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Precision in permeability: delineating reservoir heterogeneity with flow zone indicators

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PERFECT permeability prediction in heterogeneous reservoirs is critical for effective subsurface resource management. This study applies the Flow Zone Indicator (FZI) concept to delineate distinct hydraulic flow units and establish unique porosity-permeability relationships within complex reservoir systems. Core data were classified into five FZI groups (0-4), each exhibiting a characteristic exponential porosity-permeability relationship. FZI 0, representing the lowest reservoir quality, showed an exceptionally strong correlation (R2 =0.9479), indicating a highly homogeneous pore system. Higher quality units (FZI 1-3) maintained strong exponential correlations (R2 : 0.7898–0.8444), reflecting enhanced pore connectivity. However, FZI 4, despite having the highest permeabilities, demonstrated lower model reliability (R 2 =0.5234), highlighting the impact of limited data on statistical robustness. This empirical evidence demonstrates that the FZI method offers an indispensable framework for quantitatively characterizing reservoir quality, moving beyond conventional bulk-property correlations. The FZI-based methodology effectively segments reservoir heterogeneity, enabling more precise permeability modeling, enhanced fluid flow simulations, and optimized reservoir management for sustainable resource recovery.

Keywords: Flow Zone Indicator (FZI); Permeability Prediction; Porosity-Permeability Relationship; Reservoir Heterogeneity; Hydraulic Flow Units; Core Analysis; Reservoir Characterization.

1. Introduction

Permeability stands as a fundamental petrophysical parameter crucial for comprehensive reservoir characterization and the accurate prediction of subsurface fluid flow. Its three-dimensional distribution within heterogeneous reservoirs, however, remains a persistent and significant challenge in reservoir engineering. Inaccurate or unreliable permeability models inevitably lead to inefficient dynamic simulations, compromising their ability to accurately describe and predict the past, present, and future performance of oil and gas reservoirs.

In response to the persistent challenges of accurately modelling permeability in heterogeneous reservoirs, methodologies based on the concept of Hydraulic Flow Units (HFU) have emerged as superior approaches. The Flow Zone Indicator (FZI), a quantitative parameter derived from core porosity and permeability, serves as a direct link to HFUs. The core principle of FZI is that rock samples belonging to the same HFU will exhibit similar FZI ranges, reflecting consistent pore-throat size distributions and hydraulic characteristics. This quantitative nature makes FZI particularly suitable for developing robust prediction models, moving beyond simple classification. Past research has focused on predicting FZI itself from well logs, which is then used to calculate permeability (Baker et al., 2013; Amraei and Falahat, 2021; Abbaszadeh et al., 1996), or integrating FZI with fuzzy models to improve permeability estimation (Soto et al., 2001). Other studies have explored ANN models for identifying flow units and estimating permeability in heterogeneous carbonates (Aminian et al., 2003; Kharrat et al., 2009; Ali et al., 2013).

Despite these advancements, challenges remain in developing universally applicable workflows and ensuring accuracy in highly heterogeneous systems, especially in less studied formations such as tight carbonate gas condensate reservoirs (Vafaie et al., 2021; Rashid et al., 2015).

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Building upon these foundational efforts, this study aims to comprehensively characterize the inherent heterogeneity of a reservoir by rigorously classifying core permeability and porosity data into distinct Flow Zone Indicator (FZI) groups. The primary objective is to establish and analyze the unique exponential porosity-permeability relationships within each identified FZI group. By systematically examining these distinct hydraulic flow units, this research provides highly accurate and group-specific permeability prediction models, thereby enhancing the precision of reservoir characterization, optimizing fluid flow predictions, and ultimately contributing to more effective reservoir management strategies.

