

Sedimentology and palaeoenvironmental reconstruction of the Early Cambrian Kussak Formation, Salt Range, Pakistan

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Comprehensive sedimentological and sequence stratigraphic analyses of the Kussak Formation were carried out at the Nilawahon Gorge, the Karuli Section and the Khewra Gorge, Pakistan. The studied Kussak Formation has been grouped into: (1) bioturbated mudstone, (2) interbedded sandstone/shale, (3) sandy dolomite, (4) glauconitic sandstone and (5) laminated sandstone and siltstone. Hard to friable sandstone is present with condensed neobolus beds in the mud at the top. Bioturbation and glauconite are in middle parts, while a few beds of sandy dolomite are also present in the upper and middle parts of the Kussak Formation. These five depositional sequences had developed during the phase of transgression. Mineralogically, the average modal composition classifies it as quartz arenite. Rock fragments belong to the igneous origin, and feldspar grains most likely indicate an igneous and metamorphic source. The field and petrographic study indicate that the source area belongs to arid and semi-arid environments. Presence of wavy and flaser bedding indicates tidal flat deposition. Burrows, mud cracks, and synaeresis cracks indicate supra-tidal environment. Subsurface data show the fining upward sequence that confirms the deposition during transgression. In summary, the environment of deposition is subtidal, intertidal to supra-tidal environment. Palaeogeographic setting shows that the Kussak Formation source belongs to Aravalli and Malani ranges.

Keywords: Depositional environment, lithofacies, provenance, sedimentology, sequence stratigraphy.

THE Cambrian strata are present throughout the Salt Range and the Khisor Range of Pakistan, with best exposures in the eastern part, comprising the Khewra Sandstone, Kussak Formation, Jutana Formation and Baghanwala Formation¹⁻³. Wynne⁴ proposed the name ‘obolus beds’ or ‘siphonotrata beds’ to the predominant Kussak Formation. Waagen⁵ used the name ‘Neobolus

beds’ for the same unit. Noetling¹ proposed the name ‘Kussak Group’ while the Stratigraphic Committee of Pakistan formalized the name as Kussak Formation⁶. Further, a thin but widespread conglomerate bed followed by grey silty and sandy glauconitic shale, minor sandstone and a few black shale horizons were described by Bhargava⁷. The strata in the Salt Range are from Eo-Cambrian to late Miocene age⁸. Proterozoic sedimentation abruptly came to an end towards the close of the Early Cambrian^{9,10}. The Salt Range of Pakistan comprises of first rocks of the Indian subcontinent recognized to be Cambrian⁴. It is considered the type locality for several taxa with important roles in global Cambrian biostratigraphy and biogeography¹¹. Therefore, several researchers emphasize on the biostratigraphy of the Kussak Formation such as trilobites¹², brachiopods¹³, hyoliths¹⁴ and mollusks¹¹. However, there is a lack of studies on the depositional environment of the Formation. Thus, the present study focuses on the depositional environment of the Kussak Formation through various sedimentological and sequence stratigraphic parameters.

The depositional style of the Kussak Formation is possibly associated with strong tectonic movement(s) related to a major tectonic upheaval affecting the entire Indian subcontinent¹⁵. Palaeozoic sedimentation initiated in the arm of the Tethyan Ocean along the northern borders of the Indian Plate. The Salt Range area was present at marginal marine environment of the Tethys Sea¹⁶. The Cambrian sequence in the Salt Range is divided into the Khewra Sandstone, the Kussak Formation, the Jutana Formation and the Baghanwala Formation. The studied Kussak Formation is rich in glauconite, which is evidence for a marine environment. The organic-rich Kussak Formation shows reducing and humid environment, whereas Khewra represents open oxygenating environment with arid climate. This change in environment also shows transgression during the deposition of the Kussak Formation and regression during the deposition of the Khewra Formation.

The studied Kussak Formation in the Nilawahon Gorge, the Karuli Road Section and the Khewra Gorge of the Salt Range comprise of shale, greenish-grey glauconitic

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Table 1. Generalized lithofacies of the Cambrian strata (Jhelum Group) in the Salt Range, Pakistan^{3,6,8,10,21–23}

Age	Group	Formation	Lithology
Cambrian	Jhelum Group	Baghanwala Formation (salt pseudomorph beds)	Blood-red shales and flaggy sandstone; with salt pseudomorphs
		Jutana Formation (magnesian sandstone)	Massive light-coloured dolomite and dolomitic sandstone; subordinate shales
		Kussak Formation (magnesian sandstone)	Grey and purplish shales and glauconitic sandstone; pebble-bed at base
		Khewra Sandstone (purple sandstone)	Massive maroon, fine-textured sandstone; maroon shales and flags below

micaceous sandstone, interbedded light grey dolomite along with numerous sedimentary structures such as wavy bedding, flaser bedding and hummocky cross-bedding. The Kussak Formation in these sections make erosional lower contact with widespread thin layer of conglomerate at the top of the Khewra Sandstone. The upper contact of the formation in the Khewra Gorge and the Karuli Road Section is conformable with the Cambrian Jutana Formation, whereas in the Nilawahen Gorge, it reveals unconformable contact relationship with the Permian Tobra Formation.

Geologic setting

The Salt Range is the southernmost edge of the Himalayan foreland fold-and-thrust belt¹⁶. It is the result of collision of the Indian Plate with the Eurasian Plate since the Paleocene^{17,18}. The Salt Range rises up to 1500 m from the Punjab alluvial plain and is limited, to the north, by the Potwar and Kohat plateau which separate it from the main Himalayan ranges and to the south by the undeformed foreland of the Jhelum plain¹⁷. The Salt Range is bounded to the north and south by the Main Boundary Thrust (MBT) and the Salt Range Thrust (SRT) respectively¹⁹. The Jhelum Fault is the eastern while the Kalabagh Fault is the western boundary of the Salt Range¹⁹ (Figure 1).

The Salt Range is reflected as the active frontal thrust zone of the Himalaya in Pakistan. One kilometre offset of the basement acted as a decollement that caused the central Salt Range–Potwar Plateau thrust sheet to ramp to the surface, and ultimately exposed the Paleozoic and Mesozoic strata. The frontal part of the thrust sheet was folded passively as it overrode the sub-thrust surface on a ductile layer of the Neoproterozoic salt¹⁷. The thrust sheet began to override the basement offset from 2.1 to 1.6 Ma. The rate of Himalayan convergence that can be attributed to underthrusting of the Indian basement beneath the sediments in the Pakistan foreland is therefore at least 9–14 mm/yr (ref. 20).

Stratigraphy of the Salt Range extends from the Neoproterozoic to Late Miocene^{6,8,10}. Abrupt transition of sedimentation occurred from the Proterozoic to Early Cambrian, possibly due to tectonic movements that affect

the entire Indian subcontinent¹⁵. The Cambrian strata in the Salt Range are divided into four rock units of formation, namely Khewra Sandstone, Kussak Formation, Jutana Formation and Baghanwala Formation (Table 1). They combine to form the Jhelum Group^{3,6,8,10,21–23}. These sediments are deposited in shallow marine environment with fluctuating sea-level changes.

Materials and methods

The Early Cambrian Kussak Formation was comprehensively studied in the Nilawahen Gorge (72°35'16"E, 32°38'16"N), the Karuli Road Section (72°46'33.76"E, 32°43'04.50"N) and the Khewra Gorge (73°00'14"E, 32°40'12"N) of the Salt Range where its thickness is 55, 60 and 75 m respectively (Figure 1). Detailed field study, with an aim to reconstruct the depositional environment of the Kussak Formation exposed in the Khewra Gorge and the Nilawahen Gorge sections was taken up. Based on field observations, a detailed lithological log of the Kussak Formation was prepared (Figure 2). For a comprehensive study, samples of the Kussak Formation were collected from two sections, including the Khewra Gorge and the Nilawahen Gorge of the Salt Range. Twenty-two slides were prepared for thin-section study. Textural, mineralogical, depositional as well as provenance studies of systematically obtained sandstone samples were done under polarizing microscope to estimate the main constituents for their classification. Various models of sandstone classification were used to determine the detrital grains. In the present study, we used Pettijohn²⁴ and Folk²⁵ models of sandstone classification that provide the percentage of three framework grains, i.e. quartz, feldspar and rock fragment, on a QFL ternary diagram.

