IMPERIAL

26th Pore-Scale Modelling and Imaging Meeting

Pore-Scale Dynamics and Relative Permeability in CO_2 Storage

Rukuan Chai, Sajjad Foroughi, Branko Bijeljic, Martin J. Blunt

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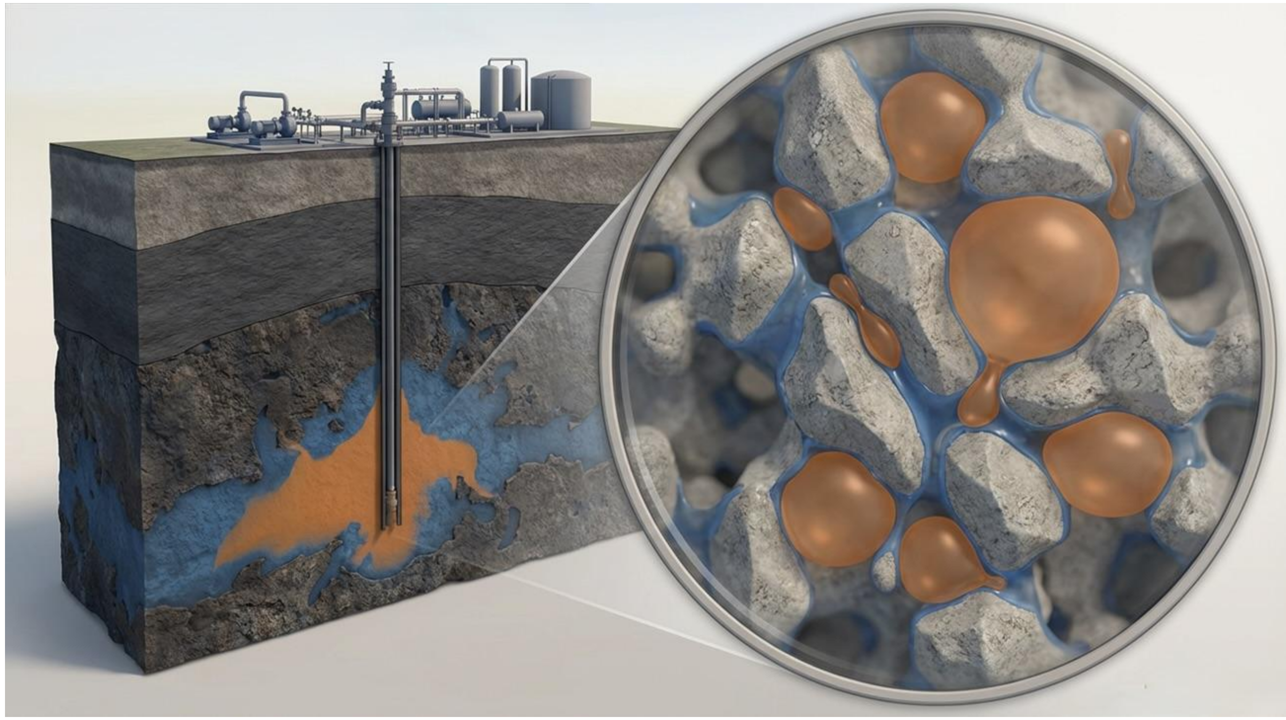
Motivation and Aim



- **Global Impact:** Carbonates hold 60% of reserves; prime targets for CCUS.
- **Key Challenge:** High heterogeneity creates uncertainty in injectivity & capacity.
- **Business Value:** Accurate Rel-Perm data de-risks simulation and optimizes field development plans.

☐ Motivation and Aim

Relative Permeability in **Sandstone**

Extensive, Consistent, Systematic, In-depth

Steady-state/Unsteady-state methods

Relative Per curves
Hysteresis characteristics

Factors: Temperature; Pressure; Structural Heterogeneity; Wettability…

(Blunt, 2017; Krevor et al.,2012; Chen et al.,2017; Bakhshian et al.,2020)

?

Relative Permeability in **Carbonate**

Limited, Inconclusive, General

Bennion and Bachu,2008
Unsteady-state method
Unclear relationship between pore structure and relative permeability.

Akbarabadi and Piri,2015
Steady-state method
low drainage relative permeability&strong hysteresis

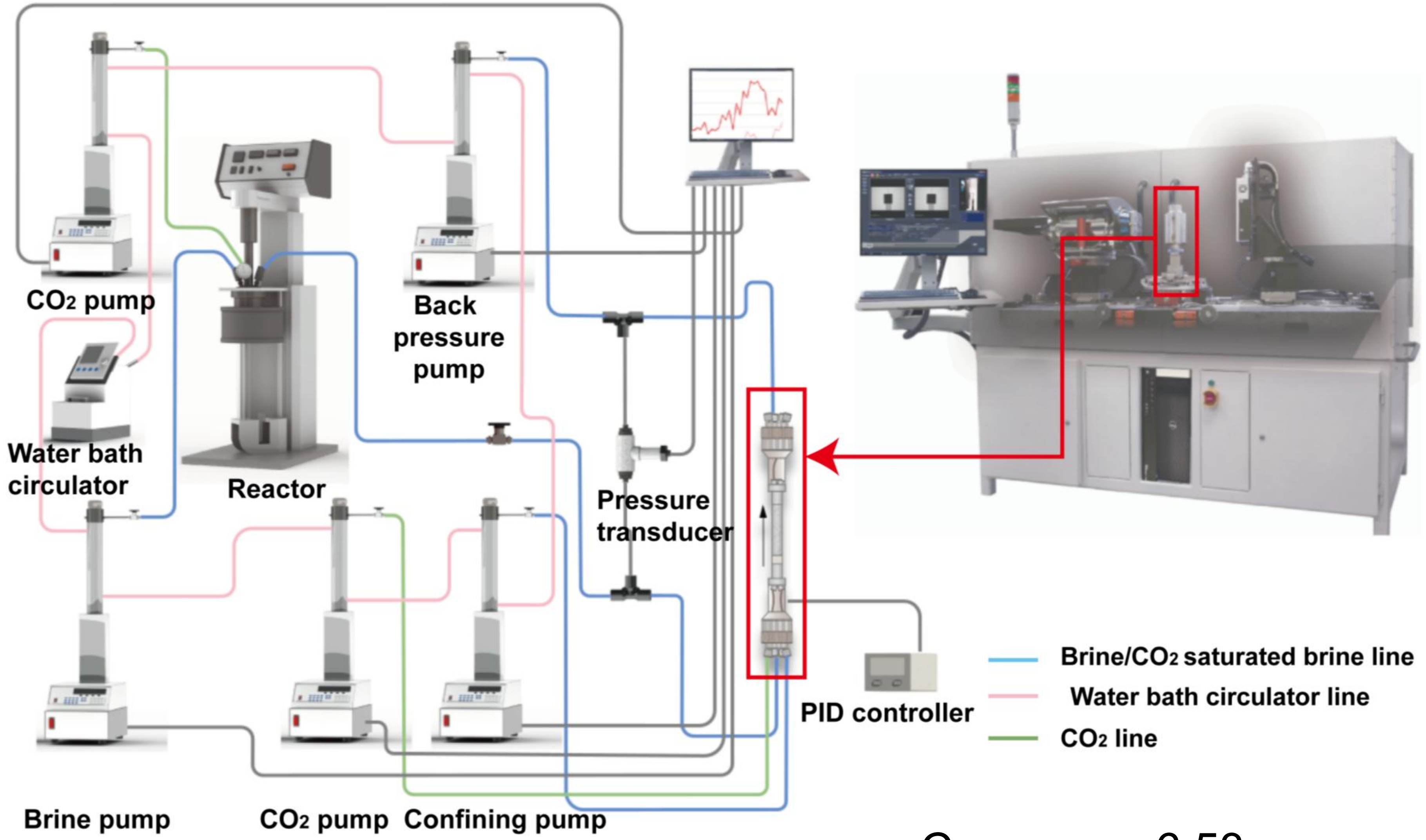
Smith et al.,2017
Steady-state method
Higher Kr in Carbonate (0.25 mD) vs. Sandstone (850 mD)

