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Fast Workflows for CO_2 Containment & Leakage Risk Assessments

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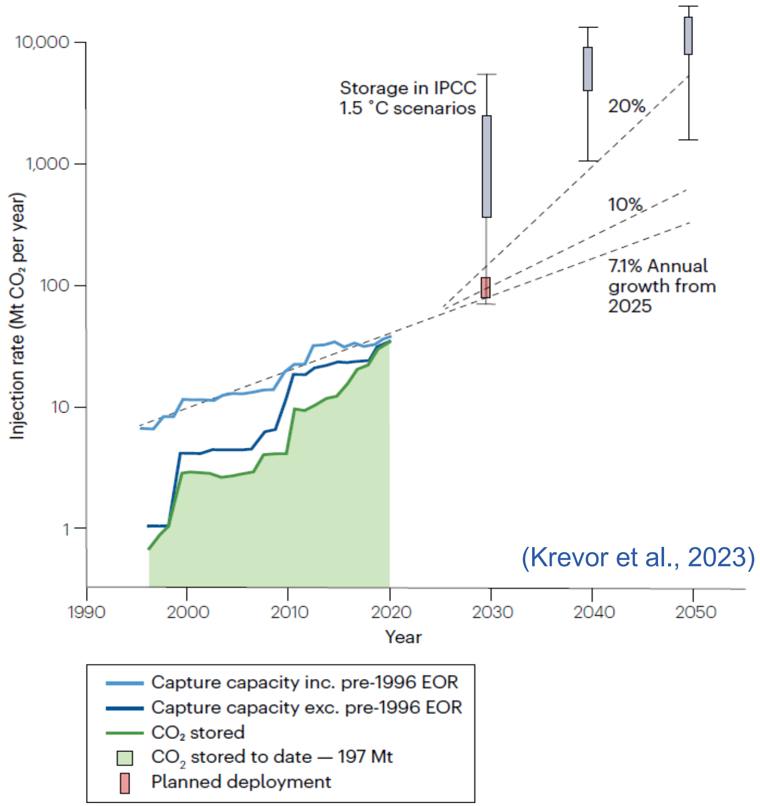
04/12/2023

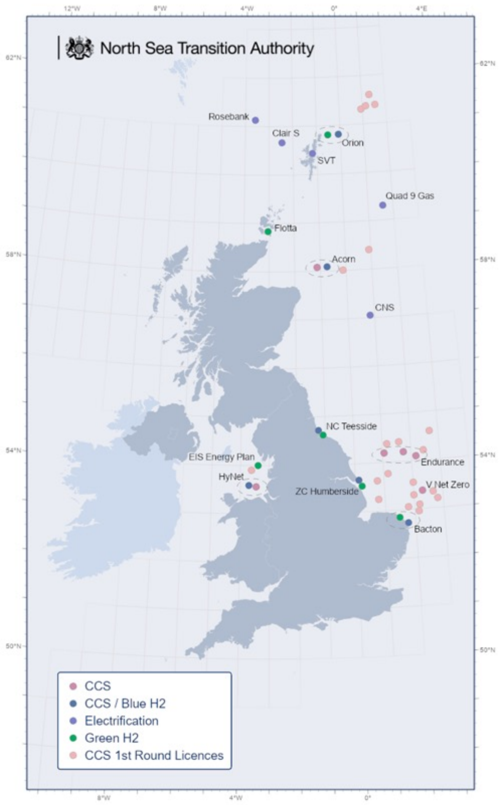
Outline

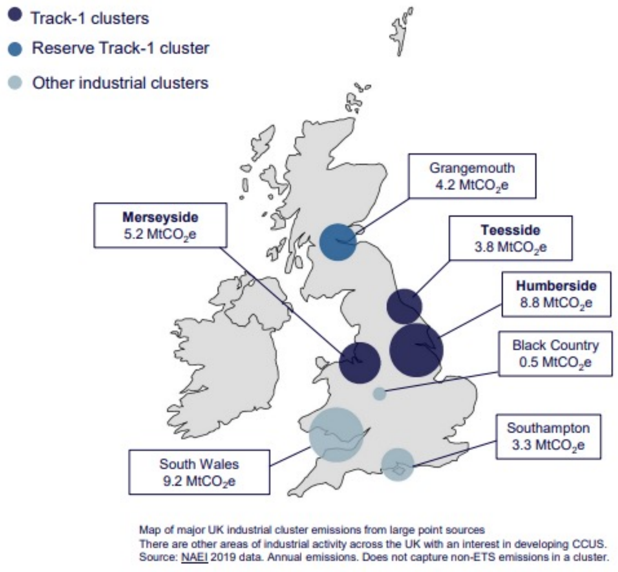
- Introduction to CCS & Storage Containment
- Vertical Equilibrium Modelling and CO2lab
- Fast workflows for CCS Assessments
  - Storage capacity and spill risk
  - Fault leakage
- Summary & Outlook

Why CCS? – Research Motivation



(Krevor et al., 2023)

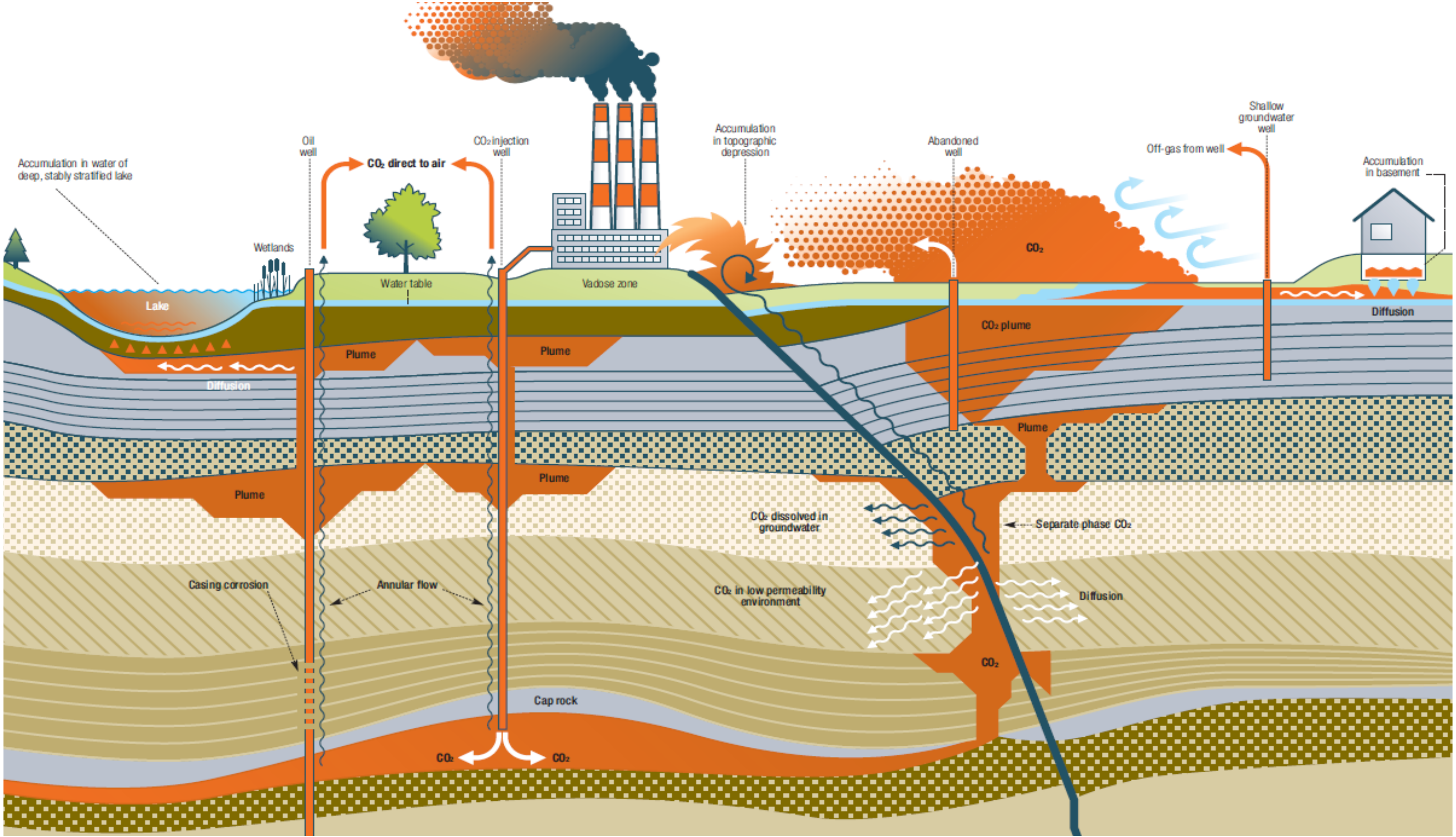




HM Government, 2023

- UK government has ambitious CCS targets (30 Mt/yr by 2030-2035, > 50 Mt/yr by 2035)
- **Message** – Storage must increase multi-fold to meet the IPCC 1.5 °C goal scenarios
  - Impetus to develop fast technologies to assess storage security, develop injection strategies, etc.

Possible Storage Concerns



(Benson., 2006)

Motivation → Fast Screening + Leakage Risk + Uncertainty?

