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Organic richness and thermal maturation of the F and G members of the Abu Roash Formation in Central Beni Suef Basin, Western Desert, Egypt: Integrated organic geochemical and geophysical approaches

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ABSTRACT

Beni Suef Basin has a promising prospect for hydrocarbon production in the Egyptian Western Desert, so it has been given priority in exploration plans. Geochemically determined TOC data are expensive and are usually obtained from limited samples as in the Beni Suef Basin. Thus, geophysical methods will be used to provide a cost effective continuum of organic richness and maturation data of the latest Cenomanian "G" and the Turonian "F" members of the Abu Roash Formation in the Azhar E-2X well. An attempt was made to differentiate between total organic carbon (TOC) content of kerogen in potential source intervals and TOC content in hydrocarbon bearing reservoir intervals using the Δ log R technique and the gas chromatography data (Gas wetness ratio: GWR%, Light to heavy hydrocarbon ratio: LHR%, Oil character qualifier: OCQ). In the source rock intervals, a good match between the geochemically determined TOC and log-derived TOC data was found, where the later TOC data reliably determined the organic richness. Additionally, the geophysically estimated maturation index (MI) values were calibrated with the geochemical Tmax data. A continuum of MI data successfully provided a reliable assessment of thermal maturation of source rock intervals. Conversely, in gas bearing reservoir intervals, both the log-derived TOC and MI data were hampered by the gas effect. Meticulous distinction between reservoir and source intervals in unconventional source rocks having intraformational reservoir interbeds is necessary to determine correctly the organic richness and maturation of these source rocks.

1. INTRODUCTION

Recent exploration activities have been conducted on the Beni Suef Basin in Central Egypt in response to the national and international demand on energy sources (Fig. 1). This basin possesses a few potential Lower Cretaceous (Albian lower Kharita Formation) and Upper Cretaceous (Turonian "F" Member of the Abu Roash Formation) source rocks. The Upper Cretaceous (lower-middle Cenomanian Bahariya Formation, upper Cenomanian "G" Member, and Turonian "A and E" members of the Abu Roash Formation) are potential reservoir rocks [1]-[3]. Only a few research papers have addressed on the source rock potential of the Lower and Upper Cretaceous in the Beni Suef Basin. [4] suggested that the Lower Cretaceous Betty and Kharita formations and the Upper Cretaceous Abu Roash "E" and "G" members in the Fayoum-1X well in West Beni Suef Basin are mature gas/oil and gas prone source rocks, and the Abu Roash "F" Member is oil prone source rock (Fig. 2). [5] studied the same Fayoum-1X well in more details and suggested that the sandstones sections of the Kharita, Bahariya, and Abu Roash “A, E, and G’’ formations are reservoir rocks. [6] suggested that the Kharita Formation in the WON-C-3X well in West Beni Suef Basin is over mature gas-prone source rock, while the Abu Roash "F" and "G" are mature gas/oil prone source rocks. This lateral variation from source to reservoir characters of the "F" and "G" members of the Abu Roash Formation in West Beni Suef Basin suggested in these scarce studies indicate that the Upper Cretaceous successions in this basin are still under-explored.

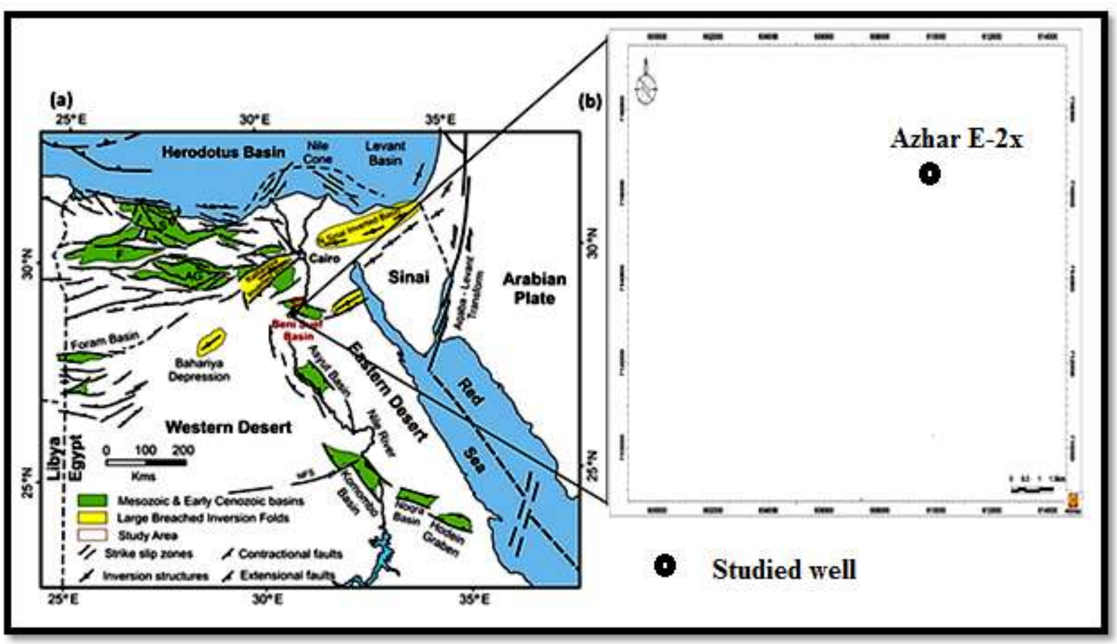

Figure 1. Location map of Beni Suef Basin and the studied Azhar E-2X well, after [1].

