Long-term stability of Carbon Storage

Assessing the potential for Diffusion-driven remobilization in porous media

SCCS Annual Research Review – May 11th 2016

Jacques de Chalendar, Charlotte Garing, Yaxin Li and Sally M. Benson
Stanford University

Marco Voltolini and Jonathan Ajo-Franklin
Lawrence Berkeley National Laboratory

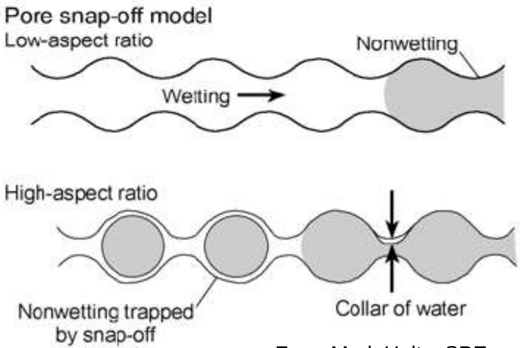
Context

Carbon Capture and Storage

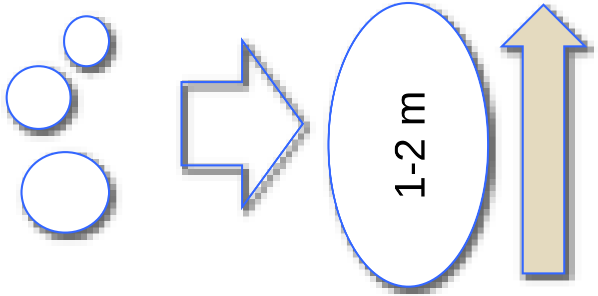
- Benson lab focuses on fundamental science to enhance predictability and performance of storage.
- Long-term stability of storage is critical.

Residual trapping

- Residual CO_2 trapping occurs when water imbibes back into the rock, typically after injection stops.



From Mark Holtz, SPE 75502



Question: Is residual gas trapping permanent? What are the mechanisms that could destabilize residually trapped CO_2?

- Focus here is potential for **diffusion-driven** remobilization.

Risk: Connected gas phase is easier to mobilize by buoyancy

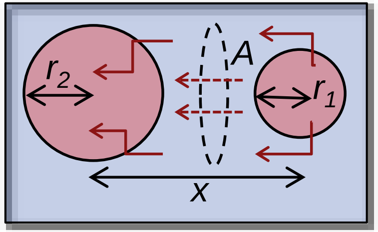
Background – Ostwald Ripening

Bubbles in a bulk liquid

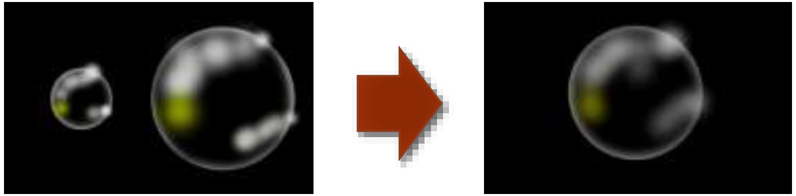
Laplace $$P_i - P_{liquid} = \frac{2\sigma}{r_i}$$

Henry $$\mathrm{P} = \mathrm{HC}$$

Fick $$\frac{\partial m}{\partial t} = DA\frac{\Delta C}{x}$$



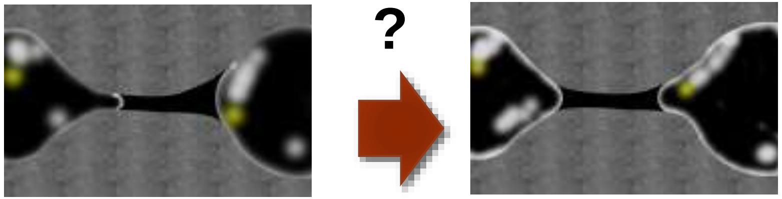
P : Pressure
C: Concentration
m: Mass
H,D: constants



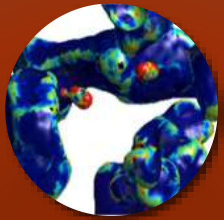
What happens in a porous medium?

- Pressure is no longer linked to cluster size but pore radius
- Morphology of pores and throats control capillary pressure gradients
- Evolution is hard to predict

Equilibrium is possible?



