Petrophysical Evaluation of the Lower Rudeis Formation in Shukheir Bay Field, Gulf of Suez, Egypt Using Open-Hole Well-Logs

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Abstract
The Shukheir Bay Field is located in the northern part of the Shukheir Marine Concession towards the southern part of the Gulf of Suez, about 300 km southeast of Cairo. It covers a shallow offshore water area of 5 km² with a total area of 22.5 km². The Rudeis sands in the Miocene sequence, which are widely distributed in the area, represent the main reservoir in the Shukheir Bay field. This study focuses on the clastic unit in the Lower Rudeis Formation usually referred to as the Lower Rudeis Sandstone. The petrophysical evaluation of this sand zone was conducted using a complete set of open-hole well-logs in three wells penetrating the formation. The lithologic composition is distinguished and identified as sand intercalated with shale, using tri and dia porosity cross plots. The shale distribution has been studied in both ways, amount and type. The amount is found to be relatively low to moderate, and the type is found to be mainly dispersed shale as indicated by the Thomas-Stieber model and the dispersed-laminated plot. The net-pay thickness also has a good value ranging from 39 m to about 42 m with high porosity (21%) and good oil saturation (76-94%). Both the vertical and lateral distributions of the petrophysical parameters are clarified, using the proper types of graphs. This research recommends drilling development wells in the central part of the study area, in addition to increase the exploration process towards the southwestern part.

Keywords: Lower Rudeis; Petrophysics; Well-log analysis; Shukheir Bay Field; Gulf of Suez

1. Introduction
The formation evaluation process is an essential factor when describing the features of the hydrocarbon reservoirs. Thus, well log is established as the main tool to describe the petrophysical characteristics including lithology, porosity, water saturation, and permeability (Albeyati et al., 2021). These petrophysical properties are very important to understand the factors affecting the quality of the oil reservoir and the quantity of its production (Al-Baldawi, 2021). Thus, the evaluation phase passes through both qualitative and quantitative processes. Qualitative phase includes determination of porous zone, sand and shale base line, water bearing formation and hydrocarbon depletion zone. Quantitative analysis includes calculation of formation temperature, mud filtrate resistivity, shale volume, porosity, and fluid saturations. Cross plots are also used to exhibit the effects of logs react to porosity and lithology and they give a visual vision into the type of lithology mixtures (Liu, 2017).

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Despite the enormous studies published about the hydrocarbon potentialities in the Gulf of Suez, the ones that focus on the Shukheir Bay Field are scarce. However, since 1970, the General Petroleum Company is running a comprehensive exploration program, where more than fifteen wells were drilled along the whole Shukheir Concession (Ibrahim, 1988). Shukheir Bay-1 (SHB-1) well is the first in the Shukheir Bay Area. Total Company drilled this well in March 1980. The main target was to detect and evaluate the Miocene Belayim and Lower Rudeis sandstones with a secondary objective as the Pre-Miocene Nubia sandstone. However, 94 feet of the Miocene Rudeis Formation were found to be oil-bearing. Since then, the exploration and development process have continued but at a very slow rate. In 2009, the Egyptian National Petroleum Company announced that the production from one of the wells has increased 1600 Bbl/d from the Lower Rudeis sandstone. During the month of October 2012, the Shukheir Bay field produced oil through two wells with a combined daily rate of about 410 Bbl/d. In 2016, the production declined to be about 250 Bbl/d. Thus, the main target of this study is to determine through integrating well-log data to evaluate the clastic part within the Lower Rudeis Formation that may help for diagnosing, analyzing and mitigating the rapid production declination, locating exploratory drilling opportunities on the Shukheir Bay field, and reduce financial losses by proposing a development direction for the field.

2. Study Area

The Gulf of Suez length is about 300 km. The width of the whole rift basin (the Clysmic rift) reaches about 50 km at its northern end, and about 90 km at its connection with the Red Sea (Robson, 1971). Shukheir Bay Field is located towards the north of the Shukheir-Marine Concession towards the southern part of the Gulf, it covers a shallow offshore water area of 5 km² with a total area of 22.5 km² (Fig. 1).