Sedaghatinasab et al.,2021
Unsteady-state method
Higher absolute permeability increases both initial and residual CO_2 saturations, amplifying hysteresis.

- **The Gap:** Existing data in reservoir carbonates are scarce and inconsistent; mechanisms governing trapping and hysteresis are poorly understood.

- **Objectives**
  - Measure relative permeabilities and quantify hysteresis effects
  - Track the evolution of CO_2 ganglia and pore occupancy to identify displacement processes
  - Analyze the contributions of structural heterogeneity and water-wet properties

☐ Experiment



Steady-State Relative Permeability

Diameter: 12.6mm
Length: 34.9mm
K_{abs}: 66mD

Reservoir Conditions

Temperature: 45℃
Pressure: 8.0MPa

$Ca=5.89\times10^{-8}$
Flow rate: 0.8mL/min

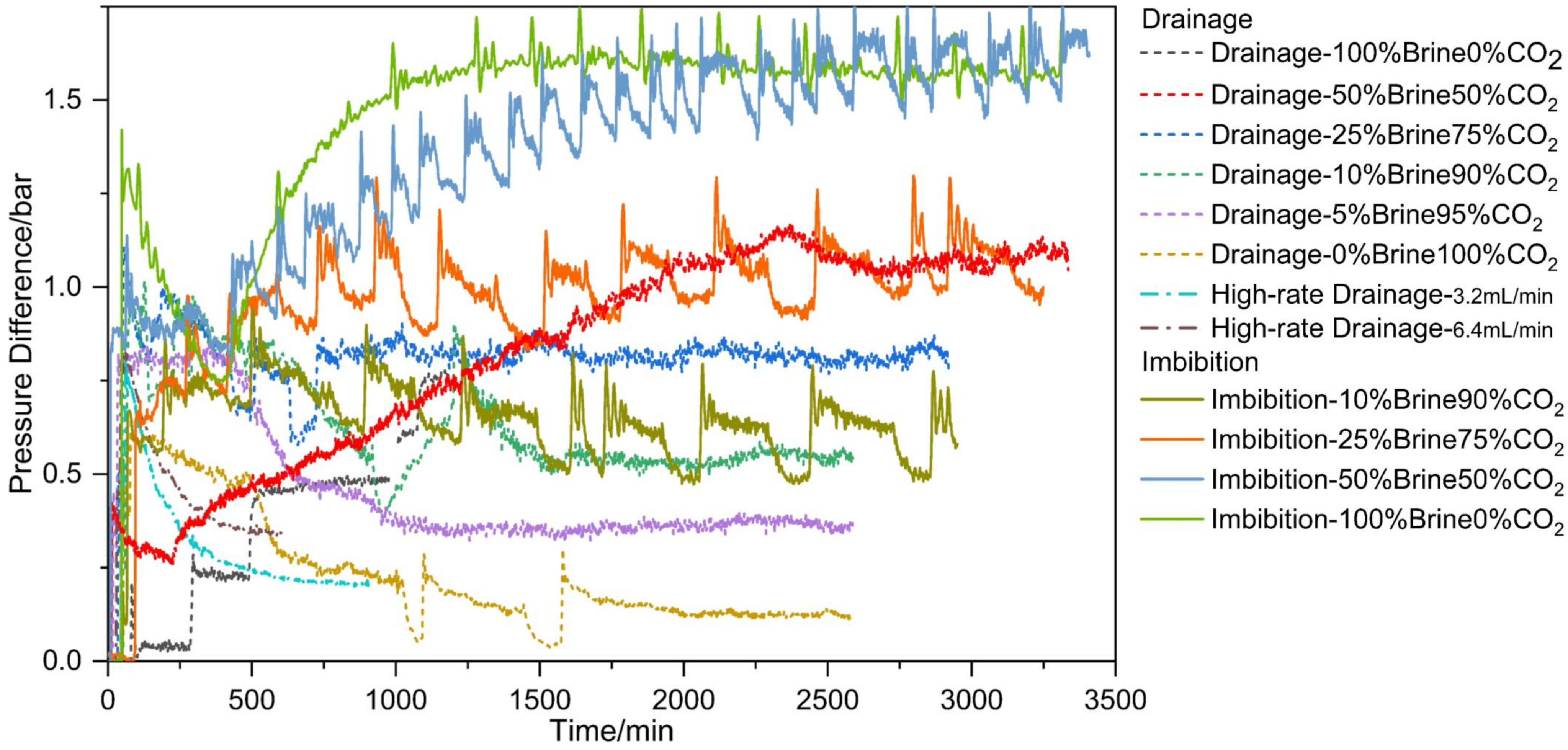
Drainage
(100%, 50%, 25%, 10%, 5%, 0%Brine)

Bump Flow
(3.2 and 6.4mL/min)

Imbibition
(0%, 10%, 25%, 50%, 100%Brine)

