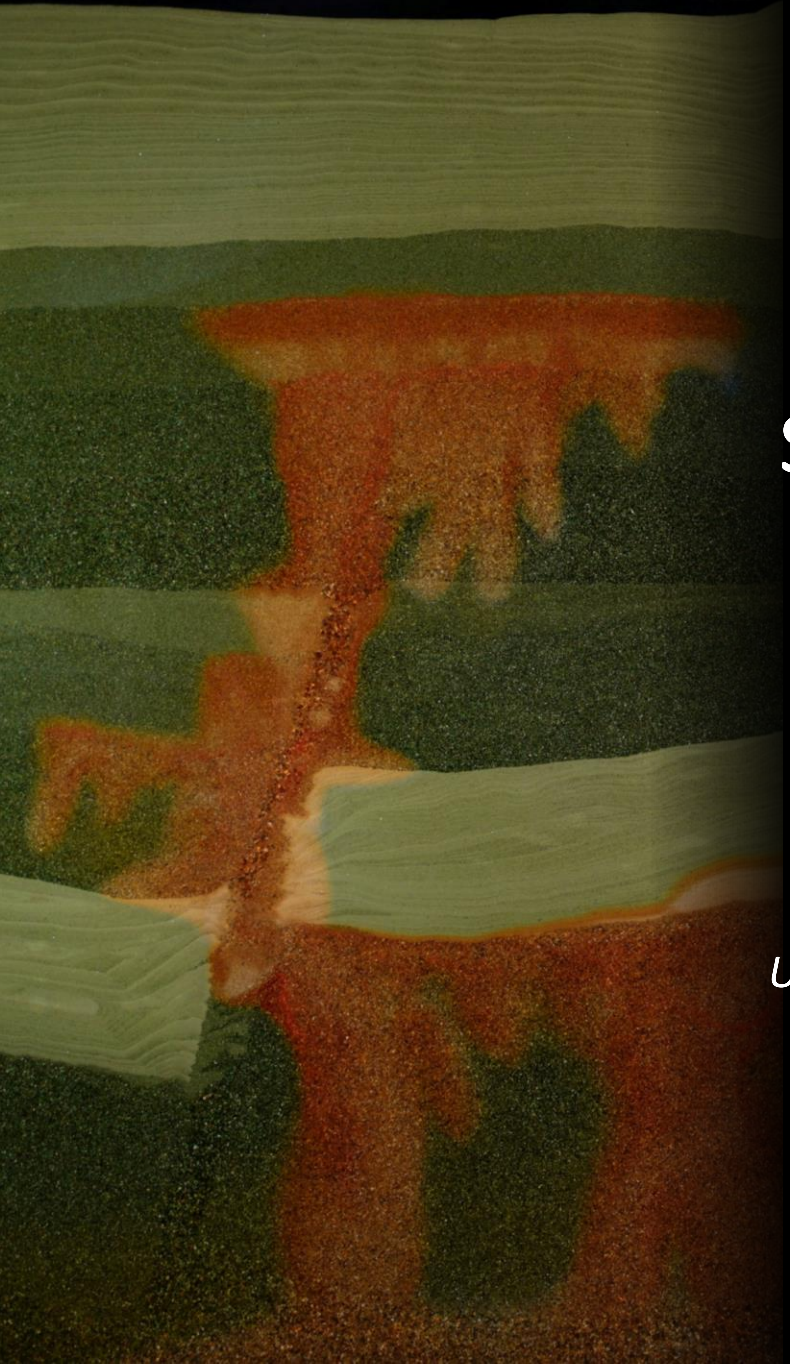
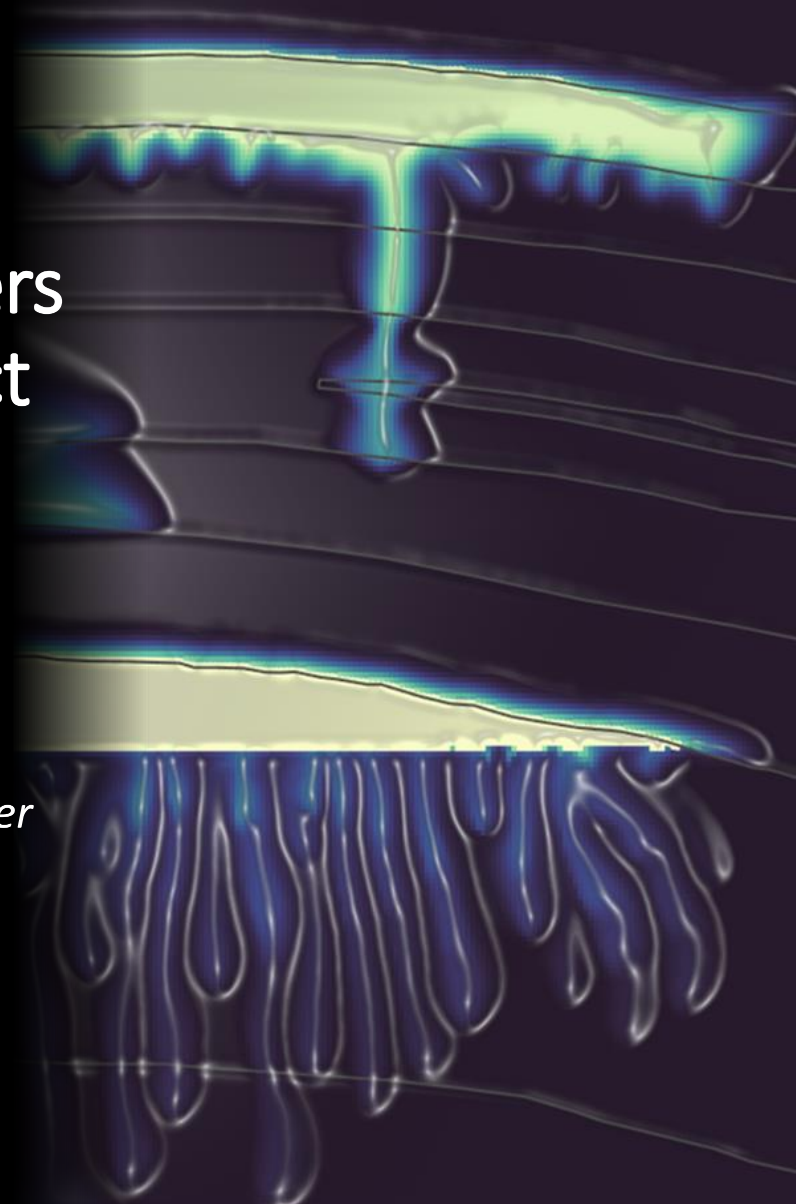


The 11th Society of Petroleum Engineers Comparative Solution Project



Proposed and organized by:

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Anthony R. Kovscek
Stanford University

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SINTEF Digital, Oslo

The 11th SPE Comparative Solution Project

- A CO_2 storage motivated CSP
- Three <u>fully specified</u> simulation problems
  - Two-phase, two-component flows with thermal effects
  - All geometry and constitutive laws precisely defined
  - In principle, a solution should exist in the mathematical sense
  - No geomechanics, no geochemistry.
- Version 11A: Lab conditions (2D), isothermal
- Version 11B: 2D transect of a hypothetical field
- Version 11C: Hypothetical full field model
- All three versions reuse the same general geology

