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Provenance Analysis and Diagenetic Control of Early Cambrian Kussak Formation, Upper Indus Basin, Pakistan

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ABSTRACT

Petrographic study of sedimentary rocks can be used to determine provenance and diagenetic histories. Thirty samples from Kussak Formation were collected from Khewra Gorge, Eastern Salt Range, Pakistan, for petrographic studies. Petrographic analysis revealed that Kussak Formation consists of quartz with mean value of 85.2%, while feldspar accounts for no more than 3% of total grains. Lithic fragments and a variety of heavy minerals were observed in traces and cumulatively amounts to 2.5%. Silica, calcite, and iron oxide, as cementing materials, were also detected in sandstone and contribute 4% overall. The amount of Monocrystalline quartz is computed to be more abundant than polycrystalline quartz. Based on McBride classification, sandstone of Kussak Formation is classified as quartz arenite. Higher quartz content most likely places the source of Kussak Formation in the Indian Shield. Compaction, iron oxide cementation, calcite cementation, replacement, dissolution, precipitation of silica as overgrowth and alteration of framework grains are the prominent diagenetic modifications, which were observed and analyzed in Kussak Formation. Deep burial, high pressure and temperature regime, as evident from quartz overgrowths and grain fracturing, point towards final phase of diagenesis for Kussak Formation.

1. Introduction

Mineralogical constituents, cementation, effect of pressure solution and degree of compaction in sandstones, can be understand using petrographic studies [1, 2]. Petrographic studies of detrital sediments, helps determined their provenance, tectonic settings and diagenetic history [3, 4]. In provenance measurement, data from detrital modes of sandstones often provide key information [5-8].

The Salt Range is located south of the famous Himalayan foreland. They have very complex geological structures developed as a result of ongoing collision of the India and Eurasian tectonic plates [9]. The Salt Range represents a longitudinal east-west trough, bounded on the east by the Jehlum River and on the west by the River Indus, between 32°15′–33°0′ N and 71°34′–73°45′ E [10]. Salt Range is the youngest and southern most compressional structure of the Himalayan Foreland [9]. Boundaries of this distinct structural zone are marked in the north by north-dipping Main Boundary Thrust [10]; in the south by the Salt Range Thrust [11]; Kalabagh Fault and Surghar Thrust to the west and in the east, its boundary is marked by Jhelum Fault respectively [12, 13]. On southern margin of the Salt Range resides the Salt Range Thrust, between Indus and Jhelum Rivers [14]. A complex salt anticlinorium of Salt Range is supported by a series of salt anticlines, which is widest in its central part, between Khewra and Warcha, where an excellent exposure of Paleozoic and Precambrian sequence is present (Fig. 1). Well exposed sedimentary sequences of Eo-Cambrian to Recent are present in the Salt Range. In the Salt Range, the Kussak formations disconformably overlay by the Khewra Sandstone, and conformably overlain by the Jutana dolomite. Shallow marine (shelf) existed at the time of Cambrian, when Greater India was present with Australia and Antarctica, during the assemblage phase of Gondwanaland [15]. Kussak Formation contains geochemical clues about the geological processes occurring during Cambrian time.

This study uses the petrographic data of samples, to help determine provenance of Kussak Formation, exposed in Khewra gorge. Petrographic data is further utilized to decipher the diagenetic history of Kussak Formation, to construct the post-depositional changes in the Formation over time.

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2. Materials and Methods

In this paper, petrographic study of 30 samples of Kussak Formation was done to track provenance, using grain counting technique. Kussak Formation was observed in Khewra, Pail, Warchha and Makkhrach gorges. However, for this study, we chose exposure of Kussak Formation in Khewra gorge, where all the sampling was done (Fig. 2). After establishment of provenance, thin sections were utilized to construct diagenetic history for Kussak Formation, in order to evaluate and analyze its geological past.

2.1 Field Data Acquisition

Detailed field work of Kussak Formation was performed in Khewra gorge in order to study its lithological characteristics, and analyze samples for petrography. For lithostratigraphy, thickness of Kussak Formation was measured and features were observed in vertical section. Field photographs were taken to record features observed in the field. Thirty samples were collected for petrographic analysis and all samples ranged from ~1 kg to ~3 kg. Sample description is provided in Table 1.

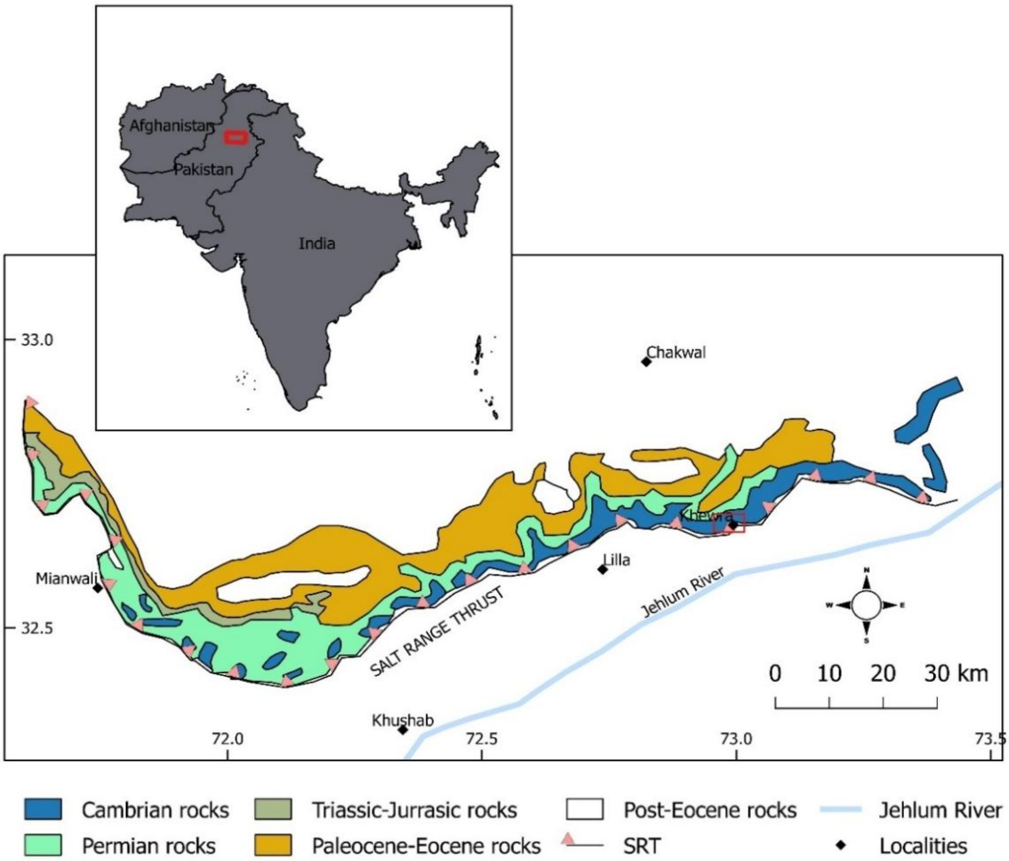

Fig. 1: Selected location map (Modified after [16]) showing different sedimentary packages cropped up due to Salt Range Thrust. The oldest rock units (Cambrian to Eo-Cambrian) are placed in the vicinity of SRT. Study area is marked as red rectangle, which was the primary site for sample collection

2.2 Petrography

Thirty stained thin sections were prepared at the Centre of Excellence in Geology (University of Peshawar, Pakistan) to determine the mineralogy and composition of sandstone of Kussak Formation. Thin sections were prepared from basal, middle and upper part of Formation. Polarized microscope was used for thin section studies. Mineralogical composition was determined by modal analysis with >300 points counted from each thin section. Using QFL and Qm-F-Lt plots [17], the class and source region of sandstone were determined.

