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Permeability estimation in carbonate rocks using multicomponent models applied to nuclear magnetic resonance data

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Abstract

The challenge of accurately estimating permeability in carbonate reservoirs stems from their pronounced heterogeneity, marked by complex pore structures with varying sizes and connectivity. This study assesses the performance of a multicomponent permeability model based on nuclear magnetic resonance (NMR) transverse relaxation time (T_2) distributions, to classify pore systems into distinct groups to aiming to enhance permeability prediction. A total of 44 coquina samples from an onshore well located in the Sergipe-Alagoas Basin (SE-AL), Brazil, were analysed. Permeability estimates from the multicomponent model was compared to the conventional models, including Schlumberger-Doll Research (SDR) and Timur-Coates (TC). The results indicates that the multicomponent approach offers significantly improved predictive accuracy, especially in highly heterogeneous rock types, as evidenced by higher R^2 values and lower error metrics (MLE and RMSLE)

Introduction

Estimating permeability in reservoir rocks, particularly carbonates, remains a critical and challenging task for the oil industry (e.g. Gonçalves et al, 2024). The complexity arises from the high structural heterogeneity and varied distribution of pore types and sizes, which are shaped by depositional and diagenetic processes. These geological processes create a highly heterogeneous pore network, significantly affecting the spatial distribution of porosity and permeability, and complicating accurate predictions fluid flow and reservoir quality (Lima et al, 2022). Although permeability is generally correlated with effective porosity, this relationship is shaped by other factors, such as grain size distribution, packing arrangement, compaction and cementation. Moreover, the arrangement of the pore structure, especially the size and distribution of the pore throats, plays a crucial role in controlling fluid flow behavior. Larger pore throats usually increase permeability, while smaller throats significantly restrict it.

The NMR technique has become established as one of the primary methods for petrophysical characterization of reservoirs, particularly for permeability estimation. T_2 distributions provide valuable information about variations in pore size, as the cumulative T_2 signal reflects total porosity and its distribution corresponds to different pore size populations. Given the limitations of conventional models in complex porous media, this study adopts a multicomponent permeability model (Han et al., 2018), which accounts for the contributions of distinct pore size populations to improve the accuracy of permeability predictions in carbonate rocks. In this context, the study assesses the applicability of the multicomponent permeability model, which segments the T_2 distribution into distinct pore populations to enable more refine and accurate permeability estimations. For this purpose, 44 coquina samples from the Morro do Chaves Formation in the SE-AL Basin, Brazil, were analysed and classified by rock types, aiming to group them according to similarities in their petrophysical properties. The results obtained were validated using the coefficient of determination (R^2), mean absolute error (MAE), and root mean squared logarithmic error (RMSLE) metrics.

Rock Types

Rock-type classification groups samples with similar petrophysical properties, thus reducing reservoir heterogeneity and improving the accuracy of predictive models. In this study, we adopted the rock-type classification for coquinas from the Morro do Chaves Formation defined by Pontedeiro et al. (2025). This classification integrates multiple characterization techniques, such as petrographic analysis, X-ray diffraction, nuclear magnetic resonance (NMR), well-log data, and laboratory tests for porosimetry and gas permeability. The dataset comprising 44 samples was segmented into three distinct rock types: Reservoir Coquinas (RT1), Closed Coquinas (RT2), and Hybrid Coquinas (RT3).

Reservoir Coquinas exhibits a high average permeability of 199.12 mD and average porosity of 16.45%, dominated by interconnected vugular and moldic pores, resulting in excellent fluid-flow capacity. In contrast, Closed Coquinas have significantly lower permeability (2.47 mD) and porosity (9.08%), reflecting higher degrees of compaction and cementation, considerably reducing the pore space. These rocks predominantly show interparticle and isolated—non-connected—vugular pores, which explains their low permeability values. Finally, Hybrid Coquinas present mixed lithological composition, combining siliciclastic minerals (quartz and feldspar) and carbonate components (mainly calcite, with occasional dolomite). This rock type has the highest average porosity (18.05%) and intermediate permeability (86.45 mD), characterized predominantly by interparticle porosity within a heterogeneous framework.

Materials and methods

Permeability Models.

