ORIGINAL PAPER-EXPLORATION GEOLOGY

Integrated reservoir characterization and quality analysis of the carbonate rock types, case study, southern Iraq

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Abstract

The reservoir characterization and rock typing is a significant tool in performance and prediction of the reservoirs and understanding reservoir architecture, the present work is reservoir characterization and quality Analysis of Carbonate Rock-Types, Yamama carbonate reservoir within southern Iraq has been chosen. Yamama Formation has been affected by different digenesis processes, which impacted on the reservoir quality, where high positively affected were: dissolution and fractures have been improving porosity and permeability, and destructive affected were cementation and compaction, destroyed the porosity and permeability. Depositional reservoir rock types characterization has been identified depended on thin section analysis, where six main types of microfacies have been recognized were: packstone-grainstone, packstone, wackestone-packstone, wackestone, mudstone-wackestone, and mudstone. By using flow zone indicator, four groups have been defined within Yamama Formation, where the first type (FZI-1) represents the bad quality of the reservoir, the second type (FZI-2) is characterized by the intermediate quality of the reservoir, third type (FZI-3) is characterized by good reservoir quality, and the fourth type (FZI-4) is characterized by good reservoir quality. Six different rock types were identified by using cluster analysis technique, Rock type-1 represents the very good type and characterized by low water Saturation and high porosity, Rock type-2 represents the good rock type and characterized by low water saturation and medium–high porosity, Rock type-3 represents intermediate to good rock type and characterized by low-medium water saturation and medium porosity, Rock type-4 represents the intermediate rock type and characterized by medium water saturation and low–medium porosity, Rock type-5 represents intermediate to bad rock type and characterized by medium–high water saturation and medium–low porosity, and Rock type-6 represents bad rock type and characterized by high water saturation and low porosity. By using Lucia Rock class typing method, three types of rock type classes have been recognized, the first group is Grain-dominated Fabrics—grainstone, which represents a very good rock quality corresponds with (FZI-4) and classified as packstone-grainstone, the second group is Grain-dominated Fabrics—packstone, which corresponds with (FZI-3) and classified as packstone microfacies, the third group is Mud-dominated Fabrics—packstone, packstone, correspond with (FZI-1 and FZI-2) and classified as wackestone, mudstone-wackestone, and mudstone microfacies.

Keywords Reservoir characterization · Carbonate rock types · Southern Iraq

Introduction

The key topic of rock typing is to capture the relationship between petrophysics and geology, and rock type might be reflected as a petrophysically and geologically homogeneous rocks group with characteristic relationships between permeability, water saturation, and porosity. Petrophysical distributions in each rock type have to be homogeneous in the domain of petrophysical and certain geostatistical performances. Moreover, it must be an exact and understandable link with geology (stratigraphy, sedimentology, lithology, and diagenesis) (Rebelle 2014).

Rock typing is the process of assigning reservoir properties to geological facies, and an ideal rock type has similar geological and reservoir properties. There are three main categories for this process including geology, reservoir (static properties), and petrophysics (Tavakoli 2018)

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Depositional environments are important to the performance of the reservoir as they have a dominant influence on the original pore network of newly deposited sediments, the pore network formation determines the characteristics of the framework grains, such as grain size and sorting, and all these parameters in turn control porosity and permeability; textural features supporting good reservoir quality of a reservoir are coarse-grained sediments with good sorting (Jumat et al. 2018).

Flow unit is a pore scale method for classification of rock types relative to flow properties based on geological parameters and flow physics, and identifying the flow units has a significant role in flow transmissivity and storage which can be helpful in secondary recovery and more production of the reservoir (Mahjour et al. 2016).

The reservoir quality of carbonate rocks is usually controlled by the interplay of both the primary depositional and secondary diagenetic parameters. The assessment of the respective impact of these controls together with the understanding of the field-scale sedimentological organization and diagenetic trends assists in the reconstruction of reservoir architecture (Jeong et al. 2017).

Yamama Formation is one of the giant reservoirs within south part of Iraq, is carbonate heterogeneous reservoir, deposited through the Lower Cretaceous period, within main retrogressive depositional cycles (Berriasian-Aptian) (Buday 1980).

Yamama Formation is up to 400-m-thick carbonate reservoir of lower Cretaceous age and shallow marine deposited on a regionally extensive carbonate platform. Yamama Formation was deposited in a series of overall regressive cycles with reservoir quality progressively improving to the top of Formation.

Yamama carbonate reservoir in the south of Iraq has been chosen to investigate the reservoir characterization, and many approaches and methods were used to investigate the reservoir characterization and Quality Analysis of Carbonate Rock-Types; these approaches involve:

1. The Depositional Reservoir Rock Types Characterization Approach.
2. Flow zone indicator (FZI) method.
3. Well logs data (Cluster Analysis).
4. Winland method (Porosity–Permeability relationship-R35).
5. Lucia Rock class typing method.

Geology Setting and background

The area of the study situated within southern Iraq, approximately 50 km north of Basra Governorate.

Tectonically, the studied area situated within the Mesopotamian basin in the Zubair subzone (stable shelf)

(Fig. 1). The zone of the Mesopotamian was perhaps uplifted through Hercynain distortion, but subsided after late Permian time onward three subzones were separated within the Mesopotamian basin: in the south (Zubair subzone), in the West (Euphrates subzone), and in the North (Tigris subzone). The isopach map of the Yamama Formation in Iraq (Fig. 2) shows the formation thickens south of the Mosul High. The formation is up to 400 m thick in the Euphrates area near Najaf and up to 360 m thick in SE Iraq (Jassim and Goff 2006).

Stratigraphically, Yamama Formation represents the regressive carbonate cycle comprising the neritic lithofacies of the cycle. Three depositional cycles included within Yamama Formation, top cycle comprises inner ramp facies (oolitic grainstone), middle-ramp (packstone, wackestone), and the third bases cycle outer ramp (chalky micrite and gray shale) (Sadooni 1993).

Yamama Formation is located at a depth of about 3499–4100 m below the sea level in the studied wells and underlain conformably by the Sulaiy Formation (Fig. 3), which made up of mud-supported argillaceous limestone with calcispheres and small benthonic foraminifera, and grades upward into the Ratawi Formation (Saleh 2014).

The Yamama Formation was defined by Steineke and Bramkamp (1952) from outcrops in Saudi Arabia, as limestone fragment units.

Yamama Formation mainly consists of limestone, and distinct some dolomitic limestone with shale, and was deposited in the environments of oolitic shoal—inner shelf (deep) and perhaps controlled by highs structural in carbonate ramp, and it is underlain conformably by the Sulaiy Formation and Ratawi Formation which has directly overlain it. The main controversy is associated with the stratigraphy of Yamama Formation and overlying Ratawi Formation. Yamama Formation comprises three depositional cycles, where top cycle contains oolitic grainstone inner ramp facies which pass down into finer-grained peloidal facies, middle-ramp (bioclastic, coral, stromotoporoid) packstone-wackestone, and outer ramp bases cycle comprises thick gray shale with stringers of chalky micrite (Sadooni 1993).

Yamama Formation within the south of Iraq has been divided into many reservoirs units, depending on the depositional environment divisions, where Yamama Formation was divided by (Al-Siddiki 1978a, b; Sadooni 1993) into five main units (YR-A, YB-1, YR-B, YB-2, and YR-C), three of these units are considered as reservoir rocks (YR-A, YR-B, and YR-C), and the two other units(YB-1 and YB-2) are considered as barrier units.

