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Pore-Scale Dynamics of Multiphase Reactive Transport in Carbonates under CO_2-Acidified Brine Injection

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Outline

1. Overview
2. Objectives: Multiphase Reactive Transport
3. X-ray Tomography Experiments and the Impact of Transport Heterogeneity
4. Observations and Conclusions
5. Future Work

1. Overview

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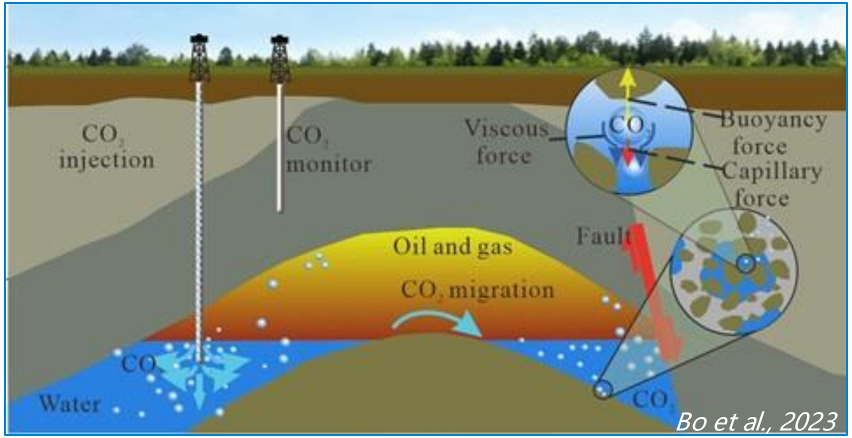
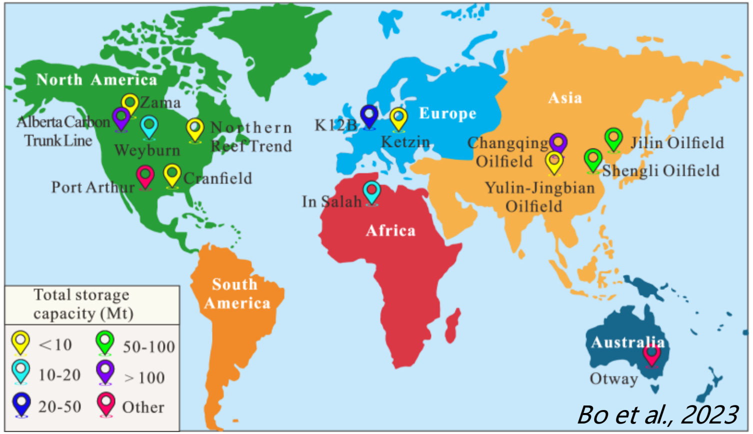
• Research background



Depleted Hydrocarbon Fields

Less additional costs to implement
Mature technical processes
Ease of management



Global CO_2 Storage Projects in Depleted Hydrocarbon Fields

Global CO_2 storage capacity of 900-1200Gt

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• Challenges

Reactive Transport & Multi-phase flow

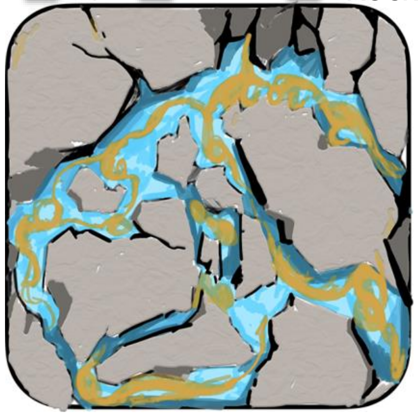
Carbonate rock partially saturated with hydrocarbon phase.

Heterogeneity

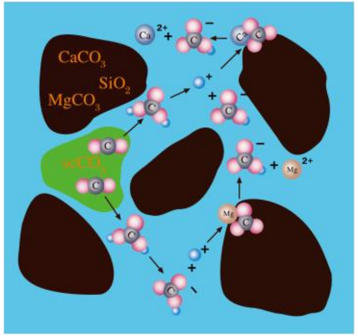
Hydrocarbon phase will change the transport heterogeneity and may block the CO_2 equilibrated brine from reacting.

Wettability & Multi-Mineral

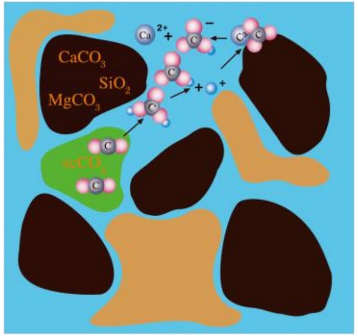
Wettability state and mineralogical complexity.



Carbonate rock saturated with oil and brine

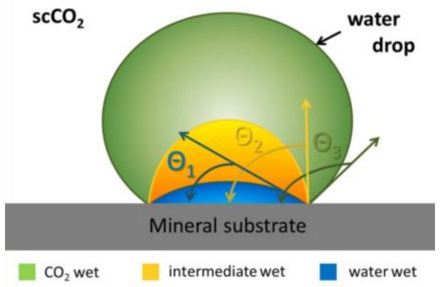


Reactive Transport Phenomena



Reactive Transport in Presence of Oil

$scCO_2$/ CO_2(l) brine rock oil



$\Theta_1 \approx 30^\circ \Rightarrow$ strongly water wet system
$\Theta_1 \approx 90^\circ \Rightarrow$ intermediate wet system
$\Theta_1 \approx 135^\circ \Rightarrow$ strongly CO_2 wet system

