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Permeability Prediction for Ajeel Oilfield/ Tertiary Reservoir by Integrating Rock Typing Approach with FZI Method

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ABSTRACT

Accurate permeability prediction is essential for reservoir characterization, especially in building three-dimensional reservoir models. However, predicting permeability in the complex Tertiary reservoir/Ajeel oil field, with its different rock types and multi-layered formations, poses significant challenges. This paper utilizes well logs and core data from cored wells to predict permeability for uncored wells and intervals, uses an approach integrating rock typing by cluster analysis techniques and the Flow Zone Indicator (FZI) method by categorizing reservoirs into hydraulic flow units(HFUs) based on a reservoir quality index(RQI). This approach includes classifying reservoir rocks and zonation based on comparable petrophysical properties in horizontal and vertical dimensions. Through cluster analysis, four distinct rock types in the Tertiary reservoir are identified, and four hydraulic flow units are defined by correlating core permeability and porosity using the FZI method. The correlation coefficient (R^2 = 0.81) is acceptable and supports the relationship reliability between FZI-derived permeability and core permeability. Then, four different rock types are linked to their corresponding permeability equations derived from the FZI method and the compensation of effective porosity values in these equations for permeability prediction. Ultimately, the permeability of uncored wells and intervals, depending on this approach, will be predicted using well-log data.

Keywords: Ajeel oil field, Cluster analysis, FZI method, Permeability prediction, Tertiary reservoir.

1. INTRODUCTION

Permeability indicates fluid movement efficiency in reservoirs through rock pores to the wellbore. Estimations commonly rely on well-log evaluation **(Abdulkareem et al., 2020)** and core measurements **(Al-Qattan and Al Mohammed, 2017)**. Permeability prediction in Carbonate reservoirs is challenging due to their potential for being impermeable and heterogeneous **(Zughar et al., 2020)**. Core samples are limited to a few wells, making cost-effective and accurate permeability prediction crucial. Therefore, developing permeability

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predictive models is highly sought (**Alobaidi, 2016).** The correlation between cored and uncored wells is crucial in predicting permeability, primarily due to the restricted availability of core plugs. Recently, there has been a notable increase in applying the FZI approach to determine rock classes within reservoir units and predict hydraulic flow units (HFUs)(**Alsinbili et al., 2013**). Using flow zone indicator and cluster analysis techniques, the reservoir formations were divided into several units that represented reservoir quality(high quality, good quality, and moderate quality) **(Ali and Alrazzaq, 2023)**. Integrating Rock types with the FZI approach provides the most effective technique for predicting permeability in heterogeneous carbonate reservoirs **(Jummaah et al., 2022)**. Estimating permeability is a critical procedure because of its impact on reservoir characterization and the construction of a 3D model **(Farman, 2024)**.

The rock typing approach, crucial for reservoir characterization, uses cluster analysis methods to classify rocks **(Zhou et al., 2018)**. Cluster analysis is a statistical technique used to group reservoir rock based on similarities in petrophysical properties. These groups are founded by analyzing well-log data **(Hussain et al., 2022).** The Hierarchical and K-means approaches are utilized **(Abed and Hamd-Allah, 2019)**. Hierarchical clusters are based on how similar or different data elements form a cluster structure by joining or separating data elements repeatedly. Using the agglomerative technique and the process of grouping separate data points based on similarities until they converge into a common cluster, a dendrogram demonstrates the hierarchical relationship between the data points **(Szabó et al., 2023)**. A single linkage is used to calculate the distance between clusters – the shortest distance between any two data elements from two various clusters **(AlHusseini and Hamd-Allah, 2023)**. K-means cluster analysis commonly utilizes clustering to partition a dataset into a pre-established set of groups. Within each cluster, data points are allocated to the closest seed. The initial selection of seed values crucially influences the algorithm's performance, highlighting the significance of determining the appropriate number of clusters, denoted as "K" **(Ashraf et al., 2024)**.

Flow Zone Indicator is a well-known technique for reservoir characterization where it is used to predict the permeability of the rock and identify the flow units **(Al-Jawad and Saleh, 2020).** The pathway in which the fluid moves through each layer makes it possible to divide the reservoir into several groups referred to as HFU Hydraulic Flow Unit **(Lazim et al., 2018).** Integrating petrophysical data, synchronous geological descriptions, and big variations between all layers from core to field are instrumental in dividing the reservoir to HFUS **(Faidhllah and Hamd-Allah, 2023).** Connected to the hydraulic flow unit concept are the FZI values derived from the RQI. For each sample that is part of the same HFU, the FZI has the same value **(Hamd-Allah et al., 2016)**. A unique correlation exists between core porosity and core permeability in the hydraulic flow unit HFU when using the Reservoir Quality Index RQI **(Baker et al., 2013**). The FZI method is considered one of the most accurate methods. Many researchers have proven this by using many methods to calculate permeability. They noted that the value of the correlation coefficient between the permeability of the core and its permeability was good and higher than other methods **(Abdulmajeed et al., 2022**; **Faidhllah and Hamd-Allah, 2023)**.

The tertiary reservoir/Ajeel oil field is characterized by being one of the complex carbonate reservoirs with different types of rocks and multiple geological formations **(Gharib and Özkan, 2022)**, like the Tertiary reservoirs in other fields, was partitioned into seven distinct zones: Jeribe (J1, J2, J3), Dhiban (D1, D2), and Euphrates (E1, E2) **(Deabl et al., 2021**). The examination of porosity and lithology reveals that the Jeribe Formation(a formation in the Tertiary reservoir of the Khabaze oil field) primarily comprises dolomite, limestone, and a small amount of anhydrite, has a low shale content of 8% **(Abdul-Majeed et al., 2020).** In the Tertiary reservoir of the Mansorya oil field, two approaches, FZI and Classical, have been employed to predict the permeability. Both methods produce similar findings for all wells (**Azeez et al., 2020**).

