

Modelling The Elephant Across Multiple Scales



Adam Butler¹, Paolo Orsini¹, Steve Furnival^{1,2}

Modeling strategies for CO₂ injection

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¹OpenGoSim, ²HoBoil Ltd.

Simulation Challenges

Two key challenges for simulation for GCS:

1) Long timescales for trapping mechanisms

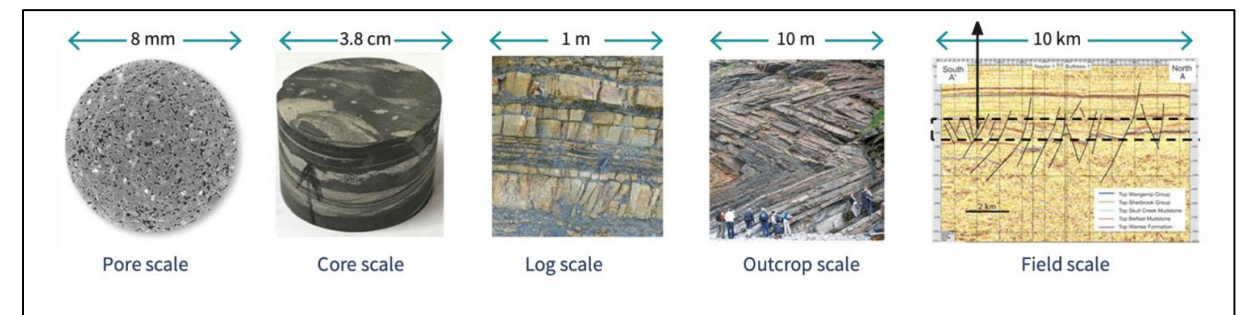
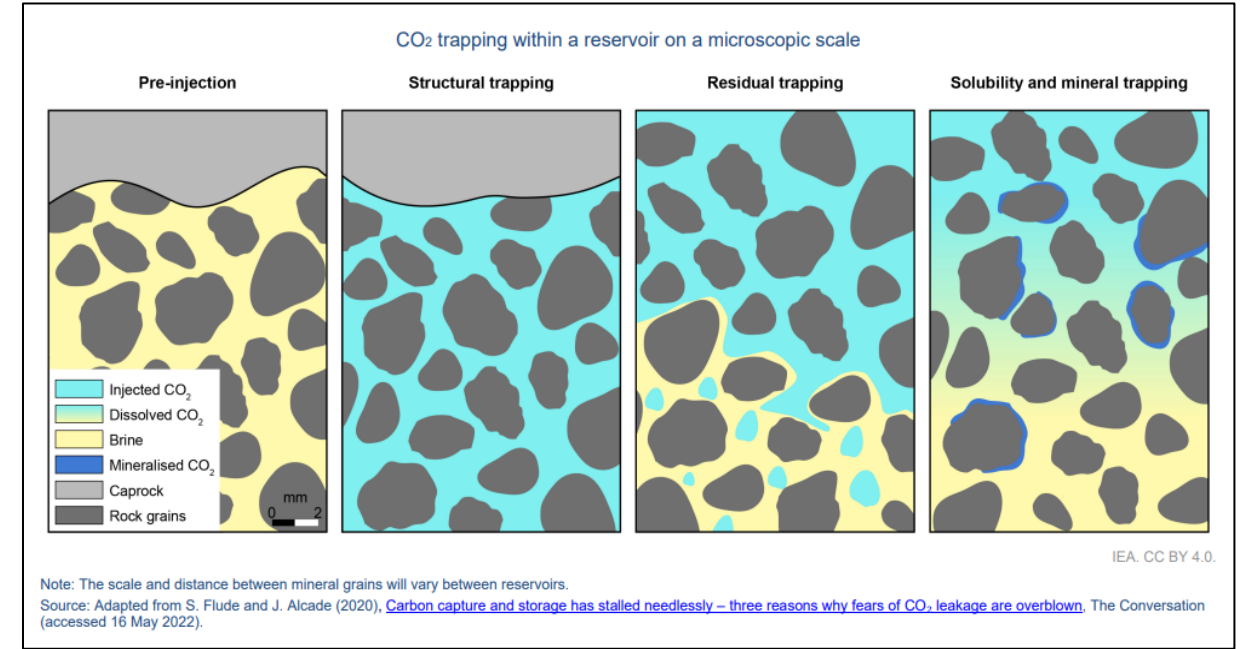
Long simulation periods to model secure trapping

2) Sensitivity to heterogeneity (across scales) but limited data available

a large parameter space of reservoir properties and resulting CO₂ behaviours

Traditional simulation approaches take hours or days per simulation – this becomes prohibitive when considering

- Large simulation domains
- Large numbers of simulations



Courtesy of Jerome Neufeld

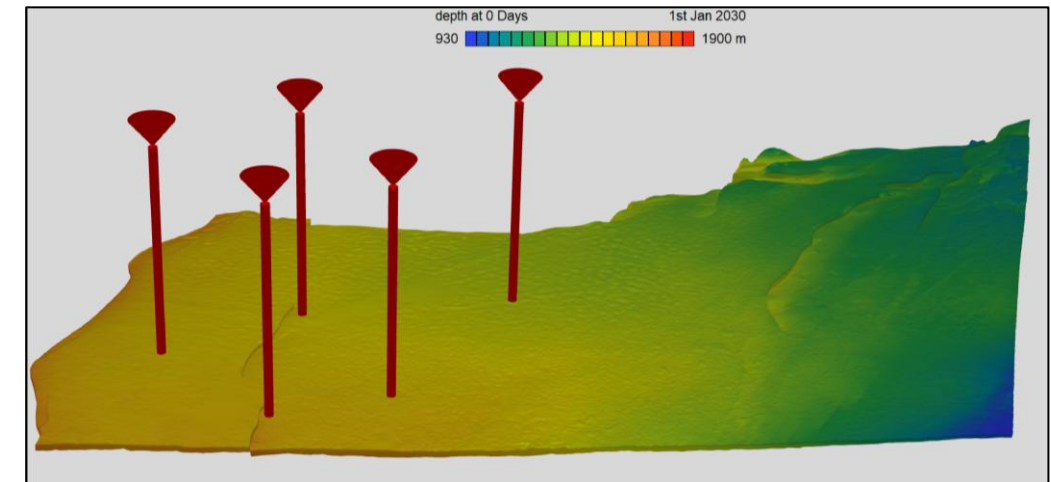
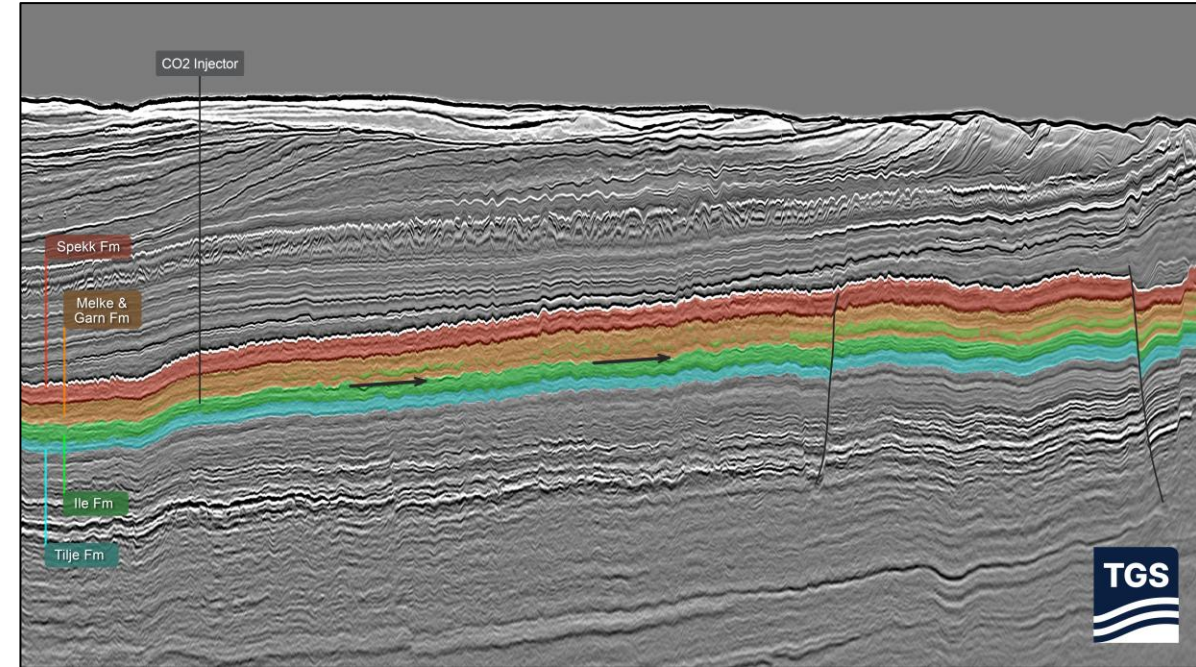
Open Saline Aquifers

Traditionally avoided in favour of closed structures with major anticlinal features, there is growing interest in them due to

- Reduced pressure-management issues
- Larger storage capacity

The CO₂ is primarily secured via residual trapping and dissolution, rather than (large-scale) stratigraphic trapping.

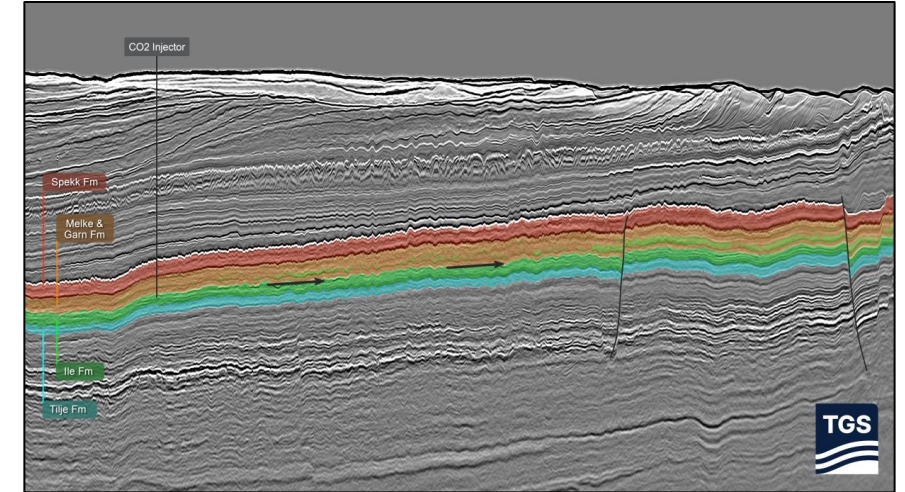
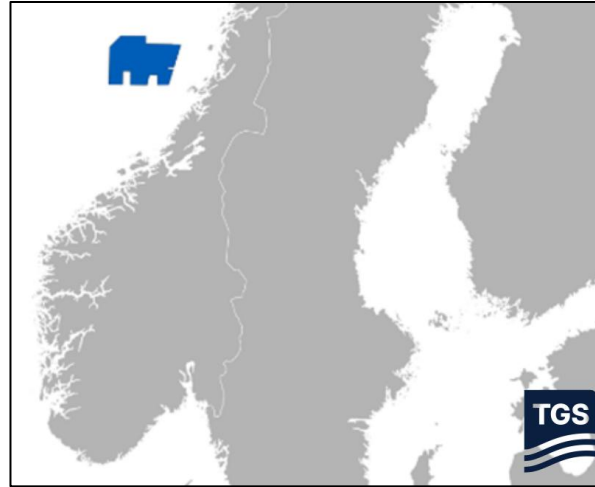
Plume monitoring is more challenging as a result, due to the larger areal extent.



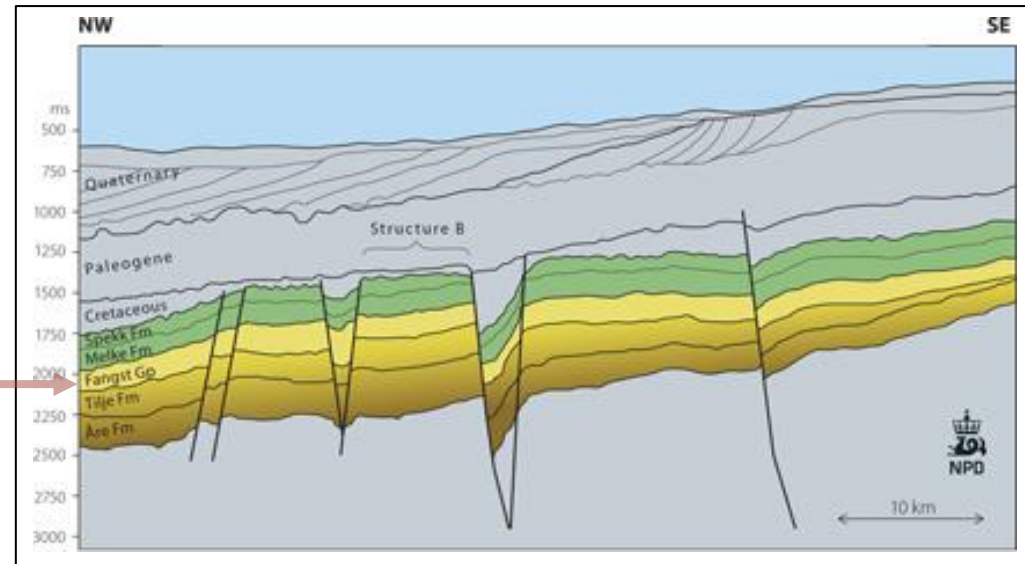
The Elephant

A large potential open saline aquifer storage site in the Norwegian North Sea.