2. Methodology

Rock typing is a process in which reservoir rocks are classified into distinct units. One of the frequently used approaches for rock typing is the FZI method. Amaefule et al. (1993) introduced this method for the first time. This technique identifies existing trends between permeability and porosity using the FZI values of reservoir rocks. The general Kozeny-Carman relation for calculating permeability is given by Eq. (1).(1)K=1014Øe3(1−Øe)2[1Fsτ2Sgv2]where, K is a core permeability in mD, Øe is an effective core porosity, Fs denotes a shape factor, τ is the tortuosity and Sgv represents the surface area per grain volume. Calculation of permeability by this equation is not an easy task because it is difficult to measure the Fs, τ and Sgv parameters for reservoir rocks. Amaefule et al. (1993) defined the FZI as the square root of the 1/Fsτ2Sgv2 term and derived Eq. (2) to obtain FZI from core data:(2)FZI=RQIØn(3)ØRQI=0.0314KØe(4)ØØØØn =Øe1−Øewhere, RQI is a parameter called reservoir quality index (μm) and Øn is the normalized porosity. The calculated FZI is then used to group the rocks into discrete rock types (DRTs) according to the following relation:(5) DRT=Round(2Log(FZI)+10.6).

The core data of S well were used in this study for rock typing based on the FZI approach. The statistical parameters of the core porosity and permeability are summarized in Table 1.

3. Results

By applying the FZI rock typing approach five different rock types were identified; which they are FZI 0, FZI 1, FZI 2, FZI 3, and FZI 4.

Table 1. Input and output data contains core porosity, core permeability, and FZI.

Core Permeability	Core Porosity Decimal	FZI
0.21	0.111	0.341762
0.37	0.138	0.319418
0.16	0.098	0.373869
0.55	0.133	0.41587
0.83	0.145	0.442712
0.37	0.113	0.447205
1.06	0.148	0.484854
1.52	0.158	0.519183
4.68	0.218	0.521773
1.04	0.137	0.546022
0.76	0.122	0.563645
2.68	0.175	0.579287
4.49	0.201	0.589937
0.70	0.113	0.613458
2.86	0.167	0.648161
5.71	0.201	0.665099
1.76	0.141	0.67585
4.99	0.183	0.732024
8.28	0.210	0.741725
4.28	0.173	0.746513
1.65	0.130	0.749325
1.67	0.130	0.753168
6.47	0.190	0.781154
4.81	0.172	0.799688
3.58	0.157	0.805099
4.99	0.172	0.814175
9.17	0.204	0.821452
3.24	0.150	0.826959
7.60	0.186	0.878283
10.6	0.204	0.883182
1.66	0.114	0.930086
0.47	0.076	0.944295
75.9	0.328	0.978609
24.4	0.243	0.980192

2.07	**0.118**	**0.982541**
1.70	**0.109**	**1.013659**
8.06	**0.170**	**1.055606**
31.1	**0.249**	**1.057892**
1.23	**0.095**	**1.07633**
8.47	**0.170**	**1.082122**
1.14	**0.092**	**1.090903**
14.1	**0.192**	**1.133601**
38.4	**0.245**	**1.211415**
104	**0.313**	**1.25628**
1.37	**0.089**	**1.261024**
2.07	**0.099**	**1.307995**
23.4	**0.203**	**1.323585**
94.2	**0.296**	**1.332264**
3.36	**0.113**	**1.344018**
6.62	**0.138**	**1.358461**
29.7	**0.213**	**1.369977**
2.05	**0.095**	**1.389536**
61.2	**0.258**	**1.390848**
1.34	**0.083**	**1.393908**
52.1	**0.245**	**1.411063**
23.7	**0.194**	**1.441904**
129	**0.307**	**1.452948**
74.3	**0.265**	**1.458286**
17.4	**0.176**	**1.461714**
36.1	**0.212**	**1.52302**
86.1	**0.264**	**1.580895**
132	**0.291**	**1.629384**
27.5	**0.187**	**1.655481**
141	**0.290**	**1.69512**
249	**0.334**	**1.709558**
17.5	**0.159**	**1.741907**
68.6	**0.233**	**1.77359**
9.83	**0.128**	**1.874597**
43.7	**0.196**	**1.923059**
218	**0.303**	**1.937433**
91.9	**0.240**	**1.945737**
106	**0.249**	**1.953995**
83.7	**0.231**	**1.98976**
76.4	**0.223**	**2.02507**
150	**0.266**	**2.056857**
163	**0.266**	**2.144851**
210	**0.282**	**2.181675**
175	**0.266**	**2.2224**
257	**0.294**	**2.229359**
297	**0.295**	**2.381025**
155	**0.243**	**2.470484**
406	**0.308**	**2.561372**
468	**0.318**	**2.583427**
648	**0.339**	**2.675993**
546	**0.312**	**2.89656**
318	**0.269**	**2.933811**
462	**0.294**	**2.989058**
808	**0.335**	**3.061186**
807	**0.330**	**3.15261**
665	**0.312**	**3.196664**
629	**0.305**	**3.249302**
199	**0.223**	**3.268285**
600	**0.296**	**3.36233**
17.4	**0.106**	**3.388115**
585	**0.273**	**3.870776**
1189	**0.326**	**3.920614**
1458	**0.336**	**4.087592**
1820	**0.354**	**4.108592**
647	**0.271**	**4.127199**
2030	**0.332**	**4.940228**
2054	**0.324**	**5.216258**

