

Reservoir simulations of the main trapping mechanisms for CO₂

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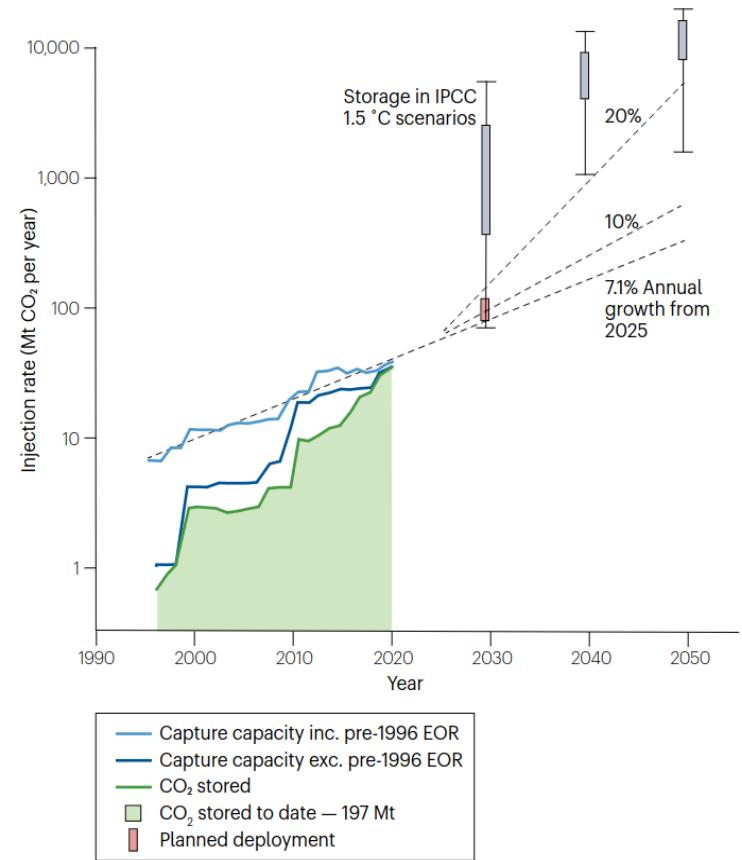


smile

European Doctoral Network
on Geo-energy

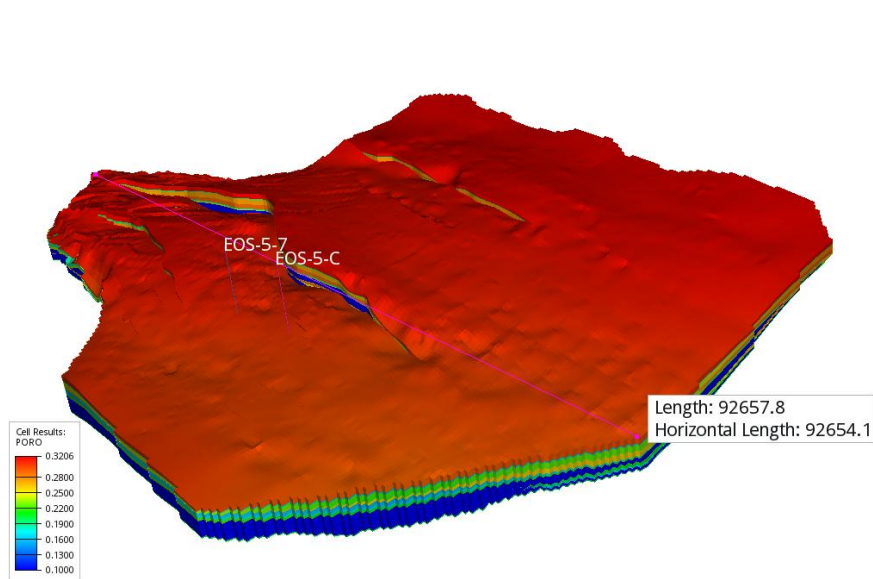
Storage needs

- Reaching climate goals requires exponential growth in storage
- Capacity of single well in mega-ton/yr range
- Need to go from tens to thousands of injection wells in a few decades