This paper aims to predict the permeability of uncored wells and intervals from well log data, based on the data of cored wells (core data and well log data), by integrating two techniques, rock typing and the FZI method (HFU identify).

2. AREA OF THE STUDY

The Ajeel oil field, typical of carbonate oil fields in northern Iraq, contains several productive strata. The Ajeel oil field is situated between the Iraqi governorates of Kirkuk and Tikrit, approximately 30 kilometers northeast of Tikrit **(Mahammed and Nasser, 2018)**, as shown in **Fig.1.** The structure usually extends parallel to the "Alnikhila" dome in the "Hemreen Oil Field", running in a North-East to South-West orientation. **Fig. 1** displays the Location of the Ajeel oil field in northern Iraq. Ajeel Field was developed in 1977 through the excavation of the AJ-1 well, which was targeted at the highest point of a seismic map **(Al-Yassery and Al-Zaidy, 2023).**

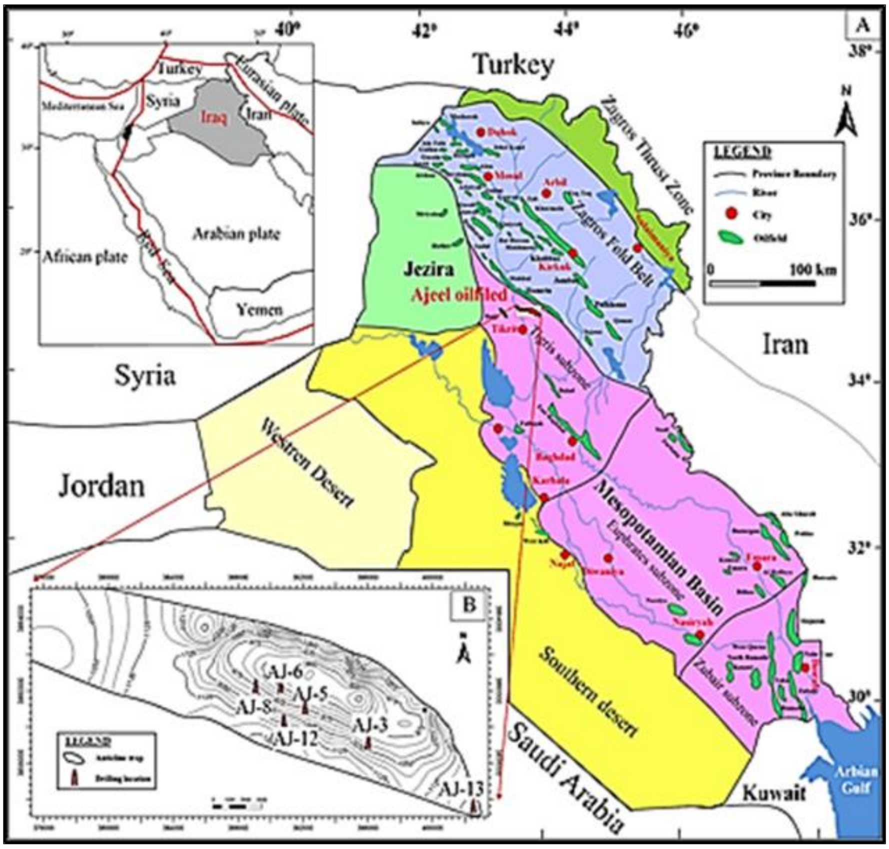


Figure 1. Location of Ajeel oil field in northern Iraq (**Gharib et al., 2021).**

The surface map of Jeribe formation and well location is shown in **Fig. 2**. The Ajeel oil field has three hydrocarbon formations within the Tertiary age reservoir:

- Jeribe formation.
- Dhiban formation.
- Euphrates formation

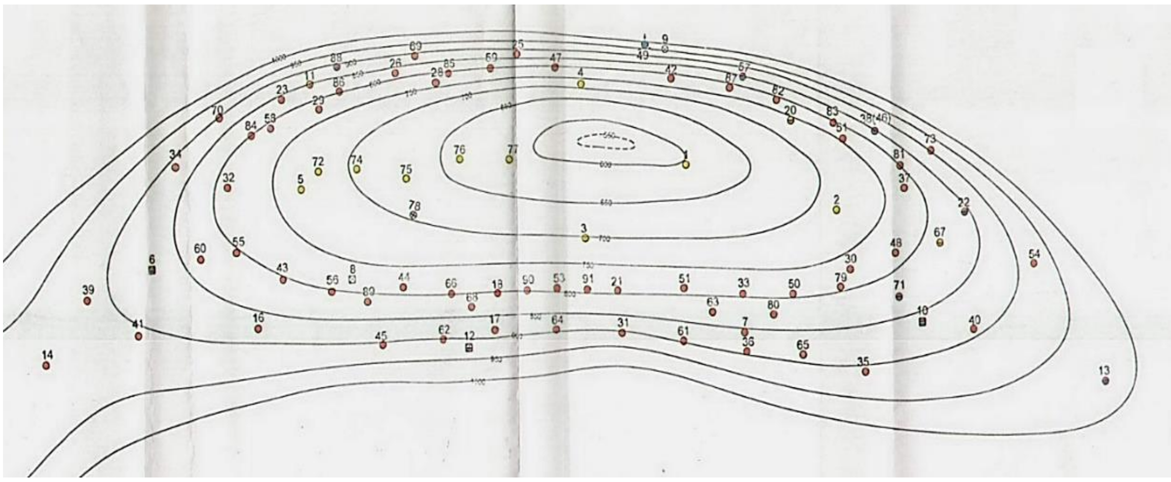


Figure 2. Surface map of Jeribe formation and well location **(NOC, 2006).**

3. METHODOLOGY

The Cluster Randomness Plot shows how many rock types the clusters seem to converge to a before-established number. The x-axis plot is the number of clusters and the y-axis plot is the index of random thickness. The average number of depth levels per cluster is represented by the average cluster thickness layer, calculated during this process. Thus, the estimated average random thickness is calculated by assuming that cluster assignments at each depth level are randomly distributed. By comparing the average sizes of clusters to the average sizes of randomly created clusters, the Randomization index is computed **(Al Kattan et al., 2018)**.