3. Results and Analysis

Lithostratigraphy is used for the classification of rock bodies. Characterization of rock units, on the basis of lithological properties and stratigraphic relationships can be carried out using lithostratigraphy [18]. Detrital sandstone composition is highly dependent on the texture, composition and structure of the source rocks, climate and relief in the source areas, depositional setting transport conditions, and diagenesis [19, 20]. Petrography of sandstone and heavy minerals suites help us to determined uplift history, evolution of orogenic belt and source rock [21].

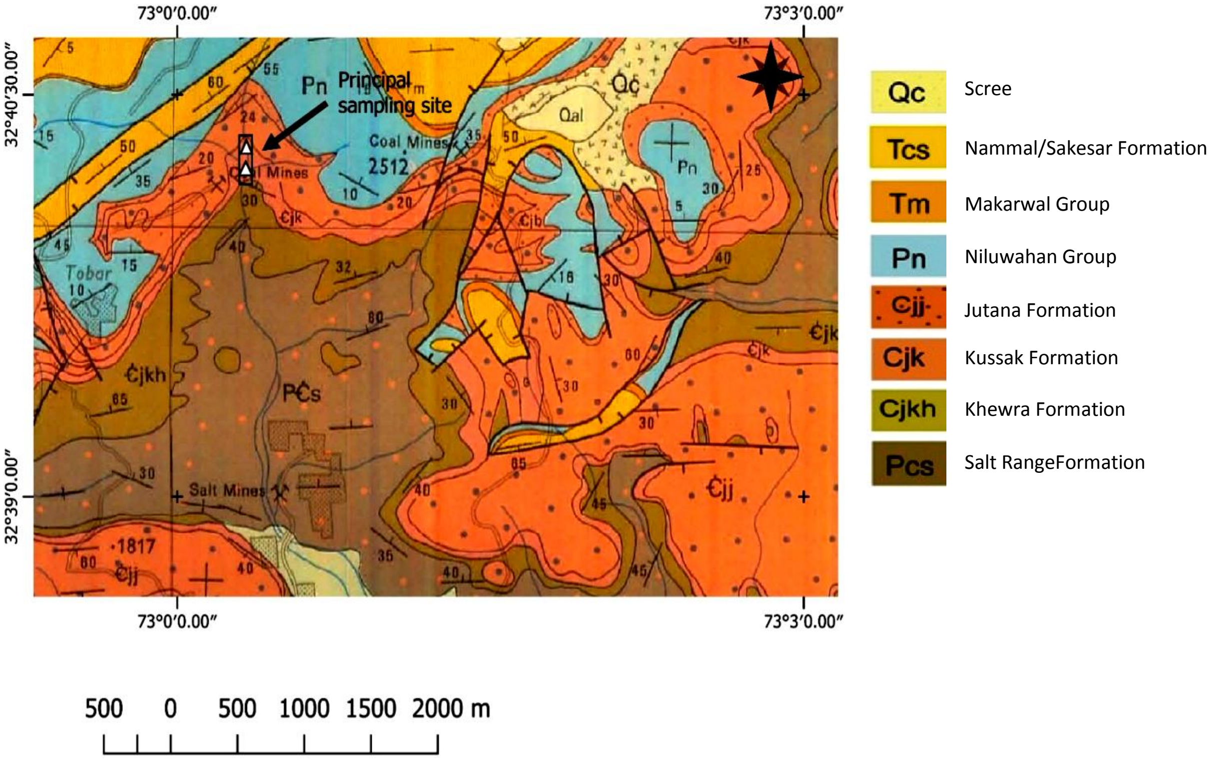

Fig. 2: Detailed map of study area depicting spatial extent of field work, carried out in Khewra gorge [22]. Exposures of Pre-Cambrian (Salt range formation) and Cambrian (Khewra formation, Kussak formation and Jutana formation) are very developed in the study area demarcated by square. Samples were collected in a vertical section where Kussak formation had top and bottom contact exposed with Jutana formation and Khewra formation

3.1 *Lithostratigraphy*

In the Eastern Salt Range, Jogi Tilla, Chidru, Khisor Range, Pail, Makkhrach and Khewra sections have excellent exposures of Kussak Formation. Disconformable contact between Kussak Formation and Khewra Formation is marked on the basis of 12 cm bed of conglomerate [23], as depicted in Fig. 3.1. Kussak Formation has grain supported matrix, with white to yellow grains of quartz and quartzite, occasionally dark grains are also present, with their edges well rounded, but grain shape ranged from sub angular to well-rounded. Grey, silty and sandy, glauconitic shales, micaceous shales and black shale layers are also present in the Formation. Sandstone of the Formation is medium to coarse grained. At the bottom of the Formation thin beds of sandstone are present. Within the Formation thin beds of rippled sandstone are also present (Fig. 3.2). The shale beds are of more than 1m thick (Fig. 3.3).

Higher up, the sandstone and sandy shales, with Annelid casts, become prominent and include two or three bands of dark purple-grey shales, each several meters thick. In the upper part of the Formation, bands of flaggy, light grey sandstone are present, which is calcareous, dolomitic, and sometimes glauconitic. Some of the beds are like overlying Jutana Formation so the upper contact of the Formation is transitional with the massive dolomite of Jutana Formation (Fig. 3.4). The thickness of the Formation in the Khewra Gorge is 80m. All of the Formation is extensively bioturbated (Fig. 3.5). Bioturbation is horizontal but mostly vertical and inclined burrows of 7 cm long tubes are also present. They are also present at bedding planes, as long as 15 cm. At places, branching is very clear (Fig. 3.6). Weathered color of sandstone is light brown in the Khewra gorge, fresh colors of the sandstone are yellow, dark brown, red, green and grey but in Pail and Makkhrach sections the dominant color is green, towards the top of the Formation [15].

3.2 *Petrographic Analysis of Kussak Formation*

Thirty samples of Kussak Formation were taken from Khewra gorge for petrographic analysis. The size of sandstone grains varied from very fine to coarse size (Figs. 4.1, 4.2, 4.3). Majority of the sandstone is fine grained. Grain size reduces from medium to very fine towards top. The shapes of sandstone grains are sub-angular (Fig. 4.4) to well rounded (Fig. 4.5). Most of the sandstone grains are sub rounded. Sandstone of the Formation is poorly (Fig. 4.6) to well sorted (Fig. 4.7). Sorting of the sandstone grains increases from poorly sorted to well sorted towards top of the Formation.

