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3D slicing of radiogenic heat production to distinguish source and reservoir rocks of Al-Wastani Formation, Sapphire oil field, Deep Marine Nile Delta, Egypt

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Abstract: Total gamma ray logs of Al-Wastani Formation clastic sediments were normalised across seven wells in the Sapphire oil field, situated in the deep marine area of the Mediterranean Sea, Egypt, to facilitate the computation of radiogenic heat production (RHP). The gamma ray logs were normalised via the Histogram method by manually modifying values for each well, with modifications varying from (−6 to +6) API. The Arithmetic mean and standard deviation of RHP values, which range from 0.05 to 1.67 μW/m^3 were calculated as 0.71 μW/m^3 and 0.23 μW/m^3, respectively as established through statistical analysis of the data. Considering the strong relationship between RHP and hydrocarbon composition, the three-dimensional slicing of radiogenic heat production reveals that the upper portion of the Al-Wastani Formation constitutes a free-hydrocarbon zone. Hydrocarbons are present in both the intermediate and lower strata. Hydrocarbons are distinctly associated with reservoir rocks in the middle region of the Al-Wastani Formation. The lower layer of the Al-Wastani Formation is considered a source rock.

Key words: Al-Wastani Formation, spectral gamma rays, radiogenic heat production, 3D slicing, and oil-bearing zones

1. Introduction

Egyptian oil fields produce natural gas that is either used domestically or in the liquefied natural gas industry. Perhaps the largest Egyptian field in terms of natural gas production is the deep Nile Delta region in the Mediterranean Sea, particularly the Pleistocene rocks represented by the Wastani

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Formation, the region's dominant reservoir for hydrocarbon gas production.

In 1995, Edison and British Gas companies developed the study area (*Alami, 2006; Mohamed et al., 2015; Ghoneimi et al., 2021*). The study area (Sapphire oil field) in the deep marine delta of the Mediterranean Sea region, is bordered by latitudes 31° 21′ 00″ and 31° 58′ 00″ N and longitudes 30° 10′ 00″ and 31° 04′ 00″ E, (Fig. 1).

The essential three radioactive elements found in rocks are potassium (K, %), equivalent uranium (eU, ppm), and equivalent thorium (eTh, ppm). These elements when, broken down, generate a heat energy known as radio-

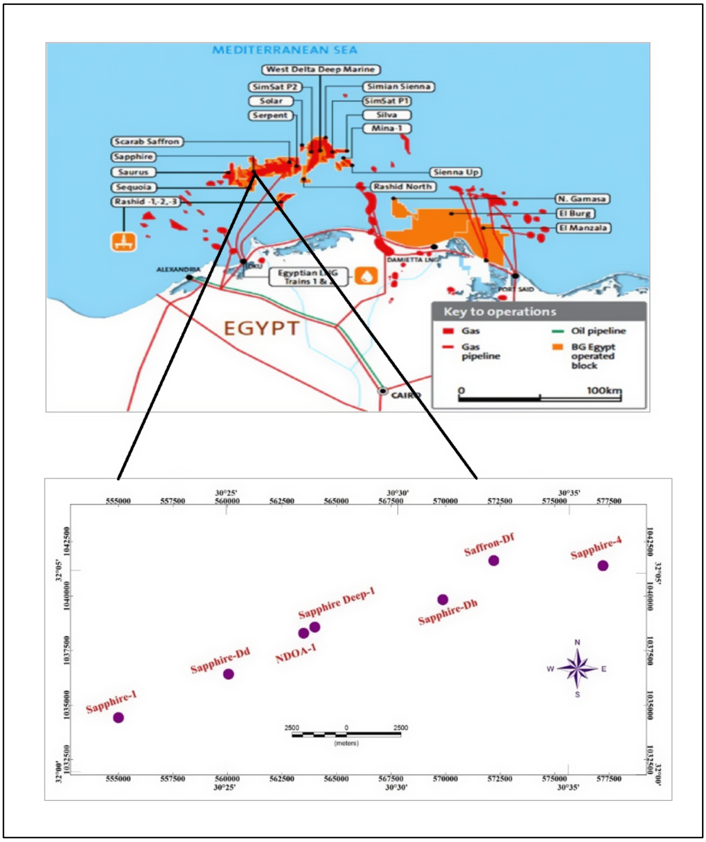

Fig. 1. Location map of the study wells in Sapphire oil field, Deep Marine Delta, Mediterranean Sea, Egypt (after, *Abdel-Rahman et al., 2025*).

genic heat production. The scientist *Rybach (1988)* determined the value of this heat by utilising the rock density value (gm/cc) and the concentration of these radioactive elements to derive an empirical equation.