NMR is a non-destructive technique widely used for the indirect estimation of permeability in rock samples. For this purpose, empirical or semi-empirical models are employed, with the most common being the TC model and the SDR model proposed by Kenyon. The TC model is widely applied because it integrates volumes of free fluid (FFI) and bound fluid (BVI), extracted from the T_2 distribution. Its expression is given by:

$$k_{TC} = a\left(\frac{FFI}{BVI}\right)^{b} \emptyset^{c}$$

where k_{TC} is the permeability, φ is the total porosity, and a, b, and c are empirically calibrated constants. The SDR model establishes a direct relationship between permeability, total porosity, and the geometric mean relaxation time, according to the following expression:

$$k_{SDR-Gen} = c\emptyset^{a}(T_{2LM})^{b}$$

where T_{2LM} is the logarithmic mean relaxation time, and, a, b and c, are empirical constants. The SDR model is based on the correlation between the T_2 relaxation time and pore size, which in turn controls permeability. In this study, the classical version of the SDR model (SDR-Class) was also applied, using a = 2 and b =2 for carbonate rocks.

Additionally, the multicomponent model proposed by Han et al. (2018) was applied, which estimates permeability in complex lithologies by segmenting the T_2 spectrum into pore size ranges, capturing the contribution of each pore population to flow. Permeability is estimated by considering the contribution from each pore class. The classification includes four classes: S1 = Micropores (T_2 < 30 ms), S2 = Mesopores (30–90 ms), S3 = Macropores (90–200 ms), and S4 = Supermacropores (T_2 > 200 ms), integrating all contributions into the calculation

$$k_{Han} = a\emptyset^{b}\frac{S_3^{c}S_4^{d}}{S_1^{e}S_2^{f}}$$

Routine and Special Core Analysis (RCAL & SCAL).

We used 44 samples of coquina rocks from the Morro do Chaves Formation, in the Sergipe-Alagoas Basin, considered analogous to the carbonate reservoirs of the Brazilian Pre-Salt due to their petrophysical and depositional similarities. The cylindrical samples (2.5 cm x 4.5 cm) were cleaned using the Soxhlet method with toluene and methanol, characterized for porosity and permeability, and fully saturated with 30 kppm KCl brine. NMR measurements were carried out on a GeoSpec2 low-field spectrometer (Oxford Instruments), operating at 0.047 T and 2 MHz.

Results and Discussion

The quantitative results demonstrate that the Han model exhibited the best performance in estimating the permeability of the analyzed coquinas, outperforming the conventional SDR (General and Class) and TC models. For the complete set of samples (Table 1), the Han model achieved the highest coefficient of determination (R^2= 0.89), associated with the lowest MAE = 0.283 and the lowest RMSLE = 0.365, indicating higher accuracy and better fit.

Table 1. Comparison of *k* estimation models, expressed by R^2, MLE and RMSLE, for the set of 44 samples and the three rock types (RT1, RT2 and RT3)

Samples	Models	R^2	MLE	RMSLE
44 Samples	Han Model	0.89	0.283	0.365
	SDR Gen Model	0.88	0.307	0.382
	SDR Class Model	0.38	0.668	0.865
	TC Model	0.82	0.391	0.471
RT1	Han Model	0.71	0.185	0.248
	SDR Gen Model	0.41	0.281	0.355
	SDR Class Model	0.17	0.318	0.412
	TC Model	0.36	0.306	0.370
RT2	Han Model	0.89	0.202	0.239
	SDR Gen Model	0.83	0.241	0.306
	SDR Class Model	0.15	0.598	0.686
	TC Model	0.81	0.261	0.324
RT3	Han Model	0.93	0.090	0.238
	SDR Gen Model	0.85	0.170	0.345
	SDR Class Model	0.20	0.695	0.807
	TC Model	0.88	0.148	0.311

When individually analyzing the R^2, MAE, and RMSLE results for the three rock types (Table 1), the superior performance trend of the Han model persists, with variations associated with the specific petrophysical characteristics of each group.