Fig. 1. Location map of the study area (Modified after Energy Egypt Online Map Store)

The Suez Gulf represents a typical interior basin (Kingston et al., 1983). The representative stratigraphy for Shukheir Bay Field represents a normal central Gulf of Suez stratigraphic succession (Fig. 2) that shows the three major depositional and tectonic stages (pre-rift, syn-rift & post-rift stages). Generally, this sequence is described here below in terms of Miocene and Pre-Miocene. The Miocene
is unconformably overlined by the relatively thin Pliocene - Recent deposits (Ibrahim, M. 1988). The stratigraphic units recorded in this area are given with a description of their general characteristics:

- **Nubia sandstone**: it is made up of quartzose sands deposited as channelized fluvial sands separated by continental kaolinitic shales.
- **Raha Sands**: characterized by glauconite, vegetal debris and marine shales.
- **Matulla Formation**: is mainly composed of shale and argillaceous limestone.
- **Sudr Formation**: is mainly composed of chalky limestone in the uppermost part and cherty brown limestone in the lower part with shale interbeds.
- **Esna Shale**: it is mainly shale.
- **Thebes Formation**: it is mainly cherty limestone with some streaks of shale.
- **Nukhul Formation**: it is unconformably overlies the Eocene sediments and composed of argillaceous limestone and shale with thin streaks of sandstone.
- **Rudeis Formation**: The Lower Rudeis has a widely varied lithology composed of limestone, sandstone, and shale. The Upper and Lower Rudeis sections are separated by an unconformity marking the Intra-Rudeis tectonic event. The Upper Rudeis is composed of shale, marl and argillaceous limestone.
- **Kareem Formation**: unconformably overlies the Upper Rudeis and consists primarily of shale, argillaceous limestone, sandstone and anhydrite.
- **The Belayim Formation**: it is composed primarily of evaporites with thin interbedded shales.
- **The area was subjected to renewed tectonic activity resulting in variable thicknesses of Zeit and South Gharib formations.**

As referred, The Rudies Formation consisting of two parts, the lower part termed the Upper Rudeis Formation, and the upper part termed Lower Rudeis formation (EGPC, 1996; Alsharhan, 2003). Two clastics zones have been recorded in the Upper Rudeis Formation, and also two in the Lower Rudeis Formation including the lower Yusr tight-sand zone. However, we commonly use the term Lower
Rudeis Sandstone (L.RUD-SD) in this study to indicate the first clastic zone since the Yusr tight-sand isn’t suitable for this study.

3. Materials and Methods

There are two types of data we need to evaluate the petrophysical properties, the first one is the log records of the studied wells, and the second one is the rock cuttings and samples (Kennedy, 2015). However, this study has been carried out using a variety of open-hole well log data from three different wells to calculate the different petrophysical parameters. The log files obtained for this study required extensive preparation of individual records prior to importing it into the log analysis software, such as defining units, adjusting formatting and spacing, and provide the standard program value for the null data. Processing steps varied according to quality of data, but the main processes include:

- Data verification
- Depth matching, shifting
- Intelligent curve splicing, merging, composing
- Sonic and density curve editing
- Curve mnemonics and unit’s standardization
- Gamma ray normalization
- Computed curve generation
- Cased hole data normalization
- Format and media conversion

Also, the wells environmental different parameters such as temperature, pressure effects, mud weight, salinity and resistivity, resistivity tools corrections, gamma-ray log corrections for borehole size and density-neutron and sonic logs corrections for borehole diameter and rugosity, mud cake thickness, borehole fluid and format ion fluids were conducted as needed. Many calculations were used to determine the shale content and mode of occurrence, where the volume of shale is critical to correct the total porosity and saturation values from the shale effect. $V_{sh}$ is calculated using a single clay indicator (gamma ray log) by assigning the gamma ray index $I_{GR}$ (Archie, 1942; Ajisafe and Ako, 2013) using the equation:

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

Where:
- $I_{GR}$ = gamma-ray index,
- $GR_{log}$ = gamma-ray reading along the studied formation rock,
- $GR_{min}$ = minimum gamma-ray reading through a clean reservoir rock,
- $GR_{max}$ = maximum gamma-ray reading through a shale zone.

