Scientific Research Publishing

Open Journal of Geology, 2017, 7, 1552-1568
http://www.scirp.org/journal/ojg
ISSN Online: 2161-7589
ISSN Print: 2161-7570

Well Log Petrophysics of the Cretaceous Pay Zones in Zubair Field, Basrah, South Iraq

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How to cite this paper: Abdulaziz, A.M., Dahab, A.S.A. and Najmuddin, M.Y. (2017) Well Log Petrophysics of the Cretaceous Pay Zones in Zubair Field, Basrah, South Iraq. *Open Journal of Geology*, **7**, 1552-1568.
https://doi.org/10.4236/ojg.2017.710104

Received: August 29, 2017
Accepted: October 28, 2017
Published: October 31, 2017

Abstract

Discovered in 1949 with a rate of (195,000) bbl/day from pay zones in Mishrif and Zubair Formation, the expected production of Zubair field is anticipated to be 1125 million bbl/day. Despite this production history, there is a major deficiency in detailed petrophysical analysis of the producing zones. In the present study well log data of 7 wells, selected from numerous wells, are investigated in details to examine the reservoir properties and characterize the reservoir architecture. The petrophysical analysis of Mishrif Formation indicated two or three pay zones. Lithologically, all zones of Mishrif Formation are dominantly clean limestone to dolomitic limestone with zone 2 and 3 reporting higher dolomitic content (20% to 40%) compared to zone 1 (6% to 13%). Mishrif pay zones indicated a relatively good porosity (18% - 24%) with zone 2 predominant in secondary porosity associating dolomitization processes. In Zubair Formation one pay zone is identified but locally could separate into two zones. The clay content is generally low with average content between 2% and 3% while the average porosity showed slightly better values in zone 1 (~0.20) compared to average porosity of zone 2 (0.17) that is rich in silt content associating deposition at a relatively deeper parts of the shelf. The average water saturation shows distinct lower values that vary between 15% and 18.7%. The petrophysical results are statistically analyzed and property histograms and crossplots are constructed to investigate mutual relationships. Such analysis is essential for understanding the reservoir architecture and calculations of reservoir capacity for future development.

Keywords

Petrophysical Analysis, Zubair Field, Mishrif Formation, Zubair Formation, Reservoir Characterization

1. Introduction

Differences in petrophysical characteristics observed in petroleum reservoir

around the world are important for reservoir evaluation and must be well understood. This requires the conjugated efforts of geoscientists and engineers in a multi-disciplinary synergistic approach to recognize the complex variations in reservoir heterogeneity and its associating hydraulic properties [1]. Such synergistic approach is discussed by Harris *et al.* in [2] and emphasized the importance of geological and engineering approaches for reservoir characterization. Integration of well logs with core data is a typical characterization approach that has been discussed by numerous formation evaluation works (e.g. [3]), but the output of such research did not provide characteristics such as flow units identification and macroscopic geologic and/or petrophysical features integratable to reservoir flow models or simulation studies. Core samples are the only representative physical element of the reservoir rock available for examination and inconsequence represent the fundamental source for reservoir description on both microscopic (pore level) and macroscopic (core plug) levels. Alternatively, well logs, wireline tests, and well tests develop megascopic reservoir properties in form of moving averages with windows vary based on the individual log resolution. Worthington and Cosentino in [4] presented the effect of cutoffs value on integrated reservoir studies and highlighted the importance of petrophysical cutoffs on reservoir characterization for both static and dynamic models that inconsequence lead to realizations of the asset value.

Southeastern Iraq represents a high hydrocarbon potential region with several high productivity fields have been discovered. The bulk Iraqi oil reserve is generally found in two distinct basins; Zagros basin and Arabian basin [5]. Discovered in 1949, Zubair field represents one of the largest oil fields in the world with 4.5 billion barrels (~6.1 × 108 t) proven reserves. At early reservoir stages production began with 195,000 bbl/day, but by 2010-2011 reached 300,000 bbl/day and is expected to reach 1125 million bbl/day [6]. Recently a substantial increase in estimations of Zubair field proven reserve has been reported as 7.8 billion bbl [6]. It is located in Southeastern Iraq to the Southwest of Basrah city with oil bearing zones fall within two main Cretaceous successions: Upper Cretaceous Mishrif Formation and the Lower Cretaceous Zubair Formation. Zubair Formation is the most significant clastic reservoir in Southern Iraq and constitutes approximately 30% of hydrocarbon reserve in Iraq. Significant hydrocarbon accumulations are trapped within 30 geologic structures developed within important producing fields including East Baghdad, Zubair, and Rumaila (north & south). Alternatively, Zubair Formation furnishes a secondary target at Ratawi, Tuba, and Luhais fields but at Majnoon, Huwaiza, and Halfaya contains only smaller reserves [6]. The sandstone reservoir quality of Zubair Formation is generally good with porosity between 15% near Iraqi border and 30% in Salman Zone to the West [7].

Mishrif Formation comprises approximately 40% of Cretaceous hydrocarbon reserve that constitutes 30% of the total Iraqi reserve [8]. Important oil accumulations are trapped on large scale north-south trending anticlines as reported at

North Rumaila, South Rumaila, Zubair, West Qurna, Halfaya and Majnoon fields [7]. In addition, other commercial oil accumulations, at least 15, have been discovered in the Mishrif Formation in Southeastern Iraq; e.g. Abu Ghurab, Dujaila, Jebel Fauqi, Kumait, Noor, Rafidain, Tuba, NahrUmr, and others. It reported mean porosities of 16% at Rumaila and 9% at Zubair fields but well developed reservoir quality with porosity up to 36% and average permeability 1560 mD is observed in rudist-rich carbonates [9]. Reulet in [10] summarized the average values of porosity and permeability for Mishrif facies in Southern Iraq and showed that shoal facies has higher porosity that ranged between 20 - 25%. However, reservoir quality decreases significantly southwest toward the Najaf intra-shelf basin with massive reservoir along the Iraqi-Iranian border [6]. Due to the promising potential of the producing zones in Zubair field, petrophysics of these zones need to be well characterized. In the present study, petrophysical characteristics of the pay zones in Zubair field are analyzed using available well log data. This encompasses detailed well log analysis to accurately identify the potential of hydrocarbon zones and develop detailed reservoir characteristics.

