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Reservoir characterization of the Burqan Formation sandstone from Midyan Basin, northwestern Saudi Arabia

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Abstract: The Early Miocene sandstone of the Burqan Formation from Midyan Basin is considered an oil-bearing unit. The outcrops of this sandstone, which are exposed in the northwestern part of the basin, have been studied through field and laboratory-based investigations. During the field work, 81 surface samples were collected for reservoir characterization. Laboratory analyses were undertaken to determine the effect of the diagenesis on the reservoir quality using integrated sedimentological, petrological, and petrophysical analyses. According to these analyses, the sandstone of Burqan Formation is predominately subarkosic and sublitharenite in nature, medium to course grained in size, rounded to subangular in shape, and poor to moderately sorted. Porosity of the studied sandstone, which is both syndepositional and diagenetic in origin, has been determined as poor to very high, with an average value of 22.73%. The observed permeability is moderate to very high, with an average estimate of 2444.2 millidarcy. Cementation coupled with compaction had an important effect on the porosity destruction after sedimentation and burial. The reservoir quality of the studied sandstone is reduced by clay minerals (kaolinite and smectite), calcite, and silica cementations, but, on other hand, it is increased by alteration and dissolution of the unstable grains, in addition to partial dissolution of calcite cements. The potential of the studied sandstone to serve as a reservoir is strongly related to sandstone diagenesis.

Key words: Saudi Arabia, Midyan Basin, deep marine sandstone, reservoir quality, diagenesis, porosity, permeability

1. Introduction

Prediction of subsurface porosity and permeability becomes a key challenge for hydrocarbon exploration and development when limited subsurface data are available. Samples from outcrops may provide an important source of data for studying correlative reservoirs and providing exploration geoscientists an opportunity to observe sedimentary structures and lateral facies changes. Samples from outcrops may also provide help in understanding the burial history and roles of different diagenetic processes on the reservoir properties, which can in turn be used to predict porosity and permeability of the subsurface reservoirs.

The porosity and permeability of reservoir rocks have been shown to depend not only on the framework mineralogy but also on authigenic minerals and the composition, texture, and structure of the rocks. The presence of authigenic minerals strongly influences and controls the sandstone reservoir properties at different stages of the diagenetic history. For example, the precipitation of authigenic clay minerals (such as kaolinite and smectite) causes reduction in permeability by diminishing the pore throats sizes, hence decreasing the reservoir quality (Pettijohn, 1972). Therefore, the study of authigenic minerals in different stages of diagenesis can be fruitful for precisely characterizing the reservoir quality.

The aim of this paper is to examine the reservoir properties (porosity and permeability) of the Burqan Formation sandstone from Midyan Basin, northwestern Saudi Arabia. An additional focus of this work is to study the influence of depositional and postdepositional heterogeneities, such as the variations of authigenic cementation and the presence of authigenic clay minerals (as aggregate structures) on the reservoir quality. Diagenetic processes and their influence on sandstone properties are described, as well. In general, this study encompasses the importance and limitations of the outcrops as a source of data to characterize subsurface sandstone reservoirs.

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2. Geological setting

The sandstone of Burqan Formation is a part of sedimentary succession in the Midyan Basin, northwestern Saudi Arabia. The thick marine siliciclastic succession of this formation is well exposed in the west of Jabal Rughama (flanking the Magna Massif) and along the Gulf of Aqaba coast (north and south of Magna village). In addition, this succession is also exposed in Wadi Al-Hamedh, which is approximately 30 km long and 18 km wide (Figure 1). The Burqan Formation has been confirmed by Saudi Aramco in the exploration well AI-Wajh South-1 (AWSO-1) at a depth of 2875-3819 m, making it 944 m thick (Hughes and Johnson, 2005). This formation is mainly composed of sandstone, which is interbedded with some siltstone and mudstone (Figure 2). The color of the sandstone is generally yellow, reddish yellow, and off-white. Grains are medium to very coarse with pebble and cobble, poorly to moderately sorted, subangular to subrounded in shape, and subarkosic to sublitharenite in origin. Mudstone in the succession is generally brownish gray to gray and is bioturbated in some places. The Burqan Formation was deposited over the tectonically controlled Red Sea rift. The depositional system has been identified as a deep marine turbidite.

According to information available from AWSO-1 (Hughes and Johnson, 2005), the Yanbu Formation of the Tayran Group is unconformably overlain by the Nutaysh Member of the Burqan Formation, which in turn is unconformably overlain by the Umm Luj Member of the Jabal Kibrit Formation (Magna Group).

In the studied outcrops, the Burqan Formation unconformably overlies the Tayran Group as well as the Proterozoic Basement. At the Jabal Al-Risha exposure, sandstone of the Burqan Formation conformably overlies the oyster-bearing carbonates of the Musayr Formation. The Burqan Formation is then unconformably overlain by anhydrite of the Kial Formation, a part of the Magna Group (Hughes and Johnson, 1999). The sandstone of the Burqan Formation has been determined as a hydrocarbon reservoir in the Burqan field area of the Midyan Basin (Hughes et al, 2005).

3. Laboratory methods

Detailed examinations of 81 samples from 6 sandstone outcrops were carried out using different analytical techniques, such as thin section microscopic observations, energy-dispersive scanning electronic microscopy (SEM, JEOL JSM6380), and X-ray diffraction (XRD).