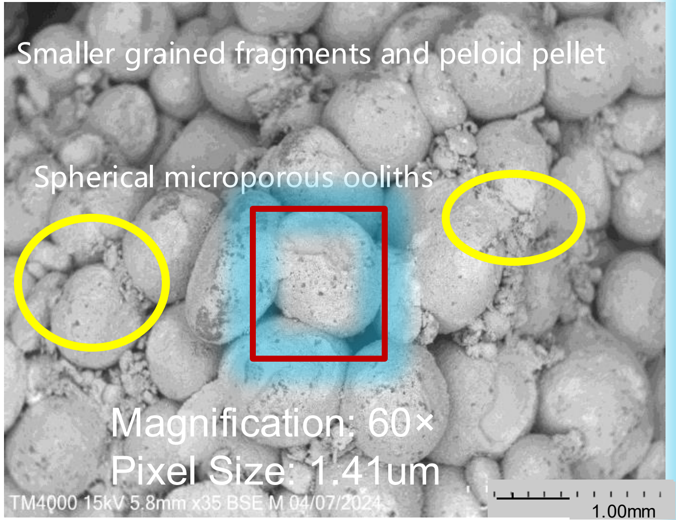
Wang et al., 2024

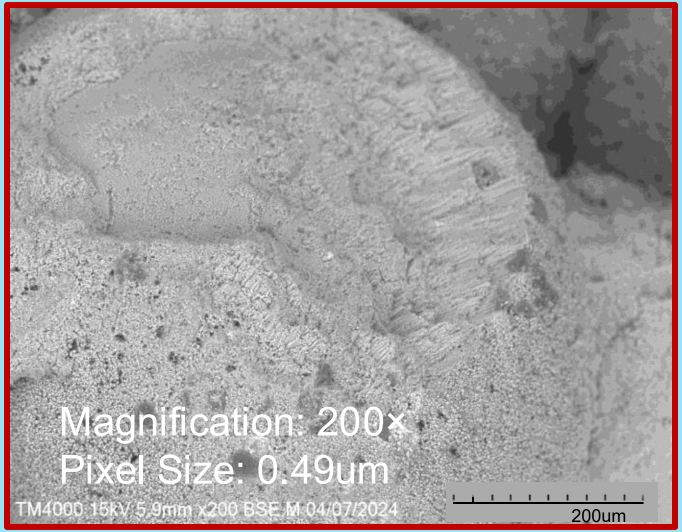
Wettability States

2. Objective:
Reactive Transport in Multiphase Flow

Objective

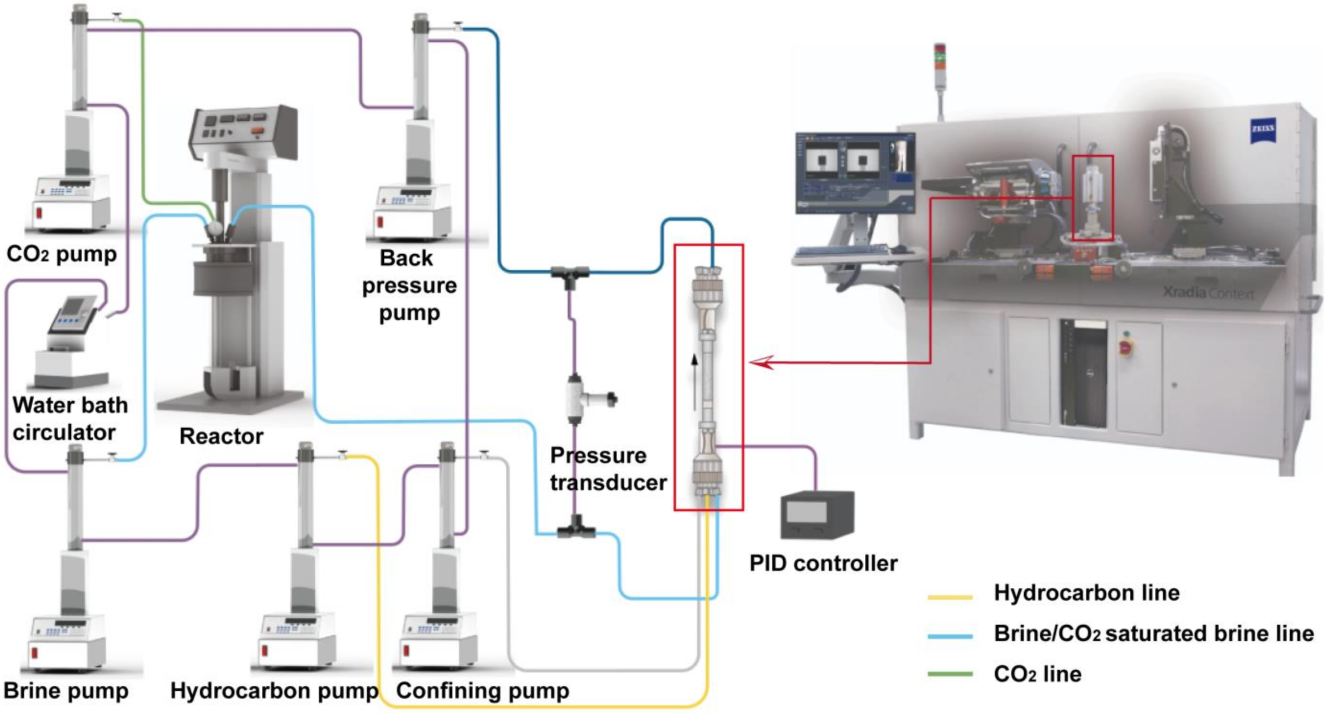
- The impact of changes in transport heterogeneity caused by the introduction of hydrocarbon phase on flow mechanisms and dissolution patterns.
- A permeable Ketton oolitic limestone (99% calcite).





