HTHP microfluidic platforms for In-situ pore-scale studies of mineral reactions

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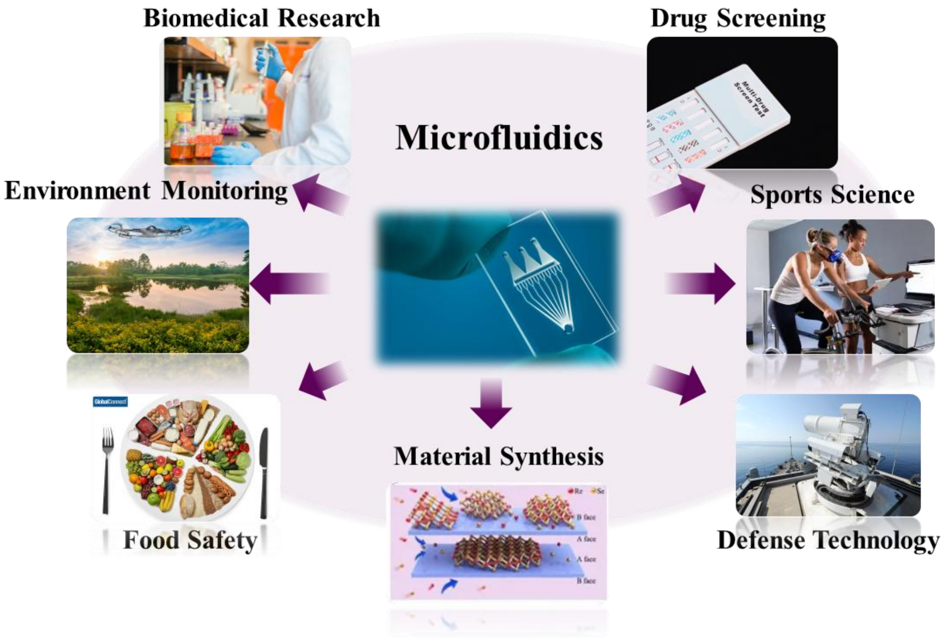
What is microfluidics



Microfluidics = precise control of fluids in micron-scale channels

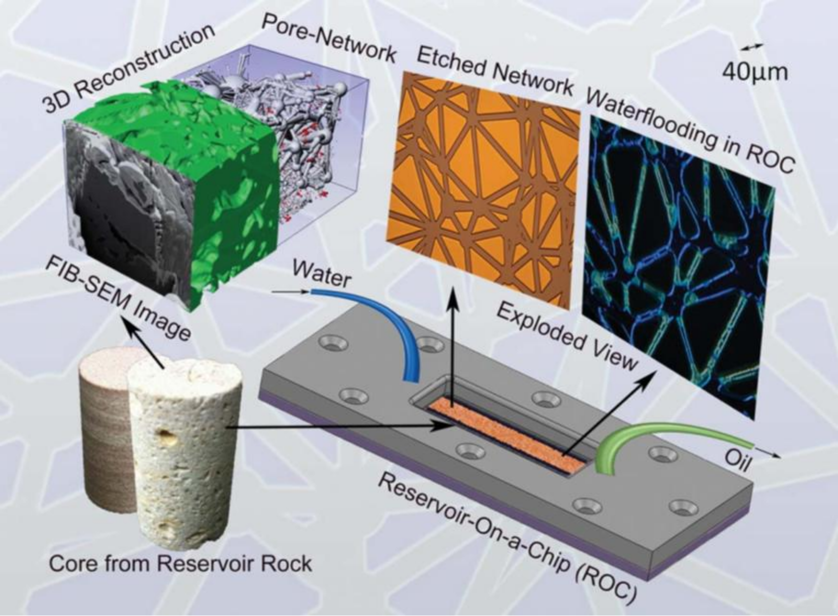
- Typical length scale: nm - μm
- Flow regime: laminar (Re << 1)
- Ultra-low reagent consumption: nL - μL
- Enables direct visualization of process

Microfluidics is widely used across many fields

- Minimal sample and reagent consumption
- Precise fluidic control
- Rapid analysis and high-throughput capability

