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The Evaluation of Reservoir Quality of Sarvak Formation in One of Oil Fields of the Persian Gulf

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Abstract
Sarvak formation, with the middle cretaceous (Cenomanian) age, is one of the stratigraphic units of the Bangestan group in the southern Iran. The carbonate rocks of this formation form the reservoir rock in the study field. Generally, Sarvak formation is subdivided into three members including Mishrif, Khatiyah, and Maddud in the Persian Gulf, and the average thickness of the reservoir unit (i.e. Mishrif) in the field varies from 55 to 73 meters. The purpose of this study is to investigate the petrophysical properties of Sarvak formation in terms of rock type and hydraulic flow unit analysis. In this context, at the first step, the geological characteristics (i.e. sedimentary texture and diagenetic features) of the reservoir rocks were studied in this field. Then, the core porosity and permeability data obtained from different facies plots of the petrophysical diagram of Lucia in which different facies distribute on the three petrophysical classes of diagram based on sedimentary and diagenetic characteristics resulted in the differentiation of eight rock types. Also, using the concept of reservoir quality index (RQI) and flow zone index (FZI), eight hydraulic flow units were recognized and named as A, B, C, D, E, F, G, and H in an ascending reservoir quality order. The results show a good relation between different identified rock types and HFUs in the reservoir, which can be interpreted based on geological attributes.

Key words: Sarvak Formation, Reservoir Quality, Rock Type, Hydraulic Flow Unit, the Persian Gulf

Introduction
The Persian Gulf is a marginal sea with the length of about 1000 km and the width varying between 180 to 250 km, covering an area of approximately 24000 km^2 [1]. It lies between latitudes 24° to 30°, North and longitudes 48° to 57°, East at the eastern parts of the Arabian Plate [1]. The Persian Gulf was formed during the Late Pliocene to Pleistocene and, morphologically, has strongly been affected by tectonic movements. Sarvak formation in Coastal Fars and the northern Persian Gulf is the equivalent of Middle Cretaceous units of Wasia Group in the southern Persian Gulf [2]. The Mishrif Member in Wasia Group (equivalent of the upper Sarvak with early Cenomanian-Turonian in age) is considered as an important hydrocarbon reservoir [3]. This field is located near Iran-Dubai water border, 90 km of the costal of Iran (Fig. 1). The aim of this study is to evaluate the reservoir properties of Sarvak formation in order to help provide a better understanding during the development of this field.

Methodology
In this study, 96 thin sections after staining with Alizarin Red-S (for the detection of calcite from dolomite) were studied by Dickson method [4]. Polarizing and scanning electron microscopes (model 1450 VPLO) were used to identify rock components, matrix, microporosity and microstructures in the central laboratory of Ferdowsi university of Mashhad. For the estimation of the abundance of allochems in any facies, the Flugel's [5] comparative charts and for the classification of reservoir rocks the Dunham's [6] classification scheme were used. In this study, in order to obtain a quantitative and qualitative evaluation of porosity in different facies, porosity was calculated by point counting method using JMicroVision-v125-win32 software.

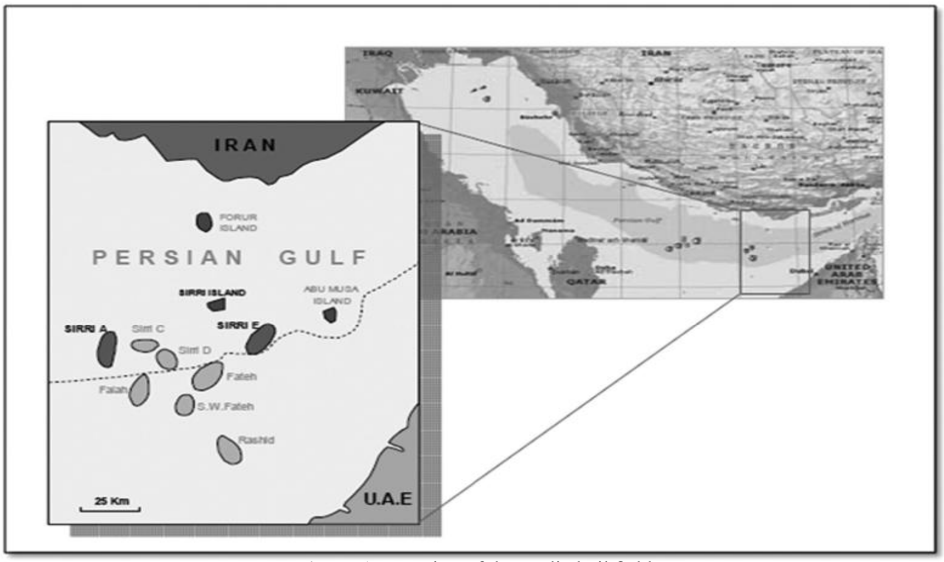


Figure 1- Location of the studied oil field

To attain and show more details of some features of the reservoir rocks (e.g. pore spaces and fractures), the SEM images of some facies were provided. Core porosity and permeability data were also used in petrophysical studies. Moreover, a set of well logs, including GR, NPHI, RHOB, and DT, associated with sedimentary and diagenetic features derived from petrography and core studies, were used for zoning the reservoir in the studied wells

Results and Discussion

The investigation of the reservoir quality is based on the integration of geological and petrophysical studies. The petrophysical properties of sedimentary rocks are determined by sedimentary and diagenetic characteristics. Sedimentary characteristics can be related to grain size, sorting, sphericity, roundness, and grain arrangement. Diagenetic features can be shown by clay mineral types, cementation, dissolution, etc. In this study, first, various types of pore spaces in the reservoir were considered, and then different rock types were introduced. In order to investigate the recognized rock types in relation to reservoir quality, hydraulic flow units were identified after determining pore space types. Since the porosity is a very important factor in determining different HFU, different types of porosities are discussed below:

Pore Types in Sarvak Formation

In this study, Lucia [7, 8] classification has been used for subdividing the pore types. Common pore types in the reservoir are interparticle, vuggy, moldic, and fracture. In Figure 2, the frequency of different pore spaces derived from image analysis software (JMicroVision-v125-win32) has been shown. As it can be seen in the histogram, the vuggy type is the dominant pore in the Sarvak formation (Fig. 3). More details are given in the following paragraphs:

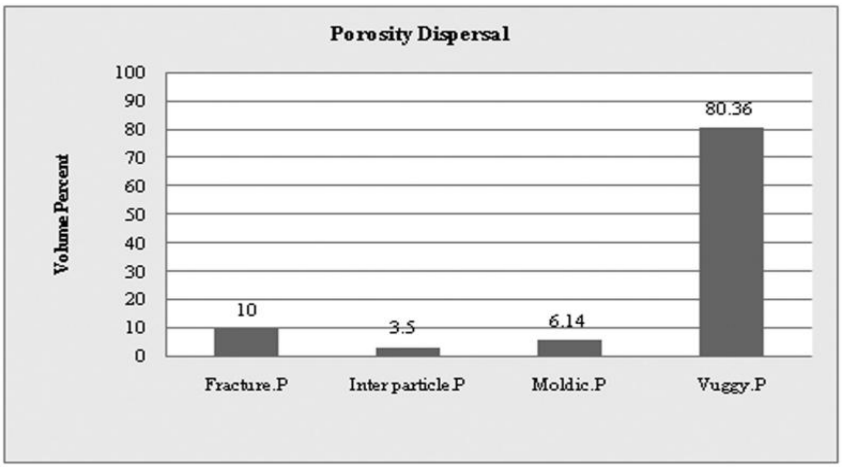


Figure 2- Histogram of volume percent of pores in the all different facies of Sarvak reservoir in the studied field. Vuggy porosity is the dominating pore (80.36 volume percent).