3. X-ray Tomography Experiments and the Impact of Transport Heterogeneity

• Experimental apparatus



Measurement System

1. Fluid Flow Unit

ISCO Pumps
High T&P Reactor
High T&P Core Holder
Back Pressure Regulator

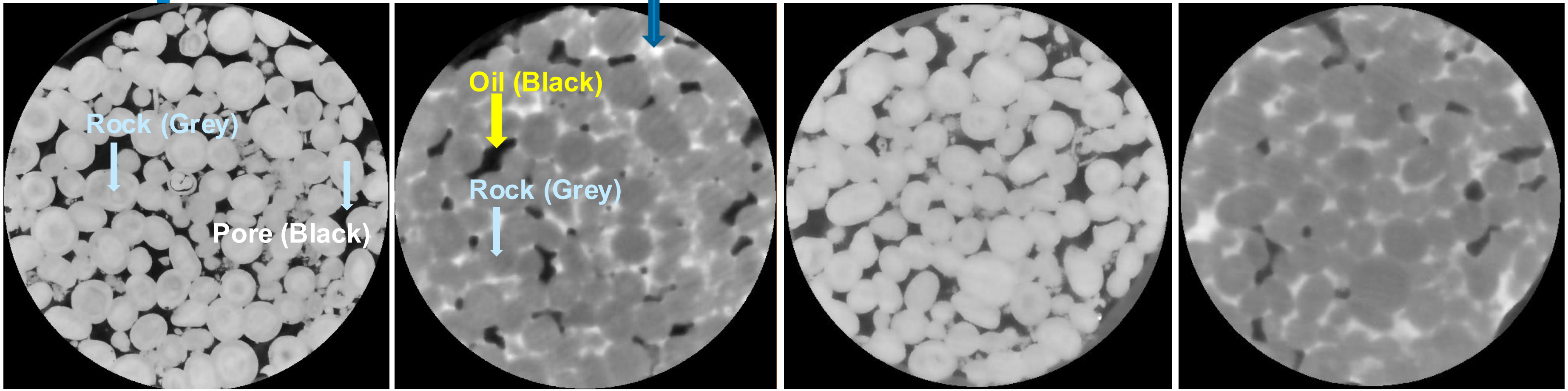
2. Monitoring Unit

X-ray CT
Pressure Transducer

3. Stability Unit

Water Bath Circulator
PID Controller
Insulation Cover for Tubings

Samples

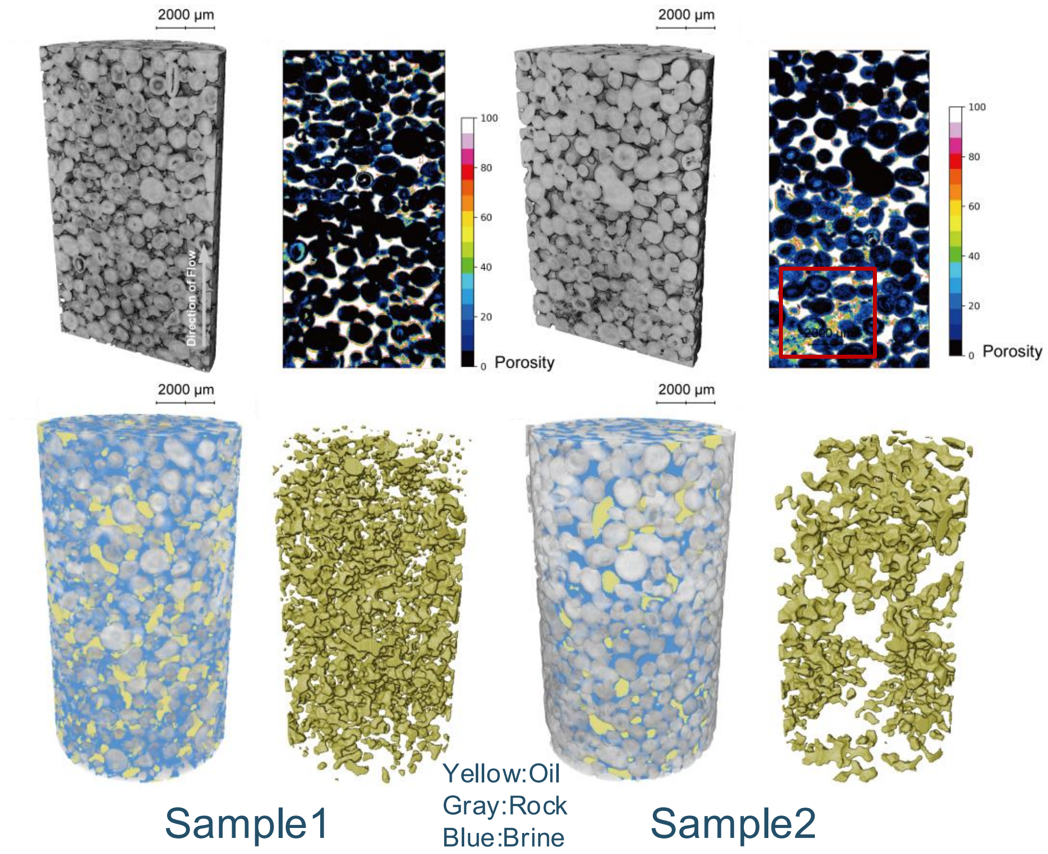


Sample1 Sor= 39.8% Sample2 Sor= 31.1%

Rock Sample	S1	S2
Length, mm	120	120
Diameter, mm	60	60
Permeability(Darcy)	2.46±0.10	2.74±0.18
Micro-CT porosity (Marco-Porosity)	0.147	0.163
Oil Saturation	39.8%	31.1%

- Water-wet Ketton limestone saturated with oil and brine in different saturations.
- Quantitatively characterize transport heterogeneity based on their velocity distribution.

Pore-scale heterogeneity



Dual heterogeneity:

- Pore-scale structural heterogeneity.
- Residual oil distribution.

Sample 1:

- A well-connected network of intergranular macropores leads to a dispersed distribution of residual oil.

Sample 2

- A dual-porosity system with intergranular macropores and poorly connected intermediate-sized pores leads to localized residual oil clusters.

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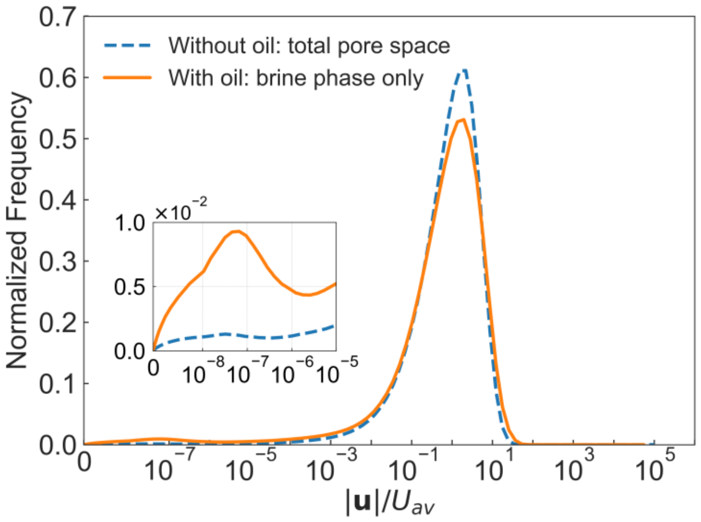
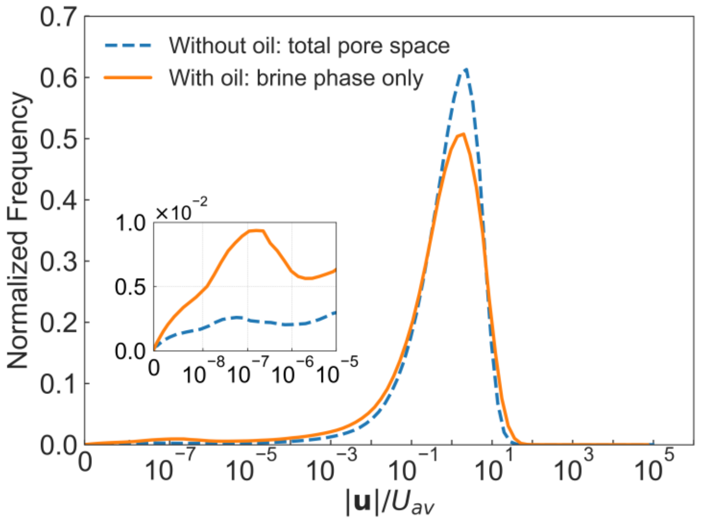
Pore-scale heterogeneity

- A finite volume solver implemented in OpenFOAM solves the Navier-Stokes and volume conservation equations simultaneously.
- Obtained voxel velocities U and then calculated probability density functions (PDFs).