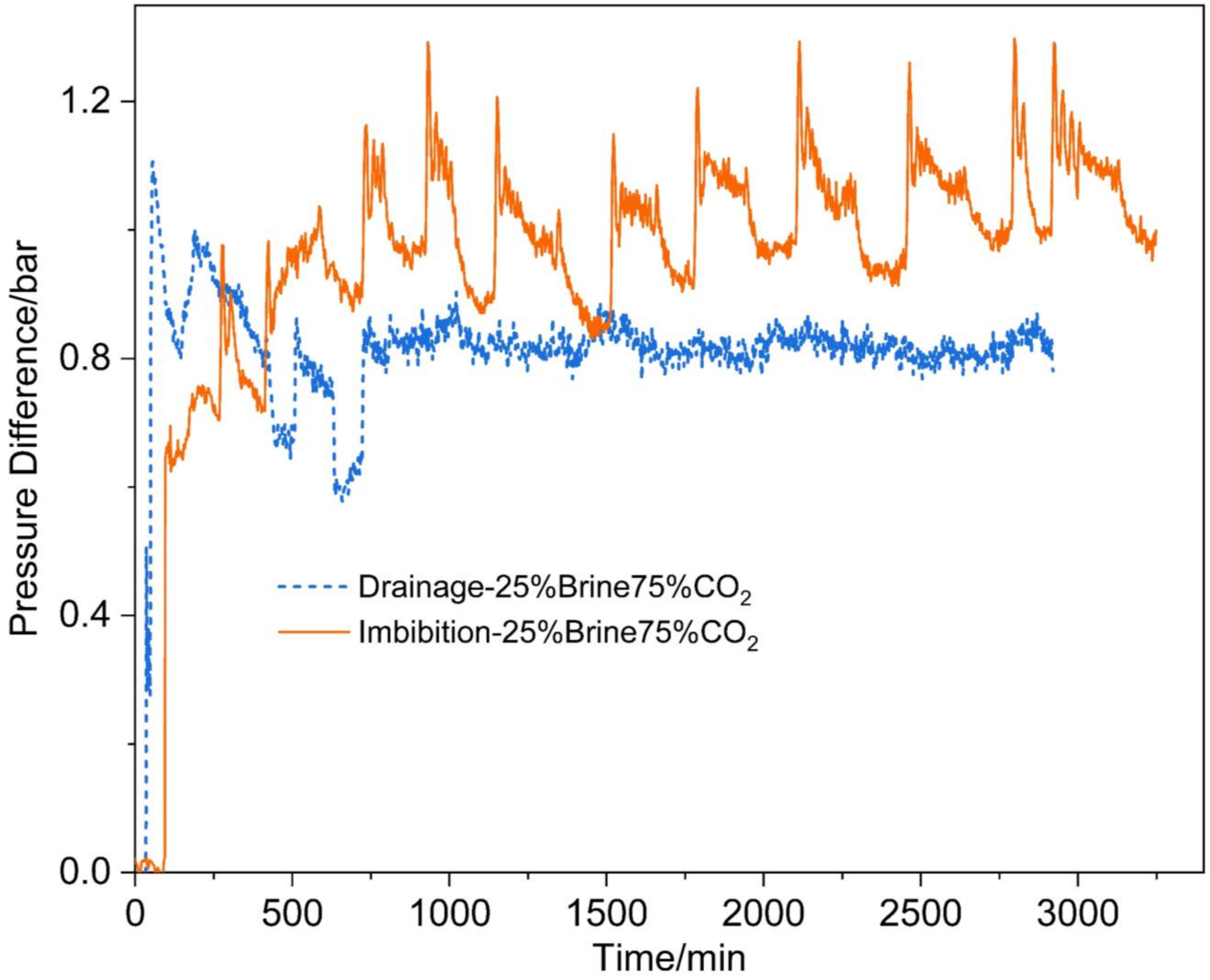
Core scan: 6.53μm
Zoomed-in scan: 2.60μm

☐ Pressure Difference



- **Overall Pattern:** Increase→Maximum at 50%Brine50%CO_2→Reduce
- **Drainage**: High initial hump (entry barrier); Minimal subsequent fluctuations
- **Imbibition**: No initial hump; Pronounced fluctuations (instability)