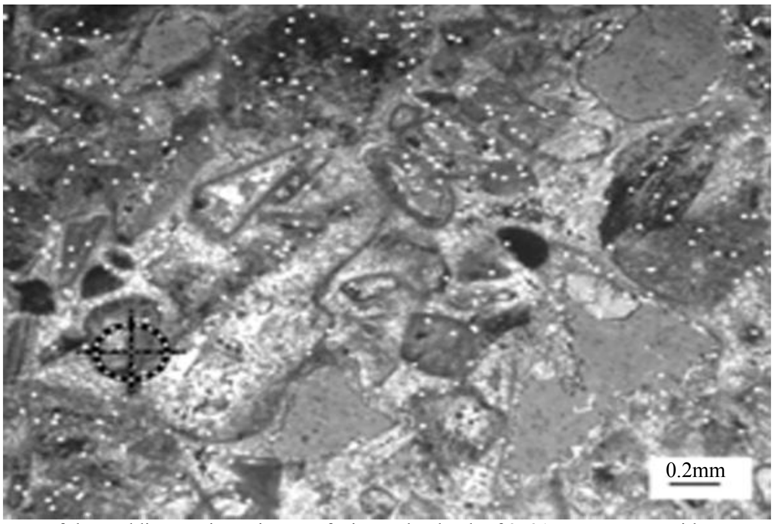


Figure 3- Microscopic image of the moldic pore in grainstone facies at the depth of 2531 meter, XPL, with gypsum blade. The pore space is counted by the point counting method with JMicroVision-v125-win32 software and is about 12.55% percent.

Interparticle Pores

This pore type is usually primary; however, in some cases, as a result of cement and matrix dissolution, it is secondary (Fig. 4A). Interparticle pores are controlled by rock fabric (fabric selective) and often observed in grainstone and rudstone facies in the reservoir. This pore type, has a limited extension, but in facies having intergranular pores, reservoir quality is assumed to be high.

Vuggy Pores

This pore type is secondary in origin and it is observed in the form of dissolved, irregular, and, in some cases, microkarstic pores, cutting the cement and grain boundaries, and thus it is non fabric selective [9]. In some cases, the good connection between spaces in this pore type is a reason for a high reservoir quality facies (Fig. 4, B). Figure 4C also shows the SEM images of this type of pores. Vuggy pore spaces have been developed in different sizes, varying from millimeter to centimeter, in all facies of the reservoir and sometimes associate with microkarstic vugs (Fig. 4D).

Enhanced Intergranular Dissolved Pores

The spaces in this pore type have been created by the enlargement and development of primary pores as a result of dissolution, and they are specially related to unstable carbonate grains [5]. Figure 4E shows this pore type between the bivalve skeleton.

Moldic Pores

Moldic pores have been mostly developed in grain dominated facies such as grainstones and rudstones (Fig. 4F). This pore type is fabric selective and associated with isolated pores in the reservoir.

Thus, the creation of these pores is associated with a change from intergranular to isolated pores and results in a significant decrease in permeability, although it apparently increases the porosity.

Fracture Pores

This kind of pores is evident in rudstone and particularly in wackestone facies (Fig. 5A). Fractures in carbonate rocks are a common phenomenon and are usually developed after the burial of sediments [9].

These fractures in rock are often developed as a group (Fig. 5B), and thereby resulting in an increase in permeability (even in low porosity rocks). In some facies such as wackestones, permeability is low, but if fractures develop, a significant increase can occur in permeability and improves reservoir quality (ruch as rock type 6).

Petrophysical Properties of Reservoir

In order to obtain an accurate reservoir evaluation from geological models of carbonate rocks, carbonate rock fabric should be correlated with petrophysical properties. Lucia [8] showed that in carbonates with no vuggy pores and permeability more than 0.1 md, there is a hyperbolic relationship between particle size and mercury capillary displacement pressure, assuming important particle-size boundaries at 100 and 20 micrometers. Thus, he introduced a specific petrophysical chart with three petrophysical fields based on particle size including Class 1 (particle size < 20 micron), Class 2 (20 < particle size <100 micron) and Class 3 (100 < particle size < 500 micron) (Fig. 6).

In this study, Lucia's [8] chart has been used in the assessment of the reservoir quality in the Sarvak formation and in the classification of rock types of the reservoir. In this respect, the core porosity and permeability data of all facies were plotted on the chart. As shown in Figure 7, the data are distributed in three distinct petrophysical groups; but some are plotted outside of these three confined classes which are probably related to diagenetic processes.

Rock Type Classification

By comparison of different facies with petrophysical properties, based on Lucia's chart [8], eight rock types were identified in the Sarvak formation. These rock types mainly differ in depositional facies, pore types, and petrophysical properties. In this case, any facies could be subdivided into two or more rock types related to pores characteristics.