3.1 Core permeability versus core porosity

The scatter plot in Fig. 1 illustrates the relationship between core permeability (y-axis, logarithmic scale) and core porosity (x-axis, linear scale) from core analysis data. A clear positive exponential trend is observed, indicating the reality about as core porosity increases, the core permeability also increases. An exponential regression model was fitted to the data, yielding the following equation: y=0.0436e0.2944x ; where y represents the core permeability in millidarcy (mD), x represents the core porosity in percentage, and e is Euler's number (the base of the natural logarithm). The coefficient of determination, R2 , for this fitted model is 0.6493.

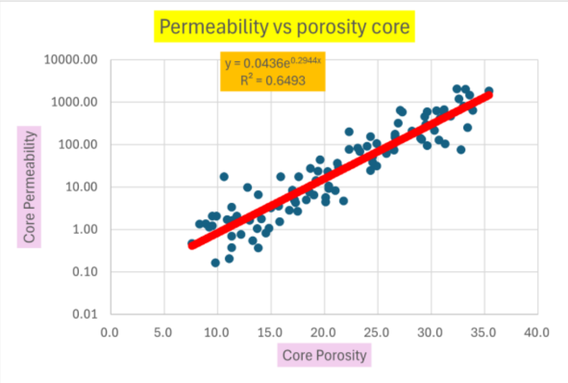

Fig. 1. Scatter plot illustrates the relationship between core permeability (y-axis, logarithmic scale) and core porosity (x-axis, linear scale) from core analysis data.

3.2 Flow Zone Indicator (FZI 0)

The provided scatter plot in Fig. 2 is for a specific rock group designated as "FZI 0". The data points exhibit a clear and strong positive exponential trend. An exponential regression analysis was performed on the data, yielding the following relationship: y=0.0412e 24.921x ; where y represents the core permeability in millidarcy (mD), x represents the core porosity in percentage, and e is Euler's number (the base of the natural logarithm). The coefficient of determination (R2) for this fitted model is 0.9479.

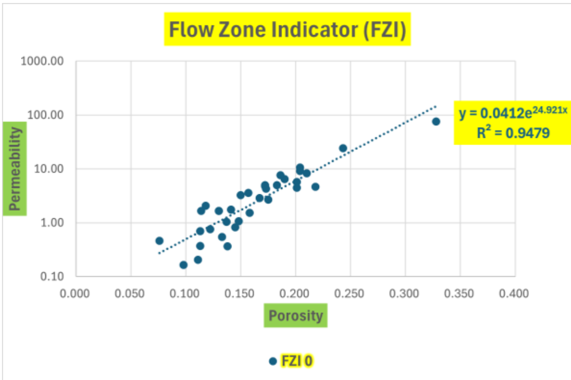

Fig. 2. Illustrates Flow Zone Indicator (FZI) for a specific rock group designated as "FZI 0".

