RESEARCH PAPER

Petrophysical evaluation of the pre-rift hydrocarbon reservoirs in the Gulf of Suez Basin

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Abstract

This study aims to perform an exhaustive petrophysical assessment to examine the oil potential in the pre-rift Late Cretaceous reservoirs along with the Eocene Thebes Formation within the Edfu–Saqqara field. This field locates in the central offshore region of the Gulf of Suez. This research employed wireline logs from four wells (GS323-1A, GS323-4A, Edfu A-3, and Edfu A-5A) drilled in the Edfu–Saqqara field. The detailed assessment of well logging data reveals encouraging petrophysical indicators for the Late Cretaceous sandstones, plus the limestones of the Thebes Formation in the studied Edfu–Saqqara field. These potential reservoirs exhibit moderate net pay thickness fluctuating between 10 and 150 ft, a fair-to-good net/gross ratio between 0.21 and 0.61, low shale content ranging from 0.00 to 0.10, good effective porosity in the range of 0.06–0.18, low water saturation varying between 0.10 and 0.30, and high hydrocarbon saturation ranging from 0.70 to 0.90. The main pre-rift oil reservoirs in the Edfu–Saqqara field encompass the pre-Cenomanian Nubia Formation together with the Coniacian–Santonian Matulla Formation. Accordingly, the current research presents the Late Cretaceous sandstones of Raha, Abu Qada, and Wata formations plus the Eocene carbonate of Thebes Formation as potential oil reservoirs within the pre-rift megasequence in Edfu–Saqqara field.

Keywords: Edfu–Saqqara field, Oil reservoirs, Petrophysical appraisal, Thebes formation, Upper Cretaceous

1. Introduction

The Gulf of Suez Basin (GOSB) stands as a significant and prolific hydrocarbon basin in Egypt, hosting numerous oil fields that exploit reservoirs ranging from Precambrian to Miocene age. The syn-rift sandstones (Miocene in age) account for around 60% of petroleum reserves in the GOSB, with the residual reserves often situated in the Nubia sandstones (i.e., pre-rift sandstones).1 Key to the petroleum architecture in the GOSB is structural fault-blocks, which were formed during the rifting period. These fault-blocks play a crucial role as primary petroleum traps and are instrumental in regulating petroleum accumulations within the oilfields of the GOSB.2 This geological setting underscores the significance of understanding the structural complexities and fault systems in the basin for effective exploration and production strategies. Well logs analysis is a vital tool for appraising the oil-reservoir potential in sedimentary basins. Well logging provides valued understandings into the properties of hydrocarbon reservoirs, offering crucial information that supports the development of exploration, besides production processes and simultaneously mitigating the associated risks. This geophysical tool represents a pivotal method in understanding subsurface conditions, such as rock properties, fluid content, and reservoir geometry, all of which are vital for making informed decisions throughout the lifecycle of oil and gas projects.3–11

The focus on the future exploration in the GOSB is crucial, considering the country’s growing energy needs. The specific objective of the study is to detect and assess the oil prospects of the Late Cretaceous–Eocene sequence in order to add a...
targeted dimension to the exploration efforts. By considering the Matulla Formation along with the well-established Nubia sandstones, the study aims to identify additional targets for hydrocarbon exploration in the pre-rift mega-sequence in the offshore GOSB. This approach underscores the importance of diversifying potential reservoirs to meet the energy demands of Egypt. Accordingly, this study performs a petrophysical assessment for the Late Cretaceous sandstone reservoirs (Raha Formation, Abu Qada Formation, and Wata Formation) and the Eocene carbonate reservoirs (Thebes Formation) in the Edfu–Saqqara field that is located in the central offshore GOSB (Fig. 1). The present study provides a more holistic understanding and broader significance beyond the specific locations in the offshore GOSB, by comprehensively examining the petrophysical characteristics of the Late Cretaceous and the Eocene reservoirs of the GOSB. The findings of this research will have broader implications and significance by suggesting that the interpreted reservoirs may extend into the Red Sea Basin, particularly in the Late Cretaceous–Eocene sediments in the eastern Red Sea provenance. Therefore, the study takes on a regional and international dimension. The anticipation that project results may contribute to the assessment and prediction of new oil targets, even extending into areas like Saudi Arabia, underscores the potential for valuable insights with far-reaching consequences.

