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Facies analysis and depositional environments interpretation and Petrophysical evaluation of the Pliocene Kafr El-Sheikh Reservoirs at Sapphire Field, West Delta Deep Marine, Egypt

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ABSTRACT

The Early Pliocene Kafr El-Sheikh channels represent potential reservoirs at Sapphire Field, located in West Delta Deep Marine Concession, Mediterranean. Despite recent advanced exploration in the Offshore Nile Delta region, the detailed depositional setting and reservoir quality of Sapphire Field are still poorly understood. This study aims to identify the depositional environment of different members of Kafr El-Sheikh formation (Sapphire-60, Sapphire-70, and Sapphire-80) and evaluate its petrophysical parameters. The analysis relies on wireline logs obtained from Sapphire-Dh (st1) deviated well, gamma ray log used in distinguishing reservoir from non-reservoir units and GR patterns contribute in understanding environment of the deposition as well as resistivity, neutron, and density logs are used in petrophysical evaluation. The left deflection of gamma ray log reflects that the main lithology of members is sandstone and the GR curve patterns include three types (cylindrical/blocky, bell-shape, and bow-shape) which indicate different depositional elements of deep marine slope channel system. The petrophysical calculations of sandstone intervals, suggesting their potentiality as reservoirs, characterized by effective porosity ranging from 22.8 to 25.6%, minimal volume of shale 14.7 and 15.7%, water saturation varying from 22.9 to 44.5%, hydrocarbon saturation ranging from 55.5 to 77.1%, and Net To Gross varying from 0.42 to 0.73. Kafr El-Sheikh Formation exhibits potential gas-bearing zones with varying degrees of reservoir quality. This analysis serves as a foundation for further exploration and development in Sapphire Field and in the neighboring regions within West Delta Deep Marine Concession.

Keywords: Facies interpretations; Depositional framework; Sapphire Channels; Petrophysical evaluation; WDDM

1. INTRODUCTION

In recent decades, Nile Delta Basin has become the most important energy source in Egypt due to recent gas discoveries. It is a primary area of interest for hydrocarbon exploration [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. The West Delta Deep Marine (WDDM) concession covers about 1,366 square kilometers, with water depths ranging from 150 to 1,200 meters (Fig.1a). It is one of Egypt's most promising areas for gas and oil exploration and production. In the Nile Delta, hydrocarbons are mainly found in the Neogene-Quaternary sequence, which is subdivided into three major sedimentary layers: Miocene, Pliocene, and Holocene [1, 12, 13].

The study area (Sapphire Field) is a Pliocene gas field in WDDM concession and is located approximately 90 km from the coast of Alexandria, on the northwestern edge of the Nile Delta. It is positioned at the coordinates 32° 01' 43.192" N latitude and 30° 21' 10.707" E longitude (Fig.1b). Sapphire Field was first discovered in 1975 by Esso while drilling and exploring deeper Miocene. Between 2000 and 2001, four appraisal wells were drilled to assess the field. Development began in 2004–2005 with eight wells targeting multiple reservoir levels, followed by additional wells in subsequent drilling phases.

Understanding the depositional environment of reservoirs influences hydrocarbon exploration and production [14, 15, 16]. Interpretation of lithofacies and depositional environments from the pattern of well-log curves as gamma ray log has been successfully achieved in different sedimentary basins [17, 18]. The quality of reservoir is largely influenced by depositional facies of the rock [19, 20, 21]. The identification of a field's depositional setting and petrophysical parameters is critical for assessment the reservoir quality

The objectives of this study are to (1) analyze the facies and depositional environment interpretation of Sapphire Field, (2) evaluate the main petrophysical parameters of sapphire field reservoirs, (3) assess the reservoir quality of different intervals of sapphire field and understand variations in hydrocarbon potential.

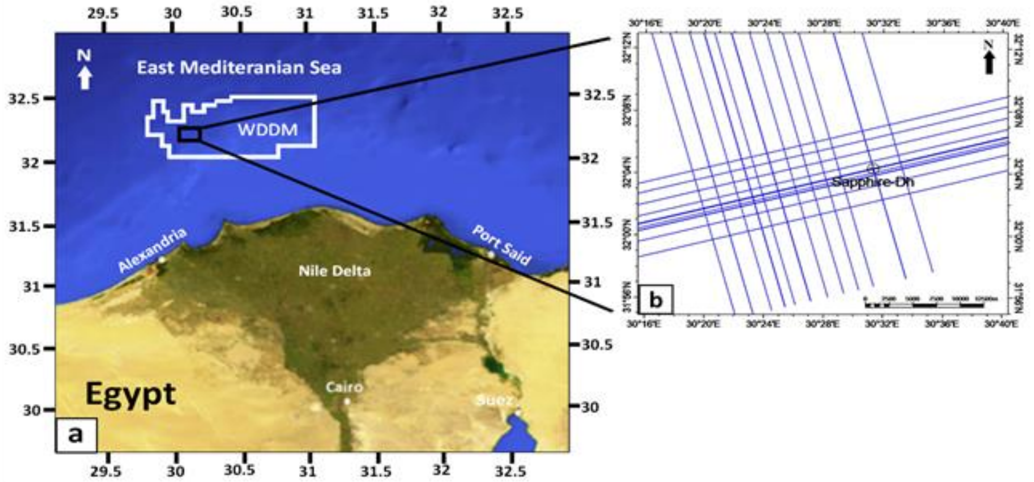

Fig (1): (a) Location of West Delta Deep Marine concession (WDDM). (b) Base Map of the Study Area

