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Reservoir and Rock Type Characterization: Case Study for Khasib Formation, Southern Iraq

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Abstract

Characterizing the reservoir accurately and understanding its rock's composition is essential in predicting performance and determining reservoir designs. In this study, the carbonate Khasib formation from the late Cretaceous period for x oil field- southern Iraq has been examined characterizing. To achieve this, different characterization techniques were utilized. Firstly, using the flow zone indicator method revealed five hydraulic flow units (HFUs) of the Khasib formation. Every HFU represents a particular quality of reservoir rock. HFU1 is the one that refers to poor quality, while bad-quality reservoir rock is displayed as HFU2. HFU3 and HFU4 signify the intermediate and good reservoir rock quality respectively. The last hydraulic flow unit was of the highest quality reservoir rock which is denoted as HFU5. Additionally, we utilized cluster analysis to identify five distinct rock types within the Khasib formation. These rock types were labeled as RT-1 (the best reservoir rock type), RT-2 (good reservoir rock type), RT-3 (intermediate reservoir rock type), RT-4 (poor rock type), and RT-5 (very poor rock type). In addition, the recognition of five different HFUs that reflected the physical characteristics unique to each reservoir rock was achieved using Winland's approach. Rock properties inside the reservoir are classified to HFU1 for best rocks, then HFU2 denotes good rock qualities through a medium one labeled as HFU3 while later HFU4 indicates poor quality, and the poorest quality is marked as HFU5. Finally, Lucia's classification for carbonate rock was employed as another analyzing rock quality method. Utilizing this technique reveals three distinct rock types within the Khasib formation. RC1 is the microfacies of grain stone, RC2 is the representative of pack-stone microfabrics and RC3 denotes muddy materials. The final rock types (facies) for Khasib formation can be identified according to the incorporation of the different characterization methods which can be utilized to create a realistic three-dimensional rock type model and distribute the properties based on the rock type.

Keywords: Reservoir Characterization; Flow Zone Indicator Method; Hydraulic Flow Unit; Cluster Analysis; Winland Correlation; Lucia Classification; Khasib Formation.

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1- Introduction

Reservoir characterization is defined as the study of reservoir factors relating to the geophysical, geological, petrophysical, and engineering fields. It entails the analyses of spatially variable geological and engineering data. There are two essential features in a reservoir characterization consist of:

1- The features of geometrical characterization of the reservoir, including the limits of the stratigraphic structures and the depositional facies.

2- The parameters of petrophysical characterization, including permeability, porosity, and saturation [1].

Understanding how the formation characteristics and fluids distribute throughout the reservoir in the setting of formation heterogeneities requires reservoir characterization. This knowledge will help build the reservoir three-dimensional model, which will be used to estimate the distribution of porosity, permeability, and fluid flow [2].

Reservoir characterization is an important tool for improving costly reservoir management options for the development of hydrocarbon fields. The early stage of the reservoir development program is reservoir characterization, which considers structural and depositional geometry, pore structures, post-deposition diagenesis, and the distribution and type of reservoir fluids. Reservoir characterization methods and techniques are continuing to advance and grow especially with the aggressive spread of three-dimensional (3D) and more recently 3D time-lapse (4D) information. However, among the most important areas of research is the creation of workflows that effectively identify and reflect geological heterogeneity and use it in the integrated environment to improve reservoir development and production modeling [3-4].

The wireline logs for six wells (AM-1, AM-2, AM-3, AM-4, AM-5, and AM-6) with the core analysis data for three wells (AM-1, AM-2, and AM-3) have been used in this work. Four different methods were applied to characterize the studied reservoir including the flow zone indicator method to describe the formation in terms of hydraulic flow units; clustering analysis to recognize rock

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type with the data of well logs; Winland correlation to classify the pore throat types, and Lucia classification to classify the microfacies.

2- Reservoir Geological Description

The studied reservoir is the Khasib carbonate formation, which is considered one of the significant petroleum reserves in the south of Iraq. The formation thickness is ranging from 35 to 56m in Basra fields and increases towards the northeast to range from 60 to 120 m in middle Iraq oil fields [5-6] while Khasib formation in X field is roughly between 75 and 80 meters thick.

The well logs interpretation for Khasib formation in X oil field clarified that the fundamental mineral components of the Khasib formation are predominately calcite, and the formation is primarily composed of limestone with shale at the formation's base [7].

