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Petrofacies investigations of the Cretaceous Pab Formation Rakhi Gorge Eastern Sulaiman Range Pakistan - Implication for reservoir potential

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Abstract: Petrologic investigations of the sixty representative thin sections from the Pab Formation within Rakhi Gorge section Eastern Sulaiman Range Pakistan have been used to characterize different diagenetic patterns, identification of primary composition and reservoir characters. Sublithic, lithic and quartzose sandstones have been the principal constituents of the formation. The processes responsible for the late-stage alteration and diagenetic processes identified during the petrographic study include compaction of lithic fragments and mud clasts, formation of quartz overgrowth structures, feldspar replacement and alteration, cementation, and replacement of grains by clay minerals other ferrous elements and diagenetic minerals. The study shows that the initial porosity has been primary intergranular, but the secondary porosity has been originated in the rocks as a result of the alteration of the primary and secondary constituents, as well as fracturing. These facies characters replicate the reservoir quality including, good, medium, low-quality, and non-reservoir. Samples displaying average total porosity greater than 10 % have been declared as good quality. While rocks samples having 7 % or greater porosity are grouped as a medium reservoir. Those samples consisting of porosity values between 1 and 4% are considered as a low quality reservoir while those samples having porosity ranges low than 1% have been called non-reservoir. Based on the investigated parameters the studied samples from the Pab Formation displayed the characters of a medium reservoir that may hold significant hydrocarbon. This different quality including good and low quality zonation can be attributed to the facies and diagenetic change in the formation.

Keywords: Reservoir, Pab Formation, Cretaceous, diagenesis, petrography

INTRODUCTION

Sandstone reservoir rocks have been studied by different authors (Ahmad *et al*., 2020) concerning its hydrocarbon potential and the processes responsible for the generation of porosity. Some researchers have proposed that the porosity generation in hydrocarbon reservoirs has been attributed to the processes responsible for the replacement of grains and cement (Estupiñan *et al*., 2010). Clastic deposits of the Cretaceous Pab Formation have been considered as important hydrocarbon reservoirs in south-west Pakistan (Sultan & Gipson, 1995; Beswetherick & Bokhari, 2000; Hedley *et al*., 2001). In Pakistan a lot of work has been carried out in the field of sedimentology and stratigraphy however petrographic studies focusing on reservoir properties in different basins are not enough, and the Middle Indus Basin is not an exception (Qureshi *et al*., 1996). Pab Formation in different geographic locations has been focused by different authors on the regional stratigraphic architecture, sedimentology, and interpretation of depositional systems (Eschard *et al*., 2002). These studies are important in terms of understanding the macroscopic reservoir and textural characters of reservoir potentials. Diagenetic alteration and understanding the processes that govern the reservoir quality are very important in the interpretation of a reservoir for its hydrocarbon potential (Bloch & Helmold, 1995; Morad *et al.*, 2000; Ketzer *et al*., 2003). Dissimilarities in the pathways of diagenetic progression are attributed to: depositional facies, depositional porosity, permeability characters, differences in intrabasinal grains, degree of bioturbation (0 to 6), sand composition and thermal history of the basin (Morad *et al.*, 2010). It is obvious that the diagenetic processes result in the complexity of the reservoir properties and mineral assemblages and is some time can lead to the production or destruction of porosities (Morad *et al.*, 2000, Kassi *et al*., 2013). This research work is therefore aimed to investigate the petrologic characteristics of the Pab Formation, the digenetic characters, and the quality of the reservoir based on these properties. Reservoir porosity has a direct relationship with the diagenetic changes and amount of the constituent's particles. The petrologic study of the Pab Formation will

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help in understanding the reservoir petrofacies with respect to its diagenetic characters and reservoir properties.

GEOLOGICAL SETTING

Geodynamic reconstruction of Pakistan shows that the paleo-margins of the south-west and the south-south-east have been derived in the Late Jurassic as a result of the separation of Indo-Pakistan, Madagascar and African Plate (Alleman, 1979; Besse & Courtillet, 1988). During the early to late Cretaceous period and separation from the Madagascar plate, the western border of the Indian Plate moved toward the north direction (Gnos *et al*., 1997). The western border of the Sulaiman Range is distinguished based on the suture zone comprising of the spasmodic outcrops of ophiolite deposits (Abbas & Ahmed, 1979; Gansser, 1979) and Mesozoic rocks fractured is linked with local faults (Wells, 1984). Earlier than the Maastrichtian period, the study area was defined by mud dominated distal delta front slope environment deposits of the Mughal Kot Formation (Fitzsimmons *et al*., 2005). A broad shelf semi-humid climate with an insignificant amount of the clastic input grades into storm-wave effected carbonate ramp of the Fort Munro Formation throughout Late Campanian-Earliest Maastrichtian time. As a result of the major fall in the regional base level, the carbonate deposition was unexpectedly ended by storm-wave subjugated fluvio-deltaic deposits enriched by the fluvial system through the Early Maastrichtian times. The Indian plate during the Late Maastrichtian time passed over a hot spot that instigated the thermal doming and succeeding prompted erosion of the Indian Craton (Hedley *et al*., 2001). A third-order depositional sequence was responsible for the deposition of the Pab Formation (Eschard *et al*.. 2002) (Figure 1). Deltaic deposits of the Pab Sandstone during Paleocene were replaced by a fluvial controlled deltaic environment of the Khadro Formation as a result of the substantial changes in the Paleo-environmental situation of Northern Indian

