Reservoir-on-a-Chip Investigation of Post-Carbon Capture Solutions for Enhanced Oil Recovery

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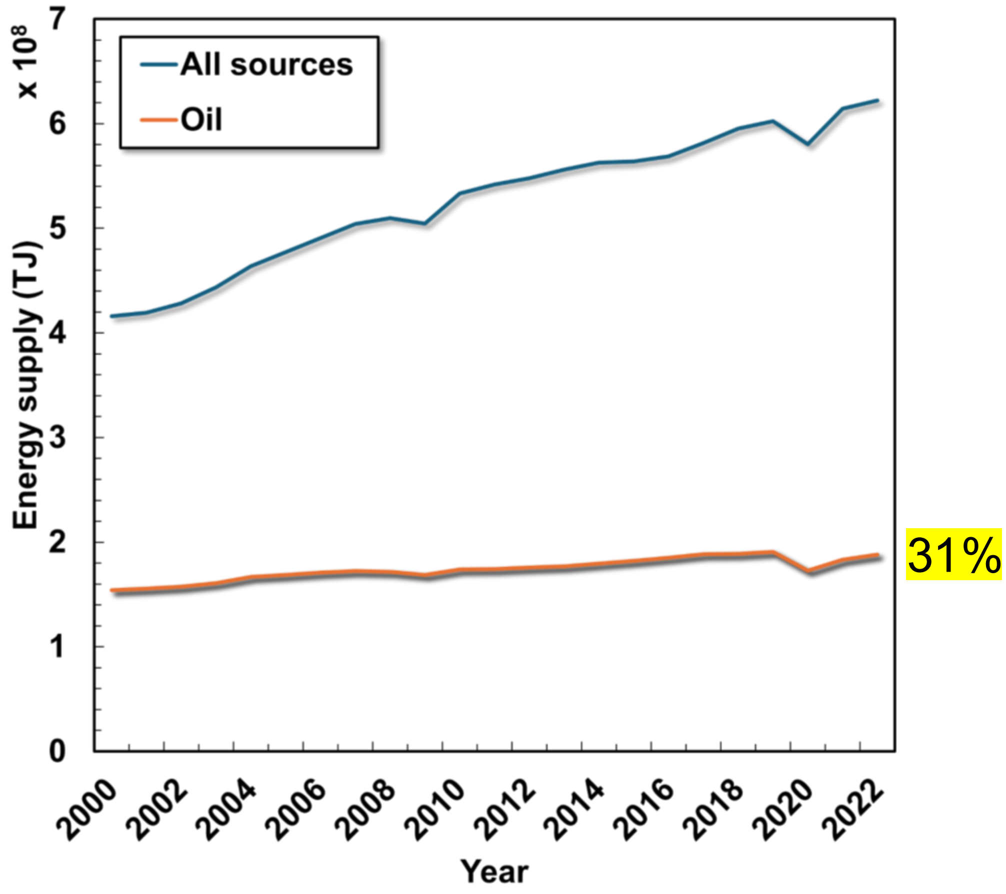
Contents

Importance of Oil

- **Global energy consumption** has increased by ≈ 40% over the last two decades, rising from 400 EJ to 558 EJ.



Oil is a finite resource.

- Many traditional oil fields, where conventional oil extraction is possible, are near depletion.

Cost ↑

- Renewable sources like **solar energy, wind energy**
- **Nuclear fission**
- **Nuclear fusion**

Costly, Variable, Location-dependent,….

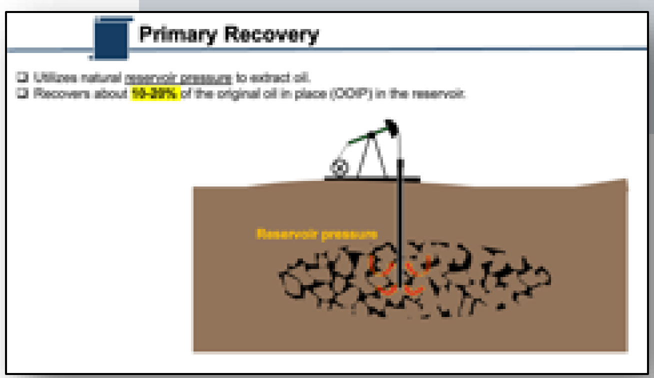
Enha

Enhanced Oil Recovery

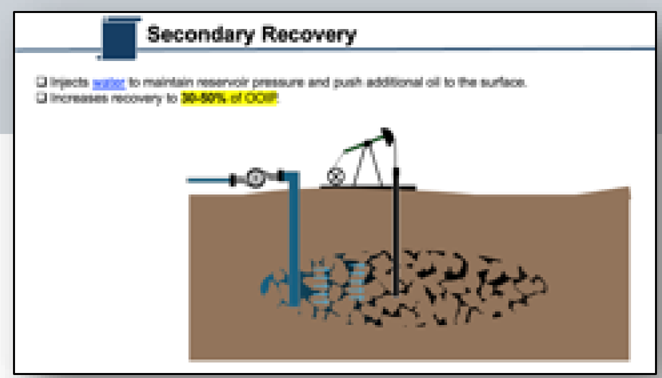
- **<u>Enhanced Oil Recovery (EOR)</u>**: Techniques to increase the amount of oil extracted from an oil reservoir beyond what is possible with conventional methods.

Multi-Stage Oil Production

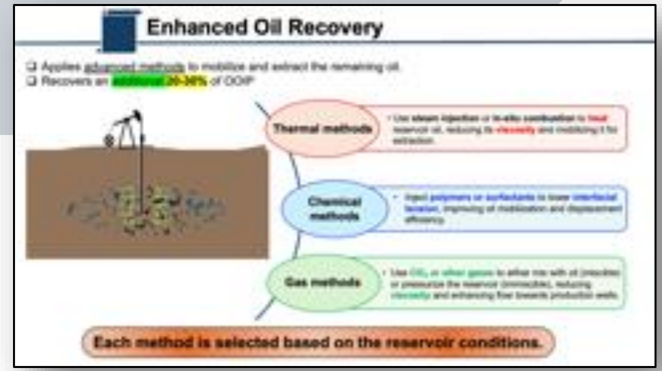
Primary Recovery



Secondary Recovery

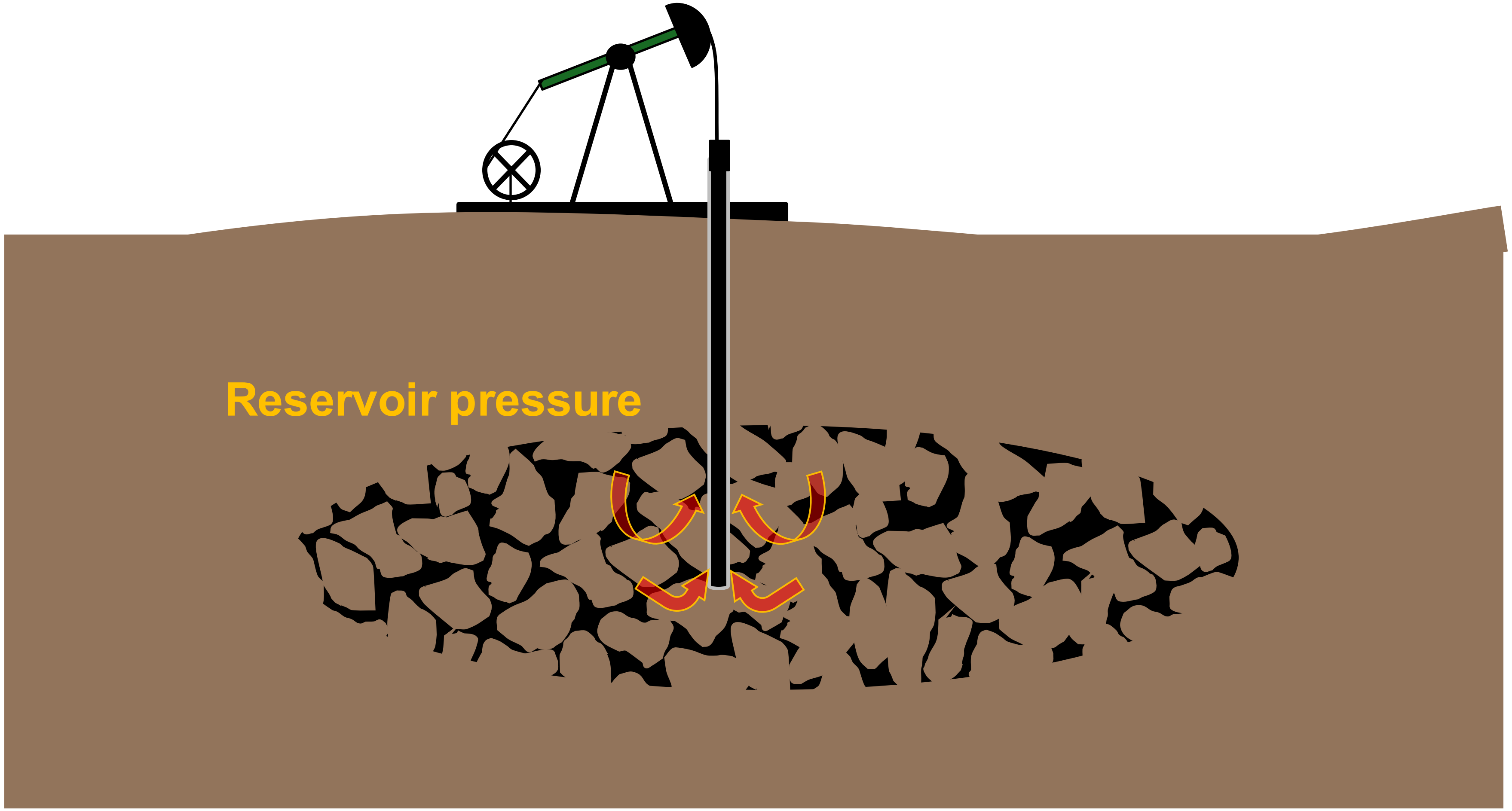


Tertiary Recovery (EOR)



