Pore-Scale Controls on Hydrogen Production and Storage in Geological Media: An NMR-Based Investigation

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INTRODUCTION

Underground hydrogen storage is a promising solution for large-scale energy storage. However, pore-scale hydrogen behavior in geological media remains insufficiently understood, particularly regarding mobility, distribution and residual trapping.

This work investigates hydrogen transport and trapping in a Silurian dolomite system using low-field NMR and drainage-imbibition experiments.

OBJECTIVES

- **Investigate pore-scale hydrogen distribution in carbonate systems**
- **Analyze hydrogen mobility and residual trapping behavior**
- **Evaluate capillary-controlled storage mechanisms**
- **Use low-field NMR for dynamic pore-scale monitoring**

METHODOLOGY

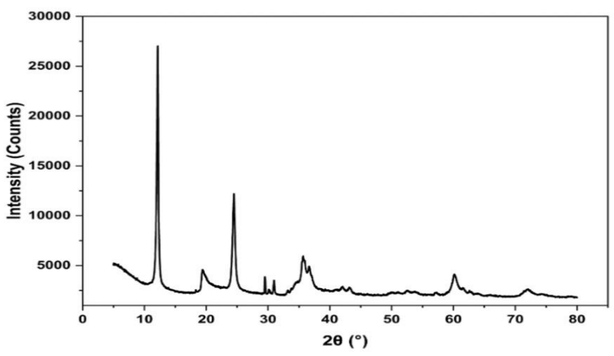
Experimental Workflow:

XRD / XRF / SEM–EDX → Core Characterization → Low-Field NMR → Drainage–Imbibition Experiments → Pore-Scale Interpretation

Methods:

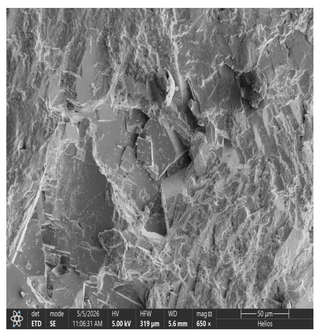
- XRD/XRF → mineral framework
- SEM/EDX → pore heterogeneity
- NMR → hydrogen mobility
- Drainage–Imbibition → residual trapping

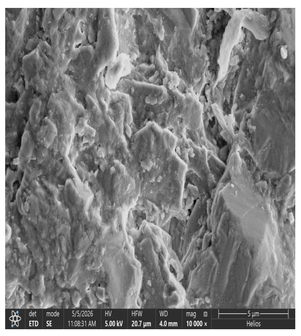
RESULTS – ROCK CHARACTERIZATION

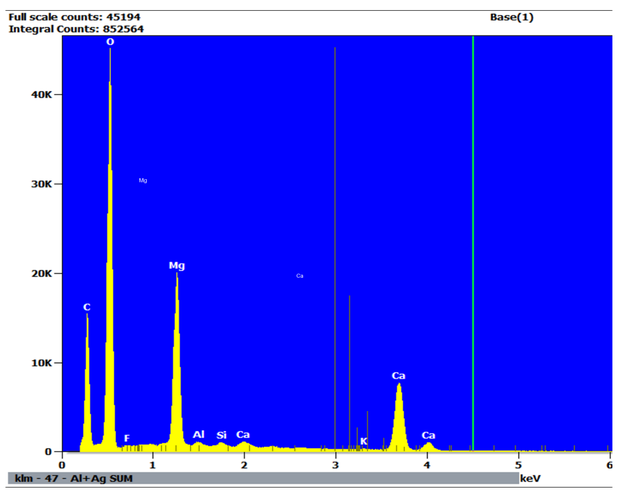


Simplified XRF composition of carbonate sample

Component	Concentration (wt.%)	Interpretation
CaCO3	51.7	Dominant carbonate
MgCO3	37.4	Dolomite component
Fe2O3	0.25	Minor iron
SiO2	0.18	Trace silicate
Others	<0.1	Trace elements