Table 1: Detailed description of samples that were collected during the field visit in Khewra Gorge, Pakistan. Kussak Formation was well exposed with top and bottom contacts exposed. KKS-1 describes sample taken at the base of Formation and KKS 30 describes sample taken at top of formation

No.	Sample name	Visible Sample Description
1	KKS 1	Greenish grey fissile shale
2	KKS2	Cross laminated brown sandstone
3	KKS3	Black shale
4	KKS4	Yellowish brown sandstone
5	KKS5	Yellowish brown sandstone
6	KKS6	Black arenaceous shale
7	KKS7	Maroon Sandstone
8	KKS8	Greenish grey shale
9	KKS9	Shale with intrusion of sand
10	KKS10	Coarse grained brown sandstone
11	KKS11	Gray sandstone
12	KKS12	Parallel laminated yellowish gray sandstone
13	KKS13	Variegated sandstone
14	KKS14	Dolomitic brownish sandstone
15	KKS15	Parallel laminated yellowish brown sandstone
16	KKS16	Black shale
17	KKS17	Brown coarse grained sandstone
18	KKS18	Sand Intrusion in shale
19	KKS19	Greyish brown sandstone
20	KKS20	Brown fine grained sandstone
21	KKS21	Shale with intrusion of sand
22	KKS22	Brown fine grained sandstone
23	KKS23	Dark brownish shale
24	KKS24	Greenish grey fissile shale
25	KKS25	Dolomitic sandstone
26	KKS26	Brownish Shale
27	KKS27	Blackish shale
28	KKS28	Yellowish brown sandstone
29	KKS29	Parallel laminated sandstone
30	KKS30	Argillaceous sandstone

Fig. 3.1: Basal part of Kussak formation is marked by the presence of conglomeratic bed of 12 cm. Exposure surface marks a disconformable contact between underlying Khewra formation and Kussak formation. Geotagged coordinates are also provided and depicted in Fig. 1.2

Fig. 3.2: Field photograph showing rippled sandstone present in Kussak Formation. Geotagged coordinates are also provided. and depicted in Fig. 1.2

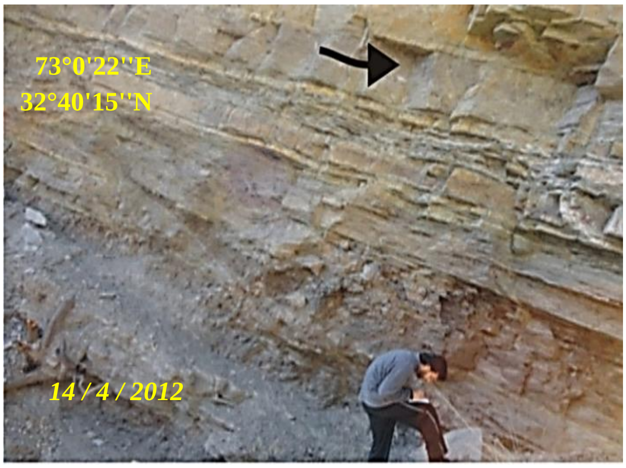

Fig. 3.3: Field photograph depicting Weathered colour of Kussak formation in Khewra gorge. 1 m thick bed of shale is marked by black arrow. Geotagged coordinates are also provided

Fig. 3.4: Upper conformable contact of Kussak Formation with Jutana formation in Khewra gorge section. Geotagged coordinates are also provided

Fig. 3.5: Bioturbation causing destruction of laminated sandstone of Kussak Formation. Geotagged coordinates are also provided

Fig. 3.6: Bioturbation at bedding plane of sandstone of Kussak formation. Geotagged coordinates are also provided

Sandstone is cement supported (Fig. 4.8) but some of the sandstone is grain supported as well (Fig. 4.9). Cement supported sandstone is present at the lower part of the Formation which further grades up into grain supported sandstone towards the top of the Formation. Percentage stacked chart representing average percentage of different constituents present in thin section is given in (Fig. 5). The quantitative petrographic data is provided in Table 2, depicting percentage of each constituent identified during petrographic analysis.

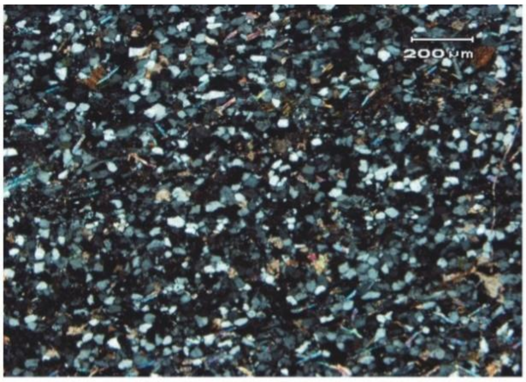

Fig. 4.1: Photomicrograph showing fine grained sandstone of Kussak formation

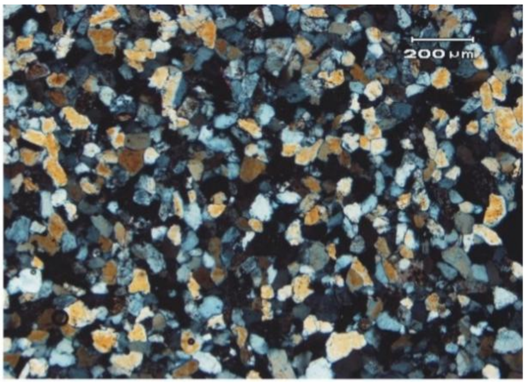

Fig. 4.2: Photomicrograph showing medium grained sandstone of Kussak formation

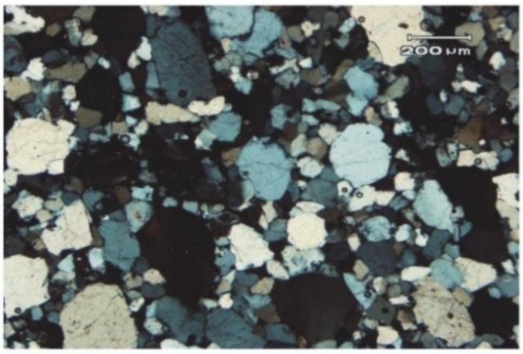

Fig. 4.3: Photomicrograph showing coarse grained sandstone of Kussak formation

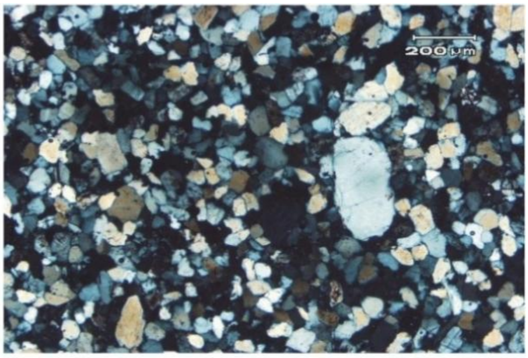

Fig. 4.4: Photomicrograph showing sub-angular to sub-rounded grains of Kussak formation

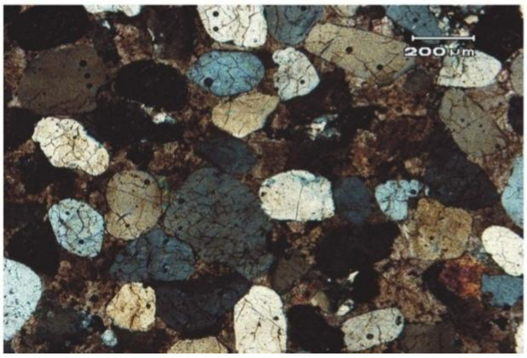

Fig. 4.5: Photomicrograph showing well rounded grains of sandstone of Kussak formation

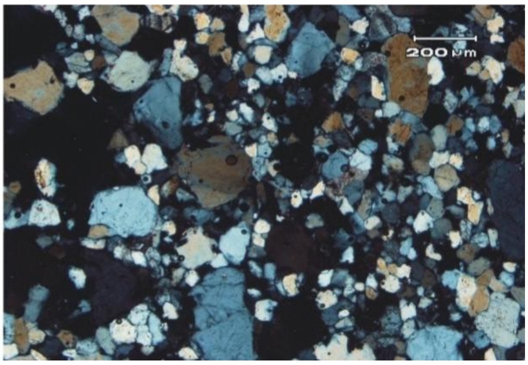

Fig. 4.6: Photomicrograph showing poorly sorted grains of sandstone of Kussak formation

