SPE-KSA (08048)

POTENTIAL SAUDI STANDARD SANDSTONE FOR APPLIED STUDIES OF PETROLEUM AND NATURAL GAS ENGINEERING

Musaed N. J. Al-Awad[1], Abdulrahman A. AlQuraishi[2], Omar A. Almisned[3], and Kamal A. Haroon[4]

[1, 4] King Saud University, College of Engineering, Petroleum and Natural Gas Engineering Department.
[2, 3]King Abdulaziz City for Science and Technology, Oil and Gas Center.

This paper was prepared for presentation at the 2008 SPE Saudi Arabia Section Technical Symposium held in Alkhobar, Saudi Arabia, 10–12 May 2008.

ABSTRACT

Core samples are a vital constituent in petroleum and natural gas engineering research activities. Newly developed techniques or theories for solving problems or improving process in petroleum and natural gas engineering with respect to formation rock, must be verified in laboratory using fairly homogenous core samples. Currently, the worldwide practice is to import homogenous sandstone core samples (i.e. Berea sandstone). The cost of importing such core samples is very high and time consuming.

The aim of this study is to investigate the possibility of utilizing sandstone formations outcroping in Saudi Arabia as a source for core samples needed for the above mentioned studies. Thus, two sandstone formations named Saq and Sarah outcroping in Al-Qassim area in addition to a sandstone formation named Um Assha'al outcroping in Al-Kharj area were selected for investigation.

Properties of the selected sandstones were thoroughly investigated by studying the geology, location accessibility, availability, values and ranges of the physical properties (permeability, k and porosity, ϕ), mineralogy (% clay content and type), rock quality designation (RQD), grain size distribution, pore size distribution, and mechanical properties.

Based on the determined properties, Um Assha'al seems to be suitable for sand production testing, Saq sandstone is good for performing permeability-stress-production rate relationship studies, and finally Sarah sandstone can be used in performing oil recovery improvement tests.

Preliminary economical feasibility study indicates that the tested sandstones are cost effective compared to imported core samples. Based on the above investigations and the performed preliminary economical evaluation, it is recommended to use those sandstones in petroleum and natural gas applied studies and academic demonstrations.

INTRODUCTION

The availability of sandstone core samples (plugs) of homogeneous properties is a vital element in verifying any newly developed techniques or theories for solving any problems that may be encountered when drilling or producing from formation rocks in petroleum and natural gas engineering practices, or for improving the productivity of petroleum and natural gas reservoirs [1].

Coring from productive formations is a difficult and expensive task and provides limited number of core samples. Therefore, sandstone samples cored from the reservoir pay-zone are only used for measuring and evaluating reservoir properties such as porosity, permeability, grain and pore sizes distribution, saturations, wettability, etc. Furthermore, those real (downhole) core samples are used only in verifying newly proved techniques for potential application in that specific reservoir.

Since real sandstone core samples extracted from the productive reservoirs are rarely available, outcrop samples of homogenous sandstone core samples are purchased from abroad (such as Berea sandstone from USA). The cost of importing core samples from abroad is very high and time consuming. Therefore, it is worth searching for local sources of suitable sandstone core samples to meet research and academic needs. For basic and applied research purposes as mentioned above, alternative sources for sandstone core samples such as local formation outcrops and synthetic rocks can be used. However, synthetic core samples behavior and properties are generally far from that of downhole cores or those obtained from outcrops.

Certain characteristics and properties must be thoroughly investigated before any alternate source for sandstone core samples are considered such as: geology, location accessibility, availability, values and ranges of physical properties (porosity and permeability), mineralogy, clay content and type, rock quality designation (RQD), grain size distribution, pore size distribution, degree of homogeneity, mechanical properties and the overall cost.

OBJECTIVE, METHODOLOGY AND RAW MATERIALS

The objective of this study is to search for local sources for sandstone cores samples of homogeneous properties suitable for research and academic studies as an alternative source for the unavailable real downhole sandstone core samples or the expensive imported samples. The methodology to achieve the objectives of this study is by conducting the following activities:

- Collecting bulk samples from local sandstone formations outcropping in the central region of Saudi Arabia including: Al-Kharj area (90 km South of Riyadh), Jabal Saq (Saq hill) between Hai'l and Al-Qassim areas, and Al-Hlaliah town in Al-Qassim area.

- Coring 1.5 inch core plugs from the collected bulk sandstone blocks.

- Characterizing the suitability of the obtained sandstone samples cores through the measurement of their petrophysical and mechanical properties.

- Performing a preliminary economical feasibility study for the utilization of the studied sandstone formations outcrops.

- Verifying the applicability and suitability of the tested sandstones in petroleum engineering studies by conducting some applied laboratory tests such as water flooding, sand production and permeability-stress relationship.

Several consolidated and friable sand formations are located in the stratigraphic column of Saudi Arabia (Figure 1) [2] such as Bahr (friable sandstone), Hadrukh (friable sand), Khafji and Safaniya (weak sandstone), Wasia (very weak sandstone), Biyadh and Buwaib (friable sand), Minjur (friable sand), Unayzah (very weak sandstone), Shiqqah (hard sandstone), Saq (hard sandstone), Um Assha'al (friable sandstone), Sarah (hard sandstone). From the previously mentioned formations, only Saq, Sarah and Um Assha'al formations are outcropped on surface and intact cylindrical core samples can be made according to petroleum engineering studies requirements. Therefore, this study was concentrated in examining the suitability of outcropping sandstone formations for petroleum and natural gas engineering applied studies. The following sections describe the geological properties of the tested formations.

Um Assha'al Formation appears on surface ten kilometers from Al-Kharj city on Al-Kharj-Riyadh main Road. This sandstone belongs to the Tertiary age in the Cenozoic era and characterized by its natural joints and yellowish color. Neither oil nor gas reservoirs are present in this formation [2].

Saq Formation belongs to transitional period between Ordovician and Cambrian age in the Paleozoic era [2]. This formation outcrops in the area of Jabal Saq between Al-Qassim and Hai'l provinces. This formation contains fresh water aquifer as indicated by the published Saudi Arabian stratigraphic column [2]. This sandstone is free of laminations or natural joints and its off-white in color.

Sarah Formation outcrops in Al-Helalliah town in Al-Qassim province. This formation belongs to Silurian age in the Paleozoic era and contains neither oil or gas nor water [2]. This sandstone is red to brown in color and free of natural joints.

Sandstone formation to be used in petroleum and natural gas engineering studies must be as follows [1]: Homogeneous and have wide ranges of porosity and permeability, Free of reactive clay minerals, Consolidated enough to withstand vibrations and coring stresses, Resist deteriorating action of coring fluids, Have high QRD value, Strong enough to withstand confining pressure during experiments and Cost effective and readily available.

EQUIPMENTS AND TESTING PROCEDURES

In this section, equipment and experimental set-ups used are presented. Furthermore, procedures followed during testing are presented.

Mineralogy and Textural Analysis

It is important to know the mineralogy and pore filling materials of any rock before its usage in petroleum engineering applied studies to overcome any unpredicted experimental difficulties such as permeability damage due to clay swelling or movement. Rock mineralogy can be identified by X-ray diffraction (XRD) and the results are supported by examining textural and elemental properties of the rock using scanning electron microscopy (SEM).

Granulometric Analysis

The importance of granulometric (grain size) characterization goes back to the fact that very small amounts of clay minerals, particularly of silt and clay sizes are highly affecting the porosity and permeability of core samples to be used in petroleum and natural gas engineering studies. Grains sorting and roundness are highly affecting rock porosity, permeability and pore size distribution [3]. There are several methods of rocks granulometric analysis. Sieving procedure was the one used in this study. This was done by stacking various sizes of standard sieves (35, 40, 45, 50, 60, 70, 100, 140 and 325 mesh numbers) ascendingly. After placing the test sample in the top sieve, the whole assembly is placed in a vibrating machine for at least 30 minutes before retained fractions on each sieve are collected. Sand fraction is weighted using an accurate balance, and then weights are used to construct the required plots.