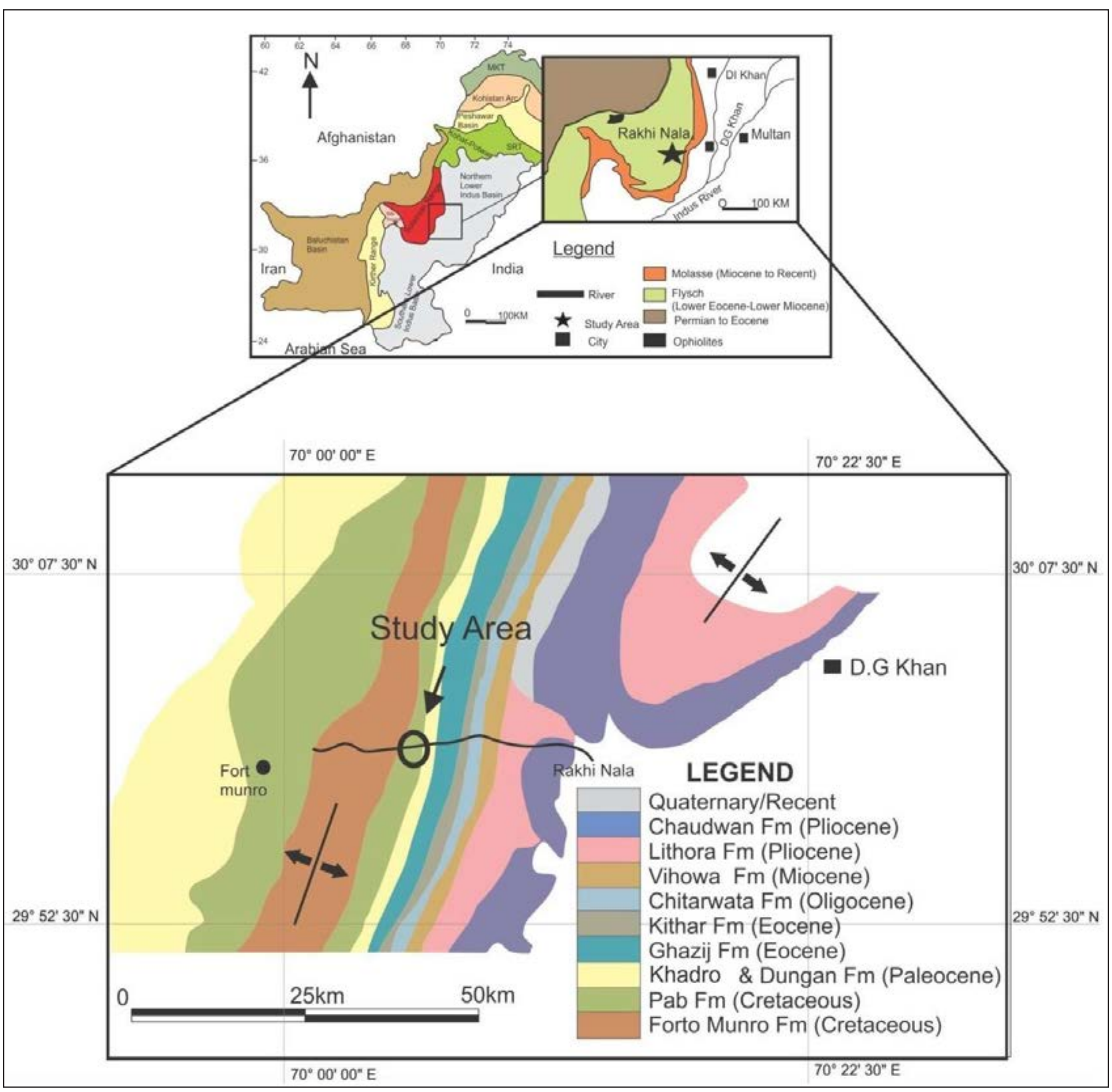


Figure 1: Map showing geographical location and different formations present in the study area.

shoreline. Clastic deposition inputs have been terminated through Early Eocene as a result of the major rise in base level in the heading to the deposition of Dungan Formation.

Collisional movements due to the Chaman fault (strike-slip fault) and the south-ward thrusting of the western boundary of the Indo-Pakistan plate have caused in the formation of the Sulaiman Range which is an extensive thrust belt situated in the south-west of the Himalayas (Lawrence & Yeats, 1979). This geologic region is situated on a transitional crust of the previously passive margin of the India, which rammed with the Afghan block on the western side through the Late Cretaceous or Paleocene (Lawrence & Yeats, 1979).