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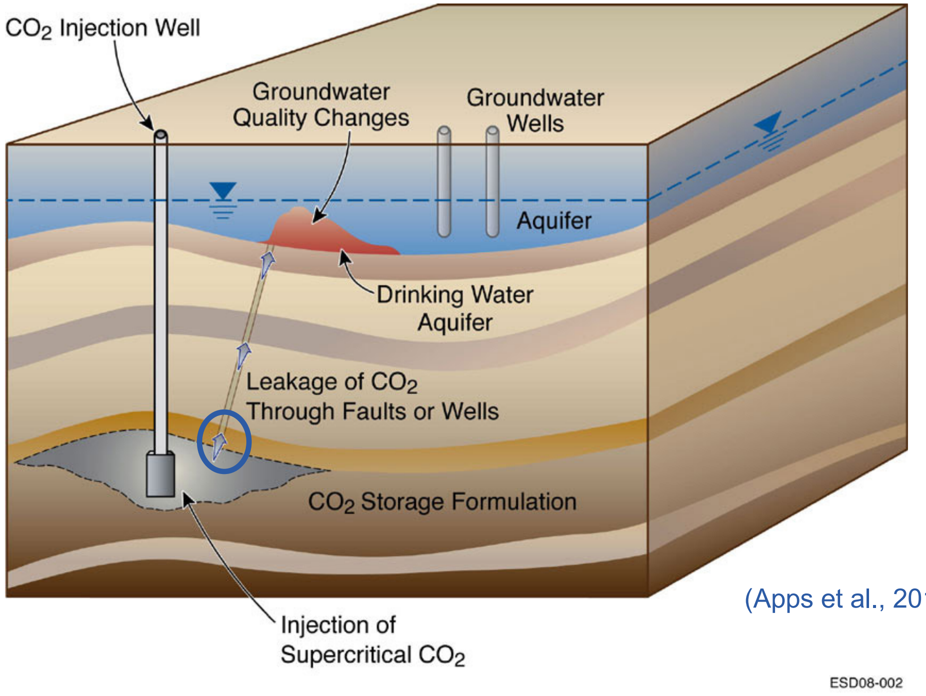


(Apps et al., 2010)

Issue

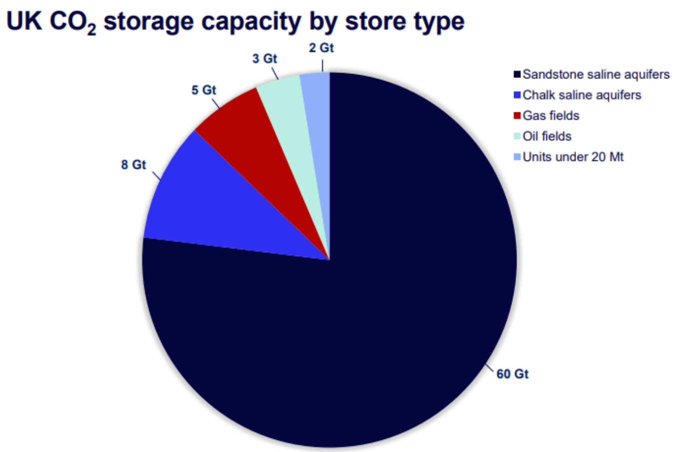
Assessing secure storage containment is computationally expensive = Flow + Geomechanics in 3D for the entire domain

Goal

Develop fast screening tools using Multiscale – Multiphysics approach to get quick estimates under uncertainty

Outline

1. Spill point Analysis
2. Capacity Estimation
3. Fault Leakage

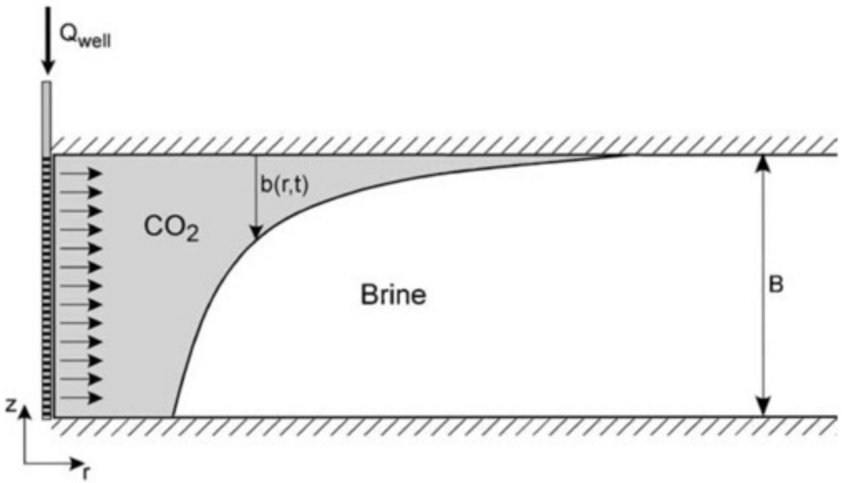


HM Government, 2023

Methods

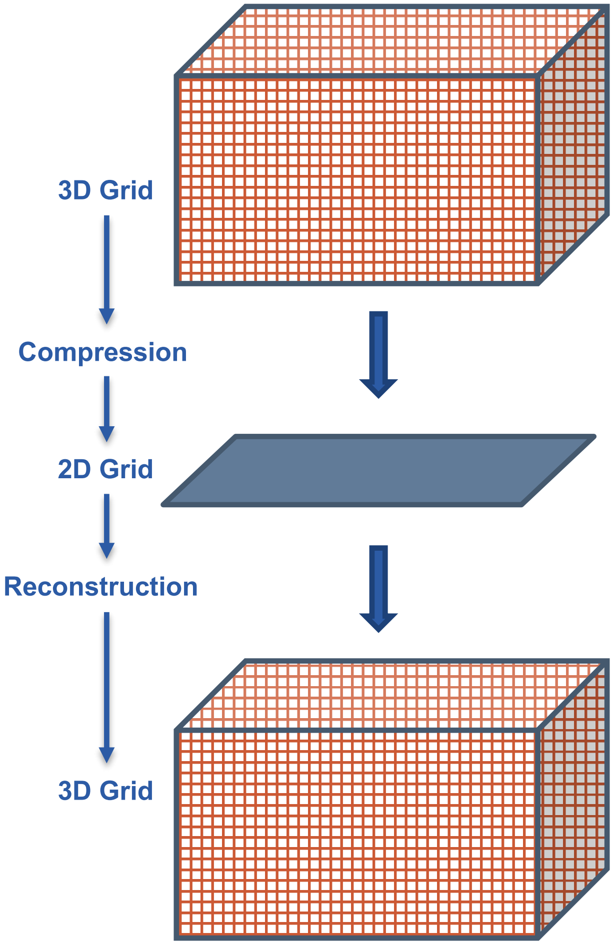
Vertical Equilibrium Models

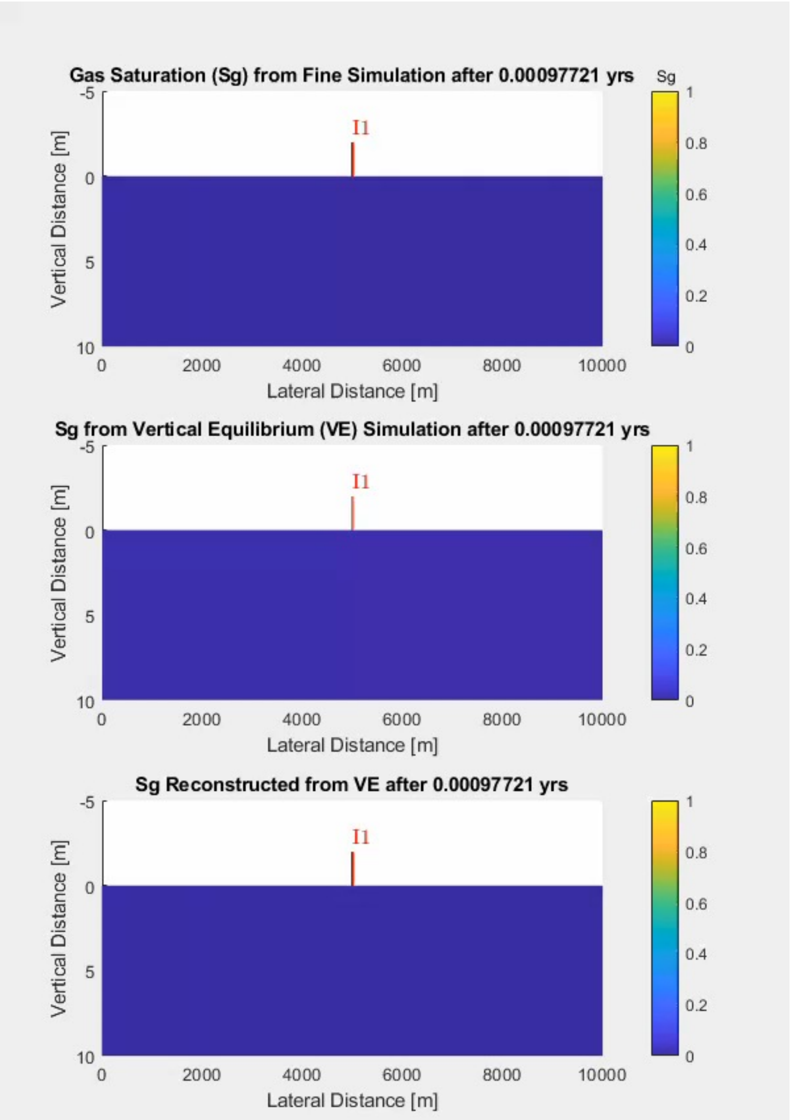
Why Vertical Equilibrium (VE) Modelling?



