



# Geophysical appraisal and oil potential for Rudeis Formation at West Hurghada area, southern Gulf of Suez: detection of stratigraphic trap

Mohammad Abdelfattah Sarhan<sup>1</sup>

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## Abstract

This study suggests a suitable stratigraphic trap in West Hurghada area at the southwest Gulf of Suez Basin based on the interpretation of seismic and well logging data. This stratigraphic trap formed by lateral and vertical facies change from porous limestone to massive marl within Rudeis Formation. The examination of the available mud logs revealed that Rabeh East-22 Well displays positive criteria opposite a thick limestone interval between depths 4550 and 4630 ft (zone 1) to be considered a potential oil-bearing zone. This thick limestone bed did not appear in the other examined wells (Nageh-1, Rabeh East-8, and Rabeh East-25) which are so close to Rabeh East-22 Well confirming the lateral facies change. The expected stratigraphic trap on seismic data extends for about 1.5 km in north-south direction and for 0.75 km in east-west direction throughout the study area. The quantitative petrophysical analysis for this thick limestone interval (zone 1) in Rabeh East-22 Well indicated that the interval between 4569 and 4595 ft (26-ft thick) represents the most promising interval within zone 1. This promising interval reflects good reservoir characteristics with average hydrocarbon saturation of 53%, average shale volume of 21%, average total porosity of 20%, average effective porosity of 15%, and average bulk volume of water of 0.07.

**Keywords** Stratigraphic trap · Geophysical appraisal · Hydrocarbon potential · Rudeis Formation · West Hurghada area · Gulf of Suez

## Introduction

Gulf of Suez Basin is one of the most promising areas for oil production in Egypt. It represents an intercontinental rift that disconnects Sinai Peninsula from the Eastern Desert (Fig. 1), stretching for about 325 km to the north from the Hurghada city in the south (El Nady et al. 2016). Although its rifting phase is initiated in the Miocene times, both pre-rift and post-rift mega-sequences hold source rocks rich in organic matter and hydrocarbon reservoirs ranging in age from Paleozoic to Miocene characterizing the high potentiality for petroleum exploration (Shahin and Shehab 1984; Egyptian General Petroleum Corporation (EGPC) 1996; Atta et al. 2002). The structural fault blocks originated at the rifting time displays

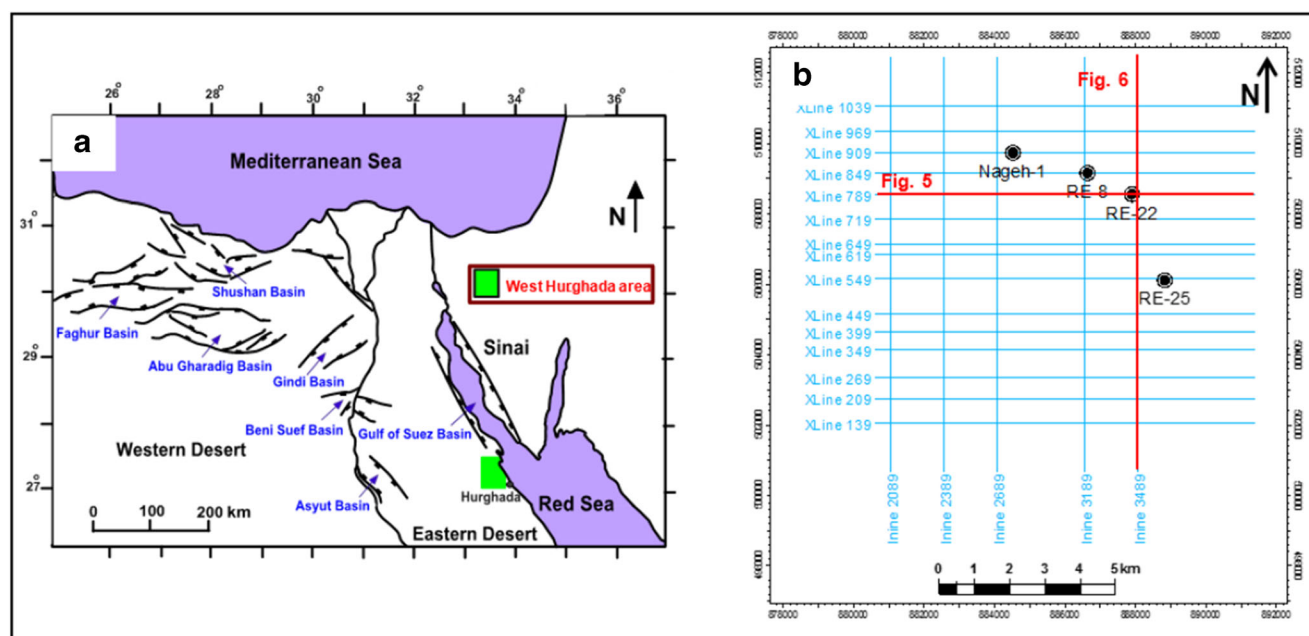
the main hydrocarbon traps in the Gulf of Suez area (Chowdhary and Taha 1987), and the existing faults have a direct or indirect effect on petroleum accumulations in it (Sultan 2002). The Gulf of Suez Basin is characterized by complicated depositional and structural patterns resulting from the superimposed syn-rift extension fault systems over the pre-rift structures (Abul Karamat and Meshref 2002).

