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CO_2 Migration: Ganglion Dynamics

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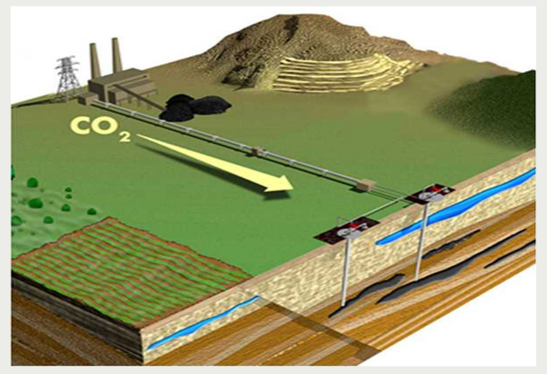
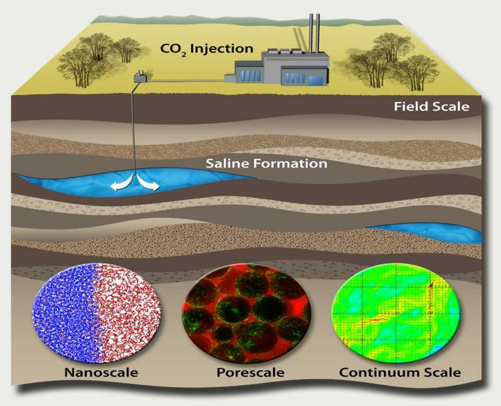
Introduction

Motivation



Global consumption of fossil fuels has significantly increased levels of atmospheric CO_2, a greenhouse gas. Carbon capture and storage (CCS) is a promising mitigation strategy.



Scientific Objective:
Understand and control *emergent behavior* arising from *coupled physics and chemistry* in *heterogeneous geomaterials* associated with injection for GCS, especially at *intermediate length scales* (cm to m) where geologic variability plays a decisive role. Processes and strategies are based on mesoscale science from which non-equilibrium and emergent behaviors arise over a large range of time and length scales.

Theme 3: Buoyantly Driven Multiphase Flow of CO_2

Our Plan:
- Perform pore-scale, meso-scale and meter scale experiments to elucidate and quantify the physics governing flow regimes from compact flow to capillary channel flow
- Develop new experimental-informed, physics-based flow models, focused on representing cm-scale heterogeneity.
- Perform nanoparticle experiments for control of the compact to capillary channel flow transition.

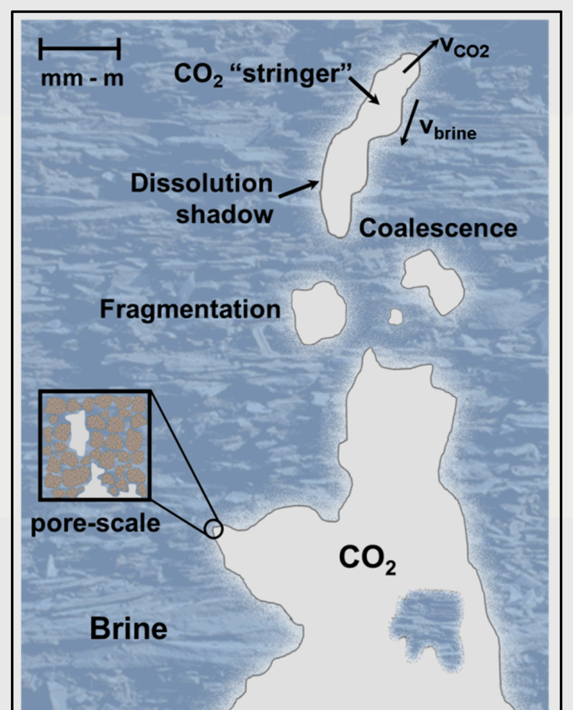
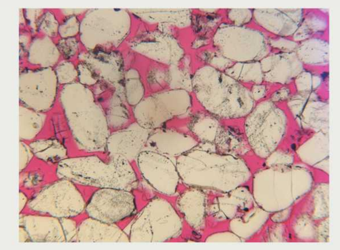
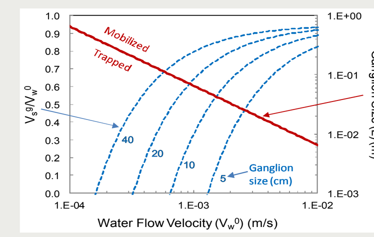


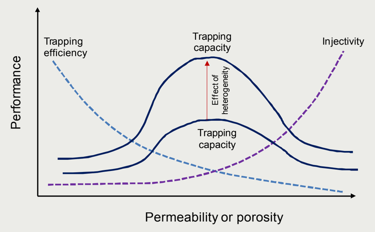
Figure: Conceptual model and mechanistic processes in buoyancy-driven ganglia dynamics (note v_{CO2}, v_{brine} of "stringer") which collectively correspond to capillary channeling.

