

Flow Unit Identification Based on Petrophysical Studies Using Well Logging of the Mauddud Formation in Ratawi Oil Field

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Abstract

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The Mauddud Formation, deposited during the Albain Stage of the Early Cretaceous is a hydrocarbon-rich reservoir and represents the second economic reservoir after the Yamama Formation in Ratawi oil field. The Mauddud Formation was studied in five wells that were distributed across the field, southern Iraq, open-hole well logs were obtained for these wells. The Mauddud Formation consists mostly of limestone, with shale interbeds, the petrophysical properties results confirmed that the shale volume of the formation is low in most wells, with a porosity distribution ranging from 10% to 26%, and the formation contains different proportions of the produced hydrocarbons. Based on results, the formation was divided into four units: MA, MB, MC, and MD. Through porosity and permeability calculations, the pore type and flow unit were determined based on the pore throat radius (r_{35}) curve. As the results showed that the type of pore ranged between macroport and megaport in unit MA, while in unit MC the type of pore ranged between microport and macroport, these variations indicate reservoir heterogeneity within the Mauddud Formation. The flow units in the Mauddud Formation were identified using the Interactive Petrophysics program, and based on the application of flow zone indicator equations. As the results showed that wells Rt-4, Rt-6, and Rt-7 consist of three hydraulic flow units, while the wells Rt-5 and Rt-3 consist of four hydraulic flow units, reflecting greater heterogeneity in permeability distribution and pore structure.

Keywords: Mauddud Formation; Petrophysical Properties; Hydraulic Flow Units

1. Introduction

The Ratawi field is one of the oil fields located in southern Iraq, approximately 20 km west of the northern Rumaila oil field, and nearly 12 km south of the Hor Al-Hammar area. The field is located between latitudes 705.40-696.36 E and longitude 3394.18-3373.80 N (Fig. 1). The Mauddud Formation is a hydrocarbon-rich reservoir and represents the second economic reservoir after the Yamama Formation in Ratawi oil field (Jassim and Goff, 2006). The Mauddud Formation was deposited during the Late Albain-Early Cenomanian time period, and average thickness ranging between 30 to 150 m (Al-Dabbas et al., 2012). The Mauddud Formation is predominantly composed of limestone with smaller amounts of dolomite (Hameed and Saleh, 2022). Many geological studies have been conducted on the Mauddud Formation in the Ratawi oil field, but in this study, the reservoir was evaluated by analyzing petrophysical properties using open-hole well logs and classifying the reservoir rocks through flow unit indicator methods, calculating R_{35} , and its relationship to permeability and how permeability affects pore size.

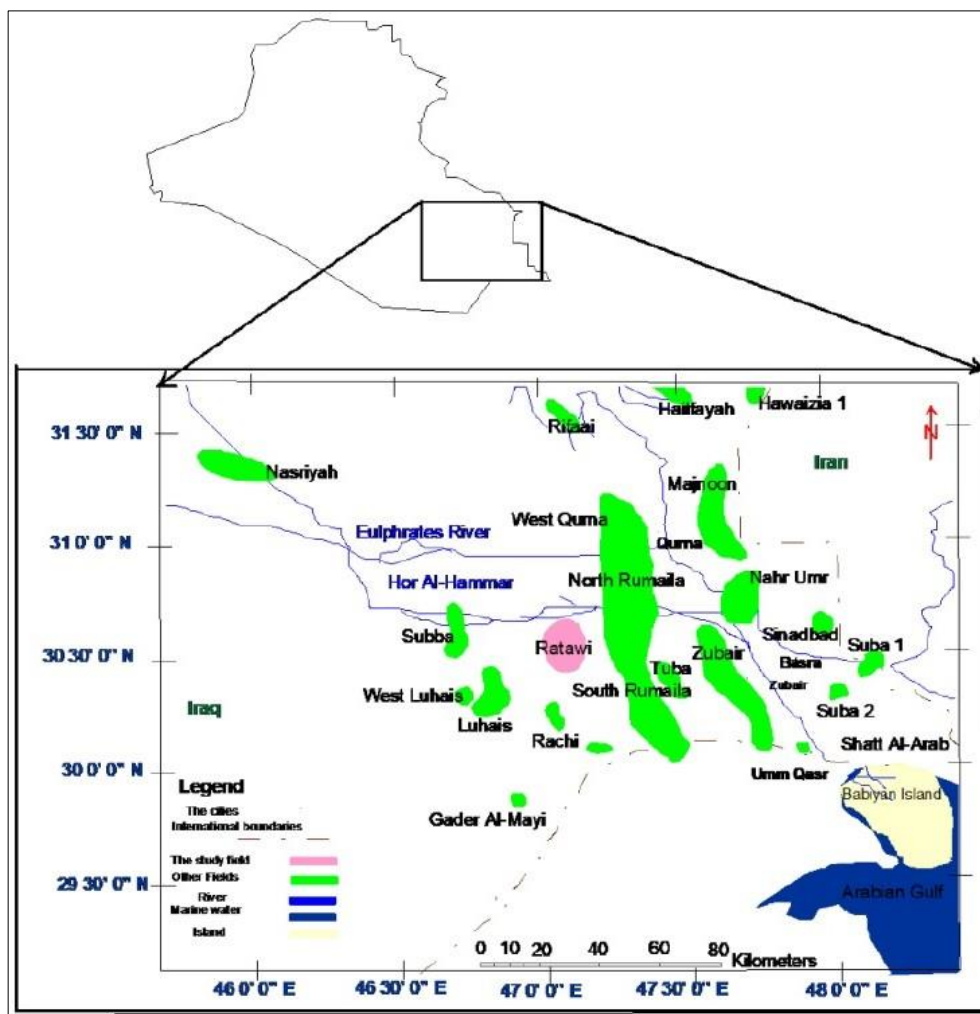


Fig. 1. Location map of the study area showing Ratawi oil field (modified after Al-Khafaji et al., 2015)

2. Geological Setting

The Stable Shelf Zone in Iraq, the Zubair Subzone represents the southern extension of the Mesopotamian Zone, and the Ratawi field is one of the fields located within it (Jassim and Goff, 2006). Geological and geophysical data indicate a structural influence attributed to the Hormuz Formation (salt). These structural phenomena appeared as negative gravity anomalies of the Ratawi and Rumaila structures and part of the Zubair structure (Jassim and Goff, 2006). The Maaddud Formation, deposited during the Albian Stage of the Early Cretaceous, represents the characteristic carbonate sequences of this period in Iraq, the Maaddud Formation is predominantly represented by dolomitized bioclastic limestone (Nasser, 2018). The lower contact of the Maaddud Formation with the Nahr Umr Formation is gradational, but the upper contact with the Ahmadi Formation is unconformable (Bellen et al., 1959). The Maaddud Formation is divided into four units (MA, MB, MC, and MD), the units (MA and MC) are regarded as reservoir units, while the units (MB and MD) are regarded as non-reservoir units (Nasser, 2018). The thickness of the formation in Ratawi field is about 120 m. The lithology of the formation is limestone with the presence small amounts of shale. The mineralogy of Maaddud Formation is composed mainly of calcite (Hameed and Saleh, 2021).

