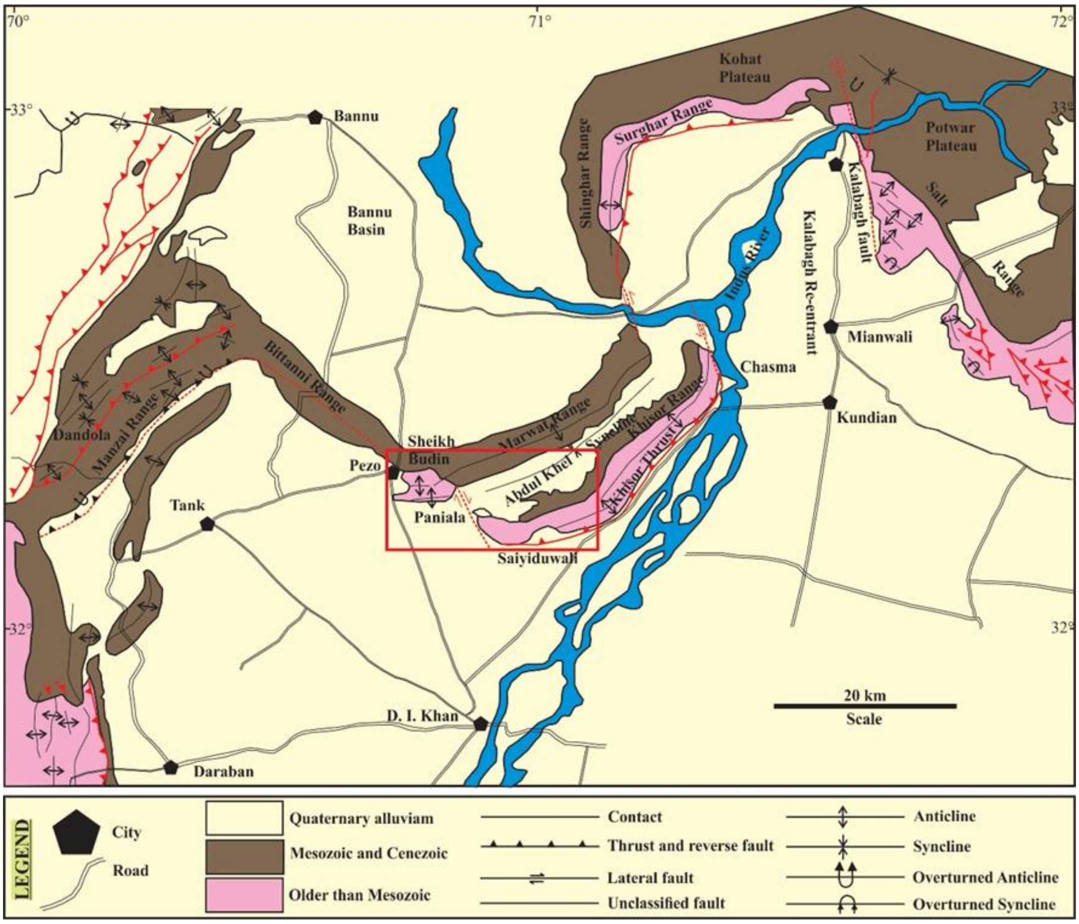

Figure 1 Geological map of the Trans Indus Range, North Pakistan, and insert show the location of the outcrop study area (modified from Powell 1979; Kazmi and Rana 1982).

provenance of the Cambrian sequence. Petrographic and lithofacies investigations were also performed to ascertain palaeo-geography and palaeo-climate. The Saiduwali Section, Trans Indus Ranges, was used to conduct measurements of the Cambrian Succession (Khewra, Kussak, Jutana), and this article evaluates the petrographic analysis and procedures used to recognise the depositional environment, provenance analysis, and vertical lithological profiling (Fig. 1). A litho-facies analysis was performed for the Cambrian Succession using an updated version of the Miall facies schemes (Miall, 1985; 1996).

Stratigraphically, the base of the Saiduwali section is comprised of the Khisor Formation (Fig. 2). The Khewra Sandstone consists of brown, grey, and purple fine-grained, medium-to-thick-bedded sandstone. The upper part of the formation contains light-gray coloured glauconitic sandstone, which is hard and compact (Fig. 2). The sandstone is quartzose and cross-laminated. The upper contact is marked with the conglomerate bed about 1 metre thick with the Kussak Formation, and the thickness of the Khewra Sandstone is +137 metres as its base is not exposed. The Kussak Formation at the Saiduwali Section is represented by whitish-grey coloured, medium to fine-grained, and medium-bedded sandstone which is highly cross-laminated (Figs. 2). Its thickness was measured at about 30 m. The Kussak

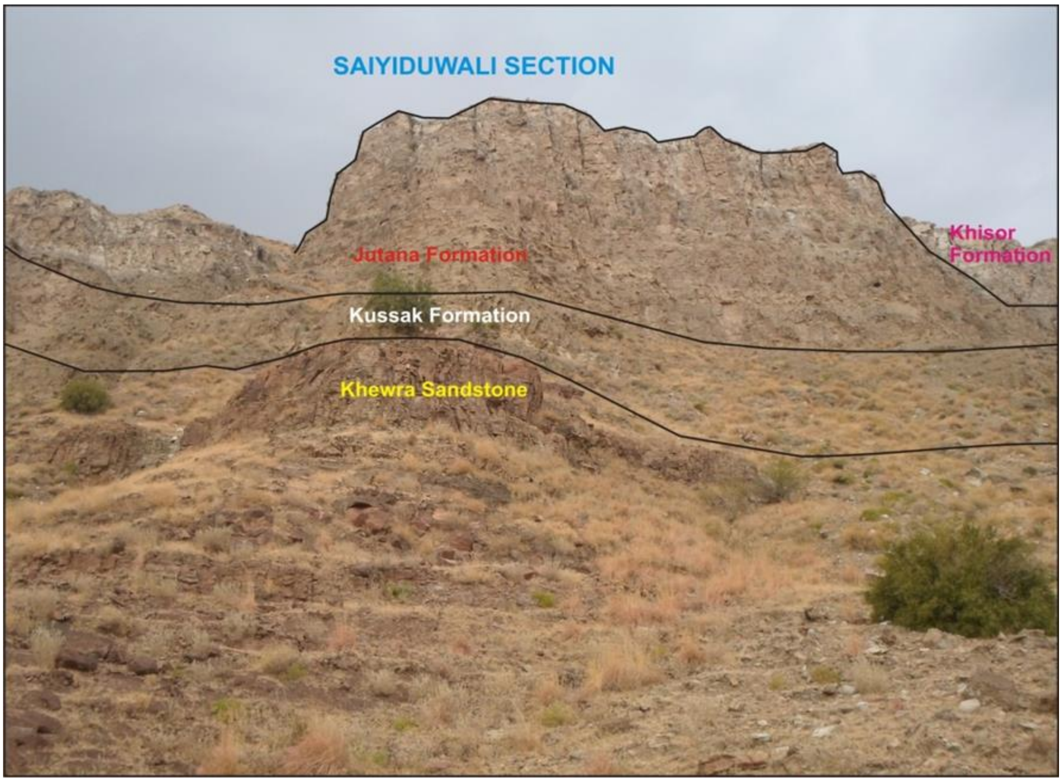

Figure 2 contact between Khewra Sandstone, Kussak Formation and Jutana Formation at Saiduwali section, Khisor Range.

Cambrian Jhelum group, including; a) Khewra, b) Kussak, c) Jutana, and d) formation has wavy, flaring, and hummocky crossbedding. In these parts, the Kussak Formation makes erosional lower contact with the Khewra Sandstone's thin conglomerate layer. In Khewra Gorge and Karuli Road Section, the top contact is conformable with the Cambrian Jutana Formation, whereas in Nilawahan Gorge, it is unconformable with the Permian Tobra Formation (Ghazi et al., 2020). The Jutana Formation mainly consists of dolomite. At the base, sandy dolomite is exposed, which is about 1.830m thick, overlain by the marly bed (5.3m), and then massive dolomite (Fig. 2).

The dolomite is hard and resistant to erosion. The thickness of the Jutana Formation is 40 m. The Kussak and Baghanwala Formation contacts are conformable. In locations where the Tobra Formation unconformably overlies the Jutana, sandy dolomite changes to conglomerate (Ahmad et al., 2013). The Jutana Formation is characterised by trough-, herringbone-, and hummocky-cross bedding and parallel stylolite. Above the shale, fine-grained dolomite becomes dolomitic sandstone. Dolomites are white or pale green in color, hard, micaceous, sandy, and glauconitic. The sandstones are fine-grained, dolomitic, silty, and glauconitic. Greenish-gray, glauconitic, micaceous shale.

2. GEOLOGICAL SETTING

The project region is in northwest Pakistan's Trans-Indus mountains. Surghar-Shinghar, Marwat-Khisor, Sheikh Badin Hills, Bhittani, and Manzai are the mountains that reveal an "S" shaped double re-entrant and set the Bannu Basin. (Fig. 1). These ranges were developed by progressive south-directive decollement-related thrusting of the Indian Plate crust's sedimentary cover sequence in the western portion of the Northwestern Himalayan foreland fold and thrust belt as a result of the continuing collision between India and the Eurasian plates (Alam, 2008; Khan et al., 2021). During many tectonic events from the Late Cretaceous to the early Tertiary, deformation spread southward (Weils. and Coleman, 1984; Yeats and Hussain, 1987; Smith et al., 1994; Beck et al., 1995). The most recent thrusting has occurred in the south, following a frontal thrust system that runs parallel to the Trans-Indus Mountains (Khan et al., 1988), (Fig. 1).

