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Microfluidic Approach for Carbon Sequestration

Myeongsub (Mike) Kim, Ph.D.

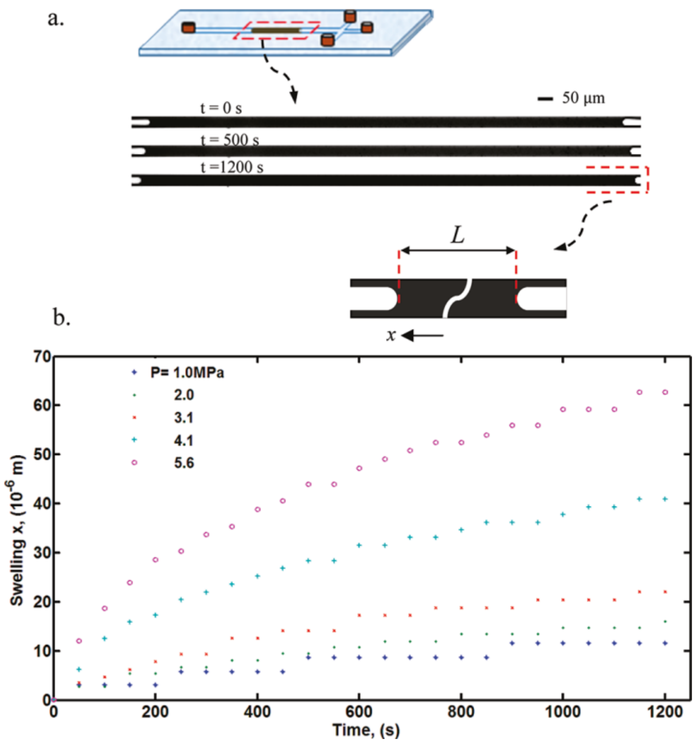
Assistant Professor

Department of Ocean and Mechanical Engineering

Florida Atlantic University

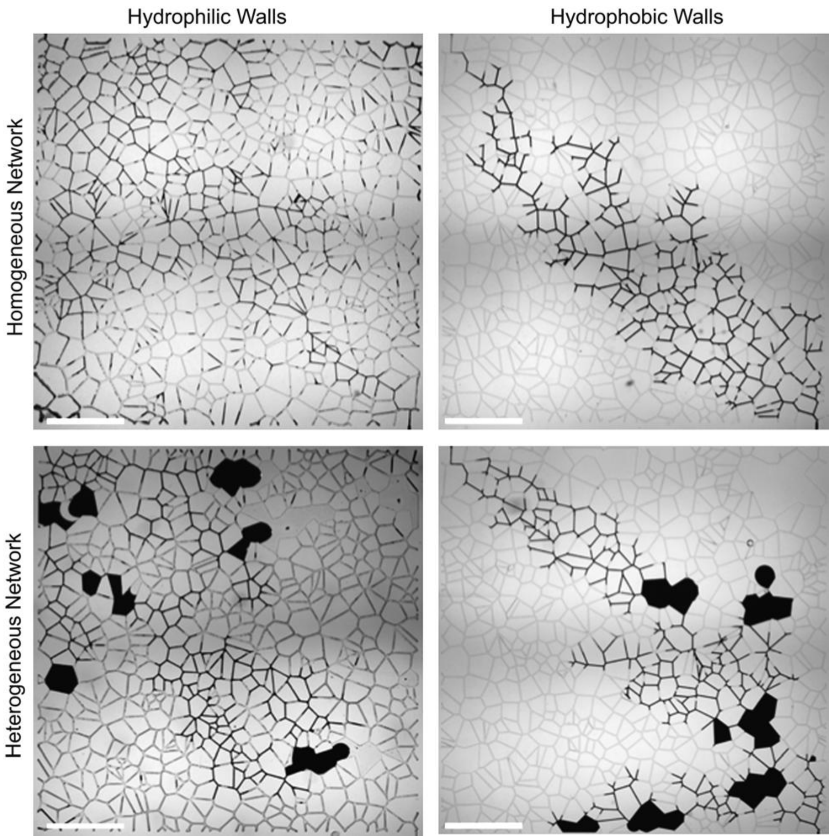
Microfluidics for Geological Research

❑ CO_2-Bitumen in Single Channel



[Hossein, Energy&Fuel, 2013]

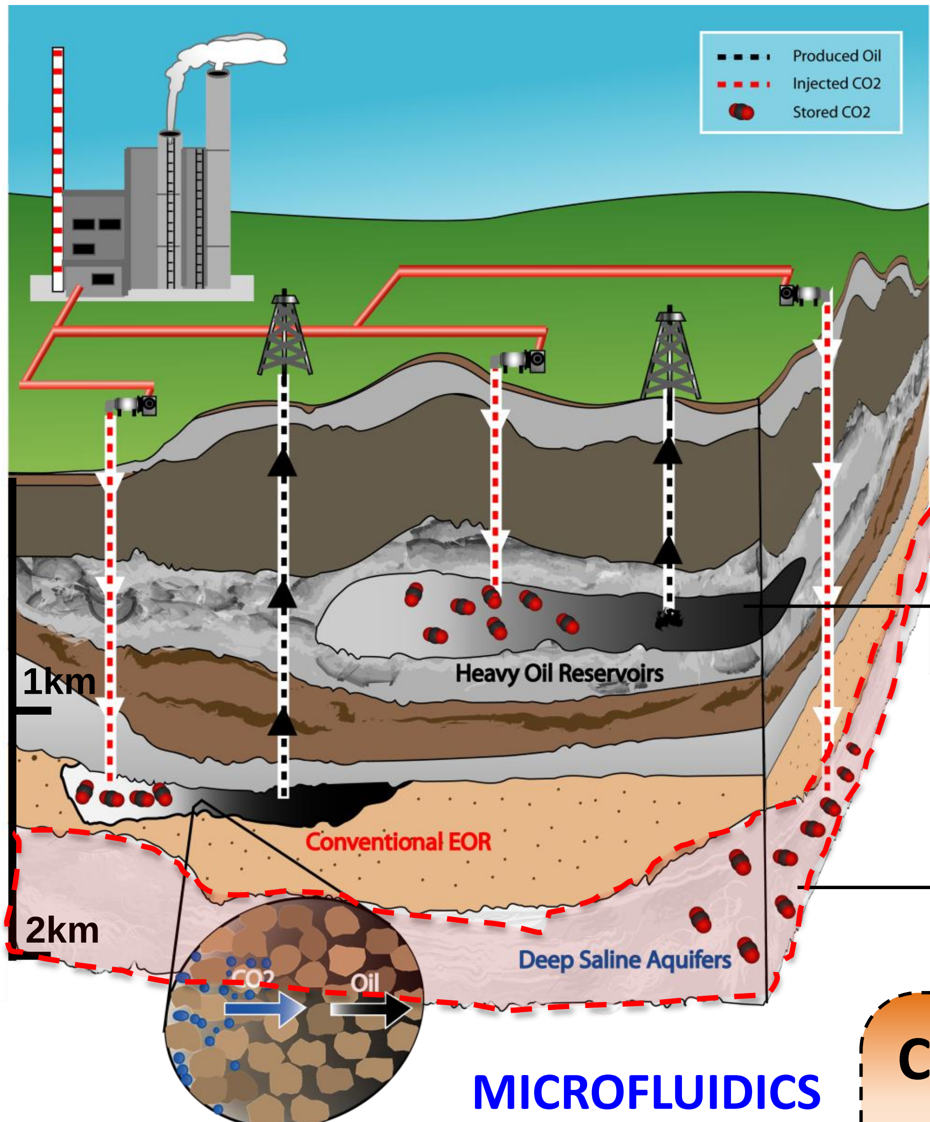
❑ Oil displacement by water in micromodels