Because spectral gamma ray logs are expensive and time-consuming to obtain, they were formerly uncommon for determining the quantities of the three radioactive elements. Consequently, *Bücker and Rybach (1996)* developed a straightforward empirical formula to calculate the RHP in wells based on total gamma ray logs. This paper utilised the equation formulated by *Bücker and Rybach (1996).*

One of the key elements that promote the maturity of hydrocarbons in rocks is temperature. The natural geothermal gradient with depth, which is the primary cause of the Earth's interior temperature rise, heat escaping from hydrothermal solutions through rock fissures and cracks, and heat produced by the breakdown of radioactive elements are just a few of the numerous sources of heat in the Earth's interior.

The amounts of RHP in the Bahariya Formation's rocks were calculated and displayed in three-dimensional figures, demonstrating that this heat was unmistakably responsible for the formation's hydrocarbons reaching the maturity stage as it stated by *Al-Alfy and Nabih (2013).* Conversely, radiogenic heat production criteria were combined with an additional radioactive approach (Thorium normalization) to identify hydrocarbon oil-bearing zones and distinguish between source and reservoir rocks within the carbonates of the Abu Rawash Formation (*Al-Alfy et al., 2025*).

The radiogenic heat production values of the Pleistocene Al-Wastani Formation rocks were calculated to determine their potential for hydrocarbon content and to classify them as source or reservoir rocks, utilising the methodology established by *Nabih and Al-Alfy (2021).*

The initial use of this technique by *Nabih and Al-Alfy (2021)* validated the results through comparisons with well log analysis and calculations of reservoir properties, including shale volume, water and hydrocarbon saturation ratios, as well as total and effective porosity. These characteristics facilitated the identification of source and reservoir rock formations. Additional researchers, such as *Al-Alfy et al. (2025)*, have employed this technique and juxtaposed the findings with reservoir property data. This has established radiogenic heat production as a dependable technique for differentiating between source and reservoir rocks.

2. Geological setting

Numerous tectonic event stages that have a major impact on the region's petroleum system are indicative of the geology of the Nile Delta and its expansion in the Mediterranean Sea. Understanding the depositional conditions and the true depth of burial reservoirs and source rocks can be aided by the area's geological evolution.

Ismail et al. (2010) indicate that the Lithostratigraphic section of the Nile Delta area (Fig. 2) demonstrates that the age of the Al-Wastani forma-

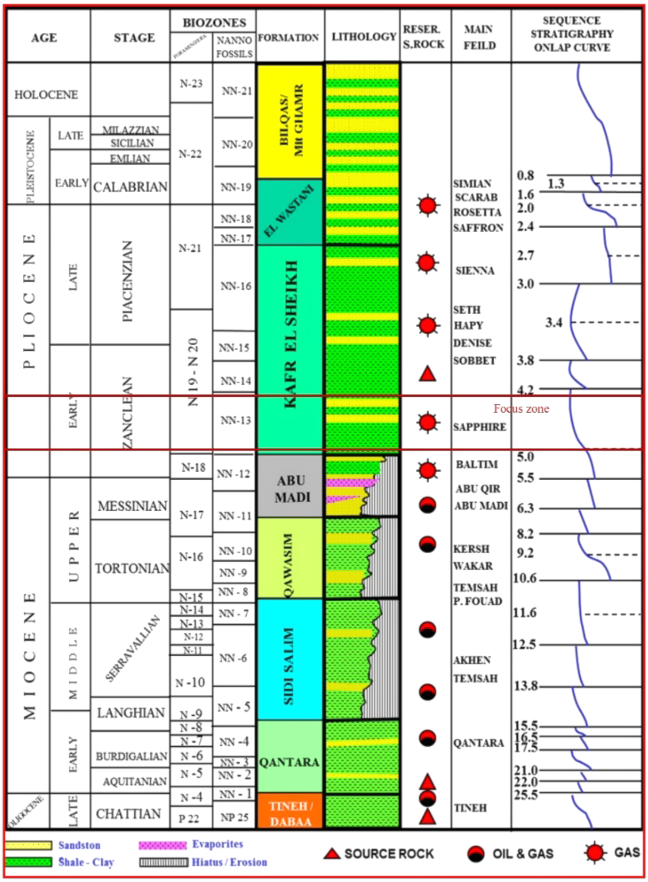

Fig. 2. Nile Delta stratigraphic column and hydrocarbon system. Modified from *Rio et al. (1991)*.