The Bannu Basin in the north, the Dera Ismail Khan Lowlands in the south, the Indus River in the southeast, and the Bhittani Range in the northwest define the Marwat-Khisor ranges and Sheikh Badin hills (Alam, 2008; Fig. 1). The valley's relief varies from 200 metres to 1300 metres at Kingriali Mountain. The Marwat-Khisor ranges go from Dara Tang in the east to Paniala in the west, with the Kundal strike-slip fault running through them. The Siwalik rock group is exposed by the Marwat Range, which is a giant anticlinal fold. In the core of the Marwat Anticline, the older Nagri Formation of the Siwaliks group is exposed. The Khisor Range is to the south of the Marwat Range. It has a structural trend from east to northeast, with Cambrian to Jurassic rocks that don't show at the surface under the Bannu Basin and the Marwat Range (Lillie et al., 1998).

The Jhelum Group rocks of Cambrian age are separated at the foot of these ranges, which are structurally composed of parallel to En-echelon fold trends. The Khisor Range was formed when Cambrian to Plio-Pleistocene rocks were forced southwards over the Punjab Foreland along the Khisor Frontal Thrust (KFT). The KFT is most likely the Salt Range Thrust's western extension (Gee and Gee, 1989). The Khisor Range and Sheikh Badin hills are primarily underlain by Cambrian to Jurassic shallow to deep marine lithologies, which are unconformably overlain by Plio-Pleistocene sediments of the Siwalik Group rocks (Fig. 1). The stratigraphy of Khisor and Sheikh Badin Hill is largely consistent with that of the Eastern Salt Range, except for the Miocene Rawalpindi group.

3. MATERIAL AND METHODS

In the Khisor southwest direction, the Saiduwali section is located, on the Indus Canal's right side. From the Saiduwali village, towards the northwest direction, the study area is located and easily accessible from the Chashma, Dera Ismael Khan Road. This section was a way to obtain the Lithofacies identification for provenance analysis through interpreting the Cambrian geology. This Cambrian geology is only preserved in this section (Fig. 1).

Extensive field work was carried out to identify the different facies in the formation. A total of 15 lithofacies were identified in the Cambrian Succession (5 from each formation) based on the lithological variation. During the field work, thorough mapping of the formation has been carried out and a detailed lithological log was created to summarize the formation characteristics. For the purpose of comprehensive petrographic studies, field samples were collected from the Saiduwali section. A total of 21 samples were collected. The thin sections were prepared from these samples and were studied under a microscope by the point counting method with a division into 400 point counts per section. Microsoft Excel was used for the statistical analysis of the data. The QmFLt and QFL diagrams were used to identify the composition and classification as well as the suggested provenance areas for the studied samples from the formation.

4. RESULTS

4.1 Lithofacies analysis

The lithofacies description of each Cambrian Formation is given below;

4.1.1 Lithofacies interpretation of the Khewra Sandstone

The main lithological constituents which make up the Khewra Sandstone are sandstone, shale, claystone, and siltstone. The sandstone is fine to coarse-grained and contributes the main lithology of the formation. All other lithologies contribute as minor constituents. For the Khewra sandstone, lithofacies interpretation has been done and identified five lithofacies (Figs. 3-5). The different types of sedimentary structures that have been recorded within the Khewra Sandstone are i) depositional sedimentary structures; containing cross bedding, laminations, ripple marks, cross ripple lamination, flaser, wavy and lenticular bedding, ii) deformational sedimentary structures; flame, ball and pillow, iii) erosional sedimentary structures; channels, iv) biogenic and origin sedimentary structures, including trace fossils, mud cracks and syneresis.

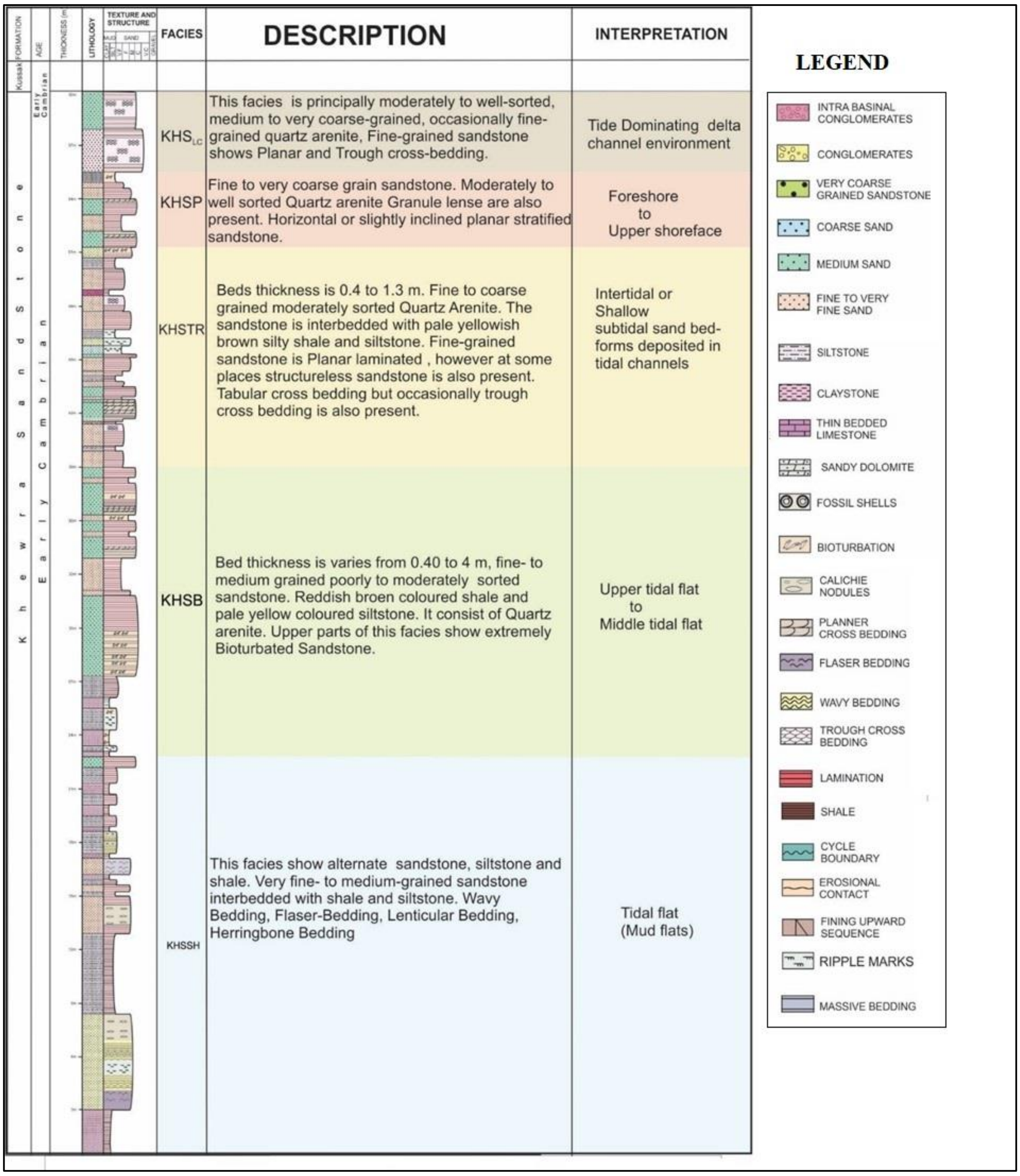

Figure 3 Sedimentological log of the Khewra Sandstone, Saiduwali area, Khisor Range, Pakistan.

4.1.2 Lithofacies interpretation of the Kussak Formation

For the Kussak Formation, 5 lithofacies are identified, (Figs. 6 & 7). Sedimentary structures that were recorded during the fieldwork included; Cross Bedding, Ripple Marks, Flaser Bedding, Concretion (Iron), Mud Cracks, Secondary Cracks, Wavy Bedding,

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amalgamation surfaces, and bioturbation (ichnofacies).