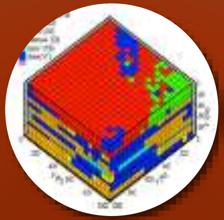
Research Approach



Assess the Potential for Ostwald Ripening

Observe Ostwald Ripening

Model Pore Scale Ostwald Ripening



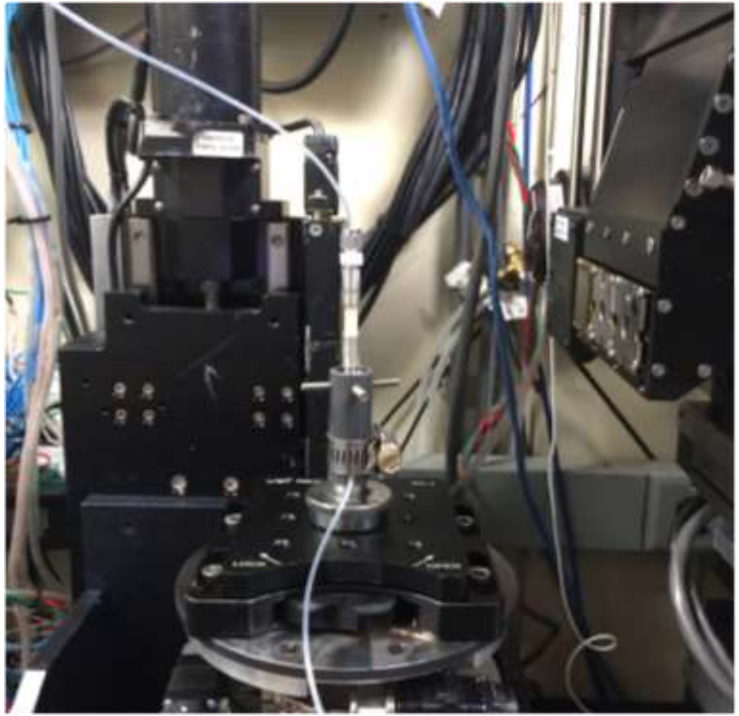
Parameterize Ostwald Ripening for Field Scale Modeling

