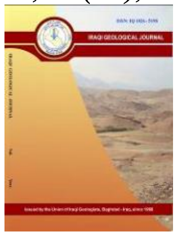
Iraqi Geological Journal

Journal homepage: https://www.igj-iraq.org



Permeability Estimation in a Heterogeneous Carbonate Field in Middle East Region Using Facies and Core-Log Integration

Nuhad A. Al-Kanaani[1,*], Mowafaq F. Al-Shahwan[1] and Mohammed S. Al Jawad[2]

[1] Department of Geology, College of Science, University of Basrah, Basrah, Iraq
[2] Department of Petroleum Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
* **Correspondence**: nuhadalnasser@gmail.com

Received: 16 July 2024

Accepted: 6 November 2024

Published: 31 January 2025

Abstract

Permeability is a crucial parameter in Mishrif reservoir characterization, management, and performance forecasting. Direct measurement methods, such as routine core analysis and well testing, are costly, necessitating the generation of correlations to estimate permeability in uncored wells. This study focuses on wells Rt 2 and Rt 5, analyzing over 200 core samples through thin section analysis. The petrographic scrutiny identified four primary and ten secondary facies in the Mishrif Formation, deposited in environments ranging from shallow marine to lacustrine settings. Diagenetic processes influencing rock properties were also confirmed. The study's novelty lies in identifying good reservoirs, understanding their extensions, and correlating facies with petrophysical and reservoir properties, aiding in the prediction of suitable drilling locations. An exponential equation models the data, with the R-squared value assessing the fit quality between core permeability and porosity, enhancing the understanding of the fluid flow properties and behavior of the formation. The Flow Zone Indicator method, revealing hydraulic units within the Mishrif Formation, achieves regression coefficients between 0.755 and 0.816. The FZI method provides the best regression for estimating permeability due to reduced heterogeneity from dividing the reservoir into multiple units. Predicting permeability from well measurements typically involves classifying well measurements responses into homogeneous subgroups based on microfacies, electrofacies, and hydraulic flow units. Classification of electrofacies offers a straightforward and inexpensive method, while microfacies and hydraulic flow units identification rely on costlier core data analysis. Porosity-permeability analysis offers valuable insights into the correlation between these two parameters, enhancing our understanding of the fluid flow properties and behavior of the studied formation. Thin section petrography and electrofacies classification were employed in the study to examine the Mishrif Formation. The work enhanced permeability forecasts and reduced the requirement for extensive coring by creating porosity-permeability relationships based on carbonate rock types. This paper demonstrates the approach's power and utility through field applications in the complex carbonate formation of Ratawi Field Unit in the south of Iraq.

Keywords: Hydraulic flow unit; Log response; Carbonate reservoir; Permeability; electrofacies; Mishrif

1. Introduction

Permeability estimation from well measurements has evolved significantly over years. Traditionally, permeability predictions have relied on cross-plotting porosity and permeability from

DOI: 10.46717/igj.58.1A.2ms-2025-1-12

core to define a regression relationship, which is then used to estimate permeability in uncored-wells based on well log porosity (Nelson, 1994). Predicting permeability in complex carbonate reservoirs is challenging due to local variations in reservoir characteristics caused by changes in depositional environments. Additionally, carbonate reservoir often exhibits a porosity and permeability mismatch, where regions of high porosity may have low permeability and vice-versa.

Understanding and characterizing carbonate reservoirs pose unique challenges due to their distinct characteristics and typology, setting them apart from clastic reservoirs. Consequently, alternative methods are essential for their successful discovery, description, and characterization (Burchette, 2012). According to Al-Dujaili et al. (2021b). There are three main layers where oil is trapped. These traps are referred to as mB2, mB1 and mA with the oldest layer being mB2. At the top of mB1 and mA, these layers are capped by rock formations, which stop oil from escaping (Al-Dujaili et al., 2023a). The deposition of the Mishrif Formation took place during the mid-Cretaceous period, aligning it with the Al-Wasi group and more specifically within the late Cenomanian to Early Turonian cycle (Hatif et al., 2020). The Mishrif Formation in the Halfaya field is classified into three primary reservoir units based on well probe responses (Al-Najm et al., 2018).

A consistent set of log replies is what distinguishes the electrofacies, which differentiate a certain rock type from other types. While influenced by geological factors, electrofacies can often be associated with particular lithofacies, though this correspondence is not universally applicable. The observational nature of electrofacies is central to the classification procedure, which involves three major phases: cluster, component, and discriminant analysis (Perez et al., 2003). Phase one is represented by the cluster analysis that looks into the process of classifying the data of the well log, into internal homogeneous and external isolated groups according to the result of measuring the corresponding or non-corresponding between them. The electrofacies can be identified by the resulting clusters through capturing a distinctive specification of the measurements of the well log, that can reflect the lithofacies and minerals in the logged interval (Perez et al., 2003). Using relatively homogeneous subgroups of well load data to estimate permeability and reference points is well recognized. Geological characteristics are what the subgroups are based on, like layering the reservoir or zonation, and the specification of petrological like the types of rock or lithofacies.

The specifications of transport like hydraulic flow units, or the response of log of the well like electorfacies. An effective data classification and powertrain recognition technique is key to the success of permeable ability predictions using data partitioning and correlation. The aim is to assess the effectiveness related to the date classification phases which will be explained later in this paper. Another definition can be used for the electrofacies which is the correspondence log set responses that distinguishes certain types of rock, allowing us to identify it from other types. The geology affects the electrofacies and it sometimes correlates with specific lithofacies, even though it is not a universal correspondence (Dorfman et al., 1990).

This study aims to comprehensively investigate the formation's facies through petrographic analysis of rock samples, elucidating major components, characterizing textural properties, and diagnosing influential diagenetic processes. The research endeavors to monitor both lateral and vertical facies changes, discerning their evolutionary trends over time. Additionally, the study seeks to ascertain the depositional environments of the formation by analyzing variations in facies, providing a holistic understanding of the geological processes shaping the studied area. The new in this paper lies in identifying promising reservoirs, understanding their extensions, determining the direction of facies development, and pinpointing locations where facies reservoir properties are likely to be present. Porosity-permeability analysis offers valuable insights into the correlation between these two parameters, enhancing our understanding of the fluid flow properties and behavior of the studied formation.