(Reading, 1996). The thickness of the middle unit is about four meters. The main lithology of this unit is shale, in

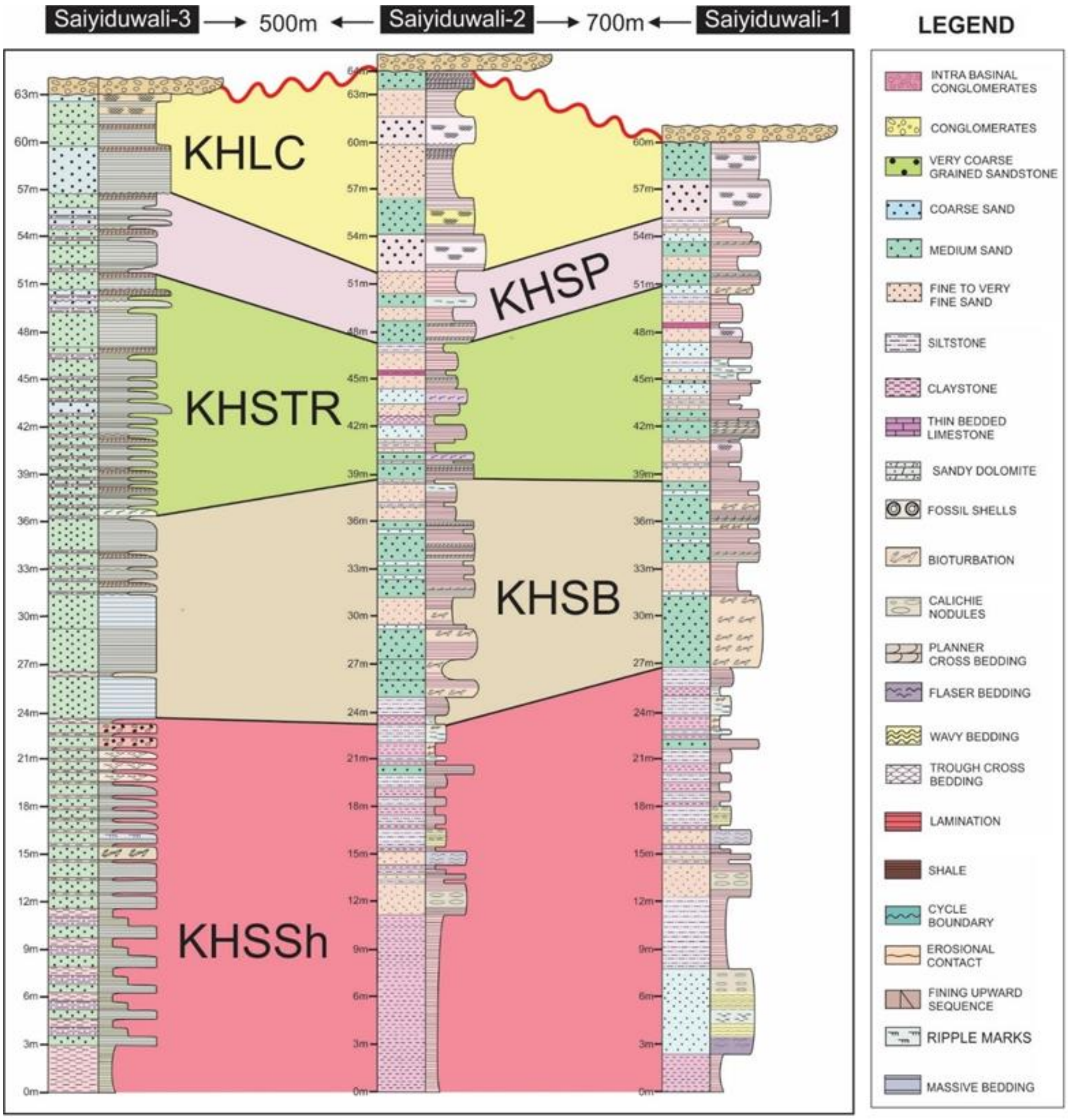

Figure 4 Correlation panel of the Khewra Sandstone from the Saiduwali area, Khisor Range, Pakistan.

4.1.3 Lithofacies Interpretation of the Jutana Formation

Based on the lithological composition, the Jutana Formation is grouped into 3 units separated by a thin shale bed; upper dolomite, middle shale, and lower dolomite (Figs. 8, & 9). The thickness of this unit is about six metres which the base consists of siltstone interbeds, then glauconitic sandstone developed above the sandstone and siltstone of maroon colour (Reading, 1996). The thickness of the upper unit is about ten meters, making it the thickest of all the units of the Jutana Formation. The dolomite of this unit has massive and hard

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beds. For the Jutana Formation, 5 lithofacies are identified (Figs. 8 & 9).

4.5 Petrographic analysis

4.5.1 Petrographic analysis of the Khewra Sandstone

For the petrographic analysis of the Khewra Sandstone, thin sections were made. For these analyses, a total of seven rock samples were selected, and then these rock samples were converted into thin sections. These thin sections were then analysed with the help of a petrographic microscope to interpret the main detrital components. The studied thin sections are named KSF-1, KSF-2, KSF-3, KSF-4, KSF-5, KSF-6, and KSF-7.

The sandstone samples selected for these thin sections were very fine-to course-grained. The model composition analyses were carried out to find out the percentages of each detrital mineral in sandstone. In these thin sections, the quartz is dominant in the detrital composition, which constitutes about 85% to 93% (Fig. 10 a-d). Feldspar

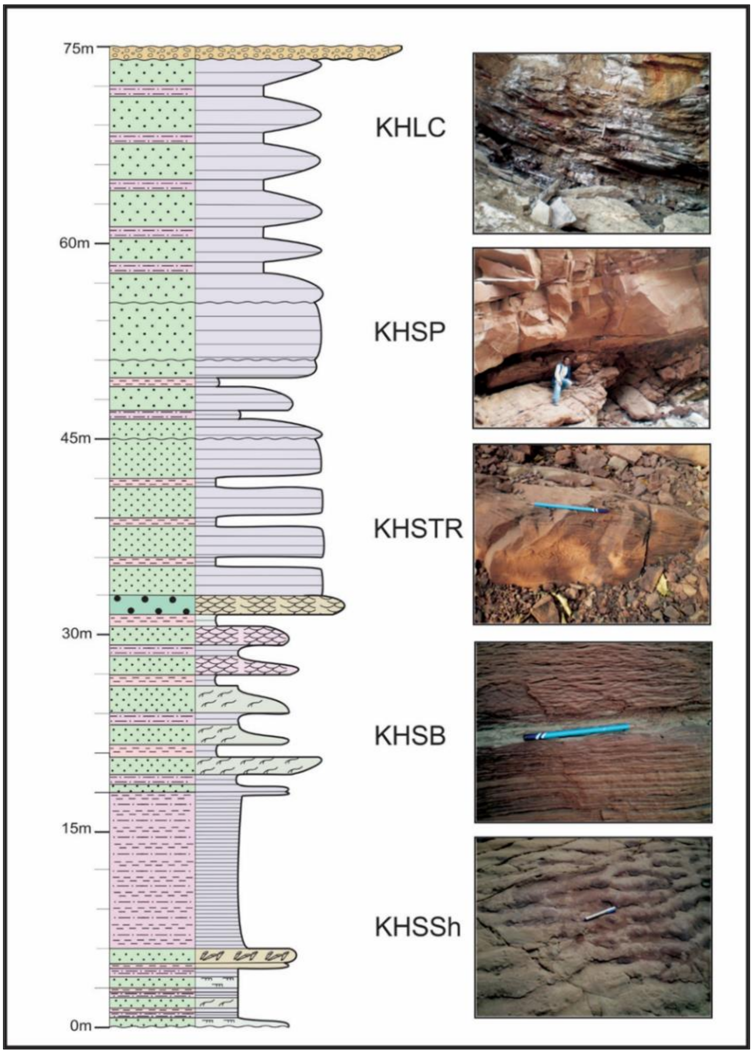

Figure 5 The representative sedimentological log of the Khewra Sandstone showing relationship of lithofacies, Saiduwali Khisor Range, Pakistan.

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makes up 1% to 5% of the total percentage, lithic fragments make up 0.5% to 3.0%, and mica makes up 0.8% to 3% of the total detrital composition. The remaining composition of these thin sections is a matrix (clay and silica type), which makes up 3 to 7%.

The quartz grains have two types: monocrystalline (most of the grains), and polycrystalline (less). These quartz grains show intermediate roundness and