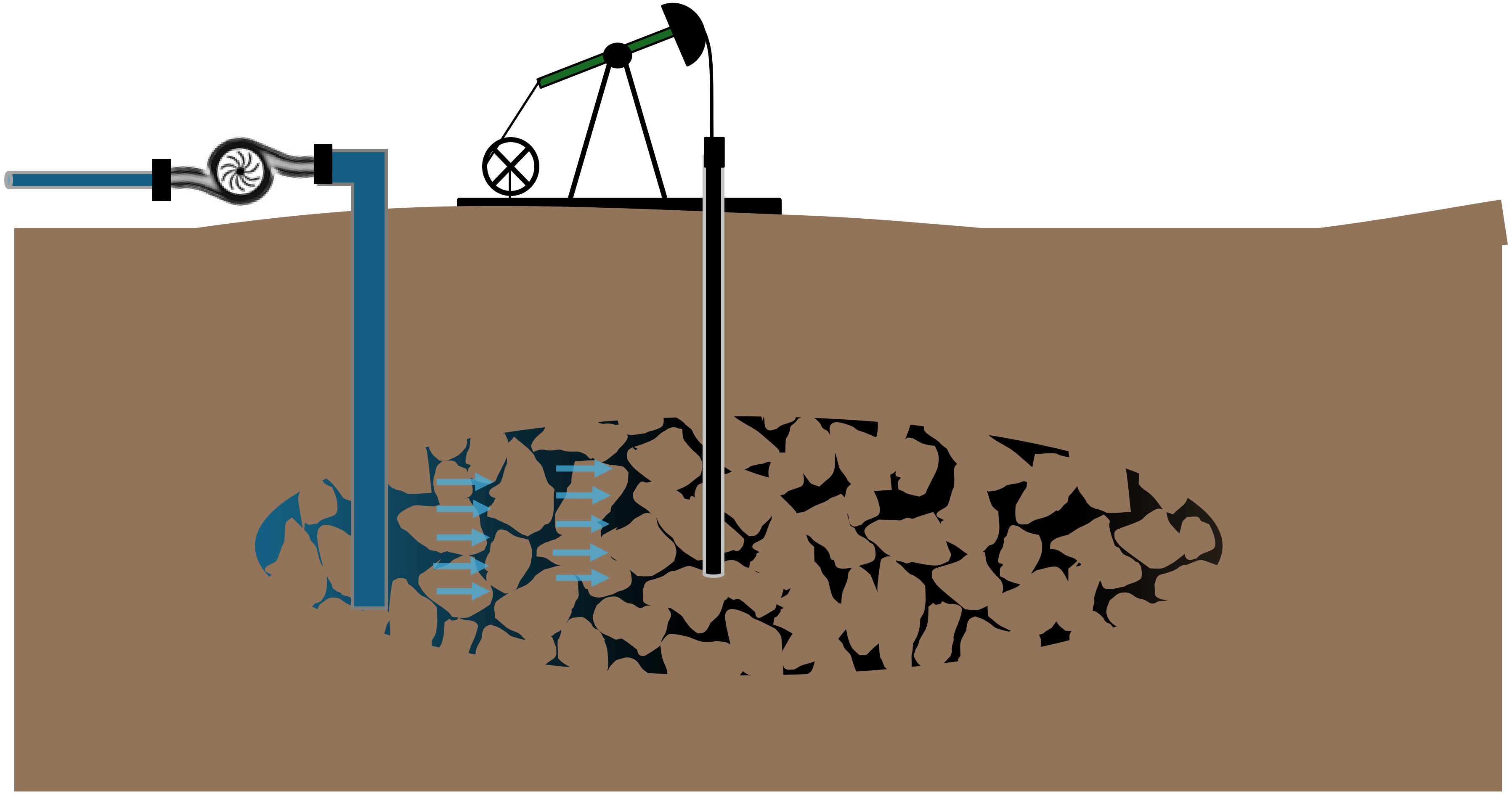
Primary Recovery

- Utilizes natural reservoir pressure to extract oil.
- Recovers about **10-20%** of the original oil in place (OOIP) in the reservoir.



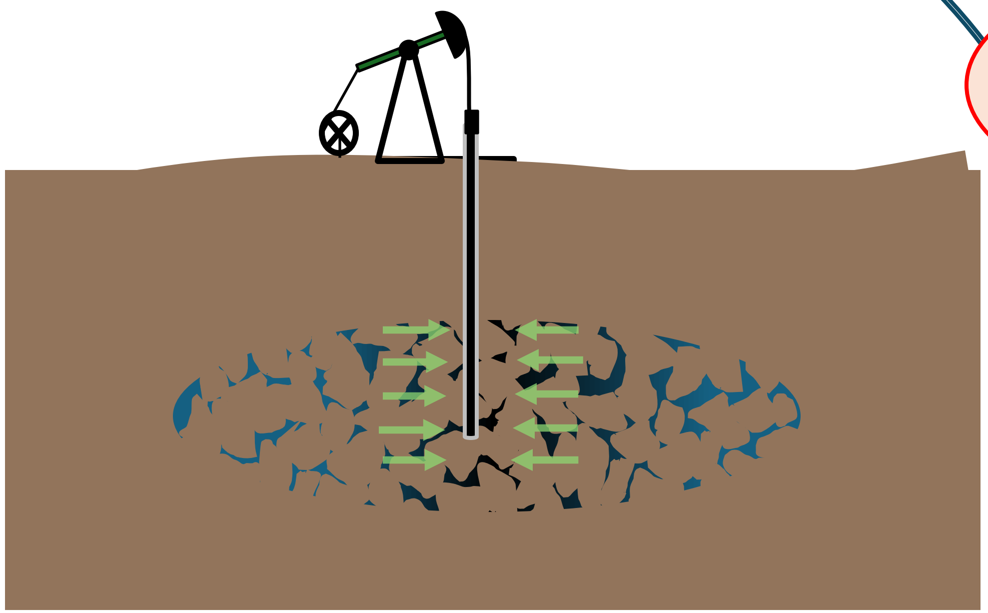
Secondary Recovery

- ❑ Injects water to maintain reservoir pressure and push additional oil to the surface.
- ❑ Increases recovery to **30-50%** of OOIP.



Enhanced Oil Recovery

- ❑ Applies advanced methods to mobilize and extract the remaining oil.
- ❑ Recovers an additional **20-30%** of OOIP



Thermal methods

- Use **steam injection** or **in-situ combustion** to **heat** reservoir oil, reducing its **viscosity** and mobilizing it for extraction.

Chemical methods

- Inject **polymers or surfactants** to lower **interfacial tension**, improving oil mobilization and displacement efficiency.

Gas methods

- Use **CO_2 or other gases** to either mix with oil (miscible) or pressurize the reservoir (immiscible), reducing **viscosity** and enhancing flow towards production wells.

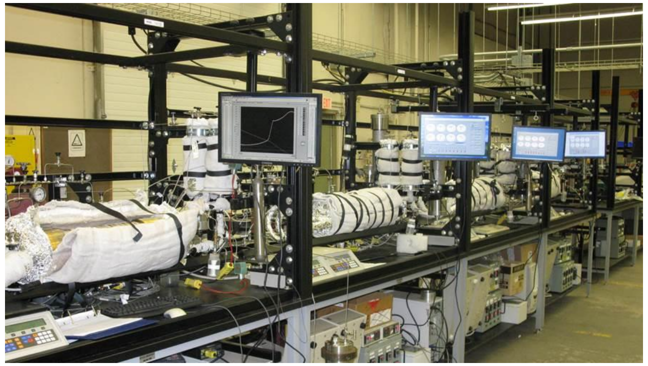
Each method is selected based on the reservoir conditions.

Contents

Core-Based Experimental Research in EOR

Reservoir Cores

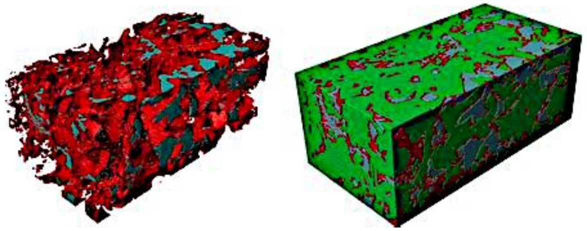
[Sola, 2007, Boswell, 2008]

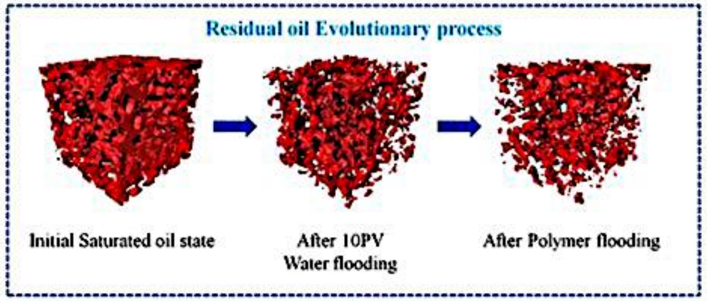


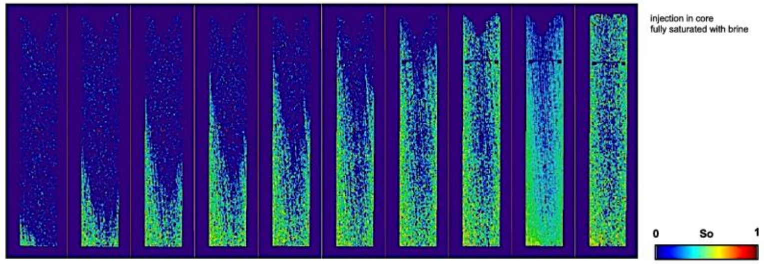
A core flooding laboratory setup for EOR / fluid transport experiments in cores under reservoir-like conditions.

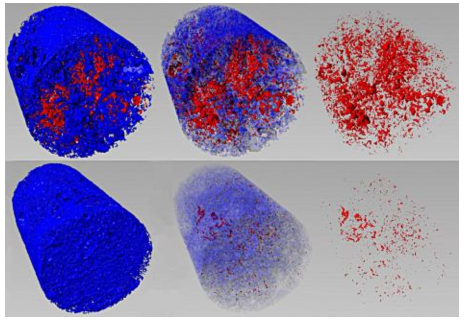
Photo of real core flooding rig setup inside a CT scanner

[Perm, Inc.]









[Yang, 2020]

Core-Based EOR – Challenges

- Although core flooding experiments capture multiphase interactions in real reservoir materials, are they suitable, practical, and adaptable for a standard research laboratory environment?

[Sola, 2007]

⏱ Time & 💰 Cost

- Experiments take long (days–weeks) and require expensive cores, equipment, and imaging facilities.

⚠ Heterogeneity

- Core samples are scarce, and natural variability makes results hard to reproduce.

🔍 Indirect Insights

- Pore-scale mechanisms (snap-off, fingering) are not directly visible without advanced CT/MRI.

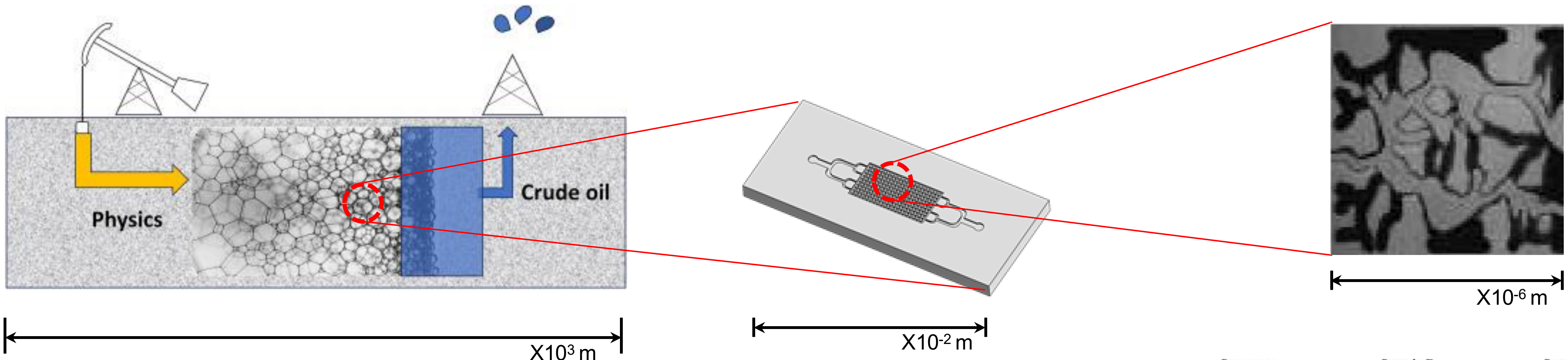
🏗 Complex Logistics

- Large rigs demand space, safety protocols, and significant operational effort for each new trial.

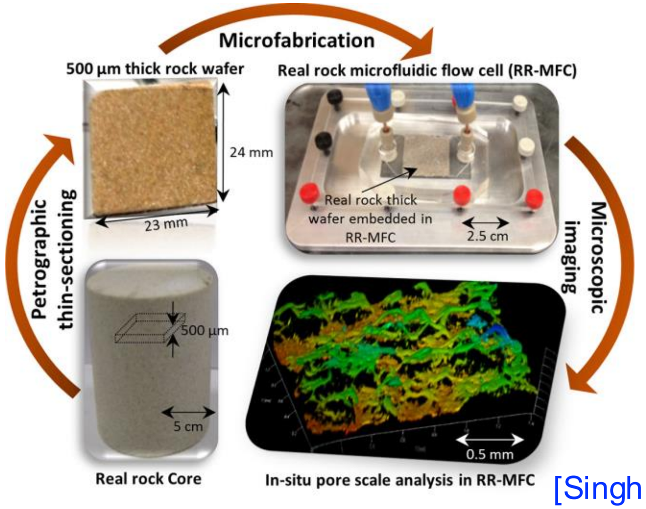
Contents

Reservoir-on-a-Chip Approach

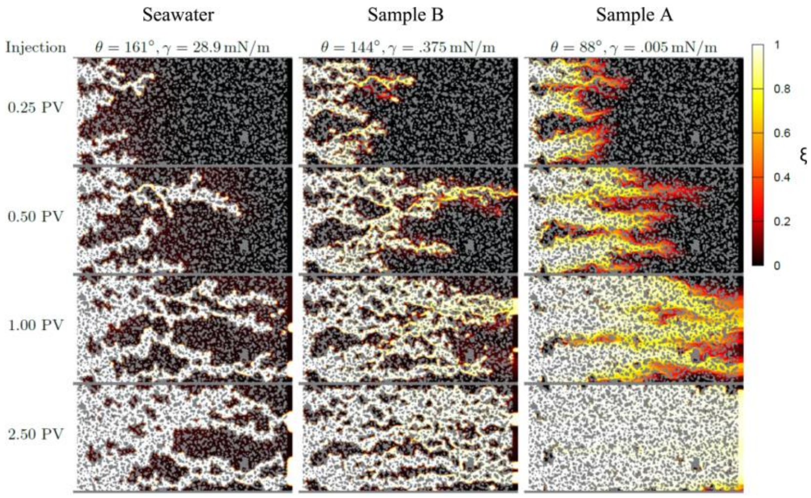
- Core flooding has been the gold standard for realistic EOR evaluation, but it is slow, expensive, and limited for rapid trials.
- Microfluidics bridges this gap by providing a reservoir-on-a-chip approach with various advantages.