2. Materials and Methods

Two wells (Rt 2 and Rt 5) with core coverage of the formation were selected, and relevant data on depths, thicknesses, and petrophysical calculations were obtained from technical and geological reports. Over 200 thin sections were examined using polarized light microscopy, focusing on hydrocarbon-containing rock samples. This analysis aimed to diagnose carbonate rock types, identify diagenetic processes and assess their impact on sedimentary lithofacies and reservoir properties. Thin section studies were crucial for recognizing carbonate lithofacies and understanding depositional environments within the Mishrif Formation. The investigation also evaluated diagenetic processes affecting porosity and permeability. The petrographic description followed Dunham's classification system (Dunham, 1962), known for categorizing framework, non-framework, and mud particles in thin sections. In a heterogeneous reservoir, a single porosity-permeability relationship derived from core samples cannot adequately capture the full variability in rock quality. A common approach to improve permeability estimation includes classification of rocks into several rock types acording to flow properties (Amaefule et al., 1993; Nelson,1994; Davies and Vessel, 1996). For each rock type, a specific porosity-permeability relationship is constructed using core samples from that particular rock type. When computing the final continuous permeability curve, the porosity-permeability relationship corresponding to the rock type at the current depth level is applied. The principle behind this approach is that rocks with similar pore geometry tend to exhibit consistent porosity-permeability relationships and, therefore, similar flow behavior. By identifying the rock type associated with each depth level, the most accurate porosity-permeability relationship for the pore geometry at that depth can be used (Fig.1).

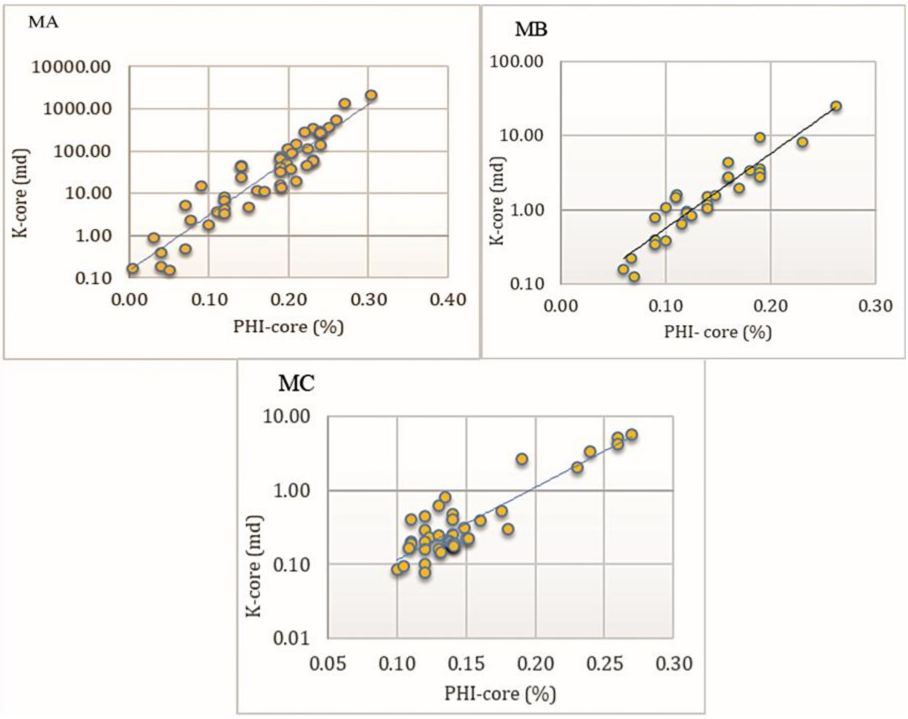


Fig.1. Porosity-permeability cross plots of core samples in MA, MB, and MC zones in Rt 5

In the examined reservoir, four distinct carbonate facies are identified, and their assessment is carried out in correlation with five well log variables: gamma ray, bulk density, neutron porosity, and deep resistivity. This analysis utilized well log data obtained from two wells, namely Rt 2 and Rt 5. A total of 200 sample data points from these two wells, along with their corresponding depths, were employed for characterizing electrofacies groups in the field. The selected well logs for this analysis include deep resistivity, neutron porosity, bulk density, and gamma ray log, all treated as independent variables. To optimize results, the number of independent variables was reduced (Table 1).

Table 1. Porosity-permeability equations obtained from regression on core samples

Zone	permeability equation	R squared
MA	y = 0.1489e30.203x	$R^2 = 0.9193$
MB	y = 0.0551e23.19x	$R^2 = 0.9218$
MC	y = 0.0119e22.57x	$R^2 = 0.9392$

Traditionally, to estimate permeability, a porosity-permeability relationship is first derived through regression analysis using core porosity and permeability data. This established relationship is then applied to porosity logs to estimate continuous permeability.

3. Results and Discussions

3.1. Petrographic Constituents to Microfacies

The groundmass primarily consists of microcrystalline calcite, known as micrite, with crystal diameters not exceeding 4 microns, appearing generally opaque under the microscope. When the crystal diameter exceeds 5 microns, it is called sparite or sparry calcite, which is further categorized into microsparite (5-10 microns) and pseudosparite (exceeding 10 microns) (Dunham, 1962). Limestone particles are divided into skeletal and non-skeletal grains. Skeletal grains include various foraminifera species such as *Praealveolina*, *Nezzazata*, *Textularia*, *Cislalveolina*, *Rotalina, Alveolinidae, Qataria, Cycledomia*, *Pseudotextularia*, *Pseudolituonella*, *Chrysalidina*, *Orbitolina*, and planktonic foraminifera, in addition to miliolids family, providing environmental indications. Non-skeletal grains, present in study wells, include peloids and pellets. Four main microfacies were identified based on grain abundance relative to the rock matrix and further divided into secondary facies, compared to the standard Wilson (1975) microfacies. Lime mudstone microfacies, found mainly at the bottom of well sections and sporadically in the middle and upper parts, represent a calm depositional environment with an organic mud base.

Secondary facies include bioclastic mudstone and unfossiliferous mudstone submicrofacies. Wackestone microfacies is common in the study area, and have secondary facies such as bioclastic wackestone, peloidal wackestone, and oolitic wackestone submicrofacies, each affected by various diagenetic processes. Packstone microfacies is influenced by neomorphism and dolomitization, are divided into bioclastic packstone, oolitic packstone, benthic foraminiferal and peloidal packstone, and planktonic foraminiferal packstone submicrofacies, each corresponding to different depositional environments (Figs. 2 and 3). Finally, dolomitic limestone microfacies, found in the lower part of the second reservoir unit in well Rt 5, are predominantly affected by dolomitization and chemical compaction, with minimal cementation impact (Fig. 4; Tables 2 and 3).