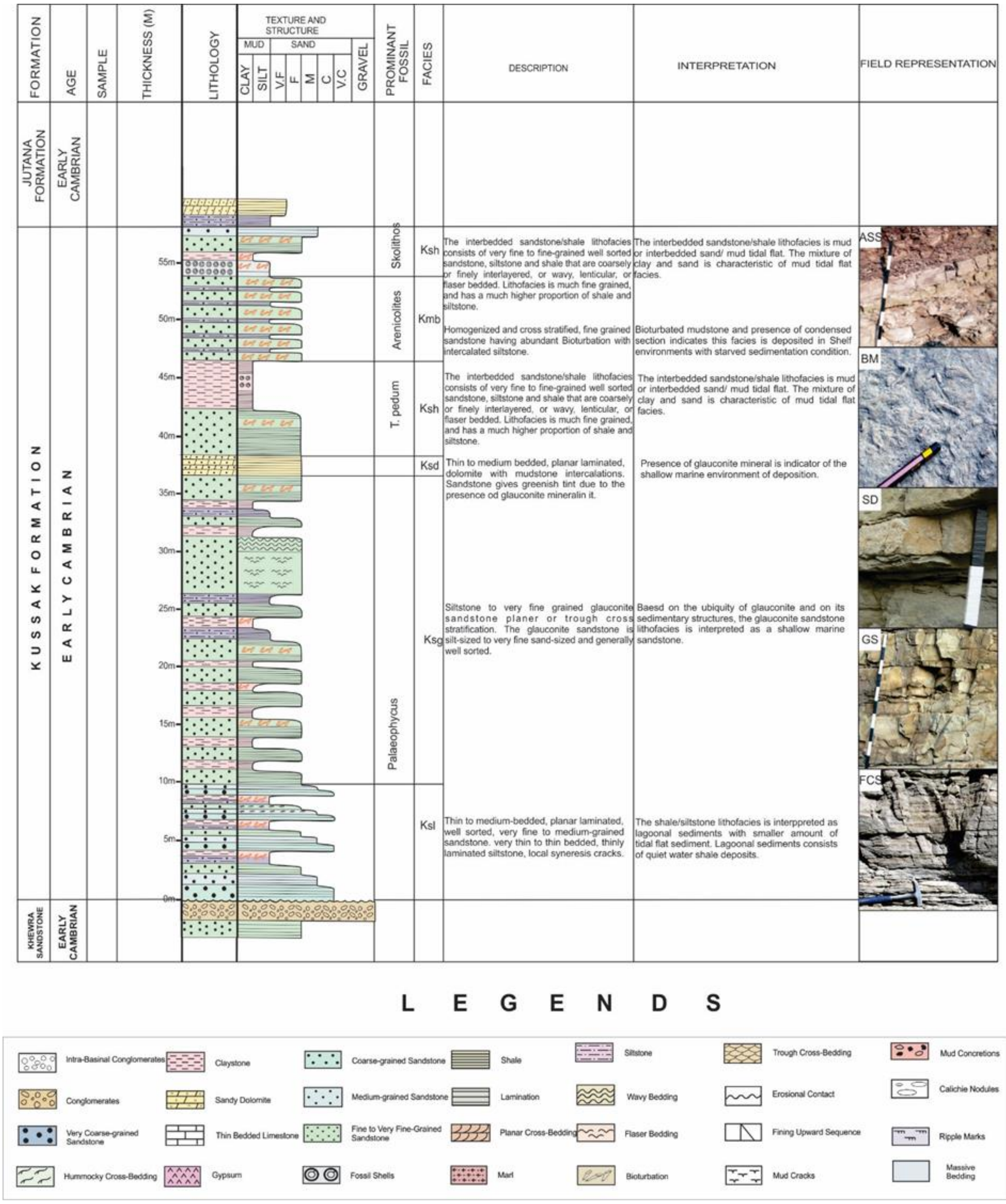

Figure 6 Sedimentological log of the Kussak Formation, Saiduwali area, Khisor Range, Pakistan.

angularity (sub rounded to sub angular), and have mostly tangential and concave, convex, suture, and point type contacts between the grains.

The cement types observed here are siliceous and hematinic. Undulate extinction was also recorded in these thin sections, which also shows that all the samples were poorly sorted. The ferruginous, siliceous, and calcareous minerals also contribute to mass, but very low concentrations were recorded (Fig. 10 a-d). The model classification of the Khewra Sandstone was adopted from the petrographic analysis. The percentages of each sandstone grain are counted and identified, in which the quartz percentage ranges from 85 to 93 percent, feldspar one to five percent, and the percentage of lithic ranges from 0.5 to 3 percent. These interpreted values for the detrital grains were then plotted on the QFL diagram of Pettijohn (1975) and Folk (1974) (Fig. 11). Based on these classifications, the sandstone sample of the Khewra Formation falls into the Quartz Arenite Category.

4.5.2 Petrographic Analysis of the Kussak Formation

For the petrographic analysis of the Kussak Formation, thin sections were made. For these analyses, a total of five rock samples were selected, and then these rock samples were converted into thin sections. These thin sections were then analysed with the help of a petrographic microscope to interpret the main detrital components. The studied thin sections are named KFF-1, KFF-2, KFF-3, KFF-4, and KFF-5.

The sandstone samples selected for these thin-sections are fine-to-coarse-grained. The model composition analyses were carried out to find out the percentages of each detrital mineral in sandstone. The quartz dominates the detrital composition in these thin sections, accounting for 80 to 90 percent of the total. The feldspar (orthoclase, plagioclase, and microcline) constitute about 2 to 5 percent of the total percentage. The contribution from lithic fragments is 0.5 to 5%. Mica and hematite (accessory minerals) add 2 to 3% to the total detrital composition. The remaining composition of the thin-sections is the matrix (clay type), which makes up 2.5 to 8% (Fig. 10 e-g). The quartz grains have two types: monocrystalline (most of the grains), and polycrystalline (less). These quartz grains show intermediate roundness and angularity (subrounded to subangular) and have mostly concave, convex, suture type, and point contacts between the grains. The cement types observed here are hematite and siliceous materials. Undulate extinction was also recorded in these thin-sections, which also shows that the sample is poorly to moderately sorted. The calcite, silica, clays, and ferruginous minerals also contribute to the cementing mass but at a very low concentration (Fig. 10 e-g). The model classification of the Kussak Formation was adopted from the petrographic analysis. The percentages of each sandstone grain are counted and identified, in which the quartz percentage ranges from 80 to 90 percent, feldspar two to five percent, and the percentage of lithic ranges from 0.5 to 5 percent. These interpreted values for the detrital grains were then plotted on the QFL diagram of Pettijohn (1975) and Folk (1974) (Fig. 11). Based on these classifications, the sandstone samples of the Kussak Formation fall into the Quartz Arenite Category.

Formation shows continuous alteration. In this, coarse-grained sedimentation is very important in areas that have sandy dolomite lithology. A petrographic analysis was done on these lithologies to interpret their mineralogical composition.

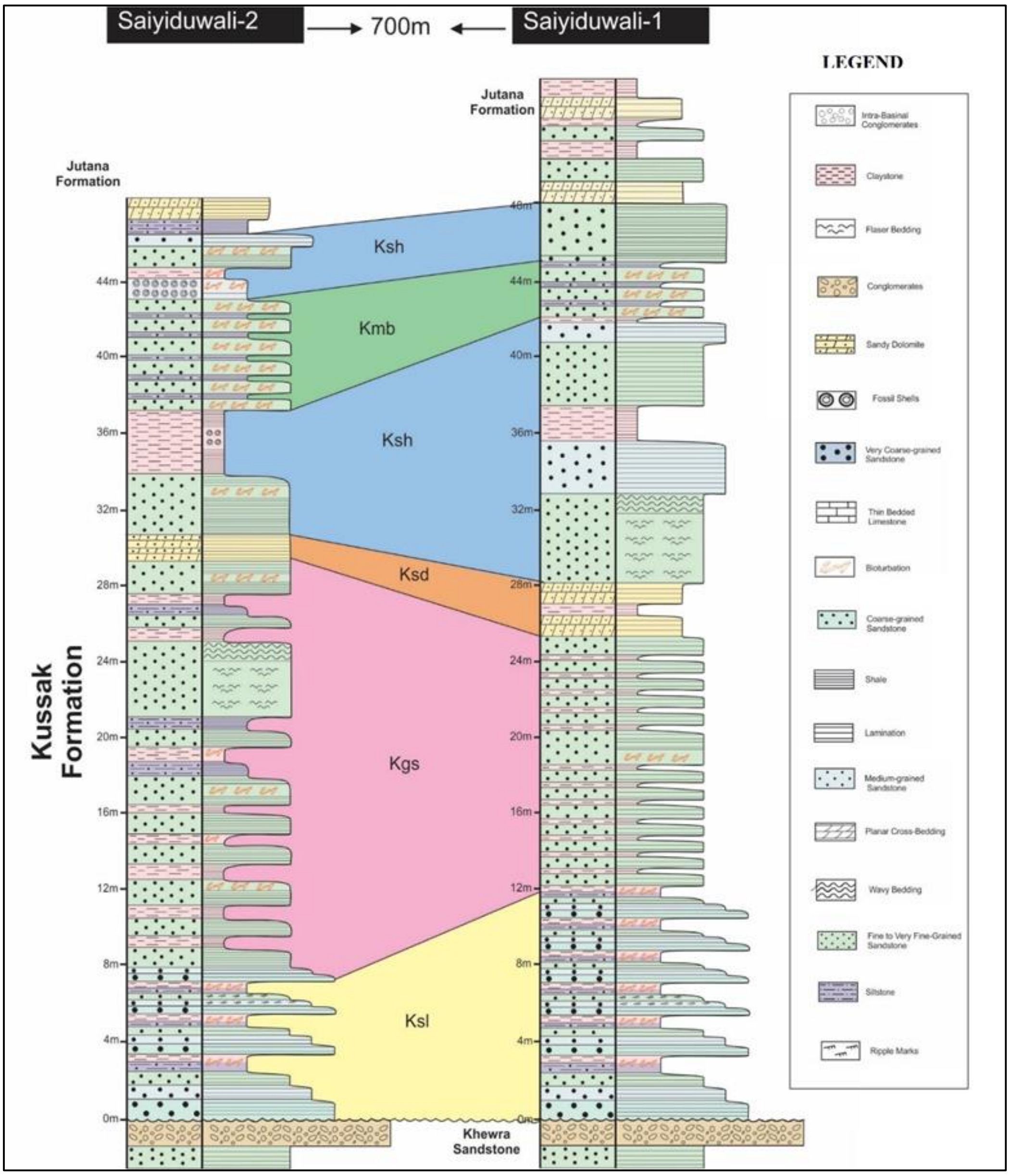

Figure 7 Correlation panel of the Kussak Formation, Saiduwali area, Khisor Range, Pakistan.

