Long-term stability of Carbon Storage

EXPERIMENTAL INVESTIGATION, MODELING AND SIMULATION OF OSTWALD RIPENING IN THE CONTEXT OF GEOLOGIC CARBON STORAGE

AGU 2016 Fall Meeting – Session H51O – December 16th 2016

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

Marco Voltolini and Jonathan Ajo-Franklin
Lawrence Berkeley National Laboratory
Background
Long term stability of carbon storage

Residual trapping
- Residual CO$_2$ trapping occurs when water imbibes back into the rock, typically after injection stops.
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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.
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Background (cont’d)
Ostwald Ripening

Two bubbles in a bulk liquid
Background (cont’d)
Ostwald Ripening

Two bubbles in a bulk liquid

- Thermodynamic equilibrium is one bubble.
Background (cont’d)
Ostwald Ripening

Two bubbles in a bulk liquid

- Thermodynamic equilibrium is **one bubble**.

1. Laplace  \[ P_{a,b} - P_{\text{liquid}} = \frac{2\sigma}{r_{a,b}} \]
2. Henry  \[ P = HC \]
3. Fick  \[ \frac{\partial m}{\partial t} = DA \frac{\Delta C}{x} \]

- Driven by capillary pressure gradients.
Background (cont’d)
Ostwald Ripening

Two bubbles in a bulk liquid

What happens in a porous medium?
- Pressure is no longer linked to cluster size but pore radius.

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The bulk case
Background (cont’d)
Ostwald Ripening

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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.
Background (cont’d)
Ostwald Ripening

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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.

**Multi-ganglia equilibrium** seems possible but needs to be assessed.
Research Approach

1. Assess the Potential for Ostwald Ripening
2. Observe Ostwald Ripening
3. Model Pore Scale Ostwald Ripening
4. Parameterize Ostwald Ripening for Field Scale Modeling

Garing et al., Pore-scale capillary pressure analysis using multi-scale X-ray microtomography (submitted).
de Chalendar et al., Pore-scale considerations on Ostwald ripening in rocks, Energy Procedia (in press).
Assessing the potential for Ostwald Ripening

Some key takeaways

**Experimental work**

• We imaged the gas phase in an air/water system for two different rocks.
• We developed a method to estimate pore-scale capillary pressure based on the measurement of interfacial curvature.
Assessing the potential for Ostwald Ripening

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Experimental work
- We imaged the gas phase in an air/water system for two different rocks.
- We developed a method to estimate pore-scale capillary pressure based on the measurement of interfacial curvature.

Major conclusions
1. We observe a distribution of capillary pressures for a population of trapped gas ganglia.
2. Pore structure has a significant impact.
3. To a first order, capillary pressure of ganglia is controlled by neighboring throats.

Armstrong et al., 2012; Andrew et al., 2014; Garing et al., (submitted).
Modeling Ostwald Ripening at the pore scale

Conceptual idea

- Satisfy physical equations (Laplace, Henry, Fick).
- Simplify the porous medium representation.
  - Continuous pore network model
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**Hypothesis**: in porous media, pore radius varies continuously, so we expect nature to find stable configurations. Can we find them ourselves?
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- Two-stage mechanism
  1. Internal equilibrium of one cluster – fast
  2. Mass transfer between clusters via diffusion – slow
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  1. Internal equilibrium of one cluster – fast
  2. Mass transfer between clusters via diffusion – slow

1. Laplace (fast) \[ P_g - P_l = \frac{2\sigma}{r} \]
2. Fick (slow) \[ \frac{\partial m}{\partial t} = DA \frac{\Delta C}{x} \]
3. Henry (couple 1, 2) \[ P_g = HC \]
Modeling Ostwald Ripening at the Pore Scale

1. Solving the internal equilibrium problem

- Pressure must be the same everywhere in a ganglion.
- Since brine pressure is assumed uniform, interfacial curvature must be the constant along the unsupported interfaces.
  - For a given volume, what is the position of the interfaces and their common radius?
Modeling Ostwald Ripening at the Pore Scale

1. Solving the internal equilibrium problem

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  ➢ For a given volume, what is the position of the interfaces and their common radius?

\[ \text{Not at internal equilibrium} \]
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Modeling Ostwald Ripening at the Pore Scale

2. Solving the mass-transfer problem

1. Find diffusion paths.
2. Use superposition theorem to calculate net mass inflow for each bubble during time step.

\[ \frac{\partial m_{ij}}{\partial t} = \frac{D A_{ij} \cdot 2\sigma}{x_{ij}} \frac{1}{H \left( \frac{1}{R_j} - \frac{1}{R_i} \right)} \]

\[ \frac{\partial m_i}{\partial t} = \sum_{i=1}^{k_i} \frac{\partial m_{ij}}{\partial t} \]
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Modeling Ostwald Ripening at the Pore Scale

