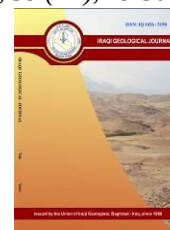




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Mineralogy, Porosity, and Permeability Relationship through the Yamama Formation in the Halfaya Oilfield, Southern Iraq

Hussein A. Abdulamer^{1*}  and Fahad M. Al-Najm¹ 

¹ Department of Geology, College of Science, Basrah University, Basrah, Iraq

* Correspondence: hussein.abdulamer@uobasrah.edu.iq

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Abstract

The present study aims to evaluate porosity and permeability in the Late Cretaceous Yamama Formation in the Halfaya oil field. The formation is divided by Maysan Oil Company into three main units (YRA, YRB, and YRC), with the upper unit (YRA) further subdivided into six subunits based on facies distribution. The dominant pore types were identified using bulk volume water relationships and include mainly chalky to intercrystalline porosity, with occasional vuggy porosity. The results show relatively low porosity values (5–12%), which significantly affect permeability, with most values below 1 mD, resulting in poor reservoir performance. Due to the limited availability of core data, the study also aimed to identify the most suitable empirical relationship for estimating permeability from well logs; 7 wells were used in the study. The XF6 well showed the best results, which is located southeast of the fold. The Wyllie equation showed better agreement with core permeability data than the Timur and Coates equations and was therefore adopted for permeability estimation. Weinland analysis indicates that most units fall within the Microport range, suggesting very low productivity unless enhanced recovery methods are applied. However, some units fall within the Macroport range of nearly 1000 BPD and exhibit better reservoir quality and higher production potential. The petrophysical results are supported by scanning electron microscope (SEM) analysis, which confirmed the identified pore types and revealed the presence of minerals (pyrite, feldspar, calcite, barite, chlorite, and minor quartz), and the presence of dolomite and the clay content both negatively affect porosity and permeability.

Keywords: Southern Iraq; Halfaya Oilfield; Yamama Formation; Permeability; Mineralogy

1. Introduction

The Halfaya Oilfield is one of the most important producing fields in Iraq, playing a pivotal role in supporting national crude oil production and contributing significantly to the country's hydrocarbon reserves. Since its discovery, the field has been the focus of numerous development programs aimed at increasing production and improving reservoir recovery, particularly given the technical challenges posed by pressure variations and the multiplicity of producing rock units (Aljibouri et al., 2022). The Yamama Formation is considered one of the most important reservoir units in the Halfaya field, forming the production column in many of the field's wells. This formation consists primarily of complex carbonate rocks deposited during the Early Cretaceous period, characterized by varying porosity, including intercalary and secondary porosity such as fractures and fissures (Wright and Burchette, 1998). These structural and petrophysical characteristics influence reservoir flow behavior,

necessitating the application of advanced analytical models to identify flow units and optimize production plans (Aoudah, 2025).

The focus of research and development efforts on understanding the Yamama Formation in the Halfaya field stems not only from its importance as a major oil reservoir but also from its direct impact on assessing recoverable reserves and determining optimal exploitation techniques. Integrating geological and surveying. Due to the importance of this formation in southern Iraq, it has been studied in various fields. Studies by Al-Shahwan (2002) show that the Yamama Formation serves dual purposes: it's both a source rock and a reservoir rock for various fields. In the Nasiriyah Oilfield, Al-Ismaili (2011) describes the Yamama Formation as a clean limestone with very little shale and low permeability in most of the formation. In the West Qurna Oilfield, Al-Issa (2012) and Al-Issa (2023) divided the formation into three reservoir units and, from a carbonate ramp perspective, placed YB as the best reservoir unit; dolomitization and compaction affect porosity. According to Chafeet's (2016) study of southern Iraq, poorly defined facies have left the descriptions of the various facies in the Yamama Formation; however, the highest reservoir quality appeared to be associated with deposits from oolitic shoal environments. Overall, however, Al-Khafaji et al. (2022) described the Yamama Formation as a shallow-water carbonate ramp deposit with some clastic input throughout the southern Mesopotamian Basin. This study in the Halfaya oilfield aims to determine the porosity and permeability of the Yamama Formation.

1.1. Study Area

The Halfaya Oilfield is one of Iraq's most prolific and strategically important oilfields, located in southeastern Iraq near the city of Amarah in Maysan Governorate. It is a northwest-southeast trending anticline, approximately 34 km long and 10 km wide, with a total field area of 288km² (Al-Bahadli, 2018). It is located between Latitude 31.53°N – 31.65°N and Longitude 47.95°E – 48.08°E (Fig. 1).

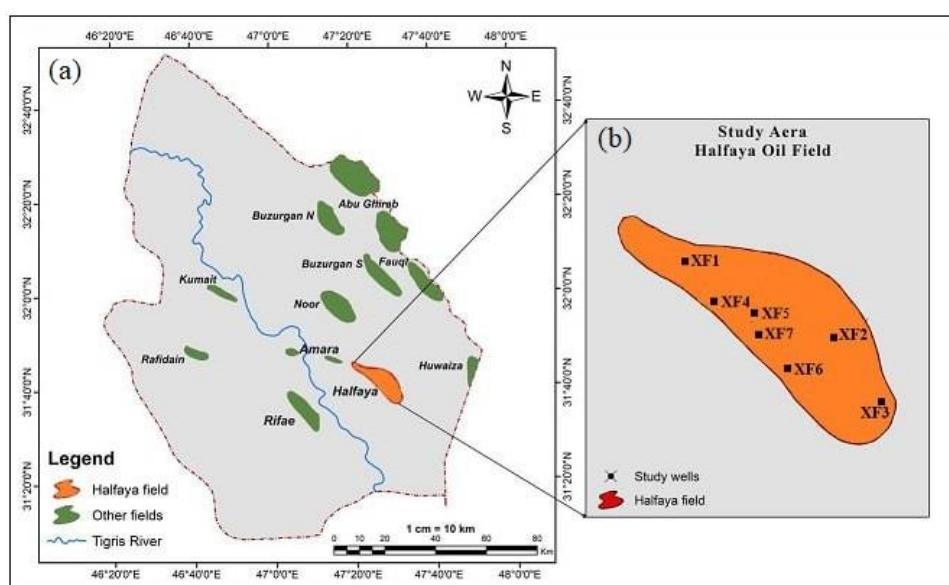


Fig. 1. a) Location of the study area and b) Location and distribution of the study wells

1.2. Geological Setting

The study area is located in the unstable shelf of Iraq (Jassim and Buday, 1987). It is of the Tigris sub-range type in the Wadi Al-Rafidain range area (Tigris-Euphrates-Arabian Gulf) and situated south part of the Wadi Al-Rafidain (South Mesopotamian Block), which represents one of the transverse

blocks that were located within. The research has been conducted on the stable shelf of the Mesopotamian Zone and the Tigris Subzone (Jassim and Goff, 2006). Also, since 1997, several broad geological surveys carried out by GEOSURV have provided new geological, geophysical, and remotely sensed data. Compilations of these updated data led to the construction of an improved tectonic map with added detail and revised for Plate Tectonic thought, which developed into the most recent version that appeared in 2012. The Outer Platform is the main section of the Mesozoic Arabian Plate's passive margin and the Late Cretaceous foreland basin, and it has been heavily influenced by Alpine orogenic deformation. According to modern views on orogenic belts and their related foreland basins, geodynamic processes vary widely across the Outer Platform. As a result, it is divided into the Mesopotamia Foredeep and the Western Zagros Fold-Thrust Belt. The Mesopotamia Foredeep is the land-based remnant of the Zagros foreland basin, stretching southeast to meet its marine extension in the Arabian Gulf. It lies between the stable continental area (the Inner Platform) and the Zagros mountain front to the northeast. This largely flat region is covered by Miocene to Holocene restricted marine and continental deposits and contains numerous buried, and in some cases neotectonically active, structures. Based on differences in mobility and activity, it is further divided into the Al-Jazira subzone in the north and the Basra subzone in the south (Fouad, 2015) (Fig. 2).

