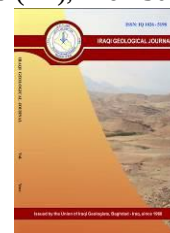




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Reducing Dependency on Core Data for Permeability Estimation Using Well Log-Derived Electrofacies and Flow Zone Indicators (FZI) in the Mishrif Formation, Nasiriyah Oil Field, South of Iraq

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Abstract

Accurate estimation of permeability is essential for reliable reservoir characterization and simulation. However, core data are often limited due to their high cost and operational constraints, leading to significant uncertainty in uncored intervals. This study aims to reduce the dependence on core data for permeability estimation by integrating electrofacies derived from well logs and flow zone indicator analysis in the Mishrif Formation, Nasiriyah oil field. Electrofacies were generated using dynamic clustering based on the log data from 13 wells. This led to the identification of five electrofacies units that represent intervals with similar log responses, formed by merging 75 electrofacies, where flow zone indicators analysis identified hydraulic flow units based on the porosity and permeability data from cored wells. The resulting model was applied to uncored wells to predict the permeability along the reservoir. The predicted permeability showed high coincidence with measured core data, with a coefficient of determination ($R^2=0.85168$), demonstrating that the integrated electrofacies-Flow Zone Indicators approach provides a reliable and cost-effective method for characterizing heterogeneous carbonate reservoirs and supporting improved reservoir modelling and field development planning.

Keywords: Electrofacies; Permeability estimation; Flow zone indicator (FZI); Mishrif Formation

1. Introduction

To construct a reliable geological model or to perform development and production forecasting scenarios, an accurate characterization of reservoir petrophysical properties is essential. These properties primarily include porosity and permeability, and water saturation, which directly control fluid storage and flow behavior within the reservoir (Selley, 1998). The permeability describes the ability of rock to transmit fluids (Ezekwe, 2011). The petrophysical properties of porosity, permeability, and water saturation play a crucial role in reservoir evaluation and dynamic simulation, and field development planning. The permeability is one of the important properties that affect the flow of fluid in a porous medium (Vianna et al., 2020). The permeability is determined through well testing, or core, well log, and the estimated permeability from the core is considered the most accurate measurement. However, core acquisition and analysis are costly, which limits the availability of core data (Shen et al., 2017). The cores are taken from different depths and wells, and they do not cover all the depths of the

wells. To obtain a relationship representing the values obtained from the cores, a hydraulic flow unit (HUF) is used.

An HFU is defined as a portion of the reservoir characterized by hydraulic properties or similar attributes that differ from other parts of the reservoir, where these properties control the fluid flow behaviour (Amaefule et al., 1993; Chu et al., 2023). To identify the similar parts in the reservoir, the flow zone indicator is used, which depends on the reservoir quality index (RQI) and the porosity ratio (Amaefule et al., 1993). To assess the behaviour of the reservoir, it is essential to understand these characteristics (Adnan and Abed, 2014). The HFU is determined based on the available core data, and its accuracy increases as more core data are available. The core data are expensive, and for estimating the permeability across all parts of the reservoir, a less costly method is used by employing electrofacies with HFU to distribute the permeability based on core data and the responses of similar well logs.

The Electrofacies (EF) is defined as a cluster of similar responses to well logs toward specific reservoir properties (Abbaszadeh et al., 1996; Lee and Datta-Gupta, 1999; Li et al., 2014). Deriving the permeability through logs is the most cost-effective method when combined with cores (Rafik and Kamel, 2017). Well logs such as GR, DT, NPHI, RHOB, and other logs are used for the purpose of dividing the reservoir into sections with similar responses, thereby generalizing the HFU equations to wells with and without cores. Many studies have been conducted to estimate the permeability through HFUs and EF. For example, Bhatti et al. (2020) used HFUs with EF to estimate permeability in an oil field in Pakistan with limited core data (Kadkhodaie-Ilkhchi et al., 2013). The porosity and permeability data were used to predict the reservoir's electrofacies using a two-sided clustering approach, sedimentary and petrophysical. Previous studies in the Nasiriyah oil field were mainly limited to cored wells for the permeability estimation, while uncored wells were not sufficiently characterized due to the lack of core data, highlighting the need for alternative approaches such as electrofacies and HFU integration to improve permeability prediction in data-limited wells.

The Mishrif Formation in the south of Iraq is characterized by a high degree of heterogeneity (Deng et al., 2018; Zhong et al., 2018; Ismail et al., 2021), and depositional facies vary significantly both vertically with depth and horizontally across the reservoir (Zhang et al., 2023).

This study aims to integrate well log-derived electrofacies with analysis of the flow zone indicator for the permeability prediction in a heterogeneous carbonate reservoir, in order to minimize dependence on costly core data and enable a reliable permeability estimation across both cored and uncored intervals in the Mishrif Formation.

2. Location of the Study Area and Geological Overview

The Nasiriyah oil field in south of Iraq is located within Dhi Qar Governorate, approximately 38 km northwest of Nasiriyah city (Khorshid and Hlelai, 2016) (Fig.1). The Nasiriyah oil field is located within the Mesopotamian Zone of the Outer Platform in the south of Iraq and is structurally characterized by gentle subsurface anticlines trending NW-SE. The Mishrif Formation is a part of the formations of the Late-Cenomanian to Early Turonian age belongs to the AP8 Megasequence (Jassim and Goff, 2006). In the southern part of Iraq, the Mishrif Formation exhibits a thickness that ranges between 150 and 200 m, gradually increasing towards the Iraqi-Iranian borders, where it can exceed 350 m. The Mishrif Formation accounts for approximately 30% of Iraq's total proven oil reserves (Abdula, 2020). The formation was deposited during the Cenomanian-Early Turonian period in a shallow carbonate marine environment ranging from open shelf to fore-reef and inner shelf settings (Aqrabi et al., 2010), and it mainly consists of heterogeneous fossiliferous limestone (Olhoeft, 2000). The reservoir is subdivided into several units, including CI, CII, MA, Shale, MB1, and MB2, where MB1 represents the main productive reservoir unit.