Furthermore, well log-based analysis was carried out for the interpretation of depositional environment of the formation by Pakistan Oilfields Limited (POL) in 1988. For this, petrophysical studies of Turkwal Deep 1 (72°59'18.23"E, 33°07'01.46"N) were carried out that was drilled at 4321 m in Rawalpindi district, about 5000 m north of Dudial town, Pakistan. The average ground elevations of the Turkwal well is 514 m and with the Kelly Bushing is 522 m respectively.

Kussak Formation

Lithofacies analysis

The macroscopic features of the Kussak Formation were comprehensively studied at the Nilawahan Gorge, the Karuli Road Section and the Khewra Gorge where it is associated with five lithofacies, which are described below.

Bioturbated mudstone (Ksb): This lithofacies forms the lower part of the formation in the studied sections (Figure 2). The facies is mainly associated with mudstone and intercalations of fine-grained sandstone and siltstone that make the condensed section of the formation (Figure 3 a). Moreover, bioturbation was observed in fine-grained sandstone (Figure 4 a). Some black shale intercalations were also present, which indicate horizontal lamination and splintery nature. This light grey to rusty brown lithofacies consists of mica in relatively large amount (Figure 3 a). The intensity of bioturbation is variable in the

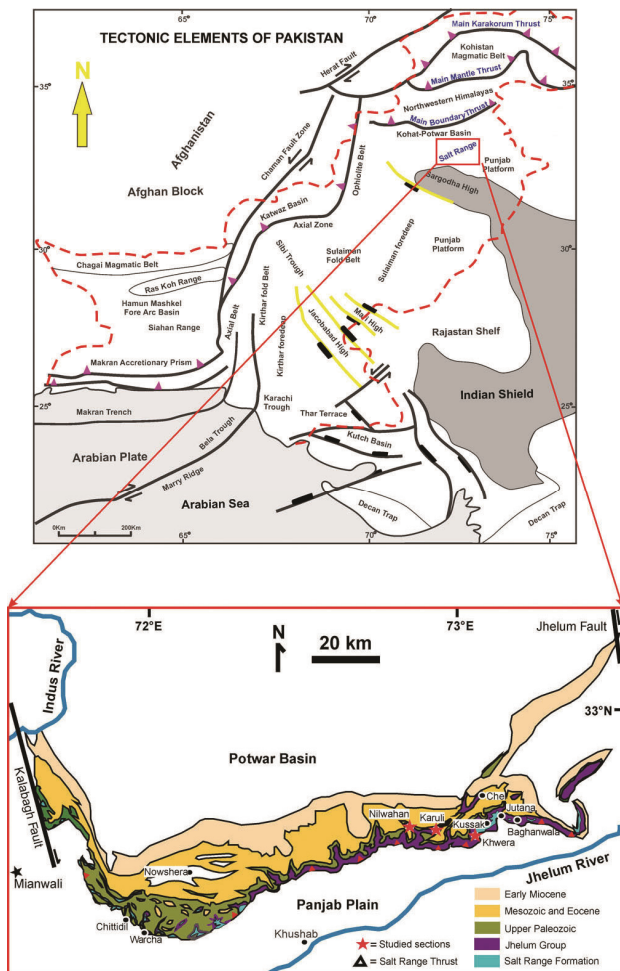


Figure 1. Geological map and location of the Nilawahan Gorge, the Karuli Road Section, and the Khewra Gorge in the Salt Range, Pakistan. Locations are shown with red star (modified after Hughes *et al.*³).

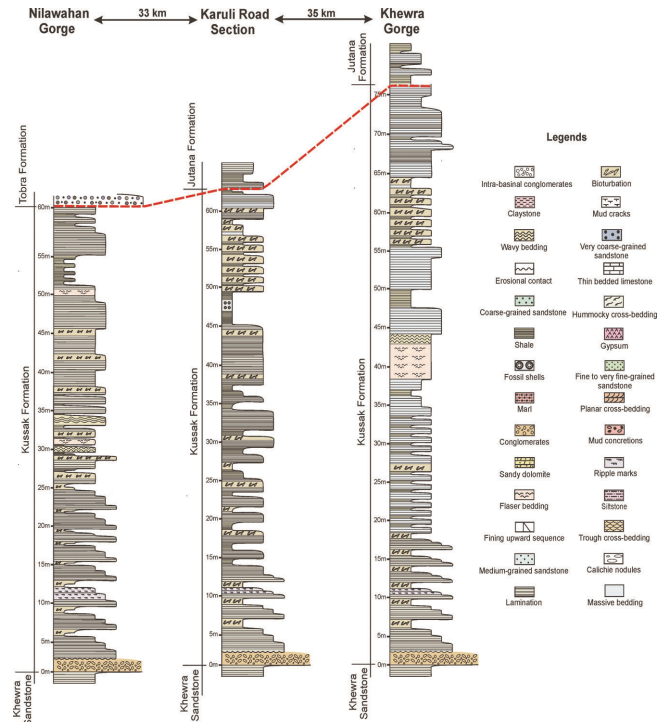


Figure 2. Stratigraphic columns of the Cambrian Kussak Formation in the Nilawahan Gorge, the Karuli Road Section and the Khewra Gorge showing the ordering of small- and medium-scale cycles in fining upward cycles.

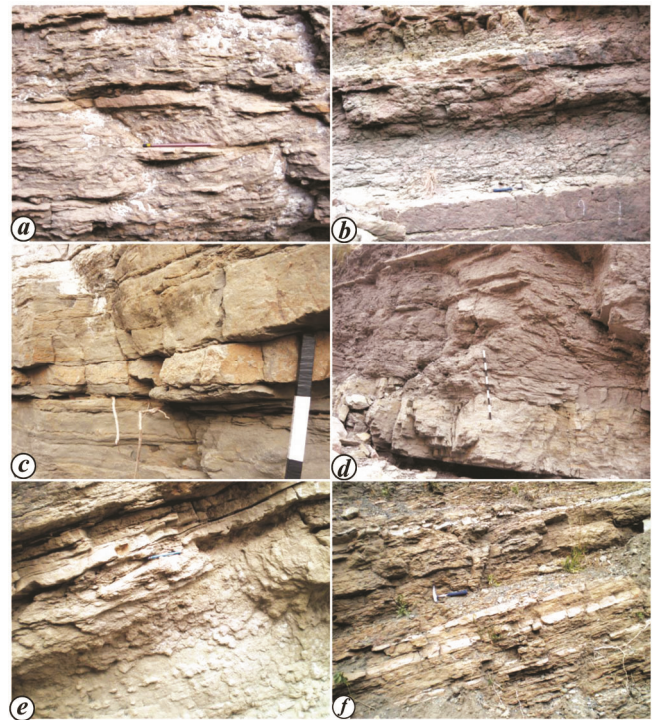


Figure 3. Association of lithofacies in the Cambrian Kussak Formation in the study region. *a*, Bioturbated mudstone; *b*, interbedded sandstone and shale; *c*, sandy dolomite; *d*, *e*, glauconitic sandstone; *f*, laminated sandstone/siltstone (hammer and pencil are for scale).

Kussak Formation (Figure 4 *a*). Some beds are intensely bioturbated and their original fabric is destroyed, while others show relatively minor bioturbation and the original fabric of the rock is preserved.

Bioturbated mudstone and presence of condensed section indicate that this facies is deposited in shelf environments with starved sedimentation condition. The condensed section represents maximum shoreline transgression.

Interbedded sandstone/shale (Ksh): The lithofacies consists of fine-grained, well-sorted sandstone, siltstone and shale that are interbedded (Figures 2 and 3 *b*). The lithofacies has higher proportion of shale and siltstone compared to sandstone (Figure 3 *b*). Shale is greenish-grey or pale yellow-green. In addition, the lithofacies also contains flasers (Figure 4 *b*), and wavy beds in ripple cross-stratified sandstone (Figure 4 *c–e*).

The interbedded sandstone/shale lithofacies is mud or mixed sand/mud tidal flat. These include thinly inter-layered bedding, coarsely interlayered bedding, flasers, wavy bedding and clay drapes. The mixture of clay and sand is characteristic of mud tidal flat facies. Flaser bedding appears to form under fluctuating depositional conditions marked by periods of current activity, when traction transport and rippling of fine sands take place,

alternating with periods of quiescence, when mud is deposited (Figure 4 *b*). Repeated episodes of current activity result in flaser bedding which is a type of ripple bedding in which thin streaks of mud occur between sets or cross-laminations (Figure 4 *b*). Flaser bedding suggests deposition under fluctuating hydraulic conditions.