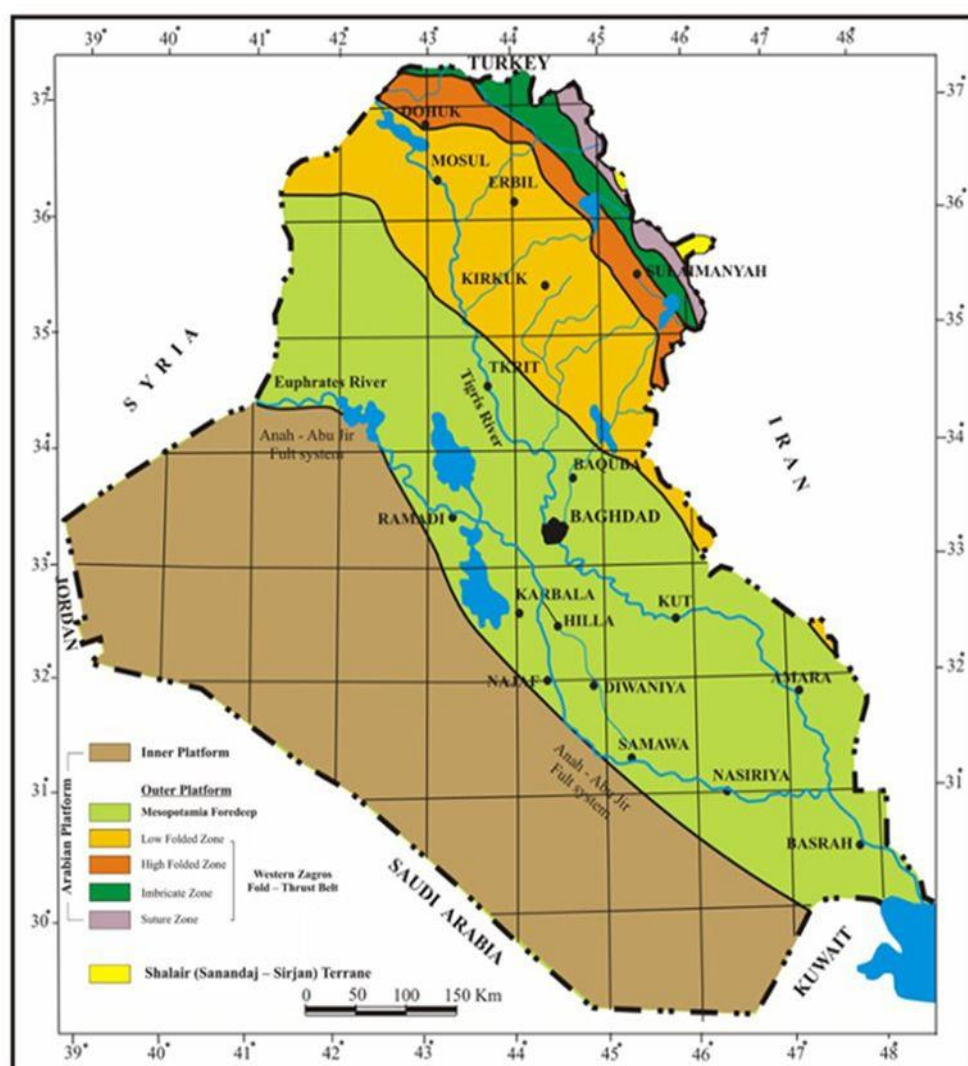


Fig. 2. Tectonic divisions of Iraq (Fouad, 2015)

2. Materials and Methods

Neutron, density, gamma ray, and resistivity probes were used to calculate the various equations.

2.1. Calculation of Petrophysical Properties

Petrophysical parameters, including shale volume, porosity, hydrocarbon saturation, and water saturation, were calculated from well logs for reservoir evaluation and fluid distribution analysis.

2.1.1. Total Porosity (Φ_{N-D}) and Effective Porosity (Φ_{eff})

Total Porosity is determined using density and neutron logs, while Effective Porosity is derived by correcting the total value for the presence of shale and also from the gamma ray log in relation to actual fluid densities of the formation (Darling, 2005; Schlumberger, 1997).

$$\Phi_{Den.} = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \quad (1)$$

$$\Phi_{N-D} = \frac{\Phi_N - \Phi_D}{2} \quad (2)$$

$$\Phi_{eff.} = \Phi_{N-D} \times (1 - V_{sh}) \quad (3)$$

Where: $\Phi_{Den.}$: Density-derived Porosity; ρ_{ma} : matrix density (2.71 g/cm³); ρ_b : Bulk density of the formation (g/cm³); ρ_f : density of fluid (1.1 g/cm³ for Salt Mud, 1.0 g/cm³ for Fresh Mud, and 0.7 g/cm³ for Gas); Φ_{N-D} : Neutron Density Porosity; Φ_N : Neutron Porosity; $\Phi_{eff.}$: Effective porosity corrected for shale content; V_{sh} : computed shale volume.

2.1.2. Water saturation (S_w)

Water saturation is determined from resistivity logs. (Archie, 1942; Arps, 1964; Asquith et al., 2004).

$$S_w = \sqrt{(F \times R_w / R_t)} \quad (4)$$

$$F = \frac{a}{\Phi^m} \quad (5)$$

Where: S_w is the water saturation in the uninvaded zone; F represents the formation factor; R_w is the resistivity of formation water ($\Omega \cdot m$); R_t denotes the resistivity of the uninvaded zone measured from resistivity logs ($\Omega \cdot m$).

Table 1. Acoustic velocities and densities of various lithologies and fluids (Asquith et al., 2004; Schlumberger, 1972)

Lithology	ρ_{ma} (g/cm ³)	Δt_{ma} (μ sec/ft)
limstone	2.71	47.6
Saltwater filtrate	1.150	185

2.1.3. Bulk Volume of Water (BV_w)

The bulk volume of water is calculated to provide insights into fluid distribution within the reservoir (Schlumberger, 1997).

$$BV_w = S_w \times \Phi_{N-D} \quad (6)$$

Where: BV_w represents the bulk volume of water in the uninvasion zone.

2.1.4. Permeability (K)

Permeability is the property of a rock by which it can transmit fluid and that fluid's ability to flow through the rock (Maute, 2003), or in other words, its conductivity. The permeability depends on the rock's grain size, shape, class of particle packing, degree of cementation and indurization, as well as the presence/absence of shale clay, among other factors (Table 2) (Darling, 2005; Djebbar and Donaldson, 2004; Schlumberger, 1972).

Table 2. Classification of permeability

Level	Permeability (K)
Poor	< 1
Moderate	1-10
Good	10-100
Very good	100-1000
Excellent	> 1000

$$\text{Hyperbolic Equation } (BV_w) = \Phi_{\text{eff.}} \times S_w \quad (7)$$

After redrawing the hyperbolic lines using Excel (Fig. 3) and projecting the porosity and water saturation values of the reservoir units of the Yamama reservoir. The analysis results showed that all units were Irreducible in all wells except for unit 2 in well 6 and unit 6 in well 7, where the first unit was displaceable and the second was non-permeable (Figs. 4 and 5). Therefore, the permeability of these units can be calculated using the specific equations used to calculate it from the boreholes, then the equation was applied to calculate the permeability and (Coates and Dumanoir, 1973) proposed the following equation for calculating permeability from boreholes. It also requires a non-displaceable water saturation state (Balan et al., 1995) and Timur's equation (Timur, 1968) was also used to calculate permeability, but it showed very low values, almost zero, in all the wells studied; therefore, its results were ignored.

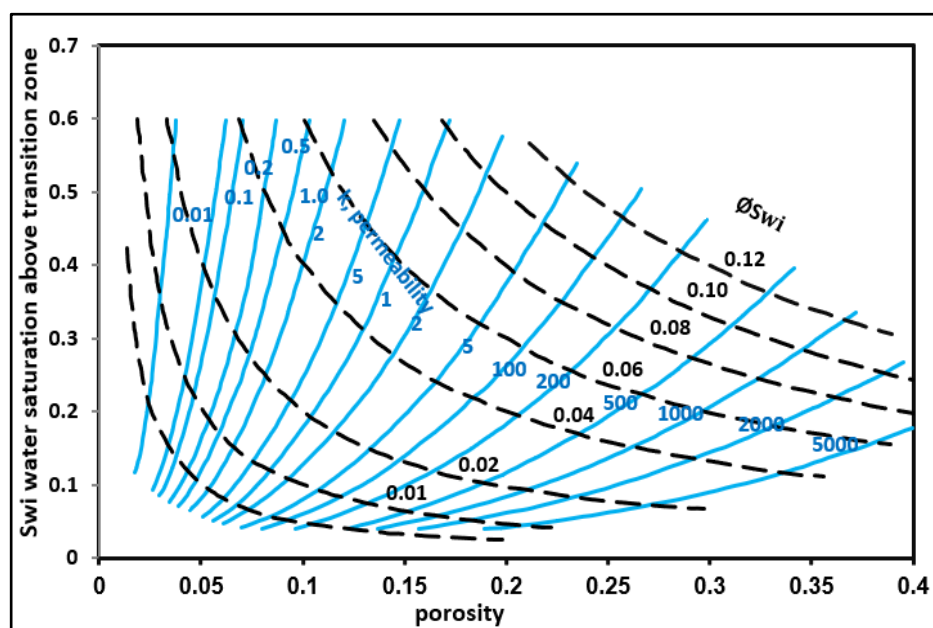


Fig.3. Chart of porosity ($\Phi_{\text{eff.}}$) versus Irreducible Water Saturation ($S_{w\text{irr}}$) for estimating Permeability (Schlumberger, 1997)

