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ORIGINAL PAPER - EXPLORATION GEOLOGY

Flow units and rock type for reservoir characterization in carbonate reservoir: case study, south of Iraq

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Abstract

The current work is focused on the rock typing and flow unit classification for reservoir characterization in carbonate reservoir, a Yamama Reservoir in south of Iraq (Ratawi Field) has been selected, and the study is depending on the logs and cores data from five wells which penetrate Yamama formation. Yamama Reservoir was divided into twenty flow units and rock types, depending on the Microfacies and Electrofacies Character, the well logs pattern, Porosity–Water saturation relationship, flow zone indicator (FZI) method, capillary pressure analysis, and Porosity–Permeability relationship (R35) and cluster analysis method. Four rock types and groups have been identified in the Yamama formation depending on the FZI method, where the first group represents the bad reservoir quality (FZI-1) (Mudstone Microfacies and Foraminiferal wackestone Microfacies), the second group reflects a moderate quality of reservoir (FZI-2) (Algal wackestone–Packstone Microfacies and Bioclastic wackestone–Packstone Microfacies), the third group represents good reservoir quality (FZI-3) (Peloidal Packstone–Grainstone Microfacies), and the fourth group represents a very good reservoir quality (FZI-4) (Peloidal–oolitic Grainstone Microfacies). Capillary pressure curves and cluster analysis methods show four different rock types: a very good quality of reservoir and porous (Mega port type) (FZI-4) (Peloidal–oolitic Grainstone Microfacies) with a low irreducible Water saturation (Swi), good quality of reservoir and porous (Macro port type) (FZI-3) (Peloidal Packstone–Grainstone Microfacies), moderate quality of reservoir (Meso port type) (FZI-2) (Algal wackestone–Packstone Microfacies and Bioclastic wackestone–Packstone Microfacies), and a very fine-grained with bad reservoir quality (Micro port type) (FZI-1) (Mudstone Microfacies and Foraminiferal wackestone Microfacies) and with the higher displacement of pressure). These capillary pressure curves support the subdivision of the main reservoir unit to flow units.

Keywords Flow units · Rock type · Reservoir characterization · Yamama formation · South of Iraq

Introduction

Recognition of reservoir quality is an important objective in reservoir characterization process, the quality of a reservoir is defined by its hydrocarbon storage capacity, and storage capacity is a function of Porosity, whereas deliverability is a function of Permeability. Thus, both Porosity and Permeability are the main reservoir quality controlling factors (El Sharawy and Nabawy 2019).

Flow units are required for identifying, describing, and quality ranking flow units include lithological, petrographic, and petrophysical data. Ideally, these kinds of data should be evaluated together to detect and interpret correspondences between them (AHR 2008).

Better understanding of reservoir characterization represents the key element and critical component for successful field development planning, and accurate reservoir characterization is a prerequisite for efficient and better management of heterogeneous (Shedid 2018).

Rock typing and flow unit identification in carbonates usually have been challenging due to the complexity of pore networks which are the results of facies changes and digenetic processes (Riazi 2017).

In this paper, many methods were used to identify and characterize the flow units and rock type within the main reservoir, and these methods included: the Microfacies and Electrofacies Character, the well logs pattern, Porosity–Water saturation relationship, flow zone indicator

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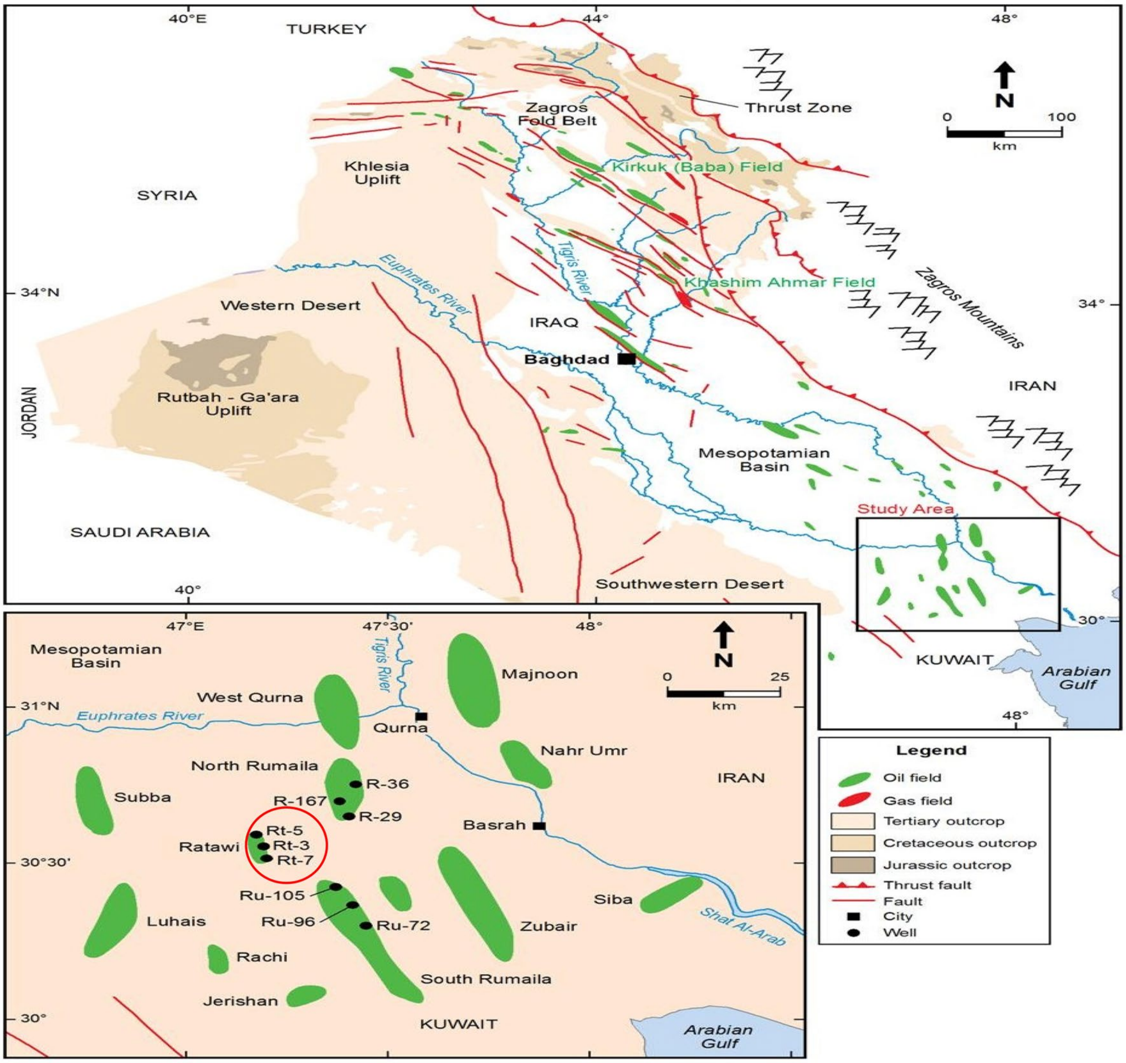


Fig. 1 Map location for studied field (Al-Ameri et al. 2009)

method, capillary pressure analysis, and Porosity–Permeability relationship (R35) and cluster analysis method, and capillary pressure curves and cluster analysis methods show four different rock types.

Yamama formation has been selected as a carbonate reservoir in five wells from Ratawi Field (Rt-3, Rt-4, Rt-5, Rt-6, and Rt-7) which penetrated Yamama formation and uniformly distributed to identify the flow units and rock type in the carbonate reservoir.

Geological background

The Ratawi Field is located about 70 km in the south of Iraq to the north of the Basra city and west of the North Rumaila Field in the flat semidesert (Fig. 1), the Yamama formation located at a depth of about 3499 m below the sea level in a well Ratawi (Rt-3) and underlain conformably by the Sulaiy formation, which made up of mud—supported argillaceous limestone with calcispheres and small benthonic foraminifera (Fig. 2), and grades upward into the Ratawi formation (Saleh 2014).

Yamama formation is considered one of the important carbonate reservoir rocks within lower Cretaceous in the southern part of Iraq; it consists of shoal rock sediments that contain Peloidal limestone, oolitic limestone, Bioclastic and fossil from algae and foraminifera; this formation belongs to the late Berriasian–Aptian cycle. This cycle is represented from shore to deep basin by the Zubair, Ratawi, Garagu, Yamama, Shuiaba, Sarmord, and Lower Balambo formations (Buday 1980).

The Sulaiy, Yamama, Ratawi, and Zubair formations represent a regressive carbonate cycle terminated by the clastic invasion of the Zubair fluvial–deltaic facies. Yamama