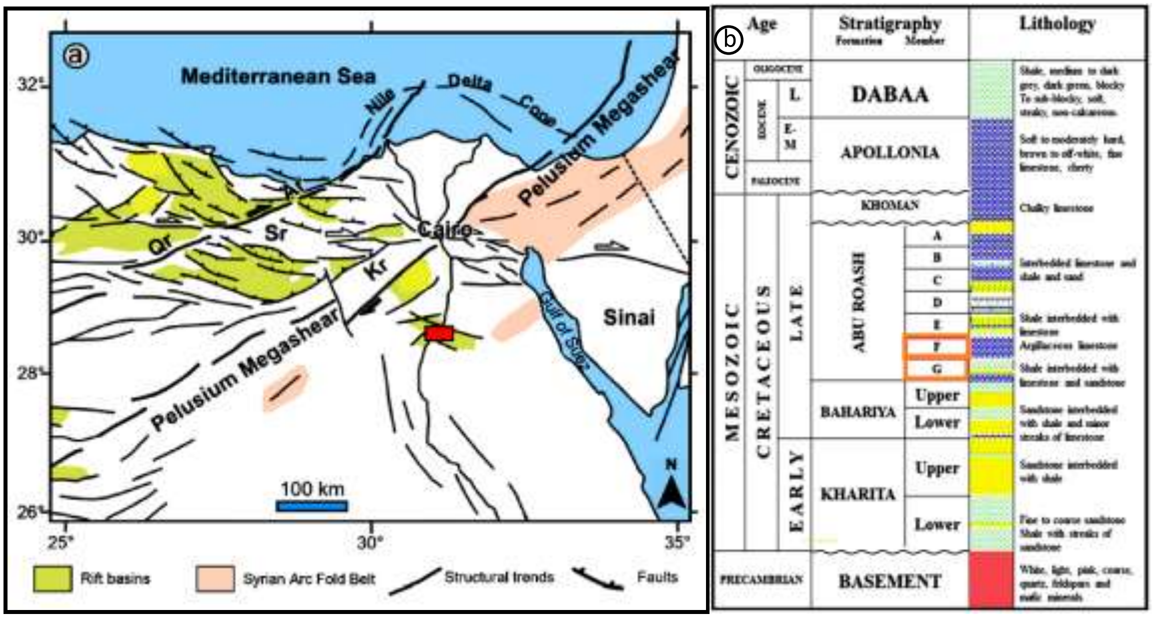

Figure 2. (a) Map of the study area indicated by a red filled rectangle, along with the regional structures of northern Egypt, after [7]. Sr, Qr, and Kr denote the Sharib-Sheiba, Qattara, and Kattaniya ridges, respectively; (b) Cretaceous-Oligocene lithostratigraphy of the Beni Suef Basin. The studied Abu Roash "G" and "F" members are marked by a blue rectangle. (b) Lithostratigraphic column of West of Nile (WON) Beni Suef sub-basin, after [1].

Determination of total organic carbon (TOC wt%) of rock sections represents a crucial step in identification of potential source rocks [8]-[10]. Organic geochemical analysis is the conventional methods used in TOC determination. This involves the elemental analysis of acid-treated and untreated portions of rock samples [11]-[13] or the pyrolysis of non-decarbonized rock samples [10], [11], [14]-[17]. Nevertheless, accurate geochemical determination of TOC is sometimes limited by contamination by oil-based drilling mud, migration of hydrocarbons, dilution of organic matter by mineral matrix, saturation of the flame ionization detector (FID) of the Rock-Eval apparatus, and low organic matter content [13]. Furthermore, geochemically determined TOC data is expensive and conventionally made on some selected samples. Therefore, several geophysical methods [18], [19] were proposed to counter the aforementioned limitations of the geochemical methods. These geophysical methods successfully provided a cost effective continuum of data, especially when numerous ditch/core samples were not available [10], as is the case here in the studied Azhar E-2X well. The second important step in the identification of potential source rocks is the appraisal of the thermal maturity of the indigenous organic matter [9], [10]. This is also conventionally performed using the pyrolysis analysis of rock samples and determination of Tmax temperature °C [8], [10], [11], [13]. Likewise the TOC data, the Tmax temperature is also affected by contamination by oil-based drilling mud, migration of hydrocarbons, mineral matrix dilution, saturation of FID, and low organic matter content [10], [13].

In the current study, there is a limited availability of ditch samples and organic geochemical data from the "G" and "F" members of the Abu Roash Formation in the Azhar E-2X well drilled in West Beni Suef Basin. Therefore, the main objective of this study is to obtain a continuum of organic richness and thermal maturation data of the two members that will be determined by selected geophysical methods and will be calibrated with the available geochemical data. This step is essential to evaluate the hydrocarbon source rock potential of the Upper Cretaceous in the under-explored West Beni Suef Basin.

2. GEOLOGICAL SETTINGS AND LITHOSTRATIGRAPHY

The Beni Suef Basin (BSB) is an Early Cretaceous intracontinental rift basin, which has been developed as a response to the breakup of the Western Gondwana and resultant opening of the South and Central Atlantic Oceans [20], [21]. This basin is believed to have formed within unstable shelf of Egypt. This basin experienced pronounced folding and faulting during the Late Cretaceous (Senonian) that formed the NE to ENE trending Syrian Arc Fold System (Fig. 2a). This tectonic event was related to the closure of Neo-Tethyan Ocean as a result of the convergence between the African and Eurasian plates [20]-[22]. The BSB lies almost 150 km south of Cairo, Egypt, and is separated by the Nile river into the Eastern of Nile (EON) and Western of Nile (WON) sub-basins (Fig. 2a).Current production from the Lower Cretaceous upper Kahrita and the Upper Cretaceous "F" Member of the Abu Roash formations along with several studies deemed classification as BSB a promising petroliferous province in Central Egypt [1], [4]-[6].