3.3 Flow Zone Indicator (FZI 1)

The provided scatter plot in Fig. 3 is for a rock group designated as "FZI 1". The data points exhibit a clear positive exponential trend, indicating that as porosity increases, permeability tends to increase at an accelerated rate.
An exponential regression model was fitted to the data for FZI 1, resulting in the following equation: y=0.2994e 21.182x where y represents the core permeability in millidarcy (mD), x represents the core porosity in percentage, and e is Euler's number (the base of the natural logarithm). The coefficient of determination (R2) for this fitted model is 0.8217.

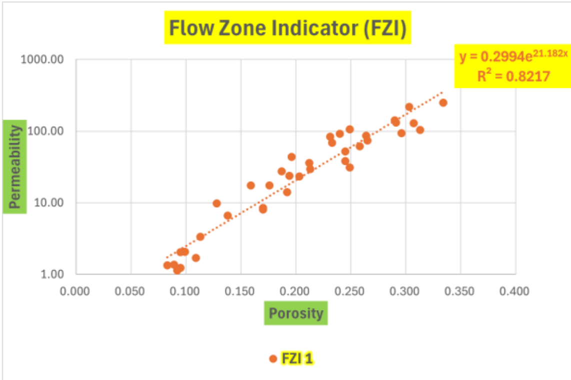

Fig. 3. Illustrates Flow Zone Indicator (FZI) for a specific rock group designated as "FZI 1".

3.4 Flow Zone Indicator (FZI 2)

The presented scatter plot in Fig. 4 is for the "FZI 2" rock group. The data points show a strong positive exponential trend.
An exponential regression model was fitted to the data for FZI 2, yielding the following equation: y=1.4823e 18.253x where y represents the core permeability in millidarcy (mD), x represents the core porosity in percentage, and e is Euler's number (the base of the natural logarithm). The coefficient of determination (R2) for this fitted model is 0.8444. Visually, the data points for FZI 2 generally exhibit higher porosities (ranging approximately from 0.20 to 0.35) and correspondingly higher permeabilities (ranging from approximately 70 mD to over 500 mD) compared to the previously analysed FZI 0 and FZI 1 groups.

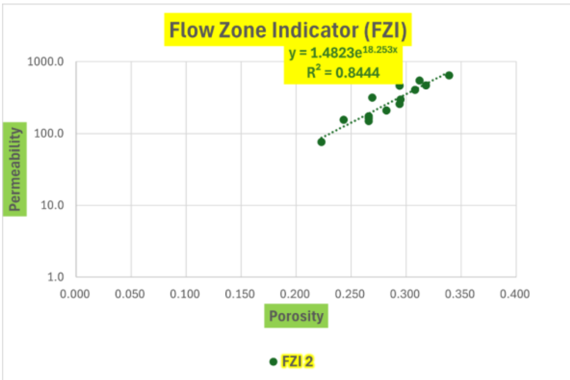

Fig. 4. Illustrates Flow Zone Indicator (FZI) for a specific rock group designated as "FZI 2".

3.5 Flow Zone Indicator (FZI 3)

The scatter plot in Fig. 5 is for the "FZI 3" rock group. Despite a relatively smaller number of data points, a clear positive exponential trend is observed, indicating that permeability increases exponentially with porosity. An exponential regression model was fitted to the data for FZI 3, resulting in the following equation:y=3.4714e 17.21x where y represents the core permeability in millidarcy (mD), x represents the core porosity in percentage, and e is Euler's number (the base of the natural logarithm). The coefficient of determination (R2) for this fitted model is 0.7898. The porosity values for FZI 3 predominantly fall in the higher range (approximately 0.25 to 0.35), correlating with high permeability values (from tens to hundreds and even over a thousand mD).