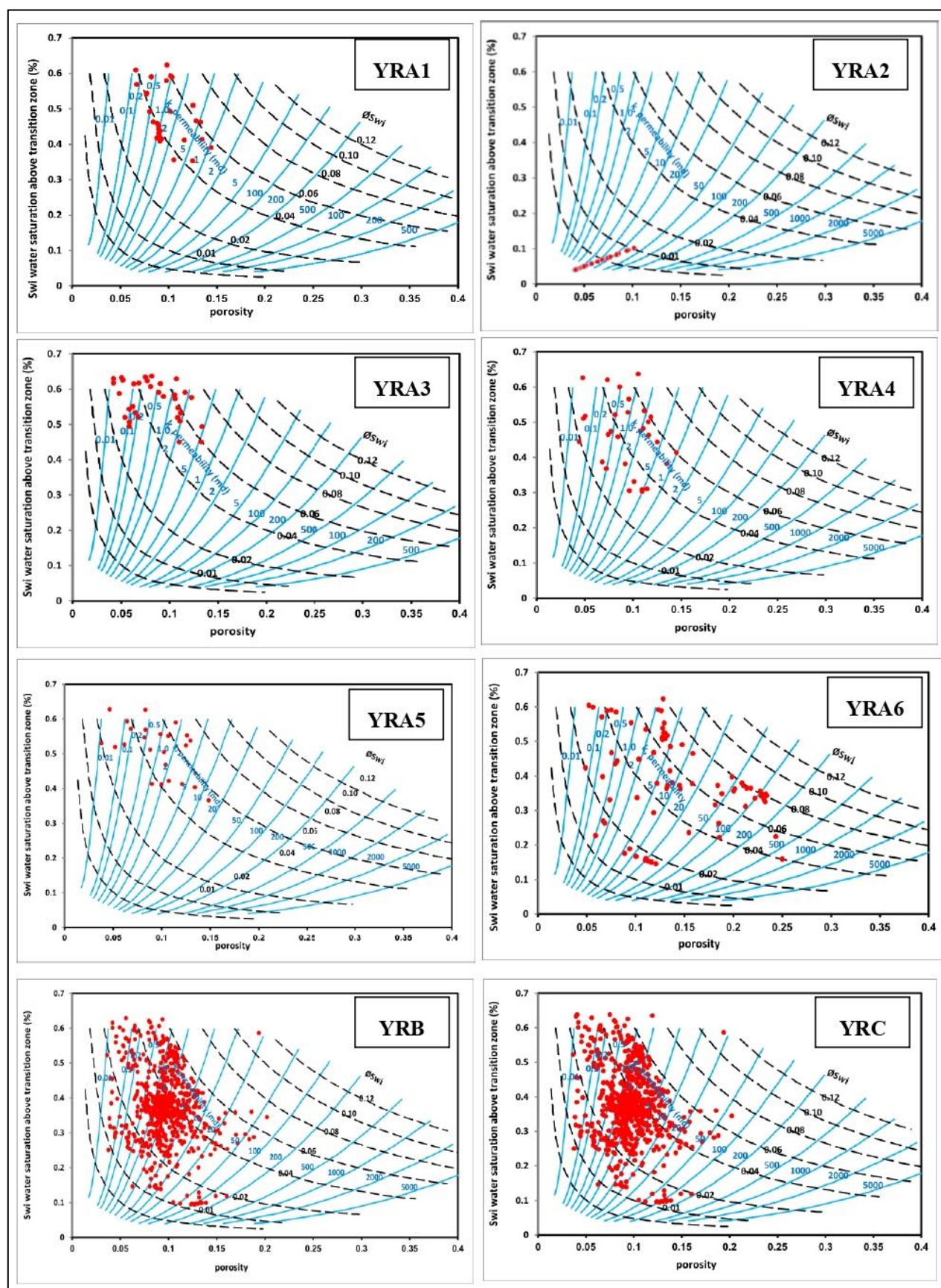


Fig.4. Charts of (Φ_{eff}) versus (S_{wirr}) for estimating permeability for reservoir units for the well XF6

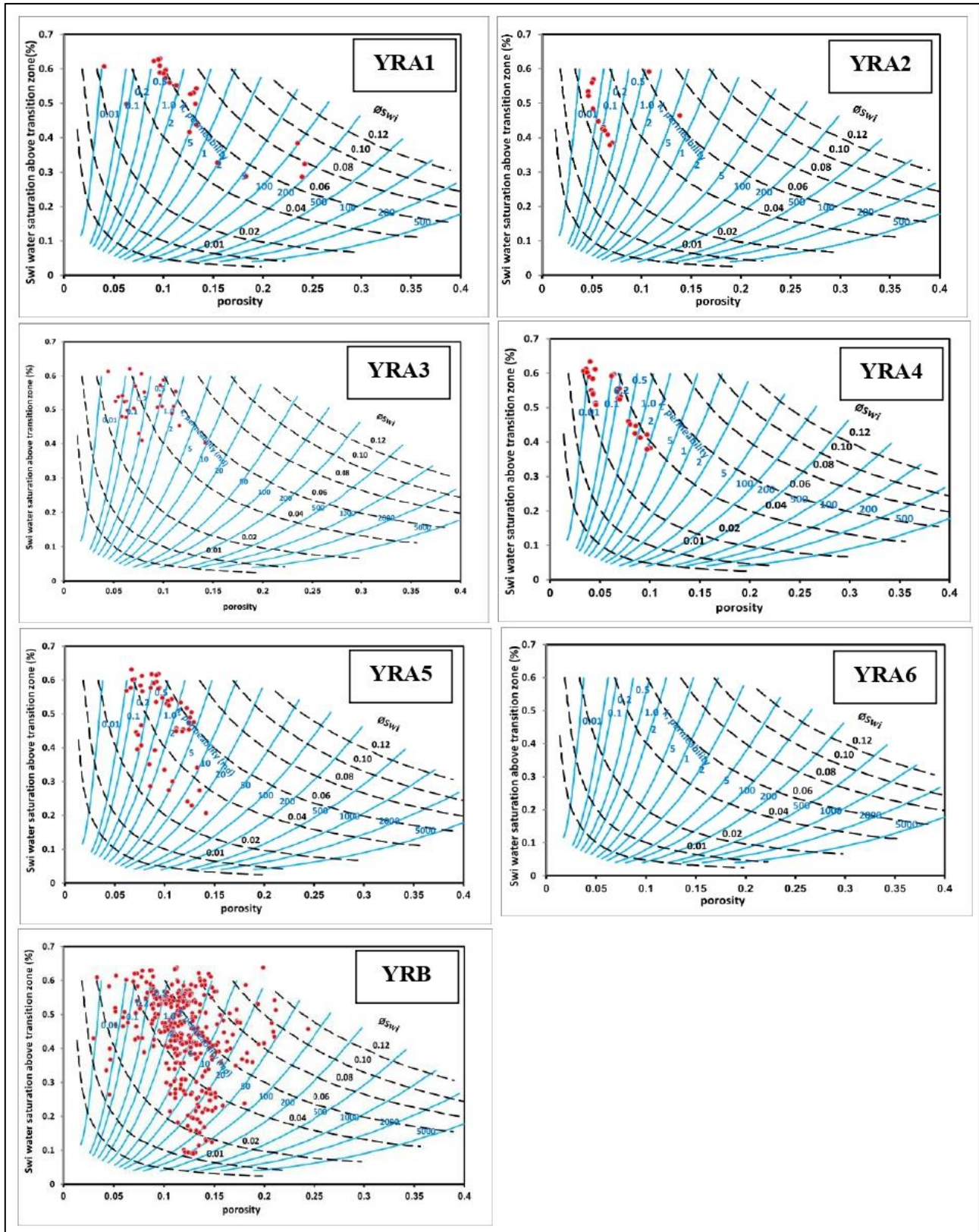


Fig.5. Charts of (Φ_{eff}) versus (S_{wirr}) for estimating permeability for reservoir units for the well XF7

$$K = \left[c \left(\frac{\Phi_{eff}^3}{S_{wirr}} \right) \right]^2 \quad (8)$$

$$K^{1/2} = \left[100 \times \left(\frac{\Phi_{eff}^2 (1 - S_{wirr})}{S_{wirr}} \right) \right]^2 \quad (9)$$

$$K = 0.136 \times \left(\frac{\Phi_{eff}^{4.4}}{S_{wirr}^2} \right) \quad (10)$$

Where: K: Permeability (mD); C: Constant, its value equals 250 for medium oil and 79 for dry gas; Φ_{eff} : Effective Porosity; S_{wirr} : Irreducible water saturation.

2.1.5. Winland Equation (R35)

The R35 curve is used to distinguish between flow units with varying inflow performance and those with identical pore-throat radii (Martin et al., 1997). The Winland equation, which uses measured K and Φ values to determine R35 for a rock sample.

$$\text{Log R35} = 0.732 + 0.588 \text{Log}(\Phi_{eff}) - 0.864 \text{Log}(K) \quad (11)$$

Where: R35: The pore throat radius (microns) corresponding to the 35th percentile.

2.2. Scanning Electron Microscopy (SEM)

SEM is a versatile tool for characterizing the morphology and microstructure of materials at the sub-micron scale, as it enables high-resolution imaging of surface features (Goldstein et al., 2017). In this study, SEM is used to identify the mineralogical composition of shale samples based on different minerals. SEM is also used to distinguish pore types and to evaluate porosity attributes, particularly microporosity associated with the clay matrix.

3. Results and Discussion

3.1. Determining the Type of Porosity from (BV_w)

Bulk volume water is defined as the product of the porosity (Φ_{eff}) of the formation (equation 3) and its water saturation. Bulk volume of water is determined in the uninvaded zone (equation 6). Where the bulk volume water values in a zone are constant or nearly constant, it follows that the zone is at irreducible water saturation, so the water in the uninvaded zone cannot move. Therefore, any produced hydrocarbon should be water-free (Asquith et al., 2004). Table 3 illustrates the relationship between the (BV_w) and the porosity (Φ_{eff}).

Table 3. Relationship between the (BV_w) and porosity in carbonates (Asquith et al., 2004)

Porosity (Φ_{eff})	Bulk Volume Water (BV _w)
Vuggy	0.005 to 0.015
[Vuggy and intercrystalline (intergranular)]	0.015 to 0.025
Intercrystalline	0.025 to 0.04
Chalky	0.05

The petrophysical analysis of the Yamama Formation shows that the reservoir is mainly controlled by variations in pore types and their distribution. The main porosity types include intercrystalline, chalky, and vuggy porosity. Intercrystalline porosity occurs between crystals and is generally associated with better permeability due to improved pore connectivity. Chalky porosity consists of very fine micropores within soft limestone, providing good storage capacity but relatively low permeability. Vuggy porosity is represented by larger dissolution cavities, which can significantly enhance fluid flow

when interconnected. Overall, the reservoir is predominantly characterized by intercrystalline, chalky porosity, with localized development of vuggy porosity, reflecting the impact of diagenetic processes on reservoir heterogeneity.

