A holistic approach to low-field NMR and MICP data integration for the accurate determination of the absolute pore size distribution in siliciclastic rocks

Michał Fajt, Grzegorz Machowski, Bartosz Puzio and Artur Tadeusz Krzyżak

AGH University of Krakow | Faculty of Geology, Geophysics and Environmental Protection

Abstract

Author

Introduction

Determining the exact **pore size distribution** (**PSD**) in a rock is crucial for predicting its reservoir properties. In the standard low-field NMR approach, the PSD estimation relies only on a linear fit of the **surface relaxivity (ρ_2)**, assuming **free diffusion** and neglecting **internal gradients (*G*)**. However, in nano- and micropore spaces, **diffusion is restricted**. Additionally, the magnitude of ***G* is inversely proportional to the pore size** and can cause substantial distortions in the registered, short **T_2 relaxation times**.

Challenges

- In fine-grained siliciclastic rocks **magnetic susceptibility (*X*)** significantly **increases the magnitude of internal gradients**.
- **Diffusion (*D*)** in nano- and micropores for attainable experimental time is in the motional averaging regime (**MAV**) thus, the **observed diffusion coefficient decreases** significantly.

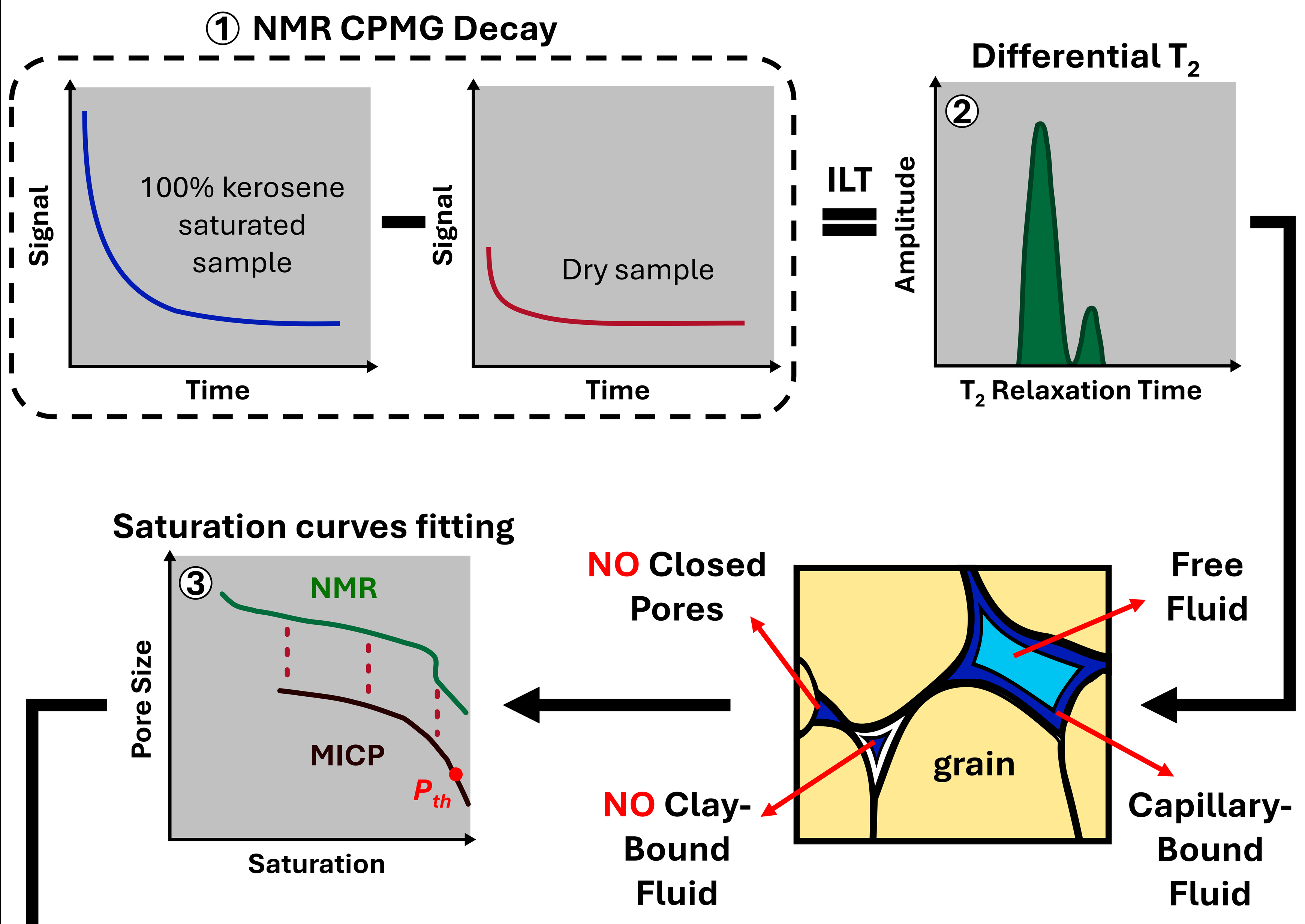
Objective

To introduce an integrated method based on **differential LF-NMR** and **porosimetry (MICP)**, allowing a realistic assessment of PSD in full range, including nano- and micropore space, by considering the influence of ρ_2, ***G*** and ***D***.

Materials

Tested materials comprise **9 siliciclastic rock-core** samples of the Miocene age. Samples were taken from the wells located in **South-East Poland**, **Carpathian Foredeep** area.

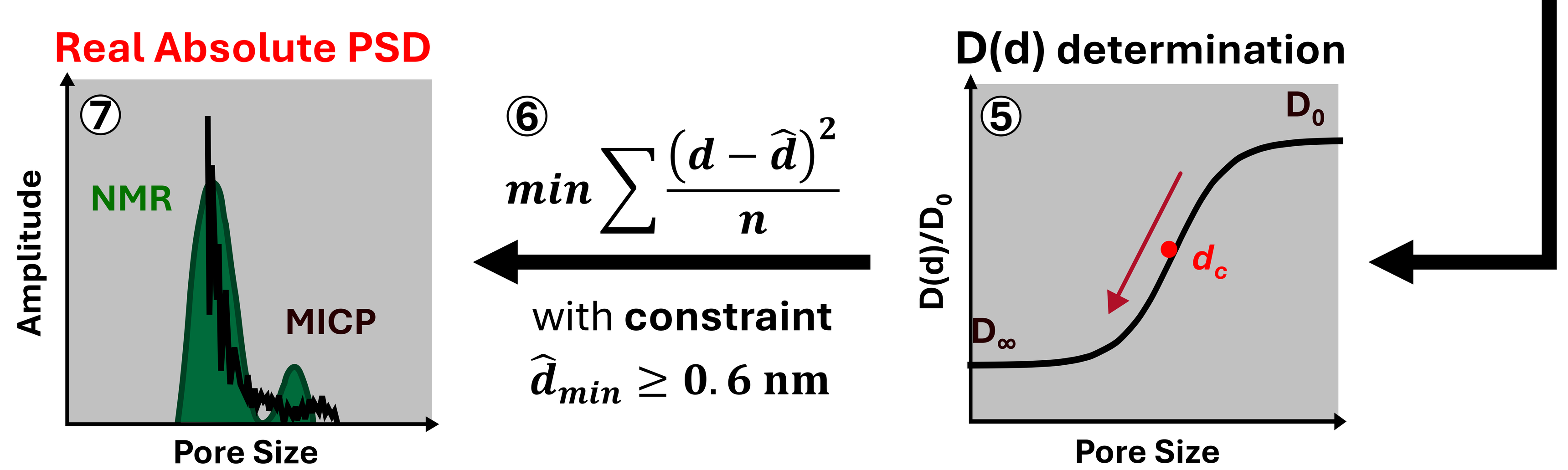
Workflow



④ Standard Approach | Proposed Approach

$$\frac{1}{T_2} \approx \frac{1}{T_{2B}} + \frac{2F_s\rho_2}{d} + \frac{D(d)\cdot(G(d)\gamma t_e)^2}{12}$$

where: T_{2B} is bulk relaxation time (s); ***Fs*** is the pore shape factor; ρ_2 is transverse surface relaxivity (m/s); ***d*** is pore size (m); ***D(d)*** is the apparent diffusion coefficient (m²/s); ***G(d)*** is the magnetic field gradient (T/m); ***γ*** is the gyromagnetic ratio (MHz/T) and t_e is echo time (s).