In a nutshell

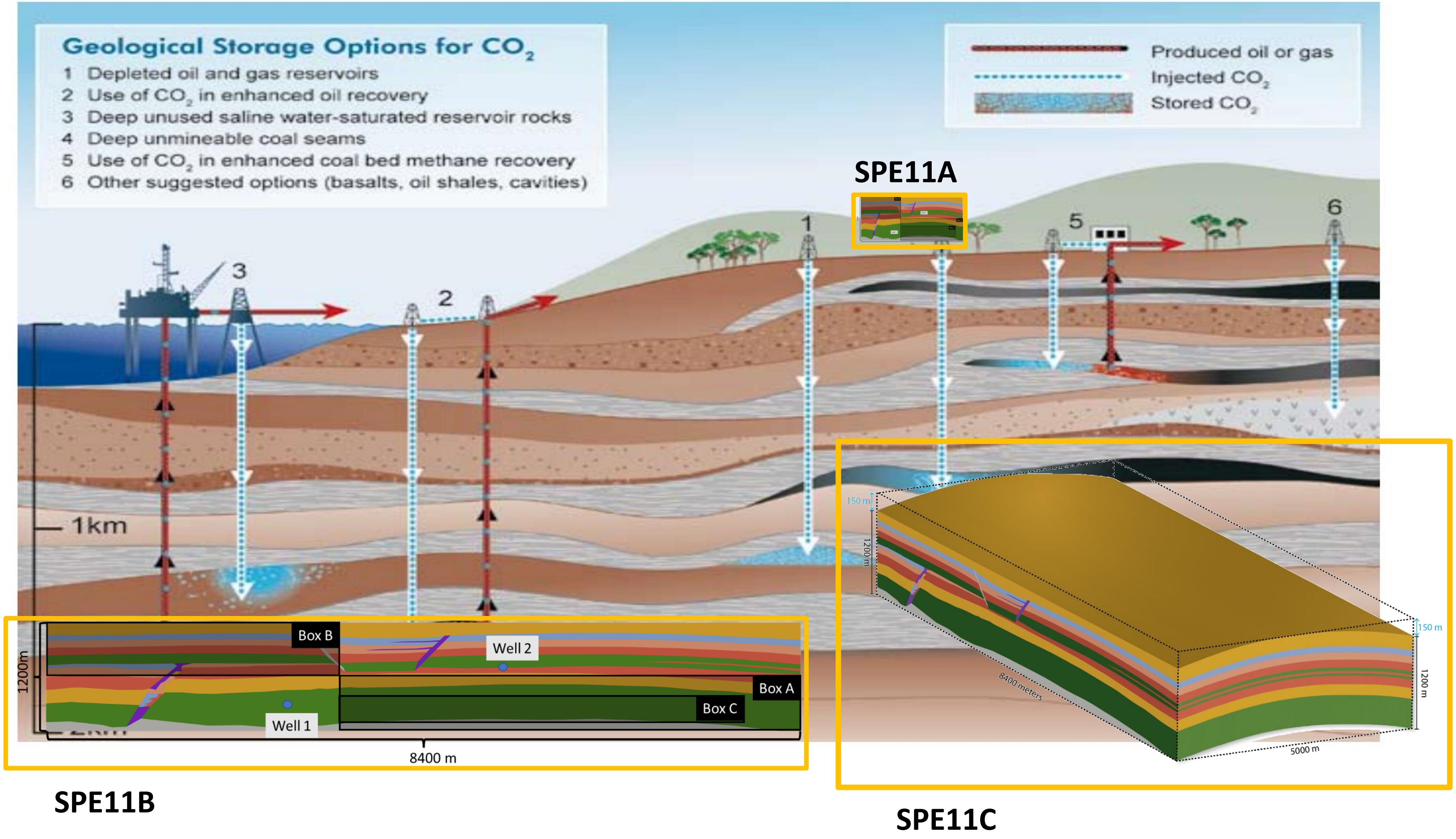
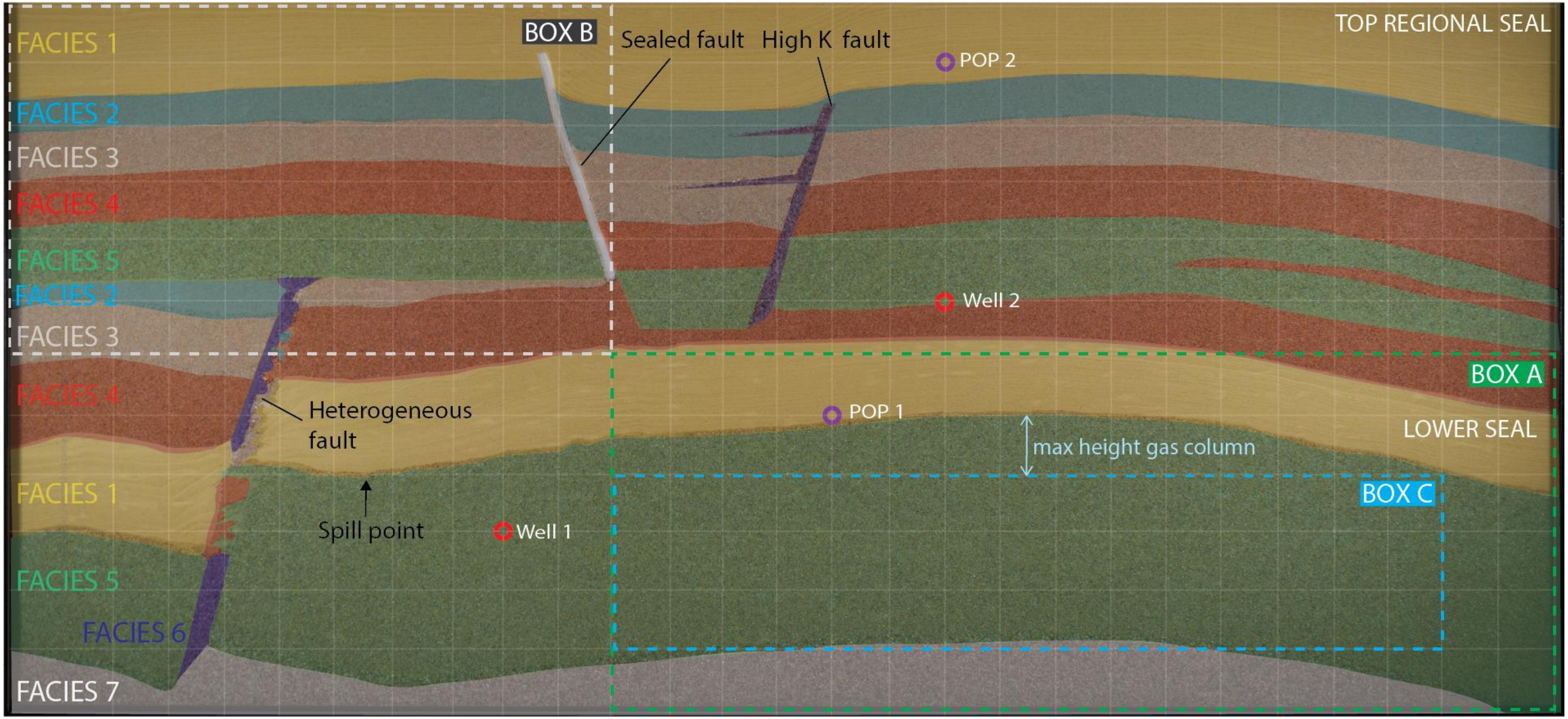


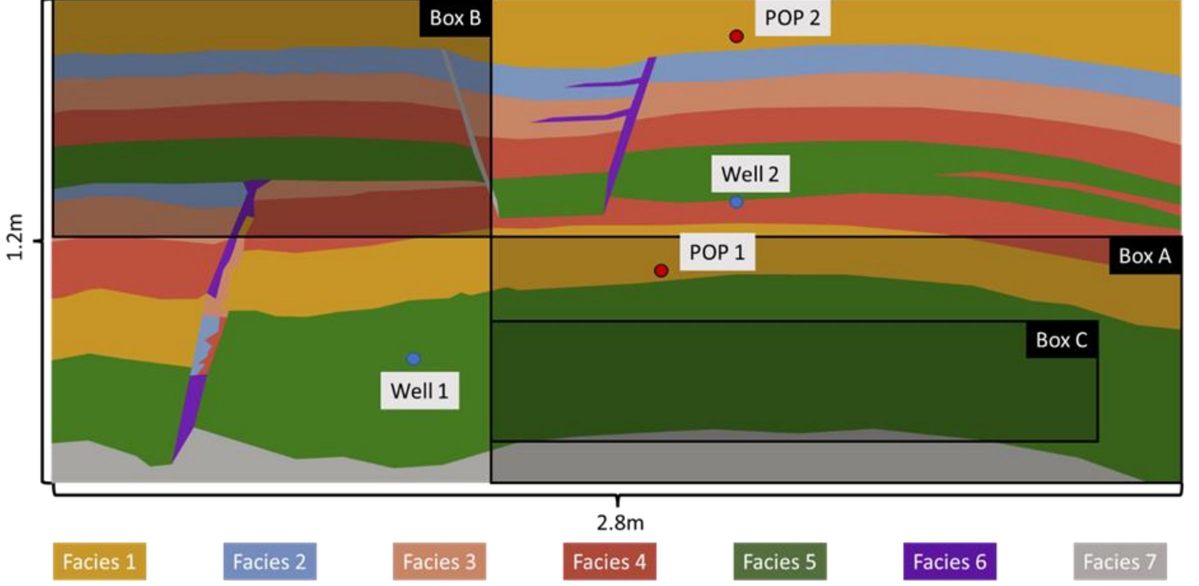
Figure: IPCC

Overview of baseline geometry



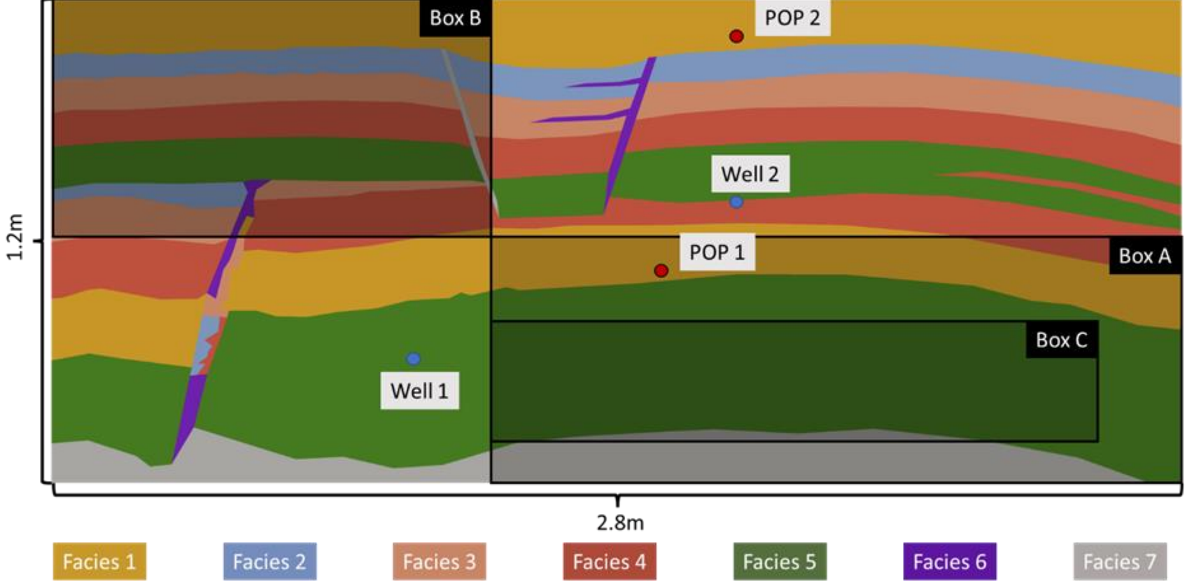
Exact geometry files available with CSP description

SPE11A



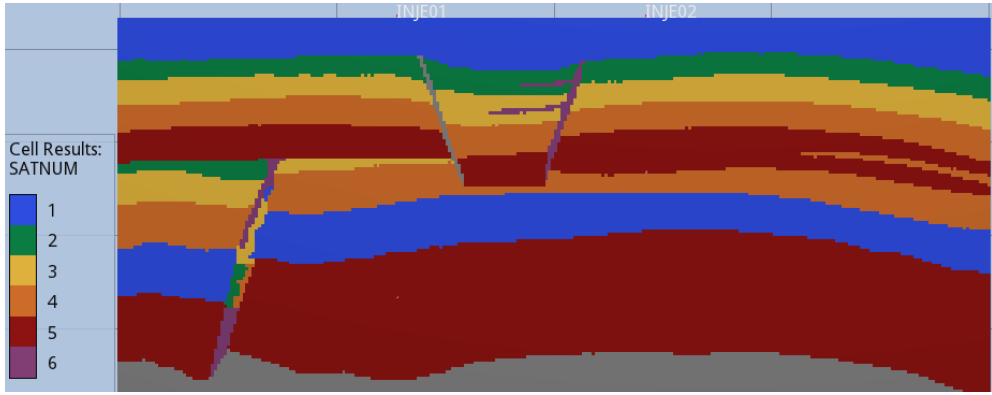
- Lab conditions
- Two-phase, two-component, isothermal
  - Unconsolidated sands, laboratory conditions
  - Brooks-Corey-type relperm and cap-pressure, no hysteresis
  - Pure-phase properties from NIST
  - Density of water dependent on CO_2-concentration, all other properties independent of concentration
  - 10:1 horizontal to vertical permeability ratio
  - No-flow (sides and bottom) and pressure (top) boundary conditions
- 5 hour injection in Well 1, 2.5 hour injection in Well 2
- 120 hour total simulation time