Talk

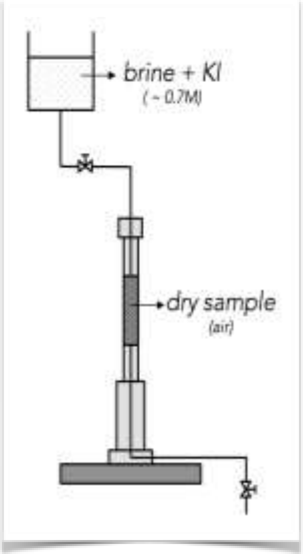
Talk

Assessing the potential for Ostwald Ripening

Advanced Light Source – Beamline 8.3.2



Gravity-driven imbibition experiment



Multi-scale synchrotron based micro-CT imaging
Voxel sizes from 4 to 0.6 μm

↓

Identification of fluid phases
Analyze connectivity, size and image resolution

↓

Interfacial curvature analysis

↓

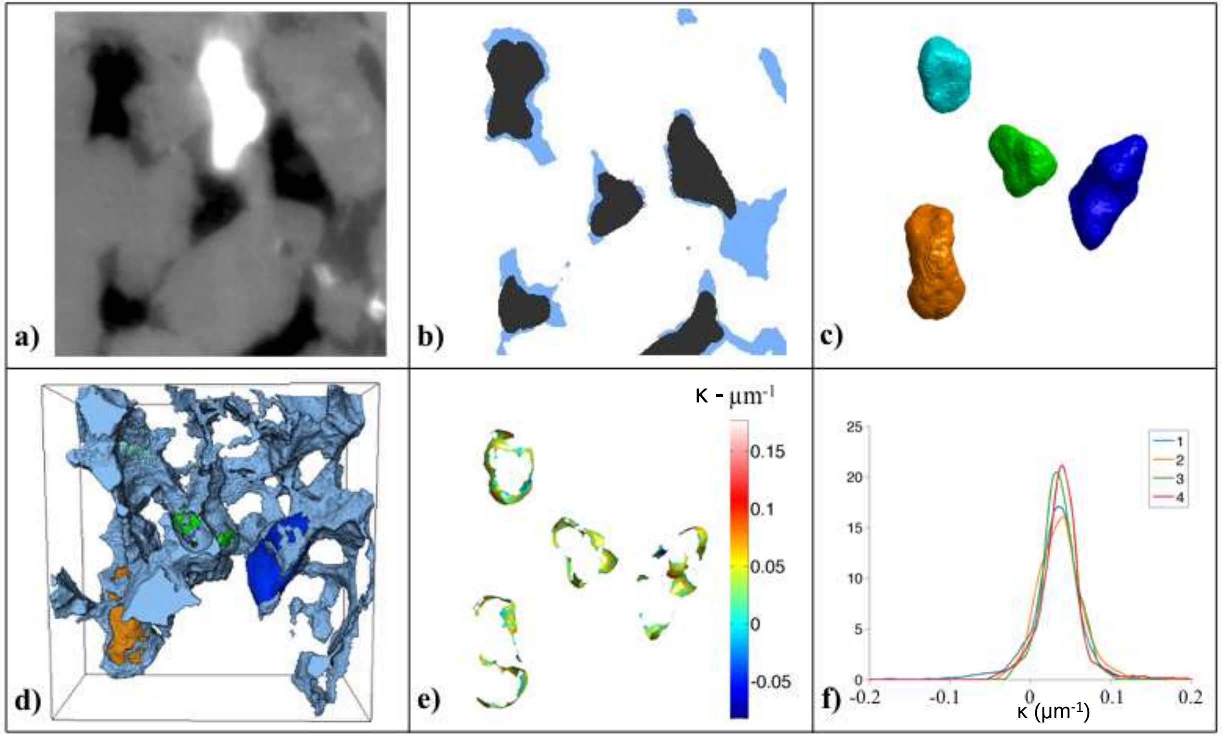
Capillary pressure distribution

Armstrong et al., 2012
Andrew et al., 2014

- 32keV, 1441 proj., PCO.4000/ 25keV, 2049 proj., PCO.Edge with OP
- reconstruction with Octopus

Assessing the potential for Ostwald Ripening

Workflow for Capillary pressure calculations



(a) Raw image
(b) Segmented image
(c) Isolate air ganglia
(d) Find interfaces
(e) Calculate curvature
(f) Output curvature pdfs