It consists of multiple sets of sands interspersed with shales, with estimates of <1Gt of CO₂ storage capacity.



We are considering multi-well injection into the Fangst group.



Simulation Challenges – Large Open Storage Sites

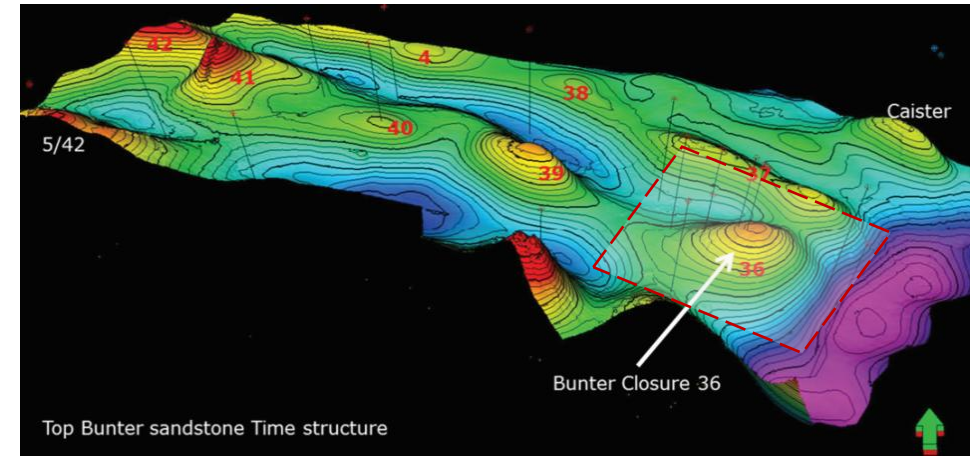
In closed systems, we can focus our simulation on the intended structural trap, defined by the topography (with large-scale buffers for pressure, etc.)

In large open systems, simulation at traditional resolution ($100m \times 100m \times 2m$) can become prohibitive (10 – 100 million grid cells).

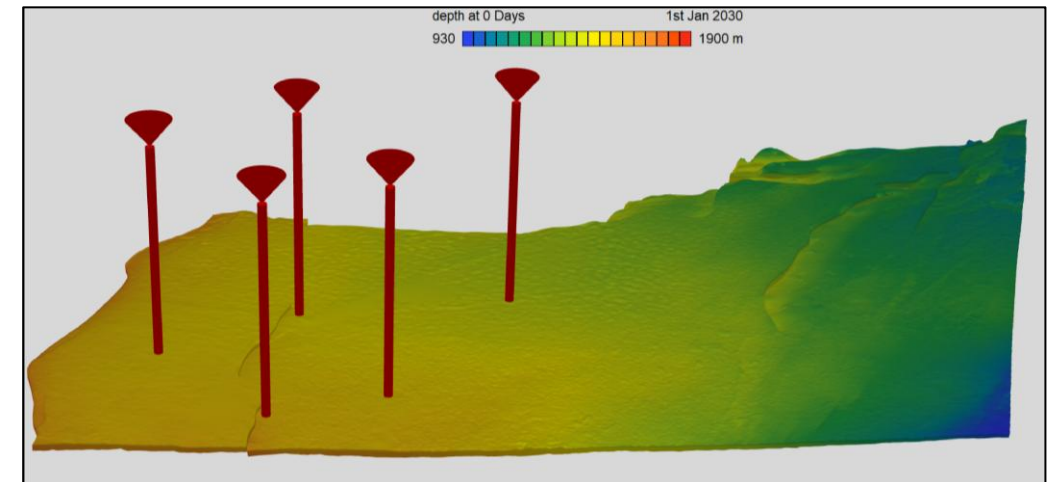
Larger sites also mean a larger parameter space of properties and behaviours.

However, only a small fraction of the reservoir will encounter CO₂. We can anticipate a long migration time until stabilisation, with the CO₂ predominantly close to the caprock. This lets us split our simulation approach into two parts:

- **Near-Well Model:** How does the CO₂ travel from well to caprock, and how much is trapped along the way?
- **Migration Model:** How does the CO₂ behave once it reaches the caprock?

