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Determination of Reservoir Hydraulic Flow Units and Permeability Estimation Using Flow Zone Indicator Method

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Abstract

Reservoir characterization plays a crucial role in comprehending the distribution of formation properties and fluids within heterogeneous reservoirs. This knowledge is instrumental in constructing an accurate three-dimensional model of the reservoir, facilitating predictions regarding porosity, permeability, and fluid flow distribution. Among the various methods employed for reservoir characterization, the hydraulic flow unit stands out as a widely adopted approach. By effectively subdividing the reservoir into distinct zones, each characterized by unique petrophysical and geological properties, hydraulic flow units enable comprehensive reservoir analysis. The concept of the flow unit is closely tied to the flow zone indicator, a critical parameter that defines the porosity-permeability relationships of each hydraulic flow unit. Additionally, the flow zone indicator method proves valuable in estimating permeability accurately. In this study, we demonstrate the application of the flow zone indicator method to determine hydraulic flow units within the Khasib formation. By analyzing core data and calculating the Rock Quality Index (RQI) and Flow Zone Indicator (ØZ), we differentiate the formation into four hydraulic flow units based on FZI values. Specifically, HFU 1 represents a rock of poor quality, corresponding to compact and chalky limestone. HFU 2 represents intermediate quality, corresponding to argillaceous limestone, while HFU 3 represents good quality, corresponding to porous limestone. Lastly, HFU 4 signifies an excellent reservoir rock quality characterized by vuggy limestone. By establishing a permeability equation that correlates with effective porosity for each rock type, we successfully estimate permeability. Comparing these estimated permeability values with core permeability reveals a strong agreement with a high correlation coefficient of 0.96%. Consequently, the flow zone indicator method effectively classifies the Khasib formation into four distinct hydraulic flow units and provides an accurate and reliable means of determining permeability in the reservoir. The resulting permeability equations can be applied to wells and depth intervals lacking core measurements, further emphasizing the practical utility of the FZI method.

Keywords: Reservoir Characterization, Hydraulic Flow Unit, Flow Zone Indicator, Permeability Estimation, Khasib Formation.

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1- Introduction

Reservoir characterization is a very difficult assignment due to the fact that there is always some degree of heterogeneity in the reservoir properties, making them change in spatial at all levels from pore to reservoir level, particularly in carbonate formation, which shows a high level of properties variation due to the environment in which it is deposited and the processes of digenetic exposure [1]. Effective reservoir characterization and utilization require a clear distinction in pore geometry among different lithofacies. These distinctions have resulted in a new subdivision described as flow units [2]. The idea of a flow unit was presented by Hearn et al. [3] in order to systematically characterize how different types of rock are distributed throughout the formation and how they effectively control the flow of fluids. A flow unit was defined as a portion of the subsurface formation that shows analogous petrophysical and bedding properties in both vertical and lateral directions. Furthermore, Ebanks [4] described the flow unit as a portion of the entire reservoir rock where the flow of fluid is affected by the geological and petrophysical properties that appear to be stable and certainly dissimilar to the properties of other reservoir rocks.

Rock typing can be defined as the process of associating a formation rock's characteristics with its geological facies. The geology and reservoir characteristics of the ideal rock type are the same. Geology, reservoir (static characteristics), and petrophysics are the three types of this procedure [5]. The main goal of rock typing is to describe the relation between petrophysics and geology. Rock type can be thought of as a petrophysically and geologically homogeneous set of rocks with distinct porosity, water saturation, and permeability relationship [6]. When using the hydraulic unit approach, the rock types can be described as parts of the rock that have specific relation between permeability and porosity, relative permeability curves, and capillary pressure profiles. It's useful for characterization and simulation studies of reservoirs. Correct rock typing leads to accurate

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initial water saturation profiles and, as a result, credible reservoir modeling studies as well as a reliable calculation of permeability in un-cored wells. [7, 8]. Characterizing the reservoir and identifying the type of rock are important tools for forecasting reservoir performance and comprehending reservoir design [9]. Integrated rock characterization can be carried out in detail using the flow zone indicator method to describe the formation in terms of hydraulic flow unit; Winland correlation to classify the pore size; Lucia classification to classify the types of rock depending on fabric rock number, and clustering analysis to recognize rock type with the data of well logs [10].

