Reservoir Evaluation by Well-Logging of the Al-Raja Field, Alif Member, Marib Shabwah (Sab'atayn) Basin, Republic of Yemen

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Abstract— This study evaluates the hydrocarbon reservoir in Al-Raja field through the well Al-Raja#41 (RJ-41), which is formed within Alif Formation of the Upper Jurassic age in Marib-Shabwah basin, Republic of Yemen. We analyzed and interpreted the well log data to determine important petrophysics parameters. We identified the lithology of the reservoir by applying Interactive Petrophysics (IP) software. The average values of the shale volume, effective porosity, water saturation, and the hydrocarbon saturation of the reservoir in the Al-Raja field are estimated as 21.5%, 14.5%, 23.5%, and 76.5%, respectively. Our results indicate that the hydrocarbon present in the reservoir is gas and the reservoir is dominated by sandstone, but minor amounts of shale are also present.

Index Terms— Alif, Al-Raja, Petrophysics, Reservoir Evaluation, Sab'atayn, Well Logging, Republic of Yemen.

1 Introduction

WELL logging analysis is one of the most common techniques used in open and cased holes to detect hydrocarbon reservoirs and to evaluate them. This technique has an effective role to estimate the hydrocarbon reservoir characteristics such as porosity, permeability, fluid saturation, and shale volume estimation. In addition, well logging has significance in determining lithology, thickness, depth of the reservoir, hydrocarbon reserve, gas-water contact (GWC), gas-oil contact (GOC), oil-water contact (OWC), and the productive zones, etc [1]–[4],.

1.1 Location of the Study Field

Al-Raja (RJ) Field is a gas condensate field located in the Marib Al-Jawf sector of the Marib Shabwah (also called Sab'atayn) Basin, Yemen (Figure 1(a)). RJ field is situated on the boundary between Block-18 and Block-5 [5],[6] (Figure 1(b)), exactly between (618000-638000 E) and (1716000-1730000 N). This field is considered one of the largest fields of block-18, with a 2D area of 15284.814 acres (61.855 km^2). This field will be studied in this work through Al-Raja#41 borehole which is situated in 630320.976 E - 1724591.040 N (15° 35' 44.6676" - 46° 12' 56.002") (Figure 1(c)) [7]. Alif Sandstone gas condensate reservoir which is one of the members of the Sab'atayn formation is the main productive zone in Al-Raja Field. It is bounded by major faults from South, West, and North, and on the Southeast by GWC. The structure of the reservoir extends to the east across Block-18 crossing the boundary into the adjacent block, Jannah Block-5 (Figure. 1b) [6].

1.2 Objective of this Study

This study aims to evaluate the hydrocarbon reservoirs formed in the Upper Jurassic age in Marib-Shabwah Basin through Al-Raja Field in block-18 by using well logging analysis. The borehole mentioned in this study will be studied by the means of Schlumberger IP software (Interactive Petrophysics ™). As a result, important petrophysics parameters such as porosity, shale volume, the existing fluid saturations (hydrocarbon and water) will be estimated. This task will be achieved in parallel with the identification of the lithology.

2 Geological Setting

Several geological and geophysical studies have been carried in Yemen since the 1980's for hydrocarbon exploration and production. The hydrocarbons are mainly produced from two rift basins in Yemen: Marib-Shabwah (Sab'atayn) Basin in western Yemen and Sayun–Masila Basin in eastern Yemen [8]. A U.S. Geological Survey report [9] and another study [10] explains the geologic evolution and the petroleum system in Marib-Shabwah Basin. Moreover, tectonics of Yemen is formed mainly by two significant tectonic periods. The first major tectonic activity occurred in the period between the Late Jurassic to Early Cretaceous [11]. The stratigraphy and evolution of the Marib-Shabwah Basin during the Mesozoic rifting have a great role in the formation of the petroleum system in the basin [9], [12], [13]. According to seismic studies, this Mesozoic rifting is divided into three main periods: pre-rift, syn-rift, and post-rift. The Sayun–Masila and Marib-Shabwah Basins developed as a result of these first tectonic activities. They generally include thousands of meters of Jurassic deposits. On the other hand, the second event occurred in the Cenozoic period and led to the opening of the Red Sea and the Gulf of Aden, the formation of new sedimentary basins in Yemen and the reactivation of the basins formed in the Mesozoic era [10], [14], [15].

The stratigraphic column of the Marib-Shabwah Basin - which contains Al-Raja Field- has sequences from the middle Jurassic to Cretaceous periods [16] lying over the basement rocks [17], is given in Figure 2. The basement rocks are mostly Precambrian age [18]. It is worth noting that an over 2.5 km thick Mesozoic sequence dominates the stratigraphic column [17]. The Kuhlan Formation is one of the first Mesozoic formations, which deposited during the Middle Jurassic. It is recorded in the Sab'atayn Basin only in the subsurface section. It is conformably overlain by the Amran group and they generally overlie the basement rocks unconformably [6], [17], [19] (Figure 2).

