Petrophysical characterization of the tertiary oil reservoir, Northern Iraq

Mohammed Y. Najmuldeen[1], Ali A. Fadhil[2,] and Yahya J. Tawfeeq[3]
[1,2,3] Petroleum Engineering Department, University of Kirkuk

Abstract

This paper introduces a comprehensive petrophysical study to re-evaluate reservoir quality of 'Main Limestone' reservoir units for one Iraqi oil field using modern software and techniques. In this study, we discussed many subjects, such as petrophysical effects on hydrocarbon accumulation, hydrocarbon mobility, and hydrocarbon productivity of the field. The determining reservoir properties include formation porosity, hydrocarbon, and water saturation, as well as net/gross thickness ratio, which is determined depending on wire-line logs data. For reservoir description, full sets of well log data such as gamma-ray, resistivity, neutron log, form three wells were interpreted and analyzed. The performed analysis includes many subjects such as lithology description, reservoir identification, reservoir fluid type identification, well correlation, reservoir porosity, saturation (for hydrocarbon and water) determination. Petrophysical properties parameter of 'Main Limestone' reservoir rocks exposed that unit 'B' has better properties compared with other units. The most overall porosity type was primary porosity through the entire formations and units. Water saturation and shale volume estimations indicated the water saturation significantly affected by an increase in the shale quantity if shale volume exceeds 10%.

Keywords: Petrophysical properties, Main limestone reservoir, North Iraq, well logs.

Corresponding Author:
Yahya J. Tawfeeq
Department of Petroleum Engineering
Kirkuk University
Iraq / Kirkuk
Email: yahyapetroleum@uokirkuk.edu.iq

1. Introduction

Petrophysics is the study of the physical properties of the reservoir rocks and their relation to fluids (gases, liquid hydrocarbons). A comprehensive study of the distribution of petrophysical properties such as porosity, permeability, and water saturation is essential for the reservoir evaluation project.

The reservoir description includes reservoir parameters determination, for example, effective porosity (Phie), permeability (K), water/oil saturation, and net pay thickness. Because reservoir rocks must be pores and permeable, we are most interested in the properties of porous and permeable rocks. Porosity measures the capacity of a reservoir to store fluids, and it is represented as a pore volume ratio to reservoir total volume. Permeability is the rock's ability to allow fluid flowing through it. Permeability is a property of interconnecting pore volume, so if a rock has an interconnected pore, it has a permeability. The fluid saturation is the percentage of pore space filled with the fluids to the total volume of the rock. A reservoir rock can be saturated either with water (S_w) or with hydrocarbon ($1-S_w$), this depending on the nature of the liquid it holds. Much sub-surface information can be obtained from drill coring and cuttings, but the technique is highly expensive and has several restrictions. The well-logging offers an inexpensive, faster technique for obtaining exact sub-surface petrophysical information. The objectives of this study are quality and quantity analysis of the petrophysical properties in order to re-evaluate the production potential of the tertiary main limestone reservoir.

The studied oil field is situated in the North of Iraq (Figure 1), and consists of three Tertiary reservoirs unit as shown in Table (1) below. The tertiary reservoir includes several economically significant main reservoir units of the pay zone.

Table 1. Formations tops and thickness of main limestone reservoir

Reservoir units	Tops (meter) / thickness (meter)		
	Well No.1	Well No.2	Well No.3
Unit A	1562/18	1579/26	1560/ 10
Unit A'	1580/22	1605 / 13	1570 / 21
Unit B	1602/55	1618 / 29	1591 / 65

2. Material and methods

2.1. Preliminary work

The study was initiated with the collection of data (electronic copies of the wire-line logs) obtained from Daoud dome from three wells. Firstly, the available scanned logs were digitized, and NeuraLog V2010.11 software was used for digitizing the logs. For the measurement of input data, one point per 0.25-meter depth was pointed. The processes of interpretation are achieved by using Interactive Petrophysics (IP) version 3.5 and PETREL 2009 Software.