2. GEOLOGIC SETTING

Nile Delta is situated on the passive margin of the African Plate [22, 23, 24, 25, 26] formed due to thermal subsidence following extensional tectonics, which separated the Afro-Arabian plate from the Eurasian plate during the Late Triassic to Early Cretaceous period [26, 4]. The structural framework of Nile Delta largely coincides with the break-up of the African Plate margin, resulting from the opening of the Red Sea and the northward movement of the Arabian Peninsula [27]. The major structures within the WDDM concession are the Rosetta fault, which trends northeast-southwest, the Nile Delta offshore anticline, which trends east-northeast to west-southwest, and a series of rotated fault blocks in the Northeast.

The stratigraphic sequence of the offshore Nile Delta is sudivided into three main cycles: Plio-Pleistocene cycle: consisting of the Bilqas, Mit Ghamr, El-Wastani, and Kafr El-Sheik formations, Miocene cycle: includes the Abu Madi and Qawasim formations, featuring two sand layers separated by the Messinian-age Rosetta Anhydrite Formation, and Middle-Lower Miocene cycle: comprising the Sidi Salem and Qantara formations, this unit is mainly shale with sand layers [28, 29] (Fig.2). The Early Pliocene Kafr El-sheikh formation is the main target in this study and subdivided into four members (Sapphire 40, Sapphire-60, Sapphire-70, and Sapphire-80).

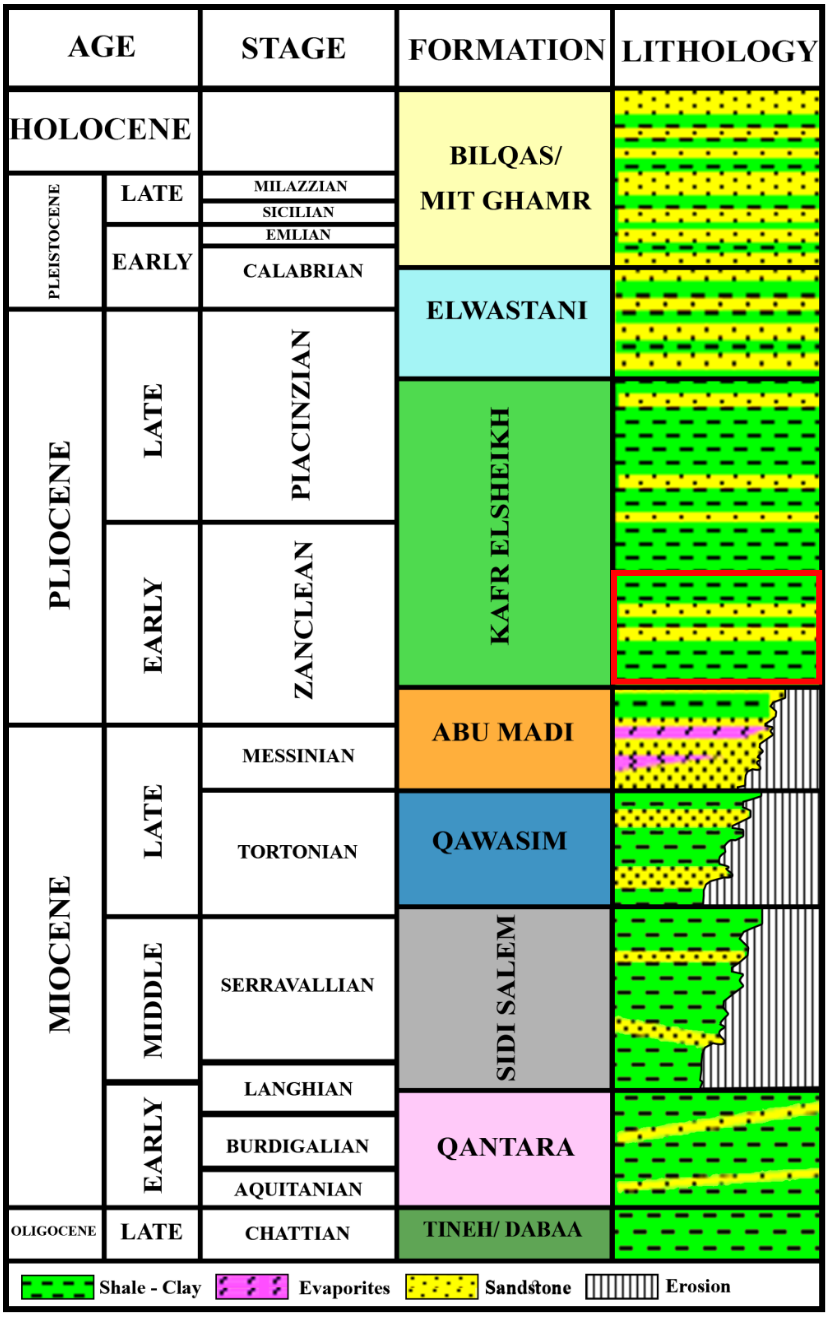

Fig (2): The stratigraphic column of Nile Delta, modified after [30]. The red rectangle marks the zone of interest in the current study.