Several researchers have investigated the lithological and petrophysical characteristics of the Maaddud Formation in the Ratawi oil field, southern Iraq.

Hussain and Hameed (2024) studied the microfacies and diagenetic processes and concluded that the formation is dominated by limestone deposited in a carbonate ramp environment.

Hameed and Saleh (2021) performed a petrophysical evaluation using well logs and subdivided the formation into reservoir units with variable porosity and shale content.

Nasser (2018) examined the petrophysical properties and developed a geological model of the Mauddud Formation (Cenomanian), assessing the probability of oil production in the Ratawi field.

In addition, Al-Dabbas et al. (2012) conducted sedimentological and depositional environment studies of the Mauddud Formation.

However, these previous investigations provide an important geological and petrographic framework for understanding the reservoir properties of the Mauddud Formation and support the interpretation presented in the current study.

3. Materials and Methods

3.1. Data Preparation

Five wells were selected and distributed along the Ratawi oil field: RT-3, RT-4, RT-5, RT-6, and RT-7. The study included collecting basic data from the wells in the research area's final reports and preparing information containing the depths and coordinates of the wells necessary for the study, as shown in Table 1. Petrophysical analysis of the logs was conducted using the open-hole wells of the study area, which included GR, RHOB, NPHI, DT, and Rt logs to identify the formation lithology. The well logs were used to obtain the shale volume, porosity, and saturation, and to calculate permeability. Diagrams were created between the various logs using the Techlog program. In addition, diagrams were created between the different well logs to identify the type of reservoir rocks.

Table 1. The tops and thickness with coordinates of studied wells for the Mauddud Formation

Well No.	Top (m)	Bottom (m)	Thickness (m)	R.T. K. B	Northern (m)	Eastern (m)
RT-3	2458.5	2583.0	124.5	34.0	700000	3386000
RT-4	2554.0	2680.0	126.0	35.2	703900	3385100
RT-5	2568.0	2688.0	120.0	27.7	700000	3392200
RT-6	2575.0	2691.0	116.0	22.4	696000	3385900
RT-7	2565.7	2674.5	108.8	39.0	701500	3373300

The calculation of the petrophysical properties was carried out using the collected well logs by applying Techlog software.

3.2. Volume of the shale

Shale volume can be calculated using several methods. In this study, the shale content was calculated using the gamma ray method, as expressed in the following two equations (Larionov, 1969; Schlumberger, 1974).

$$\text{IGR} = (\text{GR log} - \text{GR min}) / (\text{GR max} - \text{GR min}), \quad (1)$$

$$\text{Vsh} = (2(2 * \text{IGR}) - 1) / 3, \quad (2)$$

Where: Vsh = shale volume; IGR= gamma ray index; GR log = log reading (API); GR min = minimum GR; GR max = maximum gamma GR.

3.3. Porosity

Calculating porosity is very necessary for reservoir evaluation. Primary porosity is calculated from a sonic log (Wyllie et al., 1958).

$$\phi_s = (\Delta t_{\log} - \Delta t_{ma}) / (\Delta t_f - \Delta t_{ma}), \quad (3)$$

Where: ϕ_s = Sonic – derived porosity; $\Delta t_{\log}$ = Sonic log measurements of formation; Δt_{ma} = 47.6 (us/ft); Δt_f (induction) = 189.

Total and effective porosity was calculated using density and neutron logs. Density porosity was determined using the following equations (Asquith and Krygowski, 2004).

$$\phi_D = (\rho_{ma} - \rho_b) / (\rho_{ma} - \rho_f), \quad (4)$$

$$\phi_{De} = D - V_{sh} \times D_{sh}, \quad (5)$$

Porosity from the neutron log was calculated directly (Asquith and Krygowski, 2004).

$$\phi_{Ne} = \phi_N - (\phi_{Nsh} \times V_{sh}), \quad (6)$$

Where: ϕ_D = density derived porosity; ρ_{ma} = matrix density (2.65); ρ_b = the log reading; ρ_f = fluid density (1); ϕ_{De} = Shale-corrected density porosity; ϕ_N = neutron porosity; ϕ_{Ne} = Shale-corrected porosity; ϕ_{Nsh} = neutron porosity of nearby shale.

3.4. Water and Hydrocarbon Saturation

Water saturation (S_w) was calculated using Archie's equation (Archie, 1944).

$$S_w = \sqrt{(F \cdot R_w / R_t)}, \quad (7)$$

$$F = a / \phi^m, \quad (8)$$

Hydrocarbon saturation (S_h) was determined according to Schlumberger (1998).

$$S_h = 1 - S_w, \quad (9)$$

R_w is a crucial parameter in estimating water saturation. The Pickett plot method was applied, which established a relationship between the resistivity log and total porosity, as shown in Fig. 2, to predict the Archie parameters (a , m , n) and the R_w value. Fig. 3 demonstrates this value alongside the other calculated parameters. The formation water resistivity (R_w) was obtained from the Basra Oil Company and is equal to 0.018 $\Omega \cdot m$. The Archie parameters include the tortuosity factor ($a = 1$), cementation factor ($m = 2$), and saturation exponent ($n = 2$).

3.5. Bulk Volume Water (BVw) and Total Volume Hydrocarbon (BVO)

$$BVW = S_w \cdot \phi_N \cdot D, \quad (10)$$

$$BVO = S_h \cdot \phi_N \cdot D, \quad (11)$$

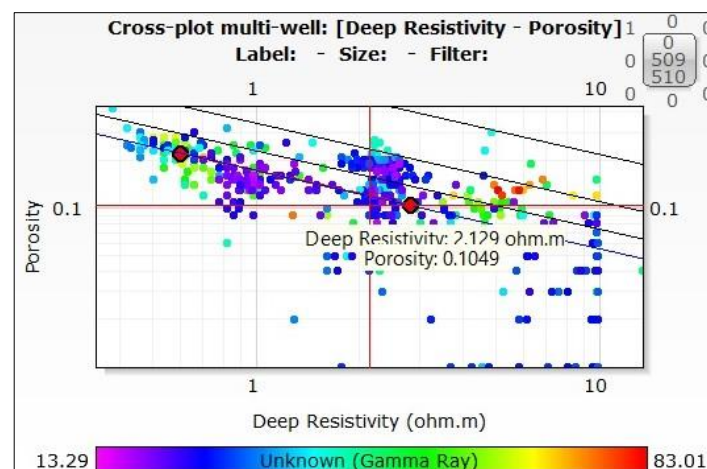


Fig. 2. The relationship between resistivity log and total porosity according to Pickett plot

3.6 Estimating Permeability from Logs (K)

Permeability is an important rock property. There are several properties that affect its permeability, including porosity, grain size, and grain shape. Using well log data, permeability was calculated with the equation proposed by Wyllie and Rose (1950).

$$K = \left[\frac{C^* (\phi^3 / S_{wir})}{\phi} \right]^2 \quad (12)$$

Where: C = 250 constant value.