3. Simulating for evolution – two-stage mechanism

1. Solve internal equilibrium problem for each ganglion

2. Solve mass-transfer problem over $\delta t$

Capillary pressure for each ganglion

Update mass of each ganglion
Modeling Ostwald Ripening at the Pore Scale
Guiding physical intuitions – different pathways to equilibrium
Modeling Ostwald Ripening at the Pore Scale
Guiding physical intuitions – different pathways to equilibrium

AGU 2016 Fall Meeting – Session H51O – Slide 10/13
Modeling Ostwald Ripening at the Pore Scale
Simulating evolution – Initial condition

T = 0
Modeling Ostwald Ripening at the Pore Scale
Simulating evolution

T = 8.6 hours
Modeling Ostwald Ripening at the Pore Scale
Simulating evolution

T = 9.1 hours
Modeling Ostwald Ripening at the Pore Scale
Simulating evolution

T = 38.8 hours
Modeling Ostwald Ripening at the Pore Scale
Simulating evolution – Final condition

T = 35 days

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Modeling Ostwald Ripening at the Pore Scale

Maximum stable saturations

• Drop simulation of evolution for now, look for stable positions instead.
• From experiments we know that the capillary pressure of residually trapped ganglia are controlled to a first order by neighboring throats.
Modeling Ostwald Ripening at the Pore Scale
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*Stochastically generated pore network model*
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Stochastically generated pore network model
Modeling Ostwald Ripening at the Pore Scale

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Equilibrium with ganglia spanning only one pore does not seem possible for realistic saturations.
Ostwald Ripening at the pore scale
Some key ideas and conclusions

- We developed a framework to model Ostwald Ripening at the pore scale using continuous pore network modeling.
- The relationship between capillary pressure and mass is fundamentally different in the bulk and porous media cases.
- In porous media, topology and initial conditions dictate evolution.
  - Pore radius distribution is likely to be continuous in a real rock.
  - Stable configuration appears possible.
Thank you
Supplemental slides
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- We developed a method to estimate pore-scale capillary pressure based on the measurement of interfacial curvature.

We observe a distribution of capillary pressures for a population of trapped gas ganglia.

Pore structure has a significant impact.

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Assessing the potential for Ostwald Ripening
Advanced Light Source – Beamline 8.3.2

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

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

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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

\[ P_c = 2\sigma\kappa \]

\( \kappa \): average curvature
\( \sigma \): 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
3.28 μm

Boise sandstone
1.8 μm

Fontainebleau
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

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Assessing the potential for Ostwald Ripening
Estimating capillary pressures

Glass beads
3.28 µm

Boise sandstone
1.8 µm

Fontainebleau
1.62 µm

# of clusters
3
38
107

Mean (Pa)
1,107
4,617
15,893*

STD (Pa)
277
2,851
16,326*

* Less certain than for rocks with larger pores
Modeling Ostwald Ripening at the Pore Scale

1. Solving the internal equilibrium problem

- Pressure must be the same everywhere in a ganglion.
- Since brine pressure is assumed uniform, interfacial curvature must be the constant along the unsupported interfaces.
- For a given volume, what is the position of the interfaces and the pressure?
  - Problem can be shown to have a closed-form cubic solution for all available volumes.
Modeling Ostwald Ripening at the Pore Scale

1. Solving the internal equilibrium problem

- Pressure must be the same everywhere in a ganglion.
- Since brine pressure is assumed uniform, interfacial curvature must be the constant along the unsupported interfaces.

For a given volume, what is the position of the interfaces and their common radius?
Modeling Ostwald Ripening at the Pore Scale

Some more results

- Determining evolution
  - Initial conditions
  - Pore structure (diffusion paths)
- Relationship between capillary pressure and mass is fundamentally different in the bulk and porous media cases.
- Current model does not handle ganglia spanning multiple pores.
Modeling Ostwald Ripening at the Pore Scale
Equilibria with single-pore spanning ganglia

- Drop simulation of evolution for now.
- From experiments we know that the capillary pressure of residually trapped ganglia are controlled to a first order by neighboring throats.
- Can use this and the information given by the internal equilibrium problem on the pore space to make some educated guesses.

Equilibrium with ganglia spanning only one pore does not seem possible for realistic saturations.
Generating Pore Network Models

Overview

Outline for the generation algorithm

- Generate bodies
- Assign coordination numbers
- Generate connections
  - Using coordination numbers
  - Take closest match to a draw from throat length pdf
- Assign throat radii

Data: Dong and Blunt, 2009.
Code: https://github.com/jdechalendar/pnm-generation
Generating Pore Network Models

Matching target distributions for various parameters

- Pore throat radius (µm)
- Pore body radius (µm)
- Pore throat length (µm)
- Coordination number

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