Stratigraphically, the BSB has incomplete sedimentary successions when compared to those encountered in the North Western Desert (NWD) of Egypt. In the WON sub-basin, the almost complete sedimentary successions are made up of sandstones of the Lower Jurassic Eghi Formation, which unconformably overlies the basement and underlie unconformably the major sandstones units of the Lower Cretaceous Betty, Alam El Bueib, Dahab, and Kharita formations. This is conformably overlain by the Upper Cretaceous sandstones of the Bahariya, fine clastics and carbonates of the Abu Roash, and carbonates of the Khoman formations. A widespread unconformity surface across the NWD and WON sub-basin separates the Upper Cretaceous from the carbonates of the Eocene Apollonia Formation, which is overlain conformably by the shales of the Oligocene Dabaa Formation, e.g. [1], [4]. In other parts of the WON sub-basin, the Lower Cretaceous Kharita Formation rests unconformably over the basement (Fig. 2b) and is conformably overlain by the deposition of the Bahariya, Abu Roash, which is overlain unconformably with undifferentiated Miocene or Recent carbonate and clastic deposits [6].

In the studied Azhar E-2X well, the Kharita Formation overlies unconformably over the basement. This is conformably overlain by the Upper Cretaceous sandstones of the Bahariya, fine clastics and carbonates of the Abu Roash, and carbonates of the

Khoman formations, which is unconformably overlain by carbonates of the Eocene Apollonia Formation.

3. MATERIALS AND METHODS

Ditch cutting samples, different geochemical and geophysical data sets were obtained for the current study. Processing of ditch samples and treatment of data are shown in the next subsections.

3.1. Material

Fifteen ditch cutting samples were obtained from depths 7270 to 6490ft (2215.9-1978.2 m) of the Abu Roash "G" and from depth 6450 to 6390ft (1965.9-1947.7 m) of the "F" members, and were subjected to Rock-Eval (RE) pyrolysis for organic geochemical analysis was made. TOC values from 15 studied samples, along with 6 readings of S_1, S_2, S_3, Tmax, production index (PI), oil saturation index (OSI) were obtained.

The digitized gas chromatography (GC) data from the Abu Roash "G" and F" members covers depths from 7445 to 6375ft (2269.2-1943.1 m) in the Azhar E-2X well, which was obtained from total 948 readings of C1 (Methane), C2 (Ethane), C3 (Propane), and C4 (Butane) and C5 (Pentan). The geophysical data includes the downhole well logging data with a total of 29,834 readings at a depth interval of 0.25 ft of the Gamma-Ray (GR), Deep Resistivity (RD), Density, Neutron, and Sonic logging in a LAS format.

3.2. Methods

Initially, petrophysical evaluation of the borehole logs was conducted over the studied interval. This was followed by reassessment of the same interval for hydrocarbon richness and thermal maturity using well log-derived parameters.. Organic geochemical data and mud-logging readings were also analyzed to support the evaluation. The results from petrophysical, geochemical, and mud-logging analyses were then integrated and compared to determine the type and phase of hydrocarbons present in the studied intervals.

3.2.1. Rock-Eval pyrolysis

The TOC wt% of the studied 15 cutting samples covering the "G" and "F" members of the Abu Roash Formation was determined using the elemental analyzer LECO C230. Seven samples were organically rich (0.61- 2.43 TOC wt%). The pyrolysis of these samples was made utilizing the Rock-Eval 6. Reader may consult [11] for more details on the elemental and Rock-Eval pyrolysis analyses.

3.2.2. Gas chromatography (GC)

When reading a mud log, it is useful to be able to estimate formation productivity in a semi-quantitative manner. A number of authors have suggested ways to combine the readings from chromatographic analysis to fingerprint the true formation content. The method of [23] suggests using three ratios to type the formation (Eqs. 1-3, Table 1). These ratios were calculated and used to define the productive hydrocarbon zones and their type of hydrocarbons. The gas wetness ratio (**GWR**%) represents the percentage ratio of wet gases C2 to C5 to total gases C1 to C5 (Eq. 1). The light-to-heavy ratio (**LHR%**) represents the percentage ratio of light gases C1 and C2 to heavy gases C3 to C5 (Eq. 2). The Oil character qualifier (**OCQ)** ratio is based on the C3 to C5 (Eq. 3) and used to interpret gas cap shows, oil/gas (O/G contact), and water-saturated zones [24].

Gas wetness ratio (GWR%) = ((C2+ C3 + C4 + C5)/ (C1 + C2+ C3 + C4 + C5)) x100 (1)

Balance ratio (Light-to-heavy ratio) (LHR%) = (C1 + C2) / (C3 + C4 + C5) x100 (2)

Character ration (Oil character qualifier) (OCQ) = (C4 + C5) / C3. (3)

The LHR correlates well with the API gravity, that is, a high LHR corresponds to low-density (high-API) hydrocarbons. The OCQ ratio is useful as a qualifier when excessive methane is present [23], [25].

Digitization of the gas chromatography (GC) data from the mud log of the Abu Roash "G" and "F" members was made at a regular depth interval of 5 ft. The obtained data were stored in the spreadsheet program Microsoft Excel data files, where different calculations were made. Subsequently, evaluation of hydrocarbon shows from gas chromatography data was made following [23].

Table 1. Hydrocarbon potential after [23].

Hydrocarbon	GWR (%)	LHR (%)	OCQ Ratio
Light dry gas	< 0.5	100 +	Very low
Medium density gas	0.5-17.5	< 100	< 0.5
Light oil	5-10	17.5	> 0.5
Medium gravity oil	17.5-40	< 10	> 1
Residual oil	> 40	5-10	> 2
Coal bed	15-20	< 100	Very low

3.2.3. Well log analysis

Different petrophysical characteristics are acquired through the studies of available well logging curves. These studies include the mineralogy, lithology, and shale content.