[Wu, Lab Chip, 2012]

- Visualize multiphase phenomena at realtime
- Model fluid flow at different surface wettability and heterogeneity

Carbon Storage - Issues



❑ CO_2 Diffusion

- Explain CO_2 transport
- Bulk PVT cell – cost, time
- *D* at different *P* and *T*

Need a well-established measurement technique

❑ CO_2 Sequestration

- Solid precipitation
- Injectivity ↓

Need to find main causes

MICROFLUIDICS PROBLEM ←

CO_2 diffusion & solid precipitation occur at <u>pore scale *O*(1-100 µm)</u>

CO_2 Diffusion to Brine

❑ CO_2 dissolution in water

$$CO_2\,(gas) \leftrightarrow [CO_2\,(aq)] \quad (1)$$

$$[CO_2\,(aq)] + H_2O \leftrightarrow [H^+\,(aq)] + [HCO_3^-\,(aq)] \quad (2)$$

$$[HCO_3^-\,(aq)] \leftrightarrow [H^+\,(aq)] + [CO_3^{2-}\,(aq)] \quad (3)$$

❑ CO_2 concentration

$$\left[CO_2(aq)\right] = \frac{\left[H^+(aq)\right]^3 - K_W\left[H^+(aq)\right]}{K_2\left(\left[H^+(aq)\right] + 2K_3\right)}$$

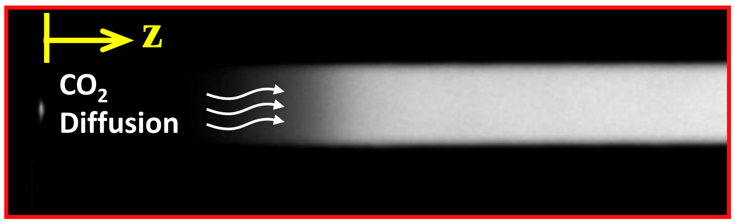
K_2, K_3: dissolution constant in Eq. (2) & (3)

K_w: dissolution constant for water

CO_2 Diffusion to Brine

- **1D diffusion - Fick's Law**

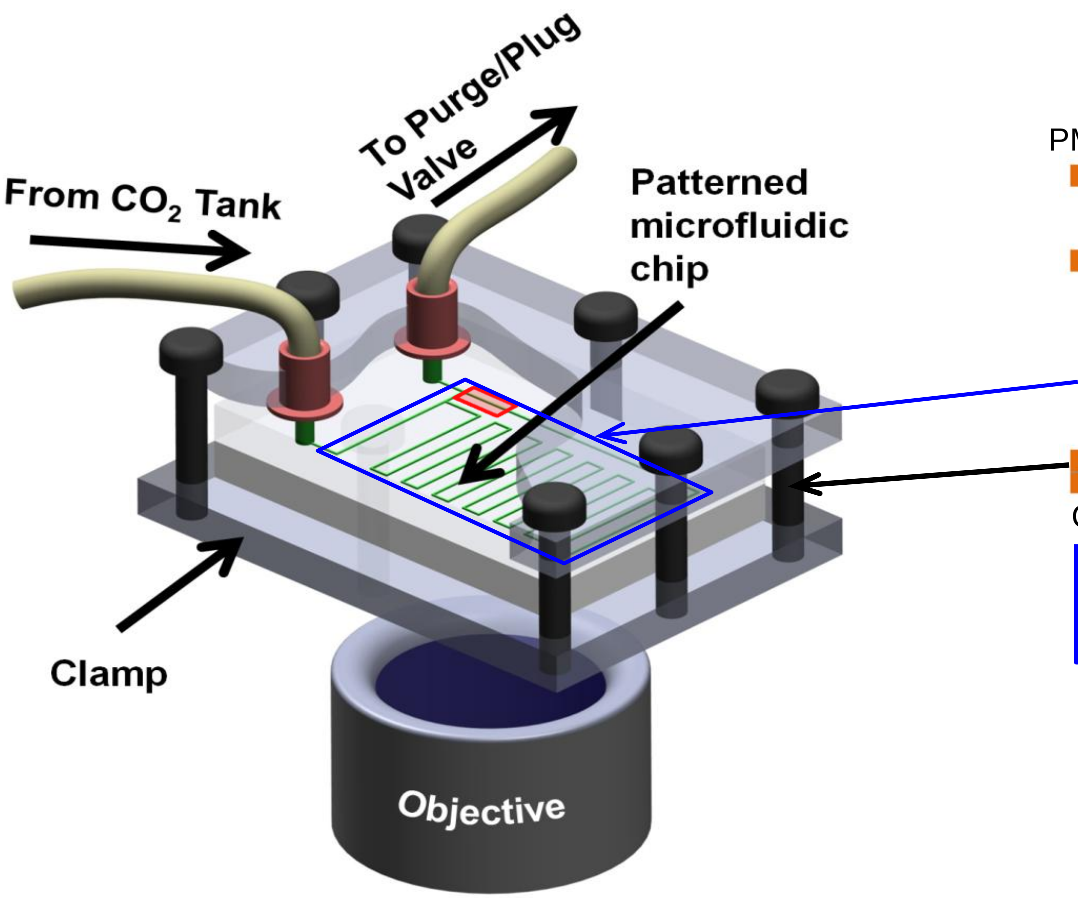
$$c = c_0 \, erfc(z), \quad \text{where } z = \left(z / \left(4Dt\right)^{1/2} \right)$$

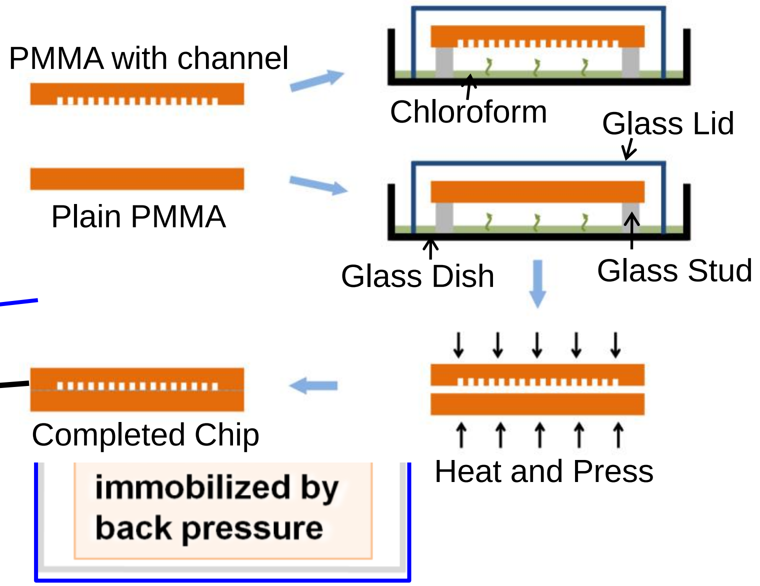


$$\left[CO_2(aq)\right] = \frac{\left[H^+(aq)\right]^3 - K_w \left[H^+(aq)\right]}{K_2\left(\left[H^+(aq)\right] + 2K_3\right)}$$