The micro facies and the digenetic processes development for Khasib formation in two oilfields (X oil field and Noor oil field) were studied. In the examined oil wells and using Dunham classification, the Khasib formation comprises five major microfacies that have been identified: grainstone, packstone, Wackstone, packstone-wackestone, and mudstone. Wakstone and mudstone are the predominant microfacies types in the upper unit of Khasib, whereas grainstone and packstone microfacies predominate in the lower unit of Khasib. In the investigated formation, four sedimentary settings (inner ramp, mid ramp, outer ramp, and open marine environments) were identified. The diagenetic processes can be seen in Khasib formation: Stylolite, Dissolution, Dolomitization, Cementation, Neomorphism, and Fracturation [8].

Furthermore, Khasib formation in X oil field were classified into different electrofacies using the analysis of clustering. The formation was characterized by five electrofacies, each facies is characterized by different reservoir properties, which consist of compressed limestone (EFC-1), argillaceous limestone (EFC-2), chalky limestone (EFC-3), porous limestone (EFC-4), and vuggy limestones (EFC-5). According to an examination of Khasib sequence stratigraphy analysis, the formation has two third-order sequences and three sequence borders the border between the Khasib and Tanuma formations, the intra-Khasib unconformity, and the Mishrif-Khasib regional unconformity which refers to historical sea levels. Each sequence is made up of a maximum flooding surface (MFS) between a transgressive system tract (TST) and high stand systems tract (HST) (MFS) [9].

3- Materials and Methods

Well-log data with core porosity and permeability measurements for three wells have been utilized to characterize the reservoir under study. Reservoir characterization has been established using the following methods:

3.1. Flow Zone Indicator Method

The flow zone indicator is one of the important methods for the classification and identification of hydraulic units, as well as for describing reservoir permeability [10]. This approach was developed in 1993 by Amaefule et al. [11] and is based on the idea of the bundle of capillary tubes put forth by Kozeny in 1927 [12] and Carmen in 1937 [13].

Since permeability might vary even among well-defined rock types, Amaefule et al. [11] used the hydraulic unit to distinguish between the different rock types in the reservoir. The HFU is employed to describe that portion of the reservoir whenever its petrophysical and geological characteristics are distinct from those of other rock portions [14].

Amaefule et al. [11] re-arranged the Kozeny-Carmen equation and introduced new parameters so that the equation can be expressed as:

$$\mathrm{RQI}\ (\mu\mathrm{m}) = 0.0314\sqrt{\frac{\mathrm{K}}{\emptyset\mathrm{e}}} \quad (1)$$

$$\emptyset\mathrm{z} = \frac{\emptyset\mathrm{e}}{1-\emptyset\mathrm{e}} \quad (2)$$

Where, K is permeability in milli darcy, $\emptyset e$ is effective porosity in v/v, RQI is the reservoir quality index, and $\emptyset z$ is the normalized porosity in v/v.
Then the flow zone indicator can be expressed by:

$$\mathrm{FZI} = \frac{\mathrm{RQI}}{\emptyset\mathrm{z}} \quad (3)$$

Taking the logarithm of both sides yield the following equation,

$$\log RQI = \log FZI + \log \emptyset z \quad (4)$$

The logarithmic cross plot for RQI on the y-axis with $\emptyset z$ on the x-axis will produce a straight line with a slope value that is equal to one. The data points that fall on a similar straight line are recognized to have the same pore throat geometries and they can be distinguished as one hydraulic unit. Furthermore, the points with various FZI values will be located on an individual parallel liner site [12].

3.2. Cluster Analysis

Cluster analysis separates data into groups (clusters), and these groups can be relevant, practical, or both. Data items are classified in cluster analyses depending on the details about the items and their connections that are found in the data [15]. Clustering can be considered as a type of classification and referred to as unsupervised classification.

Well-log cluster analysis seeks to classify data points into electrofacies by finding similarities and differences between them in the multivariate space of logs [16]. Electrofacies have a distinct set of log records that distinguish between the petrophysical properties of the rocks and fluids they contain indicated by using well-logging devices [17].

There are several types of clusters, including well-separated, prototype-based, graph-based, density-based, and shared property clusters (conceptual clusters) while the technique used in the cluster analysis involves K-means, DBSCAN, and Hierarchical Clustering.

Hierarchical clustering techniques are an essential class of clustering methods. This type of clustering is still commonly employed across several disciplines despite being relatively old in comparison to other techniques. The two fundamental methods for producing hierarchical clustering are agglomerative and dividend [15].

Ward's Hierarchical Clustering is an agglomerative hierarchical method, in which each data point is treated as a separate cluster. Similar clusters combine during each cycle to generate one or K clusters. A dendrogram, which depicts the hierarchical link between the clusters, is the primary result of hierarchical clustering.

3.3. Winland Method

Winland [18] used the pore throat radius idea to classify different types of rocks. The Winland empirical relation shows the highest statistical correlation once the size of the pore throat equals an accumulative mercury saturation curve of 35%, while R35 refers to the pore throat radius [19].