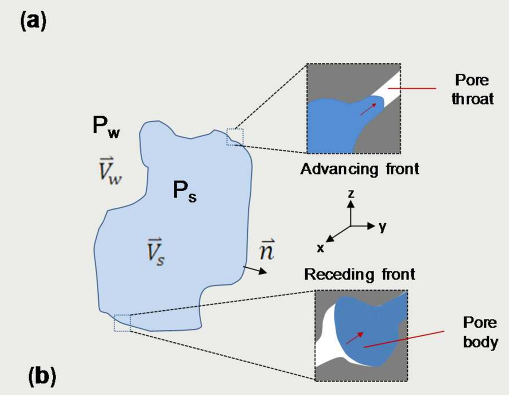
Challenges Addressed:
- Sustaining large storage rates
- Using pore scale with unprecedented efficiency
- Controlling undesired or unexpected emergent behavior

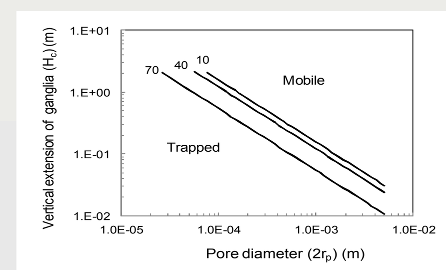
Ganglion Dynamics







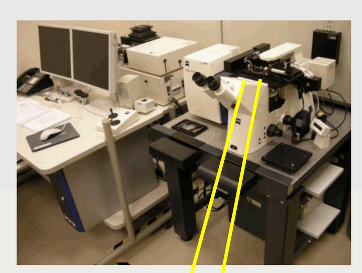




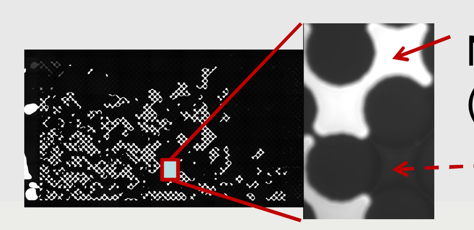
Develop engineering approaches to maximizing storage efficiency
- Mobility of a ganglion is inversely dependent on its size.
- Breaking the injected $scCO_2$ into small disconnected ganglia enhances the efficiency of capillary trapping can be greatly enhanced.
- Supercritical CO_2 ganglia can be engineered by promoting CO_2-water interface instability during immiscible displacement.
- Ganglion size distribution can be controlled by injection mode (e.g., water-alternating-gas) and rate.
- Vertical structural heterogeneity within a reservoir can inhibit the buoyant rise of $scCO_2$ ganglia.

Meso-scale Experiments

Fabricated and 3D Printed Microfludic pore networks & real-time in-situ measurement with confocal microscope

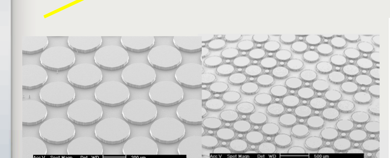


3-D imaging: Laser Scanning Confocal Microscope

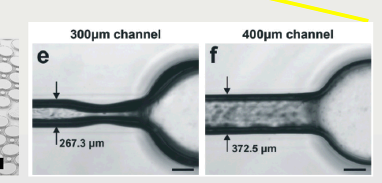


Nonwetting phase entrapment

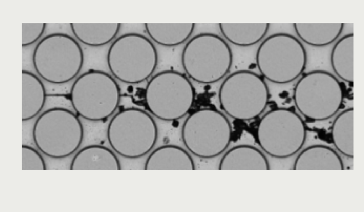
High pressure holder



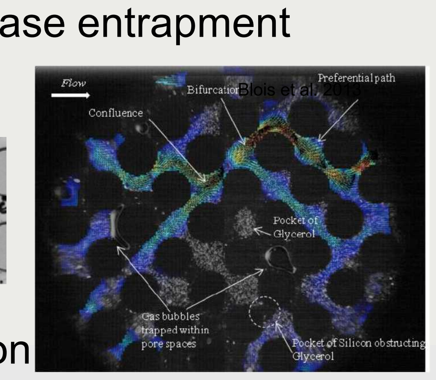
Fabricated microfludics



3D printed microfludics (Au et al. 2014, Lab on a chip)