DATA AND METHODS

Comprehensive petrographic studies were carried out on 60 thin sections from the Rakhi Gorge section. The thin sections were prepared with epoxy-impregnated samples. Characterization of the primary petrographic properties and diagenetic ingredients were studied by calculating 400 point counts per section, with the help of Gazzi & Dickinson method. Microsoft Excel was used for the statistical analysis of the data. For description of diagenetic events the terms eogenesis, mesogenesis, and telogenesis were used. Eogenesis process consists of the processes which happened under the control of depositional fluids, at a depth of about 2 km and low temperatures (about 30 and 70 °C). Processes and reactions involving water formation at relatively higher temperatures (70-200 °C) and effective burial conditions are termed as Mesogenesis. There are further subdivisions of the mesogensis depending upon the depth, temperature, and the thermal gradient of the area. The uplifting processes of the sedimentary rocks to surface environments can be associated with telogensis. Reservoir petrofacies concept used in this research has been followed after DeRos *et al.* (2010). This method comprises the grouping of the samples on the basis of statistical similarities, similar petrographic character that affects the quality of the reservoir, texture characters, diagenetic constituents, and porosity estimation.

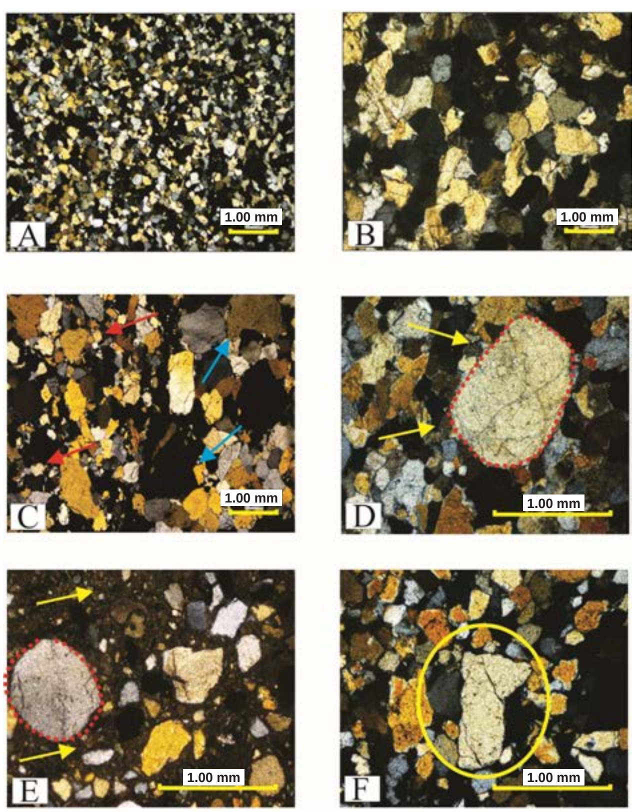


Figure 2: Textural variation and structure of the studied samples. (A) Very fine-grained, wellsorted, massive sandstone (crossed polarizers, XP); (B) Fine to medium sandstone (XP); (C) Medium grained, very poorly-sorted, massive sandstone (XP); (D) Coarse subrounded quartz grain with quartz overgrowth structure at the edges; (E) Mud Argillaceous intraclasts; (F) Fractured coarse grain angular quartz.

RESULTS

Structures, textures, and fabric

Investigated sandstones samples are fine to coarse grained (Figure 2). Deformational structures include intense bioturbation, load cast, and vertical fractures throughout the formation. Localized concretion sand fractures, sometimes filled by secondary sediments and mineral, maybe also present. The sandstone texture is moderately to well-sorted, dominantly well sorted (Figures 2A to D); angular to rounded, predominantly subrounded; while some grains showing extraordinary sphericity (Figures 2D and 2E). Quartz overgrowths and compaction pattern of the grains can be attributed to late stage processes (post depositional processes). Grain orientation is not the same and has differences in different samples.

Primary composition

The primary component is typically quartzose, with quartz arenite and rare sub-litharenites (Folk, 1968; Figure 3). The diagenetic processes, including kaolinization of feldspar and other metamorphic fragments resulting in

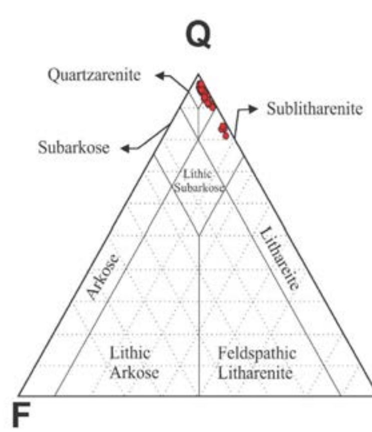


Figure 3: Detrital composition of sandstones plotted in Folk (1968) diagram. Red circles are samples from outcrop (Pab Formation).

more quartzose configurations, these changes effected the primary composition. Quartz grains are dominantly monocrystalline (average: 95.21.41%; maximum: 98.83%, Figure 2C) and polycrystalline (average: 0.73%; maximum: 11.66%). Plagioclase feldspar is rarely present (average: 0.02%; maximum: 0.33%), and it is commonly altered to clay minerals. Concentration of rock fragments are scarce, mainly of metamorphic and igneous origin (Figure 2D) (average: 0.04%; maximum: 0.39%), Chert is present about 0.47%; maximum: 3%. Other sedimentary rock particle consisting chert (averaging: 2%; maximum: 7%). Iron oxide is occurring in the form of hematite and limonite (average: 1.03%; maximum: 6% and limonite average: 0.36; maximum: 3.5%). Intra basinal constituents are clay/mud (average: 1.64%; maximum: 13.34 %, Figure 2F). These sediments are commonly found in deform condition as a result of compaction and occasionally destructed or replaced by kaolinitization. Carbonate cement is infrequent and is present in the form of calcite (average: 0.44; maximum: 1.25%). Sediments that have not been identified properly were present scarcely averaging 0.03 with a maximum number of 0.93%.

