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Petrophysical Description of Three Paleozoic Sandstones from the Qusayba Depression in Central Arabia

Abdulaziz A. Laboun[1] and Abdulrahman A. Al-Quraishi[2]
[1]*Geology Department, College of Science, King Saud Univesity*
[2] *Astronomy and Geophysics Research Institute, King Abdulaziz City for Science and Technology*

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Abstract. Three Paleozoic sandstone units of different geologic ages are exposed in the Qusayba depression in the Qassim region, Central Saudi Arabia. These sandstones represent the Late Ordovician Sarah Formation, the Early Silurian Sharawra Formation, and the Early Devonian Tawil Formation. The sandstones are key aquifers and potential hydrocarbon reservoirs in different parts of the country. Surface samples from the sandstones were collected for petrophysical analysis. Lithologically, the Sarah sandstones are dark brown, hard, fine-grained, massive and very poorly-sorted sandstone. The Sharawra sandstones are beige and brownish in color, fine-grained, thinly laminated, and very poorly-sorted sandstone with mud-supported grains. Tawil sandstones are tan white to yellowish, hard, fine- to medium-grained, thinly bedded and poorly-sorted sandstone. Petrophysically, the Tawil Formation has the best reservoir quality among the three formations with the highest permeability. The other two formations have good porosity but low permeability, especially Sarah sandstone which is characterized by its bimodal pore size distribution due to the presence of clay content that fills the pore throats and restrict the flow of fluids.

Introduction

The studied area is located in northern Al-Qassim, central Saudi Arabia (Fig. 1), and specifically in the northern part of the Qusayba depression (Fig. 2) at the northwestern corner of the Buraydah quadrangle.

The Qusayba depression is a northwest trending depression bound by two escarpments. The western escarpment is mainly formed of Silurian shales of the Qusaiba Formation and sandstones of the Sharawra Formation (Fig. 3). The eastern escarpment formed mainly of Permo-Carboniferous sandstone and mudstone of the Unayzah Formation. The escarpments are capped by Tertiary and Quaternary marls and mudstones of the Ajfar Formation. The northern part of the depression is mainly formed of Ordovician-Silurian-Devonian sandstones of the Sarah, Sharawra, Tawil, and Unayzah formations, respectively.

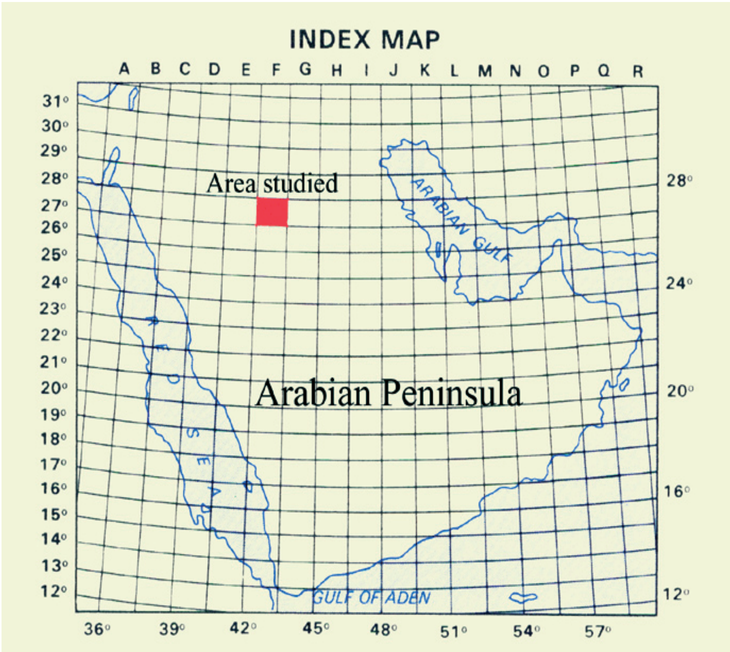

Fig. 1. Index map showing the location of the Qusayba depression in central Arabia.

Fig. 2. Generalized topographic map of the Qusayba depression.