☐ Pressure Difference



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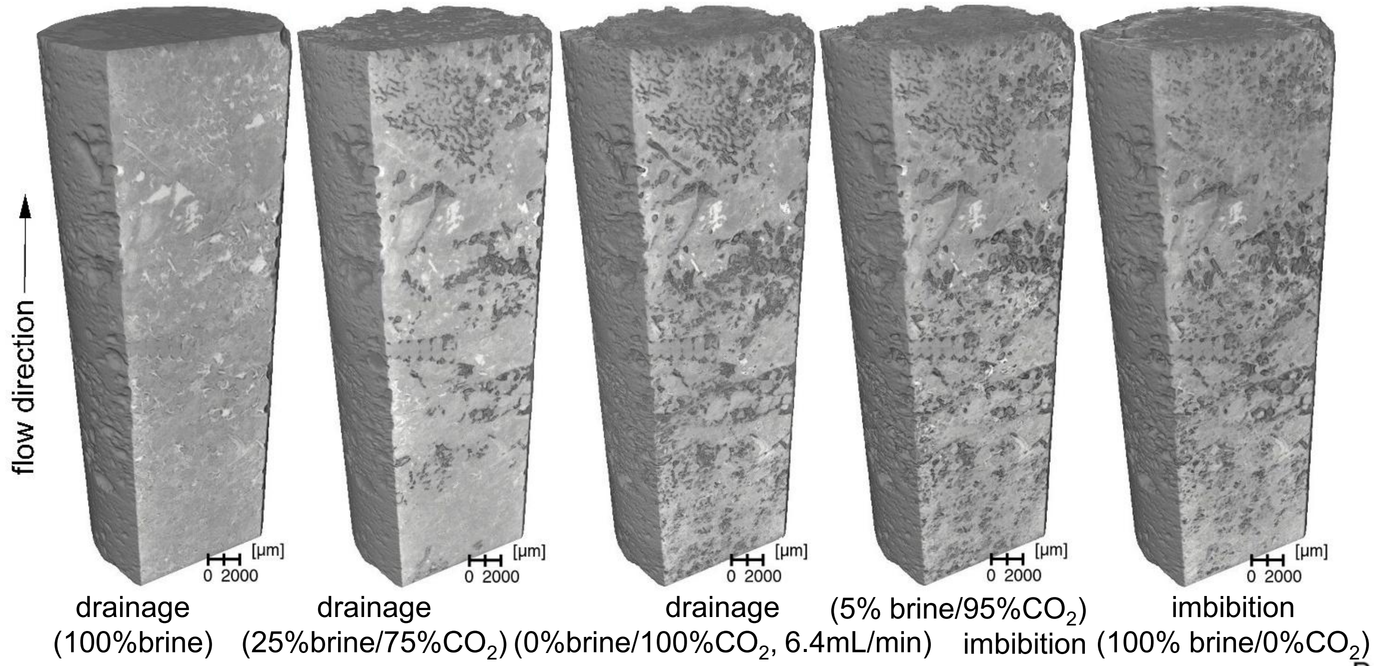
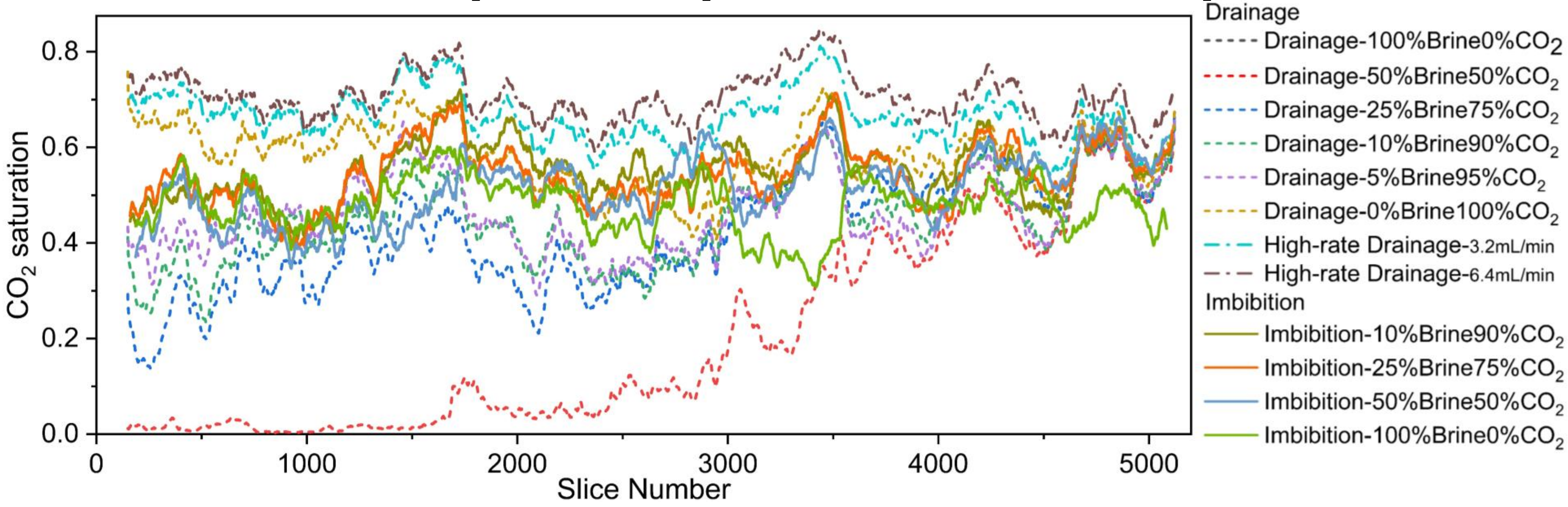
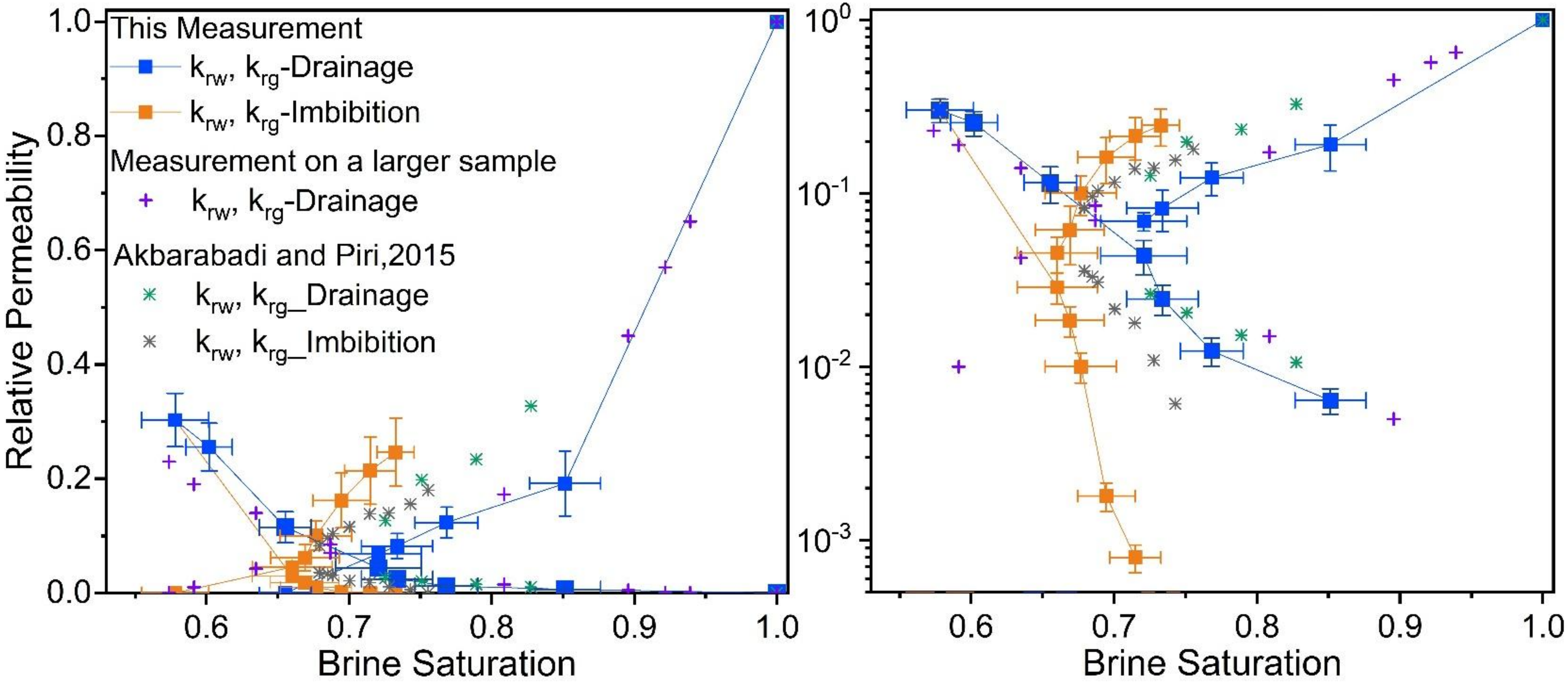
□ CO_2 Saturation