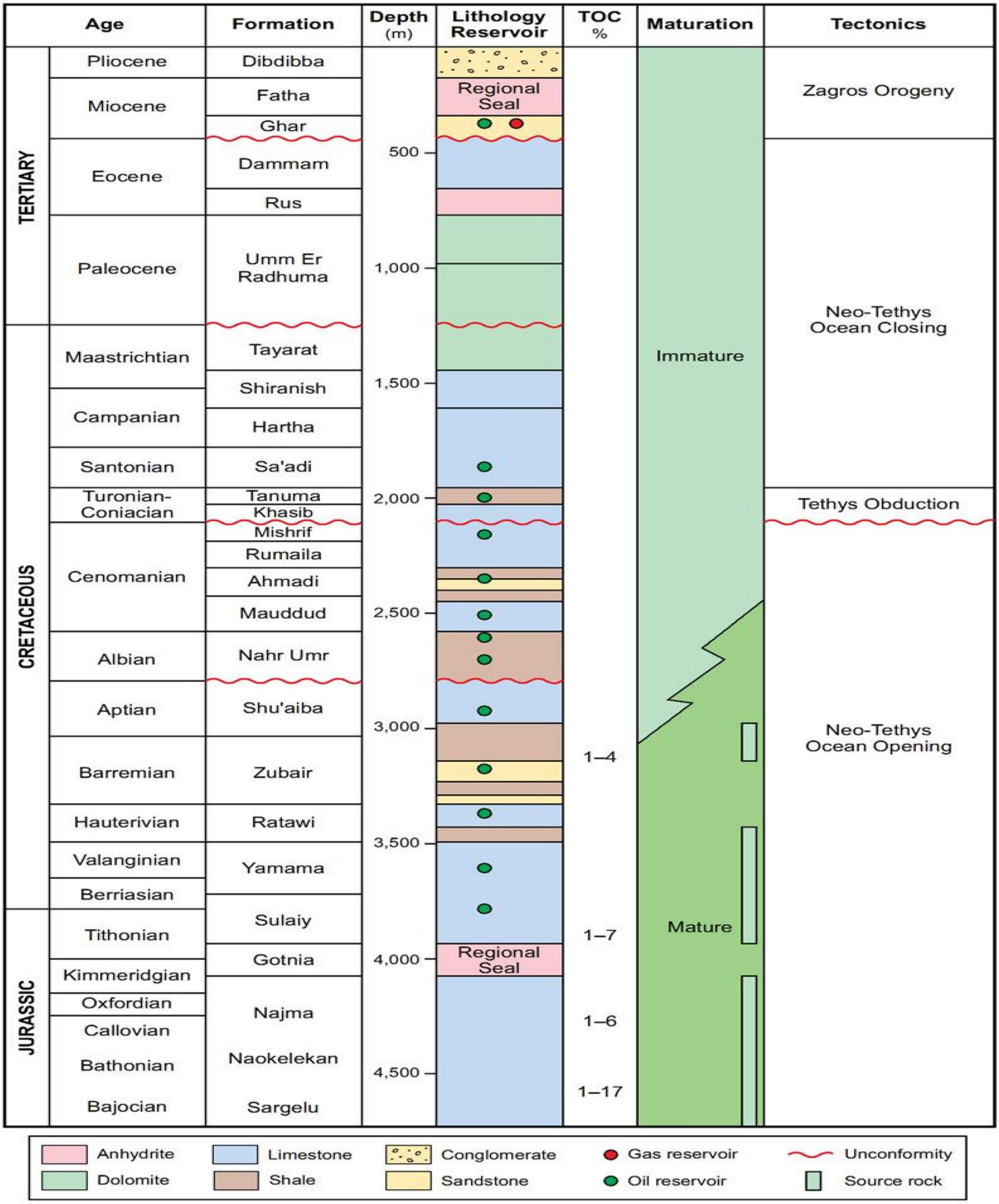


Fig. 2 Sequence stratigraphy in south of Iraq (Al-Ameri et al. 2009)

formation comprises the neritic lithofacies of the cycle (Sadooni 1993).

In the south of Iraq, Yamama formation is divided into many reservoirs, and facies and environmental divisions (Al-Siddiki 1978a, b; Sadooni,1993) are divided Yamama formation into five main units, three of which are considered as reservoir rocks (YR-A, YR-B, and YR-C); the other two are considered as barrier units (YB-1 and YB-2).

Definition of the flow units and rock types

A flow unit is defined as an interval of sediment with similar petrophysical properties such as Porosity, Permeability, Water saturation, pore-throat radius, storage, and flow capacity that are different from the intervals immediately above and below; flow units are usually grouped to define containers; rock types having similar flow capacity were grouped and used in the determination of reservoir flow units (Porras and Campos 2001).

The flow unit is defined as a reservoir zone that is laterally and vertically continuous and has similar Permeability, Porosity, and bedding characteristic (Hearn et al. 1984).

A flow unit is a stratigraphically continuous interval of similar reservoir process speed that maintains the geologic framework and characteristics of rock types. Rock types are representative reservoir units with a distinct Porosity–Permeability relationship and a unique Water saturation for a given height above free Water level (Gunter et al. 1997).

The carbonate reservoirs rocks are usually heterogeneous. Therefore, to have a better grasp of the reservoir behavior, we need to classify these reservoirs into zones, layers, and separate units with lower heterogeneity degrees (Mohebian et al. 2017).

Various methods were used to subdivide the main reservoirs into many flow units; in this study, Yamama Reservoir was divided into twenty flow units, depending on one or more from the following methods:

1. Microfacies and Electrofacies Character

The first step for flow unit identification is Microfacies analysis depending on the thin section analysis; this analysis can identify the Electrofacies and correlated with well logs data.

Saleh (2014) recognized six cyclic Microfacies for Yamama formation in Ratawi Field (Rt-3 and Rt-4 wells). These are as follows: oolitic–peloidal Grainstone, peloidal Packstone–Grainstone, Bioclastic wackestone–Packstone, Algal wackestone–Packstone, foraminifera wackestone, and Mudstone Microfacies.

Depending on these six cyclic types of Microfacies, the extension laterally for these Microfacies were identified by the similarity of logs curve characters (gamma ray, Spontaneous potential, neutron, density, and sonic) with of these Microfacies (Figs. 3, 4).

Peloidal–oolitic Grainstone Microfacies and Peloidal Packstone–Grainstone Microfacies were characterized by a negative Spontaneous potential log deflection, high resistivity, high neutron and sonic logs, and low gamma ray and bulk density, and these Microfacies reflected good reservoir properties.

Algal wackestone–Packstone Microfacies and Bioclastic wackestone–Packstone Microfacies were characterized by a negative Spontaneous potential log deflection, moderate read values for sonic, and neutron and resistivity logs, and these Microfacies reflected moderate reservoir properties.

Mudstone Microfacies and Foraminiferal wackestone were characterized by a positive Spontaneous potential log deflection, high gamma ray log, low read values for resistivity, sonic and neutron logs, and high bulk density log, and these Microfacies reflected bad reservoir properties.

These six cyclic types of Microfacies and Electrofacies Character reflected many rock types and flow units within the main reservoir unit and gave the first steps to divide the reservoir into flow units depending on the variation in these Microfacies and Electrofacies Character.

2. Log curve character and pattern

Wireline log signatures sometimes correspond with rock properties in flow units so that ranked flow units can be mapped from log character (AHR 2008).

Well logs curves were used for dividing the main reservoir unit into flow units by using well logs curves. The Well (Rt-3) has been used as a key well (Figs. 5, 6), and these flow units were correlated with other by well log curves for other wells.

The reservoir subunits (Y1-2, Y2-2, Y2-3, Y2-4, Y2-6, and Y3-5) were characterized by a negative Spontaneous potential log deflection, high resistivity, high neutron and high sonic logs, low reads for the gamma ray log, and low bulk density, and these subunits reflected good reservoir properties and represented by good Microfacies properties (Peloidal–oolitic Grainstone Microfacies and Peloidal Packstone–Grainstone Microfacies).

The reservoir subunits (Y2-1, Y2-7, Y2-8, Y2-9, Y3-1, Y3-3, and Y3-4) were characterized by moderate read values for sonic and neutron logs, a negative Spontaneous potential log deflection and moderate resistivity, and these subunits reflected moderate reservoir properties and represented by moderate Microfacies properties (Algal wackestone–Packstone Microfacies and Bioclastic wackestone–Packstone Microfacies).

The subunits (Y1-3, Y2-5, Y3-2, YB-1, and YB-2) were characterized by high gamma ray log, low read values for resistivity logs, a positive Spontaneous potential log deflection, low

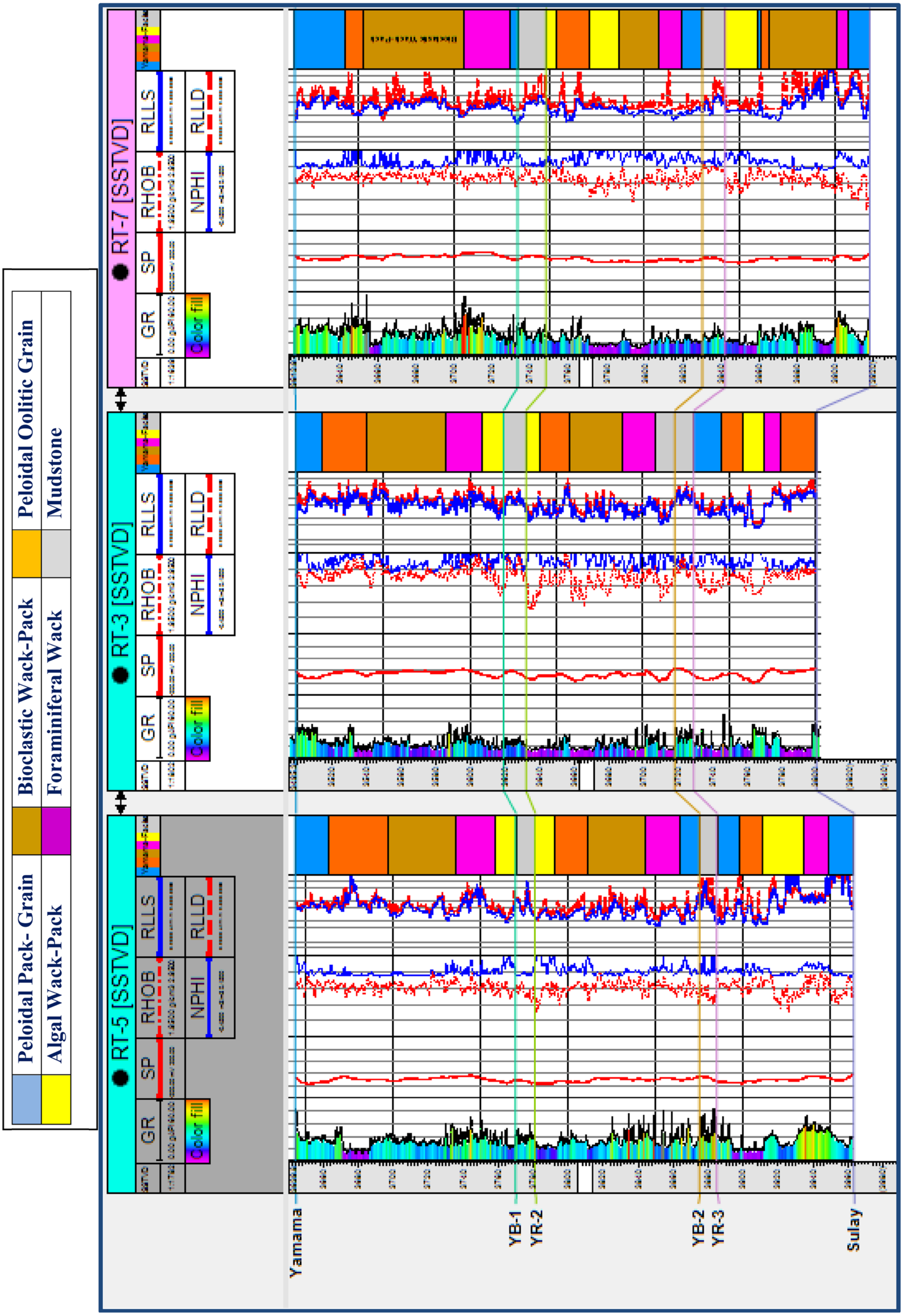
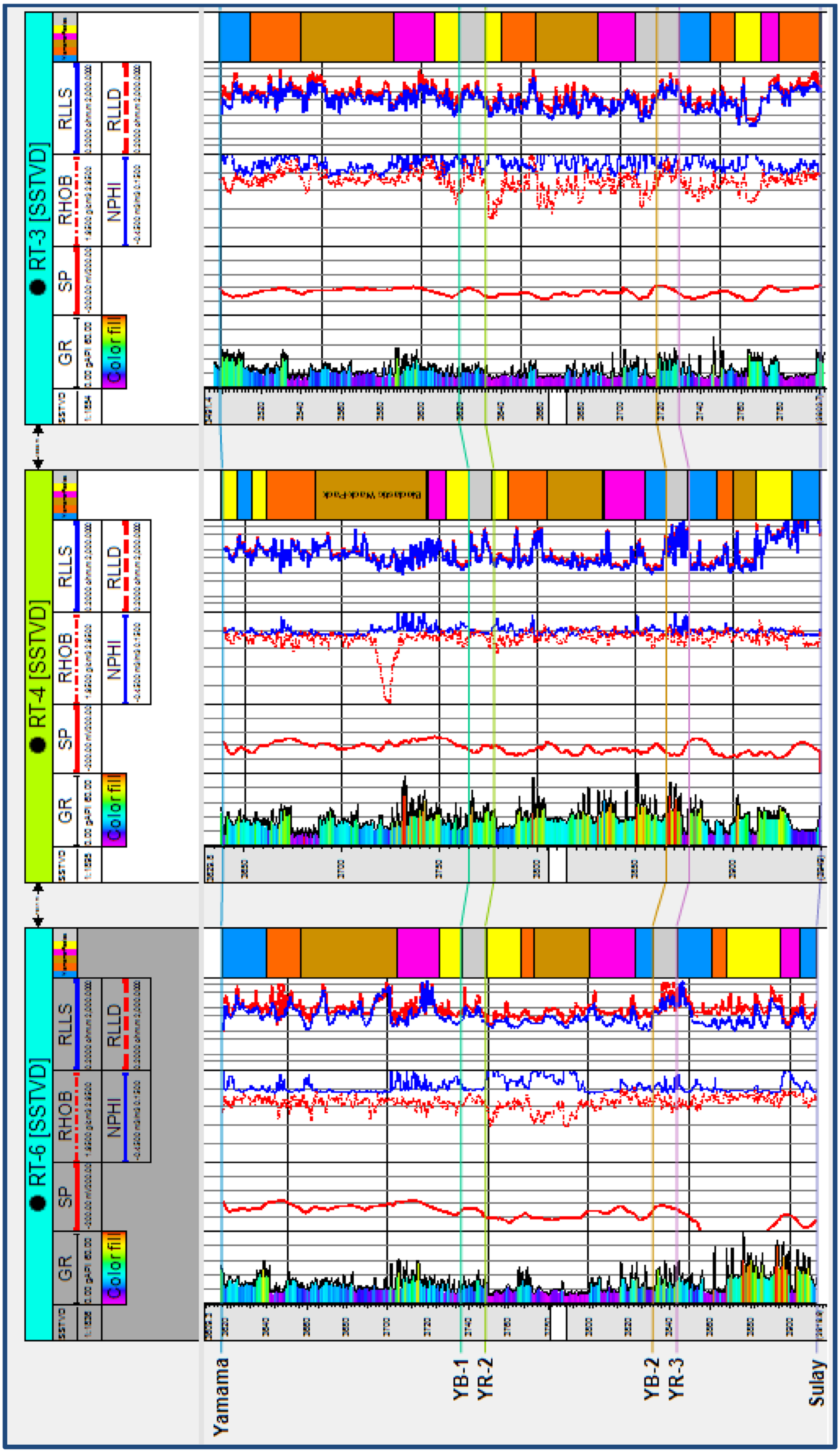