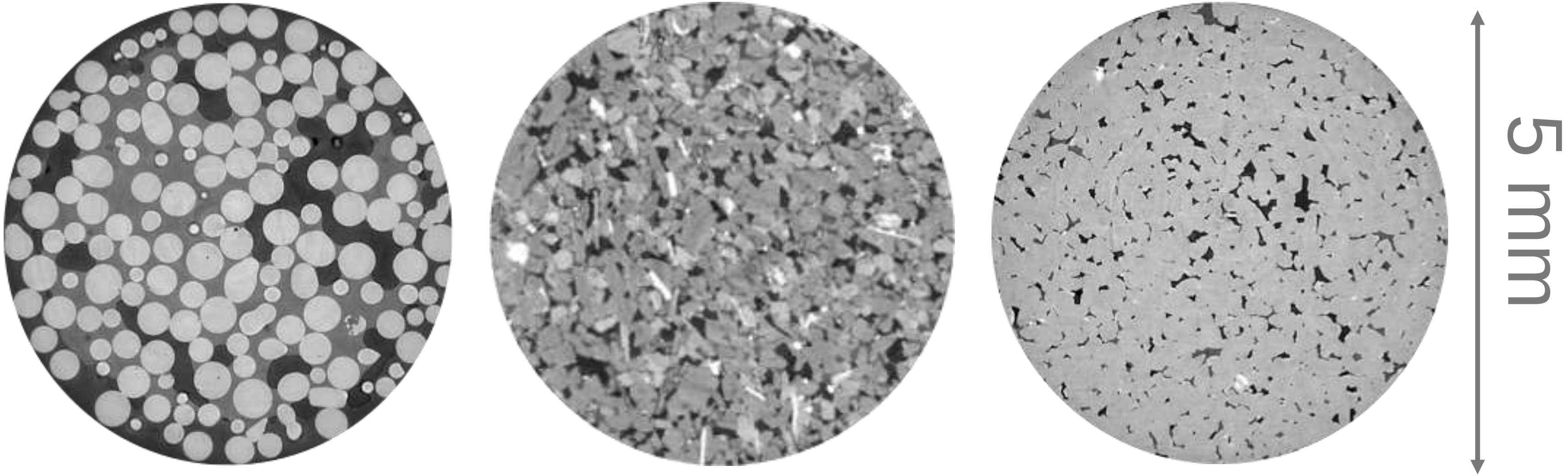
$$P_c = 2\sigma\kappa$$

κ: average curvature
σ: surface tension

Assessing the potential for Ostwald Ripening

Different rock samples

Glass beads — *Boise sandstone* — *Fontainebleau sandstone*

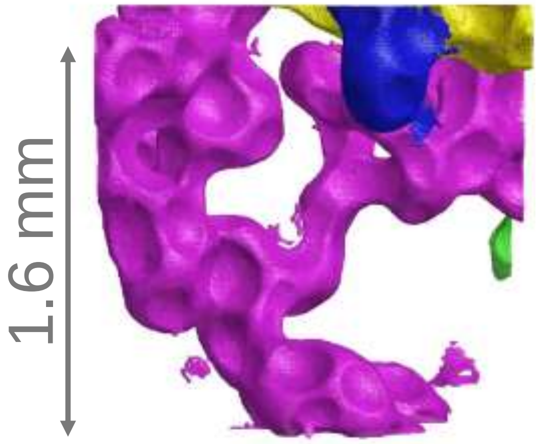


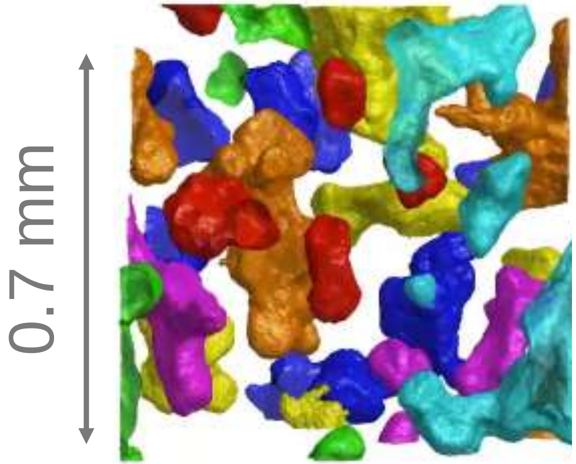
2D cross sections through the 3D reconstructed volumes

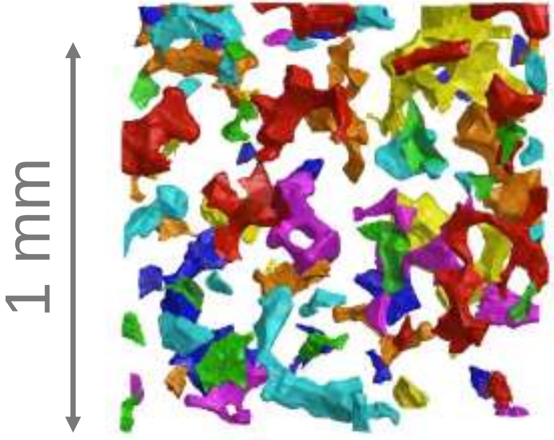
Assessing the potential for Ostwald Ripening

Imaging the gas phase

Glass beads	*Boise sandstone*	*Fontainebleau*
3.28 µm	1.8 µm	1.62 µm





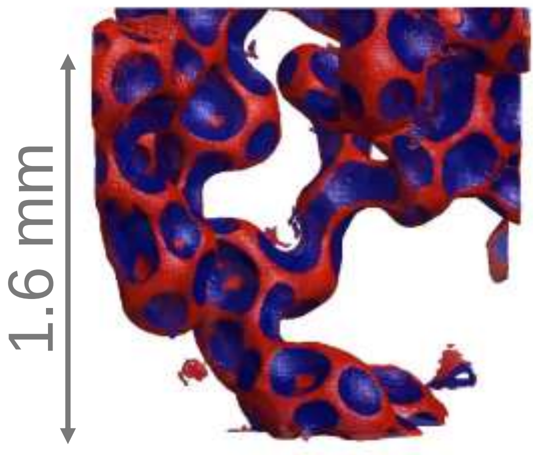


Surface of the air phase

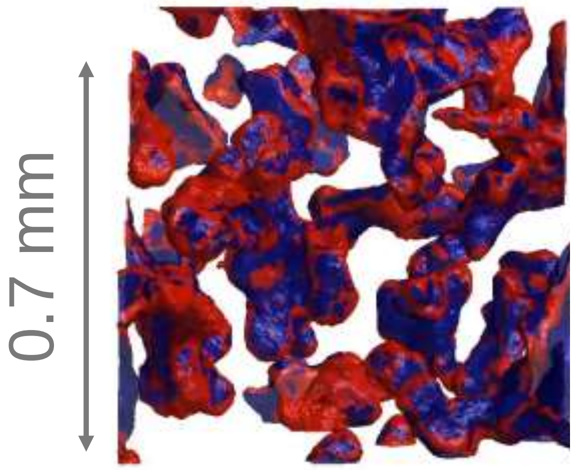
Assessing the potential for Ostwald Ripening