2.2. Data analysis

The study of petrophysical logs in this paper is based on the qualitative and quantitative determination of the characteristics of the main limestone reservoir of one Iraqi oil field.

2.2.1. Qualitative data analysis

For reservoir and non-reservoir rock information, the gamma-ray (GR) log has been investigated. In clay beds, the gamma-ray (GR) log reflects the clay contents; hence this log was utilized for recognizing of shale in the reservoir units. Using GR log assembled with resistivity log is utilized to distinguish between hydrocarbon-bearing zones and dry zones not contain hydrocarbon. For hydrocarbon zones, resistivity log signs display high values of resistivity than in water zones. The outcome is shown as panels of correlation shown in Figure (1).

2.2.2. Quantitative data analysis

The petrophysical properties are quantitatively determined using the following analytical methods:

2.2.3. Clay volume determination

Clay volume was determined from the gamma-ray log. The first step required to determine the volume of clay from the gamma-ray log is the gamma-ray index calculation from the following eq. (Bassiouni, 1994) **[1]:**

$$I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \quad (1)$$

The calculated *GRI* is then used to determine the clay volume using Larionov equation for Tertiary rocks, according to Larionov (1969) **[2]**:

$$Vcl = 0.083(2^{3.7*GRI} - 1) \quad (2)$$

where, V_{CL} is Volume of Clay, GR_{log} is Gamma Ray Log reading of formation, GR_{min} is Gamma Ray Matrix (Clay free zone), and GR_{max} is Gamma Ray Shale (100% Clay zone).

Figure 1. Correlation panel showing described the main limestone reservoir

2.2.3.1. Porosity calculation

According to the Schlumberger (1974) equation, total porosity was calculated using Neutron – Density-dependent porosities that can be stated as **[9]**;

$$\varphi_{Total} = \frac{\varphi_{Neutron} + \varphi_{Density}}{2} \quad (3)$$

Where; $Ø_{Total}$ is Total porosity derived from Neutron-Density log, $Ø_{Neutron}$ is porosity derived from Neutron log, and $Ø_{Density}$ is porosity derived from Density log. Density log porosity calculated from the total formation density with known matrix density (ρ_{ma}) and fluids density (ρ_f), using the equation below (Ezekwe. 2010) [3]:

$$Ø_{density} = (\rho_{ma} - \rho_b) / (\rho_{ma} - \rho_f) \quad (4)$$

Then effective porosity (*Øe*) can be calculated using Schlumberger's equation (1998): [4]

$$\varphi_{effective} = \varphi_{total} * \left(1 - V_{clay}\right) \quad (5)$$

Primary porosity is determined from Sonic log based on time- average (Δt) Wyllie equation **[5]**;

$$Ø_{Sonic} = (\Delta t_{log} - \Delta t_{matrix}) / (\Delta t_{fluid} - \Delta t_{matrix}) \quad (6)$$

Where; $Ø_{Sonic}$ represents sonic derived porosity; Δt_{log} is formation transit time; Δt_{matrix} is matrix transit time; Δt_{fluid} is fluid transit time.

The total and primary porosity difference will give the secondary porosity index (*SPI*) (Schlemberge. Oilfield Glossary) **[10];**

$$SPI = (Ø_{total} - Ø_{sonic}) \quad (7)$$

2.2.3.2. Water saturations determination

To calculate water saturation for the uninvaded zone, the water formation resistivity value at formation temperature is required. Water formation resistivity in this study calculated using formation water salinity and temperature by the following equation **[6]:**

$$Rw@75 = 0.0123 + \frac{3647.5}{[NaCl(ppm)]^{0.955}} \quad (8)$$

Water saturation (*Sw*) of a reservoir's un-invaded zone is calculated by the Archie Eq. **[7]:**