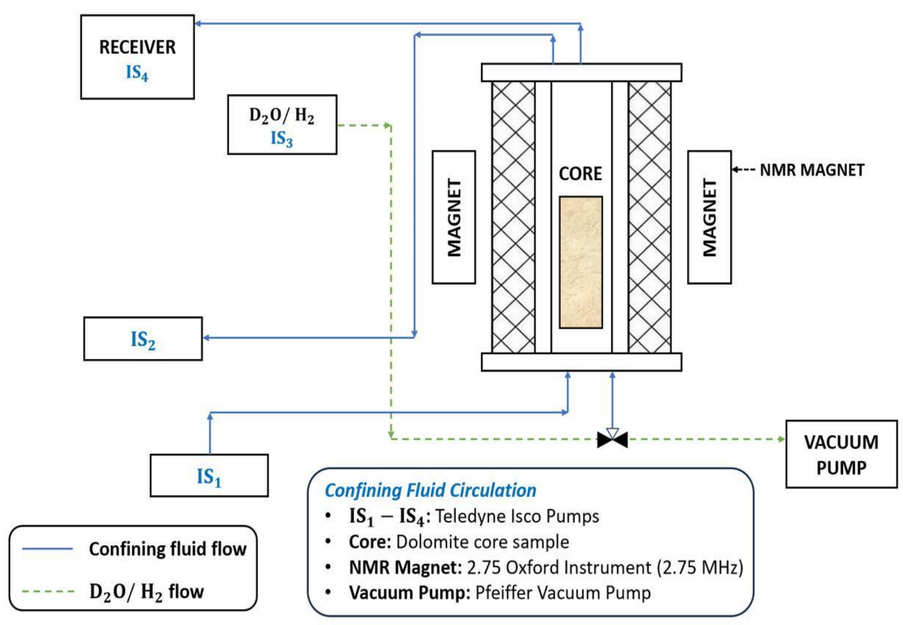


O → Carbonate/silicate framework
Mg → Mineral heterogeneity
Ca → Carbonate-rich matrix
Si → Pore-scale complexity

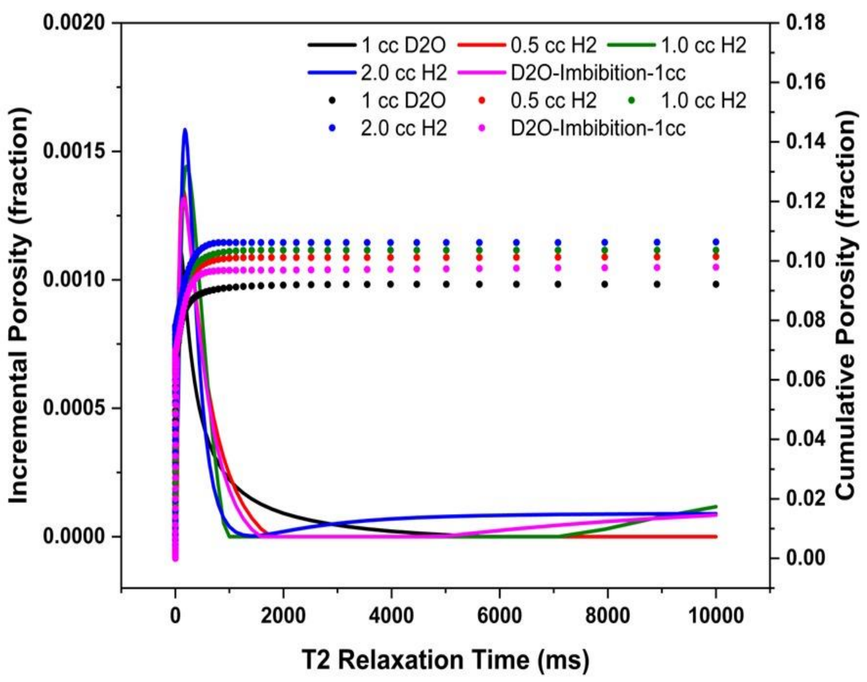
SEM/EDX reveal heterogeneous pore structures and Mg–Ca–O carbonate/silicate components associated with pore-scale transport complexity.

The results confirms the carbonate system is mineralogically stable and chemically inert, reinforcing its suitability as a hydrogen storage medium governed by pore-scale processes rather than by reactive transformations.