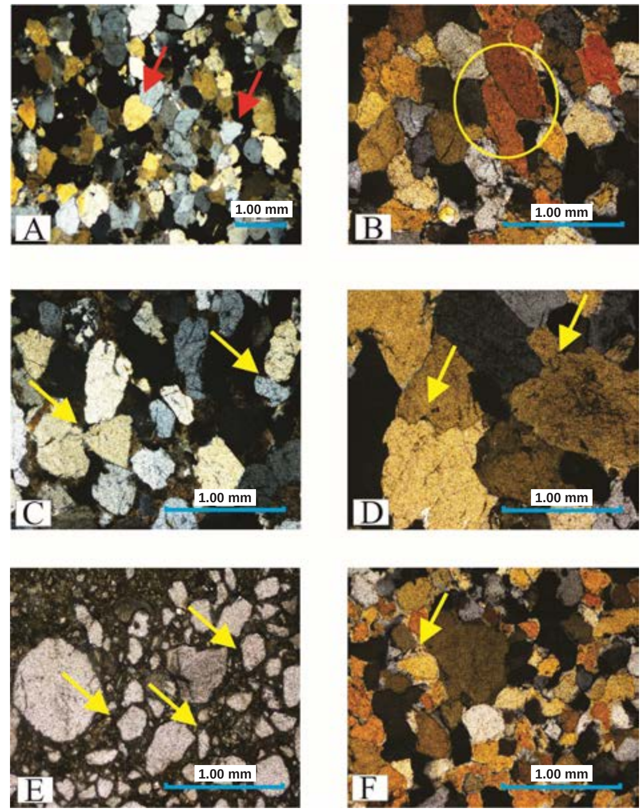


Figure 4: Diagenetic aspects from the Pab formation: (A) Conave-convex contact; (B) Plane contact; (C) Point contact (XP); (D) Intense compaction resulting in quartz suture contact; (E) Argillaceous pseudomatrix (XP); (F) Quartz overgrowth structure.

Diagenetic constituents

Diagenetic characters are important properties of the rock interpreting about the quality of the reservoir. In the present study the identified diagenetic characters includes, compaction of cratonic rocks fragments (Figure 3), quartz domination, minor feldspar overgrowth; cementation and replacement phenomenon, and formation of iron oxides. However these different characters are representing a different sequence and intensity of diagenetic event.

The intensity of diagenetic processes has led to the destruction of primary lithic fragments resulting in a more dominating quartz matrix (pseudo matrix). The origin of the pseudo matrix is related to the dominance of quartz which has occurred as overgrowths on mono-crystalline and poly-crystalline quartz grains (averaging: 4%; maximum: 13%). The late stage diagenetic processes, has resulted in the replacement of initially formed clay minerals resulting in the majority of quartz minerals (Figure 4C) (Baiyegunhi & Gwavava, 2017). Fragments of feldspar (both albite and K-feldspar) are occurring with an averaging less than 1%.. Crystal zonation is common in some samples. Pyrite is very rare, sometime replacing primary constituents (average: < 1%; maximum: 3%). Iron oxides (limonite and hematite) coats the grain margins thus limiting the quartz overgrowths. These also results in replacement of detrital grains (quartz, lithic fragments, and mud particles) and resulting in primary pore filling.

Porosity and compaction

The porosity in the studied sandstone is mostly primary in origin and intergranular type porosity principally (average: 4%; maximum: 19%, Figure 5A), however secondary porosity is also identified in some samples resulted from dissolution or grain fracturing. Though the intial porosity is intergranular but secondary porosity can be attributed with the dissolution of primary particles, (Figure 5) these rock particles consisting of low grade lithic fragments, chert, mud clasts, orthoclase and siliciclastic matrix of bioturbation. Dissolved diagenetic particle consists of mud dominating matrix and kaolinized fragments. Mechanical porosity is linked with fractures is scarce however the majority of original porosity in the rocks is destroyed because of overburden, and compaction, occurring as a part of late stage diagenetic events. The majority of bioturbation has been diagnosed in the formation on field bases which is also evident in the thin section resulting in excavation pores (Figure 5B).