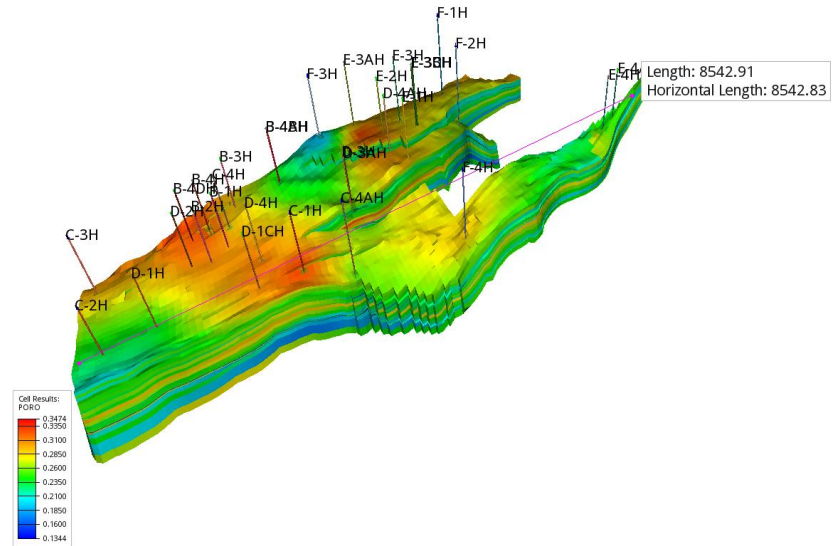


Krevor et.al., 2023

Storage vs HC models



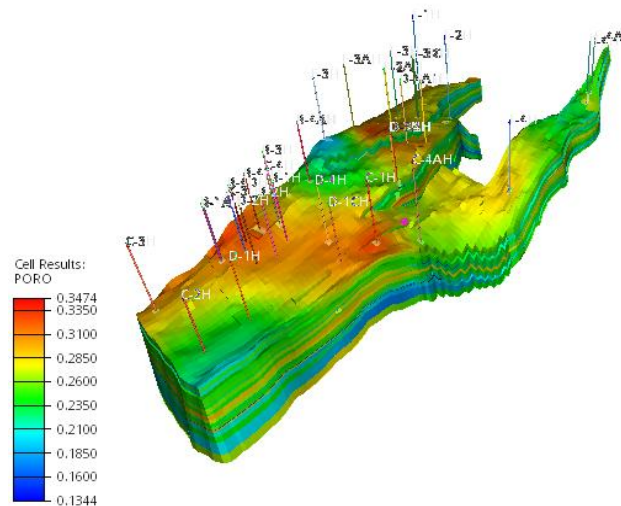
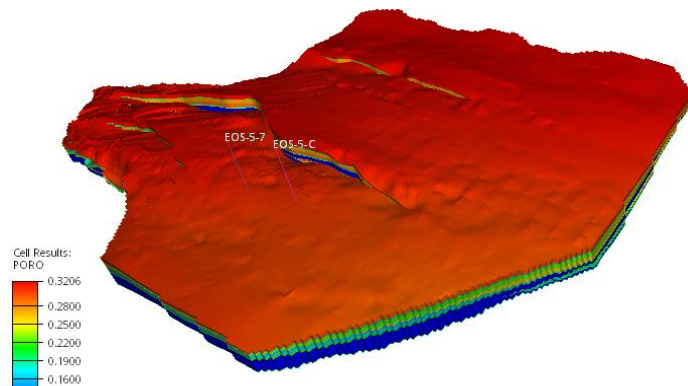
Aurora CO₂ storage site



Norne oil and gas field

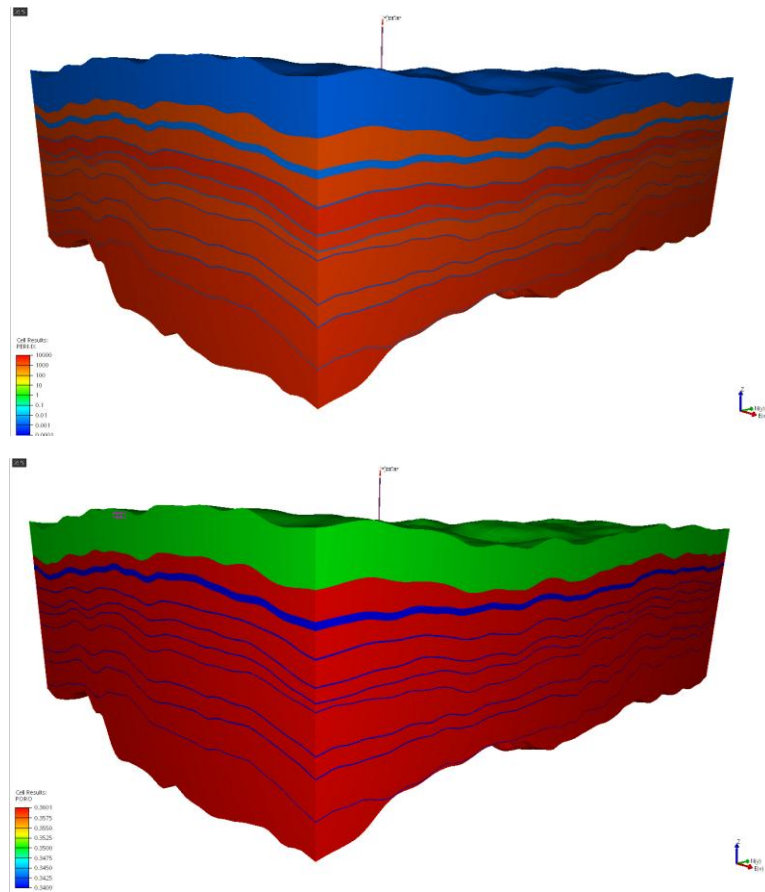
Models

- Storage models have larger physical size
 - 10km vs 100km total length
 - 100m vs 500m grid blocks
- Fewer wells
 - Inter-well distance a magnitude larger than for HC fields



