

Petrophysical Evaluation and Reservoir Quality of the Upper Cretaceous Sedimentary Formations of Block CI-M in the Ivorian Offshore Basin

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Abstract

This report focuses on the characterization of reservoirs from wells in block CI-M of the Ivorian offshore sedimentary basin. The aim of this study is to identify and evaluate potential reservoirs by characterizing the petrophysical parameters of the formations. The study was based on the interpretation of gamma ray, resistivity, sonic, density and neutron logs, as well as the evaluation of the petrophysical parameters of the different reservoir formations crossed by the wells M-1X and M-2X. The results showed that the different well strata are predominantly composed of clays, but in some wells, there are intercalations of sandstone, limestone, sand, and siltstone beds at the Turonian and Cenomanian levels. Furthermore, the development of the lithostratigraphic column and the petrophysical parameters allowed us to identify reservoirs levels. Additionally, the study of wells M-1X and M-2X indicates that the reservoir layers are located in the Campanian, Turonian, and Cenomanian stages. The establishment of the lithostratigraphic column, the interpretation of the well logs, and the determination of the petrophysical parameters of the wells have highlighted three oil-bearing reservoirs and two water reservoirs.

Keywords

Petrophysical, Evaluation, Reservoir Quality, Upper Cretaceous, Ivorian Offshore Basin

1. Introduction

Côte d'Ivoire, a West African country, belongs to the chain of countries in the Gulf of Guinea, stretching from southern Morocco to beyond Angola [1]. It has a basin that came into being during the rifting that led to the separation of the Gondwanaland super-continent into South America and Africa. In this sedimentary basin, as in most of the countries of the Gulf of Guinea, organic matter matured, leading to the accumulation of fossil fuels. Some 80% of these energies, which mankind needs for transport, heating and lighting, are produced by oil and gas, and their availability on national territory is becoming not only an economic asset, but also a strategic and even geopolitical objective. It is therefore imperative to gain a better understanding of the sedimentary basins in which hydrocarbons are formed, with a view to producing these oil and gas deposits. Furthermore, the numerous hydrocarbon exploration drillings, seismic lines and other geophysical work carried out over the last thirty to forty years in the countries of the Gulf of Guinea have raised many questions about lithostratigraphy. Work carried out in the Ivorian basin [2]-[4] has provided important information on the geology, structure, age and hydrocarbon potential of the Ivorian sedimentary basin. Thanks to previous work, the stratigraphy of the Côte d'Ivoire sedimentary basin has been reconstructed. Notwithstanding these eminently important scientific and petroleum research studies, detailed knowledge of the lithostratigraphy and nature of the formations in the Ivorian sedimentary basin is still lacking. This is evidenced by the sudden variations in facies in a relatively small geographical area of the basin. With this in mind, it became essential to understand the reservoir characterization of the CI-M block wells. The aim of the study is to evaluate potential reservoir by characterizing petrophysical parameters. The Ivorian basin is subdivided into several blocks representing the exploration or exploitation permits granted by the government of Côte d'Ivoire to oil companies. The M-1X and M-2X fields covered by this study are located in the offshore zone of the basin, precisely in the CI-M block.

2. Methodology

2.1. Sourcing and Preparation

The M-1X and M-2X fields covered by this study are located in the offshore zone of the basin, precisely in the CI-M block (Figure 1). Two wells were drilled to identify them: M-1X and M-2X in 2016 and 2017 respectively. The M-1X exploration well is located in the eastern part of block CI-527. The M-2X exploration

well is located in the eastern part of block CI-527. The P-1X exploration well has several geological levels, with depths varying between 3610 and 5000 m, for a total thickness of 1390 m. P-2X is at a depth of between 3505 and 5301 m, for a total thickness of 1796 m.

Stratigraphic boundaries were established on the basis of direct observation of lithologies, followed by automatic identification of facies changes. Dating and stratigraphic correlation were based on biostratigraphy. The mapping of the location of wells M-1X and M-2X is based on the MCNV 3D seismic survey. From this seismic volume, an EEI (extended elastic impedance) was generated. The near stack and the full stack were used to map the structure and boundaries of the sequence and the EEI was used to identify the main sedimentary channels.