2. Geological Setting

The geology of Zubair field is best described in the context of the geology of Mesopotamian Basin (**Figure 1**). Detailed geological and tectonic framework of Mesopotamian Basin have been described in literature (e.g. [11] [12] [13]) with three important subzones identified; Tikrit-Amara, Samawa-Nasiriya, and Zubair. The main lithostratigraphic units of South Iraq is presented in the composite stratigraphic column shown in **Figure 2**.

Generally, the hydrocarbon production is concentrated within the New Tethys Extension tectonics (**Figure 2**); however Zubair and Mishrif Formation remain the most producing intervals [14]. Mishrif Formation and the conformably underlying Rumaila Formation are first described at Zubair field where Mishrif Formation showed a gradual contact with both Rumaila and Kifil Formation. In parts where Kifil Formation is absent Mishrif Formation is marked by an unconformity (**Figure 2**). Mishrif Formation comprises Mid-Cenomanian to Early Turonian extensive carbonate platform that prevails Southern Iraq and extends eastward to Iran (Upper Sarvak Formation) and southeast to Oman (Natih A–C members of Natih Formation) [15]. It is heterogeneous detrital calcareous sediments that involve rudist, algal, and coral reef limestone with rare shale intercalations and predominantly covered by fresh water limonitic limestone [16] [17]. In Zubair field, Mishrif Formation is made of gray dense algal limestone with shelly foraminiferal limestone rich in rudist debris at the bottom and gastropods to shell fragments at the top [18]. Stratigraphically, Mishrif Formation presents a regressive sequence (**Figure 3**) of two sub-cycles: the early sub-cycle extends between the outer-shelf open marine and the limited lagoonal condition, while the late sub-cycle done by discontinuous sediments [10] [16]. The thickness of Mishrif

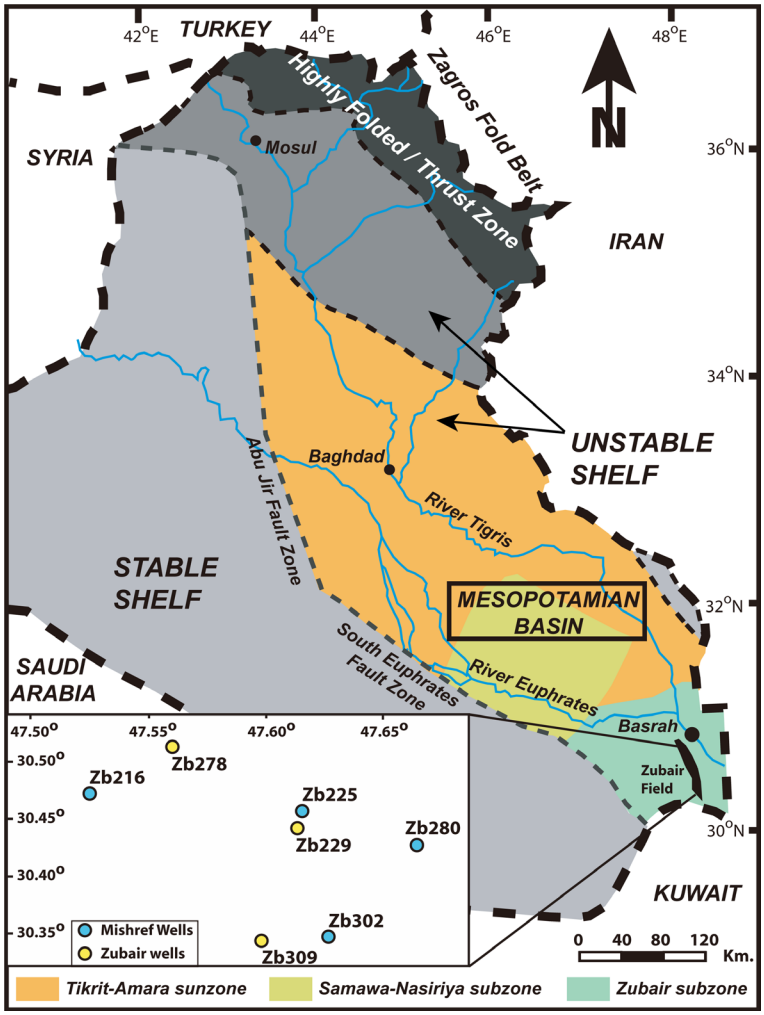

Figure 1. The geology of Zubair field in context of the Mesopotamian Basin showing a location map for the studied wells (modified from [11] [12] [13]).

Formation varies dramatically through the Mesopotamian Basin with 350 - 400 m in SE boundary (270 m Zubair field) and pinches out towards the West and SW [19]. Developed on 32 geologic structures, petroleum plays in Mishrif Formation typically occupy a relatively narrow NW-SE belt across central and Southeastern Iraq [20].