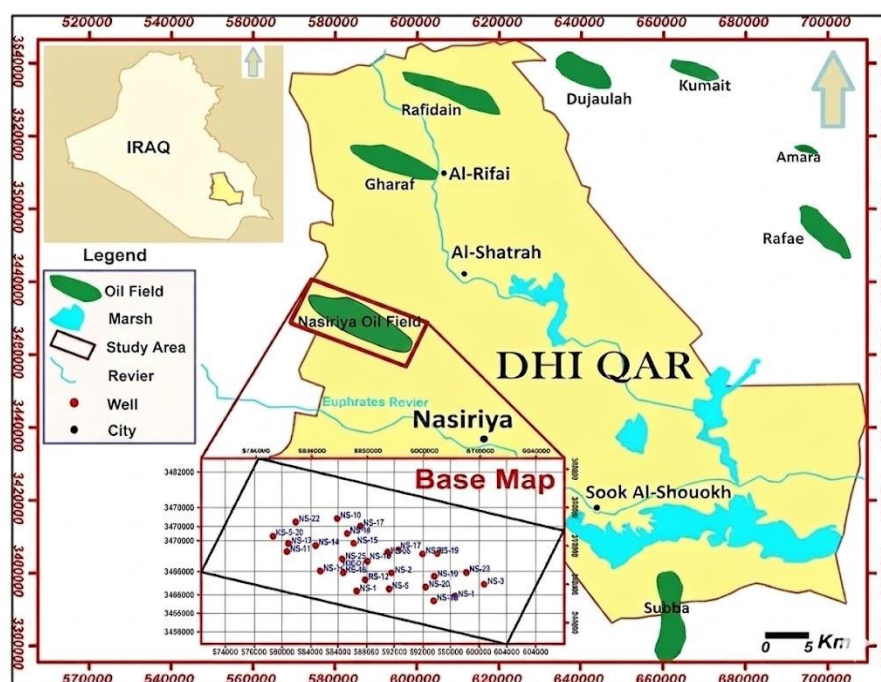


Fig. 1. Location of the study area

3. Materials and Methods

In this study, an integrated dataset comprising core measurements and well log data was utilized to characterize the reservoir's petrophysical properties and to develop a reliable permeability prediction model for the Mishrif Formation in Nasiriyah oilfield. The core permeability data are available for seven wells, namely NS-3, NS-4, NS-5, NS-7, NS-18, NS-17, and NS-20 and were used as reference data to compare and validate the electrofacies results. Several wells within the study area lack core measurements, including NS-6, NS-15, NS-16, NS-21, NS-23, and NS-25. For these wells, all reported well depths are measured depth (MD), and the permeability was estimated exclusively from the core-based relationships established from the cored wells. Detailed information regarding well status, core depth intervals, and data availability is summarized in Table 1.

Table 1. Summary of available well logs and core data

Well No.	Log Status	Core Status	Core Depth Intervals (m)
NS-3	Available	Available	2009-2074.36
NS-4	Available	Available	2006-2098
NS-5	Available	Available	1999-2082
NS-6	Available	N/A	N/A
NS-7	Available	Available	1995-2035
NS-15	Available	N/A	N/A
NS-16	Available	N/A	N/A
NS-17	Available	Available	1999-2047.5
NS-18	Available	Available	1994.7-2049.6
NS-20	Available	Available	1998.8-2028.4
NS-21	Available	N/A	N/A
NS-23	Available	N/A	N/A
NS-25	Available	N/A	N/A

The well logs selected for electrofacies classification include Gamma Ray (GR), Neutron porosity (NPHI), and Bulk Density (RHOB) logs. These logs were chosen due to their consistent availability and stable responses across all studied wells. Other log types were excluded from the analysis because they exhibited significant noise levels and data gaps or measurement inconsistencies, which could adversely affect the reliability of electrofacies classification. In this study, thirteen wells from the Mishrif Formation in the Nasiriya Oil-field in the Southern part of Iraq were selected, as shown in Fig. 2.

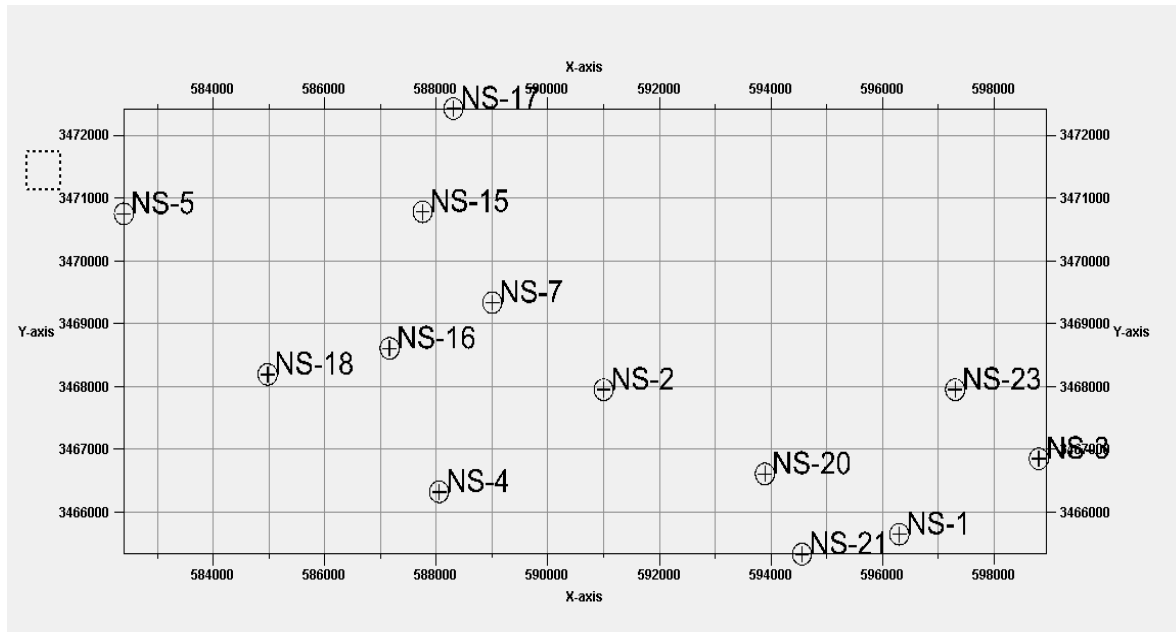


Fig. 2. Location of the studied wells in the Nasiriya oil field

3.1. Flow Zone Indicator Method (FZI)

Rock features are considered a key foundation for constructing reservoir simulation blocks, as they enable the identification and analysis of hydraulic flow units by aggregating multiple layers with similar flow behavior within homogeneous units. This approach relies on using the flow zone indicator to divide the data by utilizing the modified Kozeny-Carman equation and the concept of hydraulic radius, which allows the clustering of core data according to rock types and achieves a high-quality correlation between porosity and permeability. Accordingly, the different intervals are grouped by the reservoir quality index (RQI) and the FZI into hydraulic flow units by using equations (1-3) (Amaefule et al., 1993; Abbaszadeh et al., 1996), and the reservoir quality is evaluated.