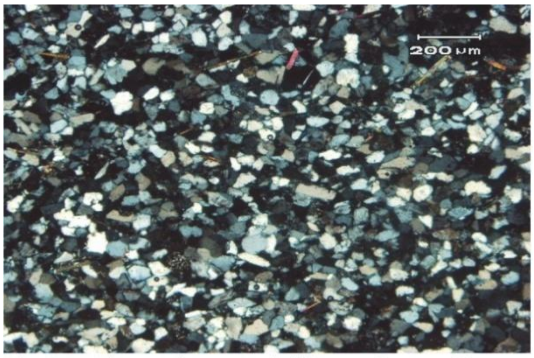

Fig. 4.7: Photomicrograph showing well sorted grains of sandstone of Kussak formation

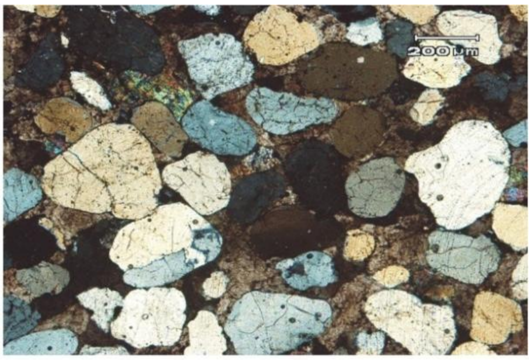

Fig. 4.8: Photomicrograph showing cement supported sandstone

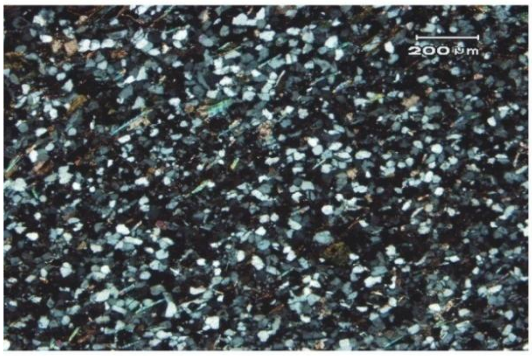

Fig. 4.9: Photomicrograph showing grain supported sandstone in upper part of Kussak formation

3.2.1 Quartz

The most abundant framework grain that is observed in Kussak Formation's sandstone is quartz (Fig. 4.23). Monocrystalline and polycrystalline quartz are observed in thin sections. Quartz percentage ranges from 67.4% to 95.6% while the mean value is 85.1% in whole sandstone composition. The percentage of non undulose monocrystalline quartz is more abundant as compared to other varieties of quartz. Monocrystalline quartz (Fig. 4.10) ranges from 67.1% to 94.4% in whole rock composition, while its mean value is 84.2% (Table 3.1). Undulose monocrystalline quartz variety (Fig. 4.11) is less abundant i.e. 0% to 2.3% with mean value of 1.2%.

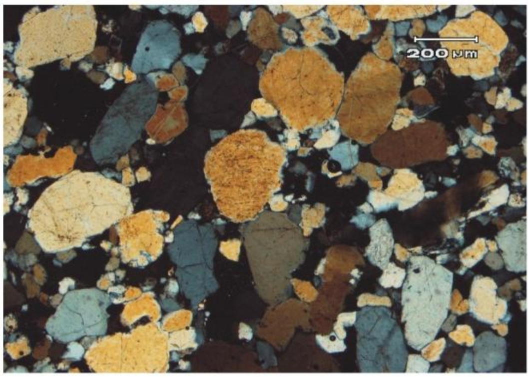

Fig. 4.10: Photomicrograph showing monocrystalline quartz of Kussak formation

Fig. 4.11: Photomicrograph of undulose monocrystalline quartz of Kussak formation

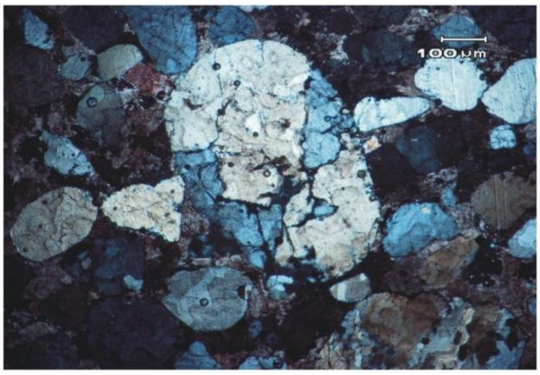

Fig. 4.12: Photomicrograph of polycrystalline quartz of Kussak formation

Polycrystalline quartz (Fig. 4.12) exists in low percentages and ranges from 0% to 1.3% and its average value is 0.23%.

3.2.2 Feldspar

Feldspar is present in minor amount. Feldspar percentage ranges from 0.9% to 2.9% in whole rock composition, while the mean value is 1.4%. Feldspar is present as plagioclase (Fig. 4.13) and K-feldspar (Fig. 4.14). Both are distinguished on the basis of their optical properties. K-feldspar percentage ranges from 0.32 to 2.3% while the mean value is 1.20%. Plagioclase percentage ranges from 0 to 0.9% while the mean value is 0.22%. Plagioclase presence is less than K-feldspar (Fig. 4.23). The distribution of feldspar is even throughout the Formation.

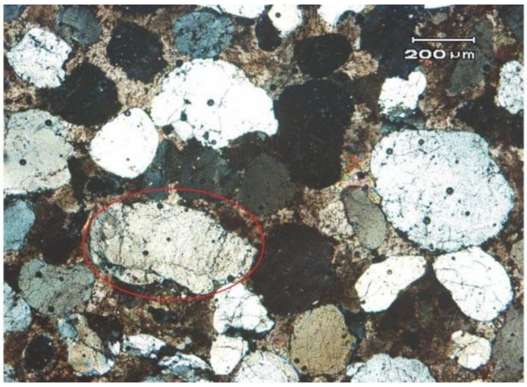

Fig. 4.14: Photomicrograph showing K-feldspar present in sandstone of Kussak formation

3.2.3 Lithic Fragments

Lithic Fragments such as chert (Fig. 4.15) and igneous lithic fragments (Fig. 4.16) are observed in the sandstones of Kussak Formation; their percentage in whole rock composition ranges from 0% to 1.9%, while the mean value is 0.32%. Chert percentage in whole rock composition ranges from 0% to 0.6%, while the mean value is 0.13% (Table 2). Igneous lithic fragment percentage in whole rock composition ranges from 0% to 1.3%, while the mean value is 0.2%. Presence of chert is almost same throughout the Formation.