Fig. 3 Cross section for wells Rt-5, 3, and 7 in the Yamama formation

Fig. 4 Cross section for wells Rt-4, 3, and 6 in the Yamama formation



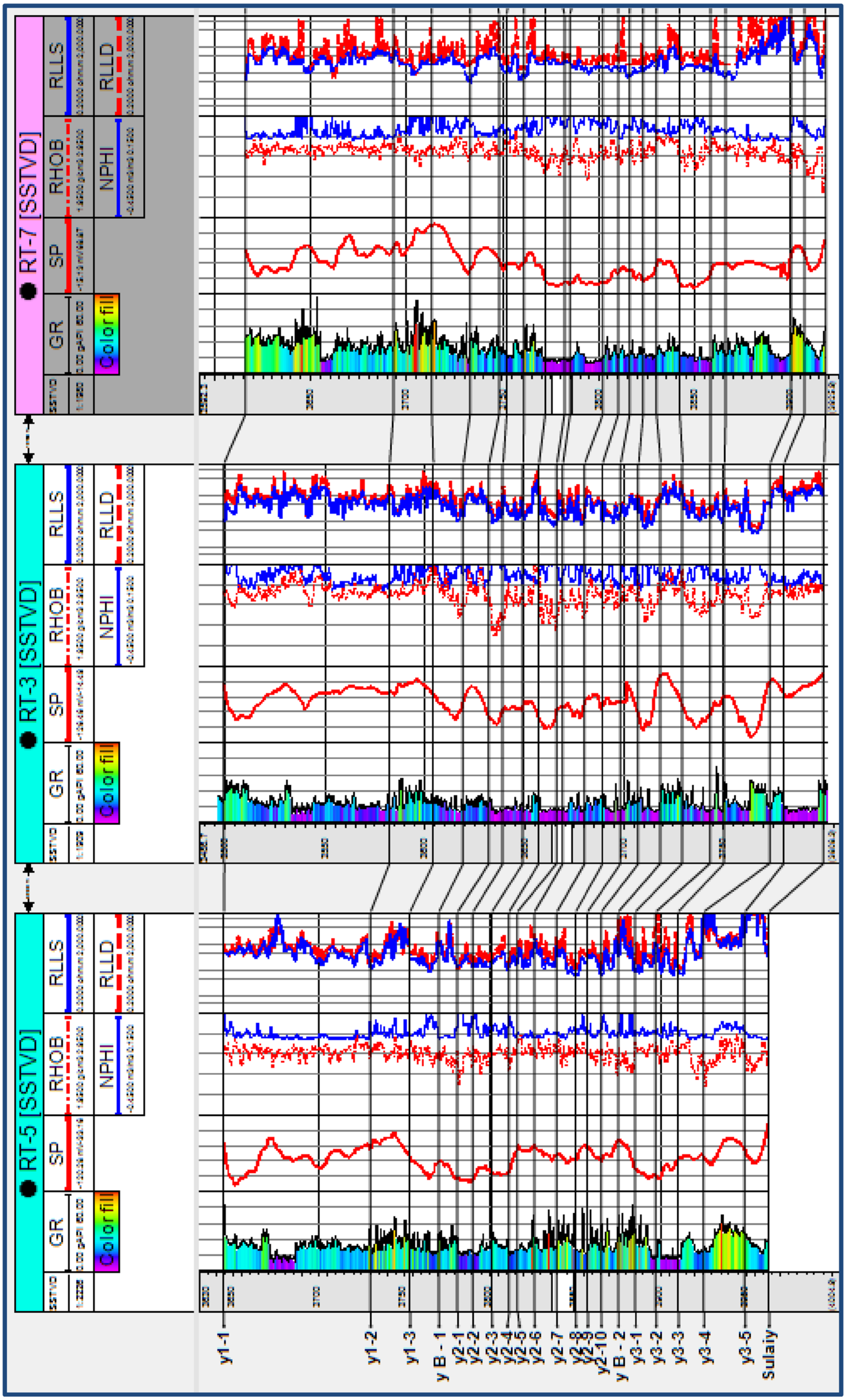


Fig. 5 Well logs section for wells Rt-5, 3, and 7 in Yamama formation

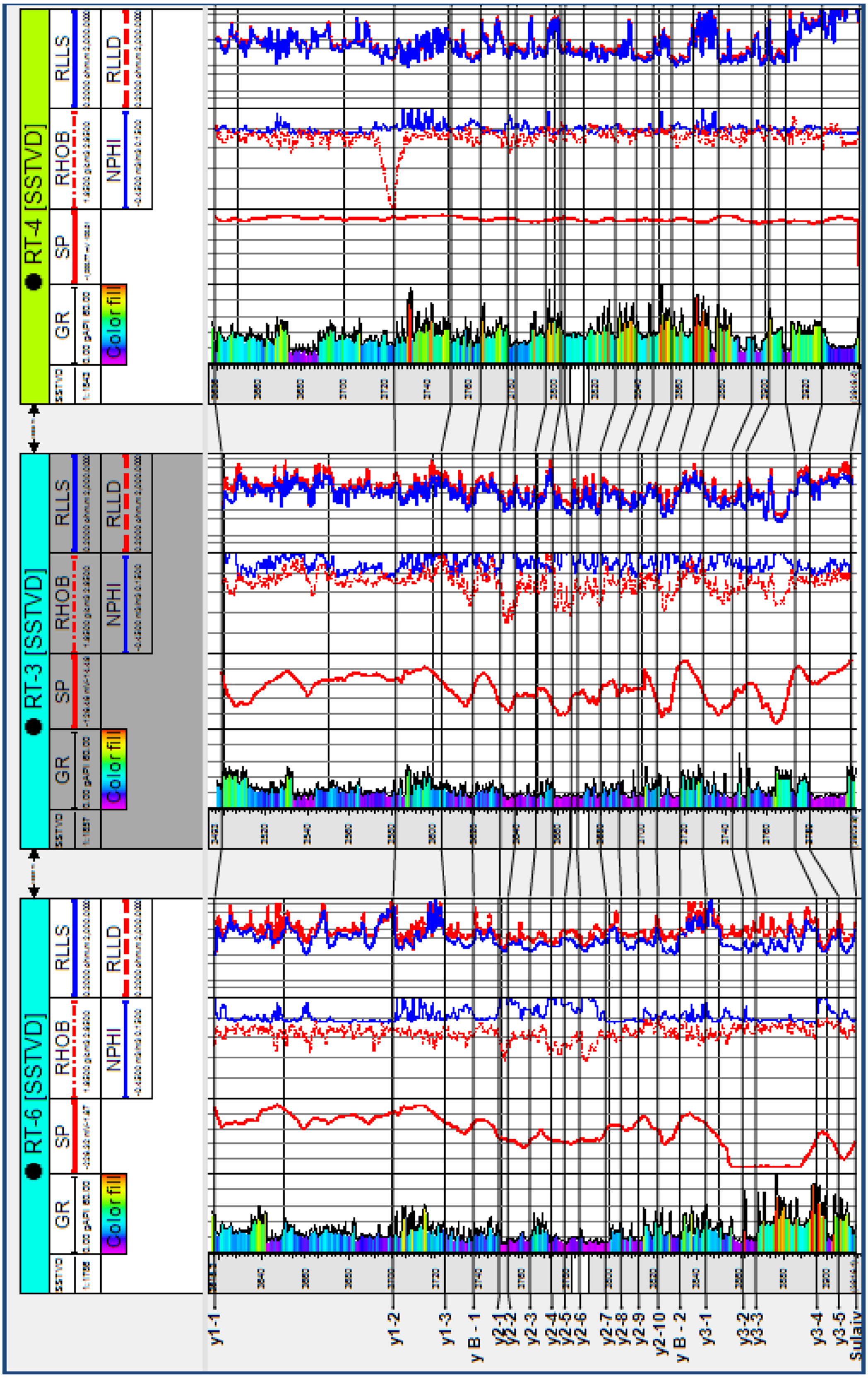


Fig. 6 Well logs section for wells Rt-6, 3, and 4 in Yamama formation

read values for sonic log and neutron logs, and high bulk density log, and these subunits reflected bad reservoir properties and represented by a bad Microfacies properties (Mudstone Microfacies and Foraminiferal wackestone).