The graphic procedures, which are commonly presented using in the granulometric data, are the histograms and cumulative curves.

Grain sorting can be used as an indirect measure of permeability and porosity. Good sand sorting indicates good porosity and permeability. Furthermore, sandstone grains distribution is predicted by comparing the grain sizes mean and median. Sand grains size is normally distributed when the calculated median value is equal to the sand sizes mean value. Otherwise, the distribution is either negatively or positively skewed [4].

Pore Size Distribution

Mercury intrusion into a porous material has been widely used to characterize pore-space microstructure and to obtain a pore throats size distribution from measurements of injected mercury volume vs. pressure applied [5]. The advantage of this technique is that small irregular rock sample is adequate to perform the required measurement if compared with other techniques, which require uniform core samples. Mercury injection capillary pressure data are a direct measure of the percentage of pore space within a rock that can be filled with a given fluid when a given amount of pressure is applied. The data are used to calculate pore throat sizes, which in turn can be used to calculate, pore size distribution for sandstones or carbonate rocks [5].

Rock Quality Designation

Most 1.5 inch core holders routinely used in the measurement of rocks permeability, porosity and mechanical properties requires samples of length to diameter ratio between 2 and 2.5 [6]. The rock quality designation (RQD) is a measure of the ease of bulk rock coring and it is defined as the cumulative length of core pieces longer than 7.62 cm (3 inch) or L/D ratio between 2 and 2.5 in a run divided by the total length of the core run. The total length of core must incorporate all lost core sections and cores of L/D ratio less than 2. Any mechanical breaks cause by the drilling (coring) process or in extracting the core from the core barrel should be ignored. RQD must be evaluated as soon as possible after drilling (coring) to avoid any damage that might be occurring during collection, packing, transportation and storage. The following scale is usually used to evaluate rock quality designation [6]. Higher RQD is necessary for mass core production and it is an important characteristic for evaluating the studied sandstone formations.

Mechanical Properties

Rock mechanical properties include unconfined compressive strength, tensile strength, confined compressive strength (failure criteria), Poisson's ratio, and Young's modulus. In this work, cylindrical sandstone test sample is placed in a Hoek cell and confined by mean of servo-controlled hydraulic pump and axially loaded by two steel platens in a test called the confined triaxial compression test. The sample must be strong enough to carry the applied external stresses without pore structure damage.

Porosity

Porosity is a measure of rock space not occupied by the solid structure or framework of the rock. Porosity depends to a large extent on the surface texture, roundness, sorting or uniformity of sand grains size and grain sizes distribution. Compaction of the grains after deposition is an important factor controlling the magnitude of rock porosity and permeability. Cementing material and clay minerals, when become a part of the sedimentary makeup of the reservoir rock, reduce effective porosity and permeability as well.

In this study, porosity measurements were done using cylindrical samples cored from the collected bulk sandstones. Subsequent to porosity measurement, all cores were dried in an oven at 100 ^{o}C for 24 hours. The dried core samples are placed in a piston-sealed cell then mounted into a computerized Helium Porosimeter. The instrument employs electronic transducers and digital read out.

Permeability

Permeability is a measure of a rock's ability, under a potential gradient, to conduct fluids. Like porosity, permeability depends on rock properties such as grain shapes, grain and cement texture, angularity, and grain size distribution.

Permeability is very much dependent on rock grain size. The smaller the grains, the larger surface area exposed to the flowing fluid. The surface area creates a drag on the fluids, which limits the flow rate [7].

Absolute permeability of Saq and Sarah sandstone core samples were measured using gas permeameter. Gas permeabilities (k_g) were then converted to liquid permeabilities (k_L).

Um Assha'al sandstone core samples were found to be out of the measurement range of the available gas permeameter therefore liquid permeameter was used to measure its permeability [7].

RESULTS AND DISCUSSION

Mineralogy and Textural Analysis

As mentioned previously, mineralogy of the studied samples was investigated using X-ray diffraction (XRD). For confirmation, energy dispersive spectrum analysis (EDX) was performed to confirm the existence of clay minerals in the tested samples. Textural analysis of the studied sandstones was done using scanning electron microscope (SEM).

Examination of Um Assha'al sandstone indicated that this sandstone is mainly composed of Quartz (91%), little amounts of Hematite (5%) and traces of the non-swelling Kaolinite clay (2.9%) as shown in Figure 2. Its yellowish color is attributed to the presence of the traces of iron oxides (Hematite). The grains of this sandstone are moderately rounded as revealed by the shape of sand grains appearing in the scanning electron micrographs (Figure 3) when compared with those shown in the standard grain roundness scale.

Examination of Saq sandstone indicated that this sandstone is mostly composed of Quartz (98.8%) as shown in Figure 4. It is free of iron oxides (Hematite) as indicated by its off-white color. The grains are well rounded as revealed by the comparison of the shape of sand grains appearing in the scanning electron micrographs (Figure 5).

Examination of Sarah sandstone revealed that this sandstone is mainly composed of Quartz (78.4%), little amounts of the non-swelling Kaolinite clay (11.1%) and Hematite (6.5%) as shown in Figure 6. Its red to brown color due to the presence of the little amounts of iron oxides (Hematite). The grains of this sandstone are sub-rounded as revealed by Figure 7.

Granulometric Analysis

Grain size distribution of the studied sandstone samples was obtained using standard sieving analysis. Data shown in Table 1 was obtained from histograms generated for the tested sandstones. Grains sorting and distribution was predicted based on calculations performed using standard sand grain sizes analysis [8].

Figure 8 is the histogram of Um Assha'al sandstone. The close agreement between grain sizes mean value (Φ=2.10) and median value (Φ=2.00) indicates that the grains of this sandstone are normally distributed and moderately well sorted throughout the sample as indicated by the calculated value of the graphical standard deviation (σ_1=0.65). As indicated by the mean value of grain sizes (Φ=2.00), this sandstone is characterized as fine to medium size sand.

Figure 9 is the histogram of Saq sandstone. The agreement between grain sizes mean value (Φ=1.70) and median value (Φ=1.75) indicates that the grains of this sandstone are normally distributed and moderately well sorted throughout the sample as indicated by the calculated value of the graphical standard deviation (σ_1=0.39). As indicated by the mean value of grain sizes (Φ=1.70), this sandstone is medium size sand.

Figure 10 is the histogram of Sarah sandstone. The agreement between grain sizes mean value (Φ=2.20) and median value (Φ=2.25) indicates that the grains of this sandstone are normally distributed and poorly sorted throughout the sample as indicated by the calculated value of the graphical standard deviation (σ_1=1.1). As indicated by the mean value of grain sizes (Φ=2.20), this sandstone is fine to medium size sand.

Pore Throats Size Distribution

Pore throats size distribution of the studied sandstones was done using mercury intrusion technique. Sandstone pore throats size distribution measurement is a direct indication of permeability quality.

Figurer 11 is the pore size distribution of Um Assha'al sandstone. The agreement between mean value (17.9 mm) and median value (18 mm) indicates that the pore throats sizes of this sandstone are normally distributed throughout the sample. Pore throats are large in size compared to Saq and Sarah sandstones.

Figurer 12 is the pore size distribution of Saq sandstone. The agreement between mean value (14.3 mm) and median value (14.1 mm) indicates that the pore throats are normally distributed and tailing towards smaller pore size throughout the sample. Therefore, pore throats of this sandstone are medium in size compared to Um Assha'al and Sarah sandstones.

Figurer 13 is the pore size distribution of Saq sandstone. The disagreement between mean value (2.7 mm) and median value (3.1 mm) indicates that the pore throats sizes are poorly distributed throughout the sample. Pore throats of this sandstone is tailing towards smaller pore sizes compared to Um Assha'al and Saq sandstones.