tion is late Pliocene, and it is predominantly constituted of thick medium to coarse-grained sand deposits with tiny feldspar and lithic pieces intercalated by soft, thin clay beds. Nile Delta was profoundly shaped from the three (Arabian, Eurasian and African) tectonic plates in the Mediterranean Sea. The most major structural element in the area is regarded to be the Hing zone, which is situated south of the Nile Delta. The Nile Delta was primarily produced by this zone, which is the consequence of the collision of the African and Arabian plates (*Cross et al., 2009*).

The Rosetta fault, oriented NE–SW, is the primary fault examined in this study. According to *Vandré et al. (2007)*, Tethyan rifting during the Pre-Pliocene epoch, which dictated the basement faults, was followed by the thick sand deposits, which are considered suitable reservoirs.

The progradational facies of the El-Wastani Formation transition into slope facies. The alteration of these facies, along with the occurrence of normal faults and gas chimney structures, hampers the delineation of this boundary on the seismic sections (*Khalifa et al., 2025*).

3. Methodology

This work was accomplished by performing several methods:

3.1. Gamma-ray logs normalization

Multiple factors directly affect the values of total gamma-ray log, requiring a procedure known as gamma-ray normalization. Factors encompass discrepancies in instrument sensitivity, variability among instrument operators across different wells, and readings obtained at significantly spread intervals. The normalization process involved creating composite gamma-ray histograms using Microsoft Excel for all wells alongside individual well histograms. By comparing the low gamma-ray ranges of each well's histogram with the corresponding ranges in the standard multi-well histogram, API shift adjustments are calculated and applied to achieve precise alignment.

Using a technique created by *Gadallah et al. (1998)*, the gamma-ray data was plotted using a histogram for each well independently, and the point where the histogram trend line intersected with the x-axis's minimum value was found. Every well's data is gathered into a single file, displayed using a histogram, and the trend line's intersection with the x-axis's minimum value is also identified.

Disparities, both positive and negative, exist when comparing the intersection values of the trend line for each well with the values derived from the comprehensive data plot. Consequently, these values must be incorporated or eliminated to correct the data across the numerous wells.

3.2. RHP calculations

RHP value was derived from the total gamma-ray log utilising an equation formulated by *Bücker and Rybach (1996)* as follows:

$$A\,(\mu\mathrm{W/m^3}) = 0.0158 \cdot (\mathrm{API} - 0.8)\,. \tag{1}$$

Nabih and Alfy (2021) conducted a new technique to differentiate between saturated and hydrocarbon free rocks, and determine the saturated hydrocarbon zones are related to source or reservoir rocks using the statistical analysis of (RHP) measurements. The reservoir rocks exhibit RHP values that align with the range between the arithmetic mean value and the arithmetic mean plus standard deviation value, whereas the source rocks display RHP values exceeding the (arithmetic mean plus standard deviation) value.

3.3. 3D slicing

The characterisation of a highly heterogeneous and multilayered reservoir cannot be comprehensively grasped through traditional geophysical representations of petrophysical characteristics, such as two-dimensional methodologies. Consequently, these conventional methods fail to effectively enhance our understanding of the hydrocarbon trapping mechanism and reservoir continuity. In contrast, the 3D-slicing illustrates the variation of the petrophysical parameters—X, Y, and Z—in three dimensions.

It gives a solid explanation of the sudden changes in reservoir behaviour as well as a clear insight into scanning. Consequently, it offers production geologists and engineers valuable information to assist them in determining where to drill. However, the image reconstruction of the reservoir characterisation that clarifies the change of the petrophysical property in three dimensions (X, Y, and Z) is obtained using the reservoir 3D-slicing and cut-offs. The interpolation method is used to attain this characteristic.