$$RQI = 0.0314 \sqrt{\frac{K}{\Phi_e}} \quad (1)$$

$$\Phi_z = \frac{\Phi_e}{1 - \Phi_e} \quad (2)$$

By substituting RQI and Φ_z with FZI can be simplified as:

$$FZI = \frac{RQI}{\Phi_z} \quad (3)$$

The RQI is the reservoir quality index in μm , and k is the core permeability in md, Φ_z is the normalized porosity (fraction), Φ_e (PHIZ) is the core porosity (fraction), and FZI is the flow zone index in μm . On a log-log plot of RQI versus PHIZ, samples with similar FZI tend to align on a straight line with unit slope, while samples with FZI values that differ from others cluster on parallel straight

lines with the same slope. This arrangement indicates that rocks with similar or close FZI values form a homogeneous flow unit.

3.2. Electrofacies

In this study, the Dynamic Clustering technique was applied using Geolog 2011 to classify Electrofacies based on the integrated response of well logs and petrophysical properties. The dataset included thirteen wells distributed across the study area to ensure adequate representation of key reservoir heterogeneities within the Mishrif Formation. The analysis utilized Gamma Ray (GR), Neutron Porosity (NPHI), and Density (RHOB) logs, along with effective porosity for each well, as the basis for the clustering process. Additionally, the FZI values derived from the core measurements were incorporated to support the correlation between electrofacies and the hydraulic properties of the rock, as shown in the histogram (Fig. 3). The dynamic clustering procedure was implemented by incrementally increasing the number of electrofacies, with continuous evaluation of the stability and distinguishability of each cluster based on log responses and hydraulic characteristics. This process continued until an optimal number of 75 electrofacies was reached, providing the best distinction of lithological and hydraulic heterogeneities, as shown in Table 2. This number was subsequently adopted as the basis for permeability analysis and the correlation of electrofacies in wells lacking core data. The FZI values in Table 2 represent derived values calculated from the core porosity and permeability data.

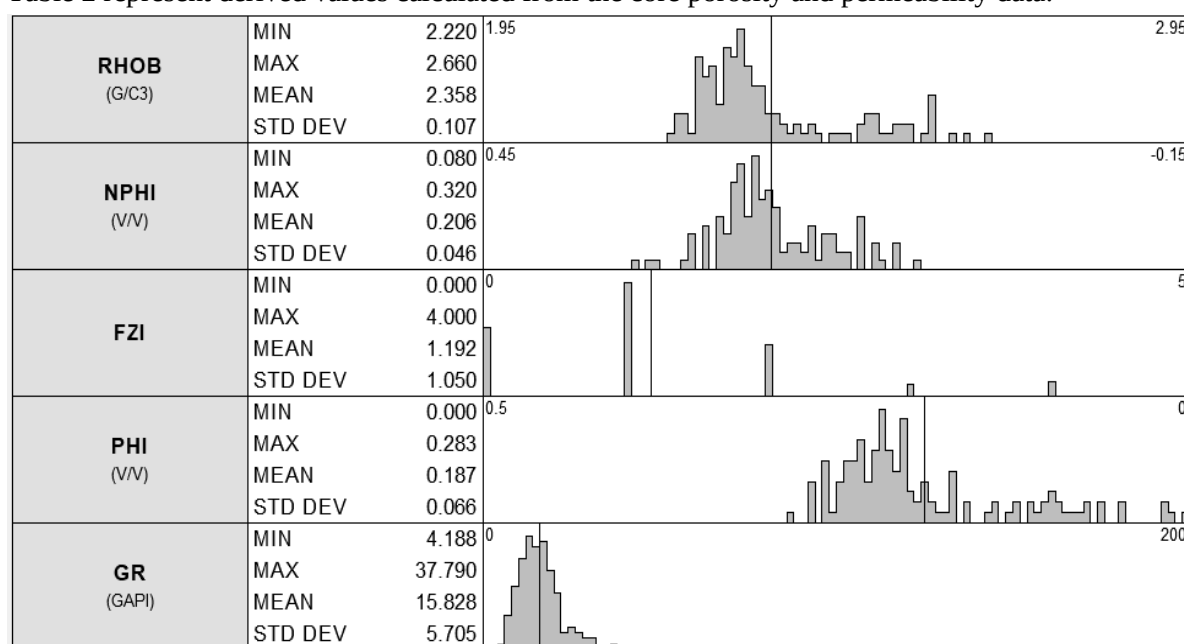


Fig. 3. Histograms of logs' models

4. Results and discussion

4.1. FZI Analysis

The Mishrif Formation was classified into five hydraulic flow units based on the core data from seven wells. Fig. 4 presents the identified hydraulic flow units. The relationships between the core permeability and porosity for each unit are shown in Fig. 5, with the concerned equations obtained from the analysis in Table 3. Fig. 6 illustrates the comparison between the core-measured permeability and the permeability calculated through processing of the hydraulic flow unit, demonstrating a strong correlation with an R^2 value of 0.97. Weak HFU values are mainly due to high reservoir heterogeneity, poor pore connectivity, and diagenetic effects that weaken the porosity–permeability relationship.