Sample1

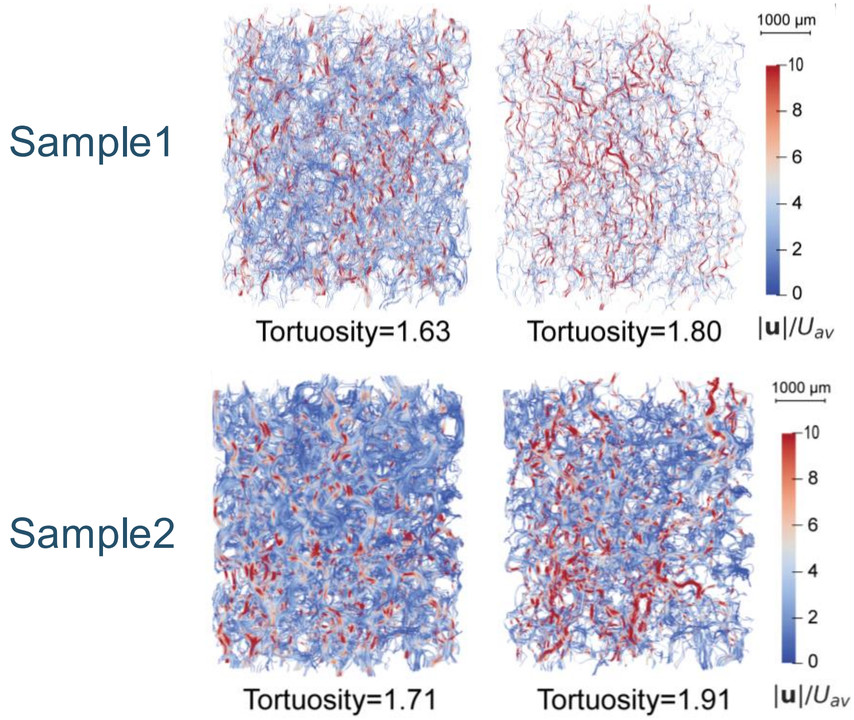


Sample2

• Pore-scale heterogeneity

Without Oil: total pore space (Initial velocity distribution)