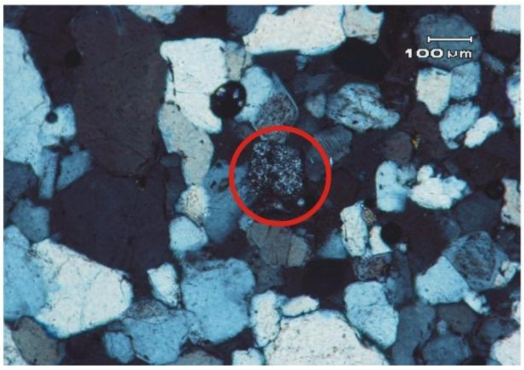

Fig. 4.15: Photomicrograph showing chert as lithic fragment in Kussak formation

Fig. 4.16: Photomicrograph showing volcanic lithic fragment in central part of Kussak formation

3.2.4 Cements

The frame work grains are cemented with calcite (Fig. 4.17), silica (Fig. 4.18) and less amount of iron oxide (Fig. 4.19). Calcite cement concentration in the whole composition of sandstone is ranging from 0% to 22% with a mean value of 4.02%, silica cement ranges

Table 2: Quantitative description for different constituents identified during petrographic analysis of 30 samples; Q_m (mono crystalline Quartz), Q_p (Polycrystalline Quartz), Q_{un} (Undulose Quartz), K-Feld (Potassium Feldspar). Plag (Plagioclase Feldspar), Lt (Lithics), Mica, FeO (Iron oxide), $CaCO_3$ (Calcite), SiO_2 (Silica), Glauco (Glauconite), n (Porosity) and Op (Opaque minerals)

	Quartz				Feldspar				Cements					
Sample no.	Q_m	Q_p	Q_{un}	Ch	K-Feld	Plag	Lt	Mica	$CaCO_3$	FeO	SiO_2	Glauco	n	Op
1	93	0	1.9	0.3	1.9	0	0	0	0	0.3	0.3	0	2.3	0
2	87.5	0	1.6	0.6	2.3	0.6	0	0	4.3	0.6	0.6	0	1.9	0
3	90.8	0	0.3	0	2.3	0	0	0	0	4	0	0	2.6	0
4	93.8	0	1.5	0.6	2	0.3	0	0	0	0.6	0.3	0	0.9	0
5	90.3	0	2	0	1.6	0.3	0	0.3	1.3	0.6	1.6	0	2	0
6	90.4	0	1.9	0.3	2	0.6	0	0	1.9	0.3	1.3	0	1.3	0
7	94.4	0.9	0.3	0	1.3	0	0	0.3	0	0	0.9	0	1.9	0
8	93.5	0.3	0.3	0	1	0	0	0	0	0.9	2	0	2	0
9	93.7	0.9	0	0	0.9	0	0	0.3	0	1.3	0.6	0	2.3	0
10	93.2	0.3	0	0	1	0.3	0	2	0.3	0	0.3	0.6	2	0
11	87.3	1.3	0.9	0	1	0	0	0.6	0	1.9	1	2	4	0
12	87	0.9	0	0	0.9	0	0	0.6	0	0.3	2.7	4	3.6	0
13	86.7	0.6	0.3	0	1.3	0.3	0	1	0	0.6	2.3	3	3.9	0
14	85.4	1.3	0.6	0	1.6	0	0	1.3	0	1.3	1.9	3.3	3.3	0
15	75.6	0.3	0.3	0	1.3	0	0	1	13	0.6	1.3	2.3	4.3	0
16	67.1	0	0.3	0	0.6	0	0.6	0.9	22	0.3	0.6	2.6	5	0
17	67.2	0	0.3	0	1	0	0.3	1.3	15	0	1.6	8	5	0.3
18	76.9	0	0.6	0	1.3	0	0.9	0.3	6.5	0	1.3	7.3	4.6	0.3
19	69.8	0	0.9	0	0.9	0	1.3	4.6	10	0	0.9	6.3	5.3	0
20	69.2	0	0.3	0	1.3	0	1.9	3.3	11.3	0.3	0.3	7.9	3.9	0.3
21	73.4	0	0.6	0	1.6	0.3	0.6	3.3	9.3	0.6	1.3	4.7	4.3	0
22	78.6	0	0.3	0	0.9	0.3	0.3	2.9	5.4	1.3	1.6	3	5.1	0.3
23	78.7	0	0.6	0	0.6	0.3	0	2.9	6.9	0.3	0.9	1.9	6.9	0
24	78.8	0	0.3	0	0.9	0	0	3.6	7.3	0.9	0.6	1.6	6	0
25	84.2	0	0.9	0	1.3	0.3	0	3.6	1.3	0.6	1.3	1.6	4.9	0
26	87.5	0	0.3	0.3	0.9	0.6	0	2.6	0.6	0.3	0.3	1.3	5	0.3
27	85.8	0	0.6	0.6	0.6	0.7	0	1.9	0.6	1.3	0.6	0.3	7	0
28	85.6	0	0.9	0.3	0.3	0.9	0	1.3	0.3	1.6	0.9	1.6	6.3	0
29	89.5	0	0.3	0.6	0.9	0.6	0	1.9	1.3	0.3	0.3	0.3	4	0
30	91.1	0	0.9	0.3	0.9	0.3	0	1.3	1.9	0.9	0	0.3	2.3	0

from trace amounts to 2.7% and mean value is 0.99% in whole rock composition and iron oxide in whole rock composition ranges from 0% to 4% and mean value is 0.73%. Calcite cement is present more than quartz cement and quartz cement is more than iron oxide. Calcite cement is prominently present in the middle part of the Formation but it's not absent in any part of the Formation. Iron oxide/hydro oxide is distributed evenly in the Formation but its presence at the bottom of the Formation is slightly stronger.

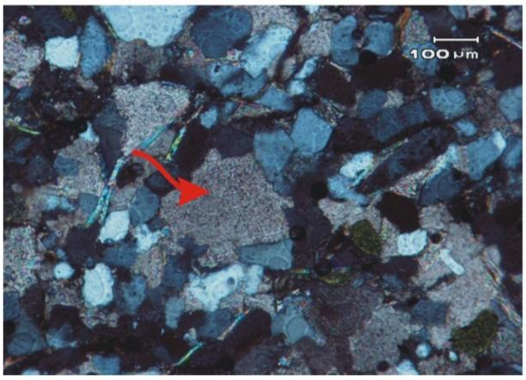

Fig. 4.17: Photomicrograph showing the calcite cement (red arrow) which has glued the framework grains

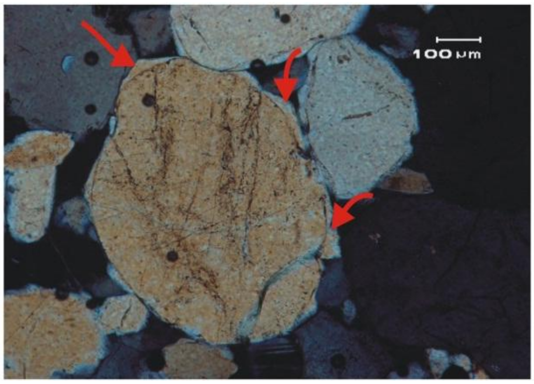

Fig. 4.18: Photomicrograph depicting silica cement (red arrows) in Kussak formation

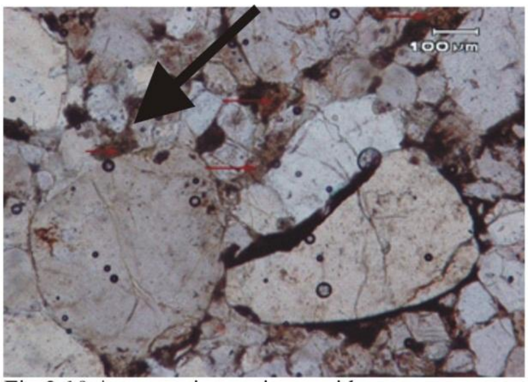

Fig. 4.19: Photomicrograph showing iron oxide cementation (black arrow) in Kussak formation