The core data for three wells (X-1, X-2, and X-3) provided information about porosity and permeability measurements [11]. These data were used to characterize the reservoir into discrete hydraulic flow units by using the flow zone indicator method. These flow units describe the formation and subdivide it into different rock types characterized by different porosity-permeability relationships. After that, for permeability estimation, we use the porosity-permeability equations that have been created for each hydraulic flow unit.

2- Area of Case Study

The target field is X oilfield, which is located in southeastern Iraq in the Missan governorate, about 10 km to the southwest of Amara city Fig. 1. The field was discovered in 1957 and put into production in 2000. The field is operated by Missan Oil Company and currently has 18 drilled wells. The field's structure is a single semi-symmetrical anticline with a Northwest to South East axis. Its length and width are approximately 18 km and 4.5 km, respectively [11]. The field is produced through three main reservoirs: Mishrif, Khasaib, and Nahr-Umr formations. The reservoir under study is the Khasib carbonate formation, which is considered one of the significant petroleum reserves in the south of Iraq. The Khasib formation in this field is roughly between 75 and 80 meters thick.

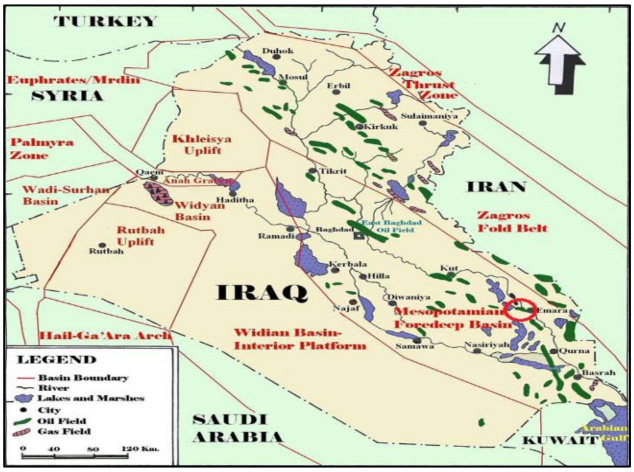

Fig. 1. The Location Map of Iraq and the Red Circle Referred to the Location of the X Oilfield [12]

3- Geological Setting of Khasib Formation

Petroleum accumulation primarily occurs in the southern and central regions of Iraq and is confined to a Mesopotamian basin anticline subsurface structure [13]. The Zubair (south), Euphrates (west), and Tigris (east) subzones make up the Mesopotamian Basin. Tigris subzone contains the X oilfield. The Mesopotamian Basin's Turonian-Campanian sedimentary cycle is fully represented by the formations Khasib, Tanuma, and Sa'di [14]. In some oilfields, these porous and fractured carbonate layers serve as particularly productive formations, alternating with numerous shale/marl units in this carbonate sequence. The entire sequence's microfacies and lithostratigraphic investigations, disregarding the diversity of the fauna and the sorts of fossils, show nearly identical depositional settings [15]. In a number of oil fields, including those in Tikrit, Balad, Samarra, East Baghdad, Ahdab, Amarah, Halfaya, Jerishan, and Majnoon, the Khasib formation is considered one of the main oil-potential rocks [16]. Nearly 14% of Iraq's Cretaceous hydrocarbon reserves and roughly 10% of the country's total proven oil reserves are included in this formation [17]. Khasib formation lies below the Tanuma formation and above the Kifl formation in the central and western regions of Iraq, while the Mishrif formation is in the southern region's equivalent of the Kifl formation Fig. 2. The majority of the Khasib formation is made up of late Cretaceous limestone and marlstones that are heavily bioturbated and contain planktonic foraminifera and calcispheres [18].