- Once CO_2 in injected into a reservoir
  - Thin and long reservoirs → vertical flow << overall flow
  - @Reservoir(P,T) → Density of CO_2 << Density of Brine
  - Gravity segregation occurs due to density difference
  - No vertical flow between phases → **Vertical Equilibrium**

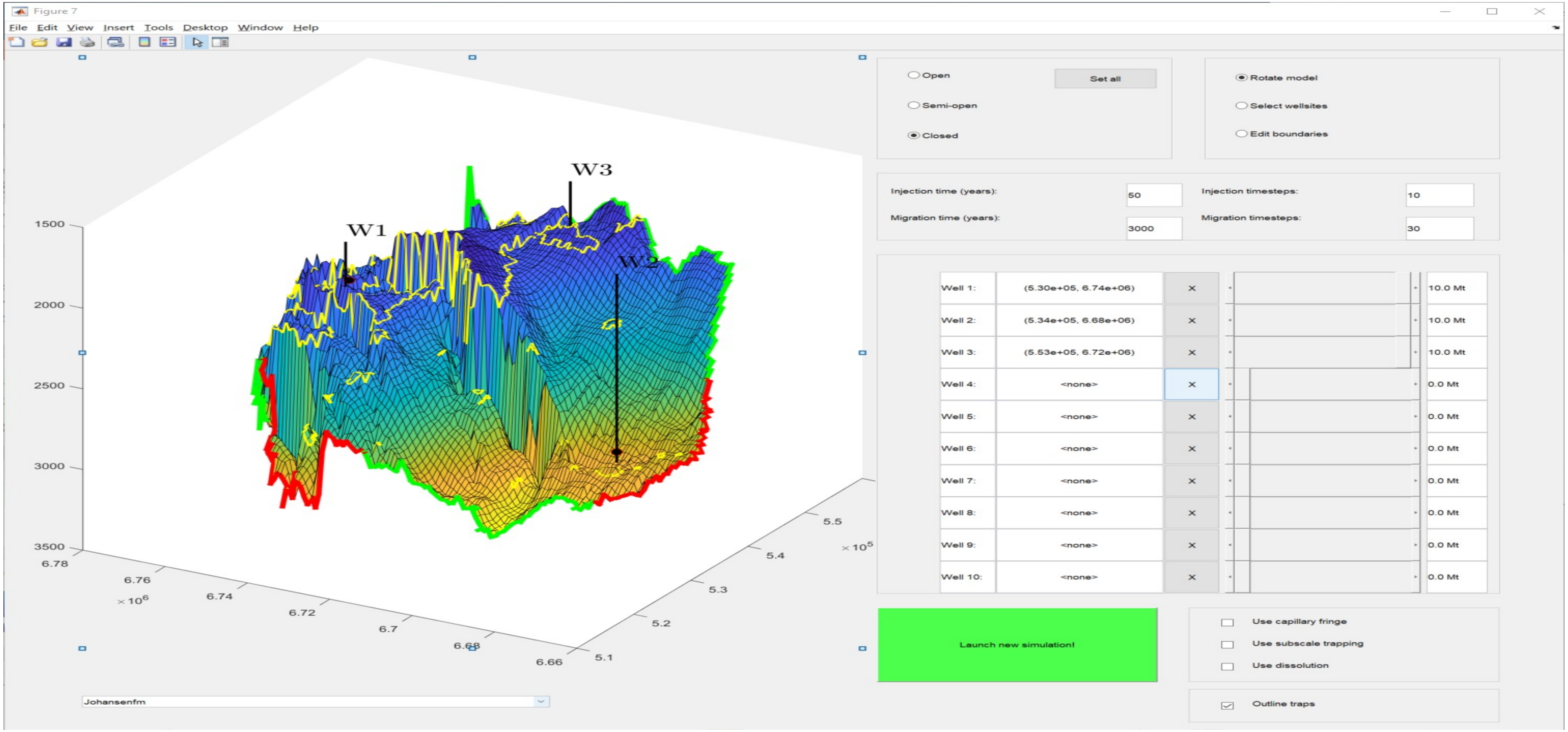
- The vertical dimension can be eliminated from the equations → 3d problems becomes a 2d problem → **Computation Advantage**





Further Reading (**Book**) – Nordbotten, J.M. and Celia, M.A., 2011. Geological storage of CO2: modeling approaches for large-scale simulation.

CO2lab of MRST



Further Reading **(Book)**- Lie, K.A., 2019. An introduction to reservoir simulation using MATLAB/GNU Octave: User guide for the MATLAB Reservoir Simulation Toolbox (MRST). Cambridge University Press.

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Storage Containment Assessment

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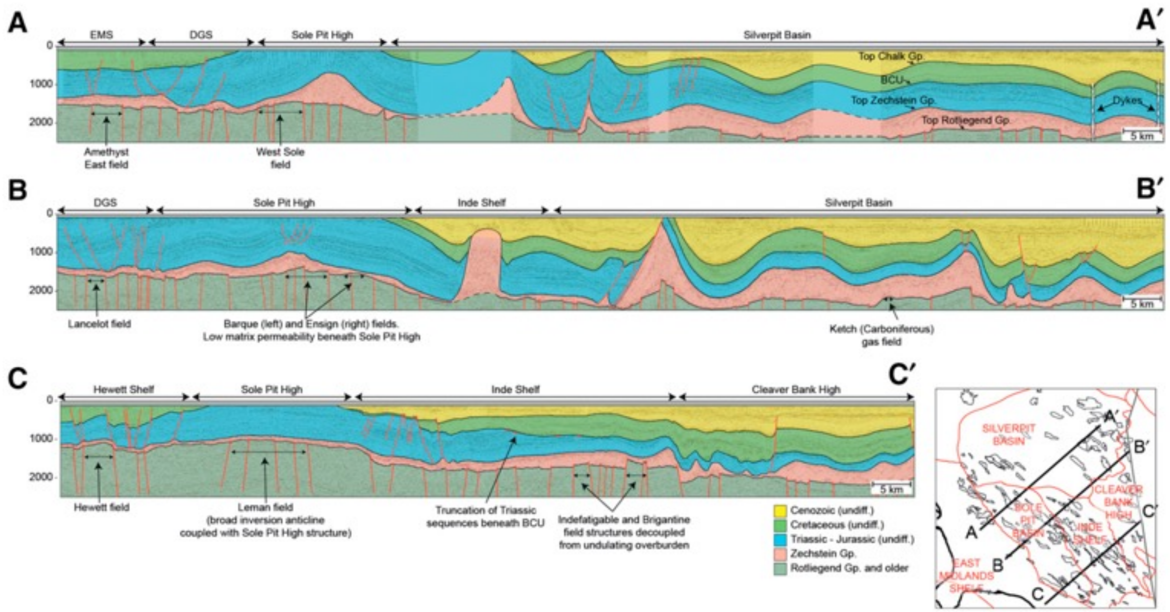
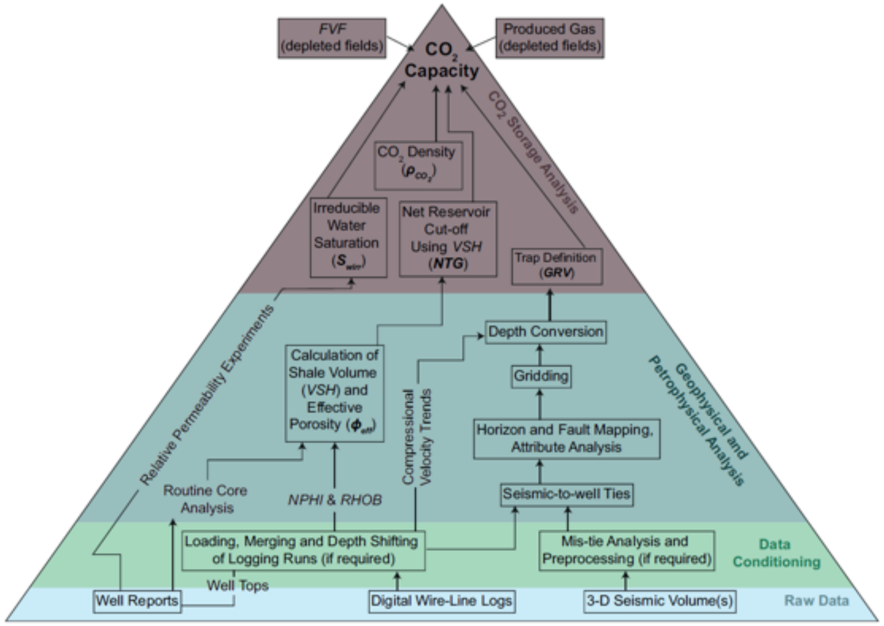
Motivation → Storage Containment (Seismic to Capacity workflows)



(Underhill et al. 2023)



(de Jonge-Anderson et al., 2022)

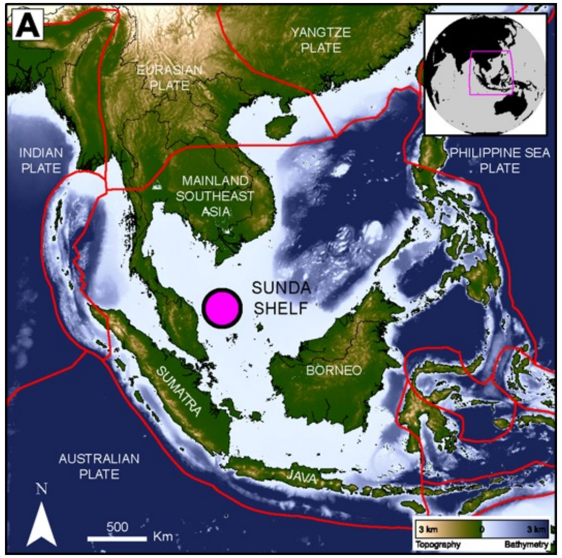
Issue → Seismic and well data used to define storage capacity based on Net Pore Volume:

$$M_{CO_2 t\_g} = GRV \times NTG \times \phi_{eff} \times (1 - S_{wirr}) \times \rho_{CO_2}$$