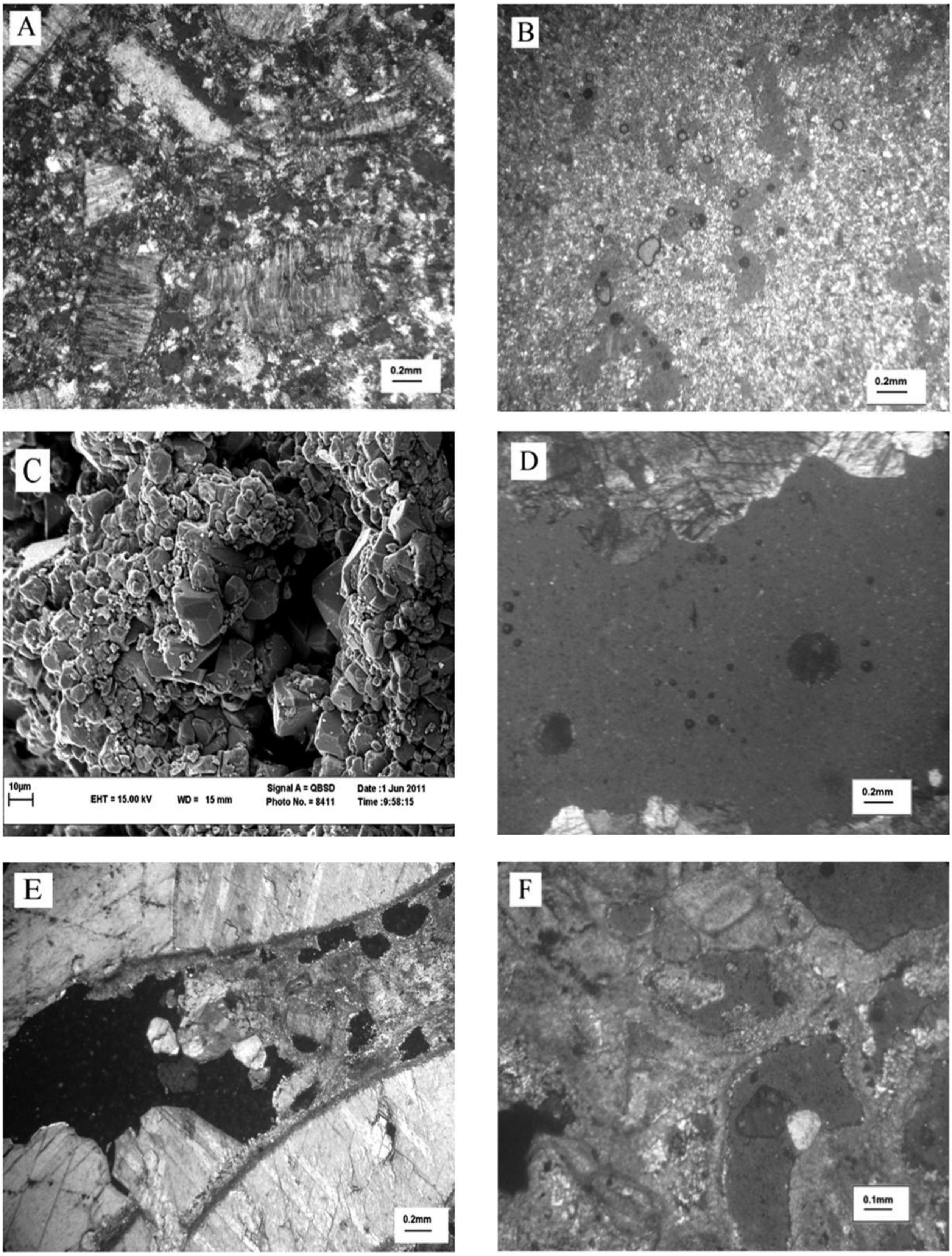


Figure 4- Types of pore space resulted from dissolution in one of the studied wells.
A) Interparticle pore created by dissolution between bivalve›s fragments (depth 3523 m) XPL, B) Touching vuggy pore (depth 3560 m) XPL with gypsum blade, C) Scanning electron microscope image of vuggy pore between calcite crystals (depth 3545)., D) The vuggy pore to form the microkarstic vugs (depth 3520 m) XPL with gypsum blade, E) Enhanced pore as a result of dissolution (depth 3521 m) XPL F) Moldic pore as a result of the dissolution of bivalves fragments; some of the vuggs are partly filled and some are completely filled with the fine crystals of dolomites (depth 3521 m) XPL with gypsum blade.

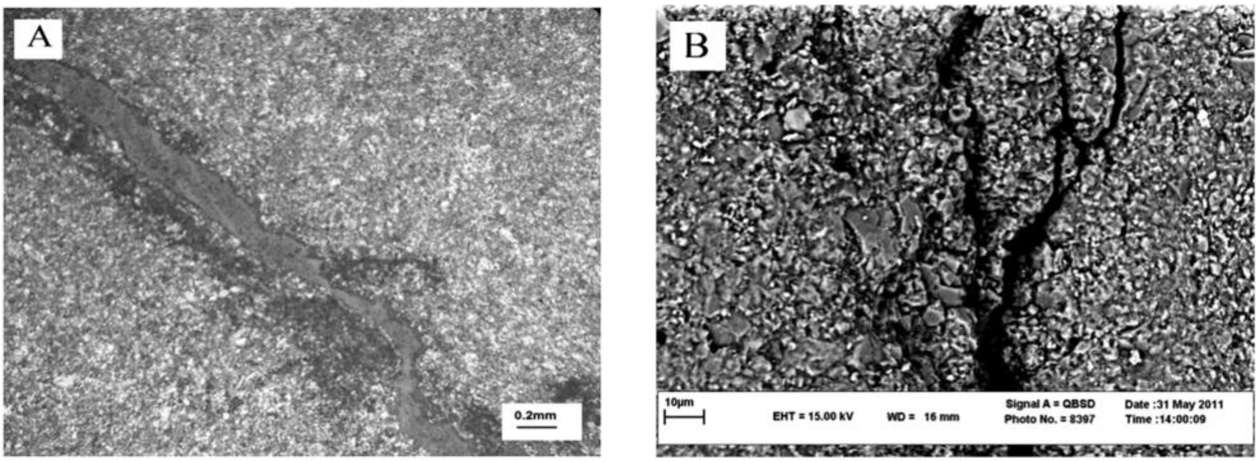


Figure 5- A) Fracture pores in the wackestone facies (depth 3566 m) XPL with gypsum blade.
B) SEM image from the fracture pore in the wackestone (depth 3575 m).

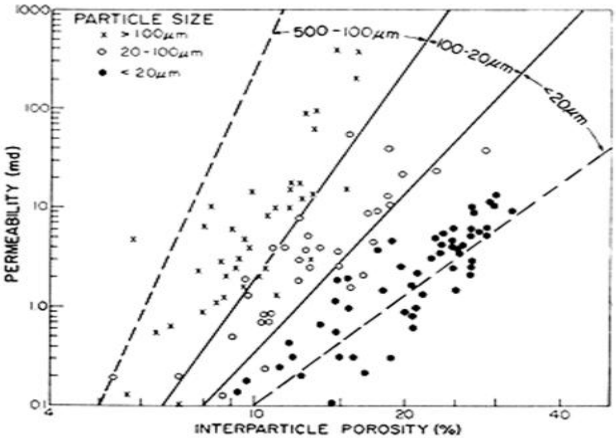


Figure 6- Porosity-air permeability relationship for various particle size groups in non vuggy carbonate rocks based on Lucia diagram [8]

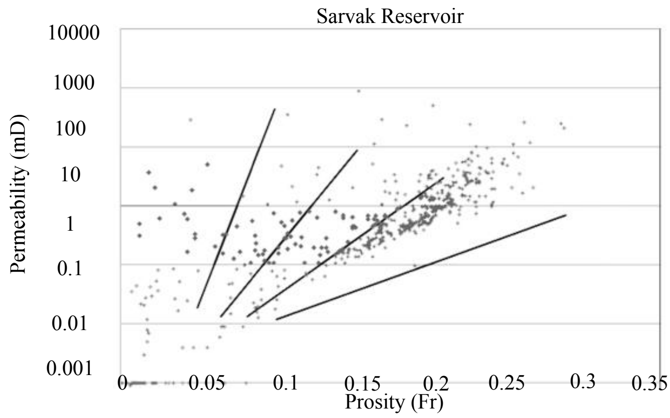


Figure 7- The distribution of porosity and permeability in all facies of the reservoir in the Sarvak formation in the three wells of the studied field on the Lucia diagram [8].

It should be noted here, from the reservoir quality view, the eight recognized rock types can generally be classified into two groups, namely rock types with reservoir quality and those with low or no reservoir quality. Thus, in the following discussion, these two groups are individually considered.

Rock Types with Reservoir Quality

Rock type 1: Grainstone with interparticle pores
Rock type 2: Grainstone with moldic pores
Rock type 3: Rudstone
Rock type 4: Grain-dominated packstone
Rock type 5: Mud-dominated packstone
Rock type 6: Wackestone with fracture and vuggy pores

Rock types without or with low reservoir quality

Rock type 7: Packstone with low reservoir quality
Rock type 8: Wackestone with isolated pores

Grainstones have highest reservoir quality. This can be attributed to exposure and meteoric erosion that lead to the development of moldic, vuggy, and interparticle porosities.