$$S_w = \left(\frac{a\ R_w}{R_t\ \varphi^m}\right)^{\frac{1}{n}} \quad (9)$$

Where *Sw* is un-invaded zone water saturation, R_w is formation water resistivity at formation temperature, R_t is true formation resistivity, φ is porosity, "*a"* is tortuosity, (assumed equal to 1), "*m"* is cementation exponent (assumed equal to 2) and "*n"* is saturation exponent (assumed equal to 2). Water saturation in the flushed zone is derived from the Archie equation, with some variables are different. In essence, instead of formation water resistivity (*Rw*), the mud filtrate resistivity (*Rmf*) is introduced, and resistivity of the flushed zone (*Rxo*) is introduced instead of un-invaded zone resistivity (*Rt*). Water saturation of the flushed zone calculated from **[7]**;

$$S_{xo} = \left(\frac{a\ R_{mf}}{R_{xo}\ \varphi^m}\right)^{\frac{1}{n}} \tag{10}$$

Where *Sxo* is flushed zone water saturation, *Rmf* is mud filtrate resistivity, and *Rxo* is shallow resistivity from micro-laterolog. Water saturation of flushed zone and water saturation of the un-invaded zone can be used as an indicator of hydrocarbon movability. The difference between Sxo and Sw represented movable hydrocarbon saturation (*MOS*) that moved or flushed out of the zone nearest the borehole by the invading drilling fluids (*Rmf*).

2.2.3.3. Determination of hydrocarbon saturation

Hydrocarbon Saturation is the fraction of pore volume occupied by hydrocarbon. Hydrocarbon saturation is estimated by subtracting the water saturation value from 100% saturation value i.e.

$$S_h = 1 - S_w \tag{11}$$

2.2.3.4. Moveable and residual hydrocarbon saturation calculation

Moveable hydrocarbon saturation was calculated based on Schlumberger's (1998) equation;

$$MOS = S_{xo} - S_w \tag{12}$$

Where, if *Sxo* >> *Sw*, the hydrocarbons will be move from the flushed zone.

Residual oil saturation (*ROS*) can be calculated from Archie water saturation using Schlumberger's (1987) equation**:**

$$ROS = 1 - S_{xo} \tag{13}$$

2.2.3.5. Movable hydrocarbon index estimation

The index of mobile hydrocarbons (*MHI*) was obtained from:

$$\mathrm{MHI} = \frac{S_w}{S_{xo}} \tag{14}$$

Where *MHI > 1* indicates immobile hydrocarbon while if *MHI < 0.6* indicates that movable hydrocarbon. The Sw and Sxo represent uninvaded and flushed water saturation, respectively.

2.2.3.6. Net to gross ratio determination

A porosity cut-off 10% and water saturation cut-off 60% were used to describe the quality of reservoir rock. Using porosity cut off value 10%, the reservoir net thickness is determined. For the net pay, if there is less than 60% water saturation in the reservoir, it is considered to contain hydrocarbon. The saturation cutoff can be used with a special core analysis to predict the relative permeability ratio **[11]**. The results were found in Table (2) below.

Table 2. Average petrophysical properties results for three wells

Unit	Well No.	Depth (meter)	Gross pay (meter)	Net pay (meter)	Ratio Net/Gross	Avg. porosity	Avg. Water Saturation
A	Well No.1	1562-1580	17.5	0.38	0.021	0.236	0.076
	Well No.2	1579-1605	26	2.25	0.087	0.13	0.346
	Well No.3	1560-1570	10	0.13	0.013	0.166	0.288
A'	Well No.1	1580-1602	23	3.25	0.141	0.192	0.157
	Well No.2	1605-1618	13	2.13	0.163	0.123	0.09
	Well No.3	1570-1591	21	9.5	0.452	0.167	0.303
B	Well No.1	1602-1655	52.5	49.25	0.938	0.181	0.331
	Well No.2	1618-1647	29	27.25	0.94	0.177	0.225
	Well No.3	1591-1656	65	26.63	0.41	0.185	0.452