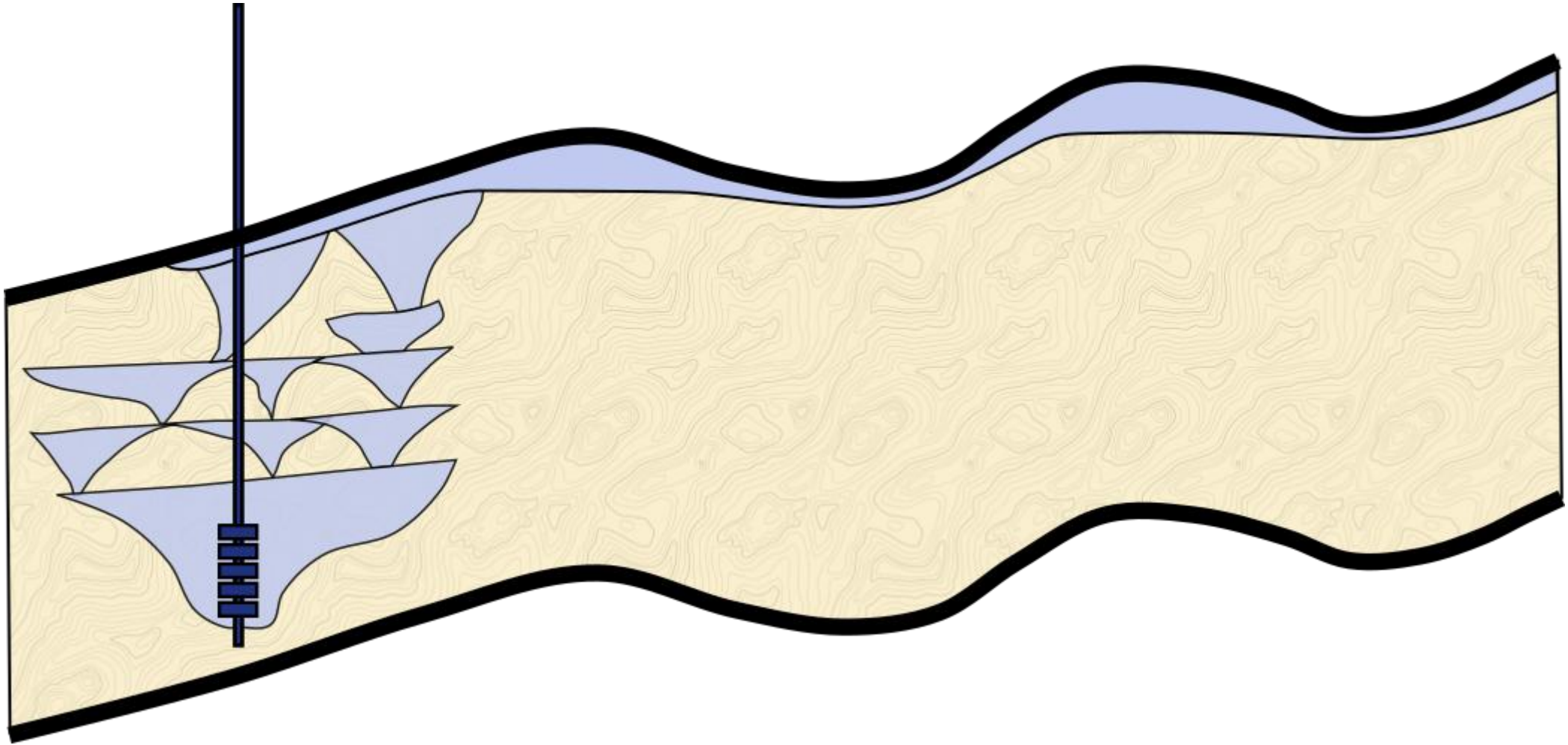


25km × 25km

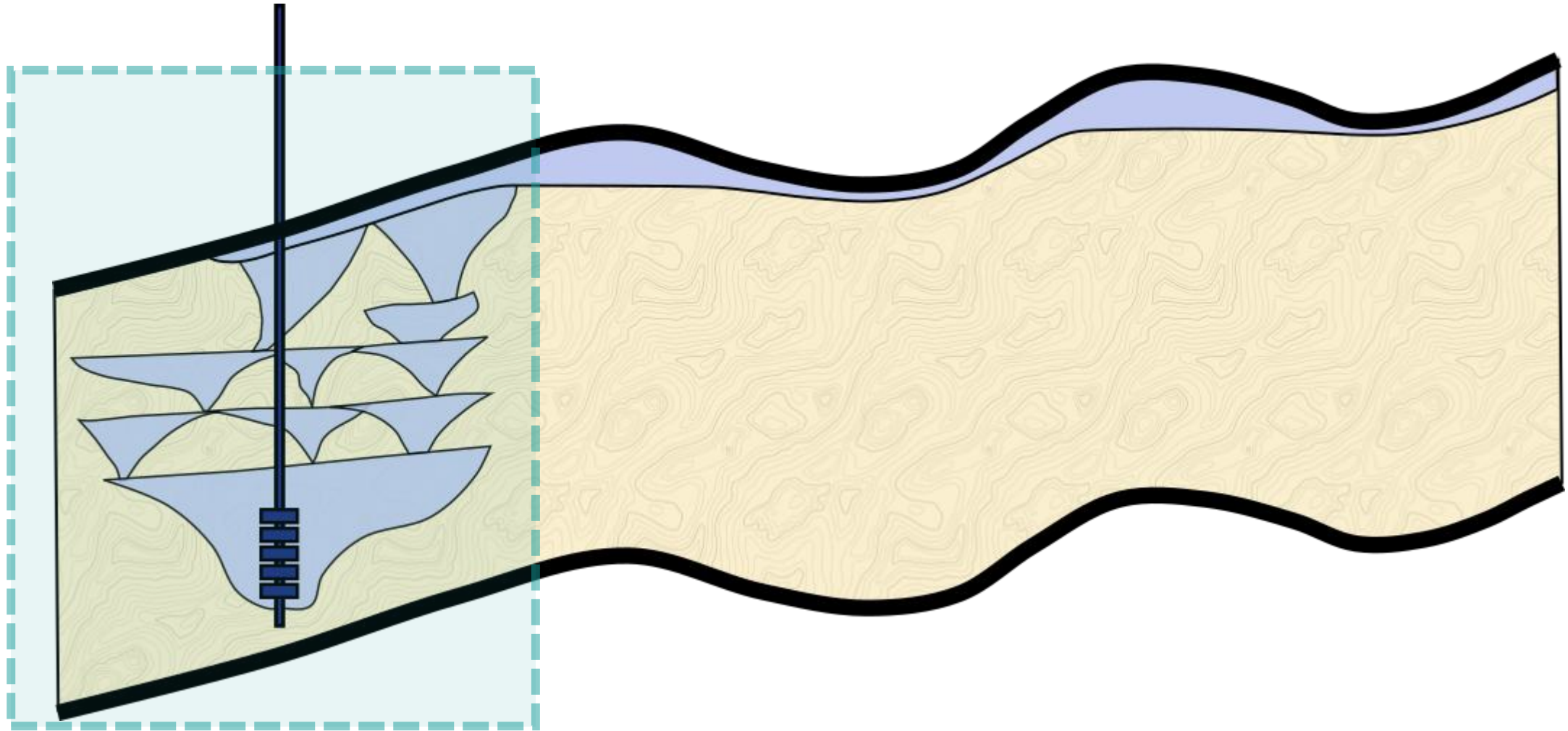


86km × 60km

Modelling Approach

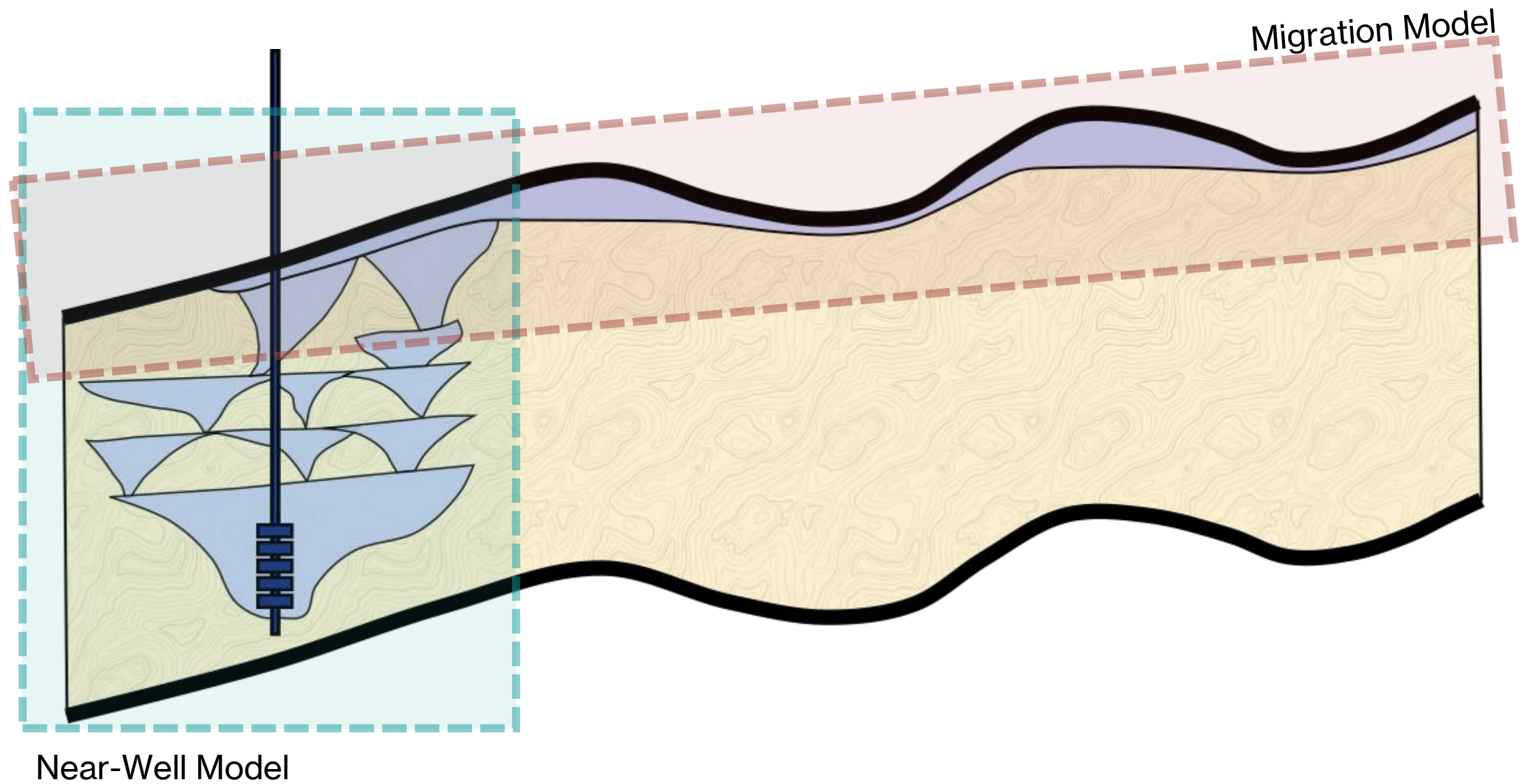


Modelling Approach



Near-Well Model

Modelling Approach



Near-Well Modelling

For large open sites, the vertical reservoir structure is likely the most important factor in the near-well behaviour.

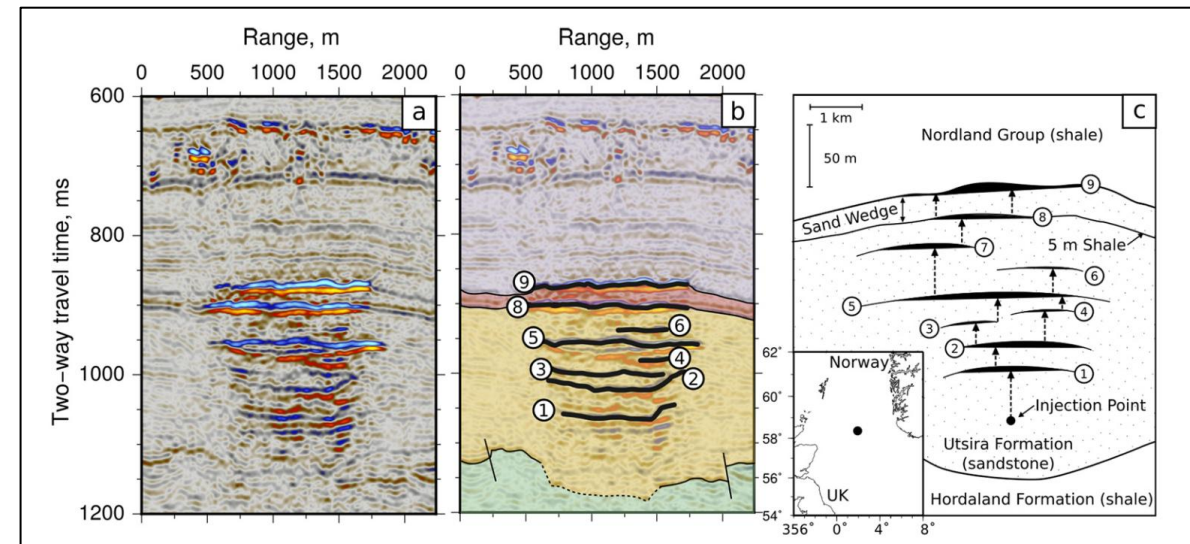
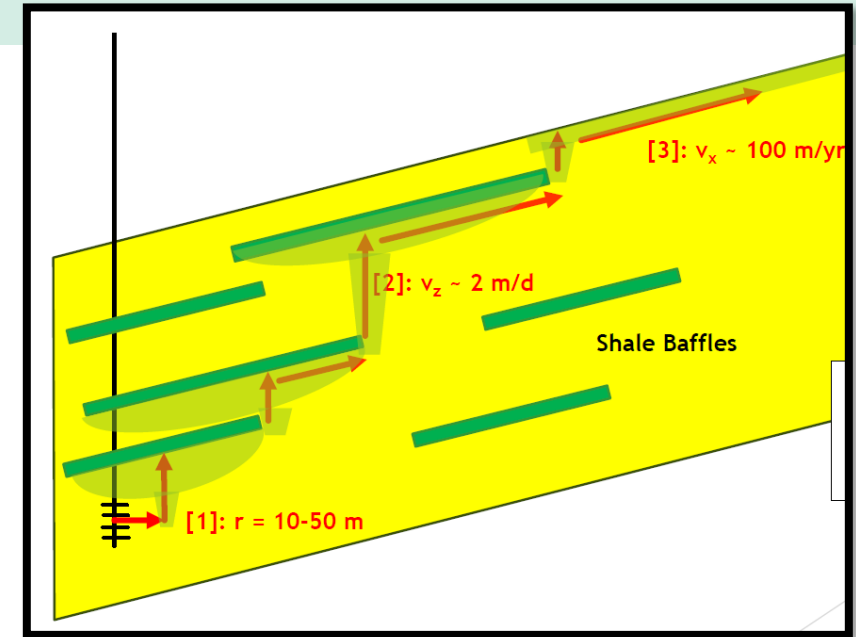
Horizontal flow typically dominates for 10s of metres, but can be enhanced by high-perm. layers and baffles (e.g. Sleipner). Breaks in seals allow CO₂ to reach the caprock.

We simulate this near-well region with a full-physics simulator (Cirrus) and focus on a localised region around the well (10km × 10km) with analytic aquifers for pressure management.

This allows us to investigate

- When (and where) the CO₂ reaches the caprock
- What proportion of the CO₂ is trapped along the way

Temperature and Pressure effects can also be very important in and around the well (particularly for shallow or depleted reservoirs).

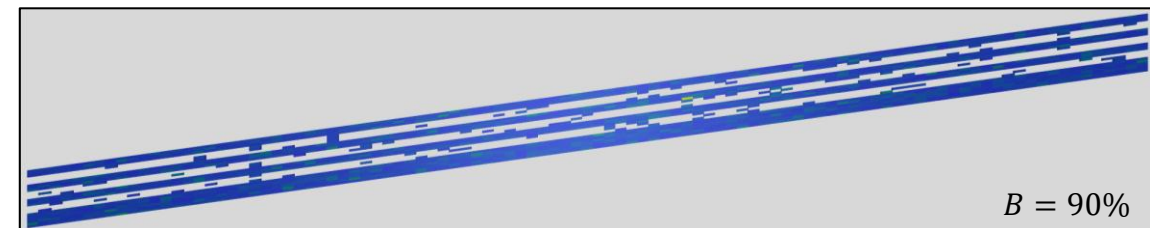
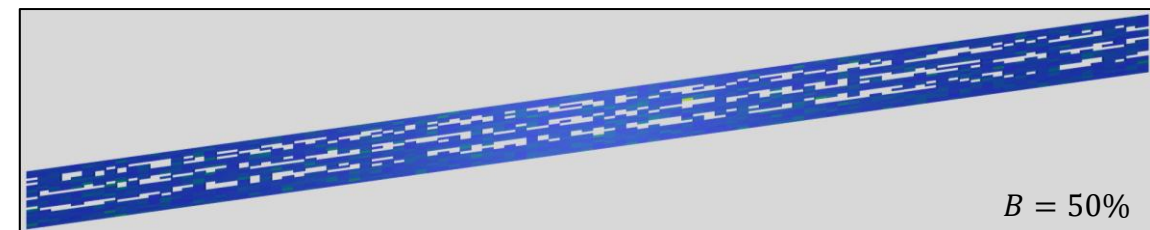
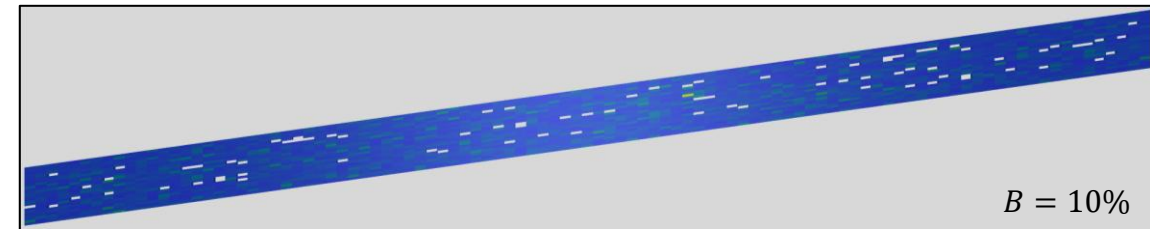
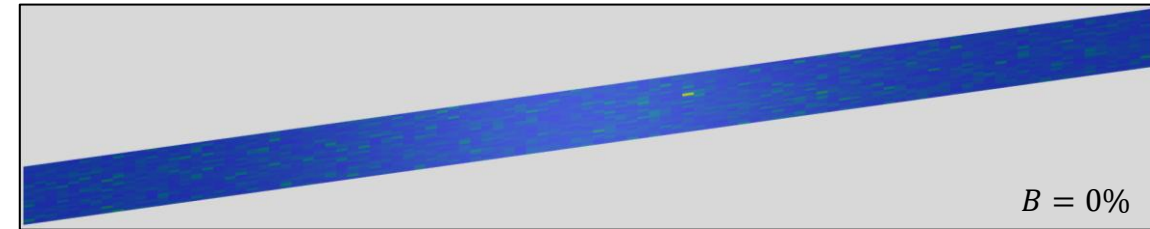
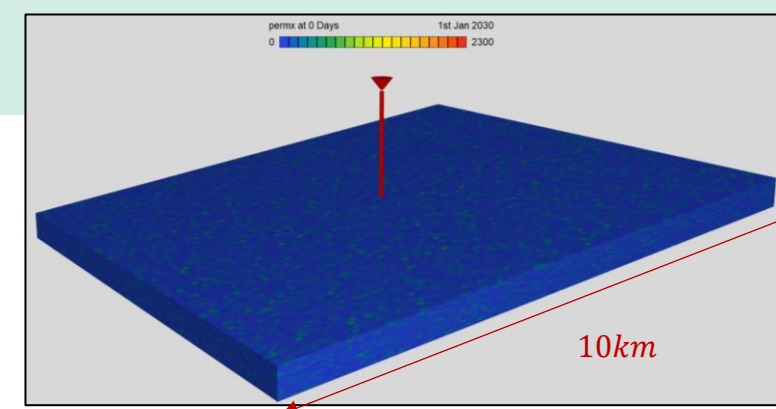


Vertical Migration – Effect of Baffles

How do baffles affect vertical migration in a domain corresponding to a near-well region for the Elephant?

Baffles: 3 layers containing impermeable baffles (proportion B) lying above the well perforation.

