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Technical Evaluation of Porosity and Permeability Measurements Using Gas Flow Tests, Nuclear Magnetic Resonance, and Micro-CT Imaging

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Characterizing carbonate rocks is challenging due to their structural heterogeneity, especially in karstified settings. This study analyses a carbonate plug using three techniques: micro-CT, NMR, and gas-based porosity and permeability measurements. Micro-CT images at 35 µm, 2.9 µm, and 0.8 µm enabled multiscale pore analysis. Segmentation via Otsu's method allowed extraction of properties like sphericity, tortuosity, and surface-to-volume ratio. NMR data revealed bimodal T_2 relaxation behavior, consistent with distinct pore systems seen in µCT. Gas-based values served as benchmarks. µCT enables direct pore visualization but is limited by resolution and computational demands, while NMR assesses larger volumes but needs calibration. Different resolutions captured different pore fractions, reinforcing the need for integrated techniques. The SDR model best estimated permeability, highlighting each method's strengths and constraints for accurate carbonate rock characterization.

Introduction

The definitions of fundamental petrophysical properties, such as porosity and permeability, are crucial for structural assessment and fluid flow analysis in reservoir rocks. However, these properties are often misused or inaccurately interpreted, which can undermine the reliability of analytical results. This study aims to evaluate how different techniques estimate petrophysical properties in a highly heterogeneous rock. The methods employed include inert gas flow experiments, micro-computed tomography (µCT) at three distinct spatial resolutions (35 µm, 2.9 µm, and 0.8 µm), and Nuclear Magnetic Resonance (NMR) measurements.

Theory

Effective porosity (ϕ_e) represents the fraction of the rock that actively contributes to fluid flow, while absolute permeability (k) quantifies the rock's ability to transmit those fluids (Schön, 2015; Tiab and Donaldson, 2016). Although these properties are well defined, their application in the literature is not always consistent, particularly when comparing methods such as gas flow tests, micro-computed tomography (µCT), and nuclear magnetic resonance (NMR) (dos Anjos, 2023; Liu et al., 2023; Kiam, 2024; Mondal and Singh, 2024). Gas flow experiments impose a unidirectional flow, capturing pore connectivity along that specific axis. µCT provides 3D images based on X-ray attenuation, with resolution constrained by voxel size. NMR infers both ϕ_e and k from the response of hydrogen nuclei, relying on semi-empirical models such as SDR and Timur-Coates to estimate permeability (Kenyon et al., 1988; Coates et al., 1999).

$$k_{SDR} = a \cdot \phi^4 \cdot {T_{2gm}}^2 \quad (1)$$

$$k_{Timur-Coates} = \left(\frac{\phi}{C}\right)^4 \cdot \left(\frac{FFI}{BVI}\right)^2 \quad (2)$$

Method

The study was conducted on a core plug sample extracted from a carbonate environment characterized by high structural heterogeneity resulting from diagenetic processes and dissolution. Initial characterization included measurements of gas porosity and permeability, µCT imaging at three spatial resolutions (35 µm, 2.9 µm, and 0.8 µm), and transverse relaxation time T_2 distributions obtained from NMR (Araújo et al., 2023; Kiam, 2024).

Results and Disussion

The experimental porosity values obtained for each spatial resolution are presented in Table 1. The µCT porosity refers to the total porosity estimated through image segmentation using Otsu's thresholding method. The "Seed" porosity, in turn, corresponds to the fraction of porosity that is interconnected—though not necessarily spanning from the top to the bottom of the sample—thus representing pore regions with some degree of connectivity.

Permeability results obtained from gas flow experiments and from NMR-based models are presented in Table 2, along with the corresponding parameters: *a*, *T2gm*, *C*, *FFI*, and *BVI*. Based on the Seed porosity, further analyses were conducted to extract distributions of volume-to-surface ratios, pore sizes, and sphericity. Additionally, the tortuosity of pore connectivity was estimated using the Dense calculation method. Average values for sphericity, volume-to-surface ratio, pore volume, and tortuosity are summarized in Table 3.