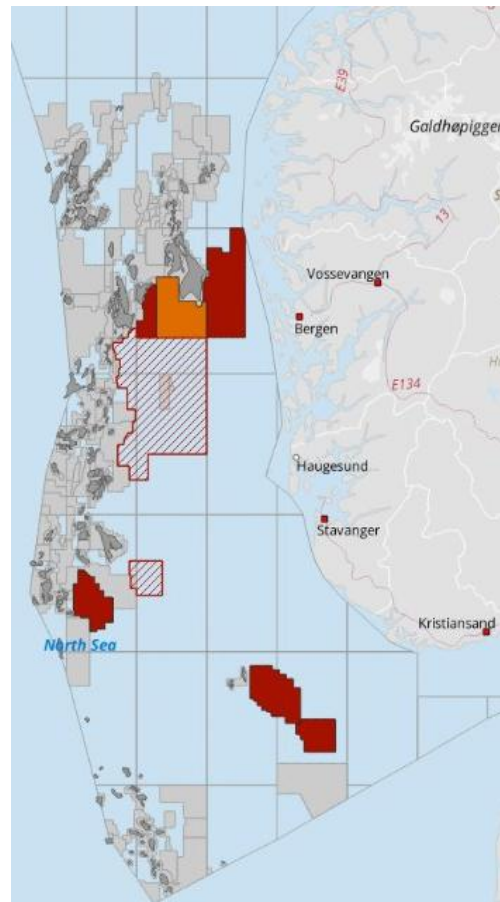
Petrophysical model

- Few wells and large well-spacing means little direct information about the reservoir
 - Logging and coring of wells
 - Rate-pressure data from wells
- This implies high uncertainty in petrophysical properties
- Could imply models that underestimate heterogeneity
- Example case to the right:
 - Sleipner model from OPM-data:
 - <https://github.com/OPM/opm-data>



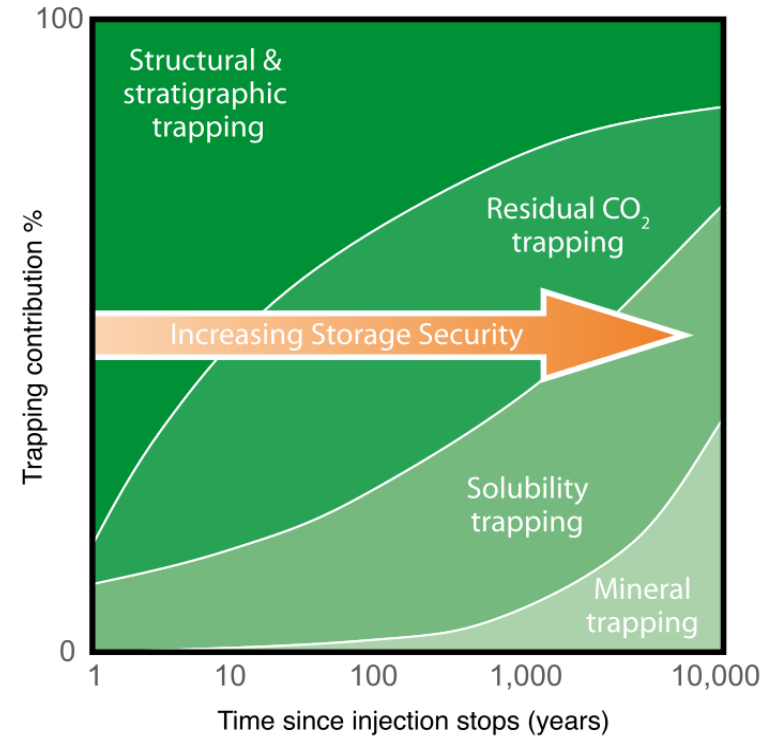
Inverted pressure problem

- Carbon-storage shares the underground aquifers
- Hydrocarbon production: Deplete underground pressure
 - Nearby fields could cannibalize each others pressure support
- Carbon storage: Pressure build-up
 - Usually only injects
 - Due to cost
 - Possible brine production
 - Could be combined with geothermal energy
 - Nearby injection sites use the same pressure window
- Earlier research have been “local”
 - Focusing on a single well and its plume
- Need to get a regional overview over pressure build-up
 - Pressure moves much faster than the CO₂ itself



Simulation time

- Injection period at same time scale as hydrocarbon production
 - Decades
- Monitoring period gives additional decades
- Plume migration continues for centuries
- Secure storage is defined as secure for millennia's
 - At these time scales, mineral trapping becomes important
- Simulators might have a max time
 - Date-time max 10'000 years