- **Advantages**
  - Real-time, pore-scale visualization
  - Faster and cheaper than core tests
  - Requires tiny fluid volumes
  - Reproducible, controlled geometries
  - Tunable surface chemistry



[Singh, 2017]



[Yun, 2020]

Contents

Carbonate Reservoirs

❑ Why carbonates matter

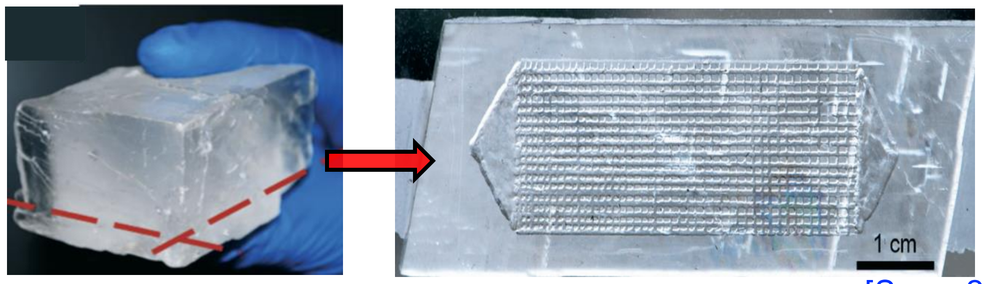
- A large share of global conventional oil: 50-60% [Garland, 2012]
- Tricky surface chemistry: The calcite surface is positively charged, attracting carboxylate in oil ➔ Oil wet ➔ Poor recovery efficiency
- Heterogeneity & fractures: Carbonates are complex pore and fracture network systems ➔ Difficult to simulate
- Challenging to recover oil from carbonate, but it has a high impact if we can improve it

Carbonate Reservoirs

[Garland, 2012]

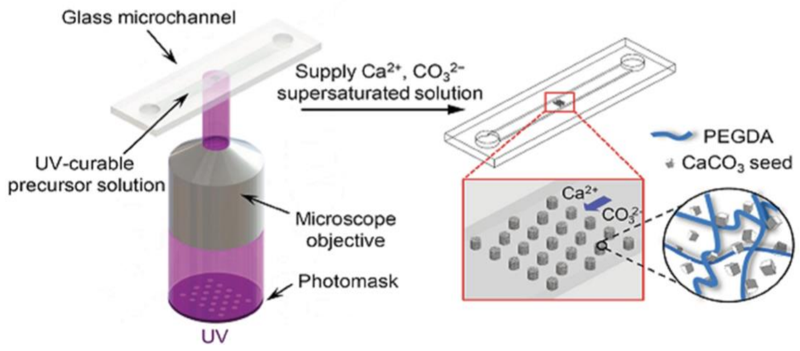
Simulated Carbonate Surfaces

- **Acid Etching of Actual Calcite Rock:** Enabled flow visualization and assessment of geochemical effects on EOR by using 2D porous networks.



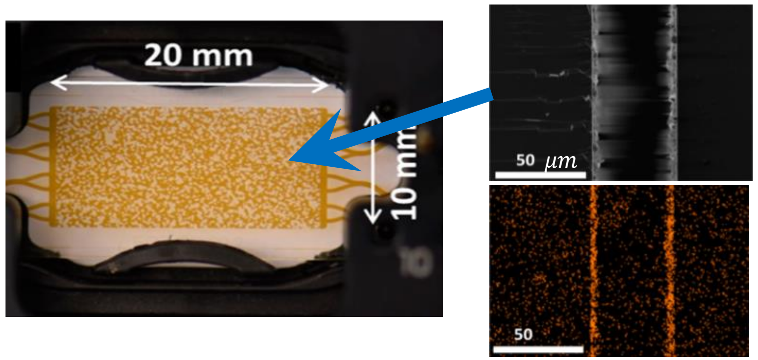
[Song, 2014]

- **In Situ Growth of $CaCO_3$ Crystals:** Mimicked synthetic carbonate rock reservoir surfaces by growing $CaCO_3$ crystals in micromodels using ion-rich solutions.



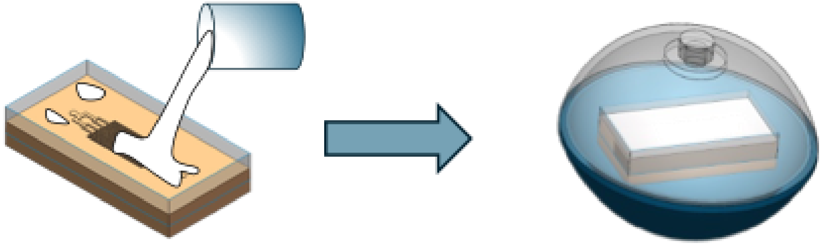
[Lee, 2016]

- **Coated $CaCO_3$ Nanocrystal Layers:** Coated borosilicate surfaces with a controlled 1–2 μm $CaCO_3$ nanocrystal layer to tailor wetting orders and realistic reservoir structures.



[Wang, 2017]

Our Approach - Carbonated Surface



PDMS–$CaCO_3$ composite casting in master mold

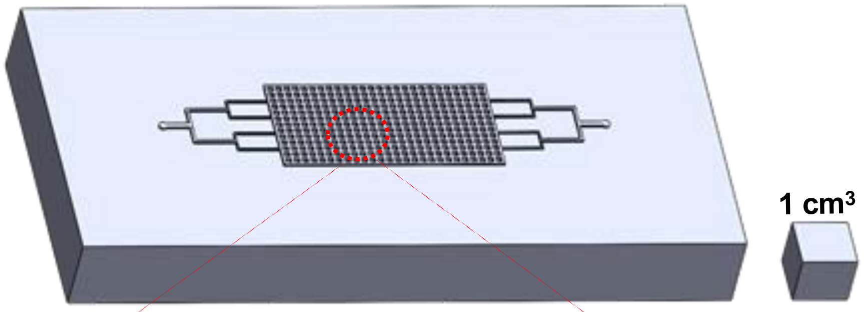
(a)

Degassing to remove entrapped air from the mold cavities and cast material

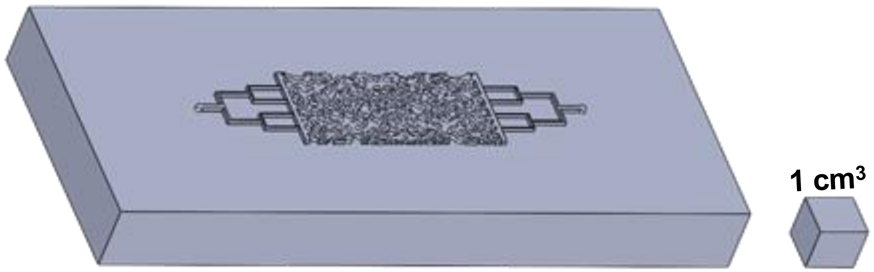
(b)

Our Approach - Carbonated Surface

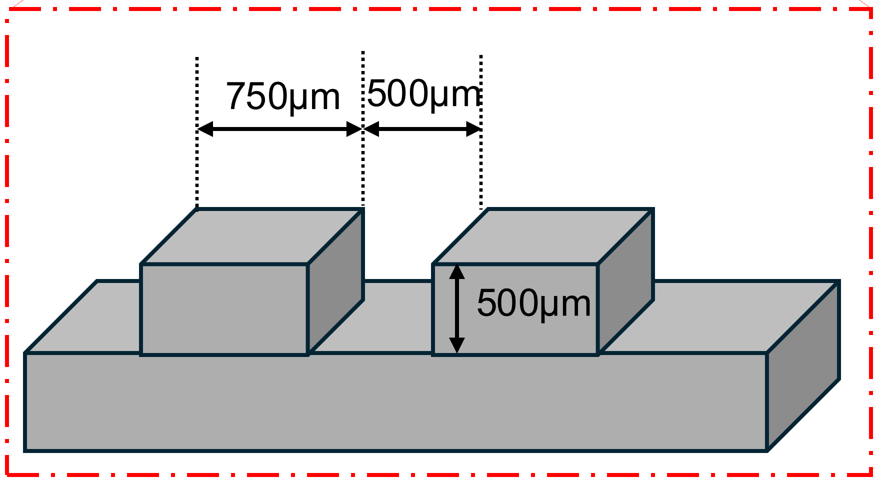
- **Novel Microfluidic Channel**: Developed using a mixture of PDMS and $CaCO_3$ powder solution molded by a 3-D printed mold.

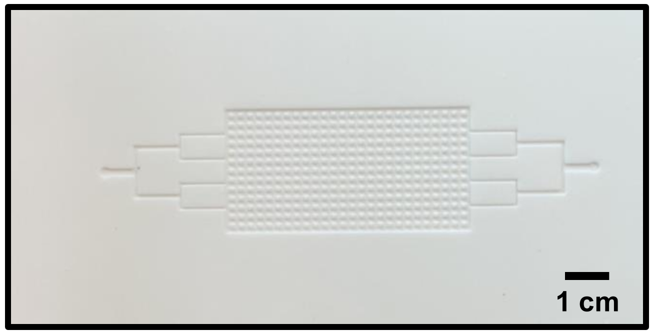


Homogeneous Pattern

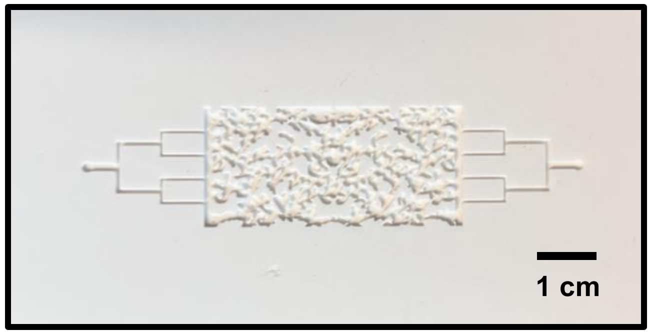


Random Network Pattern





Pore Volume : 340 μL
Porosity (ϕ): 0.85



Pore Volume : 160 μL
Porosity (ϕ): 0.4

Surface Wettability

❑ Wettability

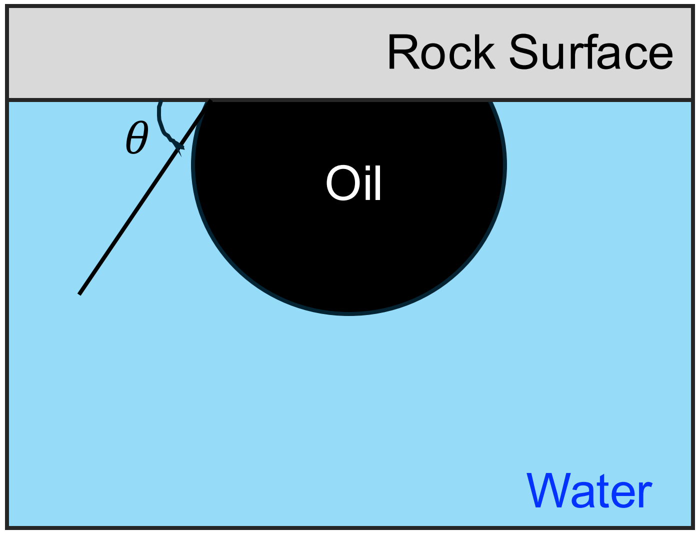
- Indicate whether a rock surface prefers water or oil.
- Quantify wettability by the contact angle θ at the line where solid, water, and oil meet.