3.2. Diagenetic Processes

Diagenesis, a pivotal geological process, significantly influences hydrocarbon reservoir properties through physical and chemical transformations that alter the original depositional porosity, petrophysical characteristics, and microstructure (Zhang, 2011). Diagenetic microstructure is crucial in permeability modeling, utilizing log measured porosity to estimate permeability and converting a static model into a dynamic flow model. There are two types of diagnostic processes: destructive and constructive processes. The following processes are destructive: dissolution, micritization, and mechanical and chemical compaction. Chemically asymmetric diagenetic processes (dolomitization and the creation of authigenic minerals) and isochemical diagenesis (cementation and neomorphism) are the two categories of constructive processes.

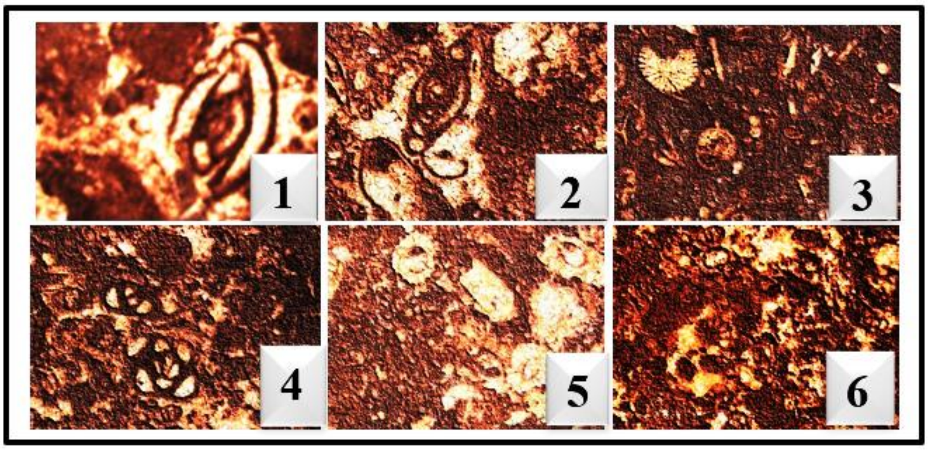


Fig. 2. 1. Benthic Foraminiferal and Peloidal Packstone submicrofacies containing benthic foraminifera and pellet; 2. Packstone microfacies containing benthic fossils of miliolid and granular cement; 3. Bioclastic Packstone submicrofacies containing bioclasts, including coral and Hedbergella (pelagic); 4. Secondary microfacies of Packstone containing benthic fossils and bioclasts; 5. Packstone microfacies containing benthic fossils of Dicyclina and Bryozoa; 6. Benthic Foraminiferal and Peloidal Packstone submicrofacies containing pellets and benthic fossils.

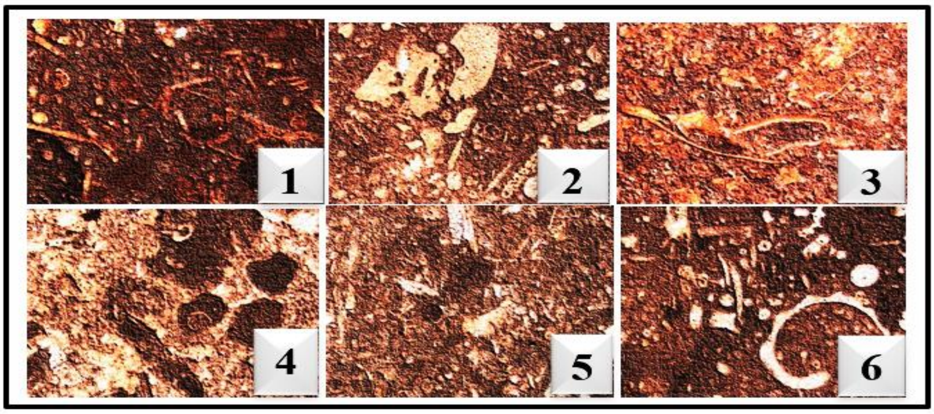


Fig.3. 1. Bioclasts (sponge) in compacted limestone containing fractures with small benthic fossils, peloids and corals; 2. Bioclastic Packstone submicrofacies bearing numerous small and medium-sized fragments of benthic fossils, such as Echinoids and Hedbergella, as well as several Foraminifera; 3. Microfacies of Wackestone bearing algae and numerous fossil fragments; 4. Microfacies of Wackestone bearing Peloids and fossils; 5. Microfacies of bearing small-sized benthic fossil fragments; 6. Bioclastic Wackestone submicrofacies bearing fossil fragments.

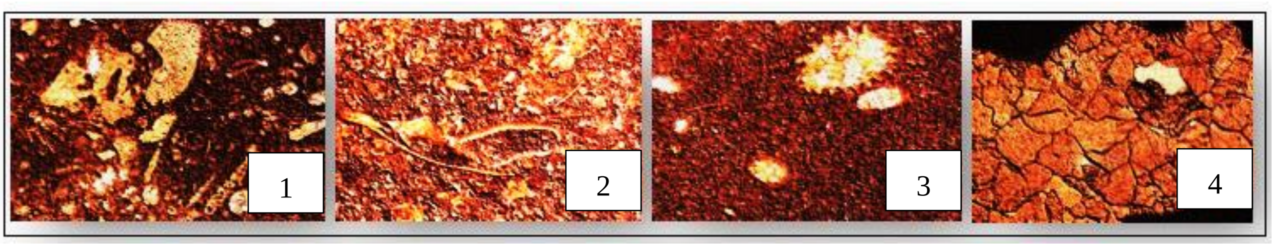


Fig. 4. Types of Microfacies (1. Packstone 2. Wackestone 3. Mudstone 4. Dolomite)

Table 2. Facies classification at ROFU/Rt 2 (depth 2115.36 – 2217.25m)

No.	Depth	Facies
1	2115.36 – 2134	Packstone
2	2134 – 2161.2	Wackestone
3	2161.2 – 2176.37	Mudstone
4	2176.37 – 2188.4	Packstone
5	2188.4 – 2191.80	Dolomite
6	2192 – 2198.75	Packstone
7	2198.75 – 2217.25	Wackestone

Table 3. Facies classification at ROFU/Rt 2 (depth 2176.32 – 2288.32m)

No.	Depth	Facies
1	2214.24 - 2224.20	Packstone
2	2224.20 - 2232.30	Dolomite
3	2232.30 – 2251.50	Packstone
4	2251.50 – 2272.10	Wackestone
5	2272.10 – 2282.15	Packstone