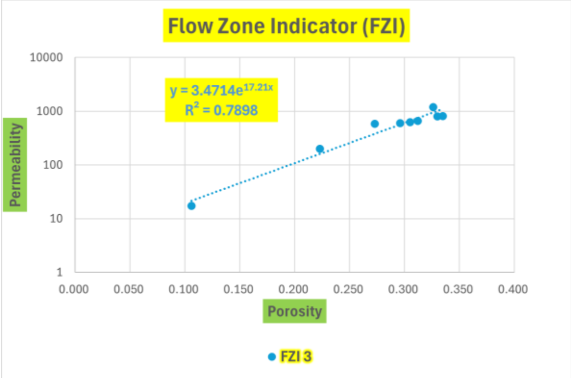

Fig. 5: Illustrates Flow Zone Indicator (FZI) for a specific rock group designated as "FZI 3".

3.6 Flow Zone Indicator (FZI 4)

The scatter plot in Fig. 4 is for the "FZI 4" rock group. The data set comprises a very limited number of points (only 6), but a general positive exponential trend is still discernible. An exponential regression model was fitted to this sparse data for FZI 4, yielding the following equation: y=19.534e 13.387x where y represents the core permeability in millidarcy (mD), x represents the core porosity in percentage, and e is Euler's number (the base of the natural logarithm). The coefficient of determination (R 2) for this fitted model is 0.5234. The FZI 4 samples are characterized by high porosities (ranging approximately from 0.27 to 0.35) and exceptionally high permeabilities (ranging from around 600 mD to over 1500 mD).

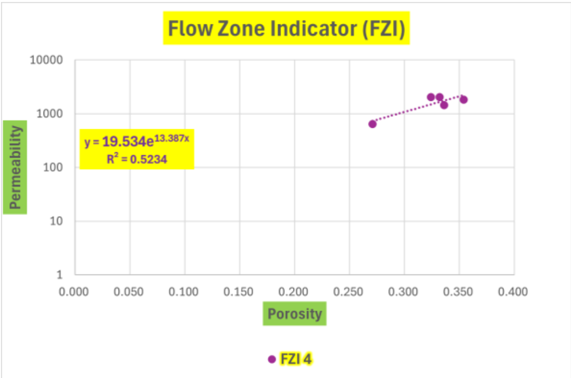

Fig. 6. Illustrates Flow Zone Indicator (FZI) for a specific rock group designated as "FZI 4".

4. Discussion

4.1 Core permeability versus core porosity

The observed exponential relationship between core porosity and core permeability is consistent with fundamental principles of petrophysics. In reservoir rocks, permeability, which is a measure of the ability of fluids to flow through a porous medium, is highly dependent on the interconnected pores and size of pore spaces. Porosity, representing the volume of void space to the total volume, provides the necessary pore volume. However, it is often the effective porosity and, more critically, the pore throat sizes and connectivity that affects permeability. The exponential nature of the relationship suggests that small increases in porosity, lead to significant increases in permeability. This is often because larger pore throats provide less resistance to flow, and increasing porosity often correlates with an increase in average pore throat size.

The R2 value of 0.6493 indicates that approximately 64.93% of the variability in core permeability can be expressed by the core porosity using this exponential model. This suggests a moderate to strong correlation between the two parameters. While the relationship is statistically significant and useful for prediction, the remaining approximately 35% of the variability in permeability is not accounted for by porosity alone. This unexplained variance can be attributed to several factors inherent in real core data such as heterogeneity of pore systems, rock type and texture, anisotropy, and measurement errors. The exponential model provides a valuable tool for estimating core permeability from core porosity in this dataset. It highlights the primary control of porosity on permeability, which is crucial for reservoir characterization, fluid flow simulations, and ultimately, predicting reservoir performance.

4.2 Flow Zone Indicator (FZI 0)

The observed exponential relationship between porosity and permeability for the "FZI 0" rock group is highly significant. This type of relationship is commonly found in porous media, particularly in reservoir rocks, where permeability is not just dependent on the total pore volume (porosity) but critically on the size, shape, and interconnectedness of the pore throats. The exponential increase in permeability with porosity suggests that as porosity increases, the efficiency of fluid flow (likely due to larger and better-connected pore pathways) improves dramatically.