Overall, variations in porosity types (Intercrystalline, Chalky, and Vuggy–Intercrystalline). This porosity variation is similar to the type of porosity observed in the Al-Issa (2012) study in the West Qurna oilfield. and BV_W – Φ_{eff} . Ranges across wells XF1–XF7 reflect reservoir heterogeneity in the Yamama Formation (Table 4), consistent with previous studies emphasizing the influence of pore systems and lithological variations on reservoir quality and performance.

Table 4. Relationship between (BV_W) and (Φ_{eff}) in Yamama Formation

Well	Unite	BV_W %	Φ_{eff} %	Porosity Type
XF1	YRA1	0.03-0.09	0.06	Intercrystalline -Chalky
	YRA2	0.02-0.08	0.03	Intercrystalline -Chalky
	YRA3	0.01-0.07	0.05	Vuggy and intercrystalline-Chalky
	YRA4	0.01-.09	0.05	Vuggy and intercrystalline-Chalky
	YRA5	0.01-0.08	0.06	Vuggy and intercrystalline-Chalky
	YRA6	0.01-0.12	0.07	Vuggy and intercrystalline-Chalky
XF2	YRA1	0.03-0.12	0.11	Intercrystalline -Chalky
	YRA2	0.03-0.11	0.06	Intercrystalline -Chalky
	YRA3	0.02-0.09	0.08	Intercrystalline -Chalky
	YRA4	0.02-0.09	0.07	Intercrystalline -Chalky
	YRA5	0.04-0.12	0.1	Chalky
	YRA6	0.05-0.06	0.05	Intercrystalline -Chalky
XF3	YRA1	0.03-0.14	0.11	Intercrystalline -Chalky
	YRA2	0.04-0.07	0.04	Chalky
	YRA3	0.03-0.09	0.07	Intercrystalline -Chalky
	YRA4	0.03-0.10	0.09	Intercrystalline -Chalky
	YRA5	-	-	-
	YRA6	-	-	-
XF4	YRA1	0.03-0.10	0.07	Intercrystalline -Chalky
	YRA2	0.02-0.08	0.05	Intercrystalline -Chalky
	YRA3	0.02-0.08	0.05	Intercrystalline -Chalky
	YRA4	0.01-0.08	0.06	Vuggy and intercrystalline-Chalky
	YRA5	0.01-0.09	0.06	Vuggy and intercrystalline-Chalky
	YRA6	0.03-0.1	0.06	Intercrystalline -Chalky
XF5	YRA1	0.03-0.11	0.05	Intercrystalline -Chalky
	YRA2	0.02-0.08	0.05	Intercrystalline -Chalky
	YRA3	0.02-0.09	0.06	Intercrystalline -Chalky
	YRA4	0.02-0.09	0.05	Intercrystalline -Chalky
	YRA5	0.02-0.01	0.06	Intercrystalline -Chalky
	YRA6	0.01-0.12	0.06	Vuggy and intercrystalline-Chalky
	YRB	0.04-0.13	0.08	Chalky
XF6	YRA1	0.03-0.12	0.07	Intercrystalline -Chalky
	YRA2	0.03-0.11	0.04	Intercrystalline -Chalky
	YRA3	0.02-0.09	0.06	Intercrystalline -Chalky
	YRA4	0.02-0.09	0.05	Intercrystalline -Chalky
	YRA5	0.04-0.12	0.05	Chalky
	YRA6	0.05-0.06	0.12	Chalky
	YRB	0.01-0.14	0.1	Vuggy and intercrystalline-Chalky
	YRC	0.01-0.14	0.08	Vuggy and intercrystalline-Chalky
XF7	YRA1	0.03-0.10	0.08	Intercrystalline -Chalky
	YRA2	0.02-0.07	0.04	Intercrystalline -Chalky
	YRA3	0.03-0.08	0.05	Intercrystalline -Chalky
	YRA4	0.02-0.05	0.03	Intercrystalline -Chalky
	YRA5	0.04-0.09	0.07	Chalky
	YRA6	0.03-0.11	0.03	Intercrystalline -Chalky
	YRB	0.01-0.13	0.09	Vuggy and intercrystalline-Chalky

3.2. Permeability

Three methods were used to calculate the appropriate permeability for the format, and the most suitable method was determined based on the logs. The results presented in Table 5, indicate that the permeability values of the reservoir units within the Yamama Formation in the studied wells range from poor <1 md to good >10 md, reflecting favorable reservoir quality. The results obtained from the logs were then compared with the core analysis and it was found that Wiley's equation was the most suitable because the R^2 ratio (Fig. 6) was greater than 0.7, thus providing confidence in its results also the permeability levels were similar to those of Al-Ismaili (2011) study in the Nasiriyah oil field.

Table 5. Permeability values for the wells of the study area (Coates and Dumanoir, 1973).

Well	Unit	Member	K (Coates and Dumanoir, 1973)				K(Wyllie et al., 1958)			
			Min	Max	Average	Level	Min	Max	Average	Level
XF1	YRA	1	0.02	2.15	0.72	Poor	0.02	0.47	0.14	Poor
		2	0.01	0.21	0.09	Poor	0.02	0.10	0.04	Poor
		3	0.01	7.72	0.89	Poor	0.01	0.55	0.11	Poor
		4	0.02	500.03	76.34	Good	0.01	350.05	49.71	Good
		5	0.01	401.3	40.89	Good	0.01	310.44	17.33	Good
		6	0.02	124.16	9.58	Moderate	0.01	60.47	3.96	Moderate
XF2	YRA	1	0.01	99.4	13.12	Good	0.03	90.47	11.27	Good
		2	0.01	17.96	2.05	Moderate	0.01	12.86	2.39	Moderate
		3	0.02	14.79	2.15	Moderate	0.01	3.25	0.87	Poor
		4	0.01	262.78	20.71	Good	0.01	489.03	36.23	Good
		5	0.01	21.54	3.94	Moderate	0.01	14.01	2.23	Moderate
		6	0.03	0.2	0.12	Poor	0.01	0.03	0.02	Poor
XF3	YRA	1	0.01	15.82	1.86	Moderate	0.02	17.02	1.56	Moderate
		2	0.01	1.56	0.44	Poor	0.02	2.65	0.62	Poor
		3	0.01	8.91	1.63	Moderate	0.01	3.61	0.83	Poor
		4	0.01	71.31	8.47	Moderate	0.01	18.46	2.98	Moderate
XF4	YRA	1	0.01	8.18	1.19	Moderate	0.01	2.33	0.39	Poor
		2	0.01	5.64	0.88	Poor	0.02	0.73	0.24	Poor
		3	0.01	2	0.32	Poor	0.01	0.54	0.12	Poor
		4	0.01	179.9	6.17	Moderate	0.01	144.79	3.36	Moderate
		5	0.02	12.3	1.53	Moderate	0.01	3.88	0.44	Poor
		6	0.02	85.75	5.93	Moderate	0.01	45.06	2.98	Moderate
XF5	YRA	YRB	0.01	28.96	5.5	Moderate	0.01	28.96	1.16	Moderate
		1	0.02	0.63	0.2	Poor	0.01	0.23	0.08	Poor
		2	0.01	4.78	0.6	Poor	0.01	0.58	0.12	Poor
		3	0.01	44.69	1.61	Moderate	0.01	7.6	0.39	Poor
		4	0.01	1.89	0.29	Poor	0.01	0.22	0.05	Poor
		5	0.01	2.26	0.28	Poor	0.01	0.39	0.11	Poor
		6	0.01	6.54	0.54	Poor	0.01	0.51	0.09	Poor
		YRB	0.01	6.04	0.01	Poor	0.01	6.04	0.31	Poor
		1	0.02	10.39	1.52	Moderate	0.03	3.63	0.47	Poor
		2			-	-			-	-
XF6	YRA	3	0.01	4.57	0.4	Poor	1.1	1.66	1.2	Moderate
		4	0.01	8.78	1.46	Moderate	0.01	3.35	0.52	Poor
		5	0.01	14.48	0.89	Poor	0.01	9.95	0.33	Poor
		6	0.01	983.3	39.81	Good	0.01	596.49	24.42	Good
		YRB	0.01	740.87	9.49	Moderate	0.01	94.05	1.72	Moderate
		YRC	0.01	73.91	3.91	Moderate	0.01	1.19	1.19	Moderate
XF7	YRA	1	0.01	203.82	15.35	Good	0.01	143.75	10.63	Good
		2	0.01	4.9	0.35	Poor	0.01	2.05	0.28	Poor
		3	0.01	9.05	0.49	Poor	0.01	3.19	0.22	Poor
		4	0.01	2.64	0.46	Poor	0.01	0.43	0.12	Poor
		5	0.01	58.89	3.35	Moderate	0.01	11.7	0.63	Poor
		6			-	-			-	-
	YRB		0.02	1.54	0.46	Poor	0.01	0.11	0.11	Poor