❑ Simple reading rule

- Smaller θ (through water) → more water-wet → water spreads and can push oil out.
- Larger θ → more oil-wet → water beads up; oil tends to stick.

❑ Why it matters

- In carbonates, crude oil acids bond to Ca^{2+} sites → often oil-wet ➔ Low recovery efficiency
- Shifting to water-wet? ➔ spontaneous imbibition and recovery ➔ High recovery efficiency



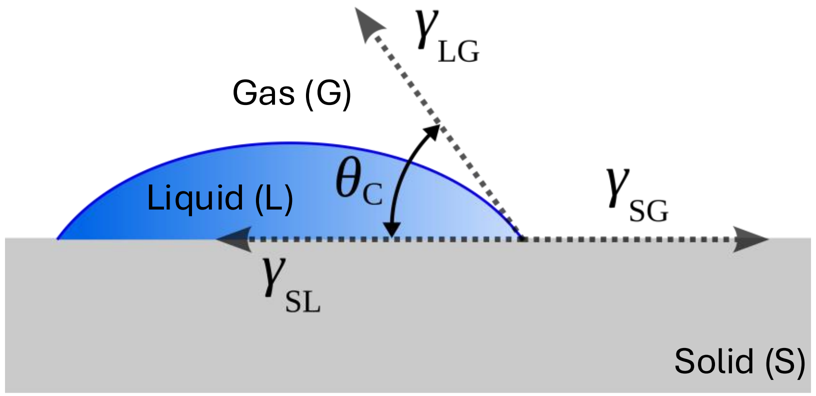
Type	Contact angle (deg)
Strongly water-wet	0 - 30
Water-wet	30 - 70
Intermediate-wet	70 - 110
Oil-wet	110 - 150
Strongly oil-wet	150 - 180

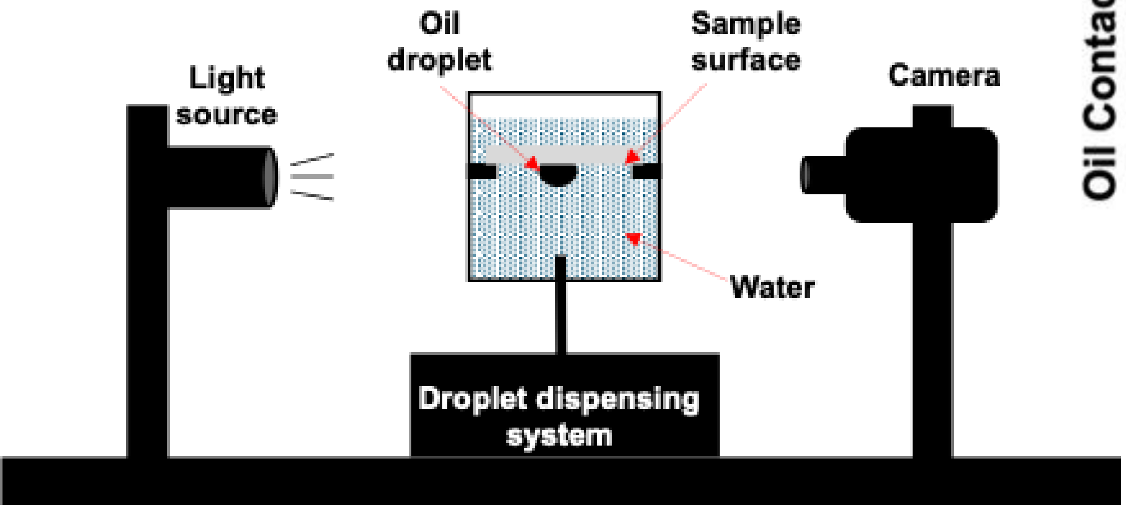
[Deng, 2023]

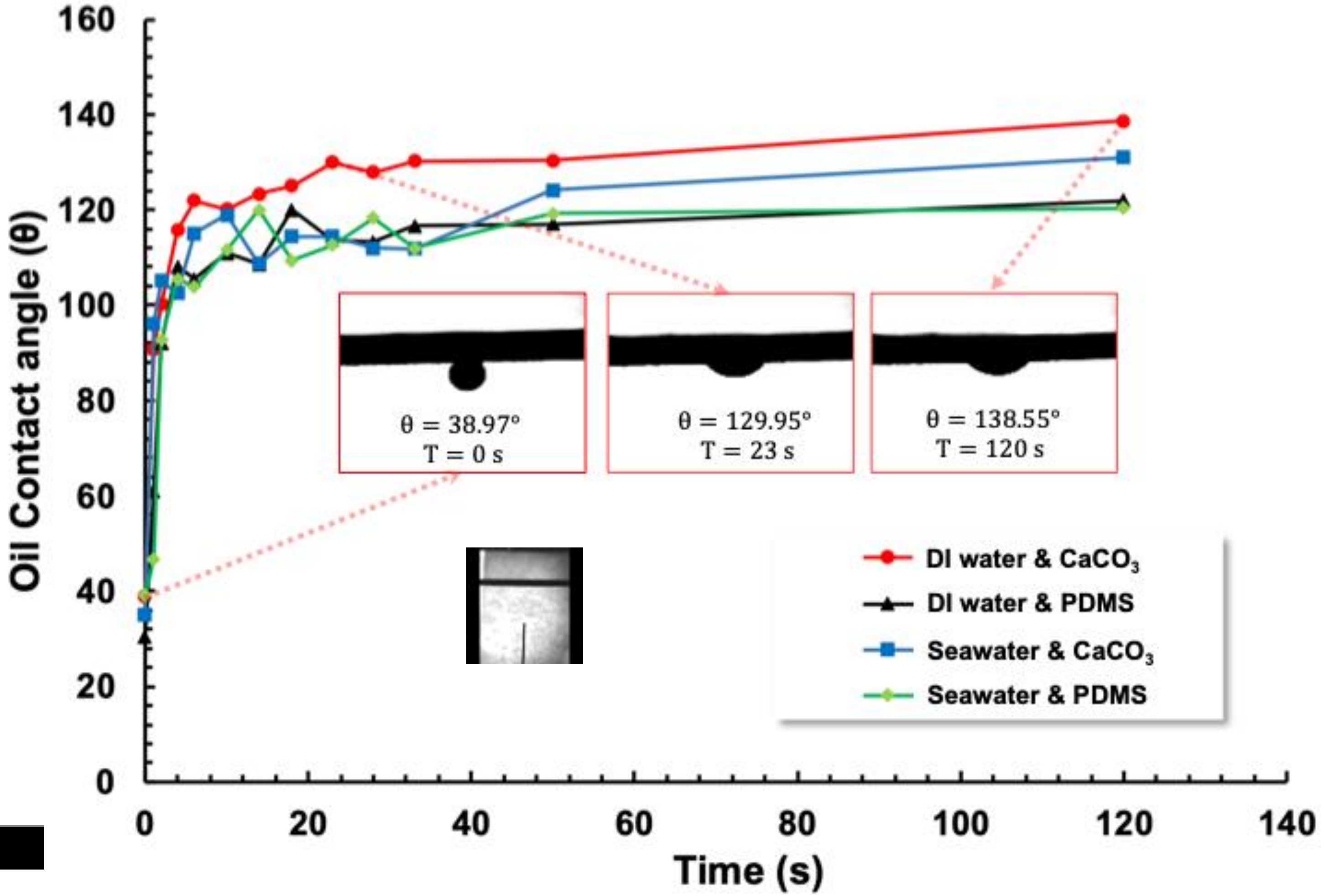
Sessile Drop Test

❑ Principle & outputs

- Profile a droplet resting on a solid under another fluid
- Outputs: static θ, advancing/receding (hysteresis)





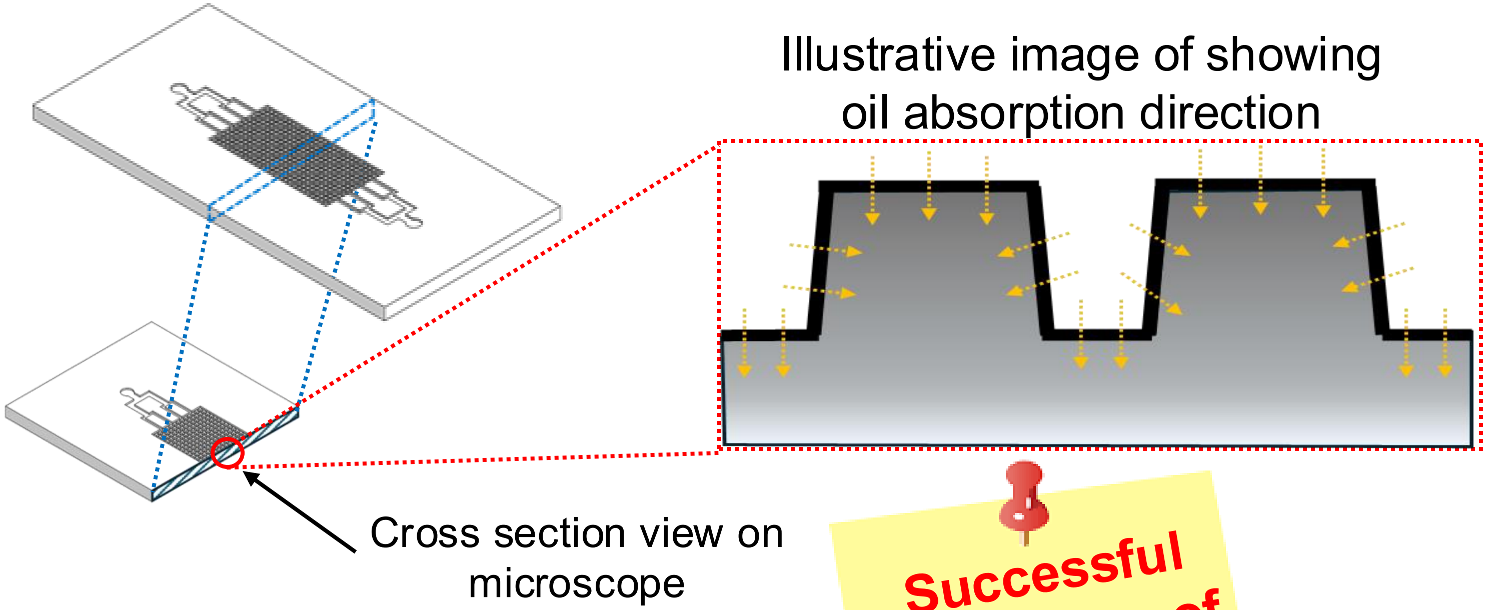


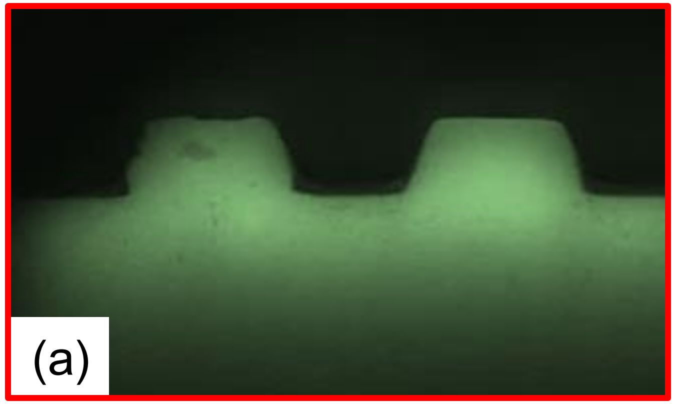
Fluorescence Imaging of Oil Adsorption

- ❑ Sessile droplet measurements: Show oil-wet behavior

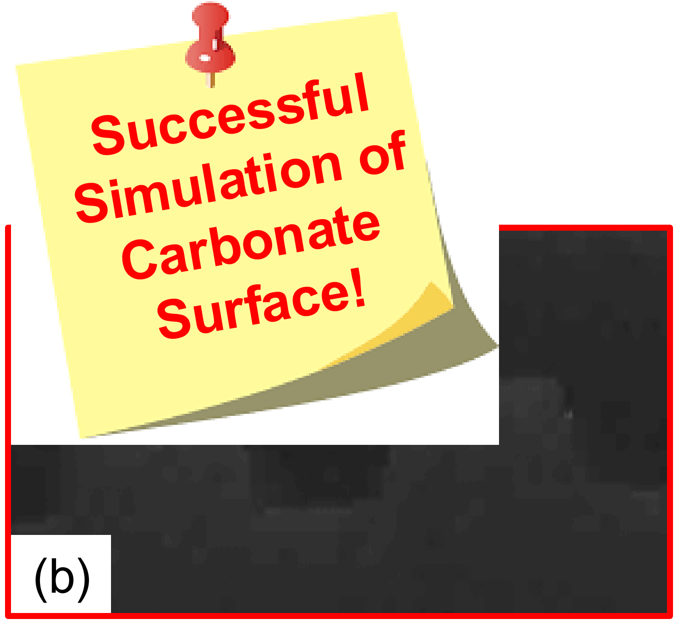
- ❑ An oil absorption test via fluorescence imaging ➔ Further validates the oil-wet characteristics of the PDMS-$CaCO_3$ composite surface

- ❑ Test Steps
  - The microchannel was filled with crude oil and aged under ambient conditions for 12 hours (Oil soaking)
  - All injected oil was carefully drained from the channel using suction
  - The channel was then cross-sectioned and imaged under fluorescence microscopy using a UV light source to excite the crude oil.