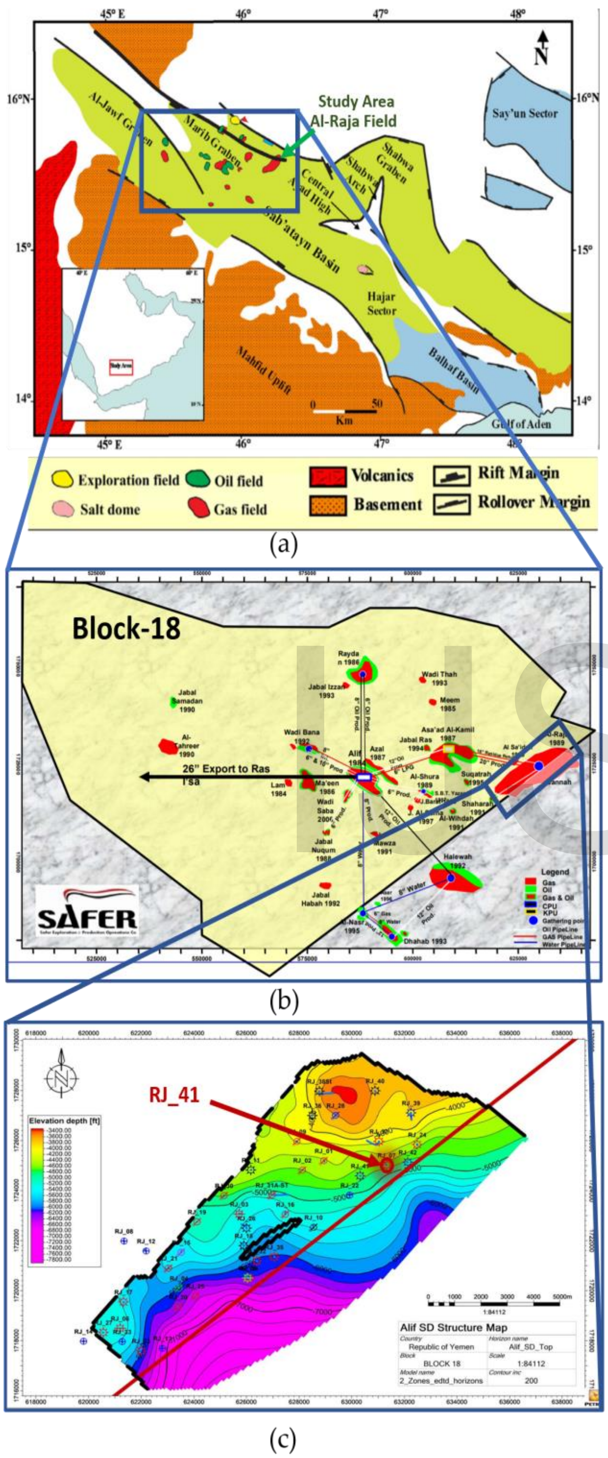

Figure 1. Maps showing (a) the location of Block-18 within Marib-Shabwah basin, Western Yemen [16], (b) the location of Al-Raja Field within Block-18 [5] and (c) the structure of Alif Member and the location of the study well within Al-Raja field [7].

The sediments of Amran Group were first described by Lamare et al. in 1930 and he called them the Amran Series according to [20]. This group was subdivided in 1964 by Beydoun [21] from up to down into Naifa, Sab'atayn, Madbi, and Shuqra.

Many researchers studied the hydrocarbon potential of the Marib-Shabwah Basin through the evaluation of the characteristics of several formations belonging to the upper Jurassic part of the Amran Group using well log data and/or core analysis concluding that the Sab'atayn Formation is a reservoir rock, and Madbi Formation is a source rock [16], [17], [22]–[27]. In summary, the evaluation results of most of the previous studies show that the Marib-Shabwah Basin is a promising basin.

2.1 Alif Member

In 1992, Yemen Hunt Oil Company (YHOC) first described this member as the "Alif Formation", and Yemen Stratigraphic Commission amended it into "Alif Member" in 1997 [20]. This member is a part of Sab'atayn Formation besides other members: Seen, Safir, and Yah [28]. The age of Alif Member is dated as Middle to Late Tithonian in Upper Jurassic. It is generally conformably underlain by the Seen Member, and it underlies the cap rocks (Safir Member) of Sab'atayn Formation unconformably [20]. The estimated top and bottom depths of the penetrated Alif Member through borehole #41 are 7670 MD and 8136 MD, respectively [38]. Thus, the thickness of the Alif Member in borehole #41 in the Al-raja Field is 466 ft. The Alif Member is predominantly composed of sandstones, thin mudstone with interbedded evaporates, local anhydrite lenses, and minor dolomitic limestones [28]. The Alif Member covers more than 90% of the recoverable hydrocarbon of the Marib-Shabwah Basin [25], [27]. Consequently, it is considered the main hydrocarbon prolific reservoir formation of its Marib-Aljawf Shabwah sector [20], [22], [25], [27], [28].