The Yamama Formation is up to 400-m-thick carbonate reservoir of lower Cretaceous age and deposited in shallow marine conditions on a regionally extensive carbonate platform.
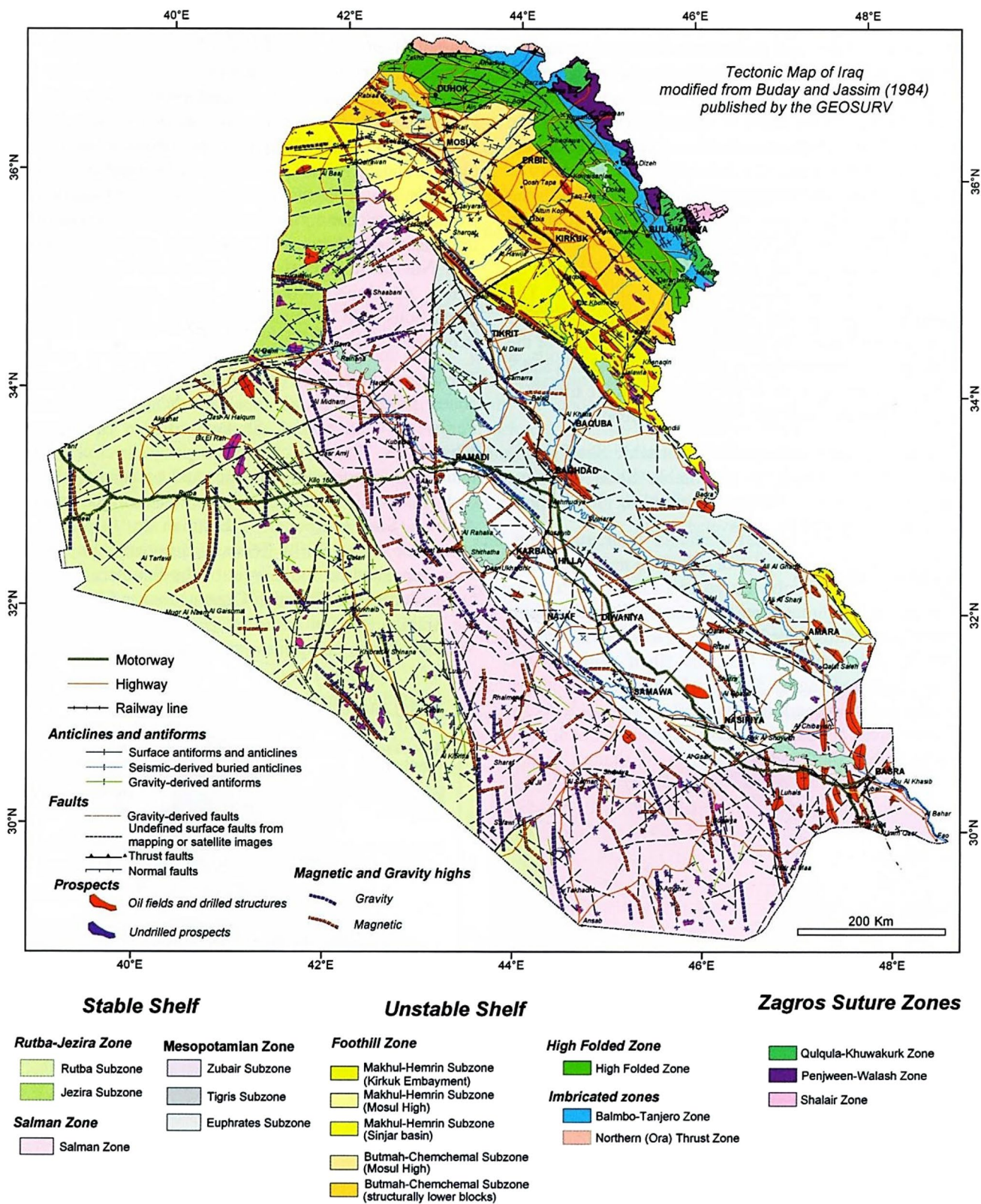
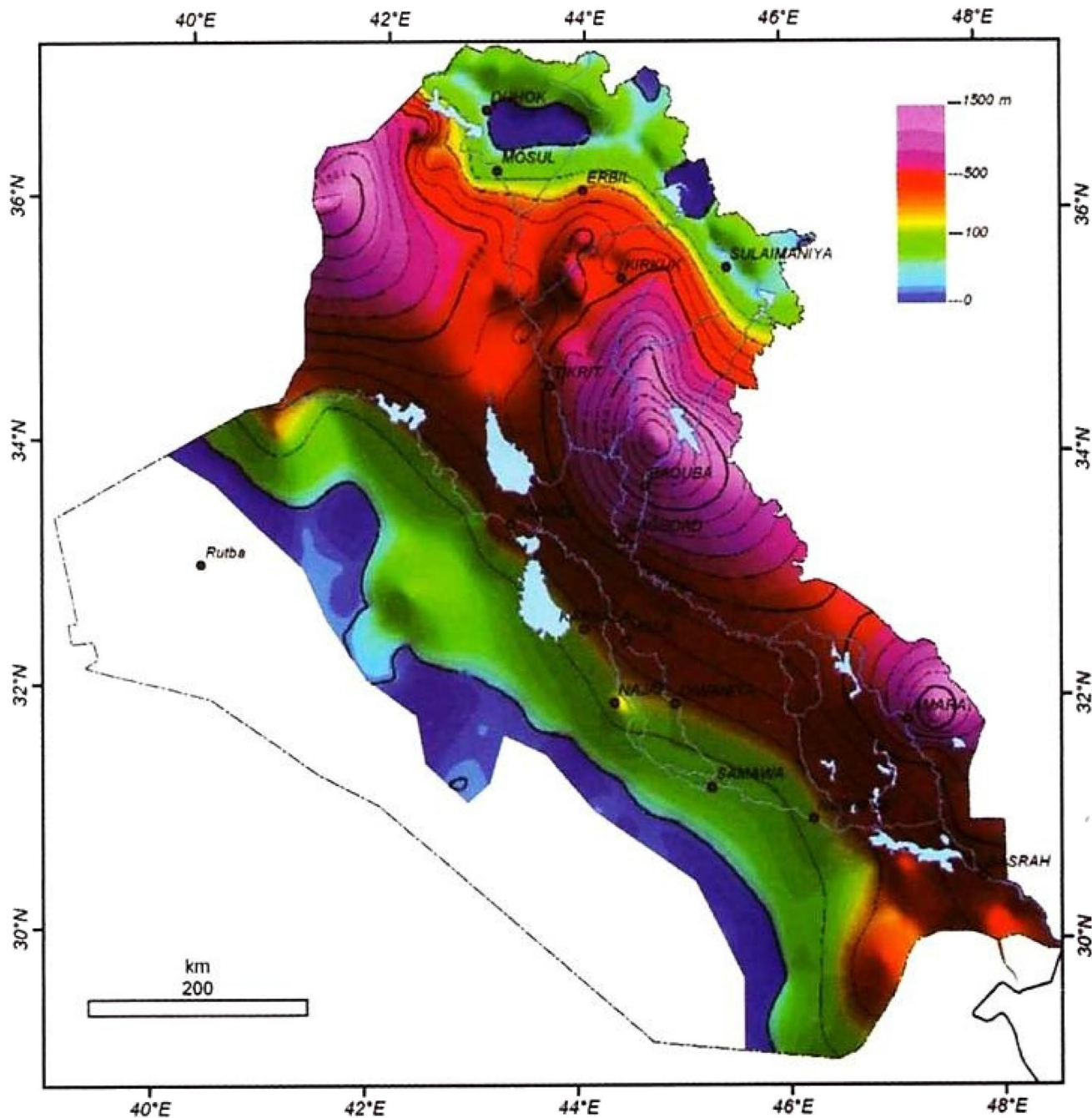**Fig. 1** Tectonic map of Iraq (Jassim and Goff 2006)

Fig. 2 Isopach map of the Yamama Formation (Jassim and Goff 2006)

Reservoir characterization and rock typing

### Depositional reservoir rock types characterization approach

These approaches are focused on a depositional environment classification, the texture, grains type (skeletal, non-skeletal grains, and other organisms), and diagenesis process influence.

Petrography analysis

The first step for characterizing the rock types and flow unit is petrographic analysis, and the petrographic analysis is used to determine and analyze the microfacies, pores types, diagenetic processes, and their effects on petrophysical properties of the rocks, and depositional environments.

The petrography of Yamama Formation components was analyzed depending on the examination of (250) thin

Fig. 3 Sequence stratigraphy of the south of Iraq
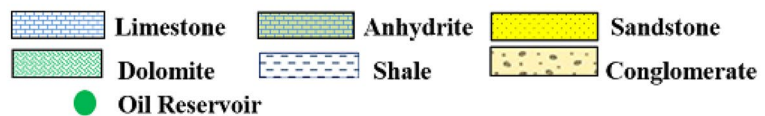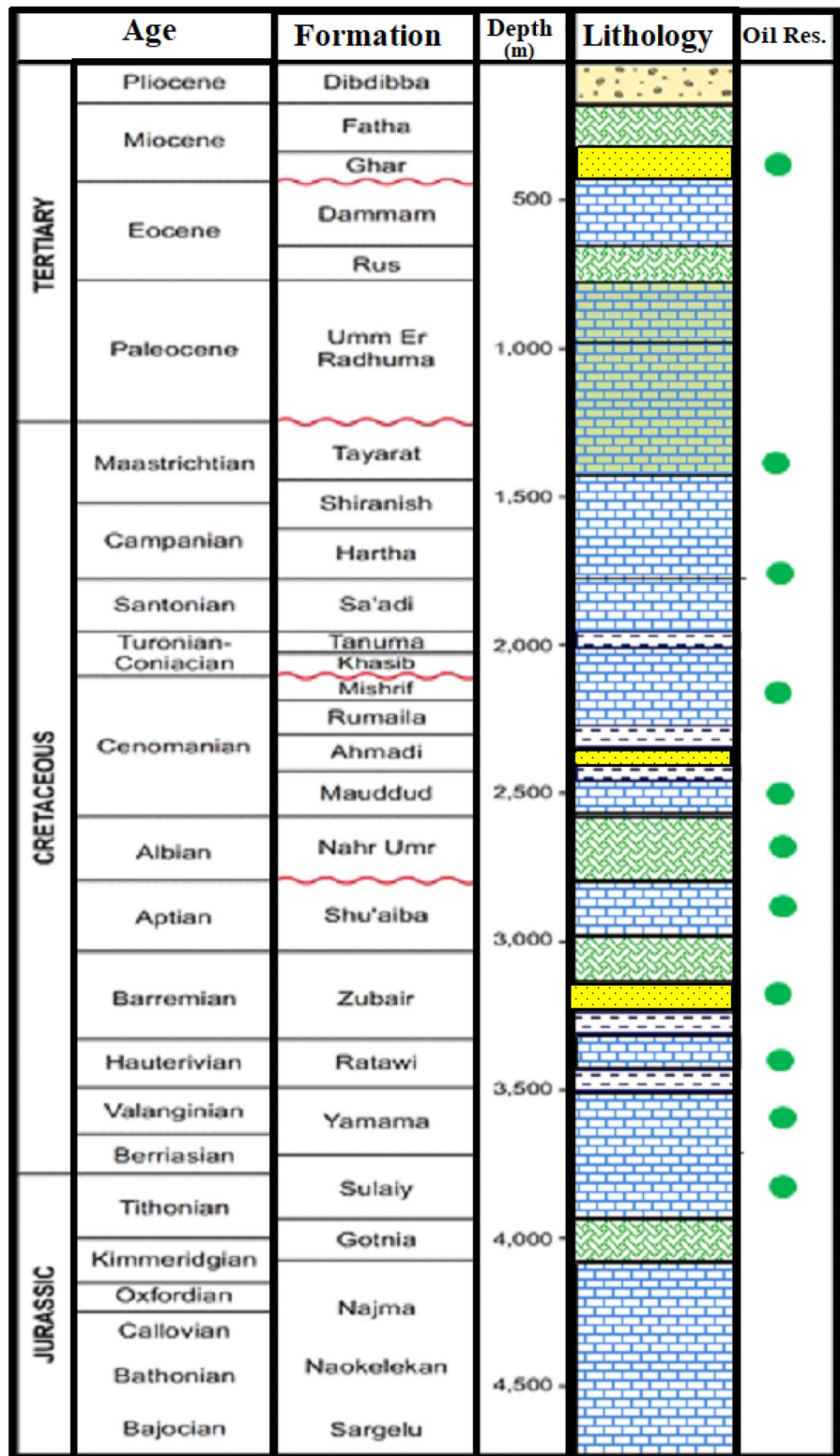
sections of cores samples for selected wells from A, B fields located in the south of Iraq, approximately 50 km north of Basra Governorate. The grains were distinct depending on their internal structure and shape and divided into the skeletal grains and non-skeletal grains.

The skeletal grains were recognized such as Foraminifera, Calcareous Algae, Echinoids, Sponge Spicules, and other organisms. The Yamama Formation contains abundances calcareous algae, especially green and red algae, green algae are abundance more than red algae and existed within middle unit more than upper and lower units of the formation mostly *(Dascycladacean species)*, and this type of algae indicated on deep marine environments is strongly protected lagoon (Fig. 4a), red algae (Fig. 4b) existed usually in the upper parts of the formation, and the abundance kinds of red algae in the formation are *(Permocalculus ampullaceal, Peyssonelia)*.

Foraminifera is an important skeletal grain in the Yamama Formation, was existed in the various facies of the formation, two types of foraminifera have existed, benthonic and planktonic foraminifera, and the benthic foraminifera is abundant in the most of the microfacies and is found in various types and different sizes, such as *Tracholina, Textularia, Praechysalidina, Pseudochratalidina Aulotortus communis*, and *Milliolid*, planktonic foraminifera less common than benthic and contain in species such as *Globigerina,* planktonic foraminifera are an indicator for the shallow marine to relatively deep water environments (Fig. 4c, d).