Rock Quality Designation

Most of petroleum and natural gas engineering laboratory equipment are designed to accommodate 1.5 inch diameter core samples. To avoid end effects, core samples of length to diameter ratio (L/D) between 2 and 2.5 should be used. Therefore, the ease of producing core samples satisfying these requirements are an important characteristic of sandstone selection. These requirements are evaluated quantitatively by calculating rock quality designation (RQD). RQD values for Um Assha'al, Saq and Sarah are 91.4% (Excellent), 92.2 (Excellent) and 84.01 (good) respectively as shown in Table 2. Thus, all of the tested sandstones are suitable for standard core samples production for petroleum and natural gas studies.

Mechanical Properties

Unconfined compressive strength (UCS), Apparent cohesion (τ_o), Angle of internal friction (ϕ) and Poisson's ratio (ν) are evaluated for the studied sandstones. The evaluation of these properties is essential for most petroleum and natural gas applied geomechanical studies.

Um Assha'al sandstone cores are friable as characterized by the measure of unconfined compressive strength (3.4 MPa). This fact makes Um Assha'al sandstone core samples unable to carry high laboratory confining stresses. Therefore, it is suitable for sand production simulation studies.

Sarah sandstone is approximately six times stronger than Um Assha'al sandstone as indicated by the measured unconfined compressive strength (19.4 MPa). This makes it suitable for petroleum and natural gas applications that require relatively higher levels of confining stresses.

Saq sandstone is approximately ten times stronger than Um Assha'al sandstone and two times stronger than Sarah sandstone as indicated by the measured unconfined compressive strength (33.7 MPa). This makes it suitable for petroleum and natural gas applications that require higher levels of confining stresses such as permeability-stress relationship.

Permeability and Porosity

Average absolute permeabilities and their standard deviations of Um Assha'al, Saq and Sarah sandstones are 6.2 Darcy (SD=1.1 Darcy), 0.841 Darcy (SD=0.37 Darcy) and 0.183 Darcy (SD= 0.2 Darcy), respectively. Average absolute porosities and their standard deviations of Um Assha'al, Saq and Sarah sandstones are 29% (SD=1.87%), 22.5% (SD=2.65%) and 27% (SD=0.46%), respectively.

The decrease in permeabilities of Saq and Sarah sandstones compared to Um Assha'al sandstone are attributed to the relative depth of these formations as shown in Figure 1. Furthermore, grain sizes and pore throats of Sarah sandstone are poorly distributed causing permeability to be very low compared to Saq and Um Assha'al sandstones. Table 3 summarizes all the measured properties of the tested sandstones mentioned previously.

PRELIMENARY ECONOMICAL ANALYSIS

At present, the most popular standard core samples are Berea sandstone.

Delivery of overseas orders of Berea sandstone takes at least 10 to 12 weeks depending on the quantity ordered and location. The cost of a linear foot of standard Berea sandstone delivered up to the core storage at the Department of Petroleum and Natural Gas Engineering at King Saud University, Riyadh, Saudi Arabia based on the diameter and absolute permeability ranges requested is shown in Table 4.

For comparison, the costs of a linear foot of the studied three sandstones are shown in Tables 5 and 6. It is noticed that Berea sandstone cost increases as requested core diameter decreases. This is attributed to the fact that cores of large diameters are easier to be cored compared to cores of smaller diameters.

It is found that studied local sandstones are cost effective by approximately 10 times and time saving compared to Berea sandstone. Furthermore, it is feasible to establish sandstone quarries in the studied sandstones areas because it lies few kilometers away from residential areas, which provide cost effective infrastructure and accommodation for quarries staff. Additionally, Um Assha'al, Saq and Sarah formations thicknesses are 28, 663 and 414 meters, respectively, which provide huge sandstone reserves that can serve both civil and petroleum engineers. There are other sandstone outcrops that might be suitable for coring in addition to the wide range of carbonates outcrops in most areas of Saudi Arabia. Therefor more research is needed to discover and investigate the suitability of such formations for petroleum and natural gas engineering applited studies.

CONCLUSIONS

The following conclusions are achieved based on the analysis of the laboratory measurements performed in this study:

- Um Assha'al sandstone outcropping in Al-Kharj area is friable sandstone characterized by natural joints and yellowish color. It is mainly composed of quartz and small amounts of kaolinite and hematite. Its grains are moderately rounded and moderately well sorted. Furthermore, grains and pore throats sizes are normally distributed.

- Sarah sandstone outcropping in Al-Helalliah town in Al-Qassim area is moderately weak sandstone characterized as red to brown in color. It is mainly composed of quartz and small amounts of kaolinite and hematite. Its grains are relatively well rounded, poorly well sorted and bi-normally distributed. Furthermore, pore throats sizes are poorly distributed.

- Saq sandstone outcropping in the area between Al-Qassim and Hail is weak sandstone characterized by off-white color. It is mainly composed of quartz. Its grains are well rounded and well sorted. Furthermore, grains and pore throats sizes are normally distributed.

- Average absolute permeabilities and their standard deviations of Um Assha'al, Saq and Sarah sandstones are 6.2 Darcy (SD=1.1 Darcy), 0.841 Darcy (SD=0.37 Darcy), 0.183 Darcy (SD=0.2 Darcy), respectively.

- Average absolute porosities and their standard deviations of Um Assha'al, Saq and Sarah sandstones are 29% (SD=1.87%), 22.5% (SD=2.65%) and 27% (SD=0.46%), respectively.

- Preliminary economical study has shown that the studied sandstones are cheap and easier to obtain compared to imported sandstone cores.

- Rock quality designation (RQD) analysis has shown that it is easy to core standard plugs from Sarah and Saq bulk sandstones and it is relatively easy in case of Um Assha'al sandstone.

REFRENCES

[1] Kamal A. Haroon: “Evaluation of Sandstone Outcroping in Saudi Arabia for Potential Use in Applied Studies in Petroleum and Natural Gas Engineering.”, M.Sc. thesis, Petroleum and Natural Gas Engineering, College of Engineering, King Saud University, Riyadh, Saudi Arabia, January, 2207.

[2] “Map of Oil and gas fields and the Stratugrapghic column in Saudi Arabia”, Bin Labbon Publishing House, Riyadh Saudi Arabia.

[3] J. W. Amyx, D. M. Bass and R. L. Whiting: “Petroleum reservoir engineering.”, McGraw Hill, 1960.

[4] M. Tucker: “Techniques in Sedimentology.”, Blackwell Scientific Publications, 1988.

[5] D. Tiab and E. c. Donaldson: “Petrophysics: theory and practice of measuring reservoir rock and fluid transport properties.”, Gulf publishing company, 1999.

[6] A. R. Jumikis: “Rock Mechanics.”, 2nd edition, Gulf publishing company, 1983.

[7] T. Ahmed: “Reservoir Engineering Handbook.”, 2nd Edition, Elsevier publishing, 2001.

Table 1 Granulometric analysis of the tested sandstones.

Sandstone type	Mean and (Median)	Phi scale					σ_1 Value	Sorting	Roundness and distribution
		Φ 5 (μm)	Φ16 (μm)	Φ 50 (μm)	Φ 84 (μm)	Φ 95 (μm)			
Um Assha'al	2.00 (2.10)	1.00 (500)	1.50 (325)	2.00 (250)	2.75 (150)	3.25 (105)	0.65	Moderately well sorted	Moderately rounded and normally distributed
Saq	1.75 (1.70)	1.00 (500)	1.00 (500)	1.75 (300)	2.25 (212)	1.50 (150)	0.39	Well sorted	Well rounded and normally distributed
Sarah	2.25 (2.20)	1.00 (500)	1.00 (500)	2.25 (212)	3.25 (106)	4.50 (45)	1.10	Poorly sorted	Relatively well rounded and normally distributed

Table 2 Rock quality designations for the studied sandstones.

Rock type	Diameter, inch	L/D	Number of samples	Length, inch	Total length, inch	RQD, %
Sarah sandstone	1.50	> 2.0	47	63.5	69.45	91.4 Excellent
		< 2.0	6	5.95		
Saq sandstone	1.50	> 2.0	12	34	36.88	92.2 Excellent
		< 2.0	3	2.88		
Um Assha'al sandstone	1.50	> 2.0	22	38	45.23	84.02 Good
		< 2.0	7	7.23		

Table 3 Summary of the analysis of testing results.