Then, the linear method is used to calculate the shale volume ($V_{sh}$) from the gamma ray index assuming that:

$$V_{Sh} = I_{GR} \quad (2)$$

Also, the shale content is also calculated from the density-neutron logs (as double clay indicator) using the following equation (Schon, 2015):

$$V_{Sh(ND)} = \frac{(\phi_{Nfl} - \phi_{Nma}) \times (\rho_{ma} - \rho_{fl}) - (\phi_{Nfl} - \phi_{Nma}) \times (\rho_{ma} - \rho_{fl})}{(\phi_{Nfl} - \phi_{Nma}) \times (\rho_{ma} - \rho_{fl})} \quad (3)$$

Where:
- $\phi_{Nfl}$ = neutron response of the fluid,
- $\phi_{Nma}$ = neutron response of the matrix,
- $\phi_{Nsh}$ = neutron response of the wet shale,
- $\rho_{fl}$ = density of the fluid,
- $\rho_{ma}$ = density of the matrix,
- $\rho_{sh}$ = density of the wet shale.
The average porosity values were calculated through the available porosity tools (i.e., BHC, FDC and SNP), then corrected for the effect of shaliness, and by turn discriminated into total- and effective-porosities. The porosity values calculated individually from each porosity log recording, and also from the neutron-density combination as follows:

\[
\phi_{\text{Den}} = \frac{\rho_{\text{ma}} - \rho_b}{\rho_{\text{ma}} - \rho_{\text{fl}}} \quad (4)
\]

\[
\phi_{\text{Neu}} = \frac{\phi_N - \phi_{\text{Nma}}}{\phi_{\text{Nfl}} - \phi_{\text{Nma}}} \quad (5)
\]

\[
\phi_{\text{Sonic}} = \frac{\Delta t_{\text{ma}} - \Delta t_{\log}}{\Delta t_{\text{ma}} - \Delta t_{\text{fl}}} \quad (6)
\]

Where:
\(\phi_{\text{Den}}, \phi_{\text{Neu}} \) and \(\phi_{\text{Sonic}}\) are the calculated porosities,
\(\rho_b, \phi_N\) and \(\Delta t_{\log}\) is the measured (logged) data,
\(\rho_{\text{ma}}, \phi_{\text{Nma}} \) and \(\Delta t_{\text{ma}}\) are the matrix responses,
\(\rho_{\text{fl}}, \phi_{\text{Nfl}} \) and \(\Delta t_{\text{fl}}\) are the fluid responses.

Then, correct them as follows (Bateman and Konen, 1978; Islam et al., 2009):

\[
\phi_{\text{N corrected}} = \phi_N - \left[\left(\frac{\phi_{\text{NS}}}{0.45}\right) \times 0.30 \times V_{Sh}\right] \quad (7)
\]

\[
\phi_{\text{D corrected}} = \phi_D - \left[\left(\frac{\phi_{\text{DS}}}{0.45}\right) \times 0.13 \times V_{Sh}\right] \quad (8)
\]

Where:
\(\phi_{\text{NS}}\) = neutron-derived shale porosity, \(\phi_{\text{DS}}\) = density-derived shale porosity.

The corrected porosity derived from neutron and density logs are then converted into effective porosity using the equations (Mustafa, 2012; Asquith et al. 2004):

For oil:

\[
\phi_{\text{ND}} = \frac{\phi_{\text{N corrected}} + \phi_{\text{D corrected}}}{2} \quad (9)
\]

For gas:

\[
\phi_{\text{ND}} = \sqrt{\frac{\phi_{\text{N corrected}}^2 + \phi_{\text{D corrected}}^2}{2}} \quad (10)
\]

The water saturation \((S_w)\) is another important petrophysical property since it is directly contributing to the determination of the volume of the hydrocarbon occurrence in the reservoir (Mamaseni et al., 2018). The Archie water saturation model was preferred because the Archie equation for calculating water saturation is well known (Janjuhah et al., 2017):

\[
S_w = \left(\frac{FxRw}{R_t}\right)^{1/n} \quad (11)
\]

Where:
\(S_w\) = water saturation, \(F = \) formation resistivity factor,
\(R_w\) = resistivity of formation water, \(R_t\) = true formation resistivity,
n = saturation exponent.