3.2.3.1. Lithology identification using cross plotting techniques

Cross plotting techniques were applied such as density-neutron crossplot to aid in the formation's lithologies interpretation [10], [26]. Another crossplot employed in this research is the M-N crossplot that depends on the fluid and log parameters which incorporated together essentially in the three porosity logs; sonic, density and neutron

(Eqs. 4, 5), for mineral identification and lithological content for each level, with respect to the standard M and N values of the common minerals and rocks experimented by [27], where the M and N functions are computed as follow:

$$\mathbf{M} = (\Delta t_{fluid} - \Delta t_{matrix}) / (\rho_{matrix} - \rho_{fluid}) \quad (4)$$

$$\mathbf{N} = (\varphi n_{fluid} - \varphi n_{matrix}) / (\rho_{matrix} - \varphi n_{fluid}) \quad (5)$$

Where Δt_{fluid} and Δt_{matrix} are the transit times of fluid and matrix, ρ_{matrix} and ρ_{fluid} are the bulk density of matrix and fluid and φn_{fluid} and φn_{matrix} are the neutron porosity values of fluid and matrix. These data were integrated to evaluate the Abu Roash "G" and "F" members and delineate their facies distribution.

3.2.3.2. Shale volume (Vcl) estimation

The estimation of the shale volume (Vcl) was made using the Gamma ray (GR) readings following [27] as follows (Eq. 6):

$$I_{GR} = (GR_{log} - GR_{min}) / (GR_{max} - GR_{min}) \quad (6)$$

I_{GR} = GR index, GR log = GR readings, GR_{max} = highest numerical values of GR of shale bed, and GR_{min} = lowest numerical values of GR in shale-clean interval. The calculation of shale volume in rock units of the "G" and "F" was made using the equation for ancient consolidated deposits of [28] as indicated below (Eq. 7):

$$Vcl = 0.33\,(2^{(2 * I_{GR})} - 1) \quad (7)$$

3.2.3.3. Hydrocarbon-bearing zones identification

Well-logging analysis are used for identifying hydrocarbon-bearing zones using Indonesian Porosity-Water Saturation method. Total porosity (ϕT) is computed using the following formula (Eq. 8):

$$\Phi_T = (\Phi_N + \Phi_D) / 2 \quad (8)$$

ϕ_T = the total porosity. ϕ_N = the average neutron porosity. ϕ_D = the average density porosity. The effective porosity (ϕ_E) can be calculated by (Eq. 9):

$$\Phi_E = \Phi_T \times (1 - V_{cl}) \quad (9)$$

ϕ_E = the effective porosity. ϕ_T = the total porosity. V_{cl} = the shale volume . Water saturation (S_w) for reservoir intervals is calculated with Archie's model. In the Archie model, the formula for water saturation is commonly represented as follows (Eq. 10):

$$S_w = [aR_w / \varnothing^m R_t]^{1/n} \quad (10)$$

S_w = the water saturation, Φ = the porosity, R_t = the deep resistivity, R_w = the connate water resistivity, **a** and **m** are empirical constants. These parameters are essential to understanding the characteristics of the reservoir.

3.2.3.4. Estimation of the log-derived TOC content

This part of the current study focused on the relation between the measured total organic carbon (TOC) and the calculated TOC for the well, which was deduced from the wireline logs by several mathematical methods used to quantitatively estimate TOC content in terms of wt% [18], [19], [29]-[31].

The occurrence of organic matter in deposits has a direct impact on the petrophysical characteristics of such rock units, where decreases in density and sonic velocity values are common. Additionally, the hydrogen content of rock units is directly linked to the existence of organic matter that is rich in radioactive elements.

The Δ log R method of [18] uses an overlay technique. The departure between the resistivity and porosity curves indicates the existence of organic matter, whereas the overlay between the two curves specifies absence of organic matter [18], [29]. The departure between the two curves is known as Δ log R, which is detected at depth increase in the resistivity log and used to deduce the TOC content. The application of the Δ log R method [18] was executed using the equations shown below (Eq. 11):

$$\Delta \log R = \log10\ (R/R\_baseline) + A^{*}\ (B - B\_baseline) \qquad (11)$$

Δ log R = departure between the porosity log and resistivity curves, R = resistivity (Ω m), B = transit time Δt (μs/ft), bulk density ρ_b (g/cc), or neutron porosity Φ_N (pu) for the sonic, density, and neutron logs, respectively. R_baseline = resistivity baseline and B_baseline = baseline corresponding to each of the three logs determined in organic-poor rock units. A is constant value = 0.02, 2.50, or 4.00 for the sonic, density, or neutron logs, respectively.

The TOC was estimated from the next equation (Eq. 12) of [18] as follows:

$$TOC = \Delta \log R * 10^{(2.297-0.168*LOM)} \qquad (12)$$

TOC = total organic content in wt%, LOM = level of organic matter metamorphism, which is deduced from vitrinite reflectance or thermal alteration index data [29].

3.2.3.5. Geophysically determined maturity

I. Maturity index (MI)

[32] proposed a thermal maturity index (MI), which is based on well log data. This MI was applied to determine the thermal maturity levels of the Abu Roash "G" and "F" members in the Azhar E-2X well. [32] proposed their MI on the assumptions that gas is generated and entrapped within the same unconventional shale source rocks. They suggested that the decreases in the saturation with water formation and density of

generated hydrocarbons are directly linked to the increase in thermal maturation and hence in the increase in the MI values. The water saturation (**Swi**) is estimated by applying in the following equation of Archie (Eq. 13):

$$S_{wi} = \left(\frac{R_w}{\phi_{d9i}^{m} R_t} \right)^{1/2} \qquad (13)$$

Rw = formation water resistivity (ohm meters); **Φd9i** = an estimated matrix porosity from density log porosity (**Φd**) by (**Φd9i = Φd - 9%**); **Rt** = deep formation resistivity; **m** = an exponent factor of rock cementation (2.0) deduced from the relationship between the measured porosity and formation factors according to [33]. The A/R "G" and "F" members are made up of shale and limestone lithology, respectively.