(a) PDMS–$CaCO_3$



(b) PDMS

Contents

Wettability Alteration – Carbonate Reservoirs

- **Engineered (“Smart”) Seawater (↑SO_4^{2-} + tuned Ca^{2+}/Mg^{2+})**
  - SO_4^{2-} adsorbs on calcite → weakens positive sites; Ca^{2+}/Mg^{2+} compete with oil carboxylates → more water-wet.

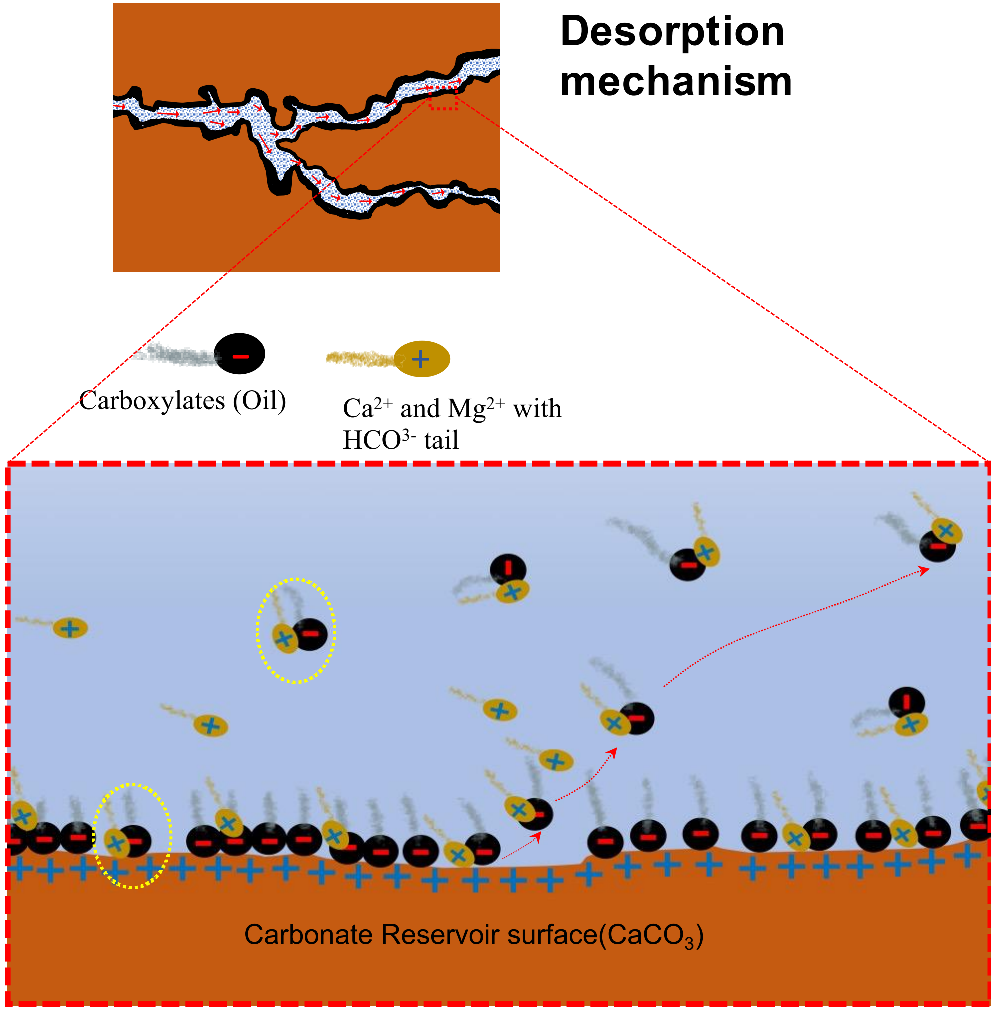
- **Surfactant Wettability Modifiers (anionic/zwitterionic/extended)**
  - Replaces organic films and reduces IFT; tunable chemistry; can be used with foam.

- **Nanofluids (functionalized silica/metal-oxide)**
  - Create a hydrophilic coating; structural disjoining pressure can unpin oil.

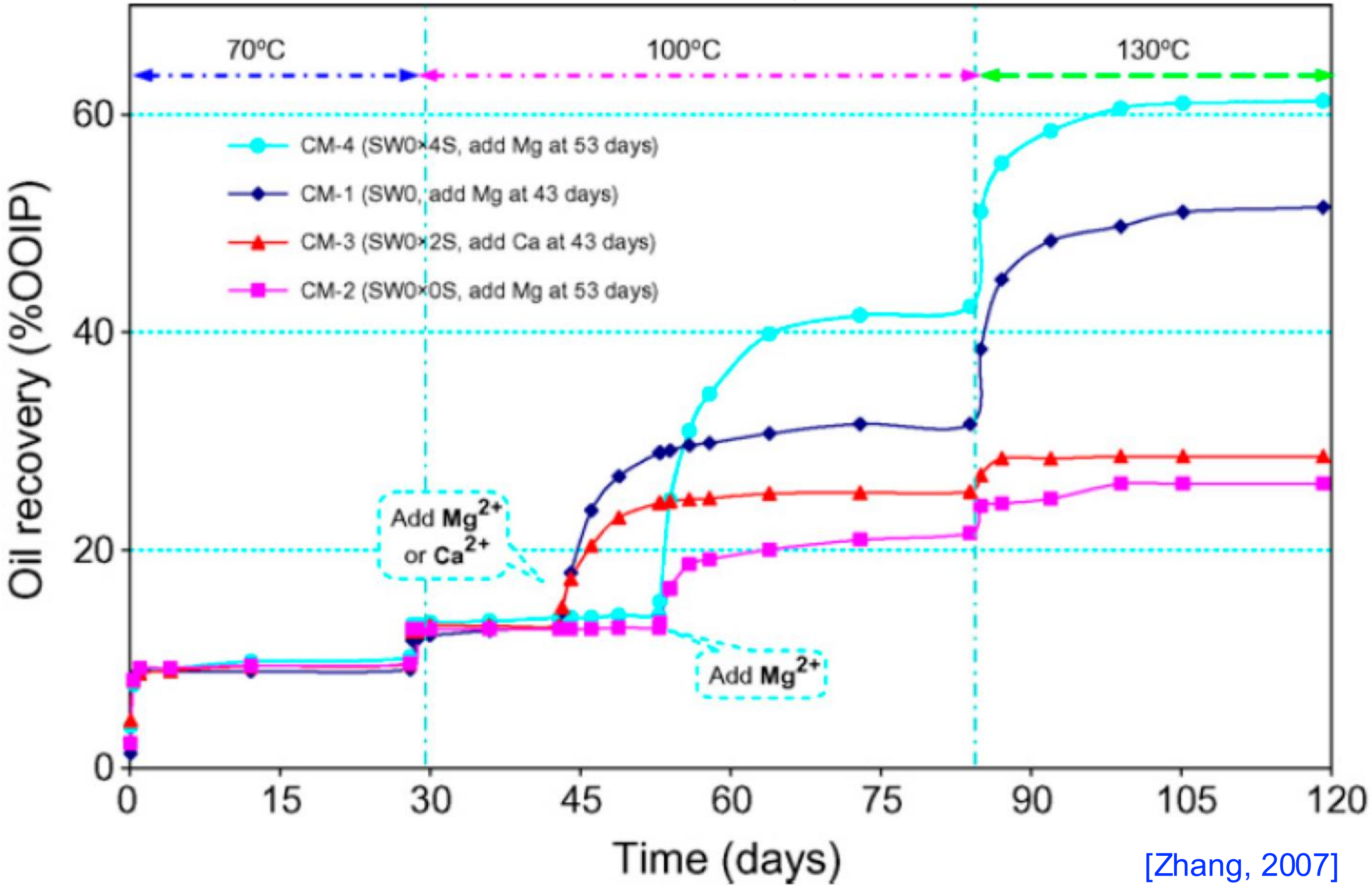
- **Foam / CO_2-Foam + Chemical Flood (hybrid)**
  - Foam slows gas in fractures, pushes treatment water into the rock, and gives it time to unstick oil.

Seawater-Assisted Wettability Alteration

- Alkaline minerals can alter the wettability of an oil reservoir by ion exchange mechanisms.



Increase in oil recovery after the addition of alkaline minerals in the flooding fluid.

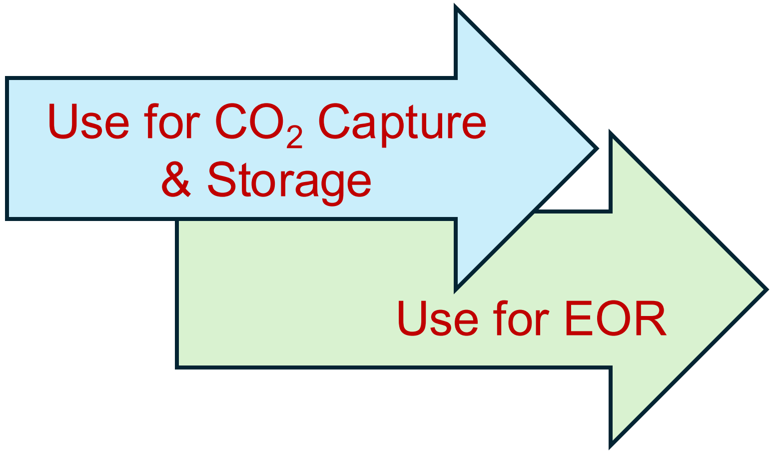


[Zhang, 2007]

Our Approach – Alkalized Seawater

- Use carbonated (via CO_2 injection) seawater + waste concrete as a flooding fluid ➔ **<u>CO_2 Capture & Storage + EOR</u>**

Seawater with waste concrete



- **High pH weakens (and breaks) the Ca–carboxylate bond.**
  - Higher pH makes the following reaction favorable
    $Ca\text{-}OOC\text{-}R + OH^- \rightarrow CaOH + RCOO^-$
    (Anchor breaks; $RCOO^-$ moves to water
  - Weakening the electrostatic attraction of Ca-carboxylate

- **Ca^{2+}/Mg^{2+} in the brine released carboxylate into the water.**
  - Ca^{2+} in water drives desorption of carboxylate from the surface
  - At > 100 °C, Mg^{2+} strengthens the pull

