*Romanian Journal of Petroleum & Gas Technology*
*Vol. VII (LXXVIII) • No. 1/2026*

# QUALITATIVE EVALUATION OF THE UPPER PINDA RESERVOIR IN THE MIBALE FIELD USING MULTI-LOG ANALYSIS AND COMPOSITE ALTERATION INDEX

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**DOI: 10.51865/JPGT.2026.01.03**

## ABSTRACT

In the context of optimizing oil production, the accurate evaluation of reservoir quality is a major factor for the profitability of oil fields. The Mibale field, located in the coastal basin of the Democratic Republic of Congo, contains the Pinda reservoir, known for its strong lithological and petrophysical heterogeneity. Although the presence of hydrocarbons is confirmed, productivity remains low, with an average permeability ranging between 2 and 5 mD, raising questions about the distribution of reservoir properties and the impact of alteration on rock behavior. This study aims to determine the dominant sedimentary and lithological facies and their influence on reservoir quality, to understand the role of alteration in modifying petrophysical properties, and to identify favorable zones (sweet spots) based on GR, NPHI, RHOB logs and the Composite Alteration Index (CAI). It is based on the hypothesis that the Pinda reservoir is dominated by carbonate and sandstone facies whose petrophysical properties vary with depth, that the CAI constitutes a reliable indicator of property degradation due to argillization, and that zones with low GR and moderate to low CAI correspond to sweet spots with favorable secondary porosity. The general objective is to evaluate the quality of the Pinda reservoir based on its lithology, level of alteration, and petrophysical characteristics, through the identification of lithological facies from GR, NPHI, and RHOB logs, the calculation and interpretation of CAI, as well as the delineation of optimal reservoir zones according to diagraphic and alteration criteria. The adopted methodology relies on the interpretation of well logs from exploration well 1-X of the Mibale field, with analytical and numerical processing of the data cross-referenced with CAI calculated from vertical variations in lithofacies. The lithological facies were identified using NPHI–RHOB cross-plots, and the favorable zones were mapped using STRATER 5 software, based on the logs and cores provided by Perenco in 2020.

**Keywords:** Mibale field, petrophysical properties, reservoir quality, well logs, depositional environments, Composite Alteration Index (CAI)

## INTRODUCTION

In a global context marked by the need to optimize the exploitation of oil resources, the precise assessment of reservoir quality is a major issue for the profitability and sustainability of production fields [1],[11]. Indeed, a thorough understanding of a reservoir's petrophysical and

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lithological characteristics directly affects its productivity and the effectiveness of hydrocarbon recovery strategies. It is within this perspective that the present study is framed, focusing on the Mibale field, located in the coastal basin of the Democratic Republic of Congo. This field hosts the Pinda reservoir, known for its lithological complexity, petrophysical heterogeneity, and relatively low productivity despite the confirmed presence of hydrocarbons indicated by logs and core data [2]. The average permeability of the reservoir, estimated between 2 and 5 mD, reflects the need for a more in-depth evaluation of the distribution of reservoir properties and the influence of alteration processes on rock behavior. The study of alteration, expressed by the alteration index (AI), allows for the quantification of the physico-chemical degradation of rocks and the assessment of its impact on the initial petrophysical properties [3]. This index, combined with the interpretation of well logs, particularly natural radioactivity (GR), neutron porosity (NPHI), bulk density (RHOB), and acoustic velocity (DT), constitutes an effective tool for characterizing reservoir quality and identifying potentially productive zones, [4],[26]. Well logs, widely used in geotechnical, hydrogeological, and petrophysical studies, enable an objective and continuous evaluation of the formations encountered [23]. The Mibale field, located about 5 km off the Congolese coast in the offshore coastal basin, covers an area of approximately 17 km² with an average depth of 15,000 feet (about 4,626 m). It extends between the latitudes south 5°50'30" and the longitudes east 12°12'30" [5]. Figure 1 illustrates the geographic position of the Mibale field in the structural context of the coastal basin of the Democratic Republic of Congo. Thus, the present study aims to assess the quality of the Upper Pinda reservoir through an integrated analysis of logs and the alteration index, with the goal of identifying favorable areas (sweet spots) and better understanding the factors controlling the variability of reservoir properties in this geological unit [6].