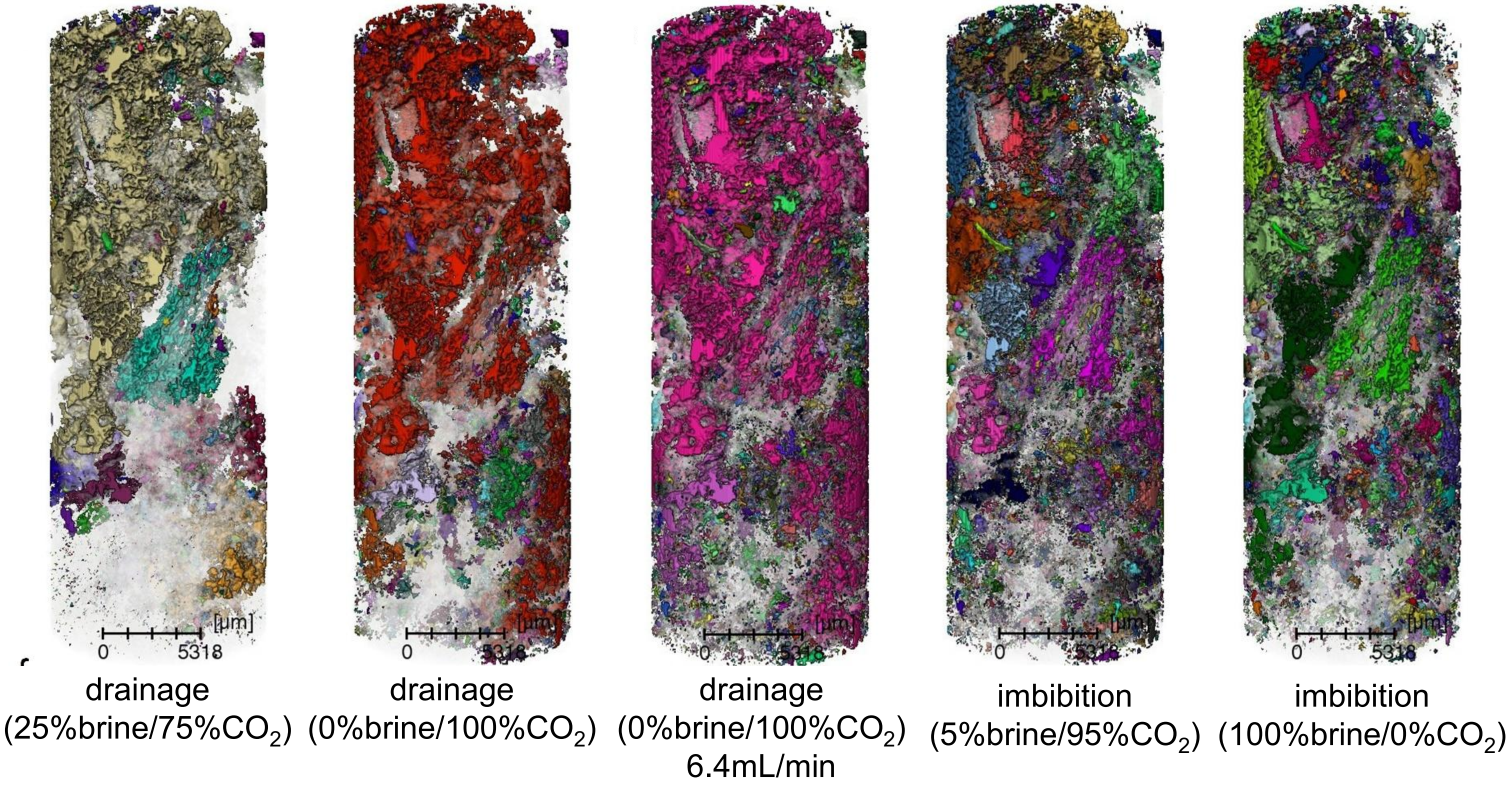
- ➢ **Drainage Endpoint**: Maximum CO_2 saturation reached 43%
- ➢ **Imbibition Endpoint**: Residual CO_2 saturation was 27%
- ➢ **Trapping Efficiency:** High residual trapping (**~63%** of initial saturation)

☐ Relative Permeability

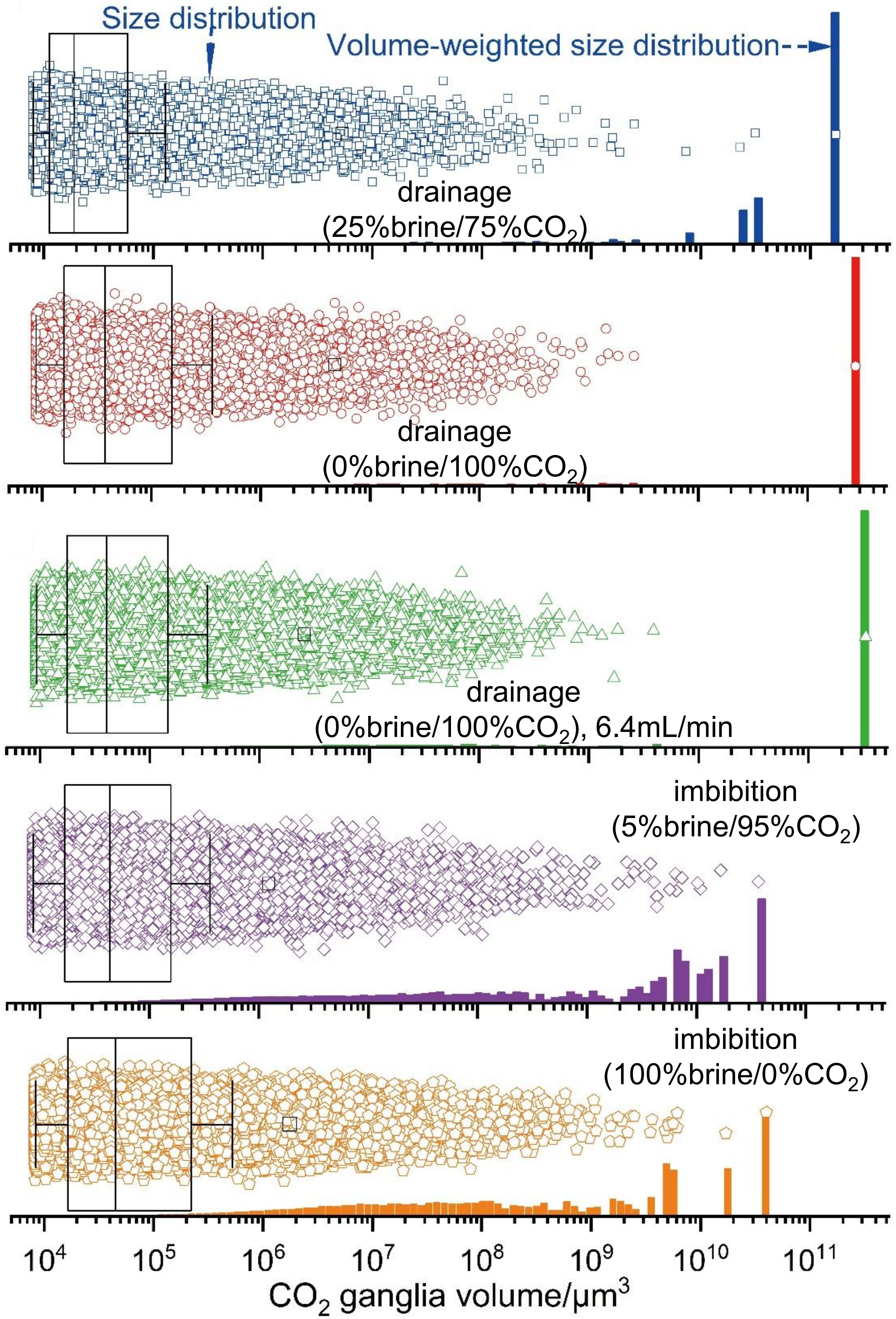


- **Validation:** Consistent with macro-scale and reference data
- **Low Mobility:** Low CO_2 phase permeability, despite high saturation
- **Strong Hysteresis:** Pronounced drainage-imbibition cycle disparity