In the Ratawi oil field, the Mishrif Formation shows significant diagenetic processes including both destructive and constructive processes. Destructive processes such as micritization, affecting fossils like benthic fragments, ostracods, shells, and algal fragments, and compaction, which is classified into mechanical compaction (ineffective beyond 300 meters due to limestone's loss of plasticity) and chemical compaction or pressure solution, specifically stylolites, play key roles. Dissolution positively impacts reservoir properties by developing various types of porosity. Constructive diagenesis includes isochemical processes like cementation, with types such as equant granular cement (filling interparticle voids in wackestone and packstone, and drusy mosaic cement (reducing porosity by filling voids). Neomorphism, identified through recrystallization, results in intercrystalline porosity due to the transformation of micrite into fine spar, particularly in mudstone and wackestone. Chemically asymmetric diagenetic processes like dolomitization produce dolomite minerals with varying crystal shapes and sizes, including xenotopic, hypidiotopic, and idiotopic dolomite. The formation of authigenic minerals, such as pyrite, which appears as scattered cubic crystals within the micritic matrix or fills voids in structural particles, negatively affects reservoir properties by reducing porosity, particularly in wackestone with organic fragments (Figs. 5, 6 and 7).

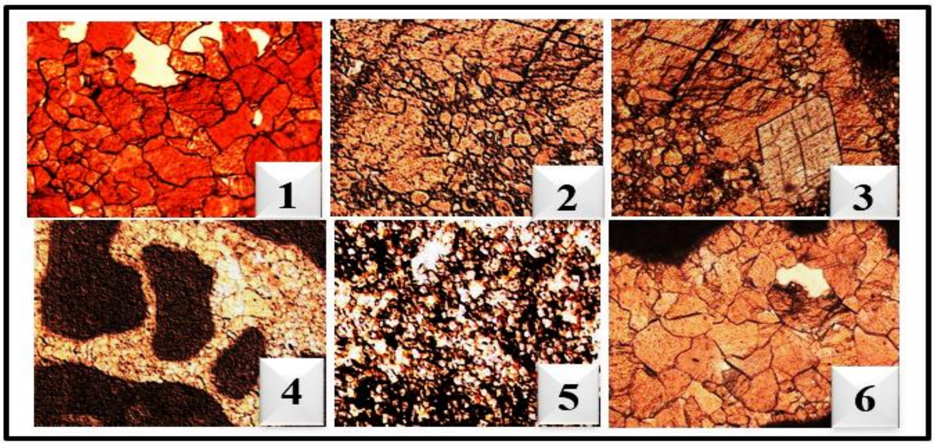


Fig.5. 1. drusy mosaic cement; 2. drusy mosaic cement; 3. granular cement; 4. granular cement; 5. Micrite and blocky cement; 6. Dolomitization.

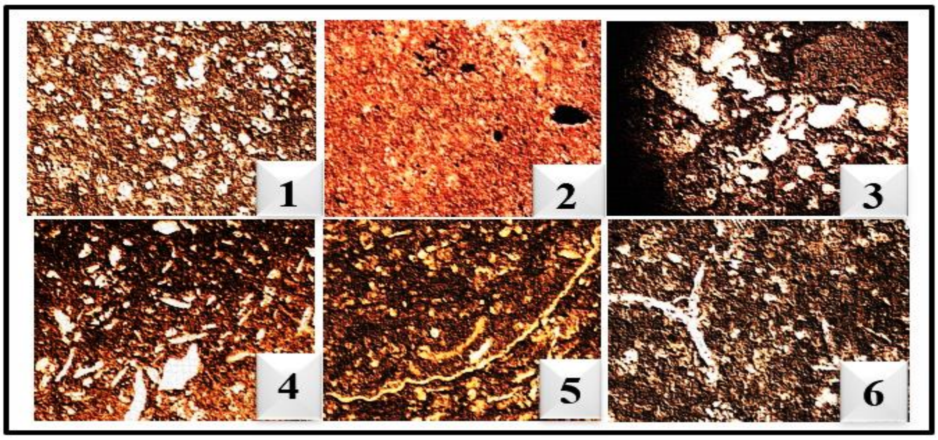


Fig.6. 1. Dolomitization 2. mudstone with pyrite; 3. vuggy porosity in wackestone; 4. Wackestone with moldic and vuggy porosity; 5. Dolomite within dissolution veins and shows channel porosity; 6 packstone with Peloids contain interparticle and moldic porosity.

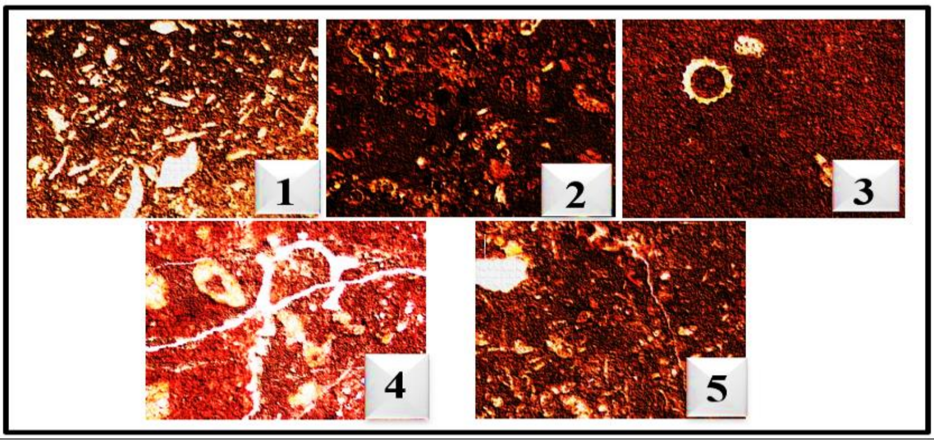


Fig.7. 1. Wackestone with moldic and vuggy porosity; 2. Packstone bearing small to medium-sized benthonic fossils; 3. Mudstone bearing benthonic fossils; 4. Wackestone bearing vugs; 5. Wackestone bearing bioclasts and shows interparticle, fractures and vuggy porosity.

3.3. Porosity Types in Mishrif Formation

Porosity in the Mishrif Formation is classified into primary and secondary types based on formation stages, with the classification of Choquette and Pray (2005) being a key system that emphasizes the relationship between rock texture and porosity development over time. Interparticle porosity, dependent on the size, sorting, and crystallinity of grains or crystals, is observed to a limited extent in wackestone and packstone microfacies (Fig.7-1). Vuggy porosity, resulting from irregular dissolution, includes separate-vug pore space and vug pore space (Fig.7-2). Separate-vug porosity, such as moldic porosity from the selective dissolution of primary components like organic matter, retains the moldic shape of original content, while intrafossil porosity occurs within structural particles, particularly benthonic foraminifera chambers, with weak permeability impact due to lack of interconnection (Fig.7-3). Vug pore space includes solution-enlarged fracture porosity, formed by selective dissolution within fractures, positively impacting permeability due to its interconnected nature and varying channel-like shapes and sizes (Fig.7-4), and fracture porosity, controlled by tectonic processes, appearing as veins and fractures with significant permeability influence, though rare in some mudstone (Fig.7-5).