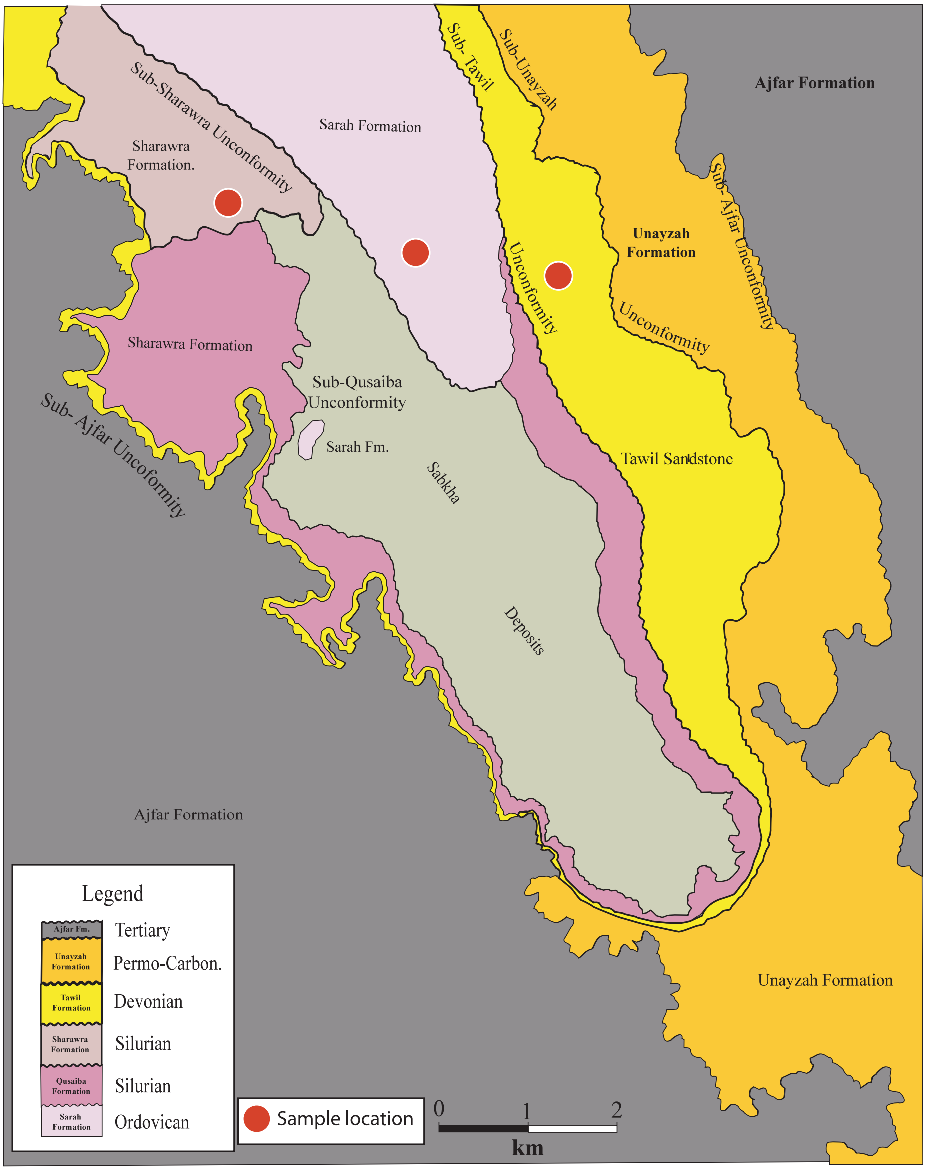

Fig. 3. Detailed geologic map of the Qusayba depression showing locations of samples.

The stratigraphy of the depression was first described and mapped by Bramkamp and others [1] within their geologic map of the Wadi Ar-Rimah quadrangle. The depression was considered as part of the DSOt (Devonian-Silurian-Ordovician) Tabuk Formation (obsolete). Laboun [2] remapped the depression by outlining the outcrops

Unayzah Formation and considering the rest as SOt (Silurian-Ordovician) Tabuk Formation (obsolete). Manivit and others [3] mapped the depression in the northwest corner of their geologic map of the Buraydah quadrangle. Later, Laboun [4] remapped the depression (Fig. 3), and established a detailed stratigraphic framework of the rock units exposed in the depression (Fig. 4).

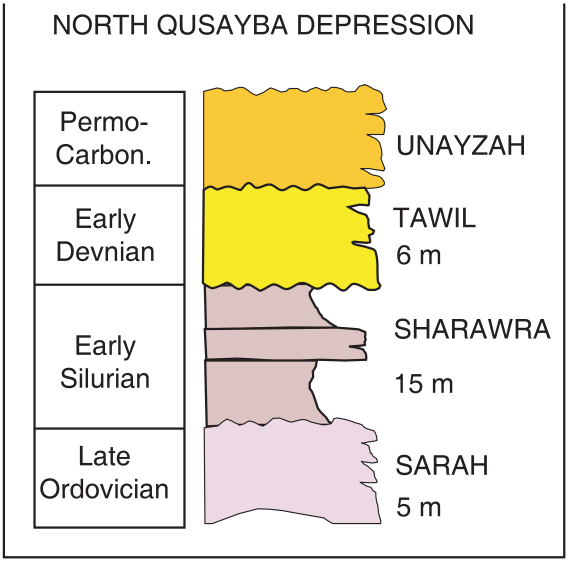

Fig. 4. Generalized geologic column of the northern part of the Qusayba Depression.

Other than generalized geological and lithologic description of the rock units cropping out in the depression, as far as the authors aware, there is no detailed petrophysical studies were conducted and published on these sandstones. Therefore, field and lab works were carried out to integrate petrophysical investigation, petrographical study, and facies description of the three sandstone units exposed in the Qusayba depression, namely; the Sarah, Sharawra, and Tawil sandstones to determine their petrophysical characteristics.

Stratigraphy and Lithology

The oldest rocks exposed in the depression are the glacio-fluvial sandstones of the Late Ordovician Sarah Formation. About 6 meters thick section of the Sarah Formation is exposed in a north-northeast trend and occupy the northern part of the depression (Fig. 3). Hand specimen description indicates that they are dark brown, hard, massive and laminated sandstone. Petrographic description indicates fine grain size (0.0625 to 0.125 mm). Grains are poorly sorted angular to subangular with longitudinal contacts. Mineralogical analysis shows composition of quartz (75%) which is mostly monocrystalline slightly undulose grains, with few polycrystalline grains (Fig. 5). The rest is made of feldspar (25%) mostly of plagioclase (albite) grains (Fig. 6), and few K-feldspar grains (microcline and orthoclase). In addition, clay occurs as a matrix, mica mostly as biotite (Fig. 7) and few muscovite grains, and heavy minerals occur as few rounded zircon grains. The rock can be classified as subarkose.