$$\text{Av. Thickness} = \frac{\text{Number of depth levels}}{\text{Number of cluster layers}} \tag{1}$$

$$\text{Random Thickness} = \sum_{i=0}^{n} \frac{\text{Pi}}{(1-\text{Pi})} \tag{2}$$

In this context, Pi represents the ratio of depth levels allocated to the i-th cluster.

$$\text{Randomness index} = \frac{\text{Av.Thickness}}{\text{Random Thickness}} \tag{3}$$

Agglomerative hierarchical clustering is accomplished by utilizing single linkage (which is a type of distance metric measure) for the calculation of the distance between clusters. The steps that are involved in this method are as follows:

- Initialization: Each data point is regarded as its cluster (independent cluster).
- Integrate closest clusters: Determine which two clusters are closest to each other using the single linkage distance metric, then combine them into a single cluster.
- Recalculate distances: Determine the distances between the newly created cluster and each of the other clusters using the single linkage measure.
- Iterate: Combine the closest clusters and adjust distances repeatedly until a predefined requirement is satisfied, either the number of clusters or the distance exceeding a given threshold **(Euzen et al., 2010)**.

The Euclidean distance approach was utilized to compute the distance between two separated subjects **(Krivoshchekov et al., 2023)**, as shown in Eq. (4).

$$dxy = \sqrt{\sum_{j=1}^{j}(xj - yj)^2} \quad (4)$$

The cluster is represented by j, and the distance between subjects xj and yj is denoted by dxy. K-means clustering is an algorithm that divides a dataset into K distinct, non-overlapping subsets or clusters. The centroid of each cluster is the average of all points within the cluster. Steps for K-means clustering:

- Random selection of k centroids (the user-specified number of clusters).
- The allocation of each data point to the cluster whose centroid is closest to it is determined by a distance metric, which is commonly Euclidean distance.
- After all data points have been assigned to clusters, the centroids are recalculated as the mean of all data points assigned to each cluster.
- Repetition of steps 2 and 3 continues until convergence is achieved, denoted by the cessation of substantial centroidal changes or the completion of a maximum number of iterations.
- Assigning each data point as a member of one of the k clusters **(Ali and Sheng-Chang, 2020)**.

The Flow Zone Indicator (FZI) is an essential technique in the characterization of hydraulic flow units and the estimation of reservoir permeability, and it represents a remarkable procedure used in this context (**Al-Ajmi et al., 2000).** Based on the capillary tube hypothesis, the methodology for the study of **(Amaefule et al., 1993)** used the concept of hydraulic units (HU) to discriminate between different types of rock in hydrocarbon reservoirs, accounting for the permeability variance **(Abed, 2014)**. The term "Hydraulic Flow Unit" (HFU) has been used to refer to geological sections that are characterized by their unique petrophysical properties that are different from their adjacent sections, and the reservoir is divided into units according to this principle **(Abdulaziz et al., 2018)**. The Kozeny-Carmen equation is represented by Eq. (5) in its generalized **(Orodu et al., 2009)** form:

$$K = \left(\frac{1}{2\times \tau\ svg^2}\right)\left(\frac{Ø_e^3}{(1-Øe^2)}\right) \quad (5)$$

In this context, K denotes the permeability in μm^2, Sgv^2 represents the specific surface area per unit volume in μm^{-1}, Øe represents the effective porosity in fraction units, and $\boldsymbol{\tau}$ represents the tortuosity is measured in the dimensionless unit. Eq. (5) was rearranged, and the parameters that remain constant for a hydraulic unit were isolated to derive the Eq. (6) **(Amaefule et al., 1993):**

$$0.0314\sqrt{\frac{K}{Ø}} = \left(\frac{1}{\sqrt{Fs}\times\tau\times Svg}\right)\left(\frac{Øe}{1-Øe}\right) \quad (6)$$

Fs is the shape factor (dimensionless unit). The aforementioned equation can be formulated by incorporating additional parameters as denoted in Eq. (7- 9). Then substituting them into the Eq. (6) to obtain the Eq. (10) **(Jin and Lin, 2004):**

$$RQI = 0.0314\sqrt{\frac{K}{Ø}} \quad (7)$$

$$Øz = \left(\frac{Øe}{1-Øe}\right) \quad (8)$$

$$FZI = \left(\frac{1}{\sqrt{Fs}\times\tau\times Svg}\right) \quad (9)$$

$$RQI = FZI \times \emptyset z \quad (10)$$

RQI is the reservoir quality index, Qz is the normalized porosity, a metric that encompasses the ratio of pore volume to grain volume and the flow zone indicator (FZI). The FZI is a characteristic factor that combines texture and mineralogy to classify hydraulic flow units into different units. Every flow unit possesses a distinct FZI value, which characterizes the arrangement of pore space geometry by establishing a correlation between the RQI and Qz. The approach obtained can be expressed as applying the logarithm function to both sides of Eq. (10) to obtain the Eq. (11). Then, the HFUs are determined.

$$\log RQI = \log\emptyset z + \log FZI \quad (11)$$

It is possible to calculate the permeability in the drilled well for each unit of hydraulic flow using the average values of FZI and effective porosity after linking it to its type of rock, and then calculate the permeability for uncored wells and intervals based on this technique from well logs **(Riazi, 2018)**.