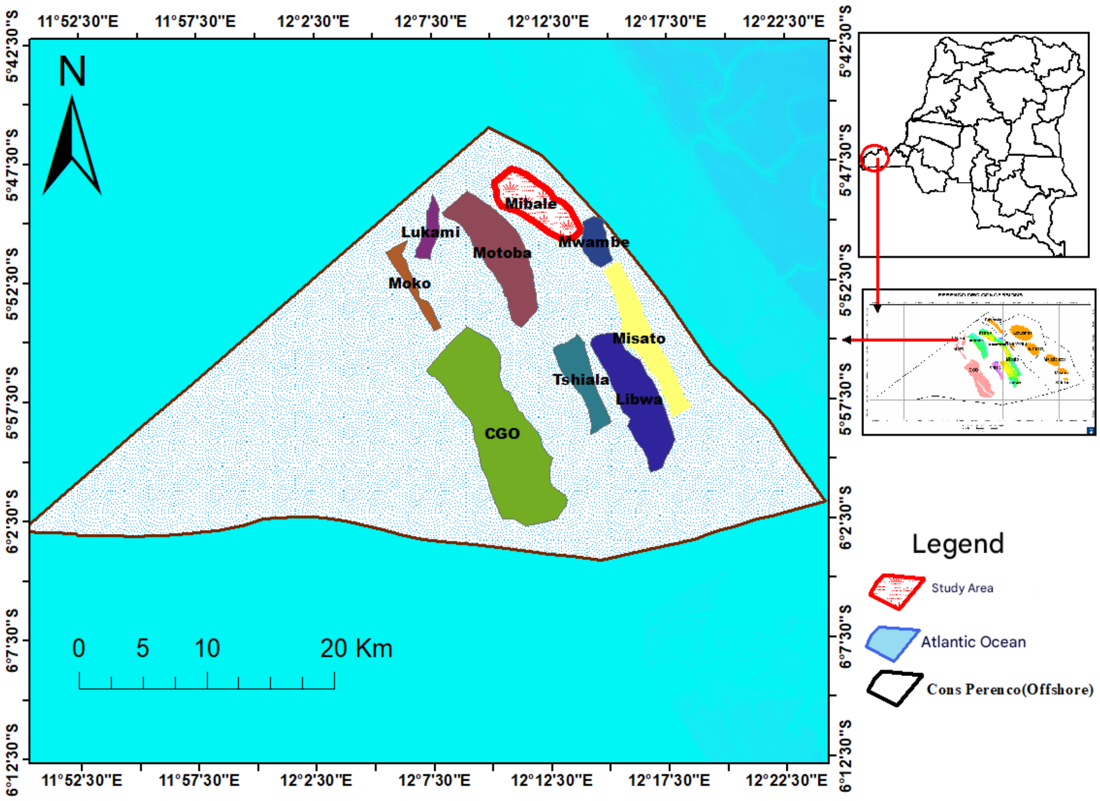


*Figure 1.* *Location map of the Mibale field*

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## DATA AVAILABILITY AND METHODS

The methodology adopted in this study is based on the integrated interpretation of delayed logs (GR, RHOB, NPHI) from the exploration well of the Mibale field. This approach combines both an analytical method and numerical simulation, allowing for a detailed characterization of the reservoir's petrophysical properties [6],[7],[24],[25]. The different curves were cross-referenced with the Composite Alteration Index (CAI), calculated from the vertical variations observed in the logs, to assess the influence of alteration on the quality of the reservoir rocks. The term "alteration" specifically refers to the diagenetic process of argillization. As noted by Aïfa et al. [3], the transformation of feldspars into clay minerals clogs the pore network, thereby significantly reducing the porosity and permeability of the Pinda reservoir. The identification of lithological facies was carried out through polarity analysis and the use of NPHI–RHOB cross-plots, enabling the discrimination of the main rock types and their respective petrophysical responses. The mapping of areas favorable for production, known as "sweet spots," was carried out using the STRATER 5 software, based on the integration of log data and interpretation results. The information used comes from the logs of exploration well 1-X and core analyses conducted by Perenco [23], as well as technical and bibliographic documentation related to the Congolese coastal basin. These weights represent the relative sensitivity of each logging tool to clay content and rock matrix modification in clastic and carbonate formations. It should be noted that this qualitative evaluation is based on a single-well analysis. While the results provide crucial insights for identifying "sweet spots," this single-well approach does not capture the full lateral heterogeneity of the Mibale field, which would require multi-well correlation.

## RESULTS AND DISCUSSION

### The Quantification of Damage using Diagraphic Analysis

The composite alteration index quantifies the physico-chemical degradation of rocks by comparing their petrophysical properties before and after alteration. Well logs (GR, NPHI, RHOB, DT) allow for an objective assessment, particularly in geotechnical, hydrogeological, and petrophysical studies of oil reservoirs [8],[9].

#### *Calculation of alteration indices from diagraphic recordings*

As mentioned above, the alteration is characterized by four types of diagraphs, and their indices are expressed as the formulas below will show.

**(1) Acoustic Deterioration Index ($I_{DT}$)**

The reduction in P-wave velocity (Vp) is a reliable proxy for alteration [10]:

$$I_{DT} = \frac{DT_{altered-DT_{Intact}}}{DT_{Intact}} \quad (1)$$

This alteration is interpreted as follows:

- $\mathbf{I_{DT}} \approx 1$: Intact rock.
- $\mathbf{I_{DT}} > 1$: Altered rock ($I_{DT} = 1.5$ indicates a 33% reduction in Vp).

**(2) Density Index ($I_{Rhob}$)**

The loss of density reflects the secondary porosity that indicates rock alteration and is quantified by expression 2 [12]:

$$I_{Rhob} = \frac{Rhob_{healthy} - Rhob_{altered}}{Rhob_{intact}} \quad (2)$$

- $I_{Rhob} \approx 0$: Intact rock,
- $I_{Rhob} > 0$: Altered rock ($I_{Rhob} = 0.2$ means a 20% loss of density).