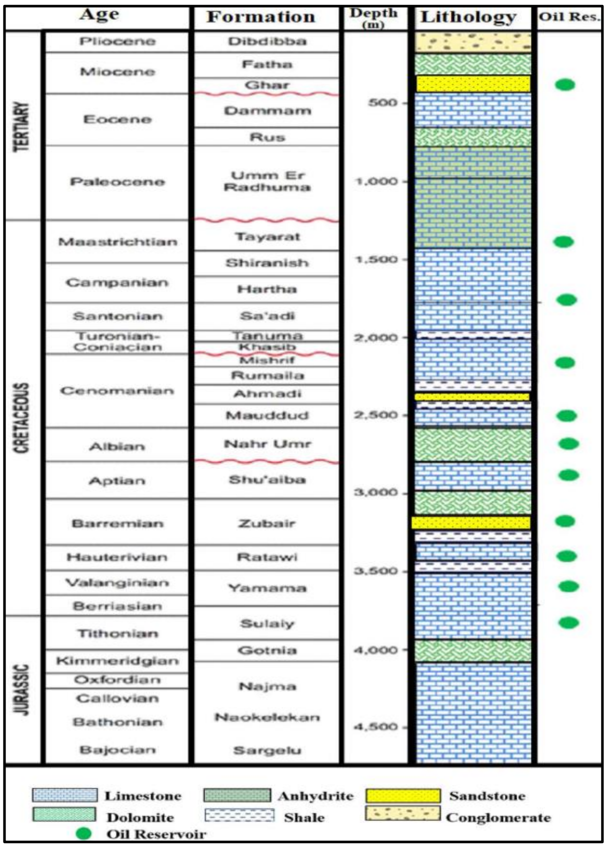

Fig. 2. South Iraq Stratigraphic Column [9]

4- Methodology

Hydraulic Flow Unit Theory

The hydraulic flow unit (HFU) method was established by Amaefule et al. [19] and it is based on the concept of the bundle of capillary tubes presented by Kozeny [20] and Carmen [21]. Amaefule et al. [19] use the hydraulic unit (HU) to recognize the various rock types in the reservoir as a result of permeability changing even in the rock type that is well defined. HFU is used to represent that part of the reservoir when the petrophysical and geological features within it differ from those of other rock parts [7].

The Kozeny-Carmen equation in its generalized form is represented by the Eq. 1:

$$K = \frac{\emptyset e^3}{(1-\emptyset e)^2} \left(\frac{1}{Fs\, \tau^2 Sgv^2}\right) \quad (1)$$

Here, K represents the permeability in µm2, Øe is effective porosity in fraction units, Sgv^2 represents specific surface area per unit grain in µm-1, Fs is shape factor, and τ is the tortuosity, both Fs and τ in the dimensionless unit,

Amaefule et al. [19] re-arranged Eq. 1 and separated the parameters that are constant for a hydraulic unit to reach the Eq. 2:

$$0.0314\sqrt{\frac{K}{\emptyset e}} = \frac{\emptyset e}{(1-\emptyset e)} \left(\frac{1}{\sqrt{Fs}\, \tau\, Sgv}\right) \quad (2)$$

The equation is presented in field units with permeability in md unit. The above equation can be expressed by introducing new parameters defined in Eqs. 3, 4, and 5:

$$\text{RQI}\ (\mu\text{m}) = 0.0314\sqrt{\frac{K}{\emptyset e}} \quad (3)$$

$$\emptyset z = \frac{\emptyset e}{1-\emptyset e} \quad (4)$$

$$\text{FZI} = \frac{1}{\sqrt{Fs}\, \tau\, Sgv} = \frac{RQI}{\emptyset z} \quad (5)$$

RQI is the reservoir quality index, $\emptyset z$ is the ratio of pore volume-to-grain volume, and FZI is the flow zone indicator, which is a unique parameter that combines texture and mineralogy in the division of distinct hydraulic flow units. Each flow unit has a different FZI value that describes the distribution of pore space geometry by correlating the RQI and $\emptyset z$.

By taking the logarithm for each side of the Eq. 5,

$$\log RQI = \log FZI + \log \emptyset z \quad (6)$$

The log-log plot of RQI vs. $\emptyset z$, will generate a straight line with a slop value that is equal to one. On the other hand, the data with different FZI values will be placed on a distinct parallel liner site [19]. The FZI mean value can be calculated from the interception of each straight line with $\emptyset z$ =1. All points located on the same line are distinguished to have similar pore throat structures, forming a hydraulic unit.