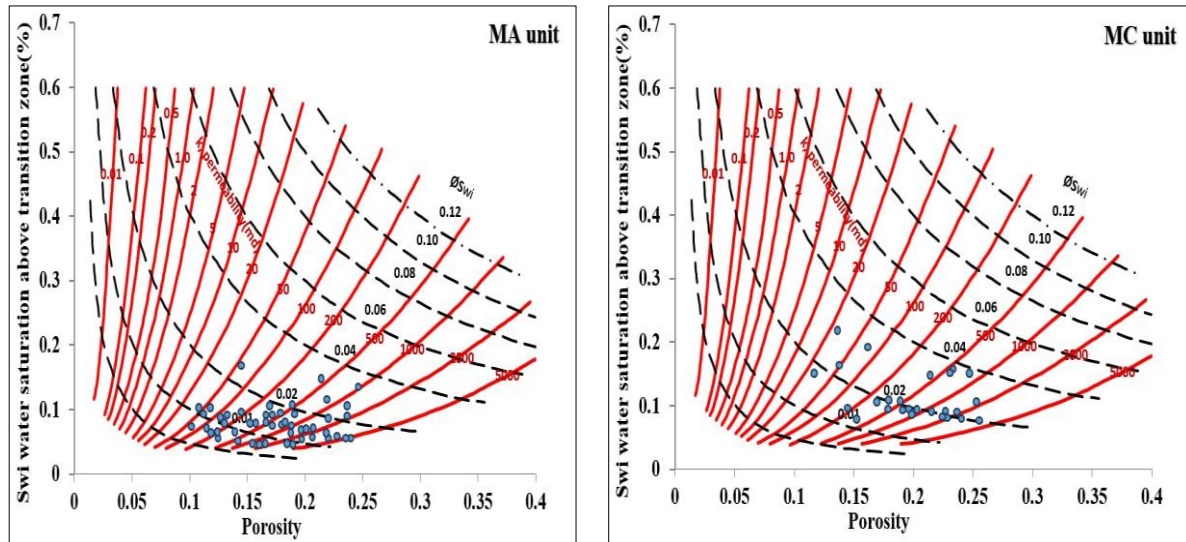


Fig. 3. Charts of porosity versus irreducible water saturation were constructed to estimate the permeability of the RT-3 well

3.7. Porosity–permeability Cross-plots (R35)

The pore radius (R35) represents an indicator based on pore size and sorting degree (Pittman, 1992). By analyzing the Winland curve (R35), calculated from porosity and permeability values, the reservoir can be divided into several flow units (Martin et al., 1997). The Winland equation uses measured permeability (K_a) and porosity (Φ) values to determine R35.

$$\log R35 = 0.732 + 0.588 \log K_a - 0.864 \log \Phi, \quad (13)$$

The original purpose of the Winland equation was to predict pore throat radius for identifying rock types in wells. Pore systems can be classified according to pore throat radius (Pittman, 1992), as shown in Table 2.

Table 2. Pore types and their size ranges are summarized for the different pore systems (after Pittman, 1992).

Pore type	Size range (μm)
Mega	>10
Macro	2–10
Meso	0.5–2
Micro	0.1–0.5
Nano	<0.1

3.8. FZI Approach

The flow zone indicator (FZI) is an important parameter in characterizing reservoir flow properties. It is used to identify fluid movement within the reservoir. Its significance lies particularly in analyzing geological features associated with variations in pore throat size, which are the controlling factors in determining permeability (Amaefule et al., 1993).

$$FZI = RQI / \Phi_z, \quad (14)$$

Where; RQI: Reservoir Quality Index, Φ_z : Normalized Porosity.

The pore quality index (RQI) relates the microscopic features of the pore space with the petrophysical parameters of the reservoir; the quality index and normalized porosity were calculated using the equations (Amaefule et al., 1993):

$$RQI = 0.0314 \sqrt{K/(\Phi_e)}, \quad (15)$$

$$\Phi_z = \Phi_e / (1 - \Phi_e), \quad (16)$$

Where: K = Permeability (in millidarcy), Φ_e = the effective Porosity (fraction).

4. Results and Discussion

4.1. Lithology of the Mauddud Formation

Based on the description and deflection of the basic logs (gamma ray, neutron, and density) in the study wells, it was observed that the Mauddud Formation consists mostly of limestone with a very small proportion of shale. From the well log readings and deflections, the Mauddud Formation was divided into four units: MA and MC, and MB and MD (Figs.4, 5, 6, 7, and 8). The variation in results indicates reservoir heterogeneity within the Mauddud Formation. The mineralogy of the Mauddud Formation is composed primarily of calcite (Hameed and Saleh, 2021).

4.2. Petrophysical interpretation of the Mauddud Formation

According to the research achievements, the formation of five wells in the Ratawi oil field was evaluated. The petrophysical property results confirmed that the shale volume of the formation is low in most wells, with a porosity distribution ranging from 10% to 26%, while the water saturation ranges from 10% to 90%. Figs. 4 to 8 show the petrophysical property results for the Mauddud Formation in the Ratawi oil field.

Unit MA: is primarily composed of limestone with shale interbeds, exhibits low gamma ray readings, and shows low shale volume values. The highest thickness of the unit 74.6 m in well Rt-5. And through petrophysical results the effective porosity rate between 12% in Rt-4 and Rt-6, and 17% in Rt-7, while hydrocarbon saturation ranges from 52% in Rt-4 to 74% in Rt-3, indicating good reservoir within this unit.