As [32] suggested, the log intervals showing water saturation < 75% are selected as potential hydrocarbon productive intervals. The log intervals showing water saturation ≥ 75% are excluded from the calculations. Based on aforementioned constrains, the MI of the Abu Roash "G" and "F" members was calculated using the equation (Eq. 14) of [32] as shown below:

$$\mathrm{MI} = \sum_{i=1}^{N} \frac{N}{\phi_{n9i}(1 - S_{w75i})^{1/2}} \qquad (14)$$

Different constrains used: **N** = total number of data samples selected showing density porosity ≥ 9% and water saturation ≤ 75%; **Φn9i** = neutron porosity for the samples fulfilling the previous two constrains.

II. Gas-Oil ratios (GOR) vs maturity index (MI)

The GOR is the ratio of total gas produced to the total oil produced from a well. According to [32], there is a strong linear relationship (correlation coefficient: $R^2 = 0.85$) between the MI and the GOR values (Fig. 3).

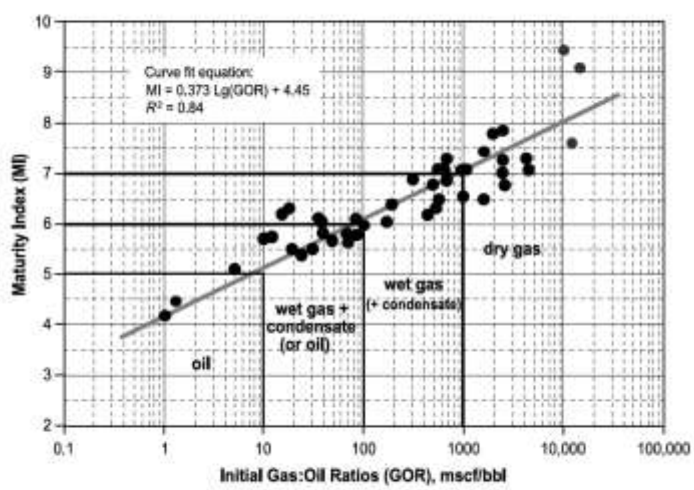

Figure 3. The MI in a linear scale showing levels of thermal maturity and the corresponding GOR in a logarithmic scale [32].

4. RESULTS AND DISCUSSION

4.1. Lithological identification from well logs

Based on well logging analysis, the neutron–density and M-N crossplots were conducted to investigate the lithological characteristics (Figs. 4a, b). The Neutron–density crossplots of the Abu Roash "G" and "F" members in the Azhar E-2X well indicate that the main lithology is shale and limestone and some dolomite. On the other hand, the M-N crossplots display the mineralogical composition of the Abu Roash "G" and "F" members in the Azhar E-2X well (Figs. 5a, b). The crossplots indicate that the examined samples of the "G" Member is composed mainly of shale, while the "F" Member is predominantly made of calcite, with some shaliness impacts.

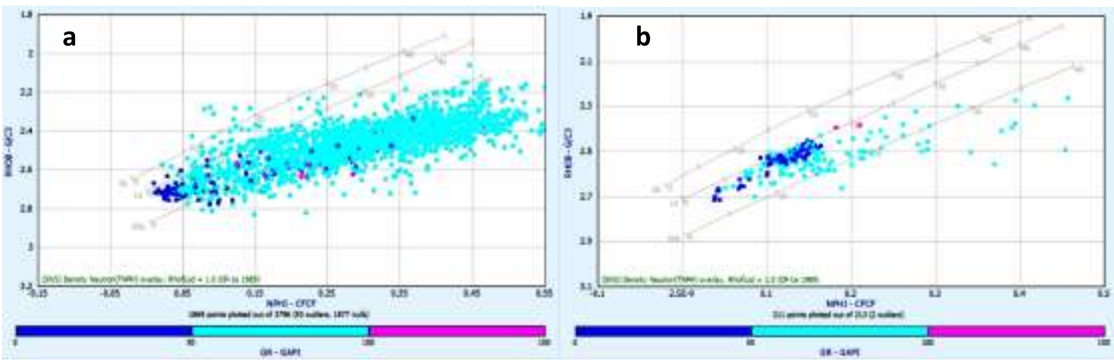

Figure 4. Neutron- Density Cross plot of the Abu Roash "G" Member (a) and A/R "F" Member (b) in the Azhar E-2X well.

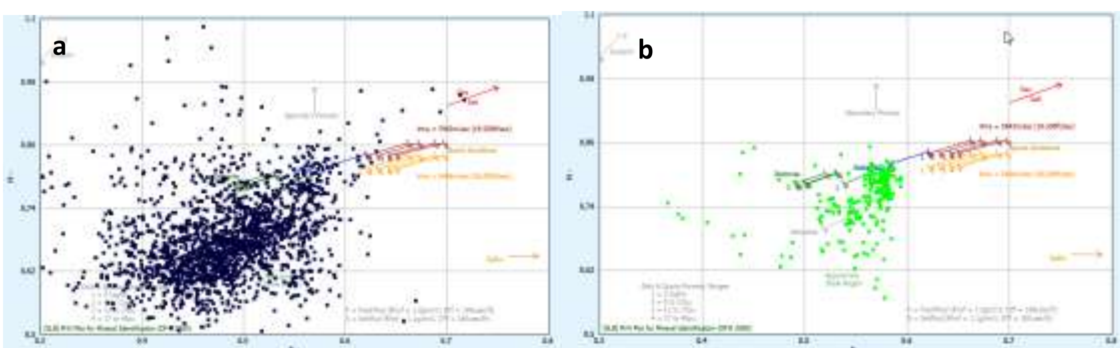

Figure 5. M-N cross plot of the Abu Roash "G" Member (a) and Abu Roash "F" Member (b) in the Azhar E-2X well.