Then, hydrocarbon saturations can be calculated using the water saturation data (Serra, 2007):

\[
S_{hr} = 1 - S_w \quad (12)
\]
4. Results

4.1. Qualitative Correlation

To track the lateral continuity of the zones in the studied area using the available well logs, a correlation profile was created (Fig. 3). This profile takes the NW-SE direction and flattened on the surface of Kareem Formation passing through three wells and showing the continuity of the zone of interest across the study area.

Fig. 3. A cross section reveal the qualitative correlation through the studied three wells

4.2. Lithology Determination

Among the varies techniques that can benefit to detect the matrix composition of a reservoir using log data, the results obtained from the main lithological identification charts used in this study will be categorized as follows:

4.2.1. Tri-Porosity Crossplot (M-N Crossplot)

M-N cross plot can be obtained through combine the three porosity logs (sonic, neutron & density tools) to detect lithology. The equations used are expressed below (Boddy and Smith, 2009):

\[ M = \frac{\Delta t_r - \Delta t_{log}}{\rho_b - \rho_r} \times 0.01 \]  \hspace{1cm} (13)

\[ N = \frac{\phi_{NRI} - \phi_{Nlog}}{\rho_b - \rho_r} \]  \hspace{1cm} (14)
Where:
\[ \Delta t_{\text{fl}} = \text{Sonic mud filtrate reading (\(\mu\text{sec/ft}\))}, \quad \Delta t_{\text{log}} = \text{Sonic log reading (\(\mu\text{sec/ft}\))}, \]
\[ \Omega_{\text{fl}} = \text{Neutron mud filtrate reading (LPU)}, \quad \Omega_{\text{log}} = \text{Neutron log reading (LPU)}. \]
\[ \rho_b = \text{Density log reading (g/cc)}, \quad \rho_{\text{fl}} = \text{Density mud filtrate reading (g/cc)}. \]

Also, a useful modification of this cross plot has been carried out by implementing a third dimension where individual points are color-coded by their shale content. If color indicates low shale content, then the point represents a clean rock (in the quartz, calcite or dolomite region). The results suggest that quartz is the main matrix components for the low-shale points, while the location of the high-shale points suggests the presence of calcareous shale (Fig. 4).

![Fig. 4](M-N Cross plot of L.RUD-SD parameters from studied well SHB-1)

**4.2.2. Dia-Porosity Cross plots**

Density-Neutron Cross plot is constructed by plotting the neutron log on the horizontal axis while the density log on the vertical axis with a reversed scale. Measured data are plotted into the designed curve set (Fig. 5a), where most of the matrix points lies on the sandstone line, and also a preliminary estimation for the porosity has been estimated (20-25%). Subsequently, the Sonic-Neutron Cross plot is constructed, and the results is considered to be a confirmation for sandstone as the main lithology (Fig. 5b).

4.3. Shale Type Determination

Shale is distributed in reservoir formations as structural, laminar, dispersed or combination of any of these types. Since each type of them is affecting the reservoir quality in a different way, the following methods were used in studied reservoir:

Fig. 5. Dia-Porosity Cross plots for L.RUD-SD: (a) Density-Neutron Cross plot; (b) Sonic-Neutron Cross plot
4.3.1. Thomas-Stieber Method

The cross plot proposed by Thomas and Stieber (1975) is used to define the type of shale distribution in a reservoir using only well-log data by plotting a "porosity tool" (Density log) and a "shale volume tool" (Gamma ray log) where the relation between total porosity and shale type within the reservoir follows certain principles (Dejtrakulwong et al., 2009).

Therefore, the resulted mathematical model can be graphically presented and used to determine the shale type within the reservoir. This model shows that most of the shale points lean towards the dispersed type vicinity, with a minor representation from some points towards the laminar type as in Fig. 6.