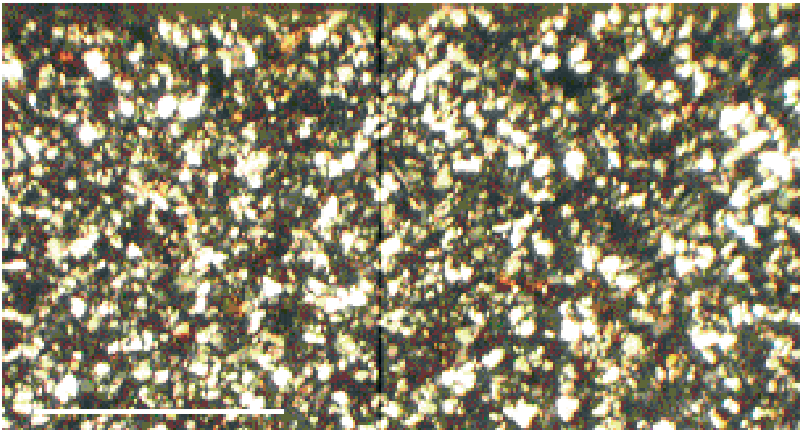

Fig. 5. Photomicrograph showing subangular to angular, poorly sorted, and monocrystalline quartz (Sarah sandstone). Scale bar is 1 mm.

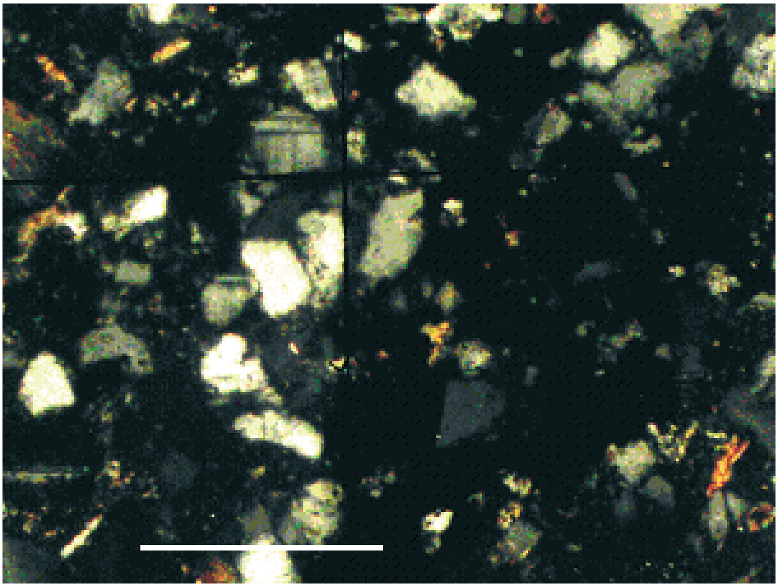

Fig. 6. Photomicrograph showing feldspar subangular grains admix with abundant quartz grains (Sarah sandstone). Scale bar is 0.25 mm.

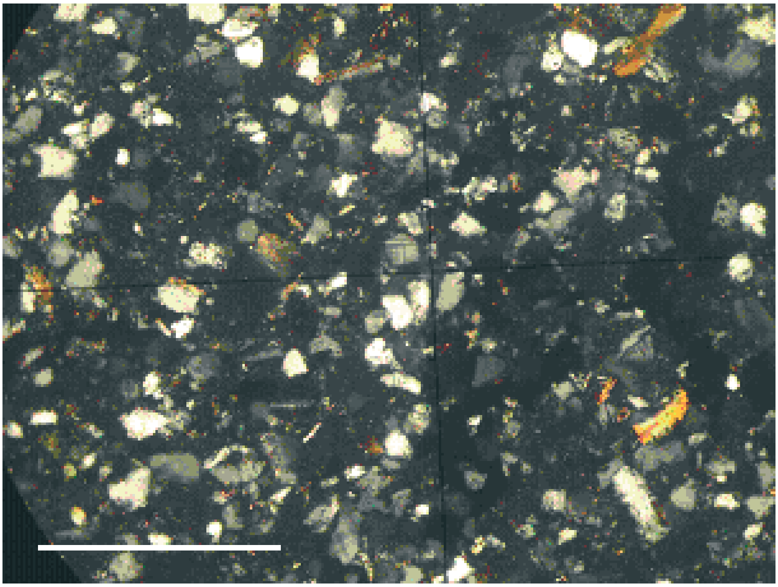

Fig. 7. Photomicrograph showing biotite grains (Sarah sandstone). Scale bar is 0.10 mm.

The Early Silurian Uqlah Formation as well as the Hawban member of the Sarah Formation are missing in the Qusayba depression and the Late Ordovician Sarah Sandstone is unconformably overlain by the Early Silurian Sharawra Formation [5]. In the northern part of the depression, the Qusayba shale is missing and the Sharawra Formation unconformably overlie the Sarah sandstone [5].

About 15 meters thick section of siltstone and sandstone the Sharawra Formation is exposed. The Sharawra sandstones hand specimen description indicates their fine-laminated silty micaceous, beige and brownish color and massive nature. Grains are cemented by koalinitic clayey matrix. The petrographic description indicates the dominance of the fine sand size (0.25 to 0.35 mm). Grains are poorly sorted, subangular to subrounded with longitudinal contacts with overgrowth seen in some quartz grains. Sharawra sandstone is composed mainly of quartz (98%) occurring in mostly monocrystalline slightly undulose grains, with few polycrystalline grains (Fig. 8). Feldspar (2%) exists as microcline and orthoclase with some grains showing alteration (Fig. 9). In addition, some clay occurs as kaolinitic matrix, mica as muscovite (Fig. 10), and heavy minerals as rounded zircon grains. Rock can be classified as quartz arenite.