The result of this evaluation represents the lithosaturation plots for A/R "G" and "F" members, Azhar E-2X well (Figs. 4, 5) which is mainly composed of limestone mainly, with shale layers and few sandstone layers, porosity and water saturation. Also, the studied members may possess reservoir quality.

4.2. Organic richness

4.2.1. Rock-Eval analysis

According to [34], samples with TOC content less than 0.5 wt% are considered to have poor organic richness, 0.5–1 wt% indicates fair richness, 1–2 wt% corresponds to good richness, 2–4 wt% represents very good richness, and samples exceeding 4 wt% TOC are classified as having excellent organic richness. The organic-rich samples in the "G" and "F" members of the Abu Roash Formation in the Azhar E-2X well have an average TOC content of 1.10 wt% in "G" Member and 0.63 wt% in the "F" Member. These values indicate fair and poor organic richness for the "G" and "F" members respectively. It is important to note that the analysis of the TOC was made on limited samples (11 samples from the "G" and 3 samples from "F") in the Azhar E-2X well. However, better constrained evaluation of organic richness of potential source rocks necessitates extensive assessment of a large number of samples, especially when formations show vertical and/or lateral facies changes [10], [14]. Therefore, well log data for the rock units of the Abu Roash "G" and "F" members in the Azhar E-2X well will be used to provide a continuum of TOC data.

4.2.2. Petrophysical analyses

Analysis of the vertical changes of the well log data (resistivity and different porosity logs) was used to differentiate between the indigenous total organic carbon (TOC) content found in the source intervals and anomalously high TOC content related to hydrocarbons accumulated in the reservoir intervals. The vertical distribution of log-derived TOC using the porosity/resistivity (Δ Log R) technique consists of a number of tracks from left to right (Fig.6): the first track is for the depth (m). The second one is the formation tops. The third track is the formation analysis (limestone, siltstone, and shale). The fourth track is the GR log (API). The fifth track is the porosity logs (Density, Neutron, and Sonic). The sixth track is the resistivity logs (Ohm.m). The seventh track is the shale volume (Dec). The eighth track is the calculated total organic carbon content (TOC wt%). The ninth track is the calculated total organic carbon content (TOC wt%) from the three overlay methods: sonic/resistivity, neutron/resistivity and density/resistivity.

High resistivity readings are indicative of a mature formation or the existence of accumulations of migrated hydrocarbons [8], [18]. On the other hand, low resistivity levels indicate the existence of immature or excessively mature source rocks [35]. Immature clastic source rocks are characterized by high density and high neutron porosity, while clastic reservoir rocks are characterized by low density and very low neutron porosity. In the Abu Roash "G" Member, there are several thick shale units (log-deficient intervals) that are characterized by relatively low resistivity, high density, and high neutron porosity values (Fig. 6). These thick shale units show geochemically determined low TOC content (0.3-2.5, avg. 1.10 wt%) and matching low log-derived TOC (0.47-0.31, avg. 1.34).

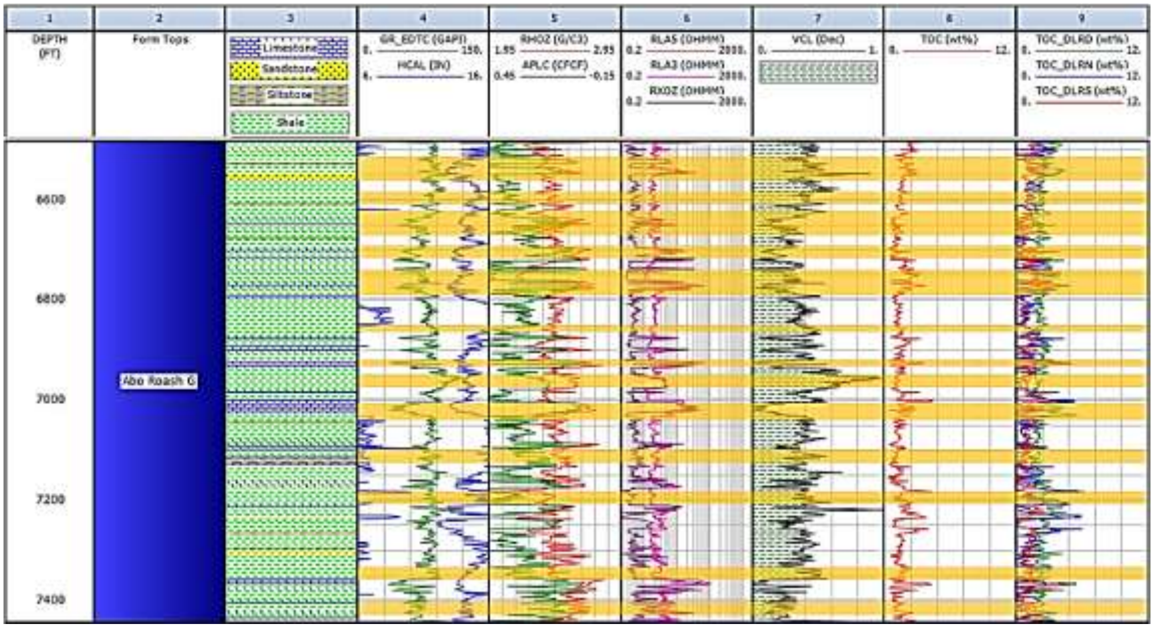

Figure 6. TOC from ΔLog R and average value in Abu Roash "G" in the Azhar E-2X well. Blank zones refer to source rock intervals, and yellow-highlighted zones refer to reservoir intervals.