The majority of the studied samples and thin sections have shown tightly packed fabric with less number of infrequently loose textures. The tightly packing of the sandstone grains exhibit mechanical compaction and local chemical compaction. Relationship between the compaction versus cementation and their subsequent relationship on primary porosity reduction is shown in the Ehrenberg's diagram (1989, Figure 6), which shows the intergranular volume (IGV) with cement percentage, consisting 25% of

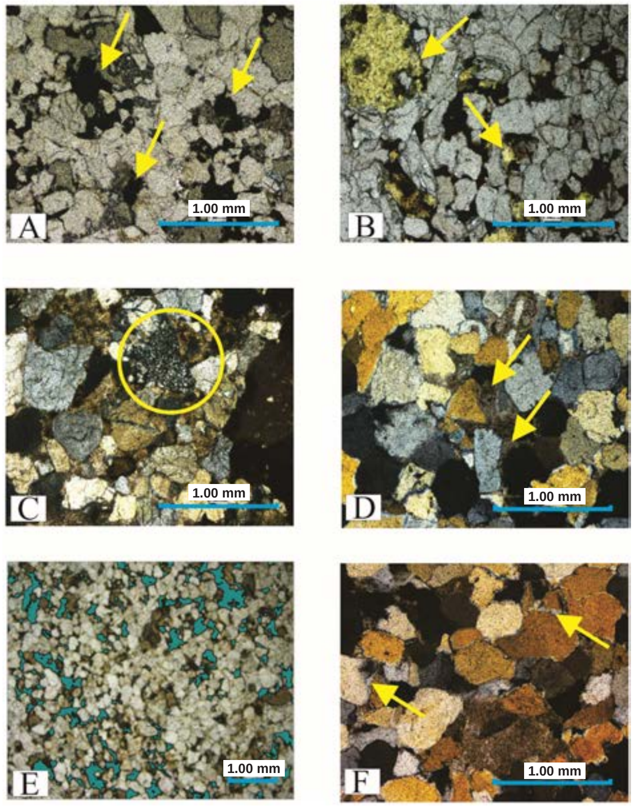


Figure 5: (A) Primary porosity widely preserved; (B) Argillaceous pseudomatrix and excavation pores; (C) Chert fragment; (D) Porosity reduction due to quartz overgrowth and dissolution of less competent clay minerals; (E) Preserved porosity (uncrossed polarizer); (F) Calcite cements resulting in porosity reduction.

the depositional (initial porosity) (Worden & Burley, 2003). Results shows that intergranular porosity are overrated for the samples analyzed since primary porosity is smaller than 40%. Ehrenberg's (1989) diagram designates that the primary porosity have been destroyed by mechanical compaction, not because of cementation. However the clay cementation as well as pseudo matrix generation has also resulted in intergranular porosity reduction (Figure 5B).

Reservoir petrofacies association

On the basis of petrographic investigation eleven reservoir petrofacies have been summarized these facies were grouped into four reservoir petrofacies associations (Table 1). These petrofacies associations are reflection of the reservoir quality (good, medium, low quality and fairly good-reservoir). Representative set of photomicrographs from studied samples have been grouped in Figure 7. Petrofacies association (Figure 7A) of good quality reservoir qualities comprising of medium to coarse grained sandstones, moderately to well sorted, with a primary composition consisting of quartz arenites and sublitharenites, and rare mud intraclasts (< 2%) and pseudo matrix (< 3%). Cementations in these rocks are averaging up to 15%, consisting of clay minerals (4-11%), and pyrite (< 1%). Primary intergranular porosity has been conserved, while the secondary porosity have attributed to be resulted from dissolutions (total porosity ranging from 12-19%). Petrofacies association (Figure 7B) comprising of good reservoir qualities includes medium to coarse grained quartz dominated sandstones, moderate to well sorted. The averaging total porosity is 8%, with a maximum of 10%. Petrofacies association consisting of low reservoir qualities (Figure 7C) includes

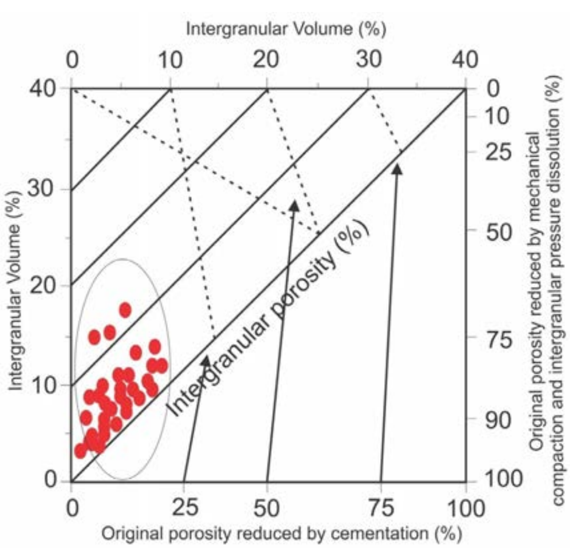


Figure 6: Ehrenberg (1989) diagram showing the relationship between intergranular volume and total cement, correlating the primary porosity reduction with cementation and/or compaction.