3 Data & Method

Technologically, one of the best tools of petroleum engineering is the well-logging analysis that can be carried out by computer software [29]. In this study, the Alif Member which belongs to the Upper Jurassic Sab'atayn Formation will be evaluated through well log tools that have been used to obtain data from the selected borehole: Al-Raja#41 (Table 1) by the Schlumberger Interactive Petrophysics (IP) software version 3.5.

Interactive Petrophysics ™ (IP™) is a software application which includes data correction and interpretation steps to evaluate the reservoir characteristics. This version of IP software was developed in Scotland by the Senergy Ltd. This IP software contains subroutines that have all the equations, formulas, relations, several cross plots, and correction environments that are used to process the data and evaluate the formation to achieve the main purpose of the evaluation which is the estimation the hydrocarbon zones in the study area [29].

4 Input and Correction of Well Log Data

The digital raw data (Table 1) is loaded into the IP software as a first step of the work (Figure 3). In this study, the log data was prepared in LAS format file. The environmental corrections of Schlumberger company have been applied to the data of this study (Table 1) in order to get rid of the effects of some factors like mud cake, mud weight, borehole fluids and diameter, and shale content on the readings of the used tools [29].

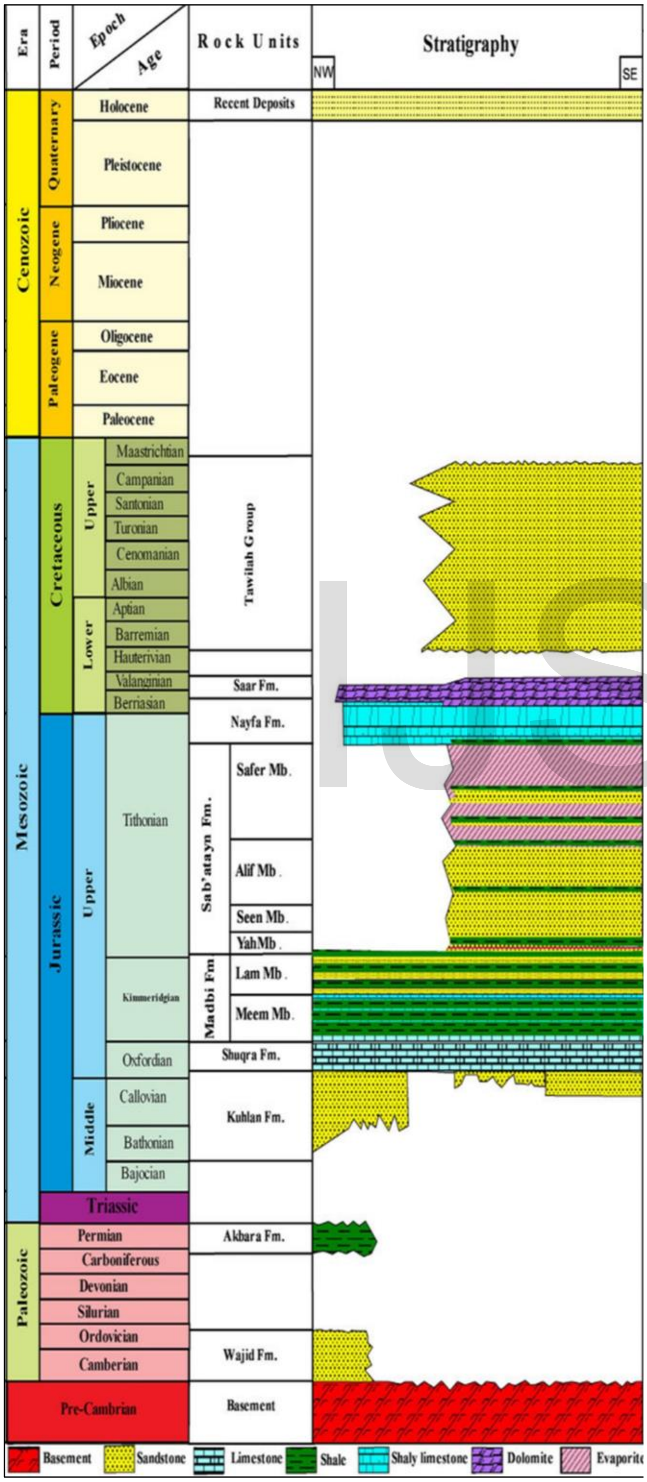

Figure 2. Stratigraphy of the Marib-Shabwah Basin [16].