**(3) Neutron Porosity Index ($I_{NPHI}$)**

Alteration increases porosity through argillization and/or dissolution. The increase in NPHI indicates the argillization or dissolution of the rock, which are measured by expression 3 [12]:

$$I_{NPHI} = \frac{NPHI_{altered} - NPHI_{intact}}{1 - NPHI_{intact}} \quad (3)$$

**(4) Gamma Ray Index ($I_{GR}$)**

The enrichment in chemical elements such as K, U, Th is typical of altered zones [13]:

$$I_{GR} = \frac{GR_{altered} - GR_{clean}}{GR_{clay} - GR_{clean}} \quad (4)$$

Where $GR_{clay}$ is the maximum value observed in the altered zone

**(5) Composite Alteration Index (CAI) and Weightings**

The combination of parameters that are part of the alteration index follows an empirical approach given by expression 5 [14]:

$$\text{CAI} = \boldsymbol{\omega_1}\, I_{DT} + \boldsymbol{\omega_2}\, I_{Rhob} + \boldsymbol{\omega_3}\, I_{NPHI} + \boldsymbol{\omega_4}\, I_{GR} \quad (5)$$

Where $\boldsymbol{\omega_1}$ is the recommended weighted value according to the type of rocks and listed in Table 1 below [12].

***Table 1.*** *Weighted values of CAI*

| Parameters | Igneous rock | Sedimentary Rock |
|---|---|---|
| **DT** | 0.4 | 0.4 |
| **RHOB** | 0.3 | 0.3 |
| **NPHI** | 0.2 | 0.2 |
| **GR** | 0.1 | 0.1 |

These weighting factors are justified by the fact that [3]:

- DT (0.4): High sensitivity to fractures (mechanical alteration).
- RHOB (0.3): Correlated with mineral degradation.
- NPHI (0.2): Indicates alteration porosity.
- GR (0.1): Complementary (depends on radioactive minerals).

**Evaluation of Reservoir Quality**

It is appropriate to note that CAI thresholds vary according to lithology [15]. The CAI Interpretation scale adapted for sandstone and carbonate reservoirs, based on Aïfa et al. [3], is given in Table 2.

***Table 2.*** *The CAI Interpretation Scale Adapted for Sandstone and Carbonate Reservoirs* [16]

| **CAI Value** | **Degree of alteration** | **Reservoir quality** | **Petrophysical Characteristics** |
|---|---|---|---|
| **0.0–0.2** | Untouched rock | **Excellent** | Predominant primary porosity, high permeability, low GR (<50 API). |
| **0.2–0.4** | Minor alteration | **Good to Very Good** | Slightly increased porosity, preserved permeability, low clay content. |
| **0.4–0.6** | Moderate alteration | **Variable** | Secondary porosity (fractures/dissolution), connectivity-dependent permeability. |
| **0.6–0.8** | Severe alteration | **Mediocre to Risky** | High clay content (smectite/illite), reduced permeability, high GR (>100 API). |
| **> 0.8** | Extreme alteration | **Degraded** | Non-productive reservoir (except for exceptional karst/fractured channels). |

The application of the composite alteration index to reservoir types indicates that [17]:

(a) Sandstone
- CAI value in the range 0.3–0.5: Optimal zone if GR < 75 API indicates a "Sweet Spot" (secondary porosity without clay barriers).
- CAI value in the range 0.6–0.8: Mediocre and high GR: Risk of permeability degradation (swelling clays).

(b) Carbonates
- CAI in the range 0.4–0.7: May indicate favorable dissolution porosity (karst/vugs) if DT > 80 µs/ft.
- CAI value in the range 0.6–0.8: with high NPHI: Risk of isolated porosity (non-connected).

(c) According to Rock Type
- Igneous rocks (granite, basalt): A CAI value in the range 0.6–0.8 indicates advanced alteration (saprolite formation). An illustrative case shows that a granite with CAI = 0.75 will be highly fractured and clay-altered.
- Sedimentary rocks (sandstone, limestone): A CAI value in the range 0.4–0.6 may indicate dissolution (limestones) or altered cementation (sandstone).
- The relationships between the Composite Alteration Index (CAI) and Reservoir Permeability have been developed by several authors, and two of them are as follows. Depending on the Rock Type, the composite alteration index shows that [4]:

- For clean sandstones:

$$log(K) = 2.5 \times CAI + 1.2 \; (R^2 = 0.82) \qquad (6)$$

- For fractured carbonates:

$$K = 250 \times e^{3.5 \times CAI} \text{ (for CAI<0.65)} \qquad (7)$$

**Lithological Reconstitution**

***Lithological proportion logs***

To develop the logs, an Excel table shows the ratios of the various types of lithological facies at each level, to create a database. The program STRATER 5 facilitates the creation of lithological percentage logs (Alteration Index). Figure 2 illustrates the various stages of developing lithological proportion logs.