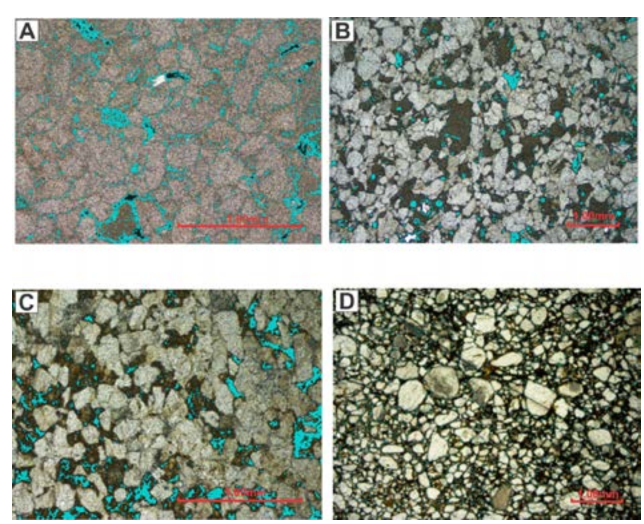


Figure 7: Reservoir petrofacies associations identified in the Pab Formation, based on petrological data. Photomicrographs of each association were taken with uncrossed polarizers. (A) Good-quality; (B) Medium-quality; (C) Low-quality; (D) Non-reservoir.

Table 1: Averages and maximum of main constituents with reference to porosities of the reservoir petrofacies defined for the Pab Formation.

Reservoir Petrofacies Associations	Poor-quality		Low-quality		Medium-quality						Good-quality											
Petrofcies	**1**		**2**		**3**		**4**		**5**		**6**		**7**		**8**		**9**		**10**		**11**	
Constituents and prosties	**Av.**	**Max.**	**Av.**	**Max.**	**Av.**	**Max.**	**Av.**	**Max.**	**Av.**	**Max.**	**Av.**	**Max.**	**Av.**	**Max.**	**Av.**	**Max.**	**Av.**	**Max.**	**Av.**	**Max.**	**Av.**	**Max.**
Total intraclasts	2.25	5.3	2.3	3.3	1.5	3.7	1.9	4.1	1.9	4.1	1.9	4.1	1.8	4.3	1.25	2	6.89	11	2.42	5.67	2.2	2.6
Total cement	13.8	20	5.1	7.2	10.1	18.3	11	13.3	11	13.3	11	13.3	10.1	12.9	13.8	20	3.22	1.67	1.75	12	0	0
Total matrix	1	.1.2	0.5	1	1.2	2	1.2	2.3	1.2	2.3	1.2	2.3	1.5	2.6	0.11	0	0	0	0	0	0.7	0.5
Total pseudo-matrix	1.5	3	3.3	6	9.84	2.3	8.4	2.6	8.4	2.6	8.4	2.6	7.4	2.8	1.5	3	8.45	3.3	1.41	3.66	0	0
Total ferrous content	2.16	8.65	10	12	11.5	13.7	10.6	12.5	10.6	12.5	10.6	12.5	8.6	11.4	2.16	8.65	3.32	4.31	22.6	33	1.2	0.9
Total authi-genic quartz	8.9	14.2	2.9	2.67	2.66	2.67	2.7	2.5	2.7	2.5	2.7	2.5	3	2.9	3.05	8.83	13.3	3.66	2.67	4.68	8.9	14
Intergranular kaolinite / total kaolinite	0.52	0.86	.9	0.4	0.39	0.5	0.39	0.4	0.39	0.4	0.39	0.4	1.39	0.6	0.24	0.43	0.52	0.86	0.3	0.7	0.1	0.21
Total porosity	0.9	1	1.4	2.5	6.5	7.1	7.1	6.9	7.1	6.9	7.1	6.9	10.5	8.2	11	8.9	12	17.4	19	17	6.9	8
Intergranular porosity / total porosity	0.5	0.1	0.7	0.72	0.9	10	0.9	0.8	0.9	0.8	0.9	0.8	1.1	0.9	0.51	1	0.17	0.92	0.98	1	0.8	1

fine to medium grained sandstones, poorly to well sorted, having quartz dominating litharenite and sub-litharenite in the primary composition, with abundant mud clasts (about 6%) and pseudo matrix (about 15%). Overall assessment of the cement constitutes for about 14%, with quartz as cement (3-6%), Clay minerals as cement (0-5%). Primary and diagenetic constituents have been replaced by some clay minerals. Pseudo matrix generation has resulted in the reduction of the primary porosity. Grain dissolution of less competent grains has been resulted in the formation of minor secondary porosity. The total average porosity is 4%, with a maximum of 7%. Petrofacies association with non reservoir properties consisting of very fine to medium grained sandstones, poorly sorted, with dominant matrix, incipient bioturbation, mud intraclasts (about 8%), and matrix (about 21%) (Figure 7D). Sum of all the porosity, originating from secondary processes including dissolution of the incompetent grains and fracturing (average total porosity is about 2%, with a maximum of 4%). The good-quality reservoir petrofacies association is characterized by average total porosity above 14%, whereas the medium association represents total porosity values above 8%. The dominant porosity in these good and medium reservoirs is intergranular. The low quality petrofacies association shows average total porosity between 1 and 5%, while the non-reservoir having less than 1%.

Establishing a relationship between the kaolinitization process and the total porosity, it has been rarely identified the presence form. Since kaolinite has replaced low grade rock fragments, feldspar, and other rock particles. Mud and argillaceous contents are generally deformed by mechanical processes and sometimes replaced by kaolinite.

DISCUSSION

Diagenetic patterns have been derived from the observed petrographic characteristics and textural variations among the primary and diagenetic elements (Figure 8). Figure 8 demonstrates the different processes and diagenetic stages.