Using the known function values $f(x_1)$ and $f(x_2)$, linear interpolation approximates the function value $f(x)$ with $x_1 < x < x_2$. The following equation can be used to represent the process (*Davis, 1986*):

$$F(x) = \frac{(x_2 - x)f(x_1) + (x - x_1)f(x_2)}{(x_2 - x_1)} \,. \tag{2}$$

When only the data at the interpolation nodes $x_1, x_2, ..., x_n$ are present. Interpolation can be used to define a piecewise linear function.

The data used and the steps and methodologies of this work were illustrated in a flowchart (Fig. 3).

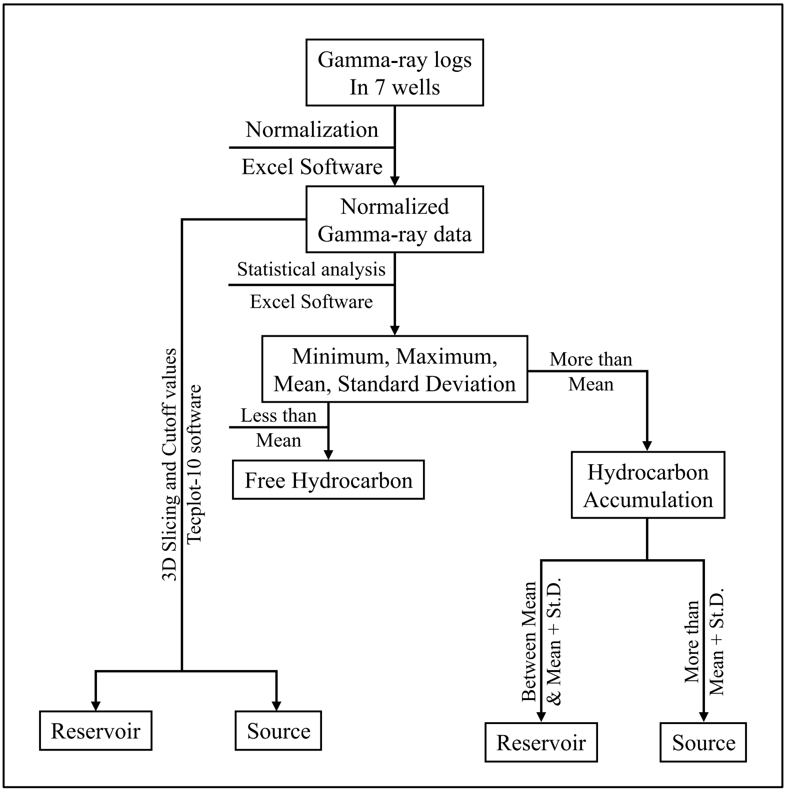

Fig. 3. Flowchart illustrates the data used and the steps and methodologies of radiogenic heat production calculation, source and reservoir differentiation of Al-Wastani Formation, Sapphire Oil Field, Deep Marine Nile Delta, Egypt.

4. Results and discussions

As explained in methodology section, the intersection point between the histogram trend line and the minimum value on the x-axis of the typical multi-well histogram of gamma-ray is 11 API, as shown in Fig. 4a. Figure 4b depicts the individual gamma ray histogram for well NDOA-1, identifying the significant point where the histogram trend line intersects the minimum