pH ➔ [CO_2] ➔ *D*

CO_2 Diffusivity Test Setup





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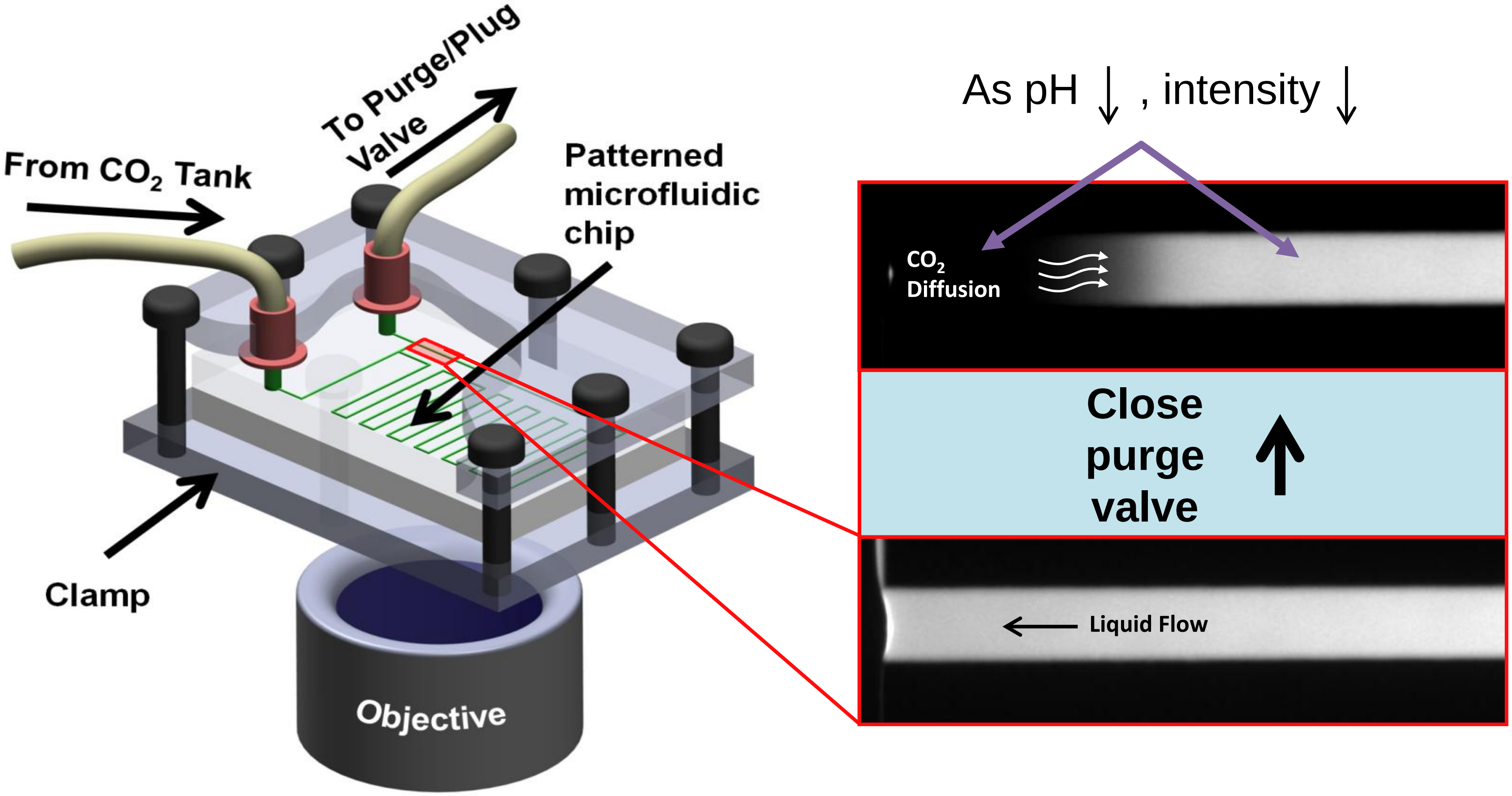


Visualization of CO_2 Diffusion

- Fluorescence-based imaging

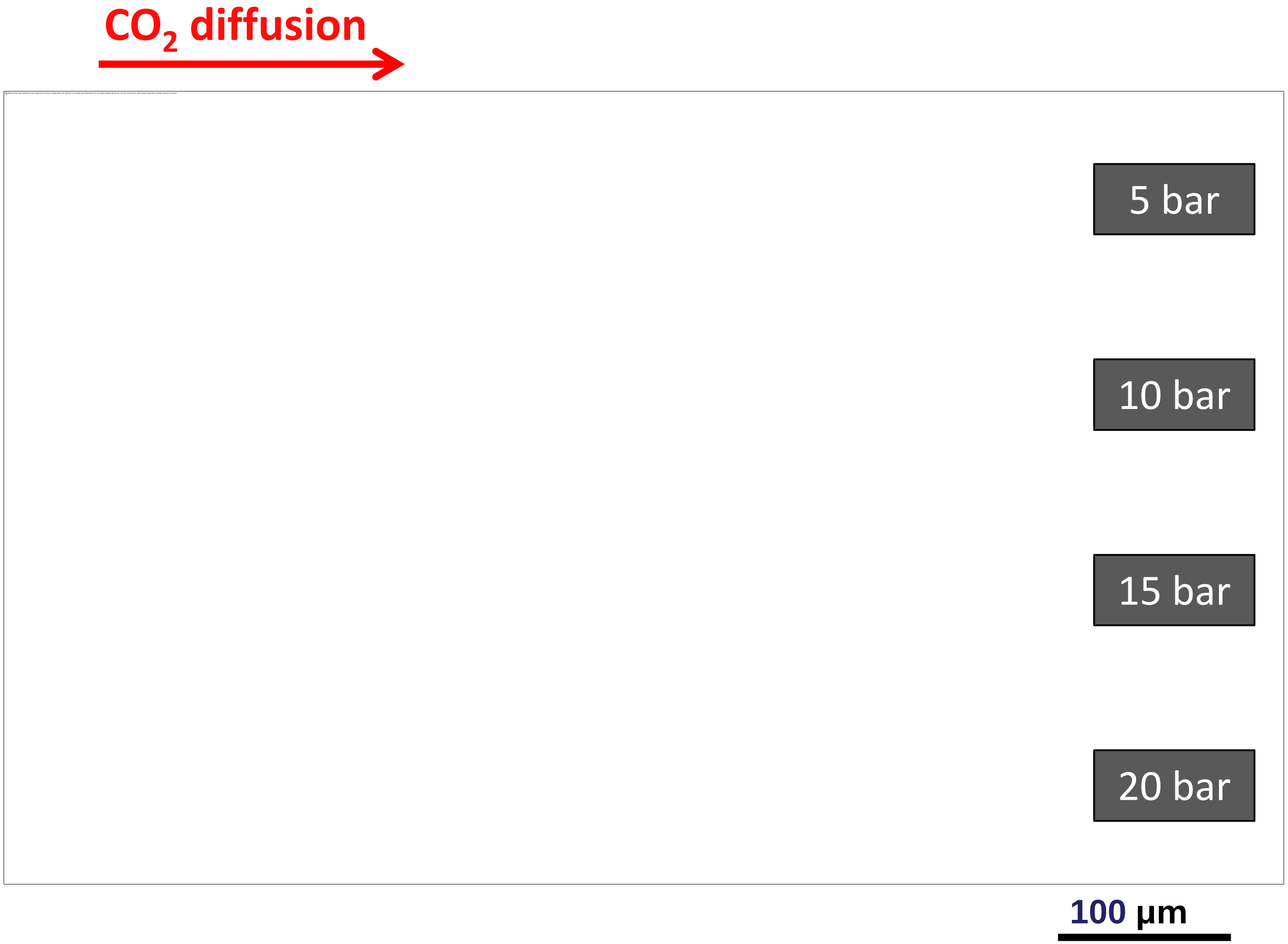
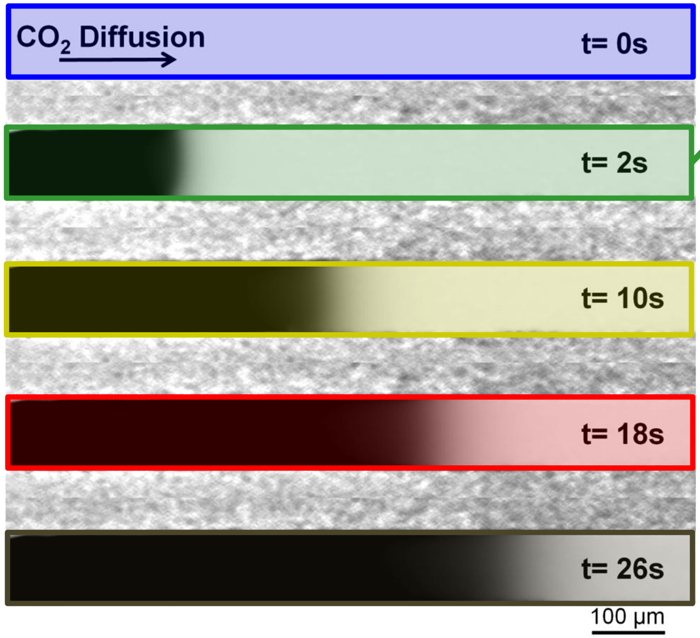
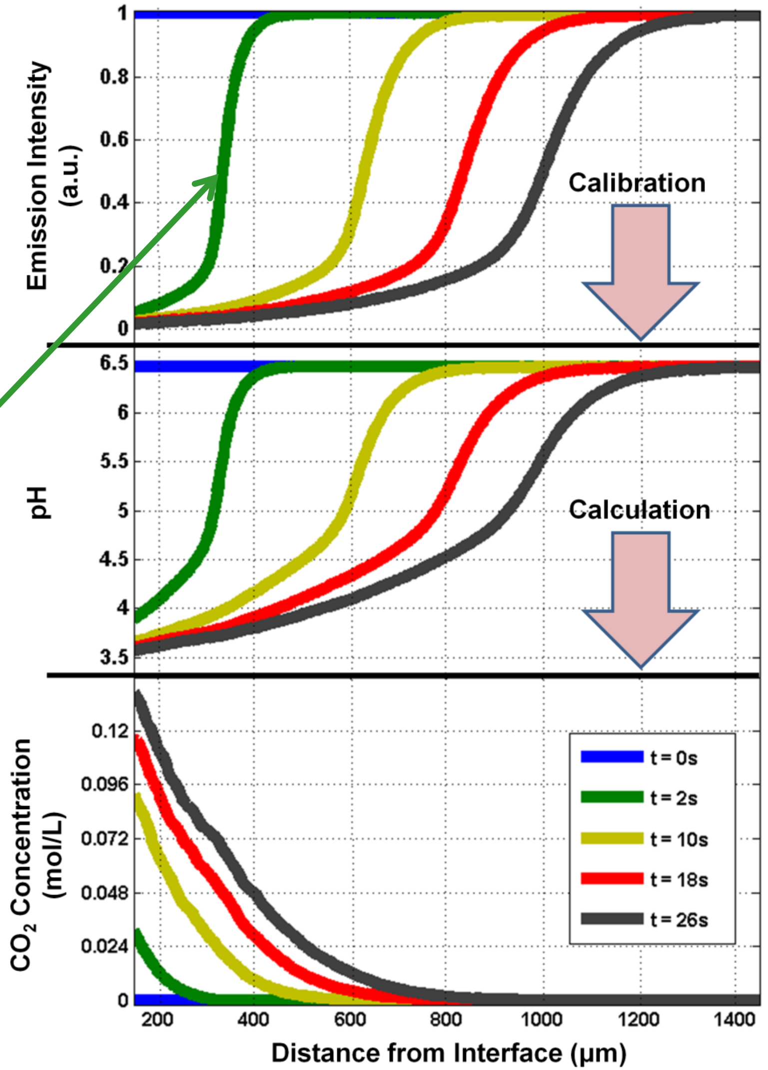