The Winland equation, which Kolodzie [19] used and published, is as follows:

$$\text{Log R35} = 0.732 + 0.588 * \log \text{K air} - 0.864 * \log \emptyset \quad (5)$$

Where: K air: the permeability measured by air (md). Φ: the porosity of the rock (percent). R35: the size of the pore throat with 35 percent saturated with mercury.

The rocks within a reservoir are categorized as multiple rock types or hydraulic flow units where the rock samples from the same rock type have similar R35 and lie on an iso-pore throat curve. Five petrophysical groups can be constructed from the reservoir rock:

- Mega pores: with pore throat radius greater than 10 microns.
- Macro pores: with pore throat radius between 2.5 and 10 microns.
- Meso pores: with pore throat radius between 0.5 and 2.5 microns.
- Micro pores: with pore throat radius between 0.2 and 0.5 microns.
- Nano pores: with pore throat radius less than 0.2 Microns.

3.4. Lucia Classification

Lucia established the concept of rock fabric classification. The theoretical basis of the Lucia classification is the quantitative idea of pore-size distribution, according to which the spatial distribution of pore sizes within a rock regulates permeability and saturation and is connected to rock fabric. To connect the fabrics of carbonate rocks to the distribution of pore sizes, it is essential to know which of the two major pore-type classes—interparticle, or vuggy, —the pore space belongs.

Lucia's method divides the carbonate into three categories based on RFN plus the size of the grain as [20-22]:

- Class 1: reflects the Grain-dominated Fabrics with RFN (0.5-1.5) microns, this class represents the grainstone microfacies.
- Class 2: reflects the Grain-dominated Fabrics with RFN (1.5–2.5) microns, this class represents the packstone microfacies.
- Class 3: reflects the Mud-dominated Fabrics with RFN (2.5-4) microns, which correspond to the packestone microfacies, wackestone microfacies, and also mudstone microfacies.

Lucia [22] presents an equation to predict rock fabric number (RFN) from permeability and porosity values defined by the following equation.

$$\text{Log } RFN = 9.7982 + 8.6711 \log \emptyset - \log K \; 12.0838 + 8.2965 \log \emptyset \quad (6)$$

Here, RFN: is the rock fabric number. K: Permeability (md). Ø: is the interparticle porosity from the core measurement (fraction).

4- Results and Discussion

This section includes the results from the different characterizing methods:

4.1. Hydraulic Flow Units Characterization Using FZI Method

The hydraulic flow unit was identified by applying the flow zone indicator method to the core data available for three wells (AM-1, AM-2, and AM-3) with 156 porosity and permeability measurements. The core measurement points with the same FZI value that fall on the same straight line are represented as a hydraulic flow unit as illustrated in the cross plot of Øz vs. RQI in Fig. 1.

Furthermore, a semi-logarithmic plot of core-derived permeability with core effective porosity is applied to demonstrate the relationship between these two important petrophysical properties for each distinct hydraulic flow unit as observed in Fig. 2.

The results of this method clarify that the examined reservoir consists of five hydraulic flow units. Each HFU has consistent ranges of FZI and represents a specific rock type with different porosity and permeability properties. The resulting HFUs groups are as follows:

- HFU 1: this group reflects a very low porosity-permeability trend and represents the worst reservoir rock quality in Khasib reservoir.
- HFU 2: this group reflects a low porosity-permeability trend and represents bad reservoir rock quality.

- HFU 3: this group reflects a medium porosity-permeability trend and represents the intermediate reservoir rock quality.
- HFU 4: this group reflects a good porosity-permeability trend and represents the good reservoir rock quality.
- HFU 5: this group reflects a very good porosity-permeability trend and represents the reservoir rock with the best quality in Khasib reservoir.