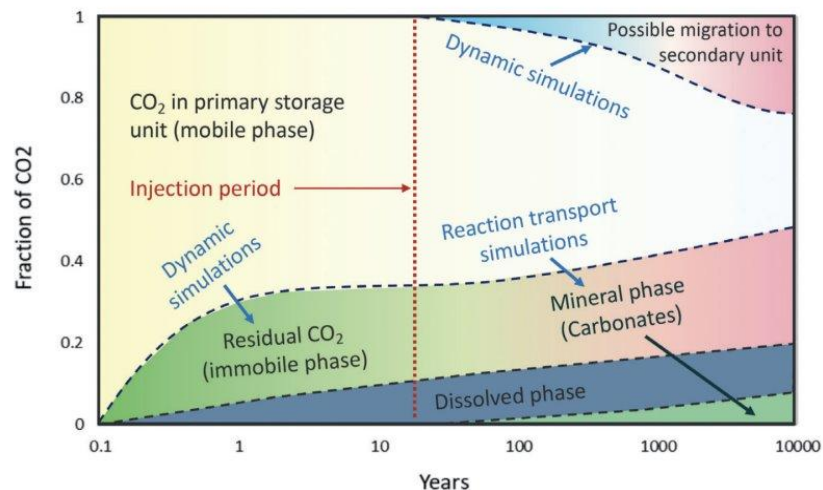
IPCC, 2005

Modeling CO₂ vs. hydrocarbon

	CO ₂ storage	Hydrocarbon production
Model size	~100 km	~10 km
Number of wells	Tens	Hundreds
Grid size	2-20 million	< 2 million
Reservoir management	Pressure buildup	Pressure depletion or voidage replacement
Time scale	Operations: decades Plume migration: centuries Mineralization: millennia	Operations: decades
PVT properties	Pressure and temperature could vary significantly vertically, and phase properties are strongly dependent on these	Changes in reservoir pressure and temperature are limited, warranting a simplified PVT description
Phase interactions	Water dissolves CO ₂	Oil dissolves gas

Modeling of storage mechanisms

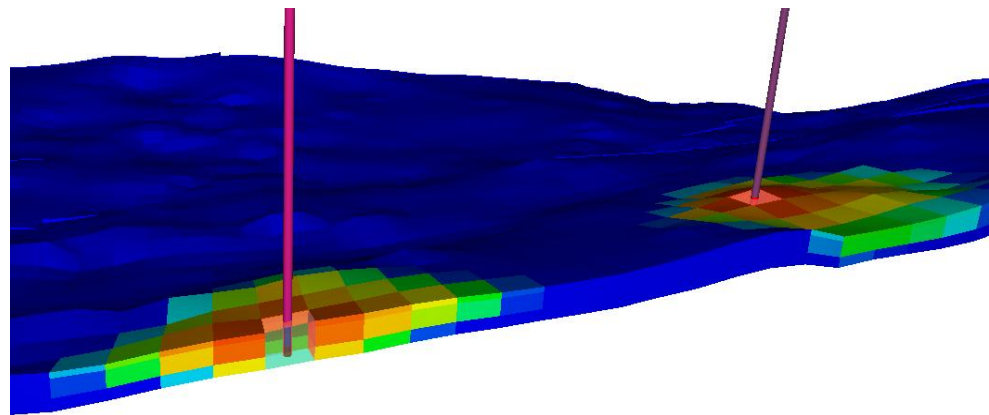
- Structural trapping
 - Need to resolve main structures
- Residual trapping
 - Flow parameters endpoints
 - Hysteresis modeling
- Solubility trapping
 - Dissolution and density contrasts
- Mineral trapping
 - Geochemical reactions
 - Long simulation times (~5000 years)
 - Often ignored in reservoir simulations