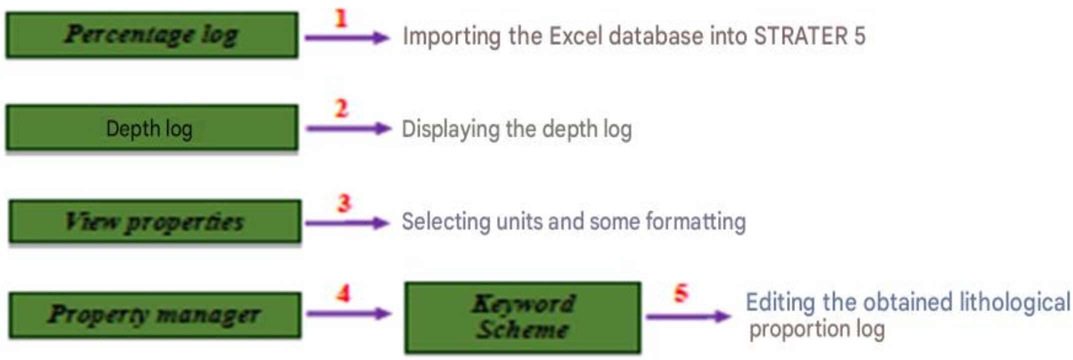


***Figure 2**. Steps for constructing a lithological proportion log using STRATER 5.*

***Lithological reconstruction***

The lithological boundaries of each type of rock in an excavation sample are not clearly defined. We therefore used well logging to distinguish the intermingled elements and determine the actual layer boundaries. This reconstruction is carried out using STRATER 5 software, which combines the log of lithological proportions with well logging information.

***Lithological interpretation from well logs***

Even though horizontal analysis is fundamental for any lithological study, here we will conduct a vertical examination of individual logs to observe trends, baseline lines, or absolute values. For example, for the GR, it is possible to draw a clay reference line considering a minimum of pure sand, limestone, etc. If the logs are displayed to scale, the association between density and neutron can be highlighted by separation curves (Figure 3). This is a very good indicator of lithology based on cross-plot [18].

***Lithological interpretation from CAI***

The CAI is a robust tool for evaluating the quality of reservoirs, provided it is combined with GR, DT, and NPHI, calibrated with core data, and the geological context (diagenesis, tectonics) is considered. In addition to this, it is also used to determine lithology. Its application involves all the formulas previously developed, and Table 3 below provides the order of magnitude of CAI and the corresponding lithology.

***Table 3.** Lithological interpretation from CAI*

| *Lithology* | *CAI Optimal* | *K max (mD)* |
|---|---|---|
| Sandstones | 0.3-0.5 | 300-1000 |
| Carbonates | 0.4-0.7 | 500-2000 |
| Clayey sandstones | <0.4 | <50 |

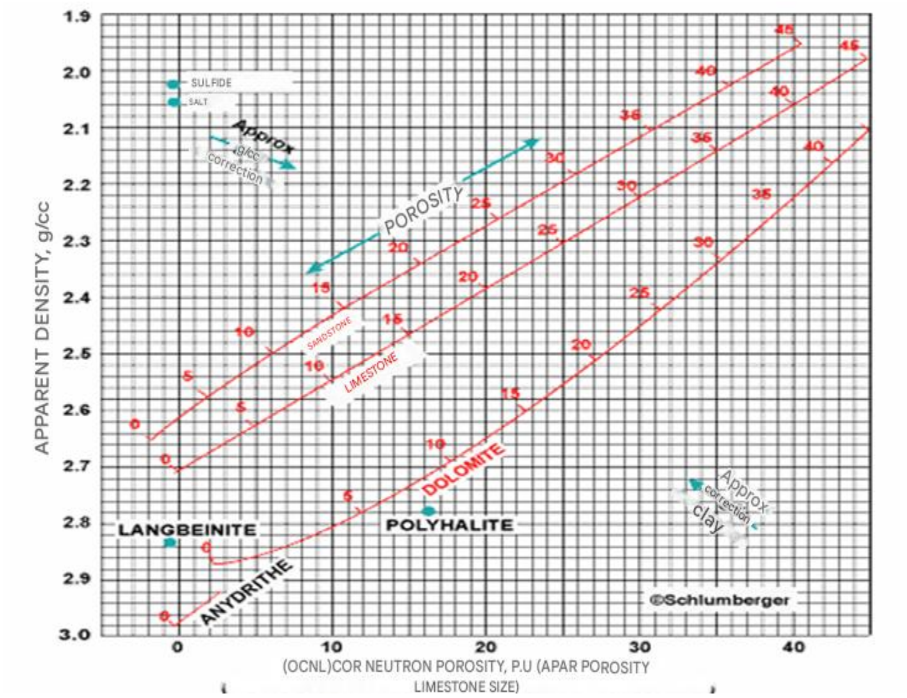


***Figure 3***. *Image showing the porosity-density relationship* [18].

### *Electrofacies*

Electrofacies is the set of log responses that characterizes a formation and allows it to be distinguished from those around it. The prefix "electro" was added to geological terms to indicate their log-based origin [19]. Traditionally, the representation of density (RHOB) and neutron porosity (NPHI) values is done on a scale adapted to limestone, which means that 0% NPHI corresponds to a density of 2.70 g/cm³. By convention, density is shown with an ascending progression to the right, which means that neutron porosity increases to the left. A preliminary visual assessment can therefore be considered, as in the case of the analyzed facies (Figure 2) [4]:

- ✓ Positive polarity electrofacies: if the RHOB curve is to the right of the NPHI curve (the gap between these two curves is usually shown in green), this usually indicates the presence of clays, dolomites, or anhydrite (differentiation based on gamma-ray and density).
- ✓ Negative polarity electrofacies: the RHOB curve moving to the left of the NPHI curve (the gap between these two curves is typically shown in yellow) generally represents sandy facies and/or the presence of gas.
- ✓ Zero polarity electrofacies: overlapping RHOB and NPHI curves indicate either the presence of limestone or a mixture of quartz and dolomite (distinction based on the Pef value).

## ON THE PINDA RESERVOIR IN THE MIBALE FIELD

Located above the Loeme salt, the Pinda reservoir in the Mibale field shows a situation as follows [20],[21]:

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- Presence of listric faults caused by the rise of the Loeme salt,
- Presence of antithetic faults,
- Pressure barriers in UP1,
- Heterogeneity of low permeability on the order of 2 to 5 mD,
- An average dynamic viscosity of 4.95 cP.

Another crucial observation from the cores is the presence of vacuoles in the dolomitic facies, which can be explained by the diagenetic processes at play. This vacuolar porosity has the potential to significantly increase permeability. The well logs recorded during the drilling of the exploration well are summarized in Figure 4. Based on the behavior of the different logs, the reservoir is subdivided from top to bottom into seven reservoir horizons (UP 1 to UP7), as shown in Figure 4. Direct analysis and the magnitude of GR indeed confirm that this section constitutes a reservoir [21],[22].

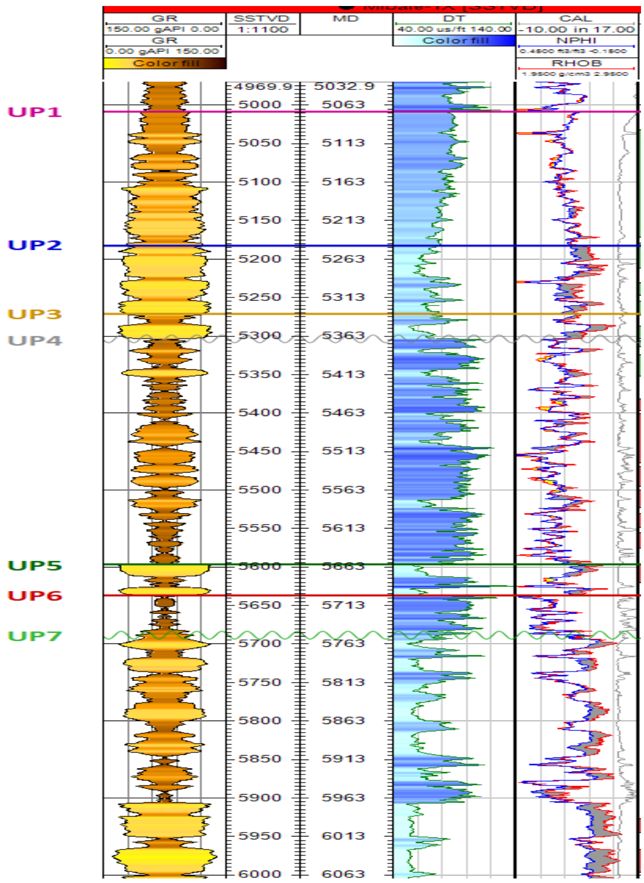


***Figure 4.*** *Composite log of well 1-X from the Mibale field* [23]

## EVALUATION OF COMPOSITE ALTERATION INDICES

### Specification of lithology

Of course, the quality of a reservoir directly depends on the lithology, and it is clear that this begins with identifying the different facies that make it up. The determination of facies involves understanding the polarity, tracing the sand and clay line, and then using cross-plotting. In accordance with “electrofacies” section, the RHOB and NPHI curves were superimposed as illustrated in Figure 5. From Figure 5, six major phases emerge, dominated by a positive polarity against a negative polarity phase beyond 5400 ft depth. After the polarity, the use of GR and cross-plotting led to the lithology recorded in Figure 6. The Upper Pinda reservoir in the Mibale field is a complex multilayer system, from top to bottom, are UP1, UP2, UP3, UP4, UP5, UP6, and UP7, as shown in Figure 4. This stratigraphy is illustrated in Figure 6 and indicates that there are six electrofacies in this reservoir, which include: Shale; Calcareous shale; Limestone; Dolomite; Carbonate sandstone; Arkosic sandstone.

