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Integration of Petrophysical Methods in Carbonates from the Potiguar Basin: Technical Complementarity and Multivariate Analysis

Integração de métodos petrofísicos em carbonatos da bacia potiguar: complementaridade técnica e análise multivariada

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Abstract: This study presents an integrated analysis of three petrophysical techniques: gas porosimetry, water immersion saturation, and nuclear magnetic resonance (NMR), applied to 89 carbonate rock samples from the Potiguar Basin, within the Grainstone, Dolowackstone, and Bioturbated lithofacies. Descriptive statistics, Pearson correlations, analysis of variance (ANOVA) with Tukey's test, and principal component analysis (PCA) were performed to evaluate complementarity and variability among methods. The Technical Complementarity Index (TCI) was 0.948, indicating high overall agreement, with the greatest similarity observed between NMR and gas porosimetry (0.963). Saturation systematically underestimated porosity, particularly in microporous rocks. ANOVA revealed significant differences ($p < 0.001$) among lithofacies, with Grainstone showing the highest average porosity. PCA demonstrated that the first principal component (PC1) explains 96.5% of the total variance, with factor loadings above 0.98 for all methods, confirming that they essentially measure the same fundamental physical attribute, albeit with different sensitivities. The results highlight that statistical and multivariate integration reduces uncertainties and improves petrophysical characterization of heterogeneous carbonates, with direct implications for fluid volume estimation.

Keywords: Porosity; Reservoir; Principal Components.

Resumo: Este estudo apresenta uma análise integrada de três técnicas petrofísicas: porosimetria a gás, saturação por imersão em água e ressonância magnética nuclear (RMN), aplicadas a 89 amostras de rochas carbonáticas da Bacia Potiguar, nas litofácies Grainstone, Dolowackstone e Bioturbado. Foram realizadas estatísticas descritivas, correlações de Pearson, análise de variância (ANOVA) com teste de Tukey e análise de componentes principais (PCA) para avaliar a complementaridade e a variabilidade entre métodos. O Índice de Complementaridade Técnica (ICT) foi de 0,948, indicando alta concordância global, com maior similaridade entre RMN e porosimetria a gás (0,963). A saturação apresentou subestimativa sistemática, especialmente em rochas microporosas. A ANOVA revelou diferenças significativas ($p < 0,001$) entre litofácies, com Grainstone exibindo as maiores médias de porosidade. A PCA demonstrou que o primeiro componente principal (PC1) explica 96,5% da variância total com cargas fatoriais superiores a 0,98 para todos os métodos, confirmando que medem essencialmente o mesmo atributo físico fundamental, embora com sensibilidades distintas. Os resultados evidenciam que a integração estatística e multivariada permite reduzir incertezas e aprimorar a caracterização petrofísica de carbonatos heterogêneos, destacando implicações diretas na estimativa de volumes de fluidos.

Palavras-chave: Porosidade; Reservatório; Componentes Principais.

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1. Introduction

The petrophysical characterization of carbonate rocks is particularly challenging due to the high heterogeneity of their pore systems, which are strongly influenced by depositional and diagenetic processes (KARGARPOUR, 2020). These rocks may contain well-connected intergranular pores as well as isolated micropores, directly affecting fluid storage and transport. Given this complexity, different petrophysical methods tend to capture distinct fractions of the pore system (AMELOKO, UHEGBU e BOLUJO, 2019), Although individually informative, these methods exhibit limitations when used in isolation, thus motivating integrated approaches capable of capturing the multiscale complexity of carbonate pore networks (MUKHAMETDINOVA *et al.,* 2020; DUAN *et al.,* 2021).

In this context, the integration of petrophysical techniques becomes essential to overcome the multiscale complexity of carbonates. This study focuses on the combined application of three complementary methodologies: gas porosimetry using (N_2) , which quantifies the interconnected volume accessible to gas; water saturation, which determines the fraction effectively occupied by liquid; and nuclear magnetic resonance (NMR), which is sensitive to micro and mesopores, including regions of residual fluids (KENYON *et al.,* 1988; COATES, 1999).

In the Potiguar Basin, carbonate rocks present high lithofacies variability. Among the lithofacies investigated, the following stand out: Grainstone, characterized by granular texture, high depositional energy, and good pore connectivity; Dolowackstone, composed of micritic matrix with intercrystalline pores and partial dolomitization; and Bioturbated facies, defined by the predominance of bioturbation with biogenic structures and irregular porosity. This heterogeneity reinforces the need for integrated methodologies for appropriate petrophysical characterization (ARAÚJO *et al.,* 2021; BAGNI *et al.,* 2022, LOPES *et al.,* 2023).