2.2.3.7. Analysis of bulk volume of water

The analysis of the bulk volume of water depends on two essential parameters; water saturation and porosity. The uninvaded zone bulk volume water (BV_W) and the invaded zone bulk volume water ($BVxo$) can be calculated according to the following equations;

$$BV_w = S_w . \varphi \tag{15}$$

$$BV_{xo} = S_{xo} . \varphi \tag{16}$$

Difference between Sw and Sxo will give movable hydrocarbons bulk volume **[8]**:

$$BV_{MO} = (S_{xo} - S_w)\ X\ \varphi \tag{17}$$

2.2.3.8. Mineral & lithological determination

The porosity combinations cross plots (M-N, and ØN- ρb) were used to identify main lithology and mineralogy, according to Schlumberger (1974) equations:

$$M = (\Delta t_{fluid} - \Delta t_{log}) / (\rho_{bulk} - \rho_{fluid}) \times 0.01 \tag{18}$$

$$N = (ØN_{fluid} - ØN_{log}) / (\rho_{bulk} - \rho_{fluid}) \tag{19}$$

The calcite appears as the main mineral in *M-N* cross plots with fewer quantities of dolomite matrix, while the *RHOB* - *PHIN* cross plots show the lithology of three main limestone reservoir units as shown in Figure (2) below. By evaluating the results of calculated petrophysical parameters for each unit using equation (1) to (19), the productivity of each delineated reservoir unit is estimated.