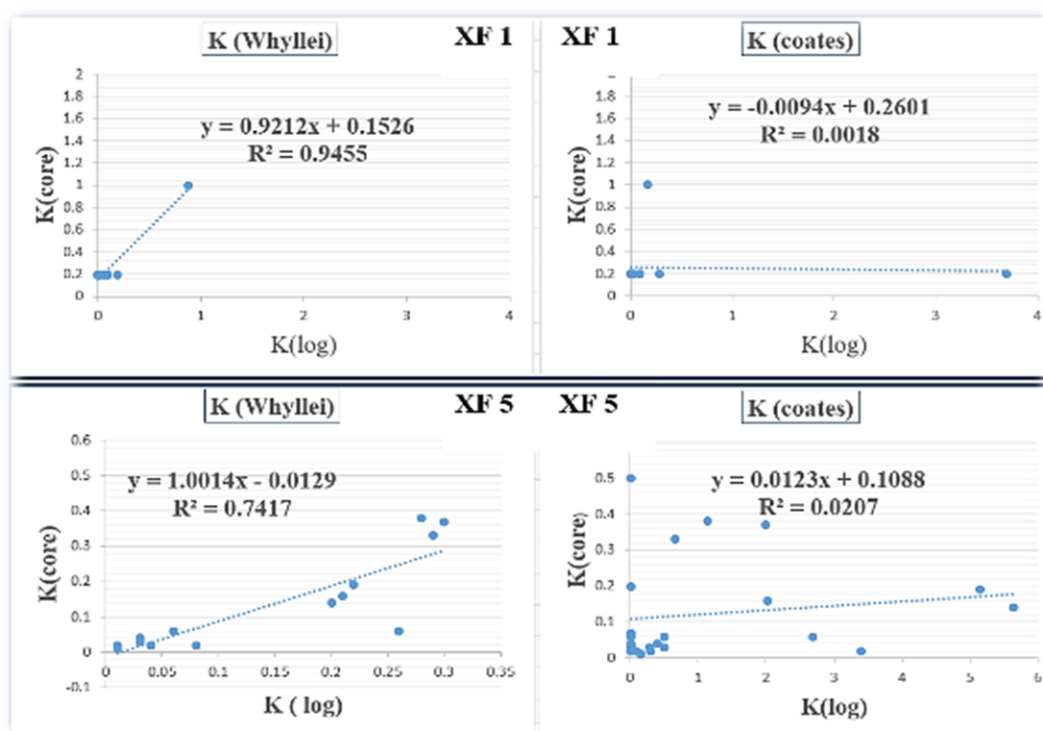


Fig. 6. Coefficient of determination for the result permeability for the wells XF1 and XF5 with core values

The distribution of permeability across each well (Fig. 7) is sorted by their position in relation to the oil field. Wells located in the central area of the oil field (XF4, XF5, and XF7) have generally poor permeability throughout most units of strata and thus poorer quality as compared to the periphery of the oil field. Wells at the field periphery exhibit much greater permeability variation (ranging from poor to good). In terms of lateral relationships among strata, YRA1 and YRA4 both provide the best-quality reservoir intervals for most wells and represent the most reliable flow units within the Yamama Formation, as evidenced by their much higher permeabilities relative to the other strata in this region.

3.3. Porosity and Permeability Relationship

The permeability values obtained in the second step are plotted against porosity using the Empirical model, and the resulting relationship is used to assess the performance of reservoir facies.

Martin et al. (1997) used the R35 parameter, along with other petrophysical, geological, and engineering data, to identify flow units in five carbonate reservoirs. Flow units are grouped by pore throat size using the designations shown in Figs. 8, 9, and 10: Megaport (> 10 microns), macroport (2-10 microns), mesoport (0.5-2 microns), and microport (0.5 microns). A completion analysis for the different R35 size ranges in a reservoir of medium thickness and medium gravity oil yielded the following:

- Megaport, 10 thousand barrels of oil per day.
- Macroport, 1000 barrels of oil per day.
- Mesoport, 100 barrels of oil per day.
- Microport, nonreservoir.

After flow units are identified, well logs and sequence stratigraphy are used to delineate zones with similar properties where no core data are available. The method works well in carbonates where flow is controlled by intergranular, intercrystalline, or interparticle pore space. The results are shown in Table 6

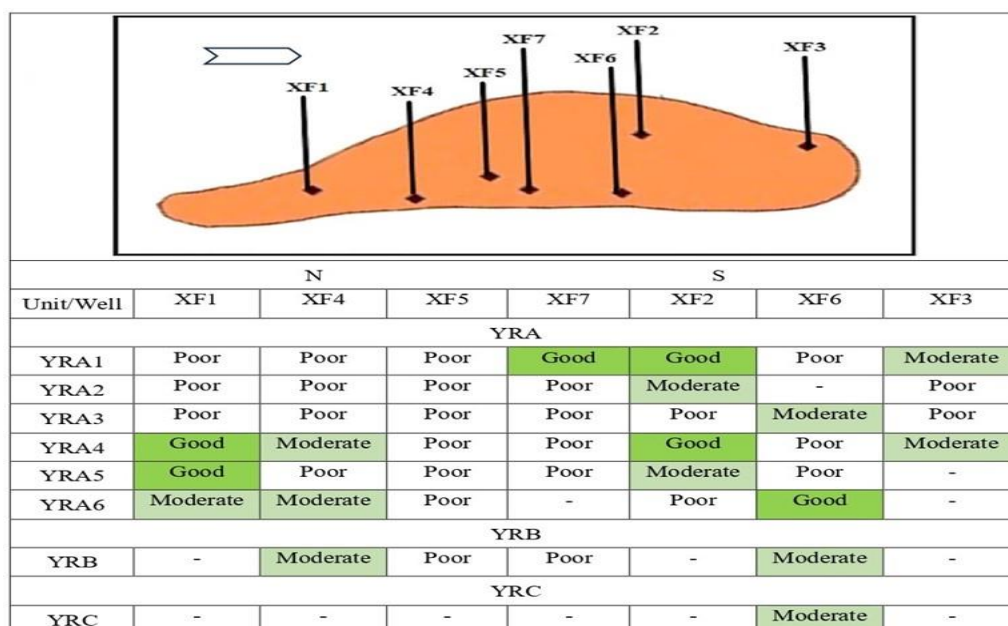


Fig. 7. Permeability distribution through the fold

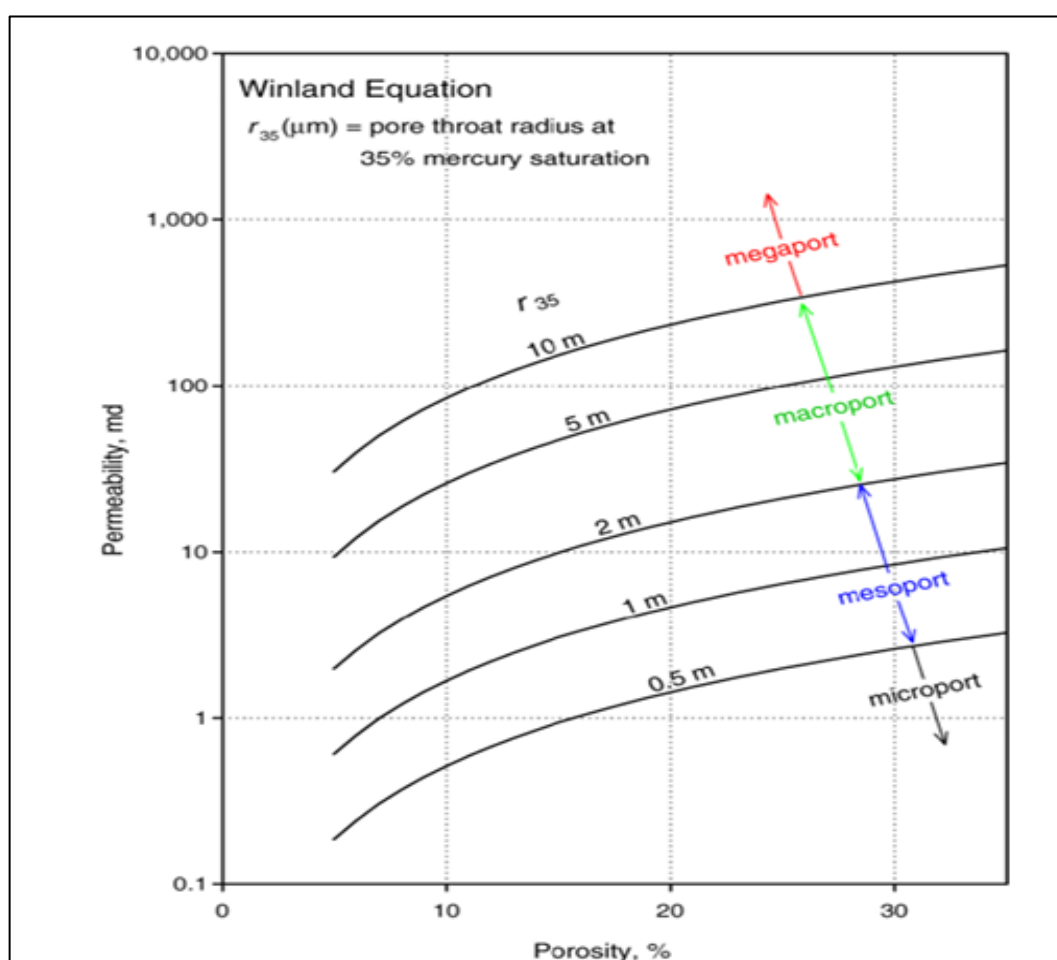


Fig. 8. Empirical model based on regression attributed to Winland, from Kolodzie, 1980. Labels for four ranges of R_{35} are taken from Martin et al. (1997).

Table 6. Permeability (K) in (md) and pore throat radius at 35% mercury saturation (R35) values for the wells of the study area.