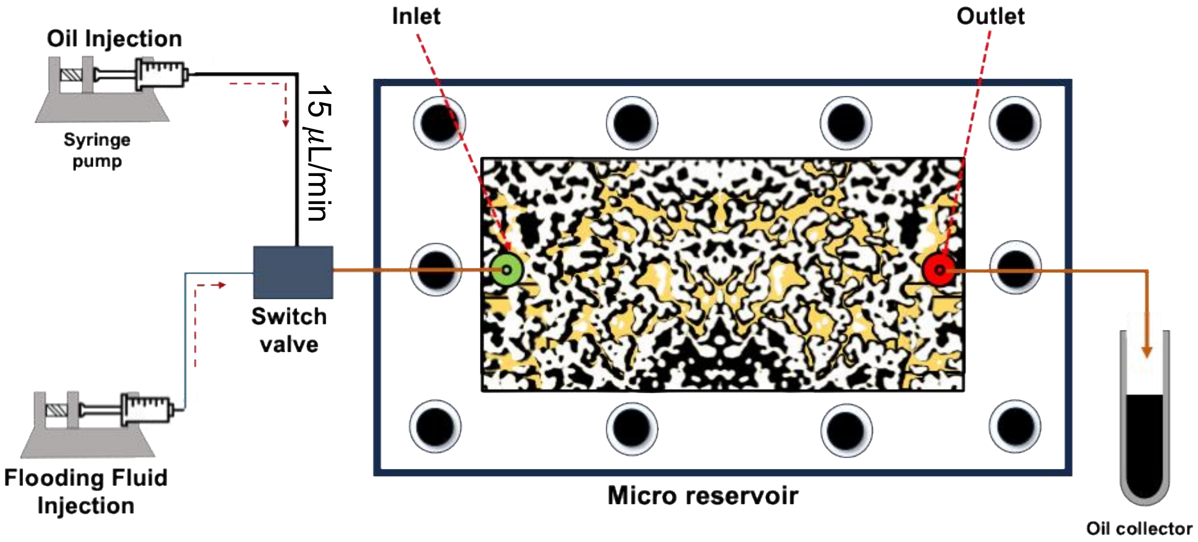
➔ <u>Net effect: The surface becomes more water-friendly.</u>

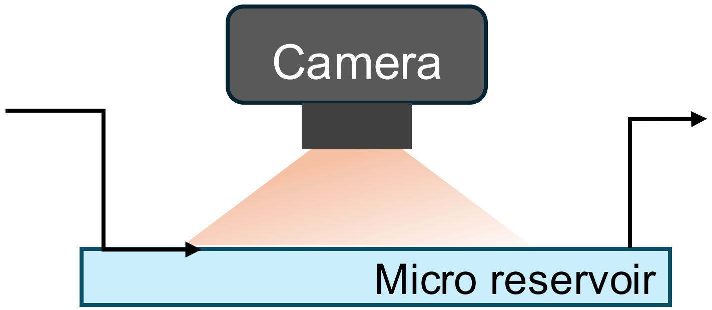
Contents

- Introduction- Enhanced Oil Recovery (EOR)
  - Core-based Investigation for EOR
  - Microfluidics (or Reservoir-on-a-Chip) for EOR
- Carbonate Reservoirs
  - Fabrication of Carbonate Surfaces (Conventional vs Our Approach (PDMS-$CaCO_3$)
  - Wettability Alteration
- Flooding Demonstration in PDMS-$CaCO_3$
  - Homogenous Network
  - Random Network
- Summary

Flooding Experiment Methods

❑ Controlled flooding in a microfluidic chip mimicking reservoir pore structure.





❑ Injection flow rate: 15 μL/min (avg. velocity = 0.037 cm/s)

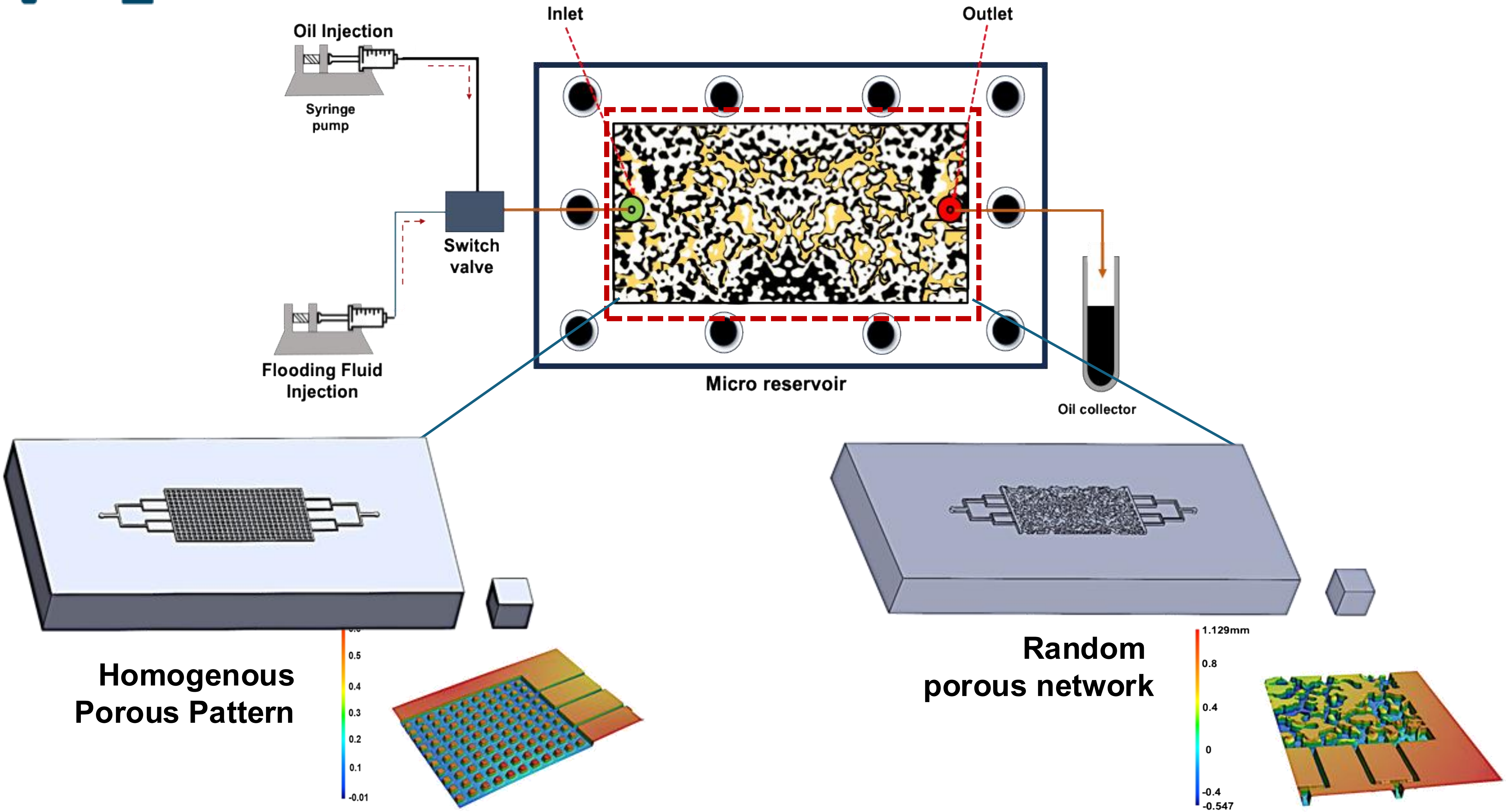
❑ Each test: 2.5 hours, 8 pore volumes

❑ Texas crude oil; viscosity 60 mPa·s, density 0.85 g/cm^3

❑ Water & seawater; viscosity 1 mPa·s, interfacial tension: 30 mN/m

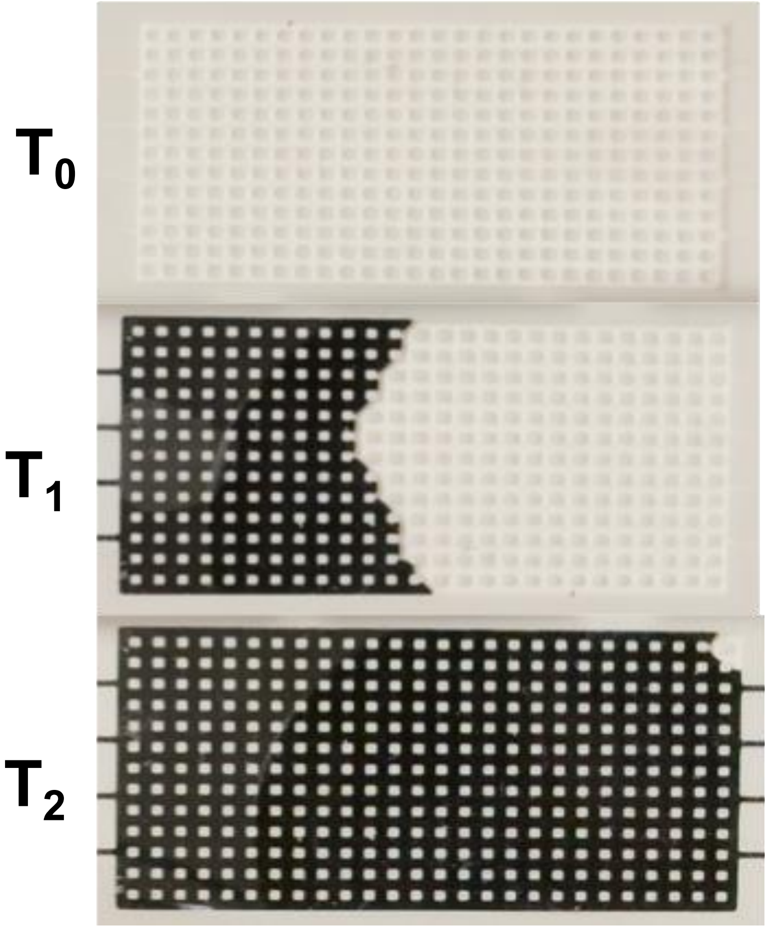
❑ Oil soaking: 12 hours for complete filling of pores

Microfluidic Platforms (Reservoir-on-a-Chips)



Flooding in Homogeneous Network

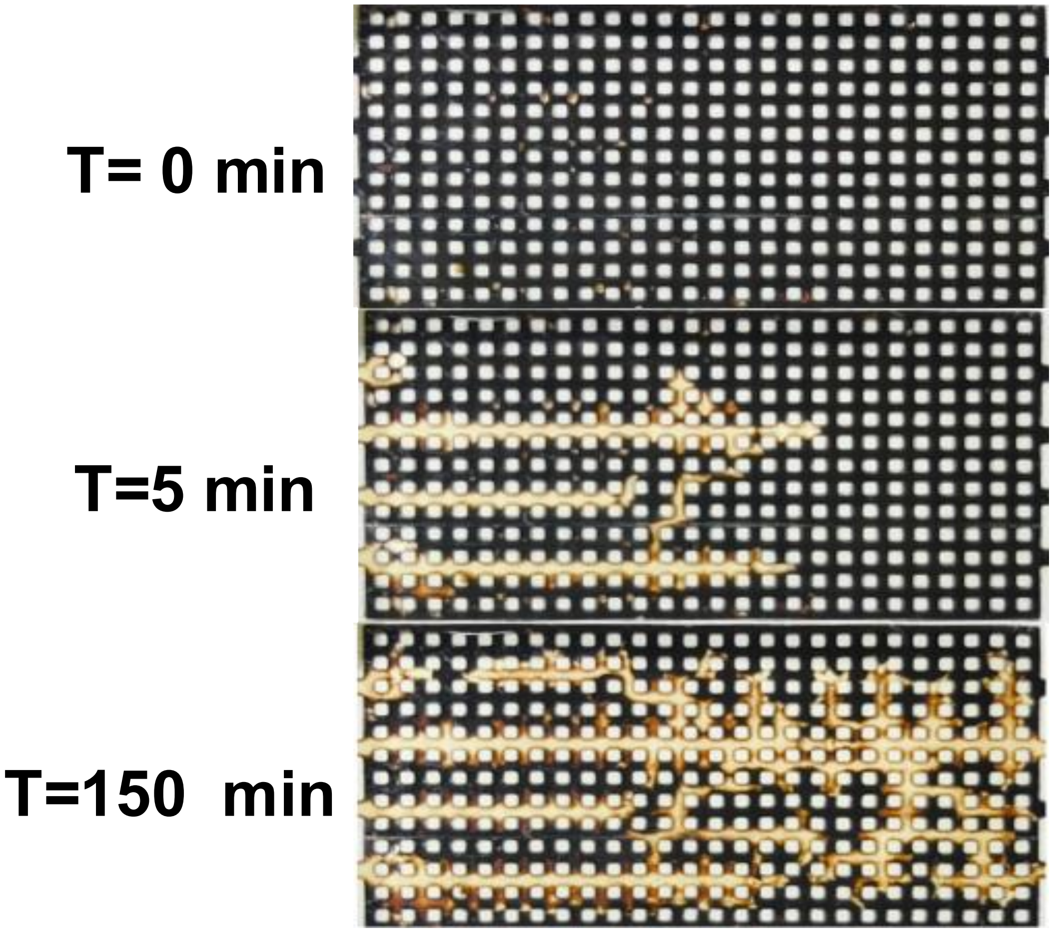
❑ Oil Injection to PDMS-$CaCO_3$



Strong Oil-Wet !