The Early Devonian sandstones of the Tawil Formation rest unconformably on the Sharawra and Sarah Formations. Tawil sandstones hand specimen description indicates their tan white to yellowish color, hard, and massive nature. The petrographic description indicates the abundance of the fine sand grain size (0.117 to 0.25 mm). Grains are poorly sorted, subangular to angular with longitudinal contacts. They are composed mainly of quartz (70%), which in mostly monocrystalline slightly undulose grains, with few polycrystalline grains (Fig. 11). Feldspar (30%) occurs mostly as plagioclase (albite) grains (Fig. 12) and few K-feldspar grains (microcline and orthoclase). In addition, some clay presents as matrix, mica mostly as muscovite and few biotite and heavy minerals such as opaque grains and few rounded zircon grains. The rock can be classified as arkose.

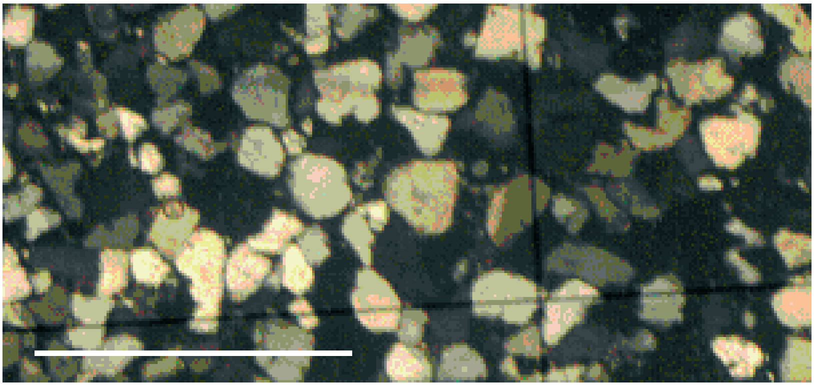

Fig. 8. Sharawra sample subangular to subrounded, poorly sorted, and monocrystalline quartz. Scale bar is 1 mm.

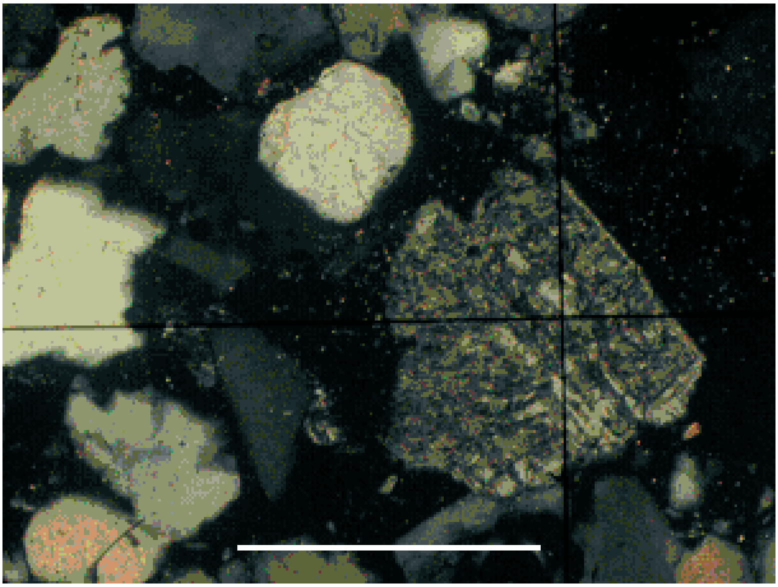

Fig. 9. Photomicrograph showing slightly altered feldspar grain. A quartz grain to the upper left of the feldspar grain showing overgrowth (Sharawra sandstone). Scale bar is 0.25 mm.

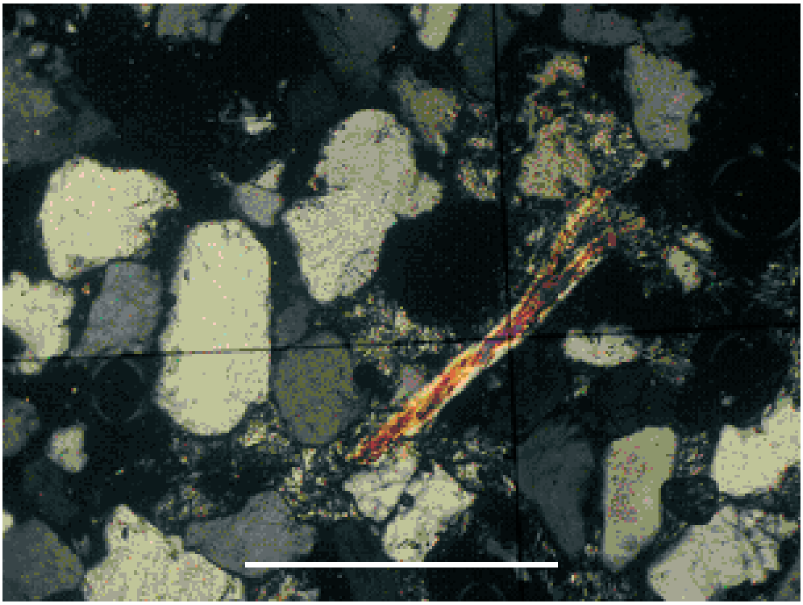

Fig. 10. Sharawra sample muscovite flake. Scale bar is 0.25 mm.