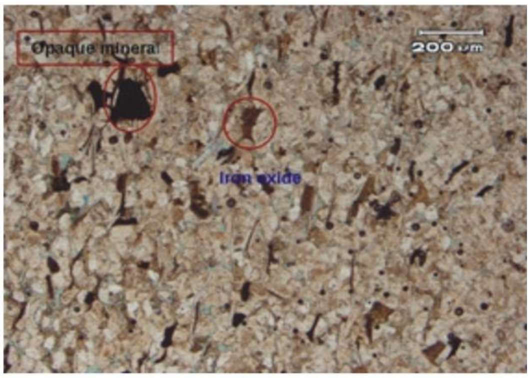

Fig. 4.20: Photomicrograph showing opaque mineral along with iron oxide in Kussak formation

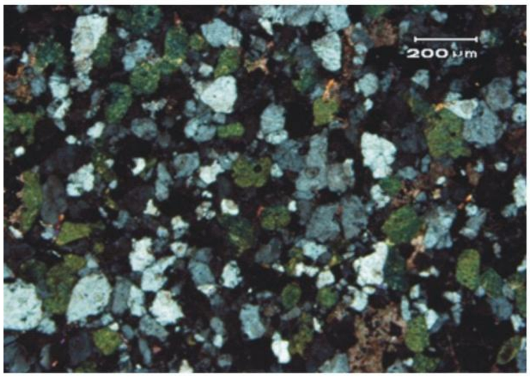

Fig. 4.21: Photomicrograph showing greenish glauconite grains in upper part of Kussak formation

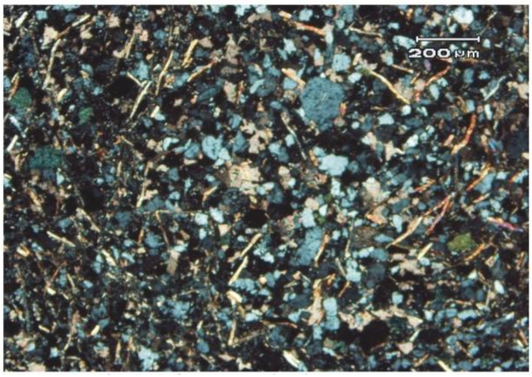

Fig. 4.22: Photomicrograph showing mica flakes in upper part of Kussak formation

Silica cement is evenly distributed in the whole Formation but in the central part of the Formation it's more abundant than other parts of the Formation.

3.2.5 Accessory minerals

Accessory minerals are present and include opaque minerals (Fig. 4.20), Glauconite, (Fig. 4.21) and micas in thin sections. Opaque minerals presence ranges from 0% to 0.3% and mean value is 0.05% in whole rock composition. Glauconite presence in whole rock composition range from 0% to 8% and mean value is 2.13%. Mica ranges in whole rock composition from 0% to 4.6% and mean value is 1.44. It is present in the form of flakes (Fig. 4.22). Opaque minerals and mica are present throughout the Formation though the amount of mica slightly increases towards the top of the Formation, Glauconite is not present at the bottom of the Formation, but it is highest in middle part of the Formation, and gradually starts to decline toward the top of the Formation.

3.3 Provenance analysis of Kussak Formation

The detrital composition of clastic rocks is significantly related to tectonic setting of their source area [28]. In provenance measurement, data from detrital modes of sandstones often provide key information [17]. Sediment composition is controlled by source rock characteristics, relief, climate, transport systems, depositional mechanisms, and diagenetic transformations [5, 18, 20]. The relationship between plate-tectonic settings and development of basins, relief, transportation, palaeo-climatic and nature of provenance, etc. have been studied under petrography time to time [5, 19]. Based on McBride classification, the Kussak Formation is lithologically Quartz Arenite (Fig. 6.1).

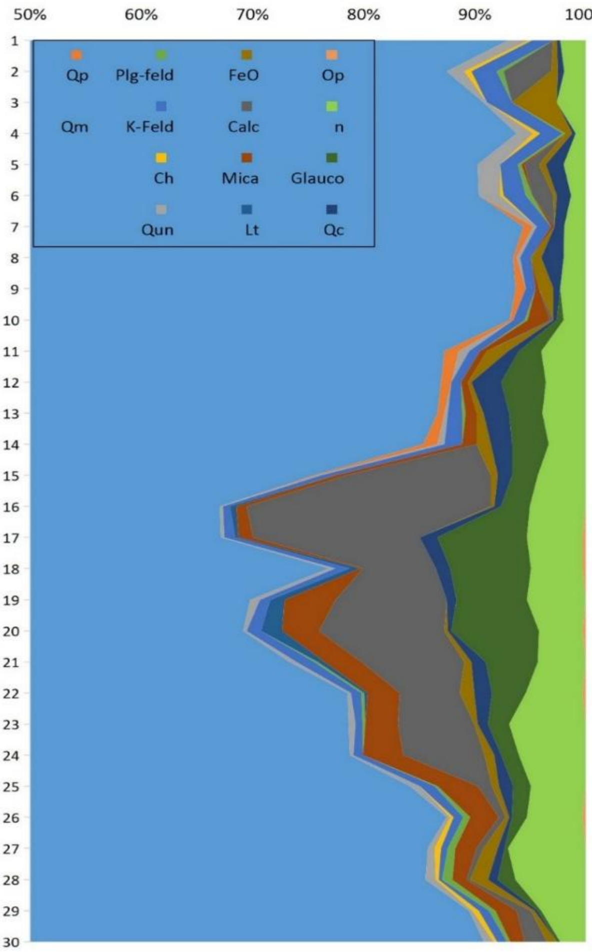

Fig. 5: Stacked percentage chart for different constituents identified during petrographic analysis. Most abundant element was Q_m (mono crystalline Quartz) that on average, makes up almost 90% of all constituents in petrographic analysis. Total Quartz content on each sample was weighted upto 98% on average due to presence of Q_p (Polycrystalline Quartz), Q_{un} (Undulose Quartz) and ch (chert). K-Feld and Plg-Feld (Feldspar) and Lt (Lithics) combined made up less than 4% of total constituents. Accessory minerals Mica, Glauco (Glauconite) and Op (Opaque minerals) made up less than 3% on average, of all constituents. FeO and Calcite cements were also identified during petrography

The point counts of detrital grains present in sandstone of Kussak Formation such as quartz, feldspar and lithic fragments including chert were recalculated into 100% (Fig. 5) to plot into a QmFLt triangular diagram. This was done to identify the source area of the Kussak Formation. Provenance shows us a Craton interior as a source area and petrographic studies suggest granitic composition of the source rock for sandstone of Kussak Formation. The source area for the sandstone of Kussak Formation is from cratonic interior of Indian shield (Fig. 6.2).

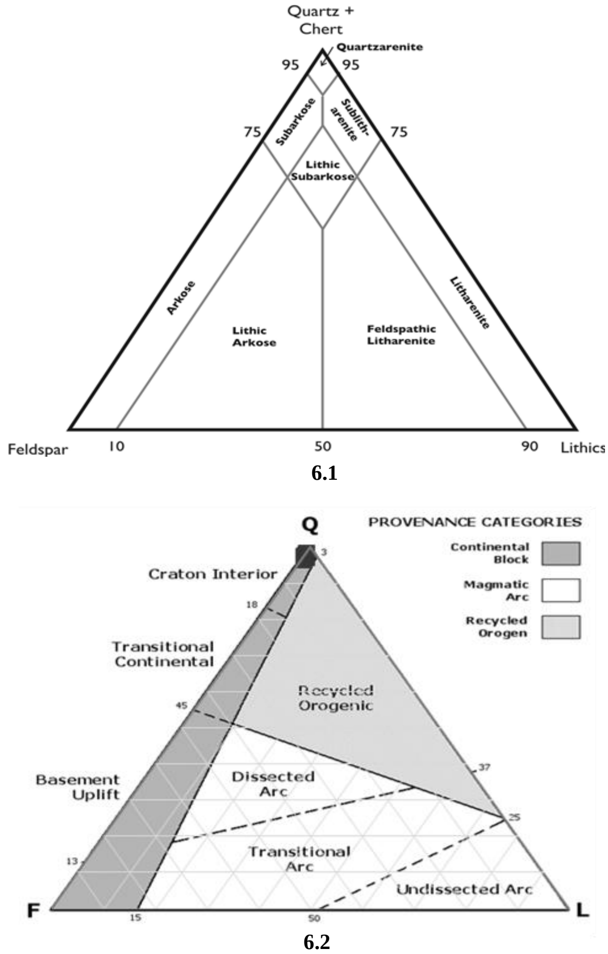

Fig. 6: QFL diagram for classification of petrographic data of Kussak formation. **(6.1)** McBride (1963) classification of Sandstone which classifies sandstone of Kussak formation as Quartz Arenite **(6.2)** Framework mode diagram designates craton interior source for Kussak formation [5, 19]

