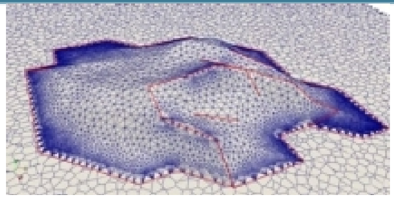
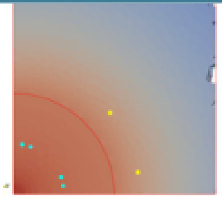
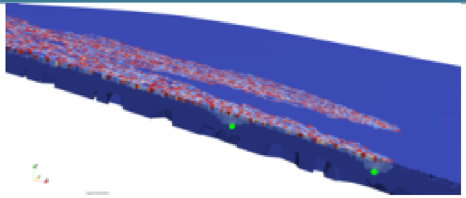
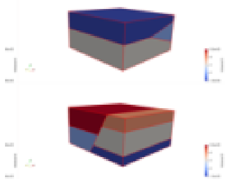
SAND2021-11370PE

Voronoi meshing to accurately capture geology in subsurface simulations

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Outline

Why Voronoi meshes? (and what are they?)

The ‘usual issues’ researchers face when using Voronoi meshes

Analytical benchmark

Simulation on four test structures

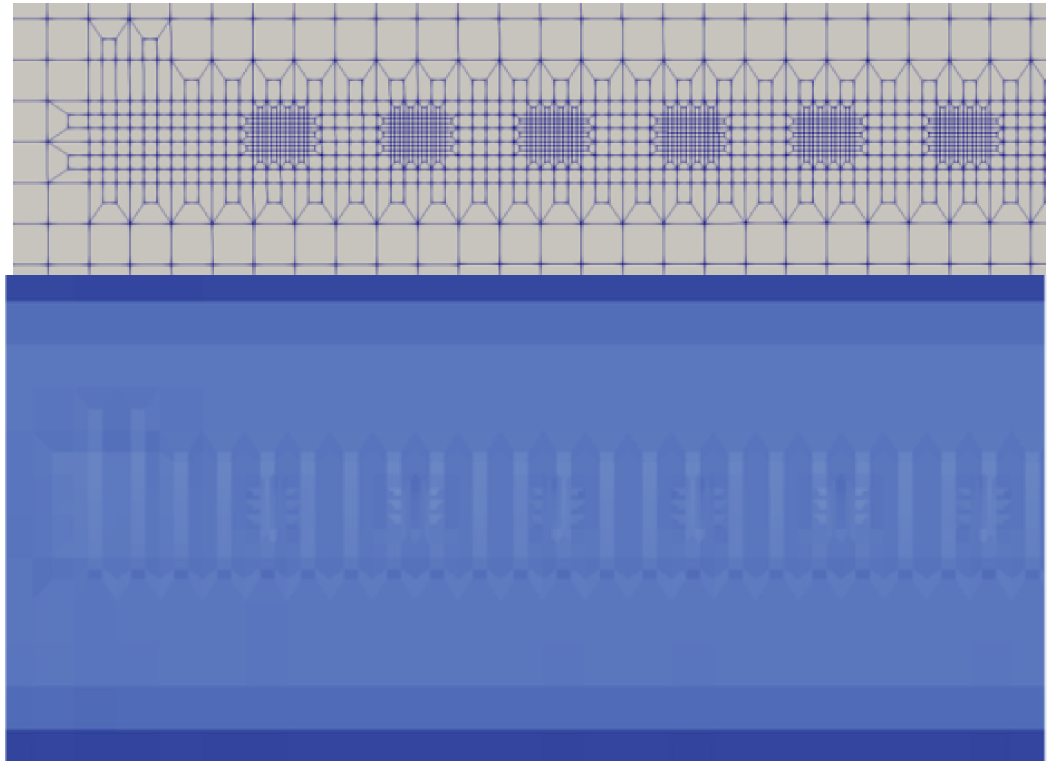
CO_2 storage in a geological model of the Rock Springs Uplift

Conclusions and future work

Why Voronoi meshes?