Rudeis Formation was deposited in the Lower Miocene age under shallow to deep marine settings in the Gulf of Suez provenance (Alsharhan and Salah 1994). It conformably overlies the Lower Miocene Nukhul Formation and conformably underlies the Middle Miocene Kareem Formation (Takasu et al. 1982). In its type locality, Rudeis Formation attains a thickness of about 2550 ft and composes mainly of sandy shale. This shale is highly calcareous with abundant planktonic foraminifera (Metwalli et al. 1978). The entire body of Rudeis Formation contains several unconformities (El Sharawy and Nabawy 2018). The sandstones of Rudeis Formation are oil producing in different oil fields such as Belayim, Sudr, Feiran, Asl, Kareem, and Um El-Yusr fields (Metwalli et al. 1978; Zaid 2012) in addition to the off-shore part of October Field in Sinai (Nabawy et al. 2018). The

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✉ Mohammad Abdelfattah Sarhan  
msarhan@du.edu.eg; msarhan12@yahoo.com

<sup>1</sup> Geology Department, Faculty of Science, Damietta University, New Damietta City 34517, Egypt



**Fig. 1** a Regional map represents the location of West Hurghada area in the southwest Gulf of Suez provenance (simplified after Bosworth et al. 2008). b Area of study with seismic lines and well locations

Upper Rudeis reservoir rocks are enormously heterogeneous since it includes multiple lithologies, porosity, permeability, and pore fluids (Afify and Hassan 2013). The clastic microfacies of Rudeis Formation may display good or poor reservoir quality based on the impacts of fracturing and dissolution diagenetic processes (Nabawy et al. 2019).

Moreover, the clastic-rich sediments in the Rudeis Formation represent potential source rocks in the Miocene sequence in the Gulf of Suez provenance (El Srogy et al. 2002; El Sharawy and Nabawy 2018). The Lowermost part of the Rudeis Formation deposited during the maximum subsidence rate of the Gulf of Suez rifting phase (Steckler et al. 1988). However, the mid-Rudeis deposited within the mid-Clysmic event (around 16.5 Ma) within which the subsidence rate and accordingly the sedimentary and structural patterns were totally changed (Evans 1988).

Stratigraphic traps are formed when hydrocarbon accumulate independent of fold or fault closure. Many stratigraphic traps were discovered by accident during drilling for a structural trap, because they are difficult to be recognized on seismic sections (Dolson et al. 1999). Accordingly, seismic data quality plays a vital role in hunting these stratigraphic traps and should have high resolution to make these traps obvious (Dolson et al. 2017). Most of stratigraphic traps represent thin hydrocarbon column heights and are usually characterized by leaky seals especially lateral seals (Dolson et al. 1999). Moreover, structural traps usually have several stacked pay zones and, accordingly, more volume per area and require only an effective top seal, whereas the stratigraphic traps require top, lateral, and bottom seals (Dolson et al. 2017).

Stratigraphic traps recently become vital targets for hydrocarbon exploration in the Gulf of Suez provenance. There are some confirmed stratigraphic traps formed by lateral and vertical facies change from porous carbonate wedge to massive carbonate in the Miocene section at Ras El Bahar area. However, in Belayim Land Oil field, the porous Miocene sandstone forms lenses which are vertically and laterally sealed by evaporites (Abd Elhady et al. 2017).

The study area located between latitudes  $27^{\circ} 9' 36.324''$  N and  $27^{\circ} 17' 0.753''$  N and longitudes  $33^{\circ} 39' 16.866''$  E to  $33^{\circ} 47' 56.145''$  E, representing the West Hurghada area on the southwestern margin of the Gulf of Suez region (Fig. 1). It contains several oil fields and is penetrated by many wells. The Nubia and Matulla Formations (pre-rift rock units) at West Hurghada oil fields display high-quality reservoirs with high net pay thickness. They represent low shale volume, high effective porosity, and low water saturation (Abd El Gawad et al. 2016; Sarhan and Basal 2019).

Since the Rudeis Formation represents one of the chief hydrocarbon reservoirs in the Gulf of Suez provenance, it is very important to perform geophysical appraisal for this formation to add new reserves in the West Hurghada oil fields. Consequently, the present work purposes to investigate and evaluate the Rudeis Formation at West Hurghada area through seismic interpretation and well log analysis. Moreover, this study is aiming to suggest a suitable stratigraphic trap in West Hurghada area, since stratigraphic traps represent a challenge in their detection everywhere especially in the Gulf of Suez provenance where most of the explored hydrocarbon is produced from structural traps.