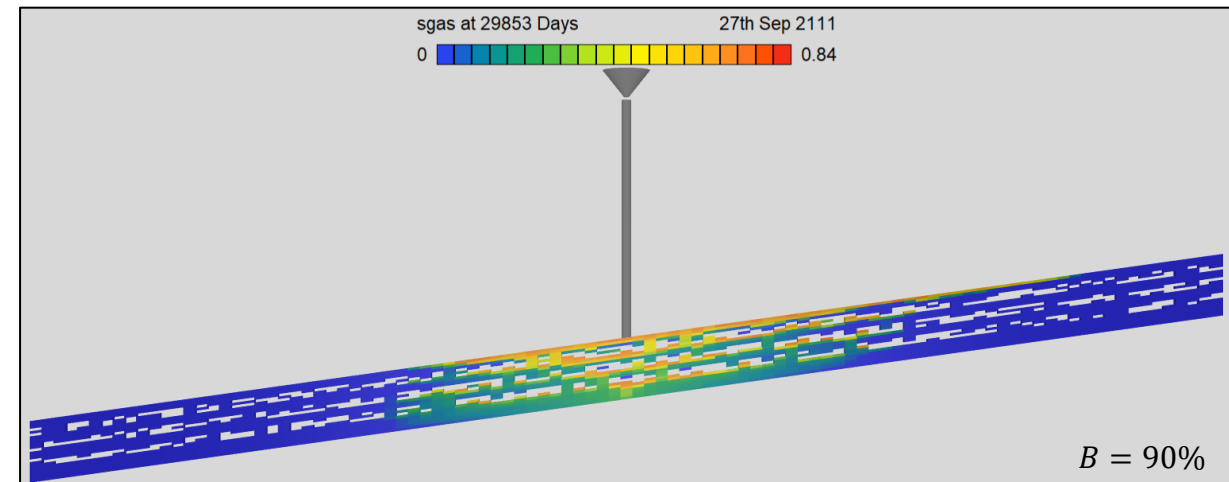
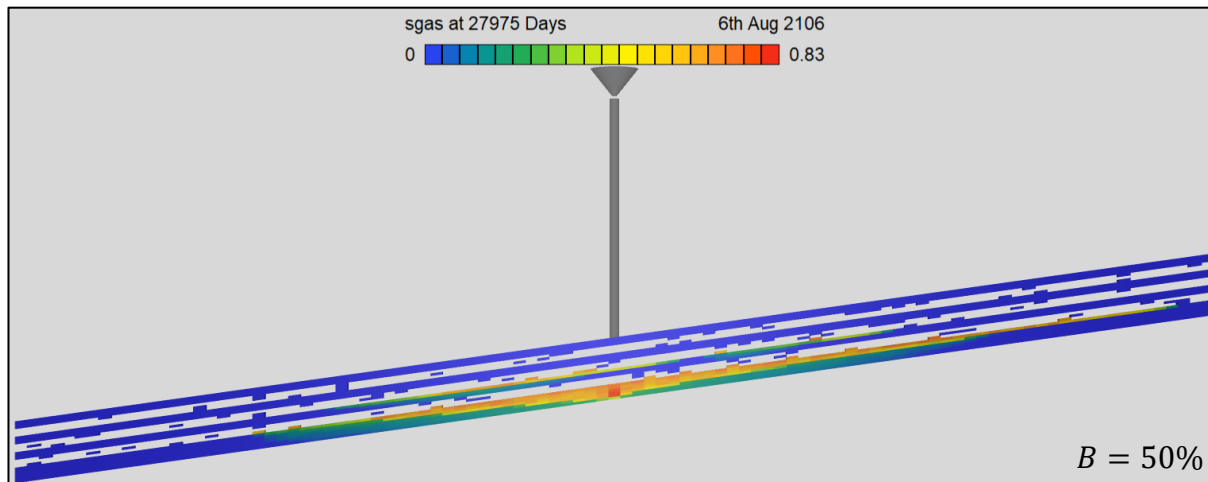
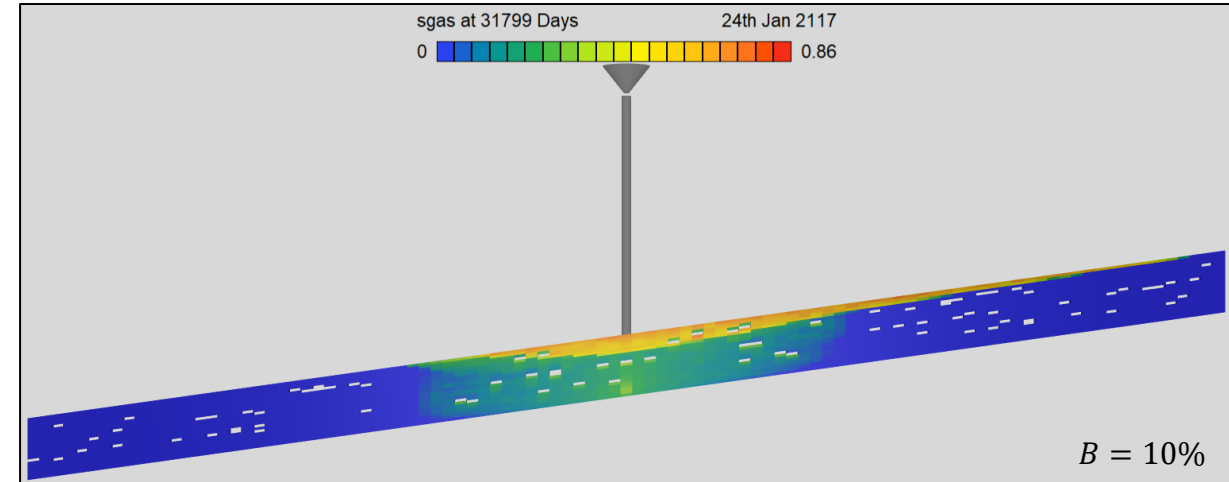
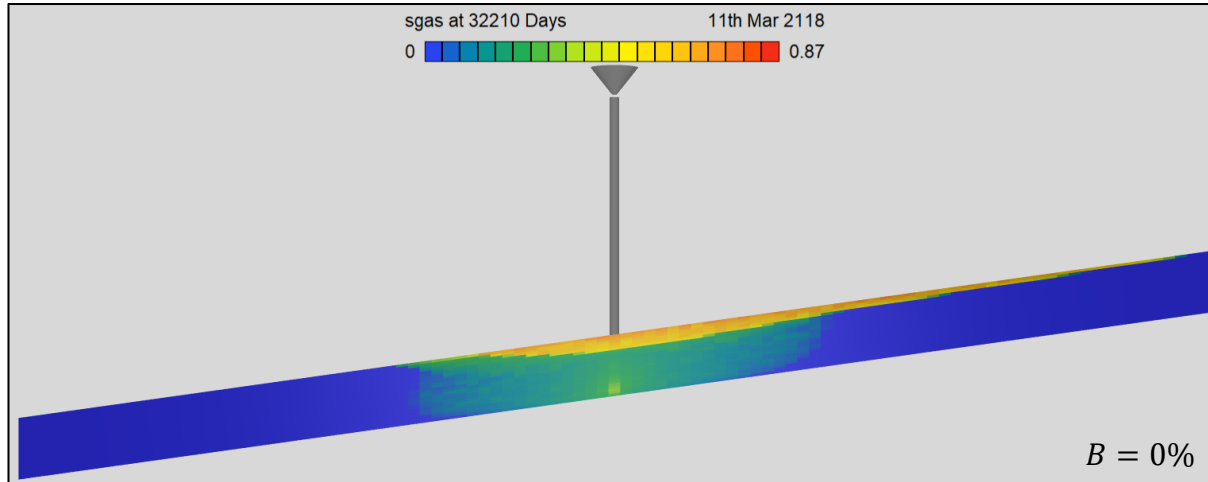
Property	Value
Numerical grid	$101 \times 101 \times 24$
Spatial extent	$10.1km \times 10.1km \times 130m$
Topography	2° slope
Depth	$1000m - 1500m$
Porosity ϕ	0.2
Horizontal permeability k_h	$10\text{ mD} - 2300\text{ mD}$
Permeability ratio k_v/k_h	0.1
Background Pressure	$100\text{ bar} - 150\text{ bar}$
Background Temperature	$47.5^\circ C$
Injection	$10Mt/yr$ for 5 years



Vertical Migration – Effect of Baffles

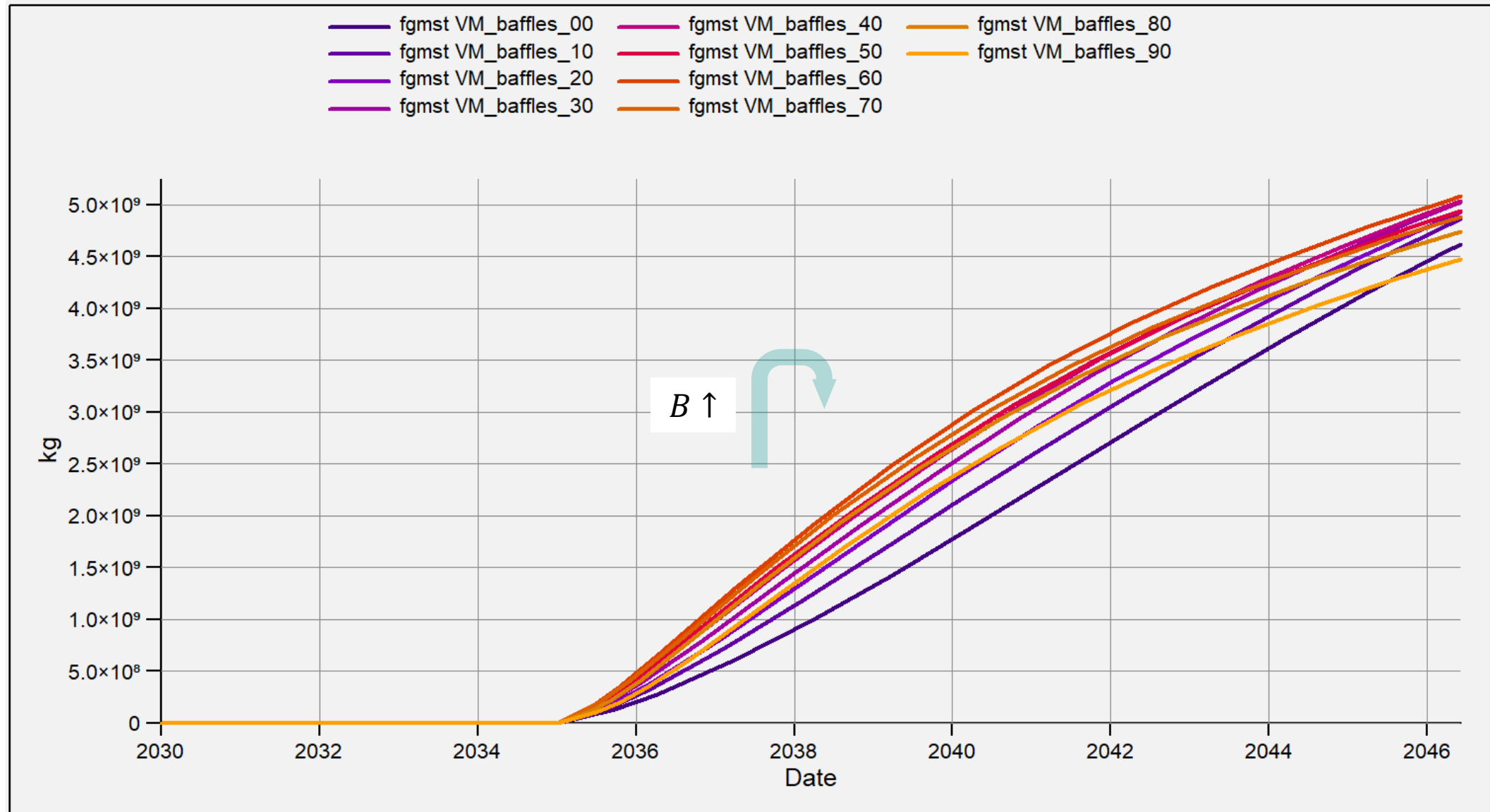
CO₂ quickly reaches the caprock (≤ 1 year), even for high degree of bafflement B .

Once we reach large-scale cohesive baffles ($B \geq 80\%$), the flow is more like individual communicating layers.



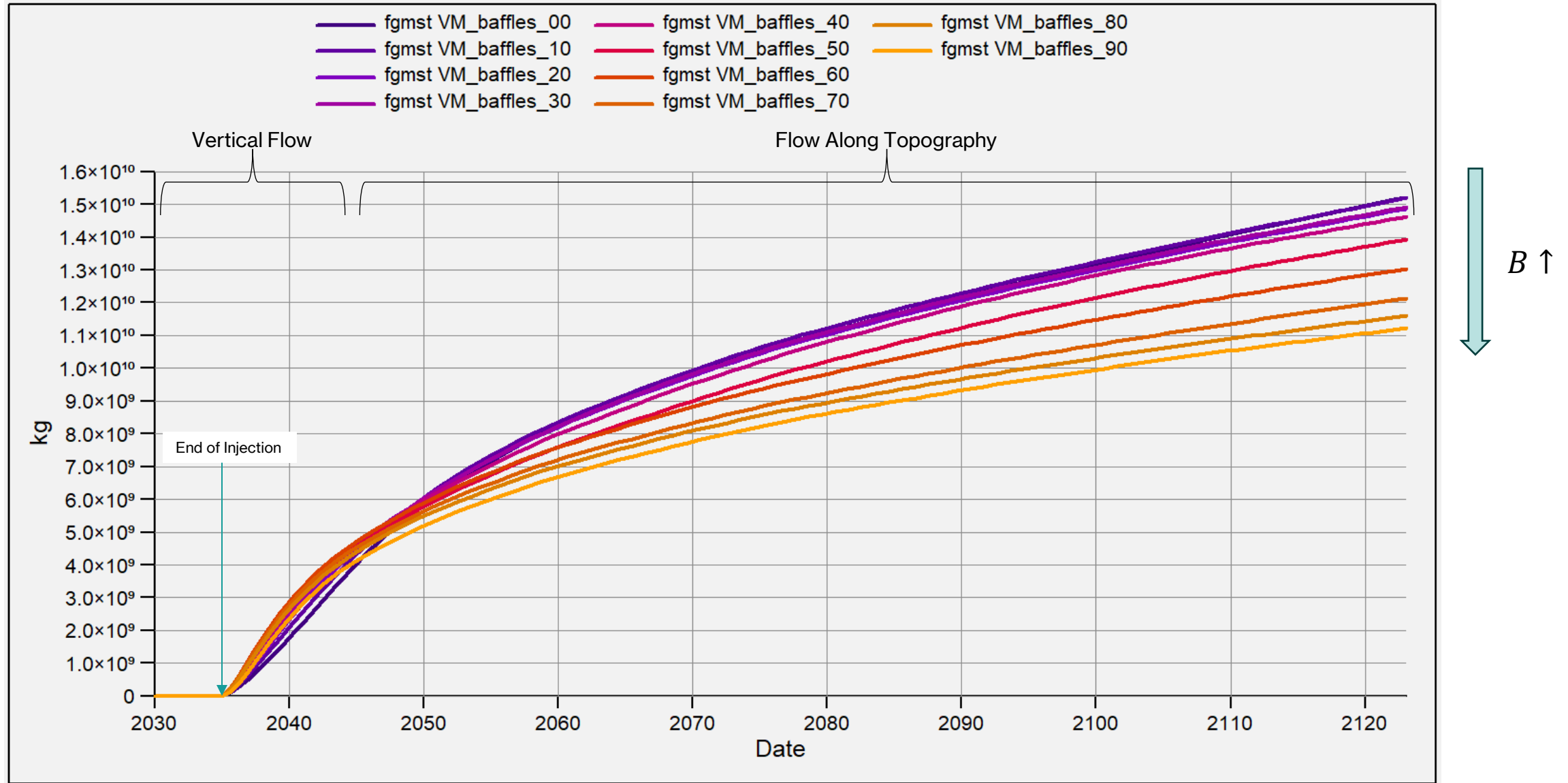
Vertical Migration – Residual Trapping

The amount of residually trapped CO₂ soon after injection (vertical migration still occurring) varies non-monotonically with B .