Finding the air-water interfaces

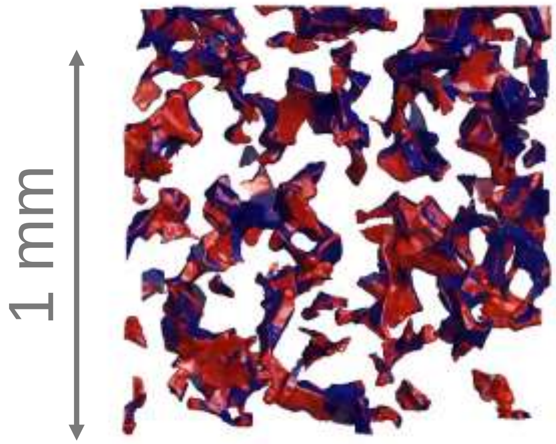
Glass beads
3.28 µm



Boise sandstone
1.8 µm



Fontainebleau
1.62 µm

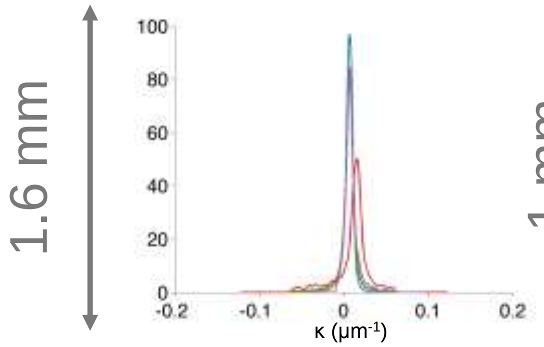


Interface identification

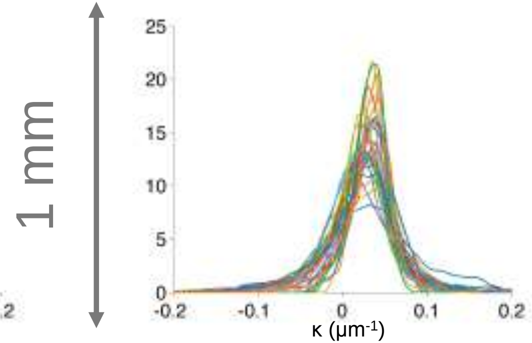
Assessing the potential for Ostwald Ripening

Estimating capillary pressures

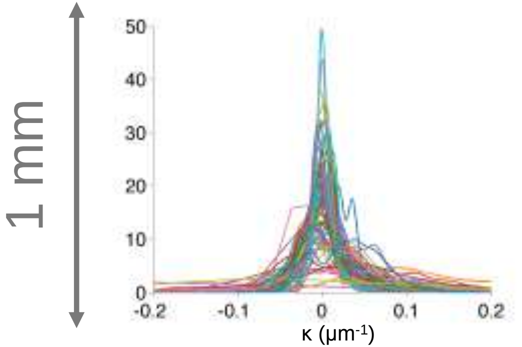
Glass beads
3.28 μm



Boise sandstone
1.8 μm



Fontainebleau
1.62 μm



Curvature estimation

# of clusters	**3**	**38**	**107**
Mean (Pa)	1,107	4,617	15,893*
STD (Pa)	277	2,851	16,326*
STD/Mean	25%	62%	103%

* Less certain than for rocks with larger pores

Assessing the potential for Ostwald Ripening

Preliminary Conclusions

- Accurate measurements of capillary pressure distributions for a population of ganglia
- Homogeneous rocks: pressures of residually trapped CO2 ganglia are similar
  - Potential for Ostwald Ripening seems limited
- Heterogeneous rocks: range of capillary pressures is larger
  - Potential for Ostwald Ripening is greater
- Additional experiments and modeling required to confirm preliminary conclusions

Observing Ostwald Ripening

↓

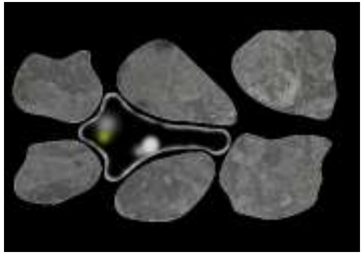
Drainage/imbibition in a Boise sandstone
Reservoir conditions
Repeated scans in time

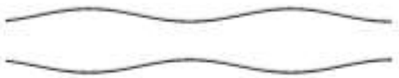
Modeling Ostwald Ripening at the pore scale

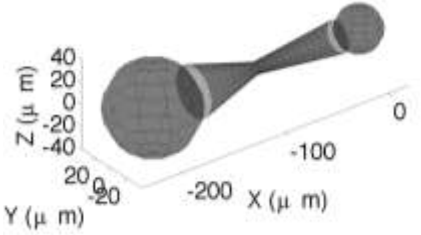
Modeling Ostwald Ripening at the pore scale