Deep buried sandstones and their evolution have a direct relationship with evolution and late-stage alterations (Morad *et al.*, 2010). Digenesis associated with deeply buried sandstone (burial diagnosis) can be associated with the degree of the fluid flow through pores spaces present in rock. Some eogenetic processes have also detected, including the dissolution of the primary ingredients, cementation, and replacement by clay minerals, iron oxides, quartz overgrowths, and generation of the pseudo matrix. Clay minerals commonly display extended textures (Ketzer *et al*., 2003; Morad *et al*., 2010), and these specific textures are the representation of occurrences before substantial compaction. Iron oxides occurred as coats over this diagenetic stage, depicting that these grains were in contact with oxidizing surface waters, representatives of the continental and humid condition. The precipitation and formation of quartz overgrowth have been resulted due to silica abundance in solution as a result of feldspar dissolution and other rock particles. Authigenic quartz originated to deposit in eogenesis (McBride, 1989; Bjørlykke & Egeberg, 1993; Giles *et al*., 2000), continuing throughout mesogenesis as lenticular structure and discontinuous overgrowths (Morad *et al*., 2000). The intensity of the compaction was superfluous strong in the lithic and sublithic sandstones.

However, the local precipitation of iron oxides and kaolinite were the products of the local fluid movements.

Differential diagenetic patterns

Distinguishing characters in the diagenetic pattern for quartz arenite and lith-arenites is that the quartz arenite demonstrates a greater amount of quartz over-growth texture. Subsequently, mechanical compaction was not too common and significant for identifies sandstone because of the textural balance proven by precipitation of quartz overgrowth and an insignificant amount of lithic fragments and intra-clasts. Compositional differentiation has thus resulted in a different diagenetic pattern and a different amount of intensity.

Provenance

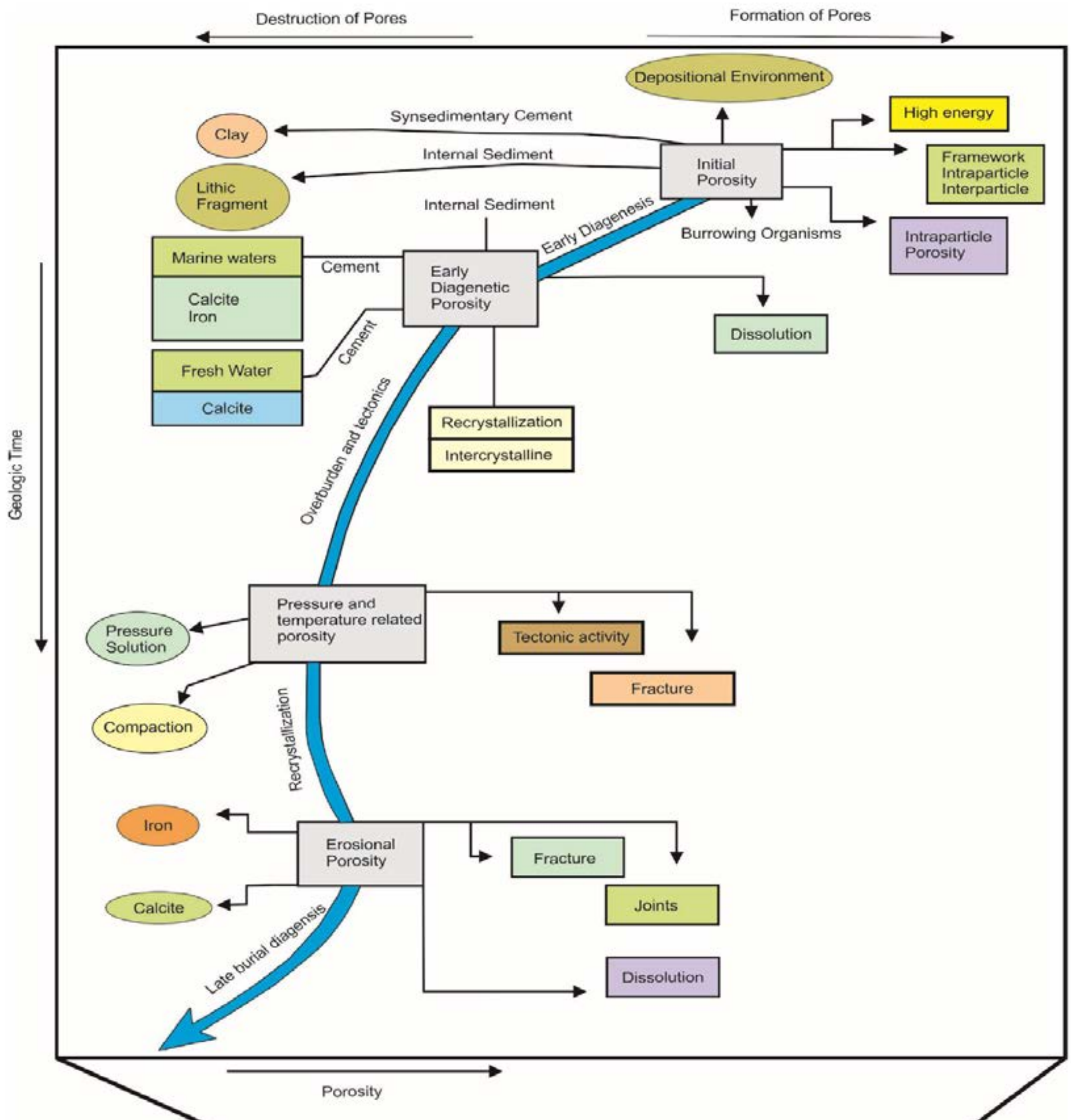
The original quartz dominating composition indicates a derivation from the Cratonic interior (Dickinson, 1985; Figure 9). Occurrences of the additional and large amount quartzose texture can be linked to the auto-cyclic controls in the depositional environment, associated with greater transporting history.