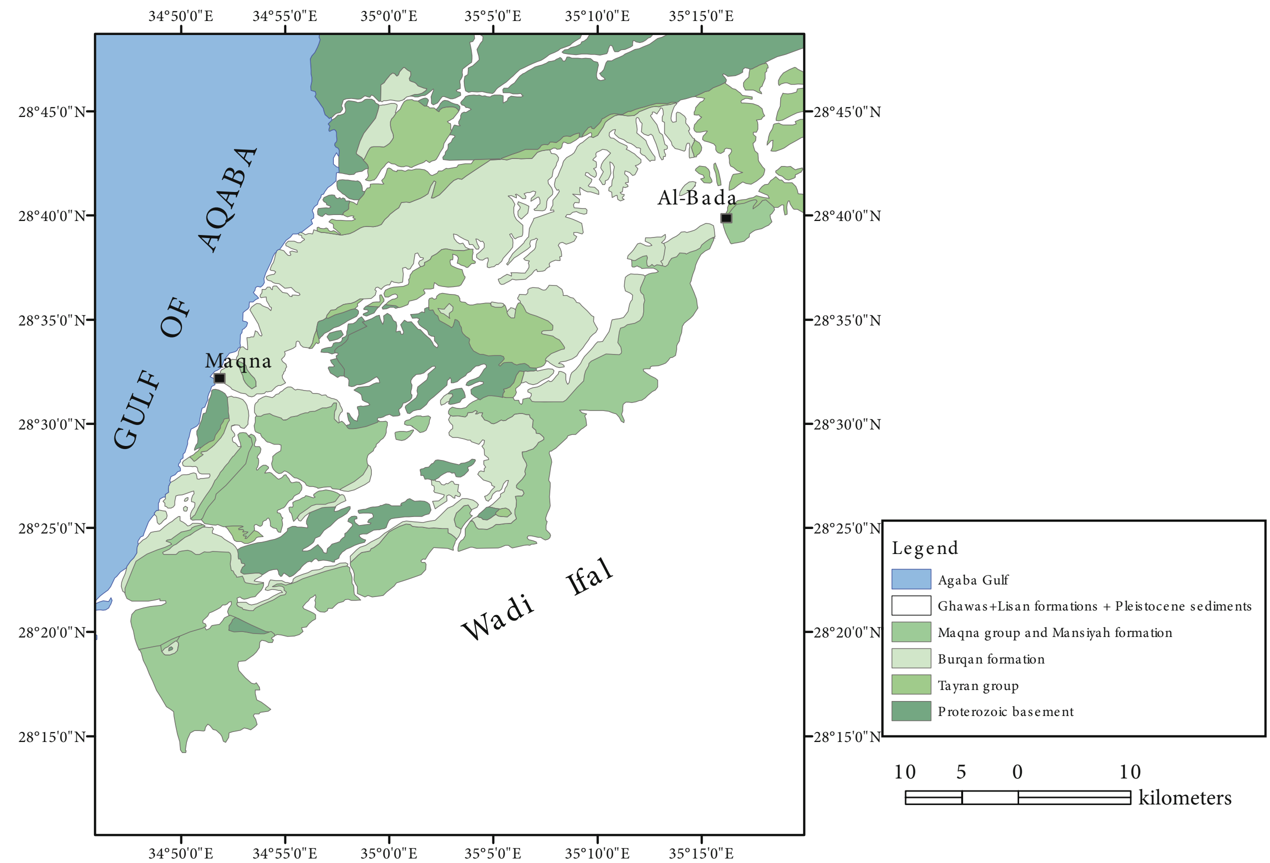

Figure 1. Detailed geologic map of the Midyan Basin showing distribution of the Burqan formation outcrops (modified from Clark, 1986 and Hughes et al., 1999).