Sandstone type	Properties	Comments
Um Assha’al	Composed of 91% Quartz, 5% Hematite and 2.9% Kaolinite clay. Yellowish in color. Moderately rounded grains. Normally distributed and moderately well sorted grains. Normally distributed pore throats sizes, Large size grains. Excellent cores of L/D>2 (RQD= 91.4%). Friable sandstone (UCS =3.40 MPa). Average porosity= 28.88%, Standard deviation= 1.87%. Average permeability= 6195.3 md, Standard deviation= 1100 md. Formation thickness= 28 m.	This sandstone is suitable for sand production simulation studies.
Saq	Composed of 98.8% Quartz. Off-white in color. Well-rounded grains. Normally distributed and moderately well sorted grains. Normally distributed pore throats sizes, Medium size grains. Excellent cores of L/D>2 (RQD=92.2%). Moderately weak sandstone (UCS= 19.40 MPa). Average porosity= 22.5%, Standard deviation= 2.65%. Average permeability= 840.87 md, Standard deviation= 369.75 md. Formation thickness= 663 m.	This sandstone is suitable for water flooding, enhanced oil recovery, permeability-stress relationship and rock mechanics studies.
Sarah	Composed of 78.4% Quartz, 11.1% Kaolinite clay and 6.5% Hematite. Red to brown in color. Sub-rounded grains. Normally distributed and poorly sorted grains. Poorly distributed pore throats sizes, Small size grains. Good cores of L/D>2 (RQD=84.02%). Weak sandstone (UCS=33.70 MPa). Average porosity= 27.1 %, standard deviation= 0.46%. Average permeability= 182.41md, standard deviation= 19.74 md. Formation thickness= 415 m.	This sandstone is suitable for water flooding, enhanced oil recovery, permeability-stress relationship and rock mechanics studies

Table 4 Estimated cost of Berea sandstone from Cleveland quarries in U.S.A.

Rock type (Diameter, inch)	Absolute permeability range, mD	Price per linear foot, $		References
		Unit price	Average price	
Berea sandstone (1.5)	50-300	525	525	Various purchasing orders as shown in Appendix II
	200-500	413		
	900-1200	635		
Berea sandstone (2.0)	200-500	413	370	
	350-700	267		
	500-700	333		
	900-1200	467		

Table 5 Estimated prices of Saq and Sara sandstones from Al-Qassim area in Saudi Arabia.

Operation	No. of units or staff required	Number of operation days	Total cost, SR
Technician and labor	2	2	1500
Transportation heavy truck	1	2	1800
Daily living cost for staff	2	2	700
Digging truck	1	2	2000
Coring and trimming machine	1	2	1000
Packing cost	1	1	N/A
Shipping cost	----	----	N/A
Approximate No. of feet cored	90		
Total cost, SR	7000		
Approximate cost/foot, SR	78		
Approximate cost/foot, $	21		

Table 6 Estimated cost of Um Assha'al sandstone from Al-Kharj area in Saudi Arabia.

Operation	No. of units or staff required	Number of operation days	Total cost, SR
Technician and labor	2	1	750
Transportation heavy truck	1	1	900
Daily living cost for staff	1	1	350
Digging truck	1	1	1000
Coring and trimming machine	1	2	1500
Packing cost	1	1	N/A
Shipping cost	----	----	N/A
Approximate No. of feet cored	30		
Total cost, SR	4500		
Approximate cost/foot, SR	150		
Approximate cost/foot, $	40		

Time			Properties				
Era		Age	Formation	Lithology	Fluid type	Thickness, m	
Cenozoic	Quarternary		Udifferentiated	Gravel+Soil+clay	-----	Variable	
			ArRaffa'a	Gravel+Soil+clay	-----	Variable	
	Tertiary	Meocene	Um Assha'al	Sandstone	-----	28	← Sample 1
			Hufuf	Limestone	-----	95	
			Dam	Limestone+Shale	-----	91	
			Hadrouk	Limestone	Water	84	
		Eocene	Dammam	Limestone	Water + Oil	33	
			Rus	Anhydrite	-----	56	
		Paliocene	Umm Er Radhuma	Limestone	Water	243	
Meozoic		Cretaceous	Aruma	Limestone	Oil	142	
			Wasia	Sandstone+Shale	Water	42	
			Biyadh	Sandstone+Shale	-----	425	
			Buwaib	Limestone	Water	18	
			Yamama	Limestone	Water	46	
			Sulaiy	Limestone	-----	170	
		Jurassic	Hith	Anhydrite	-----	90	
			Arab	Limestone	Oil	124	
			Jubaila	Limestone	-----	118	
			Hanifa	Limestone	-----	113	
			Twaqiq	Limestone	-----	203	
			Dhruma	Limestone	-----	375	
			Marrat	Sand + Shale	Oil + Gas	103	
			Manjur	Sandstone	Water	315	
		Teriassic	Jilh	Dolomite	Oil + Gas	326	
			Sudair	Sandstone+Shale	-----	116	
Paliozoic		Permian	Khuff	Limestone	Gas	171	
			Unayzah	Sandstone	Gas	33	
		Carbonian	Asshajarah	Sandstone	-----	32	
			Jubah	Sandstone+shale	-----	220	
		Devonian	Jauf	Limestone	Gas	272	
			Tawil	Sandstone	-----	200	
		Silurian	Qalibah	Sandstone	Gas	187	
			Sarah	Sandstone	-----	415	← Sample 2
		Ordovician	Qassim	Sandstone+shale	-----	283	
		Cambrian	Saq	Sandstone	-----	663	← Sample 3
			Yatib	Sandstone	-----	21	
Primary		Pre-Cambrian	Gabalah	SS+LS+Shale	-----	3000	
			Agsas	Metamorphic	-----	Variable	
			Basement	Igneous	-----	Variable	

Figure 1 Typical stratigraphic column of Saudi Arabia [4].

Energey Dispersive Spectrum (EDX) Analysis		
Elements	percentage	Comments
Silicon (Si)	91.0	Quartz
Iron (Fe)	5.0	Hematite
Aluminun (Al)	2.9	Kaolinite clay
Others	1.1	Impurities or machine components

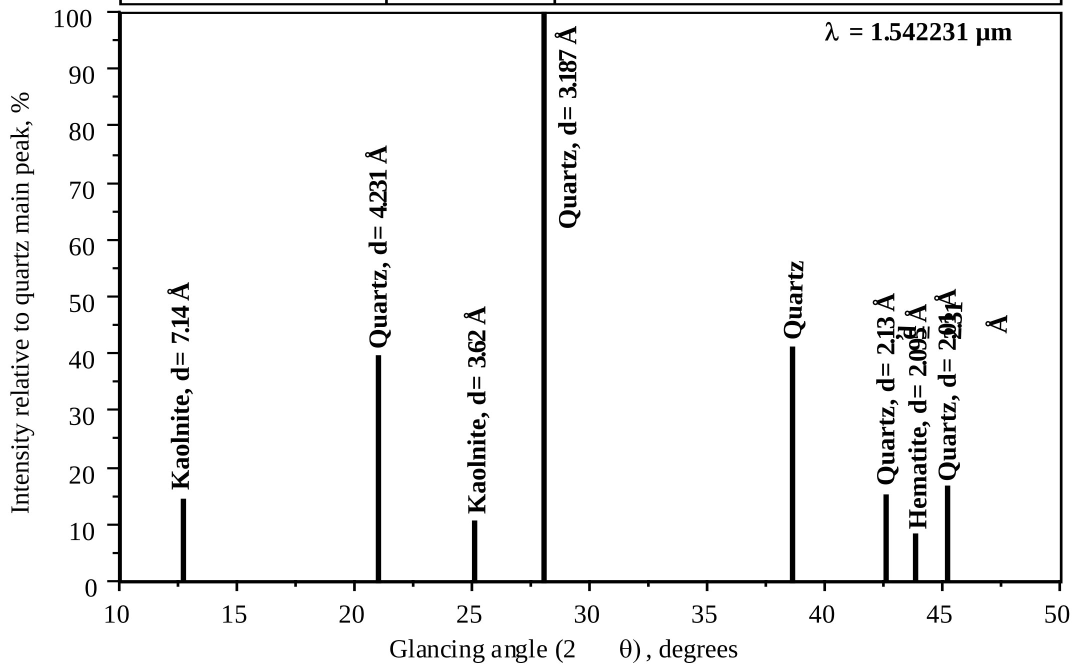

Figure 2 X-ray diffraction and EDX analysis of Um Assha'al sandstone.