Microfluidics let us see physics, chemistry and biology at the pore-cale

Micromodel for subsurface systems



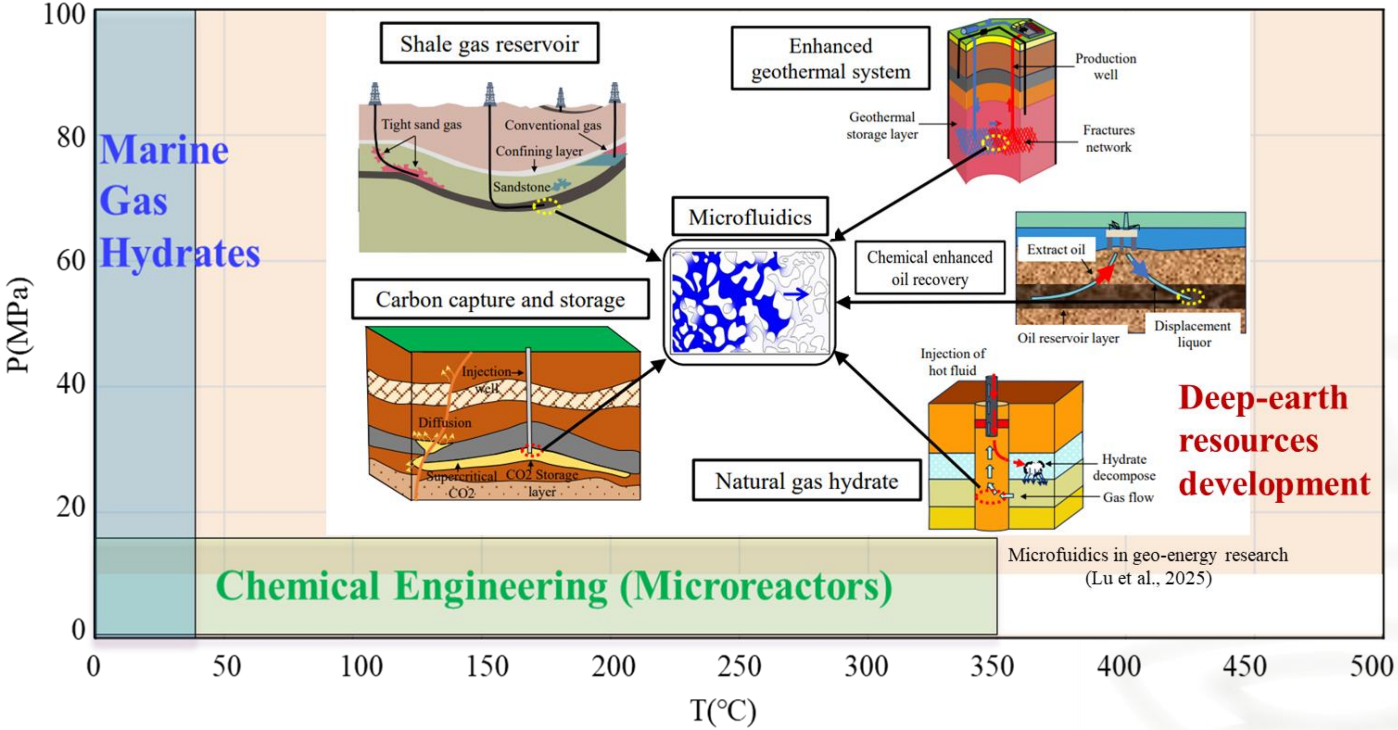
Overview of the Reservoir-On-a-Chip (ROC) Workflow
(Naga Siva Kumar Gunda, et al., 2011)

Micromodel = microfluidic representation of porous media

- Mimics pore-scale structure of real rocks
- Geometry derived from
  - Real rock imaging (FIB-SEM, micro-CT)
  - Or idealized pore networks
- Fabricated in glass/silicon/PDMS…
- Enables direct visualization of flow, reactions, and microbes in porous media

Micromodels translate real reservoir structures into observable microfluidic systems

Microfluidics in geo-energy research



Microfuidics in geo-energy research (Lu et al., 2025)

Conventional microfluidics cannot replicate the in-situ reservoir conditions

Developing HTHP microfluidics is essential & critical for deep-earth resources development

HTHP microfluidic experimental platform

Photographs of the developed equipment platform in Nanjing University.