![Figure 6](image)

**Fig. 6.** Shale type determination in L.RUD-SD Using Thomas-Stieber Method in Well SHB-1

4.3.2. Dispersed laminated plot

Laminar shale exists as layer of clay minerals within the reservoir. The effect of this type on porosity is sometimes severe. Dispersed shale is composed of clay particles occupying pore spaces. This type of shale reduces effective porosity to a great extent and should be investigated (Ghassem and Roozmeh, 2017).

This model is constructed as a connection between the shale volume (Vsh), and the porosities calculated from sonic log (\(\varnothing_s\)) and from density log (\(\varnothing_d\)). The amount (\(\varnothing_s - \varnothing_d\)) % is determined and plotted on the x-axis versus the shale volume (Vsh) %, then two variance lines are sketched to
discriminate between laminated and dispersed regions. The laminated shale line is identified using the equation (El Kadi et al., 2016):

\[(\varnothing_s - \varnothing_d) = 0.13V_{Sh}\]  

(15)

While the dispersed line is drawn using the equation:

\[(\varnothing_s - \varnothing_d) = V_{Sh}\]  

(16)

The model shows a number of points arranged around the dispersed-type line, but also with varies points lean towards the laminated-type line. (Fig. 7).

![Shale type determination in L.RUD-SD Dispersed Laminated Plot](image)

**Fig. 7.** Shale type determination in L.RUD-SD Dispersed Laminated Plot

Also, the shale type analysis conducted through the Interactive Petrophysics (IP) software provided a vertical visual representation to enhance tracking the distribution of the shale types. This plot emphasized the presence of the dispersed shale as the main type within the sand intervals, while the laminated type is well-represented in the shaly intervals, (Fig. 8).
4.4. Shale Volume (Vsh) Estimation

Shale content has been estimated from gamma-ray log as a single clay indicator, and neutron-density logs as a double clay indicator. The average value is about 6% for well SHB-1, 6.9% for well SHB-5ST, and 12.1% for well SHB-4ST. Fig. 9a shows the distribution of the shale content values over the top of L.RUD-SD to monitor the lateral changes all over the study area where the south-eastern part has the lowest shale content.

4.5. Net-Pay Determination

The recognition between productive and non-productive intervals within the reservoir, and offer a solid-base for the hydrocarbon calculations, the net pay thickness has been calculated and the resulted values are about 39.5 m for well SHB-4ST, 41.5 m for well SHB-1, and 43.75 m for well SHB-5ST. Also, Fig. 9b displays the distribution of these results on top of the L.RUD-SD where the south-eastern part has a better net pay value.

4.6. Effective Porosity ($\phi_{eff}$) Determination

The porosities corrected from shale volume effect were used to calculate the effective porosity. The effective porosity values are about 18% for well SHB-1, 18.7% for well SHB-4ST, and 20.6% for well SHB-5ST. Fig.10 shows the distribution of the calculated porosity values on the top of L.RUD-SD. Also, the south-eastern part has the highest porosity values.
Fig. 9. Contour maps reveal the distribution of (a) average shale volume values; (b) average net-pay thickness.
4.7. Fluid Saturation

4.7.1. Water resistivity ($R_w$)

The $R_w$ determination has been carried out using the Pickett’s plot method which provides a graphical solution to Archie’s equation to calculate reservoir water saturation by plotting resistivity versus porosity on a log-log scale. The $R_w$ calculated from the Pickett’s plot was found to be about 0.19 $\Omega\cdot m$ (Fig. 11).

4.7.2. Estimation of hydrocarbon saturation ($S_{oh}$)

Due to the relatively low shale content in the study area, the fundamental equation described by Archie, (1952) provided good representative values for the determination of water saturation (about 6-24%). The fact that effective pores is either filled by water or hydrocarbon makes the calculation of hydrocarbon saturation one equation away. However, the resulted values reach the maximum of 94% in well SHB-1, and 83.6% in well SHB-4ST, while declined to about 76% in well SHB-5ST. The results are graphically represented in Fig. 12.