Sandy dolomite (Ksd): The studied facies is characterized by thin to medium-bedded, planar-laminated, dolomite with intercalations of mudstone (Figures 2 and 3 *c*). Sandstone gives a greenish tint due to the presence of glauconite (Figure 3 *c*).

Presence of glauconite mineral is an indicator of shallow marine environment of deposition.

Glauconitic sandstone (Kgs): This lithofacies is associated with siltstone to very fine-grained glauconitic sandstone (Figures 2 and 3 *d*). The glauconitic sandstone ranges in size from silt to very fine, well-sorted sand (Figure 3 *e*). Moreover, this lithofacies has variable composition compared to other lithofacies, ranging from highly feldspathic arenite to highly glauconitic arenite.

Based on the ubiquity of glauconite and on its sedimentary structures, the green-sand lithofacies is interpreted as shallow marine sandstone.

Laminated sandstone and siltstone (Ksl): The observed lithofacies comprises of thin to medium-bedded, planar laminated, well-sorted, very fine to medium-grained sandstone (Figures 2 and 3 *f*). Very thin to thin-bedded siltstone along with local syneresis cracks are also observed (Figures 3 *f* and 4 *f*). Moreover, siltstone and sandstone are interlayered that contain ripple cross-stratification and fine planar stratification.

The shale/siltstone lithofacies is interpreted as lagoonal sediment with smaller amounts of tidal flat sediment. Lagoonal sediment consists of quiet-water shale deposits. The lithofacies also includes interbedded and interfingering sandstone, and siltstone and shale lithologies; these represent a number of overlapping sub-environments.

Sandstone petrography of the Kussak Formation

Petrographic studies of the Kussak Formation were performed, which comprised of grey silty and sandy glauconitic shale with intercalations of some sandstone and a few black shales. Thin sections were prepared in order to determine the detrital components of sandstone. The detailed petrographic descriptions of sandstone components in two sections are given below.

Petrographic features of the Kussak Formation in the Khewra Gorge

Thin sections of five sandstone samples of the Kussak Formation were prepared to understand the major detrital

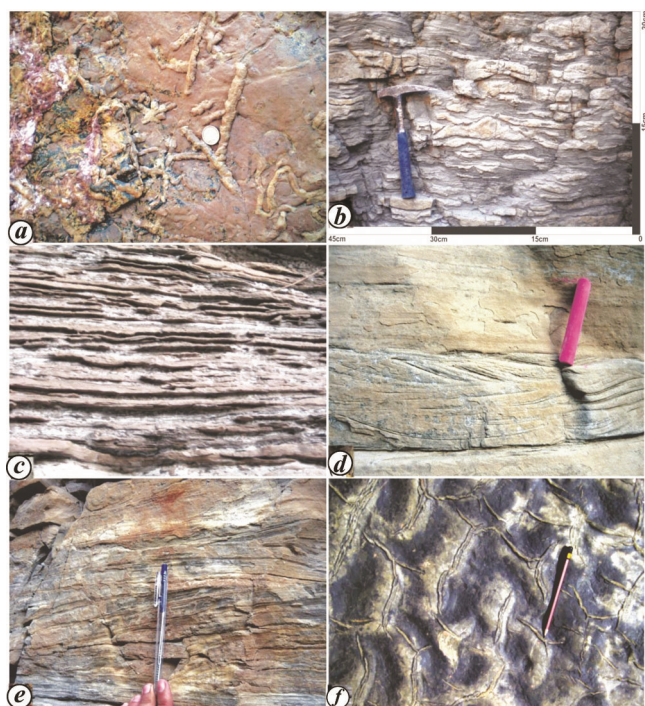


Figure 4. Sedimentary structures in studied sections of the Cambrian Kussak Formation. *a*, Bioturbation observed in bioturbated mudstone; *b*, flaser bedding; *c*, wavy bedding; *d*, hummocky cross-bedding; *e*, ripple cross-lamination. *b–e*, Structures examined in ‘interbedded sandstone/shale’ lithofacies of the Kussak Formation; *f*, Syneresis cracks observed in ‘laminated sandstone and siltstone’ lithofacies of the Kussak Formation (hammer and pencil are for scale).

components of sandstone. Detailed descriptions of these samples are given below.

Microfacies S-04: Based on textural characteristics, sandstone is medium-grained. Detrital composition is dominated by 90% quartz content. Other components are feldspars 4–5%, few lithic fragments, accessory minerals such as hematite and mica about 2%. Matrix is about 2–3% of the bulk composition (Figure 5).

Quartz grains are mostly monocrystalline and rarely polycrystalline. They are generally medium-grained, sub-angular to sub-rounded, and moderately sorted showing mainly sutured and concavo-convex contacts. These grains show undulatory extinction when examined under cross-polarized light. Feldspar grains are mainly orthoclase, microcline and plagioclase. The matrix appears to be composed of clays minerals. The major cement in sandstone is hematite. Minor amounts of calcite and silica are also present that act as cement.

Microfacies S-09: Sandstone is moderately to well-sorted, fine- to medium-grained. Detrital composition is dominated by quartz content of 85%. Other components are feldspar 5%, rare lithic fragments, accessory minerals such as hematite and mica about 2%. Matrix is about 5–7% of the bulk composition (Figure 5).

Quartz grains are mostly monocrystalline and rarely polycrystalline. They are generally medium-grained, sub-

angular to sub-rounded, showing mainly sutured and point contacts. Feldspar grains are mainly orthoclase, microcline and plagioclase. The matrix appears to be composed of clay minerals. Veins are generally filled with clay minerals and some are filled with calcite. The major cementing material in sandstone is hematite.

Microfacies S-15: Sandstone is medium- to coarse-grained, sub-angular to sub-rounded and moderately sorted. It is composed of about 85% quartz and 2% feldspar. Lithic fragments are about 2%, mica and other accessory minerals are about 2%. Sandstone contains 3% glauconite and 7% clay matrix (Figure 5).

Quartz grains are monocrystalline and few are fractured. The quartz grains have sutured and concavo-convex contacts. The dominant type of cement is silica. Ferruginous cement such as hematite is also present at some places.

Microfacies S-18: Sandstone is fine- to medium-grained. Detrital composition is dominated by quartz content of 85%. Other components are feldspar 3%, lithic fragment are very rare, and accessory minerals such as hematite and mica are about 2%. Matrix is about 5% of the bulk composition. Also, 5% glauconite is present (Figure 5).

Quartz grains are mostly monocrystalline and 5% are polycrystalline. They are generally medium-grained, sub-angular to sub-rounded, depicting mainly concavo-convex and point contacts. Feldspar grains are mainly plagioclase and some are orthoclase. The matrix is composed of clay minerals. The major cement in sandstone is hematite, while minor amounts of calcite and silica are also present.

Microfacies S-22: Sandstone is medium- to coarse-grained and comprises of 80% quartz, 4–5% feldspar, 5% lithic fragment, 2% hematite and mica, 2–3% matrix and 2–3% glauconite (Figure 5).

Quartz grains are mostly monocrystalline and approximately 10% are polycrystalline. Generally, they are medium-grained, sub-angular to sub-rounded. These grains are moderately sorted and display mainly sutured and concavo-convex contacts. Feldspar grains are mainly orthoclase, microcline and plagioclase. The matrix appears to be composed of clays minerals. The major cement in sandstone is hematite. Minor amounts of calcite and silica are also present.

Petrographic features of the Kussak Formation in the Nilawahan Gorge

Thin sections of four sandstone samples of the Kussak Formation in the Nilawahan Gorge were also prepared to determine the detrital components.