Zubair Formation involves 380 - 400 m succession of shale and sandstone with siltstone intercalations deposited in a littoral, partly deltaic environment (**Figure 3**) that started as regressive phases of prodelta, delta front, marsh and swamp and ended as a shelf [21]. It shows in most cases gradational and conformable contacts to the upper and lower Formation (**Figure 2** and **Figure 3**). At Zubair field, Zubair Formation reports 200 m thick of net sand that decreases gradually and completely disappear at Iran border. Generally, the reserve of South Iraq oil fields is originated from source rocks in the Arabian basin [7]. Al Rawi in [22] proved the prospectivity of sandstone members in Zubair Formation and showed that the total organic carbon between 1% and 24% in thin marine shale

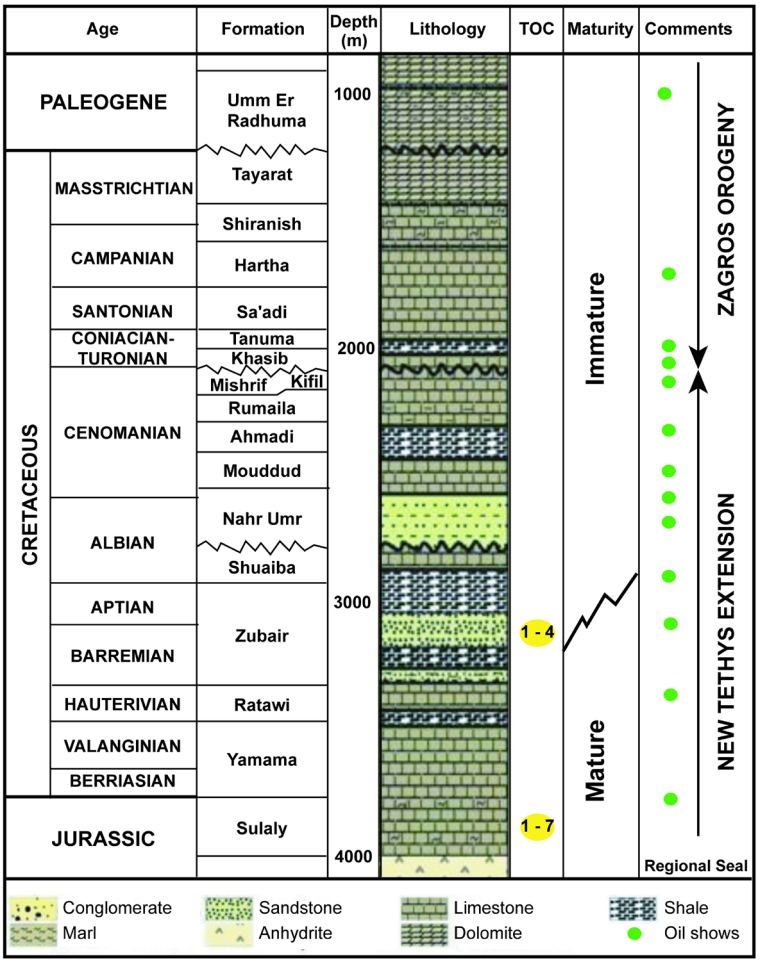

Figure 2. A composite stratigraphic column showing the main lithostratigraphic units of South Iraq (modified from [14]).

indicates deposition in the prodelta zone of offshore facies. Owen and Nasser in [23] identified five members in Zubair Formation (upper shale, upper sand, middle shale, lower sand, and lower shale) that seem identical at Zubair area and typically show different apparent thickness (**Table 1**). These members act as source and reservoir units but occasionally develop potential seal. Within Southern Rumailah Oil field, Al-Jubory in [24] recognized four sedimentary facies in the upper Zubair sand member including channel, swamp and marshes, distributary mouth bar, and prodelta facies (**Figure 3**).

3. Methods

To delineate the main reservoir characteristics, a suite of well log readings from numerous wells drilled in Zubair field, both analogue and digital format, are visually evaluated. Of these data, seven sets of well logs are selected for detailed analysis in the present study (**Figure 1**). Ideally digital well logs are directly used in analysis while paper logs are scanned and digitized to be compatible with other digital dataset. Subsequently, all data set are reviewed, edited, and in some

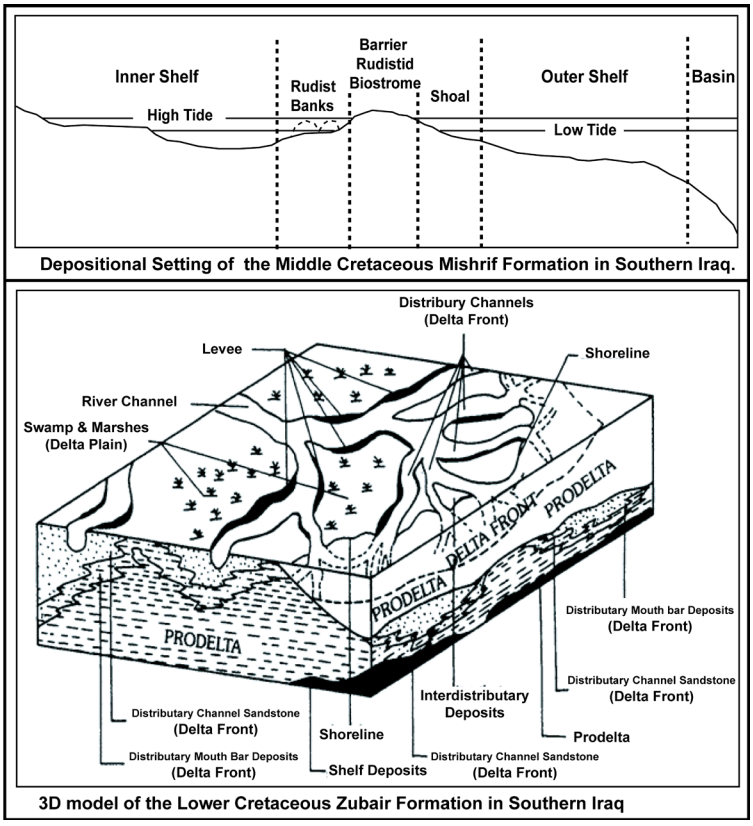

Figure 3. Depositional setting of Mishrif Formation adapted from [10] (upper) and 3D model of the Lower Cretaceous Zubair Formation in Southern Iraq from [21], (lower).

Table 1. The five members of Zubair Formation identified by Owen and Nasser in [21] in Zubair Field, South Iraq.