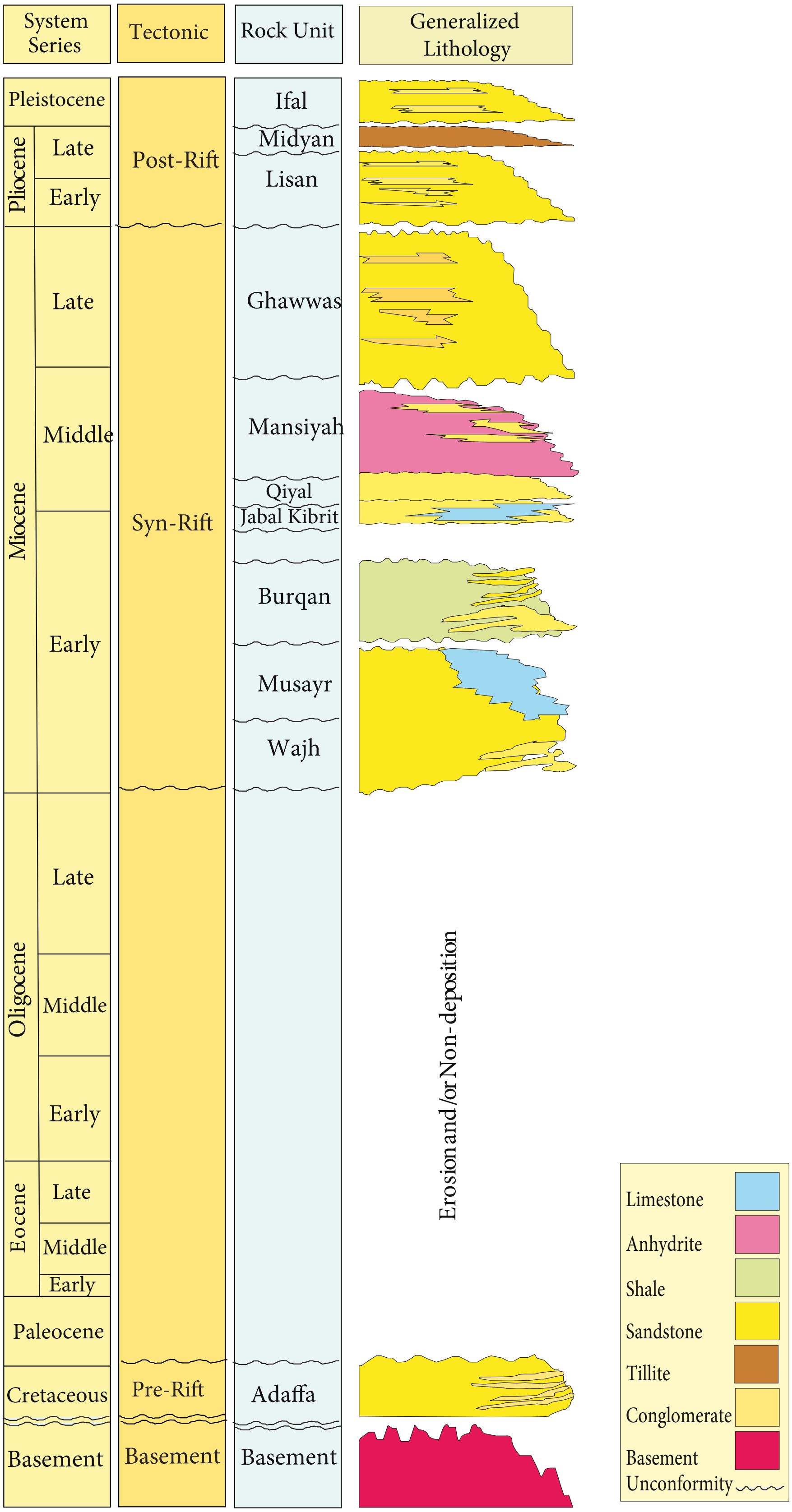

Figure 2. Lithostratigraphic column for the Midyan Region (Laboun, 2011).

Mineral composition and porosity were determined by standard point-count (300 points) analysis after the specimens were impregnated with blue epoxy resin. Quantitative evaluations of the diagenetic effects on porosity and the effect of cementation on sandstone heterogeneity were made. For this purpose, porosity measurements were performed on all 81 samples (using a helium porosimeter, HP-401), from which thin sections were prepared for microscopic analysis (Table). Grain sizes were measured using the sieving technique as well as the sorting technique. Permeability of the studied samples was measured (Table) using a field probe gas permeameter (MP-410). Variables such as total porosity, mean grain size, and cementing contents were measured to estimate the reservoir quality.

4. Analytical results

4.1. Composition and texture of the studied sandstone

Based on petrographic investigations, the studied samples from the Burqan Formation are classified as submature to mature and subarkosic to sublitharenite in origin. As shown in Figure 3, their composition is predominantly controlled by quartz contents (80%), while feldspar (9.7%) and rock fragments (10.3%) are present as subordinate members. Biotite, calcite, and iron oxides occur as authigenic grains. Kaolinite and smectite were found in most of the studied samples, where stacked booklets of kaolinite are clearly observed by SEM analysis, while smectite is identified by XRD analysis. Calcite, iron oxide, and quartz were observed as major cementing materials.

The essential framework grains, which were used to classify the studied sandstones, are quartz, feldspar, and rock fragments. The studied sandstone is generally classified as medium- to course-grained and poor to moderately sorted, while the grains shapes are subrounded to subangular. Quartz is found as the main constituent in the studied samples, showing about 80% representation in the sandstone classification diagram (QFL). The presence of monocrystalline quartz grains are dominant compared to polycrystalline grains. Feldspars were observed as a second important constituent in the studied samples with an average value of 9.6% in the QFL diagram. Feldspars are dominated by plagioclase feldspar, having albite twinning (Figure 4A) with some amount of microcline and orthoclase (Figure 4B). Rock fragments have also been found as an important constituent, which carry different percentages of metamorphic (Figure 4C), volcanic (Figure 4D), and sedimentary (Figure 4E) fragments. Ductile grains such as biotite are present in small proportions (Figure 4F).

4.2. Authigenic minerals

In addition to the above-mentioned main constituents, the sandstones of the Burqan Formation also carry some clay minerals (like kaolinite and smectite) as pore-filling materials. Three types of cementing material detected in the studied sandstone are calcite, iron oxide, and silica. Calcite, which among the most abundant cementing materials, has inconsistent distribution from trace amounts to about 20% of the entire rock volume. Quartz cementations mainly occur as euhedral overgrowths (generally the initial stage growth), but in some cases they are replaced by extensive calcite cementation.

4.3. Porosity

As shown in the Table, porosity of the studied sandstone observed by thin sections ranges from low to high, while that measured by helium porosimeter ranges from 7% to 34% (with an average value of 25%). Both primary (intergranular) and secondary (intragranular) porosities were observed in the studied samples. Densely cemented and tightly packed samples are identified as low in porosity, but loosely packed and poorly cemented samples are identified as high in porosity. A solution-related porosity (secondary porosity), created by dissolution of the calcite cement, was observed. In addition, porosity due to dissolution of the unstable feldspar grains was been observed.

4.4. Permeability

Permeability is the ability of a medium to conduct fluids without changing its structure or parts displacement. Permeability of a rock depends on its effective porosity, which can be significantly affected by grain size, grain shape, level of sorting, grain packing, and diagenetic processes. The studied sandstones from the Burqan Formation reflect a wide range of permeability values, ranging from 36 to 10502 millidarcy, with an average value of 2444.2 millidarcy (Table). These values can be qualitatively described as moderate to excellent.

4.5. Diagenetic stages of the Burqan sandstones

Based on the SEM and thin section photomicrographic observations, 3 diagenetic stages are identified in the studied sandstones: eodiagenesis occurred prior to effective burial, mesodiagenesis (stage with processes taking place during burial, including compaction, cementation, dissolution, and mineral replacement) (Chilingarian and Wolf, 1988) during burial, and telodiagenesis (stage of diagenesis processes taking place when the buried sandstone uplifted into the system of meteoric water) (Chilingarian and Wolf, 1988) during exposure after burial. The process of eodiagenesis (stage of diagenesis process taking place under the condition of depositional environment) (Chilingarian and Wolf, 1988) occurred as a result of mechanical compaction, calcite cementation, kaolinite and smectite formation, and chemical dissolution of the unstable grains. Mesodiagenesis resulted from precipitation of the calcite cement, quartz overgrowth, and formation of the

Table. Porosity (%), permeability (millidarcy: md), and average grain size of 81 outcrop samples (sandstone) from the Burqan Formation.