3. Porosity–Water saturation relationship

Water saturation distribution in the reservoir depends on the height above the free Water level, pore type, and hydrocarbon type (Hartmann and MacMillan 1992).

Porosity (PHI) and Water saturation (Sw) have been studied, which reflect different reservoir units with pore types. By using Porosity (PHI) and Water saturation (Sw) variations (Figs. 7, 8), the main reservoir units have been divided by using Porosity–Water saturation relationship into similar units to those given by the facies data and well logs.

The reservoir subunits (Y1-2, Y2-2, Y2-3, Y2-4, Y2-6, and Y3-5) were characterized by good reservoir properties (high Porosity and low Water saturation) and represent by good type of the Microfacies (Peloidal–oolitic Grainstone Microfacies, Peloidal Packstone–Grainstone Microfacies), which reflected good reservoir properties.

The reservoir subunits (Y2-1, Y2-7, Y2-8, Y2-9, Y3-1, Y3-3, and Y3-4) were characterized by moderate Porosity and low-to-moderate Water saturation, and these subunits reflected moderate reservoir properties and represent by moderate type of the Microfacies (Algal wackestone–Packstone Microfacies and Bioclastic wackestone–Packstone Microfacies).

The subunits (Y1-3, Y2-5, Y3-2, YB-1, and YB-2) were characterized by low Porosity and high Water saturation, and these subunits reflected bad reservoir properties and represent by moderate type of the Microfacies (Mudstone Microfacies and Foraminiferal wackestone Microfacies).

4. Flow zone indicator method

The flow zone indicator (FZI) defines as a unique parameter that incorporates the geological attributes of texture and mineralogy in the discrimination of pore geometrical (hydraulic units), and it is used to identify the geologic variables that control the flow of fluids, especially when the geological attributes that are based on variations in pore-throat sizes that control Permeability are considered and can be expressed as follows (Amaefule et al. 1993):

$$\mathrm{FZI} = \frac{\mathrm{RQI}}{\phi_Z} \tag{1}$$

$$\mathrm{RQI} = 0.0314\sqrt{\frac{\mathrm{K}}{\phi_{\mathrm{eff}}}} \tag{2}$$

$$\phi_Z = \left(\frac{\phi_{\mathrm{eff}}}{1-\phi_{\mathrm{eff}}}\right) \tag{3}$$

where RQI: is the reservoir quality index (µm), ϕ_Z: is a normalized Porosity (pore volume-to-grain volume ratio) (fraction), FZI: is a function of reservoir quality index and void ratio (µm), and ϕ_{eff}: is the effective Porosity (fraction).

By using Eqs. 1, 2, and 3, the functions for RQI versus ϕ_Z plot for each reservoir unit have been established for all the wells. The similar values for FZI fall on a line (same slope), and the data with same line can be reflected similar flow unit (pore throat).

Figures 9 and 10 present a plot for Porosity versus Permeability with reservoir quality index (RQI) versus logarithm of the normalized Porosity (ϕ_Z) consequently, for various values of the flow zone indicator (FZI). All points with similar (FZI) line have same pore throat.

Four rock types and groups have been identified in the Yamama formation, where the first group represents bad reservoir quality (FZI-1) (Mudstone Microfacies and Foraminiferal wackestone Microfacies), the second group reflects moderate quality of reservoir (FZI-2) (Algal wackestone–Packstone Microfacies and Bioclastic wackestone–Packstone Microfacies), the third group represents good reservoir quality (FZI-3) (Peloidal Packstone–Grainstone Microfacies), and the fourth group shows a high trend of the Permeability and Porosity which represent a very good reservoir quality (FZI-4) (Peloidal–oolitic Grainstone Microfacies).

5. Porosity–Permeability relationship (R35)

The two main microscopic scale rock properties that control fluid storage and flow in a reservoir are Porosity and Permeability. Collectively, these two properties are referred to “reservoir quality” (Roger 2006).

Winland’s equation is powerful methods used to utilize the reservoir properties as Permeability and Porosity to classify the number of rock types available in a reservoir, and Winland’s plot helps engineers and petrophysicists to understand their reservoirs’ rock properties (Al-Qenae and Al-Thaqafi 2015).

R35 represents a point on the flat portion of the capillary pressure curve (P_c), which dictates the optimum flow unit performance capacity, and the R35 curve is used to identify intervals (flow units) of similar pore-throat radii and to discriminate between flow units whose pore-throat size yields different inflow performances (Martin et al. 1997).

The following equation to calculate R35 for a rock sample using measured Ka and ∅ values (Pittman 1992) is as follows:

$$\mathrm{Log\,R35} = 0.732 + 0.588\,\mathrm{Log\,Ka} - 0.864\,\mathrm{Log}\,\emptyset$$

where R35: port radius (micron) at 35% mercury saturation, Ka: air Permeability (md), and ∅: core Porosity (%).

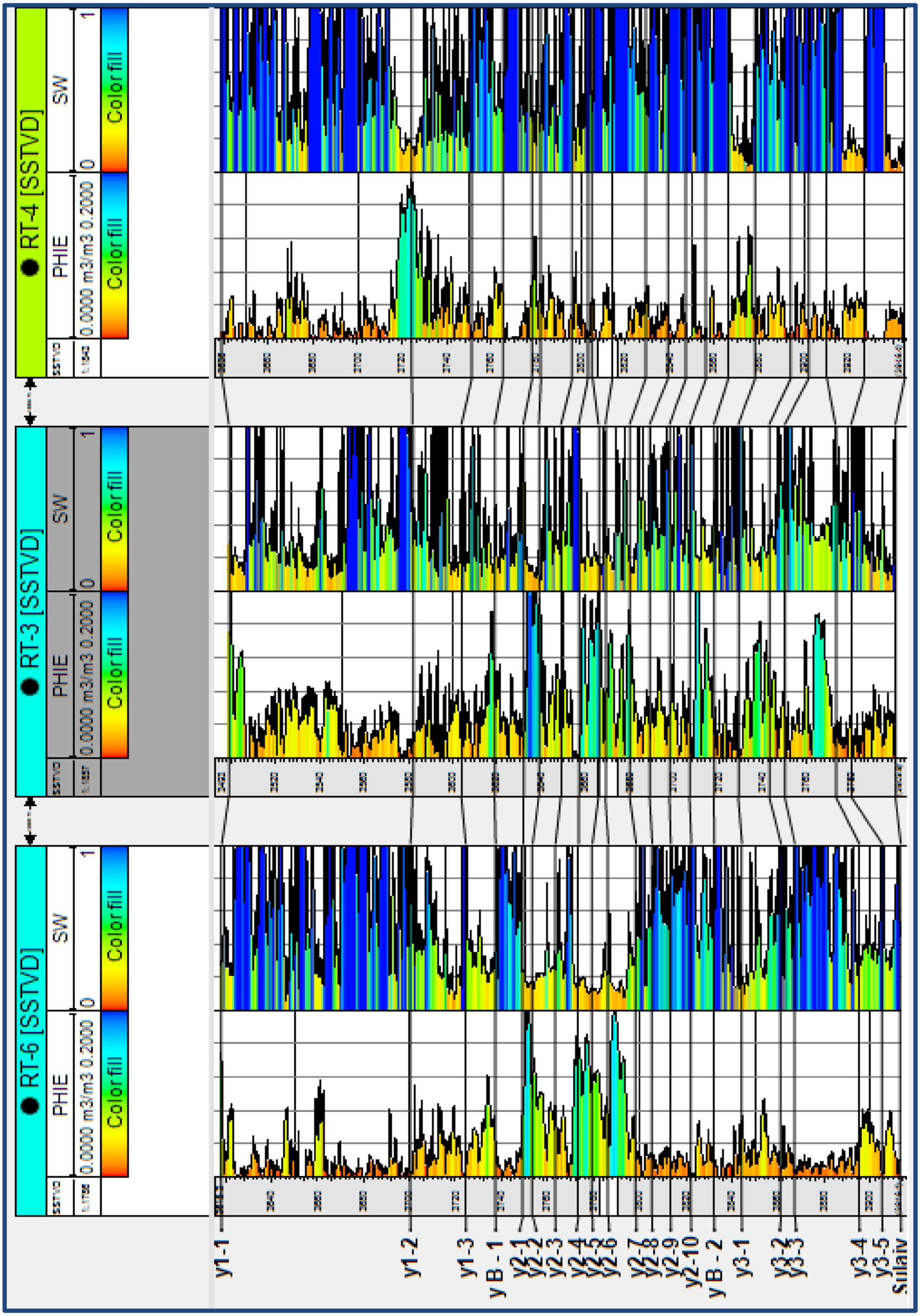


Fig. 7 Porosity and Water saturation section for wells Rt-6, 3, and 4 in Yamama formation