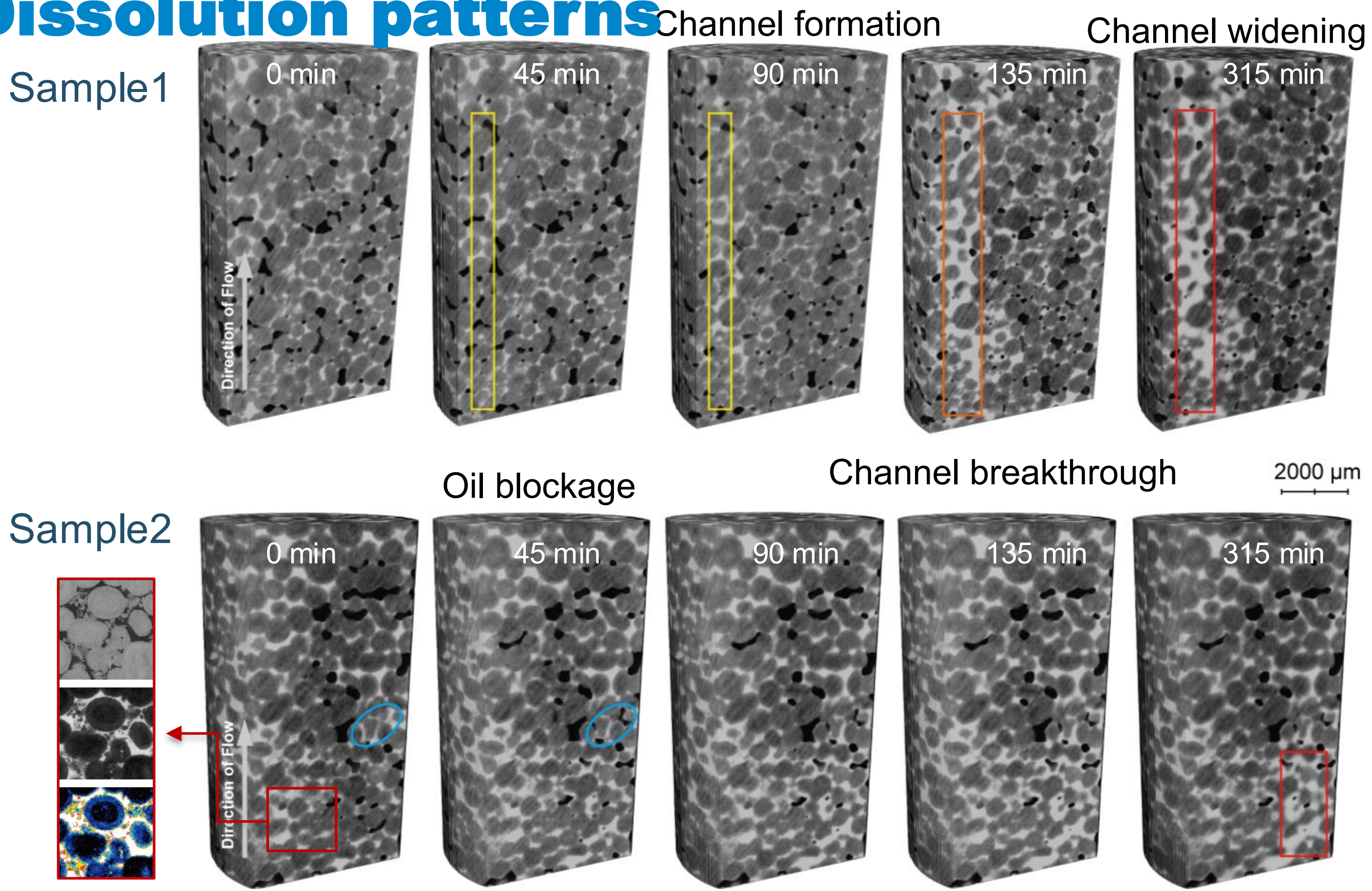
With Oil: Brine phase only



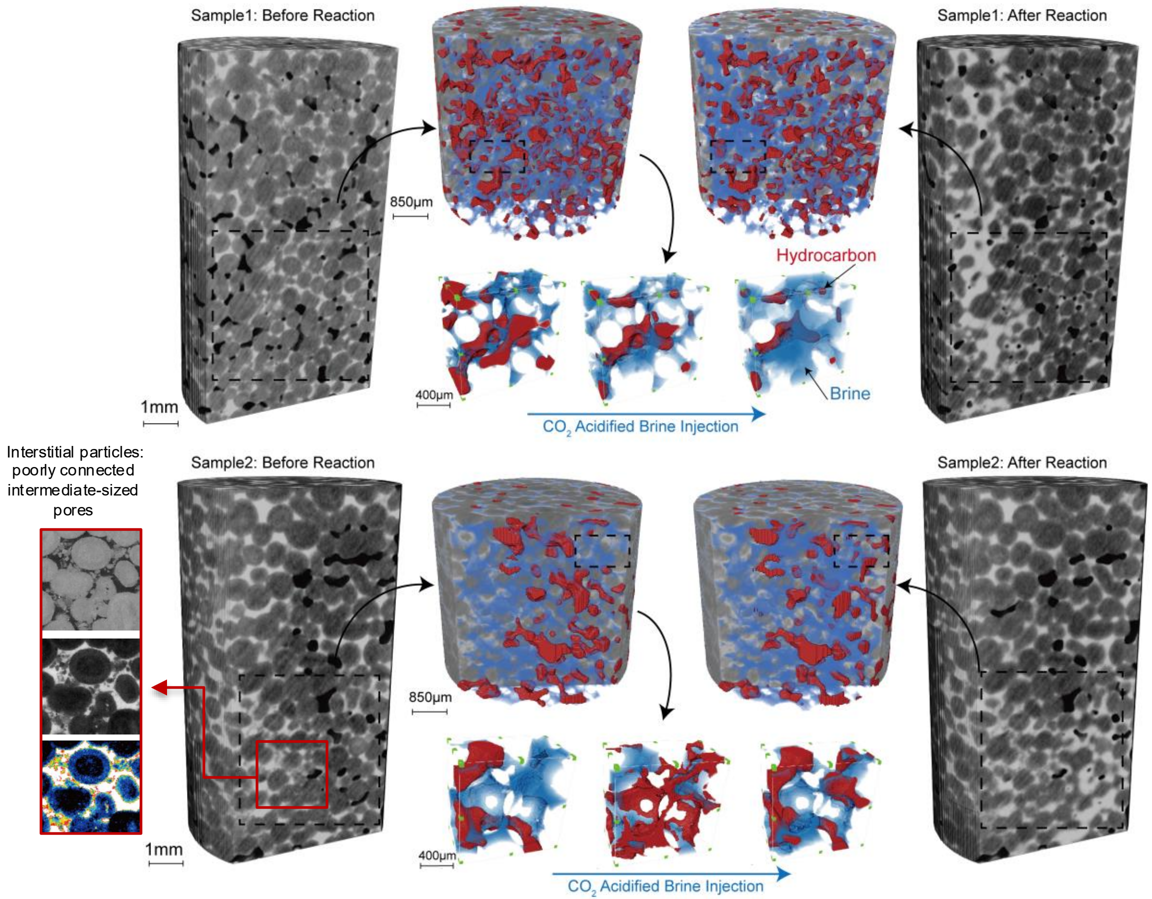
Using the tortuosity of streamlines to characterize transport heterogeneity.

- Lower tortuosity: Flow pathways are simpler and less obstructed.
- Higher tortuosity: Oil restricts brine flow, making pathways more complex.
- Sample 1: Tortuosity increased by 10.4%; Sample 2: Tortuosity increased by 11.6%.

• Dissolution patterns



Gray: Rock
White: Brine
Black: Oil



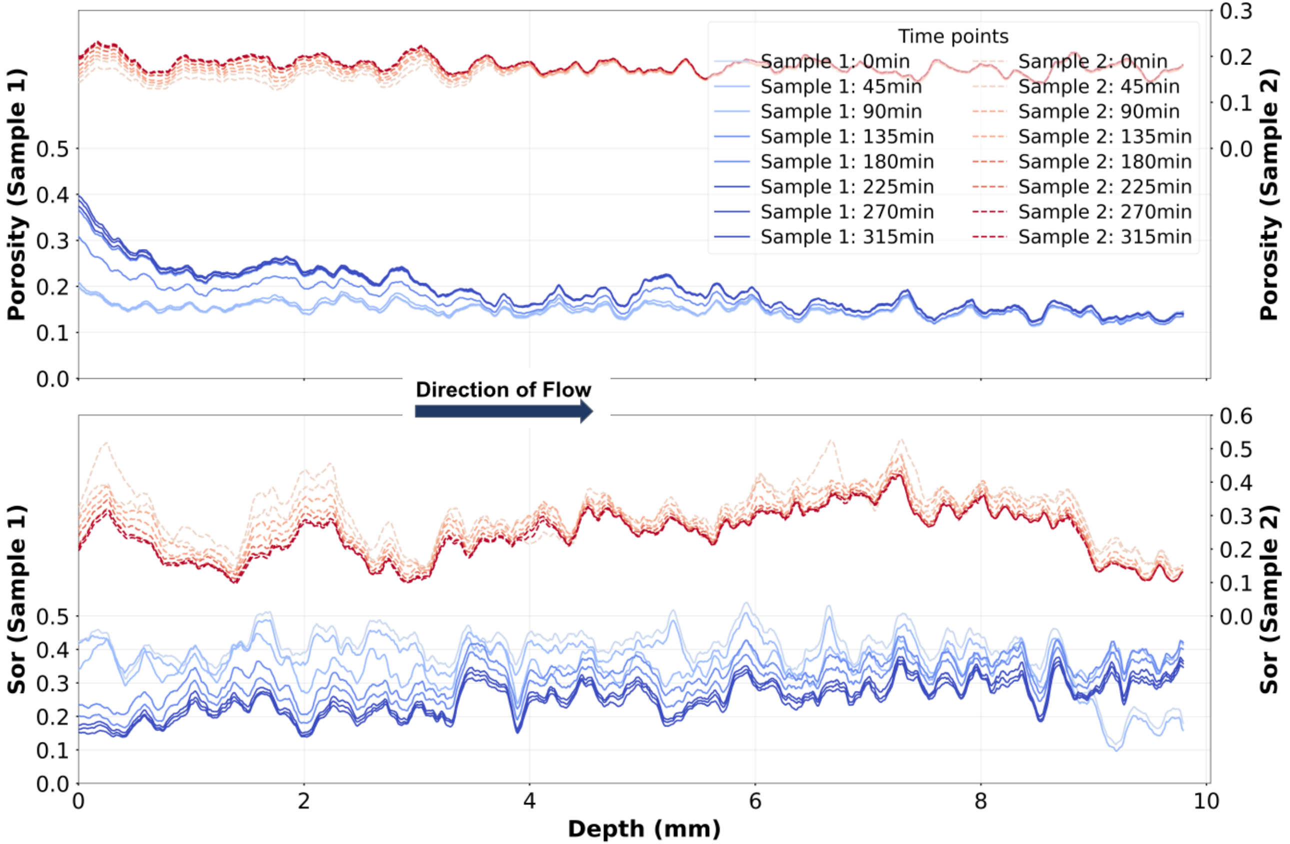
A positive feedback loop:

- Displacement-driven channel growth and widening are enhanced by dissolution, which further increases displacement.