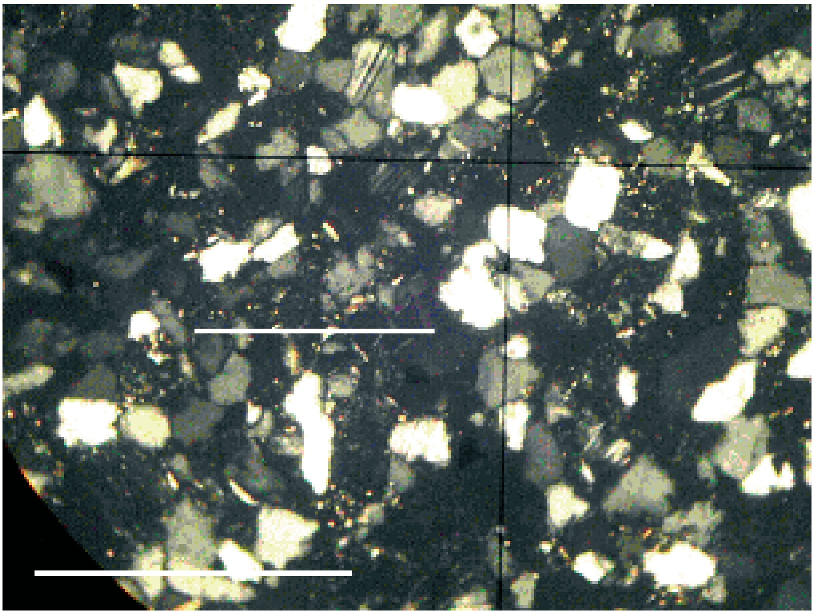

Fig. 11. Photomicrograph showing subangular to angular, poorly sorted, and monocrystalline quartz and feldspar grains (Tawil sandstone). Scale bar is 0.125 mm.

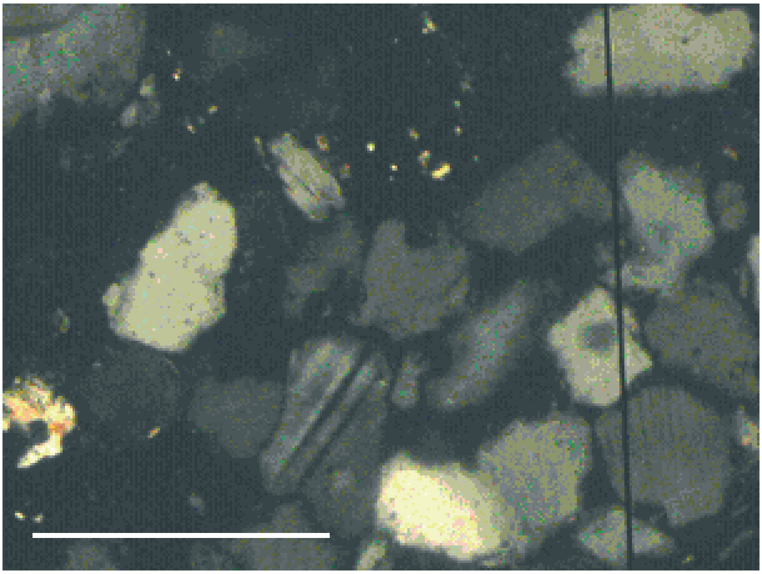

Fig. 12. Photomicrograph showing plagioclase grain surrounded by quartz grains (Tawil sandstone). Scale bar is 0.125 mm.

Petrophysical Description

Porosity and permeability

Porosity and permeability are reservoir rock properties function of several petrographic characteristics. Sample blocks of the three sands were collected from the studied locations and 1 inch diameter 3 inches long plugs were cut. Samples of porosity and permeability were measured using Helium porosimeter and gas permeameter respectively. Table 1 lists some sample plugs of physical properties of porosity and permeability for the three sand formations. All sandstones are characterized by having very good porosity values. Tawil sandstone permeability and porosity appear to be the highest compared to the other two sandtones. On the other hand, Sarah seems to be the least permeable and porous among the three formations. This is believed to be due to the presence of mud supporting the matrix grains. Sharawra shows a good porosity; however, permeability is low compared to Tawil sandstone and this is believed to be due to the fine laminated micaceous characteristic and the overgrowth seen in some quartz grains.

Table 1. Samples of physical properties data of the studied samples

Sample	Porosity (%)	K (md)
Sarah 1	22.12	< 0.2
Sarah 2	16.73	< 0.2
Sharawra	30.29	12
Tawil 1	32.25	125.63
Tawil 2	27.26	124.17

Grain size distribution

Grain size is an important textural factor related to the dynamic conditions of transportation and deposition. Pieces from the plugs cut were crushed for grain size analysis and precaution was taken not to crush the grains. Malvren Master Sizer was used to measure the particle size distribution of the three investigated sandstones. Figures 13, 14 and 15 are the incremental and cumulative frequency curves for Sarah, Sharawra and Tawil sandstones respectively. The incremental histogram indicates the presence or abundance of grains in each size range. The cumulative frequency curve is used to determine the statistical grain size parameters as stated by Folk and Ward (1957) such as graphic mean, graphic standard deviation, graphic skewness, and graphic kurtosis. Table 2 lists the values of these parameters. According to the U. S. Bureau of soils particle size classification, Sarah sandstone shows coarse silt grain size, while the other two sandstones of Sharawra and Tawil are characterized by either very fine grained nature as indicated by the mean grain diameter. Mean grain size measurements agree well with that determined through the petrographic description. Theoretically, porosity is independent of grain size; however, there exists an indirect connection. Finer sands have the tendency to be more angular and less rounded. Hence, organized in a less dense arrangement and present higher porosity than coarser grain size [6]. This explains the high porosity values characterizing the three sandstones. On the other hand, the finer the grain size, the lower the permeability value gets. Therefore, low to moderate permeability values were observed for all sands. Of the three sands measured, Sharawra sample shows clear bimodal incremental grain size distribution (Fig. 14). This is attributed to its fine laminated silty micaceous characteristic.