3.4. Depositional Environments

The depositional environment refers to a specific geographic area on the Earth's surface where sediments accumulate, characterized by distinct physical, chemical, and biological conditions (Selley, 1978). Sedimentary facies, the smallest units of this environment, result from the interplay and lateral succession of facies due to changes in subsidence, tectonic uplift, and sea-level fluctuations. Carbonate deposits are influenced by environmental factors such as water energy, salinity, temperature, climate, and other factors that play an important role in the production or distribution of sediments. Highly productive "shoal" layers, characterized by coarse grains, high porosity, and permeability, are notable for their diagenetically enhanced thief zones (Aqrawi et al., 2010; Holden et al., 2014; Song et al., 2015).

The Mishrif Formation in the Rt 2 and Rt 5 wells show several key depositional environments. The sub-basin environment, with wackestone-packstone facies containing benthic foraminifera and bioclasts (FZ-3), is deposited in relatively deep, low-energy conditions, mostly in the formation's lower parts and transitional zones, offering poor to fair reservoir quality depending on diagenesis. The lagoonal and shelf environment, featuring mudstone, wackestone, and packstone facies with large benthonic foraminifera and bioclasts, occurs in shallow, low-energy settings in the middle and upper parts, ranging from poor to medium reservoir quality. The open shelf margin environment, consisting of bioclastic wackestone facies with shells, spines, and echinoderms fragments, is found primarily in the middle of the Rt 5 well. The shoal environment, represented by packstone facies with benthic foraminifera, peloids, and echinoderm, is widespread in the middle of the formation in both wells and is considered to have good reservoir quality, depending on the diagenetic processes affecting them.

3.5. Electrofacies Analysis

The term Electrofacies refers to the numerical combination of well log responses that reflects both the composition of the rock and the physical properties within a specific interval of rock. For the purpose of determining electrofacies, many multivariate procedures are used, such as principal component analysis, cluster analysis, and discriminant analysis. Choosing a well log for electrofacies determination is influenced by the degree to which they have a high degree of resolution and are responsive to the rock properties of interest. A range of well logs from the wells of interest (Rt 2 and Rt 5) can normally be obtained for electrofacies studies, including Gamma Ray, Density, Neutron, and Acoustic log data.

Using Geolog software, log data can be interpreted and electrical faults can be predicted and described based on the use of neural and statistical network modeling methodologies. The software uses well logs as "training" data to create models for facies propagation and prediction. Training involves characterizing properties and classes based on existing data to develop an understanding of how to propagate facies. Fig.8 illustrates the process of using training well log data to generate electrofacies models. The software offers two types of clustering: Supervised and Unsupervised Classifications. The former incorporates structural information to achieve the best match between original and calculated data, while the latter explores data structure without specific guidance. In this study, the Multi-Resolution Graph-Based Clustering model (MRGC) is employed for electrofacies prediction (Fig. 9). To validate electrofacies predictions, a comparison is made with microfacies identified from thin sections of available cores (Fig. 10). This comprehensive approach enhances the understanding of subsurface rock characteristics, contributing to more accurate reservoir analyses.

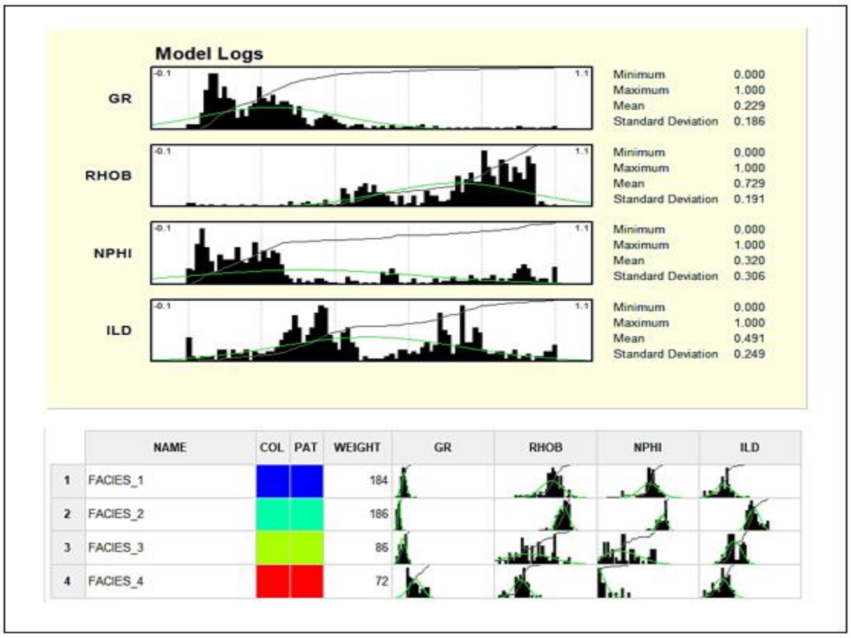


Fig.8. Training well measurements to create an electrofacies model

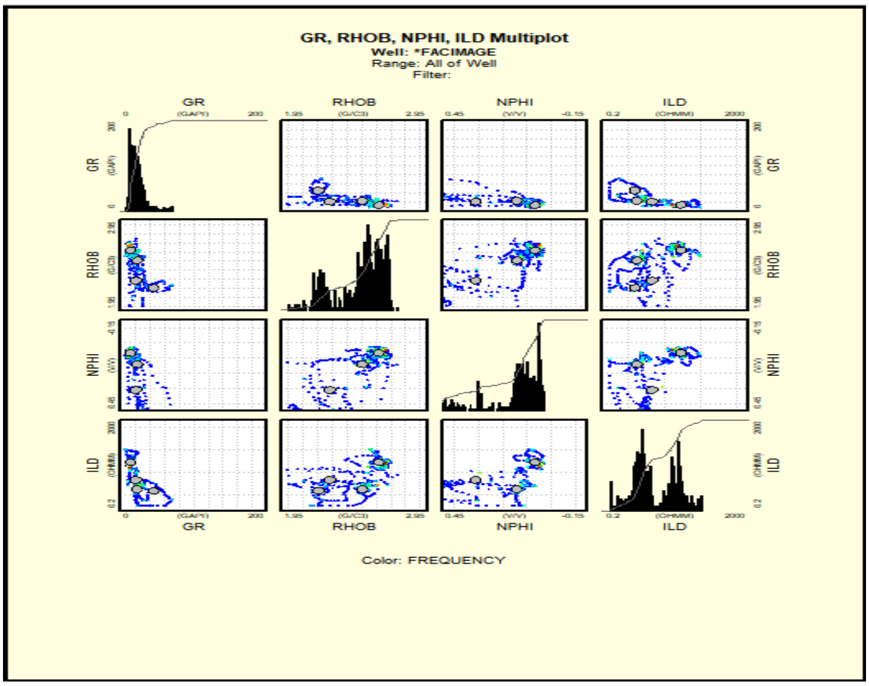


Fig.9. Multi Resolution Graph Clustering Model MRGC.