Table 2. Electrofacies properties from cluster analysis before merging facies

EFA	WEIGHT	RHOB (g/cm ³)	NPHI (v/v)	FZI (μm)	PHI (v/v)	GR (API)
1	1	2.36	0.22	0	0.18	18.54
2	2	2.26	0.2	1.5	0.24	9.74
3	2	2.23	0.24	1.5	0.27	8.06
4	1	2.31	0.21	1	0.22	6.9
5	1	2.26	0.27	4	0.26	12.54
6	3	2.63	0.1	0.33	0.01	30.23
7	2	2.31	0.23	1	0.19	23.35
8	3	2.29	0.2	3	0.23	10.36
9	1	2.51	0.13	1	0.1	16.2
10	1	2.25	0.19	1	0.2	21.04
11	1	2.3	0.27	1	0.23	17.09
12	1	2.38	0.18	0	0.19	4.19
13	2	2.32	0.24	0.5	0.22	15.37
14	2	2.31	0.22	1	0.21	16.71
15	2	2.3	0.21	0.5	0.22	12.71
16	2	2.27	0.21	3.5	0.24	10.19
17	1	2.36	0.26	0	0.21	16.7
18	1	2.27	0.27	1	0.25	14.04
19	3	2.28	0.31	1.67	0.27	13.83
20	1	2.42	0.2	0	0.17	15.72
21	2	2.26	0.25	2	0.26	6.44
22	1	2.35	0.2	4	0.2	10.97
23	1	2.34	0.19	2	0.2	10.47
24	2	2.3	0.22	1	0.23	10.57
25	1	2.59	0.08	1	0.02	28.03
26	2	2.3	0.26	2	0.23	14.88
27	1	2.34	0.21	1	0.17	20.62
28	1	2.46	0.15	0	0.14	13.91
29	4	2.32	0.22	0.75	0.22	11.16
30	1	2.52	0.14	0	0.07	26.07
31	1	2.56	0.13	1	0.08	17.84
32	2	2.35	0.19	1.5	0.19	14.69
33	2	2.31	0.23	1	0.22	13.91
34	2	2.29	0.25	1	0.23	15.22
35	2	2.24	0.23	2.5	0.26	7.6
36	2	2.45	0.16	0	0.12	19.14
37	6	2.32	0.24	0.33	0.2	18.71
38	1	2.32	0.17	1	0.19	16.35
39	3	2.41	0.17	1.67	0.16	14.04
40	4	2.35	0.22	0	0.2	13.55
41	2	2.4	0.16	1.5	0.14	18.24
42	2	2.37	0.18	1	0.17	15.48
43	1	2.34	0.21	1	0.19	17.28
44	2	2.56	0.18	0.5	0.1	18.26
45	1	2.31	0.2	2	0.21	12.78
46	2	2.28	0.23	2	0.24	11.95
47	2	2.22	0.25	1	0.24	19.23
48	1	2.29	0.23	2	0.24	7.37
49	1	2.59	0.1	1	0	37.79
50	1	2.28	0.26	1	0.24	13.71
51	1	2.27	0.25	0	0.23	17.14
52	1	2.33	0.23	0	0.17	27.28
53	3	2.28	0.23	0.67	0.22	18.02
54	3	2.32	0.21	2	0.22	10.93
55	1	2.34	0.24	4	0.21	14.1
56	1	2.25	0.21	4	0.25	9.83
57	1	2.49	0.16	3	0.11	19.41
58	2	2.3	0.21	2	0.22	12.99
59	3	2.51	0.16	1	0.1	20.08
60	2	2.26	0.22	2	0.25	9.55
61	2	2.6	0.12	0	0.05	24.5
62	1	2.26	0.28	1	0.23	23.4
63	4	2.56	0.12	0.25	0.07	21.39
64	1	2.51	0.13	0	0.09	19.31
65	1	2.3	0.24	3	0.24	11.39
66	1	2.49	0.22	1	0.12	25.13
67	3	2.26	0.22	1	0.24	13.22
68	1	2.48	0.15	1	0.1	22.29
69	1	2.36	0.16	2	0.17	16.75
70	2	2.33	0.26	1	0.22	17.6
71	1	2.55	0.15	0	0.09	19.35
72	1	2.48	0.15	0	0.09	26.6
73	1	2.23	0.26	1	0.27	12.44
74	2	2.36	0.2	1	0.2	8.74
75	1	2.3	0.22	4	0.21	18.11