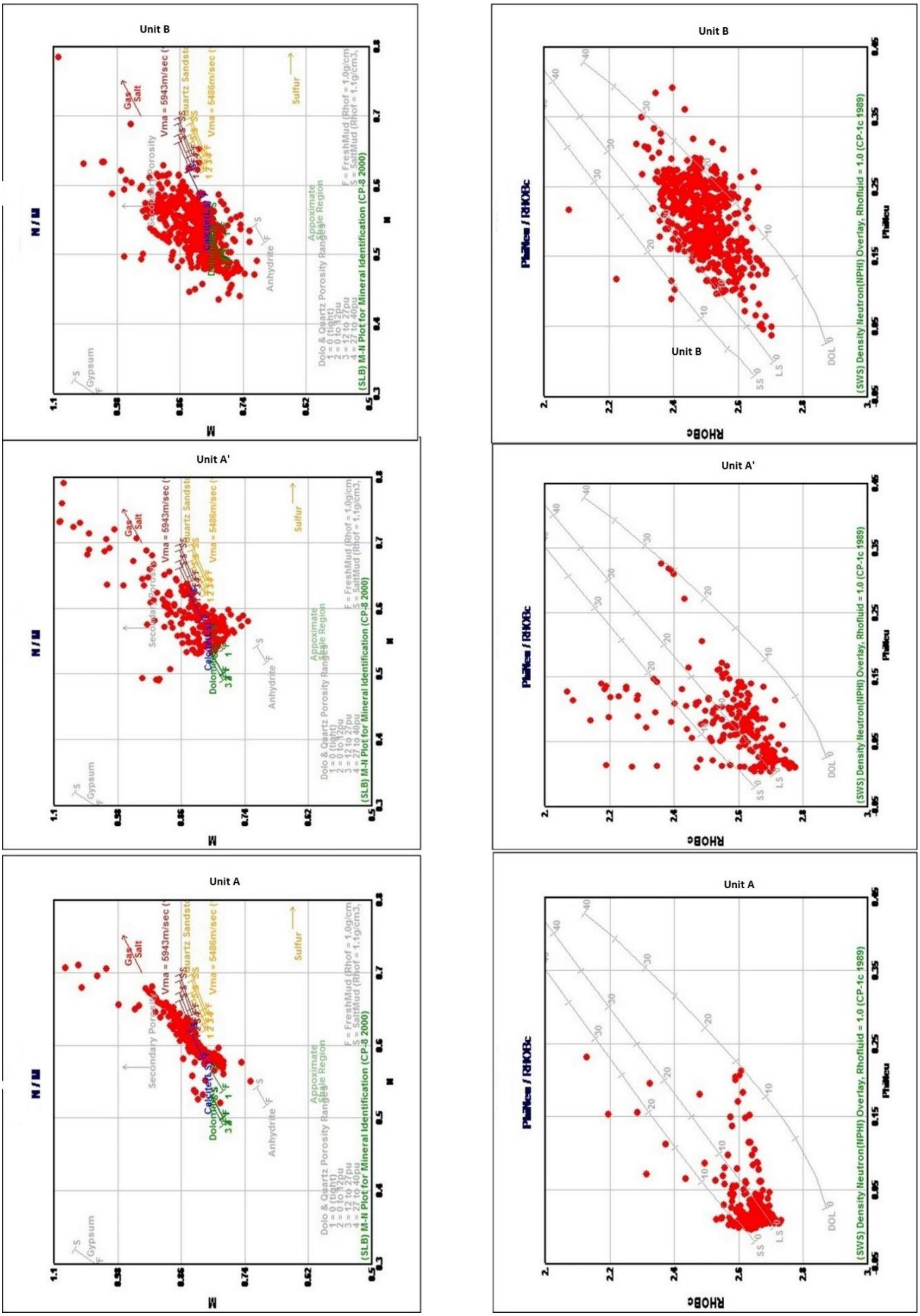

Figure 2: Lithology and mineralogy of three main limestone reservoir units

3. Results and discussion

The methodology of this research, as previously reported, is the quantitative analysis and interpretation of the described main limestone reservoirs in each well. Table (3) and Figure (3) are representing some outputting results of calculated petrophysical parameters for three well in reservoir units A, A' and B, while Figure (4) is presented some computed petrophysical parameters as correlation panels. Table (4) which represents overall average petrophysical properties for three units. Figure (2) shows that the most points of unit 'A' fall between limestone and sandstone line, and only a few points fall between limestone and dolomite line. For unit 'A" most of the points fall on the limestone line, while the most points of unit 'B' fall between limestone and dolomite line. All of these indicate that the dominance of limestone lithology in main limestone reservoir units. Whereas (M-N) cross plot in Figure (2) shows that predominant mineral in main limestone reservoir succession is calcite with some dolomite. This Dolomite resulted in dolomitization processes and formed secondary porosity, especially in unit B. The GR log values display low reading in the reservoir units (A, A' and B) because they are clean limestone formations. The resulting petrophysical properties show that the main limestone reservoir has intermediate to good petrophysical properties. From the analyzed well logs, we note that in all units, the secondary porosity values are shallow. The effective porosity (Φ) is low in unit (A) and has moderate values in the unit (A'), while it has good values in unit 'B.' Net thickness to Gross thickness values are characterized