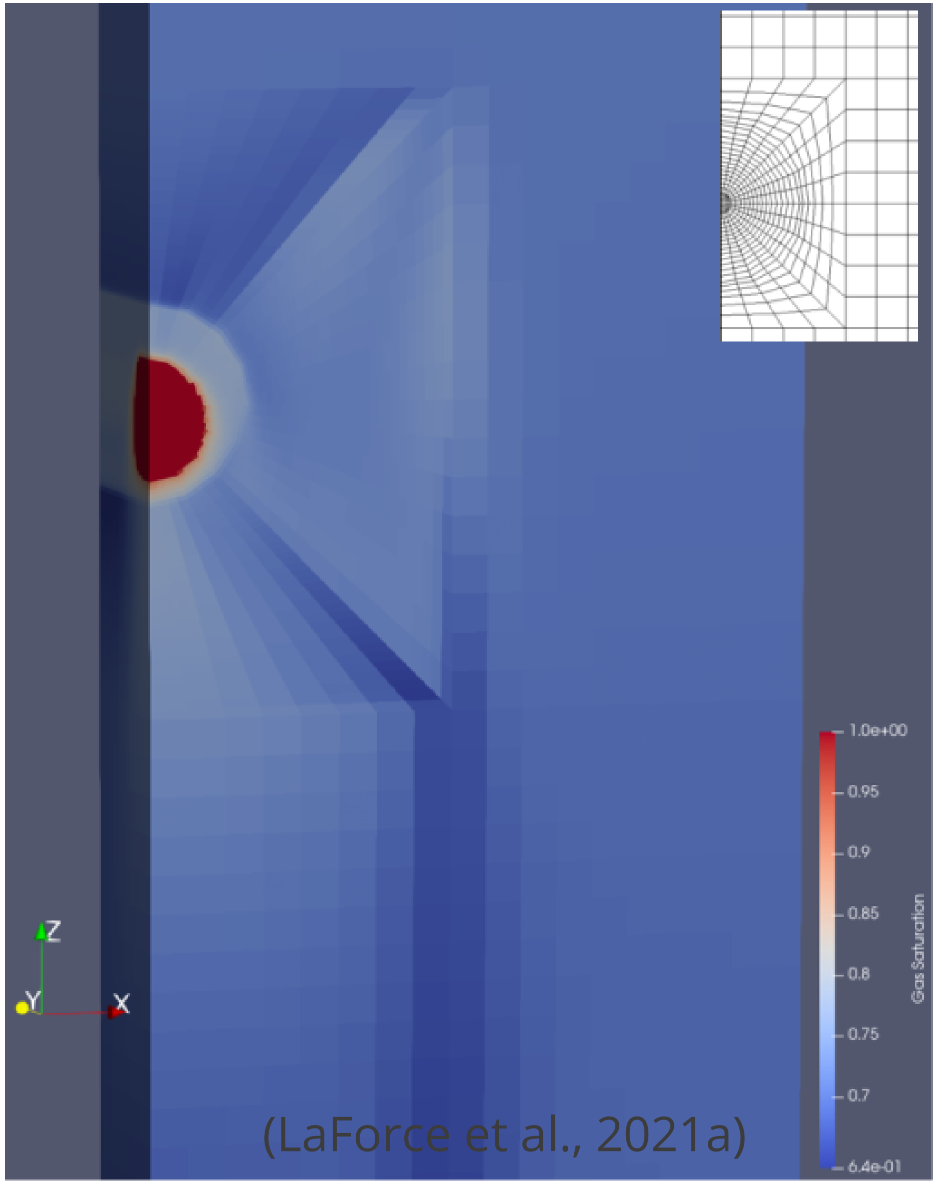
They rigorously honor complex geometries…

…without introducing non-orthogonal fluxes in simulations



Equilibration of an unsaturated heterogeneous model with infiltration using a refined hexahedral mesh.

Gas saturation around a heat source in an unsaturated model using a flexed hexahedral mesh.

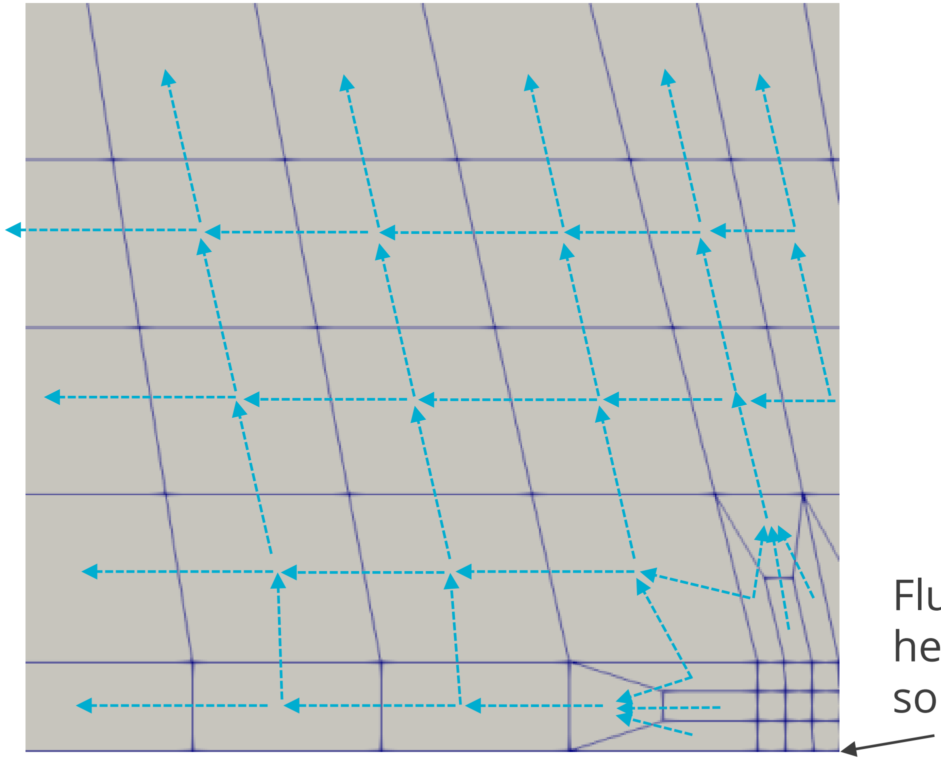


(LaForce et al., 2021a)

Why Voronoi meshes? (and what are they?)

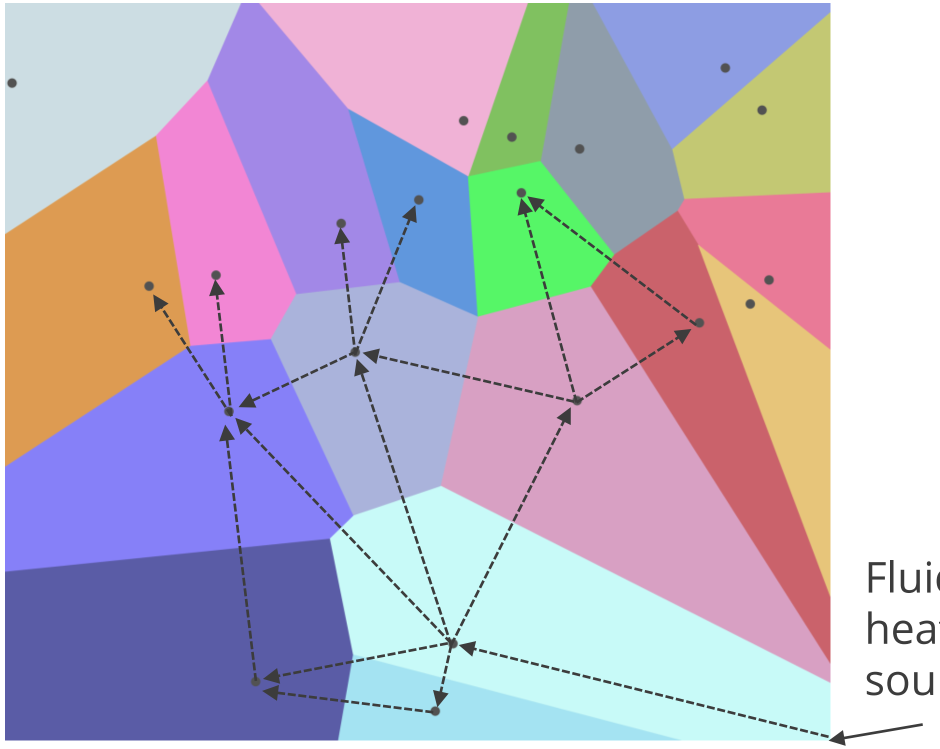
Grid refinement or flexing can bias flow directions