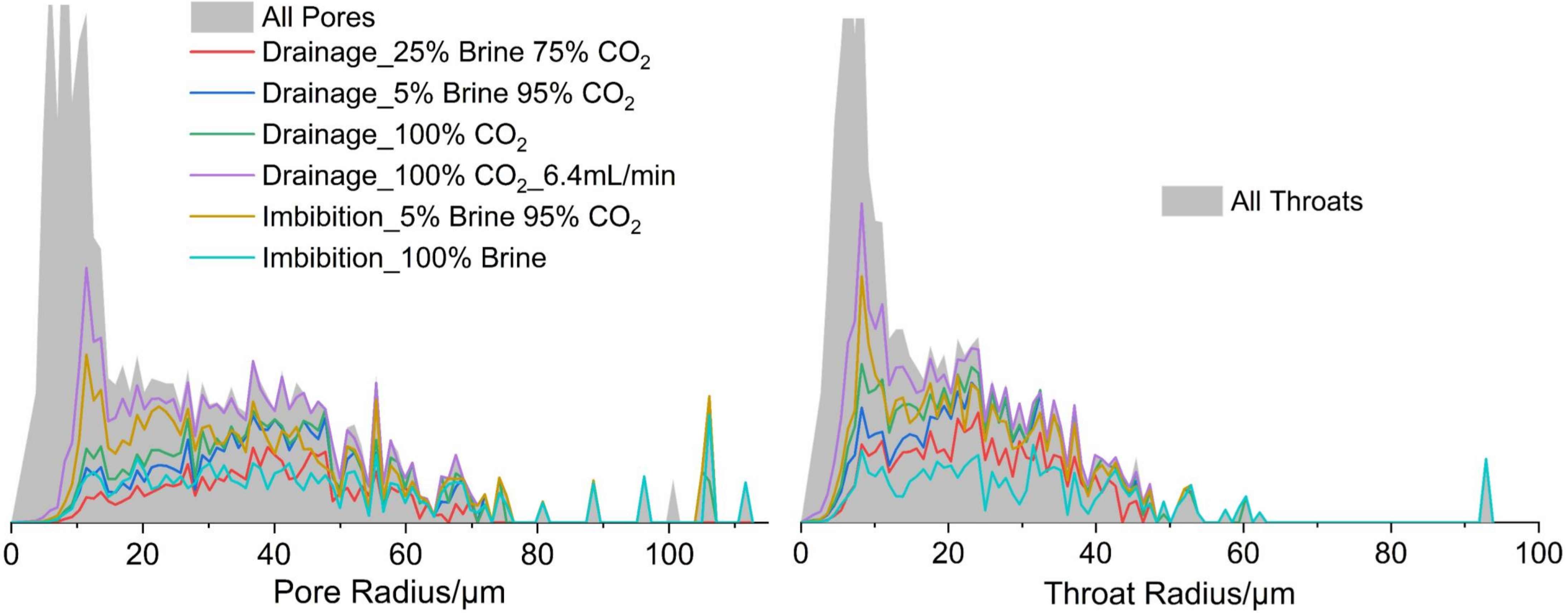
☐ Ganglia Evolution



- ➢ **Drainage:** Ganglia coalescence into a spanning cluster; Normalized χ drops from 5 (early drainage) to -16 mm^{-3} (end drainage)
- ➢ **Imbibition:** The cluster was extensively fragmented into dispersed, isolated ganglia; Normalized χ rises to 19 mm^{-3}

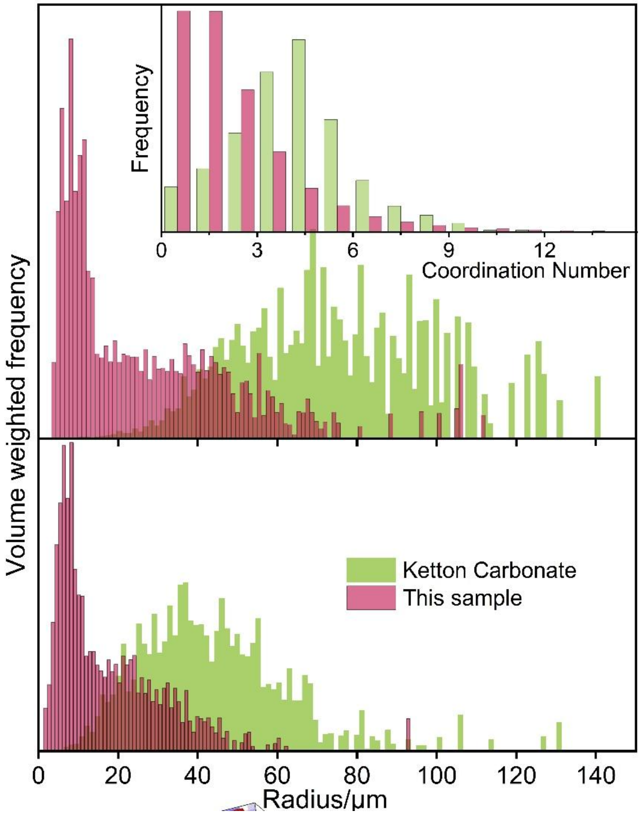


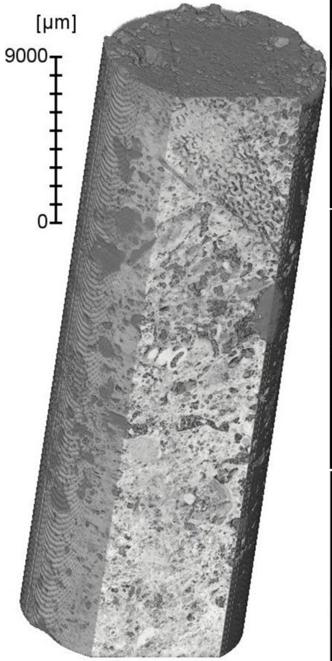
☐ Pore Occupancy

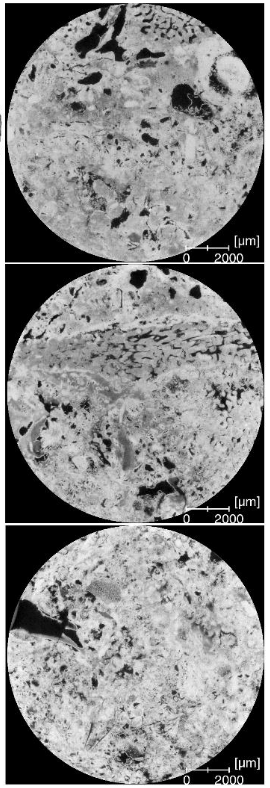


- **Drainage:** Preferential invasion of large pores→progressively smaller ones
- **Imbibition:** Water layers swell in narrow throats, causing snap-off