RESULTS – NMR STORAGE ANALYSIS



Low-field NMR flow system integrating Teledyne ISCO pumps for controlled H_2/D_2O circulation during drainage–imbibition



T_2 distributions reveal pore heterogeneity controlling hydrogen mobility and residual trapping.

Broad T_2 distributions indicate strong pore-size heterogeneity controlling hydrogen distribution, mobility, and residual trapping.

Interpretation:

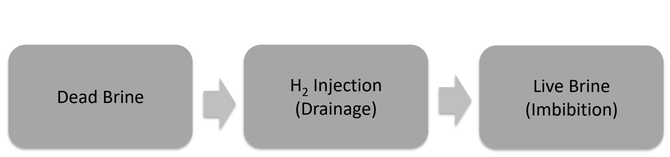
- Short T_2 → micropores / bound fluid
- Long T_2 → macropores / mobile hydrogen
- Reduced signal after imbibition → residual hydrogen trapping

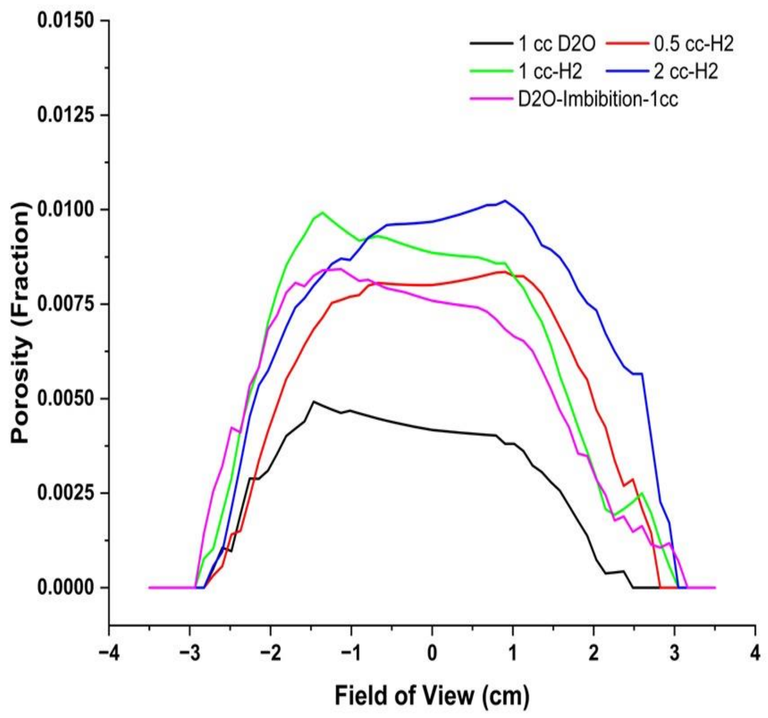
RESULTS – STORAGE DYNAMICS

Sample Description: Silurian Dolomite

- Diameter: 3.81 cm
- Height: 4.7 cm
- Dry Weight: 127.58 g
- Porosity: ~17%

Spatial NMR distributions reveal heterogeneous pore connectivity and non-uniform hydrogen flow pathways within the carbonate system.





Pore-Scale Hydrogen Transport

- Drainage → hydrogen invades larger connected pores
- Imbibition → water reinvades larger pores
- Residual hydrogen remains trapped within smaller pore networks

- Preferential pore invasion
- Capillary-controlled redistribution
- Residual hydrogen trapping

Spatial NMR distributions highlighting pore-scale heterogeneity and preferential hydrogen flow pathways.

DISCUSSION

Hydrogen storage efficiency depends strongly on pore connectivity, heterogeneity, and capillary trapping mechanisms.

CONCLUSION

Pore-scale heterogeneity and capillary forces strongly control hydrogen distribution, mobility, and residual trapping in geological media.

KEY TAKEAWAYS

✓ Pore-scale heterogeneity and capillary forces control hydrogen movement and trapping.

✓ Low-field NMR reveals dynamic hydrogen behavior and strong carbonate storage potential.