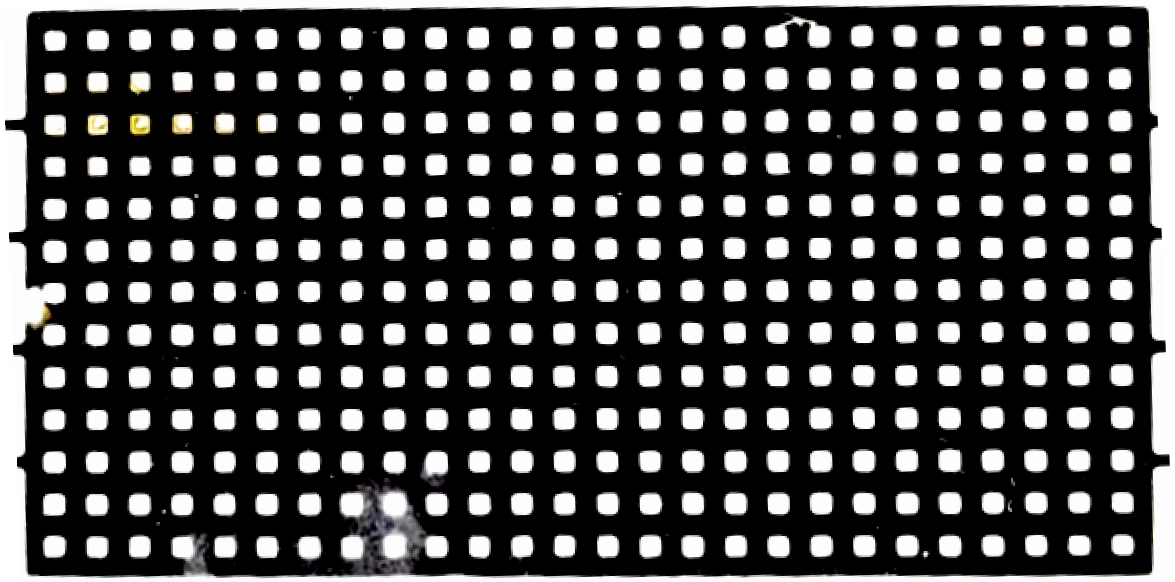
❑ **Water Flooding in PDMS-$CaCO_3$**

- Capillary number = 10^{-5} (capillary-dominant)

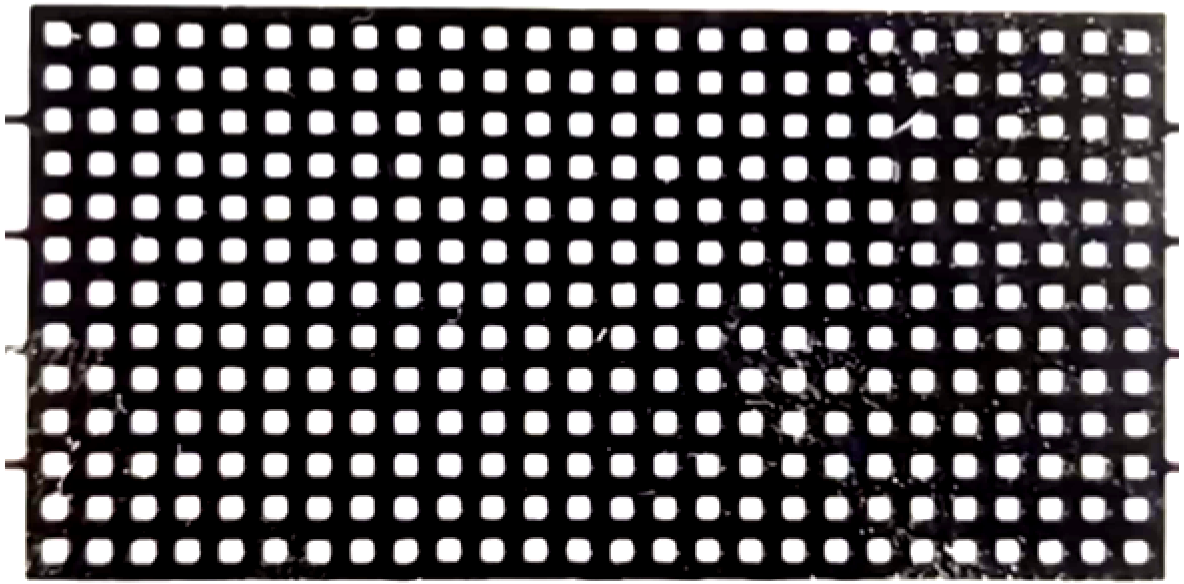


Improved Capillary-Driven Flooding

Flooding in Homogeneous Network

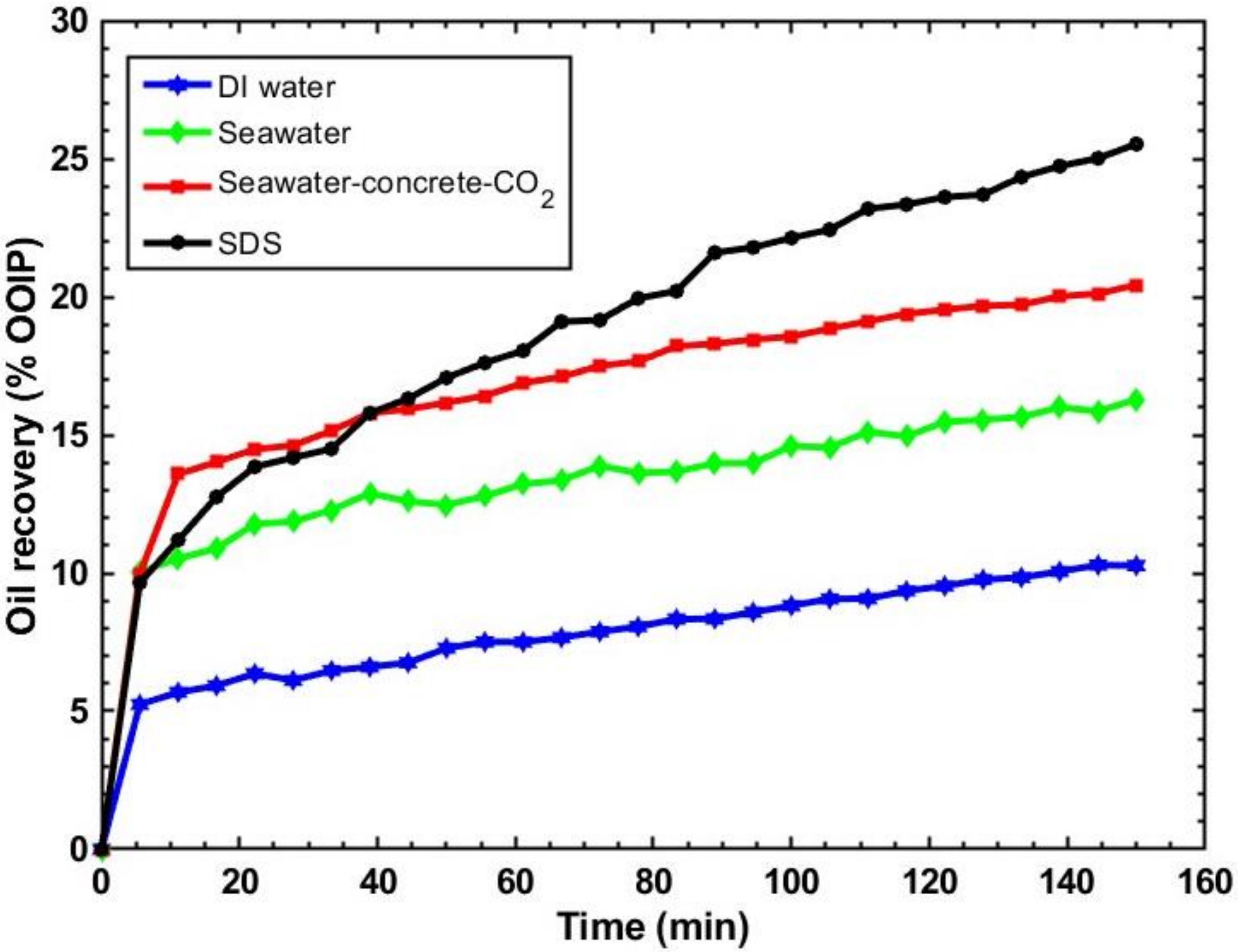


DI water



Seawater concrete

Flooding in Homogeneous Network



- **DI water:** showed the lowest recovery **(10%)** because it lacks the ions or chemical agents needed to alter wettability or reduce interfacial tension.
- **Seawater:** achieved moderate recovery **(15%)** as divalent ions such as Ca^{2+} and Mg^{2+} slightly improve wettability, but the effect remains limited. **(Wettability Alteration)**
- **Seawater–concrete–CO_2:** reached higher recovery **(20%)** because carbonate ions, Ca^{2+}, and dissolved CO_2 collectively promote wettability alteration and improve displacement. **(Wettability Alteration)**
- **SDS solution:** delivered the highest recovery **(25%)** since the surfactant strongly reduces interfacial tension, mobilizing residual oil most effectively. **(IFT Reduction)**

Contents

Flooding in Random Network

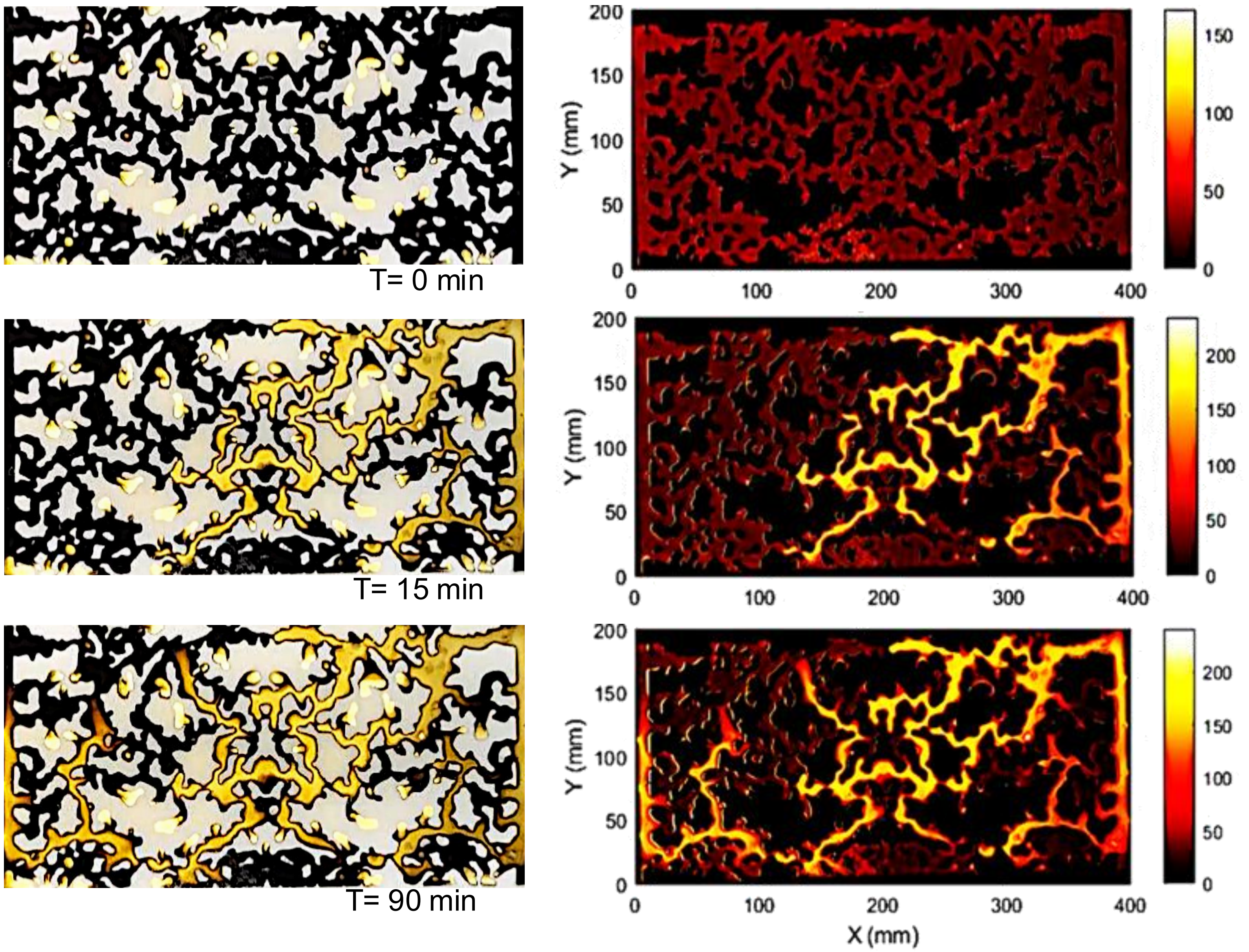
- ❑ Flooding simulation in natural carbonate reservoirs
- ❑ PDMS-$CaCO_3$ Network