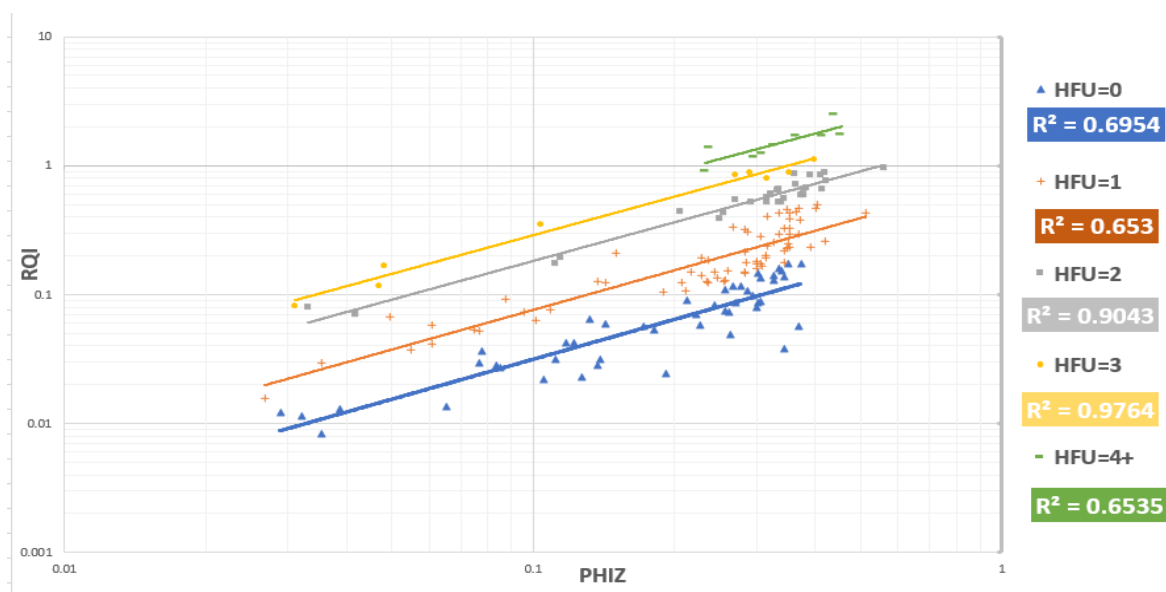


Fig. 4. RQI-PHIZ plot and flow zone indicator for the Mishrif Formation

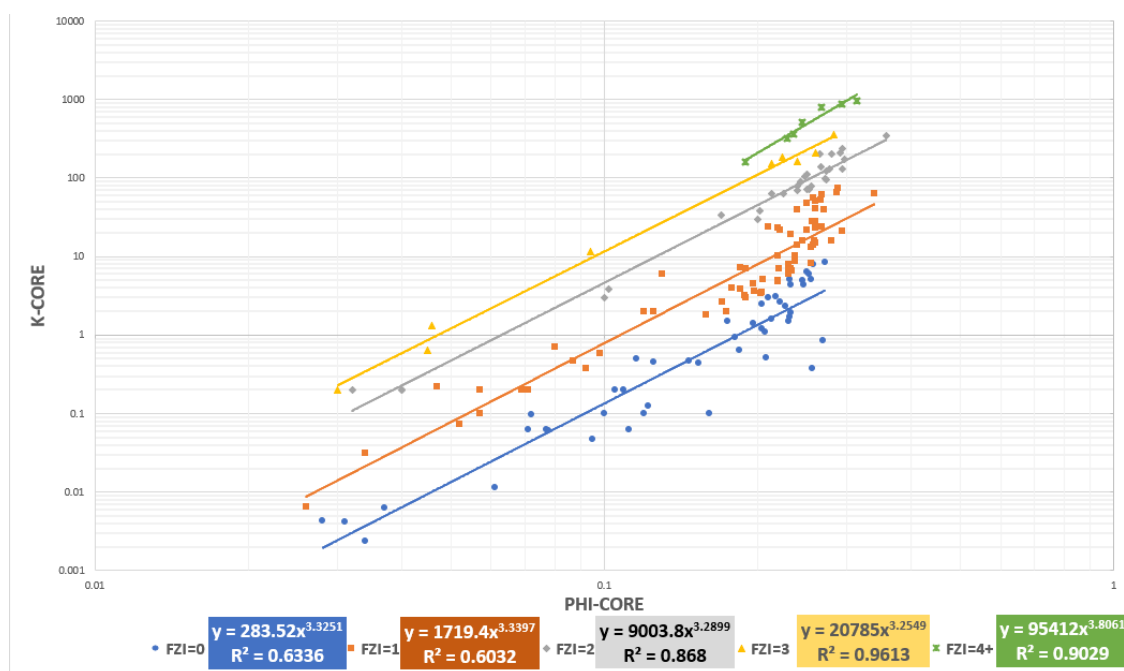


Fig. 5. K-core VS PHI-core on log-log scale for the Mishrif Formation

Table 3. FZI Permeability formula for the Mishrif Formation

HFU	Permeability Formula	R ²
0	$K=283.52\Phi^{3.3251}$	0.6336
1	$K=1719.4\Phi^{3.3397}$	0.6032
2	$K=9003.8\Phi^{3.2899}$	0.868
3	$K=20785\Phi^{3.2549}$	0.9613
4	$K=95412\Phi^{3.8061}$	0.9029

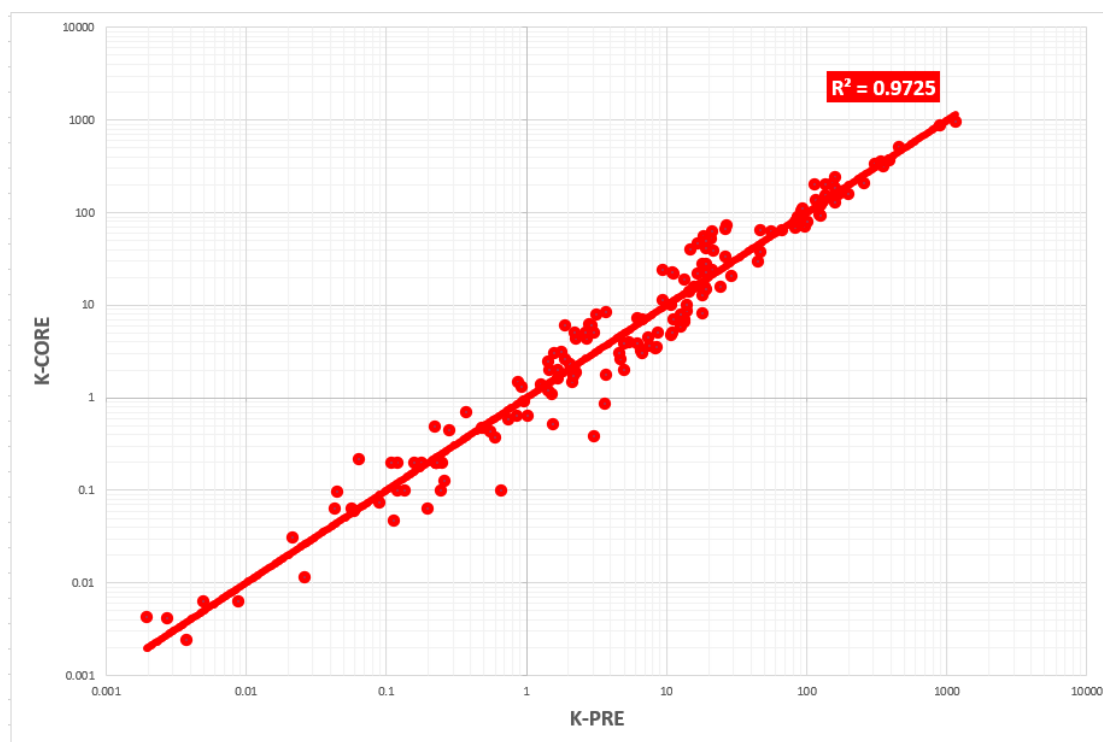


Fig. 6. K-core vs K-predicted for the Mishrif Formation

4.2. Electrofacies Analysis

Many attempts were made to represent the appropriate number of facies until the number of attempts was reached to 75. When 75 facies were used, all FZI values appeared, which gave the best results. After merging similar facies, the total number of facies was reduced to five, coinciding with the number of the permeability-to-porosity relationships, based on similarities in log response, in addition to FZI behaviour, to accurately represent the reservoir (Fig. 7). The electrofacies for the Mishrif Formation was detected using the Geolog software (Figs. 8 and 9). The FZI was linked with the electrofacies to accurately represent the permeability.