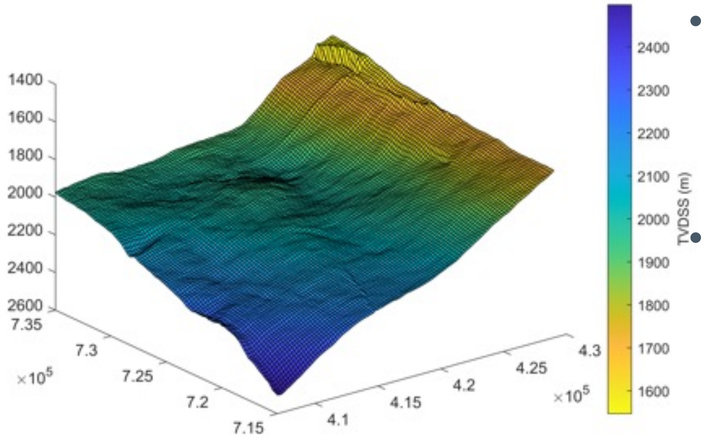
Refined using flow simulations at site-level.

Solution → Use reduced complexity models (static and dynamic tools) to arrive at a realistic capacity estimates in screening workflow

Study Area

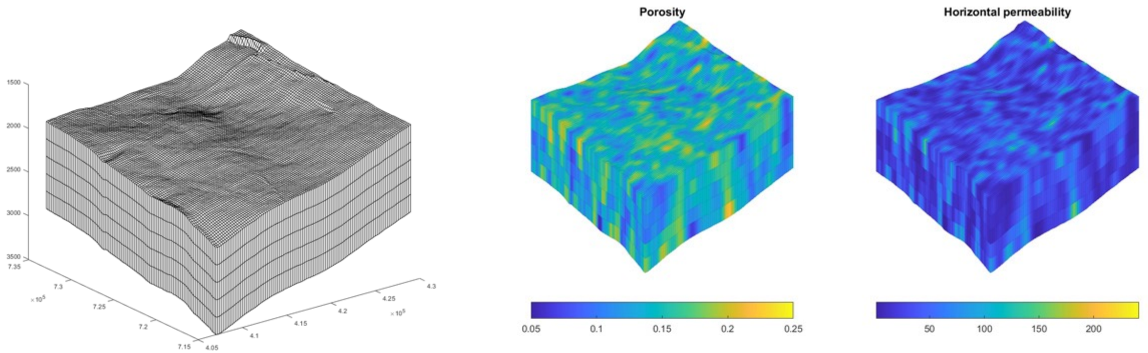


- Our study focuses on an area of the Malay Basin, offshore Peninsular Malaysia.
- This basin is being appraised for CO_2 storage potential.



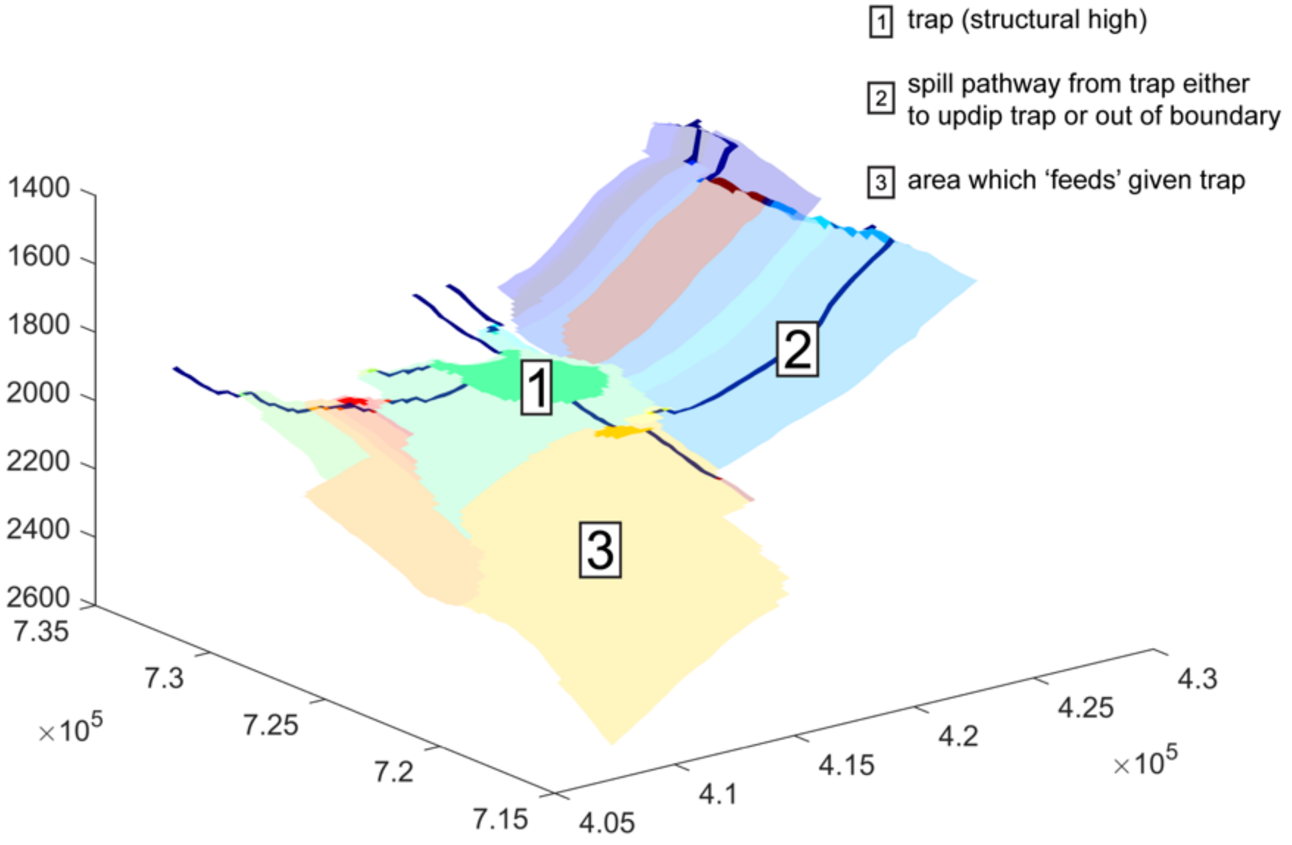
- A 440 km^2 area is mapped using 3D seismic.
- The area gently slopes downdip to the west and contains an anticline.

The total capacity of the grid



- A simple 3D grid of the reservoir is populated with porosity and permeability values obtained from gaussian distributions.
- The total capacity of the grid is **32 GtCO2**