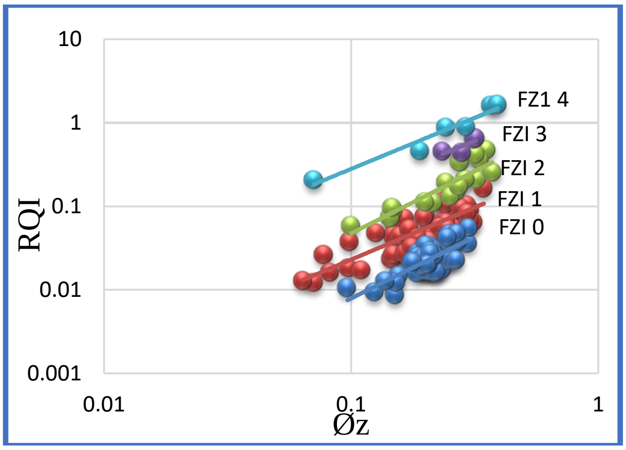

Fig. 1. RQI vs. Øz for the Three Studied Wells

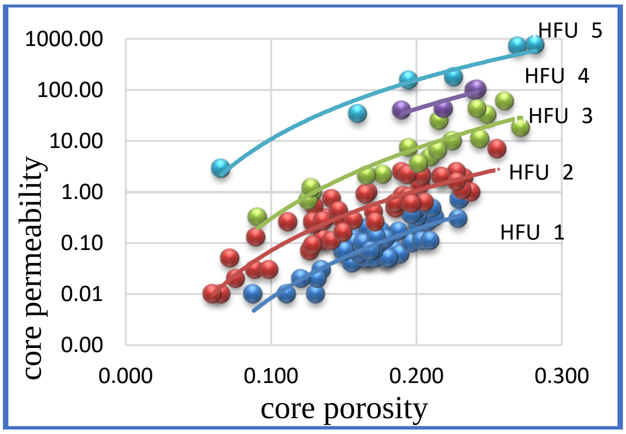

Fig. 2. Core Permeability versus Core Effective Porosity for the Three Studied Wells

4.2. Electrofacies Characterization Using Cluster Analysis

Well logs data for six wells from X oil field (AM-1, AM-2, AM-3, AM-4, AM-5, and AM-6) have been subjected to cluster analysis in order to characterize the electrofacies within the reservoir. Objects from this technique were grouped based on comparable characteristics and distinguished from other objects that were distinct using a model of the Hierarchical wards' algorithm.

Four log elements have been selected in this method: Gamma-ray (GR), sonic (DT), bulk density (RHOB), and neutron (NPHI). Five electrofacies were distinguished within Khasib formation which corresponds to five different rock types (RT).

- RT-1 (red color)

This group is characterized by very low shale content (with an average value approximately equal to 0), very good porosity, and very low water saturation. These electrofacies reflect the best reservoir rock properties in Khasib formation and define as EF 5.

- RT-2 (green color)

This group is characterized by a relatively low volume of shale, with a high value of porosity, and low water saturation. These electrofacies reflect the good reservoir rock type and are defined as EF 3.

- RT-3 (pink color)

This group is characterized by high shale content and acceptable porosity and low water saturation. These electrofacies reflect the intermediate reservoir rock properties and define as EF 1.

- RT-4 (yellowish green color)

This group is characterized by low shale volume and good porosity but relatively high-water saturation. These electrofacies reflect bad rock types and are defined as EF4.

- RT-5 (blue color)

This group is characterized by low shale volume, low porosity value, and the water saturation was very high. These electrofacies reflect very bad rock types and define as EF 2.

The resulting rock types from clustering for Khasib reservoir are demonstrated in Table 1. While the resulting electrofacies classification for the studied wells is described in two cross-sections the first one extending from the northwest to the southeast of the field as in Fig. 3 and the second cross-section is from north to south direction as in Fig. 4.

Table 1. Rock Types Obtained from Clustering with the Corresponding Mean Value of the Logs Reading, Vsh. PHIE, and Sw

Rock Type	Cluster Electro- Facies	GR Mean GAPI	NPHI Mean v/v	RHOB Mean g/cm^3	DT Mean us/ft	Vsh Mean v/v	PHIE Mean v/v	Sw Mean v/v
RT-1	EF 5	11	0.21	2.3	83	0.003	0.24	0.22
RT-2	EF 3	23	0.18	2.4	73	0.1	0.17	0.3
RT -3	EF 1	36	0.14	2.44	72	0.15	0.11	0.4
RT -4	EF 4	16	0.13	2.5	68	0.02	0.14	0.5
RT -5	EF 2	22	0.07	2.6	62	0.04	0.05	0.92