5 GEOTHERMAL GRADIENT & FORMATION TEMPERATURE

The geothermal gradient can provide a continuous curve of temperature and by this, the formation temperature can be determined [29]. In this study, the geothermal gradient calculated by IP software based on the following equation [30]:

$$GG = \frac{(BHtemp - Stemp)}{TD} \quad (1)$$

Then, formation temperature can be determined from the Formation Temperature Chart of Schlumberger [31] or from the following formula [30]:

$$\mathrm{FT} = \mathrm{Stemp} + \mathrm{GG} \times \mathrm{FD} \quad (2)$$

Where: $BHtemp$ = bottom hole temperature expressed in °F or °C, $Stemp$ = surface temperature expressed in °F or °C, TD= total depth expressed in ft or m, and GG= geothermal gradient.

TABLE 1
THE INPUT WELL LOGS DATA (RJ#41)

Log Data	Abbreviation	Unit
Depth	D	ft
Caliper log	CAL	in
Bit Size	B. S	in
Gamma Ray Log	GR	API
Deep Induction Log	ILD	Ω.m
Medium Induction Log	ILM	Ω.m
Spherically Focused Log	SFLU	Ω.m
Temperature	HTEM	°F
Neutron Porosity Log	NPHI	%
Bulk Density	RHOZ	gm/cc
Bulk Density Correction	HDRA	gm/cc
Photoelectric Factor	PEF	B/E

6 PARAMETER CALCULATION & FORMATION EVALUATION

6.1 Clay Volume

The Shale, which generally expresses clay materials, affects not only well-logging readings but also the production properties of the reservoir [2]. In this study, Gamma-ray (Gr), neutron (NPHI), and deep resistivity (ILD) curves were used as single clay indicators, whereas density with neutron curves, were used as double clay indicators [29], [32].

6.1.1 Single- Log Indicators

Single clay indicators method is one of two methods to calculate and estimate shale volume in the reservoir evaluation process. According to this technique, Gamma-ray (Gr), neutron (NPHI), deep resistivity (ILD) curves can be used individually to estimate shale volume in the reservoir [32].

6.1.1.1 Gamma- Ray

GR tool is considered one of the best indicators used for detecting, differentiating the shale zones from non-shale zones, and determine the volume of shale [33]. This tool has a standard unit called API (American Petroleum Institute) [34].

The index of Gamma-ray is determined as follows (Schlumberger, 1972 as cited in [18]):

$$GR_I \leq \frac{GR_{log}-GR_{cln}}{GR_{cl}-GR_{cln}} = X \quad (3)$$

Where: GR_I= the index of shale, GR_{cln}= the minimum value of the gamma-ray in front of the clean formation (API), GR_{cl}= the maximum value of the gamma-ray facing the shale formation (API), GR_{log}= the reading of the gamma-ray in the zone of interest (API).

6.1.1.2 Neutron Log indicator

The neutron log is used to identify the lithology characteristics and to detect and calculate shale volume in the reservoir rocks. The response of the neutron log is principally a function of the quantity of Hydrogen existing in the formation. The gas reservoir can be detected through this log by comparison to other porosity logs or to porosity measured in the lab [35]. The shale volume is calculated in this study through the neutron log indicator by the means of IP software as follows [29]:

$$V_{CLNT} = \sqrt{\frac{N_{log}}{N_{cl}} \times \frac{(N_{log}-N_{cln})}{(N_{cl}-N_{cln})}} \quad (4)$$

Where: V_{CLNT}= calculated shale volume obtained from this method, N_{cln}= the reading of the neutron log in front of the clean zone, N_{cl}= the reading of the neutron log facing the shale zone and N_{log}= the reading of neutron log in front of the zone of interest.