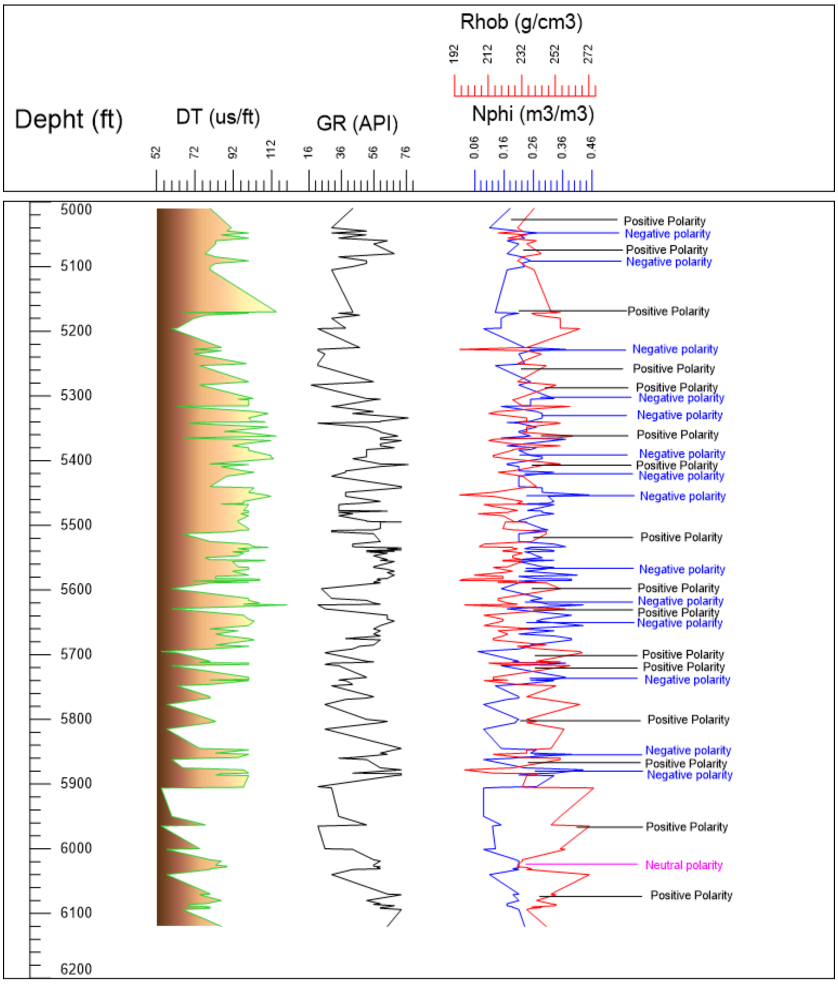


***Figure 5.*** *Curves showing the behavior of RHOB and NPHI.*

**Calculation of the Composite Alteration Index and interpretative summary**

The composite alteration index is the combination of four alteration indices developed in the previous chapter. It was calculated and the result compared with GR, two key parameters that help determine the quality of a reservoir (Figure 7). This section presents a cross-interpretation of the CAI, GR, and petrophysical indices to determine the lithology, reservoir quality, and probable depositional facies.

From Figure 7, we can observe that the alteration generally increases with depth, with the exception between 5196 and 5225 ft of depth where the dolomite was not affected by alteration.

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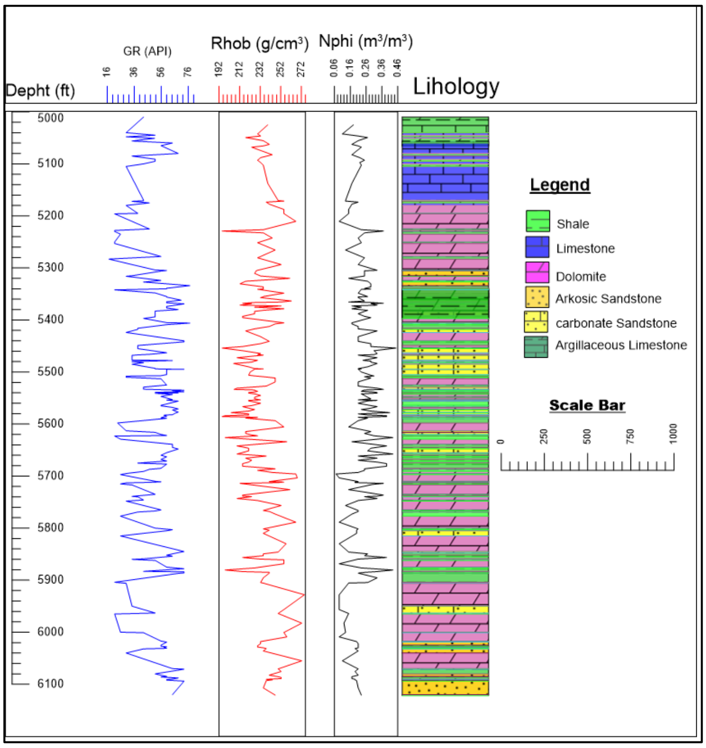