Echinoderms and echinoderm fragments are abundant within the formation, different shapes were founded in the

Fig. 4 Main skeletal and non-skeletal grains within Yamama Formation
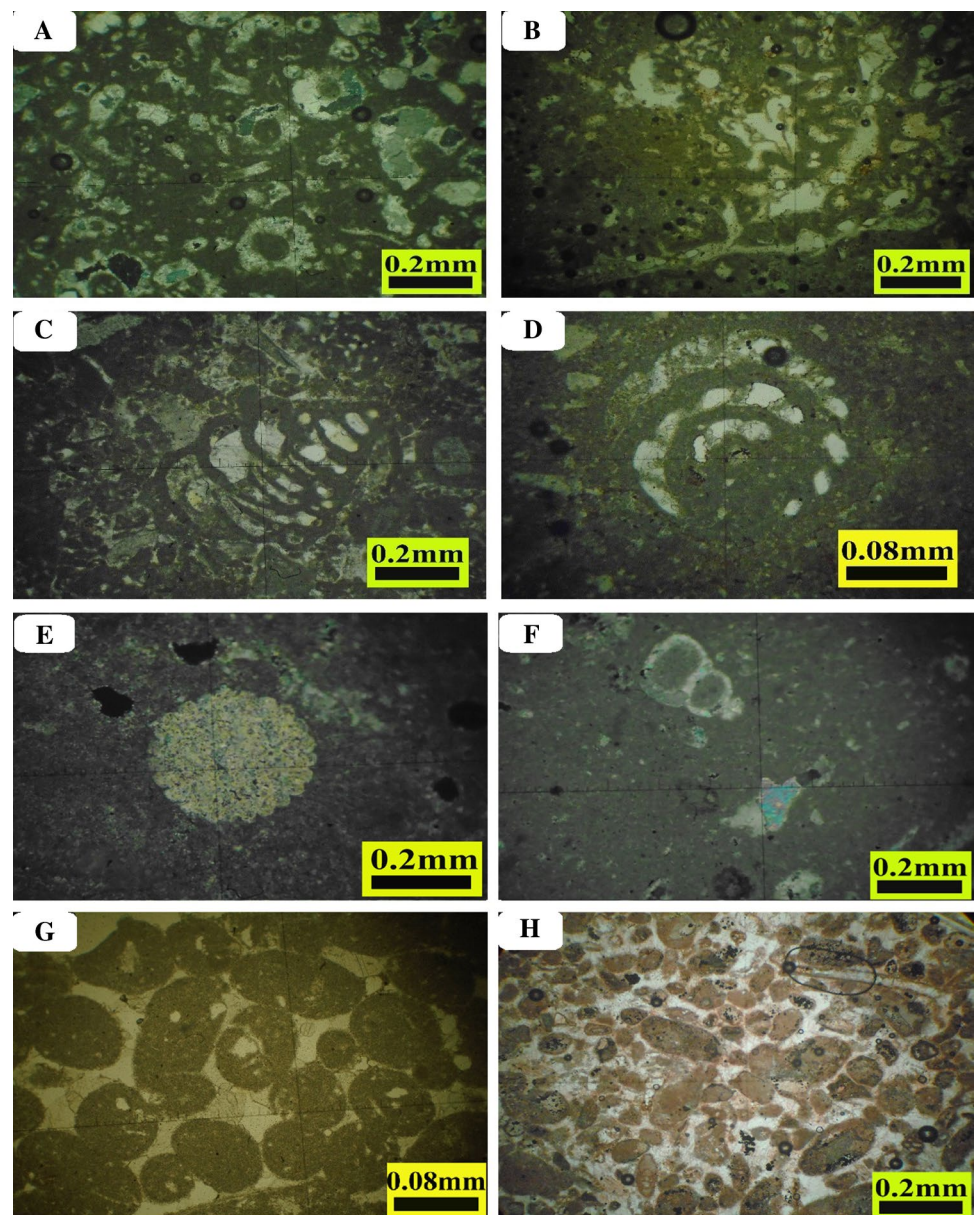
core sample as aggregation clearance, echinoderms, and echinoderm fragments index on shallow marine and high salinity environments (Fig. 4e).

Many types of organisms were recognized, such as gastropods and shell fragments, sponge spicules, and coral. The bioclasts (Fig. 4f) within the Yamama are represented by shell and echinoderms fragments.

Non-skeletal grains were diagnosed and represented by peloids, Ooids, and lithoclasts. Peloids were recognized within the Yamama Formation in various sizes and shapes in the upper and lower part of the formation, these peloids are associated with shell fragment and benthic foraminifera, and due to diagenetic processes, especially micritization, most of peloids pieces are not observed, and these peloids are recognized within high-energy environment facies that thought to be ooids affected by micritization by peloidization resulted in micritized ooids (Fig. 4g).

Ooids were recognized in the large form with (3–2) rings, their size fewer than (2 mm) in the diameter. Because of compaction, the Ooids shape tends to be protraction. The Ooids are recognized as a bed, the thickness range 3–10 m and downward the formation the size reduces and the sorting deteriorates, to the far southeast, near the Iraqi border the ooids has been not recognized, because some peloids are ooids in origin but imparted with waves and currents from shoals and distributed above the basin, and maybe because sediments particles reworked and swept basinward along the slopes, where the grains mix with autochthonous or older particles (Fig. 4h).

petrographic analysis shows that the Yamama formation consist from skeletal grains were recognized such as Foraminifera, Calcareous Algae, Echinoids, Sponge Spicules, and other organisms, and Non-skeletal grains were diagnosed and represented by peloids, Ooids, and lithoclasts.

Diagenesis processes

Yamama Formation was affected by many diagenesis processes like dissolution, fracturing, cementation, compaction, dolomitization, neomorphism, and micritization.

Dissolution and fracturing highly positive affected on reservoir quality that occupied on improving porosity and permeability and cementation, and compaction highly negative affected on reservoir quality that occupied on destroying porosity and permeability, and dissolution has greatly improving reservoir feature by forming secondary porosity (Fig. 5a, b, d).

Fractures process (Fig. 5b) had a great influence on reservoir characterization, during forming porosity, and creates a good pathway of moving fluids.

The cementation process has distracted affected reservoir properties throughout filing most of the voids so that this process distracted porosity and permeability (Fig. 5c, d).

Compaction process is made of destroying reservoir properties (porosity and permeability) (Fig. 6e). Stylolization (Fig. 6f) are thin seam of clay and insoluble material which mostly run analogous to bedding in limestone and result from pressure solution. Dolomitization process may be reducing porosity and permeability through growth crystals dolomite within porous or enhancing porosity or permeability throughout creating secondary porosity, two dolomite types were recognized xenotopic and limpid euhedral crystals of dolomite, and most of these types were not having clearly effect on reservoir properties (Fig. 5g).

Micritization process affected partially to completely micritized grains (Fig. 5a).

Neomorphism is the transformation of mineral occupying place in the water existence, this process leads to the growth of new minerals, and in Yamama Formation this process affects on both lime mud and grains (Fig. 5h).

Diagenesis processes show that the Yamama Formation has been affected by different digenesis processes, which impacted on the reservoir quality, where high positively affected were: dissolution and fractures, from during create and improve porosity and permeability, and destructive affected were cementation and compaction, from during reduce and destroyed the porosity and permeability. Other processes such as micritization, neomorphism, dolomitization, and Bioturbation did not have a high effect on reservoir quality.

Depositional environments interpretation

Microfacies analysis has been identified by thin section examination, and descriptions have appeared in various types of depositional microfacies. The main microfacies are common within Yamama Formation were: seven main microfacies association were recognized in the Yamama Formation, and these microfacies were:

Bioclastic wackestone microfacies These microfacies are common in most of the studied wells and highly spread. The micrite generally occurred from the result of chemical deposition via bacteria, or organic origin is due to biogenic activity by micritization process (Tucker and Wright 1990). Most of these microfacies consist of shell fragment which has different origins from benthic foraminifera, echinoderms, and other grains, in features dissolved most of the bioclasts and left effective stamps of bioclasts (Fig. 6a,b).

Bioclastic packstone to grainstone microfacies These microfacies consist of many organism's variables in sizes

**Fig. 5** Main diagenesis processes within Yamama Formation
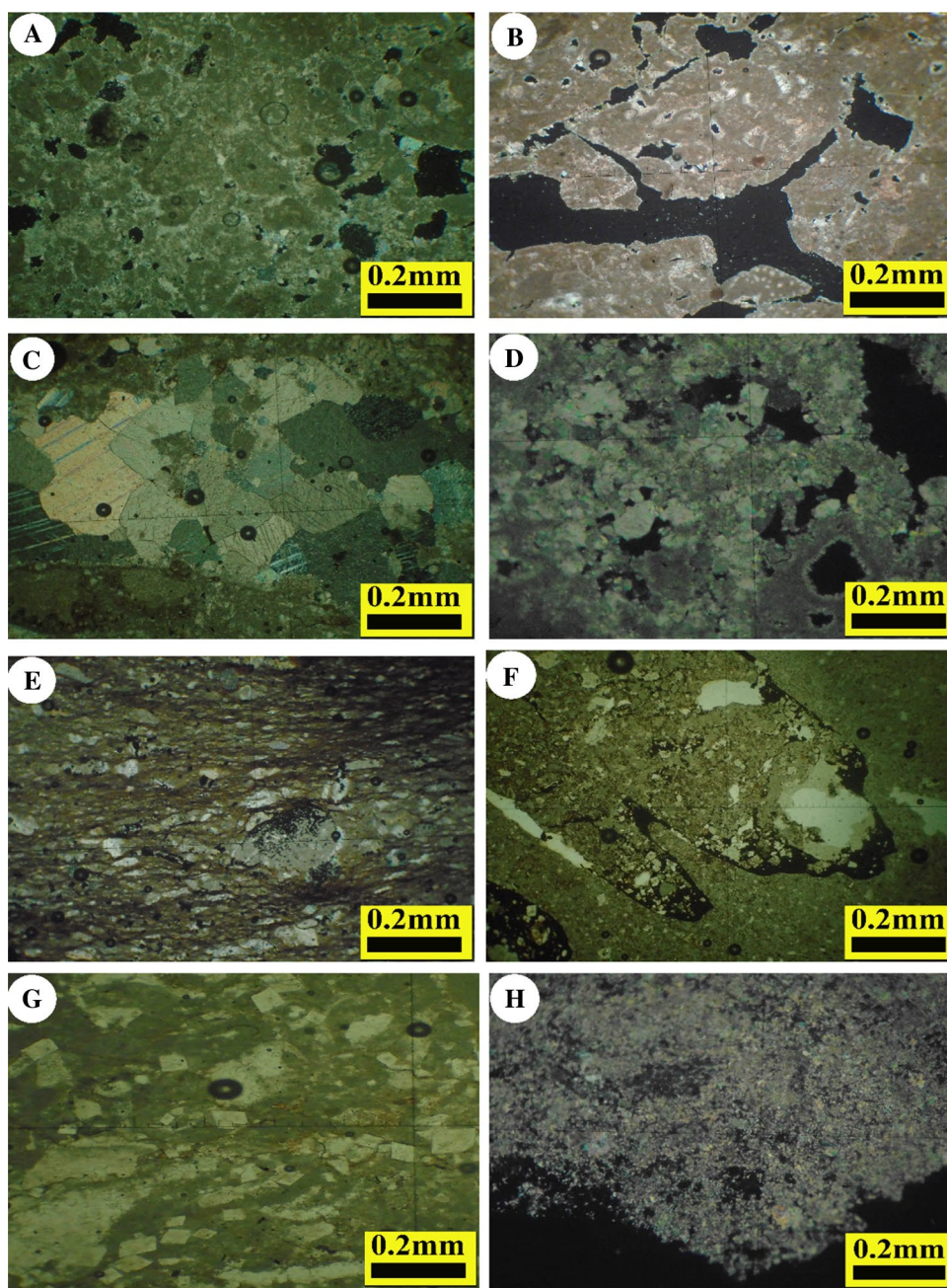
and shapes, such that this mix is an indicator to open marine environment without reef or any restriction to water circulation, and this microfacies is considered be the most important reservoir facies and most of these microfacies contain good porosity (Fig. 6c).