Well	Unit	Member	R35
XF1	YRA	1	Microport
		2	Microport
		3	Microport
		4	Microport
		5	Microport
		6	Microport -Mesoport
XF2	YRA	1	Microport -Mesoport-Macroport
		2	Microport -Mesoport
		3	Microport -Mesoport
		4	Microport -Mesoport-Macroport
		5	Microport -Mesoport
		6	-
XF3	YRA	1	Microport -Mesoport
		2	Microport -Mesoport
		3	Microport -Mesoport
		4	Microport -Mesoport
		5	-
		6	-
HF4	YRA	1	Microport -Mesoport
		2	Microport
		3	Microport
		4	Microport -Mesoport-Macroport
		5	Microport -Mesoport
		6	Microport -Mesoport-Macroport
XF5	YRA	1	Microport
		2	Microport
		3	Microport -Mesoport
		4	Microport
		5	Microport
		6	Microport
XF6	YRA	1	Microport -Mesoport
		2	-
		3	Microport -Mesoport
		4	Microport -Mesoport
		5	Microport -Mesoport
		6	Microport -Mesoport-Macroport
XF7	YRA	1	Microport -Mesoport-Macroport
		2	Microport
		3	Microport
		4	Microport
		5	Microport -Mesoport
		6	-
	YRB		Microport -Mesoport

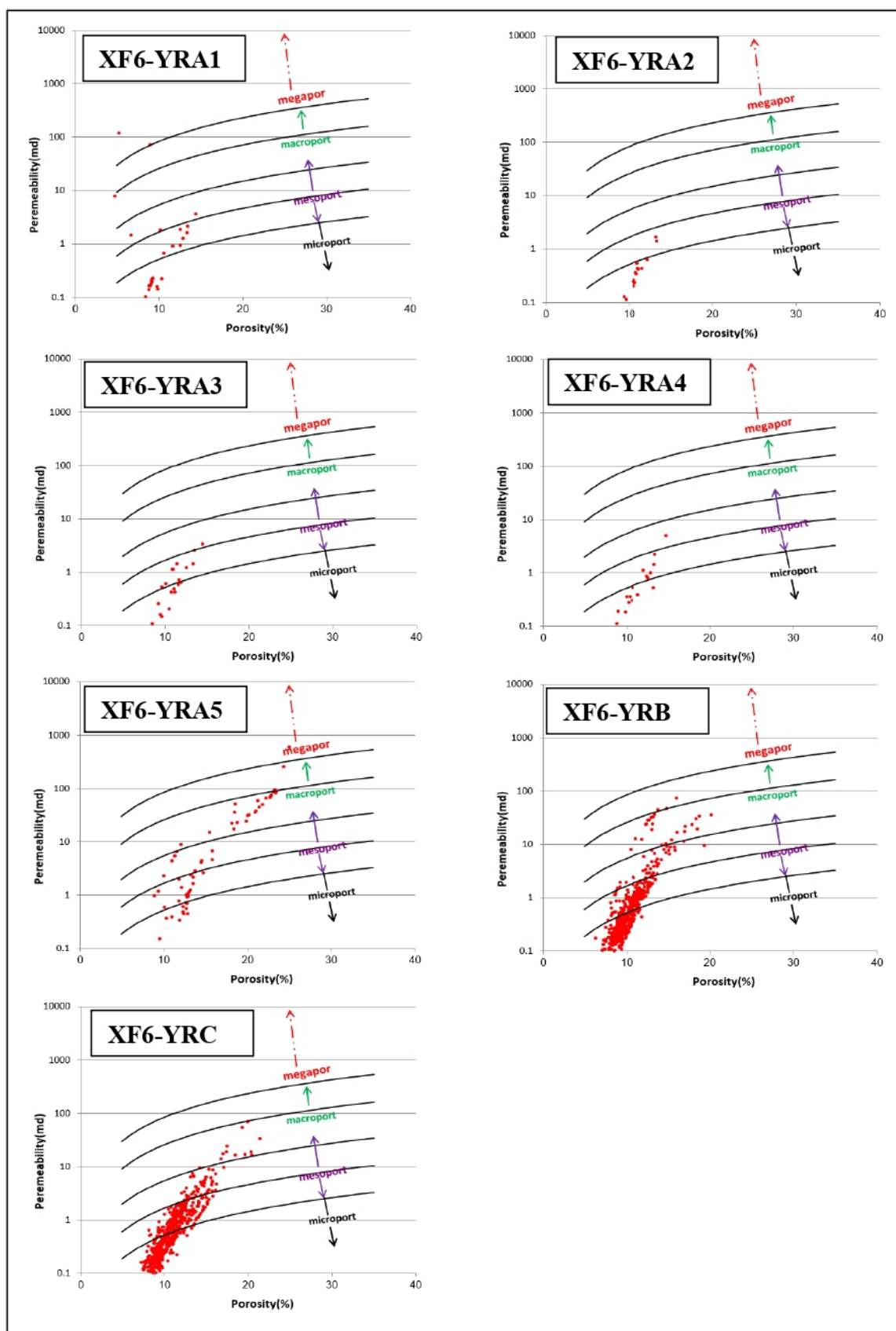


Fig. 9. Empirical model for four ranges of R35 for reservoir units of the well XF6

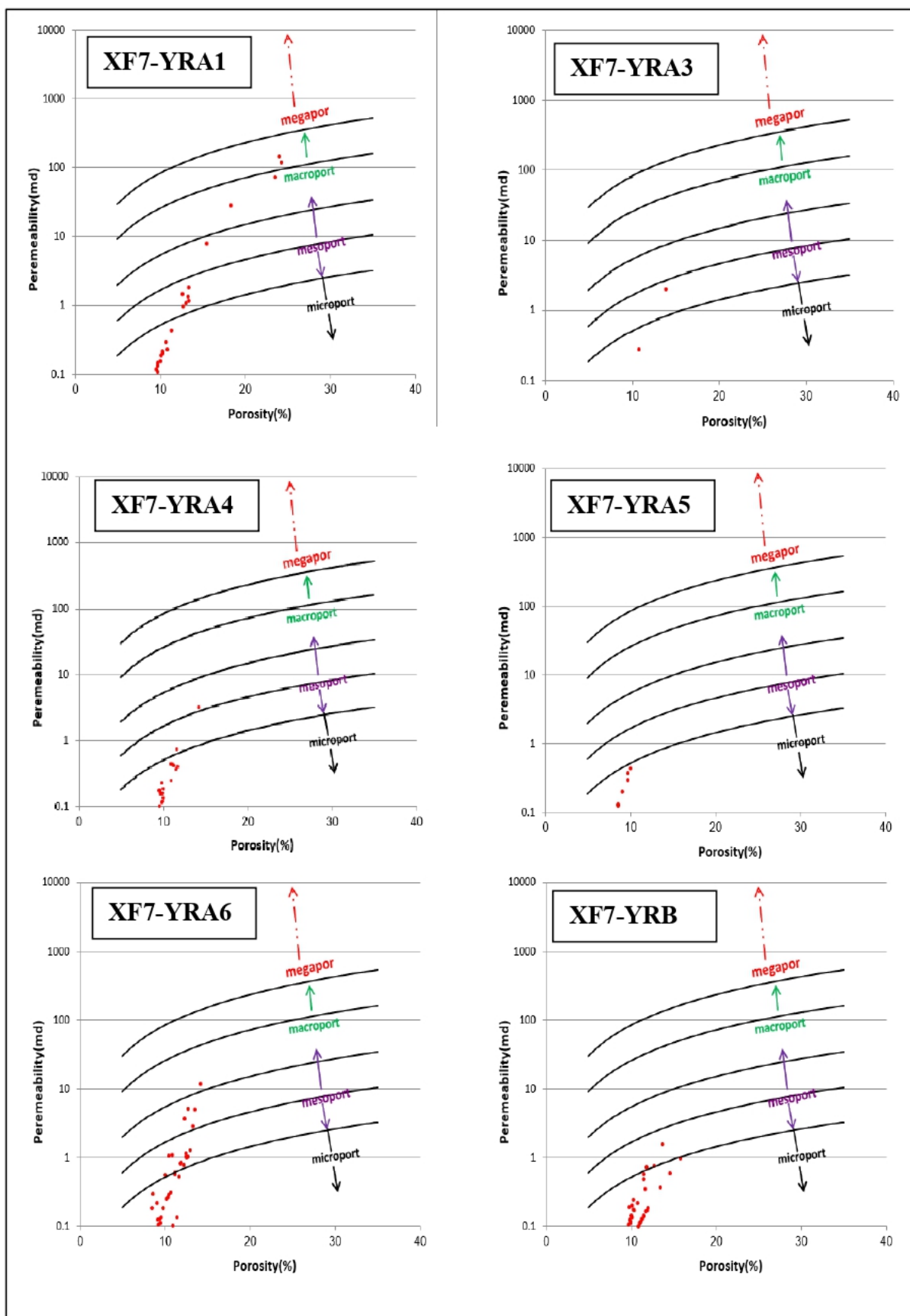


Fig. 10. Empirical model for four ranges of R35 for reservoir units of the well XF7

3.4. Scanning Electron Microscopy (SEM) Results

Scanning Electron Microscopy (SEM) was employed in this study to examine the microstructural and mineralogical characteristics of the collected rock samples. This technique allows detailed observation of mineral composition, crystal size, and pore types, providing critical information on the petrophysical properties of the samples (Table 7). Shale distribution and minerals, as well as iagenetic processes such as dolomitization, significantly affected reservoir porosity and consequently permeability, similar to the study of Al-Issa (2012) in West Qurna, with the difference being the number of samples studied.

Table 7. Lithological and mineralogical properties of core samples from the well XF5.