Mineral precipitation and dissolution

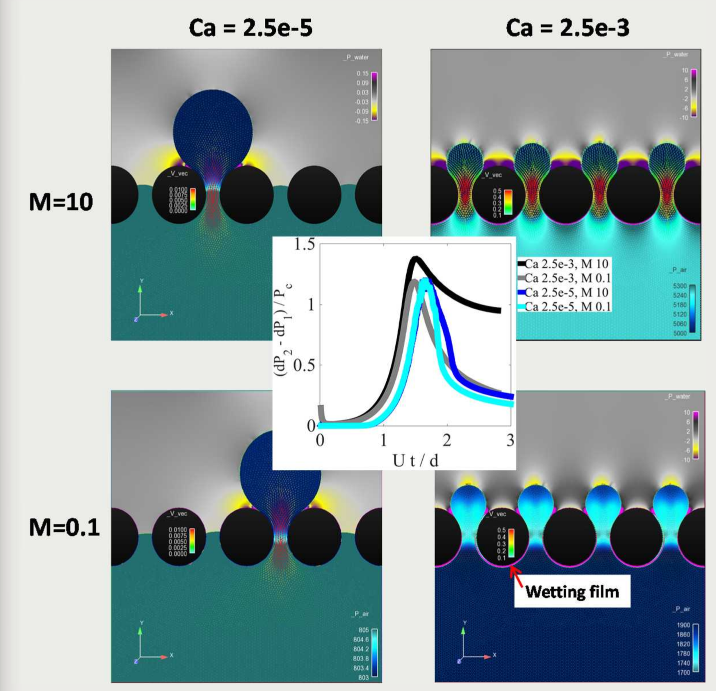


Two phase velocity vector using microscopic particle image velocimetry (μPIV) method

Experimental approaches to validate ganglion dynamics modeling
- Fabricated microfluidics: Any patterns of pore structure at micron scale can be etched with a typical depth of ~10 to 100 μm
- 3D printed microfluidics: Rapid prototyping technique to print in transparent 3D polymer structures from a liquid photopolymer resin with a focused laser, Printing resolution at 20-100's μ m corresponding to a minimum channel width of ~200 μ m
- Wettability of microfluidic surface can be easily adjusted and tested
- Direct calculation of the relationship between oil wetting properties (e.g., interfacial tension, contact angle, blob size) and interfacial area, and of the intrinsic reaction rate constant
- All inlets and outlets can be accurately controlled under high pressure condition for $scCO_2$
- 3D confocal images will allow us to identify real-time reactions on surfaces

Microhydrodynamics

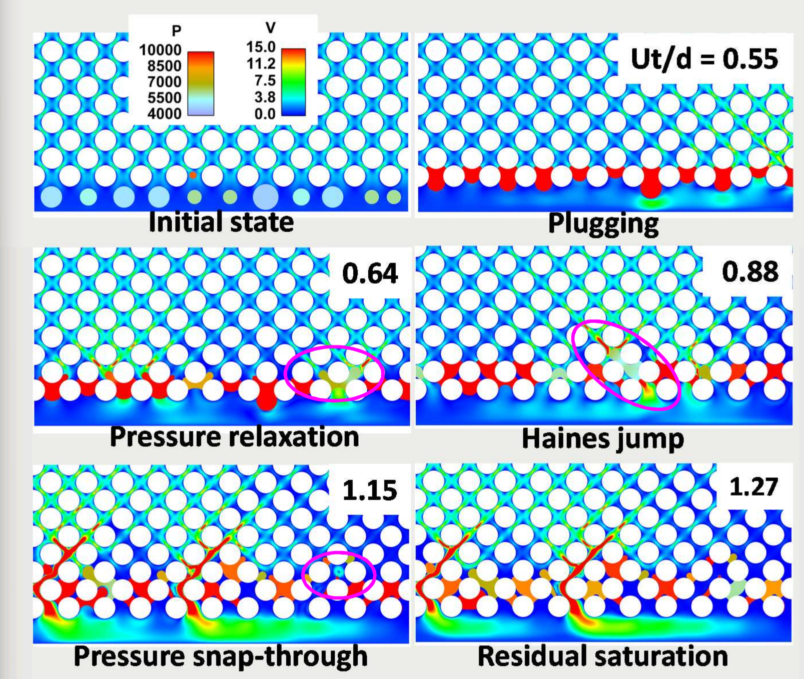
Porescale analysis of threshold pressure



Uniform injection through 12.5 micron pores over a range of Capillary numbers (Ca) and viscosity ratios (M)

Impact of Capillary no. and viscosity ratio on threshold pressure:
- Dynamic extra pressure drop is greater than static Young-Laplace: $\Delta p^+ > \sigma/R$
- Δp^+ increases with viscosity ratio
- Wetting film left behind for large Ca (higher viscous deformation)
- Low Ca increases propensity for channeling with spatial heterogeneity

Mesoscale analysis of capillary trapping



Droplets painted by pressure
Suspending fluid by velocity

Uniform injection with dispersed droplets

Porous medium 300 micron diam grains
- Porosity = 43.4%

Ca=0.00025, Iso-viscous
Observations:
- Plugging increases pressure to deform droplets through throats
- "Haines jumps" observed with droplet expansion into "pore body" and pressure relaxation
- Haines jump velocity 10x or more
- Local, transient eddys are induced
- Flow is episodic and dynamic
- Capillary trapping and fluid by-passing lead to residual saturation.

Concluding Remarks

Understanding the multiphase flow of CO_2, both during injection and in the long term, are crucial to addressing the primary challenges facing Geolgic Carbon Storage. Moreover, subsurface flow is a significant driver in fluid-induced geomechanics and geochemistry. We have initiated a tightly aligned plan combining field and lab observation with multiscale model development for predictive simulation and control, all aimed at revealing emergence of multiphase flow patterns driven by capillarity and buoyancy in heterogeneous geomaterials.

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