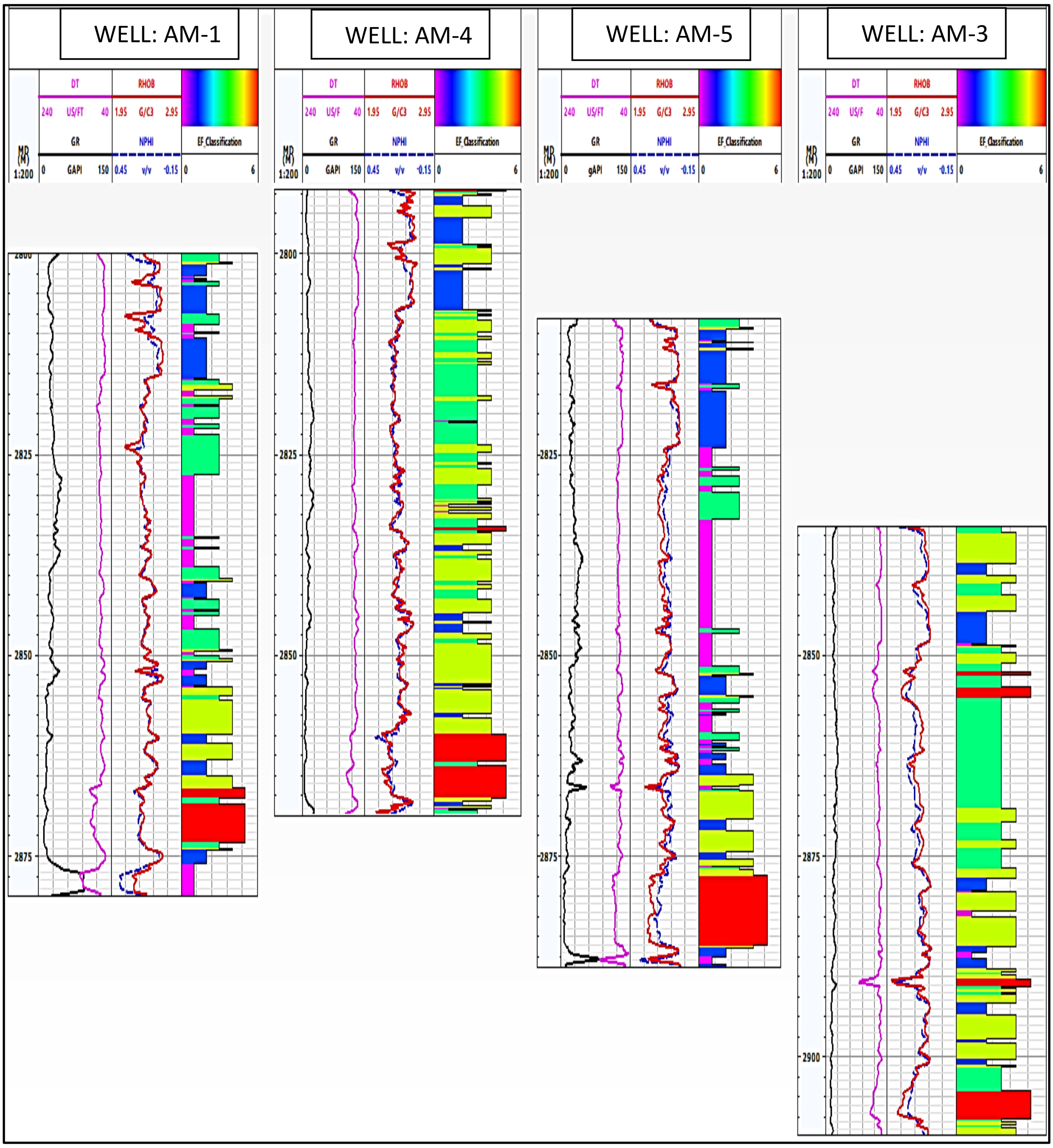

Fig. 3. Electrofacies Classification Cross-Section for Wells AM-1, AM-4, AM-5, and AM-3

4.3. Pore Throat Size Characterization Using Winland (R35) Method

The idea behind Winland (R35) was to categorize a reservoir into distinct rock types thus a single rock class with the same R35 will fall on an iso-pore throat curve [23]. The correlation established by Winland has been applied to identify different types of rock or HFUs in Khasib formation based on the permeability and porosity values.

The pore radius (R35) or pore type was identified using the available core porosity and permeability data of the three wells and applying Eq. 5, where five pore size groups or HFUs have been established in Fig. 5 and described as follows:

- Mega pore type (HFU1): this type of pore reflected the best reservoir rock properties with a pore throat radius range of (14.95-15) microns and permeability values of (718-773). This pore type is poorly represented by the core data, but it can correspond to FZI 4.
- Macro pore type (HFU2): this type of pore represents good rock properties with a pore throat radius range of (2.52-8) microns and permeability values of (25-180). This pore type corresponds to FZI 3.
- Meso pore type (HFU3): this type of pore represents the intermediate rock properties with a pore throat radius range of (0.52-1.98) microns and permeability values of (1-18). This pore type corresponds to FZI 2.

- Micro pore type (HFU4): this type of pore represents the bad rock properties with a pore throat radius range of (0.2-0.49) microns and permeability values of (0.13-1.6) md. This pore type corresponds to FZI 1.
- Nano pore type (HFU5): this type of pore represents the worst rock properties with a pore throat radius range of (0.028-0.196) microns and a permeability range of (0.01 to 0.32) md. This corresponds to the FZI 0.