Foraminiferal wackestone to packstone microfacies These microfacies consist of rocks ranging in texture from wackestone to packstone (Fig. 6d) and comprising large benthic foraminifera. These microfacies distinguish by high compaction frequently and maybe contain debris of algal and fragment of the shell (Sadooni 1993). Foraminifera flour-

ish in a shallow, normal marine environment, where benthic foraminifera common in warm, shallow seas, living within and on the sediment, planktonic foraminifera dominates some pelagic deposits.

Algal wackestone to packstone microfacies These microfacies comprise green and red algae and also shall fragments, foraminifera, sponge, and echinoderms. Generally, algae or algal debris is dissolved and filled by one or more types of cement. This microfacies may be divided according to algae types into two submicrofacies. Dasycladacean wackestone to packstone submicrofacies, this reflects the isolated

Fig. 6 Main microfacies association within Yamama Formation
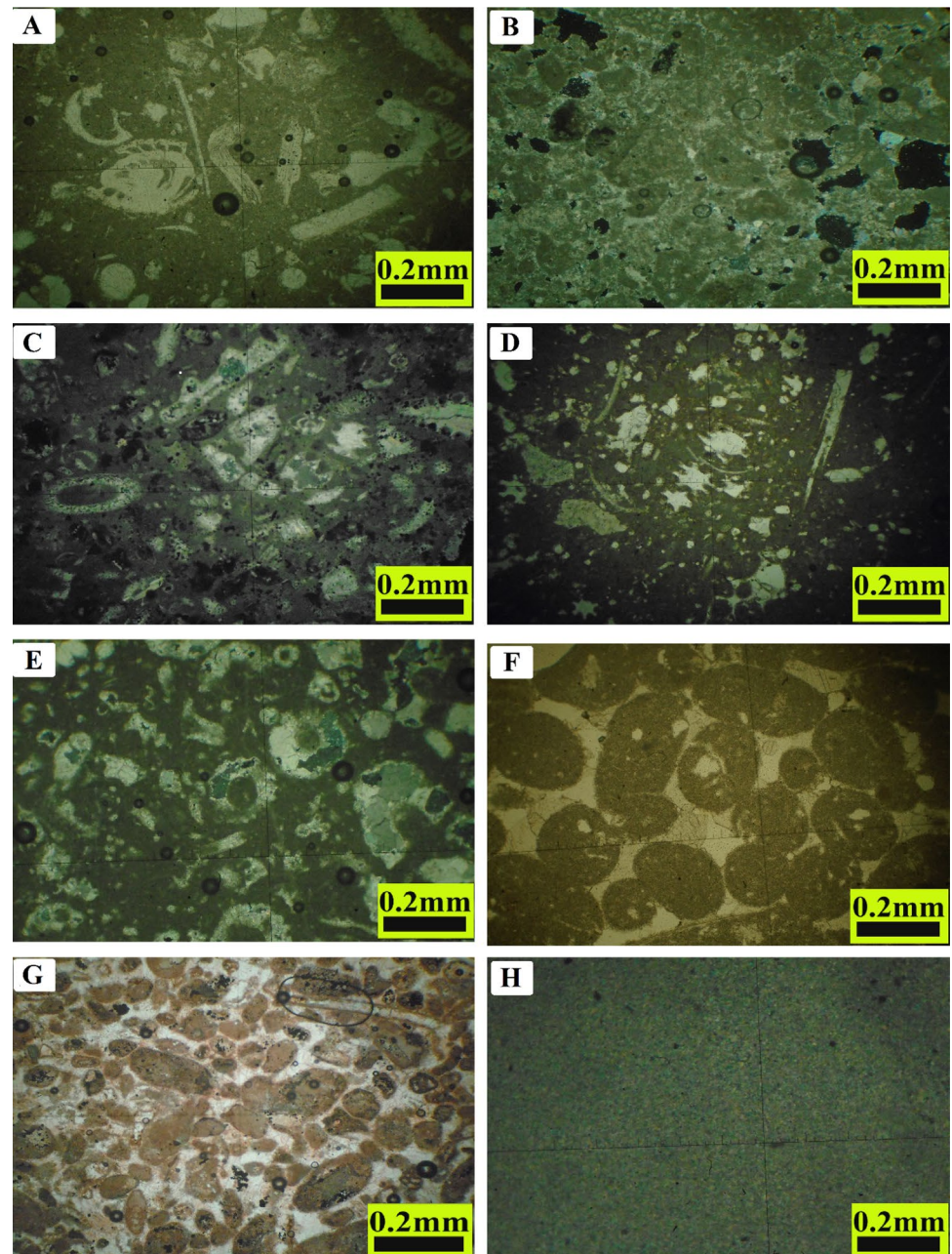
environment, like a lagoon and lagoon shelter. Most of their skeletons were dissolved to be filled by calcite cement. Red algae wackestone submicrofacies comprise red algae group like *Permocalculus algae*, *Permocalculus algae,* and less common from green algae in this formation. Red algae prefer normal marine water in subtropical areas. This submicrofacies reflect shallow marine waters with open circulation (Fig. 6e).

Peloidal packstone microfacies This Microfacies exist in some sections of the Yamama Formation, and characterized by good sorted due to high-energy waves, peloids are differ-ent in sizes, shapes, and sorting was suggested two methods to origin these grains. either fecal pellets grow in a low-energy environment, or originally ooids and transferred by waves and currents from shoals (oolite) and scattered above the basin, where gathered in local depressions and under-went such diagenetic processes as micritization (Sadooni 1993) (Fig. 6f).

Lithoclastics wackestone to packstone microfacies This Microfacies consists of lithoclasts various in shapes and sizes. Lithoclasts diagenetic in origin and may be qualified for the action of micritization or pressure solution in the

form of stylobraccia (Fig. 6g). Due to gravitational flow for unconsolidated sediments or currents effects and waves, the primary intraclasts were formed (Sadooni 1993).

Mudstone microfacies Quiet movement water currents characterized this microfacies (Bathurst 1975). The indicator of this microfacies means that the deposition occurred in quiet water prevents the organisms to accumulate and produced skeletons grains.

Two main submicrofacies were recognized: Argillaceous mudstone and bioclastic mudstone submicrofacies. Argillaceous mudstone submicrofacies comprise of dark, dense micrite with considerable amounts of siltstone and shale. Commonly, the contents of clay are comparatively high, characterized by not containing any fossils and only micritic matrix, with a clear effect of neomorphism processes. Bioclastic mudstone submicrofacies consist of well-sorted micrite grains with matrix porosity and chalky texture and characterized by containing fossils less than 10% with neomorphism process (Fig. 6h).

The extension of these seven main microfacies in all wells laterally was recognized by logs curve behaviors with these microfacies (Figs. 7, 8).

Flow zone indicator (FZI) method

Amaefule et al. 1993 defined the flow zone indicator approach to classify core data to hydraulic flow units, and this approach reflects one of the good and best techniques to describe the permeability and the reservoir particularly. The flow unit method which includes reservoir quality index on flow zone indicator (RQI/FZI) is more accurately used, and the flow unit introduced signified total reservoir volume unit within geological properties which control fluid flow and predictive different properties of other rocks, and this technique relies on physics of fluid flow within pore scale and provides correct correlations for permeability and porosity when FZI of the reservoir is known.

If permeability is expressed in millidarcy and porosity as a fraction, the equation;

$$RQI = 0.0314\sqrt{\frac{k}{\phi e}} \tag{1}$$

$$\phi z = (\phi / 1 - \phi e) \tag{2}$$

By substituting, RQI and Φz with FZI can be simplified as:

$$FZI = \frac{RQI}{\phi z} \tag{3}$$

By taking the logarithm of both sides of the equation, it can be rewritten as follows:

$$\log RQI = \log \phi z + \log FZI \tag{4}$$

By using Eqs. (1–3), RQI versus. φz plot was established in all selected wells, and Figs. 9 and 10 show a cross-plot of the logarithm of core permeability versus core porosity, and the normalized porosity (Φz) vs reservoir quality index (RQI), respectively. All core data points on the similar (FZI) straight line have equivalent pore throat, and they represent the same flow zone indicator. Four groups have been defined in Yamama Formation, where these groups are different in petrophysical properties (porosity and permeability), the first group (FZI-1) shows a low trend of permeability and porosity and characterized by the bad quality of reservoir (classified as mudstone microfacies and mudstone-wackestone microfacies), the second group (FZI-2) considers the medium trend of permeability and porosity and characterized by the intermediate quality of reservoir (classified as wackestone microfacies and wackestone-packstone microfacies), the third group (FZI-3) shows a good trend of the permeability and porosity and characterized by good reservoir quality (classified as packstone microfacies), and the fourth group (FZI-4) shows a very good trend of porosity and permeability and characterized by good reservoir quality (classified as packstone-grainstone microfacies), which mean there are four rock types within the Yamama Formation.

The great scattering in pore throat sizes indicates large variations in particle size and sorting within each rock type and highest heterogeneities, which in turn control permeability and confirm that the permeability in the Yamama Formation ranges from low-to-medium permeability. The similar FZI values fall on a line with the same slope, with the same line data being considered similar flow unit with similar pore throat (Al-Jawad et al. 2020).

Well logs data (cluster analysis) for rock types

Cluster analysis processes to illustrate the similarities and dissimilarities between data points within multivariate space of logs and for making, distribute them into groups called electrofacies, and the electrofacies unique sets to the response of logs that characterizes the rocks physical properties and fluids contained in the volume via logging tools (Al Kattan and et al. 2018).