The remarkably high R2 value of 0.9479 is a key finding. It indicates that approximately 94.79% of the variability in permeability for the "FZI 0" samples can be explained by variations in porosity using this exponential model. This signifies an excellent fit of the model to the data and a very strong correlation between permeability and porosity within this specific flow zone. Such a high R2 value suggests that the "FZI 0" group represents a petrophysically homogeneous unit where the pore architecture is consistent enough that porosity becomes an extremely reliable predictor of permeability.

In the context of Flow Zone Indicators (FZI), this results strongly supports the concept that rocks belonging to a particular FZI group share similar hydraulic characteristics and pore throat size distributions, leading to a consistent porosity-permeability relationship. The tight clustering of data points around the trendline further reinforces the idea that these samples belong to a distinct hydraulic unit. This consistency is invaluable for reservoir characterization, allowing for more accurate permeability predictions in unsampled intervals or wells where only porosity logs are available, provided the rock falls within the "FZI 0" group.

4.3 Flow Zone Indicator (FZI 1)

"FZI 1" further reinforces the fundamental petrophysical principle that permeability is exponentially dependent on porosity. The model captures this trend effectively, indicating that even within a specific flow zone, small increments in porosity can yield significant increases in a rock's ability to transmit fluids. The R^2 value of 0.8217 signifies that approximately 82.17% of the variability in permeability for the "FZI 1" samples can be explained by variations in porosity through this exponential model. This indicates a strong correlation and a good predictive capability of the model for this particular flow zone. While slightly lower than the R^2 observed in some other FZI groups (e.g., FZI 0 from previous analyses, which had an R^2 of 0.9479), an R^2 of over 0.8 still demonstrates a robust and useful relationship for practical applications. The distinction in the regression equation coefficients ($0.2994e^{21.182x}$ for FZI 1 versus $0.0412e^{24.921x}$ for FZI 0) and the different R^2 values strongly support the concept of Flow Zone Indicators. This indicates that "FZI 1" represents a rock type or hydraulic unit with a distinct pore-throat geometry and flow characteristics compared to "FZI 0" or other potential flow zones. Even with similar porosities, rocks from different FZIs will likely exhibit different permeabilities because their internal pore structures dictate flow efficiency differently. The slight increase in data scatter (leading to a lower R^2) compared to FZI 0 suggests a marginally higher degree of internal heterogeneity within the "FZI 1" group, or perhaps slightly more variability in pore connectivity for similar porosity values.

Understanding these unique porosity-permeability relationships for each FZI is critical for accurate reservoir characterization. It allows geoscientists and engineers to segment reservoirs into hydraulically similar units, leading to more precise permeability modelling, improved fluid flow simulations, and more reliable predictions of hydrocarbon recovery.

4.4 Flow Zone Indicator (FZI 2)

The observed exponential relationship for the "FZI 2" containing R^2 value of 0.8444 indicates that approximately 84.44% of the variability in permeability within the "FZI 2" samples can be explained by variations in porosity using this exponential model. This signifies a strong correlation and robust predictive capability, suggesting that "FZI 2" represents a relatively homogeneous hydraulic unit.

4.4.1 Comparison FZI 2 with FZI 0 and FZI 1:

This analysis of "FZI 2", when considered alongside the previously examined "FZI 0" ($y=0.0412e^{24.921x}$, $R^2=0.9479$) and "FZI 1" ($y=0.2994e^{21.182x}$, $R^2=0.8217$), provides compelling evidence for the efficacy of the Flow Zone Indicator concept which say Distinct Hydraulic Units: Each FZI group (0, 1, and 2) possesses a unique and well-defined porosity-permeability relationship, as evidenced by their distinct exponential equations and coefficients. This implies that even if two rock samples from different FZI groups have the same porosity, their permeabilities will likely be significantly different due to variations in their internal pore network geometry (e.g., pore throat sizes, tortuosity).

Varying Predictive Power: The R^2 values, while all indicating strong correlations, vary among the FZI groups (0.9479 for FZI 0, 0.8217 for FZI 1, and 0.8444 for FZI 2). This suggests differing degrees of internal homogeneity or consistency in pore structure within each defined flow zone. FZI 0 appears to be the most petrophysically homogeneous group in this dataset, showing the tightest porosity-permeability coupling.