A suppressed regime:

- Fine-scale heterogeneity in low-connectivity regions limits channel formation, while oil blockage prevents dissolution and channel breakthrough.

Porosity and remaining oil saturation



- The changes in Sample 1 are much more significant.
- Sample 2 shows only modest and localized changes at the inlet, confirming a spatially confined reaction.

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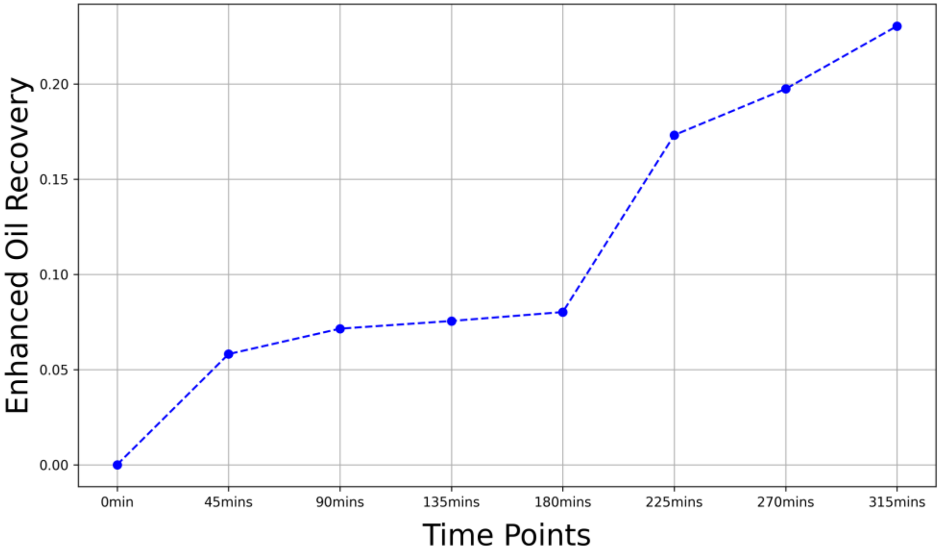
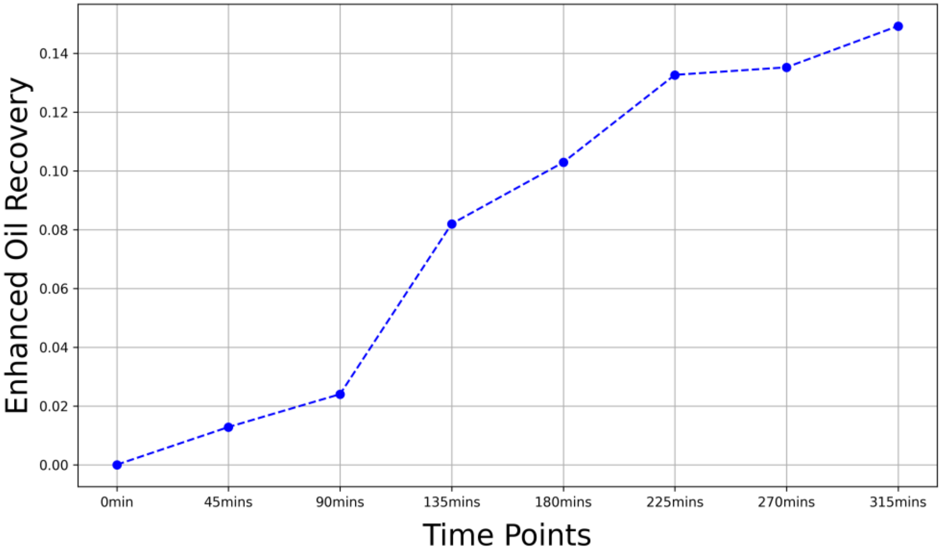
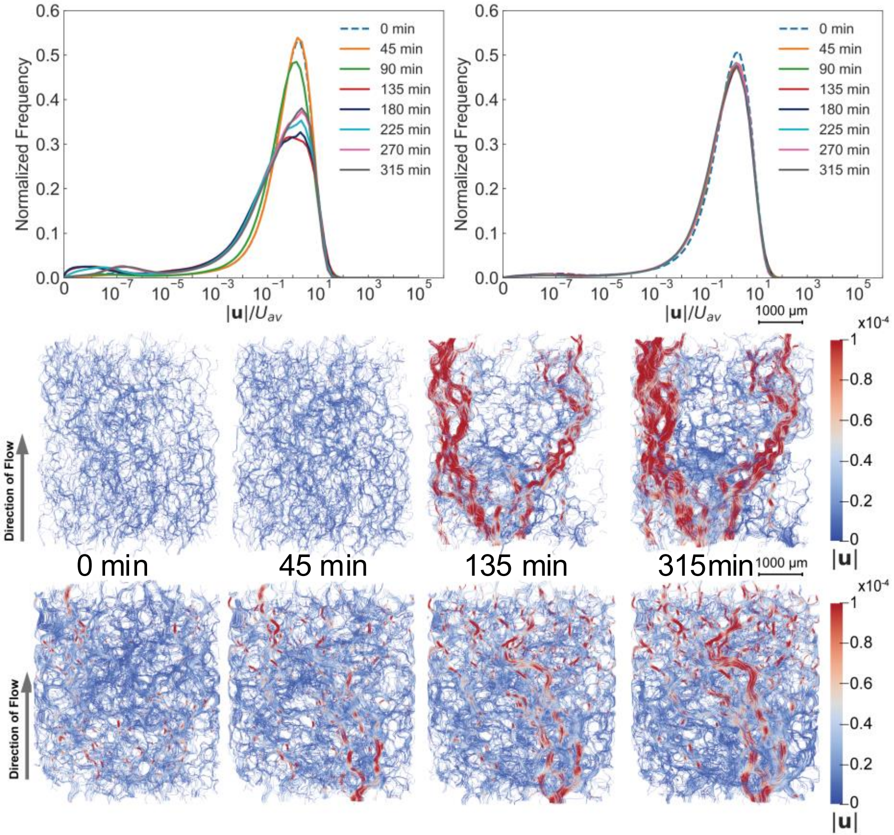
Additional oil recovery





- The injection of CO_2 saturated brine facilitates the recovery of residual oil.

Flow field evolution



Sample1

- Fast-flow channels emerged, breaking the initial flow uniformity.
- Velocity heterogeneity increased, with more stagnant regions observed.

Sample 2

- Bottom-localized channels, with dispersed flow at the top.
- Velocity distribution in Sample 2 changed less over time.