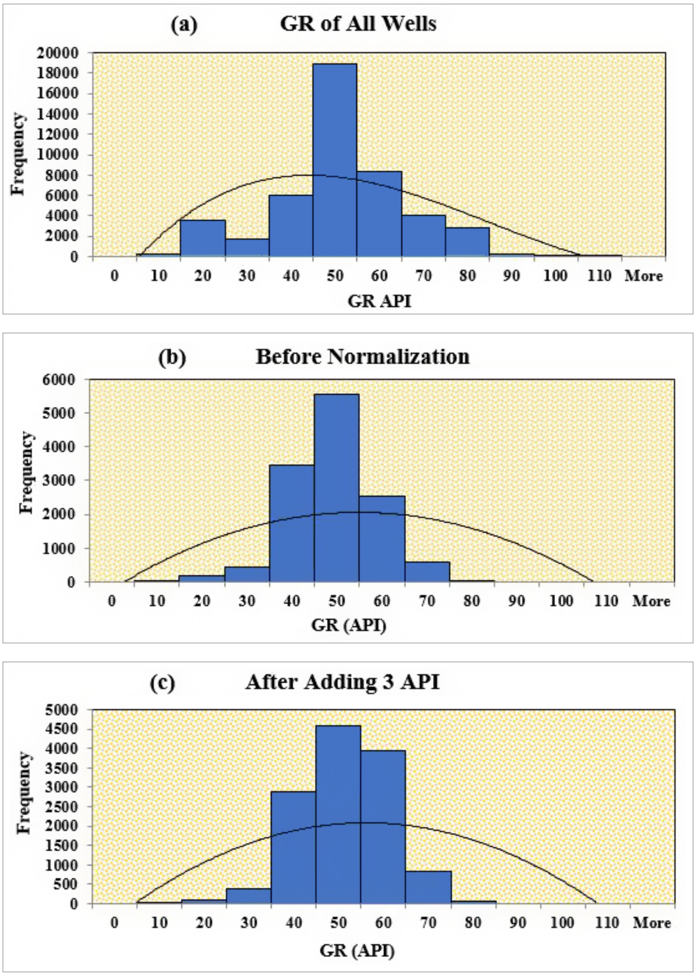

Fig. 4. Combined histograms of gamma ray log in NDOA-1 Well, Al-Wastani Formation, Sapphire oil field, Deep Delta Marine, Mediterranean Sea, Egypt.

value on the x-axis at 8 API. The conventional multi-well histogram of the entire dataset is juxtaposed with the histogram of the individual gamma ray log. The histogram's low gamma-ray region was employed for the normalization process. To achieve an optimal alignment between the standard histogram and the individual gamma ray histogram of well NDOA-1, a shift of +3 API (reflecting the difference between the intersection point of the standard multi-well histogram and that of well NDOA-1) was required to normalise the gamma ray values in well NDOA-1. Following the necessary correction, a new histogram for normalised gamma-ray values of well NDOA-1 can be produced, as illustrated in Fig. 4c.

The cumulative gamma-ray values to be added to or subtracted from the gamma-ray data obtained from each of the seven wells are presented in Table 1.

Table 1. Required data normalization adjustments for wells in Al-Wastani Formation, Sapphire oil field, Deep Delta Marine, Mediterranean Sea, Egypt.

	Well Name						
	NDOA-(1)	Saffron (Df)	Sapphire (1)	Sapphire (4)	Sapphire (Dd)	Sapphire (Dh)	Sapphire (Deep-1)
Value	**+3**	**+2**	**−6**	**−2**	**−1**	**−5**	**+6**

Considering the normalization of all total gamma ray data, Equation (1) was employed to determine the RHP values of Al-Wastani sediments in the studied wells. A statistical analysis of 45,925 samples demonstrated that radiogenic heat production amounts varied from 0.05 to 1.67 μW/m^3, with an arithmetic mean of 0.71 μW/m^3 and a standard deviation of 0.23 μW/m^3, as it shown in Table 2.

Table 2. Statistical analysis of RHP (μW/m^3), Al-Wastani Formation, Sapphire oil field, Deep Delta Marine, Mediterranean Sea, Egypt.

Sample No.	Mean	Minimum	Maximum	S.D.
45925	**0.71**	**0.05**	**1.67**	**0.23**

The heat that is produced from the decay of radioactive elements inside the sediments of Al-Wastani Formation was individually computed for each well, after which the results from the seven studied wells were consolidated into a single file for the purpose of rendering the data in a three-dimensional form using Tecplot-10 software.