Non-orthogonal fluxes cause errors in SPU/TPFA



Fluxes are perpendicular to grid cell faces using Voronoi polyhedral cells

Solvers using two point flux approximation (TOUGH2/PFLOTRAN/FEHM) get accurate results



The ‘usual issues’ with Voronoi meshes

Creating a Voronoi mesh is hard to do

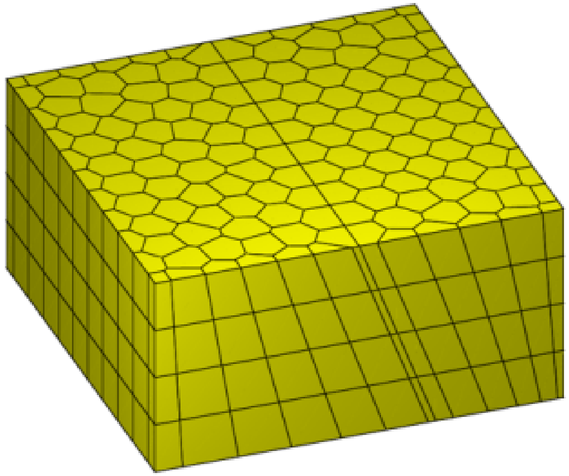


Figure 4.14: A 2.5D grid aligned with an inclined fault.

Many PEBI meshes in the literature are not Voronoi in 3D. (Berge, 2016)

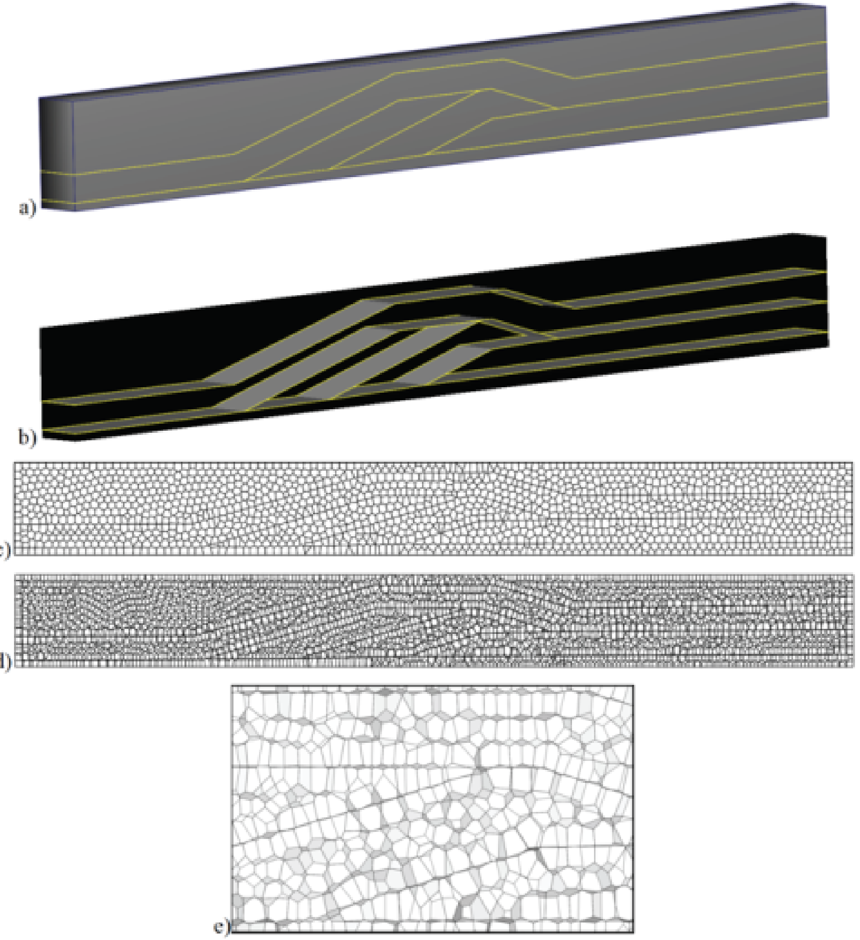
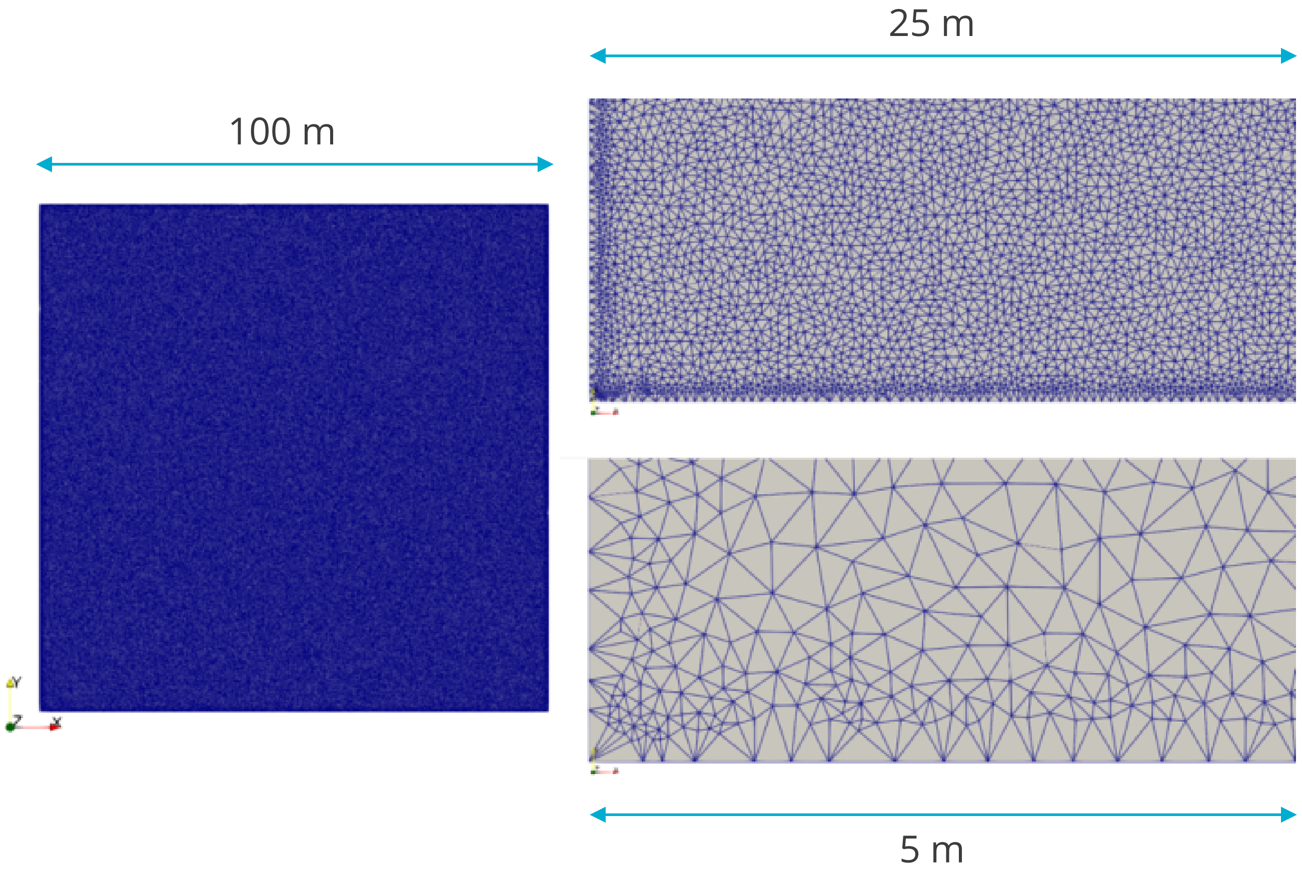