3. MATERIALS AND METHODS

Conventional logs including (Gamma ray, Resistivity, Density, and Neutron) of Sapphire-Dh were used in this study. This data interpreted and analyzed using computer software programs; Techlog 2015 and Petrel 2017 to describe the depositional environment of the sapphire field reservoir intervals and evaluate the reservoirs quality and its main petrophysical properties.

The Gamma-ray logs are essential in reservoir evaluation as it used to differentiate between reservoir and non-reservoir zones and contributes in understanding reservoir depositional environments. [31] classify the gamma ray log curve into five different patterns used to interpret the environment of deposition; a) Cylindrical/boxcar, b) Funnel shape, c) Bell shape, d) Bow shape, and e) Irregular pattern (Fig.3 and 4). The Resistivity log is used to distinguish between hydrocarbon-bearing zones and water-bearing zones and determine fluid saturation, porosity, and rock quality. The Density and Neutron logs are used in identifying the sandstone bodies and the gas content of the reservoir. The Neutron-Density Cross-Plot [32] exhibits the high porosity values and the gas effect on the distribution of the plotted points. The previous logs are used in calculating petrophysical parameters; Volume of Shale (Vsh) [33], Effective porosity (**Φ**e) [34], Net to gross (NTG), Water saturation (Sw), and Hydrocarbon saturation (Sh) which are important in defining any reservoir quality.

3.1. Volume of shale (V_{sh}): to calculate V_{sh} from the gamma ray (GR) log, it is essential to first determine the index of gamma ray (IGR), determined by using equation of [35].

$$IGR = \frac{(GR_{log} - GR_{min})}{(GR_{max} - GR_{min})}$$

Where: GR_{log} = gamma ray value of unit; GR_{min} = minimum gamma ray reading (clean sand): GR_{max} = maximum gamma ray reading (shale) [34].

$$V_{sh} = 0.33(2^{(2\,IGR)} - 1)$$

3.2. The effective porosity (Φ_e) is then measured, using equation of [36] after the correction of total porosity from volume of shale.

$$\emptyset_e = \emptyset_t(1 - V_{sh})$$

Where: Φ_t is the corrected total porosity.

3.3. Water and hydrocarbon saturation: saturation of water for the uninvaded zone was determined according to [37]:

$$S_w = \{(a \times R_w)/(R_t \times m)\}^{1/n}$$

Where: R_w = Resistivity of water formation **m** = cementation factor; **n** = saturation exponent. Archie's coefficients (**a**, **m**, and **n**)

The hydrocarbon saturation can be calculating, by using the following equation:

$$S_h = 1 - S_w$$

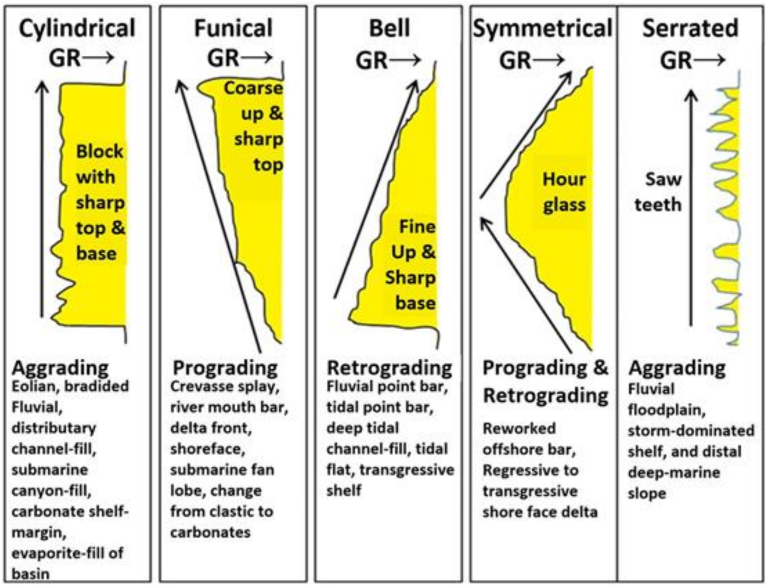

Fig (3): General gamma-ray responses [38]

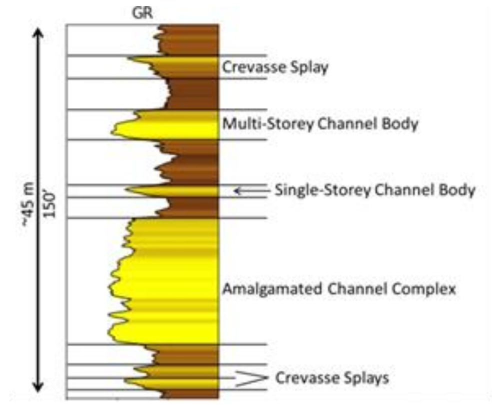

Fig (4): Gamma-ray (GR) log signatures of fluvial channel bodies [39].