In addition, EEI data was generated using wells Po-1X, Po-2A, Po-3AR and Po-4A for calibration.

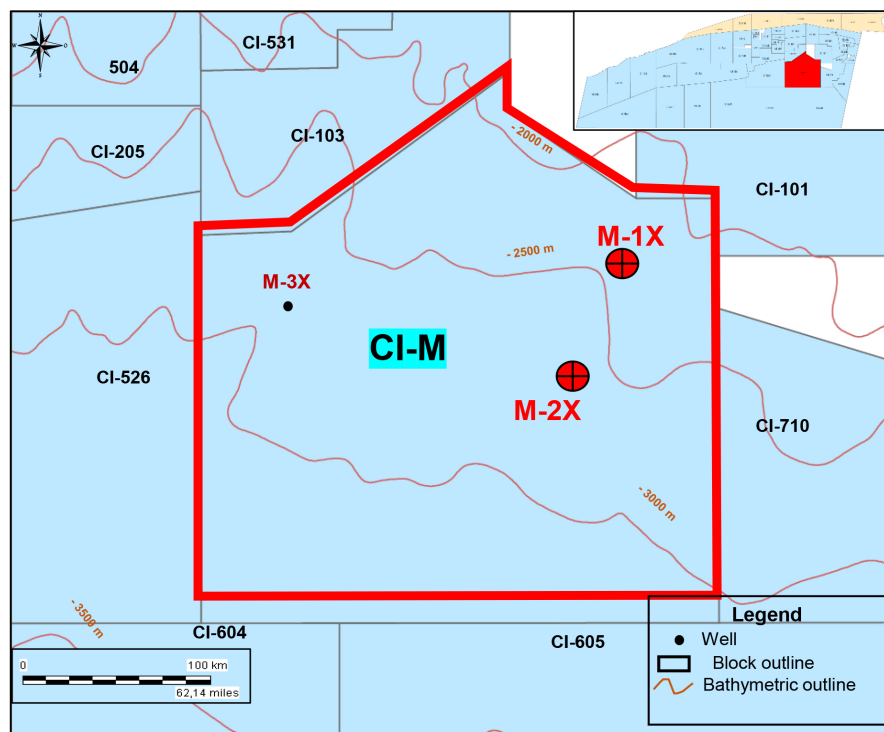


Figure 1. Geological map of the CI-M block.

2.2. Experiments

Logging measurements reveal the nature and properties of the layers traversed by the borehole in order to estimate their hydrocarbon content. The logs considered in this study are: Gamma Ray (GR), sonic (DT), resistivity (RXO, RD,...), neutron (NPHI) and density (RHOB). The Petrophysical parameters calculated are porosity (Φ), clay volume (V_{sh}), water saturation (S_w), permeability (K) and Net/Gross.

Porosity (Φ) is the fraction of a rock's volume occupied by pores, and is expressed as a percentage (%).

It is determined from log Sonic by the following formula:

$$\Phi(\text{Sonic}) = (t_{\log} - t_{ma}) / (t_f - t_{ma}) \quad (1)$$

Porosity is interpreted as follows:

- $\Phi < 5\%$: Negligible porosity;
- $5 < \Phi < 10\%$: We have Weak porosity;
- $10 < \Phi < 15\%$: Medium porosity;
- $15 < \Phi < 20\%$: We have Good porosity;
- $\Phi > 20\%$: Very good porosity

Clay volume (V_{sh}) tells us about the argillosity and nature of a sandstone formation. In other words, the intercalation of fine clay layers and the inclusion of clay nodules in the sandstone mass. For a $V_{sh} > 40\%$, the formation is considered to be clayey, and therefore unsuitable as a reservoir. V_{sh} is given by the following formula:

$$V_{sh} = (G_R - GR_{\min}) / (GR_{\max} - GR_{\min}) \quad (2)$$

The threshold value of 35 API on the Gamma Ray (GR) has been used based on the work of certain authors, notably [5]. So, on the basis of direct observation of lithologies. This is an empirical criterion for distinguishing reservoir zones (potentially permeable, such as sandstones) from non-reservoir zones (more clayey or shale-rich).