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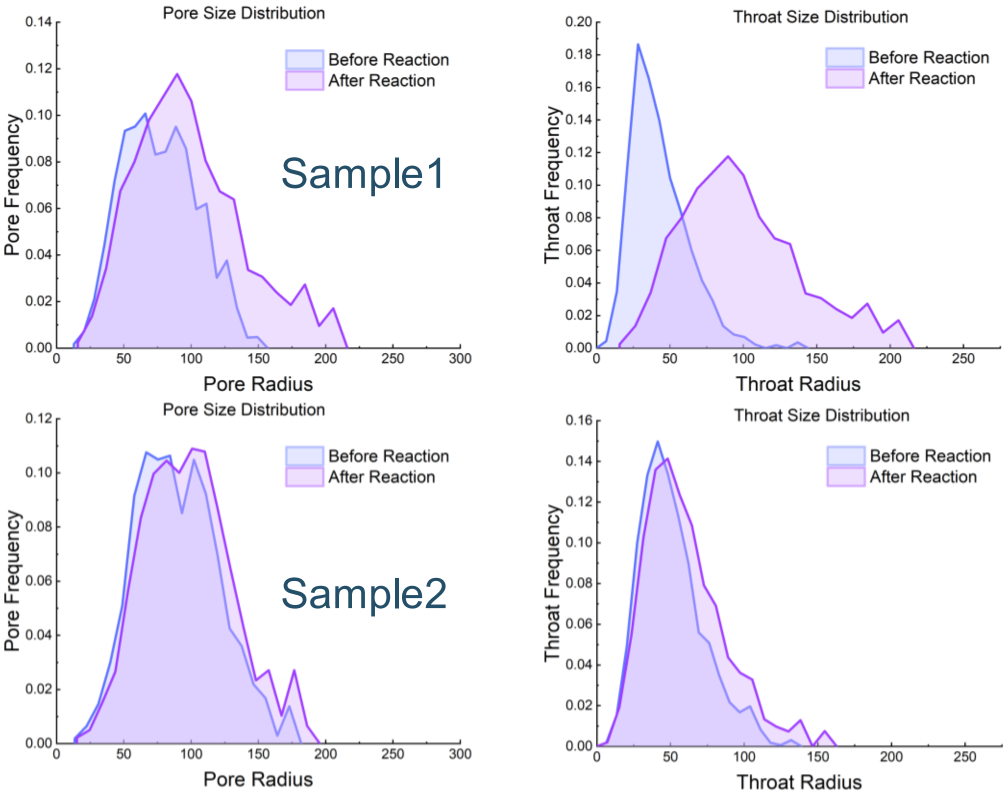
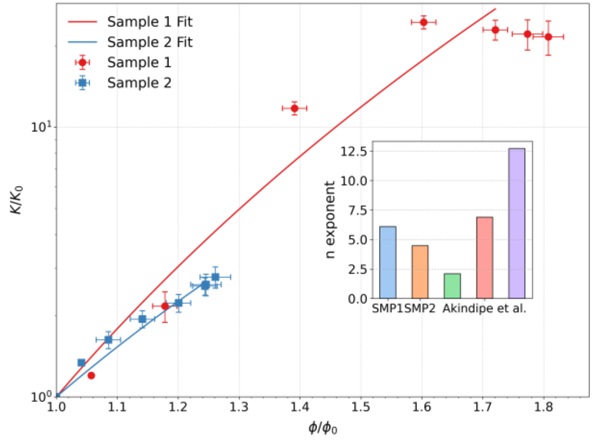
• Pore occupancy and permeability





- The reaction enlarges pores and throats, increasing effective porosity and significantly enhancing permeability by improving the connectivity and fluid flow capacity of the sample.

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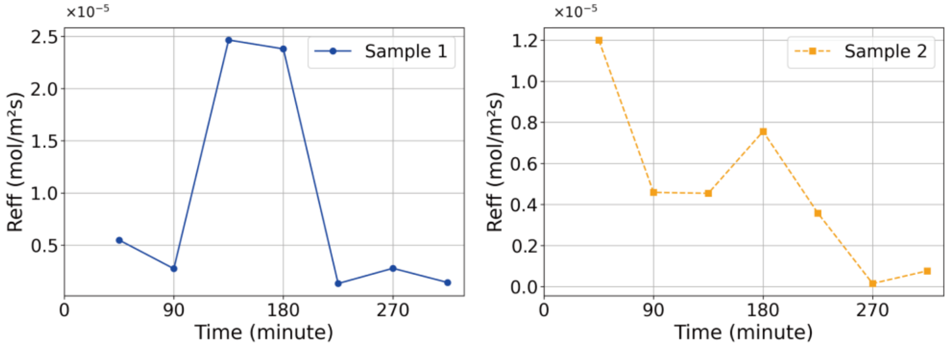
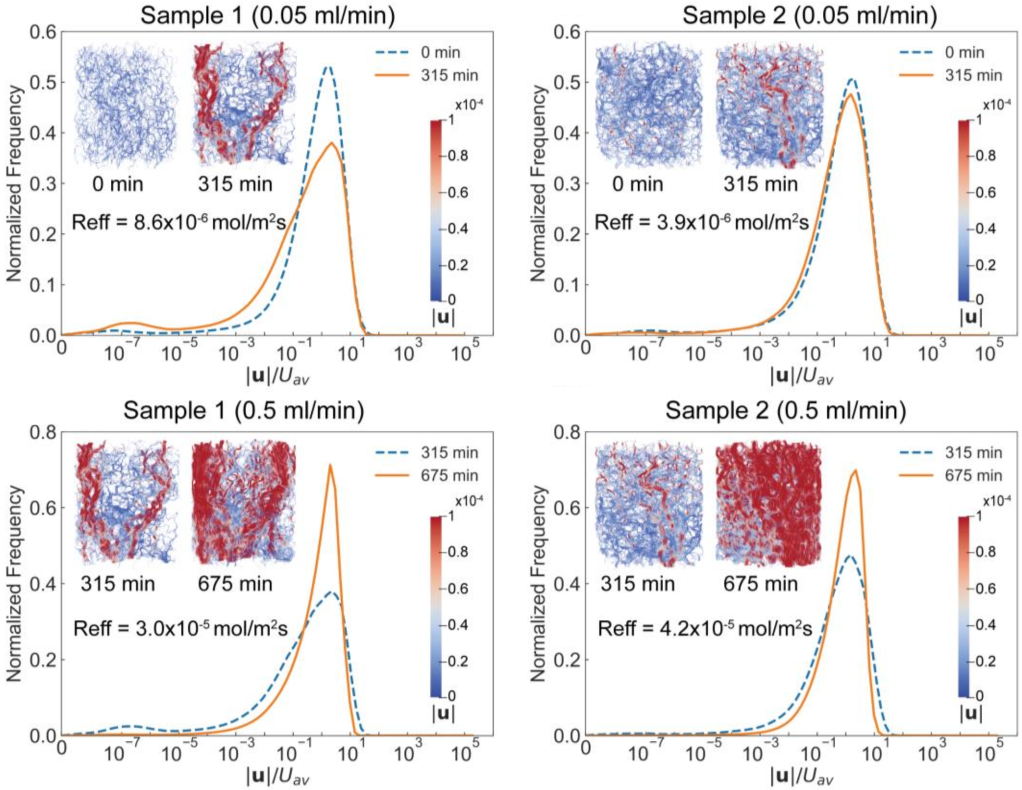
Effective reaction rate at low flow rate