Well (XF5)				
Sample No.	Depth (m)	Lithology	Minerals	Porosity
Sample 1	4354.08	Shale	Pyrite, feldspar	Micropores
Sample 2	4355.08	Argillaceous Dolomitic Microcrystalline Limestone	Calcite, dolomite, pyrite, barite	Vuggy pores, micropores
Sample 3	4356.08	Argillaceous Finely Crystalline Dolomite	Dolomite and minor clays (Cl)	Intercrystalline, hypidiotopic mosaic texture
Sample 4	4357.08	Microcrystalline Limestone	Calcite, pyrite	Vuggy pores, micropores
Sample 5	4358.08	Microcrystalline Limestone	Calcite, pyrite	Intraparticle pores, micropores
Sample 6	4359.12	Microcrystalline Limestone	Quartz, calcite	Micropores

- Sample 1 (Depth: 4354.08 m, Shale):

The sample is shale (Fig. 11), a clay-rich with minor pyrite (framboids, Py, Photo b) and feldspar (red arrow, Photo b). The porosity is restricted to the micropores of the clay matrix. Brackets in Photo a denote the region magnified in Photo b.

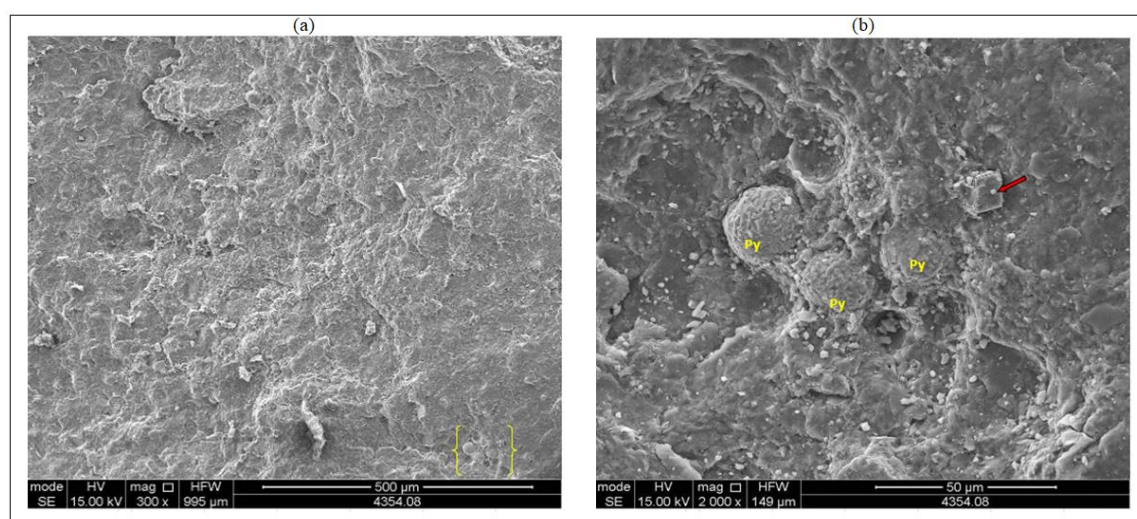


Fig. 11. SEM image of shale sample at 4354.08 m in the well (XF5). a) 500 μm magnification, b) 50 μm magnification

- Sample 2 (Depth: 4355.08 m, Slightly Argillaceous Dolomitic Microcrystalline Limestone):

The sample is a dolomitic (Fig. 12), slightly argillaceous, microcrystalline limestone with abundant calcite and minor dolomite (Dol, Photo b), accompanied by clays (green arrows, Photo b) and pyrite (red arrow, Photo b). Barite is also observed as a minor microcrystalline matrix, with rare sparry calcite. Crystal size in the matrix is on the order of $<10\text{ }\mu\text{m}$. Pores comprise vuggy pores (Vp, Photo a) and micropores associated with the matrix. In Photo a, brackets indicate the region magnified in Photo b.

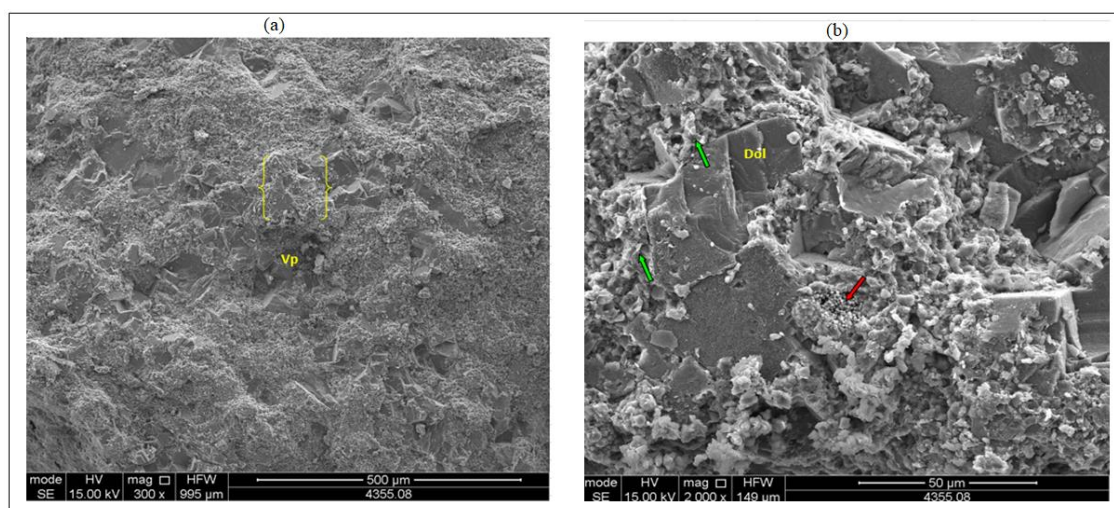


Fig. 12. SEM image of slightly argillaceous dolomitic microcrystalline limestone at 4355.08 m in the well (XF5). (a) 500 μm magnification, (b) 50 μm magnification

- Sample 3 (Depth: 4356.08 m, Argillaceous Finely Crystalline Dolomite):

The sample is an argillaceous (Fig. 13), finely crystalline dolomite with hypidiotopic mosaic texture, predominantly composed of dolomite (Dol, Photo b) and minor clays (Cl, Photo b). Dolomite crystals measure approximately 20–25 μm . Pores are mainly intercrystalline (green arrows, Photo a) with micropores associated with the clay fraction.

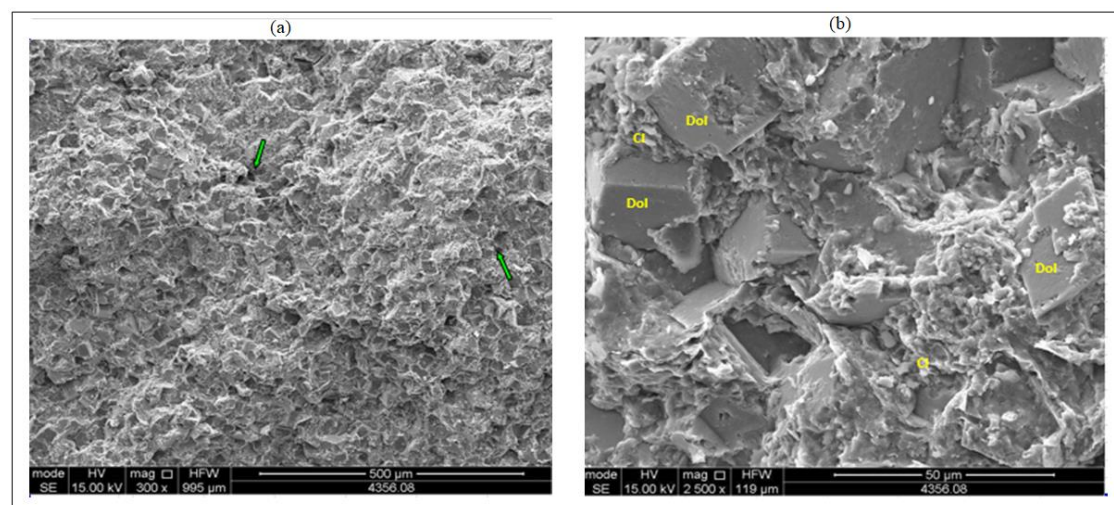


Fig. 13. SEM image of argillaceous finely crystalline dolomite at 4356.08 m in the well (XF5). (a) 500 μm magnification, (b) 50 μm magnification

- Sample 4 (Depth: 4357.08 m, Microcrystalline Limestone):

The sample is a microcrystalline limestone (Fig. 14), predominantly composed of calcite with minor pyrite (red arrows, Photo b). Calcite occurs mainly as a microcrystalline matrix, with lesser amounts of sparry calcite forming large, scattered crystals (Ca, Photo a) that partially fill vuggy pores (Ca, Photo b). Matrix crystals are typically $<10\ \mu\text{m}$. Pores include rare vuggy pores (Vp, Photo b) and micropores associated with the matrix (circle, Photo b). Brackets in Photo a indicate the area enlarged in Photo b.