Comparing these approaches enables not only the assessment of consistency among them but also the identification of their complementarity for reservoir characterization. The present study aims to integrate these techniques to: evaluate the correlation and degree of complementarity between methods; identify significant porosity differences among representative lithofacies; and apply multivariate analyses to integrate the results and reveal structural patterns in the dataset.

2. Methodology

A total of 89 carbonate rock samples from well cores and outcrops of the Potiguar Basin (RN, Brazil) were analyzed. The samples were classified according to petrographic criteria proposed by Araujo et al. (2021) and Lopes et al. (2023) into the following lithofacies: Grainstone (n = 47), Dolowackstone (n = 22), and Bioturbated (n = 20).

2.1. Petrophysical Techniques

Gas porosimetry (N_2) was performed using a Coreval 700 apparatus under a confining pressure of 1000 psi (~6.9 MPa). The method is based on Boyle–Mariotte's Law, relating changes in gas pressure to the volume of accessible pores (TIAB & DONALDSON, 2004 For the water-saturation porosity, a gravimetric procedure was conducted using a KCl saline solution (20,000 ppm), introduced under vacuum to obtain the effective porosity through the difference in mass before and after saturation. This procedure follows the experimental recommendations described by Newgord *et al.* (2020), who emphasize the importance of vacuum pressure control and solution salinity to minimize mineral dissolution effects and ensure complete and stable pore saturation. Nuclear Magnetic Resonance (NMR) measurements were carried out using a MesoMR12-060H-I instrument. The method is based on the detection of the transverse relaxation signal (T_2) of hydrogen protons using the CPMG pulse sequence. The relaxation time is correlated with pore size and is sensitive to micropores and capillary-bound fluids (KENYON *et al.,* 1988; COATES, 1999, SOUZA, 2012).

2.2. Statistical Analyses

Descriptive statistics (mean, standard deviation, and quartiles) were computed for all datasets. Pearson's correlation was applied to evaluate the linear association between pairs of techniques. Although widely used in comparative studies, Pearson's correlation presents limitations for assessing complementarity, particularly when the variables analyzed exhibit different scales or distributions (CANTOR *et al.,* 2022), Therefore, to quantify the overall agreement between the methods, the Technical Complementarity Index (TCI) was calculated, as defined in Equation 1, where *r* represents the Pearson correlation coefficient for each pair of techniques. Values of TCI close to 1 indicate high similarity between methods, whereas lower values suggest divergence.

$$TCI = \frac{r_{gas-water} + r_{gás-NMR} + r_{water-NMR}}{3} \quad (1)$$

Although the Pearson correlation coefficient is widely used in comparative studies, it presents limitations for evaluating complementarity, particularly when the variables analyzed exhibit different scales or distributions (CANTOR *et al.,* 2022). A one-way analysis of variance (ANOVA) was applied to test the existence of statistically significant differences among the mean porosity values of the lithofacies. To identify which groups differed from each other, Tukey's HSD (Honestly Significant Difference) test was employed through pairwise multiple comparisons among the lithofacies.

To enable an integrated evaluation and reduce data dimensionality, a Principal Component Analysis (PCA) was performed. The preprocessing step included Z-score normalization (mean subtraction and division by the standard deviation) to ensure that all variables contributed equally to the analysis, regardless of their original scales. PCA was conducted through the decomposition of the covariance matrix of the standardized dataset, with the objective of identifying latent variables (principal components) that explained the maximum variance in the data. Interpretation of the components was based on the scree plot and, primarily, on the factor loadings.

All statistical analyses and graphical outputs were performed using the Python programming language. The scientific libraries employed included pandas and numpy for data manipulation; scipy.stats for descriptive statistics, Pearson correlation, ANOVA, and Tukey's test; scikit-learn for PCA execution and Z-score normalization; and matplotlib and seaborn for data visualization and figure generation, including the scree plot and loading plot.

3. Results and Discussion

The results of the petrophysical and statistical analyses revealed distinct and complementary patterns among the methods. Overall, gas porosimetry exhibited the highest mean porosity values, followed by NMR, whereas the water-saturation method consistently yielded lower values. These patterns reflect the different sensitivities of each technique: gas porosimetry quantifies essentially the interconnected pore volume; NMR detects both interconnected pores and a portion of micro- and mesopores containing bound fluid; and the saturation method tends to underestimate porosity in microporous media due to capillarity, wettability, and narrow pore throats. Extreme cases, such as sample AT01-A-11 (Δ Gas–Water = 14.2%), occur predominantly in the Grainstone lithofacies. This apparently contradictory behavior, given the high degree of pore connectivity typically associated with Grainstones, may be attributed to heterogeneities such as microcrystalline zones or calcite cement that locally obstruct pore throats, creating micropores inaccessible to liquid but detectable by gas.