The electrofacies prediction process was iteratively applied to two wells (Rt 2 and Rt 5). Based on rock properties, the MRGC model identified four main electrofacies: packestone, wackestone, dolomite, and mudstone. Geolog software was used to extract electrofacies and imported into Petrel 2018 software. Therefore, the information extracted from wells was used to allocate specific rock types. A method called facies scaling was chosen, which assigns the most common rock type found in each section (Schlumberger, 2010). Fig.11 shows the correlation between Rt 2 and Rt 5 for lithofacies.

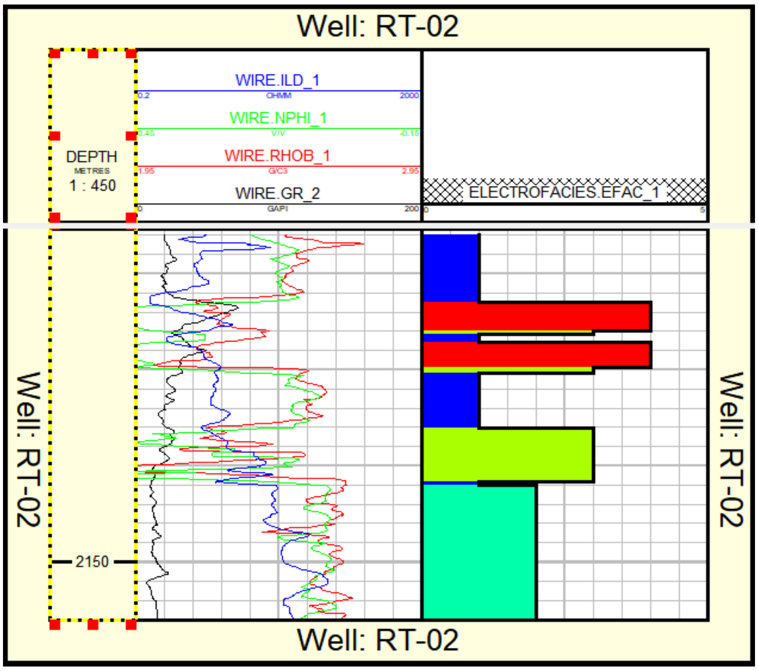


Fig.10. Predicted electrofacies using Geolog software (Rt_02).

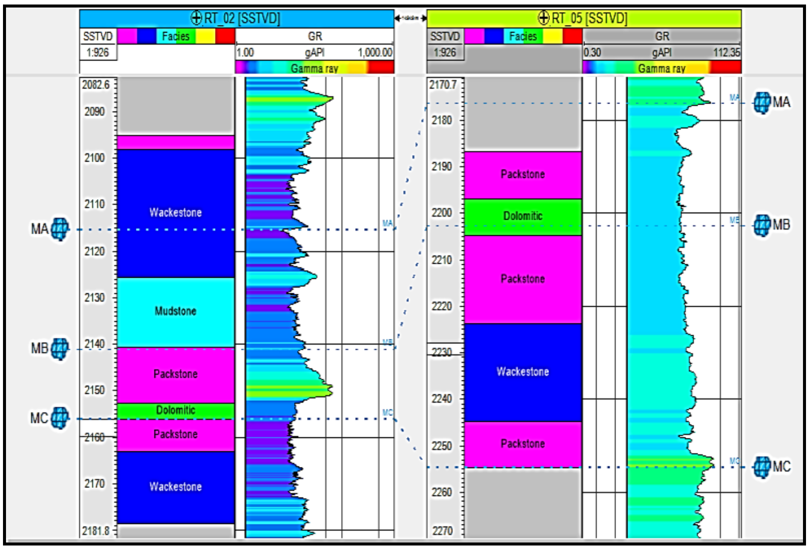


Fig.11. Correlation between Rt_02 and Rt_05 for lithofacies

3.6. Hydraulic Flow Units

The hydraulic Flow Unit (HU) technique is widely used for rock typing and permeability modeling. Hydraulic Flow Unit is related to the flow zone indicator and the reservoir quality index. This technique is important in estimating permeability in wells without core (Sheriff, 1995). In this study, Hydraulic Flow Unit for hydrocarbons was calculated from the core data. The method, explained in Al-Jawad (2018), involves calculating FZI and RQI. The equations below were utilized to calculate RQI, PHIZ (Øz), and FZI.

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

$$Øz = \frac{Ø\ core}{1-Ø\ core} \tag{2}$$

$$FZI = \frac{RQI}{Øz} = \frac{0.0314\sqrt{\frac{K\,core}{Ø\,core}}}{(\frac{Ø\ core}{1-Ø\ core})} \tag{3}$$

$$K\ Predict = 1014\ FZI2\ \frac{Ø\ core3}{(1-Ø\ core)2} \tag{4}$$

Rock cores were used to construct a system of classification based on HU. The HU classification of rocks depended on their relationship between RQI and ØZ as presented in Fig. 12. With this information, four different types of HUs have been identified in the field with varying ØZ ranges for each type.