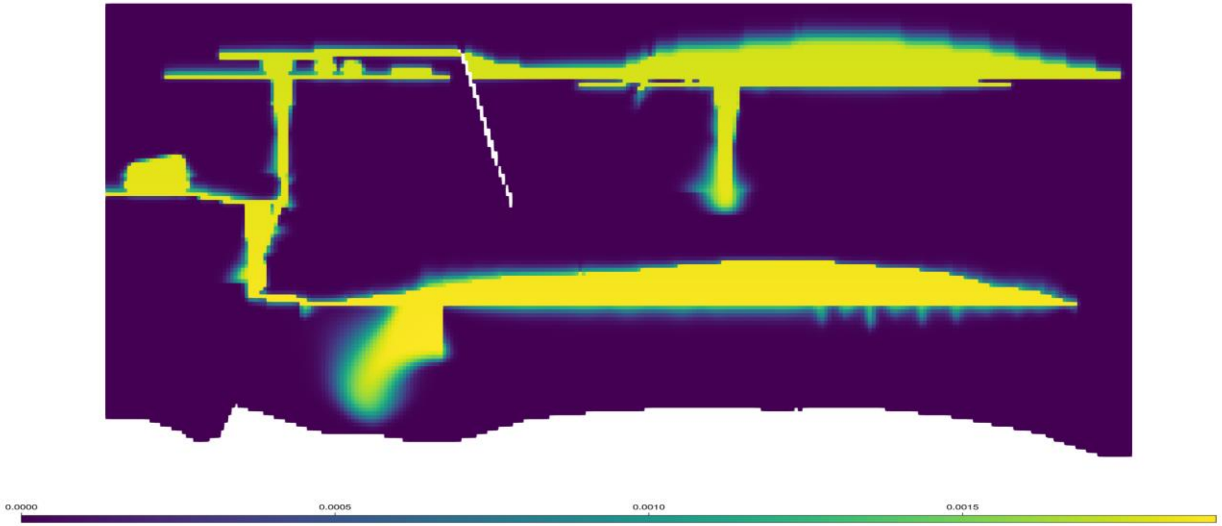
Reporting requirements



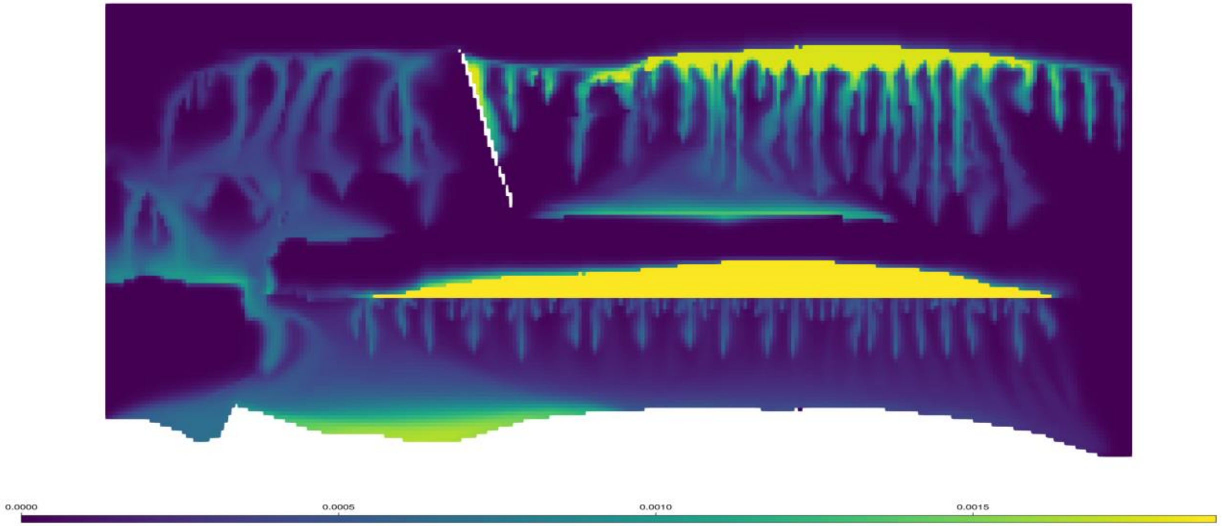
- Time-history of target quantities (proxies for storage safety)
  1. Pressure at two points in the overburden
  2. Integrated phase composition in boxes A and B
  3. A measure of convective mixing in Box C
  4. Total mass of CO_2 in overburden facies
- All field variables (saturations, mass fractions) at 1 hour intervals on a 1 cm by 1 cm grid
- Various solver performance metrics

Example simulation 11A





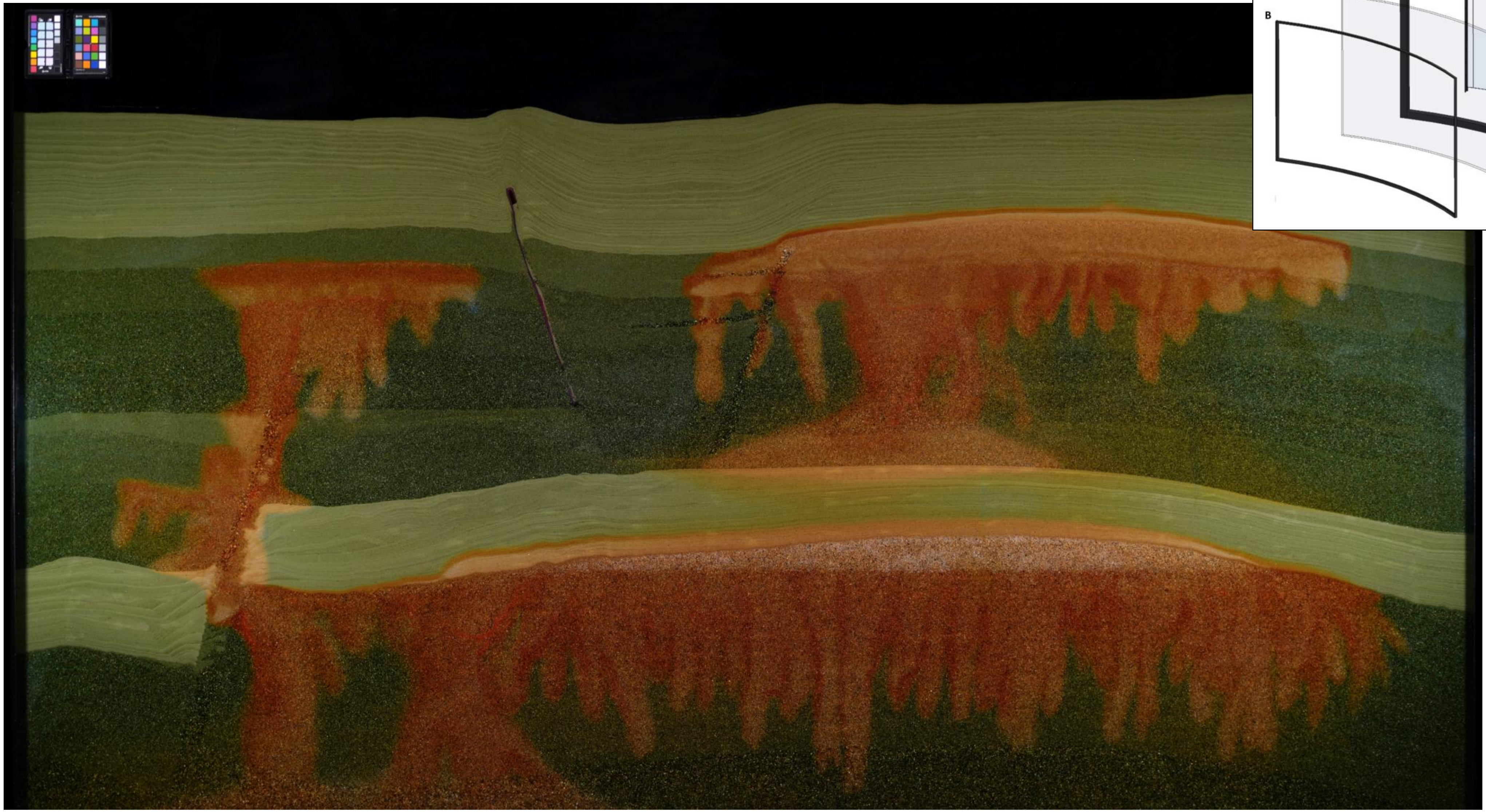
Injection stop

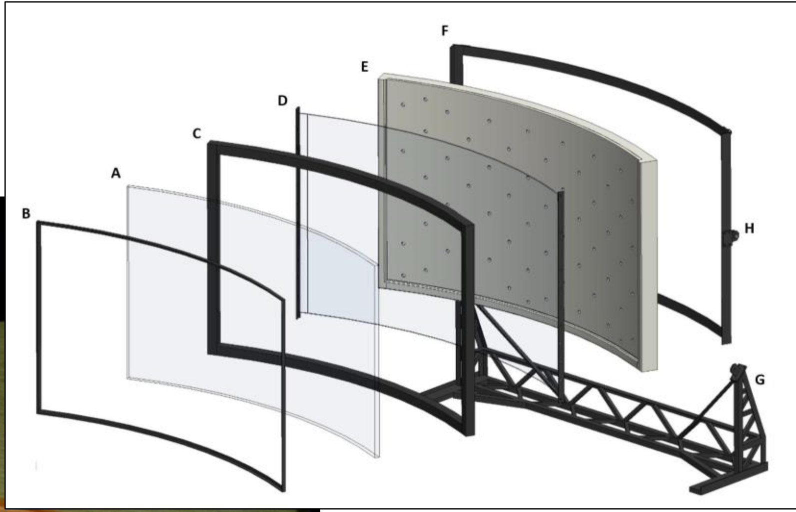


48 hours

SINTEF Digital/Matlab Reservoir Simulation Toolkit (MRST)