4.5.3 Petrographic Analysis of the Jutana Formation

The fine and coarse-grained sedimentation observed in the Jutana

The sample selected for this thin section is medium to coarse-grained. The model composition analyses were carried out to find out the percentages of each mineral in a thin section. The sand grain found in the sample is mostly monocrystalline quartz. The other mineral constituents are dolomite, dominating the composition, adding about 70 to 76% to the total mass, quartz (mostly monocrystalline), 13 to 15%, and other accessory minerals like biotite and muscovite, contributing 7 to 9% (Fig. 10 h-l). Sorted moderately to poorly in various locations of the Jutana

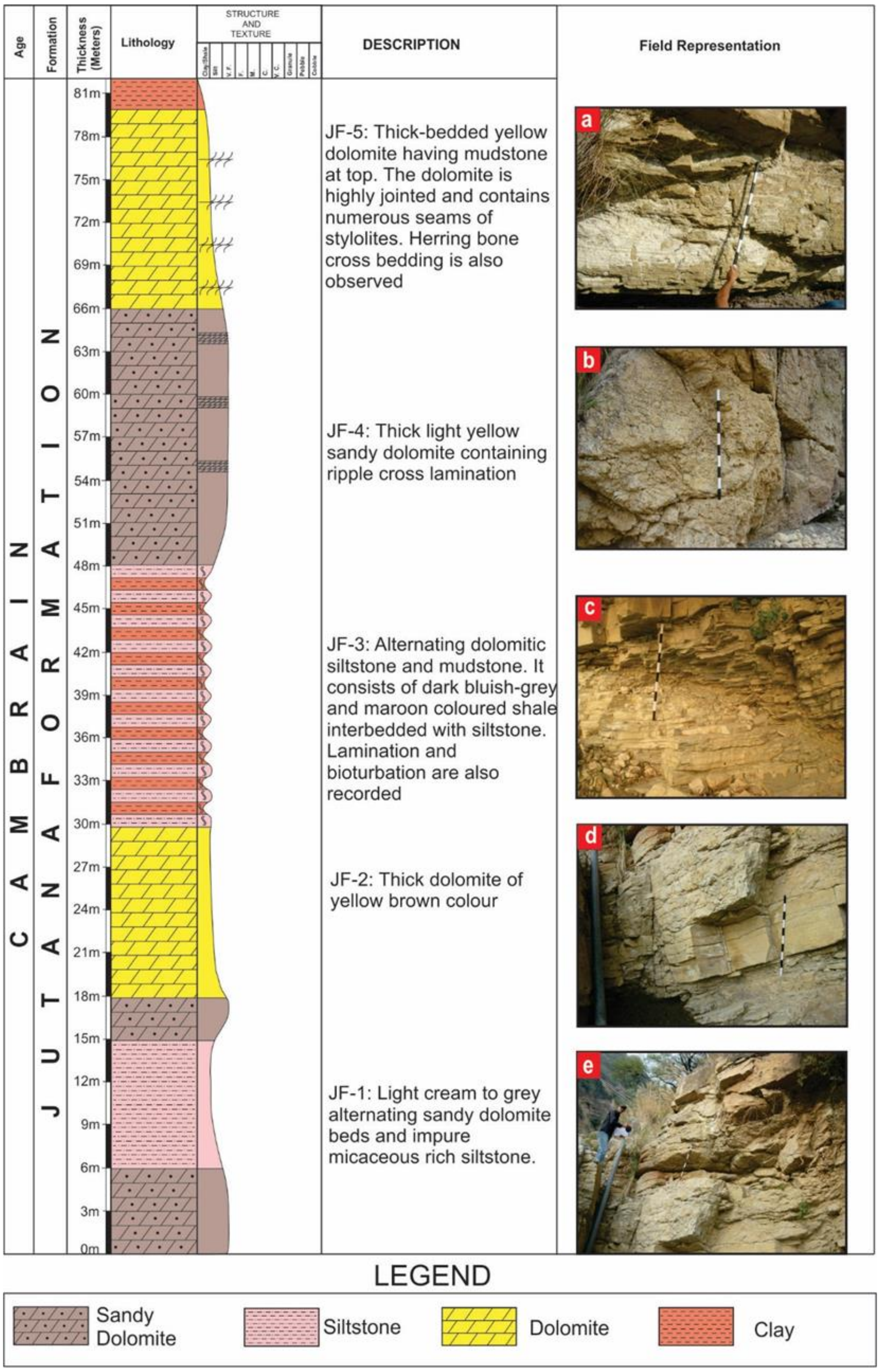

Figure 8 Sedimentological log of the Juatana Formation from the Saiduwali section, Khisor Range, Pakistan. Also showing the five major lithofacies in the Jutana Formation in the Khisor Range, Pakistan. a) Subtidal to lagoonal Sandy Dolomite alternating with Siltstone facies (JF-1) b) Subtidal to Intertidal Dolomite facies (JF-2) c) Subtidal to Lagoonal Dolomitic Siltstone and Mudstone facies (JF-3) d) Intertidal Sandy Dolomite facies (JF-4) e) Intertidal to subtidal Thick-bedded Dolomite facies (JF-5).

Formation Dolomite and quartz intraclasts (intraformational) are found abundant in sandy dolomite, and in some areas, the intraclasts are rare in dolomites (Reineck and Singh, 1973).

The matrix's main constituents are quartz, dolomite (fine-grained), lithic, and clay. And the main contributors to cement are hematite (75.0%) and ankerite (25.0%). The most abundant mineral that dominates the lithology is dolomite. The

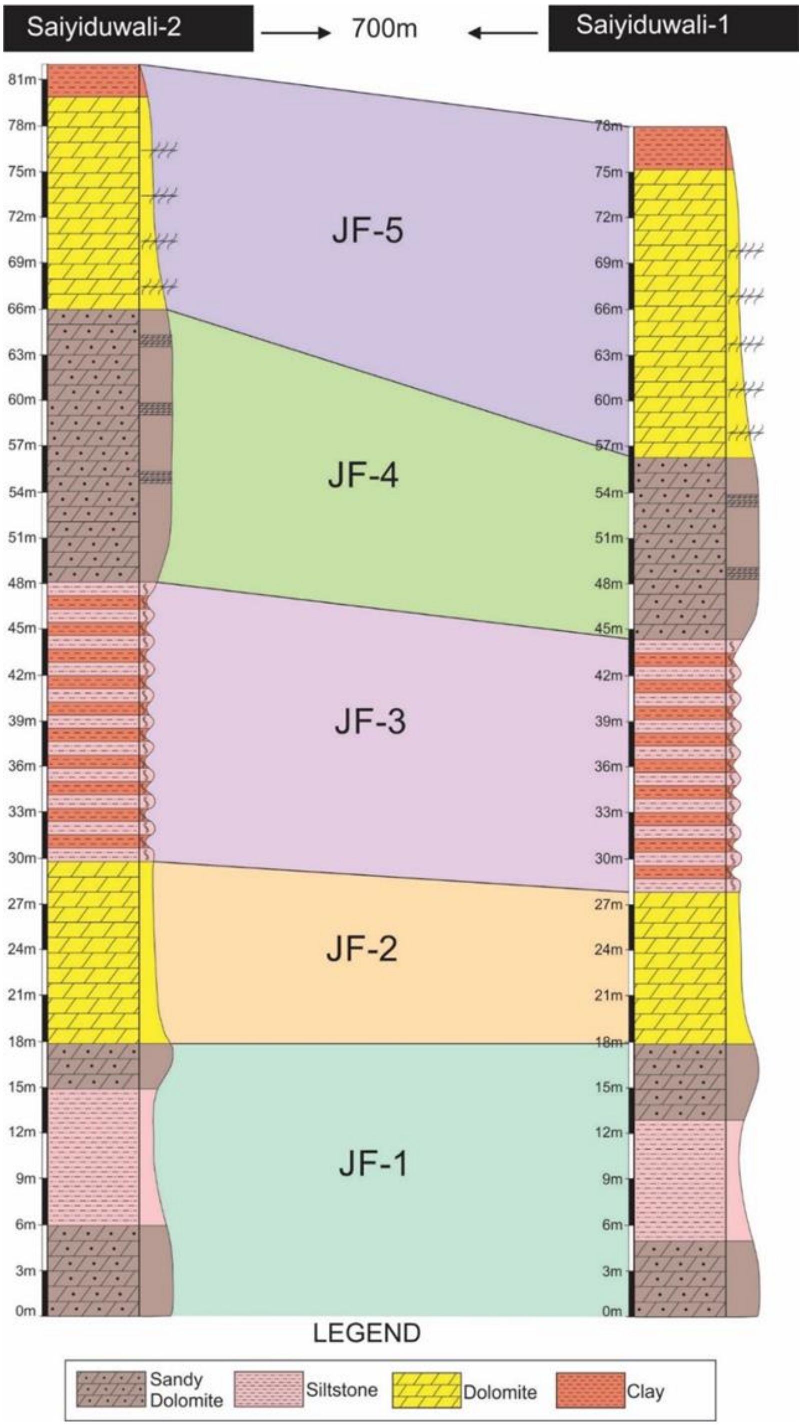

Figure 9 Correlation panel of the Jutana Formation, Saiduwali area, Khisor Range, Pakistan.

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different types of dolomite geometry that comprised the dolomite are euhedral-subhedral about 80.0%, and subhedral-anhedral about 20.0%, and the texture types that are observed here are idiotypic and xenotropic (Bosellini et al., 2003).