Ringrose, 2022

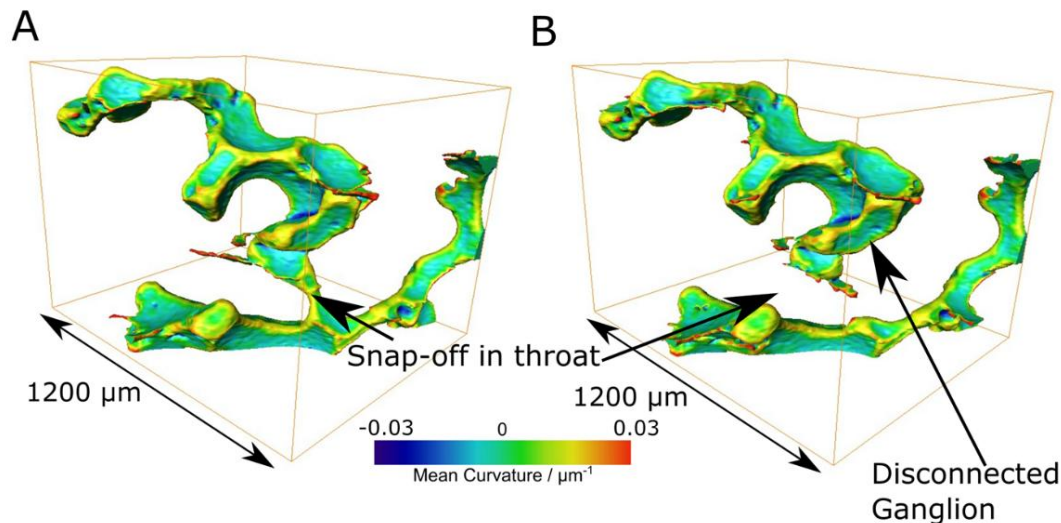
Structural trapping

- Storage models need to capture main barriers for buoyancy driven upward movement
- Direct link to geological model building
 - Static analysis of the trap volume can produce reliable estimates of storage capacity
- Some storage sites without a main barrier
 - Still structural trapping



Residual trapping

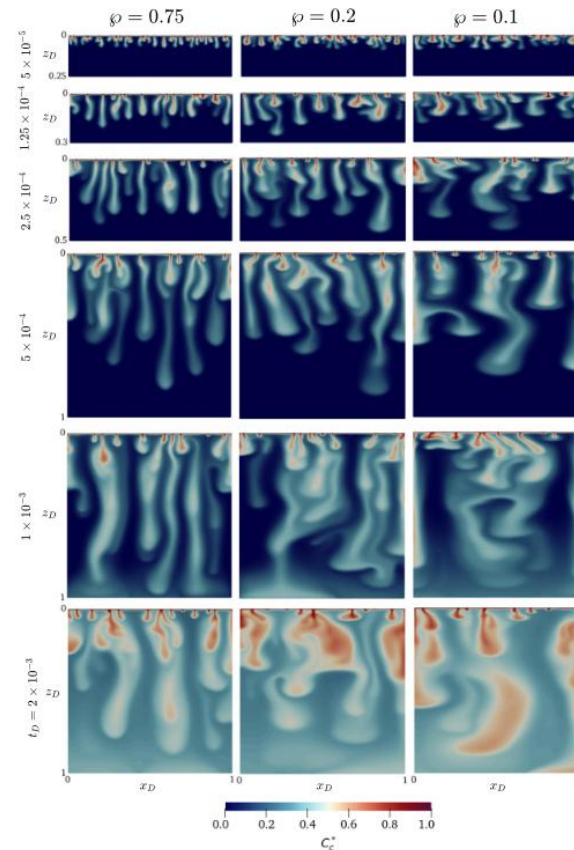
- CO₂ can become disconnected when CO₂ saturation decreases
 - CO₂ is non-wetting relative to water
- Need a hysteresis model to capture residual trapping
 - Increasing computational effort



Images of CO₂ becoming disconnected (Andrew, 2014)

Solubility trapping

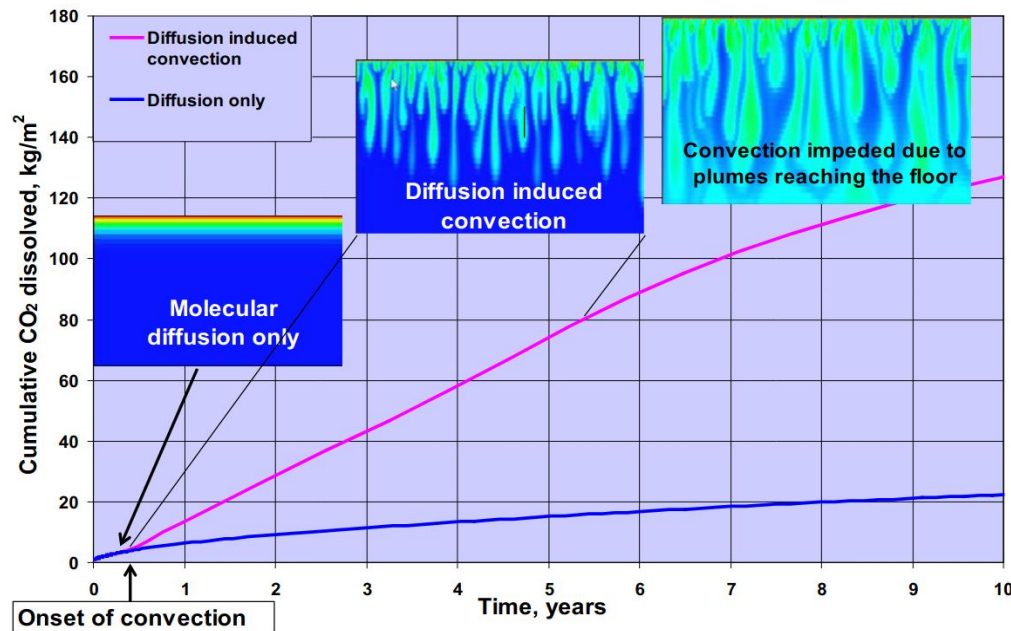
- When CO_2 is dissolved into water, the water density increase
 - Unstable situation with heavy water on top of lighter water
 - Will trigger convection
- Convection of heavy water with dissolved CO_2 occurs at a length scale not covered by the full-field grid
 - In simulations: Size of convection cycles must be larger than grid resolution
 - Could underestimate the extent of convection in reservoir grid models