Table 1 – Samples with the highest absolute discrepancies (%) between pairs of petrophysical methods.

Sample	Lithofacies	Method Pair	Δ Porosity (%)
AT01-A-11	Grainstone	Gas × Water-Saturation	14.2
AA03-A-12	Grainstone	Gas × Water-Saturation	6.9
AA05-A-06	Grainstone	Gas × Water-Saturation	5.83
AA05-A-05	Grainstone	Gas × NMR	5.4

Source: Authors (2025).

3.1. Análise Multivariada (PCA)

The Principal Component Analysis (PCA) revealed that the first principal component (PC1) accounted for 96.5% of the total variance in the dataset (Figure 1a), indicating the presence of a single dominant factor controlling the variability among the measurements. The examination of the factor loadings, which represent the correlation of each variable with the principal components, demonstrated a remarkable agreement among the methods. As presented in Table 2, all techniques exhibited extremely high and positive loadings on PC1 (Gas = 0.985; Saturated = 0.983; NMR = 0.996). This pattern is visually confirmed in the Loading Plot (Figure 1b), where the vectors of the three variables appear as elongated and nearly superimposed arrows aligned with the direction of PC1. Such convergence indicates that the three methods essentially quantify the same physical attribute, namely the effective pore volume of the rock, reinforcing the internal consistency of the dataset and suggesting a strong physical control on the observed variability.

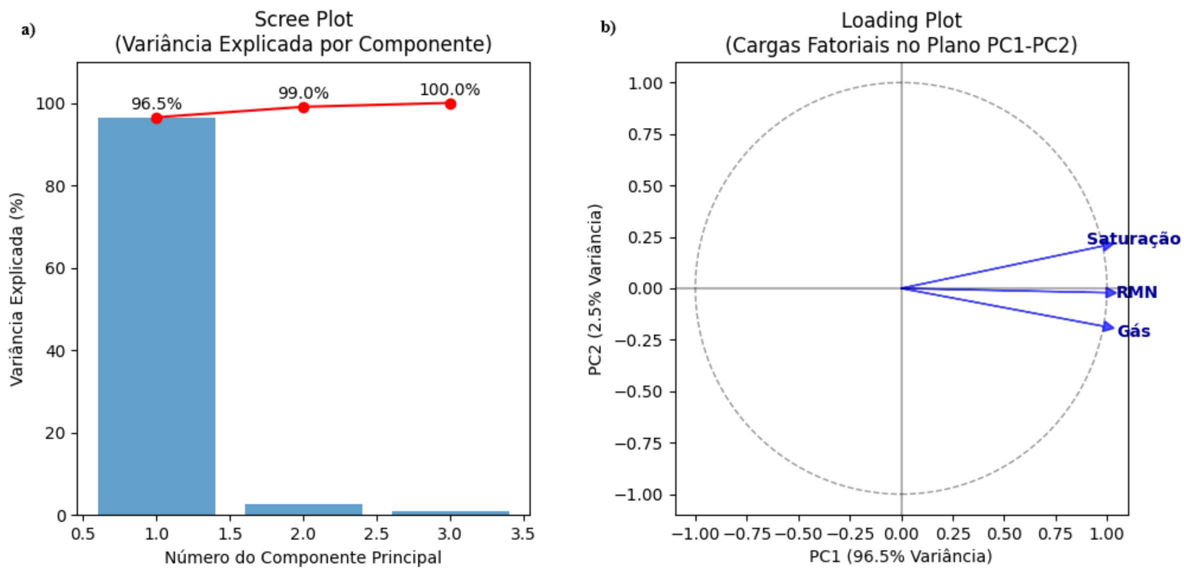

Figure 1 – Principal Component Analysis (PCA) of the porosity measurement methods.(a) Scree plot of the principal component analysis. (b) Loading plot illustrating the contribution of each method to the principal components.
Source: Authors (2025).

The subsequent components were considered irrelevant for the methodological comparison. PC2 accounted for only 2.5% of the residual variance, and its factor loadings, with low magnitude and without any coherent pattern (Table 2), do not capture any systematic discrepancy or provide any additional meaningful information between the techniques.