Sample no.	Porosity, %	Permeability (md)	Grain size (phi)
S1-1	34.12	6000.00	1.020
S1-2	25.83	5800.00	1.610
S1-3	19.20	3348.00	–0.043
S1-4	29.06	1354.67	2.100
S1-5	33.79	2765.00	2.060
S1-6	29.14	3800.00	1.750
S1-7	22.77	1306.67	1.670
S1-8	27.86	3923.00	1.250
S1-9	26.47	1883.67	1.310
S1-10	17.25	2004.50	0.520
S1-11	23.74	1141.00	1.000
S1-12	25.71	5473.00	1.380
S1-13	23.52	10,502.33	0.760
S1-14	25.15	7181.33	0.640
S1-15	27.19	6460.00	0.870
S1-16	26.38	4400.00	1.840
S1-17	28.50	4238.67	1.920
S1-18	29.02	4266.67	1.720
S1-19	27.27	8204.00	1.390
S1-20	22.64	3372.33	0.920
S1-21	24.86	4100.00	0.780
S1-22	25.23	3433.33	1.180
S1-23	20.17	4200.00	0.530
S1-24	19.08	7000.00	–0.660
S1-25	25.56	4274.67	1.130
S3-1	32.23	2567	1.900
S3-2	25.22	3613.00	0.930
S3-3	28.64	4352.00	1.500
S3-4	23.81	2045.33	1.230
S3-5	22.76	1687	0.330
S3-6	30.47	2596.67	1.310
S3-7	27.67	1748.33	1.020
S3-8	25	3090	0.090
S3-9	24.42	1700	–0.040
S3-10	27.78	5849.66	0.650
S3-11	26.20	6500	0.550
S3-12	19.64	3022	0.790
S3-13	30.83	721.333	1.890
S3-14	27.47	6512.333	1.220

Table. (continued).

S3-16	32.44	1508	1.600
S3-17	22.64	115	0.280
S4-1	29.26	936.667	1.900
S4-2	20.03	223	1.310
S4-3	7.47	40.333	1.98
S4-4	19.63	1672.33	1.330
S4-5	30.36	240	2.170
S4-6	31.68	1495	2.060
S4-7	27.01	457	1.610
S4-8	33.52	159	1.540
S4-9	25.62	1578.333	1.430
S4-10	16.62	36.333	1.55
S4-11	23.86	1003.333	1.400
S5-1	24.36	378	1.170
S5-2	15.35	499.333	0.250
S5-3	15.58	1253.667	1.740
S5-4	19.3	1322.667	–0.030
S5-5	26.37	87.48	0.870
S5-6	25.09	1996	1.720
S5-7	20.8	252	–0.240
S5-8	25.67	870	1.730
S5-9	24.7	1407	1.110
S5-10	34.72	2271	1.110
S5-11	29.4	2998.667	1.910
S5-12	22.99	4312.667	1.250
S5-13	27.86	2533.333	1.04
S5-14	23.39	5281	1.420
S5-15	24.99	3856.667	1.270
S5-16	28.93	3328.667	1.800
S5-17	25.52	5000	0.160
S6-1	23.59	455.667	1.640
S6-2	20.89	238.333	1.440
S6-3	17.57	255.667	1.870
S6-4	27.5	1380.333	2.180
S6-5	26.09	2500	1.600
S6-6	27.32	2845.667	1.940
S6-7	29.09	4105.333	1.780
S6-8	22.81	2050	1.710
S6-9	25	824.667	2.060
S6-10	27.64	10406	1.410
S6-11	29.2	2734.333	1.880
S6-13	27.97	1025.667	2.340

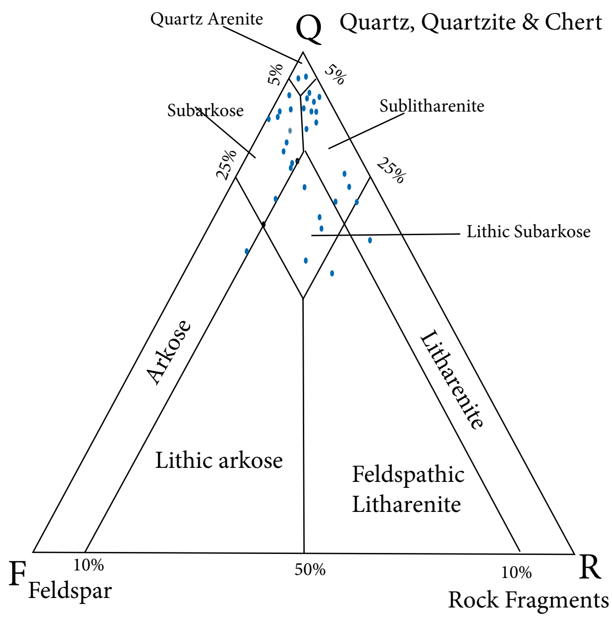

Figure 3. Classification of the Burqan Formation sandstone (after McBride, 1963).

authigenic clays. The process of telodiagenesis occurred as a result of kaolinite precipitation and partial dissolution of the feldspar grains.