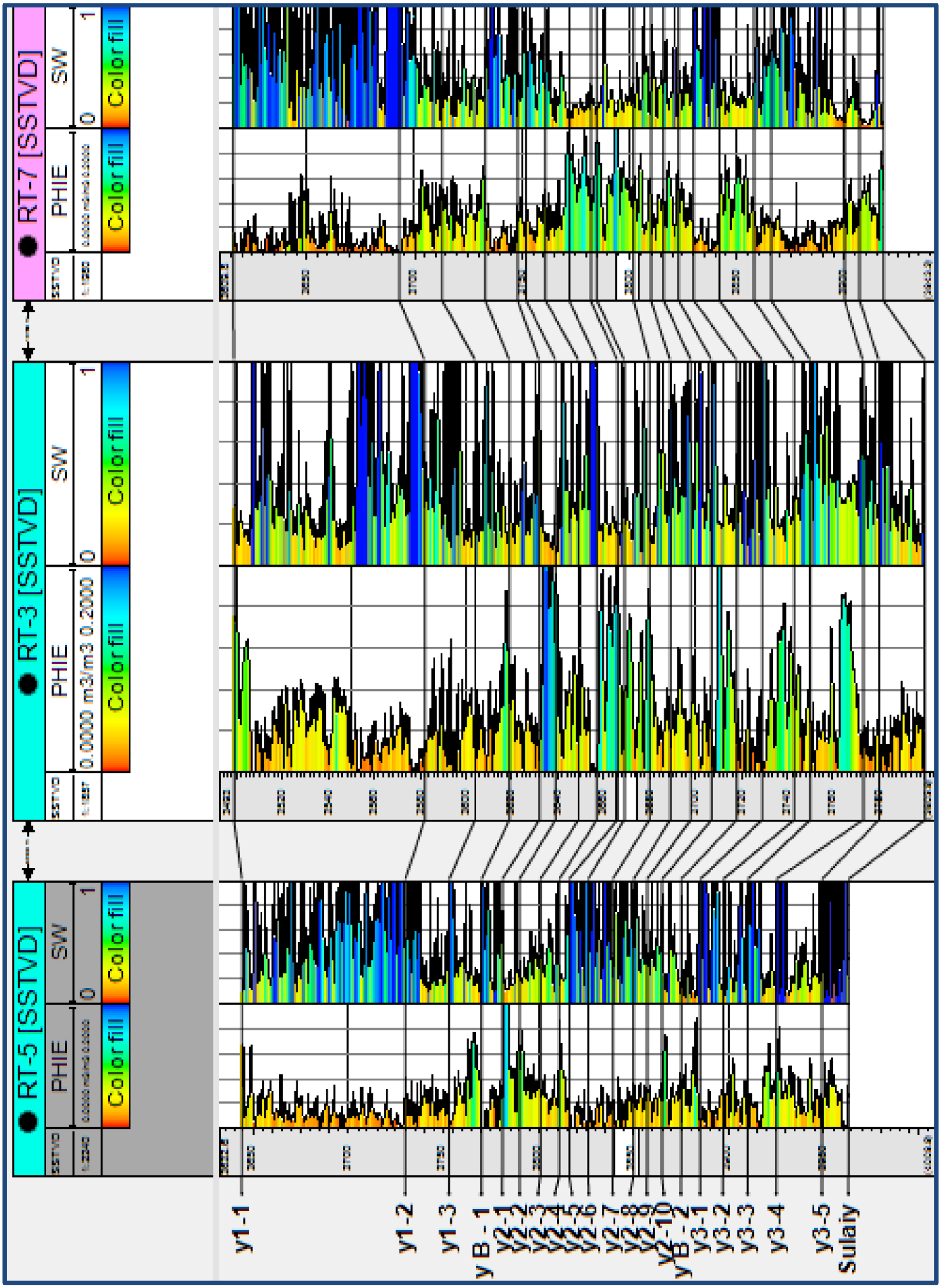


Fig. 8 Porosity and Water saturation section for wells Rt-5, 3, and 7 in Yamama formation

Fig. 9 Porosity–Permeability plot and FZI for Yamama formation

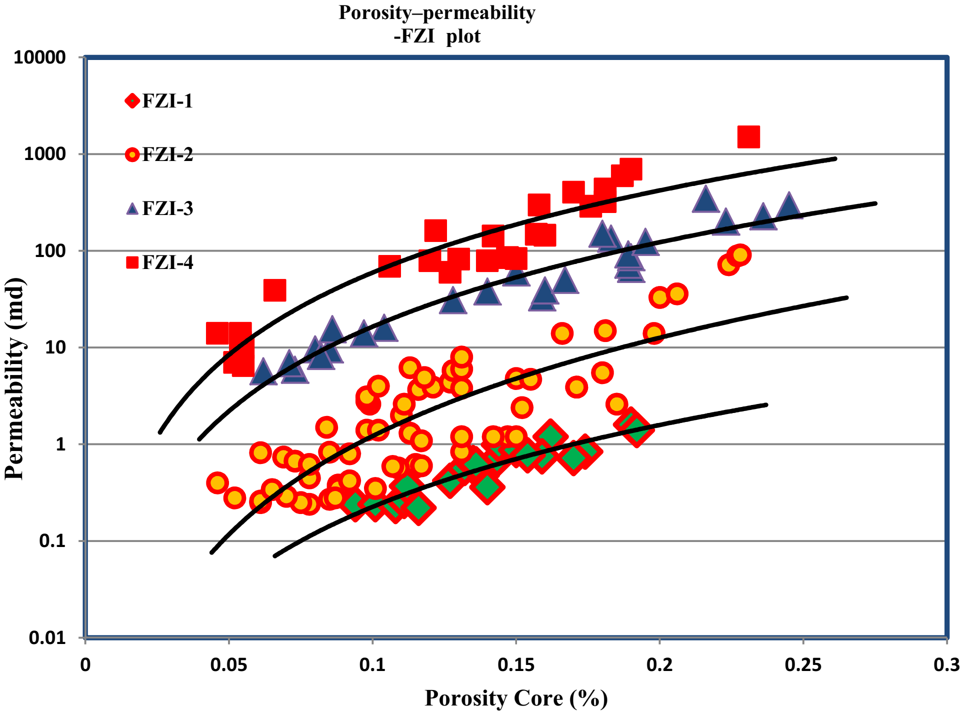
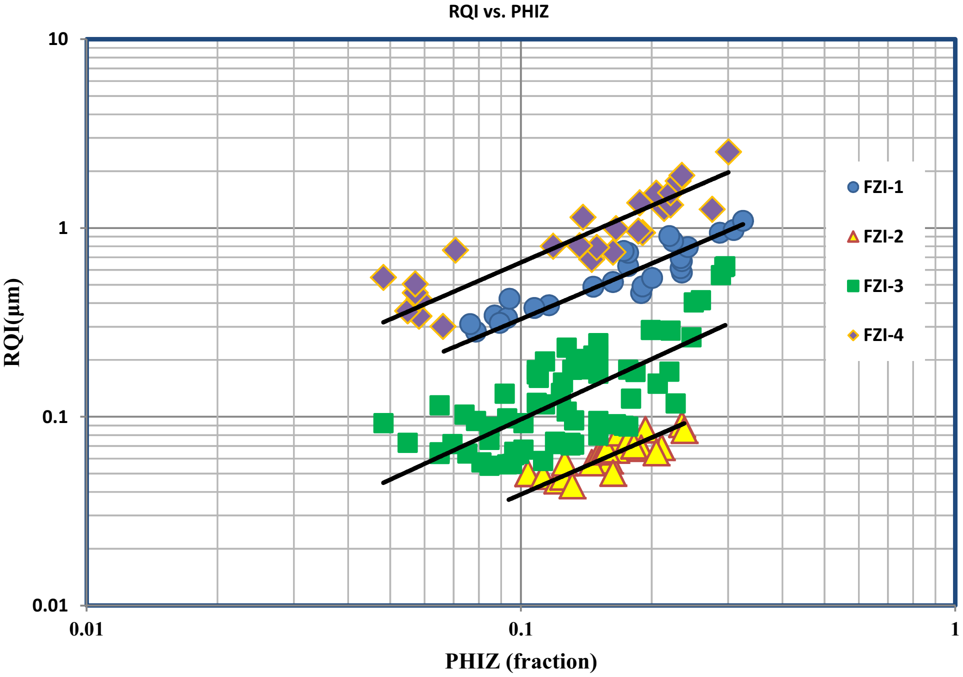


Fig. 10 RQI–PHIZ plot and flow zone indicator for Yamama formation

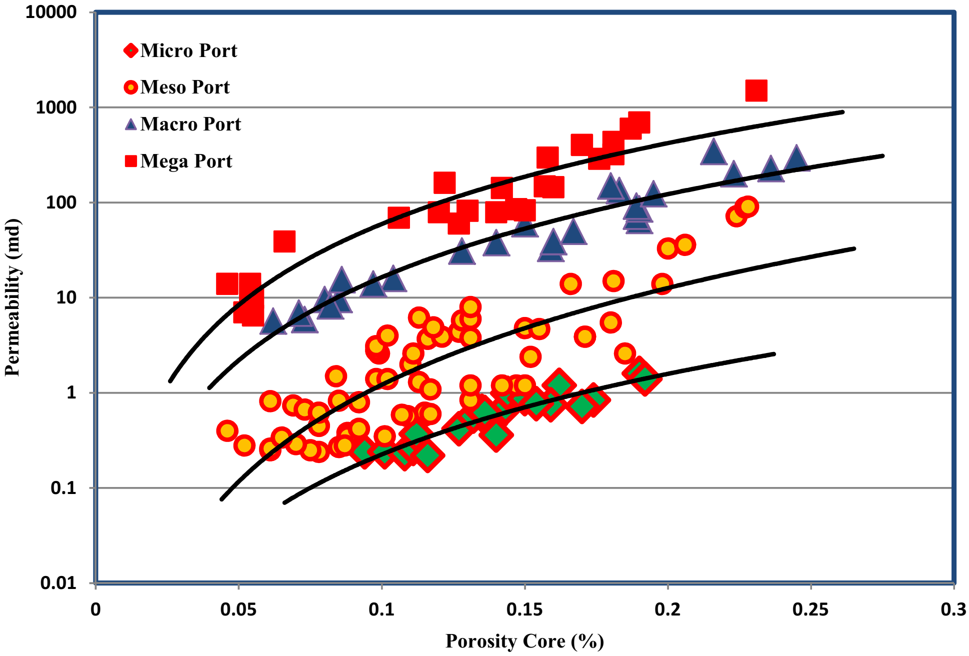


Pore-throat size (R35) determining depending on the core Permeability and Porosity in reservoir units provides best basis for defining reservoir flow units (Al-Jawad et al. 2014). R35 values are utilized to define petrophysical units as follows (Martin et al. 1997):

Mega port; units with R35 values greater than 10 μ.
Macro port; units with R35 values between 2 and 10 μ.
Meso port; units with R35 values between 0.5 and 2 μ.
Micro port; units with R35 values between 0.1 and 0.5 μ.
Nano port; units with R35 values smaller than 0.1 μ.

The available Porosity and Permeability air analysis for the Ratwai wells in the Yamama formation was used to determine pore-throat radius (R35) and identify pore type and subdivided the main reservoir into several flow units,

Fig. 11 Porosity–Permeability pore type plot



and four groups of pore-throat size have been determined for the studied flow units: Mega, Macro, Meso and Micro ports (Fig. 11) (Tables 1, 2, 3).