The mineralogical composition of the dolomite changes from fine (when quartz) to coarse-grained (without quartz) (Choquette and Hiatt, 2008). The second most abundant mineralogical constituent is quartz, which is mostly

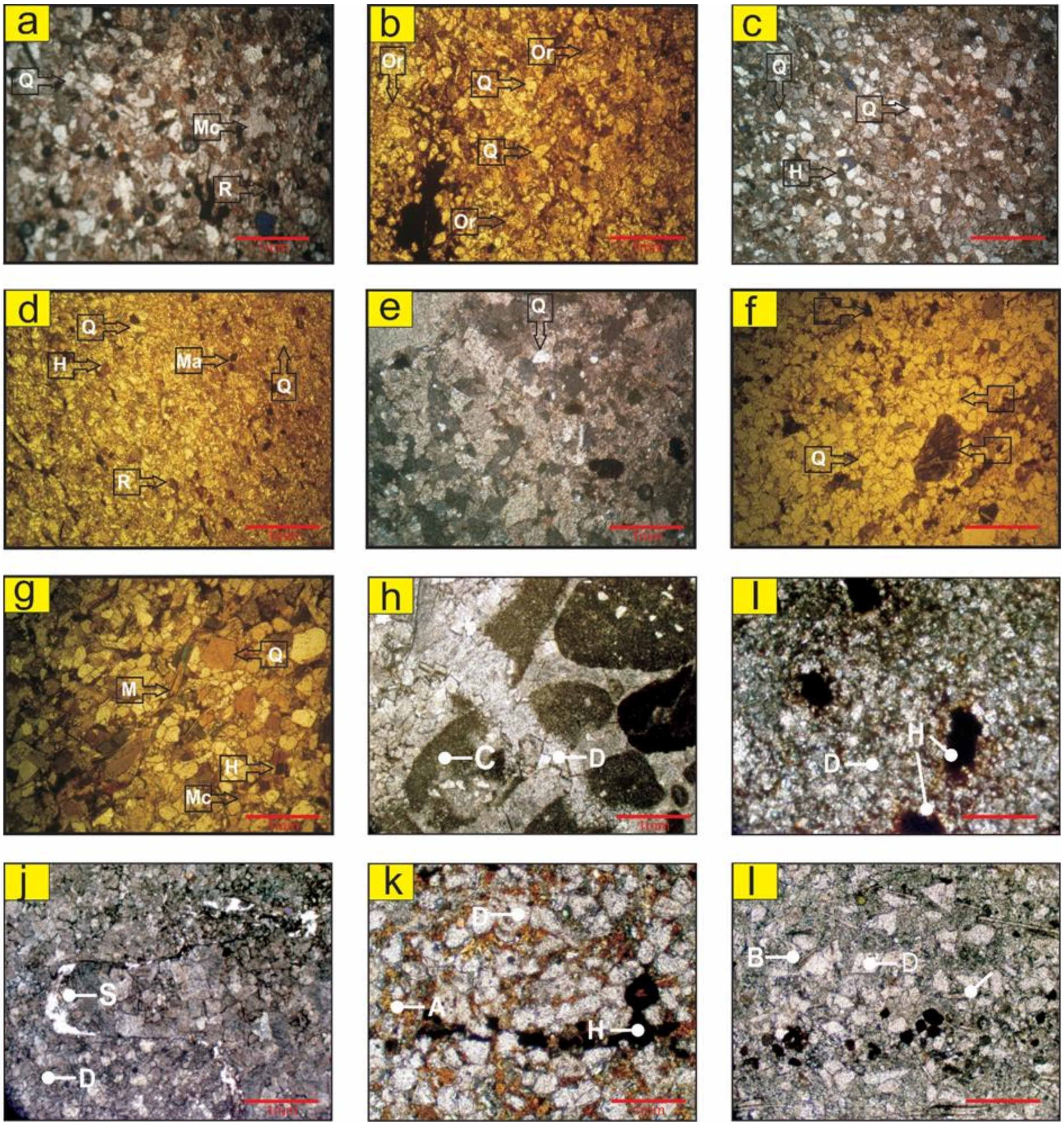

Figure 10 Microphotographs of the Khewra, Kussak, and Jutana Formation. Q: Quartz, R: Lithic Fragments, Mc: Microcline, G: Glauconite, D: Dolomite, B: Biotite, M: Muscovite, H: Hematite, S: stylolite, C: Intraclasts, A: Ankerite; (a-d) Khewra Sandstone, (e-g) Kus Microphotographs of the Khewra, Kussak, and Jutana Formation. Q: Quartz, R: Lithic Fragments, Mc: Microcline, G: Glauconite, D: Dolomite, B: Biotite, M: Muscovite, H: Hematite, S: stylolite, C: Intraclasts, A: Ankerite; (a-d) Khewra Sandstone, (e-g) Kussak Formation, (h-l) Jutana Formation Microfacies.

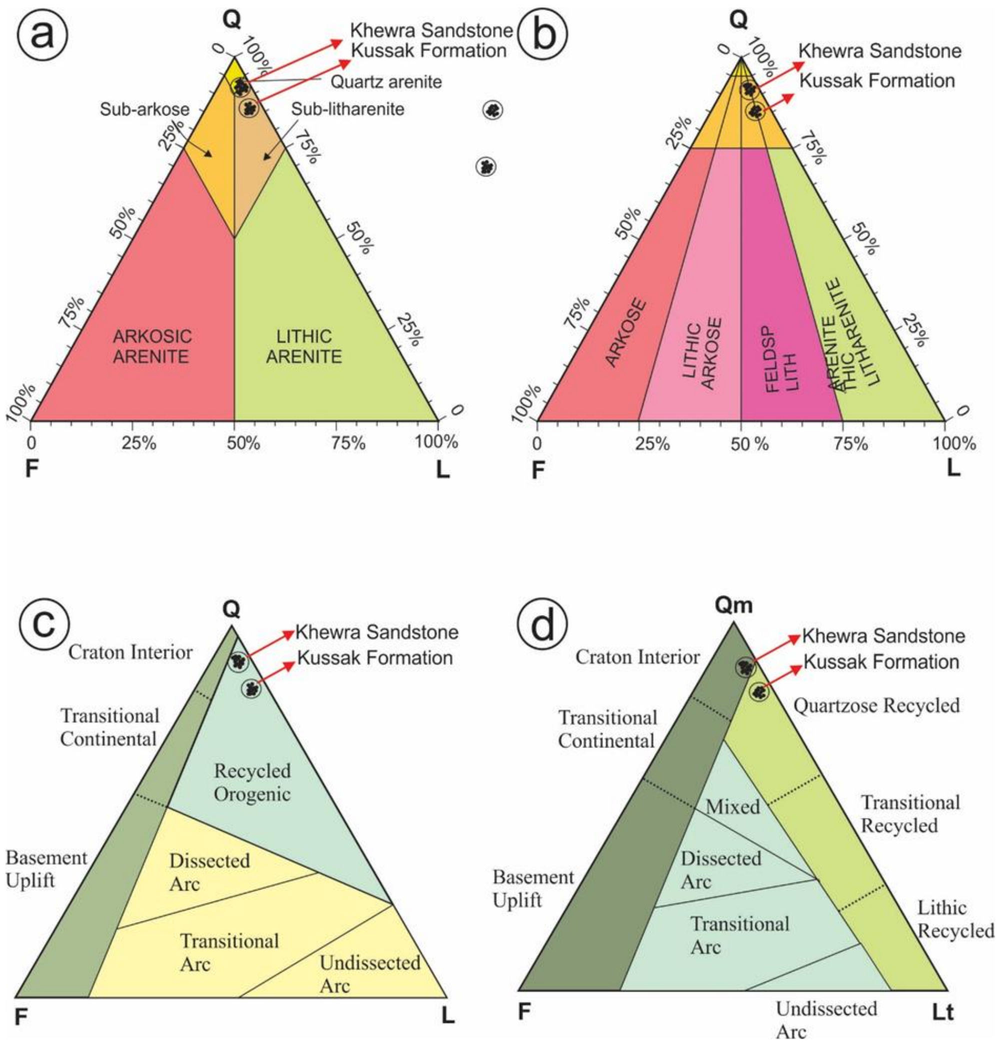

Figure 11 Interpretation of the sandstone composition from the petrography of the Khewra and Kussak Formation, showing the composition, classification as well as the suggested provenance areas for the studied thin sections. (a) QFL diagram based on the scheme of Pettijohn (1975), (b) QFL diagram based on the scheme of Folk (1980), (c and d) are modified from Dickinson and Suczek, (1979); Dickinson et al., (1983).

monocrystalline. Accessory minerals (such as mica, muscovite, and biotite) also contribute about 9% (Fig. 10 h-l).

The 3 different types of dolomite are observed from the petrographic investigation, which is pure, micaceous, and arenaceous dolomite. The most dominant dolomite that is recorded here is arenaceous dolomite (1/3 contribution), followed by the micaceous dolomite (maximum 30.0% recorded at the base), the same source of sedimentation as micas from the Kussak Formation. These micaceous components are interlaminated with arenaceous and pure dolomite content and show preferred orientation.

5. DISCUSSION

5.1 Provenance

To introduce the provenance of the sandstone, the recorded proportion of detrital grains is plotted on QFL (Quartz, Feldspar, and Lithic) and QmFL (monocrystalline quartz, feldspar, and lithic) diagrams like Dickinson and

Suczek (1979), (Fig. 11). For provenance analysis, Dickinson et al. (1983), schemes are used for interpretation of tectonic situations. Based on the QFL and QmFL diagrams of Dickinson and Suczek (1979); Dickinson et al. (1983), the source area for Khewra Sandstone and Kussak Formation was cratonic interior (Fig. 11).identification of the source area of the Cambrian sequence. The composition of sandstone and clasts showed that the source area does not change over time. The mineralogy is typical of a mature continental suit and reflects derivation from crystalline Precambrian shield complexes (Saqab et al., 2009). And through petrographic studies, we suggest the granitic composition of the source rock for the sandstone of the Kussak Formation. The source area for the sandstone of the Kussak Formation is from the cratonic interior of the Indian shield (Pervaiz et al., 2017).