Erfani et al. 2022

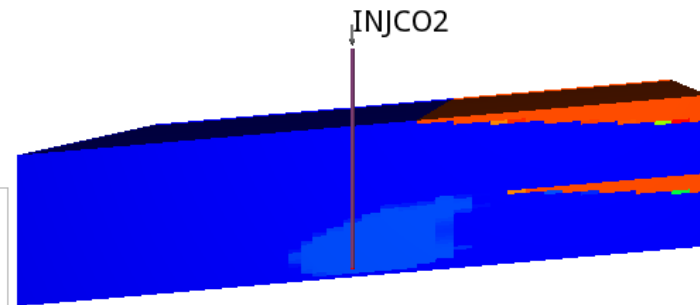
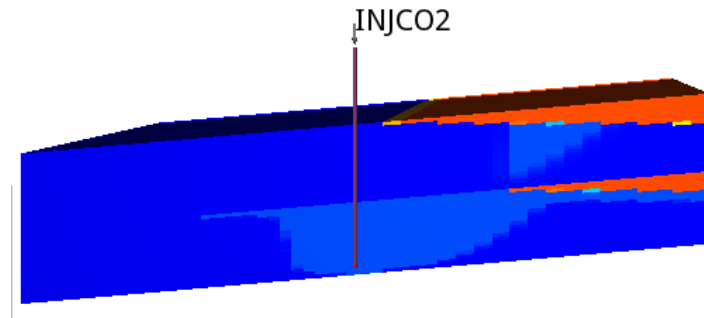
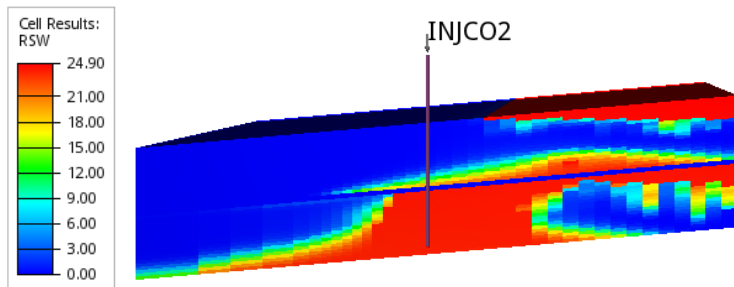
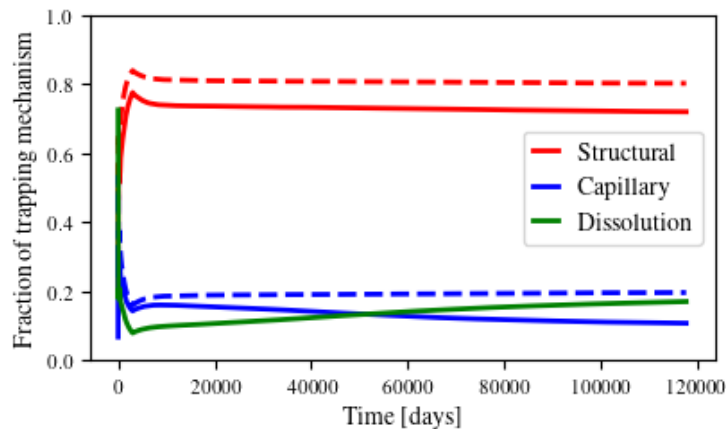
Onset of convection

- Diffusion occurs at a scale below reservoir grid size
- The onset of convection at time-scale below time steps in reservoir simulation



Lindeberg and Wessel-Berg, 2011

Effect on plume movement



No dissolution

Dissolution

Mineralization

- Occurs over a very long time-scale
 - ~1000s years
 - Mineralization in basalt are relatively fast (CarbFix at Iceland)
- For most storage reservoirs, mineral trapping happens beyond the time-span of the project life
- Most simulators do not include mineralization
 - The process is too slow and uncertain
 - Can be modelled by coupling with geochemical packages
- The related problem of salt-precipitation occurs on a shorter time scale
 - Modeling capabilities in OPM