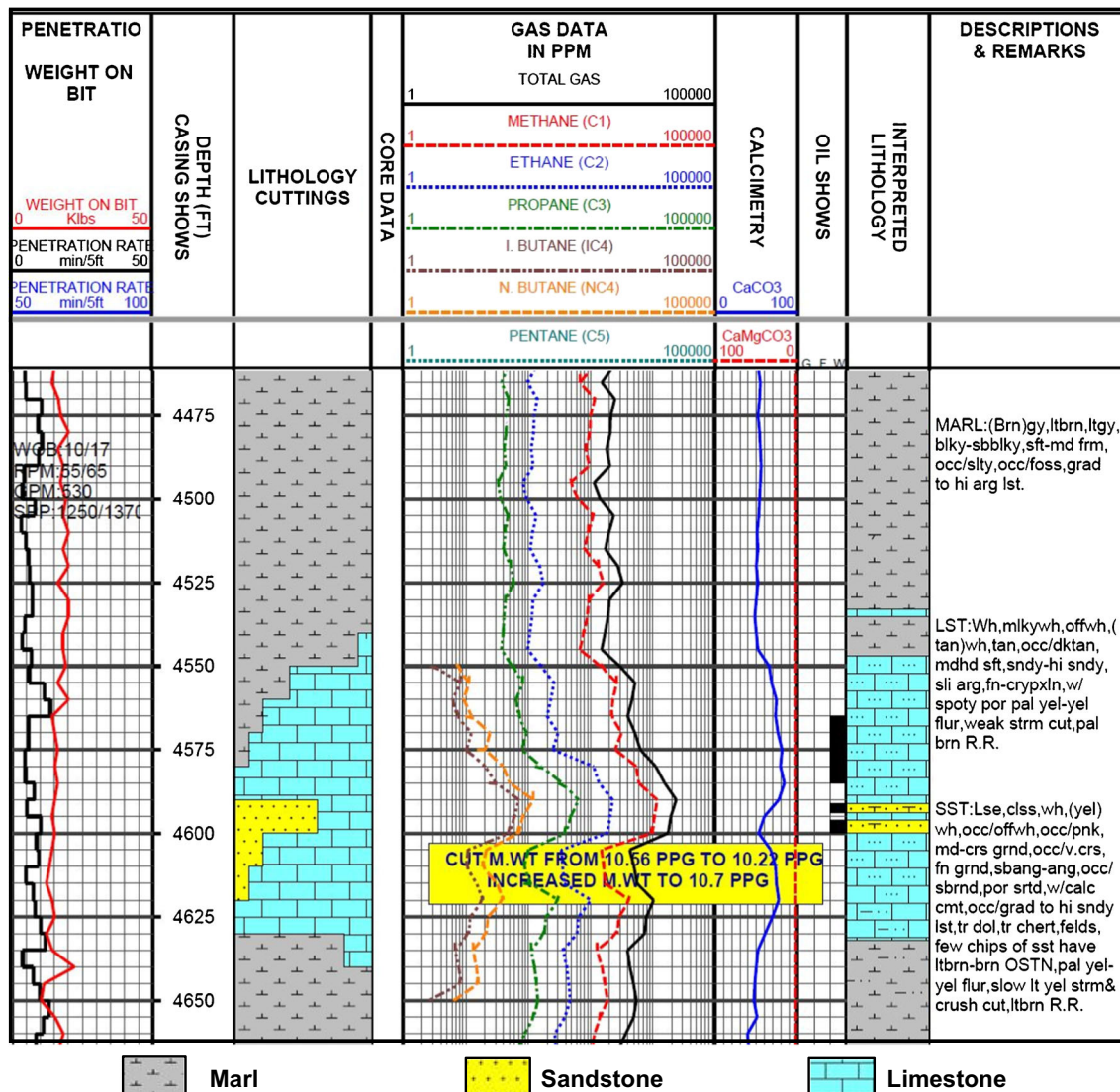


Fig. 2 Mud log shows the lithology and the ditch gas analysis for the Rudeis Formation in Rabeah East-22 Well. Note the presence of oil shows and the highest values of ditch gas analysis opposite to the thick limestone interval (zone 1) between depths 4550 and 4630 ft which topped and based by marl

**Available data**

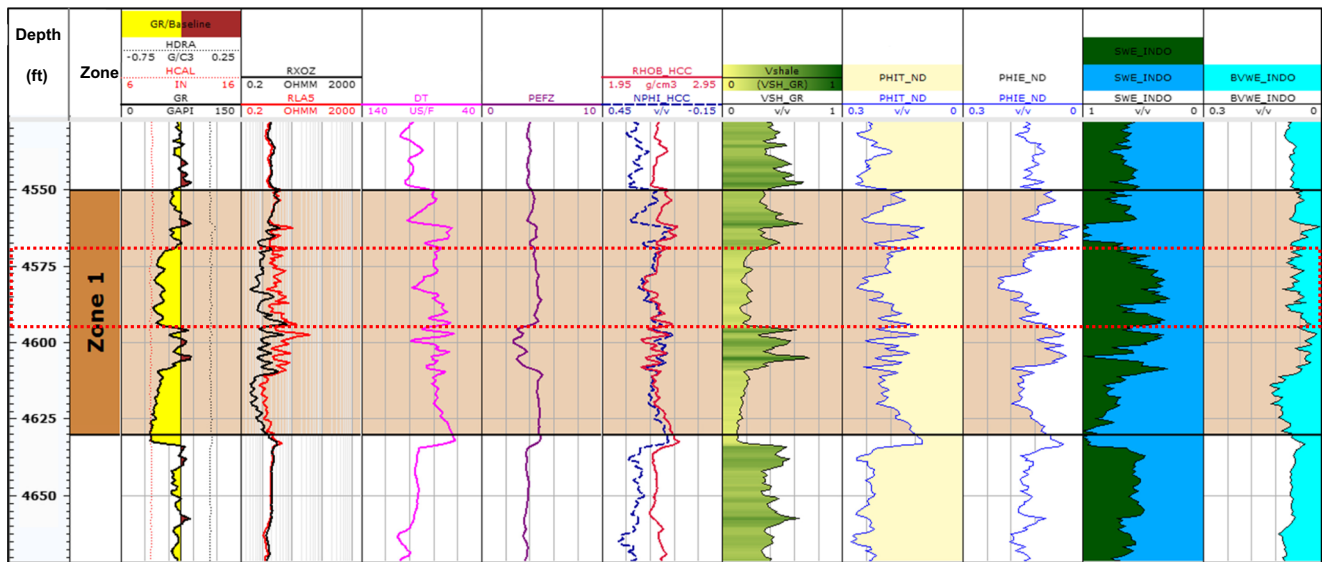
The available geophysical data in this study includes twenty 2D seismic reflection profiles; five profiles are extending north-south, and fifteen seismic sections have east-west trend (Fig. 1). These seismic data are tied to four wells distributed in the study area: Nageh-1, Rabeah East-8 (RE-8), Rabeah East-22 (RE-22), and Rabeah East-25 (RE-25) as displayed in Fig. 1. The conventional well log data for the four wells are also available including Caliper (HCAL), Density Correction (HDRA), Gamma Ray (GR), Sonic ( $\Delta T$ ), Micro Spherical Resistivity (RXO), Deep Resistivity (RLA5), Neutron Porosity (TNPH), and Density (RHOZ) and Photoelectric (PEFZ) logs. Moreover, the mud logs for these four wells are accessible in this study. Each mud log encompasses the

penetration rate, gas analysis, and oil shows, which are helpful in referring to the potential hydrocarbon zones in addition the interpreted lithology.