Petrographical studies were conducted in order to determine where the Cambrian sequence originated. Quartz grains in the investigated formations were developed by recycling and erosion of igneous and metamorphic rocks, as evidenced by the composition of sandstone and clasts, which indicates that the source area does not change over time (Dutta, 2007). Grains exhibiting undulatory extinction, indicative of plastic deformation, indicate considerable tectonic uplift of crystalline basement rocks in the source region (Fig. 10). Mono-crystalline quartz of medium-coarse grain size (Fig. 10) is thought to have originated in granites (Dickinson 1985; Dutta, 2007; Basu et al. 1975), while fine-grained mono-crystalline quartz is thought to have formed from the breakup and re-crystallization of larger quartz grains of igneous and metamorphic origins. The metamorphically formed polycrystalline quartz-grains that are elongated and stretched (Ghazi, 2009).

Quartz grains that are formed in sedimentary environments tend to be rounded or even well-rounded (Basu et al. 1975). Feldspar fragments were indicative of igneous and metamorphic source areas, most likely acidic igneous, granite or gneiss (Ghosh and Kumar 2000; Basu et al. 1975). Micas originate in both granitic plutonic rocks and low-grade metamorphic rocks, including gneiss, schist, and quartzite (Ghazi, 2009; Ghazi and Mountney 2011).

Most of the grains in the examined formations originated in igneous and metamorphic zones, as shown by the Qm, F, and Lt diagrams of Dickinson and Suczek (1979), (Fig. 11). Quartz with rounded to well-rounded grains is sedimentary in origin (Basu et al., 1975), and may have originated from the reworking of the Pre-Cambrian sedimentary rocks. All of these points suggest that, the Aravalli system as the most likely place where the Cambrian Khewra, Kussak, and Jutana formations were originated.

5.2 Depositional setting

The depositional environment for the Khewra Sandstone in Marginal Marine was developed by a prograding sequence. During the deposition of the Khewra Sandstone, clastic sediments accumulated mainly in tidal-marginal marine and delta areas. Due to the reworking of strong wave action in the tidal environment (inter to shallow/subtidal), the deposition for this formation is delta-like (Fig. 12). In the absence of barrier bars, tidal flats are formed during the prograding episode. These all show moderate to low energy environments and show high deposition of sediments (Beale, 1990).

Sedimentary structures are the most ubiquitous features of the Khewra Sandstone that were used to infer the proper depositional environment. Khewra Sandstone's abundant very fine to coarse sandstone with massive beds, as well as its planner cross bedding, laminations, and bioturbation, are all indicative of storm reworking sediments, high-density, unidirectional flows, and suspension settling (Khan et al., 2021; Ghazi and Mountney, 2011), (Fig. 12). The Khewra Sandstone was deposited by storm reworking and suspension sedimentation and through traction movement, yielding trough cross bedding, lamination, parallel laminated sandstone strata, and sandstone with

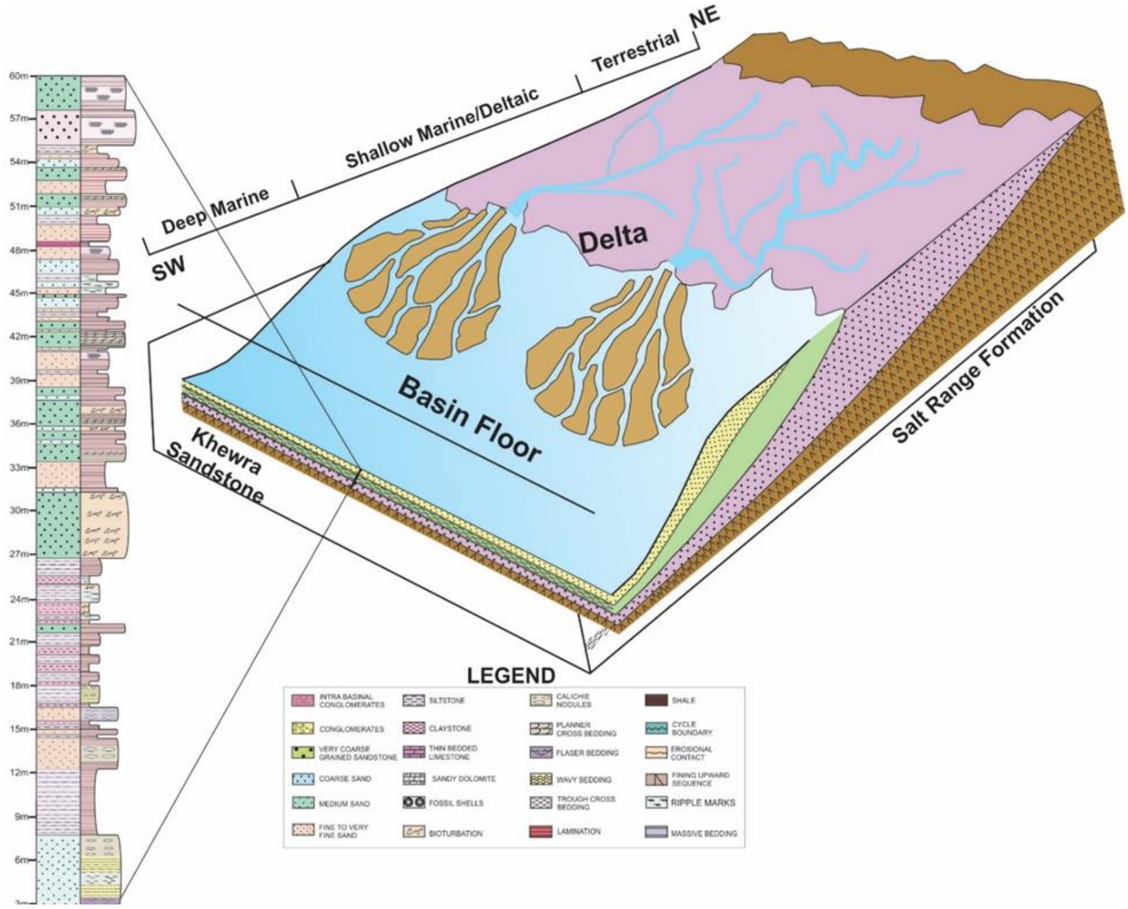

Figure 12 Detailed depositional model of the Early Cambrian Khewra Sandstone.

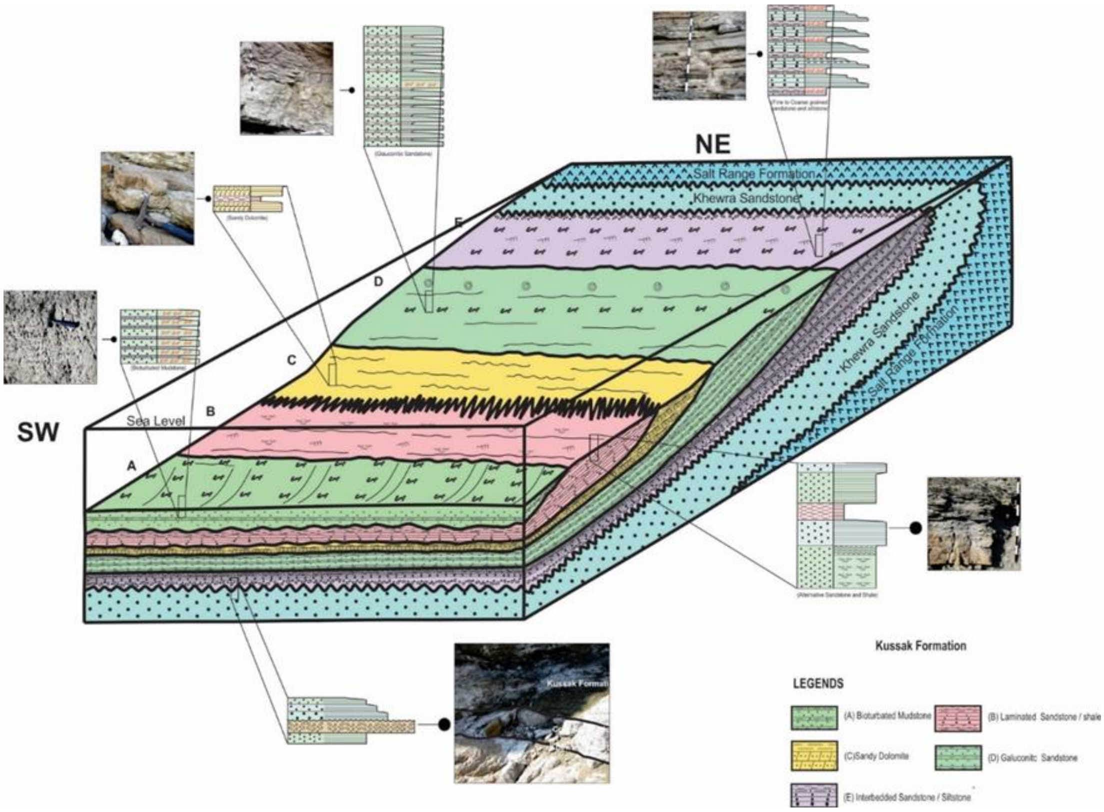

Figure 13 Detailed depositional model of the Cambrian Kussak Formation.