Figure 6: Duplex synthetic case. (a) outer view. (b) inner view. (c-e) optimization using an objective function measuring the outer volume (α=0, β=1). (c) outer view of the grid. (d) slice along the y axis. (e) zoom of the slice along the y axis.

Voronoi, but only approximates interior surfaces (Merland et al, 2011)

The 'usual issues' with Voronoi meshes

Too many grid cells



Too time-consuming for both humans and computers (after Freeman et al, 2014)

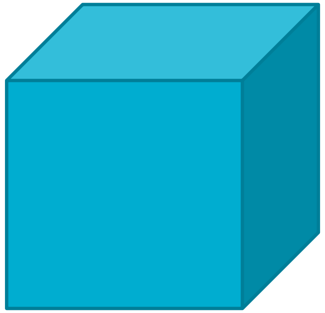
Voronoi meshes should be used when:

- They can represent geometries that cannot be efficiently meshed in other ways
- Decreased numerical performance is acceptable as there is no viable alternative

Voronoi meshes should only be used where they are suited to the demands of the problem

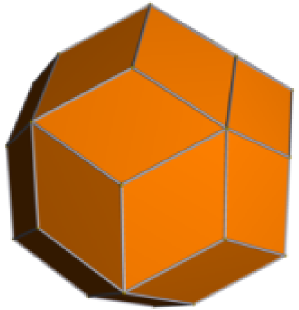
The ‘usual issues’ with Voronoi meshes

Additional computational overhead in polyhedral/Voronoi meshes



Hexahedral
6 connections

Tetrahedral
4 connections



n-sided polyhedral
n connections

$$\begin{bmatrix} x & x & 0 & & x & 0 & 0 \\ x & x & x & \cdots & 0 & x & 0 \\ 0 & x & x & & 0 & 0 & x \\ & \vdots & & \ddots & & \vdots & \\ x & 0 & 0 & & x & x & 0 \\ 0 & x & 0 & \cdots & x & x & x \\ 0 & 0 & x & & 0 & x & x \end{bmatrix}$$

$$\begin{bmatrix} Sparse, with\ just\ 4 \\ off-diagonal \\ entries\ but \\ not\ banded \end{bmatrix}$$

$$\begin{bmatrix} ? & \cdots & ? \\ \vdots & \ddots & \vdots \\ ? & \cdots & ? \end{bmatrix}$$

Robert Webb Stella software , from Wikipedia: http://www.software3d.com/Stella.php

Progress on the 'usual issues'

Meshing improvements: "The VoroCrust algorithm is the first provably correct algorithm for conforming polyhedral Voronoi meshing for non-convex and non-manifold domains with guarantees on the quality of both surface and volume elements." Abdelkader et al, 2020

In other words, VoroCrust:

- Produces genuinely Voronoi meshes
- Guaranteed to produce a mesh that rigorously honors piecewise linear faceted input surfaces that create closed volumes