***Figure 6.*** *Lithology of the Pinda reservoir in the Mibale field*

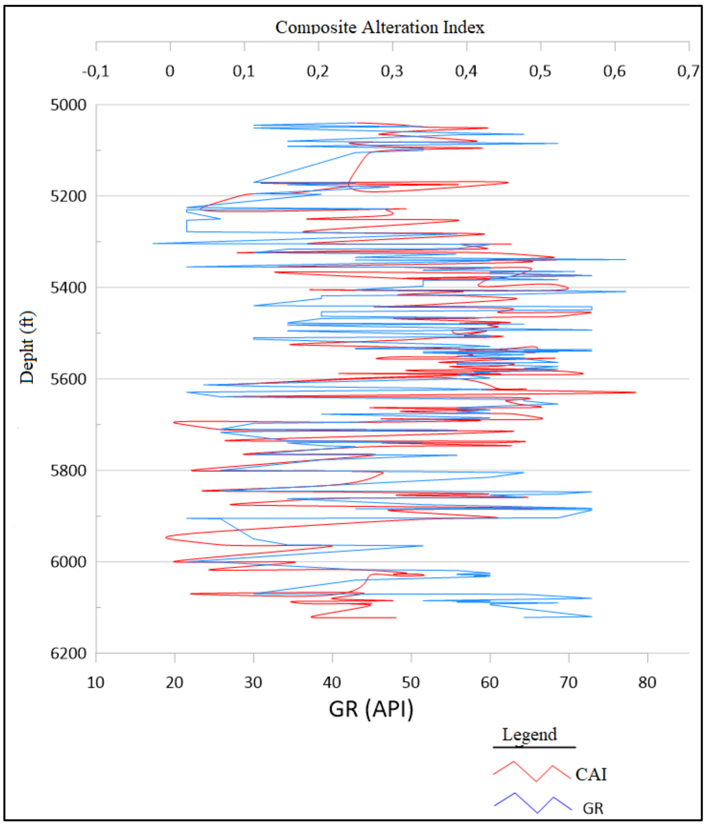


***Figure 7.*** *Curves showing the variation of CAI and GR with depth*

To enhance the clarity and reproducibility of the methodology, a detailed numerical example of the Composite Alteration Index (CAI) calculation is provided for the 5,010 to 5,040 ft interval within the Upper Pinda reservoir. First, the elementary alteration indices are determined by comparing the logged values of the altered rock ($DT_{alt}$ = 80 µs/ft, $RHOB_{alt}$ = 2.3935 g/cm³, $NPHI_{alt}$ = 0.18, and $GR_{alt}$ = 42.9 API) against the reference values for intact rock ($DT_{int}$ = 60 µs/ft, $RHOB_{int}$ = 2.71 g/cm³, $NPHI_{int}$ = 0.08, $GR_{clay}$ = 100 API and $GR_{clean}$ = 0 API). This process yields the following elementary indices:

- $I_{DT} = \frac{(80-60)}{60} = 0.333$
- $I_{RHOB} = \frac{(2.71-2.3935)}{2.71} = 0.117$
- $I_{NPHI} = \frac{(0.18-0.08)}{0.08} = 1.25$
- $I_{GR} = \frac{42.9}{100} = 0.429$

Finally, these indices are integrated into the composite formula using the assigned weighting coefficients (0.4, 0.3, 0.2, and 0.1), resulting in a final CAI value of:

$$CAI = 0.4(0.333) + 0.3(0.117) + 0.2(1.25) + 0.1(0.429)$$

$$CAI = 0.461$$

***Table 4**. Interpretation summary*

| Depth interval (ft) | CAI | GR (API) | Lithology | Quality | Facies |
|---|---|---|---|---|---|
| 5010-5040 | 0.46 | 43 | Pure limestone | Good | Carbonate facies |
| 5048-5051 | 0.43 | 30 | Weathered limestone | Variable | Karstified carbonate facies |
| 5170-5171 | 0.455 | 43 | Fractured limestone | Good | Karstified carbonate facies |
| 5196-5225 | 0.043 | 25 | Pure dolomite | Excellent | Carbonate facies |
| 5334-5342 | 0.45 | 60 | Altered dolomite | Average | Karstified carbonate facies |
| 5463-5477 | 0.44 | 45 | Limestone/dolomite | Good | Karstified carbonate facies |
| 5505-5510 | 0.4 | 30 | Sandstone | Good | Karstified carbonate facies |
| 5525-5533 | 0.36 | 50 | Altered sandstone | Good | Altered carbonate facies |
| 5600-5660 | 0.5 | 55 | Clayey carbonates | Average | Karstified carbonate facies |
| >5700 | 0.6 | 70 | Clays/Carbonates | Mediocre | Karstified carbonate facies |

- Potential Reservoir Zones (Sweet Spots): Areas with a CAI between 0.3 and 0.5, with a GR below 50 API, are interpreted as optimal reservoir zones. These areas are characterized by secondary porosity without clay barriers, favorable to hydrocarbon migration and accumulation. Two sweet spots have been identified:
  - 5010 to 5040 ft: pure limestone, CAI=0.46, GR=43, carbonate facies,
  - 5196 to 5225 ft: pure dolomite, CAI≈0.043, GR=25, carbonate facies.
- Interpreted Facies: Facies were inferred from the relationships between CAI, GR, and petrophysical properties. For the lithological facies definition, the following cut-off values were applied: the Sandstone facies is defined by Gamma Ray (GR) < 50 API and CAI < 0.3. The Carbonate facies ranges between 40 and 75 API with moderate CAI, while Shales are characterized by GR > 75 API and CAI >0.6.