Image Processing

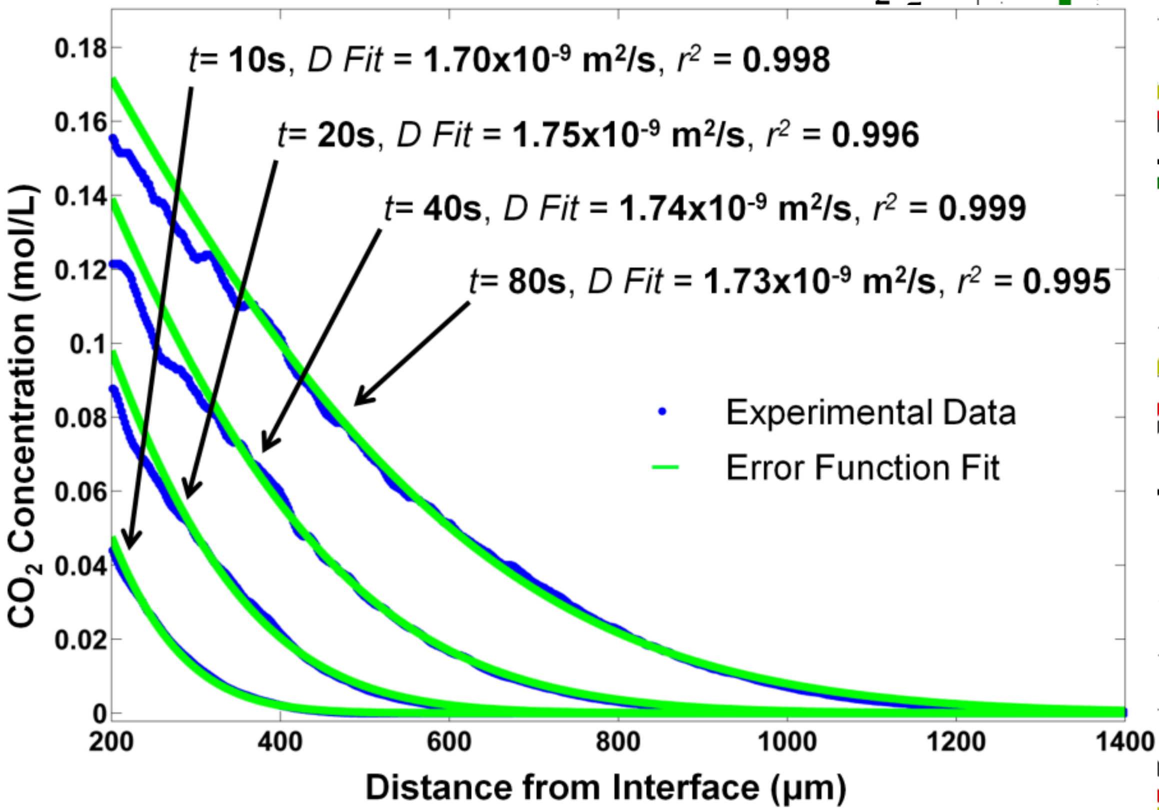
Sequential Images

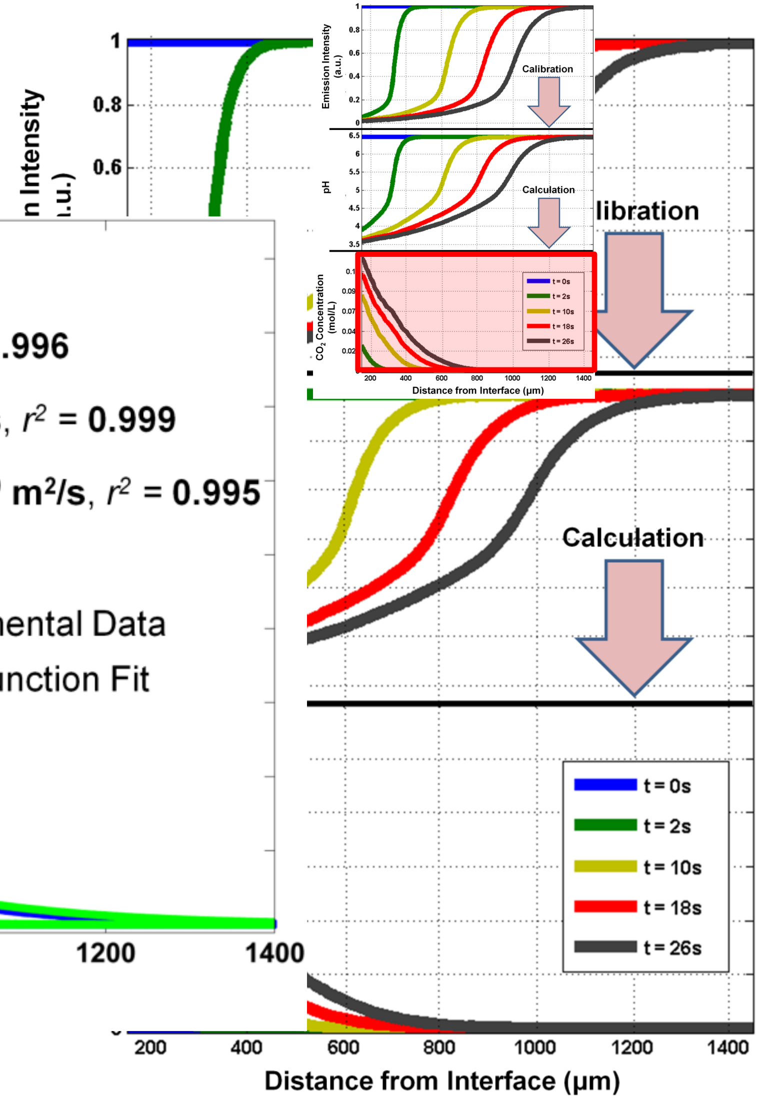




Estimation of *D*

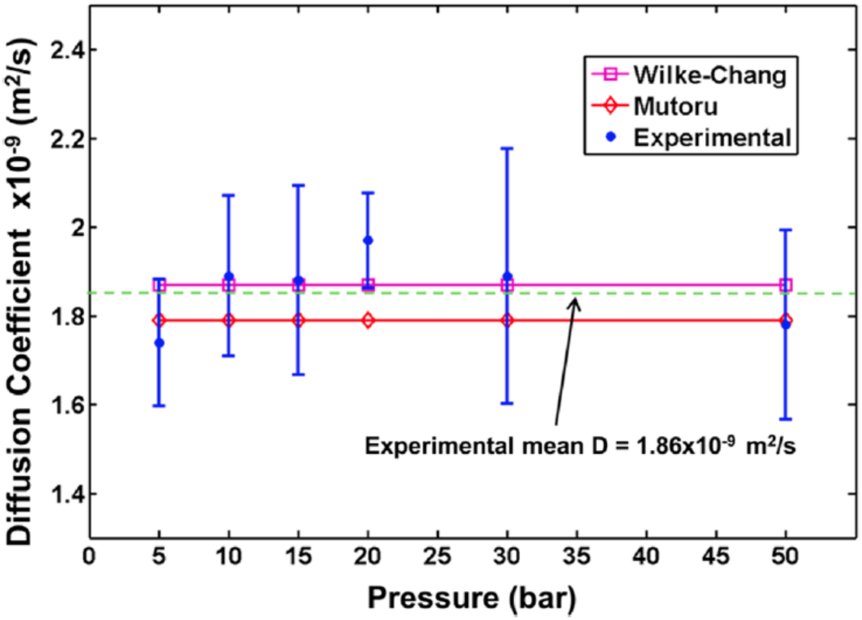
- Fit [CO_2] with the analytical diffusion model to determine *D*



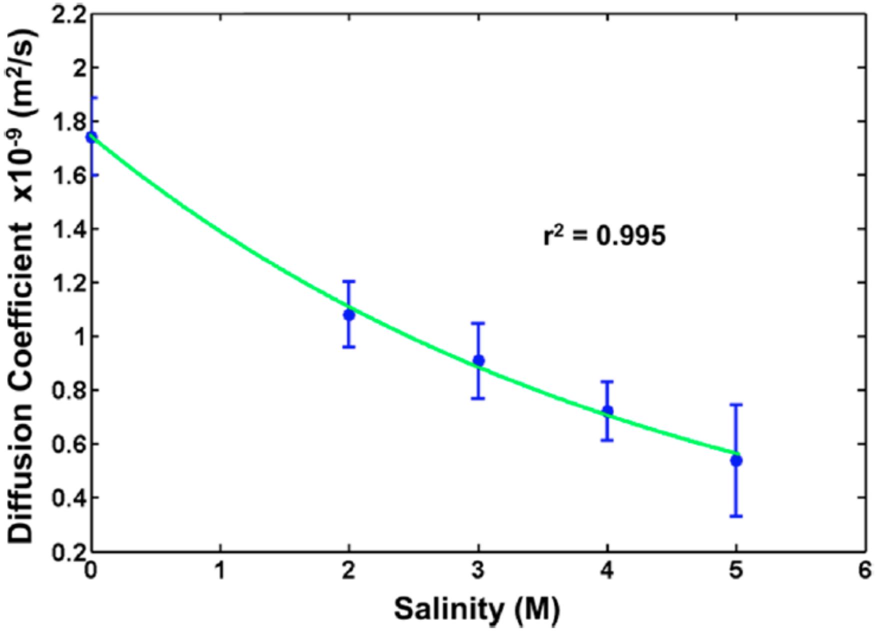


Results

❑ Pressure effect on *D*



❑ Salinity effect on *D*

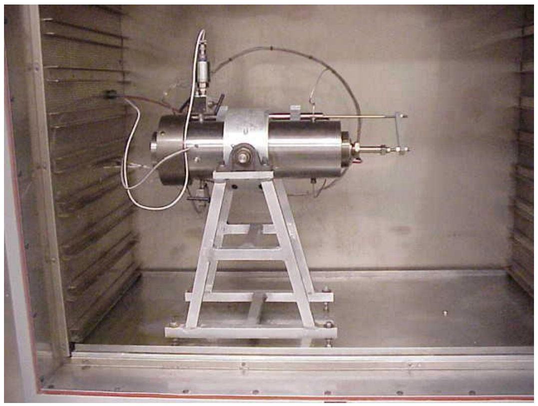


[Sell *et al*., 2013]