**Results and discussion**

Based on the mud logs for the four wells, the lithology of the Rudeis Formation is essentially composed of marl intercalated with shale and sandy limestone interbeds. The visual scanning for the Rudeis Formation in the mud logs of the examined wells shows that Rabeah East-22 Well is the only well that displays oil shows, opposite to thick limestone bed within Rudeis Formation between depths 4550 and 4630 ft (zone 1), as shown in Fig. 2. These optimistic criteria are also confirmed by the high values of gas analysis opposite to this zone





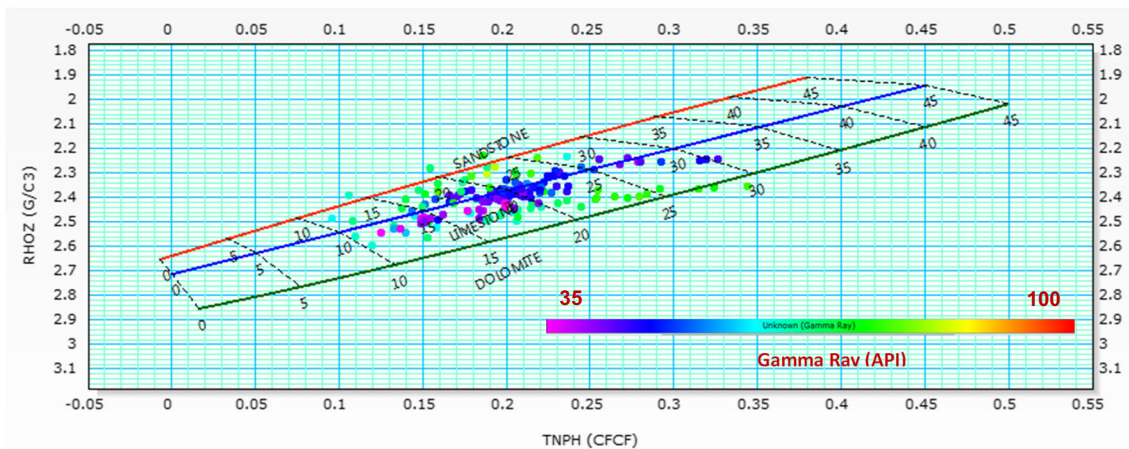
**Fig. 3** Petrophysical logs represent zone 1 (between depths 4550 and 4630 ft) Rudeis Formation in Rabeh East-22 Well. Note that the interval that locates between depths 4569 to 4595 ft (outlined by red rectangle) displays the best promising hydrocarbon-bearing interval

interval. This gas analysis displays the existence of methane (C1), ethane (C2), propane (C3), isobutane (IC4), normal butane (NC4), and pentane (C5), with total gas value reaches 10,000 ppm (Fig. 2). The existence of this combination of alkanes supports the presence of oil in zone 1 within Rabeh East-22 Well. This zone of interest was 80-ft thick and composed mainly of limestone: white, milky white, off white, tannish white, occasionally dark tannish white, moderately hard to soft, sandy to high sandy, fine to cryptocrystalline. This limestone displays oil stains with spotty pale yellow to yellow fluorescence and weak stream cut (Fig. 2). There are two thin sandstone beds between depths 4590–4600 ft. These sandstones are loose, colorless, white, yellow, off white, occasionally pink, medium to coarse grained, occasionally very coarse grained, and fine-grained, sub-angular to angular, occasionally sub-rounded, and poorly sorted with calcareous cement. Few chips of these sandstones have light brown to

brown oil stains, pale yellow to yellow fluorescence, and slow yellow streaming cut (Fig. 2).

From the above description, it can be concluded that the interval between depths 4550 and 4630 ft in Rabeh East-22 Well must be considered for further qualitative and quantitative well logging examination. The quantitative inspection involves the calculations of different petrophysical parameters required for characterizing the hydrocarbon potentiality. These parameters include shale content, porosity (total and effective), and water saturation, and bulk volumes of water have been performed using the Techlog Wellbore Software Platform of Schlumberger.