The creation of secondary interparticle can be formed by dissolution and increased permeability (up to 925 md) in this facies. Two different rock types have been identified based on porosity type in the facies. In rudstones facies, only one rock type has been detected. The reservoir packstone facies in the Lucia diagram [8] have a wide spread and they have been divided into three rock types based on reservoir quality and sorting.

In wackestone facies, porosity is lower than other facies and based on porosity type, this facies has been divided into two rock types. These rock types will be discussed in detail as follows:

Rock Type 1: Grainstone with Interparticle Pores

In this rock type, the pores are mainly interparticle and partly moldic. Thus, reservoir quality due to a good connection between pores is high. As shown in Figure 8, facies related to this rock type lie in the Class 1 of Lucia chart [8].

Rock Type 2: Grainstone with Moldic Pores

In this rock type, isolated pores are as molds in carbonate grains that are partly filled by dolomitic cement. Based on isolated pores, porosities in this facies should be classified in the Class 3 of Lucia [8]; but, as can be seen in Figure 9, they are somewhat shifted toward Class 2. This is attributed to the presence of some intergranular pores associated with isolated pores in this facies.

Rock Type 3: Rudstone

This facies is located mainly in Class 2 and Class 3 (Fig. 10). The creation of vuggy and fracture pores have led to higher permeability in this rock type. This facies have high reservoir quality too.

Rock Type 4: Grain-dominated Packstone

A group of packstones in the reservoir have a grain dominated fabric. The reservoir quality of this rock type has been influenced by both depositional texture (facies) and diagenesis. In addition to vuggy porosity, fracture porosity is also present, which results in a higher permeability in this facies. The reservoir quality of this facies is very similar to grainstone and rudstone facies (Fig.11B).

Rock Type 5: Mud-dominated Packstone

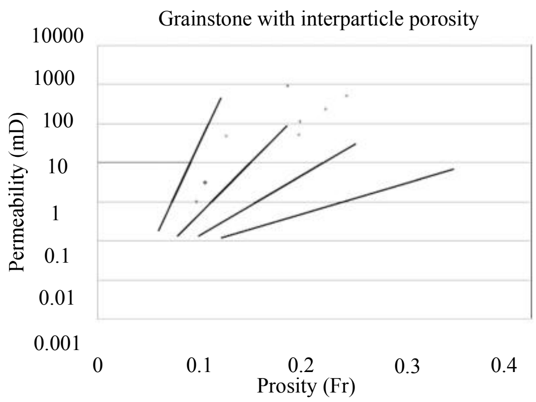
Another group of packstones are mud-dominated and those containing small bioclastic debris and peloids. Dissolution has affected this facies and thus it can be classified in the Class 3 of Lucia [8] as can be seen in Figure 12.

Rock Type 6: Wackestone with Fracture and Vuggy pores

Wackestones are mainly classified in Class 3; however, in this reservoir, the effects of some diagenetic processes such as dissolution and fractures have improved the reservoir quality in these facies and shifted most of them to Class 1. As shown in Figure 13, two dominant pore types in this class are vuggy and fractures.

Rock Type 7: Packstone with Low Reservoir Quality

This group of packstones is plotted outside of the three petrophysical classes of Lucia [8], and has small porosity and permeability values, which is ascribed to the low amount of isolated pores (Fig. 14).



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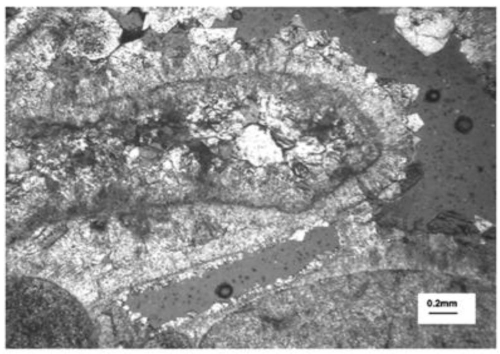

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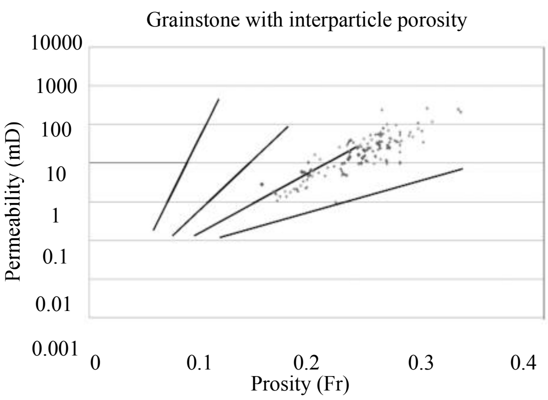
Figure 8- A) Grainstone facies with interparticle pore plot on the Lucia diagram [8]. B) The microscopic image of rock type 1 (depth of 3520 m) plot in the Class 2 field



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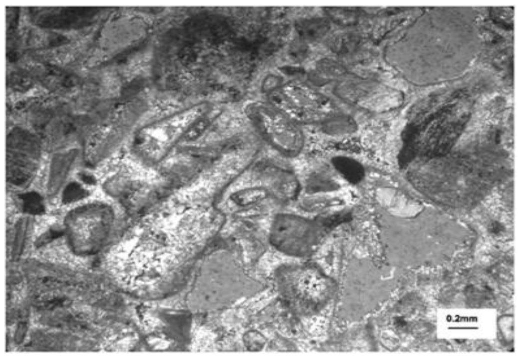

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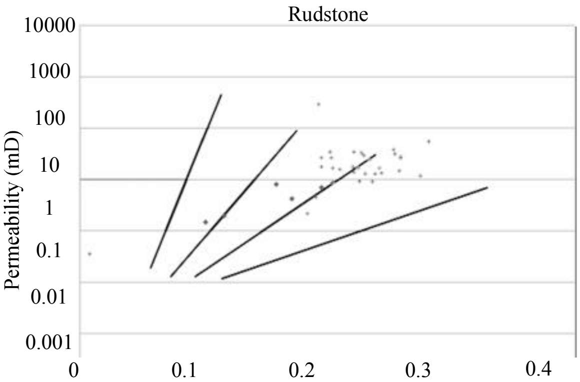
Figure 9- A) Grainstones facies with moldic and interparticle pore plot on the Lucia diagram [8]. B) The microscopic image of rock type 2 (depth of 3521 m).