4. RESULTS

The three reservoirs Sapphire-60, Sapphire-70, and Sapphire-80 were delineated across Sapphire-Dh well. This was achieved after analyzing gamma ray and facies log for identifying the depositional setting and calculating its petrophysical parameters.

4.1. Gamma ray facies related-responses of Sapphire reservoirs

Facies interpretation and depositional environments identification of Sapphire sandstone reservoirs were achieved based on the analysis of different patterns of gamma ray log as follows:

4.1.1. Cylindrical/Boxcar (Blocky) facies pattern

A number of four beds (A-B-C-D) in Sapphire-60 reservoir exhibit left boxcar motif. This pattern typically represented by relatively consistent values of gamma ray with sharp upper and lower boundaries which indicates a relatively uniform lithology. (A) Zone has a thickness about 4.6m with gamma ray minimum value 27.09 gAPI and values of its boundaries are 30.69 and 40.32 gAPI. (B) Zone is 2.31m thick with GR minimum value 34.07 gAPI and the readings of its boundaries are 37.4 and 42.25 gAPI. The thickness of (C) Zone is 8.19m with 26.66 gAPI minimum gamma ray value and its boundaries values are 38.87 and 35.83 gAPI. (D) Zone has a thickness 3.2m with GR minimum value 30.24 gAPI and its boundaries are 33.82 and 33.19 gAPI. (Fig.5a).

4.1.2. Bell facies pattern (Fining-upward)

A number of two beds (E-F) in Sapphire-60, and Sapphire-80 reservoirs, respectively shows bell pattern of gamma ray log. This pattern generally displays upward high values of gamma ray which indicates increasing of shale content and a fining upward depositional sequence.

Zone (E) within Sapphire-60 has a thickness about 6m with minimum gamma ray value 31.69 and the values of its boundaries are 50.87 and 33.69 gAPI (Fig.5a). Zone (F) within Sapphire-80 with thickness about 15.13m, its gamma ray minimum value is 31.81 gAPI and its boundaries GR values are 58.95 and 39.29 gAPI (Fig.5c).

4.1.3 Bow facies pattern (symmetrical-shape)

Only one bed (G) in sapphire-70 exhibits bow shape of gamma ray log. This pattern is generally characterized by a relative decreasing in values of gamma ray (decrease of shale content) followed by a relatively increasing in values of gamma ray (increase of shale content). (G) Zone is about 2.5m thick; its GR minimum is 26.71 gAPI (Fig.5b)

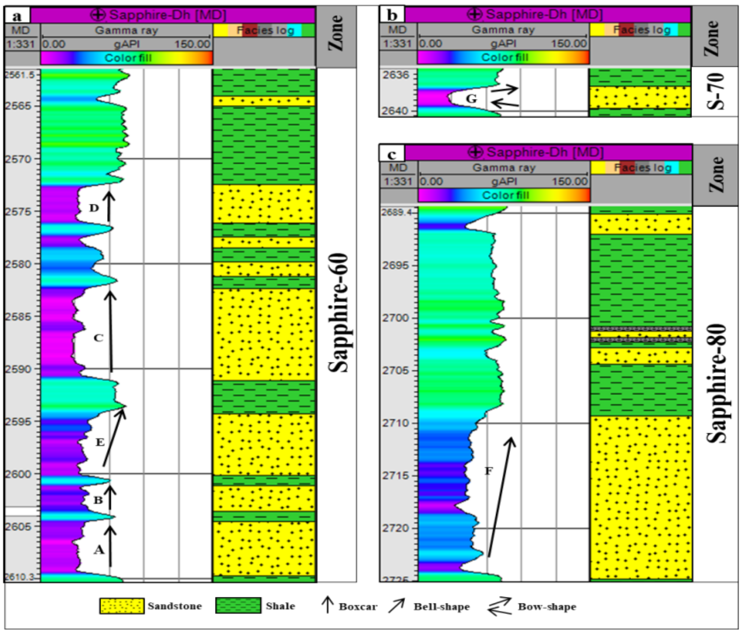

Fig (5): Gamma-ray (GR) and facies logs for: a) Sapphire-60, b) Sapphire-70, and C)

4.2 Petrophysical Evaluation

Sapphire-60, Sapphire-70, and Sapphire-80 intervals have been described in the composite log of the Sapphire-Dh(st1) well.

The composite log of Sapphire-Dh shows the following; Gamma-ray log shows left deflection in trend as clay content decreases with increase of sand. The minimum gamma ray readings of Sapphire-60, Sapphire-70, and Sapphire-80 reservoirs are 26.6, 26.1, and 31.8 gAPI, respectively.