The Mega port type recognizes for reservoir units Y2-2, Y2-3, and Y2-4, which reflected a very good reservoir quality and coincides with Microfacies-type Peloidal–oolitic Grainstone Microfacies and FZI-4. Macro port type recognizes in the flow units (Y1-2, Y2-4, Y2-6, and Y3-5), which reflected good reservoir quality units and coincides with Microfacies type (Peloidal Packstone–Grainstone Microfacies) and FZI-3. Meso port type is recognized for flow units (Y2-1, Y2-7, Y2-8, Y2-9, Y3-1, Y3-3, and Y3-4); this type reflected moderate reservoir quality and coincides with Microfacies (Algal wackestone–Packstone Microfacies and Bioclastic wackestone–Packstone Microfacies) and FZI-2. Micro port type is recognized in the flow units (Y1-3, Y2-5, Y3-2, YB-1, and YB-2); this type represents bad reservoir quality and coincides with Microfacies (Mudstone Microfacies and Foraminiferal wackestone Microfacies) and (FZI-1). Tables 1, 2, and 3 show pore-throat size (R35) and pore type in each reservoir flow unit of the Yamama formation.

6. Capillary pressure analysis

Capillary pressure is related to pore throat radius. Pore throats have complex geometries so that computed pore throat radius represents the effective pore throat radius. Rearranging the expression for P_c provides the equation to compute effective pore-throat radius. Capillary pressure measurements are useful indicators of reservoir quality (AHR 2008).

$$r_{\mathrm{eff}} = 2\sigma_{\mathrm{wo}}(\cos\,\theta)/P_{\mathrm{c}}$$

σ is the interfacial tension of the air–mercury system (480 dynes/cm), θ is the air–mercury–solid contact angle (140°), and P_{c} is capillary pressure.

The available data of capillary pressure for Yamama formation were used to derive the capillary pressure versus Water saturation curves (Figs. 15, 16, 17).

The important property that is derived from a capillary pressure test is pore-throat size and its distribution (Jaya et al. 2005).

The capillary pressure versus Water saturation curves (Figs. 15, 16, 17) for the carbonate Yamama formation show there are four groups of rock type and flow units; these capillary pressure curves support the subdivision of the main reservoir unit to flow units, and capillary pressure curves reflect different pore-throat sizes. Flow unit with smaller Porosity and Permeability values needs higher capillary pressure (displacement pressures) and is reflected smaller pore-throat sizes.

Capillary pressure analysis curves are presented for different rock types, curves samples at depths (3742 and 3705 m, Fig. 12), reflected a very good quality of reservoir and porous (Mega port type) (FZI-4) (Peloidal–oolitic Grainstone Microfacies), and with a low irreducible Water saturation (Swi).

Capillary pressure curves sample at depths 3695.2, 3804.14, 3799, and 3803 m in Figs. 12, 13, and 14 consecutively reflected good quality of reservoir and porous (Macro port type) (FZI-3) (Peloidal Packstone–Grainstone Microfacies).

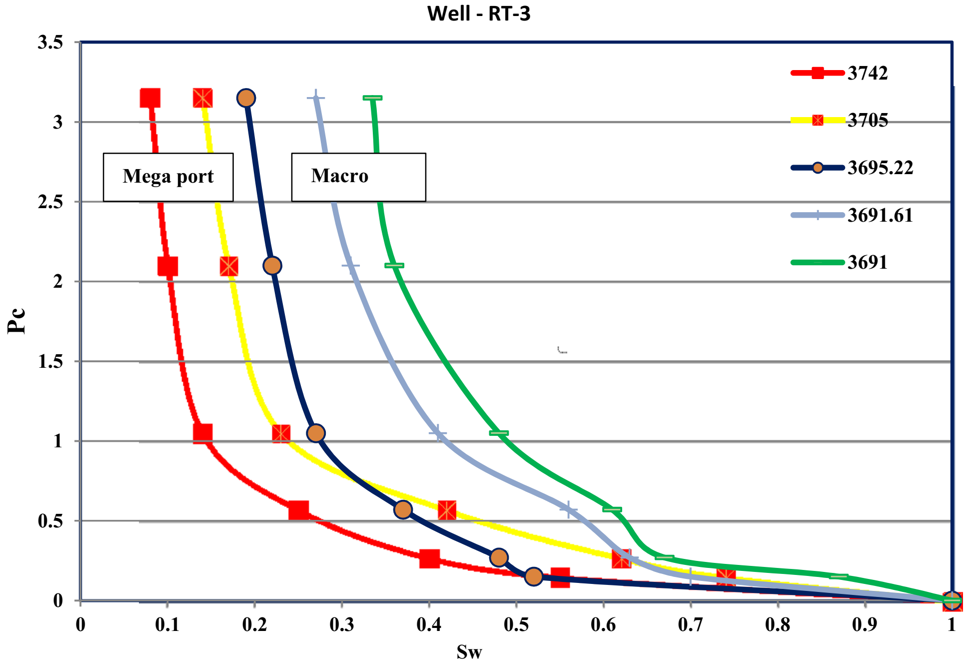


Fig. 12 Capillary pressure analysis for well Rt-3

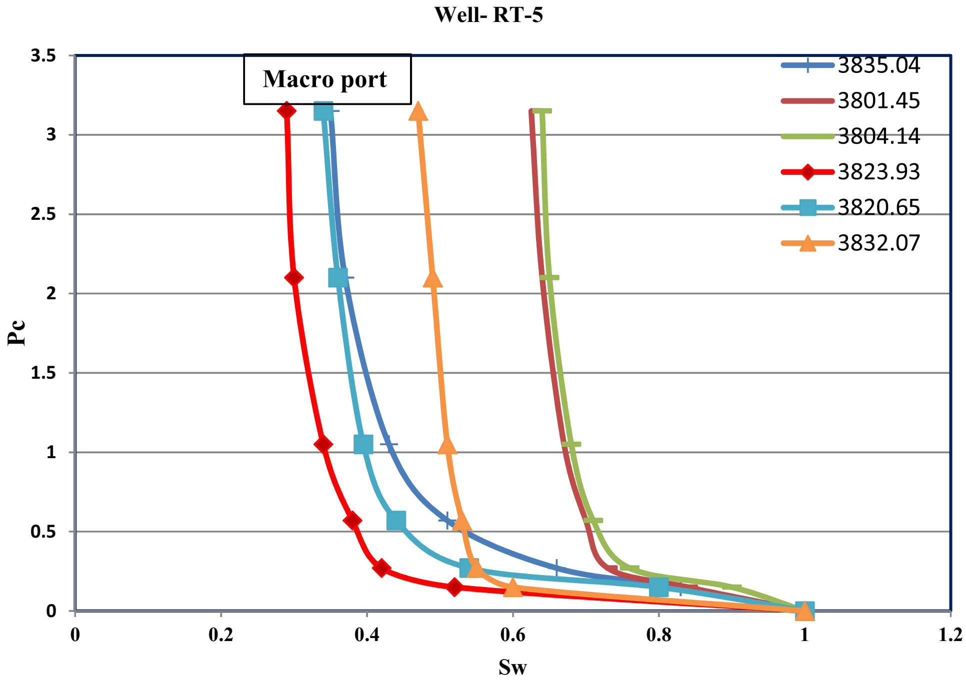


Fig. 13 Capillary pressure analysis for well Rt-5

Capillary pressure curves samples at depths (3691, 3832, 3814, 3817 m) in Figs. 12, 13, and 14 consecutively reflected the moderate quality of reservoir (Meso port type) (FZI-2) (Algal wackestone–Packstone Microfacies and Bioclastic wackestone–Packstone Microfacies).

And in Fig. 14, capillary pressure curves samples at depths (3801, 3804 m) reflected a very fine-grained with bad reservoir quality (Micro port type) (FZI-1) (Mudstone Microfacies and Foraminiferal wackestone Microfacies) and with the higher displacement of pressure).

7. Cluster analysis method

The clusters analysis defines Electrofacies on the basis of the unique characteristics of well log measurements reflecting minerals and lithofacies within the logged interval (Perez et al. 2005).

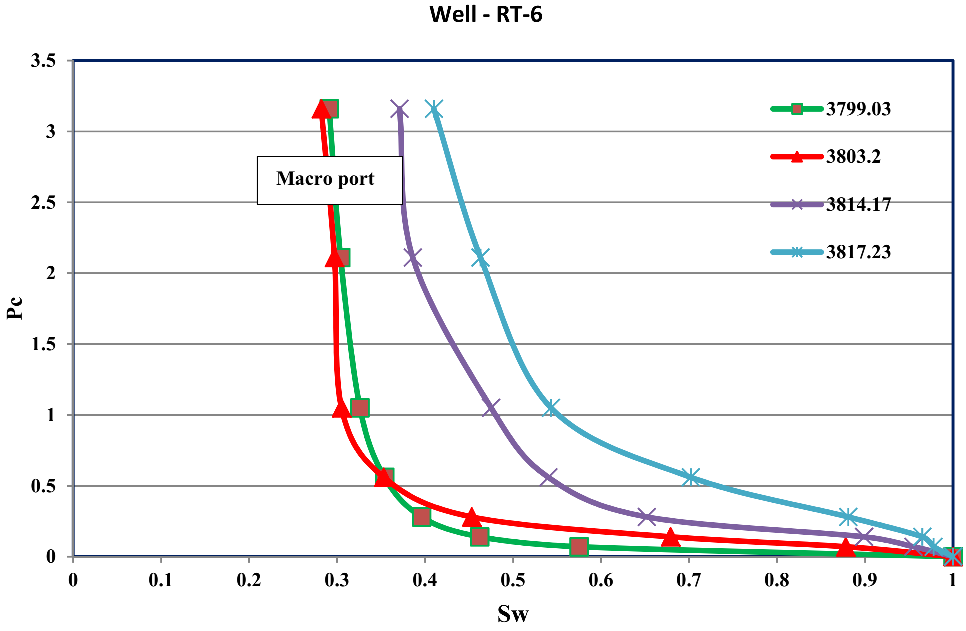


Fig. 14 Capillary pressure analysis for well Rt-6

Table 1 Pore-throat size (R35) and pore type for well Rt-3

Unit	ϕ (%)	Ka (md)	R_{35}	Pore type
Y2-4	13.99	86.32	< 10 > 2 μ	Macro
Y2-5	6.2	0.256	< 0.5 > 0.1μ	Micro
Y2-6	7.7	3.6	< 2 > 0.5 μ	Meso
Y2-7	4.9	1.37	< 2 > 0.5 μ	Meso
Y2-8	5.8	2.11	< 2 > 0.5 μ	Meso
Y2-9	2.8	2.15	< 10 > 2 μ	Meso
Y2-10	8.3	0.83	< 2 > 0.5 μ	Meso
YB-2	1.6	< 0.2	< 0.5 > 0.1μ	Micro