The log raw and interpretation data using to cluster analysis gamma ray (GR), sonic (DT), uninvaded zone (Rt), invaded zone (Rxo), effective porosity, (PHIE) and water saturation (Sw) for six wells in this study were the data utilized, and input to the Interactive Petrophysics software (IP) the data clustered into twenty groups for covering the values of the total log by using (K-mean) statistical technique

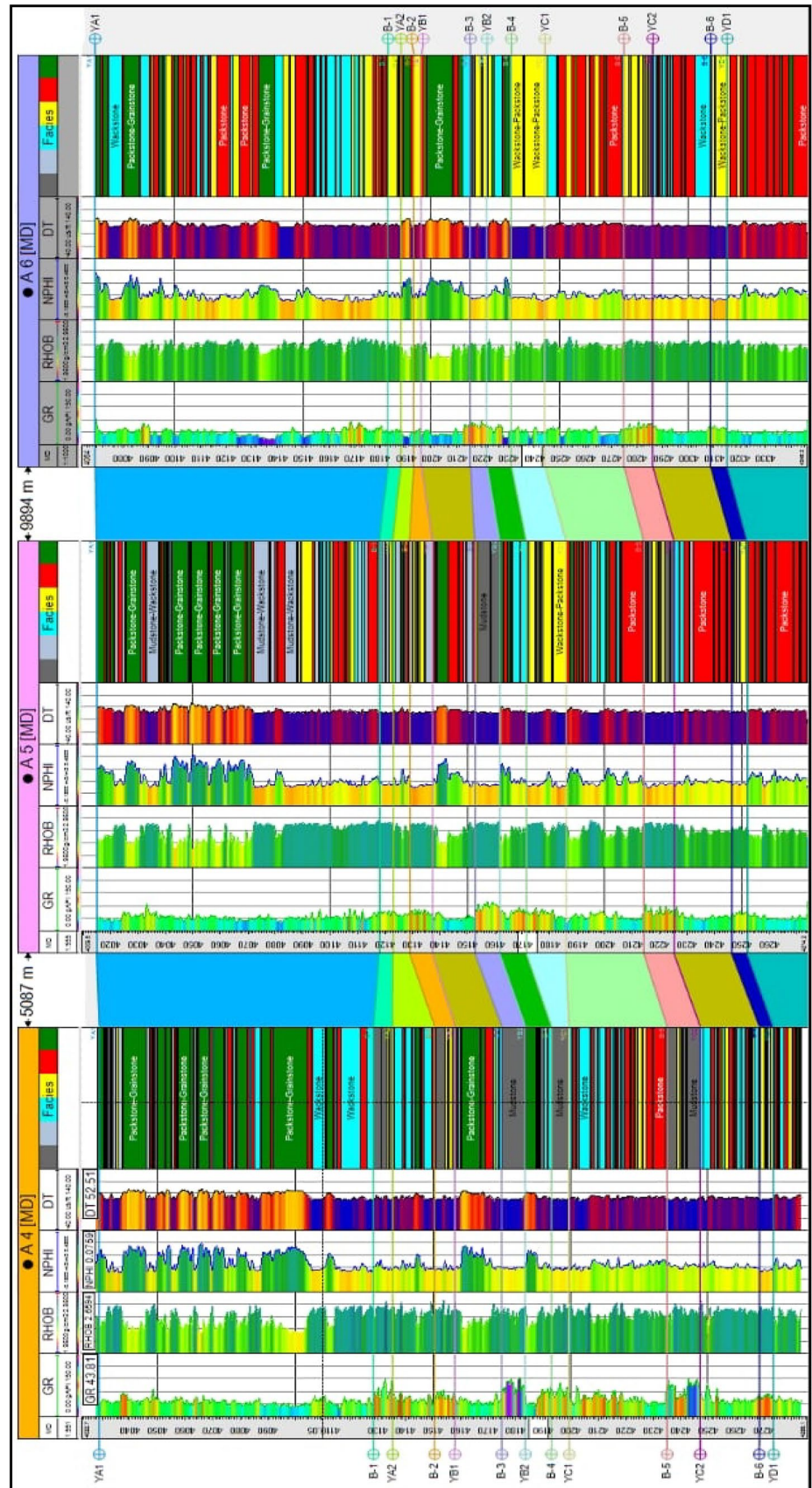**Fig. 7** Cross section for wells A4, 5, and 6 within Yamama Formation

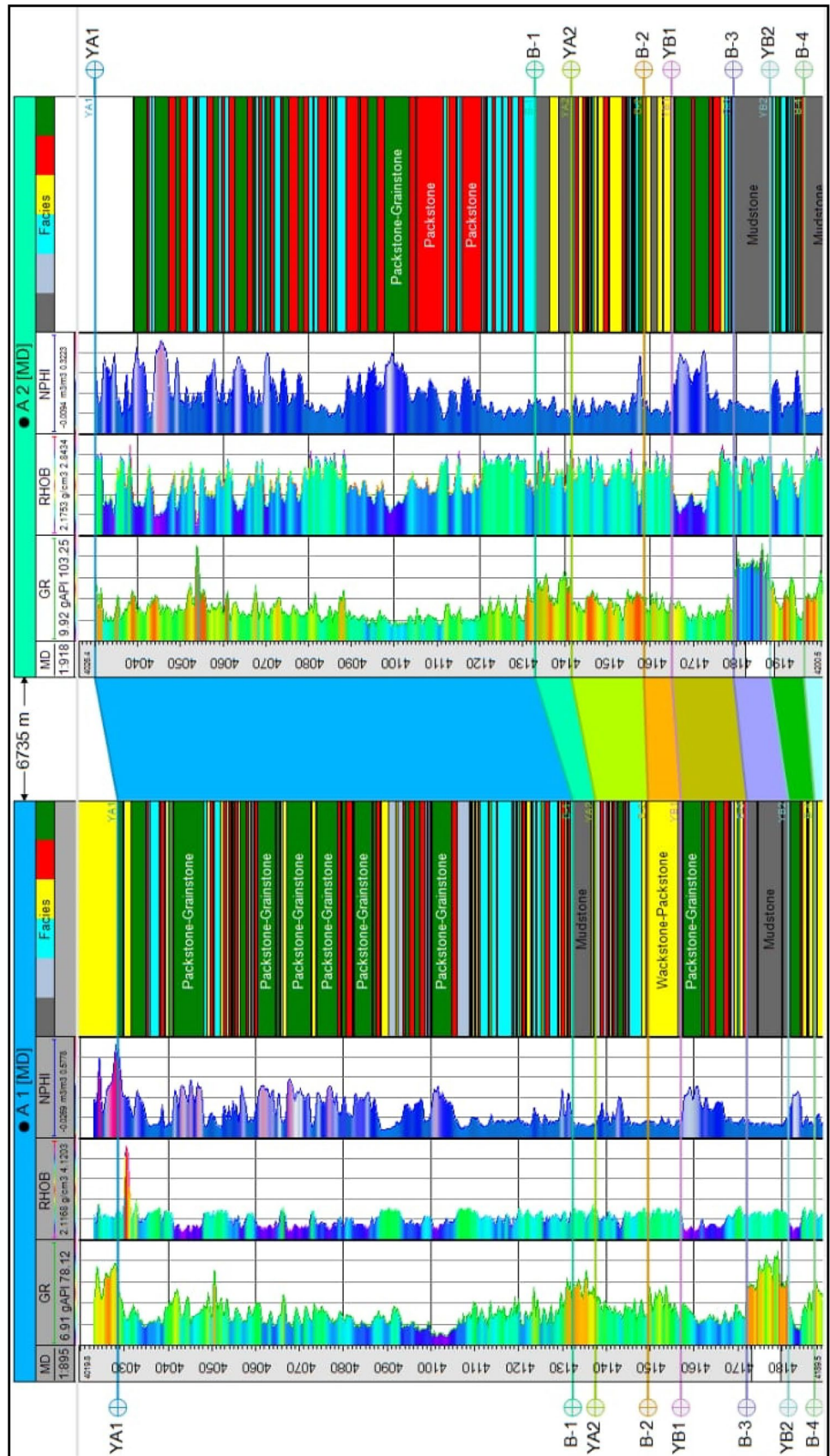**Fig. 8** Cross section for wells A1 and 2 within Yamama Formation

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Fig. 9 Porosity vs. permeability of Yamama Formation in studied wells
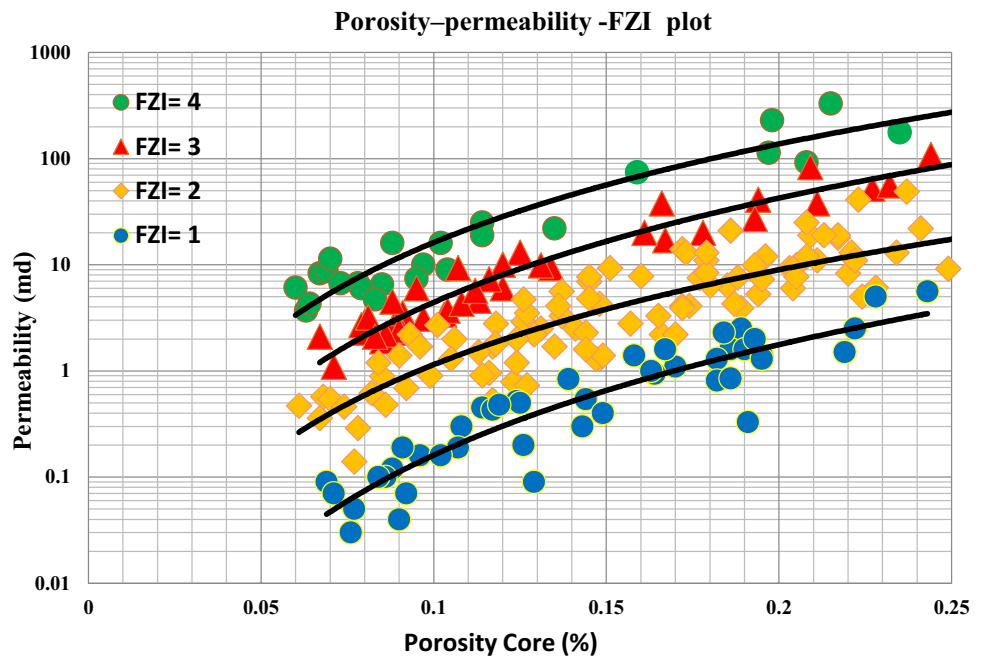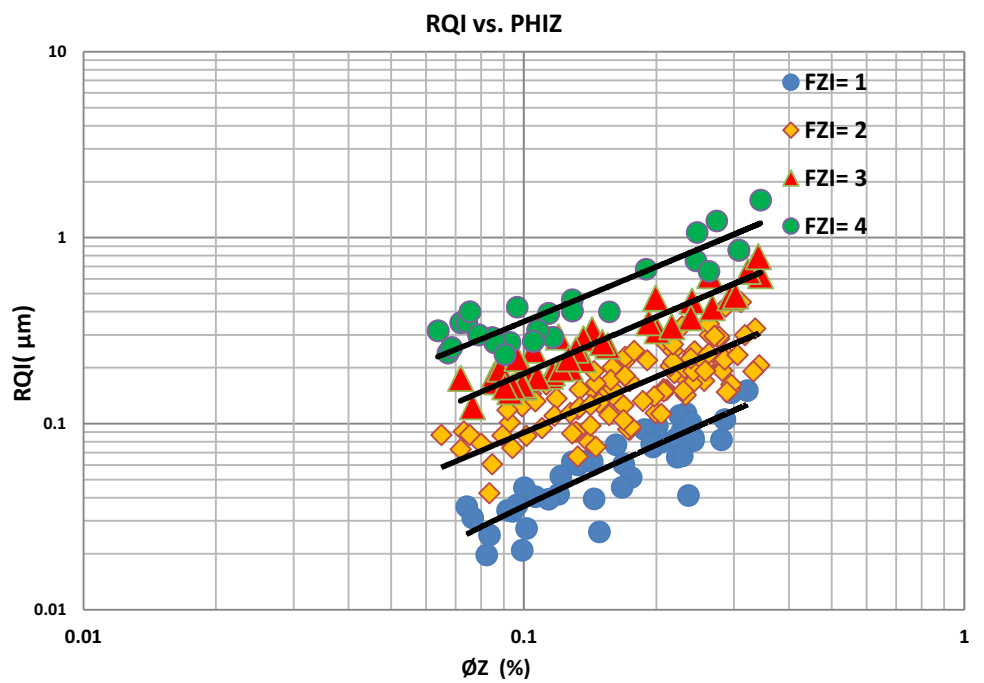