Conceptual idea

- Satisfy physical equations (Laplace, Henry, Fick)
- Simplify the porous medium representation
  - Bundle of tubes
  - Network of tubes
- Two-stage mechanism
  - Internal equilibrium of one cluster – fast
  - Mass transfer between clusters via diffusion – slow





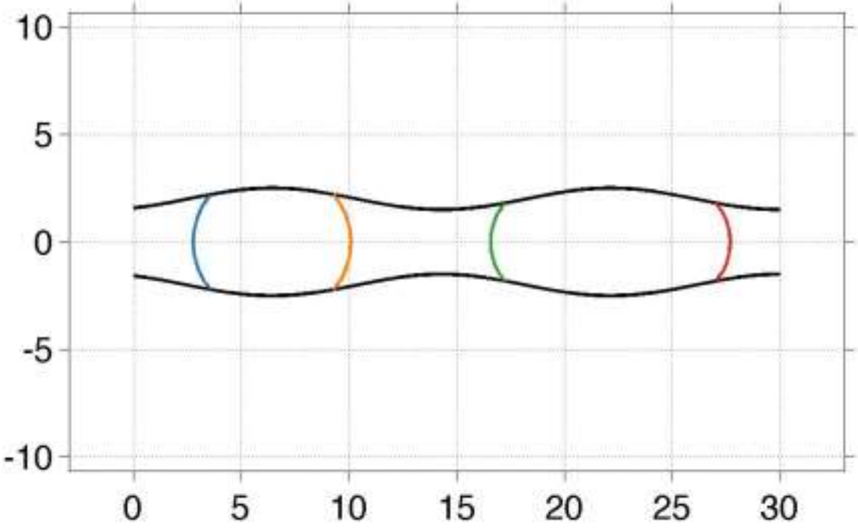


Hypothesis: in porous media, pore radius varies continuously, so we expect nature to find stable configurations. Can we find them ourselves?

Modeling Ostwald Ripening at the pore scale

Guiding intuition – Bundle of tubes model

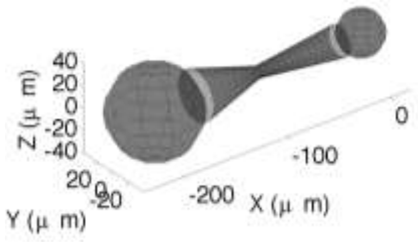
- Sequential algorithm
  1. Newton (damped) to find internal equilibrium position
  2. Volume transfer based on capillary pressure difference
- Difficult to capture complex pore geometry
- Difficult to have several bubbles interacting



Modeling Ostwald Ripening at the pore scale

Graph network representation

- Keep sequential algorithm
  1. Closed-form solution for internal equilibrium problem (solve cubic equation)
  2. For each bubble, find neighbors and diffusion paths
  3. Mass transfer based on capillary pressure difference and paths