3.3 *Diagenesis of Kussak Formation:*

Petrographic studies, supplemented with chemical staining techniques, were used to decipher the diagenetic settings of the Kussak Formation from the studied section. The diagenetic features, identified and interpreted, are grain compaction, quartz outgrowth/ cements, alteration, replacement and dissolution of framework grains and precipitation of iron oxide cement.

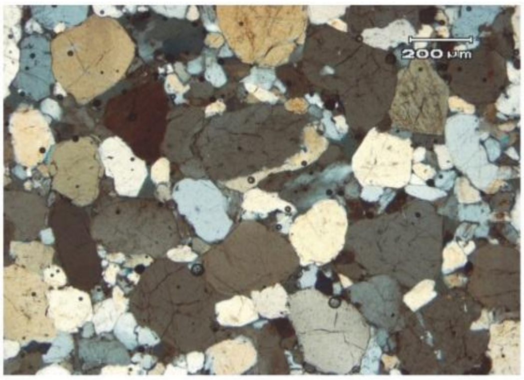

Fig. 7.1: Mechanical compaction evident by straight and concavo-convex grain contacts

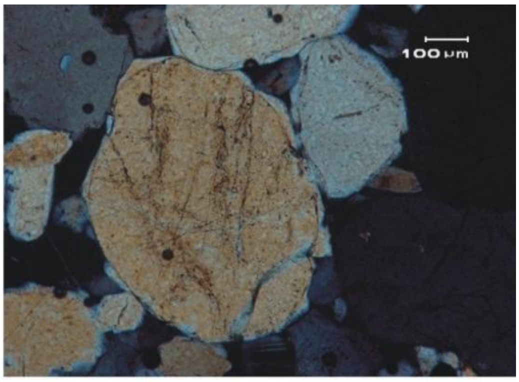

Fig. 7.2: Photomicrograph depicting quartz outgrowth in Kussak formation

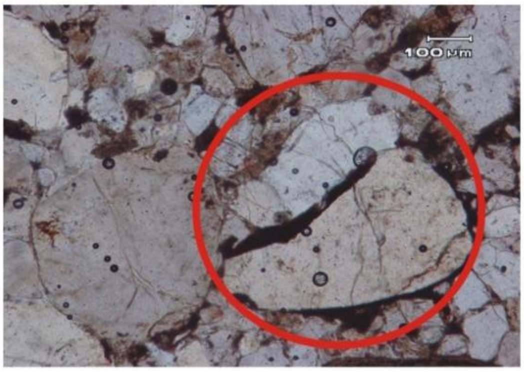

Fig. 7.3: Photomicrograph showing iron oxide cementation sandwiched between two grains (XPL)

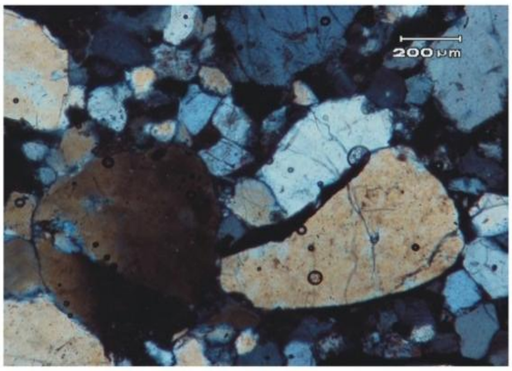

Fig. 7.4: Photomicrograph showing iron oxide cementation sandwiched between two grains (PPL)

3.3.1 Grain Compaction

Most sediments deposited under normal surface conditions have primary porosities on the order of 30% to 70%. Physical grain compaction in terms of tighter grain packing is observed as long and concavo convex grain contact of frame work grains with neighboring grains (Fig. 7.1), this grain compaction is the result of intense over burden during progressive burial of sandstone of Kussak Formation. It resulted in the reduction of the primary porosity of the sandstone of Kussak Formation. Chemical compaction (pressure solution) is evident by the precipitation of quartz cement at places of less pressure (Fig. 7.2). Mechanical compaction was ongoing till the later stages of diagenesis of sandstone of Kussak Formation. This is evident by sandwiched iron oxide cement in two tightly packed frame work grains (Figs. 7.3 and 7.4).

3.3.2 Cementation

Cement is an important diagenetic feature of the carbonate sediments, which endows strength and stability to sediment. The well-developed cement, always, resists physical, as well as, chemical compaction and fracturing episodes, if any. It is a major and must-occurring diagenetic process and takes place as per provision of favorable Pressure-Temperature and kinematic conditions and in the presence of super saturated pore fluids with even geochemical composition in the prevailing diagenetic setting [29]. The cement phases, which happen to be there in the geologic past of Kussak Formation, produced a diverse range of cement types. The identified types in the present study are iron oxide cement (Fig. 4.19), carbonate cement (Fig. 4.17) and outgrowths of quartz (Fig. 4.18). Precipitation of the carbonate and quartz cement reduced the primary porosity of sandstone. Massive calcite cementation (Fig. 7.5) occurred in the middle part of the Formation, which ultimately reduced the effect of compaction.

3.3.3 Replacement and Dissolution of framework grains

Replacement generally occurs by formation of new minerals that replace pre-existing minerals, while dissolution is a process in which rocks and minerals are dissolved by action of a fluid. In case of Kussak Formation, dissolution of the framework grains occurred during the diagenesis of the Formation, framework grains including quartz and feldspar were completely and partially dissolved and replaced by later formed cements (Fig. 7.6, 7.7). Some of the coarser grains from the bottom of the Formation are fractured (Fig. 7.9), which were later filled by calcite cement.