Fig. 10 Reservoir quality index (RQI) versus the normalized porosity of Yamama Formation in studied wells

anywhere the sum squares variance for each cluster mean and data point was calculated and assigned the point to the cluster with the minimum difference, and six groups have been featured depending on cluster randomness plot. The randomness plot evaluates the grouping to choose when the level of another cluster adding provides additional data to just noise addition, where less random index is indicated by randomness mean with higher values (Al-Jawad et al. 2020).

The randomness is performed on original logs data by computing the depth average number for each cluster. The randomness index represents the ratio of average cluster thickness to average random cluster thickness (Schlumberger 2008).

$$\text{Av. Thickness} = \text{Number of depth level} / \text{Number of cluster layers} \tag{5}$$

$$\text{Random Thickness} = \sum pi / (1 - pi) \qquad (6)$$

where Pi—the proportion of depth levels assigned to the ith cluster.

$$\text{Randomness index} = \text{Av. Thickness/Random Thickness} \qquad (7)$$

The randomness plot of Yamama reservoir are illustrated in six group types can be classified as microfacies as shown in Fig. 11, and the hierarchical technique for merging processes of different rock types in groups distinguished by different colors is explained in tree diagram illustrated in Fig. 12.

Figure 13 shows the final graphical of cluster analysis of six wells for the Yamama reservoir.

Six rock types were identified by cluster analysis technique, can be considered as depositional microfacies types (Figs. 14, 15):

1. Rock type-1 represents the very good type and the best rock type (dark color), and this type of rocks is characterized by low gamma ray, water saturation, and high values of neutron, sonic, and Rt higher from Rxo and high porosity, can be classified as packstone-grainstone microfacies.

2. Rock type-2 represents the good rock type (gray color), and this type of rock is characterized by low gamma ray, water saturation, and medium–high values of neutron, sonic, and Rt higher from Rxo and medium–high porosity, can be classified as packstone microfacies.

3. Rock type-3 represents intermediate to good rock type (yellow color), and this type of rock is characterized by low—medium gamma ray, water saturation, and medium values of neutron, sonic, and Rt higher from Rxo and medium porosity, can be classified as wackestone-packstone microfacies.

4. Rock type-4 represents the intermediate rock type (blue color), and this type of rock is characterized by medium values of gamma ray, water saturation, and medium values of neutron, sonic, and Rt higher from Rxo and low–medium porosity, can be classified as wackestone microfacies.

5. Rock type-5 represents intermediate to bad rock type (green color), and this type of rock is characterized by medium–high gamma ray, water saturation, and low–medium values of neutron, sonic, and Rt little higher from Rxo and medium–low porosity, can be classified as mudstone-wackestone microfacies.

6. Rock type-6 represents bad rock type (red color), and this type of rock is characterized by high gamma ray, water saturation, and low values of neutron, sonic, and Rt little less than from Rxo and non-low porosity, can be classified as mudstone microfacies.

The results of cluster analysis for rock types in Yamama formation are illustrated in Table 1

Fig. 11 Cluster groups type randomness for Yamama reservoir
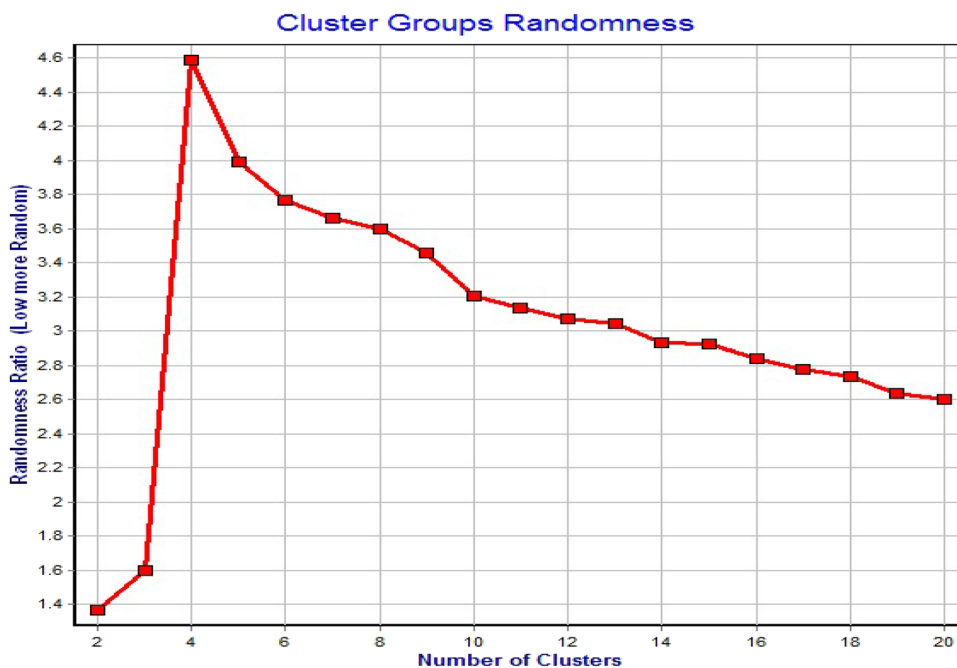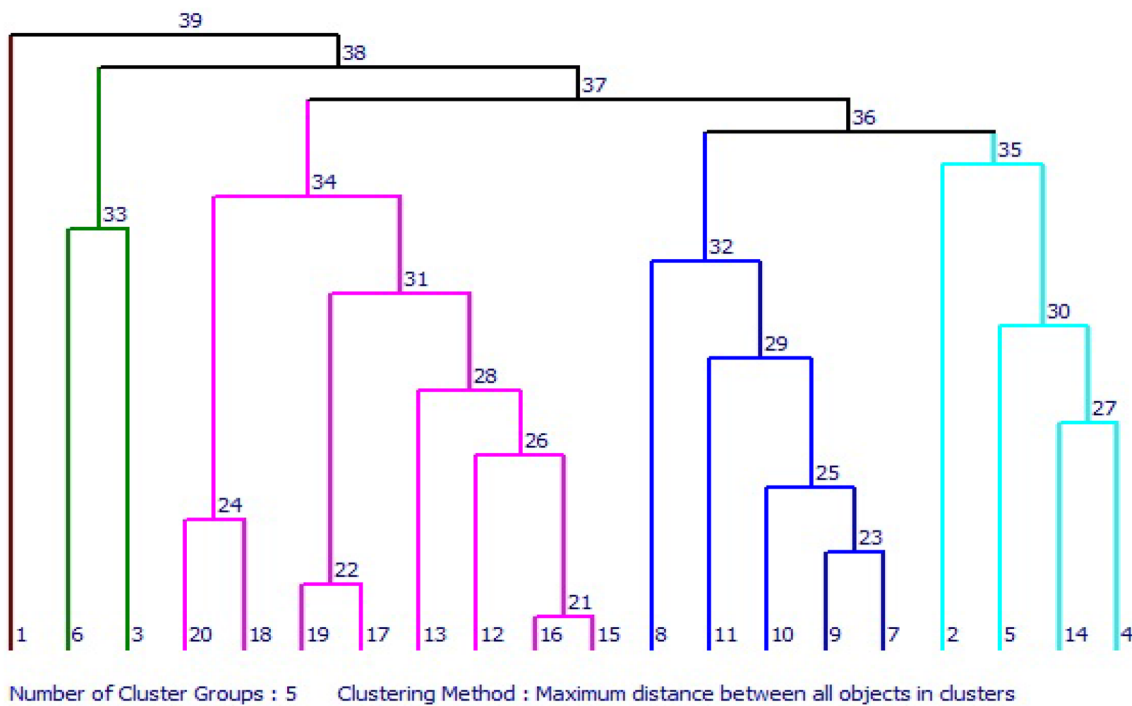
Cluster Grouping Dendrogram

Fig. 12 Cluster grouping tree diagram for the Yamama reservoir in the studied wells

Inland method (Porosity–Permeability relationship-R35)

Winland performed on a great set of samples from carbonate rock to compare permeability, porosity, and pore throats size, the better correlation coefficient is related to 35% mercury saturation, and pore throat radius of 35% mercury saturation was symbolized by R35 (Soleymanzadeh et al. 2019).

Winland's equation is used to apply reservoir properties (permeability and porosity) to categorize the number of rock types existing in a reservoir (Al-Qenae and Al-Thaqafi 2015).

The equation to determine the R35 for a reservoir using measured permeability and porosity values (Pittman 1992):

$$\text{Log } R35 = 0.732 + 0.588 \text{ Log Ka } 0.864 \text{ Log} \varnothing \qquad (8)$$

where R35 present the port radius (micron), Ka: core Permeability (md), $\varnothing$: Core porosity (%).

By using core permeability and porosity, pore throat size (R35) is identified in reservoir units and supplied a better basis for determining the reservoir flow units (Al-Jawad et al. 2014).