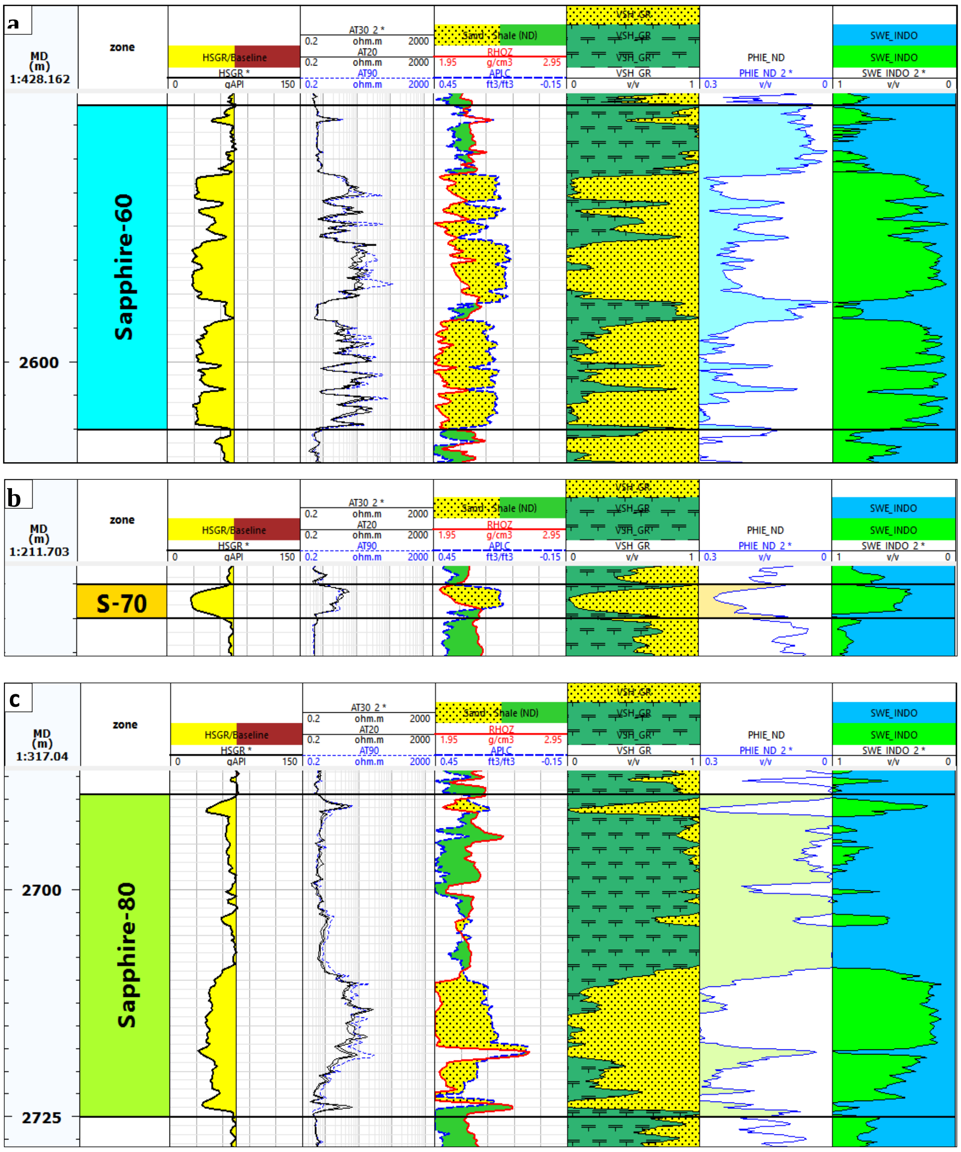

Fig (6): Interpreted composite log for: a) Sapphire-60 interval, b) Sapphire-70 interval,and C) Sapphire-80 interval.

The deep resistivity log (blue curve) shifts to right as a response to hydrocarbon-bearing sands. The dashed-blue neutron curve deflects to the right and the density log shifts to the left (solid red curve) due to low density of gas. Both curves (neutron and density) display the cross-over feature reflecting the sandstone lithology and the gas content. The maximum resistivity values of S-60, S-70, and S-80 reservoirs are 114.8, 3.1, and 29.1Ω.m, respectively (Fig.6a, b, and c).

The Neutron-Density Cross-Plot of Sapphire-60 and Sapphire-80 displays that the majority points are plotted on the region of sandstone (high porosity) and the other points plotted on the region of mud/shale while the cross-plot of Sapphire-70 exhibits low gamma ray plotted points related to sandstone (Fig.7a, b, and c).