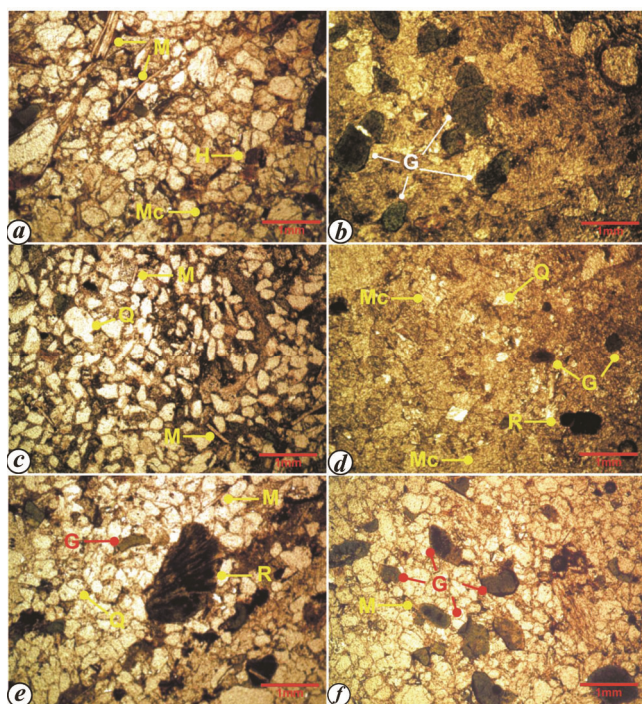


Figure 5. Representative characteristics of microfacies of the Cambrian Kussak Formation in the Khewra Gorge, and the Nilawahan Gorge. *a–f*, Plane-polarized views. Q, Quartz; R, Lithic fragment; G, Glauconite; Mc, Microcline; H, Hematite (all in same scale).

Microfacies S-17: Sandstone is medium-grained and quartz (93%) is the major detrital component of the microfacies. Besides quartz, feldspar components such as orthoclase, microcline and plagioclase are 2%, few lithic fragments, accessory minerals (i.e. hematite and mica) are about 2% and clay minerals (2–3%) are also present.

Quartz grains are mostly monocrystalline and rarely polycrystalline, and generally medium grained, sub-angular to sub-rounded showing sutured and concavo-convex contacts. The major cement in sandstone is hematite and minor amounts of calcite and silica are also present.

Microfacies S-18: Sandstone is medium-grained and dominated by 88% quartz. Orthoclase, microcline and plagioclase are about 5%, lithic fragments are rare, hematite and mica are about 2%, and matrix is about 5–7% (Figure 5).

Mostly monocrystalline grains along with few polycrystalline grains are sub-angular to sub-rounded, representing mainly sutured and point contacts and showing undulatory extinction under cross-polarized light. Veins are filled with clay minerals and some are filled with calcite. The major cement in sandstone is hematite.

Microfacies S-19: Sandstone is medium- to coarse-grained, sub-angular to sub-rounded and moderately sorted. Sandstone is composed of about 90% quartz, 2% feldspar, rarely lithic fragments, 2% mica and other accessory minerals, 3% glauconite and 3% clay matrix (Figure 5).

Quartz grains are monocrystalline. The quartz grains have sutured and concavo-convex contacts. The dominant type of cement is silica. Ferruginous cement such as hematite is also present at some places.

Microfacies S-22: Sandstone is medium- to coarse-grained. Detrital composition is dominated by quartz content of 85%. Other components are feldspar 3%, lithic fragment are rare, and accessory minerals such as hematite and mica are about 2%. Matrix is about 5% of the bulk composition and 5% glauconite is present.

Quartz grains are mostly monocrystalline and rarely polycrystalline, and generally sub-angular to sub-rounded showing mainly sutured and point contacts. The major cement in sandstone is hematite, and minor amounts of calcite and silica are also present as cementing material.

Facies association and sequence stratigraphy

The Cambrian strata in the study area of the Salt Range developed with fluctuating sea-level change that formed a depositional sequence. This complete sequence has five subsequences along with clear sequences boundaries such as maximum flooding surface (MFS), maximum regressive surface (MRS), and sub-areal unconformity (Figure 6)²⁶. Detailed descriptions of these sequences of the Kussak Formation are given below.

Sequence KK-1: laminated, medium-bedded micaceous

This is the lowermost sequence of the Kussak Formation. A bed of conglomerate is present at the base of this sequence, which is known as basal conglomerate, followed by very coarse to fine-grained, laminated sandstone intercalated with siltstone and claystone along with bioturbation (Figure 7 a and b). The sequence associated with five fining upward sequences shows cyclicity, as observed in the field (Figure 2). At places, glauconite is occasionally present. Moreover, small-scale cross-laminations are present in the sequence. Lithology is easily recognizable from the facies. There is no remarkable difference in lithology in the Nilawahen Gorge and the Khewra Gorge of the Salt Range (Figure 7 a and b).

Sequence KK-2: medium, cross-bedded, glauconitic

This greenish-grey sandstone and sandy shale sequence is about 5 m thick in the Nilawahen Gorge, and 6 m thick in the Khewra Gorge. It has two fining upward sequences which comprise of fine-grained, laminated sandstone intercalated with siltstone and claystone (Figure 2).

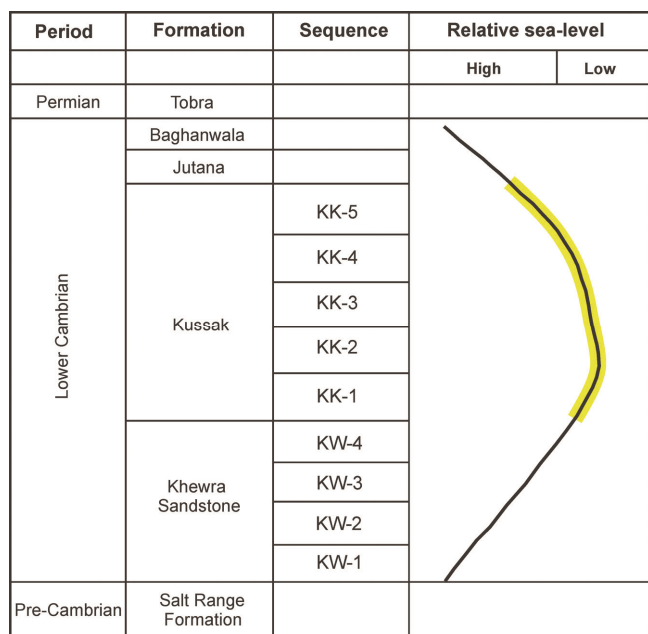


Figure 6. Relative sea-level curve of the Cambrian strata, i.e. Khewra Sandstone, Kussak Formation, Jutana Formation and Baghanwala Formation in the study area. This curve is analogous to the Cambrian curve of the North Australia basin²⁶.

Sequence KK-3: medium, planner-bedded, dolomitic sandstone

This sequence consists of five small sequences, which are composed of medium- to fine-grained laminated sandstone. Moreover, 1 m thick bed of siltstone and claystone is observed in the middle part of the sequence (Figure 2).

Sequence KK-4: fine-grained, rippled sandstone

This sequence is 25 m thick and composed of fine- to medium-grained sandstone and glauconitic shale. Sedimentary structures like bioturbation are commonly observed. It has five sequences, which are composed of fine-grained, laminated bioturbated sandstone, fine-grained sandstone with mud concretions, medium-grained sand with horizontal lamination, intercalated with siltstone and claystone (Figure 2). This is the first sequence where a coarsening upward or shoaling upward sequence has been observed.

Sequence KK-5: massive to fine-grained sandstone

This is the topmost sequence of the Kussak Formation. It is truncated by the Permo-Cambrian unconformity, which has more pronounced affect in the western and central Salt Range (Figure 7 c). This unconformity has removed the Baghanwala Formation, the Jutana Formation, and part of the Kussak Formation in the central Salt Range. Therefore, this sequence is absent in the western part of the Nilawahen Gorge (Figure 7 c). However, it is present in the Khewra Gorge (Figure 7 d) and the Karuli Road

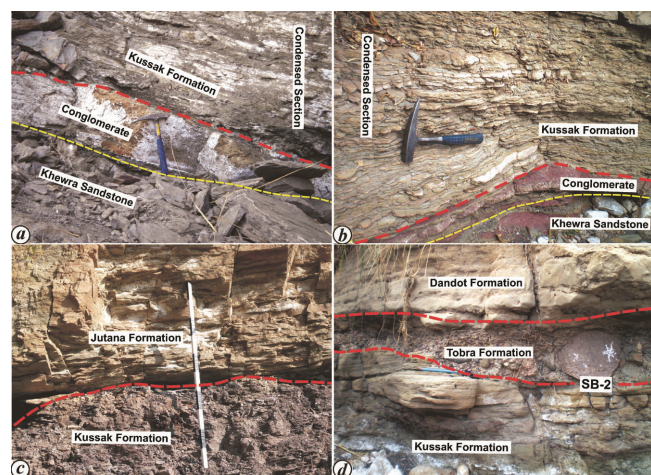


Figure 7. Sequence stratigraphic framework of the Cambrian Kussak Formation in the study area. *a*, Sequence boundary between the Khewra Sandstone and the Kussak Formation. *b*, Sequence boundary between the Kussak Formation marked by conglomerate bed. *c*, Transgressive surfaces between the Kussak and Jutana Formations. *d*, Sequence boundary II between Kussak, Tobra and Dandot Formations in the Nilawahen Gorge (hammer and pencil are for scale).

section. This sequence is composed of fine- to medium-grained sandstone with symmetrical ripple marks, bioturbation and dolomitic sandstone.