Water saturation (S_w) is the fraction of the pore volume filled with water. The rest of the pore volume contains oil or gas. The corresponding fraction is the hydrocarbon saturation.

S_w is calculated using the following formula:

$$S_w = \frac{a}{\Phi_m} \sqrt[n]{\frac{R_w}{R_t}} \quad (3)$$

Permeability (K) is the capacity with which a fluid can flow through a porous formation whose pores communicate with each other. Expressed in milli darcy (md), it is strongly dependent on grain size, so coarse-grained sediments have a high permeability, while fine-grained sediments have a low permeability. It is given by the formula of [6]:

$$K = 0.136 \frac{\Phi^{4.4}}{S_w^2} \quad (4)$$

- $K < 15$ md, we have zero to low permeability,
- $15 < K < 50$ md, medium permeability,
- $50 < K < 250$ md, good permeability,
- $250 < K < 1000$ md, very good permeability,
- $K > 1000$ md, excellent permeability.

Net/Gross is the total thickness of the sand banks encountered in this stage, and Gross is the thickness of all the lithological formations in a borehole. It is used to estimate the true thickness of the reservoir and to eliminate any clay or marl intercalations that are not reservoir rocks. It is expressed as a percentage (%).

Net/Gross is then the ratio of the sum of the thicknesses of the sand banks to the total thickness of the stratigraphic stage, noted:

$$\text{Net/Gross} = \frac{\sum \text{Sand thickness}}{\text{Total thickness}} \quad (5)$$

Three types of reservoirs are distinguished according to Net/Gross values:

- Net/Gross < 10%: poor quality reservoir;
- 10% < Net/Gross < 20%: medium-quality reservoir;
- Net/Gross > 20%: good quality reservoir.

The study of petrophysics and logging, through their tools and principles, will enable us to identify the zone of interest and determine the petrophysical parameters that will enable us to assess reservoir quality.

3. Results and Discussion

3.1. Log Analysis and Identification of Reservoir Levels in Well M1-X

The lithology reveals that the Cenomanian is absent in well M-1X, whereas it is present in well M-X2. The specific depth of the Cenomanian ranges from 5301 m to 5427 m. The Turonian in shaft M-1X extends from 5000 m to 5269 m. In shaft M-2X the Turonian ranges from 4832 m to 5301 m. As for the Campanian, this unit lies between 3890 m and 4470 m in shaft M-1X. In shaft M-2X, the Campanian ranges from 3815 m to 4475 m.

Thanks to logging signatures (Gamma Ray, Resistivity, Density-Neutron), we were able to highlight the different reservoir and non-reservoir levels of the wells. Looking at the Gamma Ray (**Figure 2**) and (**Figure 3**), we have drawn a 35API baseline that discriminates the curve into two parts. As a result, Gamma Ray values below 35API represent reservoir levels, and those above 35API indicate non-reservoir levels. We can therefore easily indicate two levels, reservoirs 1 and 2 at depths of 4382 m to 4413 m and 5139 m to 5226 m.

With regard to the Density-Neutron pair, reservoirs 4382 m to 4413 m and 5139 m to 5226 m show Density and Neutron values that progressively decrease to form

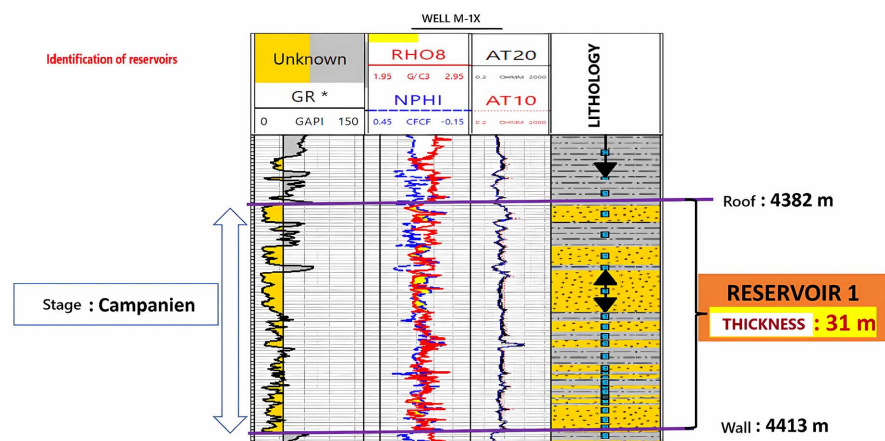


Figure 2. Identification of reservoir 1 from the M1-X well reservoir.