Vertical Migration – Residual Trapping

At later times (topography-dominated flow), more CO₂ is residually trapped for the cases with fewer baffles.



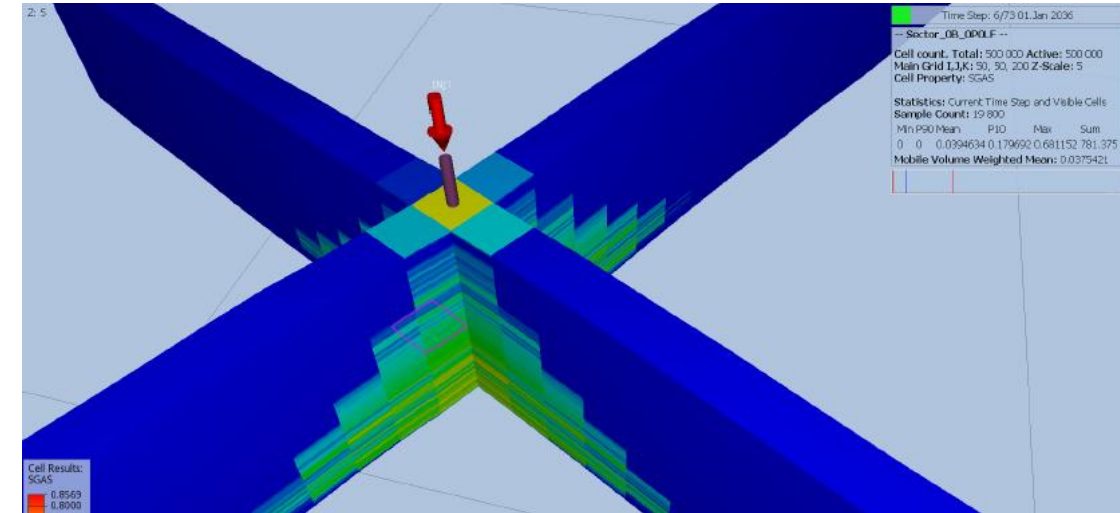
Vertical Migration – The Elephant

Steve Furnival carried out a more detailed investigation of the near-well vertical migration for the Elephant reservoir model.

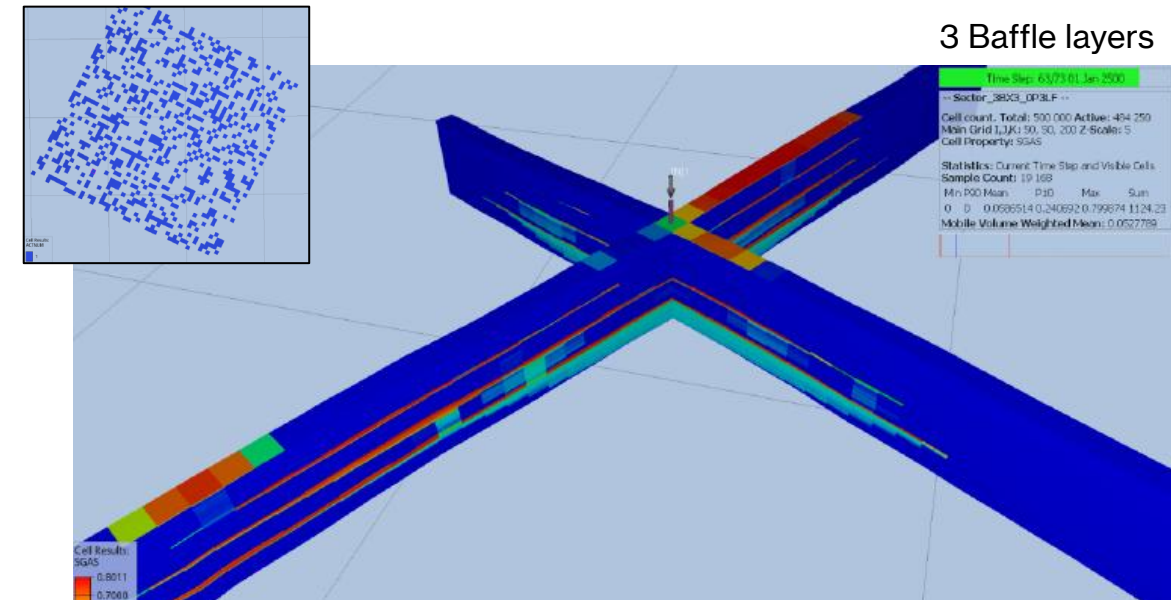
His studies found similar results: the majority of the CO₂ quickly reaches the caprock unless there are a large number of cohesive baffles present.

This is unrealistic based on measurements for the Elephant, so we can focus on the along-caprock migration.

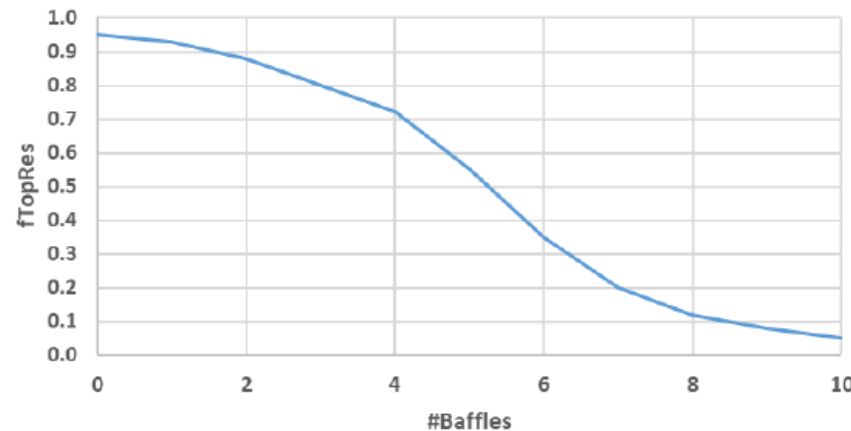
No Baffles



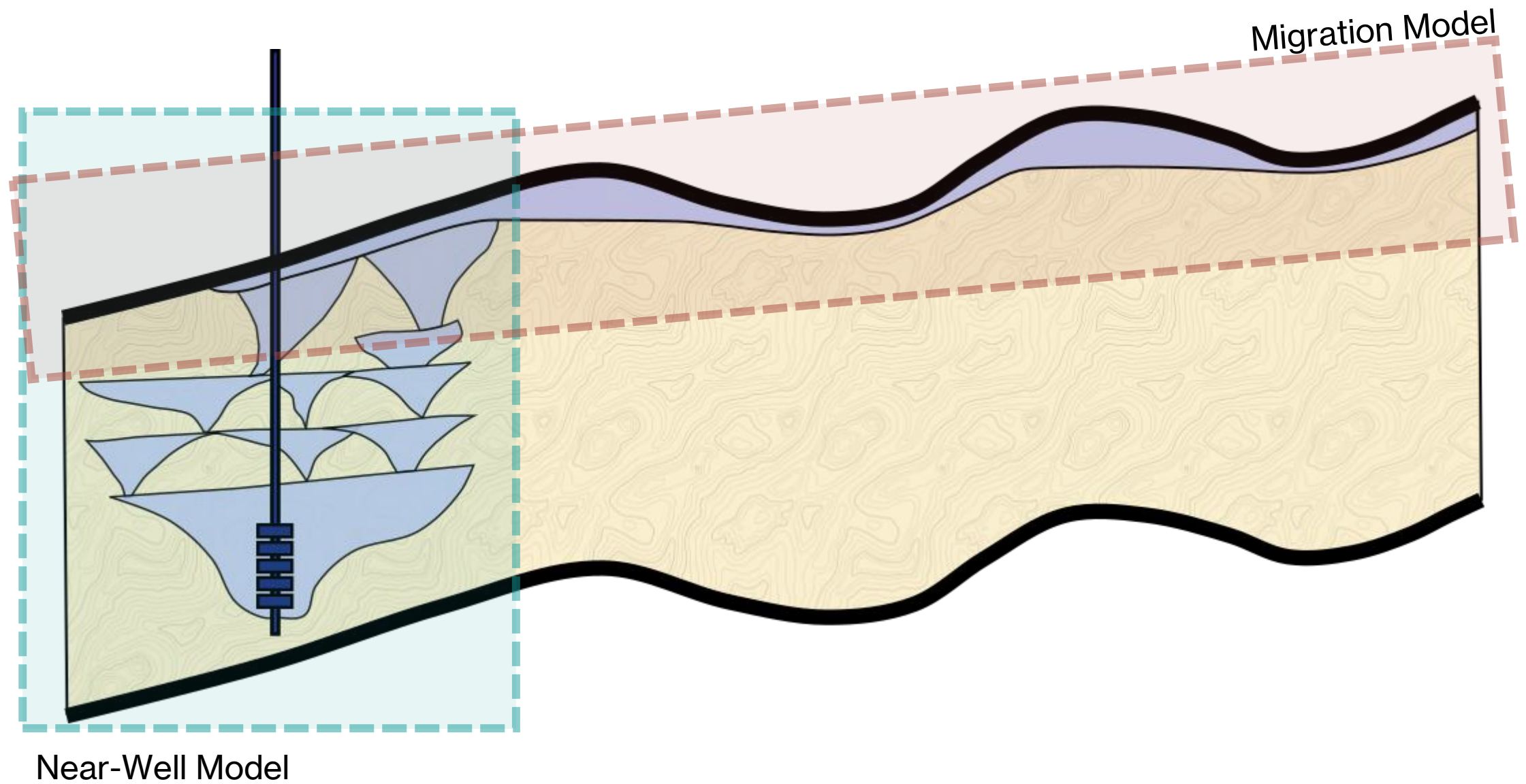
3 Baffle layers



Fraction of CO2 Mass Reaching Top Reservoir



Modelling Approach



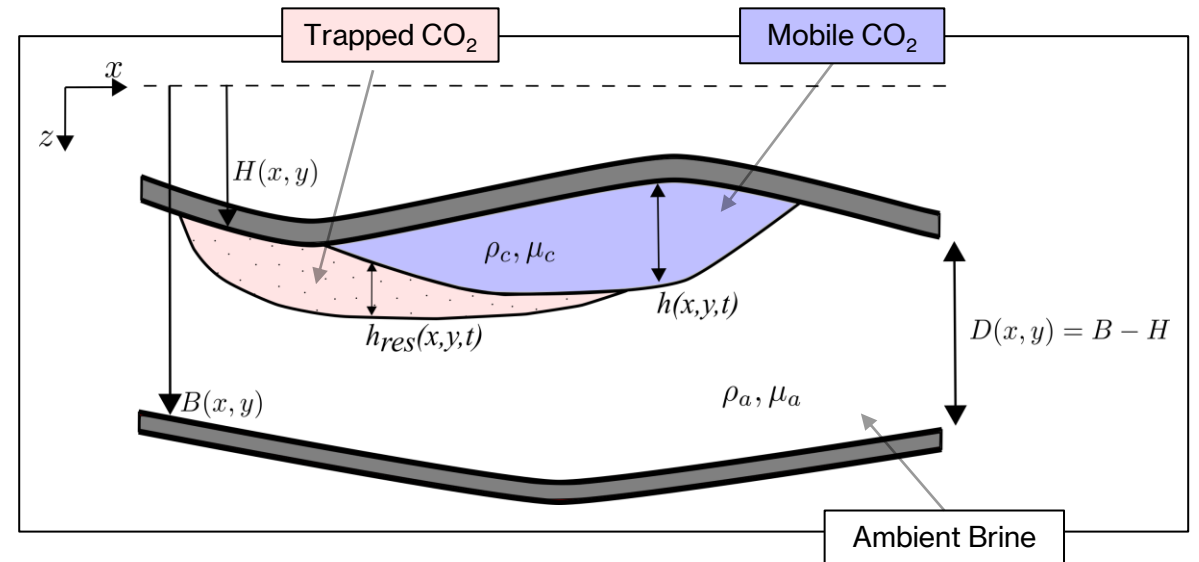
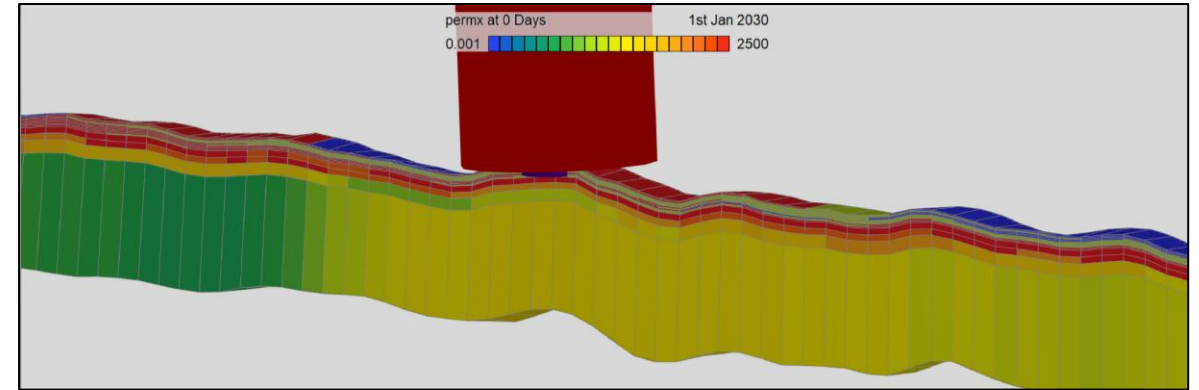
Migration Modelling

In many settings, the long-term behaviour is governed by gravity-dominated flow along the caprock.