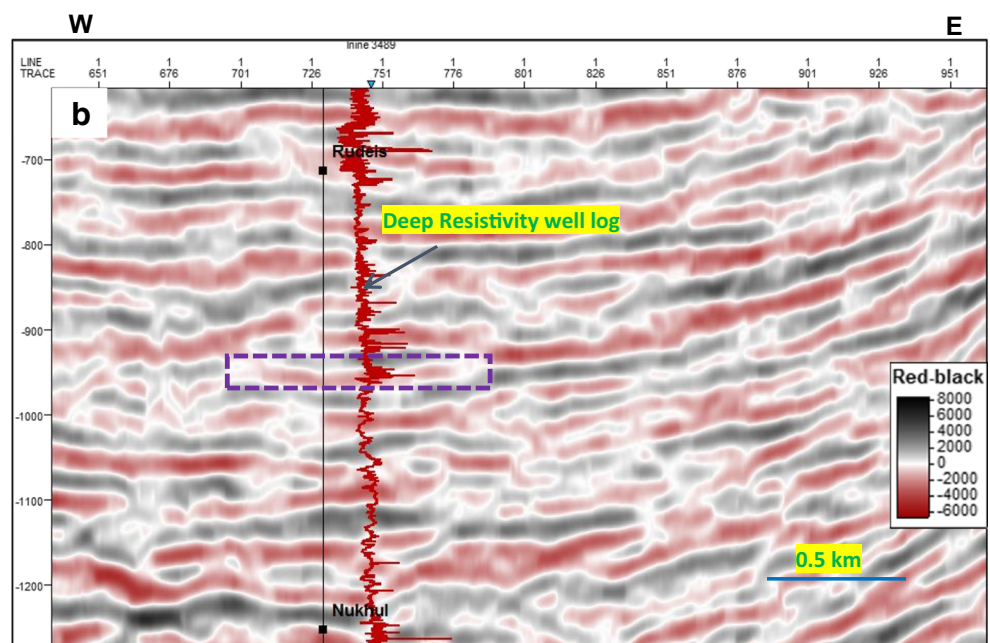
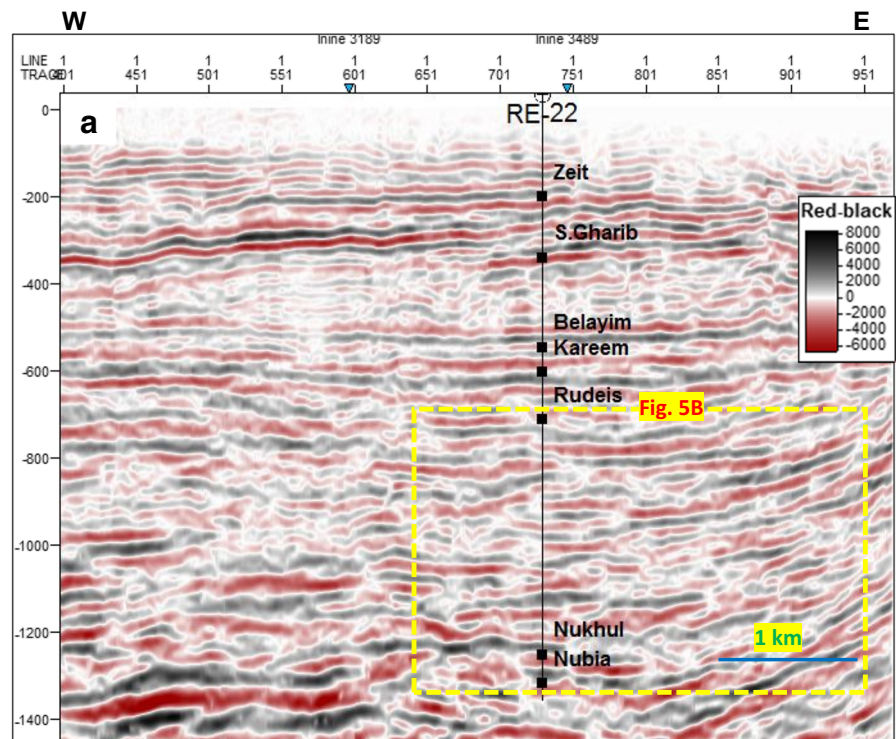
The visual inspection for the well log curves representing zone 1 (between depths 4550 and 4630 ft) within Rudeis Formation in Rabeh East-22 Well (Fig. 3) refers to good bore hole condition, since the density correction (HDRA) is zero. Zone 1 is also characterized by the occurrence of little amount



**Fig. 4** Neutron-density crossplot (Schlumberger 1972) for the whole zone 1 between depths 4550 and 4630 ft in Rabeh East-22 Well