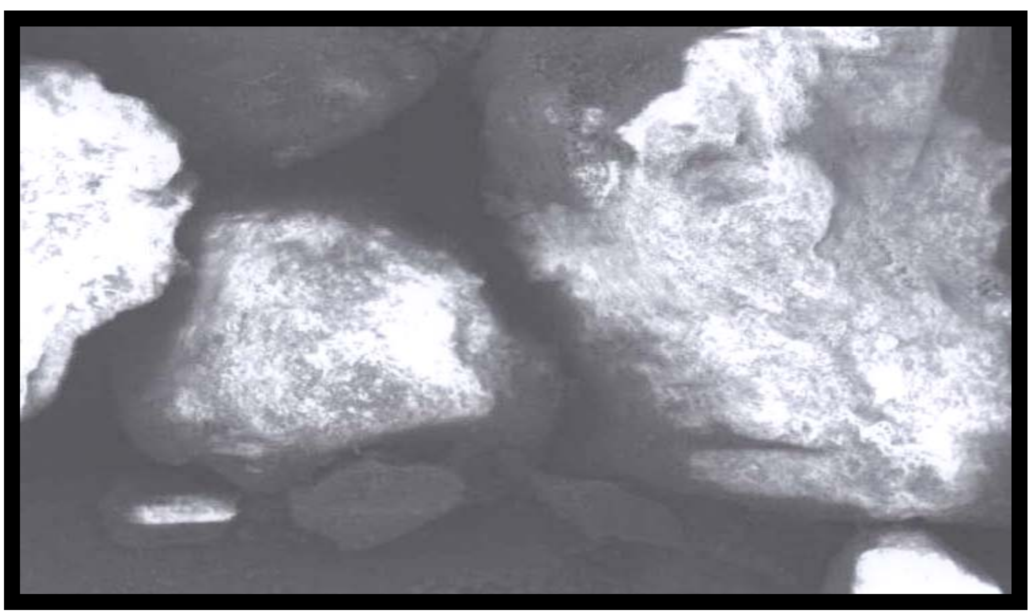

Figure 3 Scanning electron micrograph of Um Assha'al sandstone showing roundness and grain size distribution.

Energey Dispersive Spectrum (EDX) Analysis		
Elements	percentage	Comments
Silicon (Si)	98.8	Quartz
Iron (Fe)	Zero	--------
Aluminun (Al)	Zero	--------
Others	1.2	Impurities or machine components

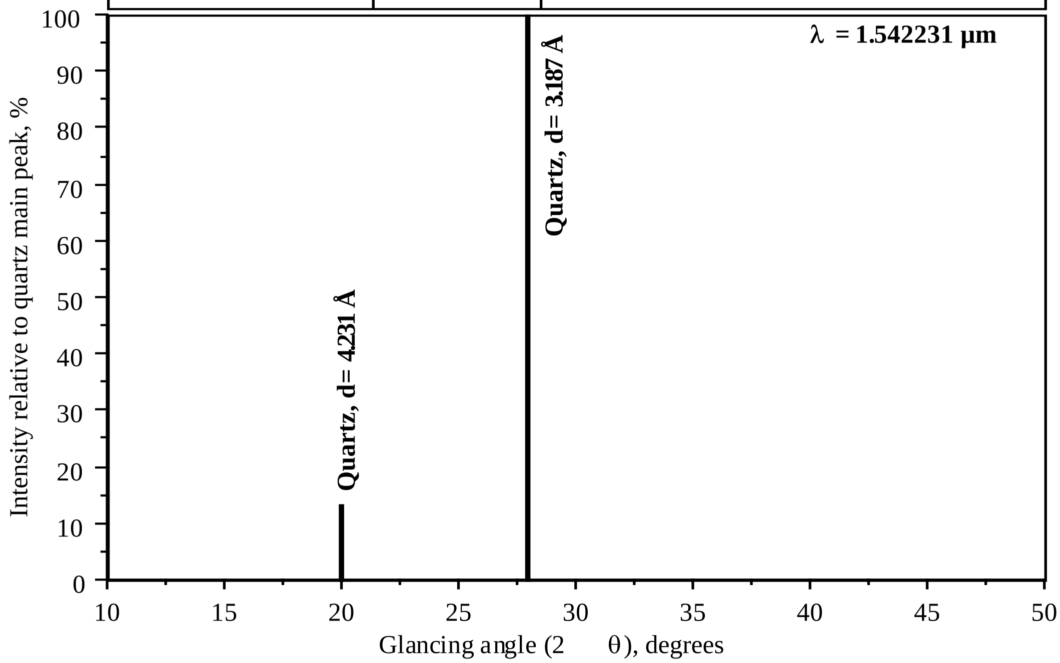

Figure 4 X-ray diffraction and EDX analysis of Saq sandstone.

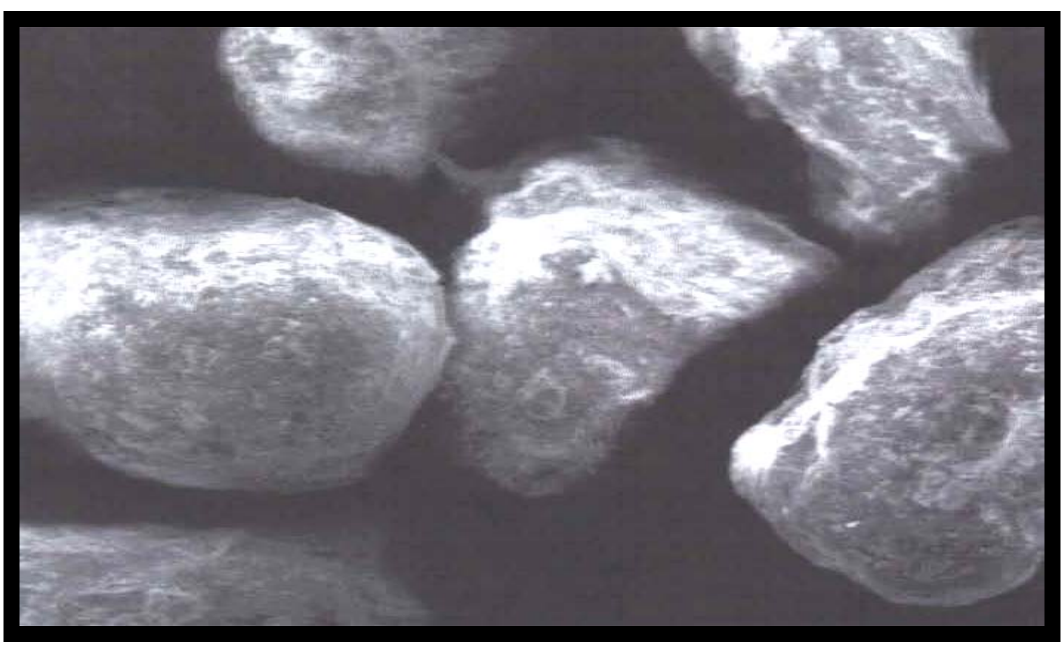

Figure 5 Scanning electron micrograph of Saq sandstone showing roundness and grain size distribution.