The permeability in a cored well can be calculated for each hydraulic flow unit by using the mean values for FZI and the effective porosity.

$$K = 1014 \times FZI_{mean}^2 \times \frac{\emptyset e^2}{(1-\emptyset e)^2} \quad (7)$$

The principle of hydraulic flow unit can be generalized to un-cored wells using artificial intelligence (AI), especially artificial neural networks. A permeability predictive model can be developed using artificial neural networks (ANN) to predict the hydraulic flow unit and estimate the permeability in wells with unavailable core measurements. This is done by building a model that correlates the available core and well-log data [22].

5- Results and Discussion

The hydraulic flow unit was identified by applying the flow zone indicator method to core measurements of three wells (X1, X2, and X3). This method offers a fairly adequate classification for the data under consideration. The results clarify that the examined reservoir consists of four hydraulic flow units. Each HFU has consistent ranges of FZI and represents a specific rock type with different porosity and permeability properties Fig. 3. The highest FZI values for the best quality rocks are represented by (FZI 3) while the lowest FZI values for the worst quality rocks are (FZI 0).

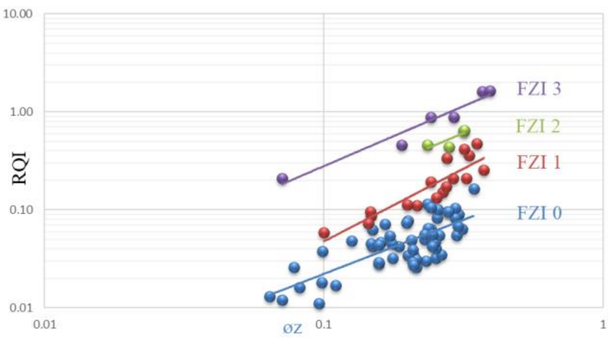

Fig. 3. Reservoir Quality Index (RQI) Versus the Normalized Porosity for Three Wells

A semi-logarithmic plot of core-derived permeability with effective porosity is applied to demonstrate the relation between these two important petrophysical properties for each distinct hydraulic flow unit. Based on the values of FZI, which represent different HFUs, four groups were recognized in the permeability–porosity plot Fig. 4. One correlation equation is determined for each HFU that correlates the core permeability and core porosity with the correlation coefficient values. It is evident that the accuracy of the HFU technique in correlating permeability with porosity is demonstrated by the R^2 of each correlation equation as represented in Table 1.

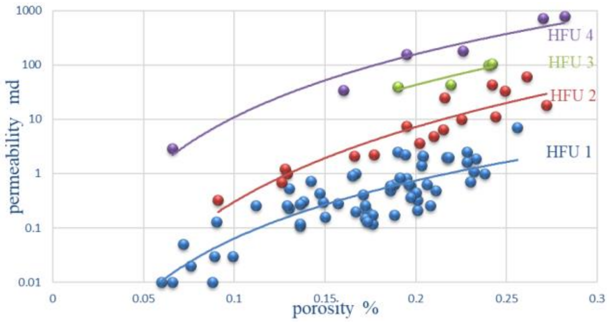

Fig. 4. Core Permeability Versus Core Effective Porosity for Three Wells

Table 1. Characterizing Reservoir Rock Using the HFU Method

HFU	K- Ø Relationships	R^2	Description
HFU 1	$y = 220.4x^{3.539}$	0.71	Poor rock properties
HFU 2	$y= 11252x^{4.573}$	0.86	Moderate rock properties
HFU 3	$y=29011x^{4.0533}$	0.78	Good rock properties
HFU 4	$y=77153x^{3.8513}$	0.96	Best rock properties

For the HFU 1, the permeability values ranged from (0.01 to 7). For the HFU 2, the permeability values ranged from (0.32 to 60). For the HFU 3, the permeability values ranged from (43 to 104). For the HFU 4, the permeability values ranged from (2.9 to 773). The porosity of the formation was ranging from 0.06 to 0.28.

Each HFU can be described as a different rock type. Relating the HFUs with their signified petrophysical properties to the geological description from the final geological reports will result in the final characterization of the rock types that make up the Khasib formation as represented in Table 2.