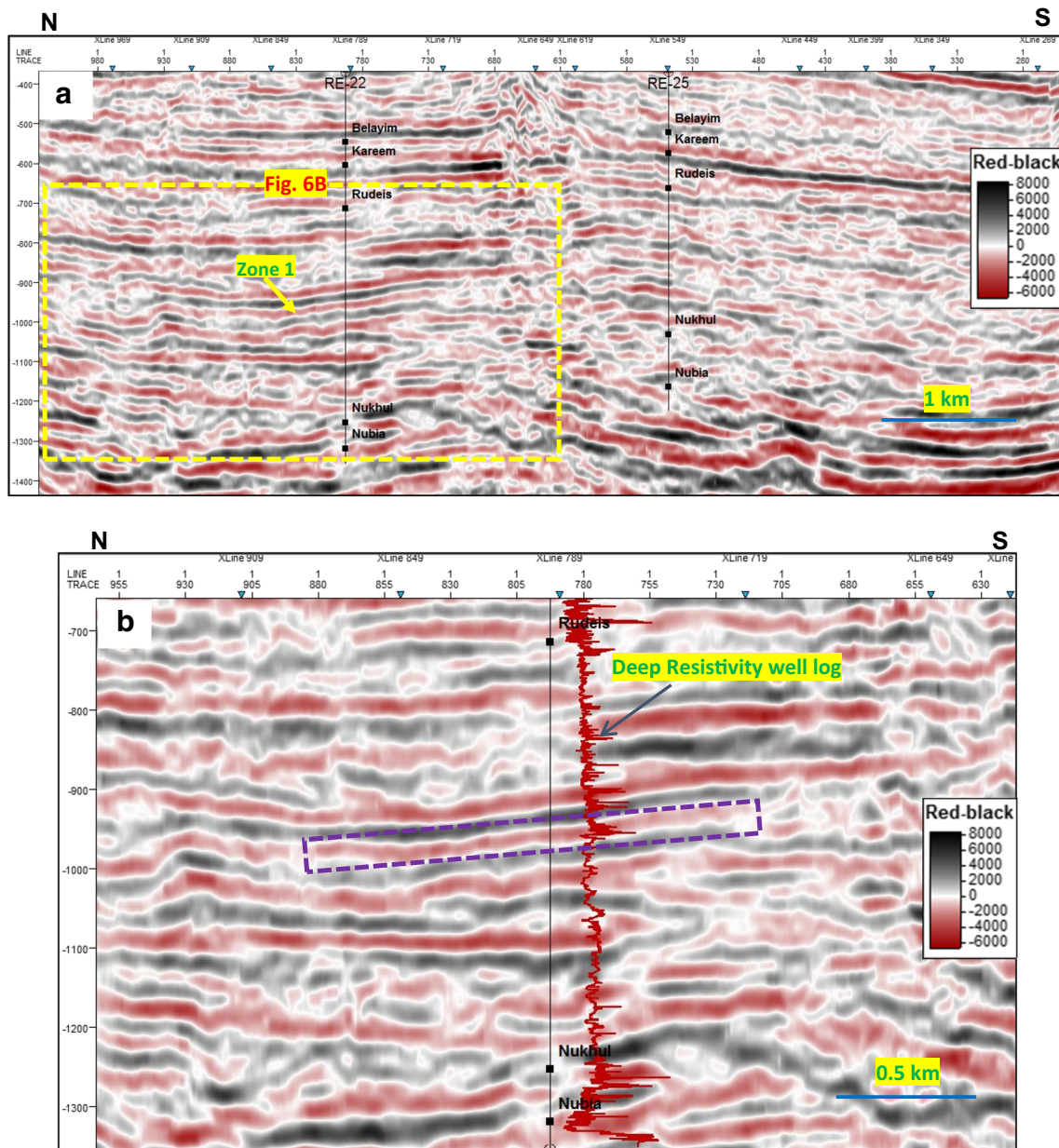


**Fig. 5** **a** East-west seismic cross-line No. 789 displays the entire seismic reflectors of Rudeis Formation as tied to Rabeh East-22 Well. **b** Zoomed part outlined by yellow rectangle in panel **a** shows that the seismic reflector (delineated by purple rectangle) representing the examined limestone bed (zone 1) displays a trough (red in color) rather than the expected peak of seismic wave, since the limestone is topped by marl (less dense than limestone), confirming that the examined limestone is not massive (porous limestone). Note that the seismic reflector corresponding to zone 1 exhibits a stratigraphic trap that (continuous reflector without any fault or fold effect) extends for about 0.75 km long in this east-west seismic section. Also, note the high value of deep resistivity curve (red wireline log shifted to right) within the examined reflector confirming the presence of hydrocarbon



of shale associated with the limestone matrix (slightly shaly limestone), which is evidenced by the relative low gamma ray values (range from 40 to 60 API). Moreover, the sonic curve displays that values vary between 70 and 80  $\mu\text{s}/\text{ft}$  (Fig. 3). The deep resistivity curve shows that values vary between 1 and 7  $\Omega\text{m}^2/\text{m}$  and display a separation with the micro spherical resistivity curve (Fig. 3). The presence of this positive separation between RLA5 and RXO (i.e., RLA5 > RXO) reflects the

invasion for the fluids of the drilling mud in addition to the hydrocarbon movability through the examined zone. This reveals the existence of hydrocarbon and permeability in zone 1. The density curve is relatively close to neutron curve, and the Photoelectric Absorption Factor (PEF) curve displays value around 4.5 b/e, reflecting the abundant limestone matrix except for depths between 4592.5 and 4610 ft, where the PEF varies between 2.62 and 3.29, which may be attributed to the



**Fig. 6** **a** North-south seismic in-line No. 3489 as tied to Rabeh East-22 Well. Note that the yellow arrow refers to the seismic reflector corresponding to zone 1, which is represented by continuous horizon and expressed by seismic wave trough. **b** Zoomed part outlined by yellow rectangle in panel **a** shows that the examined seismic reflector

(stratigraphic trap) which is delineated by purple rectangle extends for 1.5 km long in the north-south direction. Also, note the high deep resistivity curve (red wireline log shifted to right) within the examined reflector confirming the presence of oil

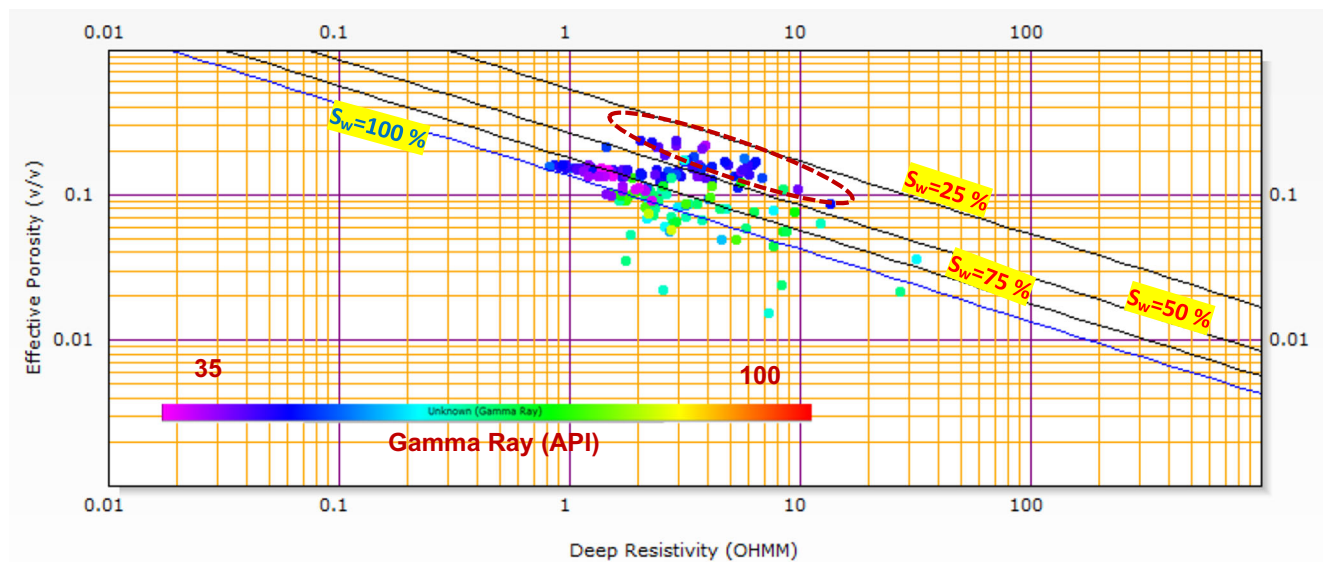
presence of argillaceous sandstone or shale streaks (Fig. 3). Moreover, the neutron-density crossplot (Schlumberger 1972) for zone 1 (Fig. 4) shows that most of plotted points clustered around the limestone line (reflecting that the pay zone is mainly limestone in lithology), with porosity values ranging from 15 to 30%.