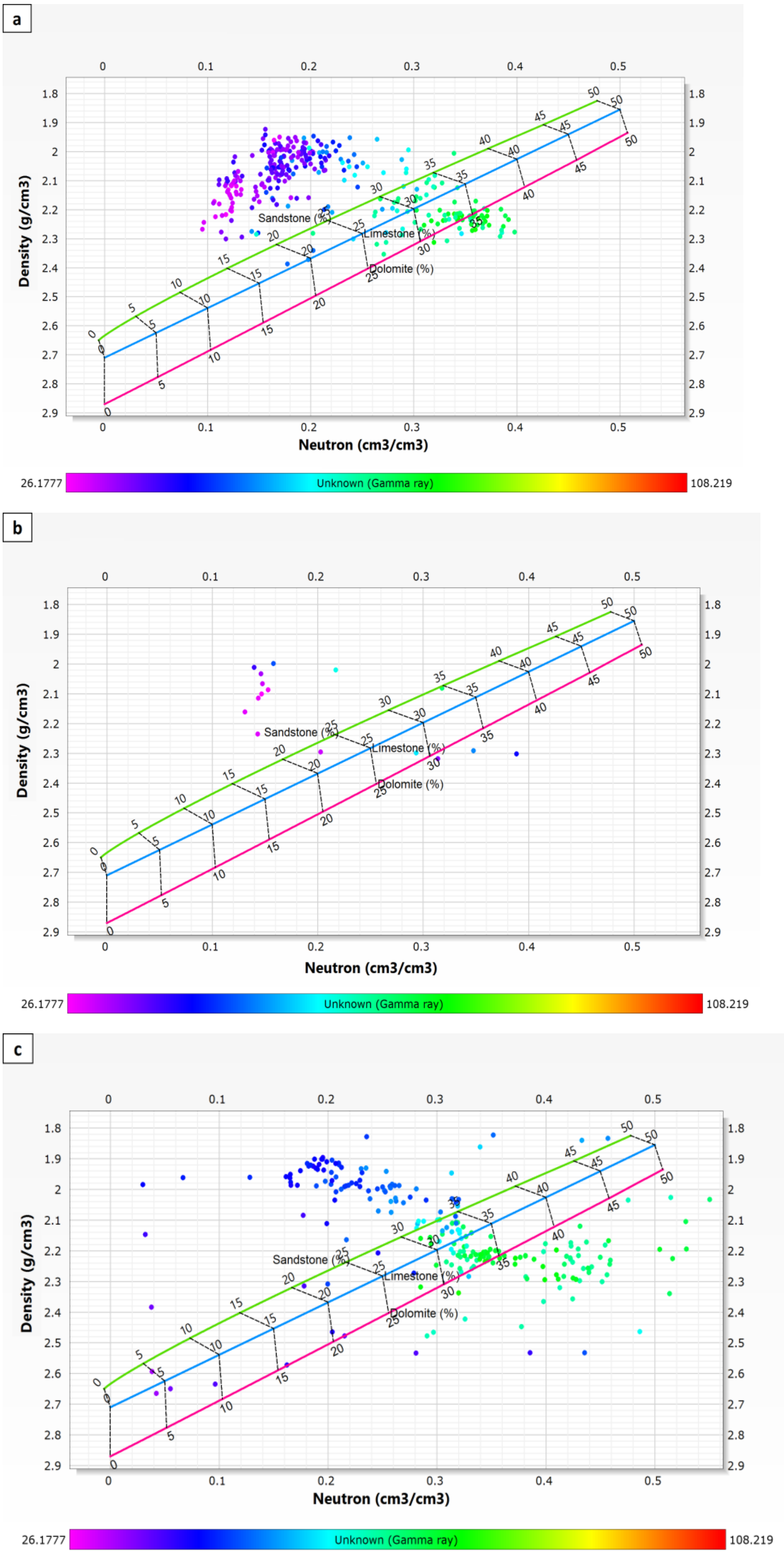

Fig (7): Neutron-Density Cross-Plot for: a) Sapphire-60 interval, b) Sapphire-70 interval, and C) Sapphire-80 interval.

Sapphire-60 interval between depths (2562 and 2610m); its volume of shale is 14.7%, its average effective porosity is about 23.9%, its avg. water saturation is 22.9%, its avg. hydrocarbon saturation is 77.1%, and net to gross is 0.628.

Sapphire-70 interval between depths (2637.5 and 2640m); it is located at the middle of the interval, its volume of shale is 15.7%, its average effective porosity is about 22.8%, its avg. water saturation is 44.5%, its avg. hydrocarbon saturation is 55.5%, and net to gross is 0.732.

Sapphire-80 interval between depths (2689.5 and 2725m); is located at the bottom of the interval, its volume of shale is 15.7%, its average effective porosity is about 25.6%, its avg. water saturation is 33.6%, its avg. hydrocarbon saturation is 66.4%, and net to gross is 0.428 (Table.1).

Table 1. Summary table indicates the petrophysical parameters of Sapphire-60, Sapphire-70, and Sapphire-80 intervals in Sapphire-Dh.

Well	Reservoir	Top(m)	Base(m)	Gross	Net /Gross	Avg. Shale Volume%	Avg. effective porosity%	Avg. Water Saturation %	Avg. Hydrocarbon Saturation%
Sapphire-Dh(st1)	**Sapphire-60**	2562	2610	40.301	0.628	14.7	23.9	22.9	77.1
	Sapphire-70	2637.5	2640	2.091	0.732	15.7	22.8	44.5	55.5
	Sapphire-80	2689.5	2725	29.571	0.428	15.7	25.6	33.6	66.4

The WDDM Concession is a gas-producing province in the Eastern Mediterranean [40, 41, 42]. It consists of deep-water turbidite systems within the Tertiary stratigraphy, primarily formed by the deposition of terrigenous sediments delivered by the Nile River [2, 40, 43, 44].