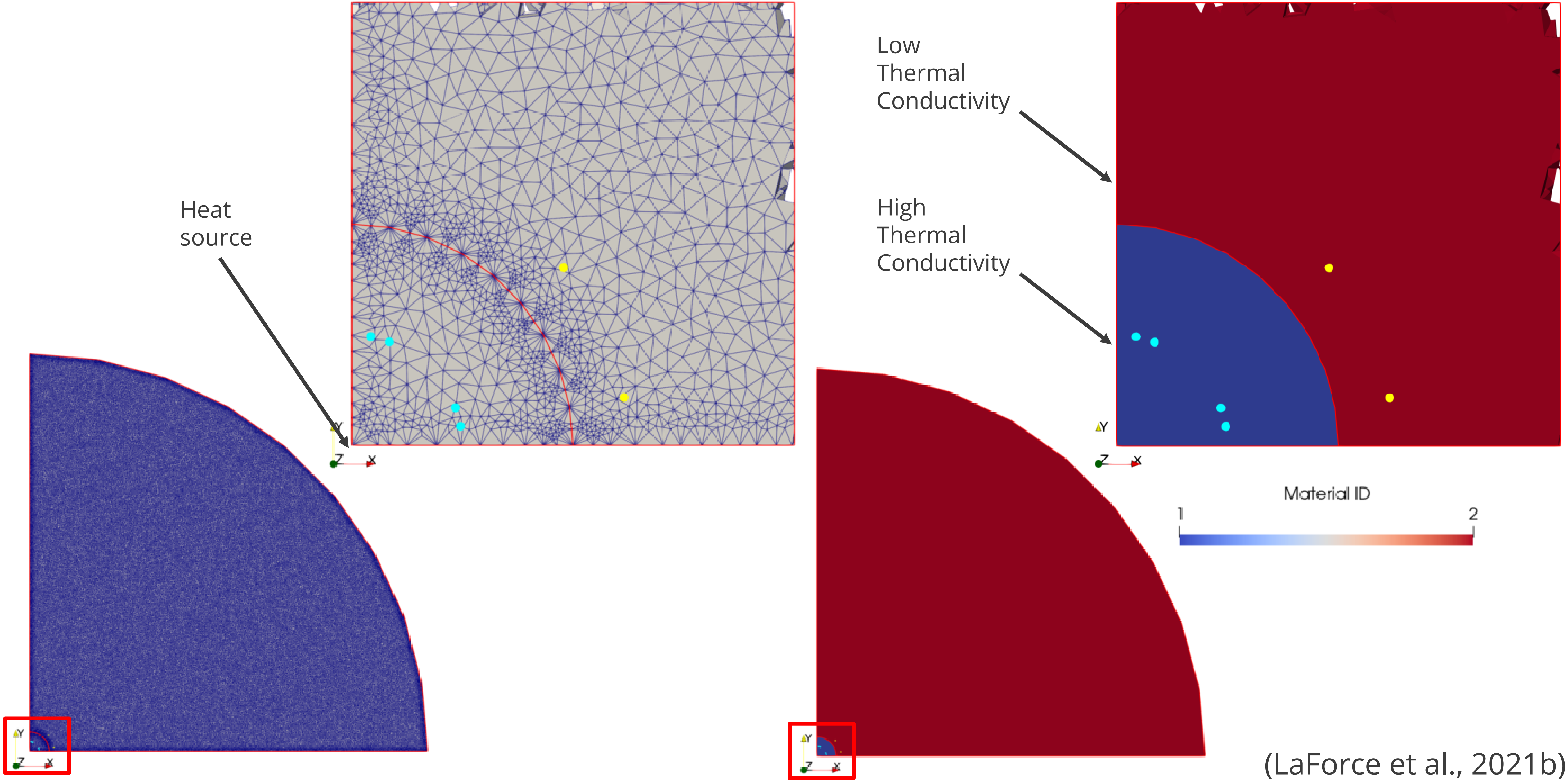
Also allows for local refinement near areas of interest and random generation of meshes

PFLOTRAN's (http://www.pflotran.org) parallel architecture makes extra computational time less of an issue

Still working on:

- Too many grid cells
- Meshing very narrow regions
- Need to consistently retain monitoring points