- Keep physical equations

Laplace $P_{gas} - P_{liquid} = \frac{2\sigma}{R}$

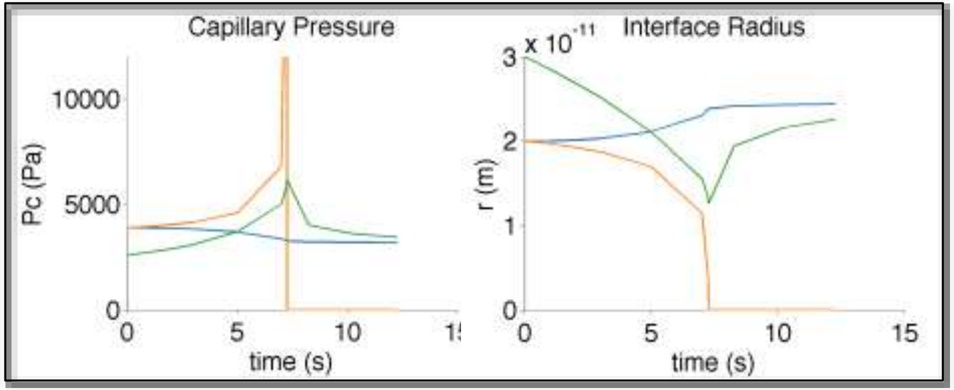
Henry $P = HC$

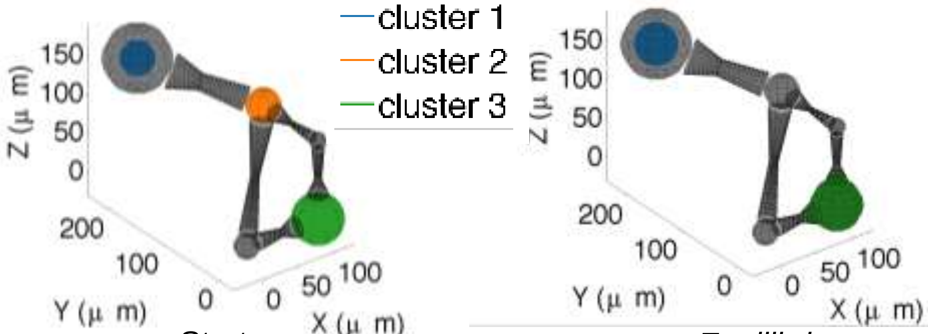
Fick $\frac{\partial m}{\partial t} = DA\frac{\Delta C}{x}$

Modeling Ostwald Ripening at the pore scale

Graph network representation - preliminary results

- Two-stage mechanism
  - Internal equilibrium (given a volume, what is the position of the interfaces and the pressure)
  - Mass-transfer (given the positions and pressures, what is the mass transfer)
- Importance of initial conditions
- Importance of pore structure



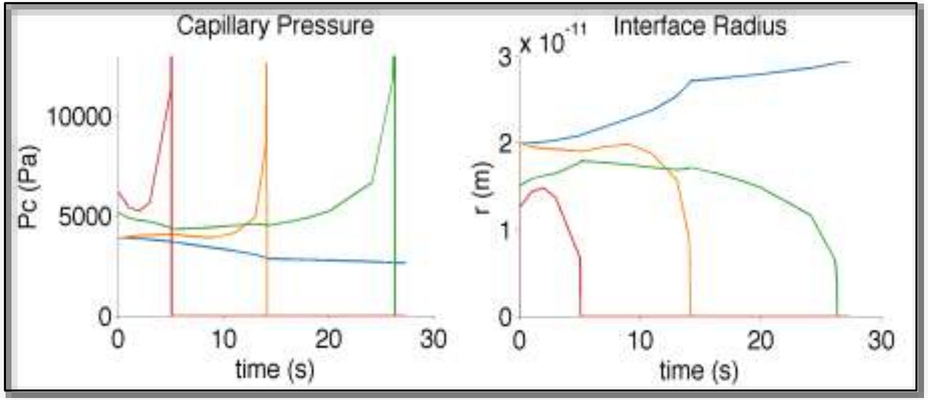


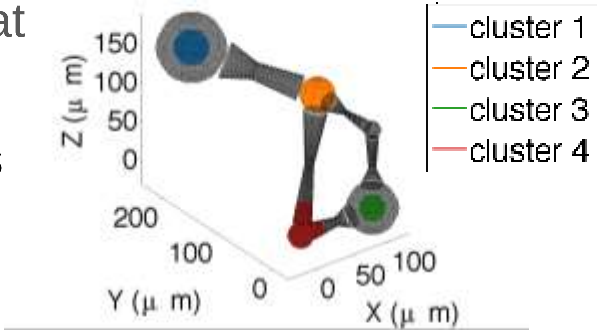
Start *Equilibrium*

Modeling Ostwald Ripening at the pore scale

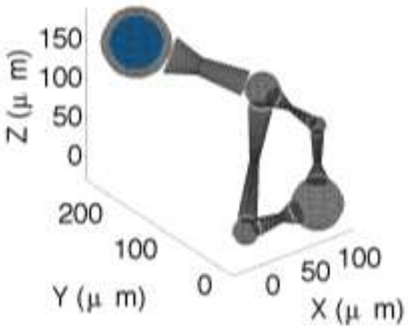
Graph network representation - preliminary results

- Two-stage mechanism
  - Internal equilibrium (given a volume, what is the position of the interfaces and the pressure)
  - Mass-transfer (given the positions and pressures, what is the mass transfer)
- Importance of initial conditions
- Importance of pore structure