4.5 Flow Zone Indicator (FZI 3)

The observed exponential relationship for the "FZI 3" group further substantiates the general principle that permeability is exponentially linked to porosity in porous media, particularly in high-quality reservoir rocks. The model adequately describes this trend, showing that this specific flow zone also exhibits an accelerating increase in permeability with porosity.

The R^2 value of 0.7898 indicates that approximately 78.98% of the variability in permeability for the "FZI 3" samples can be explained by variations in porosity using this exponential model. This represents a strong correlation, making porosity a useful predictor of permeability even for this group. However, it's worth noting that this R^2 is the lowest among the four FZI groups analysed so far. This might be partly attributed to the limited number of data points (around 9-10 points), which can influence the statistical robustness of the regression, or it could genuinely indicate a slightly higher degree of internal heterogeneity within this specific flow zone compared to others.

4.6 Flow Zone Indicator (FZI 4)

The observed positive exponential trend for the "FZI 4" group aligns with the general petrophysical understanding that higher porosities, especially when associated with large, well-connected pore networks, lead to significantly higher permeabilities. This group represents very high-quality reservoir rock with excellent flow characteristics.

However, the R2 value of 0.5234 is notably lower compared to all previously analysed FZI groups. This indicates that only about 52.34% of the variability in permeability for FZI 4 is explained by its porosity using this model. While still a positive correlation, this lower R2 warrants careful interpretation. The primary reason for this reduced confidence in the model is likely the very limited number of data points (only 6). With such a small sample size, the statistical significance of the regression is diminished, and the calculated R2 may not be fully representative of the true relationship within this FZI if more data were available. It could also suggest a higher degree of inherent heterogeneity even within this high-quality zone, perhaps due to the influence of large vugs or micro-fractures that can introduce variability in permeability not solely governed by matrix porosity.

4.7 Petrophysical Insights from FZI-Based Permeability Grouping

The comprehensive analysis across all FZI groups (FZI 0, FZI 1, FZI 2, FZI 3, and FZI 4) provides a compelling demonstration of the Flow Zone Indicator concept and its practical implications for reservoir characterization.

Unique Hydraulic Flow Units; each FZI group (0 through 4) is characterized by a unique and distinct porosity-permeability relationship, as evidenced by their individual exponential equations. This confirms that FZI effectively segregates reservoir rocks into hydraulically homogeneous units, where pore architecture dictates flow efficiency uniquely for each group.

Reservoir Quality Progression; there is a clear progression in reservoir quality across the FZI groups. FZI 0 represents the lowest-quality rocks (lower porosity and permeability), while FZI 1, FZI 2, FZI 3, and FZI 4 progressively represent increasingly better reservoir quality, culminating in FZI 4 with its very high permeabilities. This suggests a systematic change in pore throat size distribution and connectivity with increasing FZI number.

Varying Model Reliability; the R^2 values provide insight into the consistency within each FZI. FZI 0 demonstrated the highest correlation (R^2 =0.9479), indicating a highly uniform pore system. Subsequent groups (FZI 1: R^2 =0.8217, FZI 2: R^2 =0.8444, FZI 3: R^2 =0.7898) maintained strong correlations. However, FZI 4 exhibits the lowest R^2 (0.5234), primarily due to the very limited sample size, which reduces the confidence in its predictive model compared to the others. This highlights the importance of having sufficient core data for each identified FZI to ensure robust statistical relationships.

In general conclusion, while FZI 4 represents zones of exceptionally high permeability crucial for overall reservoir productivity, the predictive model derived from such sparse data should be used with caution. The FZI method, in general, remains a powerful tool for segmenting complex reservoirs into manageable, hydraulically similar units, which is essential for accurate reservoir modelling and optimizing fluid flow predictions.