Members	Lithological Description
Upper Shale	Greenish black shale encompassing a sandstone-siltstone.
Upper Sandstone	Mainly sandstone with subordinate siltstone.
Middle Shale	Black to greenish black, hard shale enclosing infrequent sandstone streaks.
Lower Sandstone	Predominant sandstone with minor shale and silt.
Lower Shale	Fissile shale with two discrete sandstone zones and negligible siltstone.

cases filtered to get rid of suspicious digitization errors. Since early time in petroleum industry, various methods and techniques have been introduced to calculate reservoir characteristics and the proper technique normally depends on the available data, reservoir conditions, and nature of the sedimentary units. Lithology, net/gross (N/G), clay volume, porosity, water saturation, net pay, and cut-offs are the main reservoir characteristics investigated in the present analysis. **Figure 4** presents a flow chart for the methods applied in this study.

Typically two lithology models of multi minerals analysis, clastic and calcareous models, are utilized for lithological interpretation. Clastic model uses

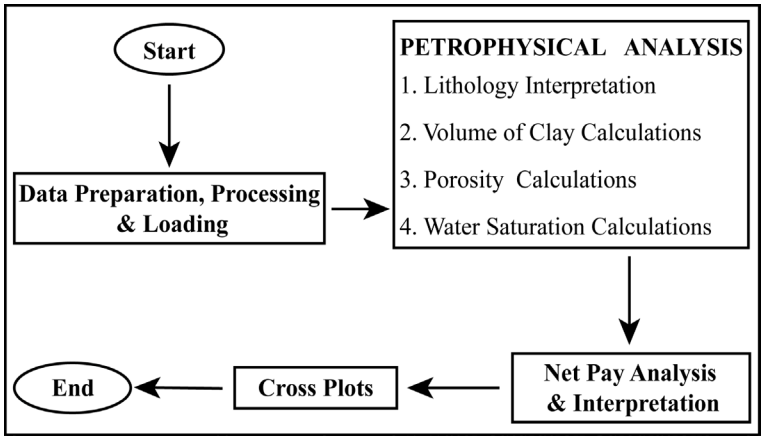

Figure 4. A flow chart showing the main steps of a standard petrophysical log analysis applied in the present study.

a mixture of sand, silt, and clay to characterize both argillaceous and arenaceous sediments while carbonate model is usually used to identify calcareous rock and evaporites together with clastic contents if present. Calcareous model is only applicable if sonic and photoelectric effect logs are available. In both models the available density, gamma ray, neutron, and resistivity logs are also used for lithology interpretation. Clay content can be calculated using gamma ray log, resistivity log, and/or a combination of neutron-density log [25]. All these models are investigated and gamma ray calculations are accepted to represent the actual clay content in the studied intervals. Larionov formula (Equations (1) and (2)) for pre-Tertiary rocks [26] is applied to quantify the clay content.

$$\mathrm{IGr} = \frac{\mathrm{Gr} - \mathrm{Gr\ clean}}{\mathrm{Gr\ clay} - \mathrm{Gr\ clean}} \tag{1}$$

$$\mathcal{V}c\ell = 0.333\left(2^{2\mathrm{IGr}} - 1\right) \tag{2}$$

where $\mathcal{V}c\ell$ is the volume of clay, Gr is the gamma ray log reading of the Formation, Gr clean is the gamma ray matrix of clay free zone, and Gr clay is the gamma ray of the shale interval (100% clay zone).

Since the presence of shale and gas severely influences the porosity calculations, the effective porosity of Zubair Formation can be calculated from the combination of density and neutron logs using both neutron and density porosity models. To start, the density porosity (ϕ_D) [27] and Neutron porosity (ϕ_N) [28] for the same interval is calculated and the results are subsequently used to define a mineral model. These mineral models help to obtain the corrected porosity (ϕ) using Equation (3).

$$\phi = \phi_{D1} + \frac{\phi_{N1} - \phi_{D1}}{1 - \dfrac{\phi_{N1} - \phi_{N2}}{\phi_{D1} - \phi_{D2}}} \tag{3}$$

where ϕ is the corrected porosity value, ϕ_{D1} and ϕ_{N1} are respectively the density and Neutron porosity corrected to matrix 1, and ϕ_{D2} and ϕ_{N2} are respectively the

density and Neutron porosity corrected for matrix 2.

To honor a particular model, several proposed methods have been tried to calculate water saturation (S_w) in Zubair field. For flexibility and involving numerous parameters in calculations, the Indonesia equation is preferred to estimate effective water saturation in Zubair reservoirs. The basic Indonesia equation is presented in Equation (4) [29].

$$\frac{1}{\sqrt{R_t}} = \left[\sqrt{\frac{\Phi^m}{aR_w}} + \frac{V_{cl}^{\left(1-\frac{v_{cl}}{2}\right)}}{\sqrt{R_{cl}}} \right] \cdot S_w^{n/2} \tag{4}$$

where R_{cl} is the deep resistivity in clay zone (read from log), R_t is the deep resistivity (read from log), R_w is the formation water resistivity (calculated using SP log), Φ is the effective porosity, S_w is the formation water saturation, 'a' is the tortuosity factor, 'm' is the cementation factor, and 'n' is the saturation exponent.

In Zubair field the default values of Archie parameters were set as a = 1.0, m = 1.6, and n = 2. These preliminary values are changed using the built-in modules of IP software to facilitate accurate S_w calculations at the various zones of both Zubair and Mishrif Formation. To delineate the net pay for Zubair field several porosity, water saturation, and clay content cut-off values have been tested. The optimum cut-off values that seem acceptable industry-wise reported 15% for porosity, 40% for formation water saturation, and 40% for shale volume cut-off. Such values wisely constrained the net pay zones for reservoir intervals with high potential to contain hydrocarbon. All calculations and analysis are completed using Interactive Petrophysics –IP V4.2 software [30].