Within 2% agreement with previously available data

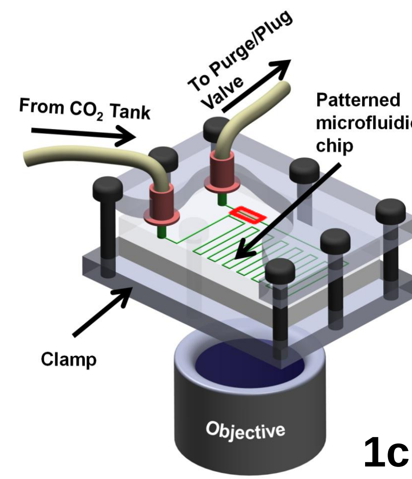
Contributions

Classical Pressure-Volume-Temperature Cell



10cm

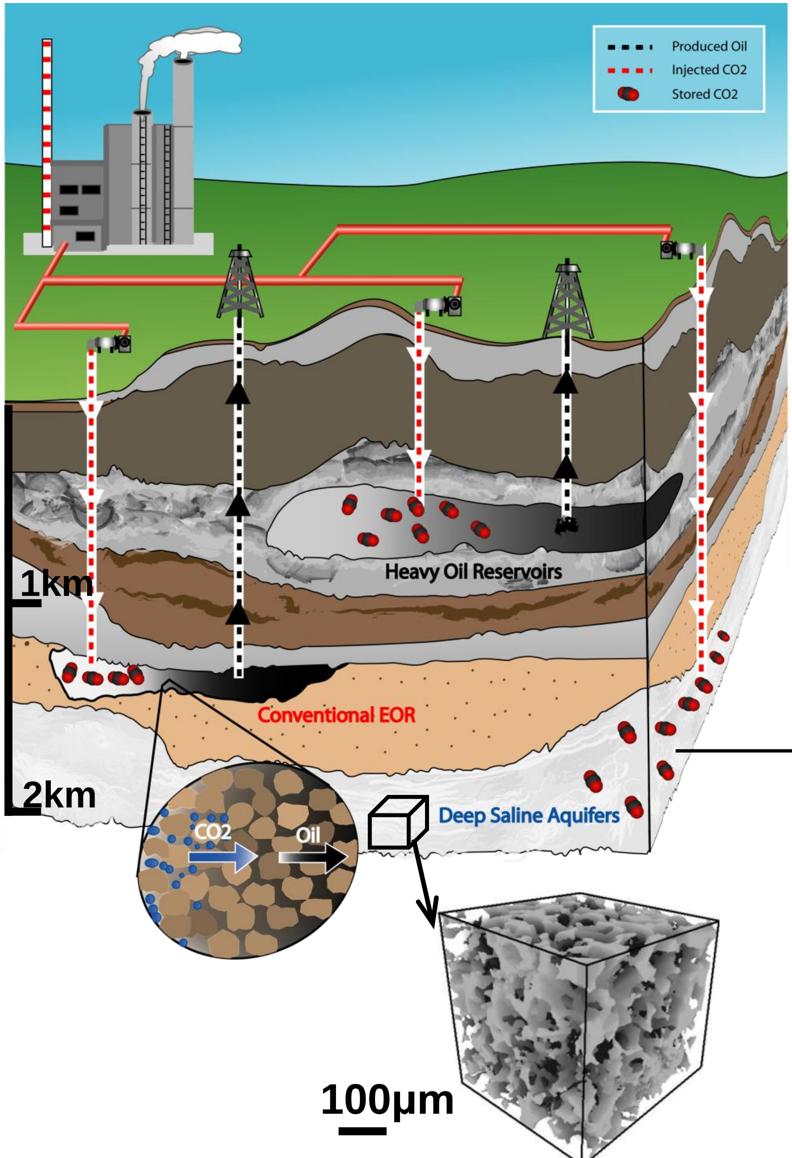
Microfluidics



1cm

Cost: > $ 100 K	< $ 200
Volume: *O*(1 L)	*O*(nL)
Time: Few days	Minutes

Water Evaporation and Solid Precipitation



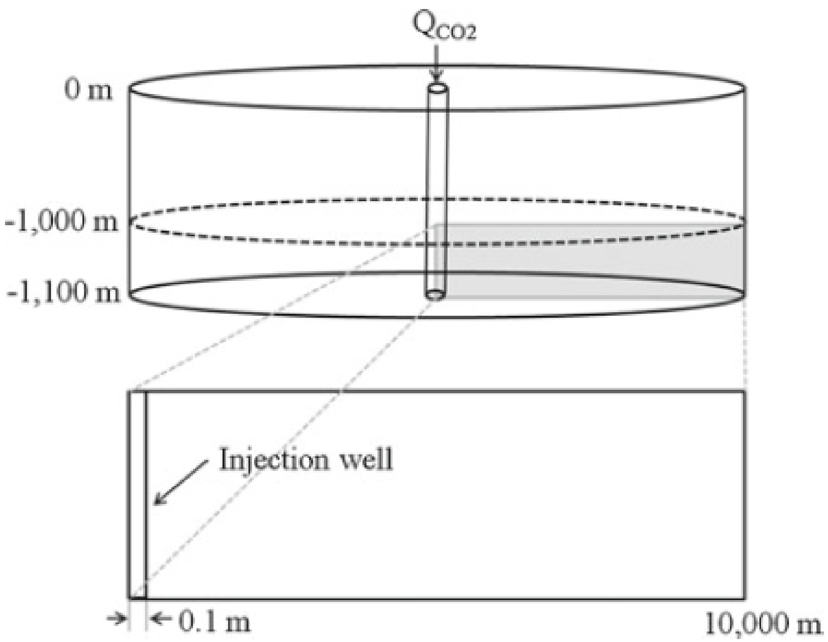
- **CO_2 injection following salt precipitation**
  - Dry CO_2 injected (10^6 ton/yr)
  - Resident water evaporated from porous media
  - Salt blocks pores/throats

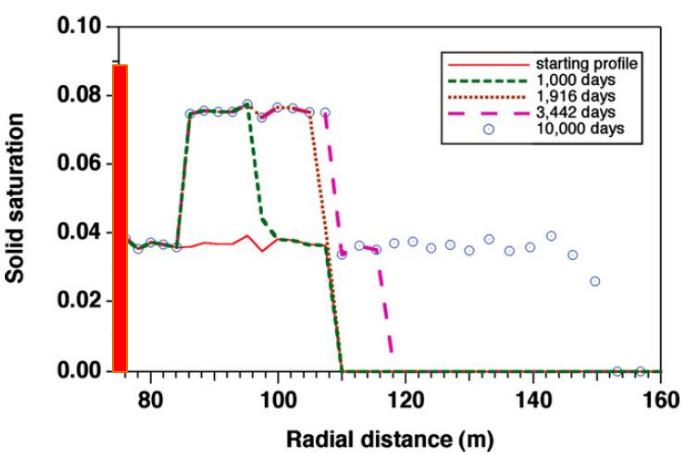
Decrease of CO_2 Injectivity

- **Why important?**
  - Increase injection *P*
  - Cost ↑, Storage capacity ↓
  - Induce fracture underground