Log-based analysis

The Turkwal Deep 1 was drilled at a depth of 4321 m in the southern undeformed zone of the Potwar basin, Pakistan. The oldest formation encountered in this well is the Neoproterozoic Salt Range Formation (133 m thick) in up-thrown block of the Turkwal thrust. The total thickness of the Kussak Formation measured in this well is 9.5 m. The upper part of the Formation is composed of sandstone, whereas the lower part has mudstone intercalated with sandstone and siltstone. Based on gamma-ray (GR) log response of the Kussak Formation, four facies were identified which have been correlated with graphic sedimentary log of outcrop in the Khewra Gorge (Figure 8). Detailed descriptions of these facies are given below.

Facies 1 represents 20% of the total succession of the Kussak Formation, which is characterized by bell-shaped log motifs in the GR log. The GR value in this facies ranges from 60–72 API, and increases towards the top. The facies has sharp base and represents overall fining upward trends (Figure 8 a).

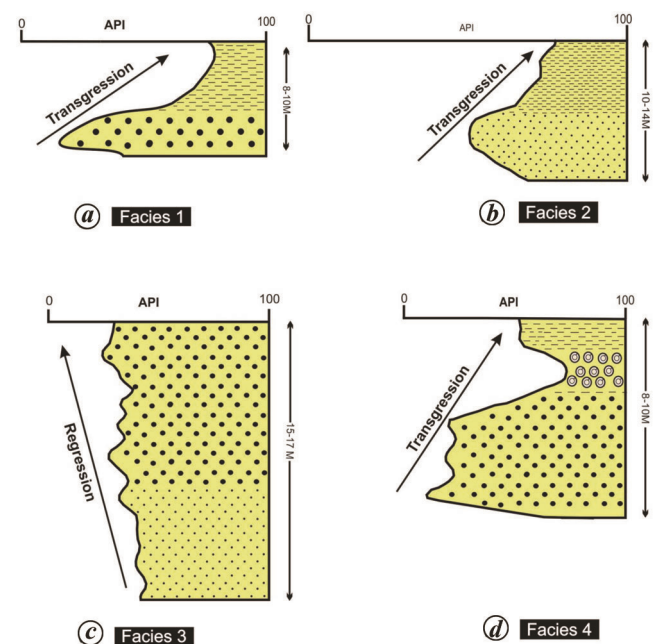


Figure 8. Well logs of the Turkwal Deep 1 ($72^{\circ}59'18.23''E$, $33^{\circ}07'01.46''N$) depict the subsurface characteristics of the Cambrian Kussak Formation in Potwar Basin, Pakistan. *a*, Facies 1 represents bell-shaped log motifs depicting the first subsequence. *b*, Facies 2 represents bell-shaped log motifs and forms the second subsequence. *c*, Facies 3 shows funnel-shaped log motifs in which coarsening upward trend is observed, and forms third subsequence. *d*, Facies 4 indicates the bell-shaped log motifs showing fining upward sequence and depicts the fourth subsequence.

Table 2. Major characteristics of lithofacies of the Cambrian Kussak Formation in the Nilawahon Gorge, the Karuli Road Section and the Khewra Gorge exposed in the Salt Range, Pakistan

Facies types	Lithology	Description	Interpretation
Bioturbated mudstone		This lithofacies is composed of thick- to massive-bedded bioturbated sandstone. Fine-grained sandstone is homogenized and cross-stratified with intercalated siltstone (Figure 3 a). Condensed section is composed of several fossils. Some black shale intercalations are present which have horizontal lamination and splintery in nature.	Bioturbated mudstone and presence of condensed section indicate deposition in shelf environments with starved sedimentation condition. Condensed section represents the maximum shoreline transgression ²⁸
Interbedded sandstone/shale		The interbedded sandstone/shale lithofacies consists of very fine to fine-grained well sorted sandstone, siltstone, and shale that are coarsely or finely interlayered, or wavy, lenticular, or flaser bedded. Lithofacies is much fine grained, and has a much higher proportion of shale and siltstone (Figure 3 b). Shale occurs as flasers, clay drapes, or wavy beds in ripple-cross-stratified sandstone, or as finely or coarsely interlayered beds. Shale is greenish gray or pale yellow green.	The interbedded sandstone/shale lithofacies is mud or interbedded sand/mud tidal flat. These include thinly interlayered bedding, coarsely interlayered bedding, flasers, wavy bedding, and clay drapes. The mixture of clay and sand is characteristic of mud tidal flat facies ²⁸ .
Sandy dolomite		Thin- to medium-bedded, planar laminated, dolomite with mudstone intercalations (Figure. 3 c). Sandstone gives greenish tint due to the presence of glauconite mineral in it.	Presence of glauconite mineral is indicator of the shallow marine environment of deposition ²⁸ .
Glauconitic sandstone		Siltstone to very fine grained glauconitic sandstone, planar or trough cross stratification. The glauconitic sandstone is silt-sized to very fine sand-sized and generally well sorted (Figure 3 d, e). The glauconitic sandstone is silt-sized to very fine sand-sized and generally well sorted. Composition is highly variable compared to other lithofacies, ranging from highly feldspathic arenite to highly glauconitic arenite.	Based on the ubiquity of glauconite and on its sedimentary structures, the glauconitic sandstone lithofacies is interpreted as a shallow marine sandstone ²⁸ .
Laminated sandstone & siltstone		Thin to medium-bedded, planar laminated, well sorted, very fine- to medium-grained sandstone (Figure 3 f). Very thin- to thin-bedded, thinly laminated siltstone, local synaeresis cracks. Intervals with abundant siltstone and sandstone are finely and coarsely interlayered siltstone and sandstone layers may contain internal ripple cross-stratification or fine planar stratification.	The shale/siltstone lithofacies is interpreted as lagoonal sediment with smaller amounts of tidal flat sediment. Lagoonal sediment consists of quiet water shale deposits. The lithofacies also includes interbedded and interfingering sandstone, and siltstone and shale lithologies, these represent a number of overlapping sub-environments ²⁸ .

Facies 2 represents 10% of the total succession and is characterized by bell-shaped log motifs in the GR log. The GR value in this facies varies from 70 to 80 API. Average shale volume increases towards the top (Figure 8 b).

Facies 3 represents 55% of the total succession of the Kussak Formation. It indicates the characteristics of funnel-shaped motifs in the GR log (Figure 8 c). These motifs highlight the coarsening upward sequence, where API values decrease towards the top.

Facies 4 denotes 15% of the total succession and comprises of the characteristics of bell-shaped motifs in the GR log (Figure 8 d). The GR value in this facies varies from 60 to 70 API. The overall succession of this facies reveals the fining upward trend (Figure 8 d).

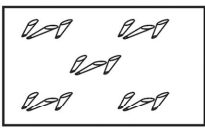
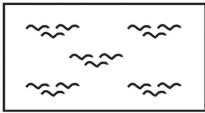
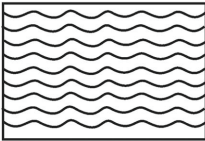
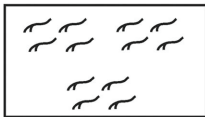
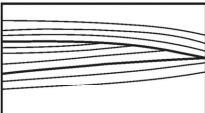
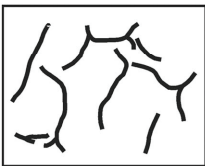
Discussion

Depositional environment of the Kussak Formation

Macroscopic interpretation of the Kussak Formation:

The Kussak Formation has been comprehensively studied at the Nilawahon Gorge, the Karuli Road Section and the Khewra Gorge exposed in the Salt Range, where its thickness is 55, 60 and 75 m respectively, representing a typical example of depositional environment of the Formation. The Formation in the study area comprises of bioturbated mudstone, interbedded sandstone/shale, sandy dolomite, glauconitic sandstone, laminated sandstone and siltstone lithofacies (Figure 3 and Table 2) that developed under certain conditions of sedimentation,

Table 3. Major characteristics of sedimentary structures of the Cambrian Kussak Formation in the Nilawah Gorge, the Karuli Road Section and the Khewra Gorge exposed in the Salt Range, Pakistan