4. Results and Discussion

Log data from seven wells producing from Mishrif Formation (Zb216, Zb225, Zb280, and Zb302) and Zubair Formation (Zb229, Zb278, and Zb309) (**Figure 1**) are numerically processed and verified consistent for petrophysical analysis. For each well, several petrophysical characteristics including porosity, water saturation, volume of clay, cut-offs, and net/gross are calculated and the full interpretation of each well is analyzed separately. **Figure 5** and **Figure 6** respectively present an example for the results of reservoir characteristics for carbonate facies in well Zb216 and clastic facies in well Zb309 while cutoffs and pay results in well Zb216 are shown in **Figure 7**. For each pay zone or reservoir interval in any well, the statistical analysis provides a set of outputs including tabulated values, histograms, and cross plot for each property involved in reservoir characterization. The mean reservoir and pay parameters calculated in all wells tapping Zubair and Mishrif Formation are presented **Table 2**. In addition, an example of histograms constructed for average porosity (ϕ_{avg}), average water saturation (Sw_{avg}), and average volume of clay (Vcl_{avg}) in all reservoir intervals of Zb216 well is shown in **Figure 8**. The heterogeneity of reservoir characteristics in all zones are statistically evaluated using standard deviation and

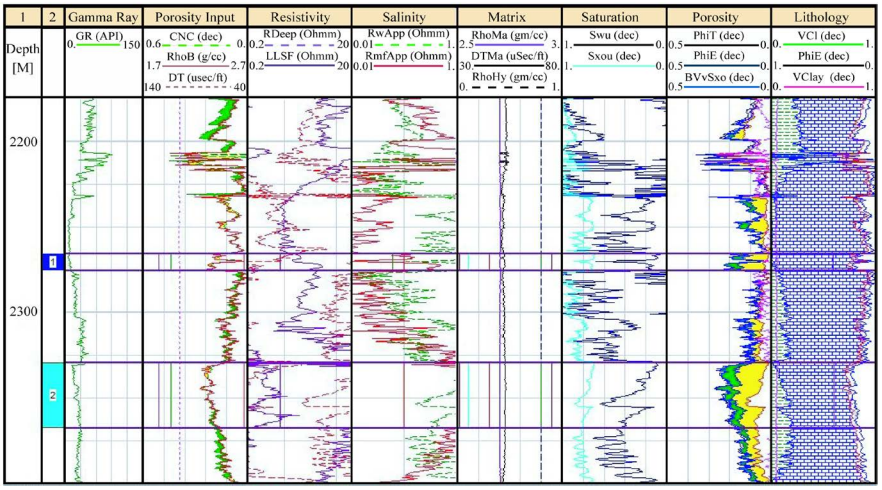

Figure 5. An example of log analysis in Zb216 well and the resulting carbonate facies of Mishrif Formation.

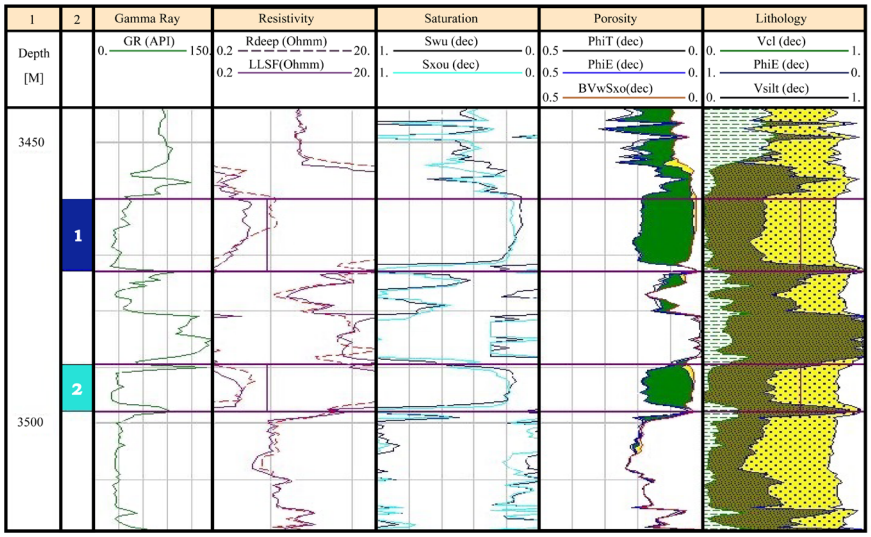

Figure 6. A sample of log analysis in Zb309 well and the resulting clastic facies of Zubair Formation.

the results are presented in **Table 3**.

4.1. Petrophysical Characterization of Mishrif Formation

Buday in [13] reported that Mishrif Formation is made of a complex of bioclastic detrital carbonates that can be simply discriminated into simple components using well log data. The present lithological and petrophysical analysis of Mishrif Formation indicated the development of two pay zones in Zb216 and Zb302 wells (**Figure 7** and **Table 2**) and three zones in Zb225 and Zb280 wells (**Table 2**). Generally, all these zones show clean formation with clay content between 2% and 10% with zone 2 and 3 showing a relatively close petrophysical values in all wells. Lithologically, all zones of Mishrif Formation are dominantly clean limestone and/or dolomitic limestone (**Figure 5**) with zones 2 and 3 reporting