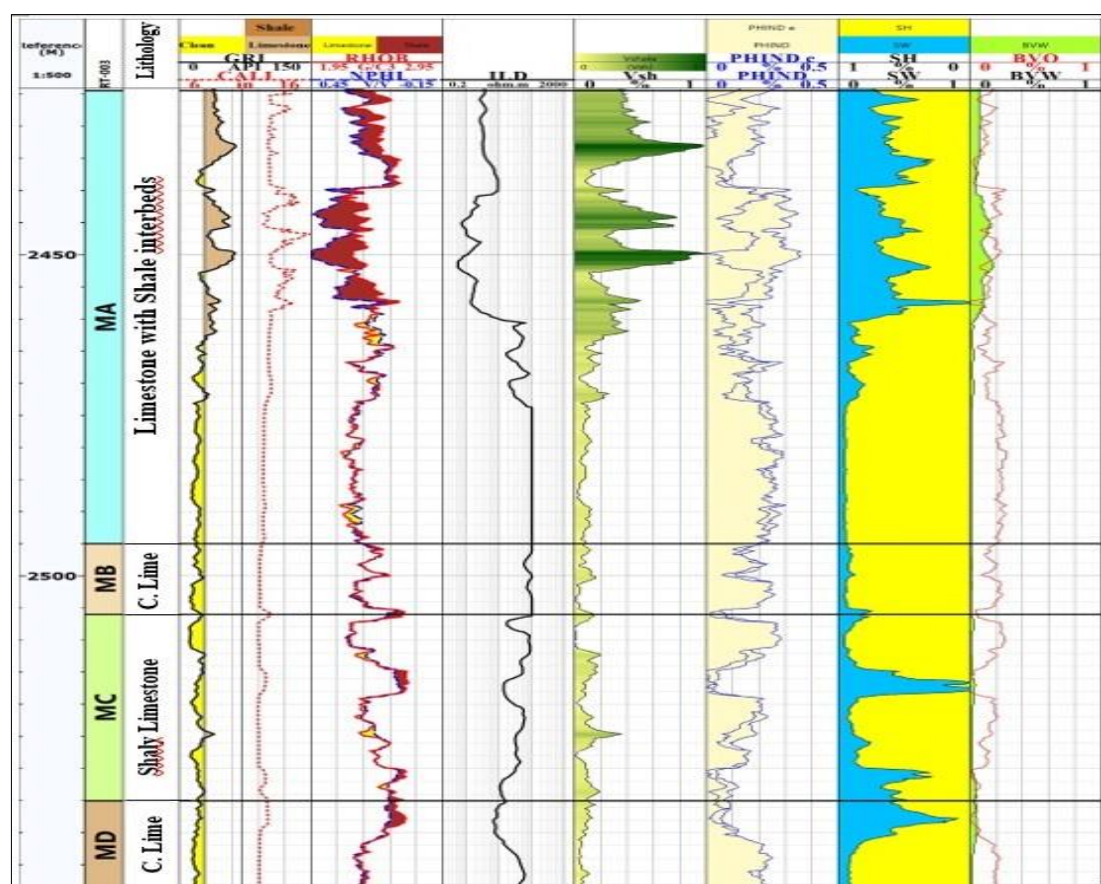
Unit MB: shows petrophysical parameters results and thickness compared to the MA unit, The highest thickness of the unit 13.8 m in well Rt-5; the effective porosity rate between 5% in Rt-6 and 19% in Rt-7, while hydrocarbon saturation ranges from 31% in Rt-4 to 91% in Rt-3.

Unit MC: is primarily composed of clean limestone or shaly limestone, with low gamma ray readings and shows low shale volume values. The highest thickness of the unit 30.9 m in well Rt-4. And through petrophysical results the effective porosity rates between 2% in Rt-6 and 12% Rt-3, while hydrocarbon saturation ranges from 8% in Rt-6 to 73% in Rt-3. These differences in values indicate reservoir heterogeneity.

Unit MD: This unit composed of limestone with low shale. The highest thickness of the unit 16.9 m in well Rt-5. Shows petrophysical properties that porosity ranges from 1% in Rt-7 to 15% Rt-3, and hydrocarbon saturation between 3% in Rt-4, and 71% in Rt-3.

Table 3. Petrophysical properties results of Mauddud Formation

Well No.	Units	Top (m)	Thickness (m)	Shale Volume (Vsh %)	Effective Porosity (Φ_e %)	Saturation (Sh %)
RT-3	MA	2424.50	70.5	0.27	0.14	0.74
	MB	2495.00	11.0	0.07	0.17	0.91
	MC	2506.00	29.0	0.10	0.12	0.73
	MD	2535.00	14.00	0.08	0.15	0.71
RT-4	MA	2518.80	73.0	0.09	0.12	0.52
	MB	2591.75	69.5	0.10	0.10	0.31
	MC	2601.30	30.9	0.05	0.11	0.14
	MD	2632.25	13.8	0.09	0.09	0.03
RT-5	MA	2540.40	74.6	0.27	0.15	0.55
	MB	2615.00	13.5	0.09	0.08	0.42
	MC	2628.80	15.4	0.08	0.11	0.10
	MD	2644.25	16.8	0.08	0.06	0.09
RT-6	MA	2552.60	66.5	0.22	0.12	0.71
	MB	2619.10	13.5	0.09	0.05	0.35
	MC	2632.60	26.0	0.11	0.02	0.08
	MD	2658.60	10.0	0.06	0.12	0.44
RT-7	MA	2526.70	58.3	0.07	0.17	0.68
	MB	2585.00	12.0	0.11	0.19	0.83
	MC	2597.00	29.5	0.06	0.12	0.27
	MD	2626.50	9.0	0.23	0.01	0.12



*C.Lime (Clean Limestone)

Fig. 4. Lithological interpretation and petrophysical characteristics of well Rt-3

The porosity and permeability values of the study wells was used to determine the radius of the throat pore (r_{35}) and its classification. Four groups of pore sizes were determined for the reservoir units: mega, macro, meso, and micro pores (Lucia, 1999). Determining pore-throat size is a primary control on reservoir quality. Megapores exhibit higher effective porosity and better permeability, reflecting carbonate rocks deposited in high-energy environments. Micropores are characterized by relatively lower porosity, indicating carbonate rocks deposited in low-energy environments (Hussain and Hameed, 2024).

As shown in Table 4, using the Winland equation and in Figs. 6 and 7. In this study, based on the petrophysical results, the permeability values (K) and, according to the classification of the radius of the throat pore r_{35} (Table 2) for units MA and MC of the Mauddud Formation in the study area, exhibit different permeability and pore-throat radius values (Nasser and Nasser, 2017), as indicated in Figs. 9 and 10.

The results indicate that the average permeability values in unit MA of the study range from 507.5 to 1075.0, and the type of pore ranges from macroport to megaport. In unit MC, the permeability values range from 8.0 to 975.0, and the type of pore ranges from microport to macroport.