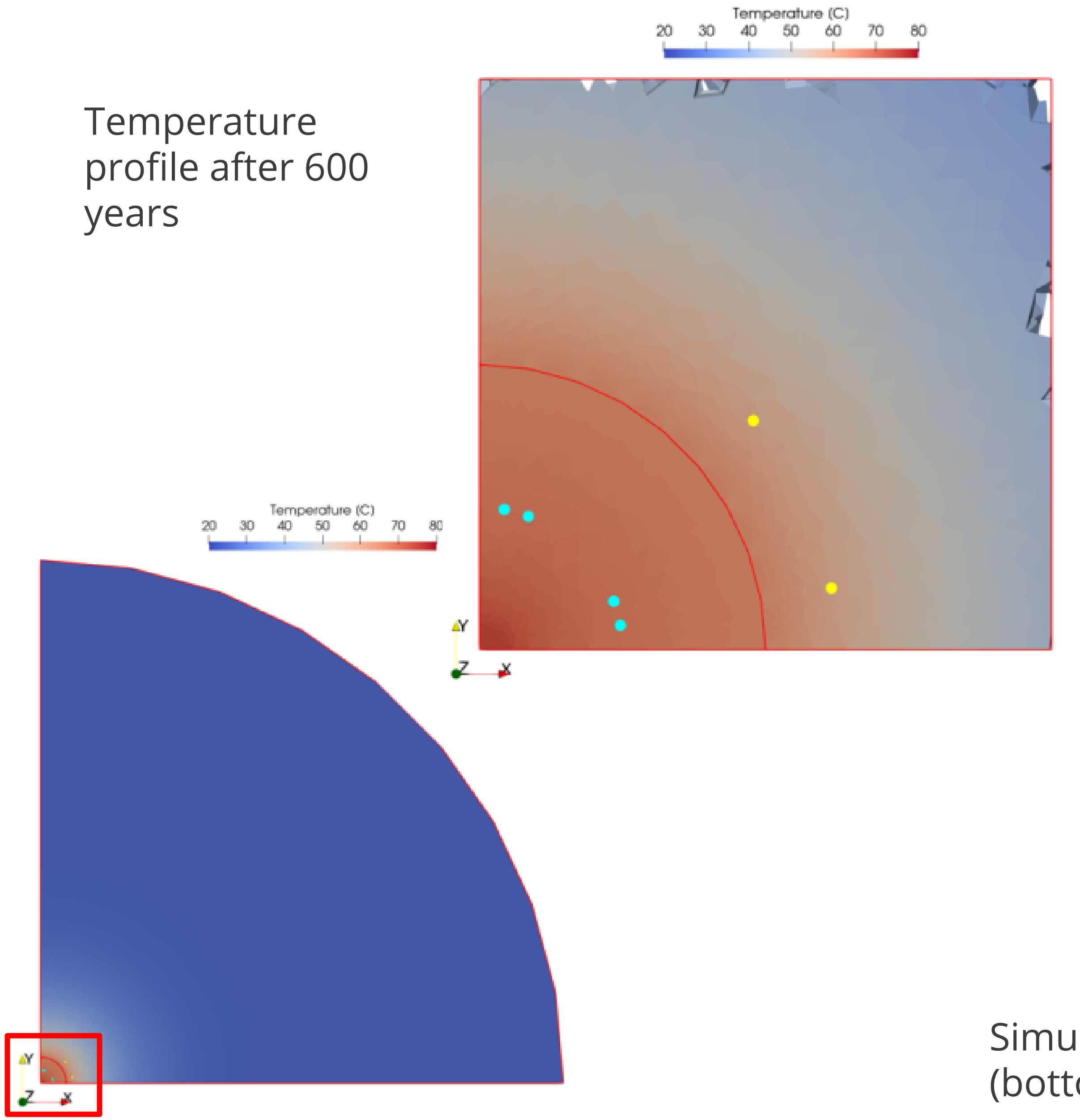
Analytical benchmark: Two domain heating

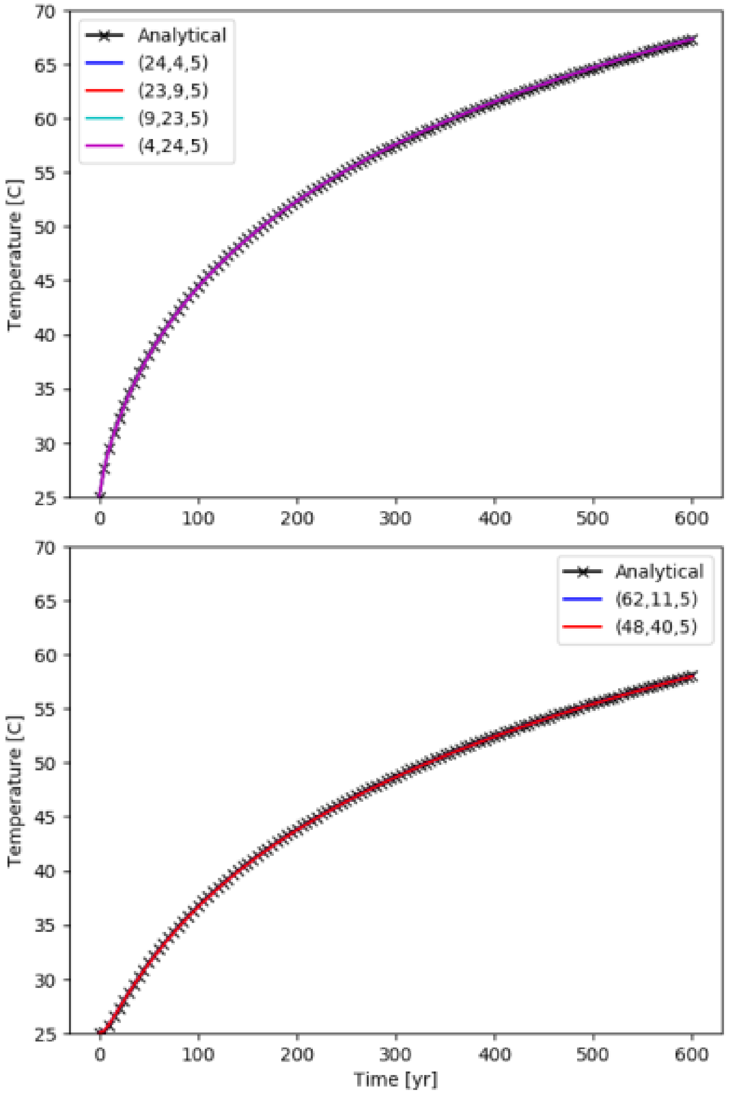


(LaForce et al., 2021b)