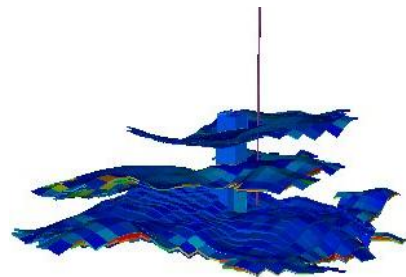
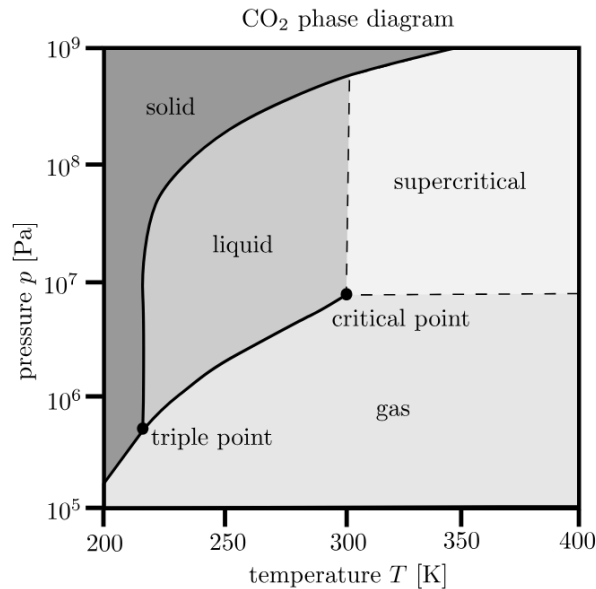


Aggregate of cubic mineral crystals in an Icelandic basalt.

Prescelli, 2025, unpublished

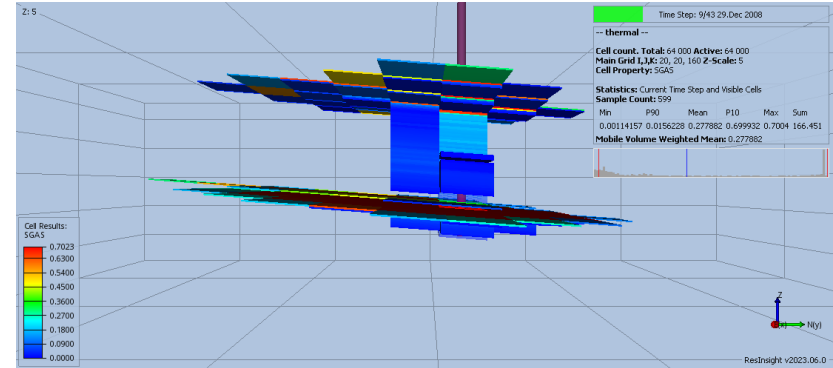
PVT properties

- Large vertical extent of fluid movement → large pressure and temperature difference
- This could have strong impact on CO₂ properties
 - Especially if close to critical point (Sleipner)

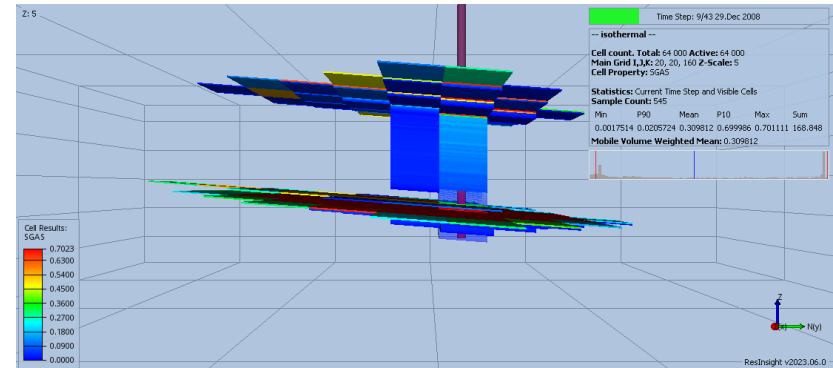


Thermal simulations

- Temperature could be important for simulation cases close to phase boundaries
 - Example: Sleipner
- Most example cases we have tested see little impact of temperature