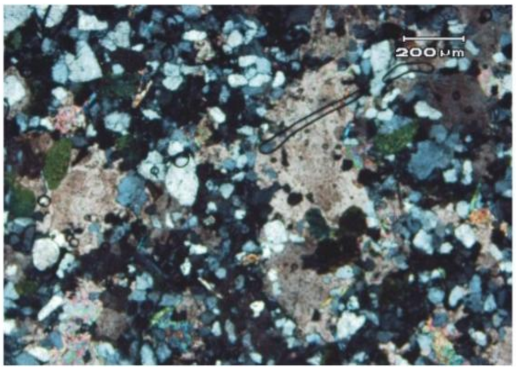

Fig. 7.5: Photomicrograph showing the calcite cementation in sandstone

Fig. 7.6: Photomicrograph depicting complete dissolution of framework grains by carbonate cement

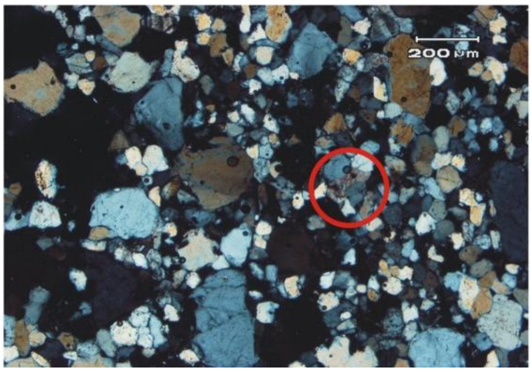

Fig. 7.7: Photomicrograph depicting partial dissolution of framework grains by carbonate cement

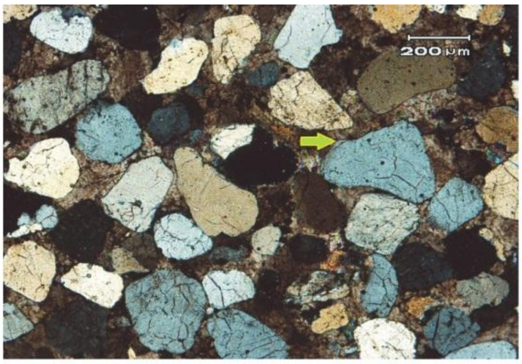

Fig. 7.8: Photomicrograph showing quartz outgrowth (yellow arrow) in Kussak formation

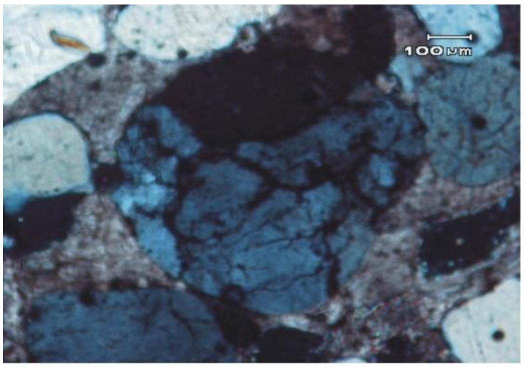

Fig. 7.9: Photomicrograph showing emplacement of calcite cement in fractures of central framework grain (XPL)

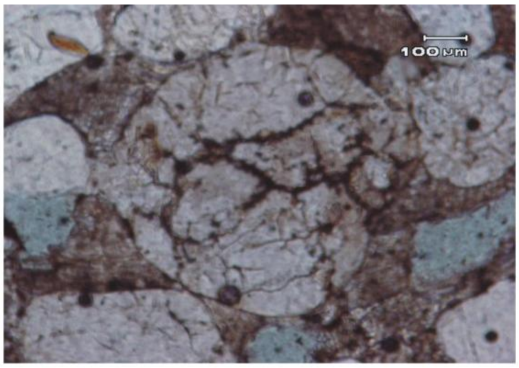

Fig. 7.10: Photomicrograph showing emplacement of iron oxide cement in fractures of central framework grain (PPL)

3.3 Diagenetic History Reconstruction of Kussak Formation

Diagenesis of the Kussak Formation sandstone started with mechanical reduction of the primary porosity due to overburden, as indicated by long, concavo-convex and sutured grain contacts (Fig. 7.1). Furthermore, cementation of the grains through iron oxide precipitation and development of quartz outgrowths (Fig. 7.2), followed by second cycle of precipitation of Iron oxide is evident by sandwiched iron oxide cement in between tightly packed framework grains (Figs. 7.3, 7.4). Porosity was further reduced by the precipitation of quartz and carbonate cement (Fig. 7.5). Quartz cement had started to precipitate in open pore spaces before massive cementation of calcite. Quartz cementation occurred after this phase, which is evident by the embedment of poorly-developed quartz outgrowth in calcite cement (Fig. 4.32). The calcite cementation took place in the central part of Kussak Formation, as indicated by the extreme values of calcite (Table 1). This massive calcite cementation started the dissolution of frame work grains, and caused their partial to complete dissolution. Dissolution of frame work grains by calcite triggered the precipitation of quartz cement for the second time. This was followed up by last episode of the diagenesis, in which fracturing of the grains took place due to tectonic forces. Filling of

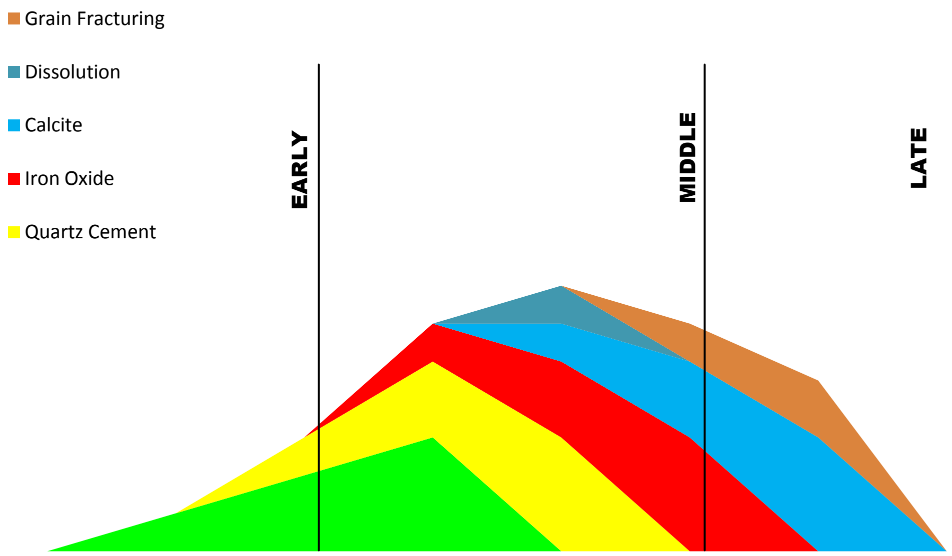

Fig. 8: Chronologic diagenetic history reconstruction model created using petrographic data, depicting different phases of diagenesis over relative time

fractures of the frame work grains by calcite portrays that calcite precipitation was going on as fracturing was taking place. (Fig. 4.33, 4.34). Paragenetic sequence of sandstone of Kussak Formation is shown in Fig. 8.

4. Conclusions

Following conclusions are attributed to this study:

- The Sandstone of Kussak Formation in Eastern Salt Range is fine to coarse grained, with poor to well sorting.
- The Kussak Sandstone predominantly consists of quartz, along with feldspar, lithic fragments, accessory minerals and traces of heavy minerals. Class of sandstone of Kussak Formation is quartz arenite, as indicated by the detrital mineralogical composition of sandstone i.e. quartz (including chert), feldspar and lithic fragments.
- Mineralogically, sandstone of the Kussak Formation is mature but in terms of texture it seems to be sub-mature to mature.
- The modal mineralogical composition, optical properties, provenance studies and relative abundance of different types of quartz grains and the nature of heavy minerals all suggest sediment derivation of the Kussak Sandstone from a source region dominated by a plutonic igneous rocks i.e. Indian Craton.
- The major cementing material present in the Kussak Formation is calcite, silica as quartz overgrowth, along with iron oxide.
- Important diagenetic events noted in the Kussak sandstone, chronologically, are compaction, silica cementation, iron oxide cementation, calcite cementation, replacement and dissolution.
- Glauconite occurs in the Kussak Formation, but its distribution is restricted to the middle and uppermost part of the Formation. The Glauconite is indicative of slightly reducing near-shore, shallow water conditions.

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