Sedimentary Structure	Morphology	Description	Interpretation
Bioturbation		The intensity of bioturbation is variable in the Kussak Formation. Some beds are intensely bioturbated and their original fabric is destroyed while some other beds show relatively minor bioturbation and the original fabric of rock is preserved (Figure 4 a).	Bioturbation is produced by a variety of organisms and it is difficult to identify the organism that produced particular types of structures.
Flaser bedding		Flaser bedding is a special type of ripple cross-lamination in which thin streaks of mud occurs between sets of ripple laminae. The mud streaks tend to occur in the ripples troughs but may partly or completely cover the crests (Figure 4 b)	They appears to form under fluctuating depositional conditions marked by periods of current activity. Flaser bedding suggests deposition under fluctuating hydraulic conditions.
Wavy bedding		Wavy bedding observed in the Kussak Formation (Figure 4 c). It is intermediate forms of flaser and lenticular bedding made up of approximately equal proportion of sand and mud. ³¹	Wavy bedding form in marine and lacustrine delta-front environments, where fluctuations in sediment supply and current velocity are common; and possibly on shallow-marine shelves owing to storm-related transport of sand into deeper-water zones of mud deposition.
Hummocky cross bedding		Hummocky cross-stratification observed in the Kussak Formation (Figure 4 d) that characterized by undulating sets of cross-laminae i.e. concave-up (swales) and convex-up (hummocks). The sets of cross-bed (15-20 cm thick) cut each other with curved erosional surfaces. Spacing of hummocks and swales is from a few tens of centimeters to several meters. The lower bounding surface of a hummocky unit is sharp and is commonly an erosional surface.	Hummocky cross-stratification forms under the action of waves and they usually appeared in ancient sediments deposited on the shoreface and shelf. Hummocky cross-stratification seems to occur typically in fine sandstone to coarse siltstone that commonly contains abundant mica and fine carbonaceous plant debris. Hummocky cross-stratification originates by a combination of unidirectional and oscillatory flow related to storm activity.
Ripple cross lamination		Cross lamination is the pattern of internal lamination that develops in sand as a result of migration of ripples (Figure 4 e). It can be seen on both bedding planes and vertical surfaces.	Ripple cross lamination forms when deposition takes place very rapidly during migration of current. The series of cross-laminae are produced by superimposing migrating ripples. These migrating ripples are deposited sediments, especially out of suspension. With rapid sedimentation, stoss-side laminae can be preserved so that laminae are continuous from one ripple to the next.
Synaeresis cracks		Synaeresis cracks occur in mudstones interbedded with sandstone. They also occur in clay rich carbonate sediments, usually where beds are thin. They tend to be discontinuous and vary in shape from polygonal to spindle shaped or sinuous. The cracks are either as positive relief features on the bases of sandstone beds or in vertical sections through muddy layers where their downward tapering sandy fills may be contorted by small-scale compactional folding. Synaeresis cracks were observed in upper part of the Kussak Formation in the Nilawah Section (Figure 4 f).	Synaeresis are subaqueous shrinkage cracks that form in clayey sediment by loss of pore water from sediments that reorganize originally high porous clays, either due to flocculation or because of salinity-induced changes of volume of certain clay minerals. Marginal marine settings may be particularly favorable where clays are likely to be subjected to changes in salinity.

reflecting a particular environment²⁷. The bioturbated mudstone and presence of condensed section (Figure 3 a) indicate that this facies is mainly deposited in shelf environments with starved sedimentation condition²⁸. Moreover, condensed section represents the maximum shoreline transgression²⁸. The interbedded sandstone/shale lithofacies is abundantly associated with a mixture of shale, clay and sand (Figure 3 b), indicating the characteristic of tidal flat setting²⁸. Moreover, the glauconitic mineral in sandy dolomite (Figure 3 c) and glauconitic sandstone (Figure 3 d and e) depict the shallow marine environment of sandstone²⁸. The shale/siltstone lithofacies in laminated sandstone and siltstone (Figure 3 f) is interpreted as lagoonal sediment with small amounts of tidal flat sediment. Lagoonal sediment consists of quiet-water shale deposits. The lithofacies also includes inter-

bedded and interfingering sandstone, siltstone and shale lithologies that represent a number of overlapping sub-environments in the Early Cambrian Kussak Formation^{28,29}.

Furthermore, depositional environment of the Kussak Formation interpreted through sedimentary structures provides invaluable information about the mode and direction of transport and deposition, as well as subsequent changes^{29,30}. The typical sedimentary structures of the Kussak Formations such as wavy bedding, flaser bedding, hummocky cross-bedding, synaeresis cracks, bioturbation and ripple cross-lamination are observed in this study area of the Salt Range (Figure 4 and Table 3), which are representative of specific environments of deposition. Bioturbation (Figure 4 a) is produced by a variety of organisms. So, it is difficult to identify the

organisms that produce a particular type of structure^{31,32}. Flaser bedding (Figure 4 *b*) appears to form under fluctuating depositional conditions marked by periods of current activity, when traction transport and rippling of fine sand takes place, alternating with periods of quiescence, when mud is deposited³². Repeated episodes of current activity result in flaser bedding (ripple bedding) in which thin streaks of mud occur between sets or cross-laminations^{27,30}. Flaser bedding suggests deposition under fluctuating hydraulic conditions^{27,30,33}. The wavy bedding (Figure 4 *c*) appears to form in environments that favour deposition of approximately equal proportions of sand and mud, whereas flaser bedding forms under conditions that favour deposition of sand over mud³⁴. These structures are common in tidal flat setting and some subtidal environments where current flow or wave activity causes sand deposition, alternating with slack-water conditions that favour mud deposition³². These beddings may also form in marine and lacustrine delta-front environments, where fluctuations in sediment supply and current velocity are common; and possibly on shallow-marine shelves owing to storm-related transport of sand into deeper-water zones of mud deposition^{30,34}. Hummocky cross-stratification (Figure 4 *d*) occurs in some manner under the action of waves and commonly appears in the ancient sediments deposited on the shoreface and shelf³⁵. Hummocky cross-stratification seems to occur typically in fine sandstone to coarse siltstone that usually contains abundant mica and fine carbonaceous plant debris³⁶. Moreover, hummocky cross-stratification originates by a combination of unidirectional and oscillatory flows related to storm activity^{35,36}. The 'ripple cross-lamination' (Figure 4 *e*) in the Kussak Formation is formed when deposition takes place rapidly during migration of current or wave ripples. A series of cross-laminae are produced by superimposing migrating ripples. These are formed when the ripples migrate and when rate of addition of sand was high and there was no net removal of sand from stoss-side^{37,38}. Synaeresis cracks (Figure 4 *f*) are subaqueous shrinkage cracks that form in clayey sediments by loss of pore water because of reorganization of originally highly porous clays, either because of flocculation or change in volume of certain clay minerals due to salinity³⁹. Marginal marine settings may be particularly favourable because changes in salinity may be due to clay³³.

Sequence stratigraphic interpretation: The Cambrian, Khewra Sandstone and the Kussak Formation have been deposited during regression and transgression of the relative sea level that developed eight depositional subsequences, indicating a similar depositional environment. The strata of the Kussak Formation comprise of marine index mineral glauconite which is helpful in the interpretation of its sequence stratigraphy. This mineral forms at or near the sediments and water interfaces, and stays there for a long period. Thus, abundant occurrence of

glauconite has traditionally been interpreted to reflect marine transgression, while lack of glauconite is associated with starvation, indicative of regression⁴⁰. The link between glauconite and sedimentation rate has gained significant attention in sequence stratigraphy⁴¹. The depositional sequences in the Kussak Formation correspond to distinct phases of sea-level subsequences, and these phases govern sedimentation rates and percentage of glauconite in them. Glauconite mineral is present in KK-1 and KK-2 sequences, which indicates that deposition occurred during rise of relative sea level, i.e. transgressive system tract (TST)⁴². These deposits (TST) typically contain detrital glauconite, particularly near the base of the sequence. Moreover, mature authigenic glauconite generally increase upwards in TST deposits due to varying depositional environments, short-term sea-level dynamics and magnitude of sediment starvation. Additionally, fining upward subsequences indicate low-energy transgressive sequences. Glauconite is also present in KK-3, which occurs at the boundary between TST and highstand system tract (HST). KK-4 is a regressive sequence formed during the relative sea-level fall. These regressive deposits are followed by irregular surface of marine erosion or regressive marine surface (RMS). However, glauconite abundance and maturity generally decrease upward through this system tract. The KK-5 sequence is absent in the Nilawahan Gorge which appears to be eroded by the unconformity, thus having a pronounced effect in the central and western Salt Range and in the Nilawahan Gorge, where it cuts the Jutana dolomite in the eastern part of the section and the uppermost sequence in the western part of the section (Figure 7 *c* and *d*).