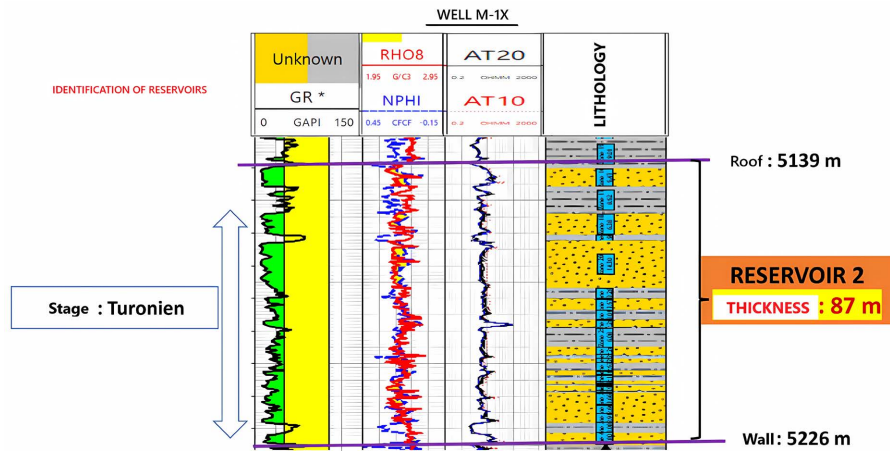


Figure 3. Identification of reservoir 2 from M1-X well reservoir.

“Cross Over” in places. This confirms the presence of reservoirs. When the “Cross Over” is very wide, it indicates the presence of gas (gas effect), more precisely sand/sandstone. In particular, we observe density and neutron values moving in the same direction, which is due to compact levels. With regard to resistivity, the interval from 4382 m to 4413 m and 5139 m to 5226 m generally show two trends in resistivity values. The first gives low values ranging from 1.80 to 1.05 ohm.m, and the second trend gives low to medium values ranging from 2 to 30 ohm.m, which could indicate water zones and a hydrocarbon-plus-water zone respectively. Log analysis of the M-1X well has enabled us to define two levels, reservoirs 1 and 2, at depths of 4382 m to 4413 m and 5139 m to 5226 m (Table 1).

Table 1. Well M-1X reservoir specifications.

WELLS	FORMATIONS	RESERVOIRS	WALL(m)	ROOF(m)	PROBABLE FLUIDS
M1-X	Campanian	reservoir 1	4382	4382	Water
	Turonian	reservoir 2	5139	5226	Water + Hydrocarbon

3.2. Analysis of Petrophysical Parameters of M1-X Reservoir

The petrophysical parameters calculated for the M-1X well are presented, in Table 2. Petrophysical parameters of the M-1X well have identified two potential reservoir levels of petroleum interest, consisting of porous and permeable sandstone and sandstone formations. The first reservoir was identified between 4382 m and 4413 m, with a total useful thickness of 31 m, in the Campanian. The petrophysical parameters showed that it is a average quality reservoir (Net/Gross = 35.4%) with an average porosity of 35% and low permeability (10.72 md). Water saturation (Sw) is 77.7% and low resistivities indicate that it contains water. The second reservoir lies between 5139 m and 5226 m, with a total thickness of 43.75 m and an effective thickness of 41.6 m, at the Turonian level. The petrophysical parameters determined showed a reservoir of very good quality (Net/Gross = 95%) with an average porosity of 12.3% and excellent permeability (1573 md). Water saturation

is 6.3%, and the low to medium resistivities observed indicate the presence of hydrocarbons in this reservoir, with a probable trace of water.

Table 2. Potential reservoir petrophysical parameters for well M-1X.