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After visualizing the results using STRATER 5.0 software, we realized that the alteration of the Pinda reservoir in the Mibale field can be summarized into three classes, as shown in Figure 8. The important information from the Figure 8 is the presence of an altered clayey facies that was not revealed by the analytical calculation around 5400 ft depth.

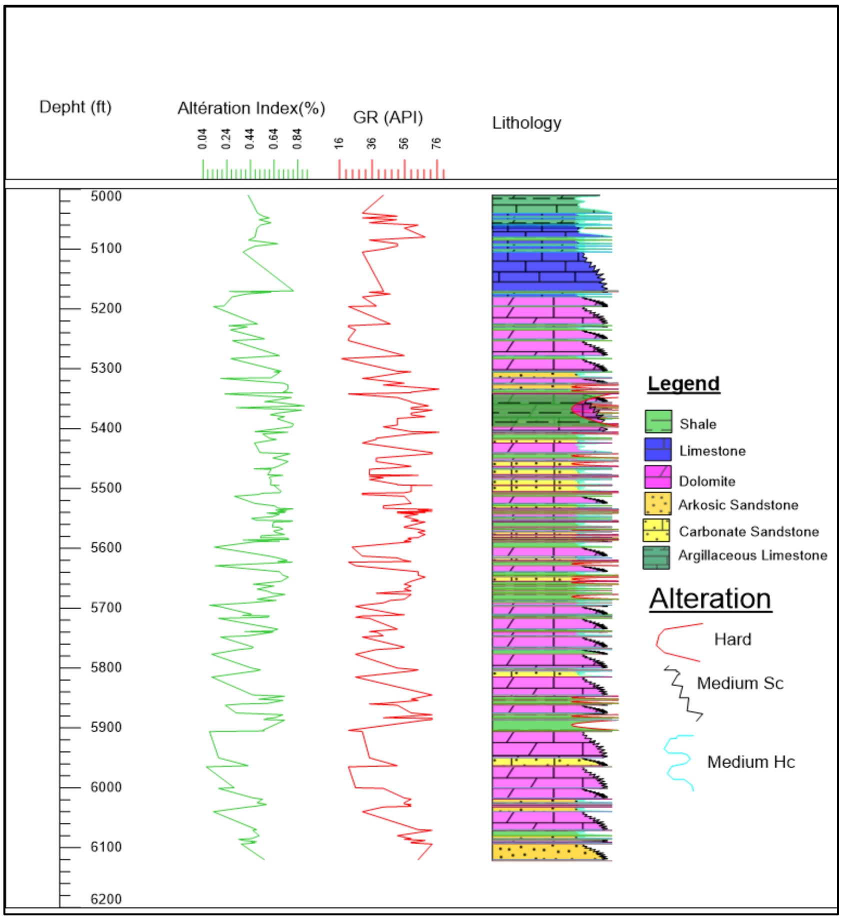


***Figure 8***. *Log showing the quality of the Pinda reservoir in the study area.*

## CONCLUSIONS

While this study is specifically based on a single-well analysis of the Mibale Field, the results demonstrate the effectiveness of the CAI in identifying reservoir quality at this location.

The combined analysis of the NPHI, RHOB, and GR logs made it possible to precisely characterize the lithology, sedimentary facies, and quality of the studied reservoir. The variations in the values recorded by the logs revealed an alternation of clean sandy layers, clayey layers, and a dominance of carbonate formations, indicating a heterogeneous depositional environment, probably of deltaic or coastal type, which is characteristic of the Mibale field. The identified reservoirs exhibit variable porosities, ranging from low to good, with often moderate densities, suggesting moderately to well-consolidated sands. Low radioactivity zones (GR < 70 API) with significant porosity (NPHI > 0.15) indicate the areas of better reservoir quality. In contrast, high GR peaks accompanied by significant neutron porosity without a decrease in density are typical of non-reservoir clayey facies. The calculation of permeability from porosities indicates that areas with good porosity (>15%) can develop significant permeability, favorable to good productivity if they are well connected. In summary, the most promising reservoir levels are those where low GR values, high neutron porosity, and low bulk density are observed within the investigated well only. These zones should be subjected to production tests to confirm their potential. The identification of facies also helps to better understand sedimentary dynamics and guide field development decisions.

In the investigated interval of well 1-X, the Upper Pinda reservoir exhibits overall favorable petrophysical quality. This assessment is supported by the Composite Alteration Index (CAI) values, which consistently indicate zones of moderate to low degradation, thereby preserving the storage and flow capacities of the formation. This single-well study validates the adopted methodology and suggests that the Composite Alteration Index (CAI) is a reliable tool for assessing reservoir quality within the investigated well only.

Further works should include core sample analysis from identified 'sweet spots' to confirm the exact nature of argillization through SEM or XRD. A correlation between CAI values and actual production flow rates is recommended to validate the dynamic performance of the identified reservoirs.

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Received: December 2025; Revised: February 2026; Accepted: February 2026; Published: February 2026