Studies at Various Scale

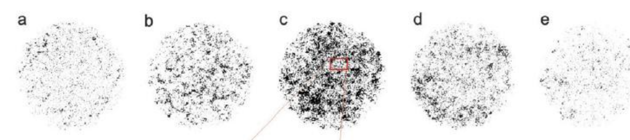
❑ Reservoir scale





❑ Core scale

Core 1 Core 2

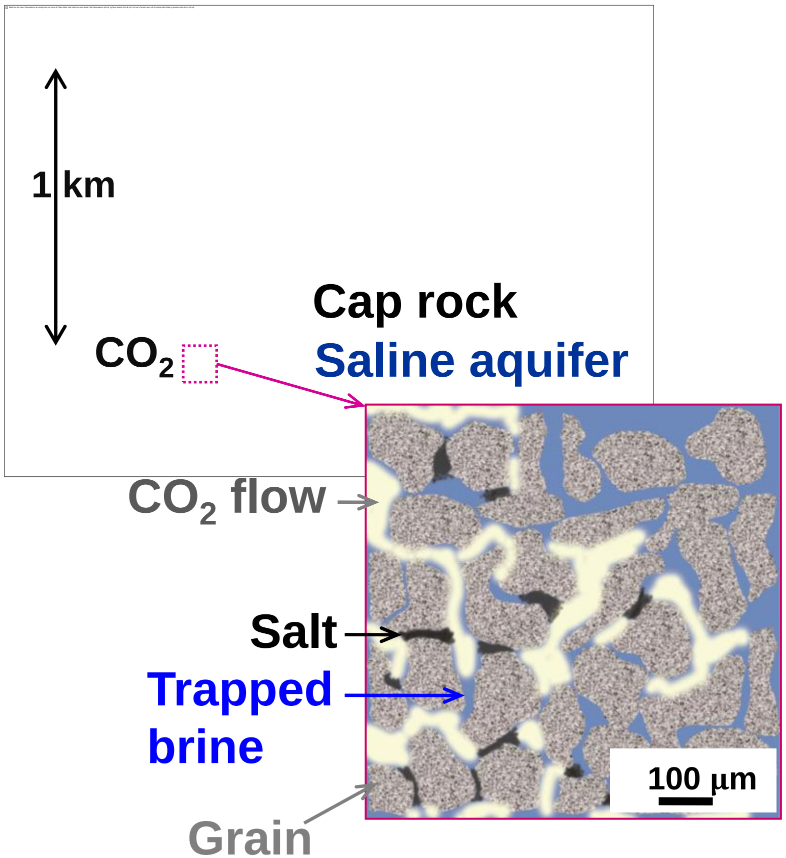


⌘ **Visualize salt precipitation at pore scale *O*(1-100 µm)?**

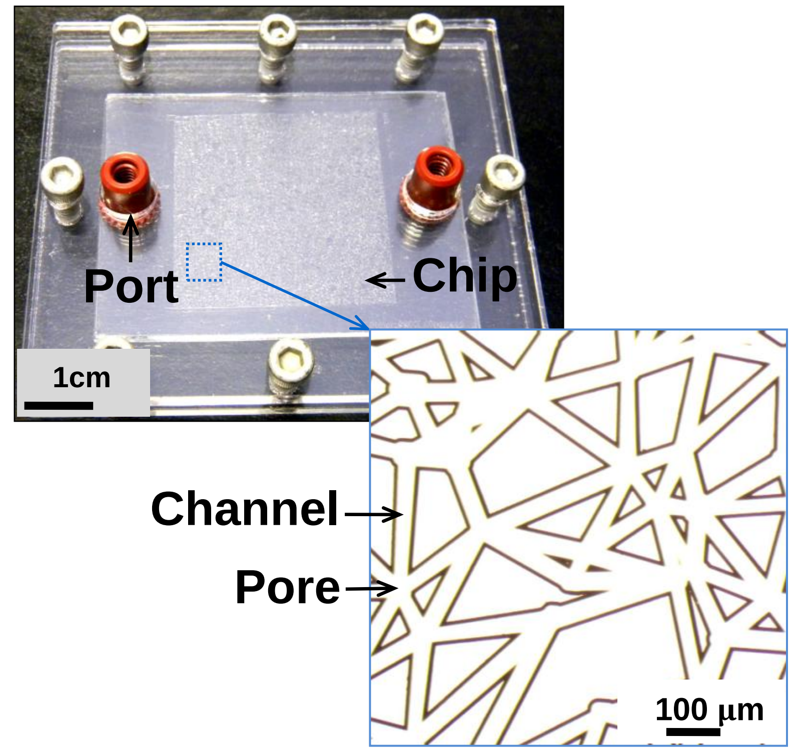
⌘ **What is main precipitation mechanism?**