□ Potential Mechanisms

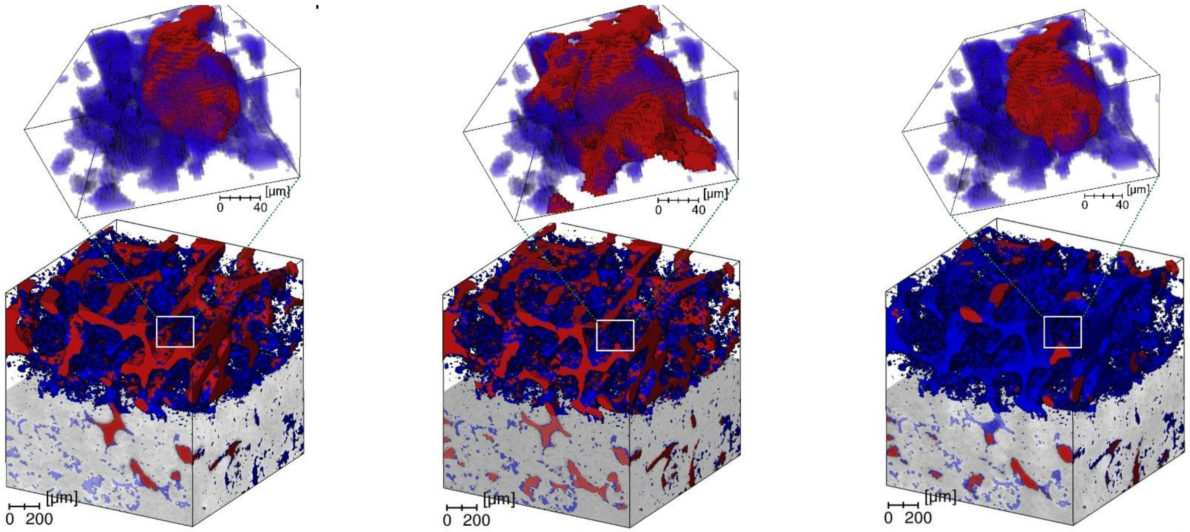


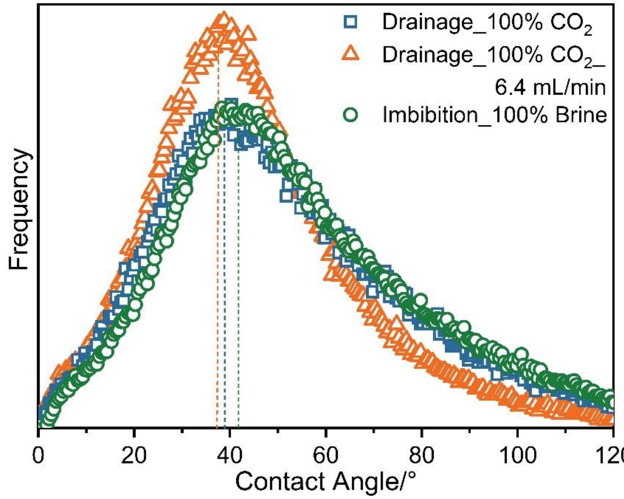


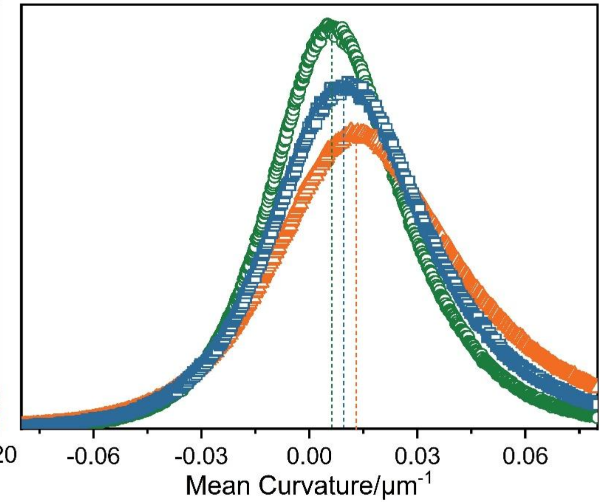


- **Structural Heterogeneity**
  - Highly skewed, multimodal pore-throat distributions
  - Low coordination number (poor connectivity)
  - Promotes snap-off and limits flow pathways

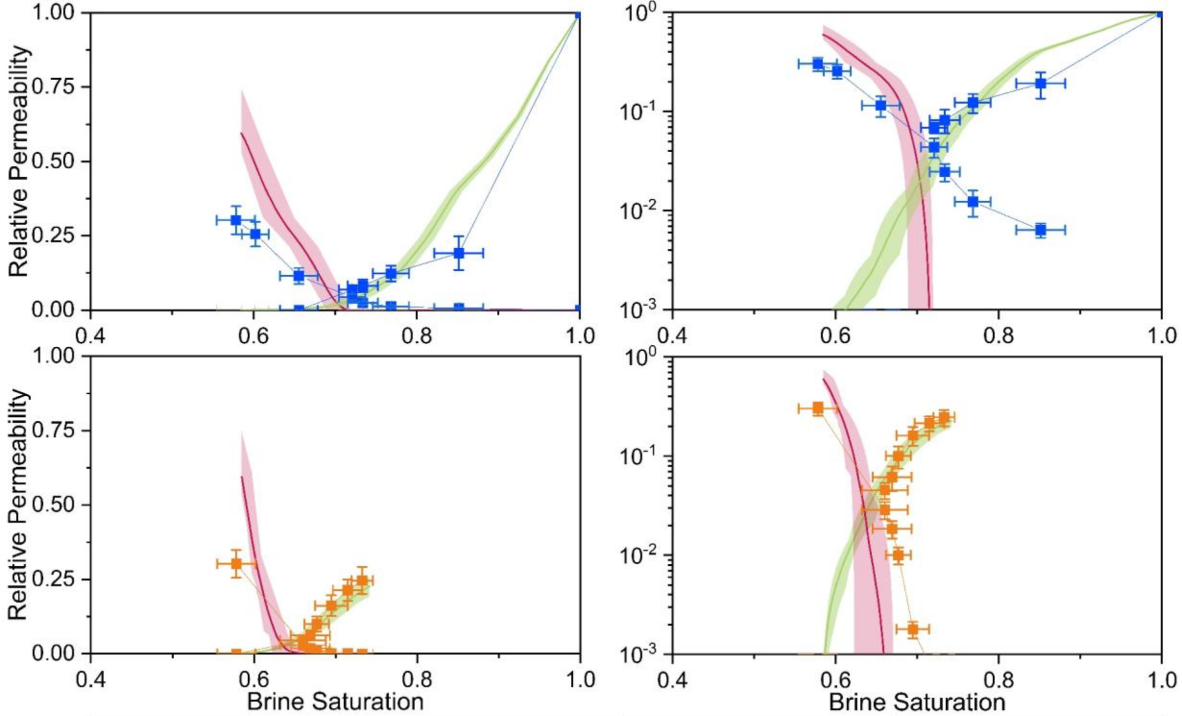
- System remains strongly water-wet throughout
- Contact angle hysteresis is minor