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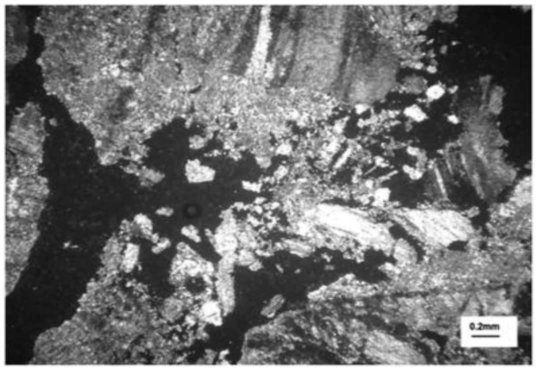

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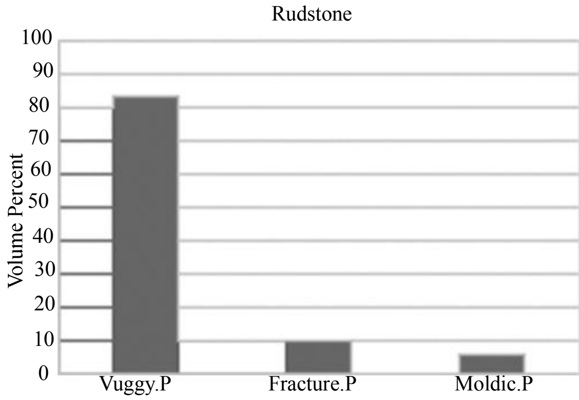
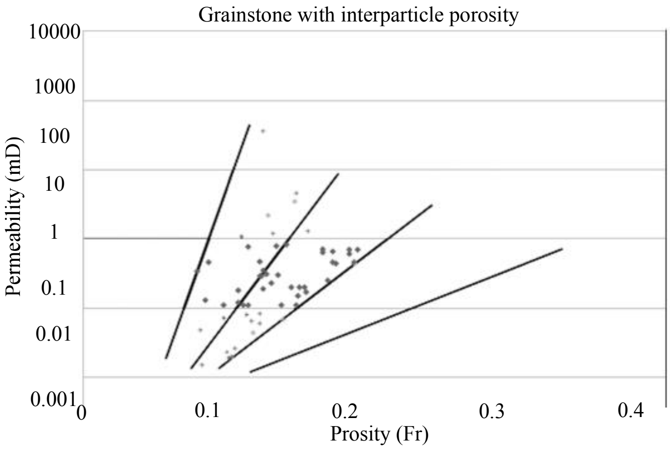


(C)

Figure 10- A) Rudstones facies plot on the Lucia diagram [8]. Most samples are plotted in Classes 2 and 3. B) The microscopic image of rock type 3 (depth of 3515 m). C) Histogram of volume percent of pores in the rudstone.



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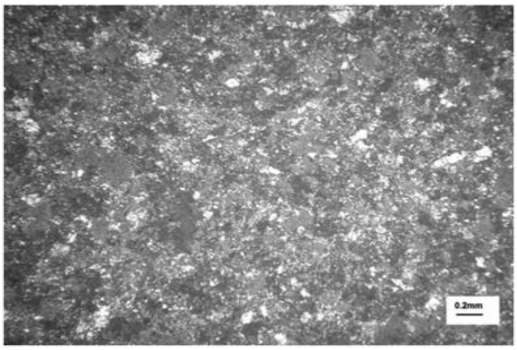

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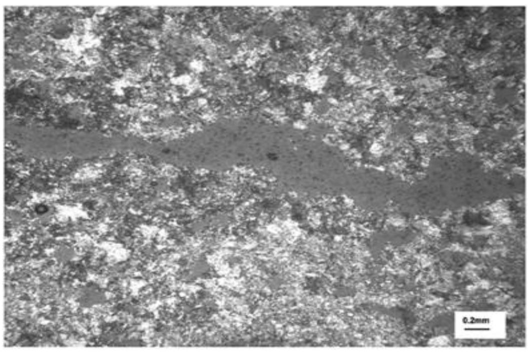
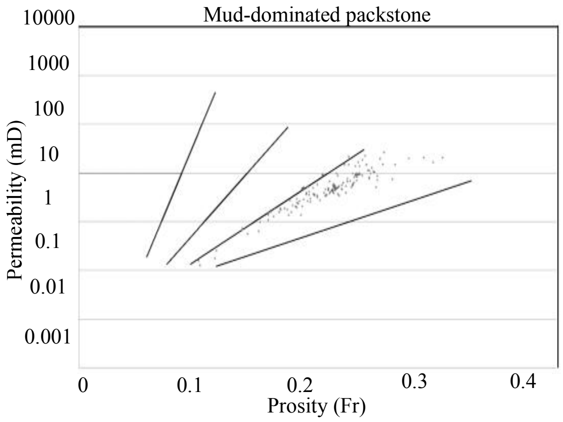


(C)

Figure 11- A) Grain-dominated packstone plot on the Lucia diagram [8]. As seen, the samples are plotted in Classes 2 and 3. The microscopic images of Rock type 4. B) Touching vuggy pore (depth of 3538 m). C) Development of vuggy pore together with fracture pore (depth of 3532 m).



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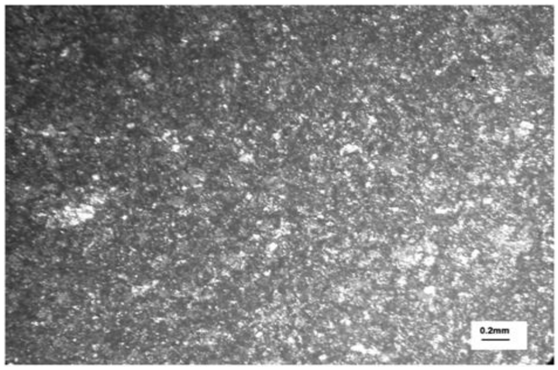
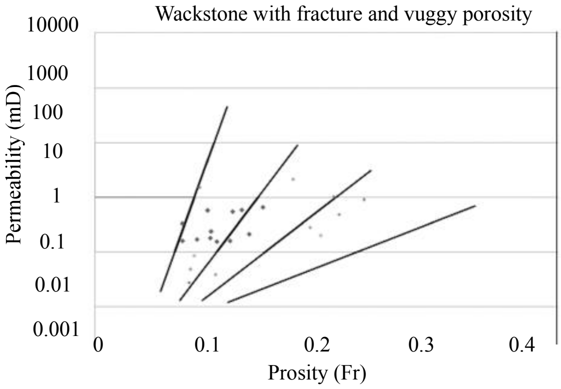


(B)

Figure 12- A) Mud-dominated packstone plotted on the Lucia diagram [8]. As seen, the samples are plotted in Class 2, B) The microscopic images of Rock type 5 (the depth of 3549 m).



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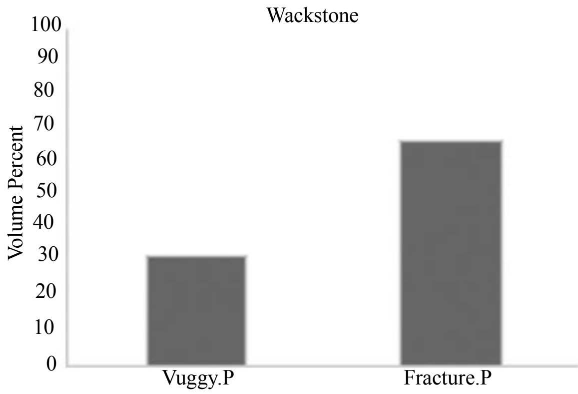
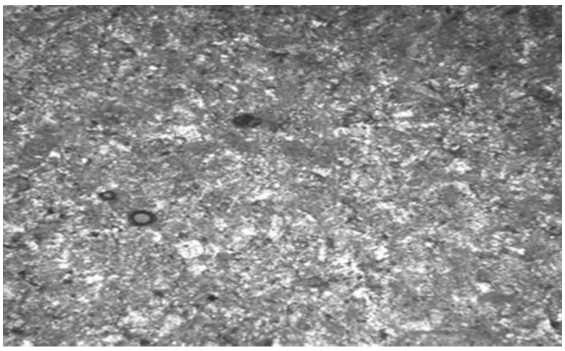


(C)

Figure 13- A) Wackestones with vuggy and fracture pores plotted on the Lucia diagram [8]. B) The microscopic image of rock type 6 (the depth 3501 mm), C) Histogram of pore volume percent in wackestones. The fracture pore has a higher volume percent.