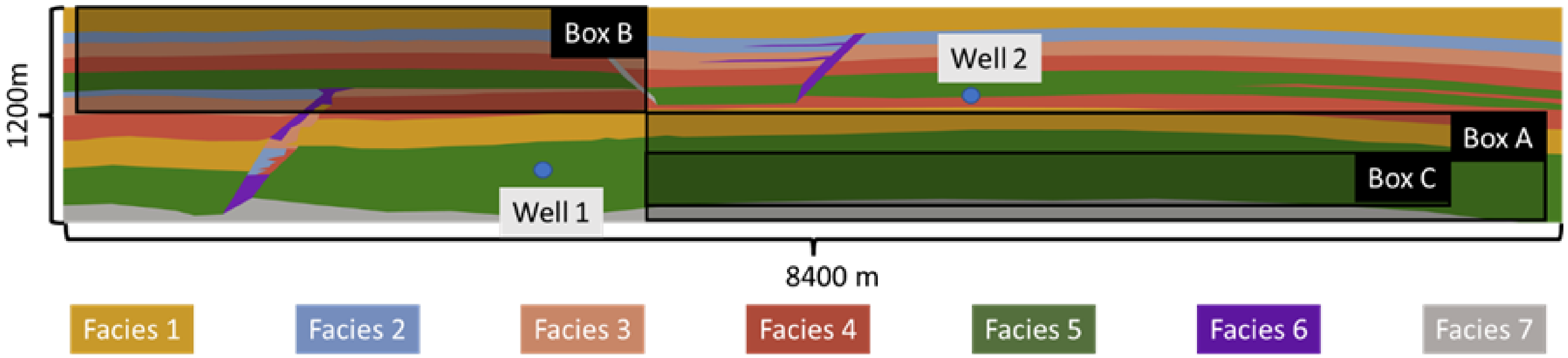
Experimental realization of 11A





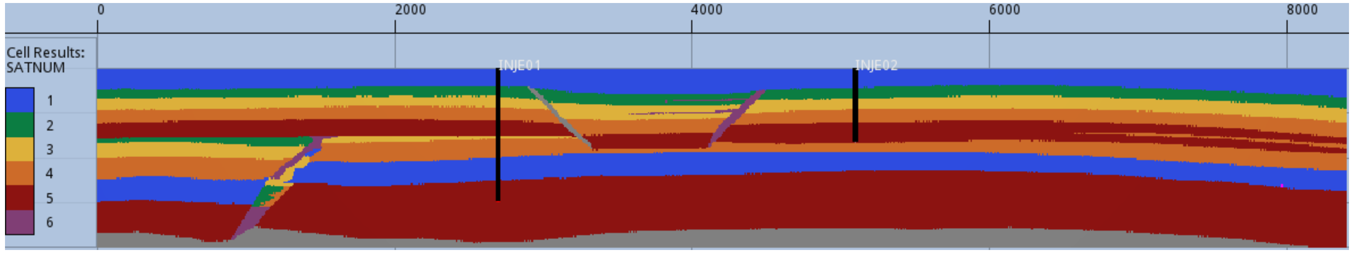
Experiment: Fernø et al., 2023

SPE11B

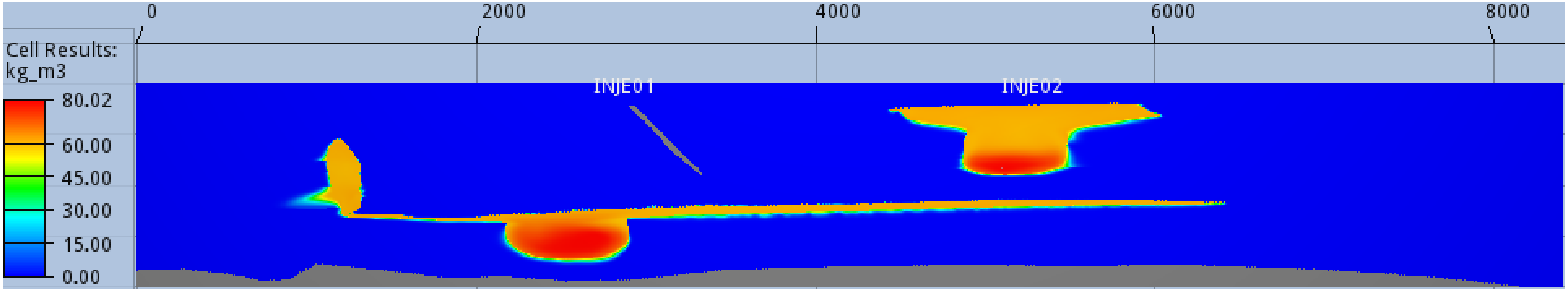


- Field transect, geometry from 11A stretched 3000:1 and 1000:1
- Two-phase, two-component, thermal
  - Sandstones typical of Norwegian Continental Shelf, about 2000 m depth.
  - Constitutive laws as in 11A
  - No-flow + insulating (top and bottom) and aquifer support (sides) boundary conditions
- 1000 year pre-injection equilibration
- 50 year injection in Well 1, 25 year injection in Well 2, at 10 degrees Celsius
- 2000 year total simulation time
- Reporting requirements as for 11A, but sparser in space and time

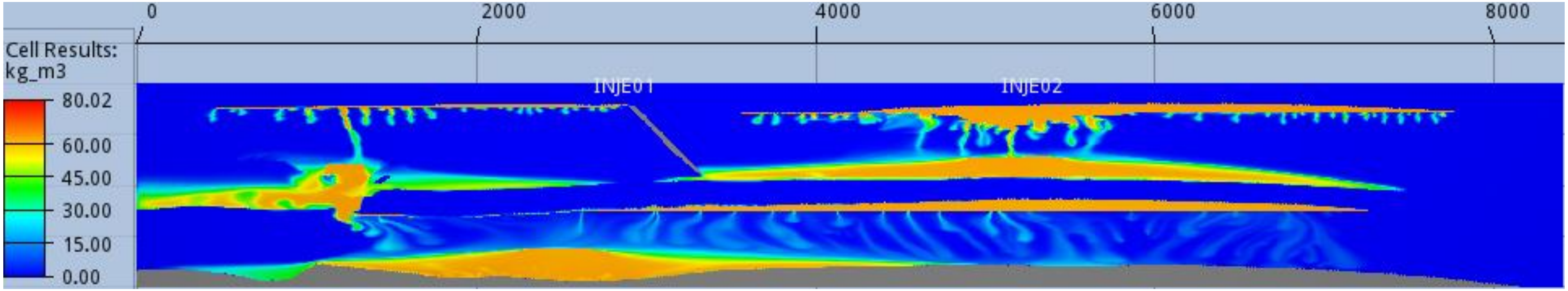
Example simulation 11B



Injection stop

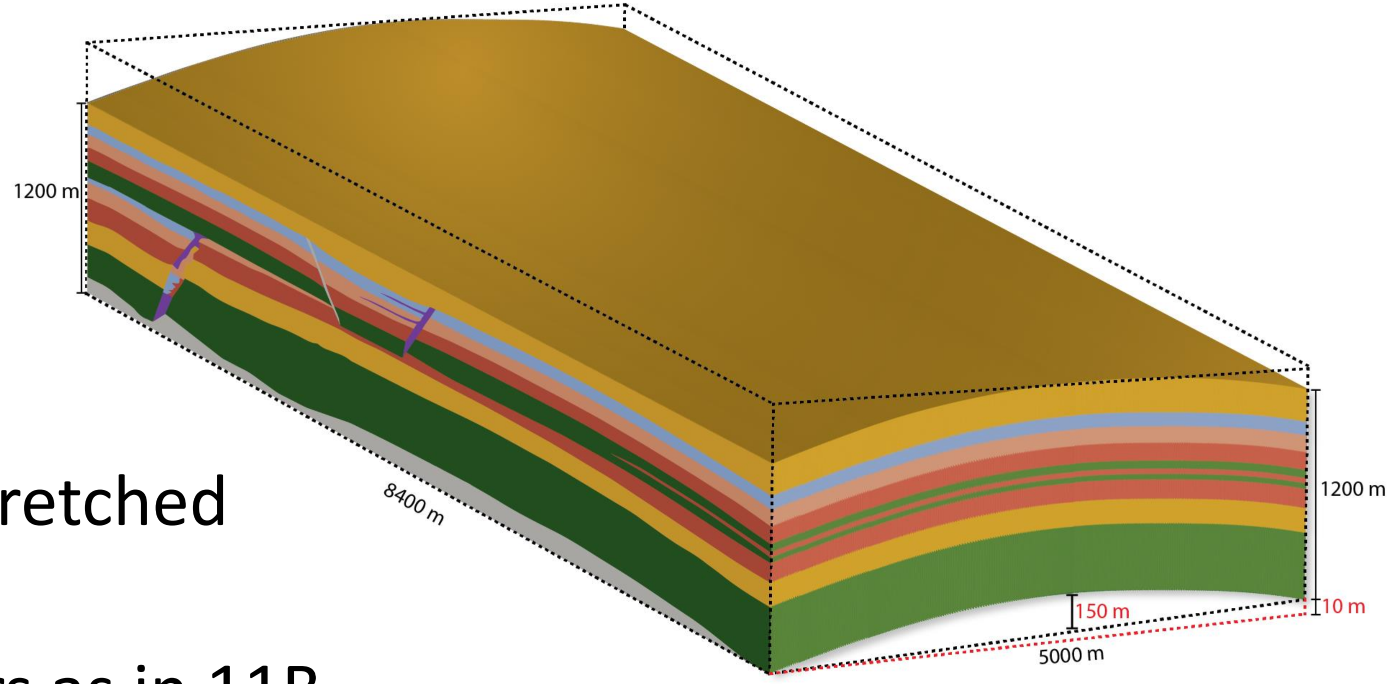


1000 years



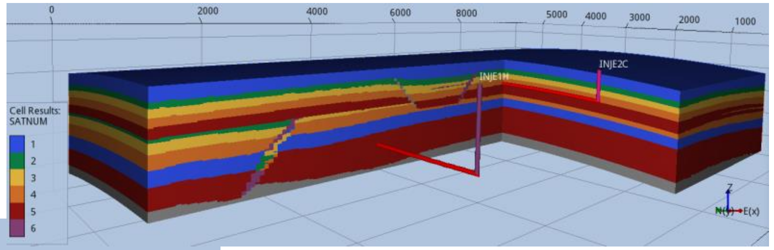
NORCE/Open Porous Media (OPM) simulator

SPE11C

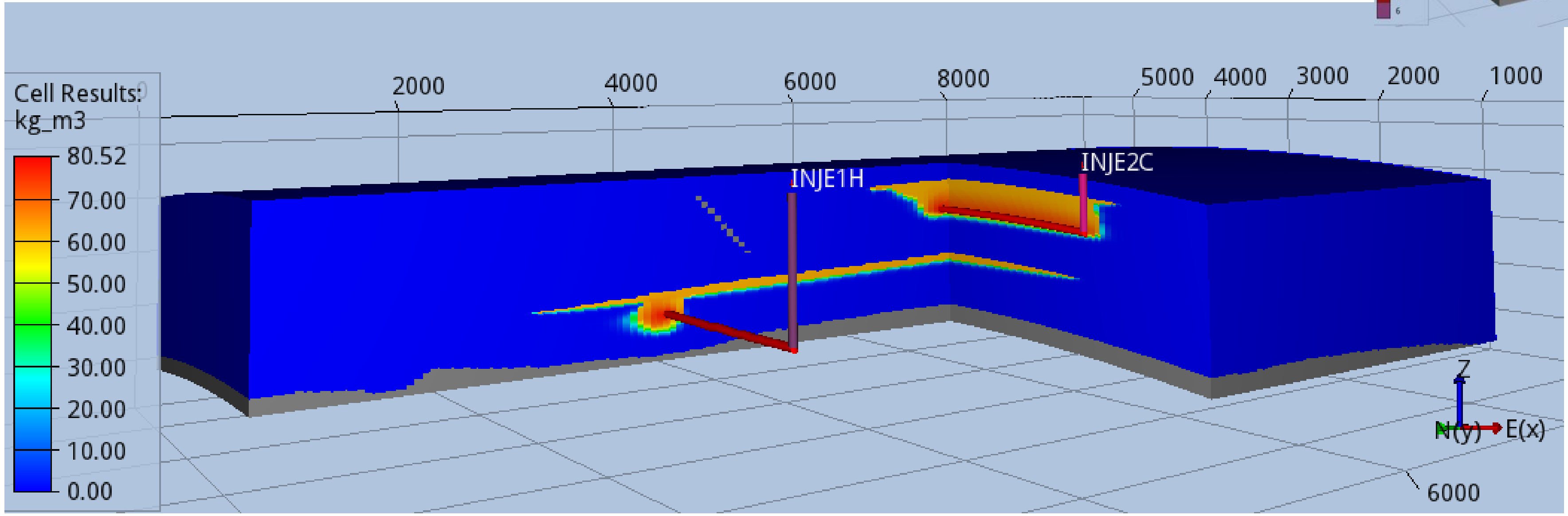


- Field model. Geometry from 11B stretched 5000 meters along a parabola
- All model equations and parameters as in 11B
- Well 1 is horizontal, Well 2 is arched following the layering
- Injection schedule and simulation time as for 11B
- Reporting requirements as for 11B, but yet sparser in space and time