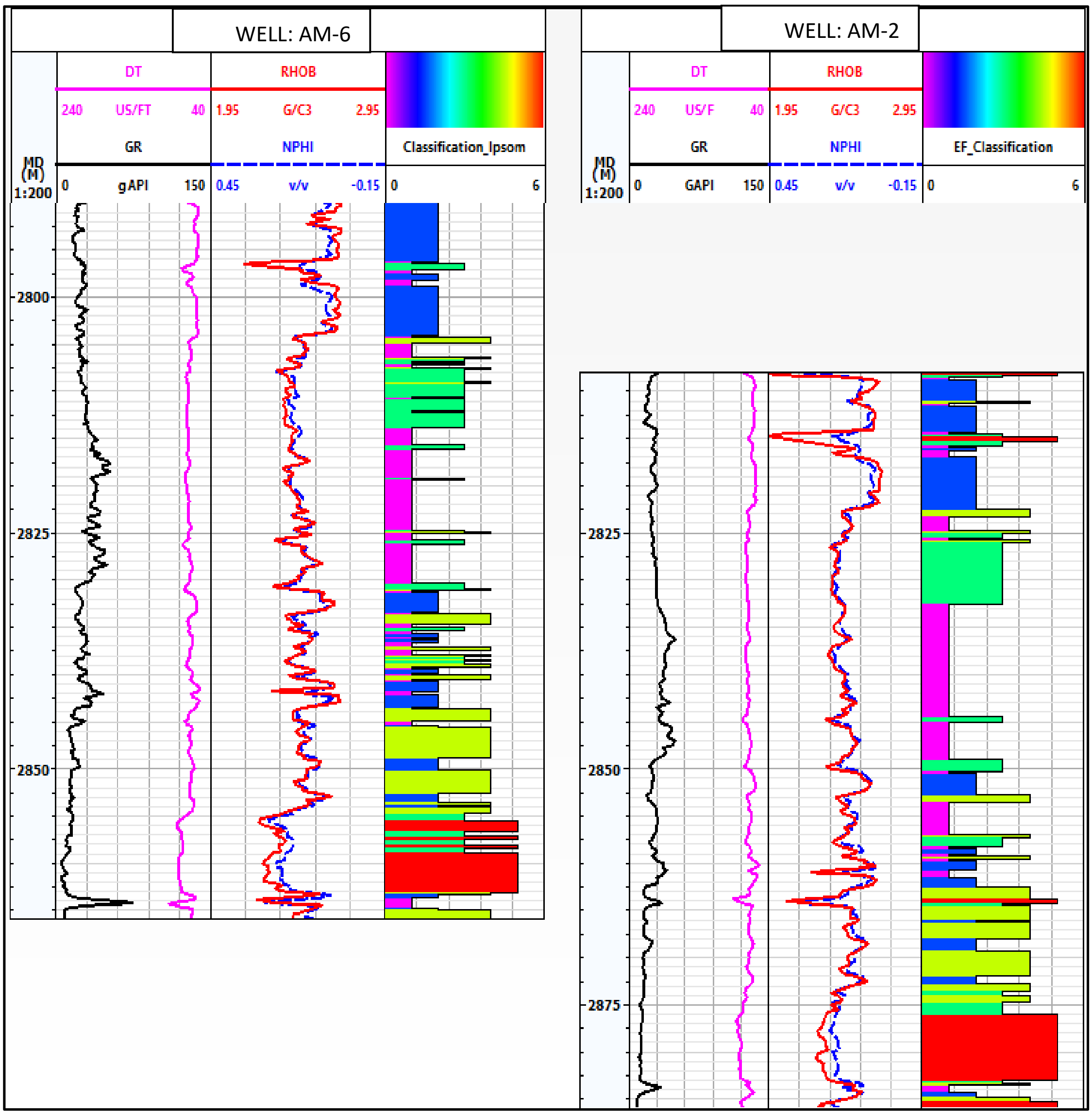

Fig. 4. Electrofacies Classification Cross-Section for Wells AM-6 and AM-2

4.4. Characterization Using Lucia Classification Method

Lucia classified the carbonated rock into three classes based on the rock fabric number. Each rock fabric class has its own porosity-permeability relationship, and permeability raising with particle sizes, sorting, and porosity increasing.