Table 2 Pore-throat size (R35) and pore type for well Rt-5

Unit	ϕ (%)	Ka (md)	R35	Pore type
Y1-1	2.6	0.69	< 2 > 0.5 μ	Meso
Y1-2	2.8	1.65	< 10 > 2 μ	Macro
Y1-3	5.4	0.21	<0.5 > 0.1 μ	Micro
YB -1	1.8	< 0.2	< 2 > 0.5 μ	Micro
Y2-1	13.1	1.13	< 2 > 0.5 μ	Meso
Y2-2	6.8	141.1	> 10 μ	Mega
Y2-3	7.3	179.9	> 10 μ	Mega
Y2-4	5.09	69.5	> 10 μ	Mega
Y2-5	2.1	0.52	< 2 > 0.5 μ	Meso
Y2-6	2.2	6.9	< 10 > 2 μ	Macro
Y2-7	3.06	1.3	< 0.5 > 0.1 μ	Meso
Y2-8	4.2	0.25	< 2 > 0.5 μ	Meso
Y2-9	5.8	0.75	< 2 > 0.5 μ	Meso
Y2-10	2.5	0.28	< 2 > 0.5 μ	Meso
YB-2	1.4	0.24	< 2 > 0.5 μ	Micro
Y3-1	4.8	1.58	< 2 > 0.5 μ	Meso
Y3-2	5.1	0.21	< 0.5 > 0.1 μ	Micro
Y3-3	2.5	0.69	< 2 > 0.5 μ	Meso
Y3-4	1.7	0.65	< 2 > 0.5 μ	Meso
Y3-5	0.74	2.63	< 10 > 2 μ	Macro

The raw and interpretation logs data (RHOB, DT, NPHI, resistivity, PHIE, and Sw) in the selected wells have been used as input data in cluster analysis model by using IP program; the input data were clustered randomly into 16 groups to cover total range of the logs data values by using (*K*-mean) statistical technique where the sum difference for the point data and each mean cluster were calculated and assigned point to cluster by the minimum difference. Once all points data were assigned to clusters, the new mean for cluster are calculated.

The sixteen groups depending on the cluster randomness plot (Fig. 15) were grouped into four groups; these groups are classifying basis on the measure of match or difference between the groups (Fig. 16). Rock-type logs along each well were produced. The randomness plot was used to analyze the grouping to decide which level adding another cluster gives extra data or to just adding noise, where the higher values of the Randomness index mean less random.

Four rock-type groups have been identified as follows:

Rock Type-1 represents the bad one (red color) where the effective Porosity is less than 0.01 and Water saturation greater than 90%. This rock type represents a bad reservoir quality, and it coincides with bad Microfacies (Mudstone Microfacies and Foraminiferal wackestone),

Table 3 Pore-throat size (R35) and pore type for well Rt-6

Unit	ϕ (%)	Ka (md)	R35	Pore type
Y1-2	2.84	< 0.2	< 0.5 > 0.1 µ	Micro
Y2-2	8.8	0.6	< 2 > 0.5 µ	Meso
Y2-3	5.9	86.74	< 10 µ	Mega
Y2-4	15.5	183.77	< 10 > 2 µ	Macro
Y2-5	9.26	1.88	< 2 > 0.5 µ	Meso
Y2-6	11.8	22.53	< 10 > 2 µ	Macro
Y2-7	2.81	< 0.2	< 2 > 0.5 µ	Meso
Y2-8	2.94	< 0.2	< 0.5 > 0.1 µ	Meso
Y2-9	2.54	< 0.2	< 2 > 0.5 µ	Meso
Y2-10	3.64	< 0.2	< 0.5 > 0.1 µ	Meso
YB-2	1.3	< 0.2	< 2 > 0.5 µ	Micro
Y3-1	4.7	0.39	< 2 > 0.5 µ	Meso
Y3-2	4.1	< 0.2	< 0.5 > 0.1 µ	Micro
Y3-3	2.76	< 0.2	< 2 > 0.5 µ	Meso
Y3-4	0.97	0.23	< 2 > 0.5 µ	Meso
Y3-5	5.2	0.20	< 0.5 > 0.1 µ	Micro

FZI-1, Micro port type, and with the higher displacement of capillary pressure.

Rock Type-2 represents bad to moderate rock type (green color); the effective Porosity ranges 0.02–0.05 and the Water saturation greater than 40%. This type reflects a moderate quality of reservoir and coincides with Microfacies type (Algal wackestone–Packstone Microfacies and Bioclastic wackestone–Packstone, FZI-2, and Meso port type.

Rock Type-3 represents moderate to good type of limestone rock (blue color) where the effective Porosity ranging between 0.06 and 0.10 % and Water saturation between 35–45%. This rock type represents a moderate to good reservoir quality and coincides with Microfacies type (Peloidal Packstone–Grainstone Microfacies), FZI-3, and Macro port type.

Rock Type-4 represents good to a very good type of limestone rock (yellow color) where the effective Porosity is more than 0.10 % and Water saturation less than 35%. This type coincides with Microfacies type (Peloidal–oolitic Grainstone Microfacies), FZI-4, Mega port

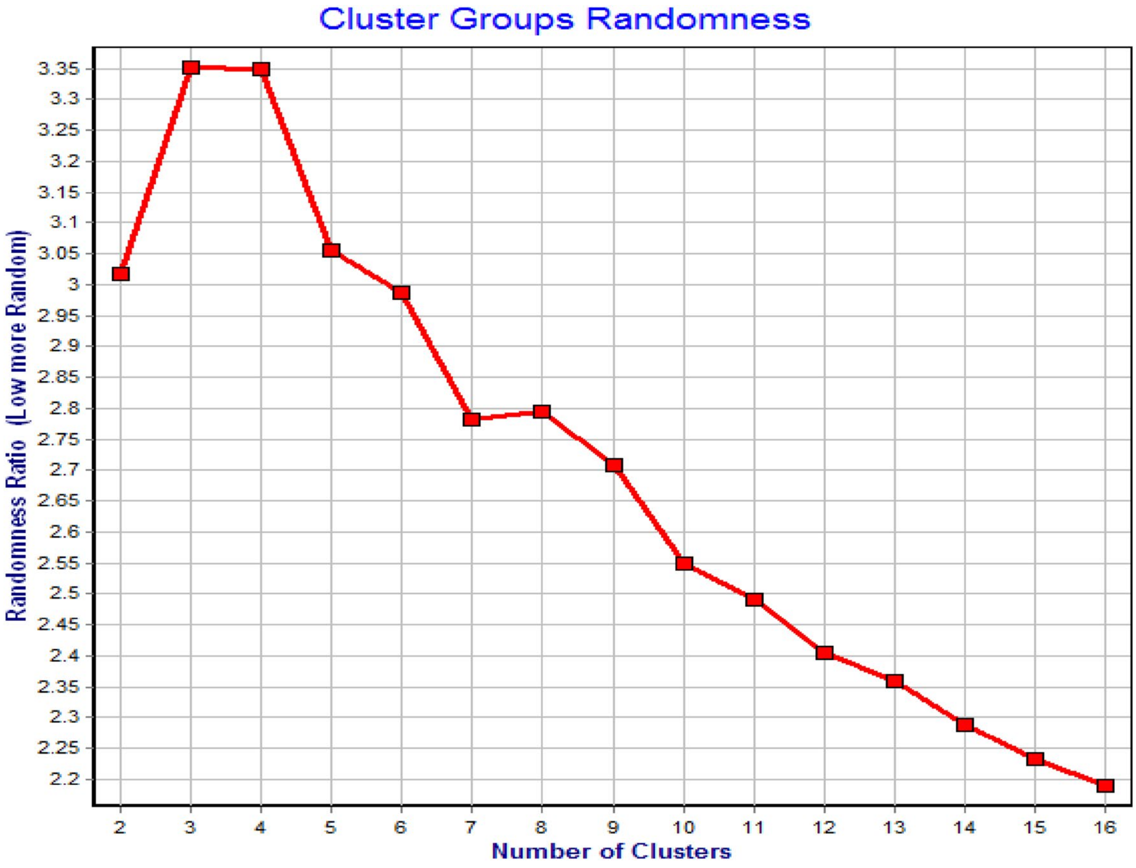


Fig. 15 Cluster randomness plot

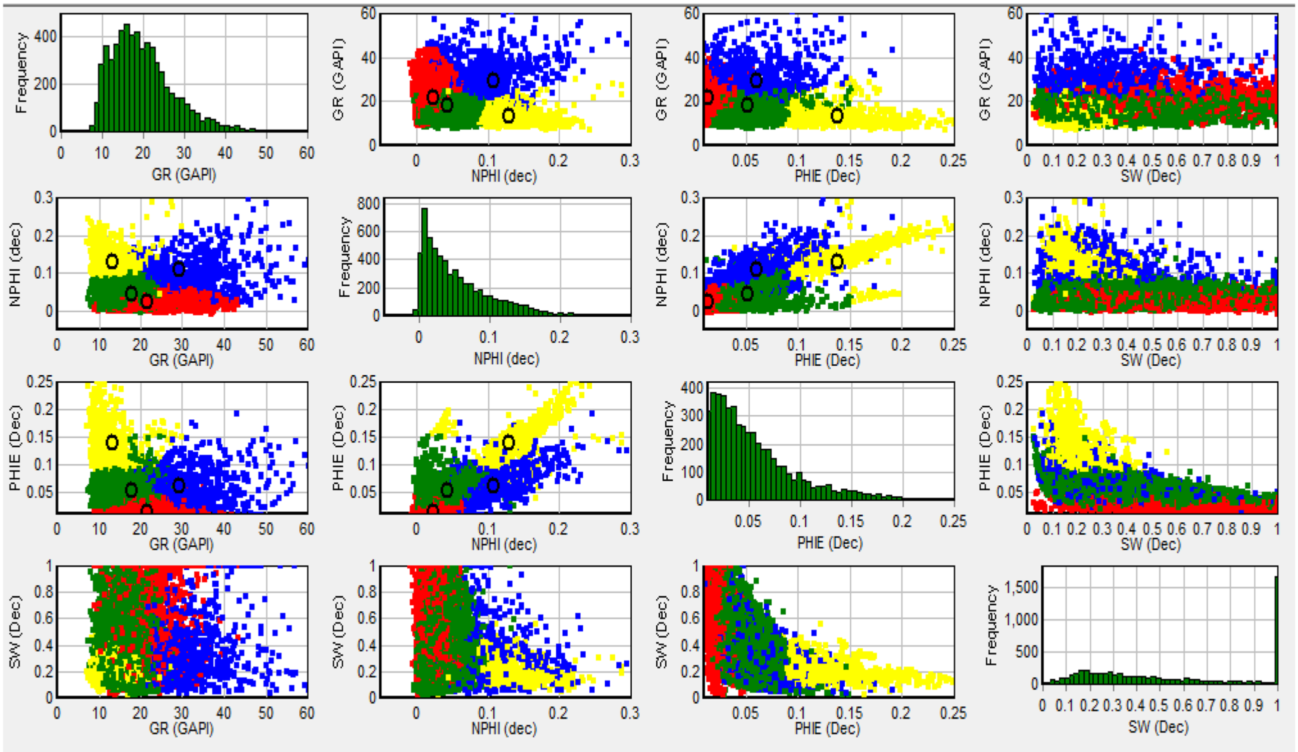


Fig. 16 Final graphical result of clustering analysis

type, and with a low irreducible Water saturation (Swi) in capillary pressure curve.