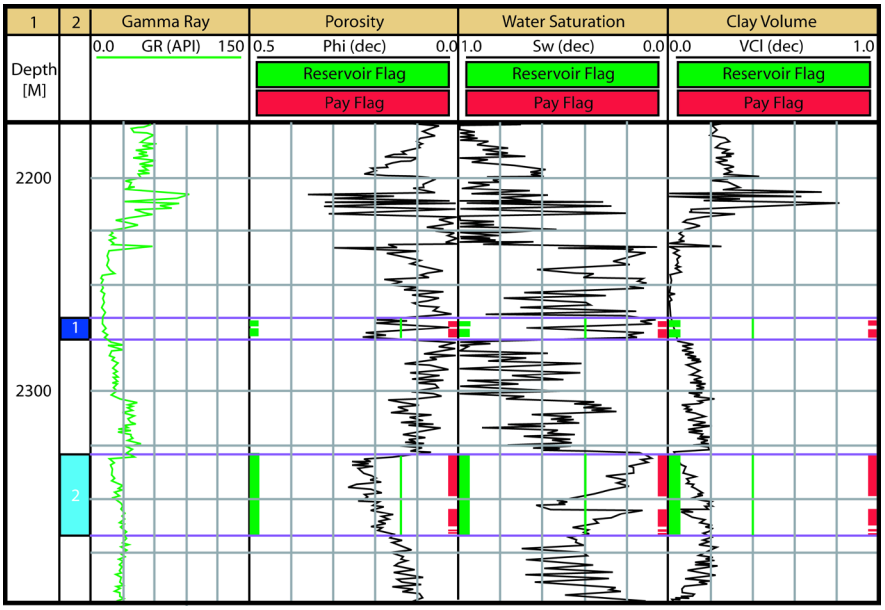

Figure 7. The pay results in Zb216 well.

Table 2. The mean reservoir parameters calculated for both reservoir and pay intervals in all wells.

Fm.	Well	Zone	Top (m)	Bottom (m)	Reservoir (decimal)				Pay (decimal)			
					N/G	Φ_{avg}	Sw_{avg}	Vcl_{avg}	N/G	Φ_{avg}	Sw_{avg}	Vcl_{avg}
Mishrif	Zb216	1	2265.5	2275.5	0.8	0.182	0.154	0.022	0.8	0.182	0.154	0.022
		2	2329.5	2367.5	0.974	0.186	0.273	0.118	0.763	0.189	0.216	0.1
	Zb225	1	2206.5	2229.5	0.957	0.18	0.285	0.036	0.783	0.178	0.242	0.029
		2	2244	2256.5	0.96	0.211	0.242	0.05	0.92	0.212	0.236	0.047
		3	2298	2328	1	0.24	0.284	0.101	0.85	0.245	0.26	0.09
	Zb280	1	2490	2508	0.972	0.211	0.418	0.124	0.903	0.215	0.397	0.114
		2	2549.5	2593	1	0.231	0.511	0.05	0.563	0.241	0.418	0.047
		3	2597	2603.5	1	0.199	0.502	0.148	0.615	0.207	0.416	0.118
	Zb302	1	2550	2570.5	0.951	0.207	0.451	0.101	0.732	0.214	0.4	0.095
		2	2576.5	2599	0.889	0.18	0.427	0.141	0.733	0.181	0.403	0.138
Zubair	Zb229	1	3277.5	3298.5	0.905	0.206	0.159	0.017	0.881	0.207	0.153	0.017
	Zb278	1	3358	3384	0.923	0.22	0.216	0.033	0.856	0.222	0.194	0.031
	Zb309	1	3460	3473	0.905	0.192	0.161	0.019	0.865	0.194	0.149	0.019
		2	3489.5	3498	0.765	0.173	0.191	0.028	0.765	0.173	0.191	0.028

higher dolomitic content (20% to 40%) compared to the lower dolomite content in zone 1 (6% to 13%). This observation may explain the relatively higher porosity in zones 2 and 3 compared to zone 1 in Zb216 and Zb225 wells (Table 2). Petrophysical analysis indicated a relatively good porosity (18% - 24%) in all pay zones of Mishrif Formation (Table 2). In most cases, the average porosity of zone 1 (17.8%

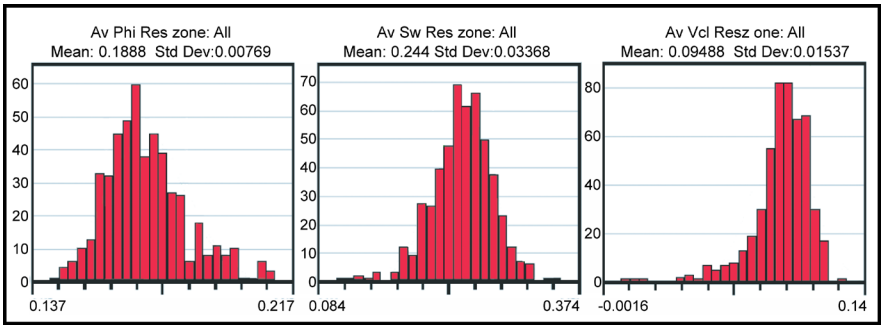

Figure 8. The histograms of ϕ_{avg} (left), Sw_{avg} (middle) and Vcl_{avg} (right) in all reservoir intervals of Zb216 well.

in Zb225 well and 21.4 in Zb302 well) is slightly lower than the corresponding values in zones 2 and 3 (18.1 and Zb302 well and 24.5 in Zb225 well).

Appraising the variation in porosity through the wells penetrating Mishrif Formation indicated some comparatively moderate fluctuations through the pay zones that in most cases do not exceed 5%. The average porosity in zone 1 (**Table 2**) shows a comparable result to the clay content shown in **Figure 5**. Alternatively, the average porosity in zone 2 showed a moderate increase in the average calculated porosity from 19% to approximately 24% (**Table 2**). Such a trend does not have any obvious relation to the clay content in zone 2 indicating that the porosity estimate of zone 2 in Mishrif Formation is independent to clay content and predominantly related to secondary porosity associating dolomitization processes. Aqrawi *et al.* in [8] marked early diagenetic microfacies as poring in planktonic foraminifera and/or occasional pyrite crystals while cloudy-centered dolomite rhombs indicate later burial diagenesis. Typically, the upper parts of the basin are strongly affected by meteoric near-surface diagenesis. Alternatively, mixing-zone diagenesis in mudstone and wackestone of intertidal flats is identified by dolomite rhombs [31] [32]. The presence of vugs, channel porosity or other dissolution features can be attributed to meteoric phreatic diagenesis [33]. Generally, porosity of all zones in wells tapping Mishrif Formation shows considerable homogeneity as indicated by a standard deviation less than 1 porosity unit except for Zb280 well that develop as standard deviation of 4.1 porosity units.