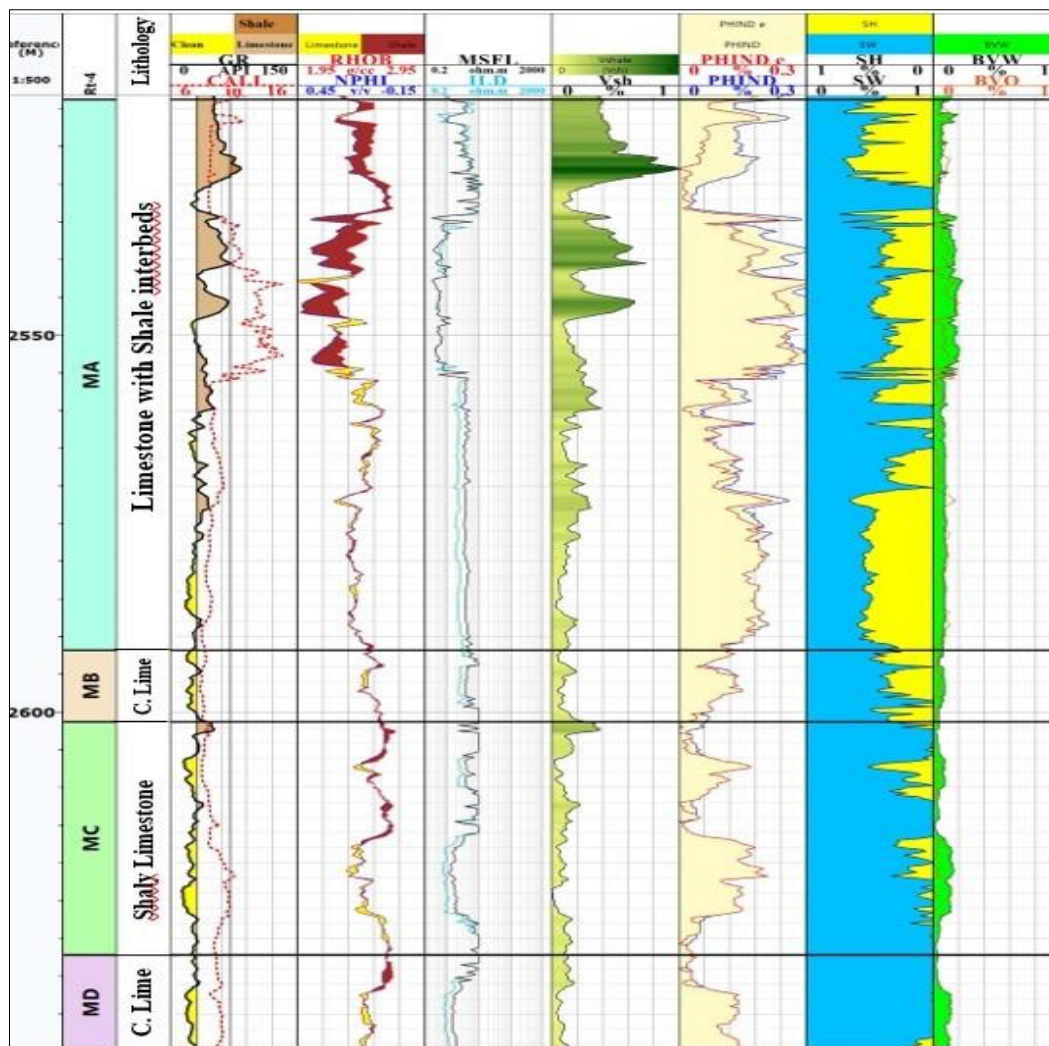


Fig. 5. Lithological interpretation and petrophysical characteristics of well Rt-4

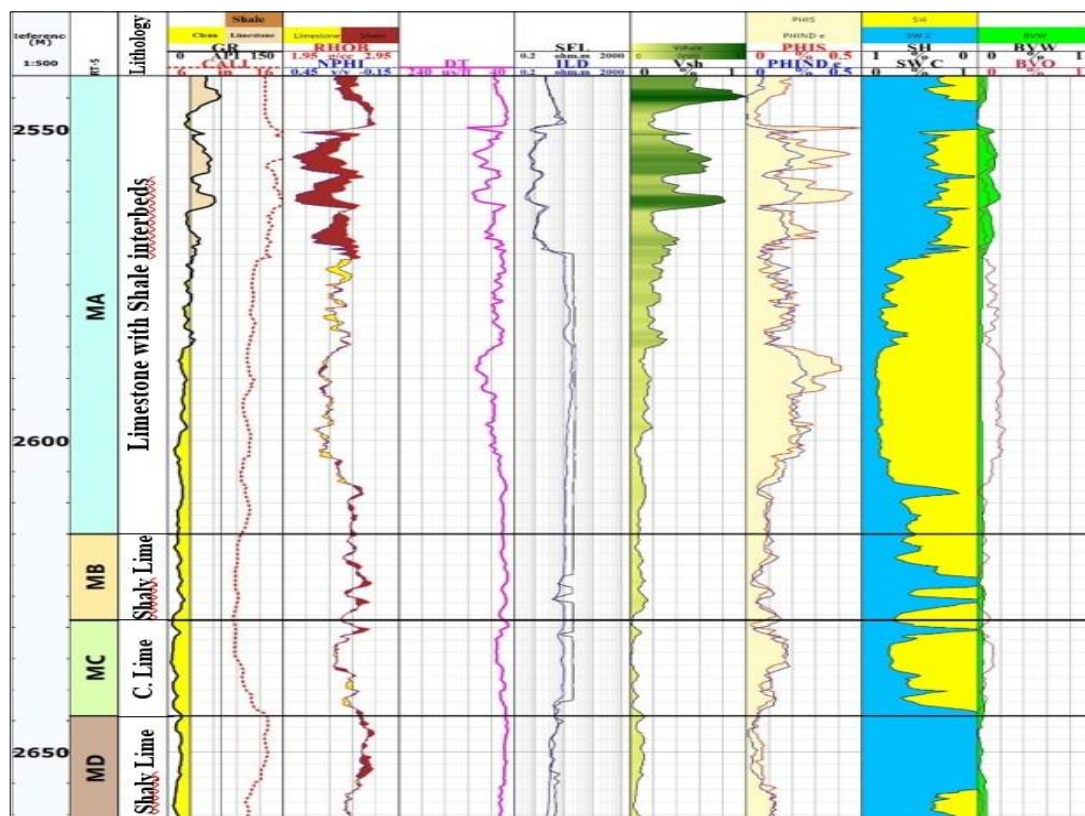


Fig. 6. Lithological interpretation and petrophysical characteristics of well Rt-5