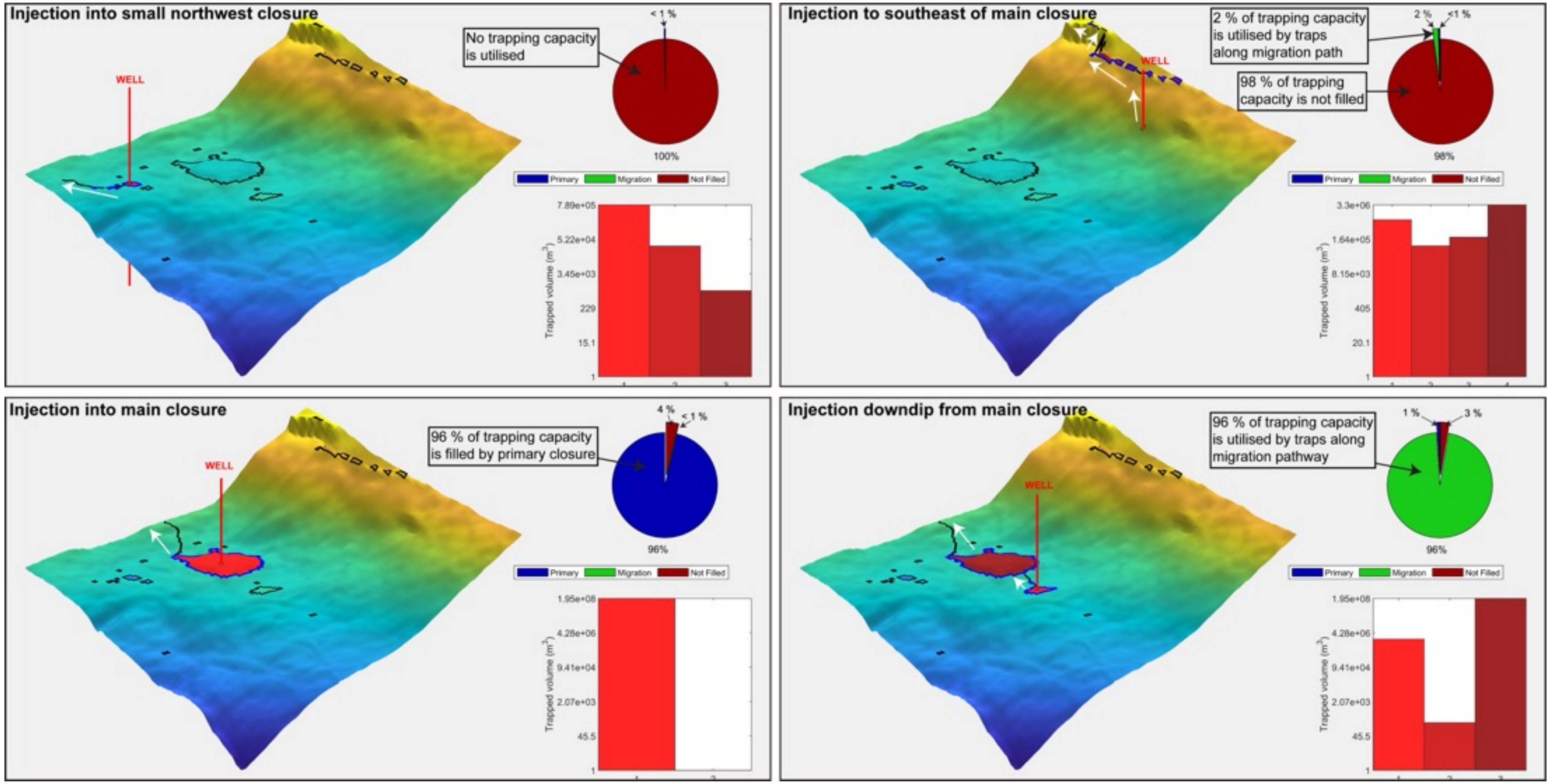
Structural Trapping



- Using just the geometry of the reservoir, a static trapping framework is built.
- The framework shows traps (structural highs), trapping regions (that feed traps) and pathways (routes from one trap to another)
- This is used to calculate the total structurally trapped capacity: **12.5 GtCO_2**

de Jonge-Anderson, I., Ramachandran, H., Doster. F., and Nicholson U.. Storage Efficiency and Reduced Complexity Modelling. MRST Conference (Poster Session), 2023.

Spill Analysis



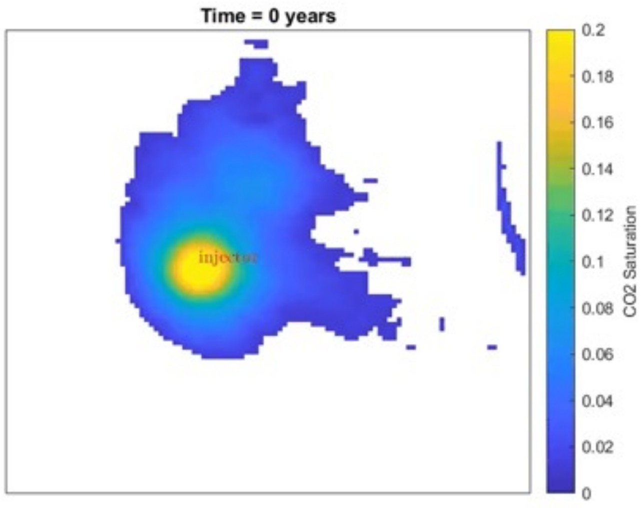
- A series of trapping chains are tested to determine the optimal well placement that allows consecutive filling of structural traps.
- A trapping chain is a series of traps along a spill path that could be filled from one injection point.

de Jonge-Anderson, I., Ramachandran, H., Doster. F., and Nicholson U.. Storage Efficiency and Reduced Complexity Modelling. MRST Conference (Poster Session), 2023.

VE Modelling

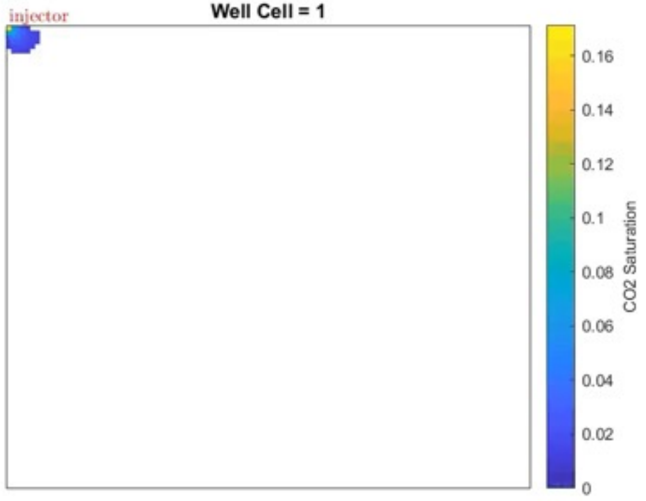
VE simulations approximate 3D fluid behaviour in 2D, thus reducing computational time

Example simulation



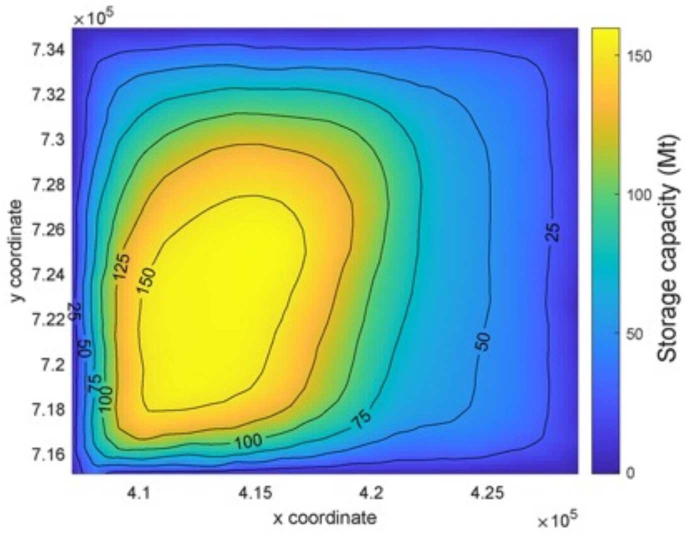
50 years of injection (3MT/year) followed 950 years of migration

100s simulations, varying injection well



440 simulations. All other parameters fixed.

Map of storage capacity by injection well location



Capacity is defined as the pore space occupied by CO_2 at end of simulation. The capacity from this optimised scenario is **150 MTCO$_2$**

de Jonge-Anderson et al., 2024 (In prep)

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Fault Leakage Risk

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Fault Leakage + Uncertainty?

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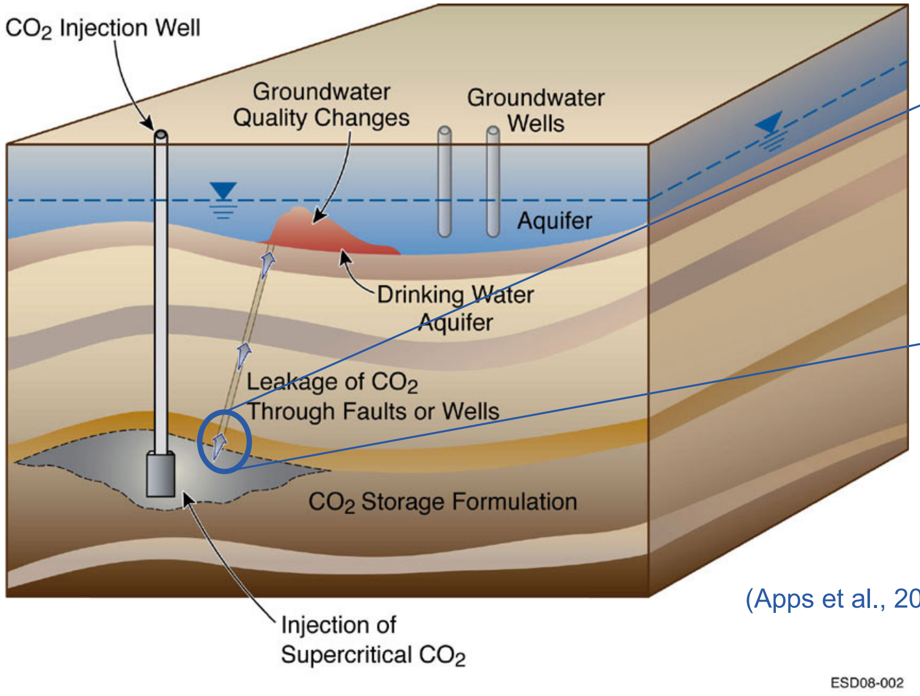
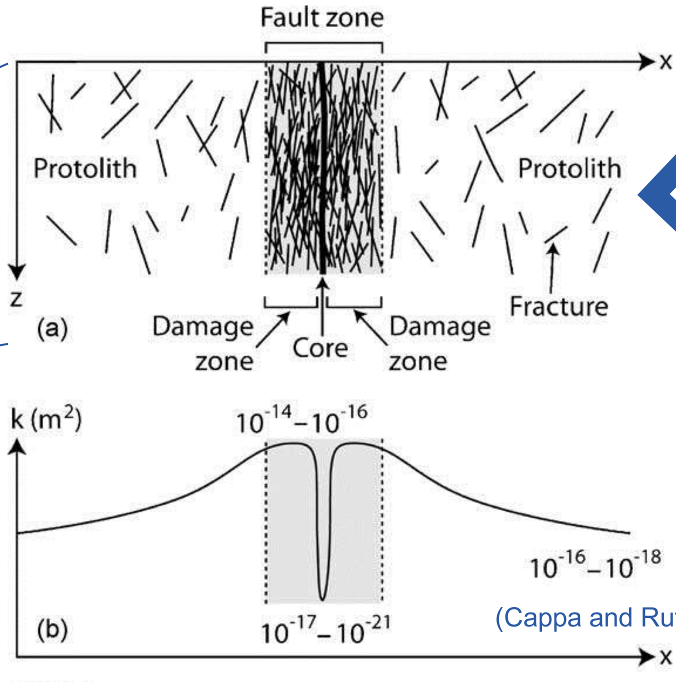