Average water saturation (Sw_{avg}) in the two zones of Mishrif Formation varies dramatically among the studied wells with minimum of 0.15 in Zb2016 well and maximum of 0.551 in Zb280 well (**Table 2**). Generally, the S_w distribution in both zones follows the common trends of clay content distribution indicating an apparent effect of clay content on S_w calculations. Among the studied wells, Zb216 and Zb225 wells showed a comparatively lower S_w values (~0.23) compared to the consistent S_w values (~0.41) calculated in Zb280 and Zb302 wells. The variations in calculated S_w had a standard deviation between 3% and 4% in all wells, but such value dramatically increased to over 10% in Zb280 well. This effect could be attributed to the diagenetic effect fostered by the relative increase in shale content. The calculated volume of clay in Mishrif Formation hardly ex-

ceeds 10% for both reservoir and pay intervals indicating clean formation (Table 2 and Table 3). Characterizations of net pay zones within the gross reservoir intervals of Mishrif Formation showed a good N/G ratio with a minimum value of 0.47 reported in zone 2 of Zb280 and a maximum value of 0.83 calculated in zone 2 of Zb225 well. In general, zone 1 of Mishrif shows a relatively consistent N/G values (~0.65) in the majority of wells compared to zone 2 that reported the maximum and minimum values observed in Mishrif Formation (Table 2). Generally, N/G calculations showed moderate standard deviation that falls dominantly below 20% but such value increased to 27% in Zb302 well due to the effect of shale. The present analysis had no evidence of an obvious oil-water contact in the studied wells of Mishrif Formation, indicating the absence of aquifer or at least a strong aquifer (Figure 5). Due to the lack of seismic data and subsurface maps for Zubair field, it was difficult to infer the reservoir boundaries or the spatial extension of the identified pay zones.

4.2. Petrophysical Characterization of Zubair Formation

Pay analysis in Zubair Formation indicated the presence of only one pay zone in Zb229 and Zb278 wells and two zones in Zb309 well only (Figure 6). Generally, the relative sand content of these zones falls between 72% (Zb278 well, located northward) and 62% (Zb309 well located southeast) but the silt content follows the opposite trend with average silt content between 25% (Zb278 well) and 35% (Zb309 well). This increase in silt is more obvious in zone 2 and therefore the N/G ratio is considerably low (0.65) compared to that of zone 1 (~0.83). This fact is also presented by higher standard deviation in Zb309 well that shows double the value reported in Zb229 well (Table 3). In addition, the clay content of all pay zones in Zubair Formation is generally low with average content between 2% and 3%. Such clean facies is supportive to the interpretation of the littoral to near shore depositional environment [34]. The average porosity of Zubair pay zones in the studied wells showed slightly better values in zone 1 (~0.20) compared to the average porosity of zone 2 (0.17) (Table 2). The change in porosity of the two zones is attributed to the higher silt content of zone 2 associating deposition at relatively deeper parts of the shelf. This pattern is closely similar to the lithostratigraphic log characteristics recognized by Ali and Nasser in [21] in Zubair Formation of Southern Iraq, where the silt content characterized the sand package into two members; clean upper member and silty lower member. Generally, the porosity of Zubair Formation shows an obvious oscillating pattern at the upper part (Figure 6) while the lower part that encompasses the pay zones is marked by a relatively stable porosity pattern. This pattern markedly changes southward at Zb309 well where the oscillating part is warped to a minimal thickness in the studied wells. However, this well reported a higher standard deviation compared to the other wells of Zubair Formation (Table 3).

The presence of laminated clay in sand is usually problematic for petrophysical analysis due to its ability to mask out the hydrocarbon zones by inducing lower Rt measurements. The average water saturation in the pay zones of Zubair

field show distinct lower values that varies between 15% in Zb229 and Zb309 wells to 18.7% in Zb278 well (Table 2). These values usually match the typical connate water values in most hydrocarbon reservoirs. Compared to zone 1, zone 2 shows slightly higher S_w values (20%) that is probably related to the nature of the fine-grained facies developed in Zone 2 (Figure 6). Careful analysis indicates the presence of well-developed aquifer system beneath the pay zones that could be masked by a thin barrier (e.g. Figure 6). This interpretation is based on the higher calculated S_w associating higher porosity values with minimal clay content.

4.3. Cross Plots

As a powerful mean to investigate the mutual relationship between two independent reservoir properties, cross plots for any couple of reservoir or pay characteristics are tested to help inferring a possible relationship. In the present work 4 cross plots (S_w vs Vclay, ϕ vs Vclay, ϕ vs S_w, and N/G vs S_w) have been constructed. As an example for such cross plots, Figure 9 shows the Vclay, S_w, ϕ, N/G cross plots for all pay intervals in Zb216 well. Generally, S_w vs Vclay cross plot