NAME	COL	PAT	WEIGHT	RHOB	NPHI	FZI	PHI	GR
FACIES_1			32					
FACIES_2			53					
FACIES_3			31					
FACIES_4			7					
FACIES_5			7					

	NAME	COL	PAT	WEIGHT	FZI	MINIMUM	MAXIMUM	MEAN	STD DEV
1	FACIES_1			32		0.00	1.00	0.13	0.34
2	FACIES_2			53		0.00	2.00	0.91	0.35
3	FACIES_3			31		1.00	3.00	1.81	0.48
4	FACIES_4			7		2.00	4.00	2.86	0.69
5	FACIES_5			7		3.00	4.00	3.86	0.38

Fig. 7. Electrofacies properties after merging facies

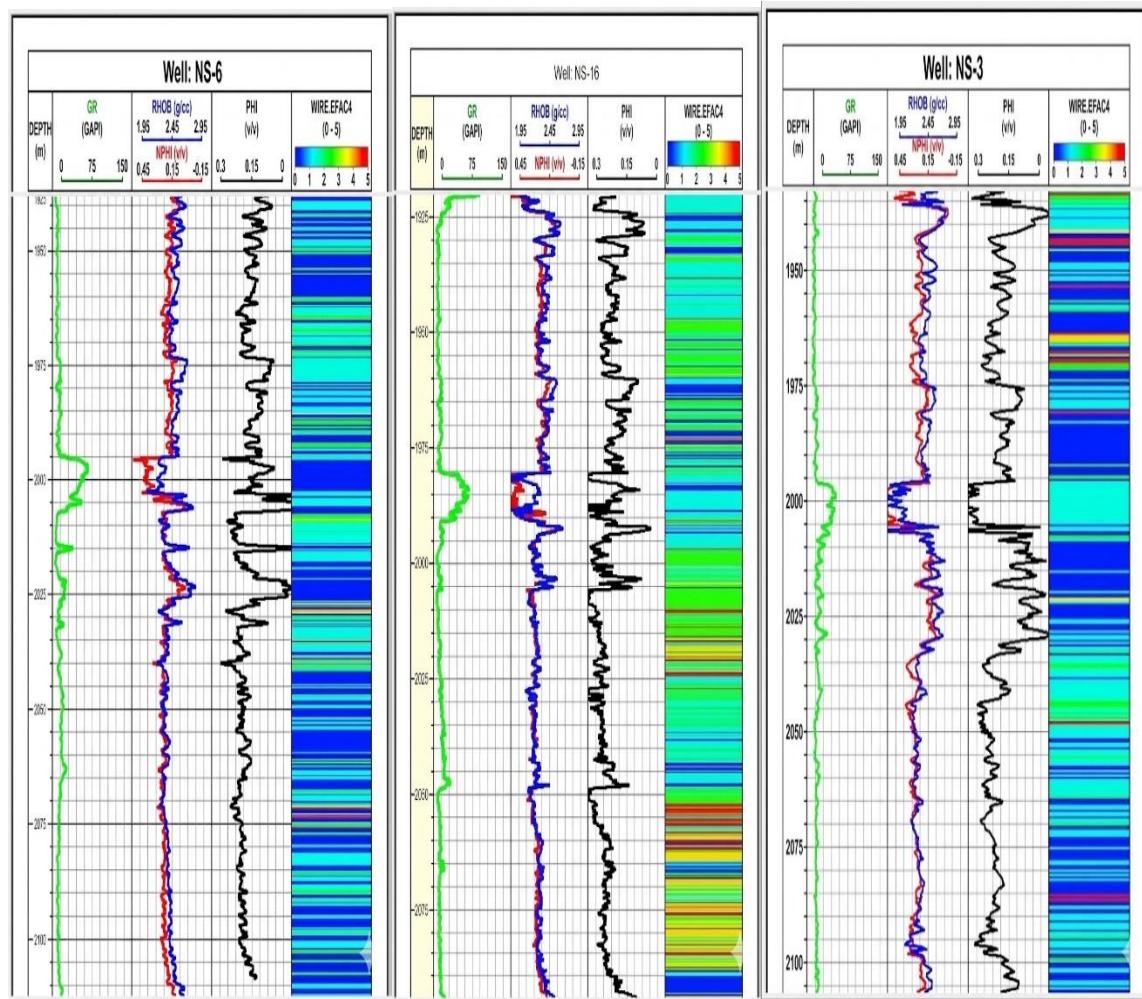


Fig. 8. Electrofacies distribution in wells NS-6, NS-3, and NS-16

4.3. Permeability Estimation

The main objective of this study is to determine the permeability of wells with and without cores in the Nasiriyah oil field, the Mishrif Formation, based on the divisions of hydraulic flow units and electrofacies. The permeability was estimated across all depths and all wells, whether with or without cores, by applying the equations in Table 4. After merging the facies and obtaining the optimal number, each facies was assigned to its corresponding permeability equation derived from HFU, as shown in Table 4. The distribution of equations was based on the relevance of each facies, with facies exhibiting superior hydraulic properties being assigned to the most relevant equations, ensuring accurate and reliable representation of the permeability throughout the heterogeneous carbonate reservoir. A high coincidence was observed between the core-measured permeability and the estimated permeability, using the electrofacies distribution. For wells containing cores, the correlation coefficient (R^2) between the measured and calculated permeability reaches 0.85168 (Fig. 10), reflecting the robustness of the methodology. Moreover, the estimated permeability for all wells shows a good coincidence with the core-measured permeability (Fig. 11). This coincidence confirms the reliability of the approach in generalising the hydraulic relationships across all depths and wells, which lack core data, highlighting the effectiveness of integrating HFU with electrofacies analysis in accurately representing the reservoir's hydraulic properties.