(Apps et al., 2010)



(Cappa and Rutqvist, 2011)

Flow through the damage zone

Flow through fracture network

Experiments to understand the fault-related fluid flow is performed by GeoEnergy Research Group at Heriot-Watt, headed by Andreas Busch

GeoEnergy Group

Issue → Assessing leakage is computationally expensive = Flow + Geomechanics in 3D for the entire subsurface domain

Goal → Develop fast screening tools using Multiscale – Multiphysics approach to get quick estimates for fault leakage under uncertainty

Accelerating CCS Technologies

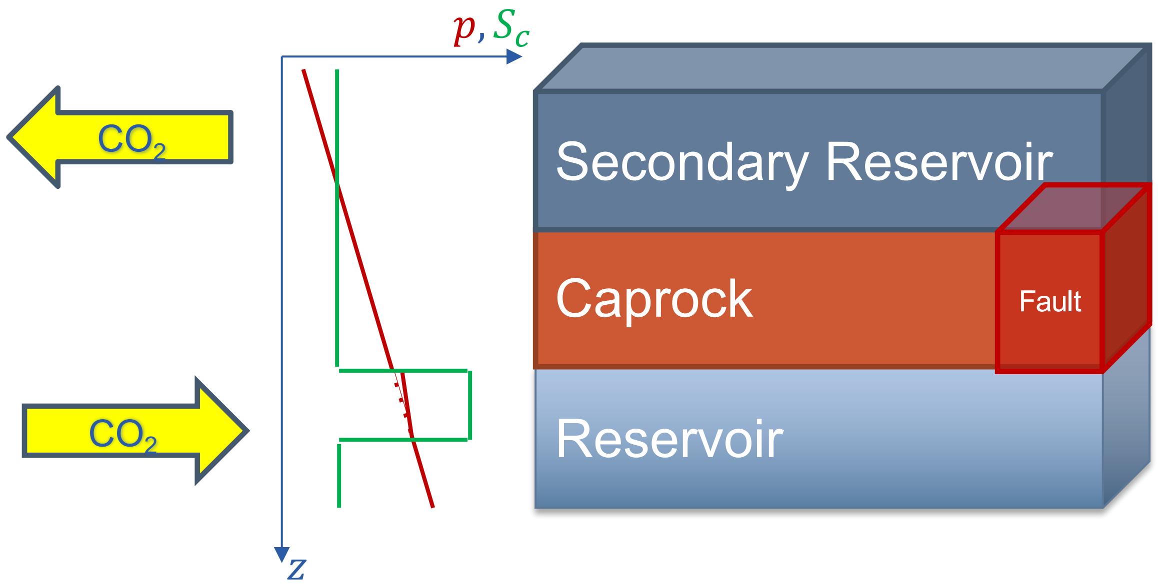
D E T E C T

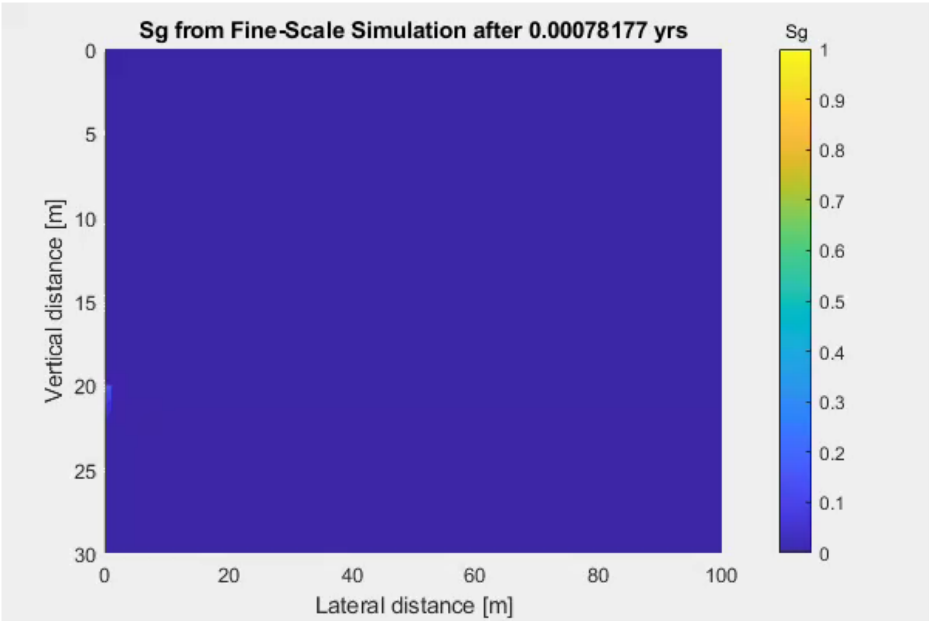
INTEGRATED GEOLOGICAL CO_2 LEAKAGE RISK ASSESSMENT

Propose → Vertically Integrated Models + Fault Leakage

Conceptual Leakage Scenario

- Pattern simulations helps build relationship for fault leakage

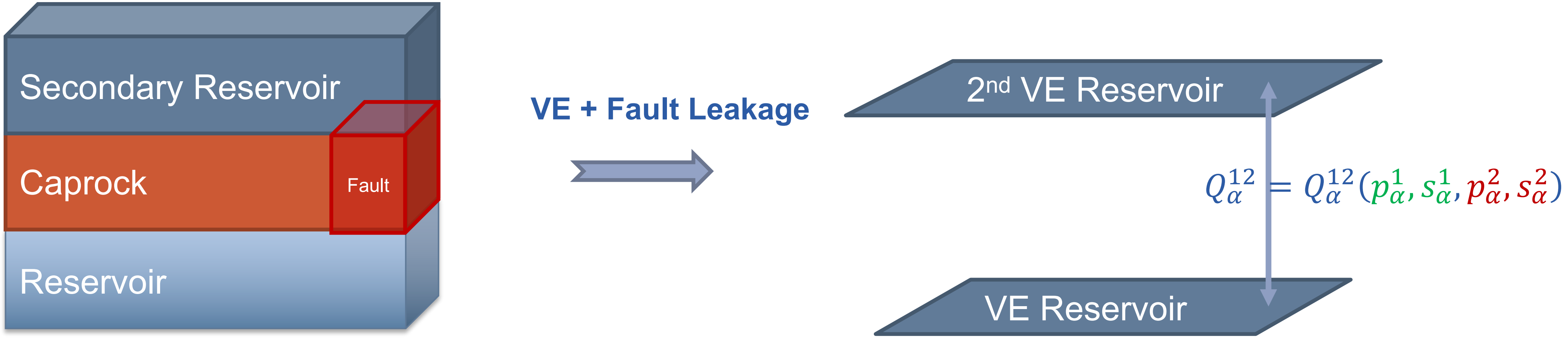




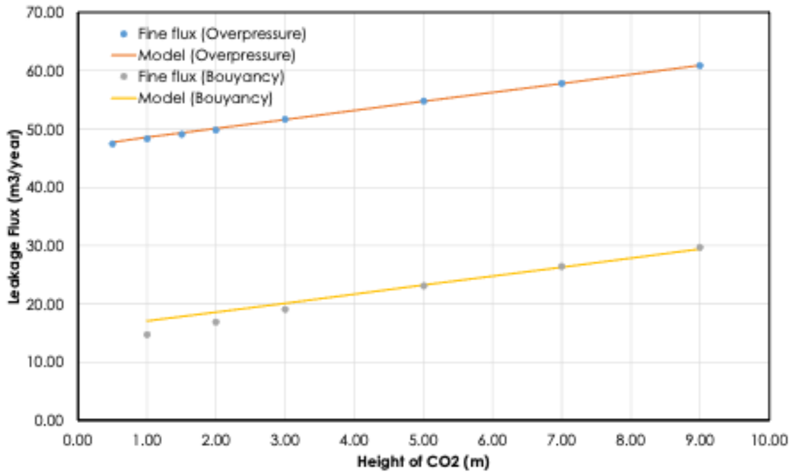
- CO2 layer below fault impedes water flow along fault
- Steady-state flux is a good conservative leakage estimate

Ramachandran, H., Doster, F., and Geiger, S.. A Quick Approach to Model Fault Leakage Modeling during CO2 Storage within Vertical Equilibrium Modelling Approach. Interpore PMTTT (Presentation), 2023. → https://www.youtube.com/watch?v=L5f5IP7Yf2U