Table 2 – Factor loadings of the porosity measurement methods in the first three principal components .

Method	PC1 (96,5%)	PC2 (2,5%)	PC3 (1,0%)
Gas Porosity	0.985	-0.185	-0.081
Saturation Porosity	0.983	0.206	-0.058
NMR Porosity	0.996	-0.021	0.138

Source: Authors (2025).

3.2. Univariate Analysis and Lithofacies Evaluation

The influence of depositional and diagenetic frameworks is evident in the mean porosity values by lithofacies (Table 3). Grainstone exhibited the highest mean values across all methods, confirming enhanced intergranular connectivity, consistent with observations reported by Lucia (2003) and Terra *et al.,* (2010). Dolowackstone presented the lowest values, which agrees with its poorly connected micritic matrix (JAFARI *et al.,* (2020). For all lithofacies, water saturation yielded the lowest porosity values, reinforcing the hypothesis that micropores are not fully filled with fluid during the saturation procedure.

The ANOVA revealed statistically significant differences ($p < 0.001$) among lithofacies for all measurement techniques. Tukey's HSD multiple comparison test indicated that Grainstone presents significantly higher porosity values, reflecting its high-energy depositional environment. Dolowackstone and Bioturbated lithofacies did not differ significantly ($p > 0.05$), suggesting potential similarities in pore structure and connectivity. These patterns align with petrographic evidence: Grainstone, characterized by an open texture and low cement content, favors enhanced connectivity, whereas Dolowackstone and Bioturbated facies contain micritic matrix components and fabrics that hinder pore interconnection.

Table 3 – Descriptive statistics (mean porosity, %) and response patterns by lithofacies.

Lithofacies	**Gas Porosity (%)**	**Saturation Porosity (%)**	**NMR Porosity (%)**	**Observed Pattern**
Grainstone	17.42	14.77	17.3	High intergranular connectivity; NMR ≈ Gas
Dolowackstone	8.5	6.38	8.04	Dense micritic matrix; highest underestimation in Saturation
Bioturbated	10.62	9.21	9.88	Microstructural heterogeneity; NMR > Saturation

Source: Authors (2025).

3.3. Correlation Between Methods and ICT

Table 4 summarizes the correlation coefficients for each pair of techniques. The Gas × NMR pair presented the highest correlation ($r = 0.963$), indicating the greatest similarity in response. Discrepancies between these two techniques may indicate the presence of pores whose T_2 relaxation times are too short to fall within the acquisition window or that experience restricted diffusion. The saturation method exhibited high correlations, although slightly lower, reflecting systematic deviations. These results explain why NMR more closely tracks the pore volume accessible to gas, whereas the saturation method tends to underestimate porosity. The Technical Complementarity Index (ICT) was 0.948, confirming the high overall similarity and the robustness of the integrated application of these techniques for more accurate porosity estimation.

Table 4 – Pearson correlation matrix (r-value) among petrophysical methods for the complete dataset.

Comparison	**r-value**	**p-value**
Gas × Water-Saturation	0.924	<0.001
Gas × NMR	0.963	<0.001
Water-Saturation × NMR	0.955	<0.001

Source: Authors (2025).

The scatter plots presented in figure 2 visually corroborate the correlations discussed. In the Gas × Saturated comparison, the data points lie systematically below the line of equivalence, confirming a consistent underestimation of water-saturated porosity relative to gas porosity. In the Gas × NMR comparison, the points cluster closely around the equivalence line, indicating strong agreement between gas-accessible pore volume and the NMR response. In the Saturated × NMR comparison, the points are slightly shifted below the line, consistent with the limitations of the saturation method in fully occupying fine pores, narrow throats, and regions dominated by capillary effects.

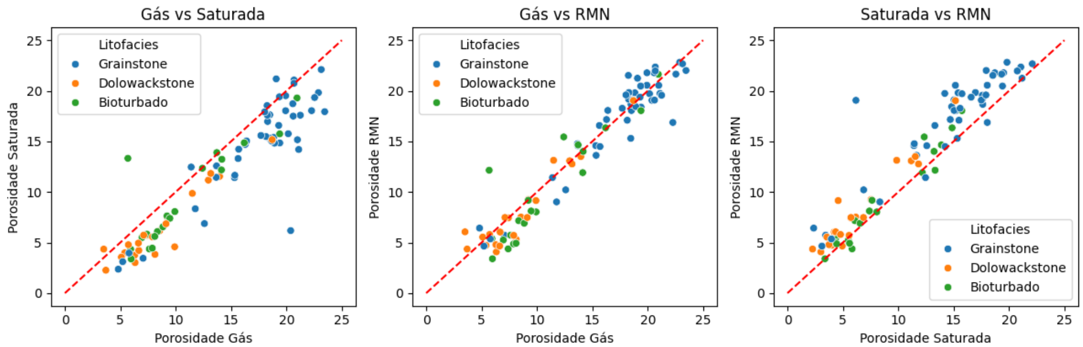

Figure 2 – Scatter plots for pairwise comparisons of petrophysical measurement methods.
Source: Authors (2025).