by low values in the unit (A), moderate values in the unit (A'). Good values are characterized in unit (B). The movable hydrocarbon index (MHI) results indicate that unit (B) has MHI less than 0.6, which indicates movable hydrocarbon. The units of the reservoir that represent hydrocarbon zones have hydrocarbon saturation between 20% and more than 70%. These hydrocarbon saturations values indicate that formation water is low, so the hydrocarbon concentration is high, which led to high hydrocarbon production. Hydrocarbon movability into each unit was estimated (see Table 3 and Table 4) and considered acceptable for the production of hydrocarbon.

Table 3. Computed average petrophysical parameters for three main limestone reservoir units

parameter	Well No. 1			Well No. 2			Well No. 3		
	Unit A	Unit A'	Unit B	Unit A	Unit A'	Unit B	Unit A	Unit A'	Unit B
BVW	0.011	0.024	0.065	0.016	0.009	0.037	0.012	0.042	0.088
PHIE	0.031	0.074	0.175	0.037	0.041	0.166	0.024	0.107	0.155
PHISEC	0.009	0.03	0.044	0.009	0.026	0.073	0.004	0.044	0.023
PHIT	0.037	0.084	0.186	0.052	0.044	0.168	0.028	0.114	0.166
SW	0.511	0.485	0.352	0.550	0.514	0.226	0.818	0.537	0.657
SXO	0.852	0.783	0.801	0.788	0.673	0.488	0.95	0.867	0.919
VCL	0.024	0.051	0.041	0.067	0.014	0.008	0.048	0.067	0.135
MHI	0.573	0.573	0.472	0.686	0.701	0.498	0.843	0.597	0.708
MOS	0.337	0.306	0.378	0.238	0.158	0.268	0.132	0.330	0.254
ROS	0.152	0.209	0.270	0.212	0.327	0.505	0.050	0.133	0.089
Di	17.853	21.402	26.657	25.821	24.261	36.026	15.537	15.143	15.370
PhiSon	0.040	0.064	0.137	0.044	0.026	0.102	0.046	0.087	0.137
PhiNeu	0.027	0.073	0.218	0.046	0.035	0.193	0.022	0.104	0.197
PhiDen	0.047	0.075	0.127	0.052	0.036	0.143	0.037	0.105	0.125
Rt	148.6	41.644	25.230	259.942	404.245	52.501	107.162	24.156	6.965
Ro	66.11	15.7	3.55	18	93.6	6.89	16.4	63.1	7.71