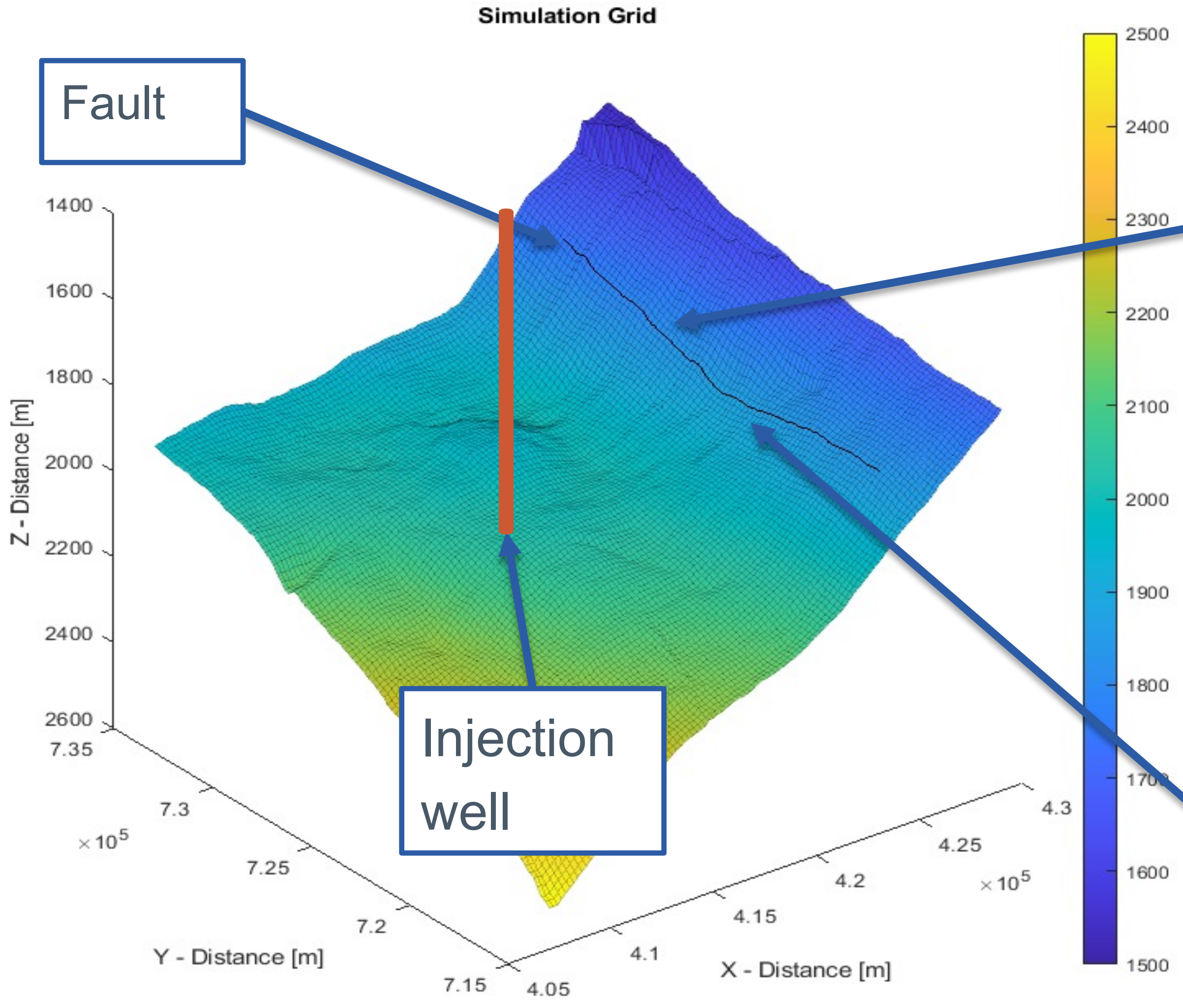
VE + Fault Leakage Function



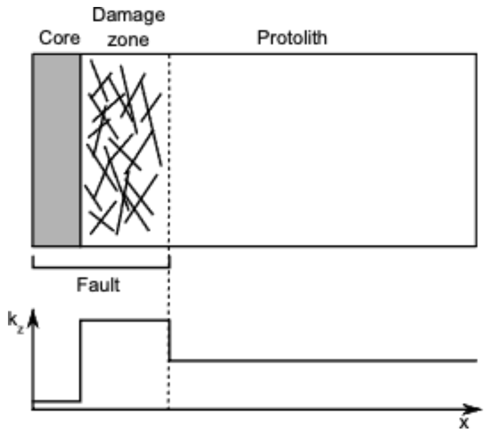
- Similar mathematical structure to multi-continuum simulations
- What is $Q_\alpha^{12}(p_\alpha^1, s_\alpha^1, p_\alpha^2, s_\alpha^2)$?
- Simplest approach:
  - $Q_\alpha^{12} = -T^{RR}\lambda_\alpha^{RR}(\Delta\rho g(s_\alpha^1 H_R + L_C) + (p_a - p_0))$
  - $T^{RR} = A_f\, L_C^{-1}$
  - λ_α^{RR} is upstream weighted



Fault Model Application



Fault transmissibility along x-direction is made zero to simulate fault core



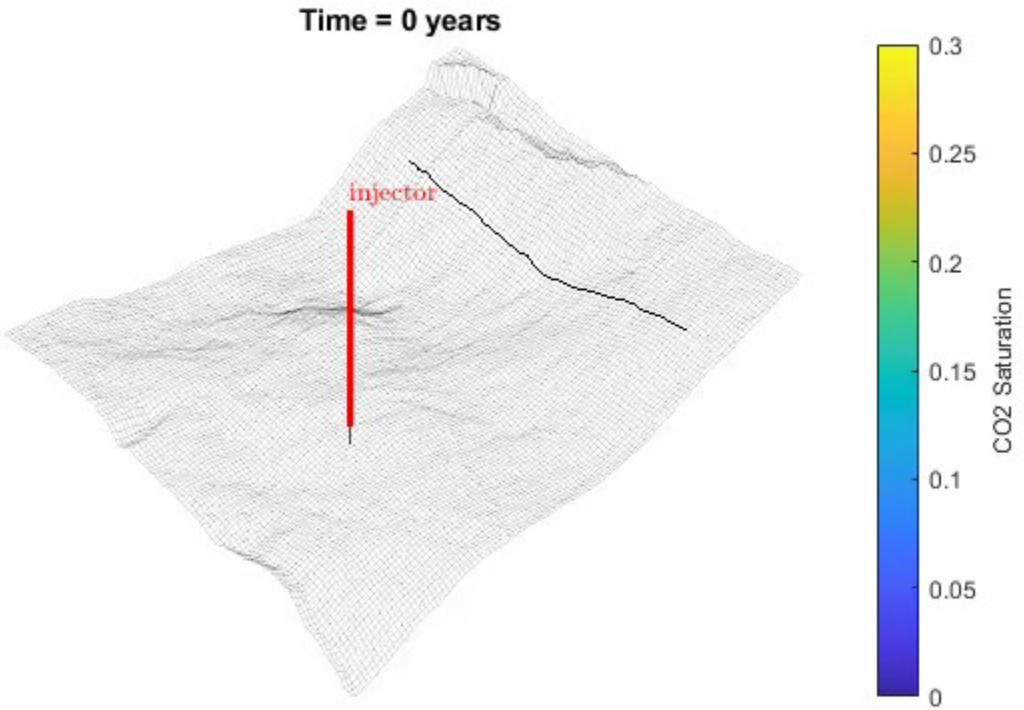
(Bachu and Celia, 2009)

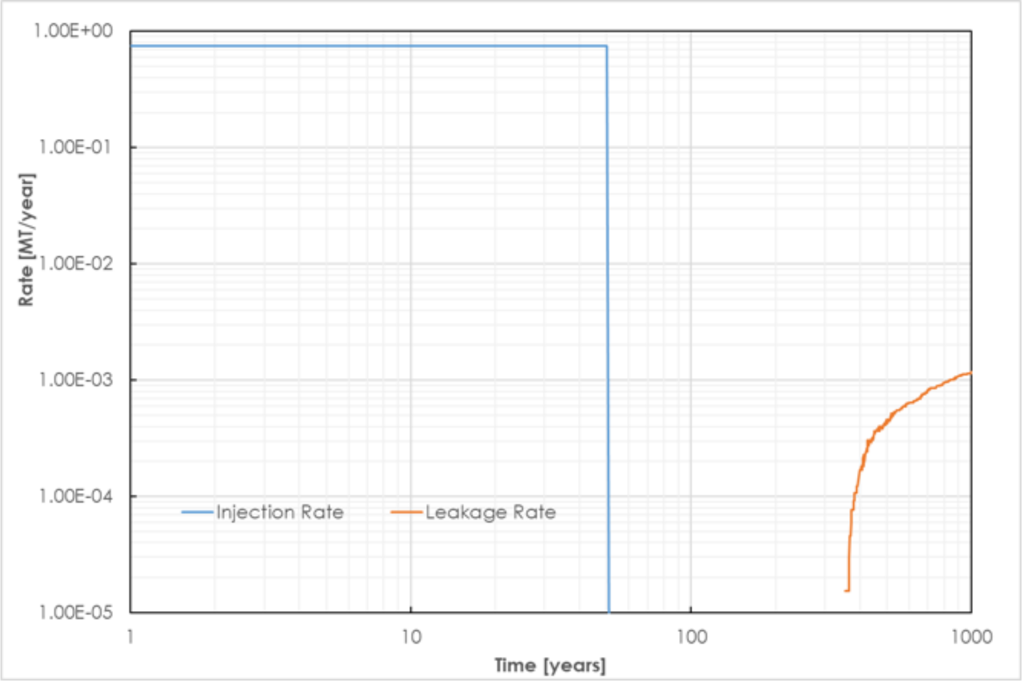
Fault leakage flux was added as a source term with Q given as

$$Q_{\alpha}^{12} = -T^{RR}\lambda_{\alpha}^{RR}(\Delta\rho g(s_{\alpha}^{1}H_R + L_C) + (p_a - p_0))$$