Fig. 10. Contour map reveal the distribution of iso effective porosities measured on top of L.RUD-SD
Fig. 11. Rw Determination in L.RUD-SD Using Pickett’s Plot Method

Fig. 12. Distribution map for hydrocarbon saturation on top of L.RUD-SD
4.8. Litho-Saturation Plots

The following litho-saturation plots display the results of the evaluation process, the Computer Processed Interpretation (CPI), for the studied zone in the available wells (Figs. 13, 14 and 15). Both inputs and outputs were sketched for each well. The input data includes gamma ray, porosity tools, deep resistivity and shallow resistivity. The results of the input data analysis contain shale volume, total porosity, effective porosity, water saturation, hydrocarbon saturation and lithology. The cutoff values used are 35% for shale content, 10% for effective porosity, and 50% for hydrocarbon saturation. Table 1 displays the average petrophysical parameters calculated for the study zone in each well.

<table>
<thead>
<tr>
<th>Well</th>
<th>SHB-1</th>
<th>SHB-4ST</th>
<th>SHB-5ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross (m)</td>
<td>65.23</td>
<td>54</td>
<td>92.11</td>
</tr>
<tr>
<td>Net (m)</td>
<td>41.53</td>
<td>39.50</td>
<td>43.75</td>
</tr>
<tr>
<td>N/G</td>
<td>0.637</td>
<td>0.731</td>
<td>0.475</td>
</tr>
<tr>
<td>Vcl %</td>
<td>6</td>
<td>12.1</td>
<td>6.9</td>
</tr>
<tr>
<td>Φeff %</td>
<td>18</td>
<td>18.7</td>
<td>20.6</td>
</tr>
<tr>
<td>Sw %</td>
<td>6</td>
<td>16.4</td>
<td>23.7</td>
</tr>
<tr>
<td>Sho %</td>
<td>94.4</td>
<td>83.6</td>
<td>76.3</td>
</tr>
</tbody>
</table>

Table 1. Summary of petrophysical parameters for L.RUD-SD

**Fig. 13.** Computer Processed Interpretation (CPI) of the studied Well SHB-1
Fig. 14. Computer Processed Interpretation (CPI) of the studied Well SHB-4ST

Fig. 15. Computer Processed Interpretation (CPI) of the studied Well SHB-4ST
5. Discussion

The Lower Rudeis Formation is found to be the most prolific and important section in the studied wells in the Shukheir Bay field where the sandstone interval referred to as the L.RUD-SD was determined as the main reservoir. Thus, this study has been carried out to determine the reservoir quality, matrix, shale content, effective porosity, water and hydrocarbon saturation which have been determined if applicable. However, each well log tool has been recalibrated to become a direct measure for the effective porosity and shale content.

The proper cross plots have been used to define the lithological components for the studied interval, and to calculate the matrix density and the water resistivity in the evaluated interval. Besides, the cross plots have been used for the determination of the shale type (structural, laminated, dispersed) contaminated within the sandstone interval. Thus, it’s possible to conclude that the existing shale within sandstone of the Lower Rudeis Formation is of the dispersed type, the laminated shale has only been determined as a minor type, while no structural shale has been detected. This dispersed and laminated shale would affect and reduced the effective porosity within the reservoir (Ghassem and Roozmeh, 2017). The L.RUD-SD represent a good reservoir with shale volume ranges between 6 and 12 %, good effective porosity varies from 18 to 21% and high gas saturation varying from 76 to 94%. Both the lateral and vertical distributions of the petrophysical parameters are presented. The lateral distribution is achieved through the iso-parametric contour maps, while the vertical distribution is expressed by the CPI plots. However, the movable hydrocarbon saturation maps show an increase in the central and southwestern direction within the L.RUD-SD of Rudeis Formation in the studied area.

6. Conclusions

The sand interval of the Lower Rudeis Formation, referred to as L.RUD-SD, is identified and evaluated. This sand interval is found to be an oil reservoir. Based on the evaluation processes and the resulted plots, it’s recommended to drill new development wells in the central and southeastern parts of the area. Also, we recommend extending the vicinity of exploration for the study area to include other levels in the Miocene section of the Shukheir Bay area.

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