Three classes of rock type have been identified according to the Lucia classification for carbonate rocks utilizing the Khasib Reservoir's accessible core data (porosity and permeability) for AM-1, AM-2, and AM-3. These classes are described as shown in Fig. 6 and described as follows:

- Rock Class 1 (RC1)
  This class is rarely signified by the core data with an RFN of 0.4, which is categorized as grainstone microfacies.
- Rock Class 2 (RC2)
  This class reflects very good reservoir rock properties with RFN (1.7-2.34) and permeability values up to 773 md which is categorized as packstone microfacies.
- Rock Class 3 (RC3)
  This class reflects the intermediate and bad rock properties of Khasib reservoir with RFN of (2.52-4) and permeability of (0.05-60) which is categorized as mud-dominated microfacies.

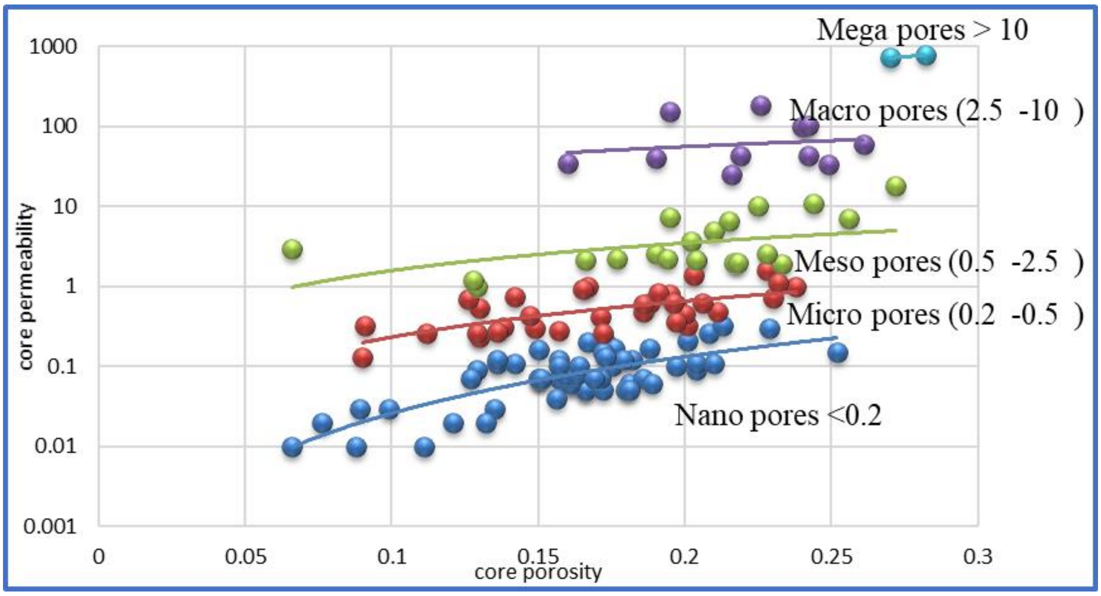

Fig. 5. Classification of the Pore Type Depending on the Pore Throat Radius

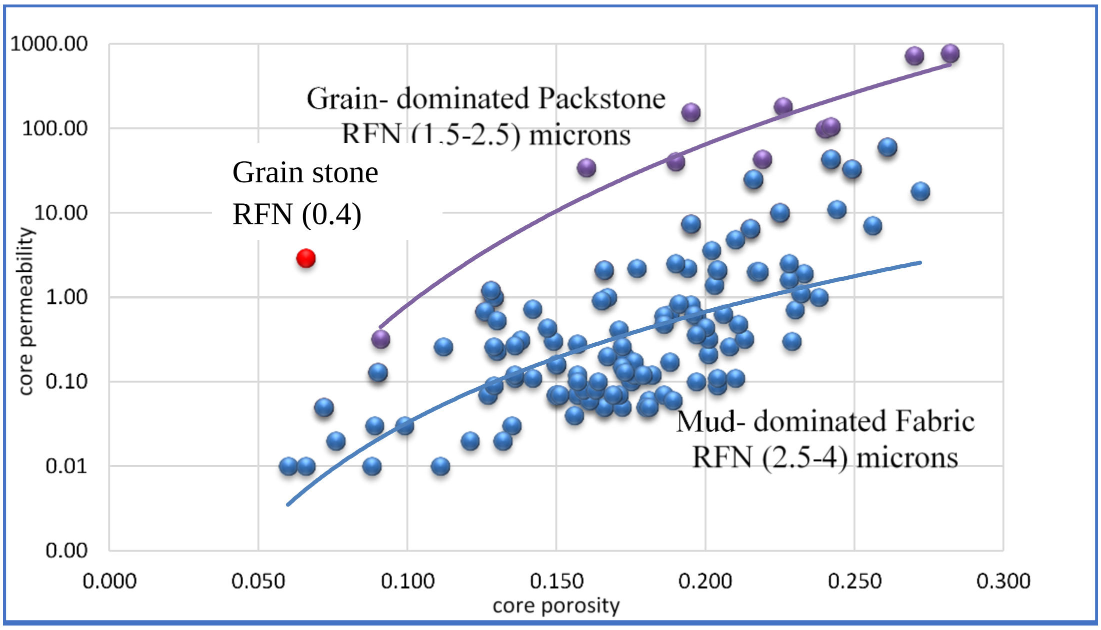

Fig. 6. This Figure is the Result of Applying the Equation of Rock Fabric Number and Classification Depending on Lucia Rock Type Classes

