Reservoir Characterisation and Modelling for CO$_2$ Storage

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Why build subsurface models?

- To simulate fluid flow
- To estimate capacity
- Predict reservoir response
- To ascertain uncertainty
- To know when and where to monitor
- To impress stakeholders: communication tool
Seek understanding!

“The purpose of computing is insight, not numbers” Richard Hamming.

• The hardest part of modelling is to develop an intuition for the physical processes.
Models should be fit for purpose

1. To address scientific questions in a generic context e.g.:
   - the effect of shale barriers on vertical migration of CO$_2$
   - the effect of a hydrodynamic gradient on CO$_2$ migration
   - Theory of convection mixing

Generic modelling example: Convection of dissolved CO$_2$

Slide courtesy of Jonathan Ennis-King, CSIRO
Models should be fit for purpose

2. To make technical predictions in a site-specific context to support decisions e.g.:
   - What is the breakthrough time of CO\textsubscript{2} in an EOR project for deep injection?
   - What is the effect of well-spacing on the maximum injectivity?
   - What is the predicted seismic response?

Image source: http://www.iogsolutions.com
Site Specific Modelling
Example: Breakthrough at monitoring well

Reference: Hosseini et al., Static and dynamic reservoir modeling for geological CO$_2$ sequestration at Cranfield, Mississippi, U.S.A. Int. J. Greenh. Gas Control,
Models can be simple...

e.g. Analytical models

\[ r_{c,\text{max}}(t) = \sqrt{\frac{k_{rc} \mu_w q t}{\phi \tau \mu_c k_{rw} h}} \]

Nordbotten et al. (2005)
Example

• A basin-scale region investigated.
• Bottom hole pressure the limiting factor on injectivity and capacity.
• Faults sealing or not sealing the uncertainty.
• Multiple scenarios investigated

Source: K. Michael, CSIRO, using MonteCarbon modelling
...or more complex

Solves a large set of linear equations at a number of given time-steps for a large number of cells
• Computationally demanding
• Can be “coupled”

Example from the Gorgon Project:
• Planned to inject and store 3.4 MT PA
• Site located beneath an “A Class” nature reserve
• Pressure management employed
• Long-term modelling and monitoring required

Governing equations & computer codes

- Starts with initial conditions: temp, pressure, salinity, saturations...
- Mass and energy conservation
- Transport law (e.g. Darcy’s law)
- Equation of state for fluids
- The heart of this method is the solution of a big set of linear equations

What (physical) processes would you like to simulate?

- “Flow” + transport + heat transport + fault reactions
  + dissolution + mineral reactions + temperature

- Code comparison
- Tested against analytical models
- Tested against previous field studies
Typical issues

- Code limitations
- Non-uniqueness
- Inappropriate boundary
- Over-simplification
- Not properly calibrated
- No relative permeability and capillary pressure data

Zhou et al. (2008)
The Foundation: A Geological Model

Aims to:

• Capture effects of structure, stratigraphy, sedimentary architecture, petrophysical properties
  Reservoirs and seals
  Lateral and vertical heterogeneity
  Faults & fractures
What it is we are trying to represent?

- Pore geometry
- Sedimentary structures
- Rock texture
Reservoir heterogeneity: bedding

Top Images: http://throughthesandglass.typepad.com/through_the_sandglass/2010/12/
Bottom image: https://www.mnh.si.edu/exhibits/backyard-dinosaurs/questions-answers.cfm?know=a24
Parasequences: Intraformational seals (baffles) increase length of CO₂ migration pathways & potential for Sgr and dissolution
Flow Unit Architecture

From: Petroleum Geoengineering

(after Weber and van Geuns, 1990)
Conceptual geological model

Simple 1D models

\[ \frac{K_v}{K_h} \ll 1 \]
Some Alternatives

Data Point Set

Simple 3D models

Pure Object Models

Network Models
The 3D static geological model

• 3D representation(s) of the subsurface

• Each cell contains values for geographic position, depth, volume, rock type, poro/perm, and other “static” properties.

• Size and complexity may be a limiting factor.

• Grid resolution a key decision: detail vs. computational limits.
Pillar Gridding

• Structural model
• Stratigraphic zones and horizons

• Grid orientation
Discretisation & parameterisation

Each grid block only has one value for porosity, permeability, saturation, composition etc. This has two important consequences:

• We cannot resolve anything in the results below the size of a grid block, i.e. may need to refine grid in areas of interest.

• Geological data measured on different scales e.g. core data, has to be “upscaled” or averaged in an intelligent way.
Stochastic modelling

Truncated Gaussian Simulation

Sequential Indicator Simulation

Indicator Kriging
Object Facies modelling

“No matter what prediction technique we apply to a variable we are unlikely to achieve an acceptable result unless we take geological effects into account.”
(Houlding, 1994)
Input data types

Hard Data:

Direct measurement from the sub surface:

- Cores (metres),
- cuttings (a few mms),
- Plugs (10s cms)
- fluid samples...
Data types

“Soft” data

Indirect interpretation of the rock and fluid properties from geophysical & petrophysical measurements:

• Well logs
• 3D seismic,
• MT, gravity, Electromagnetics,
• Remote sensing...

[Diagram showing various geological layers and properties]
Seismic

Exploration wells are on the highs, injection wells in the lows

The reservoir (and seal) characteristics seen in the exploration well may not be the same as those that will be encountered in the injection well(s) or by the migrating CO₂.
Outcrop Analogues

Top Image Source: www.aapg.org  “Austin Chalk Getting Another Look”

Bottom Image Source: www.aapg.org  “Outcrop analog for an oolitic carbonate ramp reservoir”
Modelling workflow

Small-scale (pilot projects) Vs Basin-scale

Anderson & Woessner (1992)
Small is beautiful?

Resist the “one big model” temptation.

- Multi-disciplinary workflows encourage big models you can’t easily iterate.
- Early models should be small so you can run a lot of them, and investigate sensitivities.
- Mature models can be bigger, but still allow for a suite of models.
Closing remarks

- Models must be fit for purpose
- Models are useful tools BUT be aware of the shortcomings
- The static model is a living repository for integrating all relevant information: feed the beast!
- Get to know your uncertainty

Models provide insight not answers.
Thank you

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