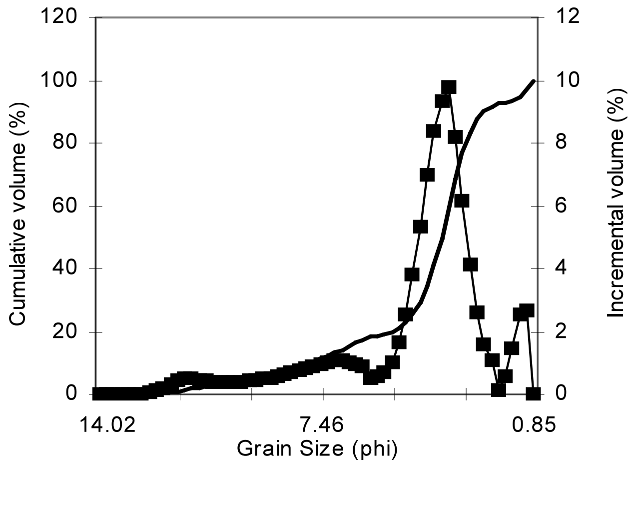

Fig. 13. Simple frequency and cumulative grain size distribution of the Sarah sandstone.

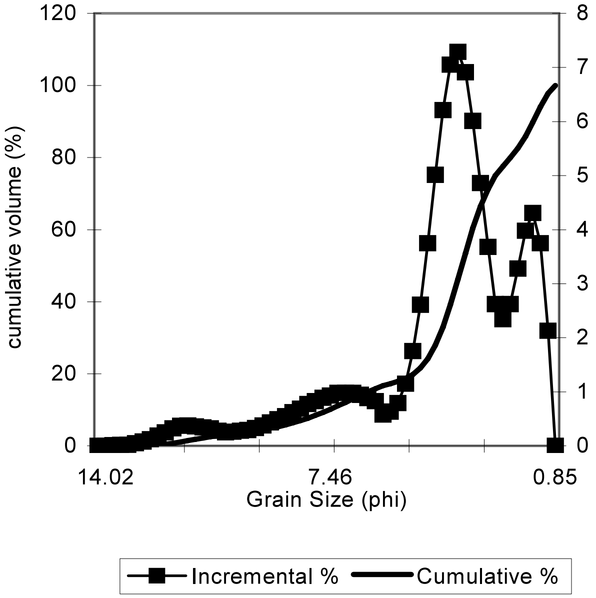

Fig. 14. Simple frequency and cumulative grain size distribution of the Sharawra sandstone.

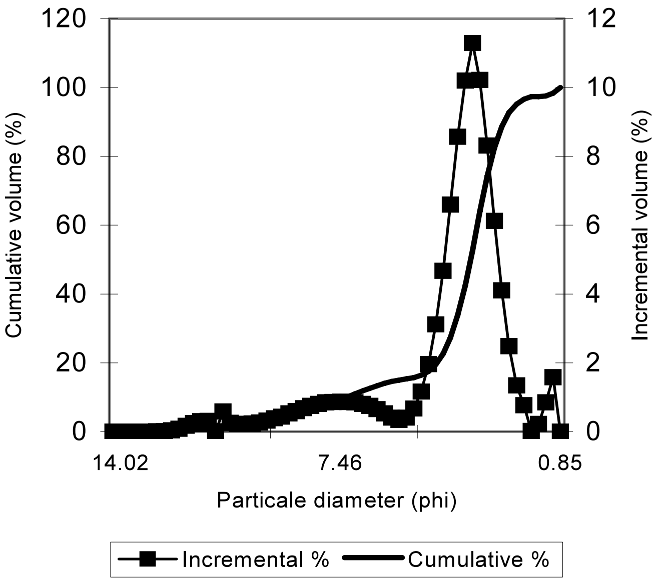

Fig. 15. Simple frequency and cumulative grain size distribution of the Tawil sandstone.

Table 2. Statistical parameters values of grain size (Folk and Ward, 1957)

Sample	Median (ϕ)	Mean (ϕ)	St. Deviation (ϕ)	Skewness (ϕ)	Kurtosis (ϕ)
Sarah 1	3.881	4.365	2.179	-0.388	2.292
Sharawra	3.685	3.878	2.263	-0.260	1.677
Tawil 1	3.434	3.594	1.570	-0.395	1.830

Standard deviation, a measure of the degree of sorting, indicates that Sarah and Sharawra sandstones are very poorly sorted, while that of the Tawil sandstone is poorly sorted. Skewness, defined as the degree of asymmetry of cumulative curve, shows a strongly negative skewness for Sarah and Tawil and negative skewness for Qusaiba sandstone. This indicates excessive coarser sizes in the grains range of the sandstone samples. All samples are excessively peaked or very leptokurtic with the center part of the distribution better sorted than ends.