This allows us to make some useful simplifications:

- Design our reservoir model appropriately, focusing the vertical resolution on the upper few metres
- Use a reduced-physics modelling approach that exploits this gravity-dominated behaviour to simplify the governing equations

For large open saline aquifers there is no large-scale structural trapping available – instead we rely on residual trapping, dissolution, and small-scale topography to trap the CO₂ as it migrates.



Reduced-Physics Modelling - Apus



Apus is a reduced-physics simulator, capturing the key physical mechanisms in a simplified manner with governing equations that are easier to solve numerically.

Key assumptions:

1. Vertical migration to the caprock is quick compared to overall migration time
2. Flow is predominantly horizontal

As a result, the vertical gradient of the pore pressure is hydrostatic at leading order

$$\frac{\partial p}{\partial z} = \rho g \Rightarrow p = \begin{cases} P_a(x, y) + \Delta \rho g(H + h) + \rho_c g z & (CO_2) \\ P_a(x, y) + \rho_a g z & (Ambient) \end{cases}$$

Fluid Properties

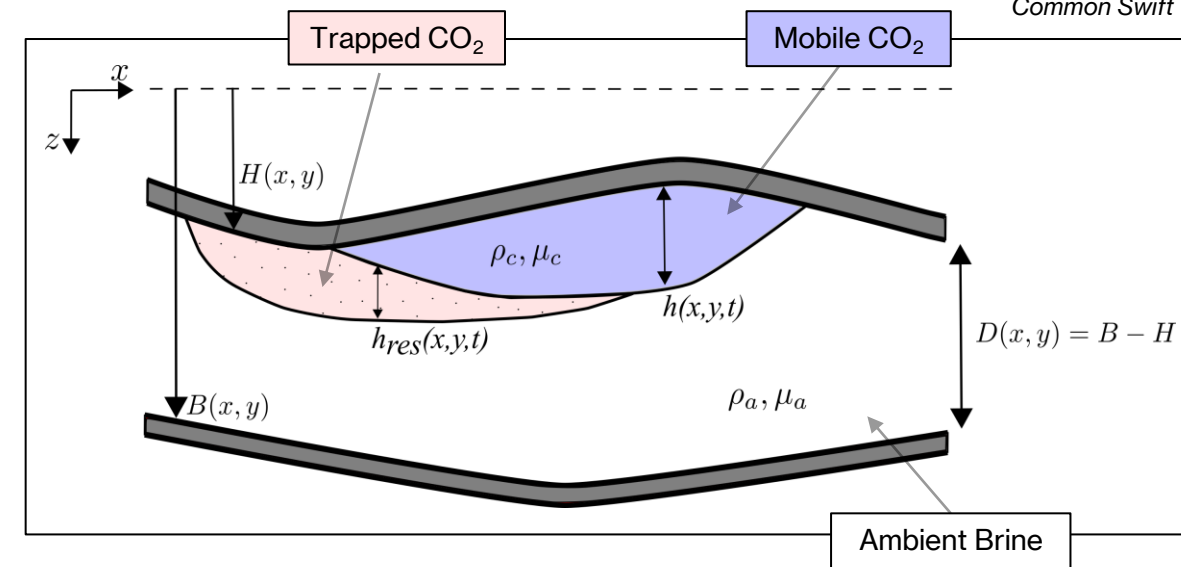
Densities ρ and viscosities μ are fixed for the two phases (supercritical CO_2 , ambient brine).

Reservoir Properties

Topography $H(x, y, z)$ & $B(x, y, z)$, porosity $\phi(x, y, z)$, and absolute permeability $k(x, y, z)$ are spatially variable.

Wetting Properties

Saturations $s(x, y, z)$ and rel. perm. $k_r(x, y, z)$ take mobile or trapped values depending on flow region.



The flow is separated into three regions:

1. Mobile region (mobile CO_2 , trapped brine)
2. Trapping region (trapped CO_2 , mobile brine)
3. Ambient region (purely brine)

Reduced-Physics Modelling - Apus

The governing equations come from vertically integrating conservation of mass (CoM) and Darcy's Law

$$\mathbf{u} = -\frac{k}{\mu} (\nabla p - \rho g \hat{\mathbf{z}})$$

over the vertical regions

$$1. H \rightarrow H + h + h_{res} \text{ (CoM for CO}_2\text{)}$$

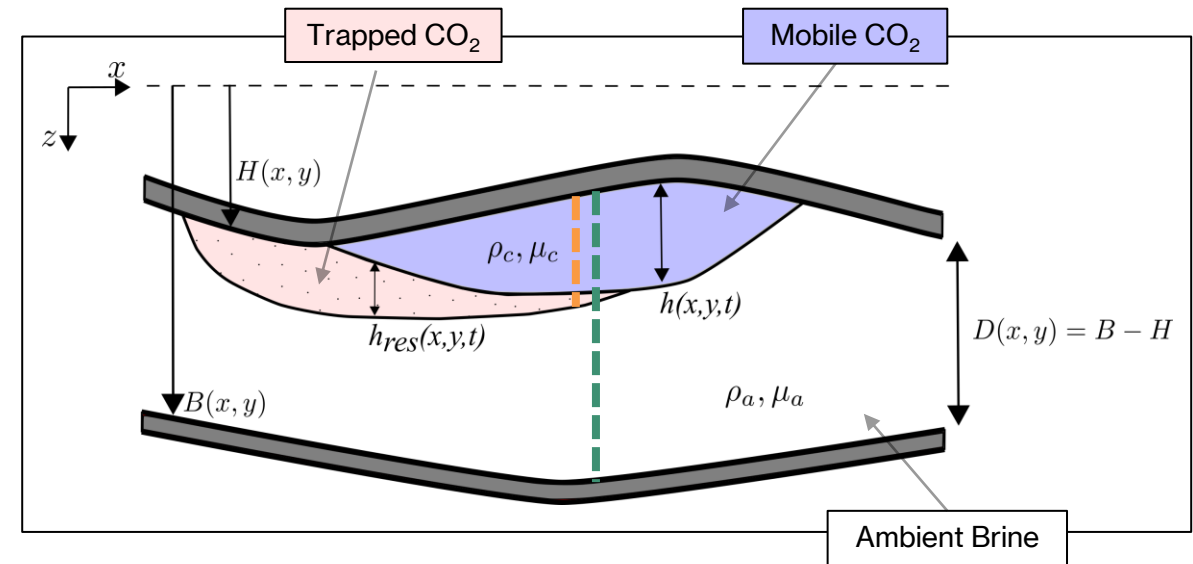
$$2. H \rightarrow B \text{ (Total CoM)}$$

This introduces the vertical permeability averages

$$\kappa_c = \frac{1}{h} \int_H^{H+h} k_{rn} \frac{k}{k_0} dz, \quad \kappa_a = \frac{1}{(D-h)} \int_{H+h}^B k_{rw} \frac{k}{k_0} dz$$

These encode the vertical structure of the reservoir and vary (through h and h_{res}) as the simulation progresses.

This leads to a system of 2D equations (derivatives in x & y , not z) governing the CO₂ regions (h , h_{res}) and the pressure (P_a).



The Elephant – Reservoir Model

A large-scale migration model was created as part of initial site assessment

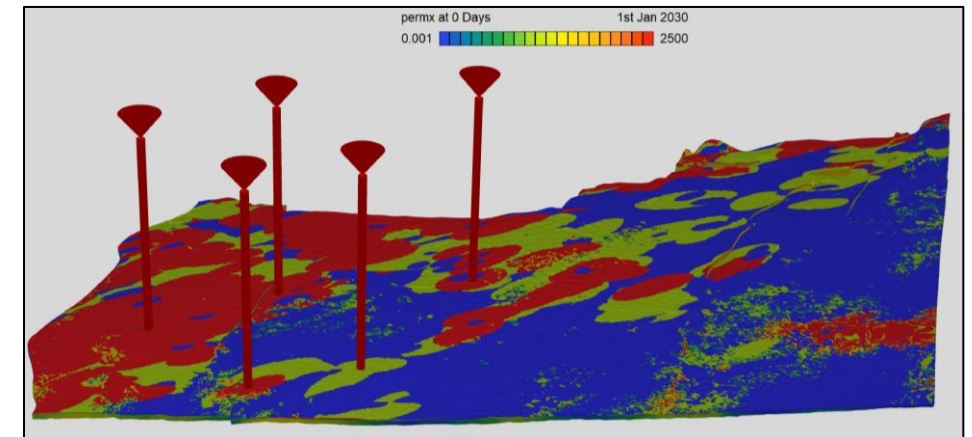
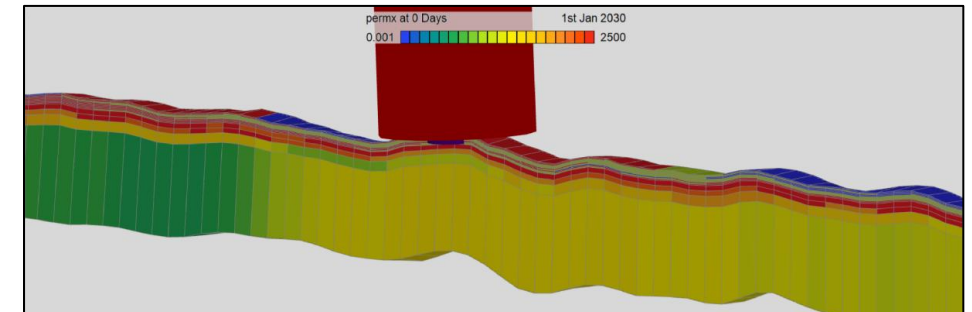
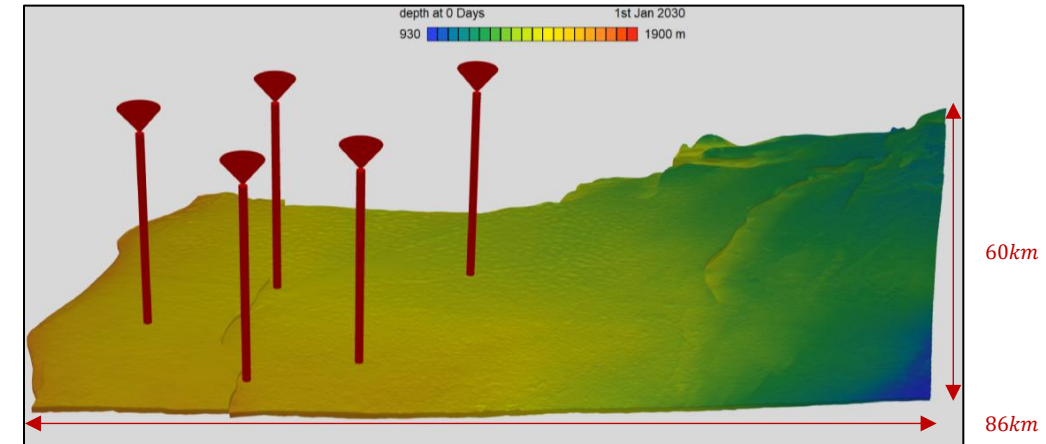
- $86\text{km} \times 60\text{km}$ extent, Average thickness 135m
- $930 - 1900\text{m}$ depth, $100 - 280$ bar, $25 - 55^\circ\text{C}$
- $718 \times 504 \times 14$ grid (5×10^6 cells, 3×10^6 active)
- Grid resolution focused within top $\sim 10\text{m}$, $\sim 120\text{m}$ grid spacing

Three flavours of model created:

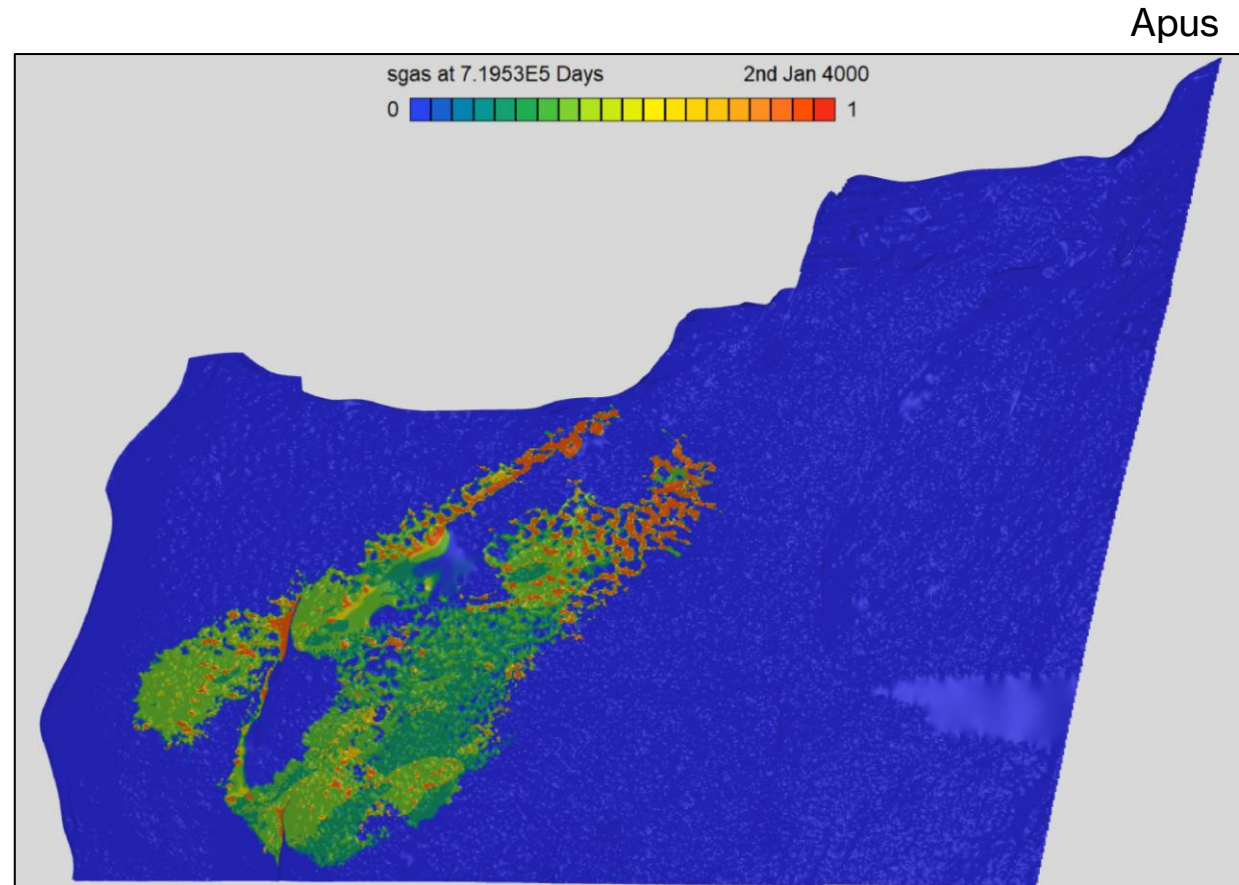
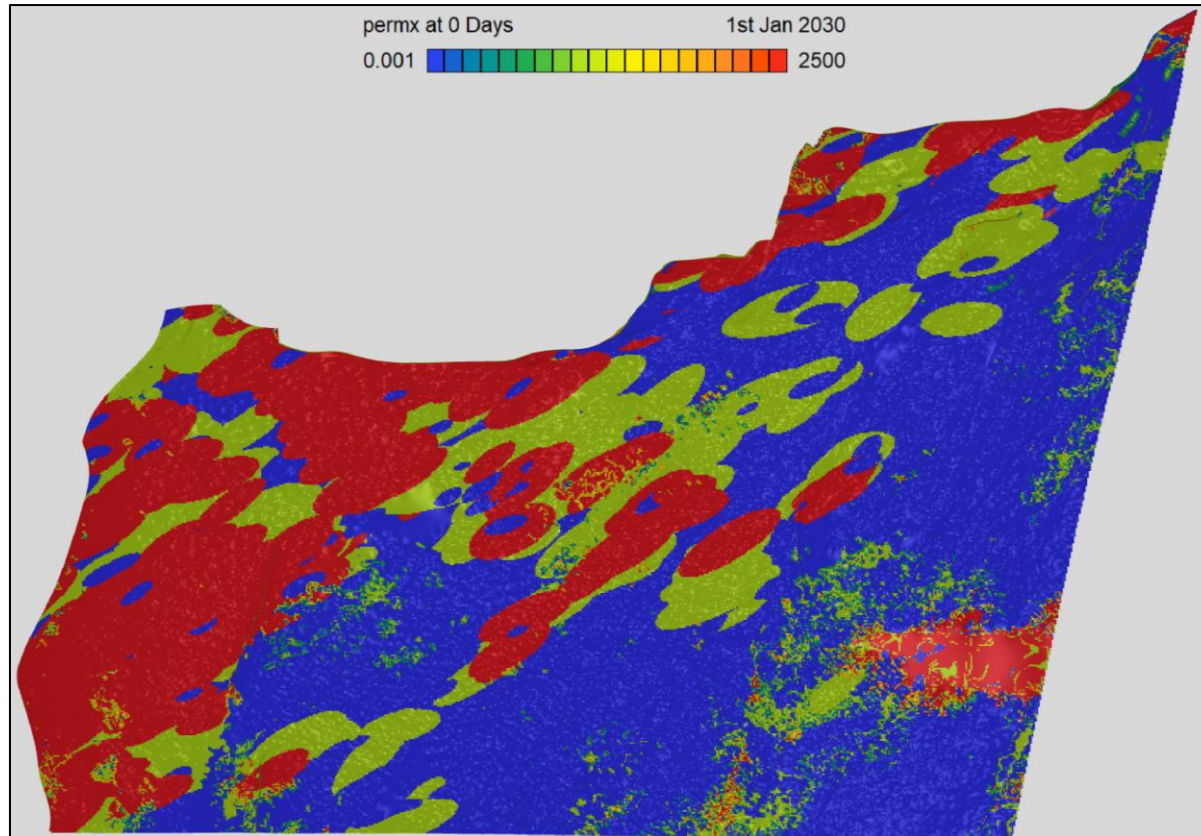
Model	Avg. Porosity (-)	Avg. Perm. (mD)
'Low' Quality	0.09	271
'Medium' Quality	0.13	662
'High' Quality	0.19	1070

Injection Scenario

- 10 Mt/yr from 5 wells each for 2030 – 2035 (250 Mt total).
- Simulate for 1970 years (2030 – 4000).

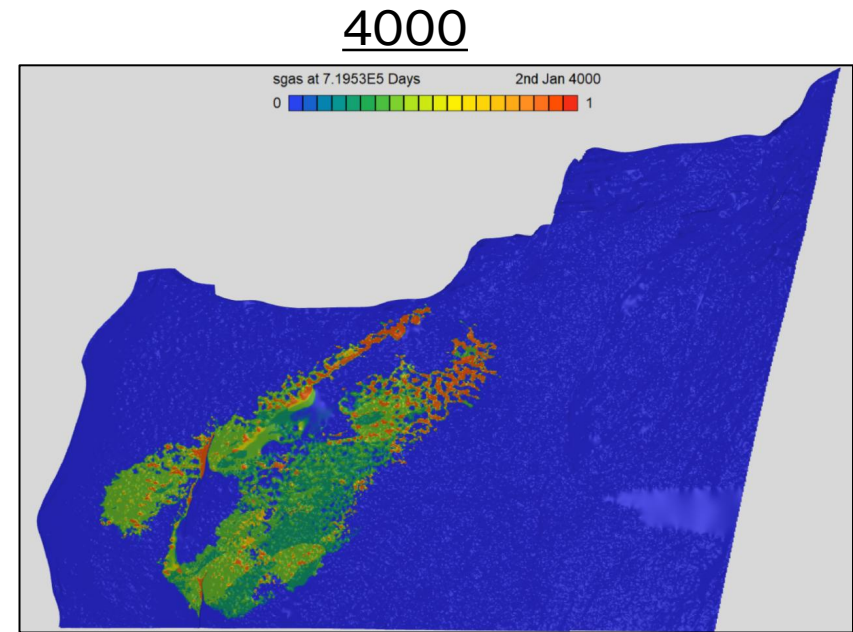
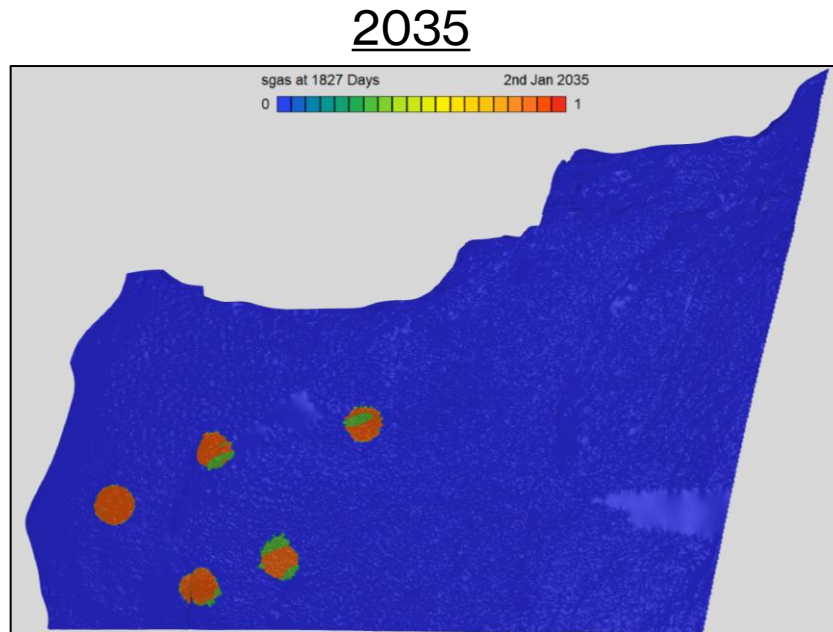


Simulations – High Perm. Model

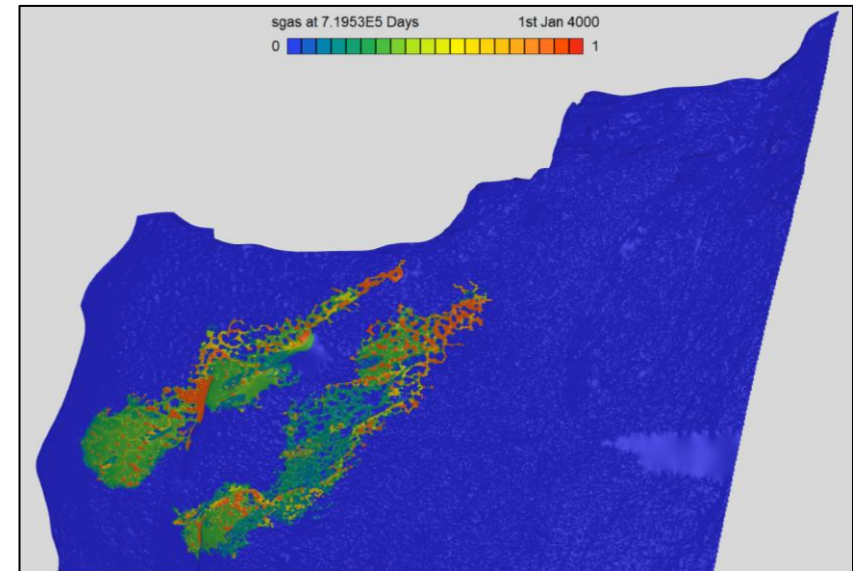
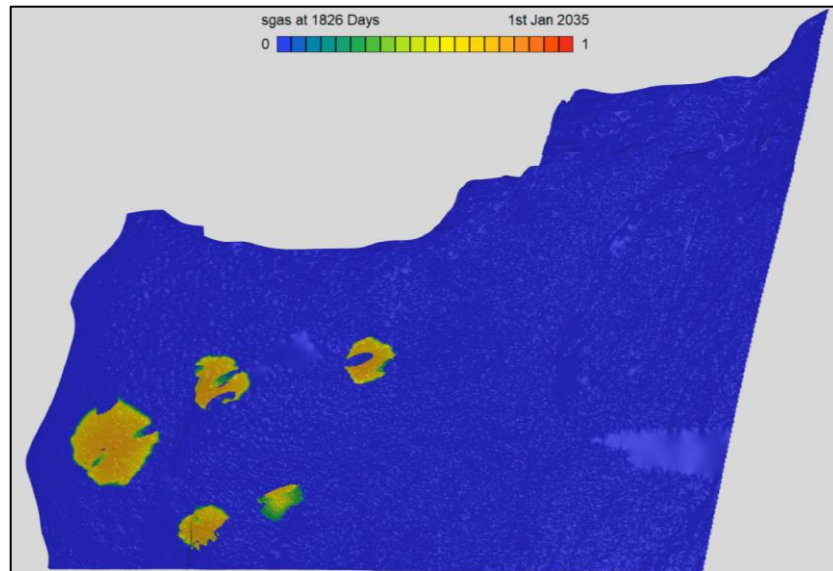