$$\min \sum \frac{(d-\hat{d})^2}{n}$$

with constraint $\hat{d}_{min} \geq 0.6$ nm

Methods

- **Low-field nuclear magnetic resonance (LF-NMR)** measurements were performed using a 2 MHz Rock Core Analyser (Magritek) with field induction of **0.05 T**. **CPMG-T_2** sequence was applied using t_e **= 60 μs**, ***RT* = 5 000 ms**, ***NoE* = 50 000** and ***NoS* = 512**.
- **Reference measurements** were conducted using **Mercury porosimetry (MICP)** and **Nitrogen adsorption (BET)** methods. In addition to the PSD, **low-field AC magnetic susceptibility (*X*)** measurements were performed.

Procedure

① **Measurements of 100% kerosene-saturated** (vacuum) and **dry** (110°C, vacuum) rock core samples.

② **Determination of differential distributions** – subtracting dry and 100% saturated sample signals before **Inverse Laplace Transform (ILT)**.

③ **Selection of NMR-MICP conversion points** based on the comparison of the **saturation curves** in the **percolation thresholds framework (P_{th})**.

④ **Calculation of PSD** via our **Proposed Approach**, incorporating the **diffusion component** and accounting for the influence of **induced gradients, *G(d)*** and **apparent diffusion coefficient, *D(d)***:

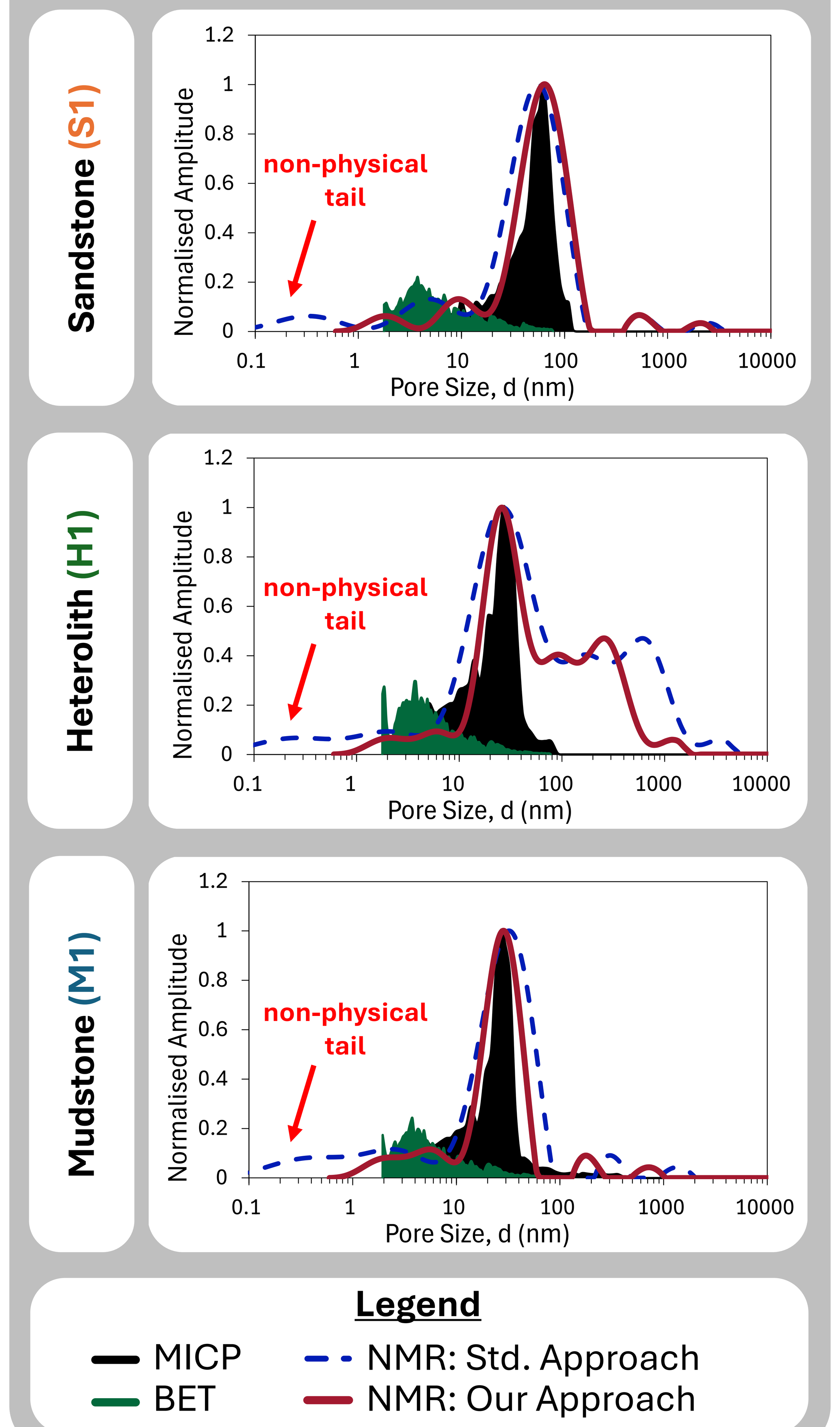
$$\frac{D(d)}{D_0} = \frac{(D_\infty - 1)d_c}{d_c + d} + 1 \quad ⑤$$