Table 4. Overall averages of petrophysical properties for three units.

parameter	Overall Average		
	Unit A	Unit A'	Unit B
BVW	0.013	0.025	0.063333
PHIE	0.030667	0.074	0.165333
PHISEC	0.007333	0.033333	0.046667
PHIT	0.039	0.080667	0.173333
SW	0.626333	0.512	0.411667
SXO	0.863333	0.774333	0.736
VCL	0.046333	0.044	0.061333
MHI	0.700667	0.623667	0.559333
MOS	0.235667	0.264667	0.3
ROS	0.138	0.223	0.288
Di	19.737	20.26867	26.01767
PhiSon	0.043333	0.059	0.125333
PhiNeu	0.031667	0.070667	0.202667
PhiDen	0.045333	0.072	0.131667
Rt	171.9013	156.6817	28.232
Ro	33.50333	57.46667	6.05

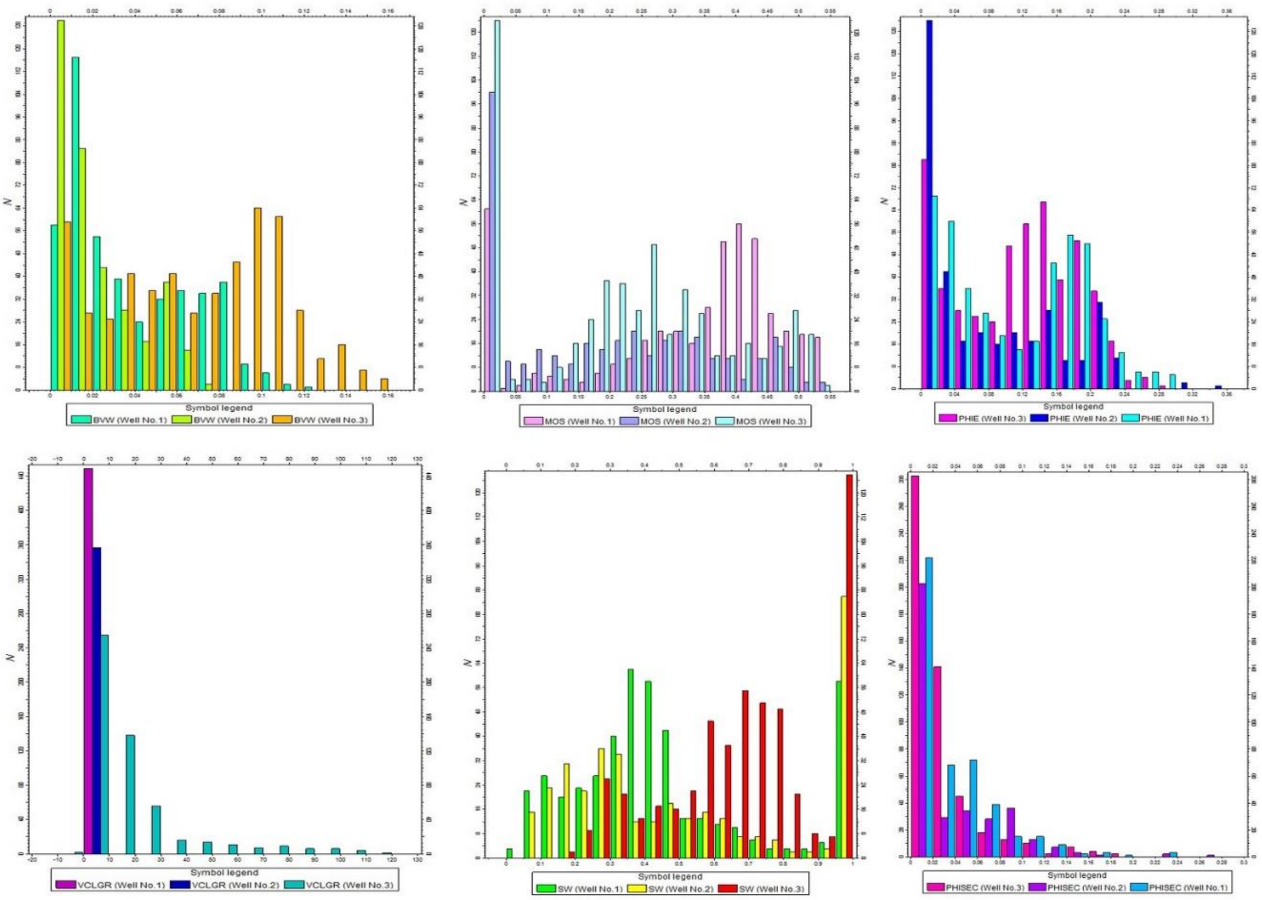

Figure 3. Chart showing relationship between three reservoir units of some computed petrophysical properties