The Kussak Formation contains shallow shelf depositional sequence composed of fine- to medium-grained sandstone, siltstone, shale, greenish-grey glauconite and sandy dolomite. The lower part of the Kussak Formation associated with TST is characterized by low to moderate percentage of glauconite (Figure 7 *a* and *b*). The KK-3 forms the middle part of the Formation during HST. The sequences KK-4 and KK-5 indicate gradual rise in sea-level, dolomitic sandy contents and increase in glauconitic content thus are transgressive sequences. Moreover, these subsequences show asymmetrical internal cycles in sediment texture and reduction in glauconitic content. Overall deposition of the Kussak Formation is associated with transgressive period.

Sequence stratigraphic interpretation of the Kussak Formation: The sequence stratigraphic framework of the Kussak Formation has been established on the basis of well-log data and outcrop analysis. The Kussak Formation represents normal regressive to transgressive deposits from bottom to top (Figures 7–9). At the base of the Kussak Formation above the type-2 sequence boundary/transgressive revivification surface, conglomerates are

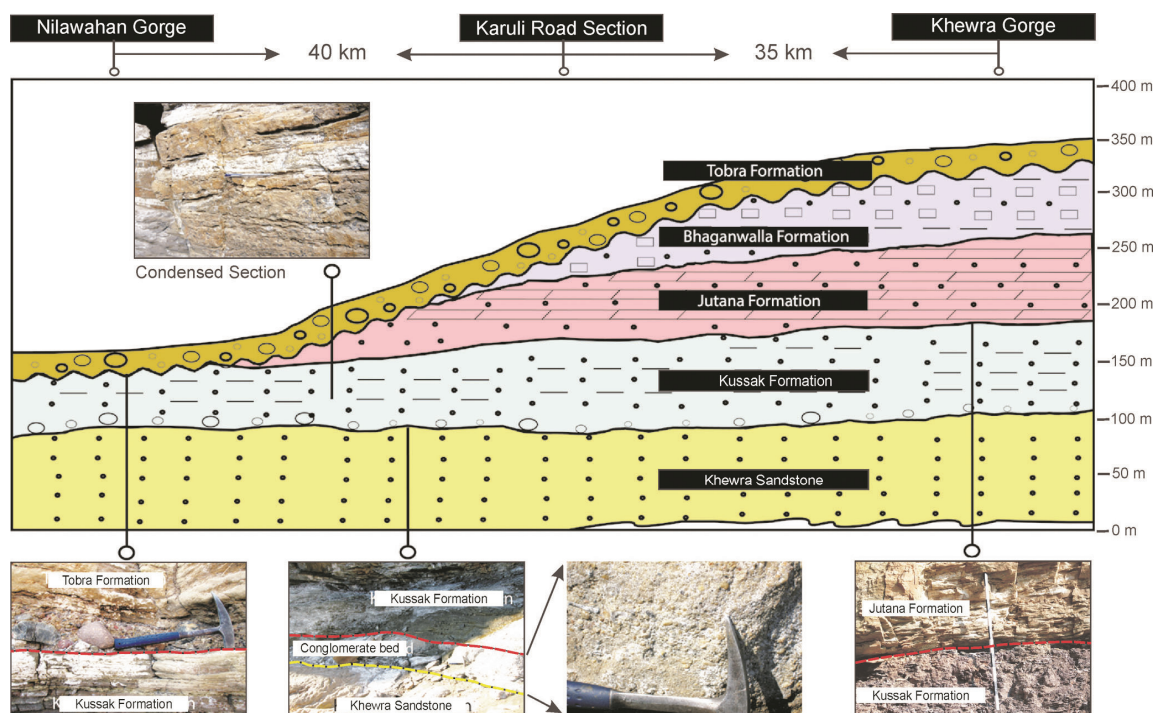


Figure 9. Stratigraphic strata at the Khehra Gorge, the Karuli Road Section and the Nilawahah Gorge of the Salt Range, Pakistan (modified after Hughes *et al.*³). (Inset) Photographs of the Khehra Gorge showing condensed section in the Kussak Formation, contact between the Kussak and Permian Tobra Formations, contact between the Khehra Sandstone and Kussak Formation, including a basal conglomerate bed, close-up of the conglomerate bed (hammer head for scale), and contact between the Jutana and Kussak Formations.

present which represent the transgressive lag deposits (Figure 7 *a* and *b*). GR log values of shale increase toward the top, which also confirms fining upward trends (Figure 8 *d*). Furthermore, abnormal high values of GR show the condensed section at the top of this facies (Figures 7 *a*, *b* and 8 *d*). After deposition of the condensed section, regression occurred in sequence KK-4 that deposited fine- to medium-grained sandstone and glauconitic shale. This is the only sequence that comprises of a coarsening upward or shoaling upward sequence. The GR log exhibits funnel-shaped motifs which also confirm the coarsening upward sequence, thus confirming that the deposition occurred during the regression phase (Figure 8 *c*). Above this, glauconitic sandstone interbedded with mud is also present. These deposits overall represent the fining upward sequence that indicates the transgression stage. Additionally, GR log shows bell-shaped motifs indicating overall fining upward trend (Figure 8 *a* and *b*). These deposits clearly depict TST (Figure 7 *c* and *d*) that make the upper part of the Kussak Formation. These sequences are bounded by TST that represents the small-scale variation of sea level during the Cambrian.

Consequently, depositional model of the Kussak Formation based on macroscopic, petrographic, sequence stratigraphic and log-based analysis was developed (Figure 10), which confirms renewed marine transgression of the formation that was probably a result of low detrital influx combined with continued eustatic sea-level rise. Zones of highly glauconitic arenite indicate that

detrital input was at times nearly suspended. There is evidence of a possible disconformity at the base of the Kussak Formation. Overall, the Kussak Formation was deposited in deeper water with reduced detrital input and stronger water sedimentation. An offshore submarine bar also formed during deposition of the Kussak Formation. Clay and silt are lagoonal deposits and tidal flats shoreward of the submarine bar. Renewed progradation of the shoreline resulted in deposition of mixed sand/mud tidal flats. These were succeeded by the foreshore/shoreface and tidal channel deposits.

Provenance of the Kussak Formation

Relationships of the Cambrian Kussak Formation with rocks on the Indian Craton: The nature of the Neoproterozoic and Cambrian strata in both the Salt Range and Panjab–Ganganagar–Nagaur basin suggests a proximal and continental interior setting³. The core data show relatively shallower basin toward the south and bounded by a fault⁴³. The lowermost strata are sandstone of the Jodhpur Group containing putative Ediacaran fossils, which are overlain at the southern margin of the basin by carbonate of the Bilara Formation and, in the basin interior, by the Hanseran evaporite³. Moreover, geochemical data clarify their contemporaneous deposition⁴⁴. These evaporites are up to 652 m thick in one borehole⁴⁵, and they grade laterally southward into 300 m thick carbonate of the Bilara