SDS

Seawater concrete

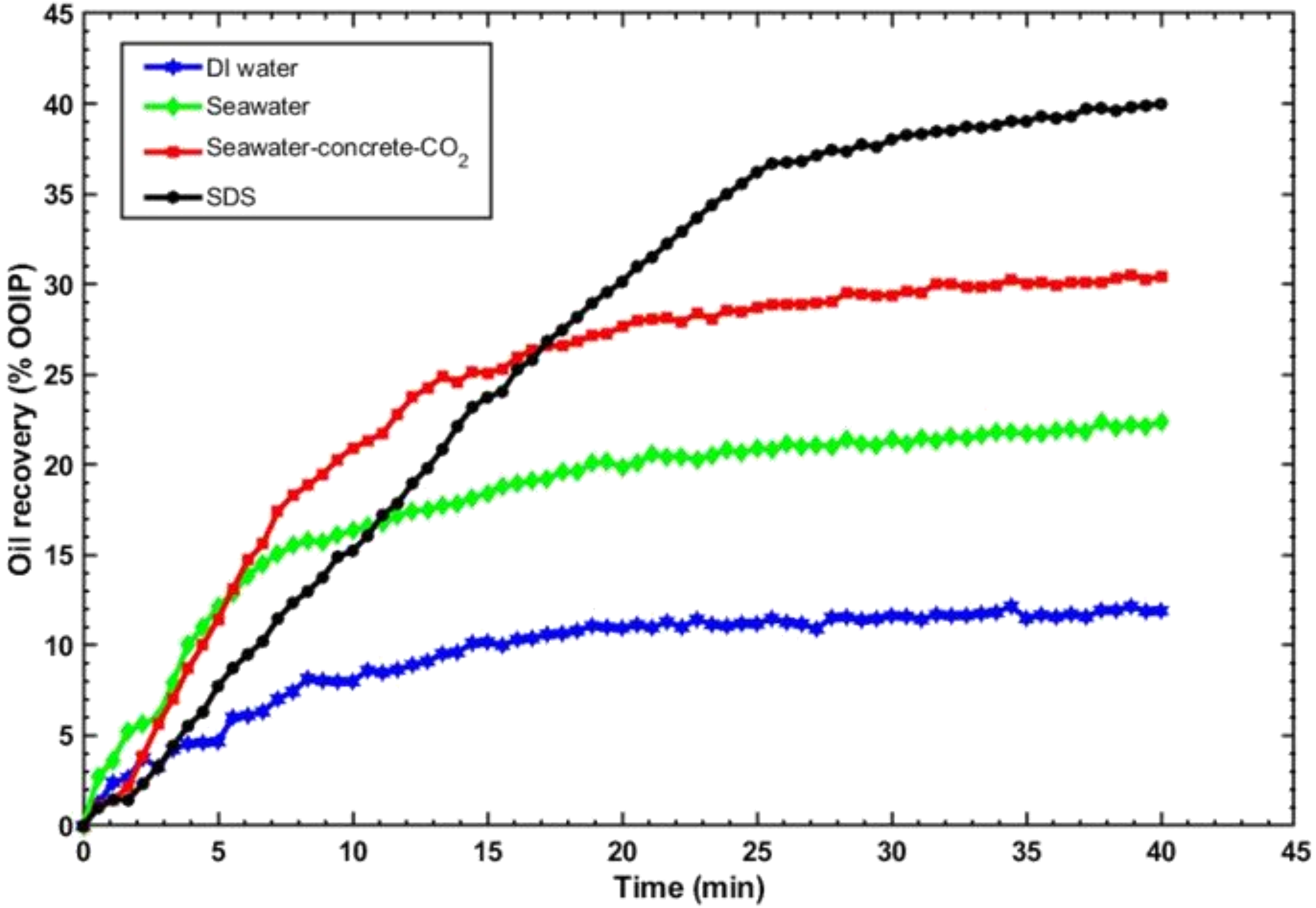
Flooding in Random Network

- ❑ Seawater-Concrete flooding



Flooding in Homogeneous Network

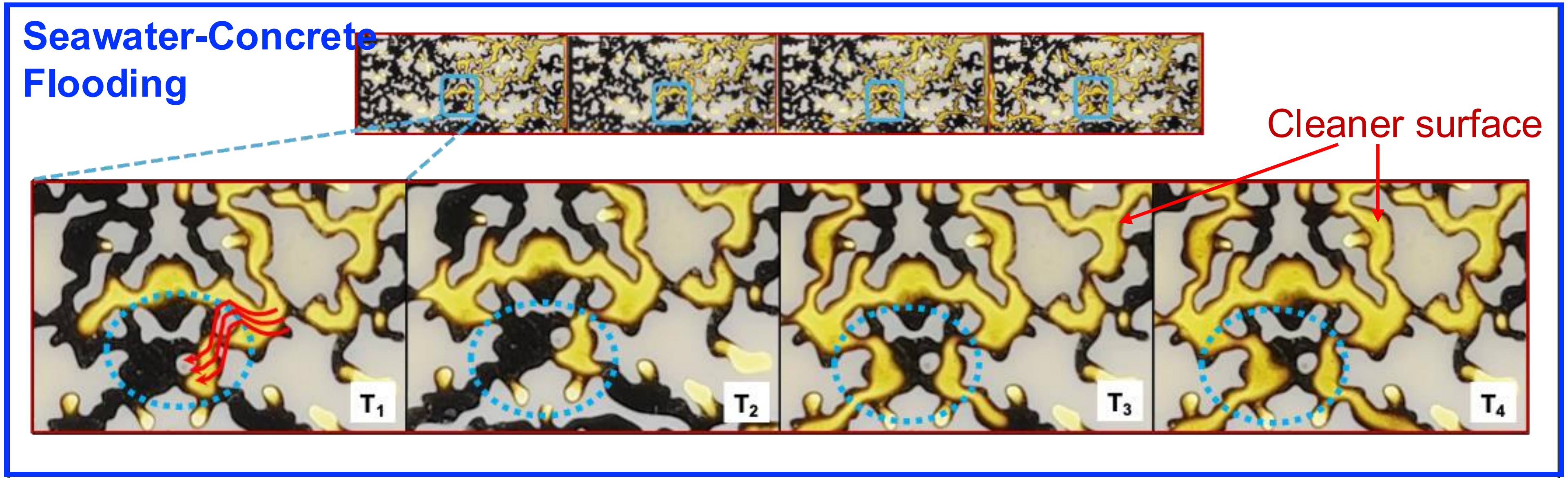
❑ Time-dependent Oil Recovery



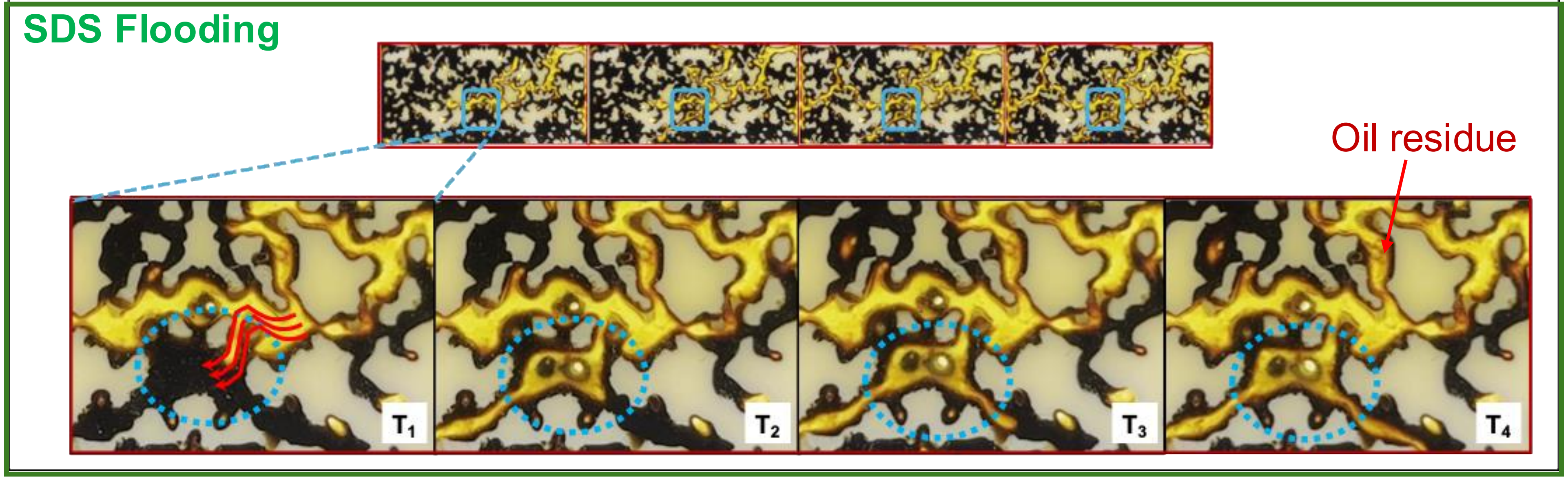
Fluids	Homogeneous Network	Random Network
DI Water	10	12
Seawater	15	22
Seawater-Concrete	20	30
DI-SDS	25	40

- ❑ **Homogeneous network:** Fluid tends to move in a straight path once a breakthrough occurs, creating a dominant flow channel and leaving large regions bypassed.
- ❑ **Random network:** Promoted broader sweep and improved access to otherwise isolated pores.
- ❑ These structural characteristics could delay preferential channeling, creating more uniform displacement. [Datta, 2019, Xu, 2022]

Flooding in Random Network – IFT vs. Desorption



30% Recovery



40% Recovery

Summary

- This work presents a novel $CaCO_3$–PDMS microfluidic chip that successfully mimics carbonate surface chemistry.

- The proposed seawater–concrete–CO_2 solution demonstrated promising enhanced oil recovery performance.

- Contact angle measurements confirmed the oil-wet nature of the fabricated surface, with an average static contact angle of 138.6° in DI water and 130.9° in seawater.

- In the homogeneous porous network, four fluids were tested: DI water, seawater, seawater–concrete–CO_2, and SDS, which achieved oil recoveries of approximately 10%, 15%, 21%, and 25%, respectively.

- In the randomly structured network, the seawater–concrete–CO_2 solution yielded 30.40%, confirming its effectiveness under complex flow conditions.

- Impacts
  - The $CaCO_3$–PDMS micromodel offers a robust and versatile platform for EOR applications.