5- Conclusions

Characterizing the reservoirs' rock type for the X oil field within Khasib formation using different characterizing methods yields the following conclusions:

- The flow zone indicator method characterized five different hydraulic flow units, where HFU 5 represents the best reservoir rock quality in Khasib formation, HFU 4 represents the good reservoir quality rock, HFU 3 represents the moderate reservoir quality rock, HFU 2 represents the bad reservoir rock quality, and HFU 1 represents the worst reservoir rock.
- The cluster analysis technique categorized five different rock types within Khasib formation, where RT-1 is characterized as the best rock type and corresponds to FZI 4, RT-2 is characterized as the good rock type and corresponds to FZI 3, RT-3 is characterized as the intermediate rock type properties and corresponds to FZI 2, RT-4 is characterized as the bad rock type and corresponds to FZI 1, and the RT-5 is characterized as the worst or non-reservoir rock type and correspond to FZI 0.
- Winland correlation recognized five HFUs where HFU1 reflects the best reservoir rock properties, HFU2 reflects the good reservoir rock properties, HFU3 reflects the intermediate reservoir rock properties, HFU4 reflects the bad reservoir rock properties, and HFU5 reflects the worst rock properties.

- Lucia classification for carbonate rock characterized three rock classes within Khasib formation, the first rock type is the grain stone rock type, the second is the grain-dominated-pack stone rock type, and the third is the mud-dominated rock type.

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Nomenclature

EF	Electro Facies
FZI	Flow Zone Indicator
HFU	Hydraulic flow unit
HFUs	Hydraulic flow units
RQI	Reservoir Quality Index
RC	Rock Class
RT	Rock Type
$\emptyset z$	Normalized Porosity

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الخلاصة

القدرة على توصيف المكمن وتحديد نوع الصخور داخل التكوين مطلوبة للتنبؤ بأداء المكمن وفهم تصميم المكمن. يتناول هذا العمل توصيف تكوين الخصيب الكاربوني من أواخر العصر الطباشيري في حقل النفط X في جنوب العراق. من طريقة مؤشر منطقة التدفق، تم تمييز خمس وحدات تدفق هيدروليكي في تكوين الخصيب، حيث يمثل HFU1 أسوأ جودة صخور مكمنية، ويمثل HFU2 جودة صخور المكمن الرديئة، ويمثل HFU3جودة الصخور المكمنية المتوسطة، ويمثل HFU4 جودة الصخور المكمنية الجيدة، و يمثل HFU5 أفضل جودة صخور مكمنية في تكوين الخصيب. باستخدام ال cluster analysis، تم توصيف خمسة أنواع مختلفة من الصخور لتشكيل الخصيب، حيث يشير RT-1 إلى أفضل نوع صخور مكمنية، بينما يشير RT-2 إلى نوع صخور المكمن الجيدة، بينما يشير RT-3 إلى نوع صخور المكمن المتوسطة، بينما يشير RT-4 إلى النوع الصخري السيء للمكمن، و RT-5 يدل على نوع الصخور السيئ للغاية. تعرفت طريقة Winland على خمس وحدات HFU مختلفة، حيث يعكس HFU1 أفضل خصائص صخور مكمنية، ويعكس HFU2 خصائص المكمن الجيدة، ويعكس HFU3 خصائص الصخور المتوسطة، ويعكس HFU4 خصائص الصخور السيئة، ويعكس HFU5 أسوأ خصائص الصخور داخل المكمن. من تصنيف Lucia لصخور الكربونات، تم تمييز ثلاث فئات صخرية، حيث RC1 هو الحجارة الدقيقة الحبيبية، و RC2 عبارة عن مجموعات حجرية تهيمن عليها الحبوب، و RC3 هي الأحياء الدقيقة التي يهيمن عليها الطين.

الكلمات الدالة: التوصيف المكمني، طريقة مؤشر منطقة الجريان، وحدة التدفق الهيدروليكي، التحليل العنقودي، ارتباط وينلاند، تصنيف لوشيا، تكوين الخصيب.