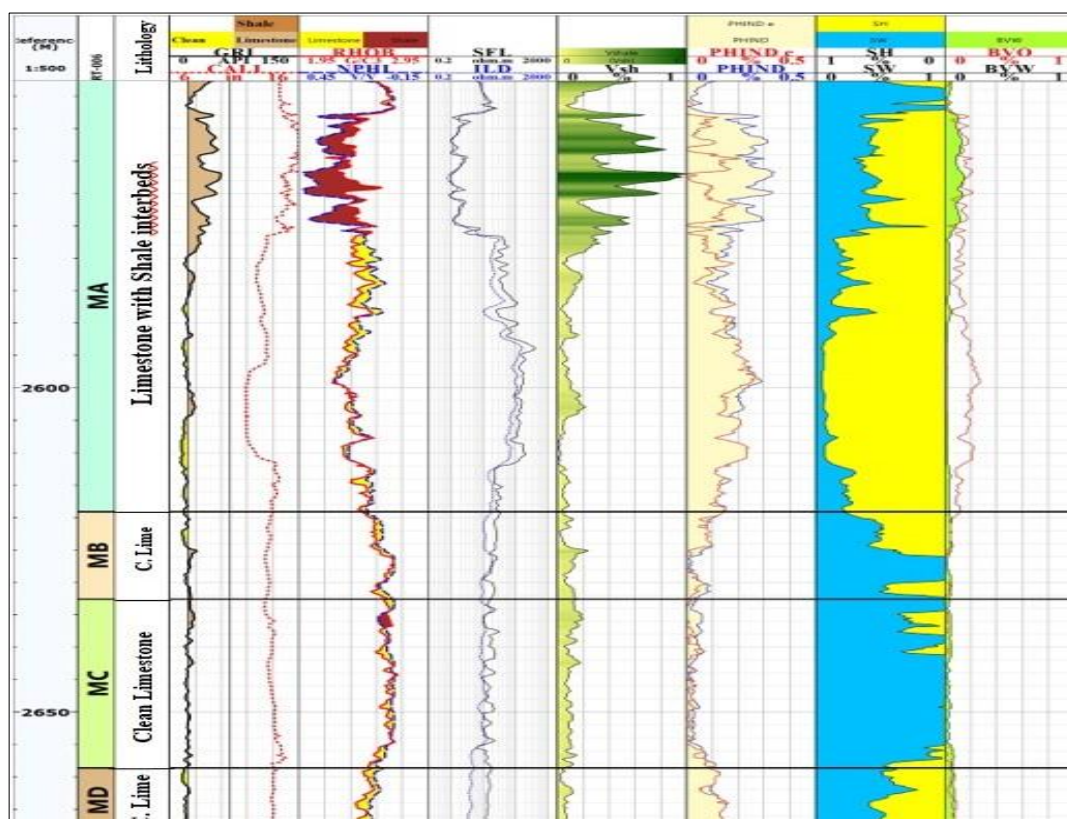


Fig. 7. Lithological interpretation and petrophysical characteristics of well Rt-6

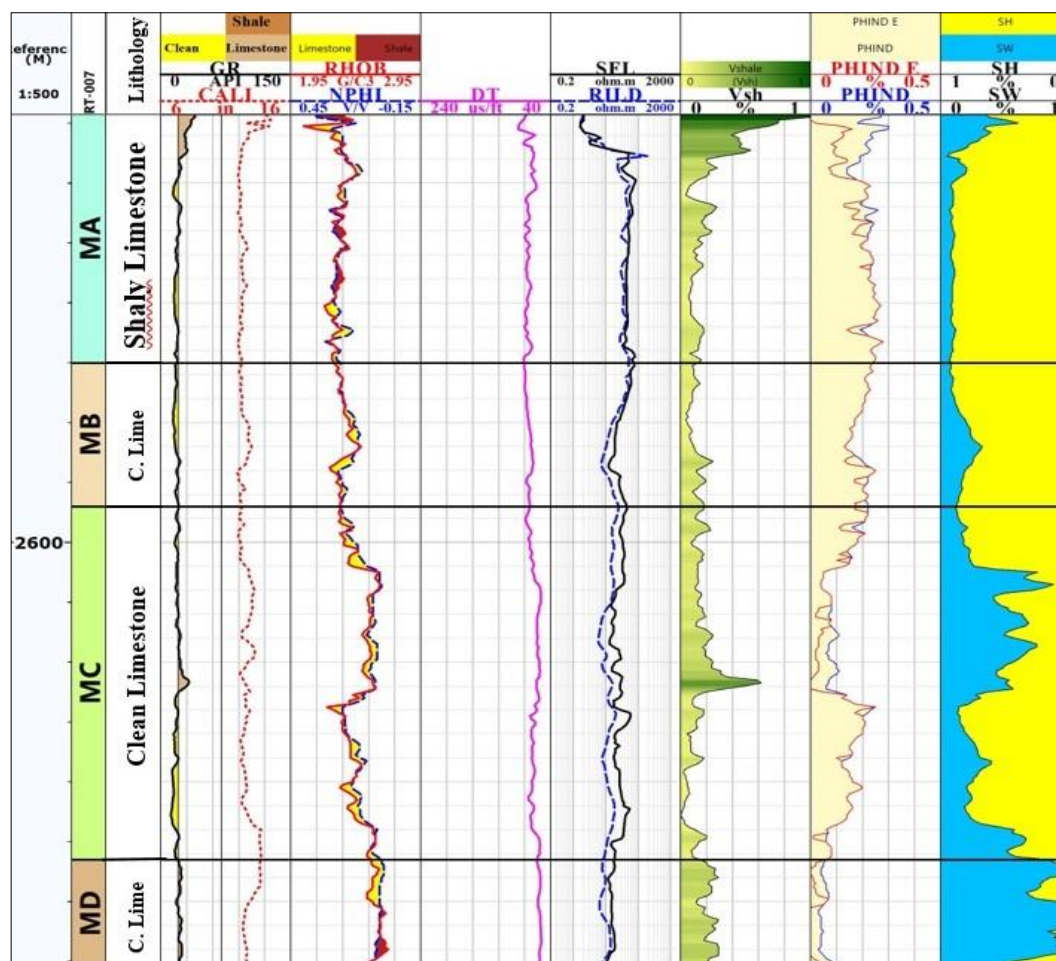


Fig. 8. Lithological interpretation and petrophysical characteristics of well Rt-7.

