Multi-scale multi-phase flow upscaling

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Handling a highly complex problem

**Goal:** Build consistent multi-scale and multi-phase reservoir flow simulation models

To do this we need:

- Consistent comparison of measurements at different scales
- Rock-specific functions for the flow processes
- A geo-statistical framework (representative models)
Pore to Field Workflow: Statfjord
Rustad et al., 2008 (SPE 113005)

1. Identify lamina and pore types from core

2. Calculate multiphase flow functions

3. Apply functions in lithofacies models

4. Upscale lithofacies models

5. Significantly improved history match
The Representative Elementary Volume (REV)
(after Bear 1972)

- Mainly smaller pores
- Mainly larger pores
Pore-space characterisation

- Example core analysis, thin section, backscatter SEM mineralogical studies and pore-scale modelling used to estimate multiphase flow properties

- In Salah CCS project (Lopez et al. 2011, Ringrose et al., 2011)

Grain characterisation
(cathodoluminescence)

Mineral identification
(BSEM)

Pore Network Modelling
The REV concept as a framework for upscaling

The Representative Elementary Volume concept gives the framework for understanding geological and measurement scales.

From Nordahl & Ringrose (2008) and Ringrose & Bentley (2015)
Multi-scale REV and fluid forces

The Balance of Forces concept merged with the REV concept is useful to indicate which scales most affect flow.

- Capillary-dominated
- Viscous-dominated
- Gravity-dominated

Measurement Volume [m^3] (log scale)

- Capillary trapping
- Lamina REV
- Capillary-dominated
- Viscous-dominated
- Fluid segregation
- Viscous fingering and channeling
- Gravity-dominated

E.g. capillary trapping is likely to be important for rocks with strong permeability contrasts at the <20cm scale.
Fluid forces and scaling group theory

- The controls on two-phase immiscible flow can be captured in a set of dimensionless ratios or scaling groups (Ringrose et al., 1993; Li and Lake, 1995)

\[
\frac{\text{Viscous}}{\text{Capillary}} = \frac{u_x \Delta x \mu_{\text{CO}_2}}{k_x \left(\frac{dP_c}{dS}\right)}
\]

Darcy’s Law

\[
\frac{\text{Gravity}}{\text{Capillary}} = \frac{\Delta \rho g \Delta z}{\left(\frac{dP_c}{dS}\right)}
\]

Length scale (grid size)

\[
\frac{\text{Viscous}}{\text{Gravity}} = \frac{q \Delta x \mu_{\text{CO}_2}}{\Delta \rho g \Delta z}
\]

Capillary Pressure gradient

Where \(\Delta x, \Delta z\) are total system dimensions, \(\Delta \rho\) is the fluid density difference, \(\mu_{\text{CO}_2}\) is the viscosity of \(\text{CO}_2\) and \(dP_c/dS\) is the capillary pressure gradient wrt saturation.

Which forces control \(\text{CO}_2\) storage?
Fluid process and domains for a hypothetical GCS reservoir
(Oldenburg et al. 2016)
Two-phase Steady-State Solutions

Numerous recipes for solving multi-phase flow problems (incl. dynamic, non-steady state)

Steady-state solutions for immiscible two-phase flow are the end-member cases:

- **Viscous limit (VL):** The assumption that the flow is steady state at a constant fractional flow. Capillary pressure assumed to be negligible.

- **Capillary equilibrium (CE):** The assumption that saturations are controlled by the capillary pressure curves. Applied pressure gradients assumed to be negligible.

- **Gravity-Capillary equilibrium (GCE):** Similar to CE, except that the saturations are controlled by the effects of gravity:
  - **Vertical equilibrium (VE):** a simplified gravity equilibrium assumption but with capillary forces neglected
Analytical solutions for a buoyant plume

• Nordbotten et al. (2005) and Nordbotten & Celia (2006) proposed a dimensionless group, $\Gamma$, to characterise an ideal solution for CO$_2$ injection into a confined aquifer (a version of the viscous-gravity ratio):

$$\Gamma = \frac{2\pi \Delta \rho k \lambda_b B^2}{Q_{well}}$$

• Okwen et al. (2010) derived the storage efficiency factors, $\varepsilon$, as a function of $\Gamma$ for various mobility ratios (residual brine saturation, $S_r = 0.15$)

• For higher gravity numbers $\Gamma > 10$ there is a significant loss in storage efficiency

Storage efficiency $\varepsilon$ vs. gravity factor $\Gamma$
(from Okwen et al. 2010)
Insights from Sleipner

- Important insights into CO₂ flow dynamics from the seismic time-lapse data
  - Gravity segregation and top-structure control of plume shape
  - Multi-layer system with thin-bed effects on seismic
  - Insights on dissolution rate
- High-resolution simulation from Cavanagh (2013):
  - Sleipner Layer-9 reference model (time = 2008)
VE applied to Sleipner

- Nilsen et al. (2011) tested various VE models to look at vertical segregation of CO₂ and brine for the Sleipner (Layer 9) reference model.
- They showed that vertical segregation occurs in a relatively short time and that the system reaches vertical equilibrium before the end of the injection period.

Example VE simulation result from Nilsen et al. (2011):
- Layer 9 cross-section after 32 years injection.
CE applied to Snøhvit

- Analytical CE upscaling for a layered medium with CO₂-brine functions
- Based on Snøhvit Tubåen data: lithofacies-scale, fluvio-deltaic system, assumes 20:1 permeability contrast
- Note how anisotropy in CO₂ flux varies with saturation

Upscale Layered Model
Analytical Capillary Limit Solution

Input rock functions

Relative Permeability / Pc (bars)

Sw

Horizontal CO₂ flow
Vertical CO₂ flow

Rock 1 = 100md
Rock 2 = 2000md

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Summary: CO₂ storage flow upscaling

• Well-established routines for building multi-scale and multi-phase reservoir flow simulation models

• This highly complex problem should be handled using the multi-scale REV concept – geology has inherent characteristic lengthscales

• The CO₂-brine flow modeling problem requires careful assessment of the gravity, viscous and capillary force ratios

• CO₂ storage is dominated by gravity and capillary forces

• Multi-scale approaches should be used to improve forecasts and models of CO₂ storage processes
Multi-scale, multi-phase flow upscaling

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References


• Kjaer, A. F. 2015. Fitting top seal topography and CO2 layer thickness to time-lapse seismic amplitude maps at Sleipner. *Interpretation*, 3(2), SM47-SM55.