Energey Dispersive Spectrum (EDX) Analysis		
Elements	percentage	Comments
Silicon (Si)	78.4	Quartz
Iron (Fe)	6.50	Hematite
Aluminun (Al)	11.1	Kaolinite clay
Others	4.0	Impurities or machine components

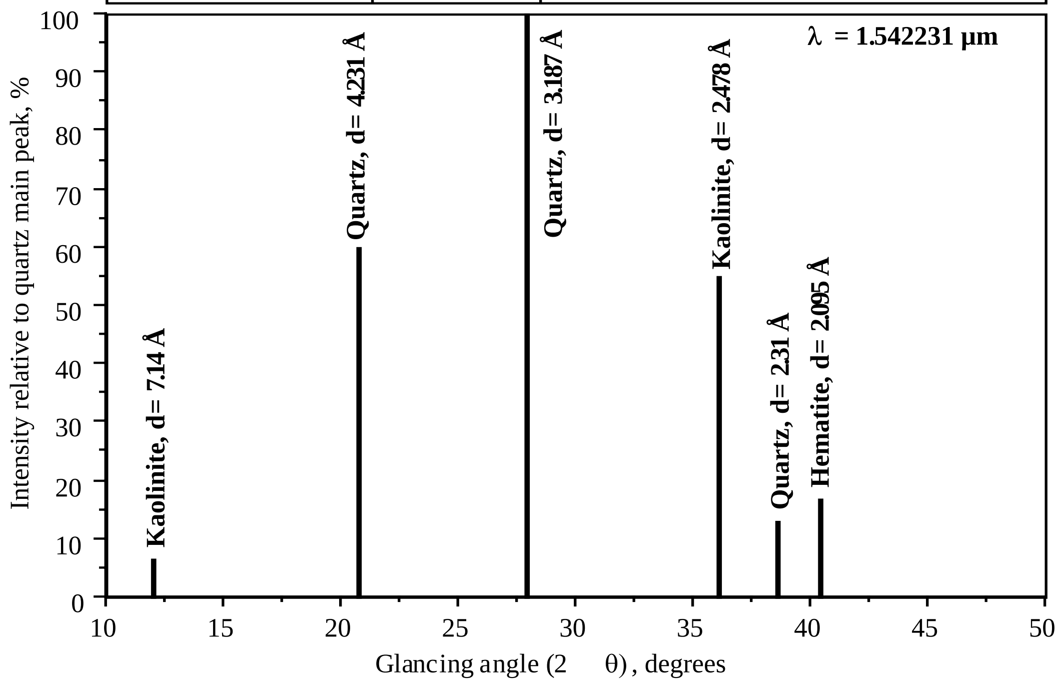

Figure 6 X-ray diffraction and EDX analysis of Sarah sandstone.

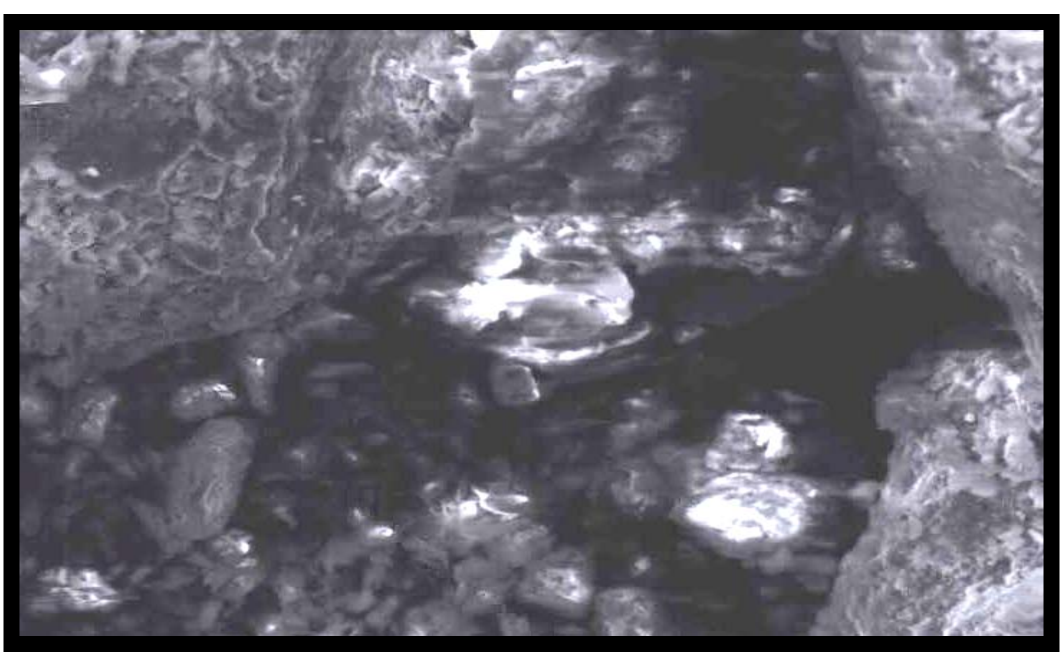

Figure 7 Scanning electron micrograph of Sarah sandstone showing roundness and grain size distribution.

Sorting	Moderately well sorted
Roundness	Moderately rounded
Distribution	Normal
Median	ϕ = 2.00 (250 µm)
Mean	ϕ = 2.10 (250 µm)

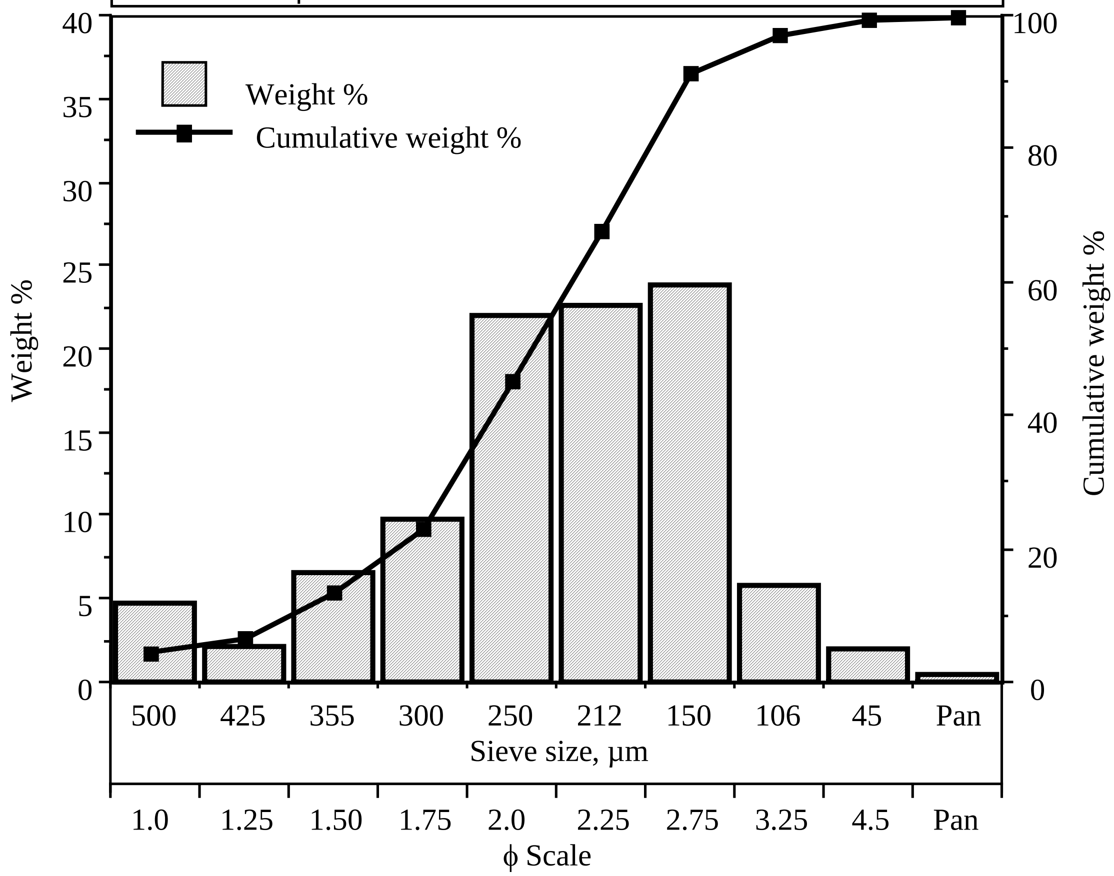

Figure 8 Granulometric analysis of Um Assha'al sandstone.