Figure 5a illustrates the distribution of radiogenic heat production values across the three dimensions (x, y, and z) of Al-Wastani Formation within the study area, indicating that the minimum computed values (blue colour) were observed in the central region of the upper section of the study area and these low RHP values refer to low contents of hydrocarbons and shale, whereas the highest values are in the southern and southwestern regions of Al-Wastani Formation of the study area. By slicing the investigated for-

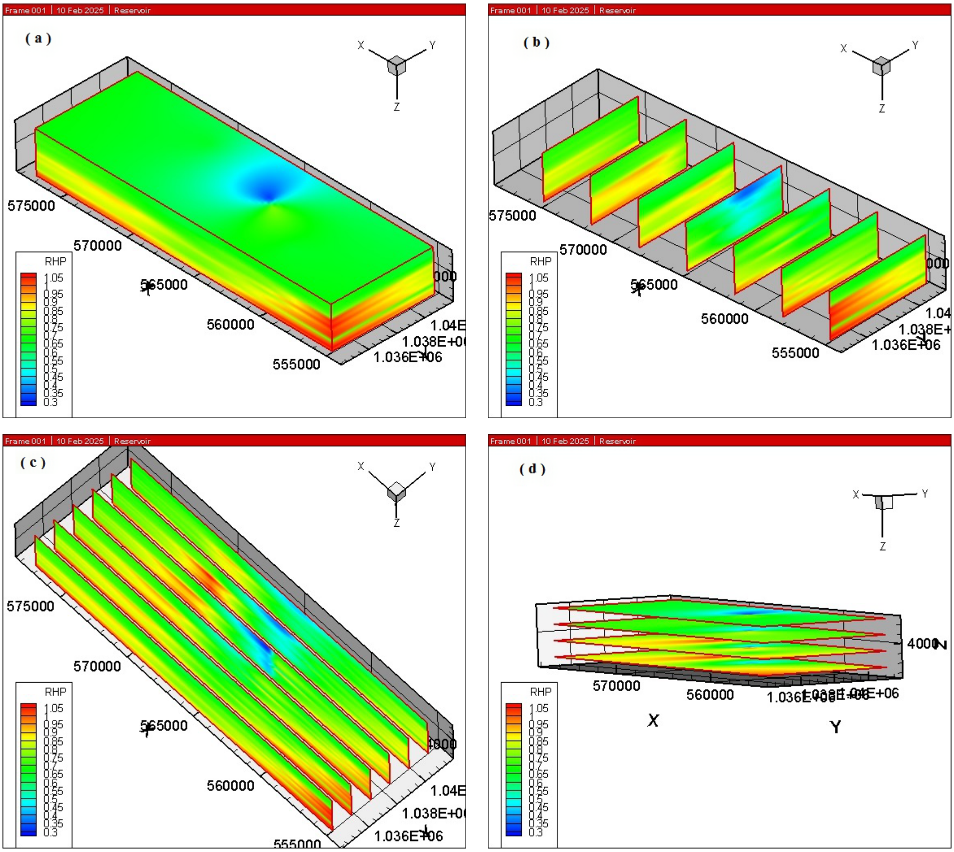

Fig. 5. External perspective and 3D slicing for RHP of Al-Wastani Formation, Sapphire Oil Field, Deep Marine Nile Delta, Egypt. (a) External perspective, (b) dissecting in x direction, (c) dissecting in y direction, (d) dissecting in z direction.

mation along the x-axis, it is evident that the RHP readings exhibit their lowest values in the entire upper zone, increasing gradually as one moves farther down the axis. The values increase in the bottom section as one progresses from right to left, as illustrated in Fig. 5b. The analysis along the y-axis indicates that the southwestern region of the study area exhibits the greatest radiogenic heat production values, while the northern zone, particularly the middle part, displays the lowest values, as illustrated in Fig. 5c. The identical outcomes are apparent when analysing the z-axis, as illustrated in Fig. 5d, where highest values are observed in the southern