4. Conclusion

This comprehensive investigation into the intricate relationship between porosity and permeability, rigorously approached through the lens of the Flow Zone Indicator (FZI) concept, profoundly underscores its utility in deciphering reservoir heterogeneity. By systematically categorizing core data into five distinct hydraulic flow units (FZI 0 through FZI 4), we have unequivocally demonstrated that each unit embodies a unique and characteristic exponential relationship between porosity and permeability. This confirms the efficacy of FZI in segregating reservoir rocks into truly hydraulically homogeneous domains, where the nuanced interplay of pore architecture dictates flow efficiency with remarkable specificity for each group.

Our analysis revealed a clear progression in reservoir quality across the FZI spectrum. FZI 0 consistently represented the lowest-quality reservoir rock, characterized by lower porosity and permeability values, yet exhibited an exceptionally high model reliability (R2=0.9479), indicating a highly uniform pore system. As we advanced through FZI 1, FZI 2, and FZI 3, we observed a progressive enhancement in reservoir quality, marked by increasing permeability values and robust, albeit varying, model correlations (R2 values ranging from 0.7898 to 0.8444). This systematic evolution in flow characteristics strongly suggests a corresponding transition towards larger and more interconnected pore throat networks. FZI 4, representing the pinnacle of reservoir quality with exceptionally high permeabilities, also followed this exponential trend. However, its lower model reliability (R2=0.5234) served as a critical reminder that while a correlation may exist, the statistical robustness of predictive models is inherently tied to the quantity and representativeness of available core data.

In essence, this study provides compelling empirical evidence that the Flow Zone Indicator method transcends conventional bulk-rock property correlations. It offers an indispensable framework for understanding and quantitatively characterizing the continuum of reservoir quality, moving beyond simplistic classifications to capture the complex geological controls on fluid flow. By accurately delineating these unique hydraulic flow units, petrophysicists and reservoir engineers can develop more precise permeability models, significantly improve the accuracy of fluid flow simulations, and ultimately optimize reservoir management strategies for sustainable hydrocarbon recovery. The insights gleaned herein underscore the imperative of FZI-based characterization in unlocking the full potential of heterogeneous reservoirs, particularly in an era demanding ever-increasing efficiency and predictive power in subsurface modelling.

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دقة النفاذية: تحديد عدم تجانس المكامن باستخدام مؤشرات مناطق التدفق

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يُعد التنبؤ الدقيق بالنفاذية في المكامن غير المتجانسة أمرًا بالغ الأهمية للإدارة الفعالة لموارد باطن الأرض. تطبق هذه الدراسة مفهوم مؤشر منطقة التدفق (FZI) لتحديد وحدات التدفق الهيدروليكية المميزة وإنشاء علاقات فريدة بين المسامية والنفاذية ضمن أنظمة المكامن المعقدة. تم تصنيف بيانات اللب إلى خمس مجموعات متميزة من(4-0) FZI ، حيث أظهرت كل مجموعة علاقة أسية مميزة بين المسامية والنفاذية. أظهرت مجموعة0 FZI ، التي تمثل أدنى جودة للمكمن، ارتباطًا قويًا للغاية(R2=0.9479) ، مما يشير إلى نظام مسامي عالي التجانس. حافظت الوحدات ذات الجودة الأعلى (FZI 1-3) على ارتباطات أسية قوية (تتراوح R2 من 0.7898 إلى 0.8444)، مما يعكس تحسينًا في توصيلية المسام. ومع ذلك، أظهرت مجموعة4 FZI ، على الرغم من امتلاكها أعلى قيم نفاذية، موثوقية أقل للنموذج (R2=0.5234)، مما يسلط الضوء على تأثير محدودية البيانات على المتانة الإحصائية. يوضح هذا الدليل التجريبي أن طريقة FZI توفر إطارًا لا غنى عنه للتوصيف الكمي لجودة المكمن، متجاوزة الارتباطات التقليدية للخصائص الكلية. تعمل منهجية FZI على تجزئة عدم تجانس المكمن بفعالية، مما يتيح نمذجة نفاذية أكثر دقة، ومحاكاة محسّنة لتدفق السوائل، وإدارة مُثلى للمكامن لتحقيق استدامة استخلاص الموارد.