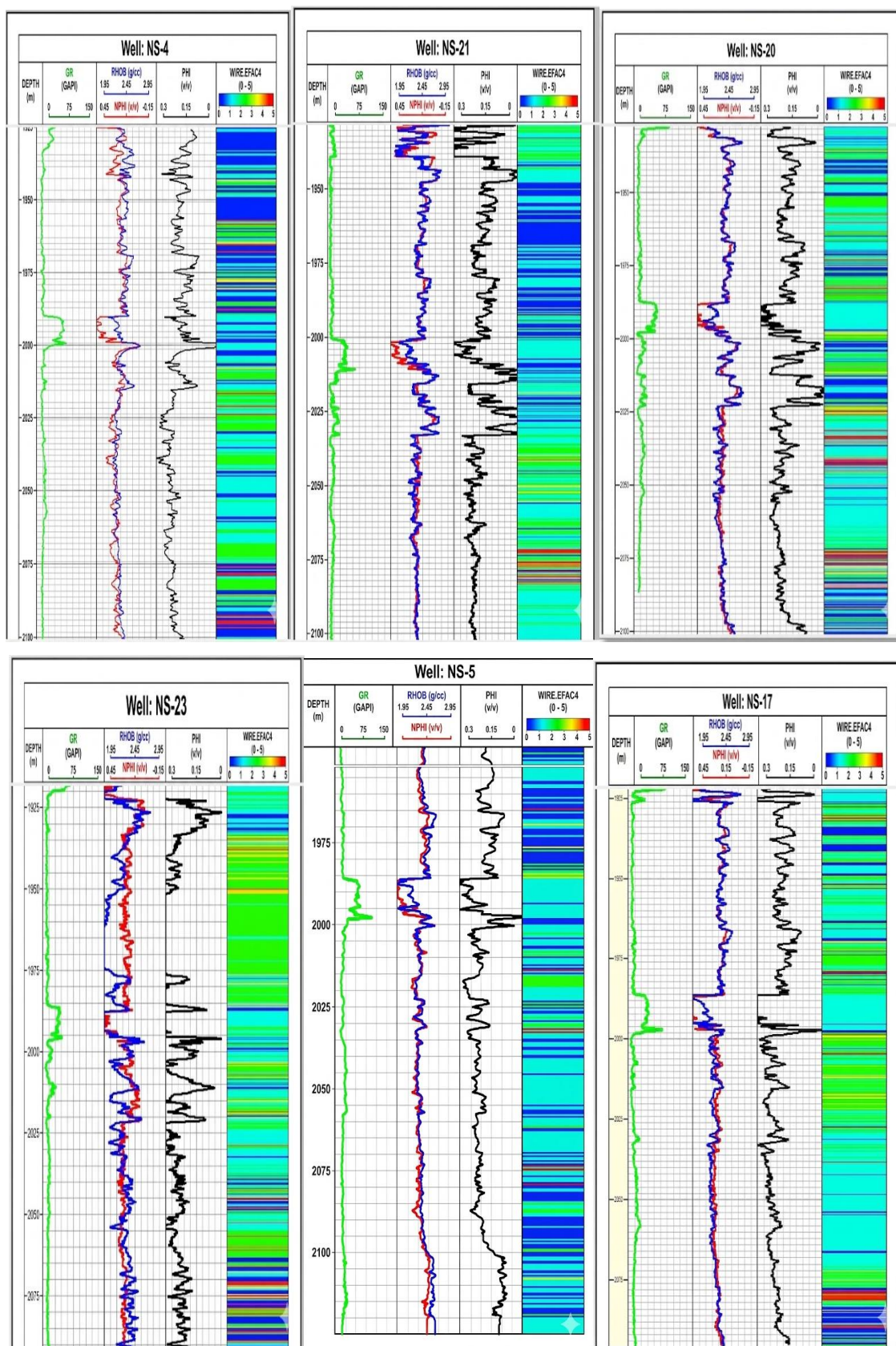
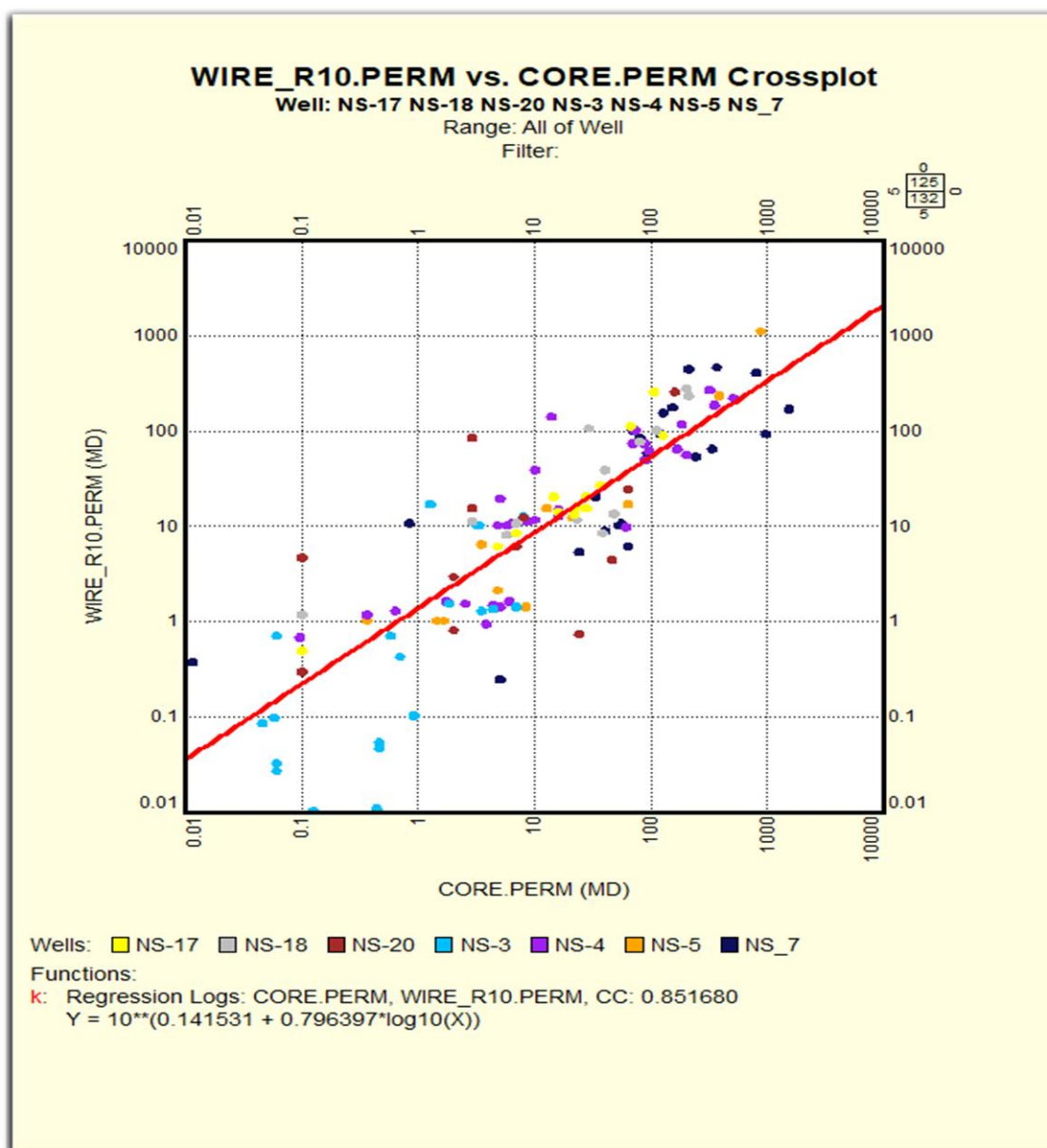