Table 2. Rock Types of Khasib Formation

HFU	Final Geological Reports Description	Rock Type
HFU 1	Compact limestone and Chalky	RT1
HFU 2	Argillaceous limestone	RT2
HFU 3	Porous limestone	RT3
HFU 4	Vuggy limestone	RT4

In order to verify the reliability of the permeability value from the above equations, we compared the resulted permeability with the core permeability as shown in Fig. 5. The correlation coefficient was 0.96, which describes how the calculated permeability is close to the core permeability, and this high value of the correlation coefficient gives an idea about how accurate it is to estimate permeability using the hydraulic flow units from FZI methods.

The results were plotted and described for one well using Techlog software as shown in Fig. 6. The estimated permeability from the FZI method and the core permeability are represented in the first column, the corresponding FZI groups in the second column, and HFUs in the third column are described by a different color for each zone.

Khasib formation was characterized by five electrofacies using cluster analysis. These facies consist of vuggy, porous, argillaceous, chalky, and compacted marl limestone [23]. These electrofacies from cluster analysis can be compared to the rock types characterized using the FZI method, which shows the similarity between the results of the two methods in characterizing khasib formation.

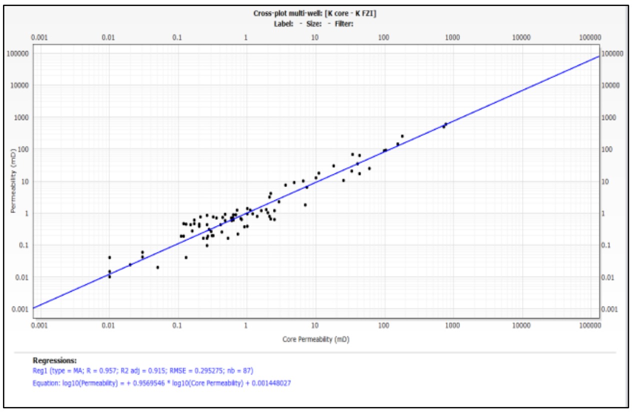

Fig. 5. Comparison between Estimated Permeability and Core Permeability

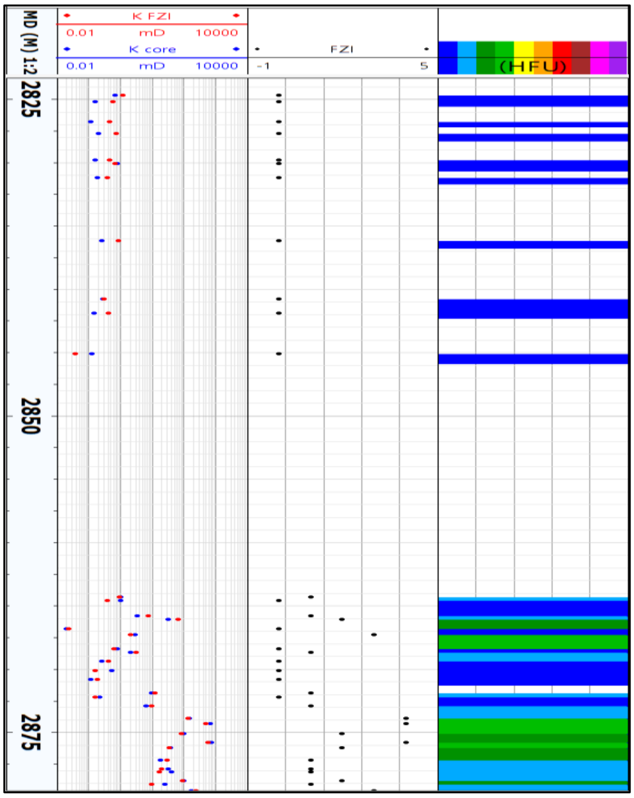

Fig. 6. Estimated Permeability Versus Core Permeability with the Values of FZI with HFU for Well X2

6- Conclusions

- The flow zone indicator method is such an effective tool for characterizing the reservoir into distinct hydraulic flow units that reflect different types of rock.
- Four hydraulic flow units are characterized in the Khasib reservoir (HFU 1 represents poor reservoir rock quality, HFU 2 represents intermediate reservoir rock quality, HFU 3 represents good reservoir rock

quality, and HFU4 represents excellent reservoir rock quality).