where: D_0 is the self-diffusion coefficient of the bulk kerosene (0.88·10⁻⁹ m²/s), D_∞ is the effective diffusion coefficient (m²/s) and d_c is the characteristic pore size (m) corresponding to the centre of the sigmoid.

⑥ **The Mean Squared Error (MSE) minimization** between estimated (NMR) and measured (MICP) pore size to solve for ρ_2 and D_∞.

⑦ **Validation of the NMR T_2-PSD** transformation results.

PSD Estimation Results



X vs D_∞ Results

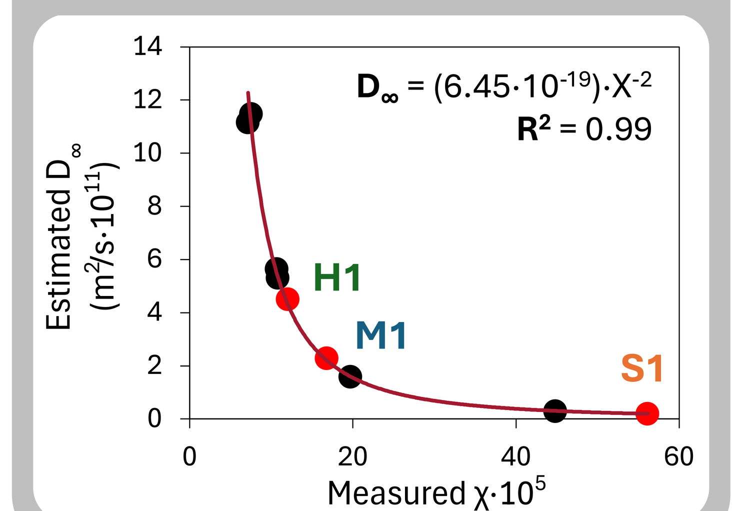


Table of Parameters

Approach	Measured	Standard	Proposed	
Sample	X	ρ_2 (μm/s)	ρ_2 (μm/s)	D_∞ (m²/s)
Sandstone (S1)	$5.6\cdot10^{-4}$	1.03	0.36	$2.0\cdot10^{-12}$
Heterolith (H1)	$1.2\cdot10^{-4}$	0.61	0.15	$4.5\cdot10^{-11}$
Mudstone (M1)	$1.7\cdot10^{-4}$	0.87	0.32	$2.3\cdot10^{-11}$

Conclusions

- The results obtained with the **standard approach** exceed the physically possible pore size values in tight pore space.
- The **proposed approach** enabled precise PSD estimation in rocks with high X values.

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