RESERVOIRS	RESERVOIRS AREA		RESERVOIRS PETROPHYSICAL PARAMETERS					
	WALL	ROOF	Net/Gross (%)	Φ (%)	V_{sh} (%)	S_w (%)	K (md)	Potential fluids
RESERVOIR 1	Toit (m)	Mur (m)	Net/Gross (%)	Φ (%)	V_{sh} (%)	S_w (%)	K (md)	Water
	4382	4413	35.4	12.4	29.3	77.7	10.72	Water
RESERVOIR 2	5139	5226	95	12.3	31.6	6.3	1573	Water + Hydrocarbon

3.3. Log Analysis and Identification of Reservoir Levels in the M2-X Well

With regard to the Gamma Ray (**Figure 4**) and (**Figure 5**), we have drawn a 35API baseline which also discriminates the curve into two parts. As a result, Gamma Ray values below 35API represent reservoir levels, and those above 35API indicate non-reservoir levels. We can therefore easily identify three potential levels, reservoirs 1, 2 and 3 at depths of 4990 m to 5025 m, 5323 m to 5352 m and 5367 m to 5371 m respectively. With regard to the Density-Neutron pair, reservoir 4990 m to 5025 m, 5323 m to 5352 m and 5367 m to 5371 m show Density and Neutron values that progressively decrease to form “Cross Over” in places. This confirms the presence of reservoirs. In particular, we observe density and neutron values evolving in the same direction, which is due to compact levels. With regard to resistivity, the intervals from 4990 m to 5025 m, 5323 m to 5352 m and 5367 m to 5371 m generally show three trends in resistivity values. The first gives average values ranging from 4 to 42 ohm.m, the second trend gives low values ranging from 4 to 23 ohm.m and the third gives maximum to average values ranging from 20 to 294 ohm.m, which could indicate respective water plus hydrocarbon zones, a completely water-filled zone and a hydrocarbon zone.

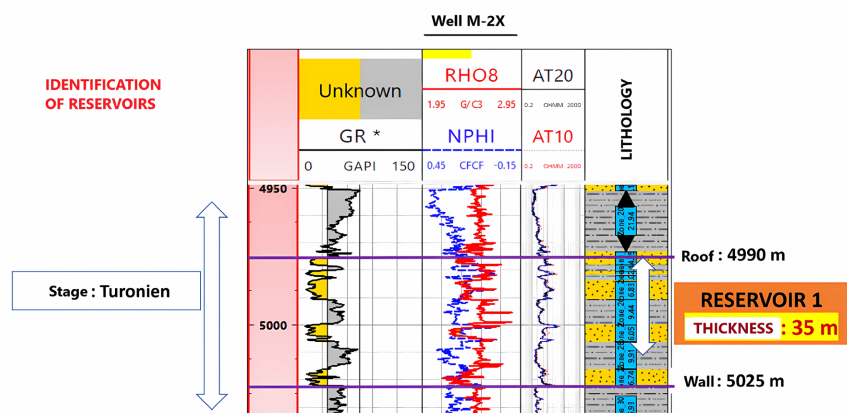


Figure 4. Identification of reservoir 1 from M2-X well reservoir.

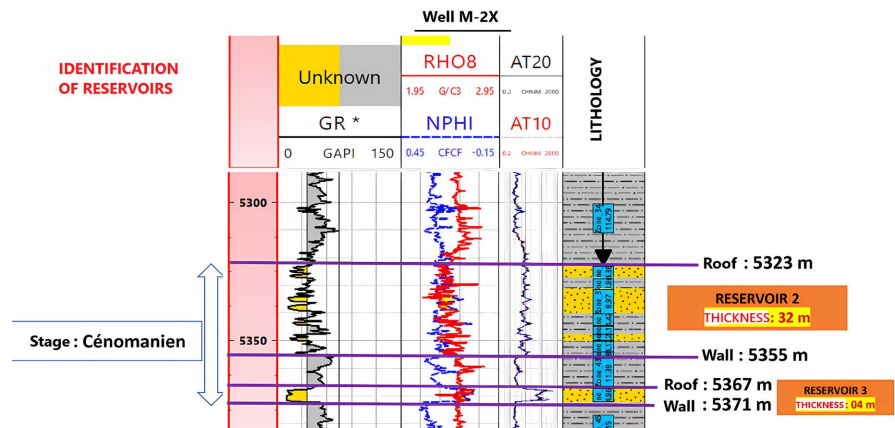


Figure 5. Identification of reservoir 2 and 3 from M2-X well reservoir.