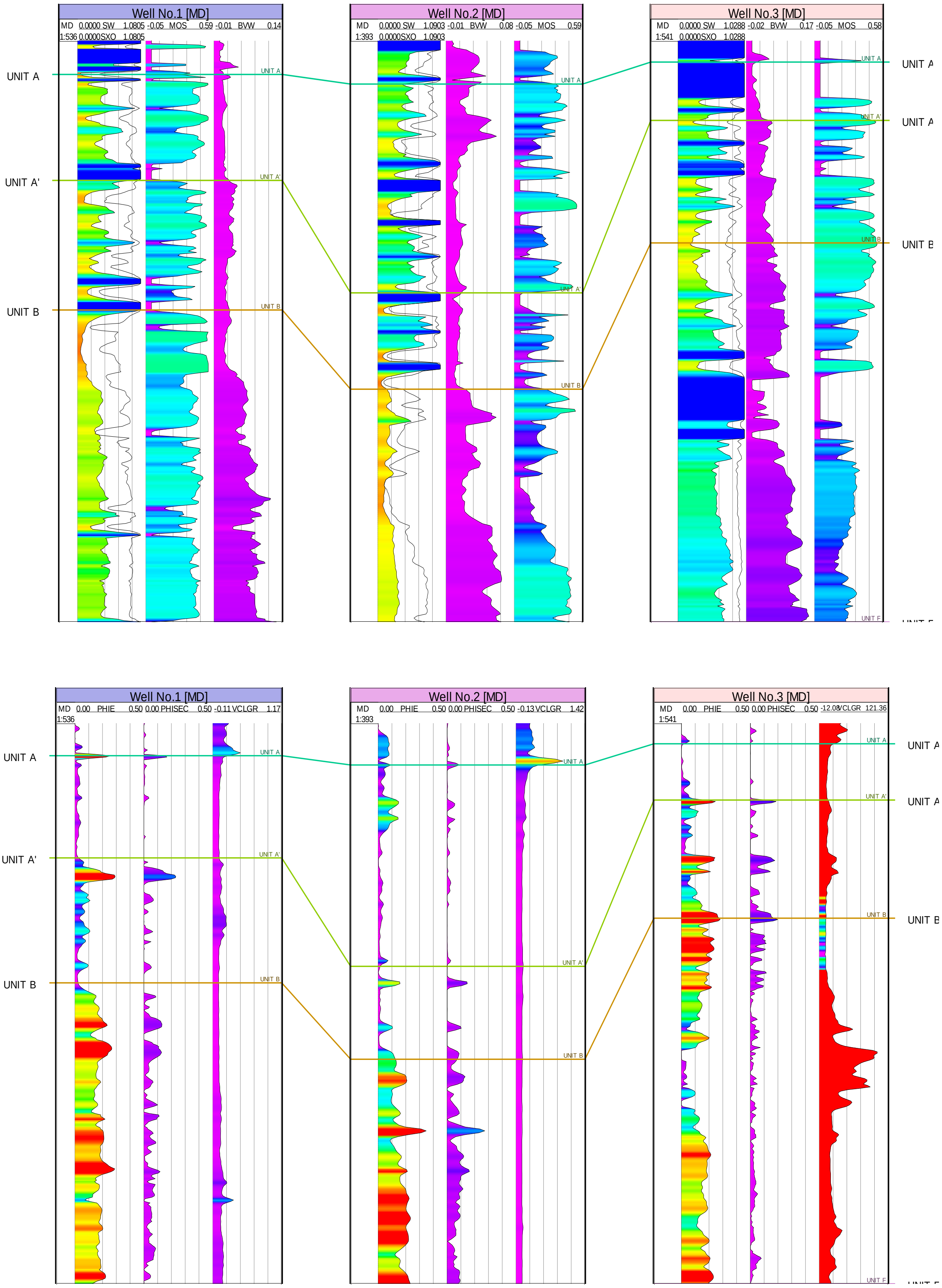

Figure 4. Correlation panel showing some computed petrophysical parameters for three main limestone reservoir units

4. Conclusions

Evaluation of petrophysical properties of the tertiary reservoir was made by analysis and interpretation of well logs. The outcomes illustrated that reservoir unit B has an average porosity of 16%, which indicates a suitable reservoir quality and average hydrocarbon saturation of more than 60%, which led to high hydrocarbon production. These results in additions with the other reservoir parameters such as oil movability index (MHI) values and pay zone thickness indicated that the hydrocarbon potential in this unit is high and acceptable for hydrocarbon production. The statistical analysis indicates that unit (B) has an excellent reservoir property as compared to the unit (A) and unit (A') within the same field.

References

[1] Zaki Bassiouni. “Theory Measurement and Interpretation of Well Logs.” Richardson, TX: Henry L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers, 1994.

[2] Ghassan H. Ali, Yahya J. Tawfeeq, and Mohammed Y. Najmuldeen, "Comparative estimation of water saturation in a carbonate reservoir: A case study of northern Iraq," *Periodicals of Engineering and Natural Sciences*, Vol. 7, No. 4, December 2019, pp.1743-1754, 2019.

[3] Nnaemeka Ezekwe. “Petroleum Reservoir Engineering Practice.” Upper Saddle River, NJ: Prentice-Hall, 2010.

[4] Schlumberger. “Log Interpretation Principles / Applications.” Houston: Schlumberger Wireline and Testing, 198 p, 1989.

[5] Wyllie, M.R.J., Gregory, A.R. and Gardner, L.W. “Elastic Wave Velocities in Heterogeneous and Porous Media.” Geophysics, 21, 41-70, 1956.

[6] Djebbar Tiab, Erle C. Donaldson. “Petrophysics: Theory and Practice of Measuring Reservoir Rock and Fluid Transport Properties.” Third edition. Gulf Professional Publishing, 2011.

[7] George Asquith and Daniel Krygowski. “Basic Well Log Analysis,” Second Edition, Tulsa, Oklahoma: The American Association of Petroleum Geologists,2004.

[8] G. M. Hamada et. Al, “Uncertainty analysis of Archie parameters determination techniques in carbonate reservoirs” Springer, 2013.

[9] Schlumberger. “Log Interpretation Manual/Applications”. Houston: Schlumberger Well Series, Inc., Ridgefield, Vol. II, 1974.

[10] Schlumberger. Oilfield Glossary.Retrieved from: http://www.glossary.oilfield.slb.com.

[11] Andy May, “Net Pay Cutoffs from Capillary Pressure,” Search and Discovery Article #120008,2009.