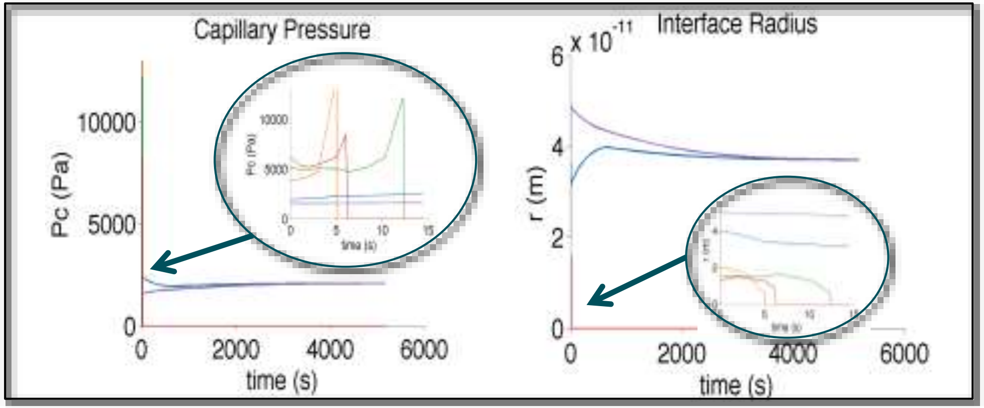
Start

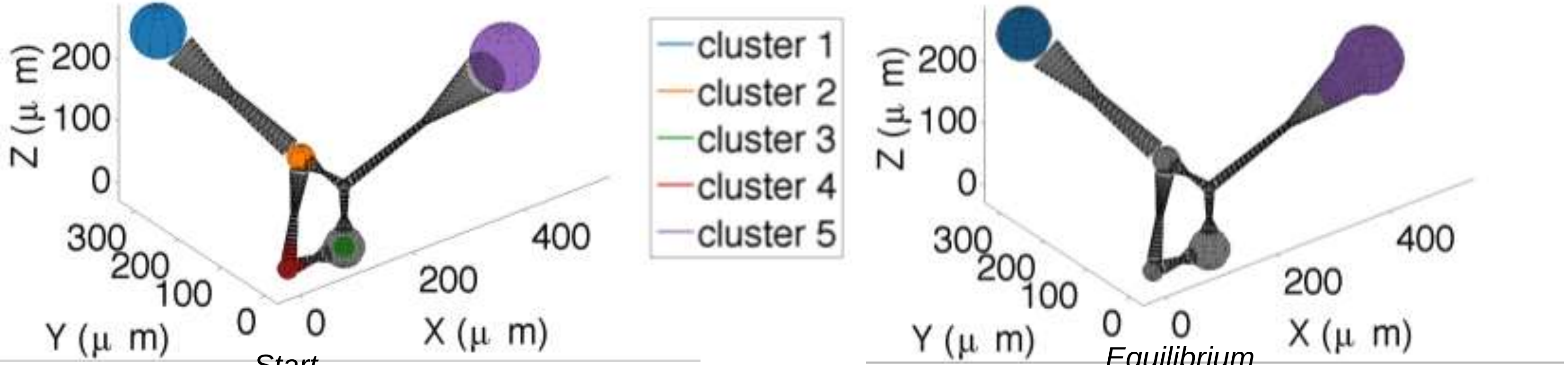


Equilibrium

Modeling Ostwald Ripening at the pore scale

Graph network representation - preliminary results

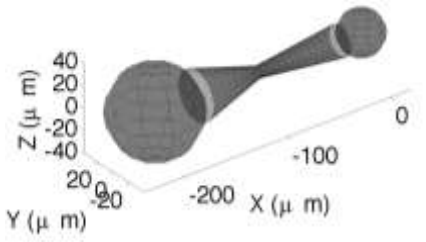




Start *Equilibrium*

Modeling Ostwald Ripening at the pore scale

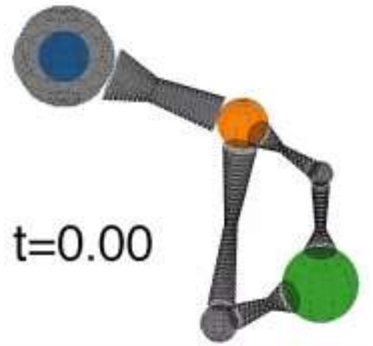
Graph network representation



- Keep two-stage mechanism
  - Closed-form solution for internal equilibrium problem (solve cubic equation)
  - For each bubble, find neighbors and diffusion paths
  - Volume transfer based on capillary pressure difference and paths
- Work in progress
  - Extending to statistically representative geometries
  - Dealing with Haines jump case

Ostwald Ripening at the pore scale

Some key ideas and conclusions



- In porous medium, topology dictates evolution
  - Pore radius distribution is likely to be continuous in a real rock
  - Stable configuration appears possible
- Inside a homogeneous region, best guess so far is equilibrium
- But between regions?
  - Field scale modeling – see Yaxin's poster