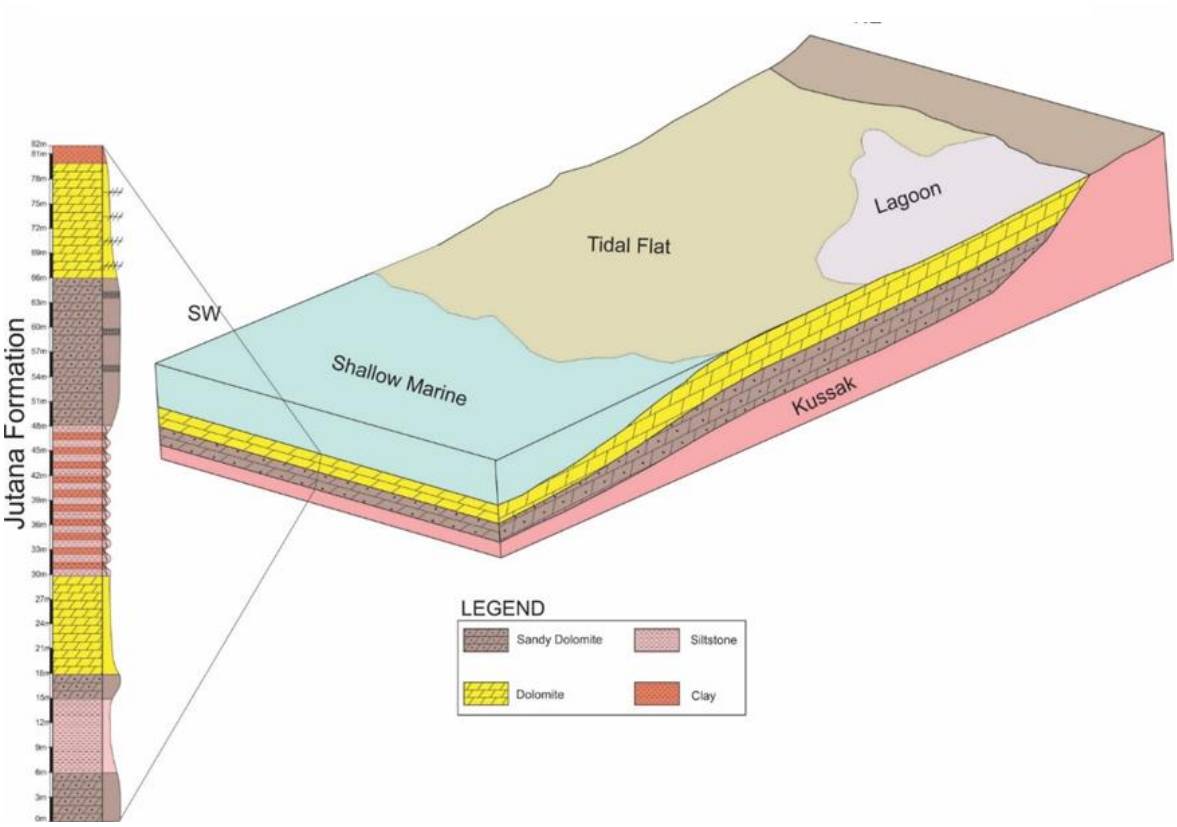

Figure14 Detailed depositional model of the Cambrian Jutana Formation.

bioturbation (Reineck and Singh 1973; Nelson et al. 1982). Sandstone, as massive and thick as it is now, is the sole product of storm erosion (Mulder and Alexander 2001; Kassem and Imran 2001). The Khewra Sandstone has channel deposits that are highly eroded, mixed, and growing, which shows a high energy flow state and the bypass process.

The lithofacies interpretation shows that the lithofacies KHSSH represents clay traps and also lenticular, wavy, or flaser bedding, which is the characteristic feature of a tidal flat environment (Nichols, 2009). According to Nichols (2009), the lithofacies of KHSB have a high faunal concentration in the upper and middle zones of the tidal flat and a low concentration at the base of the tidal flat. In this lithofacies KHSTR, the presence of tabular cross-stratification indicates that movement was primarily by wave action on the sand, which causes migration in dunes setup. So the tidal depositional environment (inter to shallow/sub tidal) for these lithofacies is interpreted. The lithofacies of KHSP, containing cross-bedding (inclined and horizontal), and ripple cross laminations, have similarities to the coastal environment developed by the shoal currents. Some trough cross-beds (minor scale) also show up, which are found at the shore face upper side, develop sand waves and ripples, all of which are the characteristics of longshore currents and drifting of sand. KHSLC lithofacies have cross-bedding (via cross-bedding).This lithofacies was formed by upper flow regime currents. Based on these characteristics, it is interpreted that this lithofacies was deposited in a delta channel environment, dominated by tides.

The most favorable site for the deposition of the Kussak Formation is the restricted Marin condition (maybe lagoonal etc.). The project area has fine to very coarse sandstone, mudstone, siltstone, and shale (black). These lithologies show repetition, recorded during the outcrop measurements. These fine lithologies indicate a calm environment (Khan, 1971). Fig. 14 illustrates the Kussak Formation model for depositions. The sequence arrangement of lithofacies in the Kussak Formation at places shows fining upward. The different sedimentary structures recorded in the Kussak Formation are: cross bedding, ripple marks, lenticular bedding, Syneresis and mud cracks, wavy or flaser beds, iron concretion, amalgamated surfaces, are some of them. Glauconitic rocks are found at the bottom and top of the formation, which suggests that the ocean environment where the rocks were laid down was smaller or more limited (Fig. 13).

The lithofacies interpretation shows that the lithofacies KMB shows a low sedimentation rate, the presence of bioturbation, and a condensed section, all of which suggest a shallow marine environment. The lithofacies KSH interpretations show that wavy, or Flaser bedding, interbedded sandstone and shale, and a mixture of clay and sand lithologies all support the tidal flat environment for deposition. The lithofacies KSD was a shallow marine facies, because the glauconitic sandstone and dolomite indicate these environments. The lithofacies KGS was also a shallow marine facies, because the glauconitic sandstone and different sedimentary structures indicate these environments. The lithofacies KSL represents the lagoonal depositional environment, as interpreted from this lithofacies that contains sandstone, siltstone, and interbedded shale and claystone.

The ichnofossils study is also very important for depositional environmental interpretation. The different types of ichnofossils are bioturbation, burrowing activity (Arenicolites, Skolithos), and these show the marine environment and during the Cambrian time, these ichnofossils were abundant in nature. Treptichnuspedum ichnofossils developed in calm water systems like lagoonal or mouth bar systems (MacNaughton, 1997). Treptichnuspedum is mainly found in the Cambrian strata, which are very important for environmental interpretation (Wilson et al., 2011).

In the Jutana Formation, the clastic sedimentation comes from the foreign basin (mostly igneous and sedimentary rocks from the surrounding areas). These sediments may be derived from the Cambrian Sea, which was near to the source (Pfeil and Read, 1980). Analyses show that during this time, the sea level has cyclic fluctuations. Dolomite and quartz intraclasts (intraformational) are found abundant in sandy dolomite, and in some areas, the intraclasts are rare in dolomites (Reineck and Singh, 1973). Pure and sandy dolomite, silty sandstone (micaceous), and sandstone (dolomitic) developed alternate beds at the basal part, and the upper part showed bioturbation, which suggests a transitional environment between intertidal to subtidal. The bioturbation activity was not recorded in the Jutana Formation, and the middle part shows thick to massive beds containing different sedimentary structures, like herringbone and trough cross-bedding, which are mostly characteristic of tidal flats. All the information collected from the investigation suggests a supratidal to intertidal environment of deposition (Fig. 14).

The lithofacies JF-1 shows a high energy depositional environment, as the siltstone is present, but it is assumed that these sediments have come from an external source. The presence of ripple marks in the sandy dolomite shows a warm, shallow marine environment. The lithofacies JF-2 has the characteristic sedimentary structures like herringbone and trough cross-bedding that characterise the intertidal to subtidal depositional environment. The lithofacies JF-3 shows a calm depositional environment (intertidal), which is suggested for this lithofacies due to the presence of lamination, bioturbations, and alternating dolomitic, mudstone, and siltstone (Shinn, 1968; Reading, 1996). Due to the presence of glauconitic content, the sedimentation rate recorded in this lithofacies is very slow, which generally develops in a lagoonal environment. At JF-4, the characteristic sedimentary structures are ripple marks and cross-bedding, which mostly developed in the shallow marine environment (Shinn, 1968; Reading, 1996). These ripple marks were formed by current action (Allen, 1982). Cross bedding was originated both by the migration of current ripples (Collinson, 1982). In this lithofacies JF-5, the characteristic sedimentary structures are herringbone and cross-bedding, which mostly developed in the shallow marine depositional environment (supratidal to intertidal) caused by the sea level rise, which deposited the carbonate lithofacies instead of clastic (Shinn, 1968).

6. CONCLUSIONS

The depositional environment interpretation was done through lithofacies analysis, which shows that the Khewra Sandstone was deposited in a marginal marine environment, developed by prograding sequence. For the Kussak Formation, the most favourable site for the deposition is restricted to Marin conditions (maybe lagoonal etc.). And for the Jutana Formation, the information collected from the investigation suggests a supratidal to the intertidal environment of deposition.

In the field study and through the lithologic log, 15 litho-facies are characterised (5 in Khewra, 5 in Kussak, and 5 in the Jutana Formation), which are KHSSH, KHSB, KHSTR, KHSP, and KHLC in the Khewra Sandstone; KMB, KSH, KSD, KGS, and KSL in the Kussak Formation; and JF-1, JF-2, JF-3, JF-4, and JF-5 in the Jutana Formation.

The detrital mineral composition shows that the sandstone sample of the Khewra and Kussak Formation falls into the Quartz Arenite Category. Based on Dickinson and Suczek's (1979) and Dickinson et al.'s (1983) QFL and QmFLt diagrams, the source area for the Khewra Sandstone and Kussak Formation is from the cratonic interior of the Indian shield. The composition of sandstone and clasts showed that the source area does not change over time.

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