5. Discussion

5.1. Factors controlling the reservoir quality

Reservoir quality of the studied sandstones is a function of both depositional and diagenetic processes. Depositional controls include grain size, framework composition, sorting, and primary fabric. In general, textural parameters such as grain size and sorting have effects on the porosity and permeability of the reservoir facies. The finer the grain sizes are, the lower the permeability of the rock is (Figure 5). Better sorted sandstone tends to have higher porosities (Figure 6). Other parameters such as rock composition could also have an influence on reservoir quality. For instance, the higher the quartz content is, the greater the mechanical stability is, and hence there is less porosity destruction from compaction. Sandstone with abundant unstable grains such as rock fragments and or feldspar grains have more secondary porosity through dissolution activities.

5.2. Diagenetic processes and properties of the studied sandstones

Diagenetic processes are related to both physicochemical activities and the burial depth. The most commonly occurring diagenetic processes in the physicochemical category are the formation of calcite and authigenic clay minerals. Both calcite cementation and authigenic clay mineral precipitation play an important role in controlling the properties of sandstones as a reservoir. The influence of these processes on the porosity and permeability of the studied sandstone occurred throughout the diagenetic history. For example, during the process of eodiagenesis, mechanical compaction, early calcite cementation, and formation of the kaolinite and smectite were the main diagenetic processes that influenced the reservoir quality, as evident from thin sections and SEM and XRD analyses. Meanwhile, the process of mesodiagenesis produced observable amounts of calcite cementation and quartz overgrowth as major factors that reduced porosity and permeability in the studied sandstones. However, the later stage of dissolution of the feldspar grains and calcite cements led to a significant increase in secondary porosity (Figures 7A–7C). In case of the studied sandstones, 3 porosity-reducing diagenetic processes were observed: 1) mechanical compaction, 2) authigenic mineral cementation, and 3) formation of the authigenic clay minerals.

5.3. Role of compaction

Mechanical compaction played a role in reducing the primary porosity and permeability of the studied sandstone. Deformation of the ductile grains instigated by the adjacent rigid grains reduced the primary porosity, as evident from thin section photomicrographs. During the early stage of diagenesis, mechanical compaction of the Burqan sandstone also caused proportionate reduction of pore throats that led to a quick loss of permeability compared to porosity. Abundance of deformed ductile grains in the studied sandstone indicates that reduction in the primary intergranular porosity began soon after the burial (Figure 8A). These findings suggest that most of the porosity might have been lost rapidly via mechanical compaction before the occurrence of any significant cementation. Furthermore, mechanical compaction also played a role in the processes of grain rotation and rearrangement.

5.4. Role of cementation

Four main types of cementation were recognized in the sandstone of the Burqan Formation. These include quartz overgrowth, silica cementation, an early calcite cementation, and iron oxide cementation (Figures 8A–8E). The main type among these 4 is the calcite cementation, which played an important role in the porosity and permeability evolution of the Burqan sandstone. During the early stage of diagenesis, calcite cementation generally played a key role in preserving primary porosity in the form of pore fillings. Calcite cementation then frequently filled spaces between the grains during the subsequent burial, which caused the loss of porosity and permeability. In contrast, dissolution of calcite cementation occurred during different stages of diagenesis that resulted