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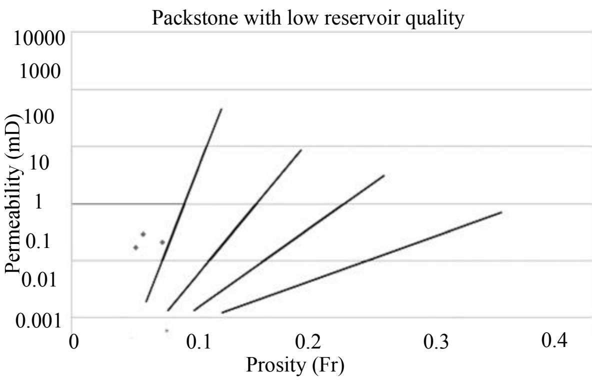


(B)

Figure 14: A) Packstones with low quality reservoir plotted on the Lucia diagram [8]. As can be seen, most samples have permeability less than 0.1 md. B) The microscopic image of rock type 7 (the depth 3531 mm).

Rock Type 8: Wackestone with Isolated Pores

Another category of wackestones, due to having mud dominated fabric and a small value of porosity, are related to isolated vuggy pores and have no good reservoir quality. Wackestones in this rock type are also plotted outside of petrophysical classes of Lucia [8], (Fig. 15A). The microscopic image of this rock type is shown in Figure 15B.

The histograms of different rock types in relation to porosity and permeability (reservoir properties) are shown in Figure 16. Also, Table 1 summarizes the characteristics of the rock types. As it is inferred from these characteristics, rock types 1 to 6 have good reservoir quality. In contrast, rock types 7 and 8 are associated with low reservoir quality.

Hydraulic Flow Units

Every hydraulic flow unit has similar petrophysical properties (homogenous porosity and permeability) which are related to specific characteristics such as pore and pore throat; these characteristics can be attributed to depositional system and diagenesis.

The core porosity and permeability data were used to identify flow units in the reservoir. The steps are as follows:

1. The calculation of pore to matrix ratio (PMR):

PMR= φ /1- φ

2. The calculation of reservoir quality index according to Amaefule et al. (1993):

$$RQI = 0.0314\sqrt{K/\varphi}$$

where, K is permeability (mD) and φ is porosity in fraction

3. Finally, the calculation of flow zone indicator (FZI):

$$FZI = \frac{RQI}{PMR}$$

After calculating log FZI, the data were plotted and shown in Figure 17A. Based on the plotted data, eight hydraulic flow units (HFU) (named as A, B, C, D, E, F, G, and H) have been identified for the Sarvak formation within the studied reservoir. The cut off values used for the differentiation between hydraulic flow units are as follows.

HFU A: Log FZI < -0.5
HFU B: -0.5< Log FZI<-0.25
HFU C: -0.25<Log FZI<0
HFU D: 0<Log FZI<0.25
HFU E: 0.25<Log FZI< 0.5
HFU F: 0.5<Log FZI< 0.75
HFU G: 0.75<Log FZI<1.5
HFU H: Log FZI>1.5

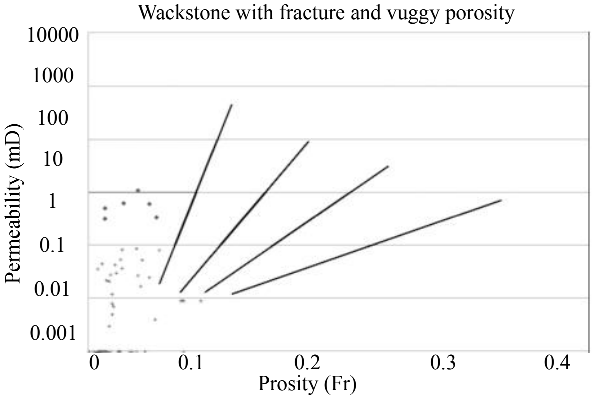
As shown in Figure 17A, there is an increasing trend in reservoir quality from hydraulic flow unit A towards H. Our study shows that different HFUs are differentiated based on depositional facies and diagenetic features that control the pore geometry and pore throat properties. This is well illustrated in Figure 17B in which any hydraulic flow units are plotted in a certain district area.

In a correlation between carbonate facies and different HFUs in the reservoir, as shown in Figure 18, the results demonstrate that in grain dominated facies (i.e. grainstone, rudstone, and packstone) reservoir quality is governed by HFU C and D, whereas wackestones show a wide range of HFUs varying from low to high. This is attributed to both primary sedimentary texture (being mud dominated) and diagenetic effects (i.e. fracture and dissolution) in these facies.

Reservoir Zonation in the Sarvak Formation in the Study Field

Considering that different parts of Sarvak (Mishrif) formation have distinct reservoir properties, it would be suitable to consider and classify the reservoir in individual vertical zones. This classification is based on the integration of the results from core porosity and permeability data, petrophysical well logs (i.e. neutron, density, and sonic), and petrographic studies. Thus, as shown in Figure 19, four reservoir zones (I, II, III, and IV) were recognized from the bottom to the top of the formation respectively. Also, zone IV can be classified into four subzones. The general characteristics of each zone are summarized in Table 2.

Zone III and VI show higher reservoir quality, because the amount of porosity and permeability is high and, also, these facies are grainstone and rudstone.



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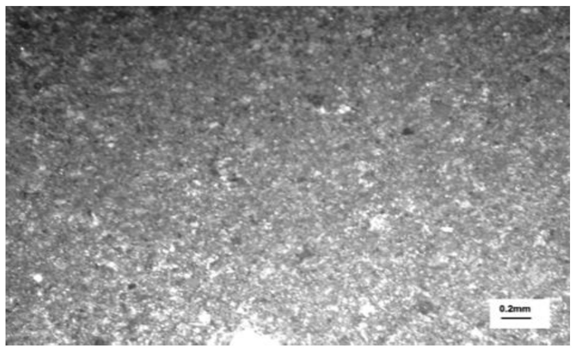
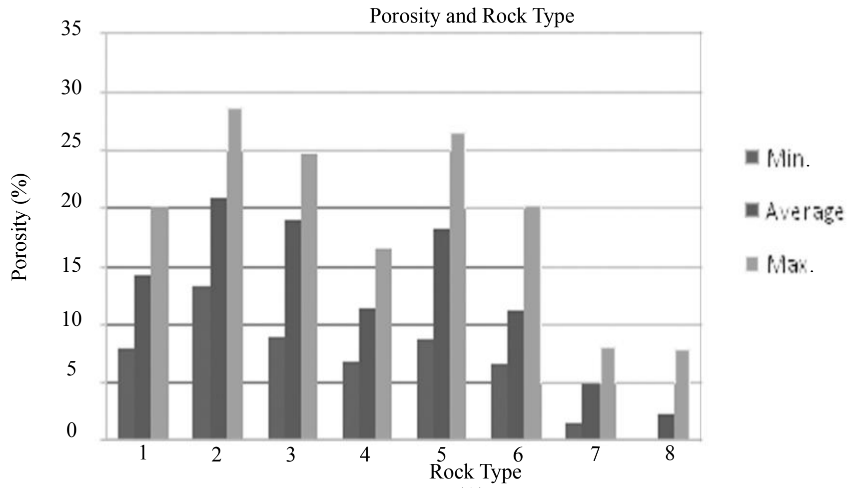


(B)

Figure 15- A) Pores on wackestones facies plotted on the petrophysical diagram Lucia [8]; they do not have good reservoir quality due to the effects of depositional facies and diagenesis. B), The microscopic image of Rock Type 8 (the depth 3567 m).