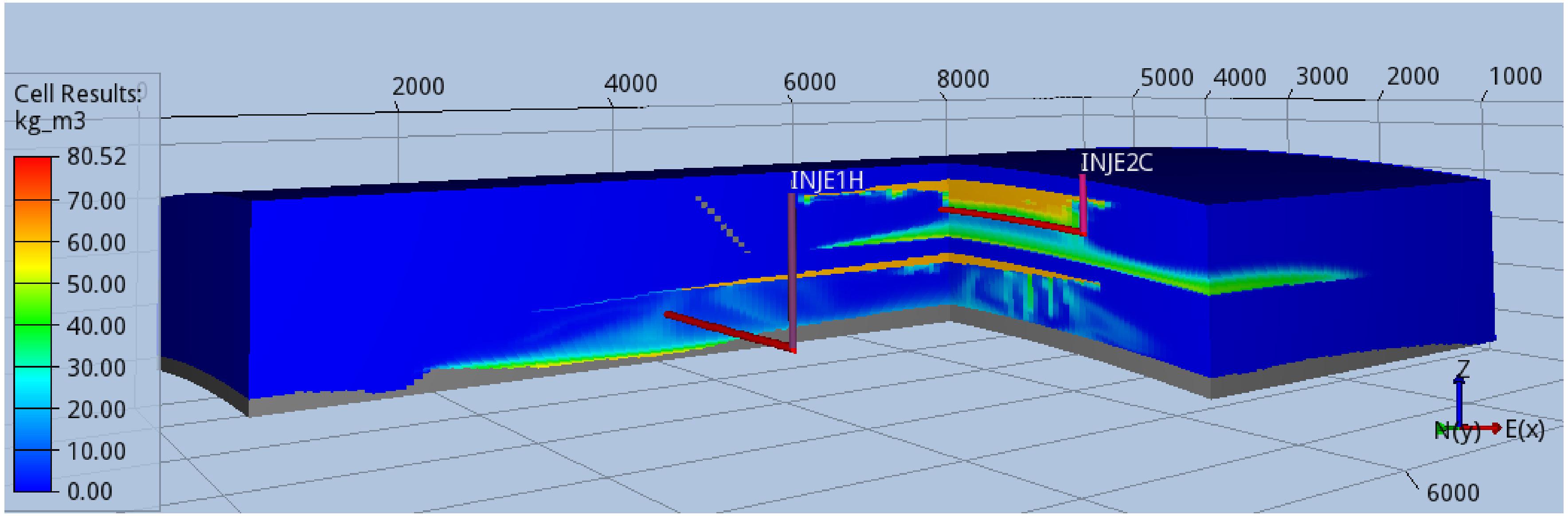
Example simulation 11C



Injection stop



1000 years



NORCE/OPM

Some known challenges

- Common for all three versions:
  - Capillary entry pressure is a leading storage mechanism during injection
  - Injection of dry CO_2 leads to essentially immobile water saturation with very high capillary presssure values
  - Convective mixing is the dominant physical process post-injection, but is difficult to resolve without an excessive number of grid cells
  - Cartesian grids tend to give unphysical "stair-case-like" dissolution rates post-injection.
  - Reporting metrics are sensitive to numerical errors
- SPE11A:
  - Low density of CO_2 in gas phase leads to particularly strong non-linearities as gas "vanishes" into the water phase.
- SPE11B:
  - Two-phase flow physics easier(?) than 11A, but thermal effects must be resolved.

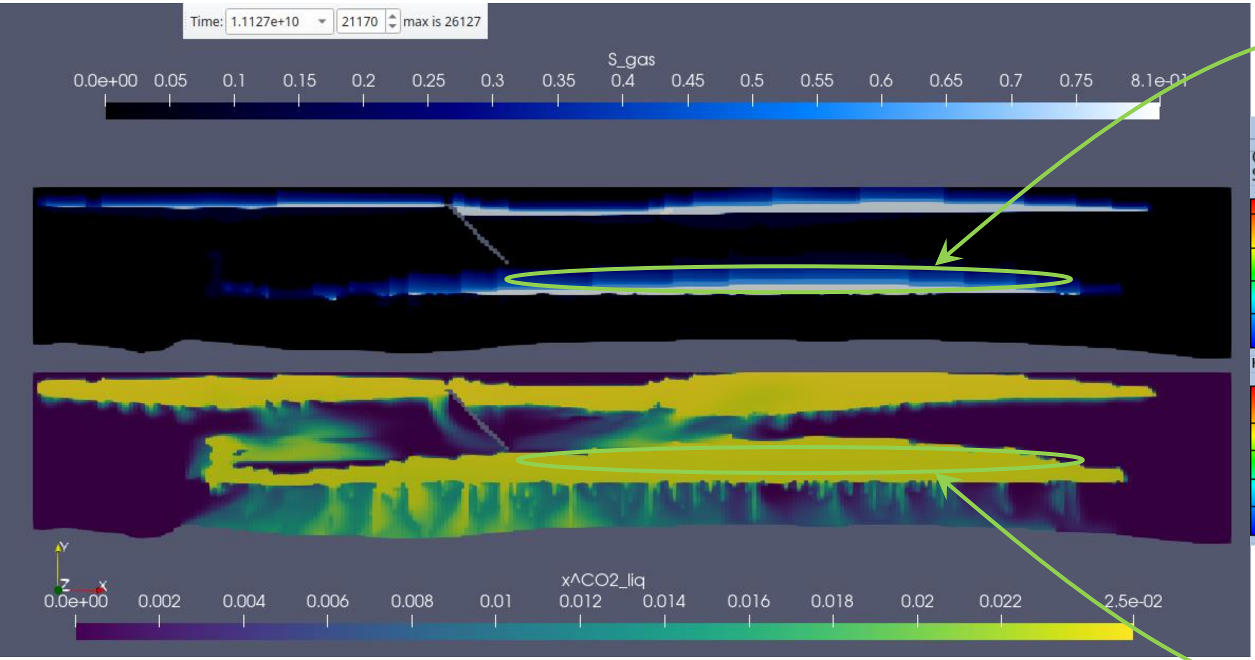
Easiest?

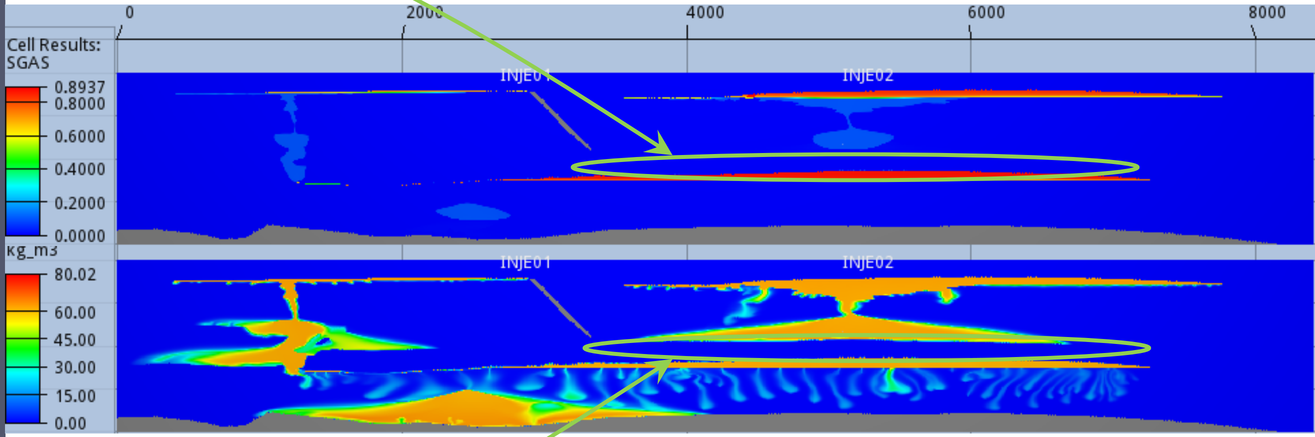
- SPE11C:
  - The computational cost of three dimensions implies that properly resolving convective mixing is almost impossible on standard hardware.
  - Results will likely show strong grid dependence, or require upscaling methods.

Hardest?

Example challenge: Capillary entry pressure (11B)

CO_2 in low-permeable seal?





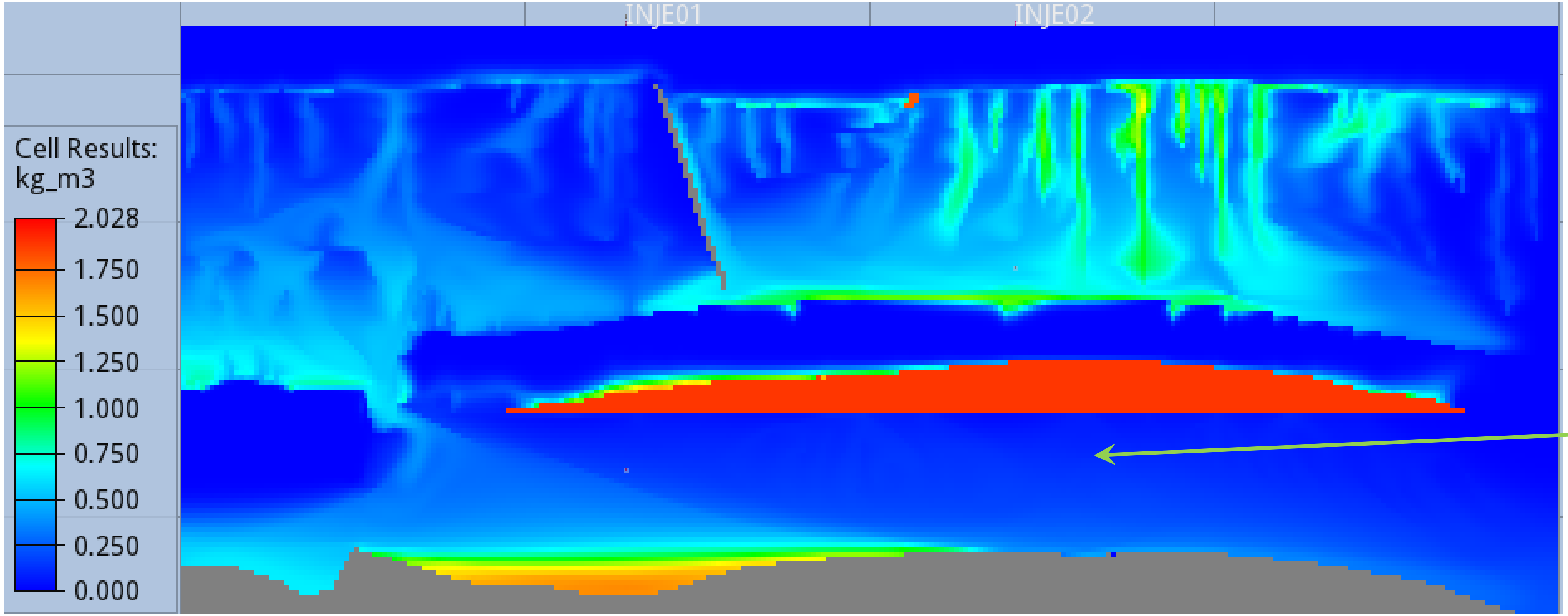
CO_2 in low-permeable seal?