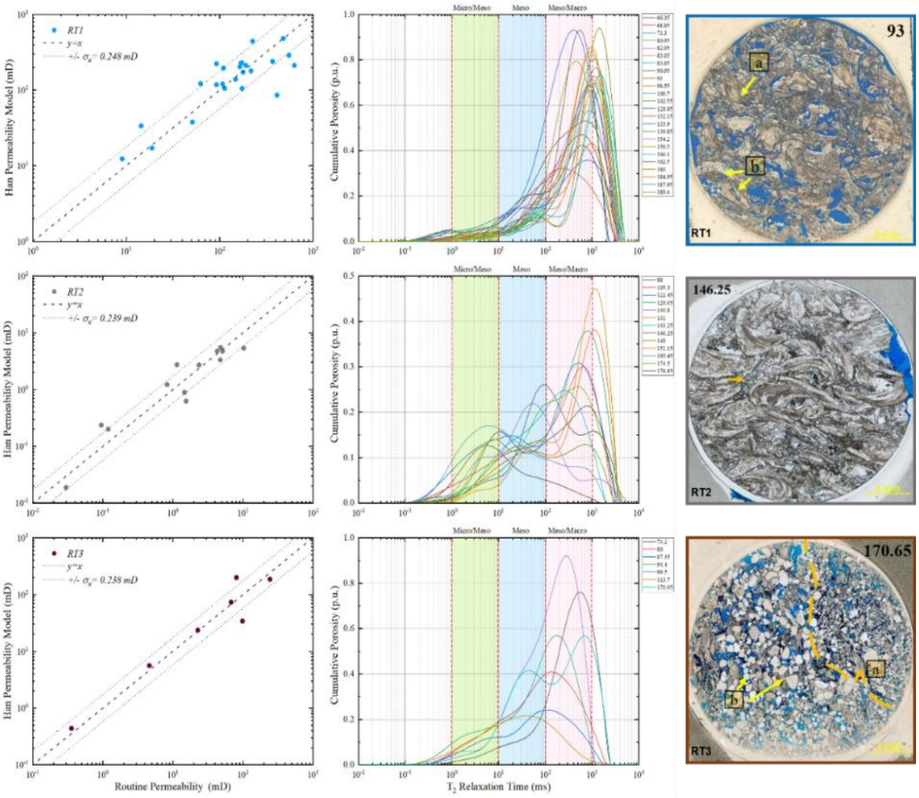

Figure 1. Correlation between *k* estimated by Han's model and routine *k* (left); T_2 distributions highlighting the T_2 ranges associated with the different pore sizes (center); and petrographic images representing the rock types (right).

For RT1, the Han model showed the best performance, with R^2 = 0.71 and the lowest MAE (0.185) and RMSLE (0.248) values, indicating a greater ability to capture permeability variability, even in environments with more complex textures, as evidenced in the image associated with RT1 (Figure 1). In the case of RT2, characterized by predominantly isolated vuggy pores with low connectivity, the Han model also showed an excellent fit (R^2 = 0.89), outperforming traditional models. The SDR General model, despite performing well (R^2 = 0.83), exhibited higher error (RMSLE = 0.306 versus 0.239 for the Han model). The SDR Class model, once again, performed unsatisfactorily (R^2 = 0.15).

For RT3, characterized by a more homogeneous and granular texture, the Han model achieved the best overall result (R^2 = 0.93), with minimal errors (MAE = 0.090; RMSLE = 0.238). These values reflect greater structural uniformity and the predominance of macro- and mesopores, as indicated by the T_2 distribution and petrographic images, which show an interparticle porosity arrangement with greater heterogeneity. The SDR General model also performed well in this scenario (R^2 = 0.85), although with relatively higher error

The application of the multicomponent model proved effective by incorporating different pore populations identified from the T_2 distributions, highlighting the coexistence of micro-, meso-, and macropores in the analyzed samples. This heterogeneity, which undermines the accuracy of traditional models, is appropriately accounted for by the Han model, resulting in more accurate and consistent permeability estimates in complex carbonate rocks. The superior performance of the model is corroborated by statistical metrics, such as high R^2 values and low errors, and by the good visual agreement between the measured and modeled permeability values.

Conclusions

This study showed that the multicomponent permeability model, derived from transverse relaxation (T_2) distributions obtained via NMR, delivers more accurate and consistent estimates in heterogeneous carbonate rocks than traditional models such as Kenyon (SDR) and Timur-Coates (TC). With a high correlation (R^2 up to 0.93) and reduced errors (MAE and RMSLE), the Han model effectively captures the complex pore size distributions and connectivity found in the studies coquinas. The results confirm the importance of multicomponent segmentation in addressing the shortcoming of conventional models, representing a valuable advancement in petrophysical characterization and flow prediction in carbonate reservoirs, an area of critical relevance to the petroleum industry.

Acknowledgments

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