Simulations – High Perm. Model

Apus
Reduced Physics Model

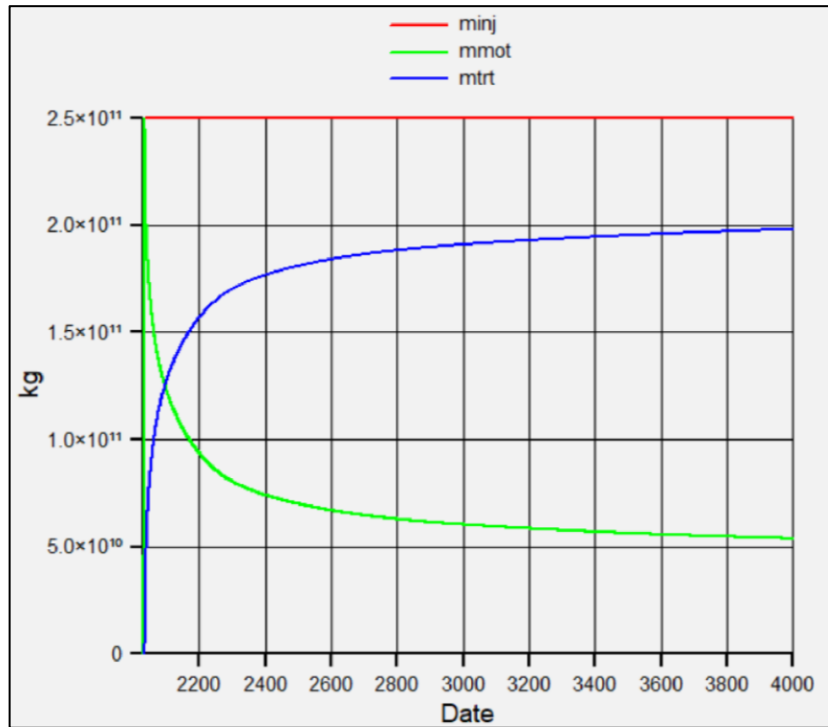


Cirrus
Full Physics Model



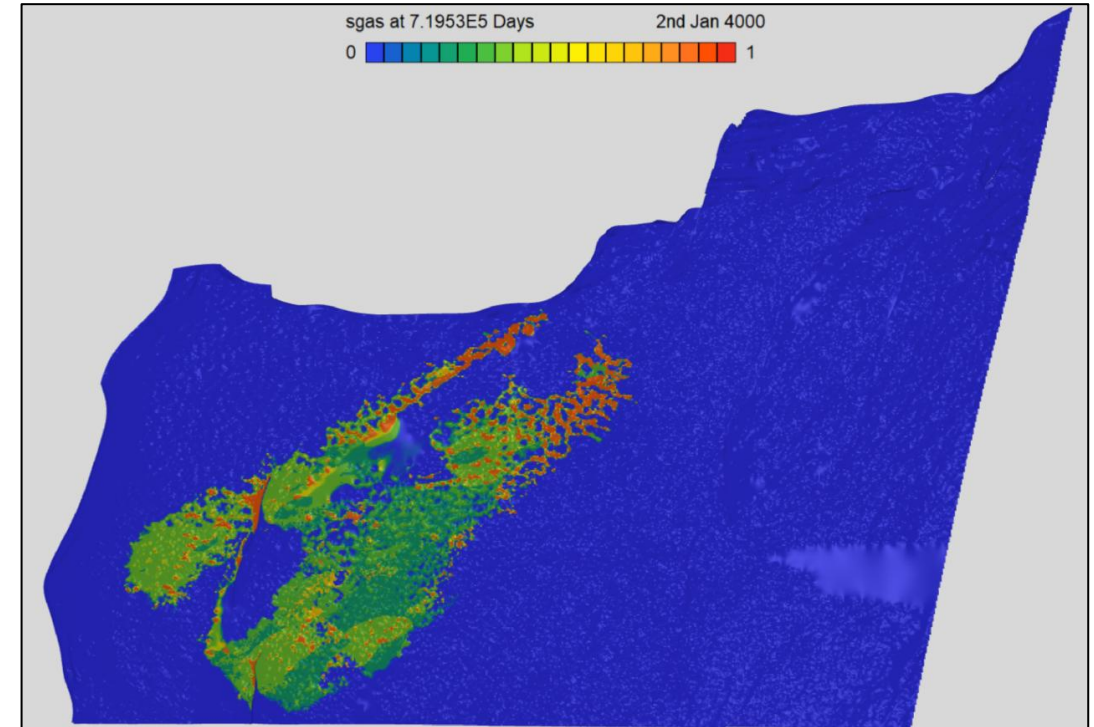
Storage at the Elephant

By the end of the simulation, the majority of the CO₂ is residually trapped:



Trapped ~ 79%

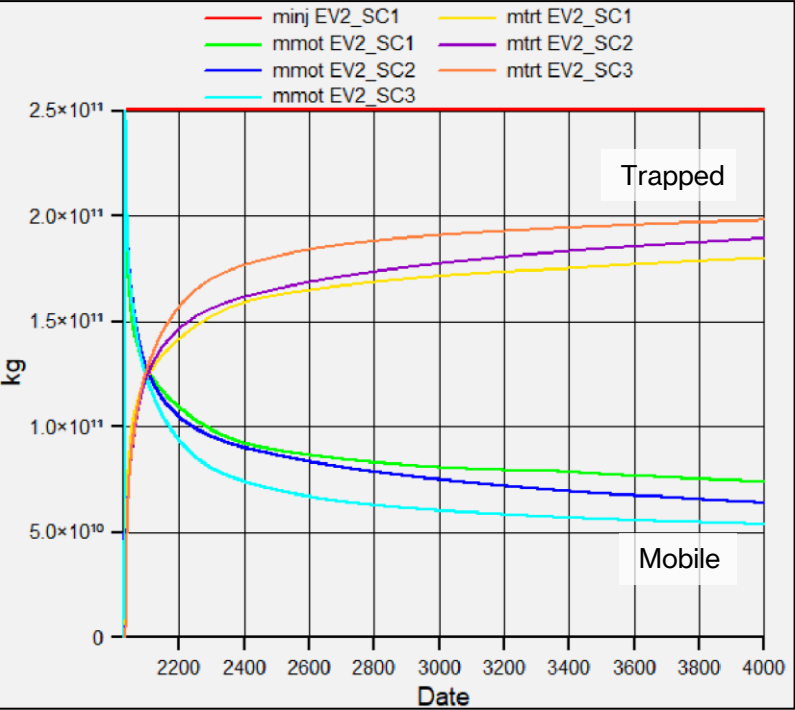
Mobile ~21%



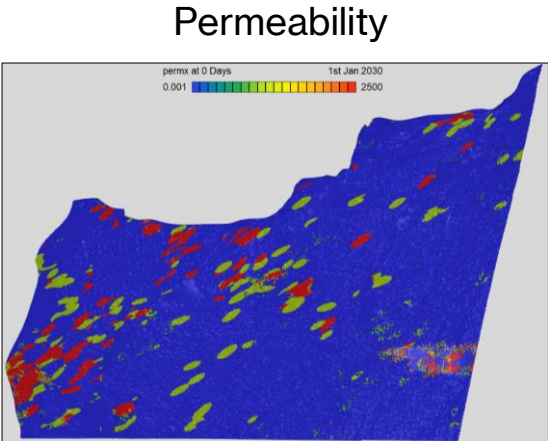
Dissolution would increase the amount of trapping over this period, but it is currently difficult to correctly model it at this scale. These simulations (no dissolution, high injection rate) look at a potential 'worst case' scenario.

Reservoir Model Comparison

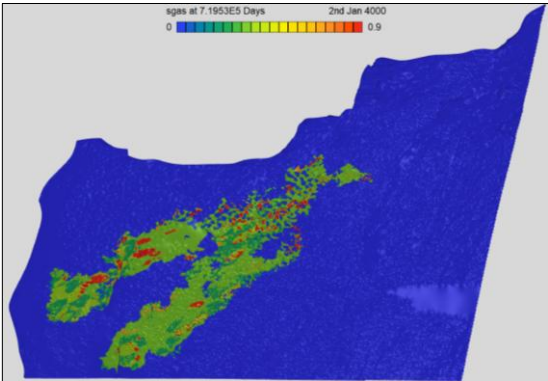
We can repeat this process for each of the reservoir models generated.



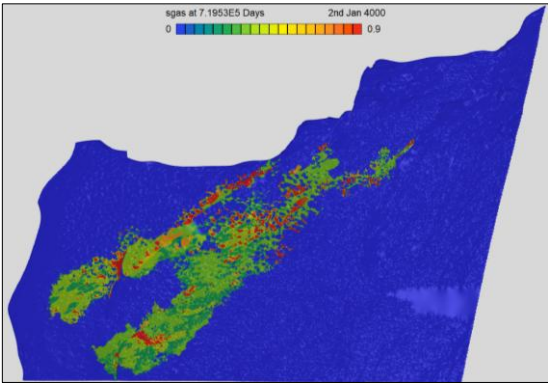
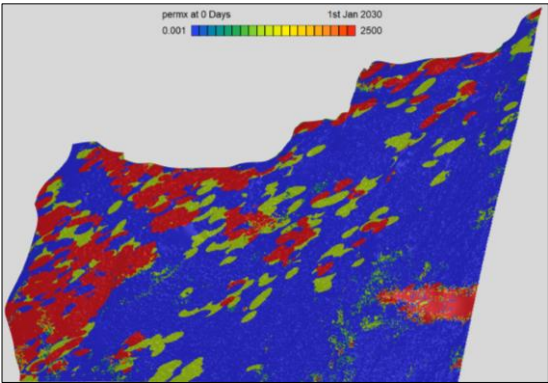
‘Low’ Quality



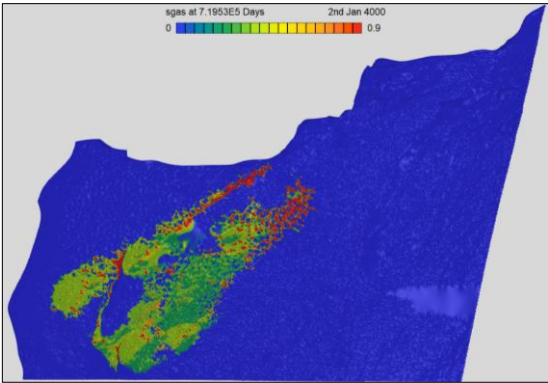
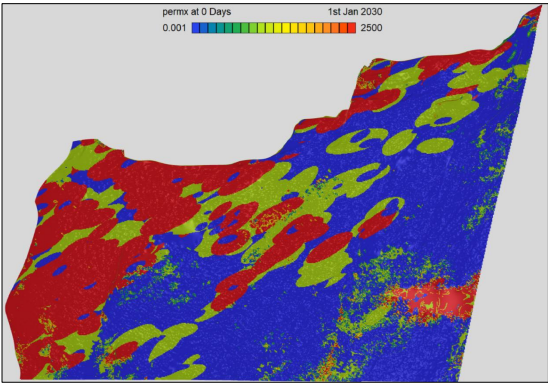
Final Saturation Distribution



‘Medium’ Quality



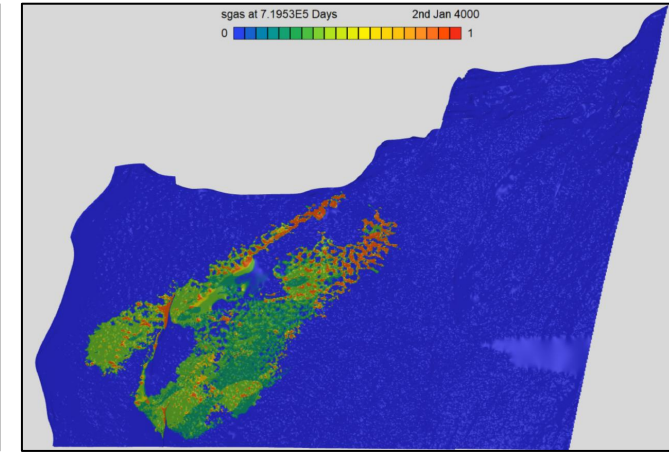
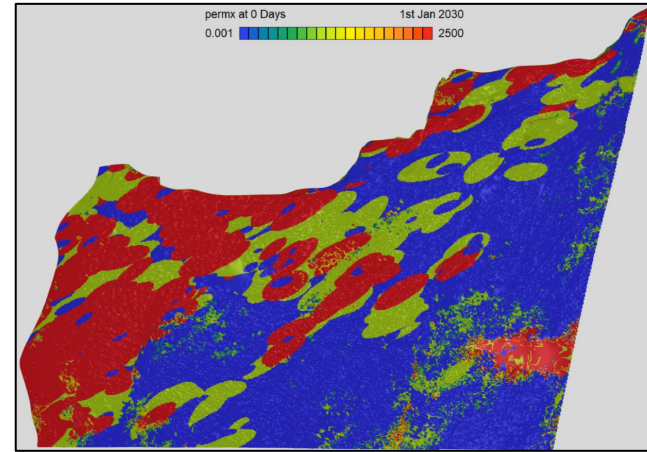
‘High’ Quality



Variation, Uncertainty, and Ensemble Modelling

The behaviour of the CO₂ is strongly influenced by heterogeneity of permeability and porosity, the topography of the caprock, etc. The measurements associated with each of these have corresponding uncertainties.

To get statistical information or confidence levels for simulation predictions, we need to work with ensembles.



For the Elephant simulations:

Simulator	Runtime	Hardware
Apus	1.5 hours	Laptop
Cirrus	4.5 hours	Cluster (2 nodes, 128 MPI procs)

While Cirrus is highly parallelised, Apus is serial, so multiple simulations can be run at once. This kind of simulation approach is well suited for Uncertainty Quantification.



Keta (https://commons.wikimedia.org/wiki/File:Apus_apus_flock_flying_1.jpg),
“Apus apus flock flying 1”, <https://creativecommons.org/licenses/by-sa/3.0/legalcode>

Conclusions

- Large-scale, open storage sites cannot be simulated fully at traditional resolutions. Buoyancy allows us to split them into Near-Well and Migration models.
- Near-Well modelling can tell us when, and at what rate, CO₂ reaches the top of the reservoir, and how much is trapped along the way.
- For long-term migration, we can design our reservoir models appropriately and make use of vertically integrated, reduced-physics simulation approaches.
- Simpler physics-based models are well suited for early prototyping and Uncertainty Quantification.

Acknowledgements

- Nick Lee and Bill Powell of TGS (Elephant data),
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