The cluster analysis results for rock type are shown in Table 4.

The final flow units and rock-type depths for Yamama Reservoir in studied wells are shown in Table 5.

Conclusions

The current work is the flow unit and rock type for reservoir characterization in carbonate reservoir. Yamama formation in south of Iraq (Ratawi Field) was selected, and this study is depending on the logs and cores data from five wells which penetrate carbonate Yamama formation, and the following conclusions were reached:

1. Carbonate Yamama reservoir was divided into twenty flow units and rock types, depending on the Microfacies and Electrofacies Character, the well logs pattern, Porosity–Water saturation relationship, flow zone indicator method, capillary pressure analysis, and Porosity–Permeability relationship (R35) and cluster analysis method.
2. Four rock types and groups have been identified in the Yamama formation by using flow zone indicator (FZI) approaches, where the first group represents bad reservoir quality (FZI-1) (Mudstone Microfacies and Foraminiferal wackestone Microfacies), the second group reflects moderate quality of reservoir (FZI-2) (Algal wackestone–Packstone Microfacies and Bioclastic wackestone–Packstone Microfacies), the third group represents good reservoir quality (FZI-3) (Peloidal Packstone–Grainstone Microfacies), and the fourth group shows a high trend of the Permeability and Porosity which represent a very good reservoir quality (FZI-4) (Peloidal–oolitic Grainstone Microfacies).
3. Four groups of pore-throat radius (R35) have been determined (Mega, Macro, Meso, and Micro ports) for the studied flow units by Porosity–Permeability relationships.
4. Capillary pressure curves show four different rock types: a very good quality of reservoir and porous (Mega port type) (FZI-4), good quality of reservoir and porous (Macro port type) (FZI-3), moderate quality of reservoir (Meso port type) (FZI-2), and a very fine-grained with bad reservoir quality (Micro port type) (FZI-1).
5. Four rock types groups were identified depending on the cluster analysis methods; these groups are: Rock Type-1 represent the bad one (red color) where the effective

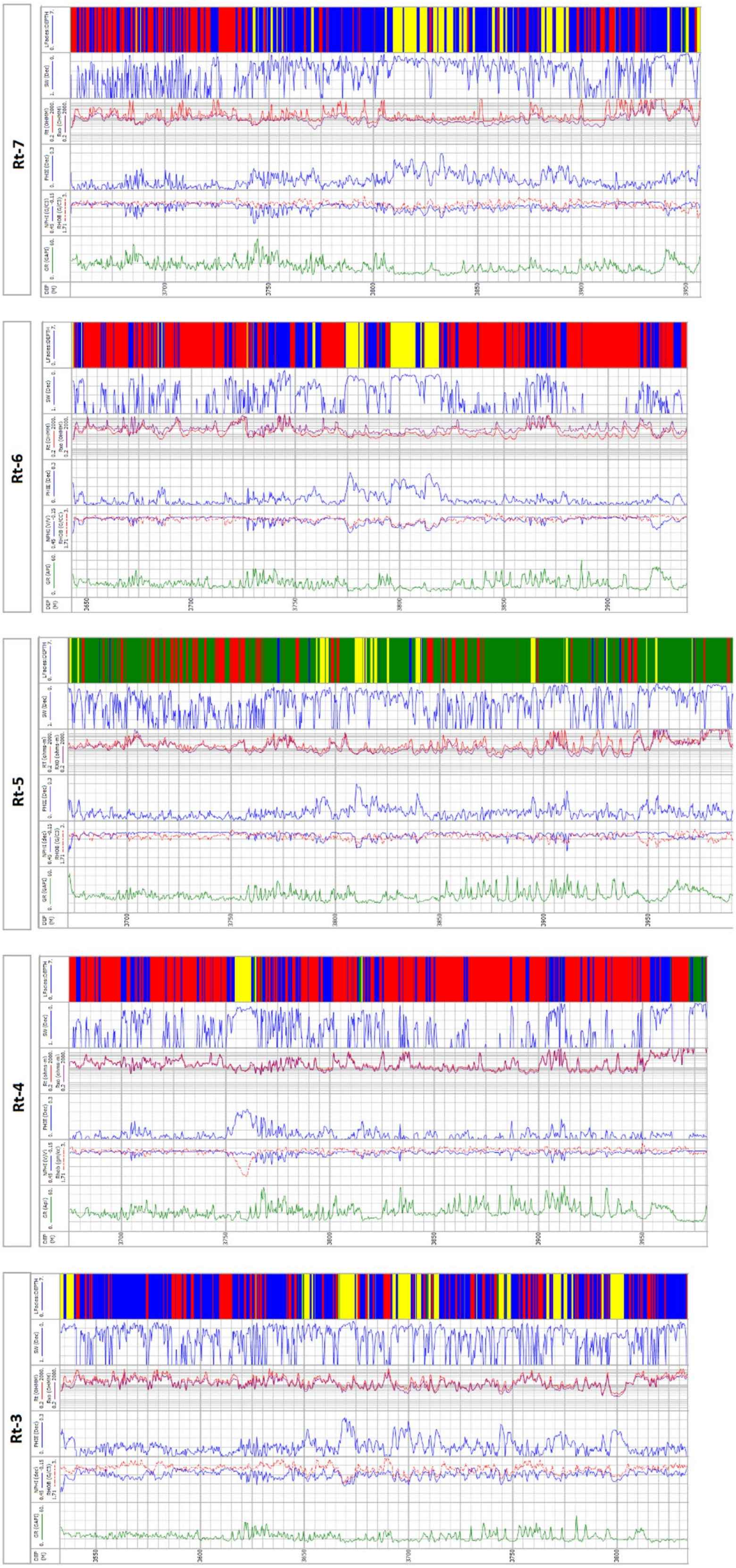
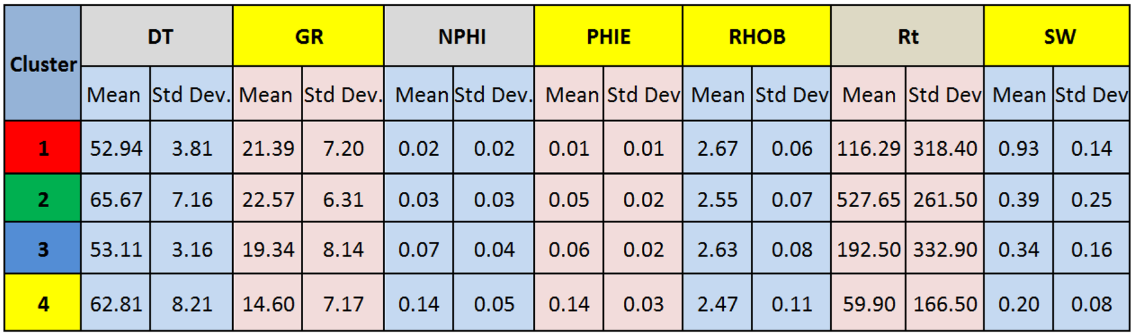


Fig. 17 Rock-type identification for wells Rt-3, 4, 5, 6, and 7

Table 4 Cluster analysis results for each rock type



Cluster	DT		GR		NPHI		PHIE		RHOB		Rt		SW	
	Mean	Std Dev.	Mean	Std Dev.	Mean	Std Dev.	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
1	52.94	3.81	21.39	7.20	0.02	0.02	0.01	0.01	2.67	0.06	116.29	318.40	0.93	0.14
2	65.67	7.16	22.57	6.31	0.03	0.03	0.05	0.02	2.55	0.07	527.65	261.50	0.39	0.25
3	53.11	3.16	19.34	8.14	0.07	0.04	0.06	0.02	2.63	0.08	192.50	332.90	0.34	0.16
4	62.81	8.21	14.60	7.17	0.14	0.05	0.14	0.03	2.47	0.11	59.90	166.50	0.20	0.08

Table 5 Flow unit depths for Yamama formation in Ratawi Field

Unit	Rt-3 KB (m) = 34	Rt-4 KB (m) = 36	Rt-5 KB (m) = 28	RtV6 KB (m) = 25	Rt-7 KB (m) = 39
Y1					
Y1-1	3533	3675	3672	3643	3655
Y1-2	3616	3760	3758	3725	3732
Y1-3	3638	3787	3781	3749	3752
YB-1	3653	3801	3798	3762	3772
Y2					
Y2-1	3666	3814	3809	3774	3787
Y2-2	3673	3818	3818	3778	3791
Y2-3	3683	3832	3829	3788	3800
Y2-4	3691	3839	3839	3798	3811
Y2-5	3700	3841	3844	3804	3821
Y2-6	3703	3850	3854	3811	3824
Y2-7	3714	3865	3867	3823	3841
Y2-8	3723	3875	3878	3830	3849
Y2-9	3732	3883	3885	3838	3855
Y2-10	3741	3892	3893	3847	3862
YB-2	3752	3902	3903	3857	3869
Y3					
Y3-1	3763	3914	3913	3869	3881
Y3-2	3777	3930	3925	3886	3897
Y3-3	3784	3938	3938	3892	3905
Y3-4	3807	3946	3953	3920	3939
Y3-5	3814	3963	3977	3930	3946
Sulaiy	3834	3981	3991	3938	3957

> Porosity less than 0.01 and Water saturation greater than 90%, Rock Type-2: represents bad to moderate rock type (green color), the effective Porosity range 0.02–0.05 and the Water saturation greater than 40%, Rock Type-3: represents moderate to good type of limestone rock (blue color) where the effective Porosity ranging between 0.06 and 0.10 % and Water saturation between 35 and 45%.

Rock Type-4 represents good to a very good type of limestone rock (yellow color) where the effective Porosity more than 0.10 % and Water saturation less than 35%.

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