4. RESULTS AND DISCUSSION

Cluster analysis was conducted employing the Interactive Petrophysics program version 2018 to determine the type of rock comprising the tertiary reservoir in the Ajeel oil field. As input data for cluster analysis, effective porosity (Øe) and shale volume (Vclay) logs of the eight wells were utilized; 15 clusters were assumed to encompass all data variation. The randomness plot for the tertiary reservoir shows four groups that can be classified as different types of rocks based on counting the number of peaks, as shown in **Fig. 3**.

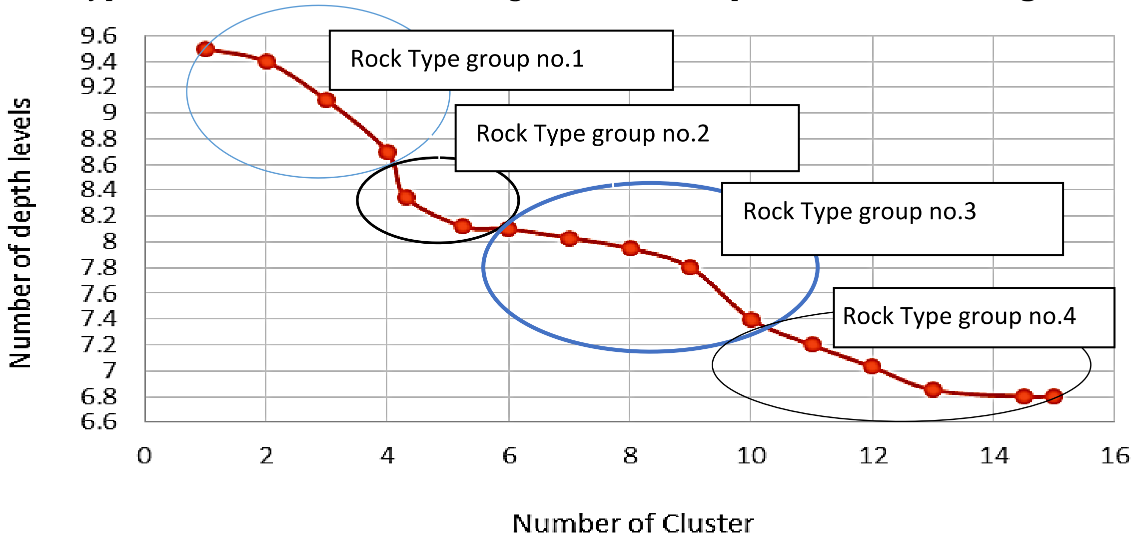


Figure 3. Randomness of cluster groups.

The hierarchical clustering technique was used to consolidate 15 clusters. The process involves repeatedly calculating distances between clusters, merging the two closest clusters, and then recalculating distances until all clusters converge into a single cluster. This hierarchical technique is visualized through a tree diagram, depicting the merging process of different colored groups of rock types. The **Fig. 4** illustrates the acquisition of four distinct groupings of rocks. From the hierarchical cluster technique, four different types of rocks were obtained (colored green, blue, pink, and red). Tertiary reservoirs are characterized by multiple rock types, such as limestone, dolomite, anhydrite, and the amount of shale in most northern Iraq fields.

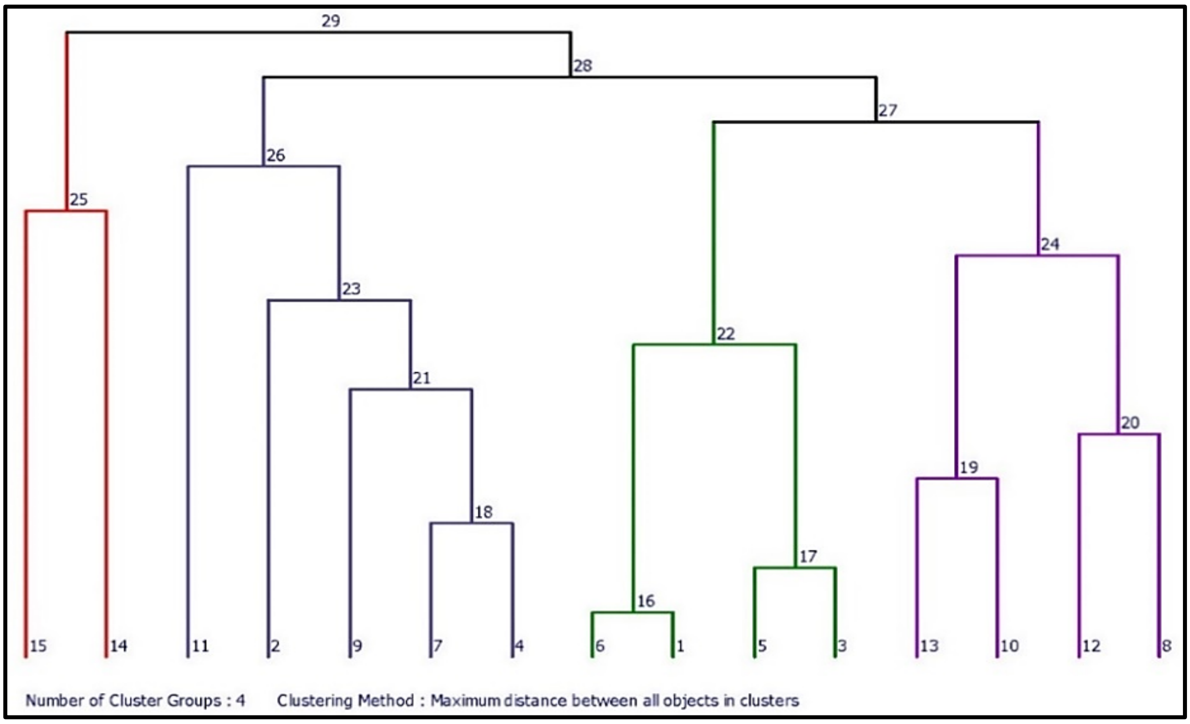


Figure 4. Hierarchical cluster.