2. Geologic setting

The Red Sea–GOSB rift originated in the Early-Miocene age and produced a series of normal faults, with orientations ranging from NW–SE to NNW–SSE. These normal faults, propagating in the NNW direction, exerted significant control over the Messinian succession within the Nile Delta Basin. The Nubia sandstones, stratigraphically representing the Cambrian–Early Cretaceous sedimentary sequence (i.e., Pre-Cenomanian), constitute about 17% of GOSB petroleum production. These sandstones can be categorized into three distinct depositional sequences, as identified by Salman et al.

The Cenomanian–Turonian succession comprises a combination of carbonate and clastics originating from the Raha Fm., which is superimposed by the Abu Qada and Wata formations. In terms of biostratigraphy, this sequence was intricately divided into five distinct ammonite zones. Notably, these intervals are contemporaneous with five corresponding foraminiferal zones.

The Raha Fm. besides Abu Qada Fm. was deposited during the Cenomanian and Turonian in a shallow marine environment under a ramp setting. The inner ramp had bivalves and benthonic foraminifera, transitioning to the mid ramp with echinoderms and oysters, and finally to the outer ramp with planktonic foraminifera. This sequence reflects changing environmental conditions and water depths along the ramp. The interval corresponding to the Cenomanian–Turonian boundary is situated in the lower section of the Abu Qada Formation. This section is distinguished by the occurrence of black shales and a diminished abundance of both foraminifera and ostracods.

However, the Wata Formation represents the Late Turonian in age and mainly composed of dolomite and fossiliferous limestone, with few streaks of shale, sandstone, and argillaceous limestone. It was deposited in a moderately shallow marine shelf or possibly lagoon. The Wata sandstones are predominantly composed of quartz, feldspar, and a lesser proportion of rock fragments. These sandstones contain quartz overgrowth and calcite cement. They are moderately to well-sorted, mature, and exhibit fine to very fine-grained texture, with subangular to subrounded grains and a notable presence of clayey material, as detailed by Farouk et al. Additionally, the pore system within the Wata sandstones is characterized by primary intergranular porosity, displaying good pore connectivity. Furthermore, secondary porosity is induced by the alteration of feldspar grains along cleavage planes, contributing to the development of additional pore space.

On the other hand, the limestones of Thebes Fm. were laid down during the significant Tethyan transgression on the northeastern region of Africa during the Eocene period. These limestones are recognized as potential source rocks, exhibiting a total organic carbon content of 3.2%, primarily consisting of type-I/II kerogens. Moreover, the fractured limestones within the Thebes Fm. contribute approximately 1.1% of the oil production in the Gulf of Suez Basin (GSB). These limestones exhibit porosity of 13%, and the net pay thickness varies within the range of 15–17 m. Several fields, including, Asal, Rahmi Kareem, Sudr, Ras Matarma, Bakr, Issaran, Shaob, West Bakr, and Ali, are noteworthy for extracting oil from the entire carbonate reservoirs within the Thebes Formation, as detailed by Alsharhan.

3. Data and techniques

This research utilizes the mud logs as well as the conventional wireline logs obtained from four wells (GS323-1A, GS323-4A, Edfu A-3, and Edfu A-5A) within the Edfu–Saqqara field, an offshore field located in the central region of the GOSB (Fig. 1).
Fig. 1. (A) Map displays the location of the Edfu–Saqqara Field in the Gulf of Suez Basin. (B) Map shows the four well locations in Edfu–Saqqara Field.
The study commenced with the examination of mud logs to identify potential reservoir zones in the analyzed wells. Subsequently, wireline logs were employed to compute the key petrophysical parameters. The calculations of shale volume and porosity were based on the equations proposed by Asquith and Gibson.24 However, the water saturation has been inferred following the Indonesian model.25 It is worth mentioning that the applied cutoff values for the reservoir zones through the quantitative appraisal step in the examined wells are shale volume less than or equal to 0.20, effective porosity greater than or equal to 0.10, and water saturation greater than or equal to 0.35.

4. Results

The visual inspection of the mud logs available for the studied wells in the Edfu—Saqqara field reveals that the sandstone within the Raha, Abu Qada, and Wata formations, along with the limestone in the Eocene Thebes Formation, displays promising indications of oil retention. These encouraging criteria encompass the observation of an oil stain and elevated values in gas chromatographic analyses.