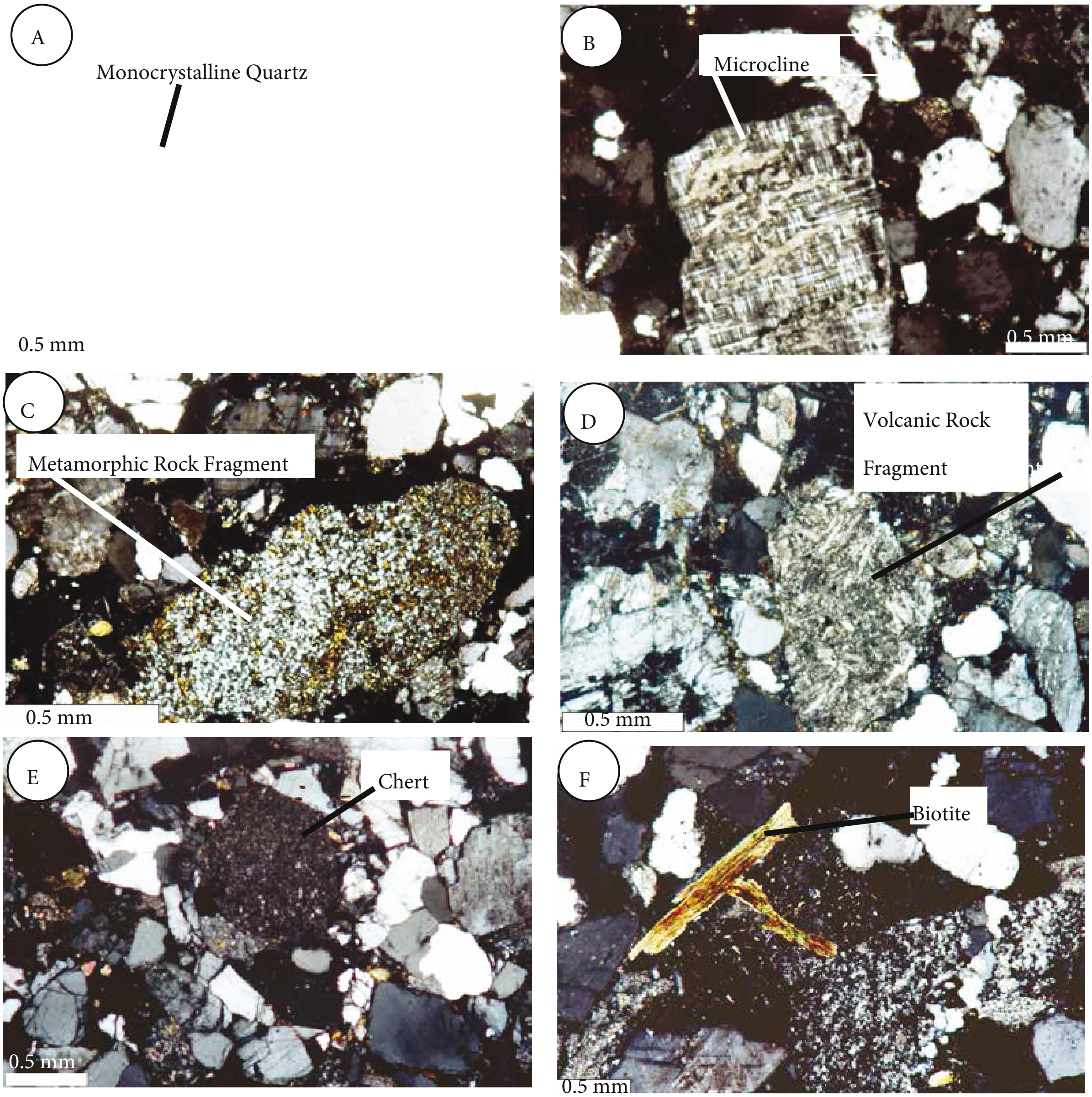

Figure 4. Thin section photomicrographs: A) monocrystalline quartz and plagioclase grains with albite twining; B) coarse microcline grain; C) detrital metamorphic rock grain; D) detrital volcanic rock grain; E) detrital sedimentary rock grain (chert); F) 2 flakes of biotite between the feldspar and quartz grains.

in a secondary porosity development. Silica-related cementation in the studied sandstones derived from pressure solution through contact points, along which high density grains were displaced. In addition, the quartz overgrowth occurred as a result of recrystallization. Late diagenetic iron oxide cementation occurred as pore-filling ingredients in the studied sandstone.

5.5. Role of feldspar alteration

In the studied sandstone samples, some of the plagioclase grains are partially or completely altered to sericite (Figure 8F). This alteration was caused by the acidic environment that prevailed at that time, by which the stability of feldspar grains was reduced and a localized increase in porosity occurred.

5.6. Role of clay minerals

Authigenic clay minerals also played an important role in controlling permeability and porosity in the Burqan sandstones. Stacked booklets of kaolinite were observed clearly in the SEM analysis (Figures 9A and 9B) and were confirmed by XRD analyses (Figure 10), which could be counted as a significant constituent in determining a reservoir quality. Various individual kaolinite booklets,

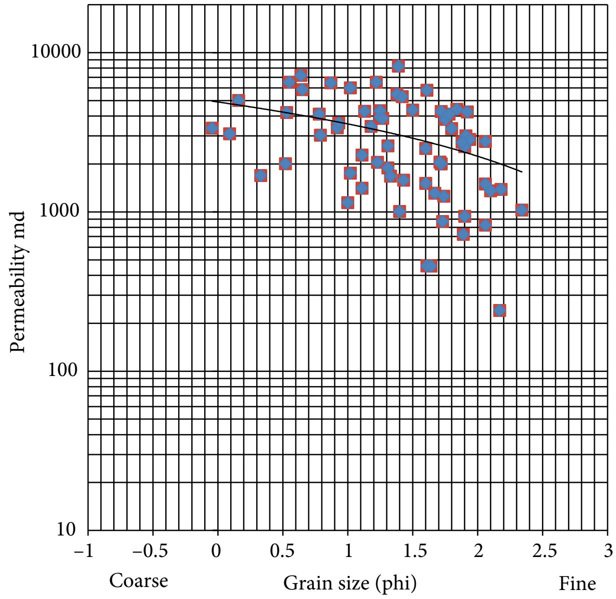

Figure 5. Relationship between permeability and mean grain size of the samples from the Burqan Formation.

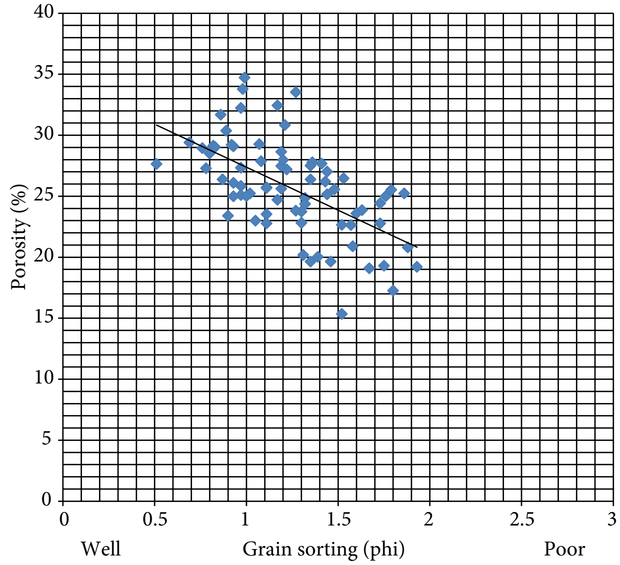

Figure 6. Relationship between the porosity and grain sorting for sandstone samples from the Burqan formation.

which have no preferred orientation relative to each other, occupied a large part of the original pore spaces, hence affecting the primary porosity. Simultaneously, kaolinite distribution in the central flow paths also played a role in reducing the permeability. The presence of smectite was confirmed by XRD analysis, which probably played a role in reducing porosity in the studied sandstone (Figure 11).