Top figures: Saturation. Bottom figures: CO_2 concentration in water phase

Stuttgart/DuMuX vs NORCE/OPM

Example challenge: Convective mixing (11A)

- Convection correlates with high permeability
  - Lower reservoir should have highest convection
- But: Standard implementations on Cartesian grids «choke» the convection!



No convection cells?

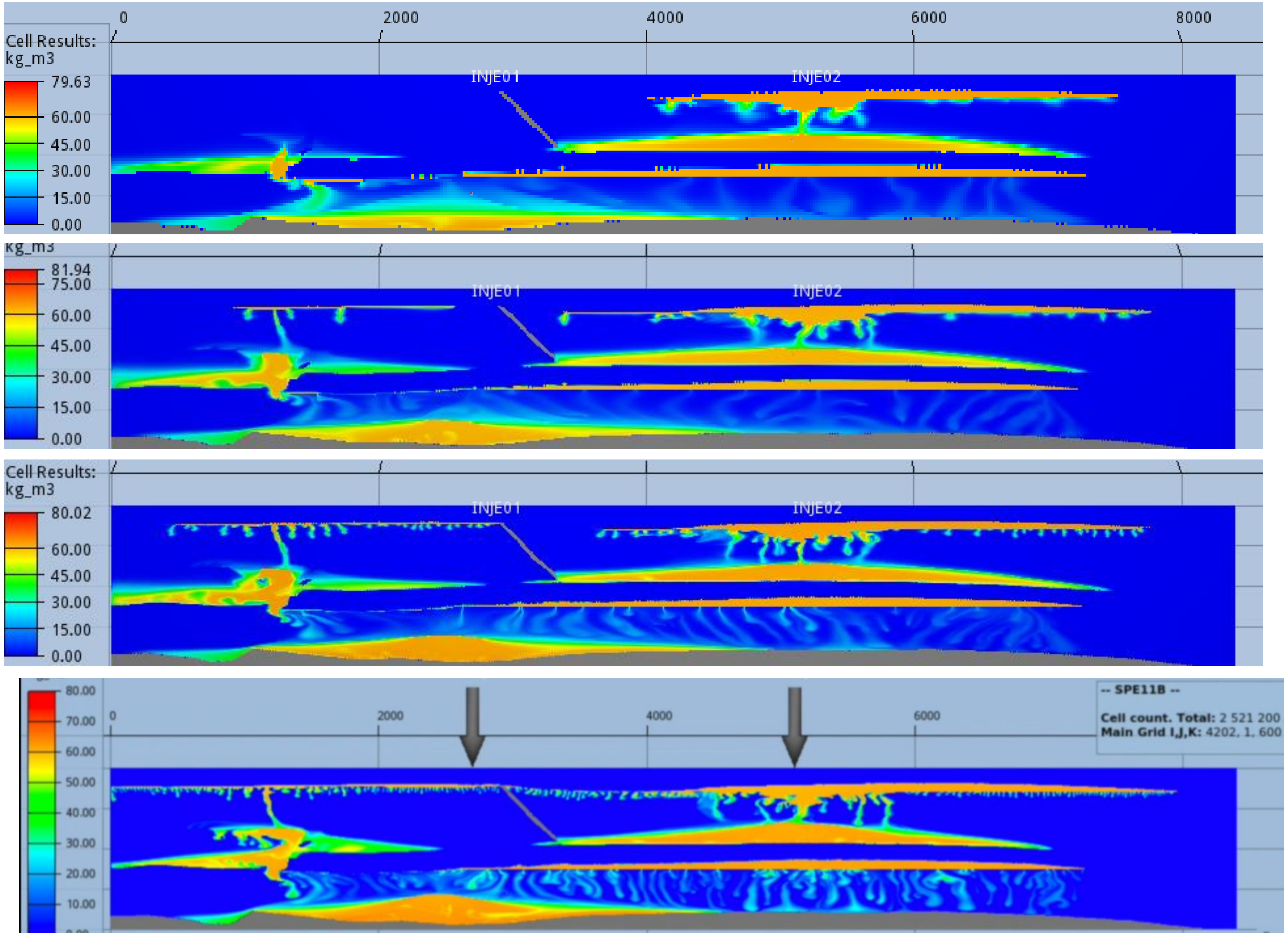
Example challenge: Grid dependent dissolution rate (11B)