4.1. Late Cretaceous reservoirs

Since the Wata Formation is the thickest Late Cretaceous reservoir in the examined wells (65–238 ft thick), its entire sandstones were described in the available mud logs. These sandstones are colorless, fine to very fine-grained, infrequently coarse-grained, grade to silt size, subrounded to rounded, loose, moderately hard to hard, with silica cement, moderately sorted, spotty dark-brown oil stain, golden-yellow oil fluorescence, yellow stream-cut, and yellow crush-cut. However, the intercalated shale beds exhibit gray, light gray, tannish gray, subblocky to blocky, soft, rare glauconitic, rare pyritic, nonsiliceous, and noncalcareous. Upon qualitative analysis of the wire-line logs for the Raha, Abu Qada, and Wata formations in the examined wells, it is evident that three wells meet the favorable criteria, suggesting that the sandstones within these formations hold promise as potential oil reservoirs. Specifically, the wells identified as meeting these standards are Edfu A-3, GS323-1A, and GS323-4A, as illustrated in Fig. 2. The favorable standards used for evaluating the potential of these reservoirs include several key criteria. These criteria involve the clean nature of the reservoir zones, as indicated by low shale volume, which is corroborated by low gamma-ray readings and photoelectric log readings around two. Additionally, the presence of high deep-resistivity logs is considered, reflecting the likely attendance of hydrocarbons. Furthermore, the high-porosity values observed in the neutron logs provide additional confirmation of the good quality of the potential reservoirs in question. Furthermore, these hopeful standards contain the distinguished crossover shape between the density and neutron curves, which authorizes the sandstone matrix. These combined indicators contribute to the assessment of the examined formations as promising oil reservoirs in wells such as Edfu A-3, GS323-1A, and GS323-4A.

The calculated petrophysical properties for sandstone reservoir zones within these formations across three promising wells reveal varying thicknesses, ranging from 10 ft in the Edfu-A3 well to 80 ft in the GS323-4A well. Among the wells, GS323-4A stands out with the highest-recorded net/gross ratio of 0.61, while the lowest value, 0.21, is noted in the GS323-1A well. The Wata reservoirs in GS323-4A and Edfu-A3 wells exhibit the highest shale volume at 0.10, whereas the lowest values of 0.00 are documented within the Raha reservoir in Edfu-A3 well and the Abu Qada reservoir in GS323-4A well. Maximum effective porosity, reaching 0.18, is identified in the Abu Qada reservoir in the GS323-4A well, while the minimum value of 0.10 is observed in the Wata reservoir in the same well. Regarding saturation, Wata sandstones in the GS323-4A well show a maximum water saturation of 0.30 and the smallest hydrocarbon saturation of 0.70. In contrast, Raha sandstones in the Edfu-A3 well and the Abu Qada reservoir in the GS323-4A well exhibit the minimum water saturation of 0.10 and the highest hydrocarbon saturation of 0.90 (see Table 1). These detailed findings provide critical insights for the assessment and management of sandstone reservoirs of the Late Cretaceous sequence in the context of hydrocarbon exploration and production.

4.2. Eocene reservoirs

The limestone of Thebes Formation was defined in these mud logs as composed of brownish gray, occasionally dark tannish, cryptocrystalline to very fine-cristalline, moderately hard to hard, argillaceous, occasionally highly argillaceous, carbonaceous, mottled, with sharp-edge chert fragments, and no visible porosity. However, the qualitative examination of the wire-line logs for the limestone of the Thebes Formation in the studied wells indicates that only two wells have the favorable standards for considering the entire limestones as promising oil reservoirs. These wells are Edfu A-3 and GS323-4A as highlighted in Fig. 3. These favorable standards comprise the clean nature of the reservoir zones with
Fig. 2. Well logging data with assessment for the Raha, Abu Qada, and Wata reservoirs in the inspected wells.
low shale volume, as confirmed by low gamma-ray readings and photoelectric log readings around four, the high deep-resistivity log reflecting the hydrocarbon attendance, and the high-porosity readings of the neutron logs approving the good quality of the potential reservoirs. Besides these optimistic standards, both density and neutron curves track each other, which authorize the limestone matrix.