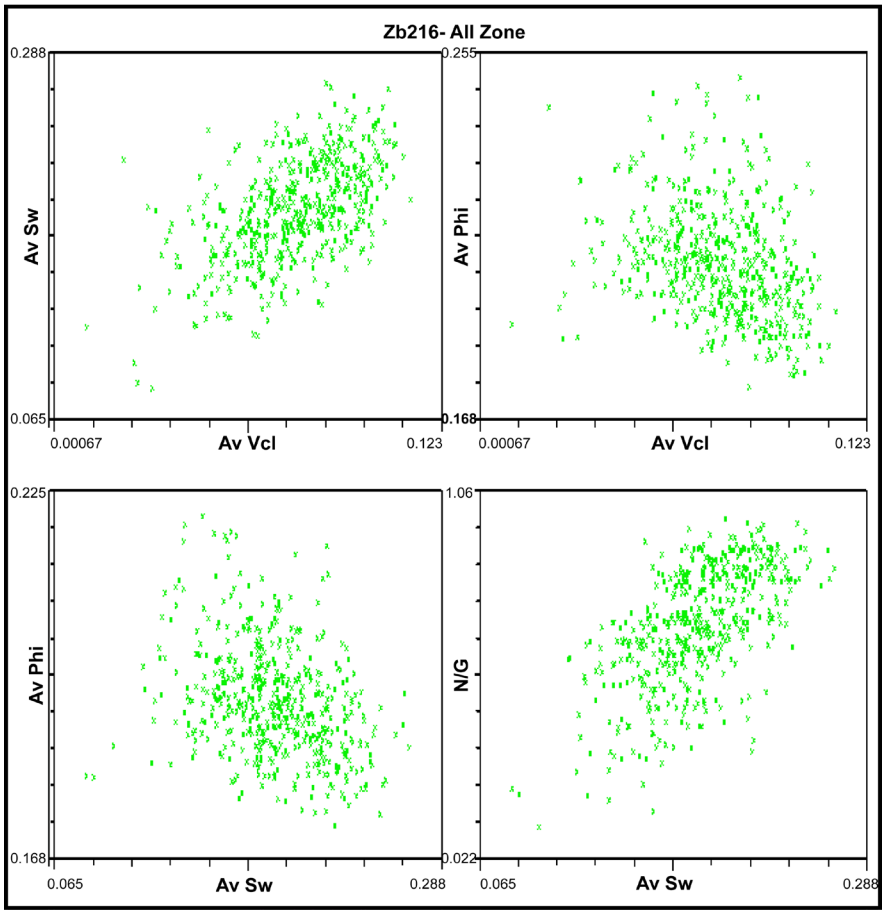

Figure 9. The cross plots for average values of S_w versus Vclay (upper left), ϕ versus Vclay (upper right), ϕ versus S_w (lower left) and N/G versus S_w (lower right) for all pay intervals in Zb216 well.

Table 3. The standard deviation of reservoir parameters calculated in all zones of reservoir and pay intervals of Zubair and Mishrif Formations.

Formation	Well	Zones	Reservoir			Pay			
			Phi	S_w	Vcl	Phi	S_w	Vcl	N/G
Mishrif	Zb216	All	0.8	3.4	1.6	0.8	2.9	1.8	15.4
	Zb225	All	0.9	3.1	2.0	1.1	3.5	2.2	19.9
	Zb280	All	4.1	10.5	3.7	4.6	12.9	3.0	2.8
	Zb302	All	0.9	4.1	5.1	1.4	4.8	5.0	27.2
Zubair	Zb229	All	0.6	2.3	0.7	0.6	2.1	0.7	8.2
	Zb278	All	0.7	2.9	0.8	0.7	2.6	0.8	11.8
	Zb309	All	1.5	4.5	1.1	1.5	4.5	1.1	16.5

shows widely scattered points in most wells but shows a noisy direct relation in Zb278 well. This may indicate that S_w and Vclay calculations are independent in most wells. A similar relation is visualized in ϕ vs S_w cross plot as indicated by the scattered points (Figure 9) but in Zb302 and Zb278 wells a marginally negative relationship can hardly be depicted. On the other hand, the ϕ vs Vclay cross plot shows an obvious inverse relationship that disagrees with typical positive relationships in most reservoirs. This can be explained in the context of the mode of shale occurrence as in the present case may constitute minute particulates occupying part of the pore space within the pay zone. The N/G-S_w cross plot shows a direct relation in most wells but such a relation was slightly obscured in Zb229 and Zb278 wells indicating large changes in S_w values within these wells. Among the studied wells, Zb309 well showed a small range of S_w that lead to false relations.

5. Conclusions

Zubair field produces oil from two packages; Mishrif Formation normally encountered at the depth of 2200 - 2600 m and Zubair Formation located at the depth of 3000 - 3600 m below land surface. The lithological and petrophysical analysis of log data in wells penetrating Mishrif Formation indicated the development of two pay zones in two wells, and three zones in the other two wells. Generally, all zones of Mishrif Formation are dominantly clean to dolomitic limestone with zones 2 and 3 reporting higher dolomitic content (20% to 40%) compared to low dolomite content in zone 1 (6% to 13%). Petrophysical analysis indicated a relatively good porosity (18% - 24%) in the pay zones of Mishrif Formation with zone 2 predominantly related to secondary porosity associating the diagenetic history. Characterizations of net pay zones within the gross reservoir intervals of Mishrif Formation showed a good N/G ratio with the minimum value of 0.47 and maximum value of 0.83.

Lithological interpretation of well log data of three wells in Zubair Formation indicated the presence one pay zone in two wells and two zones in one well. The

clay content of all pay zones in Zubair Formation is generally low with the average content between 2% and 3%. The average porosity of Zubair pay zones in the studied wells showed slightly better values in zone 1 (~0.20) compared to average porosity of zone 2 (0.17). The change in porosity of the two zones is attributed to the higher silt content associating deposition at relatively deeper parts of the shelf. The average water saturation in the pay zones of Zubair Formation shows distinct lower values that vary between 15% and 18.7%. Careful analysis for the petrophysical characterization results of Zubair Formation indicates the presence of well-developed aquifer system beneath the pay zones that could be masked by a thin barrier. Such interpretation is disputable and may disagree with the impression of the operating company that assumes deficiency of aquifer support in Zubair field.

Acknowledgements

The Authors acknowledge and appreciate very much the Southern Petroleum Company (Basrah, Iraq) for providing the technical support and well log data. Many thanks to Prof. Dr. Selim Zidan, Petroleum Engineering Department of Al Azhar University and Prof. Dr. Abdel Zaher Abu Zaid from Mining, Petroleum, and Metallurgical Engineering Department of Cairo University for the fruitful comments and initial drafting work.

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