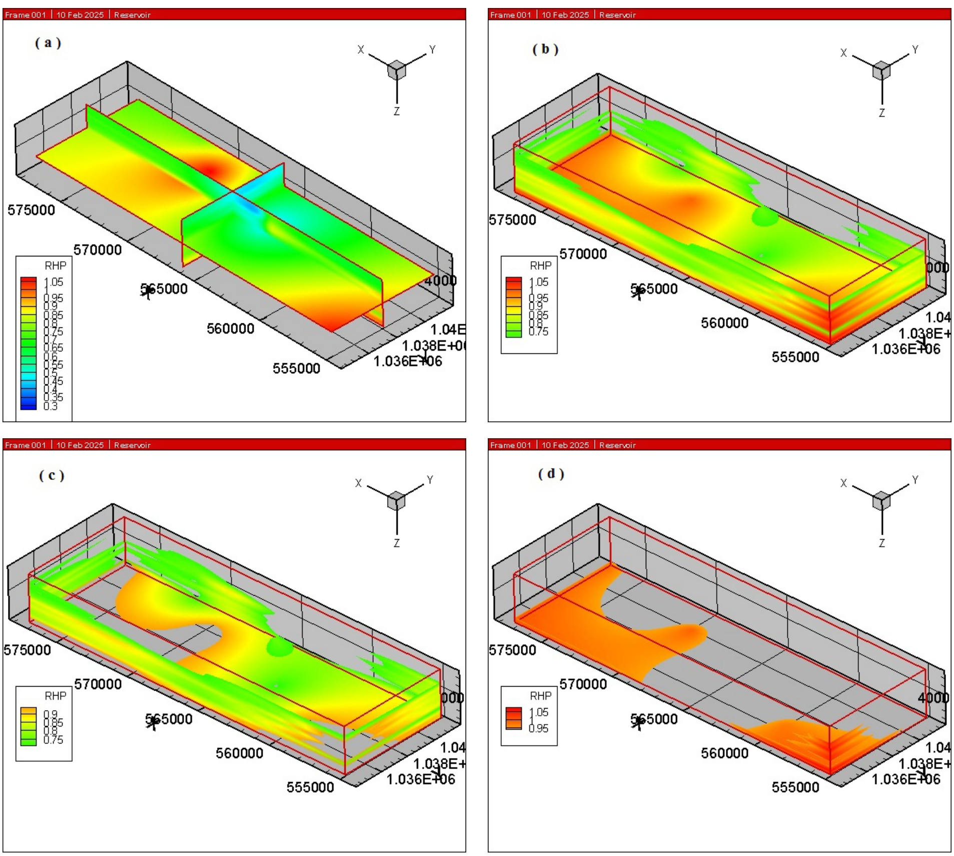

Fig. 6. Interior perspective and cutoff values for RHP of Al-Wastani Formation, Sapphire Oil Field, Deep Marine Nile Delta, Egypt. (a) Slicing in x, y and z directions, (b) hydrocarbon zones, (c) reservoir zones, (d) source zones.

region, particularly the southwest, with a drop in values as it moves up, mainly towards the central section of the research area.

The internal distribution of RHP values indicates that low values are found in the upper central region, while values increase with depth, particularly in the southwestern zone, as illustrated in Fig. 6a. Subtracting radiogenic heat values below the mean value 0.71 $\mu W/m^3$ reveals an absence of values in the upper section of the study area, while values are present in the middle and lower parts. This signifies that the upper section is devoid of hydrocarbon accumulations, whereas hydrocarbons are present in both the middle and lower strata, as illustrated in Fig. 6b.

Figure 6c illustrates the radiogenic heat production values ranging from mean of 0.71 $\mu W/m^3$ to the mean plus one standard deviation of 0.94 $\mu W/m^3$. This range aligns with the reservoir rock zone of the Al-Wastani Formation, as previously explained. This image clearly indicates that the central and predominantly lower sections constitute reservoir rock. Figure 6d displays temperature values exceeding 0.94 $\mu W/m^3$, indicating that the highest values occur in the lower section of the investigated area, particularly in the northern and southwestern regions, suggesting that these locations serve as source rocks for hydrocarbons.

5. Conclusion

The total gamma ray values that can be adjusted in the seven examined wells penetrating the sediments of the Al-Wastani Formation in the deep marine Nile Delta for normalization range from -6 to $+6$ API. The statistical analysis of RHP values of the Al-Wastani Formation rocks, derived from total gamma ray logs, indicates a range of 0.05 to 1.67 $\mu W/m^3$, with an arithmetic mean of 0.71 $\mu W/m^3$ and a standard deviation of 0.23 $\mu W/m^3$. The lower strata of the Al-Wastani Formation exhibit the greatest temperature values, particularly in the southwestern zone, with a gradual decline in values as elevation increases, culminating in the lowest temperatures observed in the upper layer of the investigated rocks, notably in the centre area of the upper zone. The central layer of the Al-Wastani Formation is categorised as reservoir rocks, whereas the lower strata are deemed source rocks; no hydrocarbon accumulations have been observed in the upper zone of the study rocks of the Al-Wastani Formation.

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