The analyzed petrophysical properties for the identified reservoir zones within the Thebes limestones in the Edfu A-3 and GS323-4A wells reveal variations in thickness. Specifically, the pay zones range from 100 ft in the Edfu A-3 well to 150 ft in the GS323-4A well. The net/gross ratio fluctuates between 0.36 and 0.43 in both wells, while the shale volume remains constant at 0.10. Moreover, the effective porosity differs between 0.06 and 0.08 in both wells. Notably, the Edfu A-3 well exhibits a maximum water saturation of 0.20, corresponding to a minimum hydrocarbon saturation of 0.80. In contrast, the GS323-4A well records a minimum water saturation of 0.10 and the highest hydrocarbon saturation of 0.90. Accordingly, these findings provide valued insights into the reservoir’s characteristics, including thickness, composition, and fluid content. Such information is crucial for effective reservoir evaluation and management in the realm of hydrocarbon exploration and production from the Thebes limestones.

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<th>Depth to base (ft)</th>
<th>Gross thickness (ft)</th>
<th>Net pay thickness (ft)</th>
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5. Discussion

With over 80 oil fields, the GOSB extracts oil and gas from reservoirs ranging from the Precambrian to the Pliocene. The Miocene reservoirs, identified as syn-rift reservoirs, account for about 60% of the GOSB’s petroleum reserves, while the rest is commonly found in the Nubia sandstones.

This study provides a deeper understanding of the petrophysical characteristics of the Late Cretaceous–Eocene reservoirs (Raha, Abu Qada, Wata, and Thebes formations), presenting them as potential additional oil targets alongside the well-established Pre-Cenomanian Nubia sandstones as well as the Coniacian–Santonian Matulla sandstones within the GOSB. As a result, the significance of the present study lies in its crucial role in augmenting petroleum reserves and enhancing the prospects of discovering additional hydrocarbon reservoirs within the GOSB. These findings are pivotal in addressing the escalating demand for energy supplies in the country. The qualitative and quantitative assessment of wireline log data conducted on four drilled wells has indicated the presence of potential oil-bearing zones in three specific wells. These identified wells are Edfu A-3,
GS323-1A, and GS323-4A. The recognized potential reservoirs demonstrate a moderate net pay thickness, spanning from 10 to 150 ft. Additionally, they exhibit a fair-to-good net/gross ratio, falling within the range of 0.21–0.61. These reservoirs show low shale content, ranging from 0.00 to 0.10, and possess good effective porosity, with values in the range of 0.06–0.18. Moreover, they display low water saturation, varying between 0.10 and 0.30, and high hydrocarbon saturation, ranging from 0.70 to 0.90. The average values for the calculated petrophysical parameters for all of these promising zones within the whole Late Cretaceous–Eocene section are shown in Fig. 4. The mention of the interpreted reservoirs potentially extending beyond the examined area into the Red Sea Basin adds an intriguing dimension. The anticipation that project results may aid in assessing and predicting new oil targets through the Late Cretaceous–Eocene sediments in the eastern Red Sea provenance, including Saudi Arabia, underscores the regional and potentially international implications of the findings. This perspective enhances the study’s relevance and impact in the context of broader geological

Fig. 3. Well logging data with assessment for the Thebes reservoir in the inspected wells.
considerations. Accordingly, this perspective not only enhances the study’s relevance but also positions it within the context of broader geological considerations and regional exploration strategies. The potential impact on the understanding of petroleum systems beyond the immediate study area adds a layer of significance to the research, making it relevant to a wider audience and contributing to the collective knowledge in the field.

5.1. Conclusions

(1) The detailed petrophysical assessment exhibits optimistic petrophysical signs for the sandstones of the Raha, Abu Qada, and Wata formations as well as the limestones of the Thebes Formation, for being possible reservoirs in the Edfu—Saqqara Field, offshore Gulf of Suez Basin.

(2) These reservoirs show moderate net pay thickness (10–150 ft), fair-to-good net/gross ratio (0.21–0.61), low shale content (0.00–0.10), good effective porosity (0.06–0.18), low water saturation (0.10–0.30), and high hydrocarbon saturation (0.70–0.90).

(3) Consequently, this study enhances our comprehension of the petrophysical attributes of the Late Cretaceous—Eocene reservoirs, including the Raha, Abu Qada, Wata, and Thebes formations. It identifies these formations as potential additional oil targets, supplementing the already well-established Pre-Cenomanian Nubia sandstones and the Coniacian—Santonian Matulla sandstones in the Gulf of Suez Basin.

Authors contribution

All authors were equally contributed.

Conflicts of interest

There are no conflicts of interest.

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