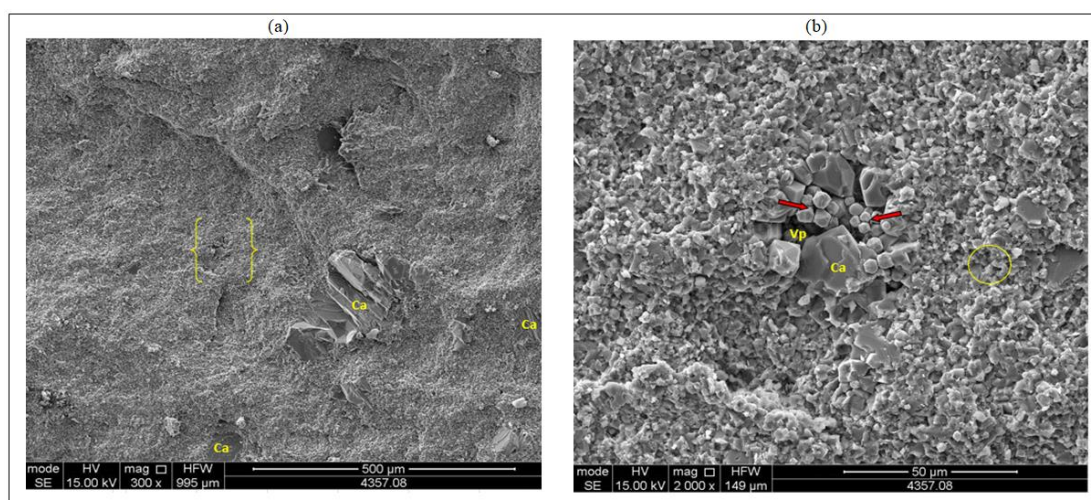


Fig. 14. SEM image of microcrystalline limestone at 4357.08 m in the well (XF5). (a) 500 μm magnification, (b) 50 μm magnification

- Sample 5 (Depth: 4358.08 m, Microcrystalline Limestone):

The sample is a microcrystalline limestone (Fig. 15), predominantly composed of calcite with minor pyrite (red arrows, Photo b). A circular feature associated with the pyrite likely represents a dissolved fossil. Calcite occurs mainly as a microcrystalline matrix, with lesser sparry calcite (green arrows, Photo a). Matrix crystals are typically $<10\ \mu\text{m}$. Pores include rare intraparticle pores related to fossils (IrP, Photo b) and micropores associated with the matrix (circle, Photo b). Brackets in Photo a indicate the area enlarged in Photo b.

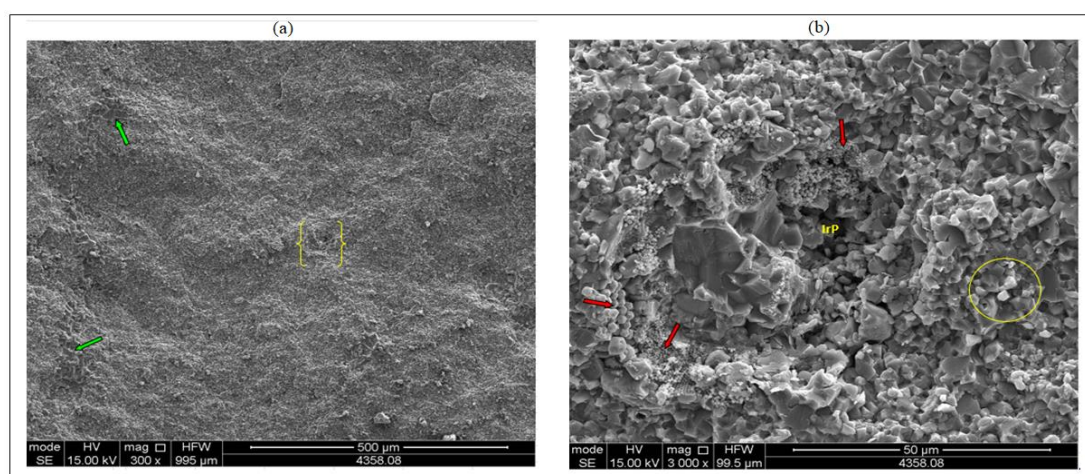


Fig. 15. SEM image of microcrystalline limestone at 4358.08 m in the well (XF5). (a) 500 μm magnification, (b) 50 μm magnification

- Sample 6 (Depth: 4359.12 m, Microcrystalline Limestone):

The sample is a microcrystalline limestone (Fig. 16), rich in calcite with little authigenic quartz (Q, Photo b). Calcite is mainly present as micrometric matrix, and the crystals are commonly <10 μm . Pores are predominantly formed by micropores related to the matrix (circle, Photo b). Brackets in a show the area enlarged in b.

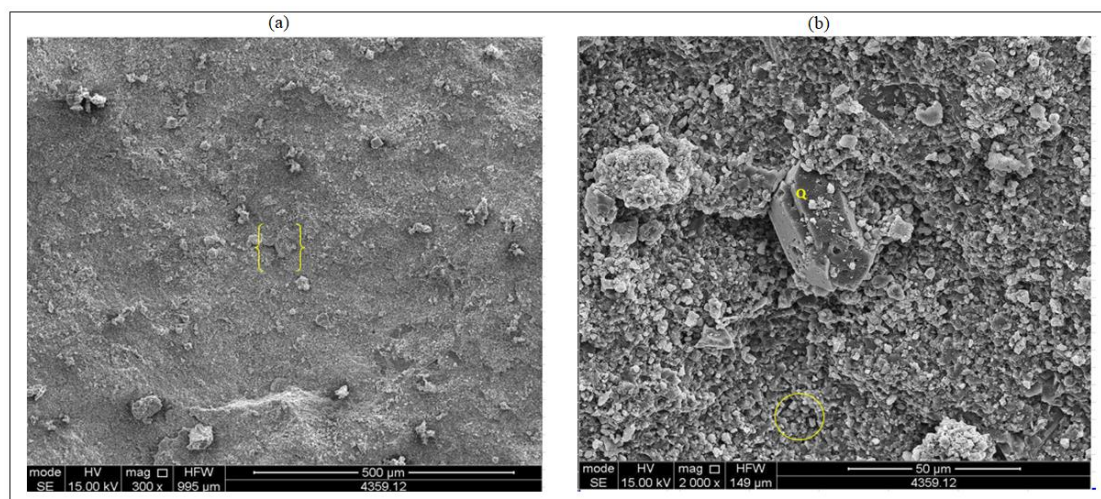


Fig. 16. SEM image of microcrystalline limestone at 4359.12 m in the well (XF5). (a) 500 μm magnification, (b) 50 μm magnification

4. Conclusions

According to the Winland pore-throat classification, wells XF4 and XF6 represent the best reservoir quality among the studied wells. In well XF4, most units (YRA4-YRA6 and YRB) show a clear shift from the micropore field toward the mesopore and macropore regions, particularly in YRA6 and YRB, indicating improved pore-throat size and better production potential. A similar trend is observed in well XF6, where several units, especially YRA6, YRB, and YRC, display a strong distribution toward the macropore and megaport regions. The presence of these larger pore-throat sizes corresponds to higher permeability ranges, where macropores (10-100 mD) indicate good permeability and megapores (100-1000 mD) indicate excellent permeability, supporting the classification of XF4 and XF6 as the most favorable wells in the study area, which is located southeast of the fold. In contrast, wells XF5 and XF7 exhibit the poorest reservoir quality, as most units are predominantly clustered in the micropore region, corresponding to low permeability (<1 mD) and therefore indicating limited reservoir quality and low production potential. The SEM study of 6 m in YRA2 of well XF5 provides a detailed view of porosity, complementing the petrophysical analysis based on bulk water volume (BVW). While BVW showed that the entire 13.56-meter YRA2 unit is dominated by intercrystalline-to-chalky porosity, SEM reveals a more nuanced distribution, including micropores, vuggy pores, and intercrystalline pores within the analyzed interval. This confirms the general porosity trend from BVW while highlighting micro-scale heterogeneity that can influence permeability and fluid flow. Overall, SEM enhances the understanding of pore types and distribution, providing more precise insights into reservoir quality than petrophysical data alone.

Author contributions: CRediT

- Conceptualization: Abdulamer developed the research idea and overall study framework for the Yamama Formation in the Halfaya oilfield.

- Data Curation: Abdulamer collected and organized all well data from Maysan Oil Company and managed SEM images.
- Formal Analysis: Abdulamer performed the data analysis and applied the chosen equations; Fahad guided the selection of equations and Excel procedures.
- Funding Acquisition: Minimal; research was primarily self-funded by Abdulamer.
- Investigation: Abdulamer conducted all research work, including data analysis and evaluation of permeability and porosity
- Methodology: Abdulamer applied the research methods; Fahad guided the overall approach and methodology.
- Project Administration: Fahad oversaw and directed the progress of the research.
- Resources: Data and SEM images were provided by Maysan Oil Company.
- Software: Hussein used Excel for analysis and calculations, and Paint and Word to create figures.
- Supervision: Fahad supervised all stages, providing guidance and review throughout.
- Validation: Abdulamer's study is the first to analyze porosity, permeability, mineralogy, and SEM relationships in the Yamama Formation of the Halfaya oilfield. Findings were compared with previous studies in other oilfields, such as Al-Issa (2012) in West Qurna and Al-Ismaili (2011) in Nasiriyah, which showed similar trends in reservoir properties.
- Visualization: Abdulamer created all figures, including maps and plots of wells, units, porosity, and permeability relationships.
- Writing – Original Draft: Abdulamer prepared the initial draft of the manuscript.
- Writing – Review and Editing: Fahad reviewed and edited the draft; both authors refined the content and finalized the manuscript.

Declaration of Competing Interest

The authors, Hussein Abdulamer and Fahad M. Alnajm, 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 supporting the findings of this study are not publicly available due to confidentiality agreements with Maysan Oil Company. Access to the data can be requested from the corresponding author under appropriate conditions.

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