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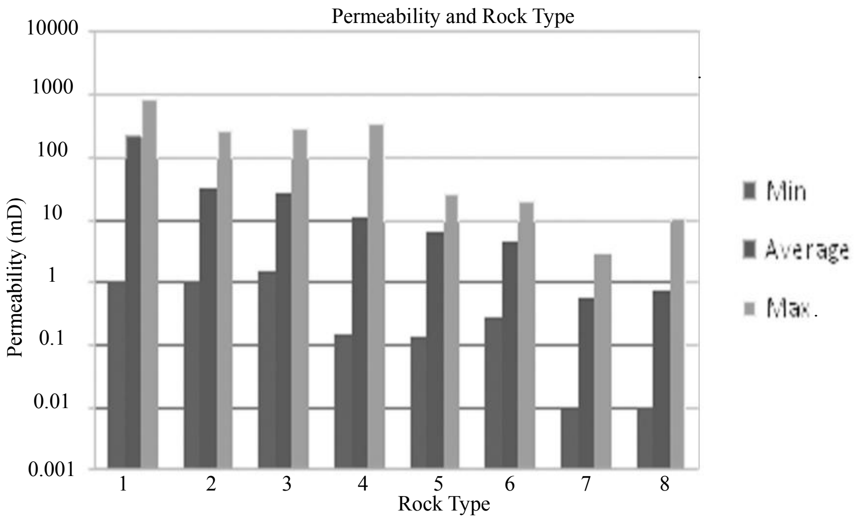

(B)

Figure 16- Histogram of rock types in relation to pore (A) and their permeability (B), in the Sarvak reservoir in the studied field.

Table 1- All kinds of rock types in relation to porosity and permeability in the Sarvak reservoir in the studied field

Petrophysical Group Lucia [8]	Permeability (md)			Porosity (%)			Microscopic Facies	Rock Type
	Min	Average	Max	Min	Average	Max		
1	1	238.775	925	8	14.237	20.2	Grainstone with inter particle pore	1
3	1	33.573	270	13.3	20.848	28.7	Grainstone with moldic pore	2
2,3	1.5	26.448	301	8.9	19.057	24.7	Rudstone	3
1,2	0.15	11.353	366	6.8	11.435	16.5	Grain-dominated Packstone	4
3	0.13	6.527	27	8.8	18.260	26.7	Mud-dominated Pack-stone	5
1	0.28	4.616	21	6.6	11.144	20.4	Wackestone with frac-ture and vuggy pore	6
Whith low Reservoir Quality	0.01	0.575	2.9	1.5	4.942	8.1	Packstone with low reservoir quality	7
	0.009	0.716	11	0.1	2.305	7.9	Wackestone with sepa-rarate vuggy pore	8

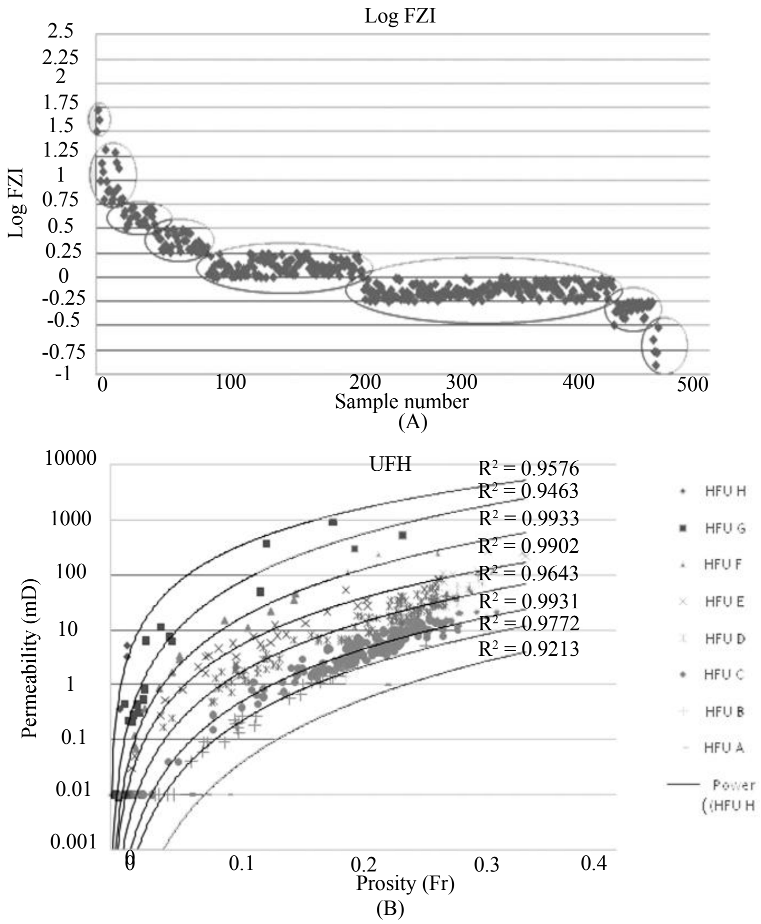

Figure 17- A The graph of flow zone indicator and **B** The graph of hydraulic flow units in the Sarvak reservoir in the studied field.