The port radius (R35) values were applied to delineate the rock type as follows (Spearing et al. 2001);

Mega-port; rock type with port radius (R35) values more than 10 μ.

Macro-port; rock type with port radius (R35) values between 2 and 10 μ.

Meso-port; rock type with port radius (R35) values among 0.5 and 2 μ.

Micro-port; rock type with port radius (R35) values among 0.1 and 0.5 μ.

Nano-port; rock type with port radius (R35) values lesser than 0.1 μ.

The available core analysis (porosity & permeability) have been used to identify the pore type & pore radius (R35), were four groups of the pore size have been recognized (Fig. 16), Mega pore type, Macro pore type, Meso pore type, and Micro pore type.

Mega-port type reflected a very good reservoir rock quality type and corresponds with the fourth group type of the flow zone indicator (FZI-4) and can be classified as packstone-grainstone microfacies.

Macro-port type reflected good reservoir rock quality type and corresponds with the third group of the flow zone indicator (FZI-3) and can be classified as packstone microfacies.

Meso-port type reflected intermediate reservoir rock quality type and corresponds with the second group of the
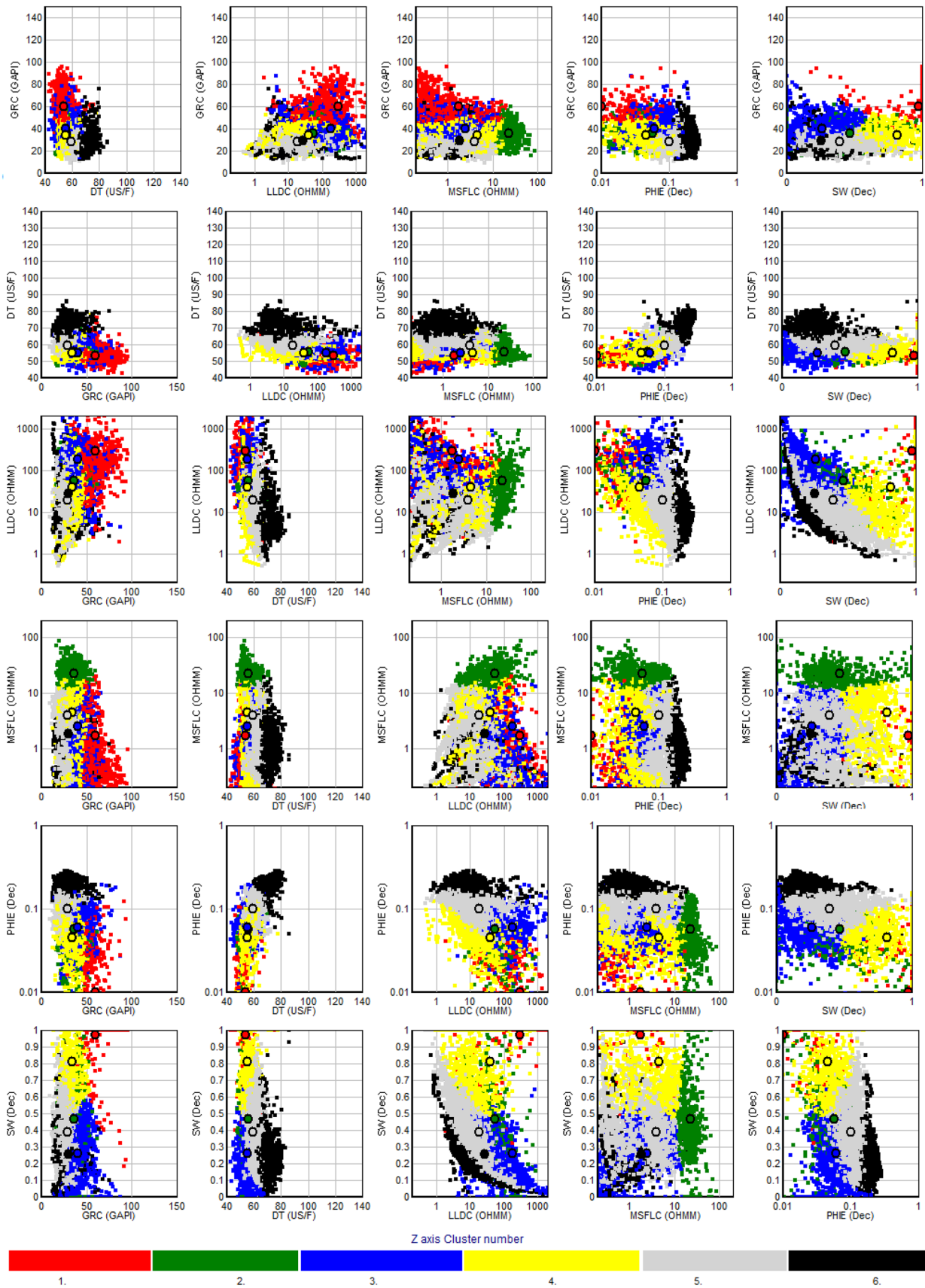
Fig. 13 Final graphical result of the clustering analysis of Yamama Formation

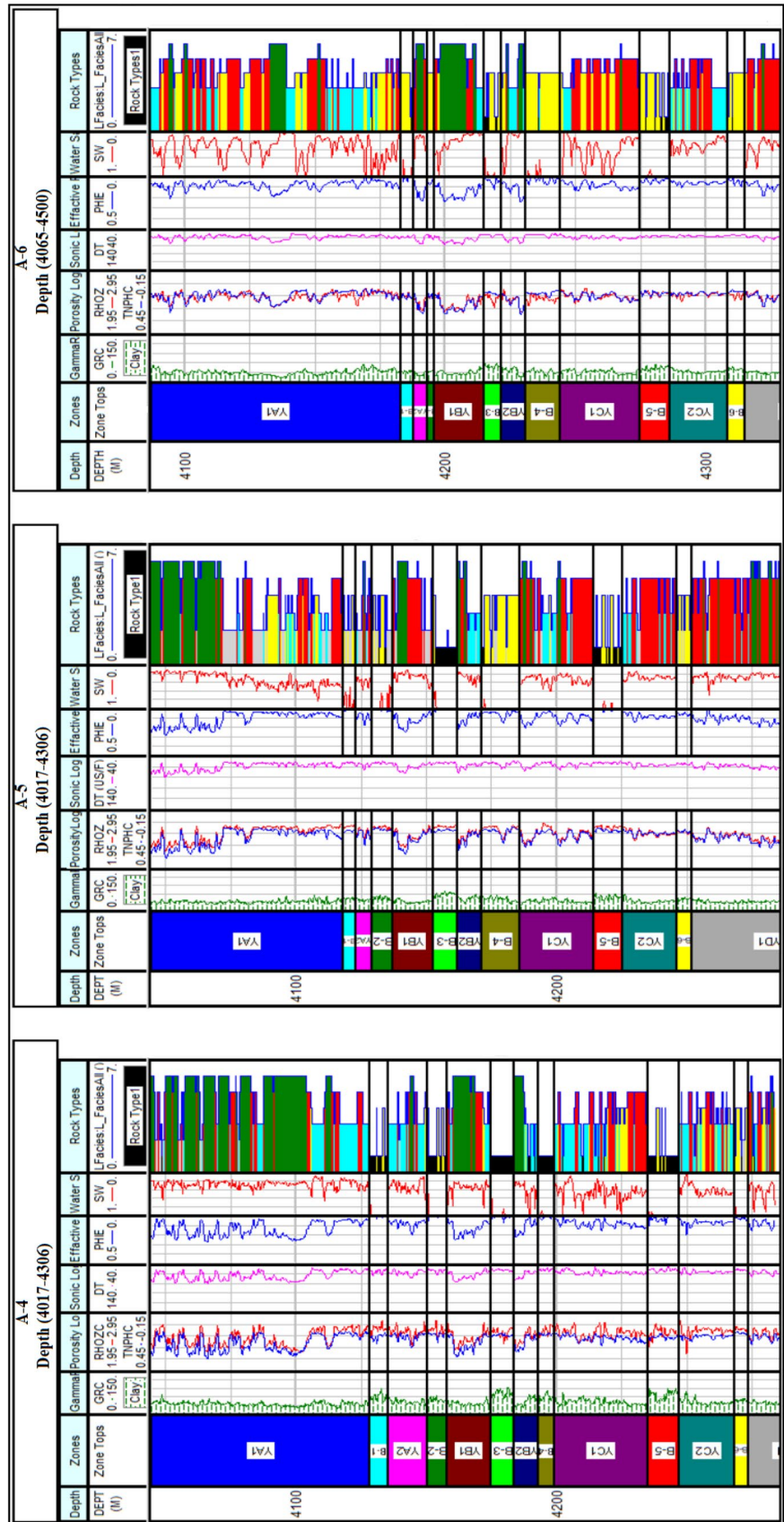**Fig. 14** Rock types cross section for wells A4, 5 and 6 within Yamama Formation by clustering analysis