The low Tmax temperatures (424-428, avg. 425 °C), and low maturation index (MI) values (2.3-5.7, avg. 3.6) indicate these shale units are immature with no hydrocarbon generation and/or accumulation (Fig. 7). The good match between the geochemically determined TOC data and log-derived TOC data indicate that the continuum of the later TOC data is reliable and reflect the generally low TOC content in the "G" Member in the Azhar E-2X well. The anomalously high MI values within the immature source rocks correspond to carbonate and sandstone horizons, where the latter is characterized by low GR values [36] (Figs. 6, 7), which represent potential intraformational reservoir intervals. These sandstone and carbonate horizons indeed show relatively high content of light hydrocarbons (C1-C5), which correspond to high LHR (Fig. 7) as suggested by [23], [25].

The Abu Roash "F" Member is a thick carbonate unit with few thin siltstone interbeds. The carbonate section is characterized by high resistivity, high density, and high neutron porosity values (Fig. 8). This carbonate unit shows geochemically determined low TOC content (0.4-0.9, avg. 0.6 wt%). In contrast, the log-derived TOC (2.10-9.2, avg. 4.8) values are high and show no matching trend with those determined by the pyrolysis. The low Tmax temperatures (431-428, avg. 430 °C), and anomalously high maturation index (MI) values (2.8-8.5, avg. 6.3) indicate that this carbonate unit is immature with no hydrocarbon generation, but contains accumulations of hydrocarbons (Fig. 7). This carbonate unit shows relatively high amounts of light hydrocarbons (C1-C5) as indicated by the high LHR, low GWR, and low OCQ (Fig. 7). The gas effect resulting from the occurrence of light hydrocarbons in the carbonate units causes a discrepancy between porosity data derived from the density and neutron density logs [37]. When gas occurs in the pore spaces of the formation, it shows a different response under pressure in comparison to other liquids, such as oil or water, because of the compressibility of gas. The unmatching between the geochemically determined TOC and the log-derived TOC data in gas-bearing zones is hampered by the gas effect and provides unreliable estimates of the TOC content.

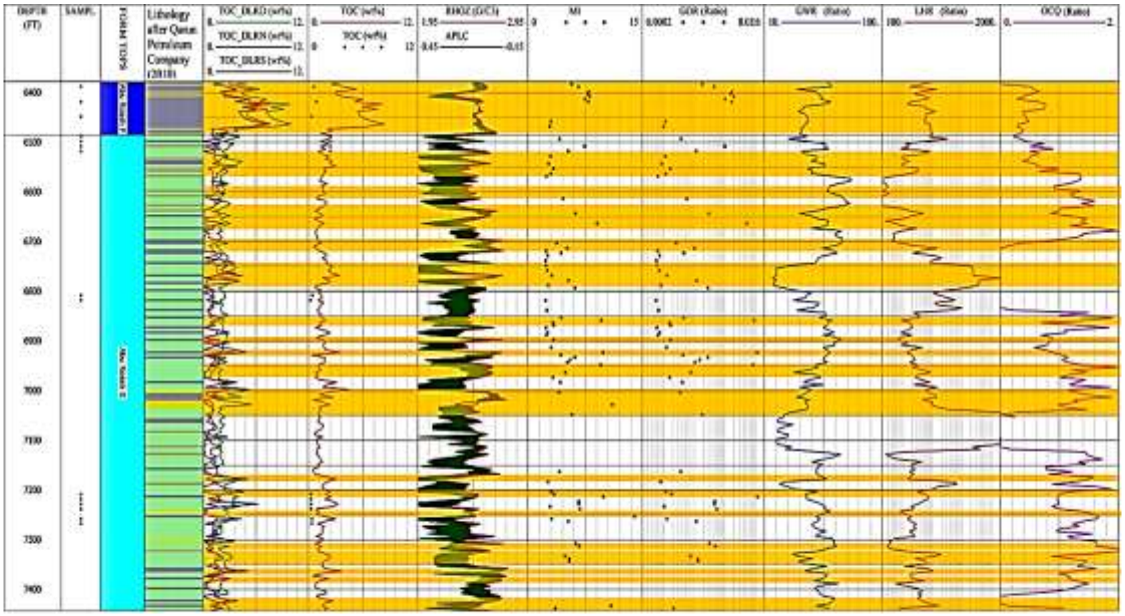

Figure 7. Average TOC data from ΔLog R, neutron-density crossover indicating gas shows, MI and gas chromatography parameters (GOR, LHR, OQC) for the Abu Roash "G" and "F" members in the Azhar E-2X well. Blank zones refer to source rock intervals, and yellow-highlighted zones refer to reservoir intervals.

