Capacity estimation of capillary trapping of $\text{CO}_2$ in heterogeneous saline aquifers through 3-D invasion percolation simulations at the cm-to-m scale

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Problem conceptualization

1. Single-phase CO$_2$, ‘dry-out’ zone, strong pressure gradients and inertia effects are important.
2. Two-phase flow region, buoyancy, capillarity, and pressure gradients control plume behavior.
3. Far-field region where buoyancy-capillary effects dominate.

Pressure management and plume control strategy via Brine Extraction Storage Test (BEST)
Main features of CO$_2$ plume detected from seismic images:

- Preference to **vertical migration** at early stage
- Accumulation underneath a **caprock**
- **Layered accumulation** following stratigraphy
- Qualitative estimation of **residual** and **mobile phase**
**Research approaches**

- **Tank experiments**
  - Synthetic sandbox (2D)
  - Surrogate fluids
  - Realistic behavior

- **Core flooding**
  - Real rock core (3D)
  - Reservoir fluids + nanoparticles
  - Experiments + IP simulation

- **Bedform models**
  - Realistic crossbedding (3D)
  - Reservoir fluids
  - IP simulation

- **Sedimentary-relief peels**
  - Real crossbedding (2D)
  - Reservoir fluids
  - IP simulation

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**Synthetic models**

- Experimental observations

**Medium fluids application**

- Real sedimentary structures

**Numerical simulations**
Objectives of sandbox experiments

• To mimic flow behavior of supercritical CO₂ and observe mechanisms that are relevant to the field scale in a controlled laboratory environment

• To provide experimental datasets for numerical benchmarking

• To evaluate strategies for optimization of storage capacity

Darcy-based model prediction
Intermediate scale approach
from small & simple to large & complex setups

Trevisan et al. 2014 (IJGGC)
Trevisan et al. 2015 (WRR)
Trevisan et al., in preparation
IP model of large heterogeneous sand tank

Capillary threshold pressure field

Capillary $P_{th}$ (kPa)

0.05 1.5 2.4

natural log of permeability
No background water flow in Permedia’s static simulation.
Objectives of IP simulations of bedform models

• To understand the effects of meso-scale heterogeneity on local capillary trapping capacity of CO₂ during capillary/buoyancy-dominated flow regime

• To identify emergent behavior* of a type of geological reservoirs (fluvial depositional environment)

• To define an efficiency function to predict CO₂ trapping, based on fundamental properties of geology and fluids

*Behavior of a system that is not explicitly described by the behavior of its individual components, and is therefore unexpected to an observer.
Natural fluvial deposits (dm-scale)  

Fig. 5  

Rubin 1987 (USGS book)  

Numerical synthetic analog (binary model)  

Fig. 19  

Fig. 42a  

Fig. 63  

Numerical synthetic analog ($P_{th}$ REV model)
Selection of REV

Fraction of matrix content vs. sample volume (m$^3$)

- Orange line: Fig. 5
- Blue line: Fig. 19
- Yellow line: Fig. 42a
- Green line: Fig. 63

Sample volume (m$^3$):
- 1.00, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0

Fraction of matrix content:
- 50%, 60%, 70%, 80%, 90%, 100%

Volume parameters:
- 0.28 m, 0.28 m, 8.2 × 10$^{-3}$ m$^3$
54 textural classes - 25 facies combinations

decreasing grain size

poorer grain sorting
Invasion percolation conceptual model

Seismic survey at Sleipner

Arts et al. 2008 (First Break)

Primary independent variable, **capillary threshold pressure**:

\[ P_{th} = \frac{2\gamma \cdot \cos\theta}{r} \]

Primary dependent variable, **average model saturation** (fraction of domain invaded):

\[ \langle S_{CO_2} \rangle = \frac{\text{cells invaded}}{\text{total cells}} \]

**Static migration** simulated with Permedia™ until CO₂ plume spans whole domain. 200 equiprobable realizations of \( P_{th} \) field for each facies combination.
Distance between means, \( \delta \):

\[
\left| \mu_1 - \mu_2 \right| \over \sigma_1
\]

\[
\delta = 1.1 \\
\langle S_{CO_2} \rangle = 3.7 \pm 0.6
\]

\[
\delta = 3.3 \\
\langle S_{CO_2} \rangle = 12.7 \pm 2.6
\]

\[
\delta = 7.5 \\
\langle S_{CO_2} \rangle = 32.9 \pm 4.8
\]
Fig. 5 $P_{th}$ field

Extremely Well Sorted
Very Well Sorted
Well Sorted
Moderately Sorted
Poorly Sorted
Effect of stratigraphic contrast on storage capacity

25 facies combinations applied to 4 sedimentary models
Are these trends predictable?

Fitting a parametric nonlinear regression model to simulated results

\[ y = D + \frac{A - D}{1 + \left(\frac{x}{C}\right)^B} \]

\[ R^2 = 0.94 \]

\[ R^2 = 0.97 \]

\[ R^2 = 0.99 \]

\[ R^2 = 0.96 \]
Conclusions

• Thanks to low computational demand, IP approach can be applied to stochastic analysis of local capillary trapping capacity for a wide range of stratigraphic contrasts

• A non-linear correlation exists between such contrast and the average saturation of the plume

• This correlation appears to be strongly dependent on some geometrical feature of the bedform model
Ongoing research

- Do these models make sense, geologically?
- What is the influence of the sedimentary model on plume entrapment (maximum plateau)?
- What controls the variance (error bars) of plume saturation?
- How is groundwater flow going to affect the plume?
- Scale effect
Questions?