Pore size distribution

The determination of pore geometry and pore aperture size using mercury injection is a helpful technique that can be used to categorize rocks by pore types (i.e. nanno, micro, meso, macro or mega). Autopore III 9420 mercury intrusion unit was used on core plugs one inch long, one inch diameter to determine the capillary pressure, pore throat accessibility, and pore level heterogeneity of the three formations. Figure 16 through 18 are the capillary pressure curves and pore size distribution for the three Sarah, Sharawra and Tawil samples. The capillary pressure curves show some sort of heterogeneous pore geometry for Sarah and Sharawra sandstones. Pore size distribution (PSD) plots indicate the obvious clear bimodality of Sarah sandstone where two pore throat types are present, one with larger flow capacity than the other. The pore heterogeneity is believed to be the reason behind the low permeability value of that sample. Bloch and McGowen [7] indicated that in rigid grain sandstones, such as that of Sarah, bimodality could influence reservoir quality. Tawil sand shows quite homogenous pore size distribution. Sharawra sand pore size distribution is skewed towards finer pore throat size, which negatively impacts the permeability of that formation compared to Tawil. Capillary pressure and pore size distribution curves are integrated with corresponding thin section photomicrographs. The shape of capillary pressure curves can be associated with changes in pore geometry due to sorting deterioration, grain size reduction and the increase of clay matrix as shown in thin sections.

Winland [8] indicates that on average, pore throats entered by mercury at 35% non-wetting saturations or less during capillary pressure analysis (R35) represent the pores dominating fluid flow on rock samples. R35 for the three samples are found to be 1.5, 2.4 and 6 μm for Sarah, Sharawra, and Tawil sandstones respectively, indicating meso pore type rock for Sarah and Sharawra and macro pore type rock for Tawil.

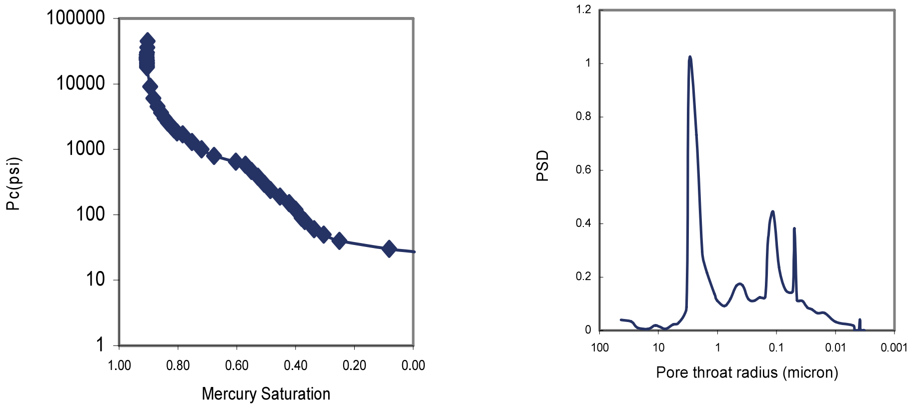

Fig. 16. Capillary pressure and pore size distribution of sandstone from the Sarah Formation.

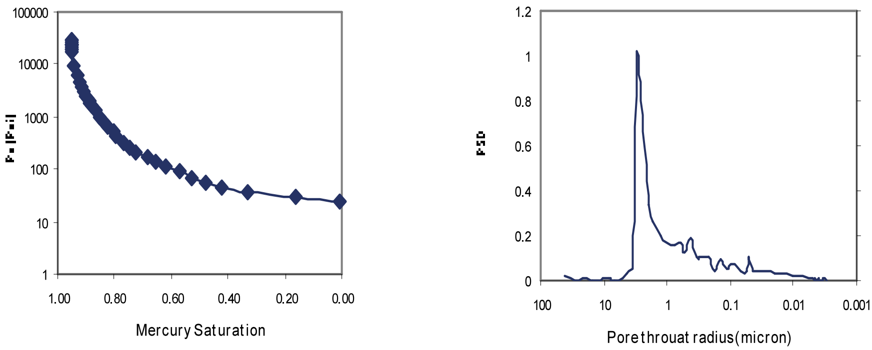

Fig. 17. Capillary pressure and pore size distribution of sandstone from the Sharawra Formation.

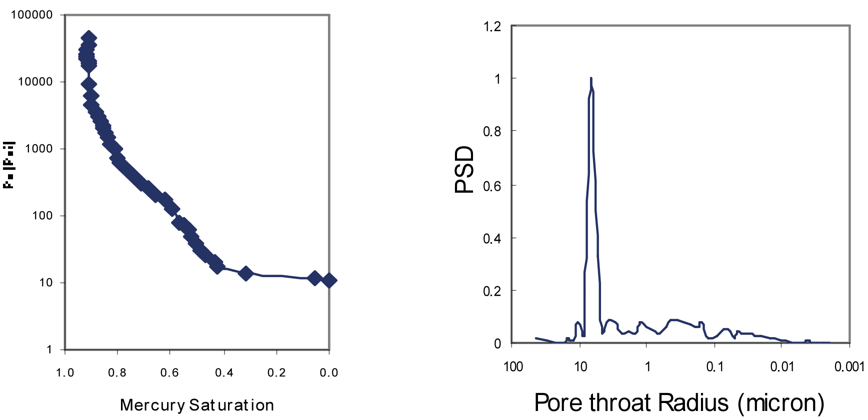

Fig. 18. Capillary pressure and pore size distribution of sandstone from the Tawil Formation.