20m x 20m

10m x 10m

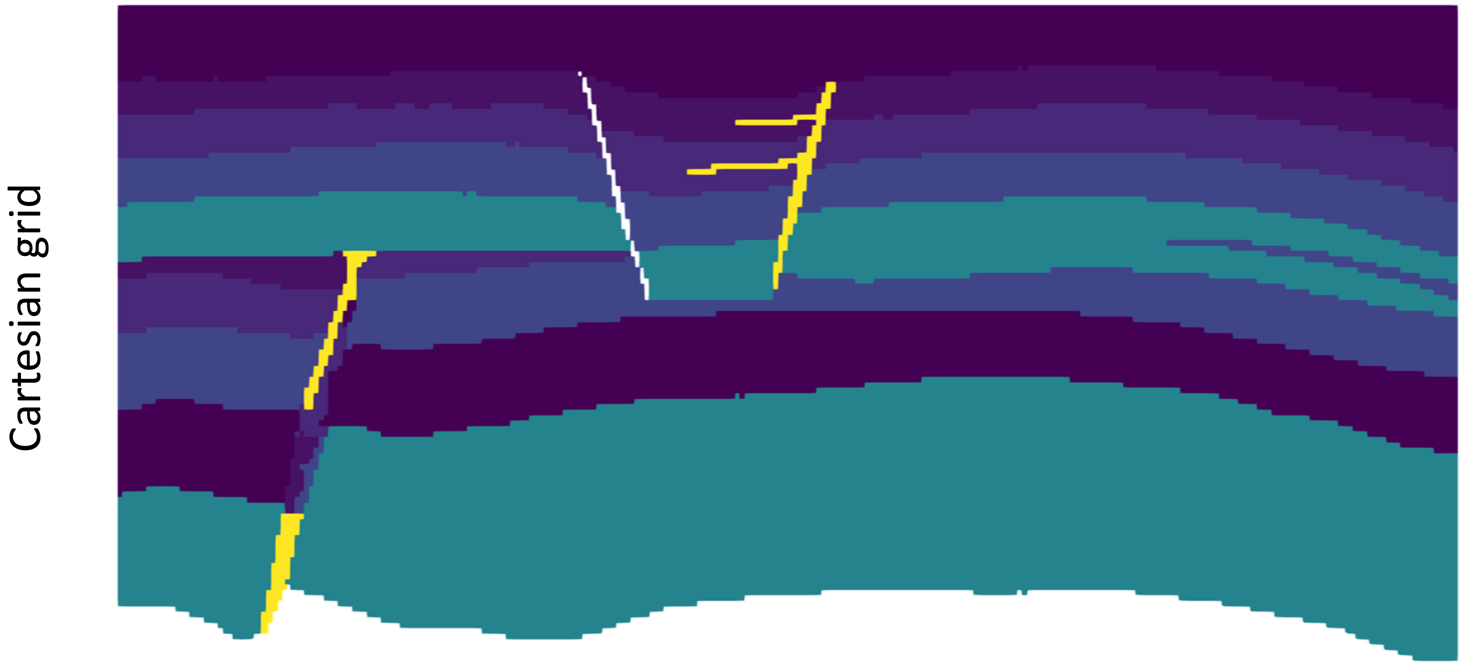
5m x 5m

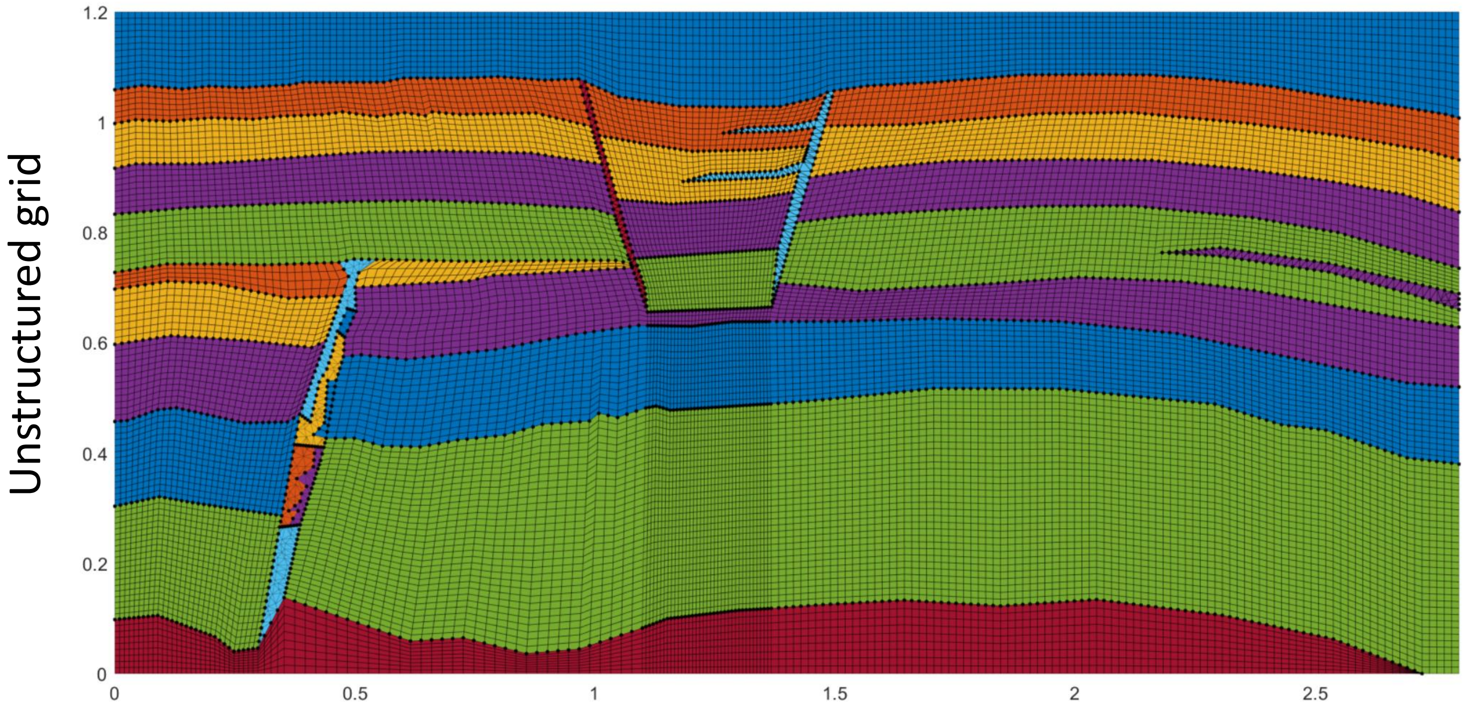
2m x 2m



NORCE/OPM

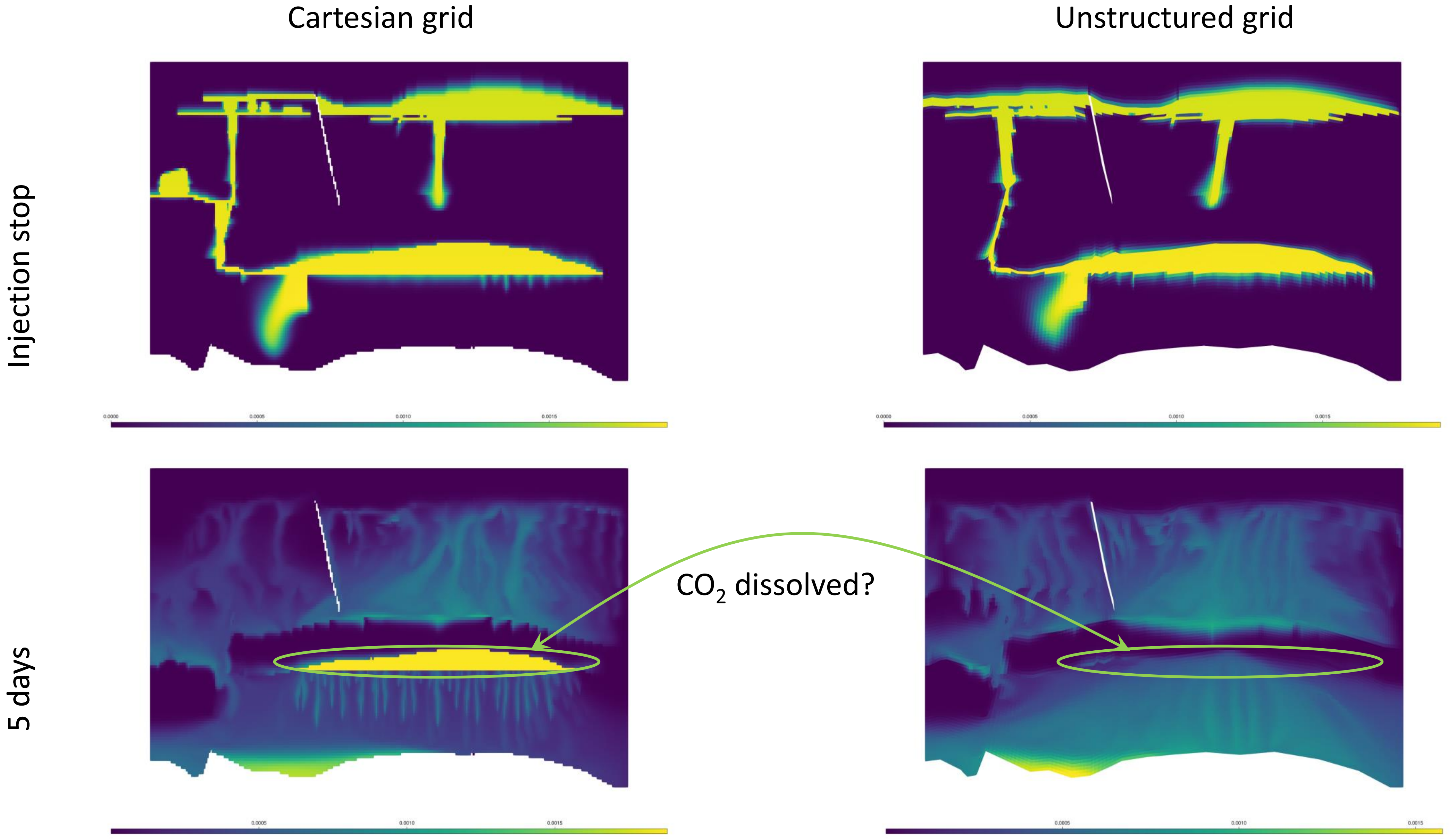
Example challenge: Gridding 11A





NORCE
SINTEF Digital

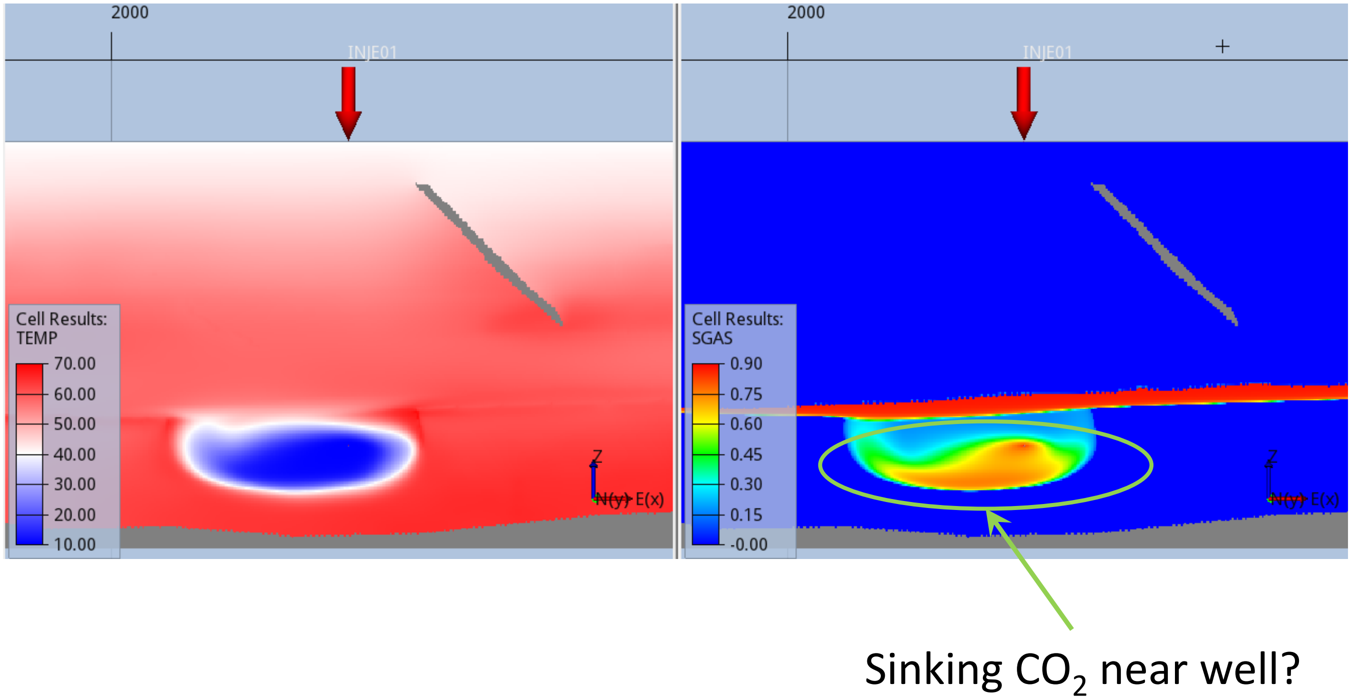
Grid-dependent solutions (11A)

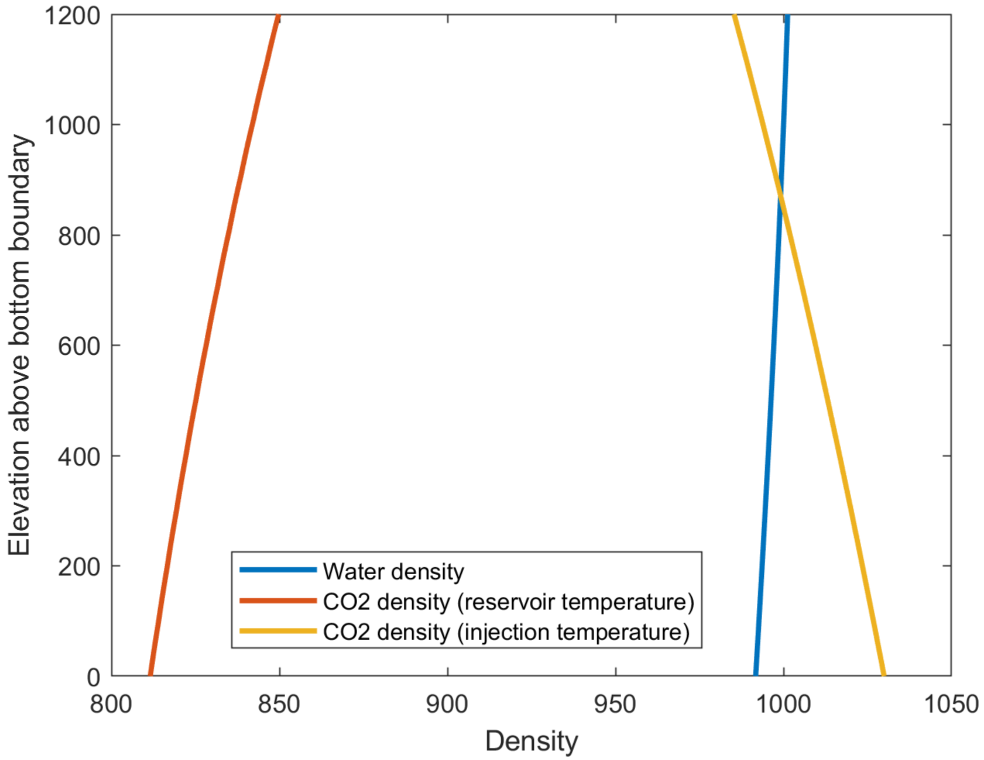


SINTEF Digital/MRST

Example challenge: Thermal effects

- For the CSP 11B and 11C conditions, water has an inverse density-depth profile, and injected CO_2 can be denser than water
  - Potential for water convection cells
  - Near-well cooling may lead to sinking CO_2