Table 4. The Porosity, Permeability and R35% values for the wells in the study area

Well No.	Units	Top (m)	Porosity (Φ %)	Permeability average (K) md	Pore throat radius at (35%)
RT-3	MA	2424.50	0.14	1075.0	Megaport
	MC	2506.00	0.12	975.0	Macroport
RT-4	MA	2518.80	0.12	1010.0	Megaport
	MC	2601.30	0.11	100.0	Macroport
RT-5	MA	2540.40	0.15	507.5	Macroport
	MC	2628.80	0.11	14.0	Mesoport
RT-6	MA	2552.60	0.12	1001.2	Megaport
	MC	2632.60	0.02	8.0	Microport
RT-7	MA	2526.70	0.17	1002.5	Megaport
	MC	2597.00	0.12	10.7	Mesoport

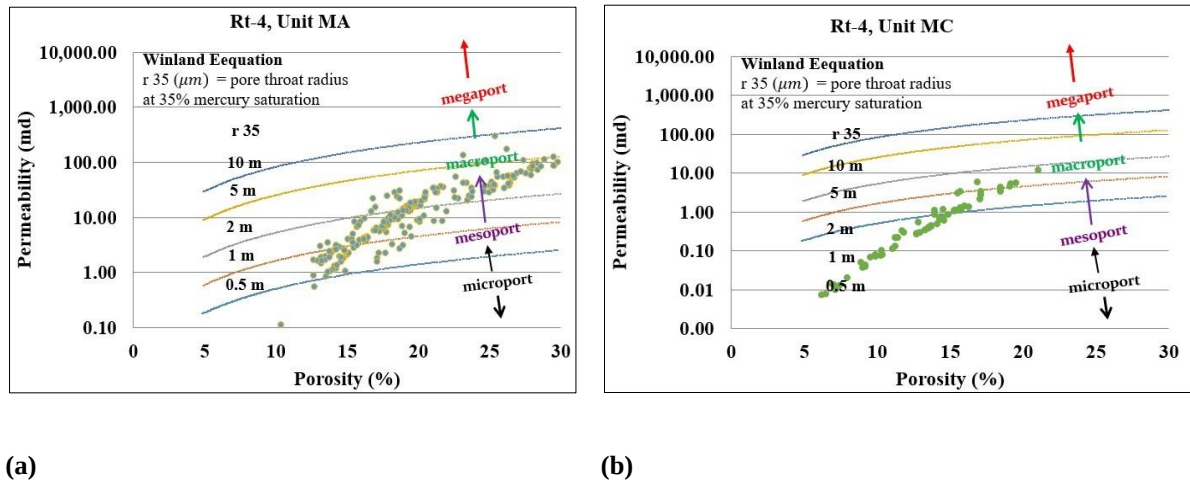


Fig. 9. a and b) The value of R35% from the relationship between ϕ and K for reservoir units.

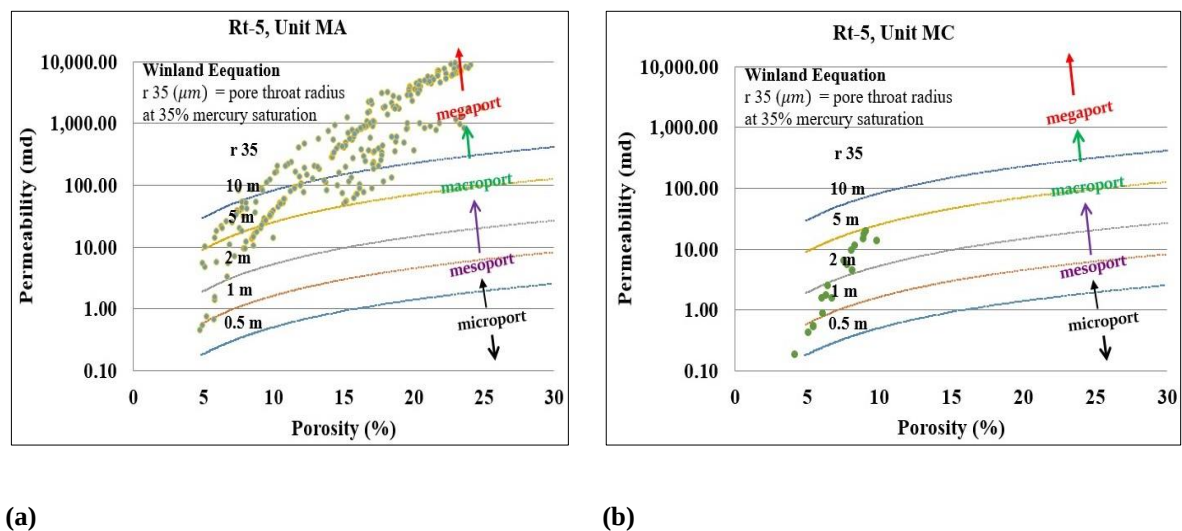


Fig. 10. a and b) The value of R35% from the relationship between ϕ and K for reservoir units.

4.3. Flow Unit Identification of the Mauddud Formation

The flow units of the study wells in the Mauddud Formation of the Ratawi Oil Field were identified and plotted using the Interactive Petrophysics (IP) program, based on the application of equations (14, 15, and 16). From the relationship between RQI and ϕ_z , the results indicate that wells Rt-4, Rt-6, and Rt-7 consist of three hydraulic flow units, whereas wells Rt-5 and Rt-3 consist of four hydraulic flow units within the studied interval of the Mauddud Formation. These differences reflect variations in pore structure and reservoir properties. And each line considered a hydraulic flow unit (HFU), as shown in Figs. 11 to 15.

The first and second hydraulic flow Units are characterized by low values of the hydraulic flow quality index (RQI) and small pores (micropores). This indicates low permeability and poor reservoir quality. While, the third and fourth hydraulic flow Units are characterized by the highest values of hydraulic flow quality index (RQI) and large pores (megapores), indicate good reservoir quality with improved permeability distribution. This illustrates the heterogeneity of the reservoir within the Mauddud Formation.

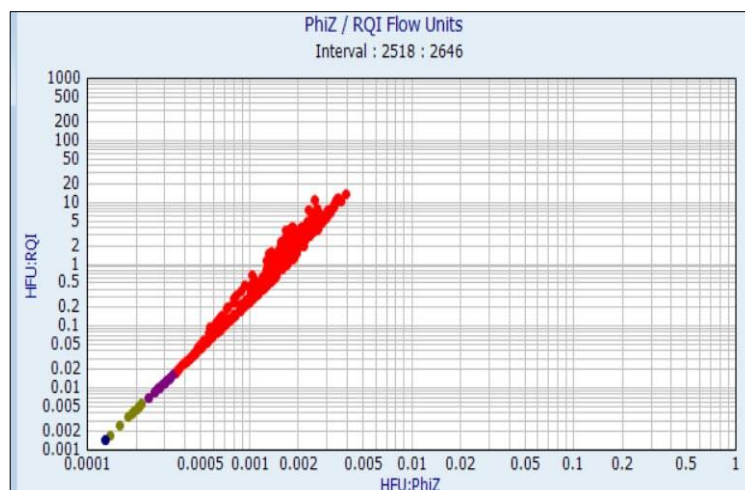


Fig. 11. Hydraulic flow quality index (RQI) & Phi-z (ϕz) for Rt-4 well.