Condition	Reaction Rate (mol/m^2s)	
Ketton limestone multiphase	Sample 1	Sample 2
Low flow rate	8.6×10^{-6}	3.9×10^{-6}
High flow rate	3.0×10^{-5}	4.2×10^{-5}
Silurian dolomite single-phase	Heterogeneity A	Heterogeneity B
Low flow rate	3.15×10^{-6}	1.35×10^{-6}
High flow rate	5.47×10^{-6}	10.6×10^{-6}
Ketton limestone single-phase	5.0×10^{-5}	
Batch reaction rate[35]	6.9×10^{-4}	

- Sample1: a sharp initial reaction rate increase followed by a decline.
- Sample 2: a stable but lower reaction rate
- Reaction rates in multiphase flow are significantly lower compared to single-phase flow and batch experiments.

High flowrate vs. Low flow rate



- Sample 1: a sub-linear, three-fold reaction rate increase.
- Sample 2: a near-linear reaction rate increase, surpassing Sample 1.
- Higher injection rates narrow velocity distribution, reduce stagnant voxels, and produce symmetric streamlines.

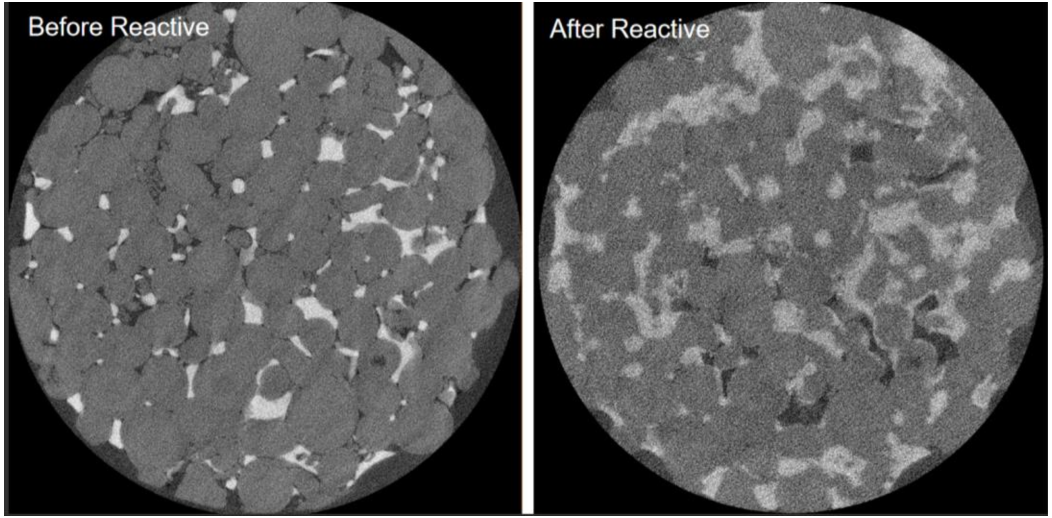
4. Observations and Conclusions

Observations and Conclusions

- Heterogeneity of pore structure, hydrocarbon distribution and re-mobilization control dissolution patterns and effective reaction rates.
- We capture micron-resolution displacement dynamics, leading to channel formation that enhances CO_2 transport properties.
- Two-phase flow reaction rates are transport-limited and lower than single-phase or batch rates
- Injecting CO_2-saturated brine facilitates the recovery of residual oil.

5. Future Work

• Wettability



- The reaction rate was noticeably slower compared to the water-wet samples.
- For the first time, we have captured the wettability alteration in rocks caused by CO_2-acidified brine injection.

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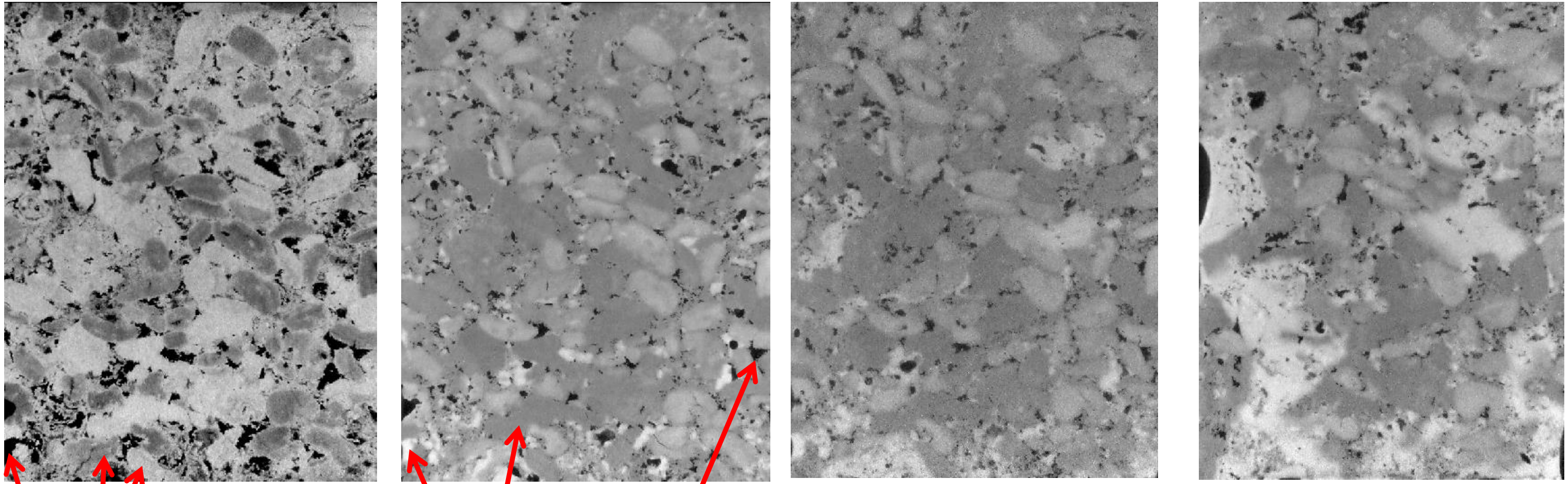
• Physical heterogeneity

Dry scan

Residual oil saturation scan

Acidified brine injection 10 h

Acidified brine injection 20 h



Gary: Rock
Black: Pore

Gary: Rock
Black: Oil
White: Brine

Acknowledgement

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中国石化 SINOPEC

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