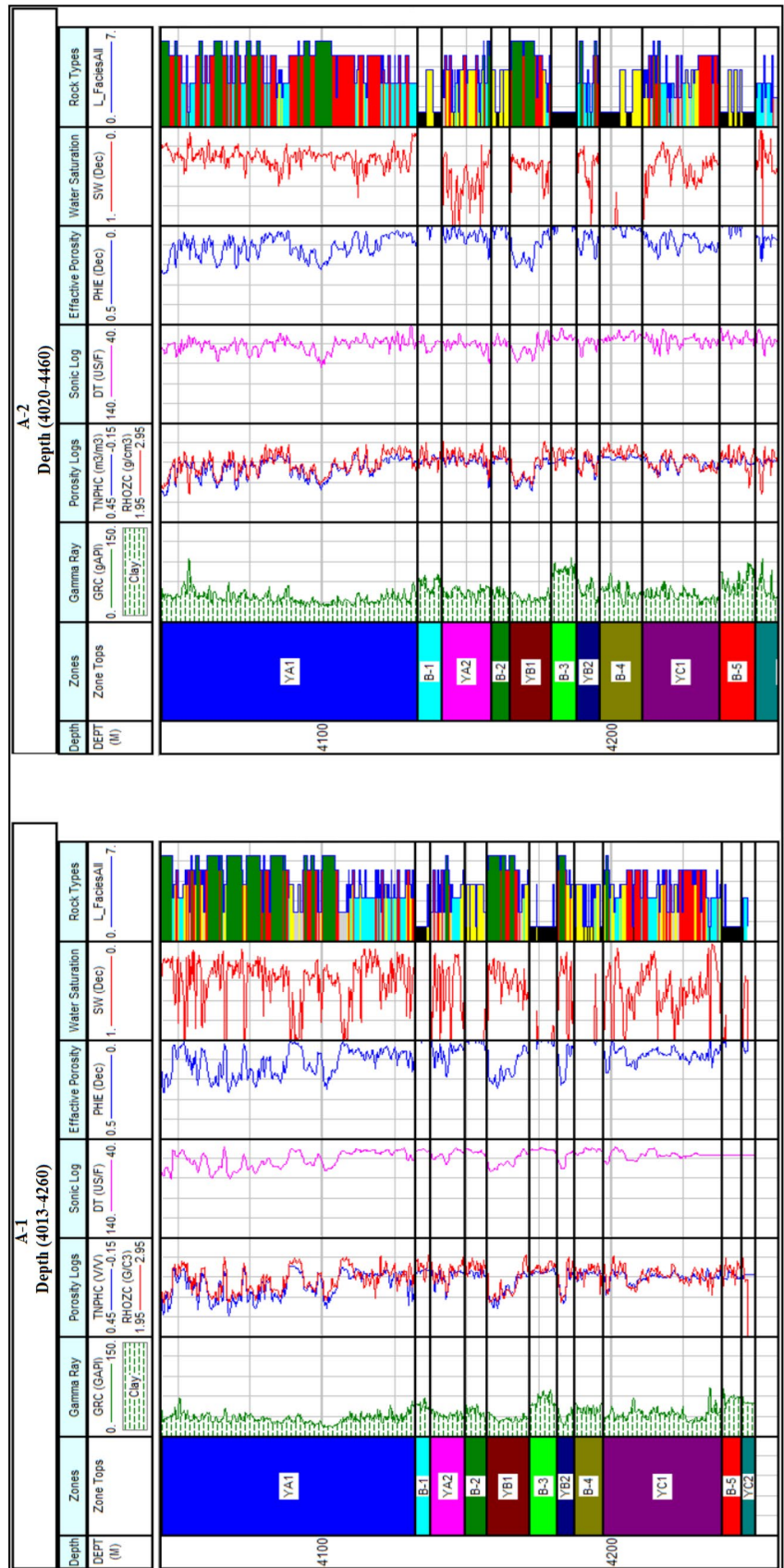**Fig. 15** Rock types cross section for wells A1 and 2 within Yamama Formation by clustering analysis

Table 1 Results of cluster analysis for each rock type in Yamama Formation

Rock type	GR		DT		NPHI		MSLF		LLDC		PHIE		SW	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Type-1	1.55	0.10	55.03	3.78	0.07	0.044	28.57	9.23	28.57	9.23	0.050	0.031	0.48	0.26
Type-2	1.66	0.13	54.18	3.79	0.07	0.027	2.196	2.89	2.19	2.89	0.021	0.023	0.96	0.09
Type-3	1.53	0.10	55.50	3.35	0.08	0.0293	2.296	2.12	2.29	2.12	0.064	0.022	0.36	0.18
Type-4	1.52	0.09	56.77	3.54	0.09	0.028	12.33	3.48	12.33	3.48	0.069	0.026	0.51	0.20
Type-5	1.42	0.10	61.45	3.40	0.14	0.038	2.606	2.50	2.60	2.50	0.118	0.027	0.37	0.19
Type-6	1.47	0.12	70.31	4.48	0.24	0.056	1.687	1.61	1.68	1.61	0.191	0.041	0.24	0.11
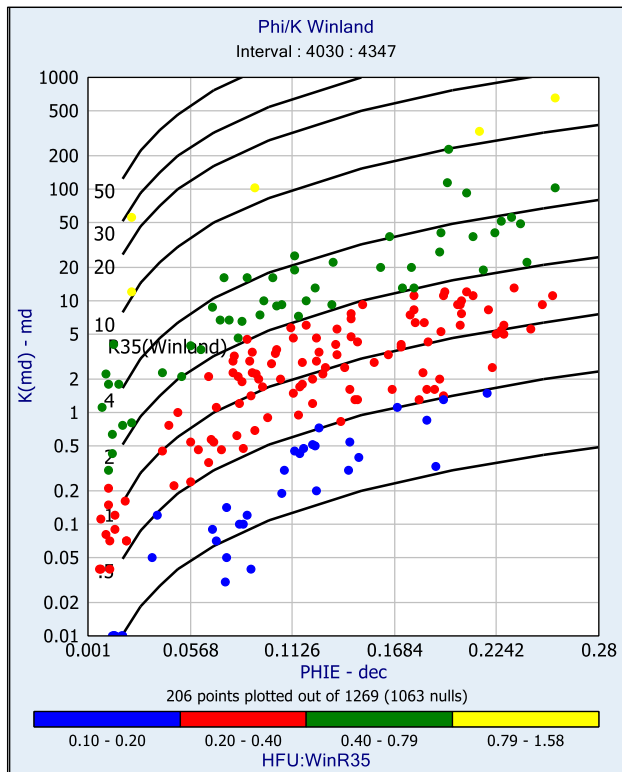
Fig. 16 Core Porosity–permeability and Winland -R35 port radius plot

flow zone indicator (FZI-2) and classified as wackestone microfacies.

Micro-port type represents bad reservoir quality and corresponds with the first group of the flow zone indicator (FZI-1) and can be classified as mudstone-wackestone and mudstone microfacies

Lucia rock class typing method

Lucia (1983) by using particle size boundaries of 100 and 20 microns established three permeability groups, and a correlation shows limited particle sizes fewer than 500 microns.

Lucia defined three types of carbonate reservoir rock classes defined by their Rock Fabric Number (RFN) and grain size as follows:

- The first class (class 1):
  This class represents the Grain-dominated Fabrics (grainstone) (RFN's of 0.5–1.5).
- The second class (class-2):
  This class represents the Grain-dominated Fabrics (packstone) (RFN's of 1.5–2.5).
- The third class (class-3):
  This class represents the Mud-dominated Fabrics (packstone, wackestone, and mudstone) (RFN's of 2.5–4.0).

And the equation of the Rock Fabric Number (RFN) is calculated from:

$$RFN = A \log \left(\frac{9.7982 + 8.6711 Log(\emptyset) - Log(K)}{12.0838 + 8.2965 Log(\emptyset)} \right) \quad (9)$$

where RFN: Rock Fabric Number, K: core Permeability (md), and $\emptyset$: Core porosity (%).

Each rock fabric class has a distinct group for porosity–permeability and permeability increasing with the increasing the grain size, sorting, and porosity.

By using the available core porosity and permeability analysis for the Yamama Formation, three types of rock type classes have been recognized (Fig. 17), the first group is Grain-dominated Fabrics—grainstone, which represents a very good rock quality type and corresponds with the fourth group type of the flow zone indicator (FZI-4) and can be classified as packstone-grainstone.

The second group is Grain-dominated Fabrics—packstone, which reflected good rock quality type and corresponds with the third group of the flow zone indicator (FZI-3), and classified as packstone microfacies.

The third group is Mud-dominated Fabrics—packstone, wackestone, which reflected intermediate to bad rock quality type and corresponds with first and second groups of the flow zone indicator (FZI-1 and FZI-2), and classified
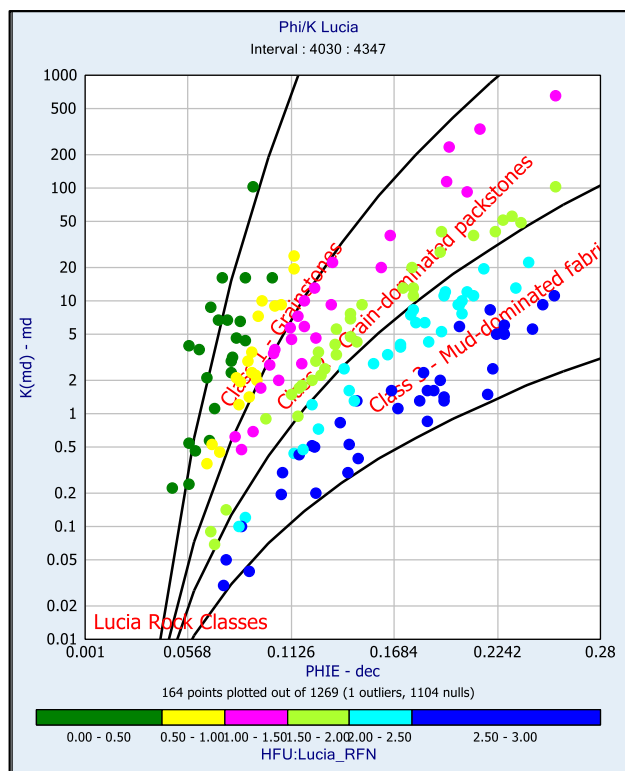
Springer

Fig. 17 Core porosity–permeability and Lucia Rock class plot

as wackestone, mudstone-wackestone, and mudstone microfacies.

Conclusions

- The reservoir quality of the Yamama Formation has been affected by different digenesis processes, where high positively affected were: dissolution and fractures, from during create and improve porosity and permeability, and destructive affected were cementation and compaction, from during reduce and destroyed the porosity and permeability. Other processes such as micritization, neomorphism, dolomitization, and Bioturbation did not have a high effect on reservoir quality.
- Microfacies are significant to the performance of the carbonate reservoir, six main types of microfacies have been identified were: packstone- grainstone, packstone, wackestone-packstone, wackestone, mudstone-wackestone, and mudstone, and the best reservoir facies were packstone-grainstone, packstone, wackestone-packstone microfacies, which indicate good rock types and reservoir quality.
- Four groups of rocks have been recognized by using flow zone indicator (FZI) method, where the first group (FZI-

1) is characterized by the bad quality of the reservoir, the second group (FZI-2) is characterized by the intermediate quality of the reservoir, the third is characterized by the good quality of the reservoir, and the four group is characterized by the good quality of the reservoir.
- The distribution and scatter of the pore throat sizes within the reservoir indicate to the high variations in the grain size and sorting of the particle size and texture within each rock type and highest heterogeneities.
- Many rock types have been identified for carbonate Yamama reservoir by using cluster analysis technique, six different rock types were: Rock type-1 represents the very good type, Rock type-2 represents the good rock type, Rock type-3 represents intermediate to good rock type, Rock type-4 represents the intermediate rock type, Rock type-5 represents intermediate to bad rock type and, and Rock type-6 represents bad rock type.
- Three classes of rock types have been recognized by using Lucia Rock class typing method, the first group is Grain-dominated Fabrics—grainstone, which represents a very good rock quality corresponds with FZI-4 and classified as packstone-grainstone, the second group is Grain-dominated Fabrics—packstone, which corresponds with FZI-3 and classified as packstone microfacies, the third group is Mud-dominated Fabrics—packstone, wackestone, correspond with (FZI-1 and FZI-2), and classified as wackestone, mudstone-wackestone, and mudstone microfacies.
- The reservoir characterization and rock typing is a significant tool in the performance of the reservoirs and understanding reservoir architecture.

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