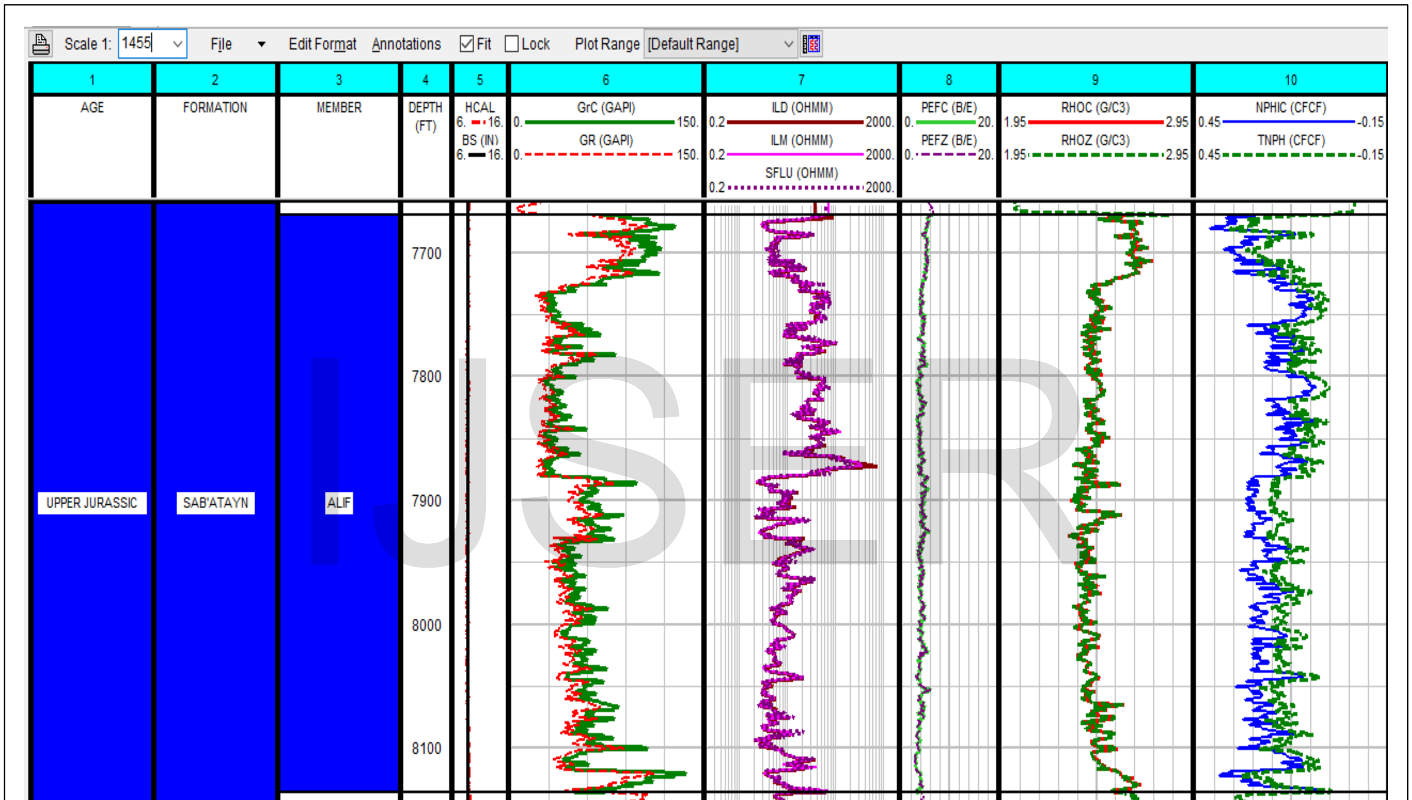

Figure 3. The raw and corrected data by Schlumberger IP Software (Interactive Petrophysics).

6.1.1.3 Resistivity log indicator

Shale content can be detected and calculated through the indicator of resistivity log. The existence of shale causes the diminution of the resistivity values. As a result, the hydrocarbon content can be differentiated from water content by taking advantage of the contrast of resistivity values [18].

The shale volume is calculated in this study through the clay single indicator of resistivity log V_{CLRT} by the means of IP software as follows [29]:

$$X = \frac{R_{cl}}{R_t} \times \left(\frac{R_{cln}-R_t}{R_{cln}-R_{cl}}\right) \quad (5)$$

$$V_{CLRT}\,(\%) = \begin{cases} 0.5 \times (2 \times X)^{0.67\times(X+1)} & , R_t > 2 \times R_{CL} \\ X & , \text{the other cases} \end{cases}$$

(6)

Where: R_t= the reading of resistivity log in front of the zone of interest (Ω.m), R_{cln}= the reading of the neutron log in front of the clean zone (Ω.m), R_{cl}= the reading of the neutron log facing the shale zone (Ω.m) and V_{CLRT} = the shale volume determined by the resistivity log through IP software (%).

6.1.2 Double shale content indicators

It simply means the combination of the readings of two tools together in order to obtain the correct reservoir shale volume ratio [32]. The double indicator used in this study was the density and neutron curves as given in Figure 4.

By applying the IP software, the shale volume (V_{cl}) chosen in this study will be equal to the minimum value obtained from the following clay indicators: gamma-ray, neutron, density, and density – neutron as given in Figure

4.

6.2 Effective Porosity

Porosity is one of the most important petrophysics properties in the reservoir evaluation that enters effectively in the calculations of the fluid saturations [29], [36]. The effective porosity is determined basically according to how much the pores of the rocks are interconnected which forms channels. These channels make the fluids movement through the lithologic contents easier. Contrary to the shale rocks, the effective porosity of sandstone is good [35]. The effective porosities are calculated through the following equation [33]:

$$PHIE = PHIT \times (1 - V_{sh}) \tag{7}$$

Where: $PHIE$= The effective porosity (%), $PHIT$= The total porosity (%) and V_{sh}= shale Volume (%).

The porosity curves (total and effective) have been estimated by Schlumberger IP software as given in Figure 6.

6.3 Water Saturation

Water saturation is defined as the rate of the volume of pore containing water to the total volume of the formation in percent [29].