Example challenge: Computational times

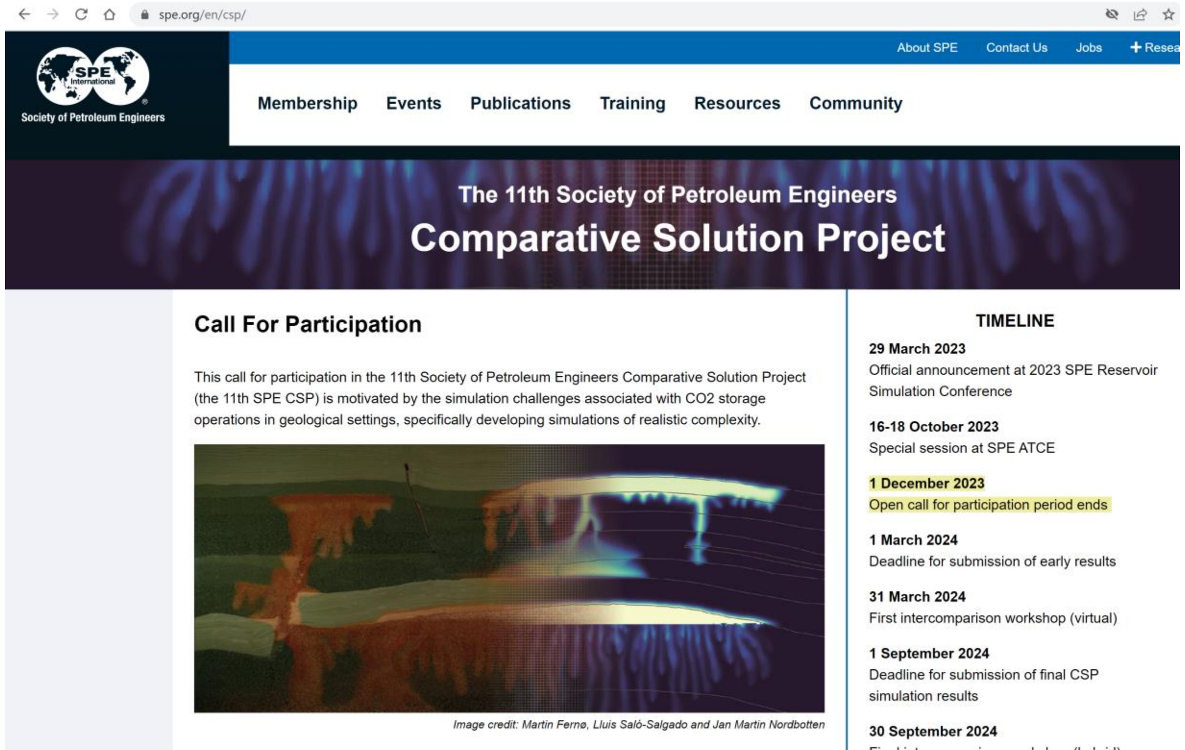
Case	Dimensions [m]	Max. grid size [m]	No. grid cells	Total no. cells	No. active cells	Solver time step [d]¨	Total simulation time [s]
spe11a^	[2.8, 0.01, 1.2]	[0.01, 0.01, 0.01]	[280, 1, 120]	33600	31034	1e-5	2118.30
spe11b^*	[8400, 1, 1200]	[10, 1, 10]	[842, 1, 120]	101040	93318	50	1420.15
spe11c^*	[8400, 5000, 1350]	[50, 50, 10]	[170, 100, 120]	2040000	1885200	50	25450.68

^ All three cases were run with 70 MPI processes and 2 threads per MPI process. i.e., 140 cpu cores.
* spe11b and spe11c have an extra layer [1 m] of grid cells on the left and right boundaries to include the buffer volume
¨ The solver time step is the maximum value allowed by the simulator

Resources

Official webpage spe.org/csp/ hosts:

- A "**sign up here**" button
- The full benchmark description
- CSP Timeline
- Participation registration and agreement form
- Link to github resource page
- Data submission portal



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The 11th Society of Petroleum Engineers

Comparative Solution Project

Call For Participation

This call for participation in the 11th Society of Petroleum Engineers Comparative Solution Project (the 11th SPE CSP) is motivated by the simulation challenges associated with CO2 storage operations in geological settings, specifically developing simulations of realistic complexity.

Image credit: Martin Fernø, Lluis Saló-Salgado and Jan Martin Nordbotten

TIMELINE

29 March 2023
Official announcement at 2023 SPE Reservoir Simulation Conference

16-18 October 2023
Special session at SPE ATCE

1 December 2023
Open call for participation period ends

1 March 2024
Deadline for submission of early results

31 March 2024
First intercomparison workshop (virtual)

1 September 2024
Deadline for submission of final CSP simulation results

30 September 2024

Draft Description:

The 11th

Society of Petroleum Engineers

Comparative Solution Project

Jan M. Nordbotten[1], Martin A. Fernø[2], Bernd Flemisch[3], Anthony R. Kovscek[4], Knut-Andreas Lie[5]

This is a working document. Please be advised that changes are likely and may apply to any aspect of the CSP description, including parameters, boundary conditions, initial conditions, and injection schedule. The document is expected to be made static on or before October 1st, 2023, at which time this notice will be deleted.

Abstract

This document contains the description of, and call for participation in, the 11th Society of Petroleum Engineers Comparative Solution Project (the 11th SPE CSP). It is motivated by the simulation challenges associated with CO_2 storage operations in geological settings of realistic complexity. The 11th SPE CSP contains three versions: Version 11A is a 2D geometry at the laboratory scale, inspired by a recent CO_2 storage forecasting and validation study. For Version 11B, the 2D geometry and operational conditions from 11A are rescaled to field conditions characteristic of the Norwegian Continental Shelf. Finally, for Version 11C, the geometry of Version 11B is extruded to a full 3D field model. The CSP has a two-year timeline, being launched at the 2023 SPE Reservoir Simulation Conference, and culminating at the 2025 SPE Reservoir Simulation Conference.

Illustration figure containing a collage of a laboratory experiment (left, see Fernø et al., 2023) and a numerical simulation (right, see Saló-Salgado et al., 2023) on the same geometry as SPE CSP 11A.

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1

Big thanks to the Early Access Team!

- Norwegian Research Center (NORCE)*:
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  - David Landa Marban
- SINTEF Digital:
  - Halvor Møll Nilsen
  - Odd Andersen
  - Olav Møyner
  - Vetle Nevland
- SLB:
  - Marie Ann Giddins
  - Jarle Haukås
- Stuttgart University
  - Holger Class
  - Dennis Gläser
  - Kai Wendel

* Funded by CLIMIT project 622059

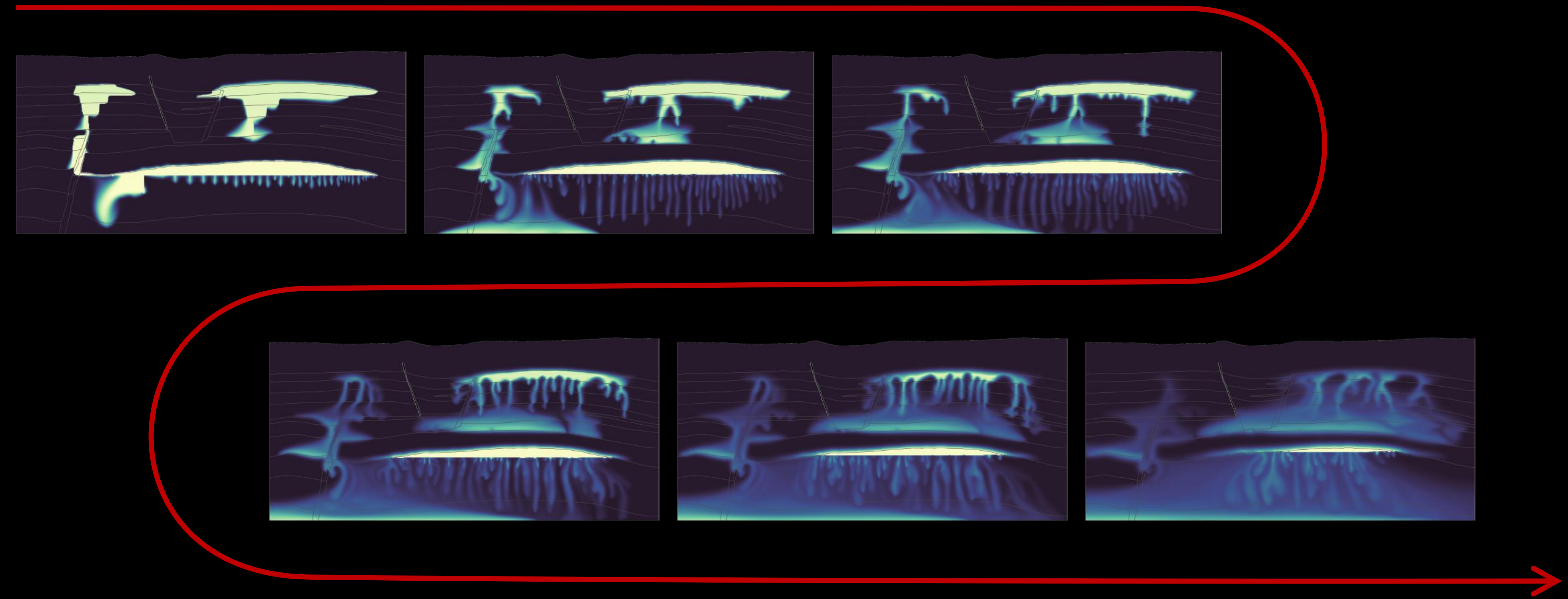
Related references

Project homepage and all information: https://spe.org/csp

References for background material to this CSP announcement:

- Fernø, M. A., M. Haugen, K. Eikehaug, O. Folkvord, B. Benali, J. W Both, E. Storvik, C. W. Nixon, R. L. Gawthrope and J. M. Nordbotten, *Room-scale CO_2 injections in a physical reservoir model with faults*, submitted Transport in Porous Media. Preprint: http://arxiv.org/abs/2301.06397
- Flemisch, B., J. M. Nordbotten, M. A. Fernø, R. Juanes, et al., *The FluidFlower International Benchmark Study: Process, Modeling Results, and Comparison to Experimental Data*, https://arxiv.org/abs/2302.10986
- Kovscek, A. R., J. M. Nordbotten, M. A. Fernø, Scaling up FluidFlower results for carbon dioxide storage in geological media, submitted to Transport in Porous Media. https://arxiv.org/abs/2301.09853
- Saló-Salgado, L., M. Haugen, K. Eikehaug, M. A. Fernø, J. M. Nordbotten, R. Juanes, Direct Comparison of Numerical Simulations and Experiments of CO2 Injection and Migration in Geologic Media: Value of Local Data and Predictability, submitted to Transport in Porous Media. Preprint: http://arxiv.org/abs/2301.08875

Thanks!



Saló-Salgado et al., 2023. Simulations use MRST, and show CO_2 concentration