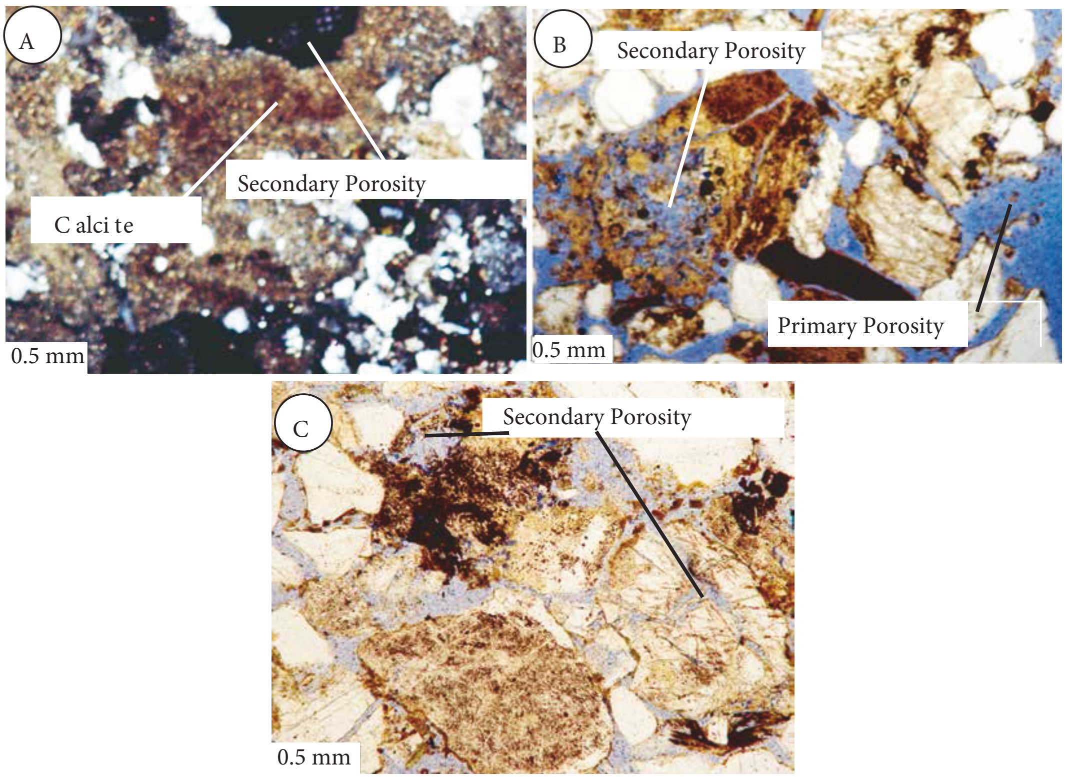

Figure 7. Thin section photomicrographs: A) secondary porosity created by dissolution of calcite cement; B) secondary porosity created by dissolution of feldspar grain; C) secondary porosity created by dissolution of the unstable detrital grains and cements.