Accordingly, the qualitative inspection for the well logs raw data reveals that zone 1 displays the most positive signs for the presence of hydrocarbon in Rabeh East-22 Well. These

criteria include the variation in the resistivity curves and the high porosity values with relatively low shale contents.

On the other hand, the seismic reflector corresponding to zone 1 within Rudeis Formation on the interpreted seismic profiles is represented by relatively moderate amplitude reflector (Figs. 5 and 6). This reflector extends for about 0.75 km long in the east-west direction (Fig. 5) and for about 1.5 km long in the north-south direction (Fig. 6) throughout the study area.





**Fig. 7** Pickett plot for zone 1 within Rudeis Formation in Rabeh East-22 Well. Note that the plotted points located between  $S_w = 50\%$  line and  $S_w = 25\%$  line (outlined by red circle) represent the promising interval for hydrocarbon potentiality within zone 1

The seismic sections display an important observation which can be used as a confident criteria for the existence of secondary porosity (e.g., vuggy or fracture) in this zone, since the lithologic description in mud log for the limestone of zone 1 is fine to cryptocrystalline as described above. This observation concerns with the nature of the seismic reflector representing zone 1 on seismic sections. This reflector displays a trough (red in color in the currently applied seismic attributes) (as shown in Figs. 5 and 6), although the transition from marl to limestone in lithology expected to produce peak (black in color in the currently used seismic attributes) in the seismic wave because massive limestone is expected to be harder than the overlying massive marl and consequently has higher velocity and density than marl. But the change in the seismic wave behavior from the expected peak to the present trough is attributed to the lower acoustic impedance (density times velocity) in the limestone of zone 1 than the overlying marl. This supports that the limestone of zone 1 contains type of secondary porosity (not massive limestone) that led to this lower acoustic impedance than the covering massive marl. This secondary porosity declines the overall density of the entire limestone and decreases the velocity of the reflected seismic wave (Sarhan et al. 2017). Accordingly, the contrast in acoustic impedance gives negative polarity which resulted in a red trough not black peak as expected in the case of massive limestone instead. In this concern, the applying of different seismic attributes may be effective to differentiate between non-massive (porous) and massive carbonate sedimentary successions on seismic data (Sarhan 2017).

Water saturation for zone 1 has been also graphically represented using Pickett plot (Pickett 1972) in order to have a general evaluation for hydrocarbon saturation in this zone. Pickett plot has been constructed using connate

water resistivity ( $R_w$ ) equal to  $0.018 \Omega m^2/m$  (according to Ganoub El-Wadi Petroleum Company), cementation exponent ( $m$ ) set equal to 2, saturation exponent ( $n$ ) set equal to 2, and tortuosity factor ( $a$ ) set equal to 1. The constructed Pickett plot shows that the plotted points clustered between the line of  $S_w = 25\%$  (hydrocarbon saturation equals 75%) and line of  $S_w = 50\%$  (hydrocarbon saturation equals 50%), as displayed in Fig. 7. This result matches the qualitative analysis, which specifies the promising nature of zone 1 for being a hydrocarbon-bearing zone.

The calculations of the most common well logging parameters for zone 1 show that the most promising interval is located between depths 4569–4595 ft (26-ft thick) within zone 1. This promising zone has average total porosity equals to 0.20; the average shale volume is 0.21 and the average effective porosity is 0.15, as shown in Fig. 3 and summarized in Table 1. Regarding to the water saturation, the presence of shale in the inspected zone 1 makes Archie water saturation equation (Archie 1942) unsuitable to be applied. Accordingly, the Indonesian model (Poupon and Leveaux 1971), which comprises a correction to Archie’s equation in case of presence of shale, has been used for calculating water saturation. Water saturation according to this model can be calculated as follows:

$$S_w = \left[ \frac{\sqrt{\frac{1}{R_t}}}{\left( \frac{V_{sh}^{(1-V_{sh})/2}}{\sqrt{R_{sh}}} \right) \left( \frac{\sqrt{\rho_w^m}}{aR_w} \right)} \right]^{2/n}$$

where  $R_t$  = deep resistivity ( $\Omega m^2/m$ ),  $R_{sh}$  = shale resistivity ( $\Omega m^2/m$ ),  $R_w$  = connate water resistivity ( $\Omega m^2/m$ ) (has been given from Ganoub El-Wadi Petroleum Company and set equal