Ramachandran, H., Doster, F., March, R., Maier, C., Geiger, S., de Jonge-Anderson, I., and Nicholson U.. Fast Workflow for Fault Leakage Modeling During CO2 Storage. MRST Conference (Presentation), 2023. → https://www.youtube.com/watch?v=jloaOP-F5Lk

Open Fault Leakage



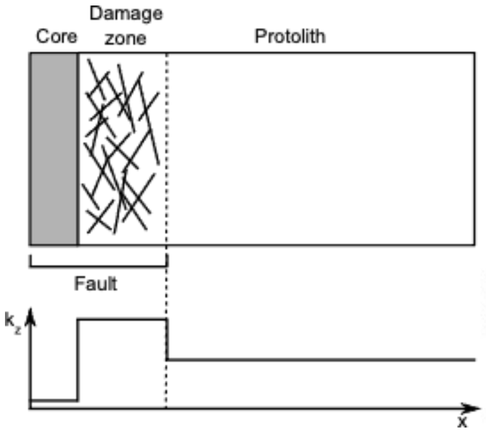


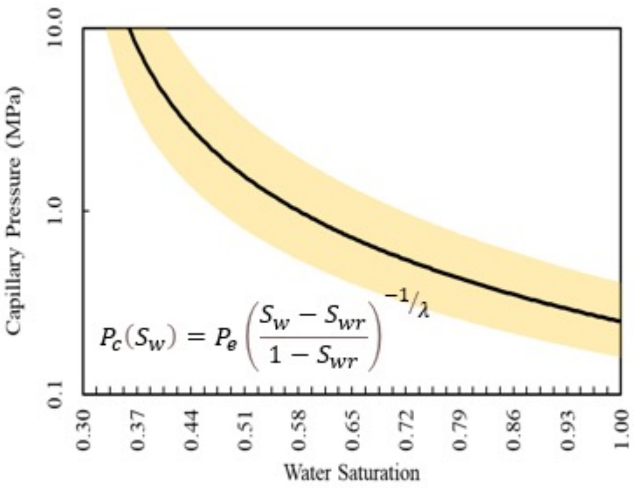
- Injection rate = 0.75 MT/year for 50 years
- Fault permeability = 0.01md, width = 5m
- Total injection = 37.5Mt
- Total Leakage = 0.46MT or 1.23% of injected

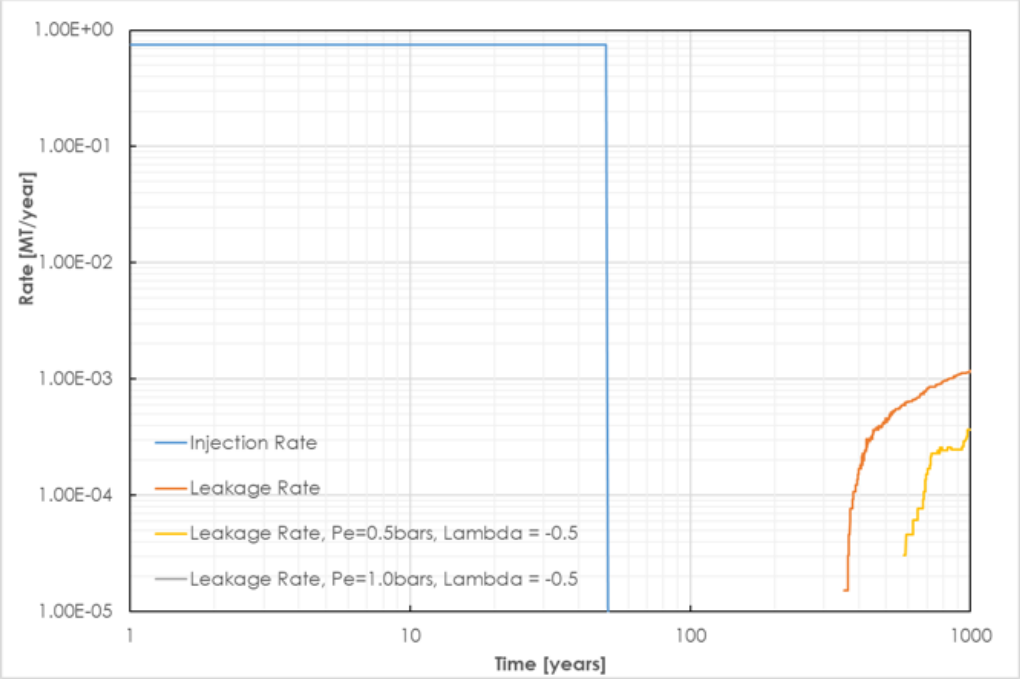
- CO_2 leaks once it encounters the fault

Ramachandran et al., 2024 (In prep)

Fault Capillary Pressure





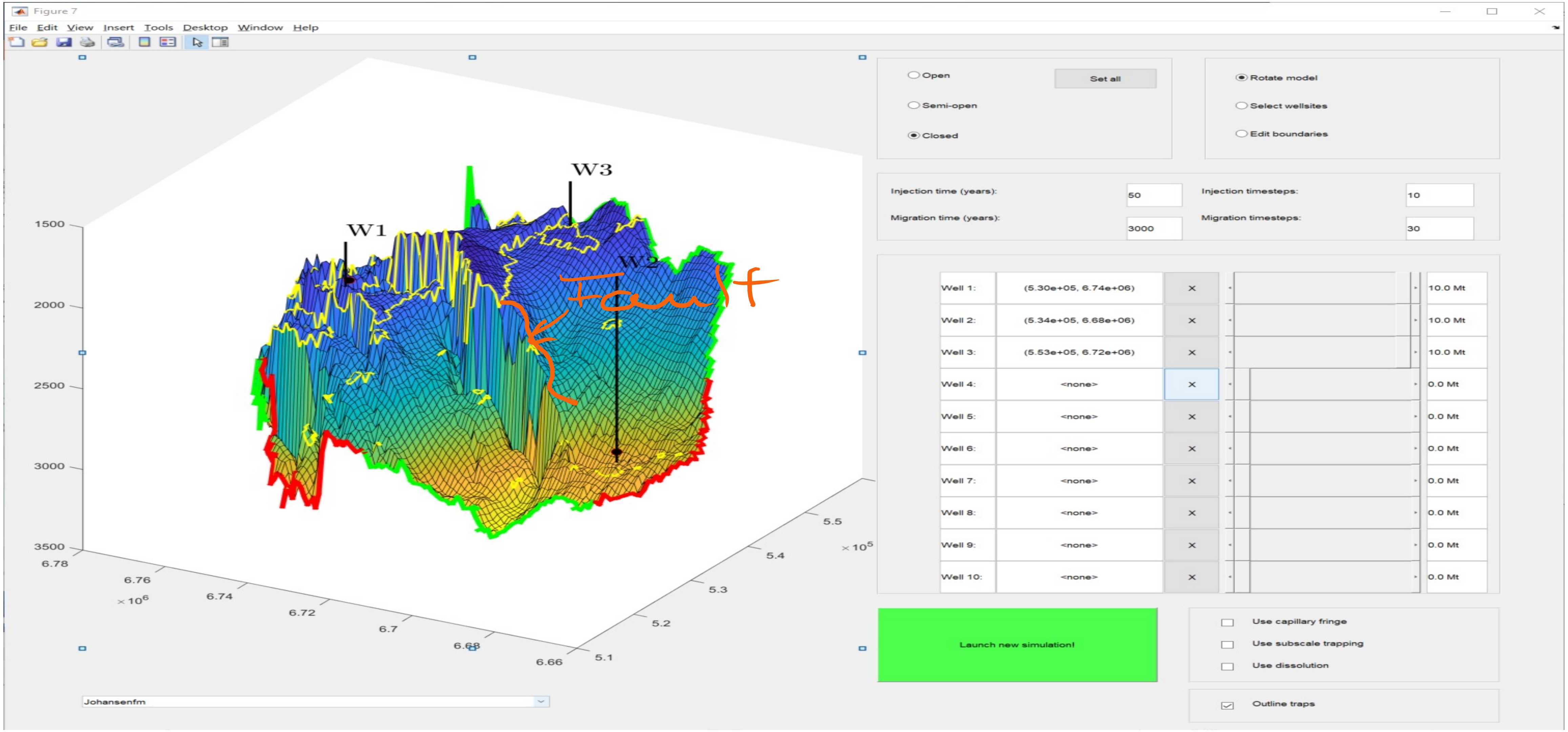


- Injection rate = 0.75 MT/year for 50 years, Total injection = 37.5Mt
- Fault permeability = 0.01md, width = 5m
- Total Leakage = 0.08MT or 0.22% of injected (Pe = 0.5 bars)
- Total Leakage = 0.00MT or 0.00% of injected (Pe = 1.0 bars)
- Capillary pressure will delay and decrease leakage

- Next → Fault geomechanics
  - Pressure impact on perm/poro
- Refine Flux function

Ramachandran et al., 2024 (In prep)

What’s next: CO2lab of MRST



Summary & Outlook

Summary

- Fast workflows presented here are very useful to perform assessments of CO_2 storage capacity and containment
  - Plume behaviour and fault leakage risk can be assessed under uncertainty
  - Fast running times means these are ideal for uncertainty modelling, sensitivity analysis and value-of-information assessments.

Outlook

- CO2lab with dynamic capacity predictor tool
- CO2lab with leakage risk
  - Refined fault leakage models with geomechanics

Thanks for listening! Questions

Acknowledgements: The research is made possible by generous support from Petronas

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