Table 1. used K-mean values of effective porosity and shale volume as input parameters for cluster analysis to assess the quality of four different rock types. Calculating the K-means values for each of the 15 clusters involved minimizing the difference in the sum of squares between the data points and the cluster mean value. This calculation was performed while assuming an initial estimate of the mean value (seed) for the input log data. The clay content in the rocks affects the quality of the rocks, as the dispersion of clay within the rocks affects the porosity and permeability. As the volume of clay in the rock decreases, it is classified as good quality. **Fig. 5** shows the effective porosity and shale contains (shale volume) with their frequencies.

The FZI value is calculated using the routine core samples data using Eq. (10). The reservoir quality index (RQI)responses and FZI values were utilized to categorize core samples into four groups (HFUS); the formula for the permeability equation for each hydraulic flow unit was obtained, as illustrated in **Fig. 6**. From **Fig. 6**, it is clear that the curve FZI -3, the green colored points have high values of permeability (best permeability), while the blue colored curve (FZI-2) has good values of permeability, while the pink curve (FZI-1) has moderate permeability values. In contrast, the red colored curve (FZI-0) represents the lowest values of permeability, and this confirms the presence of several hydraulic flow units (4-HFUs), as shown in **Fig. 7.**

Plotting RQI against $\emptyset z$ yields a straight line with varying FZI values. Data with varying FZI values will form distinct parallel lines. The mean FZI value can be determined from the intersection of these lines with $\emptyset z$ = 1. Identifying a hydraulic unit in the formation (has the same FZI values) is represented by points that lie on the same line, which signify similar pore throat structures, as illustrated in **Fig. 7.** The permeability for each hydraulic flow unit in the cored well is calculated after determining the FZI values, then identifying the permeability equation for each hydraulic flow unit and knowing the effective porosity value from well logs, as shown in **Table 2.**

Table 1. The K-mean analysis result.

Clusters			Cluster	Porosity (%) Ø		Caly Volume Vclay (GR)	
Cluster	Groups	Points	Spread	Mean	Std. DEV.	Mean	Std. DEV.
1	1	3398	0.109	0.00257	0.00949	0.2009	0.01211
2	3	1482	0.2658	0.35591	0.02415	0.03174	0.02551
3	1	1808	0.2323	0.17267	0.02206	0.04067	0.01956
4	3	1509	0.277	0.25116	0.02476	0.04526	0.02516
5	1	2075	0.2725	0.09848	0.02228	0.05462	0.02633
6	1	1965	0.1744	0.00616	0.01356	0.06896	0.01992
7	3	1498	0.3167	0.18352	0.03248	0.11783	0.02391
8	2	1238	0.3917	0.06239	0.03659	0.16443	0.03287
9	3	749	0.4481	0.29707	0.04038	0.18099	0.04054
10	2	1037	0.3593	0.17361	0.03314	0.22545	0.0309
11	3	148	0.9253	0.5046	0.07235	0.25483	0.09228
12	2	674	0.4542	0.06909	0.04205	0.30036	0.04052
13	2	640	0.5044	0.23884	0.04905	0.3248	0.04455
14	4	404	0.6132	0.10777	0.06278	0.45594	0.05032
15	4	134	0.7724	0.09301	0.04644	0.69017	0.0983