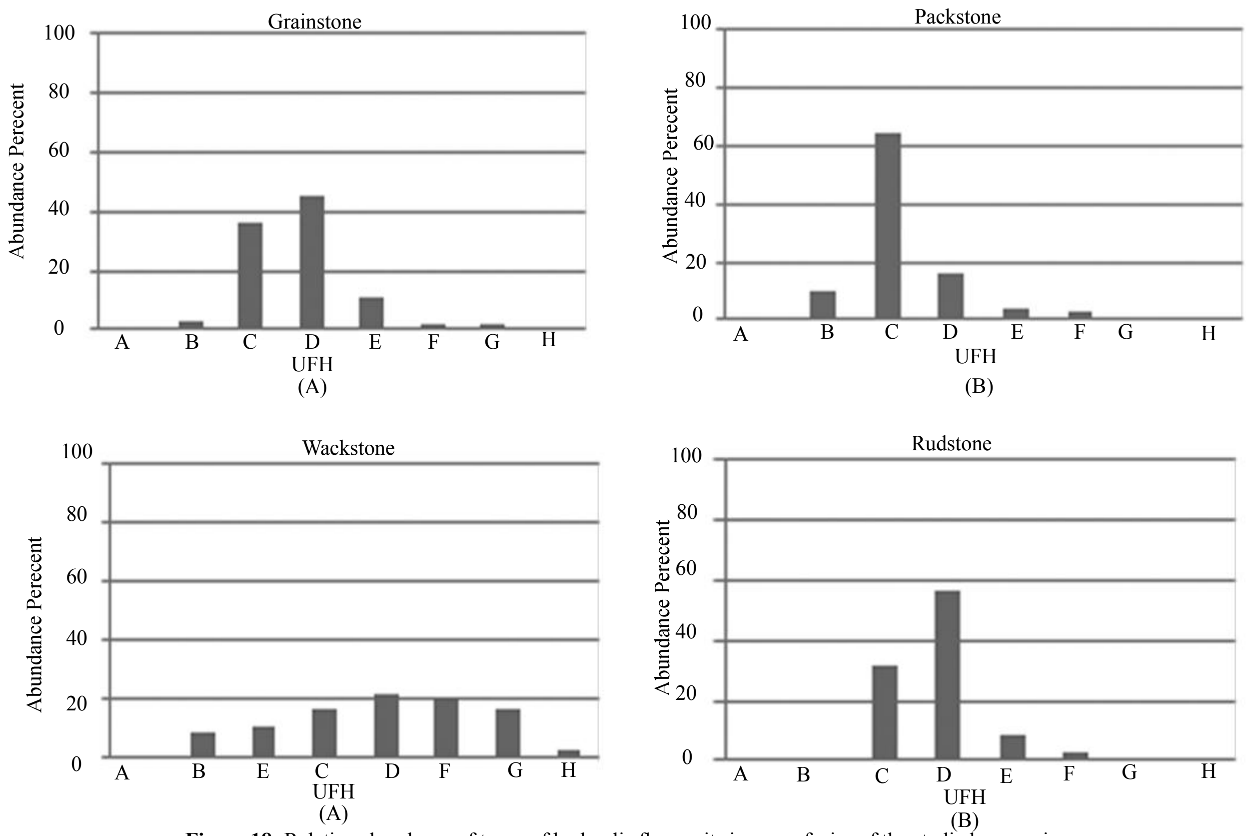

Figure 18- Relative abundance of types of hydraulic flow units in every facies of the studied reservoir.

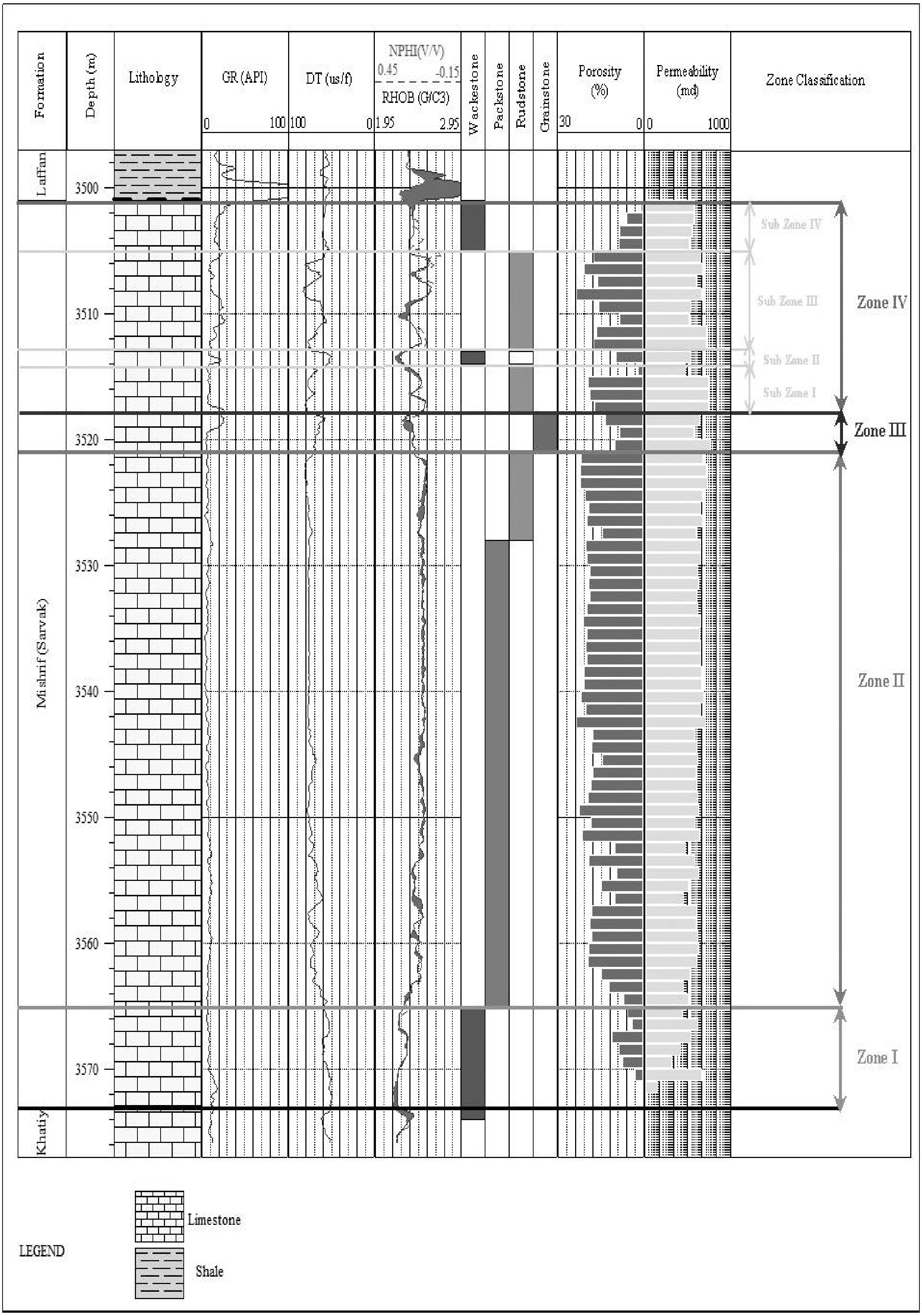

Figure 19- Sarvak reservoir zone classification in one of the studied wells

Table 2- Characteristics of three identified zones in theSarvak reservoir in the studied field

Zones	Facies	GR (API)			DT			RHOB			NPHI			Porosity			Permeability		
		Min.	Average	Max.	Min.	Average	Max.	Min.	Average	Max.	Min.	Average	Max.	Min.	Average	Max	Min.	Average	Max.
Zone IV	Rudstone -Wackestone	6.308	16.320	50.25	51.1	66.452	83	2.184	2.471	2.718	0.020	0.131	0.240	1.2	13.86	24.1	0.83	12.51	35
Zone III	Grinstone	5.226	7.216	16.671	63.6	70.675	81.2	2.374	2.478	2.616	0.107	0.135	0.214	8.7	13.36	22.7	3.2	16.93	49
Zone II	Packstone	3.785	7.766	13.031	54.7	73.519	81.4	2.358	2.434	2.664	0.017	0.169	0.212	6	18.06	24.2	0.48	6.49	20.1
Zone I	Wackestone	6.098	10.645	18.781	49.5	54.480	61.2	2.566	2.660	2.739	0.003	0.033	0.076	0.6	5.55	11.66	0.009	3.28	11

Conclusion

In order to understand the reservoir characteristics of Sarvak formation in the field studied, the integration of geology and petrophysics have been used. In the Sarvak formation, reservoir quality can be interpreted based on both depositional and diagenetic features. These factors qualitatively and quantitatively control reservoir characteristics in different facies of the reservoir. Eight rock types were identified in this reservoir rocks by using the petrophysical chart of Lucia; they are related to different carbonate facies and digenetic processes operated in this reservoir rocks since deposition. Also, a more detailed study of facies in the framework of hydraulic flow units properly demonstrates a reasonable relationship between pore properties and reservoir quality in different facies; additionally, 8 hydraulic flow units were recognized.

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