➔ OPTOFLUIDIC PROBLEM

Microfluidic Approach



Native porous media

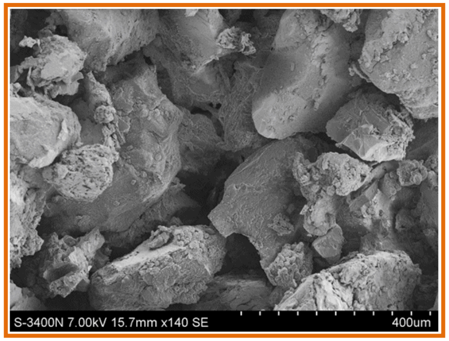


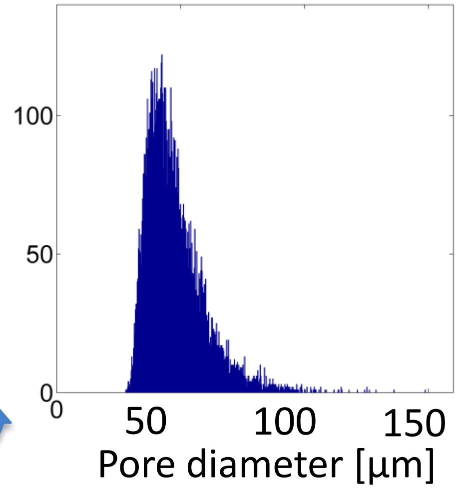
Microfluidic chip

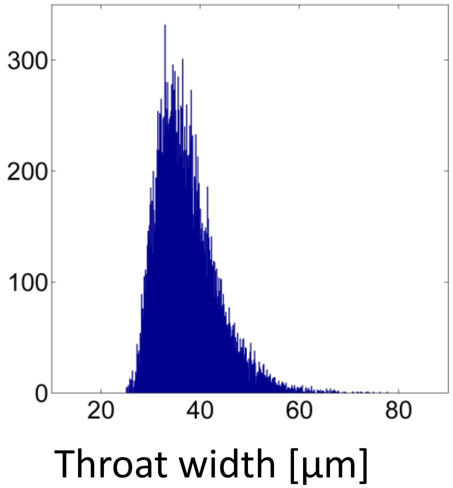
Porous Micromodels

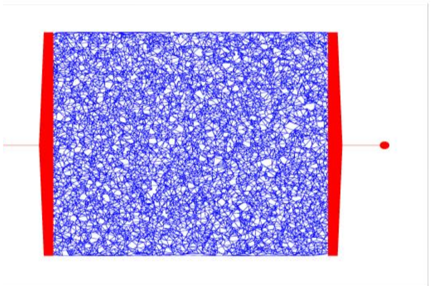
Pore / Throat Distributions

Natural Porous Media

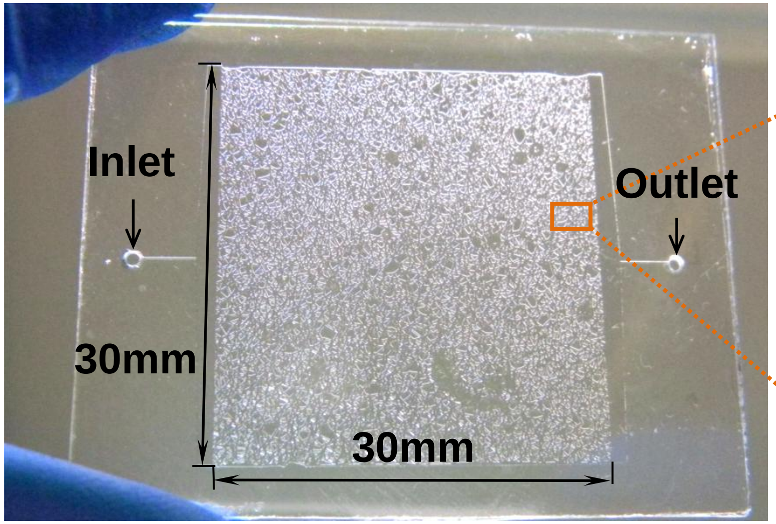


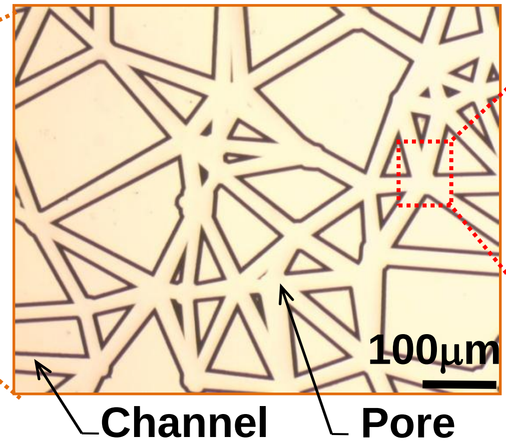


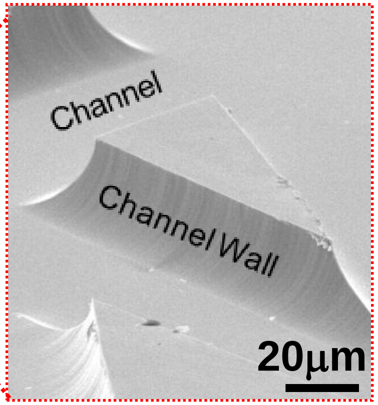




Delaunay Algorithm

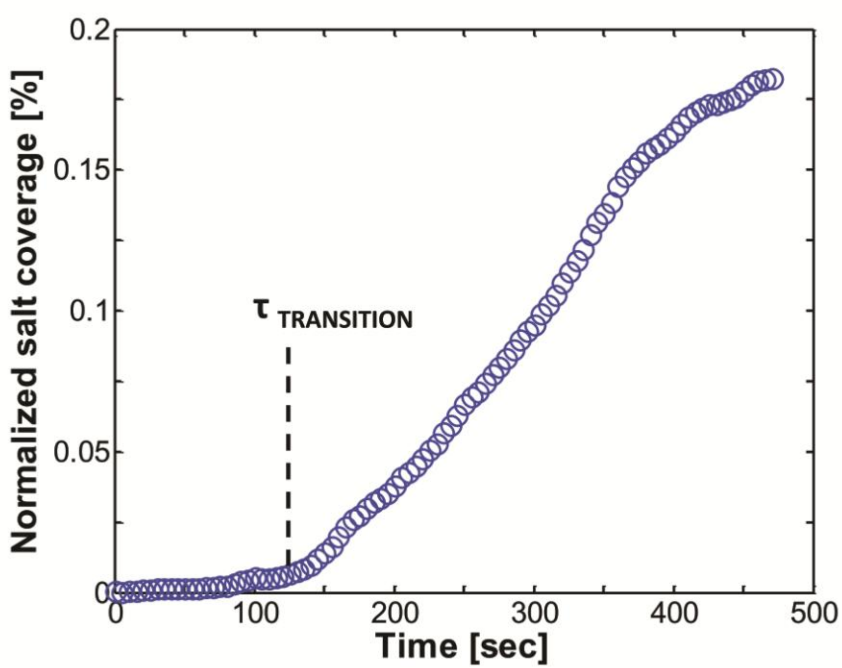






Visualization and Quantification

❑ Visualization (video frame = 50x faster)



❑ Transition time, τ

- **Before**: phase redistribution, evaporation, NO salt precip.
- **After**: salt precipitation occurs LINEARLY to 18% coverage
- Salt precipitation front velocity: 14 μm/s = 2% superficial vel. of CO_2 phase **[Kim *et al.*, 2013]**

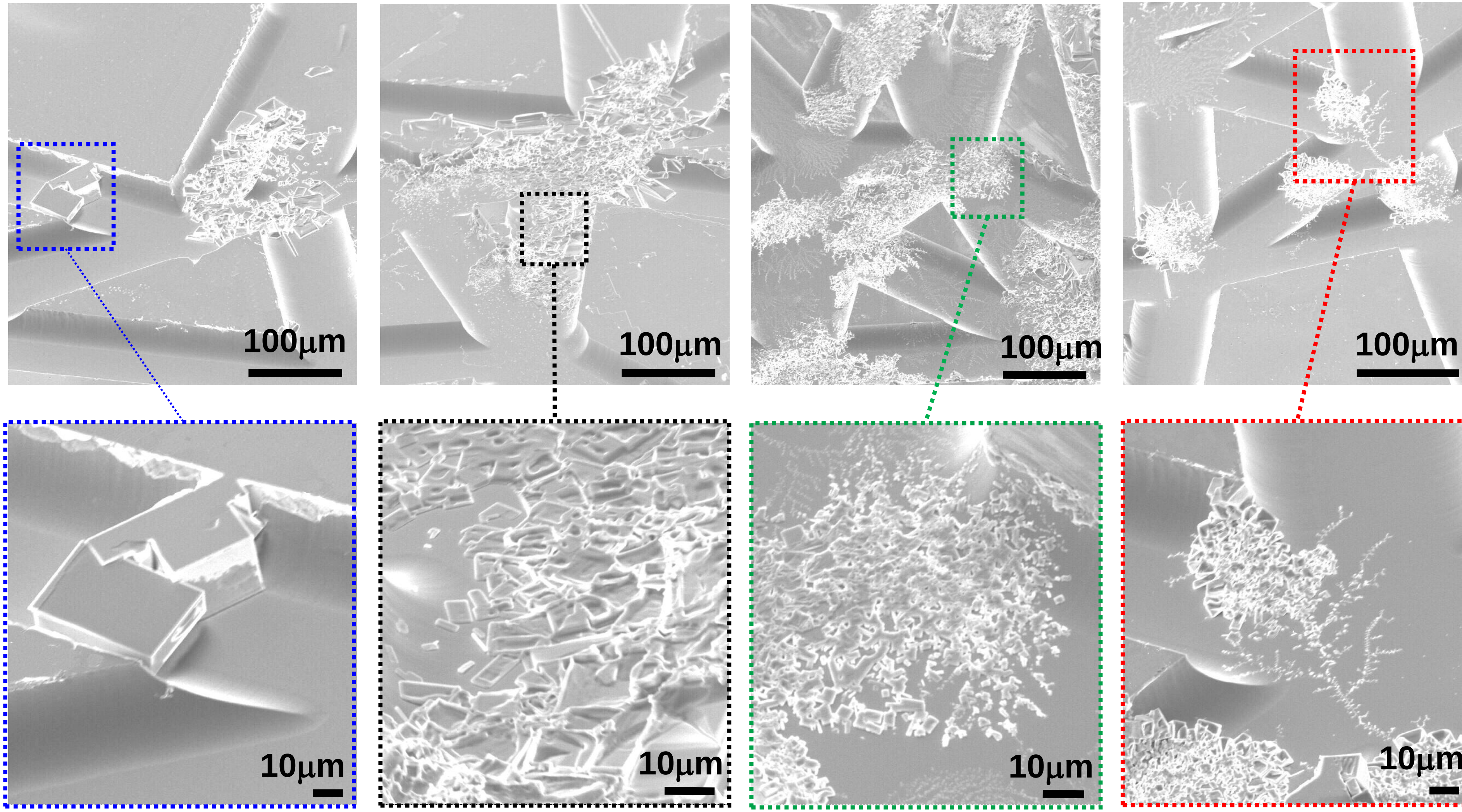
Precipitation Mechanism

❑ Exploded View (video frame = 50x faster)

Important Observations

1. Types of salt formation:
   - Early forming large crystals in “trapped” liquid-phase
   - Late forming poly-crystalline structures in gas-phase
     ➔ **more significant formation type** **[Kim *et al*., 2013]**
2. Driving force: highly concentrated film flow
3. Hydrophilic formations (*e.g*., sandstone) might have higher precipitation

SEM Images of Precipitated Salt



Summary

Using microfluidic approaches,

- **Measure CO_2 diffusion coefficient in aqueous solutions**
  - Cheap, straightforward, and fast method
  - Applicable to any combinations of gas-liquid systems

- **Visualize solid precipitation at real time during CO_2 injection**
  - Provide visual evidences of known phenomena at the same scale to natural formations
  - Poly-crystalline structure precipitation has more significant effect
  - Reveal new findings opposite to common understandings