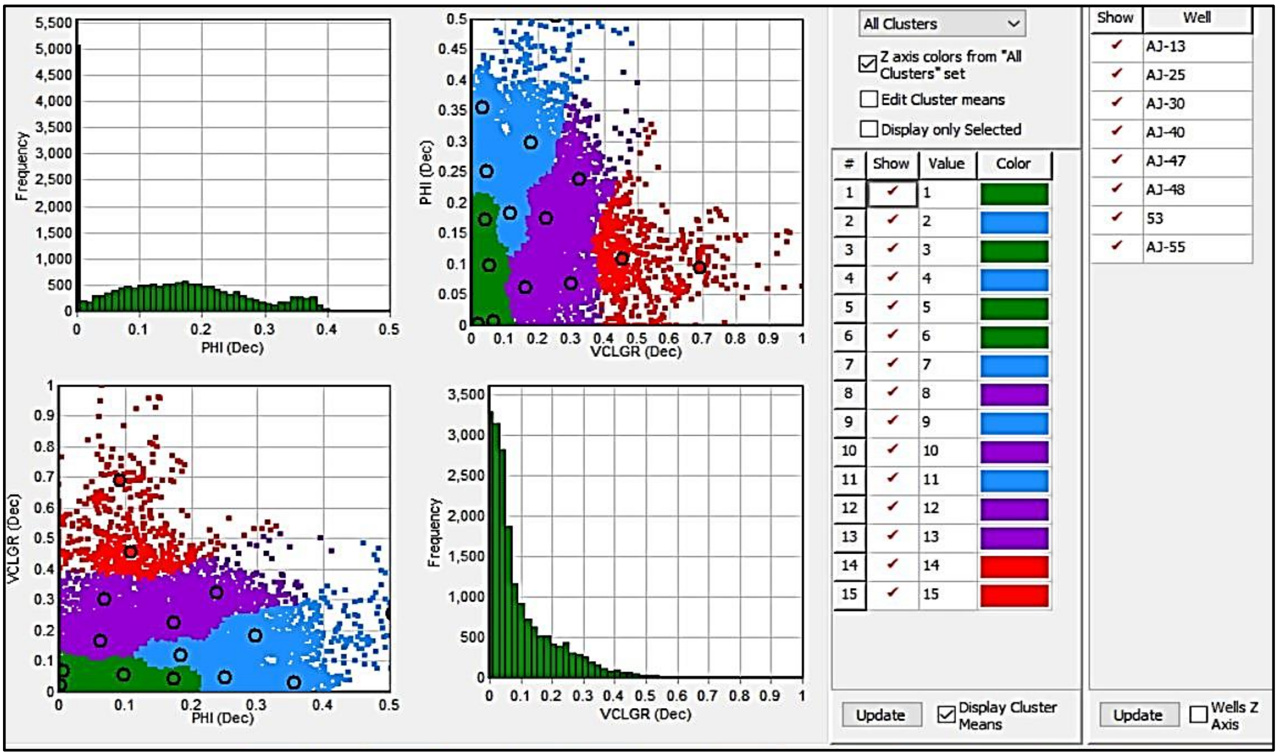


Figure 5. Cluster Analysis Result-ROCK Quality.

Calculating an FZI value from Eq. (10) to determine the range of FZI, then estimating the permeability from the corresponding equation for the permeability (identifying permeability formula) of that zone is applied, representing a specific hydraulic flow unit (same FZI-value). The FZI method provides the agreement correlation coefficient (R^2=0. 81), as shown in **Fig. 8.** To compare the FZI method with the Classical method, where the relationship between the porosity of the core and the permeability of the core is obtained as shown in **Fig. 9**. The value of the correlation coefficient(R^2) is 0.48, and this confirms the accuracy of the FZI method.

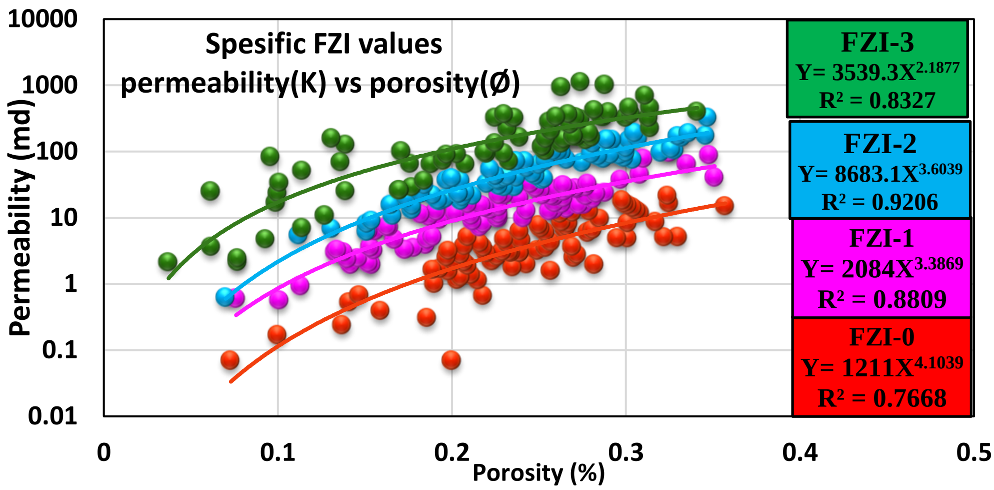


Figure 6. Specific FZI values of Tertiary Reservoir in in Ajeel oil field.

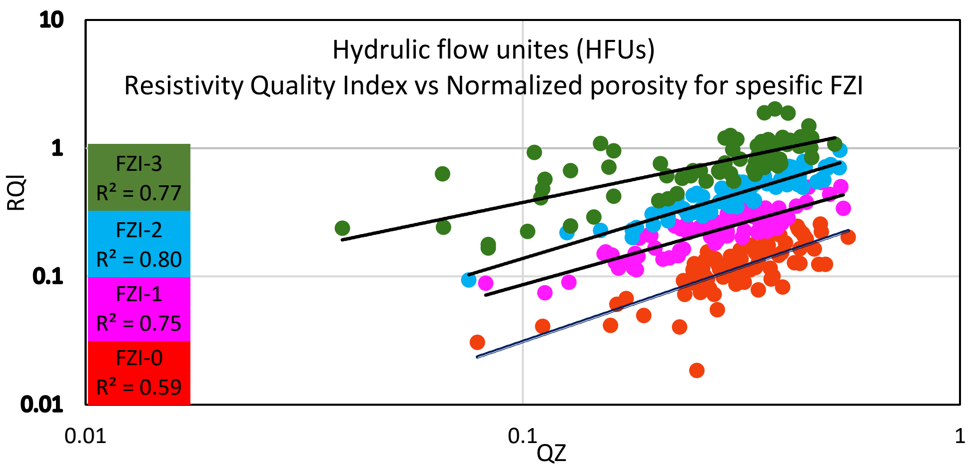


Figure 7. Hydraulic flow unites for specific FZI.

The permeability in a cored well can be determined for each unit of hydraulic flow by utilizing the average values of FZI and effective porosity, which are then correlated with the corresponding rock type, as shown in **Table 3.** and **Fig. 10**. Ultimately, this approach can predict the permeability of uncored wells and intervals using well log data by identifying rock types and linking them to their corresponding Permeability equation. The permeability is calculated by compensating the value of effective porosity (from a well log) into the Permeability equation

Table 2. The FZI and permeability formula.