Numerous deep turbidite channels and lobes were created throughout the Pliocene along the prograding slope, forming submarine channel-lobe systems. The slope-channel systems in the Nile Delta providing examples a wide range of possible sand body types and geometries which may be present [42]. The main controls on the development of the Pliocene deep-water systems include relative sea-level changes, supply of fluvial sediment, tectonic activity, and mass transport [40, 42, 44].

Sapphire Field represents a submarine delta slope channel system with complex turbiditic channel and lobe reservoirs. Sapphire reservoirs can be interpreted to be deposited in a deepwater slope setting, dominated by channels. These Lower Pliocene sands lie at base of the Kafr El-Sheikh Formation. From seismic and other deepwater analogs, several channel and overbank could be identified. Channels may also be either sand or mud-filled; hydrocarbon is being produced from these various overbank and channel deposits. In this study, the following depositional setting is recognized, based on conventional well logs; The facies log provides information on the depositional environment based on gamma ray response; low gamma ray (GR) values indicate coarser grained clean sand, suggesting deposition in high-energy environment. High gamma ray (GR) values represent clay-rich sediments, associated with low-energy environment.

Sapphire-60 interval may represent frontal splay deposits (lobes) which are deposited at the terminus of channels at the base of slope or out on the basin floor [46, 47]; it is can be distinguished on vertical seismic profile by sheet-like, parallel, and high-amplitude reflections with moderate to good continuity and the gamma-ray log frequently exhibits a blocky pattern, with very thin shale breaks between the splay elements (stacked sand bodies). These shale breaks can act as seals within frontal splay reservoir bodies [48] (Fig.8). The alternation of sand-rich and finer-grained layers is characteristic of a splay rather than a confined channel. Sand sheets represent good quality reservoirs due to the lateral continuity, good vertical connectivity. **Sapphire-70** may be interpreted as a confined single submarine slope channel with a high-energy sand-rich fill; it is characterized by moderate- to high-amplitude reflections, sheet-like in cross section and the gamma-ray log shows a symmetrical shape a transition from high gamma-ray values (mud) to very low values (sand body). Isolated channels are smaller than confined channels.

Sapphire-80 suggested being an amalgamated channel with levee development which occurs when multiple turbidite channels stack on top of each other, often due to repeated cycles of sediment deposition. They typically form in high-energy depositional environments; it is characterized by thick sand-rich deposits at the base, followed by interbedded muddy facies. This suggests a high-energy turbidite system, with sediment bypassing further downslope. These channels often have high net-to-gross ratios (NTG) (Fig.8).

5. DISCUSSION

The WDDM Concession is a gas-producing province in the Eastern Mediterranean [40, 41, 42]. It consists of deep-water turbidite systems within the Tertiary stratigraphy, primarily formed by the deposition of terrigenous sediments delivered by the Nile River [2, 40, 43, 44].

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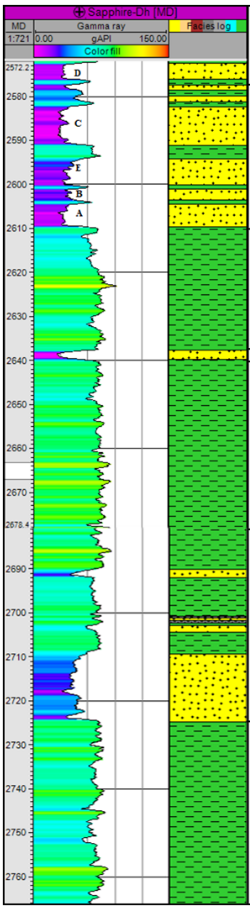

interval	Gamma Ray Response	Description	Petrophysical parameters
S-60	(A, B, C, and D) represent Cylindrical/blocky (left car-box) motif, relatively sharp-based units with thick low GR interval. (E) Represents bell-shape(fining up-ward) motif, with sharp base. High GR peaks in between (A, B, C, D, and E).	The gamma-ray log shows stacked sand bodies(high-energy environment) interbedded with thin mud (low-energy environment); it may represent frontal splays(Lobes).	Volume of shale is 14.7%, average effective porosity is about 23.9%, avg. water saturation is 22.9%, avg. hydrocarbon saturation is 77.1%, and net to gross is 0.628.
	Right blocky log with serrated or irregular shape.	Muddy slope/Mud back fill.	
S-70	Bow shape (symmetrical)	It may represent a single channel with sand-fill deposits.	Volume of shale is 15.7%, average effective porosity is about 22.8%, avg. water saturation is 44.5%, avg. hydrocarbon saturation is 55.5%, and net to gross is 0.732.
	Right blocky log with serrated or irregular shape.	Muddy slope/Mud back fill.	
S-80	Serrated right blocky log (high GR values) with thin interbedded sand	The gamma-ray shows thick sand body with sharp base (erosive surface) grading to mud at the top; it may represent an amalgamated channel with muddy overbanks.	Volume of shale is 15.7%, average effective porosity is about 25.6%, %, avg. water saturation is 33.6%, avg. hydrocarbon saturation is 66.4%, and net to gross is 0.428 .
	Bell-shape pattern (fining-upward from top with sharp base)		
	Right blocky log with serrated or irregular shape.	Muddy slope/Mud back fill.	