Analytical benchmark: Two domain heating

Temperature profile after 600 years

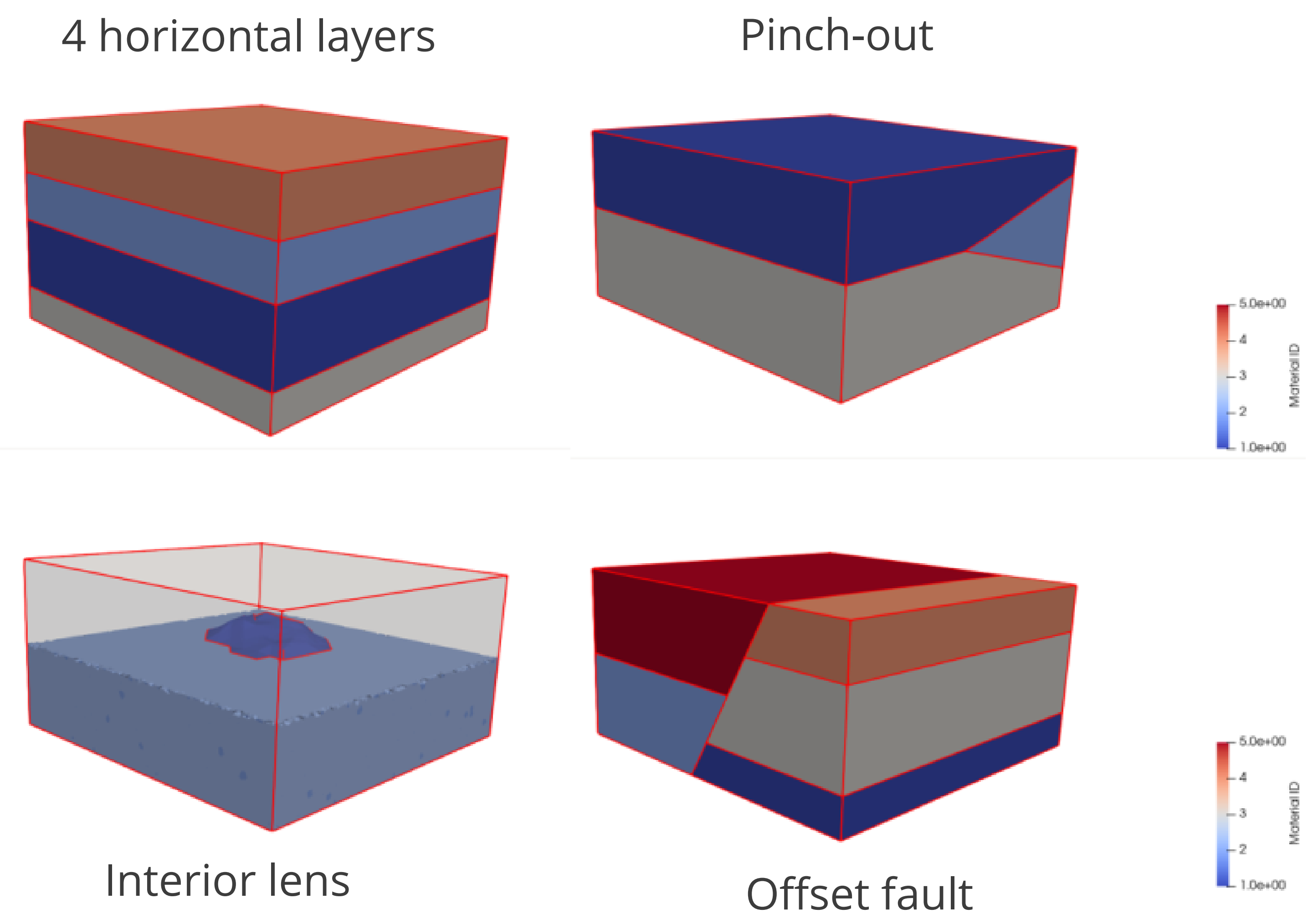




Simulated and analytical temperature at r = 25 m (top) and r = 62.5 m (bottom) for two-domain heating analytical benchmark. Error < 0.2%

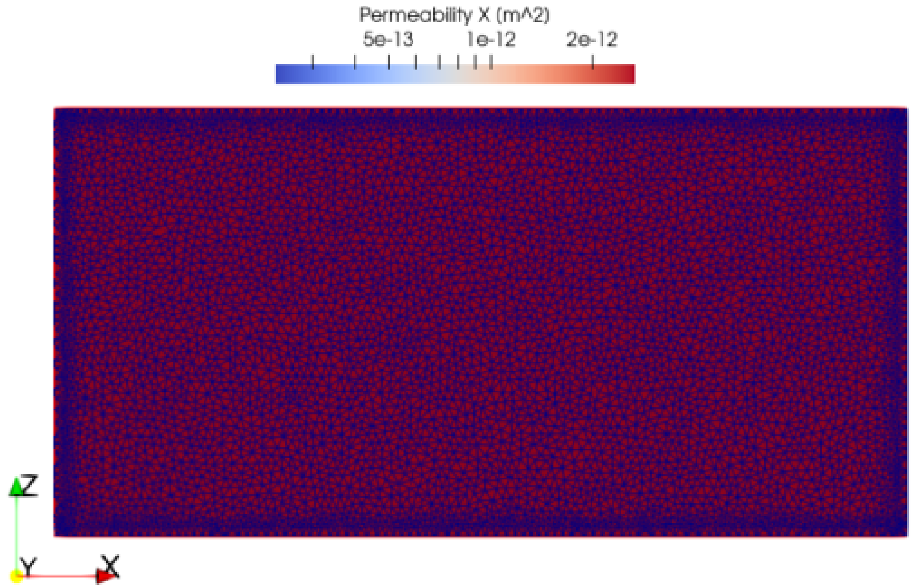
Four test case geometries (Gross et al. 2019)