FZI range	Hydraulic flow unit	Permeability Formula	R^2	Hydraulic flow unit permeability
1.821-9.67	FZI-3	$K = 3539.38 \times Ø^{2.1877}$	0.83	best
1.13-1.182	FZI-2	$K = 8683.1 \times Ø^{3.6039}$	0.92	good
0.60-1.129	FZI-1	$K = 2084 \times Ø^{3.3869}$	0.88	modrite
0.01-0.599	FZI-0	$K = 1211 \times Ø^{4.1039}$	0.77	bad

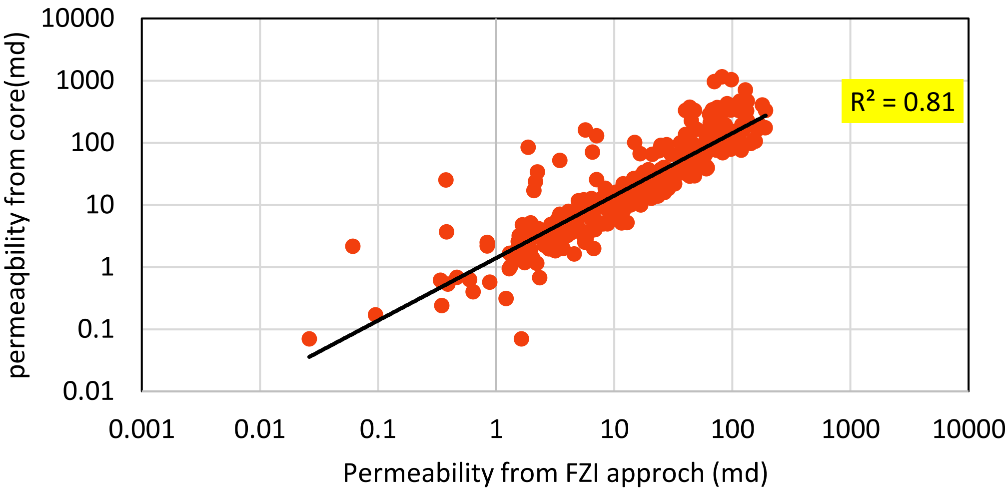


Figure 8. The agreement correlation coefficient between K-FZI and K-Core

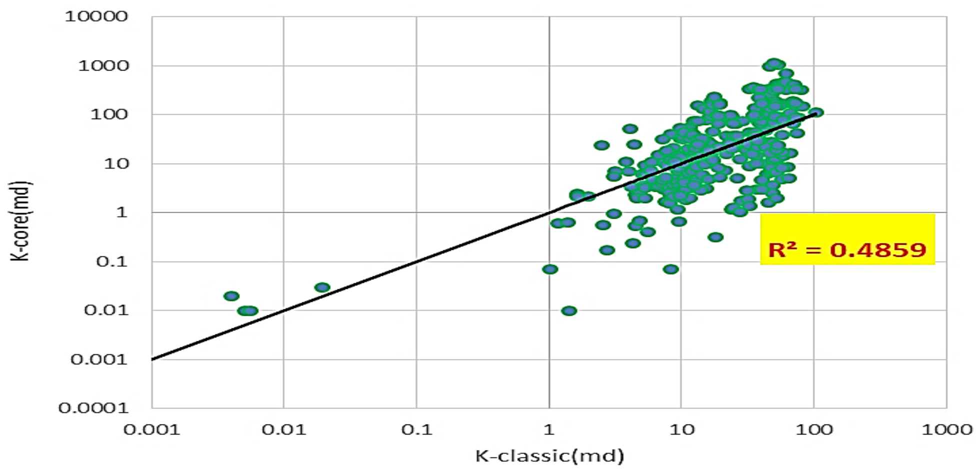
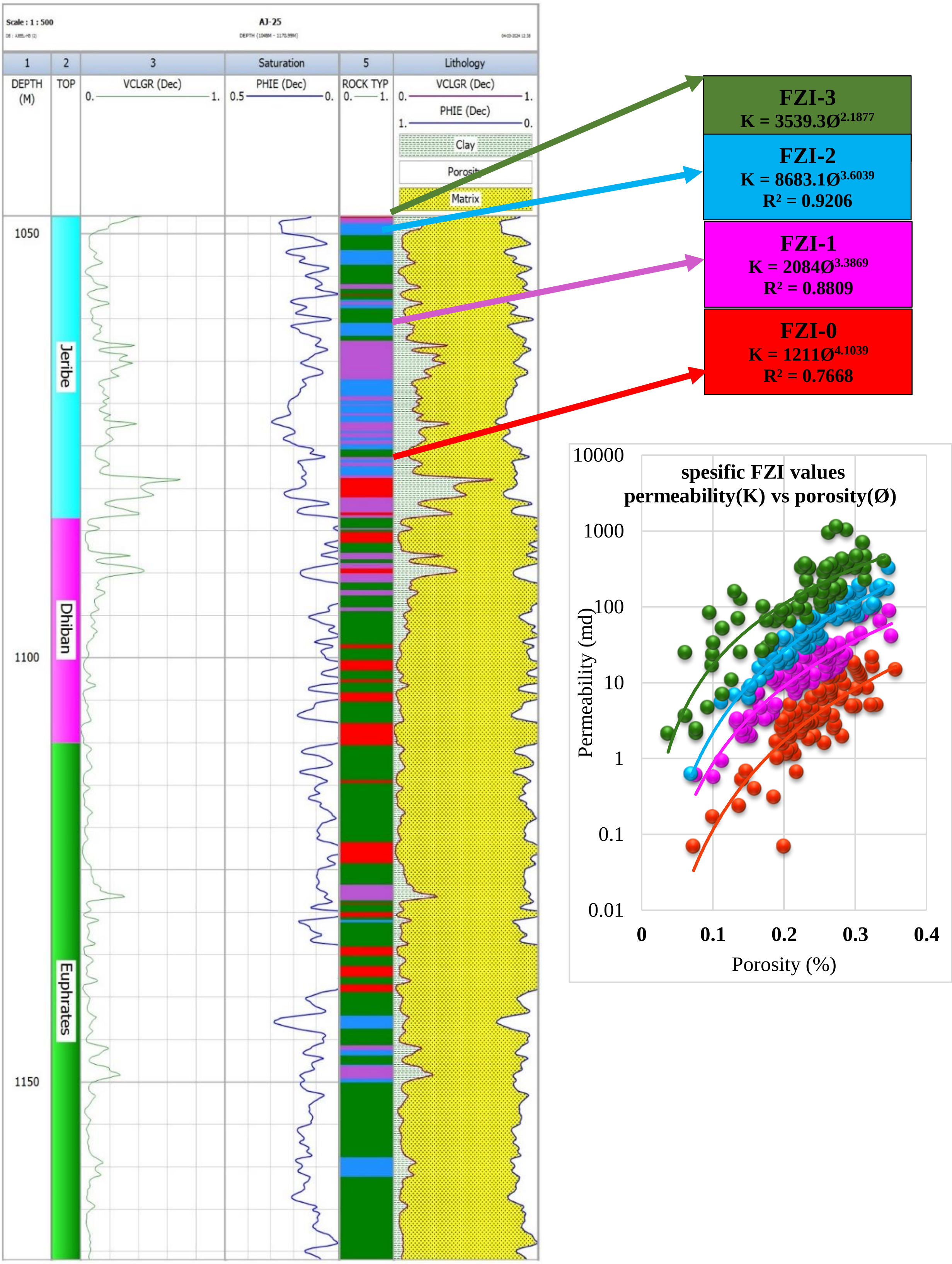