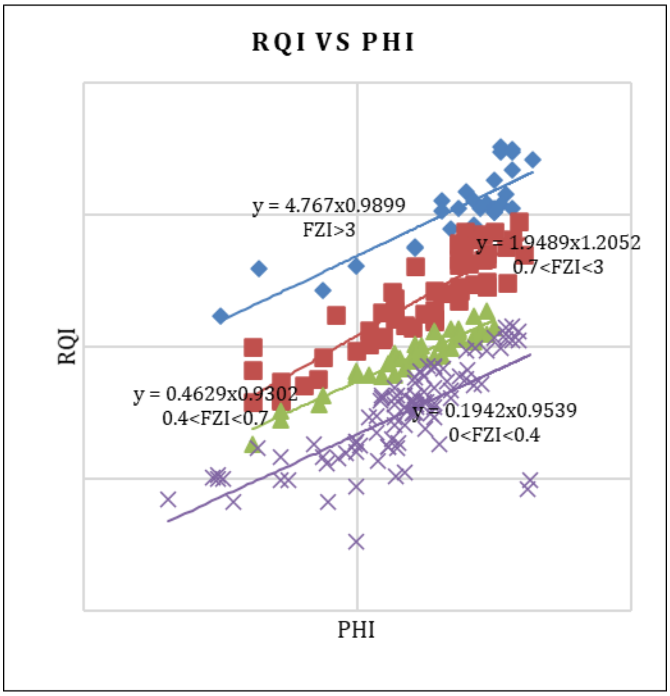


Fig.12. The relationship between RQI and PHIZ (ØZ) plot for different HUs.

In Fig. 13, core samples are shown as scatter plot according to their permeability and porosity. As depicted in Fig.14, the resultant model is for permeability across the Mishrif Formation within the studied wells.

The Ratawi oilfield is in the southern part of Iraq, where we employed classification tree analysis, a technique that uses well log data to categorize lithofacies and hydraulic flow units. This technique aimed at enhancing predictions with regard to how easily fluid can move through the rock compared to previous methods (Mathisen et al., 2001; Amaefule et al., 1993). As an alternative, they opted for electrofacies, which indicate rocks' electrical characteristics even for wells without cores (Barman et al., 1998; Lee and Datta-Gupta, 1999). Ratawi field has many different carbonate reservoirs and it is relatively complex. This involved making numerous measurements such as radioactivity (GR), electrical conductivity (ILD), porosity (NPHI, RHOB), and rock density (RHOB). Consequently, we adopted four major logs used in investigations. In this paper, we found four distinctive points on electrofacies, four types of rock based on core sample analyses (microfacies), and lastly four groups of hydraulic flow units.

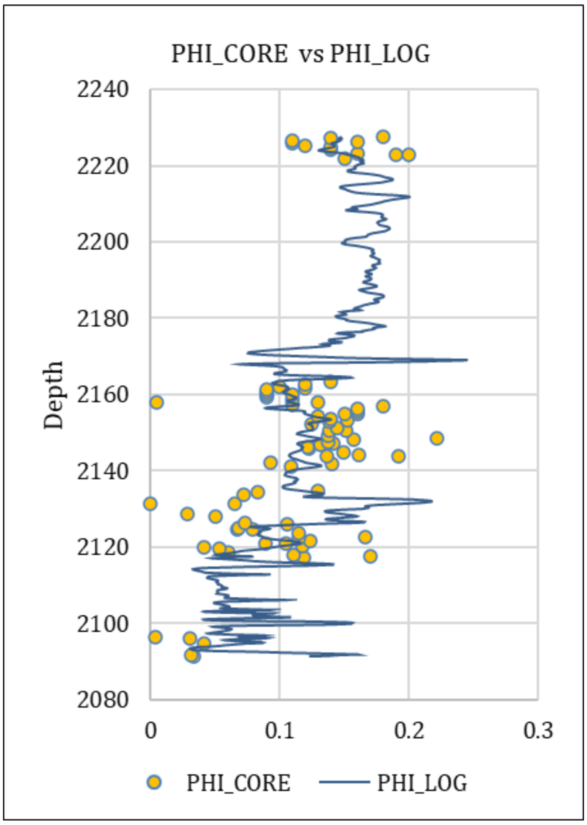


Fig.13. The relationship between Log Porosity (Sonic log) and Core Porosity for well 17

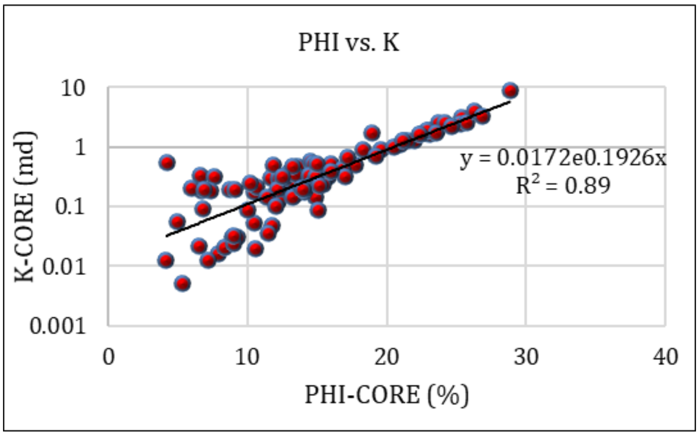


Fig.14. The relationship between Porosity vs. Permeability for different HUs.

4. Conclusions

The Ratawi oilfield is in the southern part of Iraq, where we employed classification tree analysis. It is a technique that uses well log data to categorize lithofacies and hydraulic flow units. This technique aimed at enhancing predictions with regard to how easily fluid can move through the rock compared to previous methods (Amaefule et al., 1993; Mathisen et al., 2001). As an alternative method, electrofacies is applied, which indicate rocks' electrical characteristics even for wells without cores (Barman et al., 1998; Lee and Datta-Gupta, 1999). Ratawi field has many different carbonate reservoirs and it is relatively complex. This involved making numerous measurements such as radioactivity (GR), electrical conductivity (ILD), porosity (NPHI, and RHOB), and rock density (RHOB). Consequently, we adopted four major logs used in investigations. In this paper, four distinctive electrofacies are found, in addition to four types of rock based on core sample analyses (microfacies) and lastly four groups of hydraulic flow units.

The Mishrif Formation exhibits complex facies properties, comprising four main facies (mudstone, wackestone, packstone, and dolomite) and ten secondary facies. These variations reflect significant changes in sea levels and tectonic activity during deposition. The vertical distribution of these facies indicates diverse depositional environments, including sub-basin, lagoonal, open shelf margin, and shoal. Petrographic analysis identified several diagenetic processes—dissolution, cementation, dolomitization, and recrystallization—that have significantly influenced rock properties, particularly porosity. Dissolution processes, in particular, have been crucial in altering porosity characteristics. Among the studied wells, the Rt 2 well exhibited the best reservoir characteristics, dominated by packstone and wackestone facies, which are favorable for reservoir quality.