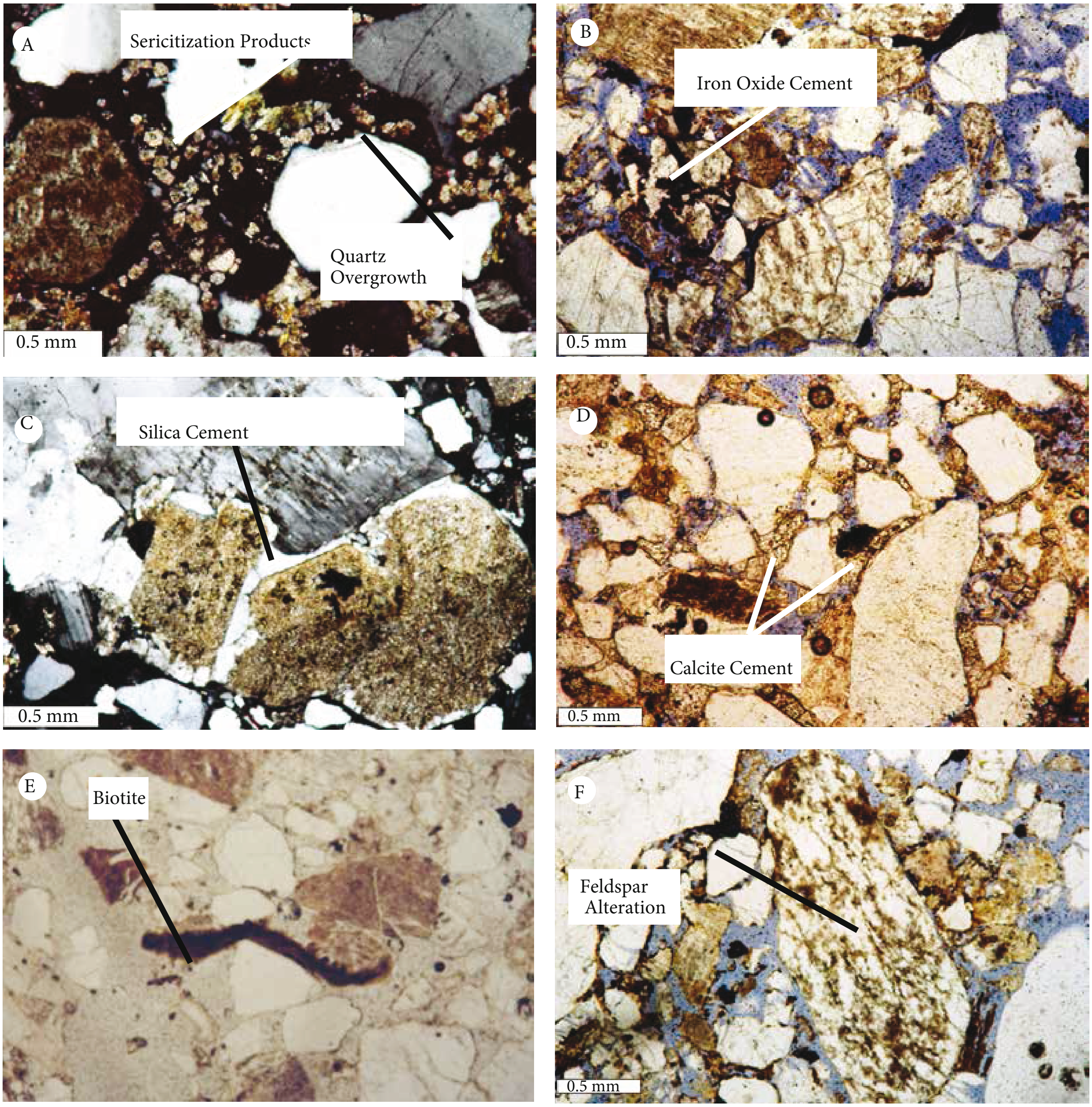

Figure 8. Thin section photomicrographs: A) quartz overgrowth reduces the porosity and the fine-grained minerals fill the pore spaces that are produced by sericitization of the unstable grains (feldspars and rock fragments); B) late diagenetic iron oxide cementation; C) silica cement filling the pore spaces between 3 detrital grains; D) poikilitic calcite cement filling the pores; E) flake of biotite deformed by compaction of 2 quartz grains; F) alteration of feldspar grain.

Based on these observations, the following conclusions can be made:

1. Diagenetic processes that occurred during progressive burial of the Burqan sandstone at various depths resulted in heterogeneous reservoir properties.

2. The potential of the studied sandstone to serve as a reservoir for producible hydrocarbons is strongly linked to its diagenetic history.

3. Calcite cementation has been found as one of the main factors controlling the porosity and heterogeneity in the Burqan sandstones.

4. The initial clast composition involving a mechanical response is one of the factors that contributed to a reduction of primary porosity in the studied sandstone.

5. Abundance of clay minerals (kaolinite and smectite) has a significant impact on the reservoir properties.

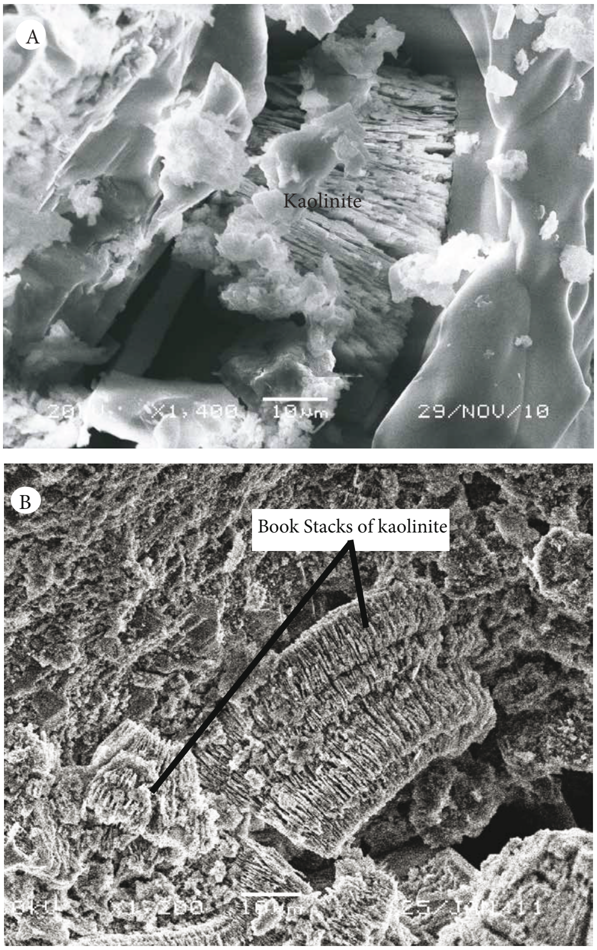

Figure 9. SEM photomicrographs: A) book stack of kaolinite occurred as pore-filling material; B) more than one book stack of kaolinite.

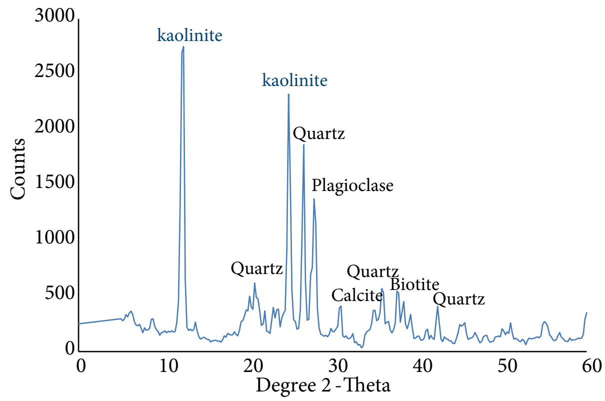

Figure 10. Chart of XRD analysis shows peaks of kaolinite in the studied sample from the Burqan formation.

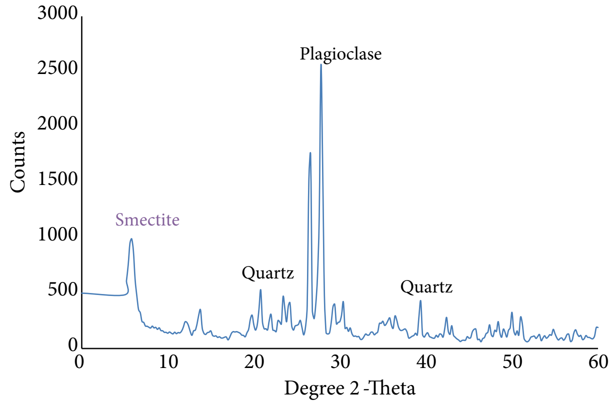

Figure 11. Chart of XRD analysis shows peak of smectite in the studied sample from the Burqan formation.

6. Partial and complete dissolution of some unstable detrital grains and calcite cementation were found as important controlling factors for increased secondary porosity in the studied sandstone.

7. Reservoir quality of the studied sandstone was reduced by clay minerals and cementations, but an increase in it occurred by alteration and dissolution of the unstable grains and partial dissolution of the calcite cements.

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