Based on the results obtained, an operational synthesis is proposed (Table 5), serving as a practical guideline for selecting appropriate methods in the characterization of heterogeneous carbonate reservoirs. The analysis demonstrates that gas porosimetry establishes itself as a reference technique for estimating effective porosity in well-connected rock frameworks. Nuclear Magnetic Resonance (NMR) complements the characterization by being sensitive to micro- and mesopores, while also providing information regarding fluid mobility. In contrast, although it is a simpler and more economical technique, water saturation systematically underestimates total porosity in microporous media due to capillary effects and wettability constraints. Therefore, it is concluded that the synergistic integration of the three techniques represents the most robust approach, enabling a reduction in uncertainties inherent to each individual method and supporting the development of more reliable petrophysical models, particularly in heterogeneous carbonate reservoirs such as those investigated in this study.

Table 5 – Operational synthesis of the evaluated petrophysical techniques: functions, advantages, limitations, and ideal applicability.

Technique	Advantages	Limitations	Ideal Applicability
Gas Porosimetry (N_2)	High precision and broad applicability; reference benchmark for comparison.	Does not detect volumes of capillary-bound fluids; does not differentiate pore types (interparticle, intracrystalline).	Calibration of petrophysical models; inter-technique comparison; characterization of well-connected rocks.
Nuclear Magnetic Resonance (NMR)	Provides relaxation time (T_2) distributions related to pore geometry.	Requires specialized and high-cost instrumentation.	Dedicated studies of microporosity and pore-size distribution; characterization of residual fluids.
Water Saturation Method	Simple methodology with low operational cost.	Systematically underestimates porosity in microporous media due to capillarity and wettability effects.	Evaluation of effective saturation.
Integrated Approach	Exploits technical complementarity and enables a more robust diagnostic framework.	Requires significantly greater effort in data acquisition and multivariate integration workflows.	Construction of integrated petrophysical models.

Source: authors (2025).

4. Conclusions

This study demonstrated, through an integrated statistical and multivariate approach, the strong agreement and complementarity among gas porosimetry, immersion saturation, and nuclear magnetic resonance (NMR) techniques in the characterization of carbonate rocks from the Potiguar Basin. Among the evaluated methods, NMR stood out as the technique that most reliably represents effective porosity, exhibiting the highest correlation with the reference method (gas porosimetry; r = 0.963) and the highest factor loading on PC1 (0.996). Its ability to detect fluids within micropores and regions affected by capillary restriction makes it not only a robust alternative, but also a complementary technique with broader applicability relative to gas porosimetry, by providing additional insights into pore-size distribution and fluid mobility.

Conversely, the immersion saturation method systematically underestimates total porosity, particularly in microporous systems or samples with narrow pore throats, owing to limitations imposed by capillarity and wettability. Its application therefore requires caution and a clear understanding that it effectively represents a porosity volume accessible to the saturating fluid.

The high correlations among methods and the value of the Technical Complementarity Index (ICT = 0.948) confirm that, despite operational differences, all techniques describe the same petrophysical attribute. The principal component analysis (PCA) reinforced that, for operational purposes, methodological selection may be guided by factors such as cost, availability, and the specific objectives of the investigation.

It was also observed that the depositional framework exerts a significant influence on the results, with the Grainstone lithofacies exhibiting the highest porosity values, consistent with its higher depositional energy and intergranular connectivity. However, this same lithofacies also presented the largest absolute discrepancies among the methods, revealing intra-facies heterogeneity and highlighting the importance of methodological integration even in seemingly homogeneous contexts.

In summary, the results reinforce that the selection of petrophysical techniques in carbonate studies must be strategic and driven not only by availability and cost, but primarily by the scientific or applied objectives of the research. The integration of methods, supported by multivariate statistical analyses, is consolidated as an indispensable approach to reducing uncertainties, validating interpretations, and improving the construction of more robust predictive models, with direct impact on exploration and production in complex carbonate reservoirs.

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