The log analysis of the M2-X well allowed us to define three levels, reservoirs 1, 2 and 3 at the respective depths of 4990 m to 5025 m, 5323 m to 5352 m and 5367 m to 5371 m (**Table 3**).

Table 3. Characteristics of the Reservoirs of Well M-2X.

RESERVOIRS	FORMATIONS	INTERVALS	WALL	ROOF	PROBABLE FLUIDS
	Turonian	Reservoir 1	4990	5025	Water + Hydrocarbon
M2-X	Cenomanian	Reservoir 2	5323	5352	Water
	Cenomanian	Reservoir 3	5367	5371	Hydrocarbon

3.4. Analysis of the Petrophysical Parameters of the Reservoirs of the Well M-2X

The petrophysical parameters calculated at the level of the well M-2X are presented in **Table 4**. The analysis of the petrophysical parameters of the M-2X well reveals that it has three levels that are potentially reservoirs of oil interest. These levels are made up of layers of porous and permeable sandstone and sand. The first layer was identified between 4990 m and 5025 m with a total thickness of 35 m and 4.5 m of useful thickness, at the Turonian level. The petrophysical parameters show that it is a good quality reservoir (Net/Gross = 40.5%) with an average porosity of 12.7% and excellent permeability (1932.2 md). The water saturation is 6.10%. The resistivities observed showed that it is a reservoir that contains hydrocarbon with traces of water. The second layer was identified between 5323 and 5352 m with a total thickness of 29 m and a useful thickness of 10.8 m, at the Cenomanian level. Its petrophysical parameters show a very good quality reservoir (Net/Gross = 48.6%) with a good porosity of 16.7% and a low permeability (5.9 md). The water saturation is 75%. The observed resistivities vary from low to medium and show that this reservoir contains water. The third layer was identified between 5367 and 5371 m with a total thickness of 4 m and 3.73 m of useful thickness, at the Cenomanian level. The calculated petrophysical parameters show that it is a good quality reservoir (Net/Gross = 28.4%) cleaner than the first two

($V_{sh} = 13.7\%$) with a good porosity of 12.9% and an excellent permeability (21334.7 md). It has a water saturation of 1.9% and the observed resistivities that range from average to very high show that this reservoir contains hydrocarbons. The very high permeability observed in the well is explained by a combination of favourable geological and petrophysical factors. In particular, the dynamic sedimentary context marked by turbiditic deposits or high-energy channels, generating clean, well-connected facies. In addition, the very low clay content limits the effects of clogging and promotes effective permeability.

Table 4. Petrophysical parameters of the potential reservoirs of the well M-2X.

RESERVOIRS	RESERVOIRS AREA		RESERVOIRS PETROPHYSICAL PARAMETERS					
	ROOF	WALL	Net/Gross (%)	Φ (%)	V_{sh} (%)	S_w (%)	K (md)	Potential fluids
RESERVOIR 1	4990	5025	40.5	12.7	13.5	6.1	1932	Hydrocarbon
RESERVOIR 2	5323	5352	48.6	16.7	55	75	5.9	Water
RESERVOIR 3	5367	5371	28.4	12.9	13.7	1.9	21,334	Hydrocarbon