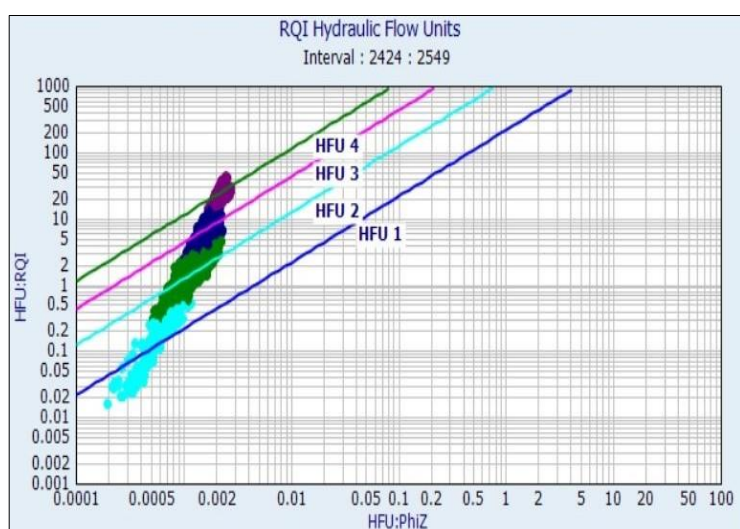


Fig. 12. Hydraulic flow Units (HFU) of the well Rt-3.

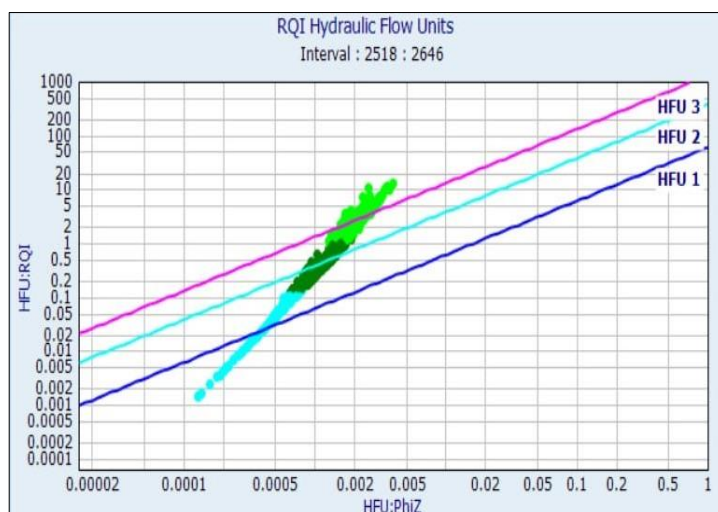


Fig. 13. Hydraulic flow Units (HFU) of the well Rt-4.

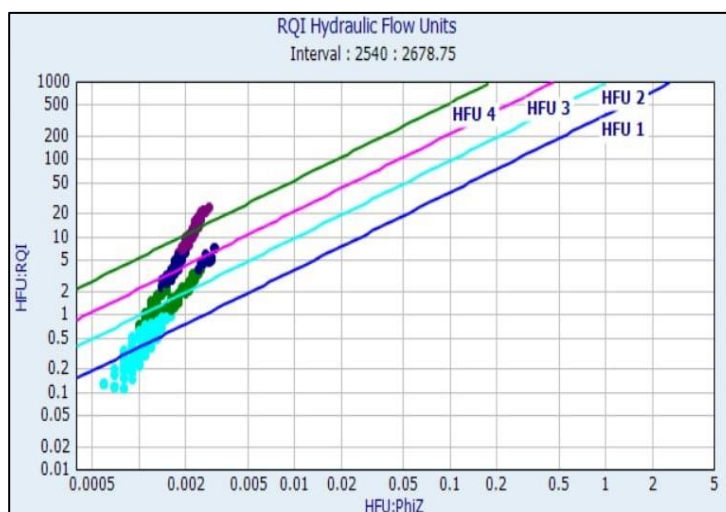


Fig. 14. Hydraulic flow Units (HFU) of the well Rt-5.

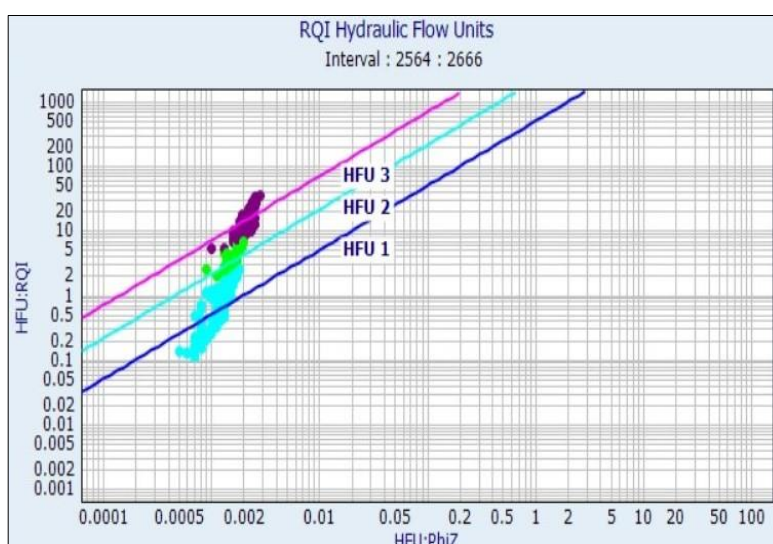


Fig. 15. Hydraulic flow Units (HFU) of the well Rt-7.

5. Conclusions

The Maaddud Formation is predominantly composed of limestone, as evidenced by the low readings of the gamma-ray log, except at intervals that contain shale percentages. Based on log behavior and petrophysical analysis, units MA and MC of the Maaddud Formation are classified as good reservoir units, whereas units MB and MD are considered poor.

Petrophysical results showed that the porosity values range between 10% and 26%, while water saturation ranged between 10% and 90%. R35, pore types and hydraulic flow units were determined using porosity and permeability values. In unit MA, permeability values range between 507.5 and 1075.0 mD, with pore types classified from macroport to megaport. In unit MC, permeability values range between 8.0 and 975.0 mD, with pore types ranging from microport to macroport.

The hydraulic flow units in the reservoir were identified based on Hydraulic flow quality index RQI and FZI. The results showed that wells Rt-4, Rt-6, and Rt-7 contain three hydraulic flow units. However, wells Rt-5 and Rt-3 contain four hydraulic flow units, reflecting greater heterogeneity in permeability distribution and pore structure.

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