Fig (8): A summary for gamma ray patterns and related depositional environment interpretation for Sapphire channels, Sapphire-Dh Well.

The quality of Sapphire field reservoirs primarily depends on petrophysical properties; Sapphire-80 has the highest effective porosity, followed by Sapphire-60 and Sapphire-70. Shale volume remains relatively consistent across all three intervals. However, water saturation varies significantly, with Sapphire-70 exhibiting the highest value, followed by Sapphire-80, while Sapphire-60 has the lowest. This trend is inversely related to hydrocarbon saturation, where Sapphire-60 has the highest hydrocarbon content and represents the most promising reservoir. Sapphire-80 also shows favorable hydrocarbon saturation but is slightly lower than Sapphire-60. In contrast, Sapphire-70 has the lowest hydrocarbon saturation due to its higher water content and its thin thickness, which may reduce its potentiality for production. These suggest that Sapphire-60 interval has the best quality of reservoir (Fig.9).

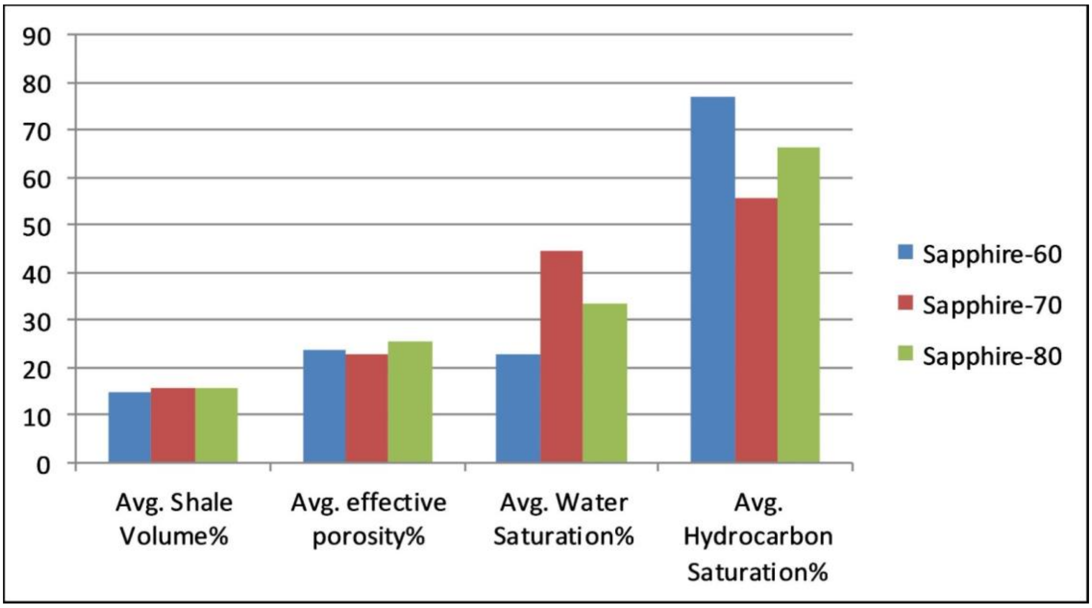

Fig (9): A bar chart represents a comparison of four reservoir properties; Shale Volume (%), Effective Porosity (%), Water Saturation (%), and Hydrocarbon Saturation (%) of the three intervals Sapphire-60, 70, and 80.

6. CONCLUSION

- The Deep marine slope channel system depositional environment of West Delta Deep Marine suggests that Sapphire Field is a prolific thermogenic gas field and favorable for further exploration and production.
- The interpretation of well log data for the Early Pliocene Kafr El-Sheikh Formation sandstone intervals in Sapphire field suggests they are gas reservoirs. A detailed petrophysical evaluation of Sapphire-Dh (st1) well provides gas-bearing sand intervals (Sapphire-60, Sapphire-70, and Sapphilre-80). These zones exhibit a low shale volume, a high effective porosity varying between, 22.8 to 25.6% and a moderate water saturation ranging from 22.9 to 44.5%, hydrocarbon saturation ranging from 55.5 to 77.1%, and net to gross (NTG) varying from 0.42 to 0.73; indicating good reservoir quality.
- In Sapphire-Dh well, the promising sandstone zones (A, B, C, D, and E) within Sapphire-60 member have a cumulative thickness of 25m and (F) zone within sapphire-80 sand interval with thickness about 15m, present a strong case for further exploration.
- It is highly recommended to: (1) drill new wells in the Sapphire Field and surroundings to discover extra potential gas-bearing reservoirs within the sandstone of Kafr El-Sheikh formation, (2) use advanced seismic techniques, such as high-resolution seismic inversion and attribute analysis, in future studies to improve reservoir characterization by delineating reservoir boundaries and identifying fluid distributions, (3) integrate all available geological, geophysical, and petrophysical data to construct a high-resolution static and dynamic reservoir models, and (4) apply machine learning techniques to enhance reservoir modeling and simulation.

7. Acknowledgement

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8. Conflict of Interest

We confirm that there are no conflicts of interest associated with this work.

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