The permeability heterogeneity in the Mishrif limestone complicates completions and production. To address this, the study employed a neural network approach to identify Electrofacies from well logs and developed porosity-permeability relationships for each Electrofacies based on core measurements from a key well. The Electrofacies modeling approach more accurately captures permeability variations compared to a single porosity-permeability relationship derived from all core samples. The Electrofacies and their associated porosity-permeability relationships can be applied to well logs in offset wells to predict permeability accurately, eliminating the need for extensive coring. The predicted permeability using Electrofacies modeling is highly consistent with measured permeability on core samples, demonstrating the effectiveness and reliability of this approach.

Acknowledgements

The authors are deeply grateful to Basra Oil Company for supplying the thin section that was necessary for this study. Their collaboration and assistance were essential to this study's effective conclusion.

References

Abdulateef, D.A., Zarzor, A., Al Jawad, M.S., 2000. Electrofacies characterization of an Iraqi carbonate reservoir. Iraqi Journal of Chemical and Petroleum Engineering, 15(4), 15-24.

Al-Dujaili, A.N., Shabani, M., Al-Jawad, M.S., 2021a. Characterization of flow units, rock and pore types for Mishrif Reservoir in West Qurna Oilfield, Southern Iraq by using lithofacies data. Journal of Petroleum Exploration and Production Technology, 11(11), 4005–4018.

Al-Dujaili, A.N., Shabani, M., Al-Jawad, M.S., 2023b. Lithofacies and electrofacies models for Mishrif Formation in West Qurna Oilfield, Southern Iraq by deterministic and stochastic methods (comparison and analyzing). Petroleum Science and Technology, 42(13), 1656–1684.

Al-Jawad, M.S., Ahmed, I.J., 2018. Permeability estimation by using the modified and conventional FZI methods. Journal of Engineering, 24 (3), 59-67.

Al-Najm, M., Al-Saadi, S., Ali, H., 2018. Three-dimensional geological-reservoir model of the Mishrif Formation in the Halfaya Field. Thi-Qar University Journal for Engineering Sciences, 9 (2), 40-52.

Amaefule, J.O., Altunbay, M., Tiab, J., Kersey, D.G., Keelan, D.K., 1993. Enhanced reservoir description using core and log data to identify hydraulic flow units and predict permeability in uncored intervals/wells. SPE Annual Technical Conference and Exhibition, SPE 26436.

Aqrawi, A., Goff, J., Horbury, A., Sadooni, F., 2010. The petroleum geology of Iraq. Beaconsfield, U.K.

Barman, I., Sharma, A.K., Walker, R.F., Datta-Gupta, A., 1998. Permeability predictions in carbonate reservoirs using optimal non-parametric transforms. An Application at the Salt Creek Field, Kent County, TX, SPE/DOE Symposium on Improved Oil Recovery, Tulsa.

Bize-Forest, N., Lima, L., Baines, V., Boyd, A., Abbots, F., Barnett, A., 2018. Using machine-learning for depositional facies prediction in a complex carbonate reservoir. SPWLA 59th Annual Logging Symposium, London, UK.

Burchette, T.P., 2012. Carbonate rocks and petroleum reservoirs: a geological perspective from the industry. Geological Society, 370 (1), 17.

Davies, D.K., Vessel, R.K., 1996. Flow unit characterization of shallow shelf carbonate reservoir: North Robertson Unit, West Texas. SPE/DOE Symposium on Improved Oil Recovery, Tulsa, Oklahoma.

Dorfman, M.H., Newey, J.J., Coates, G.R., 1990. New techniques in lithofacies determination and permeability prediction in carbonates using well logs. Geological Society, 48, 113-120.

Dunham, R.J., 1962. Classification of Carbonate Rock According to Depositional Texture. In: Ham, W.E. (Ed.), Classification of Carbonate Rocks. American Association of Petroleum Geologists Memoir, 1, 108-121.

Hatif, M., Al-Shahwan, M.F., Al-Yaseri, A.A., 2020. Comparative organic geochemical study of Cretaceous Reservoirs of Zubair Oil Field, Southern Iraq. Iraqi Geological Journal, 53(2D), 128-147.

Holden, A., Lehmann, C., Ryder, K., Scott, B., Almond, K., 2014. Integration of production logs helps to understand heterogeneity of Mishrif in Rumaila. SPWLA 55th Annual Logging Symposium, May 18-22.

Lee, S.H., Datta-Gupta, A., 1999. Electrofacies characterization and permeability predictions in carbonate reservoirs: role of multivariate analysis and nonparametric regression. SPE Annual Technical Conference and Exhibition, Houston, Texas, SPE-56658-MS.

Liu, Y., A. Harding, W. Abriel, S. Strebelle., 2004. Multiple-point simulation integrating wells, three-dimensional seismic data, and geology. AAPG Bulletin, 88(7), 905–921.

Mathisen, T., Lee, S.H., Datta-Gupta, A., 2001. Improved permeability estimates in carbonate reservoirs using electrofacies characterization: A case study of the North Robertson Unit, West Texas. SPE Reservoir Evaluation & Engineering, 6 (03), 176–184.

Nelson, P.H., 1994. Permeability-porosity relationships in sedimentary rocks. The Log Analyst, 3, 38.

Perez, H.H., Datta-Gupta, A., Mishra, S., 2003. The role of electrofacies, lithofacies, and hydraulic flow units in permeability predictions from well logs: A comparative analysis using classification trees. SPE Reservoir Evaluation & Engineering, 8 (02), 143–155.

Schlumberger, 2010. Property Modeling Course. Petrel software, Houston.

Selley, R.C., 1978. Ancient Sedimentary Environments (2nd ed.). Chapman and Hall. London.

Sheriff, R.E., Geldart, L.P., 1995. Exploration Seismology. Cambridge university press.

Song, B.B., Zhu, Y.X., Fu, X.P., Wei, C.J., 2015. Hydrocarbon volume uncertainty of Mishrif Reservoir in Rumaila field; Implications from surveillance data. European Association of Geoscientists & Engineers, Third EAGE Workshop on Iraq, 1-5.

Tang, H., 2008. Improved carbonate reservoir facies classification using artificial neural network method. Canadian International Petroleum Conference, Calgary, Alberta, Canada.

Wilson, T.L., 1975. Carbonate Facies in Geological History. New York, Springer-Verlag.

Zhang, T., 2008. Incorporating geological conceptual models and interpretations into reservoir modeling using multiple-point geostatistics. Earth Science Frontiers, 15, (1), 26–35.

Zhang, Z., Jeffrey, R.G., Bunger, A.P., Thiercelin, M., 2011. Initiation and growth of a hydraulic fracture from a circular wellbore. International Journal of Rock Mechanics and Mining Sciences, 48, 984 -995.