It should be noted that in this study the Indonesian equation was applied by IP software as the main equation for the calculation of water saturation.

$$\frac{1}{\sqrt{\mathrm{Resis_t}}} = \left(\sqrt{\frac{(\mathrm{Phi})^m}{a(\mathrm{Resis_W})}} + \frac{(\mathrm{V_{sh}})^{\left(1-\frac{\mathrm{V_{sh}}}{2}\right)}}{\sqrt{\mathrm{Resis_{sh}}}} \right) (\mathrm{S_W})^{\left(\frac{n}{2}\right)} \tag{8}$$

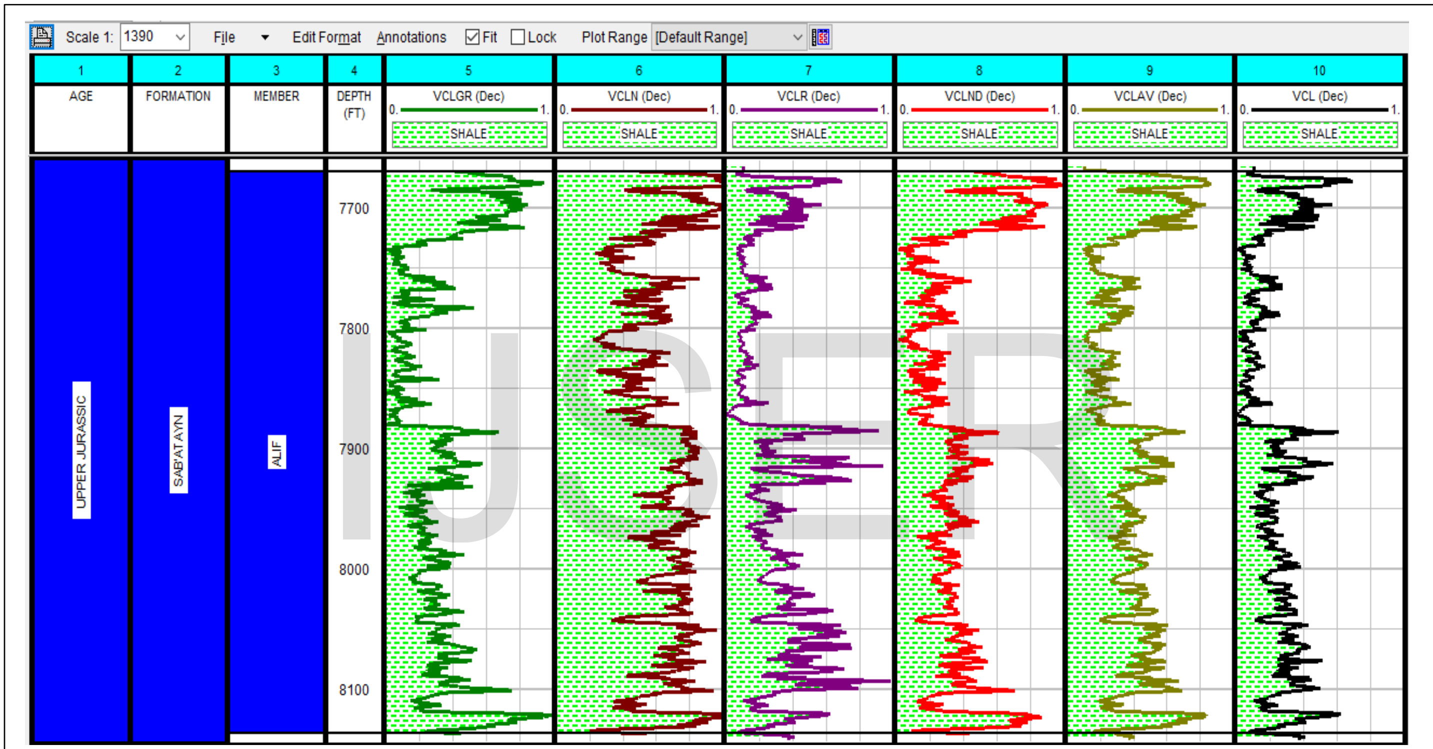

Figure 4. Clay volume of Alif Member (7670 ft- 8136 ft) through Al-Raja #41 well determined using different methods and obtained by IP software.

Where: Phi= The porosity of the formation (%), $PHIT$= The total porosity of the formation (%), $Resis_W$= The resistivity of formation water (Ω.m), S_W= The uninvaded zone water saturation (%), $Resis_{tr}$= the uninvaded zone true resistivity (Ω.m), $Resis_{sh}$= Shale zone resistivity (Ω.m), V_{sh}= Shale volume (%), a= Tortuosity factor; its value varies according to the formation components. If it is non-consolidated sand a=0.62, while it is 0.81 if the formation is consolidated sand, and 1 in carbonate, n = saturation exponent whose value is between 1.8 and 2.5, commonly taken as 2 which is the case in this study, m= cementation factor. Its value varies according to the formation type (for consolidated sands and carbonates m=2 like in this study, but m=2.15 for non-consolidated sands.