Impact of diagenetic constituents in reservoir quality

Results derived from the petrographic studies have shown that the reservoir quality has been significantly affected by the diagenetic processes (Morad *et al*., 2010). Since the majority of the studied samples from the formation were coarse-grained therefore the depositional texture does not differs considerably. The generation of the pseudo matrix and kaolinite cementation in the sandstones has resulted in the reduction of the primary porosity. Consequently, the detrital composition has a substantial effect on the porosity decline. However, the sandstones consisting of more lithic fragments have shown an elevated amount of decrease in porosity by mechanical compaction. Based on the observation and assessment of the petrofacies including low quality as well as non reservoir, dissolution occurred in the late stage diagenetic events has resulted in significant formation of secondary porosity. For the maintenance of the primary porosity in sandstones, the quartz overgrowths texture of quartz was important because the overgrowth structure of the quartz helped the framework in restraining mechanical compaction.

CONCLUSIONS

Petrographic analyses of 60 thin sections from the formation in the Rakhi Gorge section of Eastern Sulaiman Range Pakistan indicated that:



Event	Relative Timing		
	Early	Middle	Late
Mechanical Compaction	...............••••••••••••.........		
Dissolution of lithic fragments	........................••••••		
Chemical compaction	...................•••••••		
Quartz cement	.............•••••••••••••••••••		
Calcite	•••••••••.............		
Grain fracturing	..........•••••••••••		
Iron Oxide	......•••••••••.......••••••••		
Dissolution	........•••••••		

Figure 8: Summarized flow chart proposed for all the processes including deposition, diagenesis, compaction, destruction of porosity and summary of paragenetic sequence in the inset table.

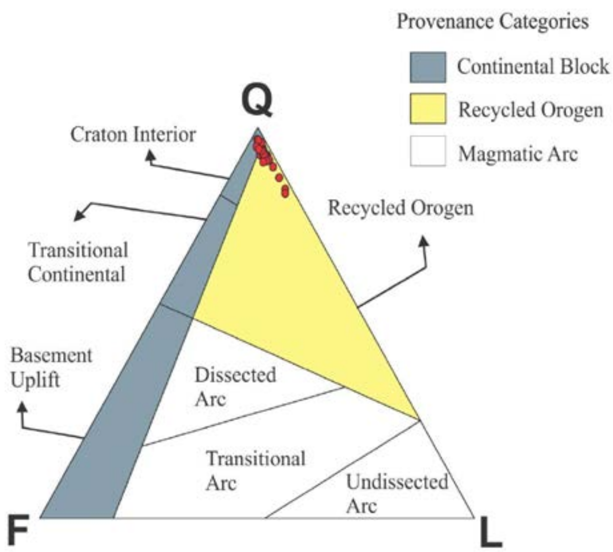


Figure 9: The provenance Dickinson I diagram (Dickinson, 1985), showing the main contribution of Craton interior Orogen provenance and subordinate contribution of recycled Orogen.

- Studied samples show differences in the grain pattern of arrangement resulting in the information that the formation has been subjected to late-stage processes probably diagenesis and regional stresses.
- Diagenetic events and associated products are compactions of rock articles and clay fragments, the formation of the pseudo matrix, quartz overgrowths, cementation, and replacement by kaolinite, pyrite; iron oxides have been considered as the products of diagenesis. However, dissolution events have also played their role during different stages of the diagenesis.
- The role of mechanical compaction has been prominent and destroyed the original porosity through cementation by kaolinite and generation of the pseudo matrix. However primary porosity has been preserved due to the quartz overgrowth framework of the grains.
- Paragenetic, diagenetic, and depositional flow chart was constructed for the observed thin sections. The model shows that initial deposition holds a significant number of porosity which were destroyed due to the effect of late-stage processes, mechanical compaction, and regional stresses.
- On the basis of composition, petrologic characters and diagenetic properties eleven reservoir petrofacies were defined. These facies have been categorized into four petrofacies classes which show diverse reservoir potentials including the good to medium and low quality as well as non-reservoir.
- The entire identified parameter of sandstone the studied samples shows medium to good quality reservoir characters. However, the studied formation has been identified that the formation is intermingled with different facies belonging to low, medium, and good quality.

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AUTHOR CONTRIBUTIONS

MM worked as a principle investigator and carried out this research, SG presented this idea and supervised this research along with AAN, while MY and QZD helped in the field work. MJK. helped in statistical analysis. US and AZ helped in thin section study and porosity calculations.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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