- Four rock types were identified by the FZI method. RT1 represents the poor rock with bad porosity-permeability values, which correspond to the compacted limestone and chalky limestone. RT2 with moderate properties corresponds to argillaceous limestone, RT3 corresponds to porous limestone with good porosity-permeability values, and RT4 with the best petrophysical properties corresponds to the vuggy limestone rock.
- The permeability equations resulting from using the FZI method show a good correlation coefficient R^2 for each HFU, and when comparing the permeability that was calculated from the HFU with core permeability, the correlation coefficient shows high agreement. The resultant empirical equations can be generalized and used for estimating permeability in wells or intervals that are with unavailable core data based on the value of porosity from the log.

Acknowledgments

The authors would like to express sincere thanks and gratitude to Missan Oil Company (M.O.C) for providing the data used.

Nomenclature

AI	Artificial Intelligence
ANN	Artificial Neural Network
FZI	Flow Zone Indicator
HFU	Hydraulic flow unit
HFUs	Hydraulic flow units
R^2	Correlation Coefficient
RQI	Reservoir Quality Index
RT	Rock Type
$\emptyset z$	Normalized Porosity

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تحديد وحدات التدفق الهيدروليكي للمكمن وحساب النفادية باستخدام طريقة مؤشر منطقة التدفق

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الخلاصة

يعد توصيف الخزان جانبًا مهمًا لفهم كيفية توزيع خواص التكوين والسوائل في جميع أنحاء المكمن في ظل وجود تغايرات التكوين. ستساعد هذه المعرفة في بناء نموذج مكمني ثلاثي الأبعاد يستخدم للتنبؤ بتوزيع المسامية والنفاذية وتدفق السوائل. إحدى الطرق التي تم استخدامها بنجاح لتوصيف المكمن هي وحدة التدفق الهيدروليكي. تعتبر وحدة التدفق الهيدروليكي أداة فعالة لتقسيم الخزان إلى مناطق مختلفة. تتميز كل منطقة بخصائصها الخاصة (البتروفيزيائية والجيولوجية) التي تميزها عن المناطق المجاورة الأخرى. يرتبط المفهوم الذي تم إنشاؤه لوحدة التدفق بما يسمى مؤشر منطقة التدفق. يتميز هذا المعامل الخاص بكل وحدة تدفق هيدروليكي بعلاقات المسامية والنفاذية. علاوة على ذلك ، يمكن تقدير النفاذية بنجاح باستخدام طريقة مؤشر منطقة التدفق. يوضح عمل هذا البحث أنه وفقًا لطريقة مؤشر منطقة التدفق ، تم تمييز أربع وحدات تدفق هيدروليكي داخل تكوين الخصيب، حيث تمثل (HFU 1) الصخور ذات الجودة الرديئة والتي تقابل نوع الصخورالجيرية المضغوطة والطباشيرية، (HFU 2) تمثل الصخورذات الجودة المتوسطة والتي تقابل نوع الصخور الحيرية الحجرية، (HFU 3) تمثل الصخور ذات جودة جيدة والتي تقابل نوع الصخور الجيرية المسامية، وتعتبر آخر وحدة تدفق هيدروليكي (HFU 4) هي صخور المكمن ذات الجودة الممتازة والتي تقابل نوع الصخور الجيرية المتشققة. تم تقدير النفاذية باستخدام المعادلة الناتجة عن المسامية والنفاذية لكل وحدة تدفق هيدروليكي، وبمقارنة قيم النفاذية المقدرة مع نفاذية اللباب، كانت قيمة معامل الارتباط عالية وتساوي ٠,٩٦٪. أخيرًا، تعتبر طريقة مؤشر منطقة التدفق طريقة فعالة لتحديد وحدة التدفق الهيدروليكي للمكمن، وتعتبر النفاذية المقدرة بها دقيقة وموثوق بها، لذلك يمكن تطبيق معادلات النفاذية الناتجة على الآبار والاعماق غير المتاح بها قياسات لباب.

الكلمات الدالة: توصيف المكمن، وحدة التدفق الهيدروليكي، مؤشر منطقة التدفق، تقدير النفاذية، تكوين الخصيب.