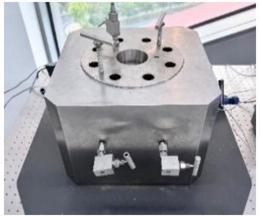
Four parts

1. HTHP cabin
2. Displacement system
3. Data acquisition system
4. Microfluidic chips

Microfluidic platforms can simulate the conditions of subsurface resource exploitation

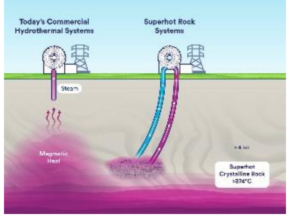
HTHP cabin

- **Micromodel holder 1（150℃ 70MPa）**



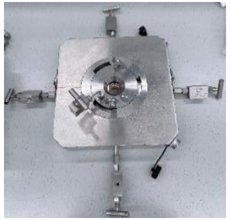
Ultra-deep Oil and Gas Development

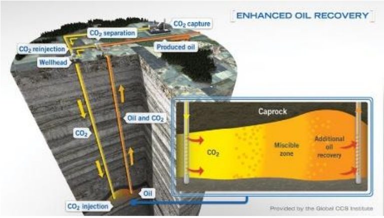
- **Micromodel holder 2（300℃ 30MPa）**



Hot Dry Rock and Supercritical Geothermal

- **Micromodel holder 3（100℃ 10MPa）**





CCUS and EOR

- Adopt the “**sealed cabin**” design
- Hastelloy and sapphire windows
- Fluid-delivered (water) confining pressure
- **Independent, high - precision control** of confining / pore pressure and temperature

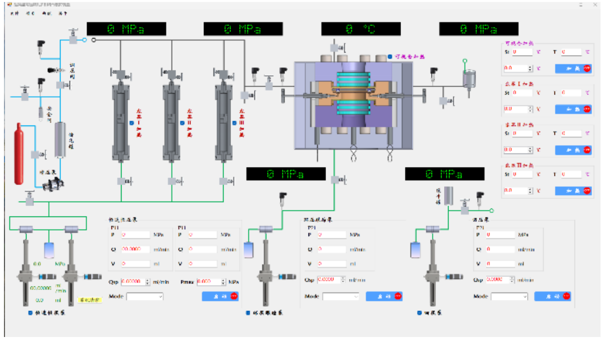
Replicates deep subsurface reservoir conditions up to 70 MPa and 300 °C

NANJING UNIVERSITY

Displacement & Data acquisition system

➢ Displacement system

Containers and back pressure value



Integrated operating interface

- **High-precision, highly stable** flow rates (0.00001ml/min-30ml/min)
- **Multiphase** and **multi-component** injection (3 containers)
- **Integrated system** controlling the flow rates, temperature and pressure.