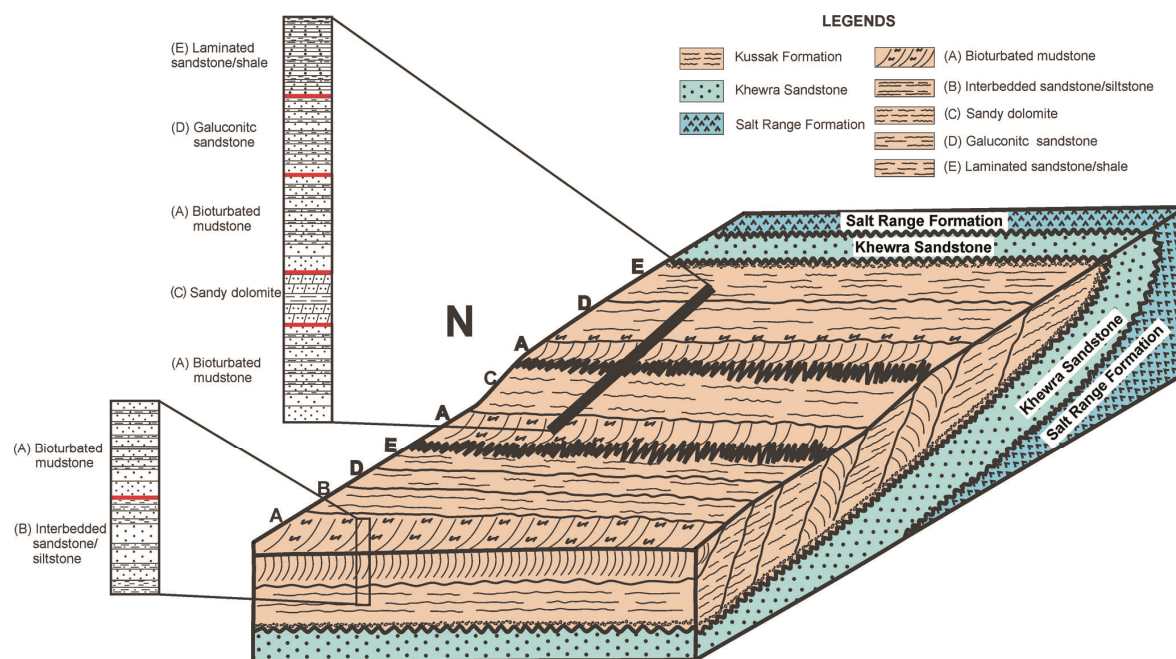


Figure 10. Depositional model of the Cambrian Kussak Formation, Salt Range, Pakistan.

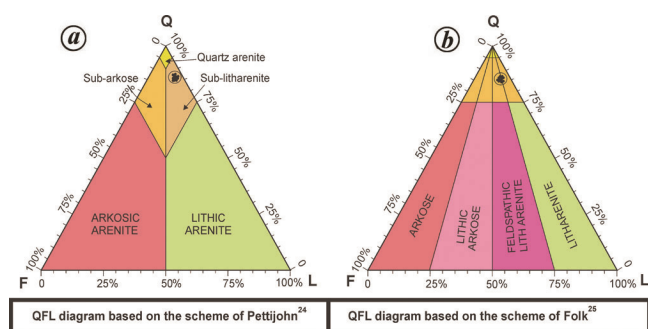


Figure 11 a, b. Representation of characteristics of microfacies of the Cambrian Kussak Formation on the quartz, feldspar and lithic fragments diagram.

Group, and further southwards are less than 100 m in outcrop⁴⁶.

The overlying siliciclastic succession of the Nagaur Group (i.e. Nagaur Sandstone and Tunklian Formation) ranges from 75 m thick in outcrop to over 750 m thick in the subsurface Rajasthan basin⁴⁵⁻⁴⁷. The Nagaur Sandstone is the lower part of the Nagaur Group that comprises of cross-bedded red sandstone and thin mudstone beds, which locally has a basal, 5 m thick polymictic conglomeratic unit, the Khichan Conglomerate⁴⁶. At depths within the Rajasthan basin, the Nagaur Sandstone contains evaporite horizons up to 100 m thick⁴⁶. The overlying Tunklian Formation is locally coarse-grained⁴⁸. The lithofacies of the Nagaur Sandstone is comparable with the Khewra Sandstone and Kussak Formation of the Salt Range. A lateral equivalent of the Tunklian Formation in core is the ‘upper carbonate’ unit, which is up to more than 500 m thick^{3,47}, and which may correlate with either

the Jutana Formation or Khisor Formation, north of the Himalayan Frontal Thrust.

Petrographic interpretation: Thin-section studies of sandstone were carried out to determine the provenance of the Early Cambrian Kussak Formation. The petrographic studies depict that the major types of grains in sandstone are nonundulatory monocrystalline quartz, undulatory monocrystalline quartz, some polycrystalline quartz, orthoclase, plagioclase, microcline, few perthites, lithic fragments, abundant glauconite and accessory minerals such as mica and hematite. The QFL diagram of detrital grains of the Kussak Formation was constructed (Figure 11), which depicts 85–86% quartz, 3–4% feldspar and 1% rock fragment, representing the abundance of quartz arenite in the sandstone samples.

Monocrystalline detrital quartz is medium- to coarse-grained and is most likely derived from weathering of granites⁴⁹, whereas fine-grained monocrystalline are most probably a product of breakage chipping of larger quartz grains derived from an igneous provenance. By contrast, polycrystalline elongated and stretched quartz grains are possibly derived from a metamorphic source⁵⁰, such as granite gneiss or schist. In addition, the exceptionally rounded to well-rounded nature of some quartz grains is indicative of a recycled sedimentary source⁴⁹.

Detrital K-feldspar grains are mainly derived from either acidic igneous rocks or from granite and gneisses, whereas plagioclase feldspar grains are mainly derived from low-grade mica schist⁵¹. The detrital feldspar grains therefore likely indicate both an igneous and a metamorphic source. Detrital micas were most likely derived from low-grade metamorphic rocks like quartzite, schist and

gneisses, or from plutonic igneous rocks of granitic composition².

The above discussion confirms that the main detrital components of the Kussak Formation are monocrystalline quartz, feldspar, polycrystalline quartz, few lithic fragments and accessory minerals like mica and hematite. Monocrystalline quartz is about 95% of the total quartz showing nonundulatory to slightly undulatory extinction. Single quartz units contain inclusions and some grains are fractured. Their main source is plutonic rocks; mainly granitic rocks². The main source of polycrystalline quartz which is about 5% of the total quartz is plutonic and low-grade metamorphic rocks². Dominant feldspar types are orthoclase and microcline, angular to sub-rounded, mainly derived from plutonic rocks such as granites and gneiss². Mica flakes are average <0.2 mm long and their source is mainly low-grade metamorphic rocks such as quartzite, schist and gneiss; and igneous rocks like granite². Therefore, based on the above detrital components, the source of these grains is most probably: the Aravalli system, and the Malani Range.

(a) Aravalli system: The Precambrian Aravalli Supergroup is exposed in a range of hills in the region around Udaipur, Rajasthan, India, more than 600 km to the southeast of the Salt Range, and is composed of a complex suite of granitic, sedimentary and metamorphic rocks which themselves rest on an earlier banded gneiss complex. The provenance analysis presented herein demonstrates that rocks of the Aravalli Supergroup formed in uplifting, during which they were actively shedding detritus to the northwest.

(b) Malani range: The Malani Suite forms a series of volcanic porphyritic rhyolite lavas, intrusive granites and ash beds that cover an area of 51,000 km² in the Barmer district, Rajasthan, India. It extends into the Sindh Province of Pakistan, which is more than 500 km to the south of the Salt Range. The grains of the Malani Range are also common within the early Cambrian sequence². Therefore, the Malani Range is most probably another source area of the Kussak Formation that shed detritus northwards at that time.

Conclusions

The sedimentological and sequence stratigraphic characteristics of the Early Cambrian Kussak Formation were studied at the Khewra Gorge, the Karuli Road Section and the Nilawahon Gorge of Salt Range, Pakistan, where the Kussak Formation exhibits fining upward sequence and shows cyclic depositional trend. The intercalations of silt and claystone were present throughout the succession. At the top of the succession, medium-grained sandstone with shale intercalations resulted from renewed marine transgression. Moreover, this is the result of low detrital influx that continuously raises the eustatic sea-level. The

zone of highly glauconitic arenite indicates that detrital input was at times nearly suspended, which was confirmed by disconformity at the base of the Kussak Formation. Overall, the Formation is deposited in deeper water with reduced detrital input and clearer water sedimentation. Clay and silt reveal lagoonal, whereas mixed sand/mud shows tidal flats environment. Moreover, sedimentary structures in the Kussak Formation confirm the tidal flats origin of the Formation. The petrographic studies represent abundance of glauconite that indicates marine continental shelfal environment. Consequently, lithofacies and petrographic analyses confirm the subtidal, intertidal to supratidal depositional environment of the Early Cambrian Kussak Formation. Additionally, sequence stratigraphy confirms that deposition of the Formation occurred during TST and HST. Petrographic studies demonstrate that the Kussak Formation shows quartz to feldspar, and very high grains to matrix ratios which confirm that sandstone of the formation is chemically and physically quite mature. In addition, quartz arenite of the Kussak Formation depicts the mixed provenance. However, relative abundance of quartz represents the Aravalli and Malani Ranges as the source area, which are about 550 km away from the present Salt Range.

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