4. Discussion

The calculated petrophysical parameters showed that these layers have the characteristics of a good hydrocarbon reservoir. This is in accordance with [7] who states that a layer can only be declared as a potential reservoir if the $V_{sh} < 40\%$, otherwise it is a clayey formation. According to [8] the Cenomanian sandstones of the Abidjan margin are of good quality and have the capacity to store hydrocarbons. This is consistent with our results. The work of [9] showed that the Cretaceous sandstones of the offshore basin have good petrophysical parameters and constitute oil reservoirs that are Upper and Lower Cretaceous. In addition, for the first and second reservoirs, the Net/Gross (N/G) is 35.4% and 95% respectively. In similar geological formations, an N/G ratio of 35.4% could be considered moderately good. A N/G ratio of 95% is exceptionally high and indicates continuity and near pure reservoir quality. Studies such as that of [10] present a detailed analysis of the petrophysical properties of Cretaceous sedimentary rocks in the Southern Benue Trough, Nigeria. These authors suggest that formations with high N/G ratios are crucial for identifying high-potential reservoirs for hydrocarbon exploration in the region, as they indicate continuity and relative purity of the reservoir, thus increasing the ease of hydrocarbon production. The well correlations carried out in the CI-M block, combined with the use of geological analogues from the Benue Trough, enhance the understanding of stratigraphic architectures and reservoir systems. This integrated approach strengthens the consistency of geological models, improves the prediction of reservoir extensions, and reduces uncertainty in poorly constrained areas. This confirms the importance of a high N/G ratio for accurate reservoir evaluation and exploration planning. Our results may have implications for hydrocarbon storage capacity. Indeed, a N/G ratio of 35.4% means that only a relatively small portion of the total thickness is actually

usable as a reservoir. This potentially limits the total hydrocarbon storage capacity per unit area of the formation. Furthermore, with an average porosity of 12.3% and an excellent permeability of 1573 md, the second reservoir has a hydrocarbon storage potential that has significantly increased compared to the first reservoir. In doing so, previous studies indicate that reservoirs with high N/G ratios such as this are often associated with high recovery efficiency, with potentially robust production capacity and fewer technical challenges during operation [11].

5. Conclusion

The interpretation of the logs and the determination of the petrophysical parameters of the wells allowed us to highlight three reservoirs containing oils and two water reservoirs. The pooling of the results of lithological and log analyses, and the interpretations of the petrophysical parameters allowed us to highlight reservoir levels. Furthermore, the study of the petrophysical parameters of the M-1X and M-2X wells reveals that the latter have potentially reservoir levels with oil interest. These levels are made up of layers of porous and permeable sandstone and sand, so for the M-1X well, we have three reservoirs: the first layer was identified between (4382 m and 4413 m) with a total useful thickness of 17.55 m and 6.1 m, at the Campanian level. The physical parameters showed that it is an average quality reservoir (Net/Gross = 35.4%) with medium porosity (35%) and low permeability (10.72 md). The water saturation is 77.7% and the low resistivities indicate that it contains water. The second reservoir is located between (5139 m and 5226 m) with a total thickness of 43.75 m and a useful thickness of 41.6 m, at the Turonian level. The determined physical parameters showed a very good quality reservoir (Net/Gross = 95%) with medium porosity (12.3%) and excellent permeability (1573 md). The water saturation is 6.3%, and the low to medium resistivities observed indicate the presence of hydrocarbons in this reservoir with a probable trace of water. And for the M-2X well, we identified three reservoirs: Between 4990 m and 5025 m depth, we identified the first reservoir with a total thickness of 10.02 m and 4.5 m of useful thickness, at the Turonian level and physical parameters show that it is a good quality reservoir (Net/Gross = 40.5%) with medium porosity (12.7%) and excellent permeability (1932.2 md). The water saturation is 6.10%. The observed resistivities showed that it is a reservoir that contains hydrocarbons with traces of water. The N/G ratios of 35.4% for the first reservoir and 95% for the second show significant differences in terms of reservoir quality and continuity, with direct implications for hydrocarbon storage capacity and recovery efficiency. These comparisons with previous work by different authors allow for a better understanding of the potential challenges and opportunities offered by each reservoir type in the context of the oil and gas industry. In conclusion, the accurate identification of stratigraphic boundaries and reservoir bodies is a key tool for guiding exploration and development decisions. It enables the targeting of the most productive units, optimization of well placement, reduction of geological uncertainty, and improved reservoir model performance. These

findings therefore strengthen the robustness of the development plan and support future investment decisions.

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Conflict of Interest

The authors declare that there are no conflicts of interest.

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