Figure 9. The correlation coefficient between K- K-Classical and K-Core.

Table 3. Corresponding Rock typing with FZI method.

FZI	Permeability Formula	Rock type groups	Reservoir ROCK Quality
FZI-3	$K = 3539.38 \times Ø^{2.1877}$	1	best
FZI-2	$K = 8683.1 \times Ø^{3.6039}$	2	good
FZI-1	$K = 2084 \times Ø^{3.3869}$	3	modrite
FZI-0	$K = 1211 \times Ø^{4.1039}$	4	bad



Figuer10. Corresponding Rock typing with FZI method to predict permeability.

5. CONCLUSION

By combining two techniques, the rock typing approach and the FZI method (HFU identification), can predict the permeability of uncored wells and intervals from well log data (effective porosity and shale volume) based on cored wells data (well logs and core), obtain:

1. Four rock types were identified in the tertiary reservoir of the Ajeel oil field by using cluster analysis methods from well-log data.
2. Four permeability equations were derived from the FZI method to identify the Hydraulic Flow (from core data).
3. Compared with core permeability, The FZI approach predicts permeability with an acceptable correlation coefficient (R^2=0.81).
4. The facies profile was accurately anticipated through cluster analysis of log data, linking different rock types to their corresponding permeability equations.
5. This procedure effectively establishes homogeneous reservoir intervals for predicting permeability in a heterogeneous carbonate environment.

NOMENCLATURE

Symbol	Description	Symbol	Description
Fs	Shape factor	RQI	Reservoir Quality Index
K	Permeability (md)	Ø	Porosity
r	Poures media radius (μm)	Øcore	Core porosity
Sgv	Surface area of grain (cm^2/cm^3)	Øe	Effective porosity
FZI	Flow zone indicator	Øz	Normalize porosity
Fus	Flow units	τ	Tortuosity
HFUs	Hydraulic flow units		

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Credit Authorship Contribution Statement

Vian M. Ahmed: Writing –review & editing, Writing –original draft, Validation, Software. Ayad A. Al-Haleem: Writing–review & editing, Supervision, Methodology, Reviewing & support.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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التنبؤ بالنفاذية لحقل عجيل النفطي/ المكمن الثلاثي بدمج طريقتين تصنيف الصخور معFZI

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الخلاصة

يعد التنبؤ الدقيق بالنفاذية أمرًا ضروريًا لتوصيف المكمن، خاصة في بناء نماذج المكمن ثلاثية الأبعاد. ومع ذلك، فإن التنبؤ بالنفاذية في المكمن الثلاثي المعقد/حقل العجيل النفطي، بأنواعه الصخرية المختلفة وتكويناته المتعددة الطبقات، يفرض تحديات كبيرة. تستخدم هذه الورقة بيانات مجسات الآبار وبيانات اللباب من الآبار الماخوذة فيها اللباب للتنبؤ بنفاذية الآبار لفترات غير ماخوذ فيها اللباب، وتستخدم منهجًا يدمج تصنيف الصخور من خلال تقنيات التحليل الاحصائي وطريقة مؤشر منطقة التدفق (FZI) عن طريق تصنيف المكامن إلى وحدات التدفق الهيدروليكي (HFUs) بناءً على مؤشر جودة المكمن (RQI). يتضمن هذا النهج تصنيف صخور المكمن وتقسيمها إلى مناطق بناءً على خصائص بتروفيزيائية قابلة للمقارنة في الأبعاد الأفقية والعمودية. من خلال التحليل الاحصائي، تم تحديد أربعة أنواع صخرية متميزة في المكمن الثلاثي، وتم تحديد أربع وحدات تدفق هيدروليكي من خلال ربط نفاذية اللباب والمسامية باستخدام طريقة FZI. يعتبر معامل الارتباط ($R^2 = 0.81$) مقبولًا ويدعم موثوقية العلاقة بين النفاذية المشتقة من FZI ونفاذية اللباب. بعد ذلك، تم ربط أربعة أنواع مختلفة من الصخور بمعادلات النفاذية المقابلة لها المستمدة من طريقة FZI وبتعويض قيم المسامية الفعالة في هذه المعادلات ليتم التنبؤ بالنفاذية. وفي نهاية المطاف، سيتم التنبؤ بنفاذية الآبار والمقاطع غير الماخوذة فيها اللباب، اعتمادًا على هذا النهج، باستخدام بيانات جس الآبار.

الكلمات المفتاحية : التنبؤ بالنفاذية، التحليل الاحصائي، طريقة FZI، الخزان الثلاثي، حقل عجيل النفطي.