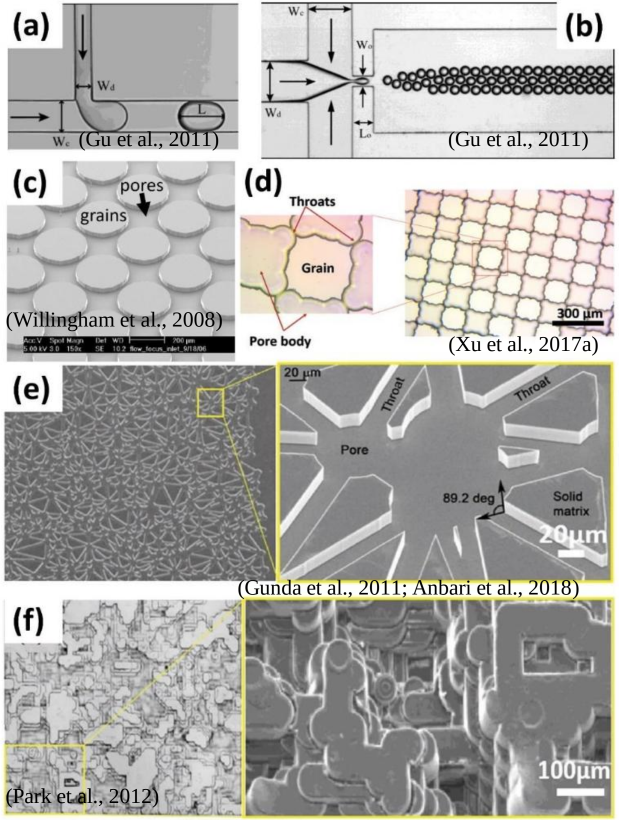
➢ Data acquisition system

Long-focal-length optical microscope

Fluorescence microscope

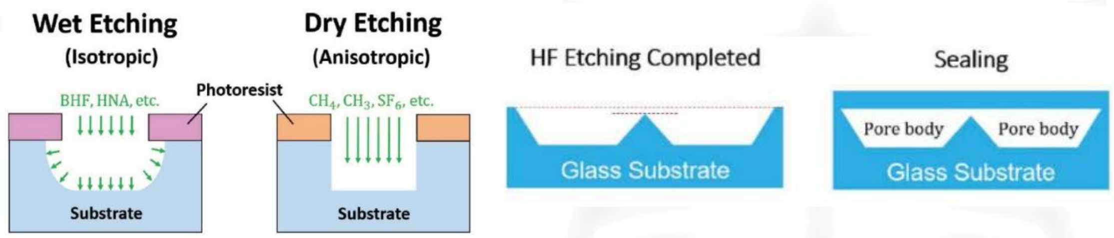
- **Microscope + high-resolution camera** to observe and capture the dynamic displacement process
- Features an anti-vibration platform, enabling **stable high-resolution imaging**

Microfluidic chips



Examples of geometries of microfluidic void spaces

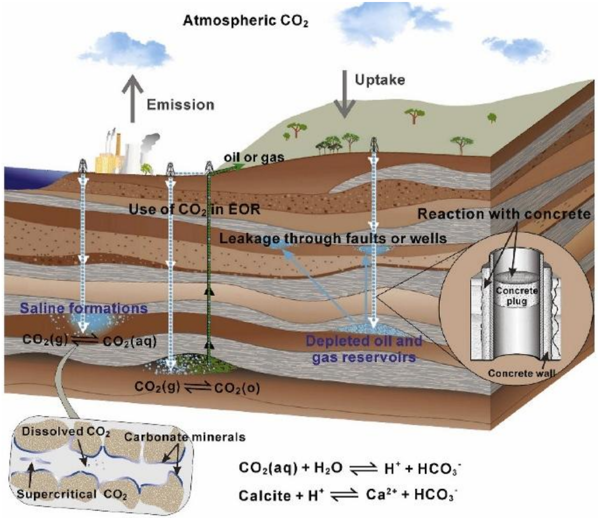
- Two important elements in the design and fabrication process
  - **Geometry** of the small volid space in the chip
  - **Materials** used to fabricate the chip (eg. silicon, glass)



Schematics for dry etch and wet etch (Anbari et al., 2018)

Microfluidic Chips are made for different research goals (multiphase flow, wettability, mineral reactions…) and rock structures.

Geochemical processes in fractured system



Chemical reactions in GCS sites (Dai et al., 2020)

Formation of carbonic acid

↓

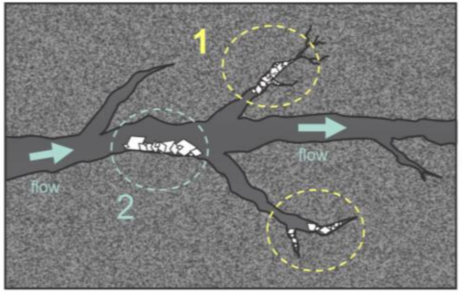
Carbonate rocks dissolution

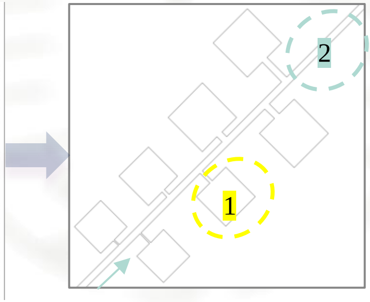
↓

Formation of secondary precipitation

Pore space is decomposed into two regions:

1. Dead-end fractures (immobile zone)
   - Diffusion-dominant reaction zone
   - No impact on primary flow channels
2. Flowing fractures (mobile zone)
   - Depends on ratio of flow to dissolution
   - Precipitation can cause clogging





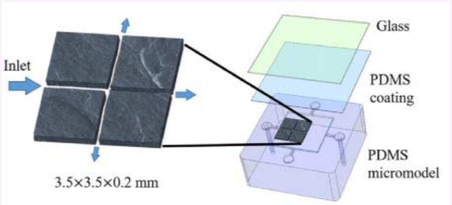
Investigating how fracture characteristics impact reactions using micromodel.