Fig. 9. Electrofacies distribution in wells NS-4, NS-5, NS-23, NS-20, NS-21, and NS-17

Table 4. Permeability equations for each facies

HFU	Facies	Permeability Formula
0	Facies_1	$K=283.52\Phi^{3.3251}$
1	Facies_2	$K=1719.4\Phi^{3.3397}$
2	Facies_3	$K=9003.8\Phi^{3.2899}$
3	Facies_4	$K=20785\Phi^{3.2549}$
4	Facies_5	$K=95412\Phi^{3.8061}$

**Fig.10.** Crossplot between k-core vs k-estimation from FZI and electrofacies

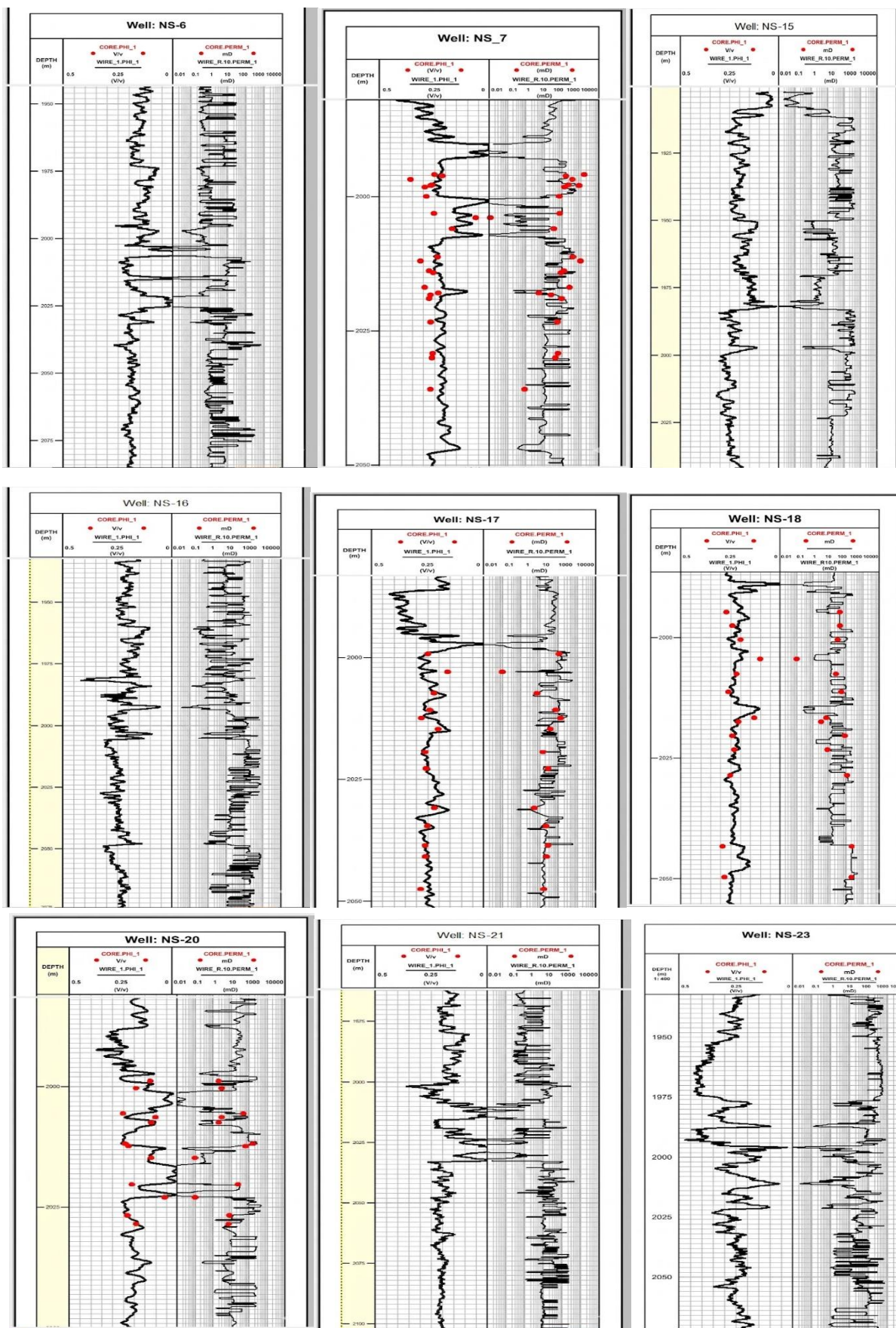


Fig. 11. Derived permeability profile using FZI and Electrofacies

5. Conclusions

- This study integrates Hydraulic Flow Units (HFU) derived from core data with well log-based electrofacies to improve the permeability estimation in the heterogeneous Mishrif Formation, Nasiriyah oil field. The FZI method was successfully used to define five hydraulic flow units, showing a good relationship between the Reservoir Quality Index (RQI) and normalized porosity, along with a strong correlation with the core permeability ($R^2 = 0.97$).
- The electrofacies classification based on GR, NPHI, and RHOB logs resulted in 75 initial facies, which were merged into five representative units consistent with the identified hydraulic flow units. This provided a practical way to relate log responses to core-based petrophysical behaviour across the studied wells. The integrated HFU-Electrofacies approach was applied to estimate the permeability in both cored and uncored intervals. The comparison between the measured and predicted permeability in the cored well shows reasonable coincidence ($R^2=0.85$), indicating that the applicability of the method for permeability prediction in the studied formation.
- Overall, the results suggest that combining HFU analysis with electrofacies classification can support permeability estimation in intervals with limited core data, while maintaining consistency with core-derived trends. This approach can be useful for reservoir characterization in heterogeneous carbonate formations such as the Mishrif Formation.

Author contributions

Ali Saeed Al-Khaqani: Conceptualization, Data curation, Methodology, Formal analysis, software, Investigation, Writing – original draft

Dahlia A. Al-Obaidi: Supervision, Writing – review and editing

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this study.

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Data Availability

The data that support the findings of this study are not publicly available due to confidentiality, legal, or commercial restrictions.

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