**Table 1** Log evaluation table for the most promising zone interval within Rudeis Formation in Rabeh East-22 Well

Raw data											Results				
DEPT (ft)	HCAL (IN)	HDRA (G/C3)	GR (GAPI)	DT (US/ F)	RXO ( $\Omega\text{m}^2/m$ )	RLA3 ( $\Omega\text{m}^2/m$ )	RLA5 ( $\Omega\text{m}^2/m$ )	TNPH	RHOZ (G/C3)	PEFZ (B/E)	PHIT_ND	PHIE_ND	VSH_GR	Sw	BVW
4569	8.71	0.00	61.95	74.11	1.71	6.41	7.71	0.18	2.47	4.38	0.15	0.08	0.31	0.48	0.04
4570	8.57	0.00	52.88	76.61	1.30	1.78	2.19	0.16	2.41	4.43	0.16	0.11	0.23	0.71	0.08
4571	8.51	0.00	52.69	78.46	0.90	2.29	2.69	0.22	2.38	4.28	0.20	0.14	0.23	0.51	0.07
4572	8.46	0.00	49.87	78.49	1.29	2.19	2.65	0.19	2.40	4.36	0.18	0.13	0.21	0.57	0.07
4573	8.52	-0.01	47.44	80.16	0.87	2.54	2.98	0.20	2.36	4.47	0.19	0.15	0.19	0.49	0.07
4574	8.51	0.00	49.84	80.09	0.82	1.31	1.58	0.20	2.39	4.47	0.19	0.14	0.21	0.69	0.10
4575	8.44	0.01	47.88	80.26	0.87	2.40	3.08	0.19	2.40	4.49	0.18	0.13	0.20	0.52	0.07
4576	8.39	0.00	53.09	77.19	0.89	2.20	2.90	0.20	2.36	4.49	0.19	0.14	0.23	0.51	0.07
4577	8.42	0.00	48.76	77.28	1.21	3.86	5.37	0.19	2.38	4.57	0.18	0.13	0.20	0.39	0.05
4578	8.53	-0.01	44.30	82.09	0.72	1.90	2.61	0.23	2.29	4.74	0.22	0.19	0.17	0.42	0.08
4579	8.54	0.00	43.04	88.98	0.55	2.14	2.93	0.27	2.24	4.66	0.26	0.22	0.16	0.34	0.07
4580	8.49	0.01	42.49	88.63	0.76	2.74	3.81	0.27	2.27	4.54	0.24	0.21	0.16	0.31	0.07
4581	8.41	-0.01	47.89	90.15	0.74	1.71	2.28	0.32	2.25	4.55	0.27	0.23	0.20	0.37	0.08
4582	8.55	-0.01	47.62	98.36	0.52	1.50	2.04	0.32	2.24	4.67	0.28	0.23	0.19	0.38	0.09
4583	8.56	0.00	52.20	89.39	0.47	2.65	3.49	0.25	2.29	4.67	0.23	0.18	0.23	0.37	0.07
4584	8.51	0.00	45.98	77.56	1.65	2.61	3.45	0.21	2.37	4.62	0.20	0.15	0.18	0.43	0.07
4585	8.53	0.00	47.84	77.78	2.39	4.75	6.28	0.24	2.35	4.73	0.21	0.16	0.19	0.31	0.05
4586	8.62	-0.01	50.44	80.22	1.15	2.54	3.28	0.23	2.29	4.94	0.22	0.17	0.21	0.39	0.07
4587	8.55	0.00	46.25	75.40	0.91	4.72	6.07	0.18	2.37	4.79	0.18	0.14	0.18	0.37	0.05
4588	8.53	0.01	45.82	71.00	0.73	1.41	1.68	0.18	2.40	4.62	0.18	0.13	0.18	0.71	0.09
4589	8.50	0.00	43.74	74.86	0.82	2.00	2.35	0.17	2.38	4.62	0.18	0.14	0.17	0.58	0.08
4590	8.55	-0.01	47.24	68.77	0.87	2.14	2.47	0.17	2.42	4.52	0.16	0.12	0.19	0.64	0.08
4591	8.58	0.00	49.56	75.17	2.17	3.39	4.15	0.18	2.38	4.36	0.18	0.13	0.21	0.46	0.06
4592	8.48	-0.01	49.09	83.82	1.22	3.85	4.73	0.23	2.31	4.52	0.21	0.17	0.20	0.34	0.06
4593	8.40	-0.01	42.32	70.73	3.72	4.42	5.61	0.22	2.42	4.73	0.18	0.14	0.16	0.37	0.05
4594	8.57	0.00	48.71	68.79	6.68	10.43	13.70	0.16	2.49	4.27	0.13	0.09	0.20	0.36	0.03
4595	8.46	0.00	66.37	85.46	1.06	2.00	2.53	0.17	2.34	3.29	0.19	0.11	0.36	0.63	0.07
Average											0.20	0.15	0.21	0.47	0.07

to  $0.018 \Omega\text{m}^2/\text{m}$ ,  $V_{sh}$  = volume of shale,  $\theta_e$  = effective porosity,  $m$  = cementation exponent (set equal to 2),  $n$  = saturation exponent (set equal to 2),  $a$  = tortuosity factor (set equal to 1).

The results show that the zone interval between depths 4569 and 4595 ft has average water saturation ( $S_w$ ) equals to 0.47 (Fig. 3 and Table 1). Moreover, the bulk volume of water (BVW), which is the product of porosity times water saturation (Buckles 1965) has also been calculated for this zone of interest. The average bulk volume of water is 0.07, reflecting the relatively low bulk volume of water and consequently, the expected high hydrocarbon content (Table 1).

## Conclusions

The inspection of the seismic and well logs data at West Hurgada area in the southwest Gulf of Suez Basin revealed

that Rabeh East-22 Well includes a limestone bed between depths 4550 and 4630 ft (zone 1), displaying the optimistic criteria to be an oil-bearing zone within Rudeis Formation. This thick limestone bed (zone 1) did not appear in the other available wells (Nageh-1, Rabeh East-8, and Rabeh East-25), which were drilled near to Rabeh East-22 Well, confirming the pinching out of zone 1 due to lateral facies change from limestone to marl, forming the expected stratigraphic trap. Also, the examined seismic data proved that this limestone bed is not a massive limestone (porous and permeable bed) and sealed by massive marl bed, which displays higher acoustic impedance than the lower limestone. This expected stratigraphic trap extends for about 1.5 km in north-south direction and for 0.75 km in east-west direction on seismic data covering the study area.

The comprehensive petrophysical analysis for the zone 1 exhibits that the most promising interval to be suitable as oil

reservoir locates between depths 4569 and 4595 ft within zone 1. This interval has average water saturation of 47% (i.e., average hydrocarbon saturation of 53%), average shale volume of 21%, average total porosity of 20%, average effective porosity of 15%, and average bulk volume of water of 0.07.

Accordingly, it is highly recommended for Ganoub El-Wadi Petroleum Holding Company to drill new close-spaced wells in West Hurghada region that surround the study area to search for another promising limestone bed representing potential stratigraphic trap within the Rudeis Formation. These new targets will be the extra goals for oil production in addition to the main structural sandstone reservoirs (Nubia, Matulla, and Nukhul Formations) in West Hurghada oil fields.

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