Micromodel design

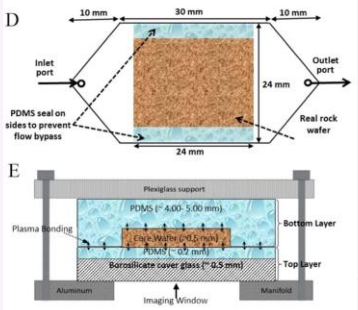
Conventional microfluidic chips

- Lack of real mineral composition and geochemical reactivity
- Smooth surfaces, absence of natural pore surface roughness
- Uniform and unstable wettability

Rock-on-a-chip

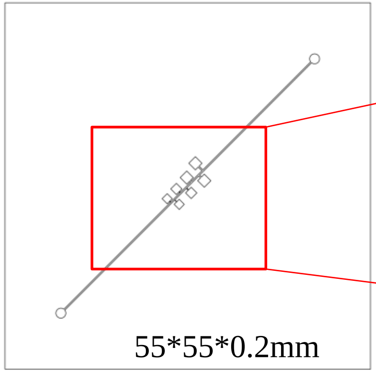


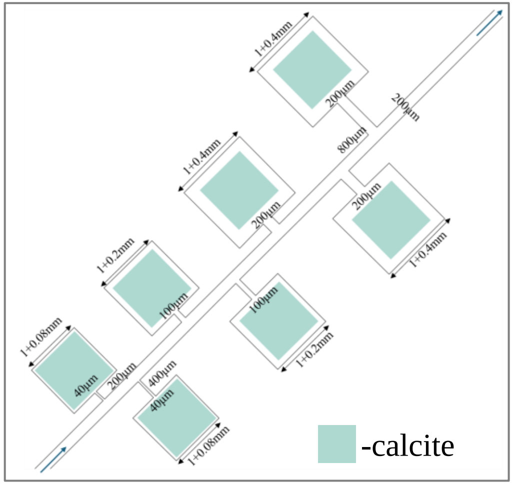
(Bowen Ling et al., 2021)



(Rajveer Singh et al., 2017)

➢ Flow channel design





- Micromodel with **a main channel and lateral cavities**
- Main channel : 200μm
- 7 dead-end channels
- DEP aspect ratio:1, 2, 4, 5, 10
- Calcite grains were placed inside the cavity

Exploring how dead-end geometry affects mineral reactions.

Micromodel Fabrications

➢ **Samples preparation**


Calcite


Thin slices


Grind and polish

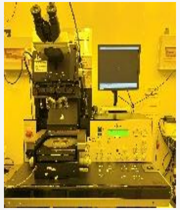

1*1*0.2mm

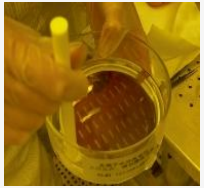
➢ **Fabrication workflow**


Photomask preparation


Preprocessing


Photoresist deposition


Photolithography


Development

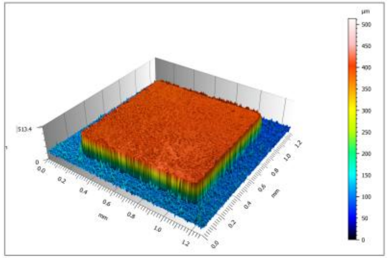

Deep silicon etching

Drilling for inlet/outlet holes
Loading the calcite samples into the cavity.
Anodic bonding to a cover glass plate.
Cutting for favorable chip size.

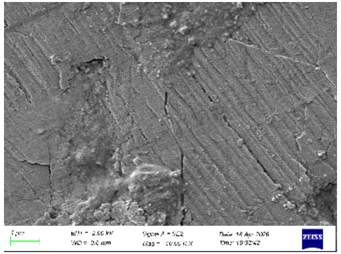
Experiments in dead-end fractures

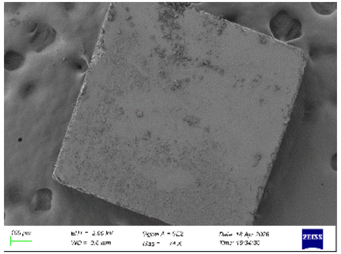
Post-Experimental analyses

Confocal Laser Scanning Microscope



Scanning Electron Microscopy (mineralogy)





Experimental conditions

T(℃)	P_{conf}	P_{back}	Flow Rates(μL/min)
50	9	8	0.1 or 1 or 10

- Simulating authentic reservoir conditions
- Different flow rates corresponding to varying Péclet numbers
- Constant-flow injection

➢ *Future work*

1. Conduct microfluidic experiments to visualize **calcite dissolution (**and subsequent **reprecipitation** inside dead-end pores at 50 ℃ and 8 MPa.
2. Study the correlation between **micro-scale dissolution regimes and Péclet numbers** in dead-end pores under confinement.
3. **Quantitatively** interpret the experimental phenomena using the lattice Boltzmann method (LBM).

Thank you for listening！

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