The analysis of connected pore volume distribution from µCT images (Figure 1-a) revealed a bimodal pattern similar to that observed in the transverse relaxation time distributions (Figure 1-b), suggesting a comparable underlying pore structure.

Table 1 – Assessment of Porosity Using Different Techniques Across Multiple Resolution Scales

Sample	Porosity Gas (%)	Porosity RMN (%)	Top-to-bottom connected Porosity	Porosity micro-CT (%)	Porosity Seeds (%)
400-35	15,55	11,18	No	2,23	2,04
400-2,9	X	8,48	No	3,62	0,65
400-0,8	X	X	Yes	8,51	6,41

Table 2 – Gas Permeability and NMR-Based Estimates with Corresponding Model Coefficients for Each Sample

Sample	Permeability Gas (mD)	Permeability SDR (mD)	Permeability Timur-Coates (mD)	a	C	T_{2gm}	FFI	BVI
400-35	0,088	0,086	0,031	1,1	0,1	22,47	0,12	0,88
400-2,9	X	0,091	0,025	0,9	0,2	44,18	0,46	0,54

Table 3 – Average Values of Sphericity, Volume-to-Surface Ratio, Pore Volume, and Tortuosity

Sample	Sphericity	Ratio Volume/Surface	Volume (mm³)	Tortuosity
400-0,8	0.640827	0.000887	0.000002	1.268060
400-2,9	0.691810	0.003426	0.000023	1.244601
400-35	0.255450	0.231421	94.222468	1.341394

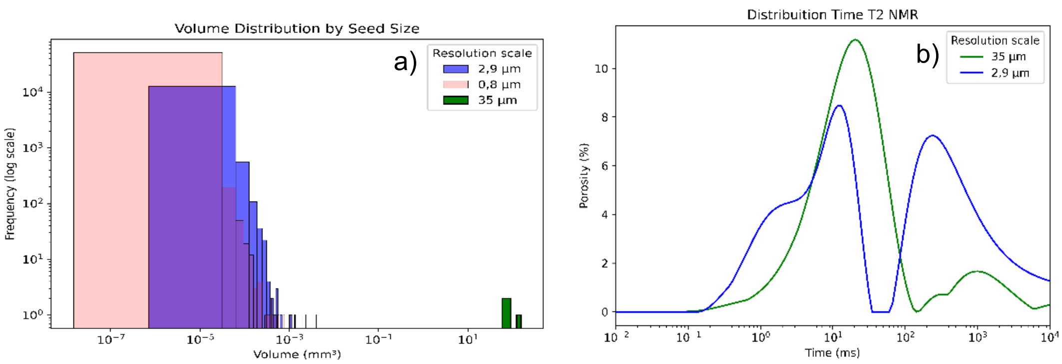

Figure 1 – NMR Test Results: (a) Connected Pore Volume Distribution Derived from µCT Images, and (b) T2 Relaxation Time Distribution Curve

Conclusions

Each technique offers distinct advantages. While gas flow testing provides effective porosity and absolute permeability values along a single flow direction, it may not accurately capture the true behavior or morphological complexity of the pore structure. µCT is highly valuable for visualizing and quantifying pore architecture, enabling detailed observation of structural features while preserving the sample for further analyses. However, its effectiveness depends on high-quality imaging and precise segmentation. Moreover, in highly heterogeneous samples, subvolumes may lack representativeness, and processing large datasets can become computationally demanding. Conversely, NMR offers the benefit of measuring larger sample volumes, providing insights into porosity and indirect permeability estimates. Yet, it does not deliver direct visualization of pore networks and requires calibration through cross-validation with other petrophysical techniques to ensure reliability. Therefore, understanding the behavior, strengths, and limitations of each method is crucial to conducting a robust and meaningful analysis.

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