6.3.1 Bulk Volume Water (BVW)

The Bulk Volume Water represents the water amount existing in the rock. BVW curve is obtained from the product of multiplying the effective porosity with water saturation. It is expressed in the following formula [29]:

$$BVW = S_W \times PHIE \tag{9}$$

6.4 Hydrocarbon Saturation (S_{hyd})

The hydrocarbon total saturation in both flushed and uninvaded zones was calculated by the means of Schlumberger IP software according to the formula below [33]:

$$S_{hyd} = 1 - S_W \tag{10}$$

6.5 Neutron-Density Cross-plot

This study indicates that the lithology of Alif Member is dominated by sandstone with the presence of minor amounts of shale, as seen in Figure 6. The density (RHOC) - neutron (NPHIC) cross-plot (Figure 5) of the Alif Member in the study well shows the plotted points that represent the lithology of Alif member. The reciprocal influence of gas and shale resulted in some change in the distribution of the plotted points. Some data points are pulled down to the right lower part of the plot due to shale effects. Similarly, some data points were pulled up towards the plot's upper left part because of gas effects, which explains the presence of some points near the Limestone and Dolomite lines. The Alif Member consists of intercalated layers of different rocks. So, the existence of Calcite and Dolomite is inevitable, but their amounts are much less and may only be present as cement. That's why we only mention the sandstone and shale which make the main lithology, which is also corroborated by the Yemeni operating company SEPOC [6] as shown in Figure 2.

6.6 Cut-off and Summation

The module of "Cut-offs and Summation" presented by IP software enables the definition of the criteria as well as the zones of cut-off and the determination of pay flag and reservoir flag. The cut-off values were set according to the SEPOC conditions in the study area as follows: PHI ≥ 8%,V_{sh} ≤ 40% and S_W ≤ 55% [7]. This study determined the net pay of Alif Member within the study borehole as seen in Figure 6.

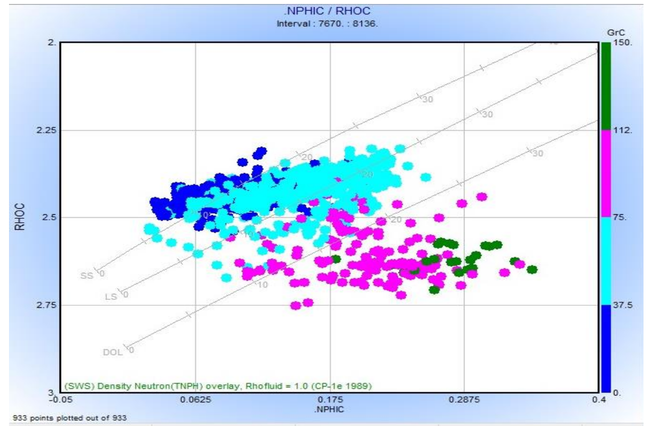

Figure 5. N-D Cross-plot obtained by IP software of the Alif Member through the studied well in the Al-Raja field.