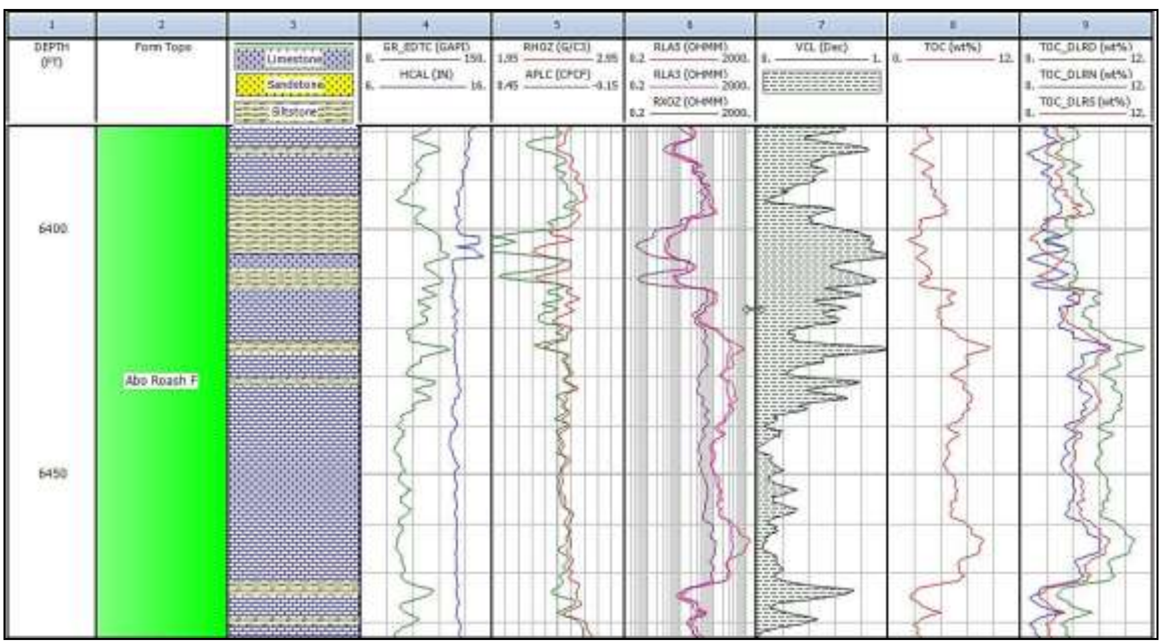

Figure 8. TOC from ΔLog R and average value in Abu Roash "F" in the Azhar E-2X well.

4.3. Maturation assessment

4.3.1. Rock-Eval estimated Tmax temperature

The Tmax values range from 424 to 431 ◦C and have an average value of 426 ◦C, which point to the immature stage [33], [9]. The plot of Tmax versus HI (Fig. 9) indicate that the shales of the "G" Member and siltstone interbeds of the "F" Member are immature (avg. 426 ◦C).

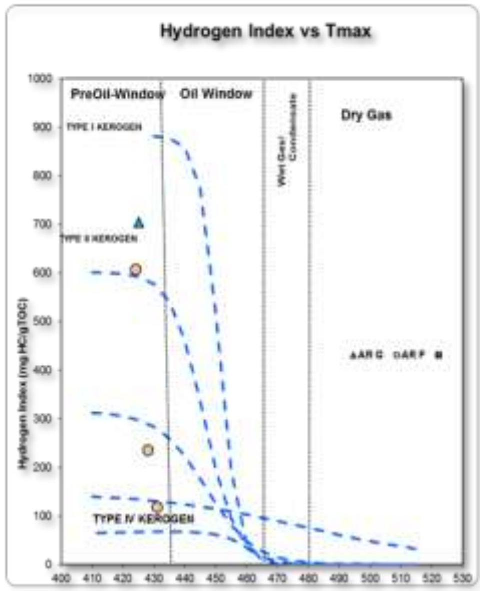

Figure 9. The HI vs Tmax plot of the Azhar "G" and "F" members of the Abu Roash Formation showing their maturation levels.

4.3.2. Geophysically determined maturation index (MI)

In the Abu Roash "G" Member, the source rock intervals are immature (Tmax 424-428, avg. 425 °C). These intervals show low maturation index (MI) values (2.3-5.7, avg. 3.6) with depth indicating a low maturation stage of potential source rocks as suggested by [32] (Fig. 7). However, in the reservoir intervals, the MI values are abnormally high, which are related to an increase in hydrocarbon saturation (i.e., 1-S_{w75i}) and inversely to decreasing in the porosity (Eq. 14).

In the same context, the carbonate reservoir of the Abu Roash "F" Member shows high MI because of the gas effect as mentioned above. The gas effect is manifested by the high LHR, low GWR, and very low OCQ ratios (Fig. 7). Based on this discussion, it is clear that the MI can determine the maturation levels successfully with the source rocks intervals, however, it fails to provide a reliable indication of the maturation levels in the hydrocarbon bearing reservoir intervals.

Therefore, a meticulous differentiation of reservoir from source intervals in unconventional source rocks that contain intraformational reservoir interbeds is necessary to determine correctly the organic richness and maturation.

CONCLUSION

The main conclusions from this study can be summarized as follows:

- Vertical changes of the overlying resistivity and different porosity logs using the Δ log R technique were used to differentiate between the total organic carbon (TOC) content of kerogen found in the source intervals and the high TOC content related to hydrocarbon accumulations in the reservoir intervals.
- In the source rock intervals, there is a good match between the Rock-Eval TOC and log-derived TOC data, where the continuum of the latter TOC data reliably determines the organic richness.
- In the reservoir intervals, there is an inconsistency between the geochemically determined TOC and the log-derived TOC data in gas-bearing zones because of the gas effect.
- In the source rock intervals, the geophysically estimated maturation index (MI) values were calibrated with the geochemical Tmax data. A continuum of MI data successfully provided a reliable assessment of maturation levels.
- In the hydrocarbon-bearing reservoir intervals, the MI data were found to indicate abnormally high maturation levels because of the gas effect.
- A careful distinction between reservoir and source intervals in unconventional source rocks having intraformational reservoir interbeds is necessary to determine correctly the organic richness and maturation of these potential source rocks.

Declaration of competing interest

All authors declare that they have no conflicts of interest, they have read and approved the manuscript and agree with its submission to Assiut University Journal of Multidisciplinary Scientific Research.

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