Sorting	Well sorted
Roundness	Well rounded
Distribution	Normal
Median	ϕ = 1.75 (300 µm)
Mean	ϕ = 1.70 (300 µm)

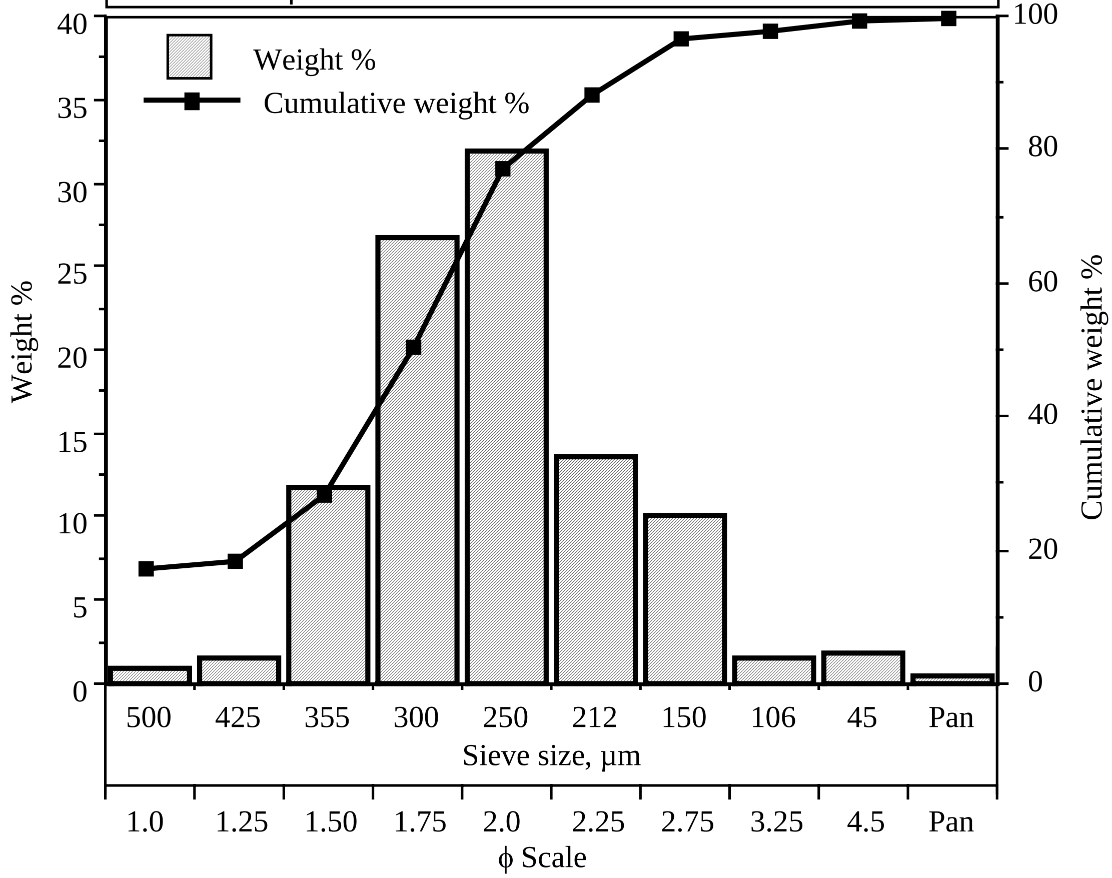

Figure 9 Granulometric analysis of Saq sandstone.

Sorting	Poorly sorted
Roundness	Sub-rounded
Distribution	Bi-Normal
Median	ϕ = 2.25 (212 µm)
Mean	ϕ = 2.20 (212 µm)

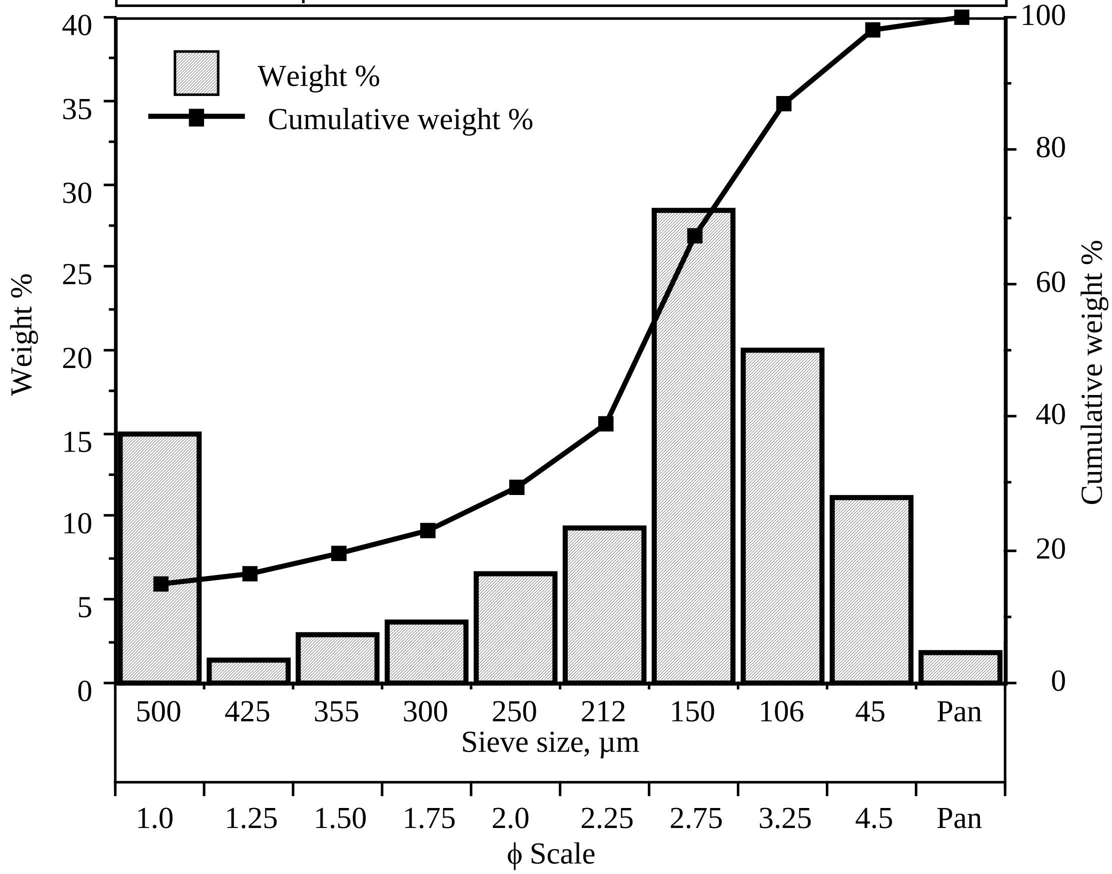

Figure 10 Granulometric analysis of Sarah sandstone.