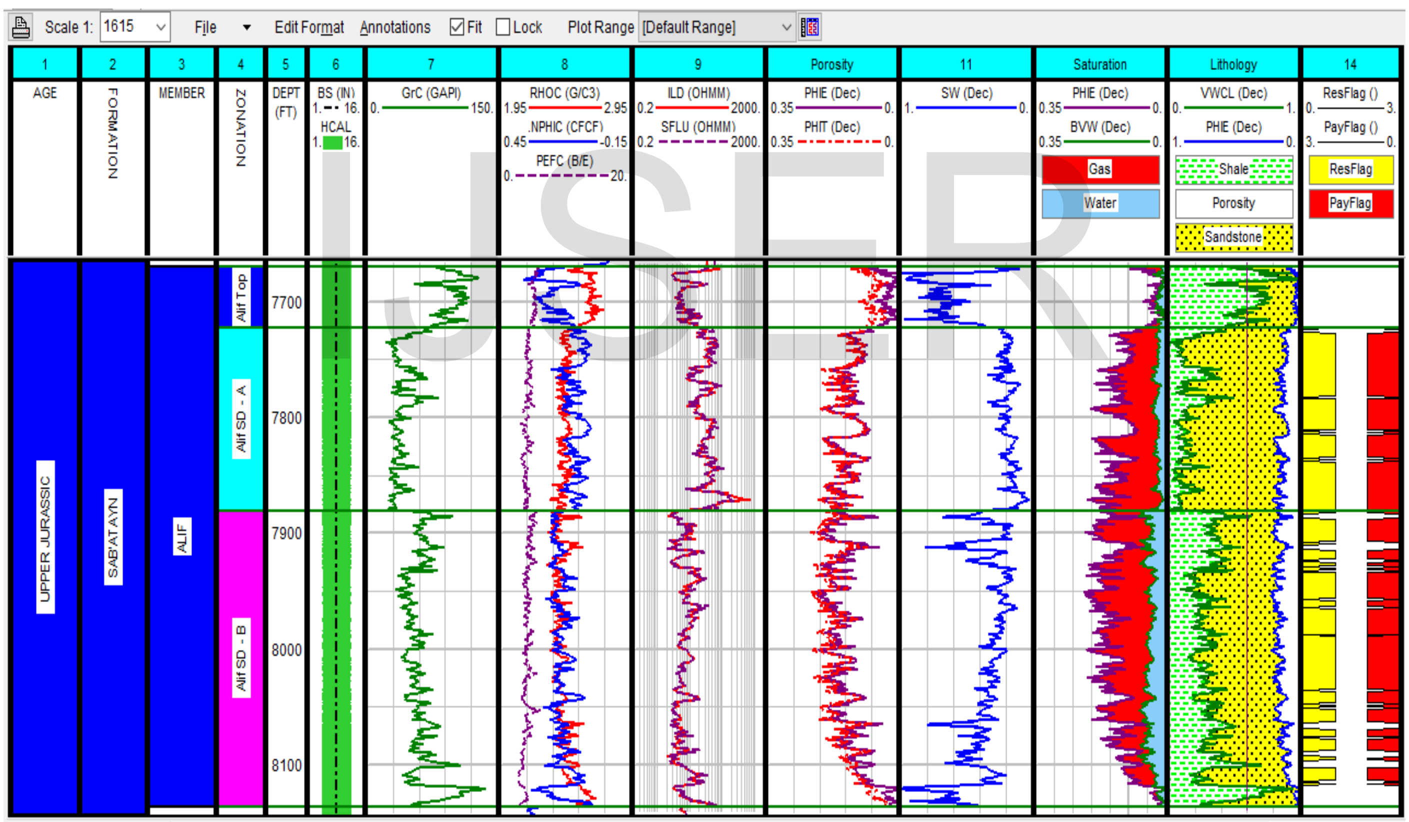

Figure 6. Shows the obtained litho-saturation and the corrected log dataset of Alif Member through Al-Raja #41 well by IP software.

Figure 6 shows the dataset plot of the borehole Rj-41 created to evaluate the saturation of hydrocarbons quantitively in Al-Raja Field through petrophysical parameters and based on the well logging data. This plot consists of a certain number of tracks. The first, second, third, and fourth tracks display age, formation name, member name, and the zonation of the targeted formation (Alif Member), respectively vs the depth which is represented in the fifth track. The sixth track displays the corrected Gamma-Ray log. The seventh track represents the corrected logs of the density (RHOC), neutron (NPHIC), and Formation Photoelectric Factor (PEFC) logs while the eighth track represents the values of resistivity logs for both deep or invaded zone (ILD) and flushed zone (SFLU). The next track shows the values of total porosity (PHIT) and effective porosity (PHIE) curves. Then, the tenth and the eleventh are the fluid saturation curves (water and gas). The next track displays the lithology of the Alif Member while the last track displays the reservoir and net pay flag in the Alif Member.

We divide the Alif Sandstone into two zones: Alif Sandstone A and B and they are given in Figure 6. The low Neutron and Density readings indicate the presence of hydrocarbon in zones A and B. Note that the quality of Alif Sandstone A is better than B in terms of petrophysical parameters as shown in Figure 6. There are different factors, in our case, that could impact the values of the Neutron and Density that cause their high readings. One of the highly probable factors making the values high in some intervals is the shale content present in the Alif Member.

7 Results & Conclusions

As a result of this study, the average values of the important petrophysics parameters (shale volume, effective porosity, water saturation, and hydrocarbon saturation) of the Alif Member were estimated to evaluate the reservoir of Alif Member through the Al-Raja Field by using well log data. The average shale volume was estimated as 21.5%, and the estimated average porosity is 14.5%, while the average water saturation and the average hydrocarbon saturation were calculated as 23.5% and 76.5%, respectively. The observed hydrocarbon in the reservoir is gas. The productive zone of the Al-Raja Field is Alif Sandstone gas condensate reservoir which is a member of the Sab'atayn Formation. The total thickness of Alif Member in RJ-41 is 466 ft which was penetrated totally in this well. Besides, the estimates of the reservoir thickness and the net pay thickness are 341.5 ft. and 340.5 ft., respectively. The productive zones of the Alif reservoir are divided into two zones according to their petrophysical characteristics: Alif Sandstone A and B, as given in Figure 6. This study indicates that the quality of the Alif SD-A zone is better than B in terms of petrophysical parameters. The obtained results indicate that sandstone is the dominant lithology throughout the reservoir, whereas minor amounts of shale are also present. In conclusion. Al-Raja is a promising field due to its good potential and production characteristics.

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