Conclusion

Three thin sandstone bodies representing the Sarah, Sharawra, and Tawil sandstone facies, exposed in the Qusayba depression were studied for their lithological and petrophysical properties and the following observations were obtained:

- All sandstones are fine grained and poorly to very poorly sorted. Sharawra and Tawil are thinly laminated.
- Lithofacies with the best characteristics are generally corresponding to the best quality reservoir rocks. Reservoir quality is controlled, to a large extent, by the depositional facies and specifically by rock texture as illustrated by lithological and petrophysical descriptions. Tawil sandstone is characterized by its good pore and grain size distributions have the best reservoir quality with very good porosity and good permeability.
- In clastic rocks, reservoir quality is affected by the bimodality of the grain size distribution than by diagenesis. This is true for Sharawra sandstone facies, which is characterized by its bimodal grain size distribution and low reservoir quality (permeability). This agrees well with the lithological investigation, which indicates the very poor sorting characteristics.
- Sarah sandstone has the least reservoir quality (permeability) of the three sandstone bodies. It is characterized by its heterogeneous bimodal pore size distribution due to the presence of clay content that fills the pore throats and restricts the flow of fluids.

References

[1] Bramkamp, R.A.; Ramirez, L.F.; Brown, G.F. and Pocock, A.E. "Geologic Map of the Wadi Ar-Rimah Quadrangle, Saudi Arabia." *U. S. Geological Survey Miscellaneous Geological Investigations Map-I-206 A*, 1963d.

[2] Laboun, A.A. "Unayzah Formation: A New Permo-Carboniferous Unit in Arabia." *The American Association of Petroleum Geologists Bulletin*, 71, No. 1 (1987), 29-38.

[3] Manivit, J.; Vaslet, D.; Berthiaux, A.; Le Start, P. and Fourniguet, J. *Geologic Map of the Buraydah Quadrangle, Sheet 26G, Kingdom of Saudi Arabia (with text).* Saudi Arabian Deputy Ministry for Mineral Resources, Jeddah, Geosciences Map GM-114C, 1986.

[4] Laboun, A.A. "The Qusayba Depression: A Window on the Influence of the Caledonian and Hercynian Orogenies in Central Arabia." *The Eighth Arab Conference on Mineral Resources*, Sana'a, Yemen, 13-16 October 2003.

[5] Laboun, A.A. "Geology of the Qusayba Depression." In press.

[6] Alhomaidi, E. and Hamada, G. "Determination of Petrophysical and Mechanical Properties Interrelationships for Simulated Sandstone Rocks." *Proceedings of the Sixth Nordic Symposium on Petrophysics*, Trondheim, Norway, 15-16th of May, 2001.

[7] Bloch, S. and McGowen, J.H. "Influence of Depositional Environment on Reservoir Quality Prediction." In: M.D. Wilson (Ed.), *Reservoir Quality Assessment and Prediction in Clastic Rocks.* Tulsa Oklahoma: SEMP (Society of Sedimentary Geology), 1994, p. 41.

[8] Kolodzie, S.J. "Analysis of Pore Throat Size and Use of the Waxman-Smits Equation to Determine OOIP in Spindle Field." Paper SPE 9382, *55th Annual Fall Technical Conference*, Colorado, 1980.

وصف الخصائص الصخرية لثلاثة أحجار رمل تابعة لحقب الحياة القديمة (الباليوزوي) من منخفض قصيباء في وسط جزيرة العرب

عبدالعزيز بن عبدالله بن لعبون[١] وعبدالرحمن بن أحمد القريشي[٢]

[١] *قسم الجيولوجيا، كلية العلوم، جامعة الملك سعود، الرياض*

[٢] *معهد بحوث الفلك والجيوفيزياء، مدينة الملك عبدالعزيز للعلوم والتقنية، الرياض*

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ملخص البحث. تنكشف في منخفض قصيباء شمال منطقة القصيم في وسط المملكة العربية السعودية ثلاث طبقات من أحجار الرمل مختلفة الأعمار الجيولوجية لحقب الحياة القديمة (الباليوزوي). تمثل أحجار الرمل هذه متكون صارة التابع للعصر الأوردوفيشي المتأخر، ومتكون شرورى التابع للعصر السيلوري المبكر، ومتكون الطويل التابع للعصر الديفوني المبكر. تعد أحجار الرمل المذكورة طبقات خازنة للمياه ومكامن محتملة للنفط والغاز في مناطق مختلفة من المملكة. جُمعت عينات من منكشفات أحجار الرمل ودرست لمعرفة مكوناتها الصخرية وطبيعتها الفيزيائية. تظهر أحجار رمل متكون صارة بنية داكنة اللون حبيباتها ناعمة، وقاسية، وكتلية التطبق، ورديئة الفرز (التصنيف)، بينما تظهر أحجار رمل متكون شرورى بنية فاتحة اللون، ومصفرة (بيج) ناعمة الحبيبات، ومترققة، ورديئة الفرز والحبيبات مدعمة بالطين. أما أحجار رمل متكون الطويل فتظهر فاتحة اللون مصفرة–بيضاء، وناعمة إلى متوسطة الحبيبات، وقاسية، ورقيقة التطبق، ورديئة الفرز. تشيرالخصائص الفيزيائية للعينات المدروسة إلى أن أحجار رمل متكون الطويل هي الأعلى مسامية ونفاذية ومتجانسة من حيث حجم مساماتها، أما أحجار الرمل لمتكوني صارة وشرورى فمساميتها جيدة ولكنها ضعيفة النفاذية، وبالذات أحجار رمل متكون صارة التي تسبب وجود الطين بين حبيباتها في ملء مساماتها مما أدى إلى إعاقة سريان السوائل خلالها.