Thermal

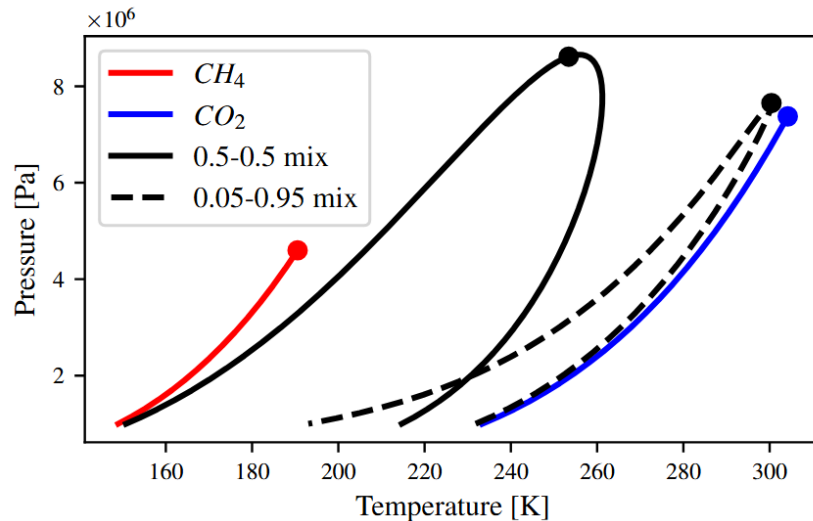


Isothermal

Simulation cases by Alireza Mohsenifesebandis, 2023

Impurities

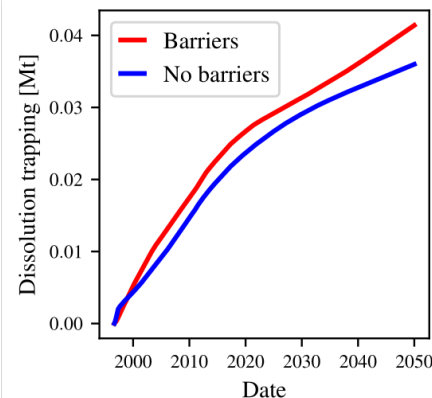
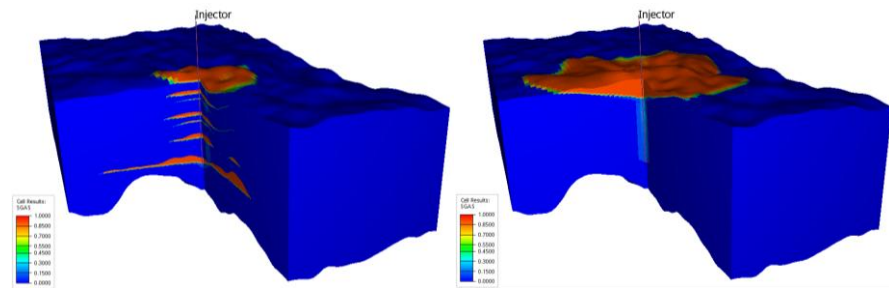
- Simulators often have built-in PVT simulators
 - These can assume simplified fluid systems
 - Pure CO_2
- Can set the water salinity
 - Large impact on CO_2 solubility
- CO_2 impurities are uncertain and often not included



Generated using a cubic Peng–Robinson EOS in *thermopack*

Heterogeneity

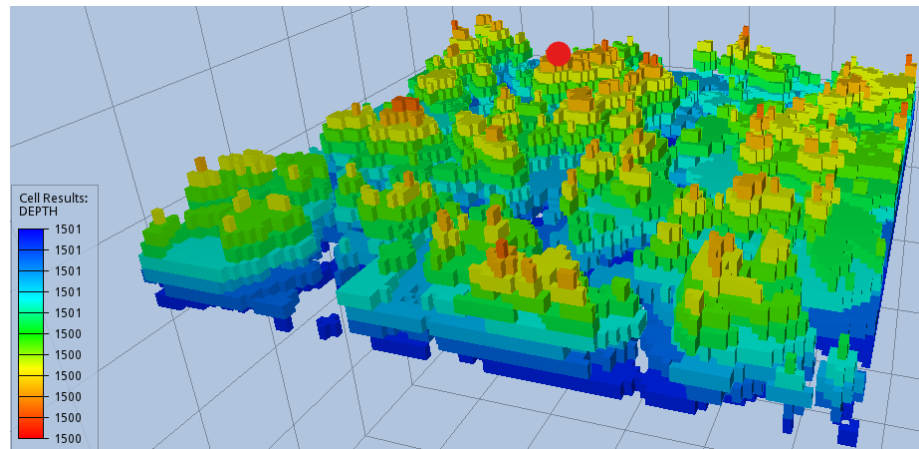
- Including realistic heterogeneity in simulation models can change storage capacity significantly
 - Internal barriers can give internal structural traps
 - Internal barriers can increase sweep
 - Increase residual trapping and dissolution



Heterogeneity

- Upscaling of flow processes can give significant changes to flow parameters
 - Example: Effective break-through saturation → adjusting end-point
- Small scale effects, such as Ostwald ripening, could have large impact on residual trapping (Singh, 2022, Blunt, 2022)
- Too homogeneous models can underestimate trapping

Macut, 2025, unpublished



CO₂ invaded cells at the moment of breakthrough in a 10x10x1 meter model. Breakthrough is marked by the red dot.

Geomechanics

- Compressibility essential for proper modeling of pressure build-up
 - Often simplified to a total compressibility
- Seismicity, fault reactivation etc. not modelled
- Coupling reservoir flow with geomechanics
 - Advanced options in several software (pFlotran, Intersect, etc.)
 - Currently uncommon with grid deformation
 - Prototype available in OPM Flow

Summary

- Most available simulators have capabilities to simulate structural, capillary and dissolution trapping
 - Mineral trapping is not commonly modelled
- There are different PVT implementations
 - Built-in PVT calculators are typically for pure CO₂-water systems
- Thermal options are available
 - Could be of importance if CO₂ is close to phase transitions
- Geomechanics is often simplified (total compressibility)
 - More advanced options are under implementation
- FluidFlower project indicates that how models are set up (humans) has a bigger effect compared to differences within the simulators

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