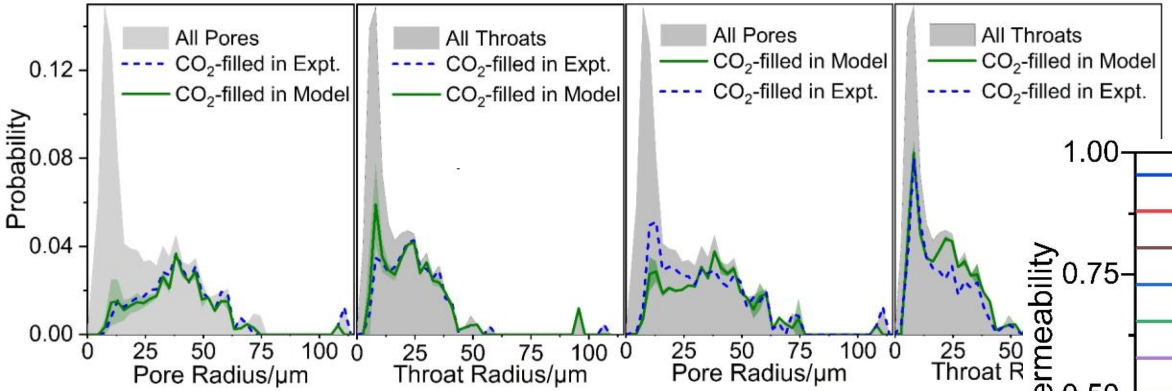




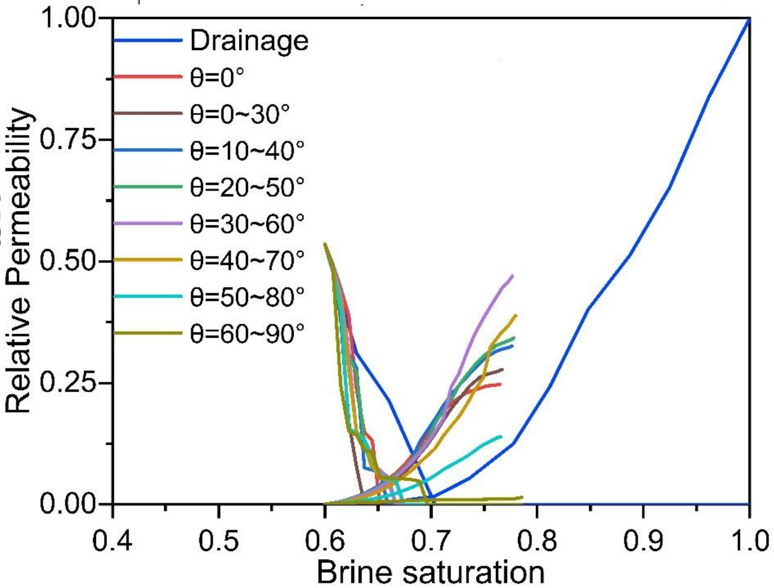


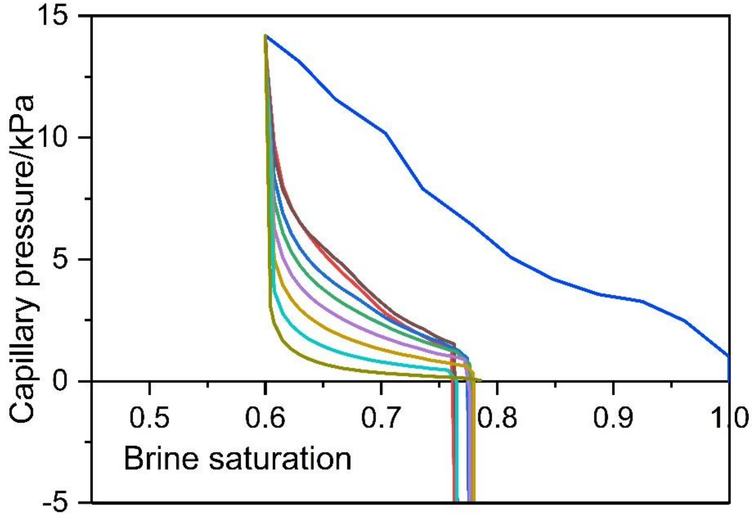
☐ Pore-Scale Modeling





- **Mechanism Quantification:**
  - **Snap-off** accounts for **17%** of throat-filling events during imbibition.
  - **Cooperative pore filling** accounts for **38.6%** of pore events.
- **Sensitivity Analysis:** Varying contact angles showed only modest impact on rel per, confirming structural heterogeneity as the primary control.





- **Accuracy**: PNM accurately reproduces experimental relative permeability and hysteresis.

https://github.com/ImperialCollegeLondon/pnflow

Conclusions

- Quantified low CO_2 relative permeability and pronounced hysteresis in a reservoir carbonate.
- Poorly-connected CO_2 ganglia resulted in low relative permeability, while ganglion fragmentation during imbibition led to hysteresis.
- Modeling indicated that snap-off was the dominant mechanism leading to a high residual CO_2 saturation.
- These observations advance mechanistic knowledge of flow hysteresis and trapping in carbonates, facilitating more accurate modeling for CO_2 sequestration projects.

Future research: will account for **Ostwald ripening** to better predict long-term cluster dissolution and refine estimates of trapped CO_2 in complex porous systems.

Acknowledgments

PETRONAS

Thank you!

Questions/Comments?

r.chai@imperial.ac.uk