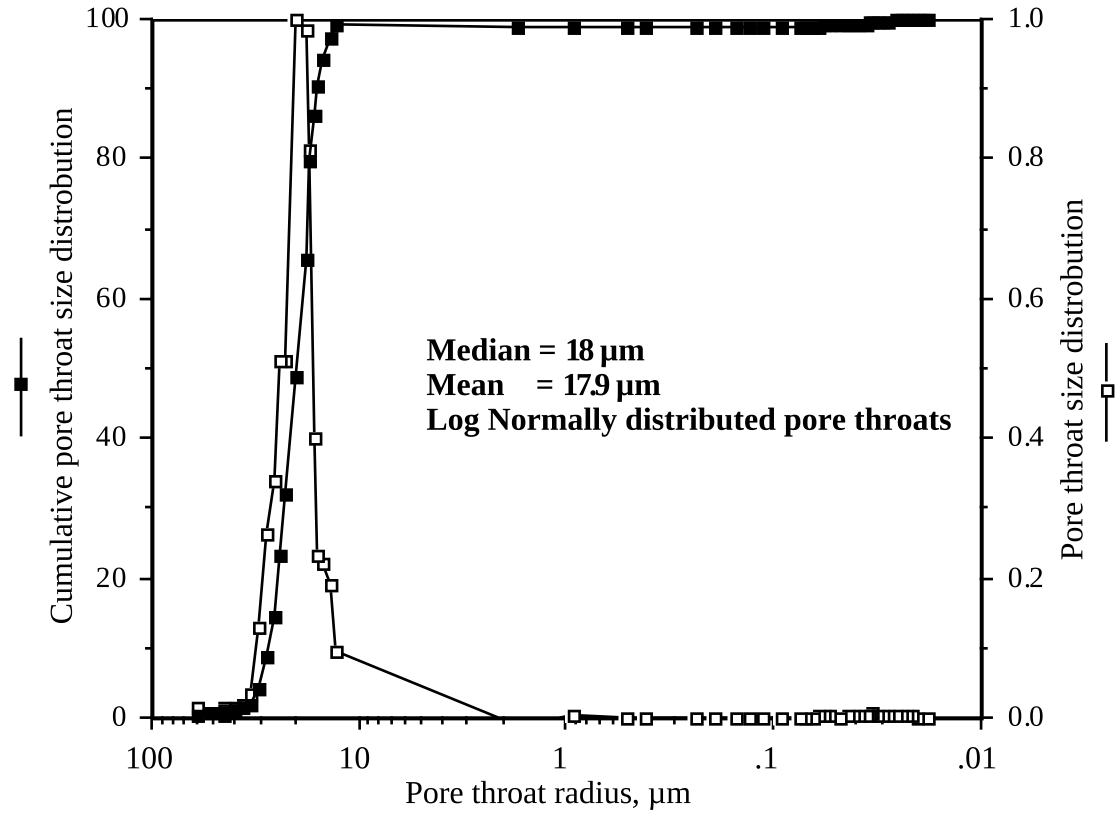

Figure 11 Pore throat size distribution of Um Assha'al sandstone.

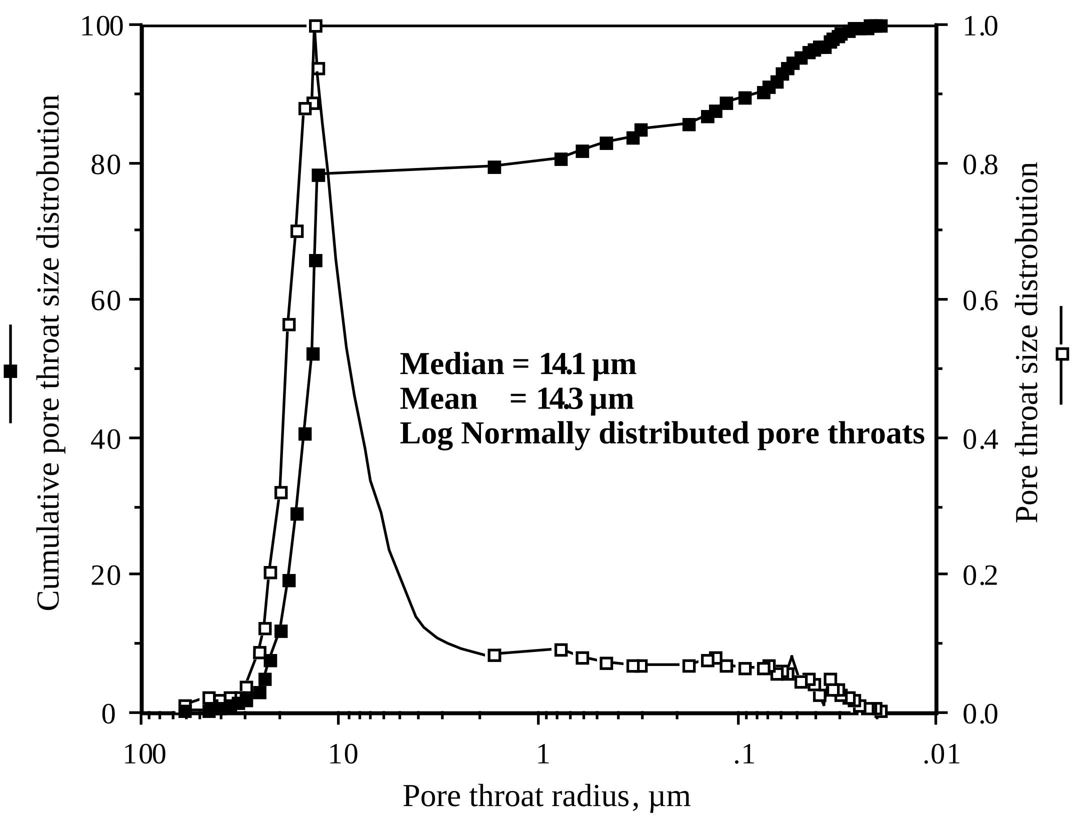

Figure 12 Pore throat size distribution of Saq sandstone.

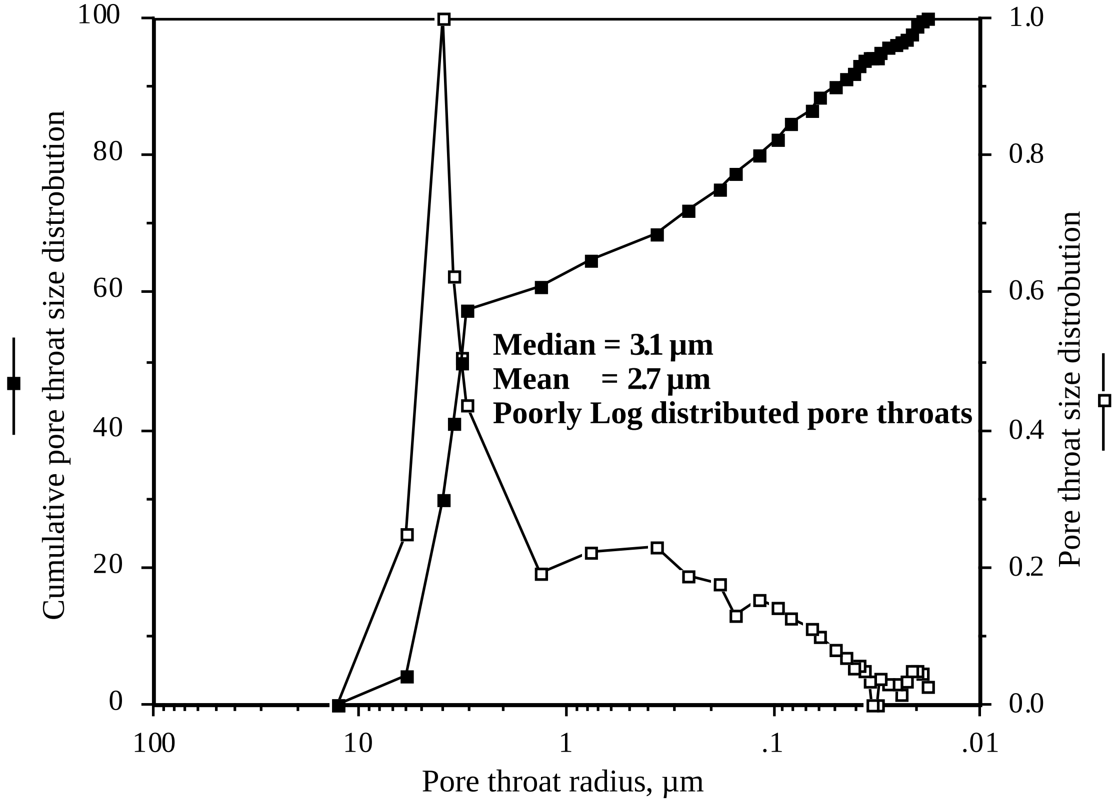

Figure 13 Pore throat size distribution of Sarah sandstone.