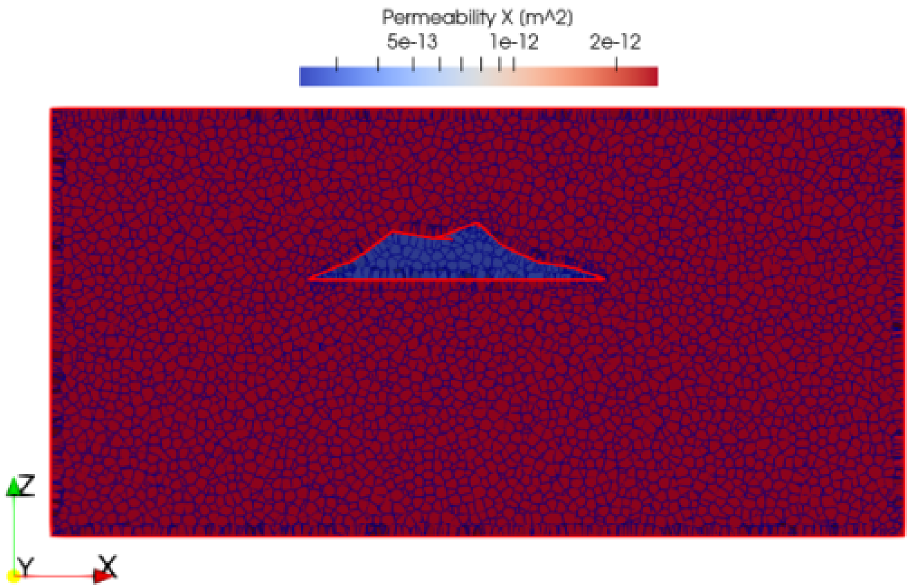
- 4 simulations on each model geometry
- 1.4-4.4 Heterogeneous, two phase (Richard's) downward flow
  - Constant flux at top boundary
  - Constant saturation and pressure at bottom boundary
  - Side boundaries are closed

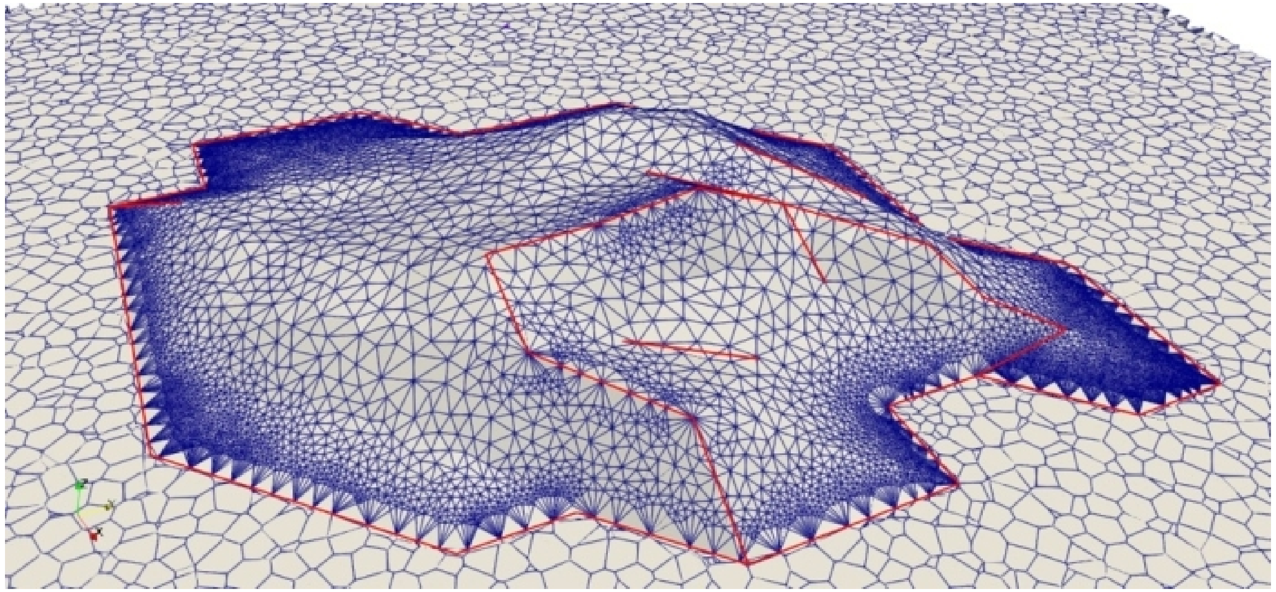


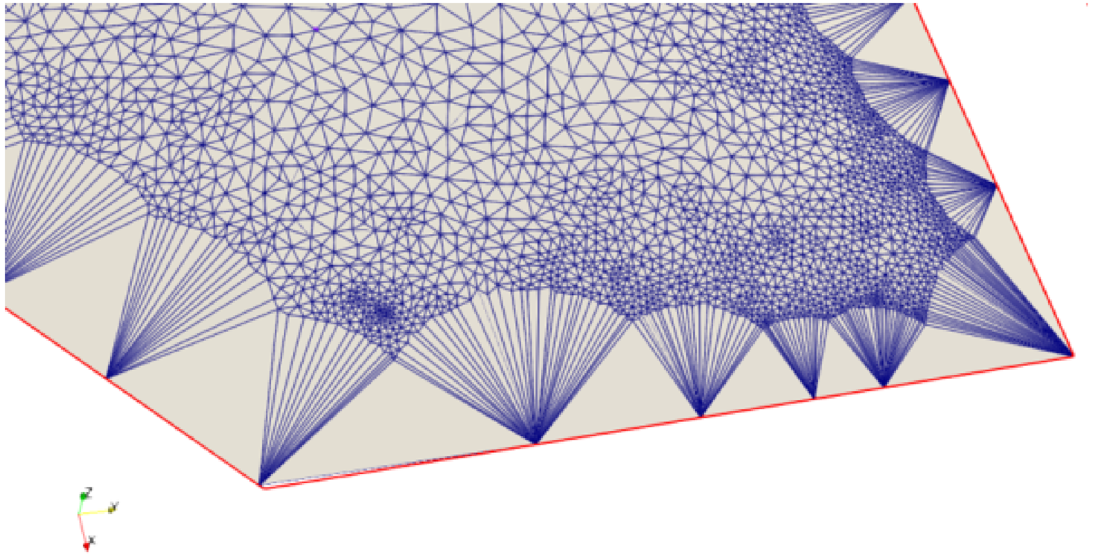
(LaForce et al., 2021a,b)

Test structure 3 mesh





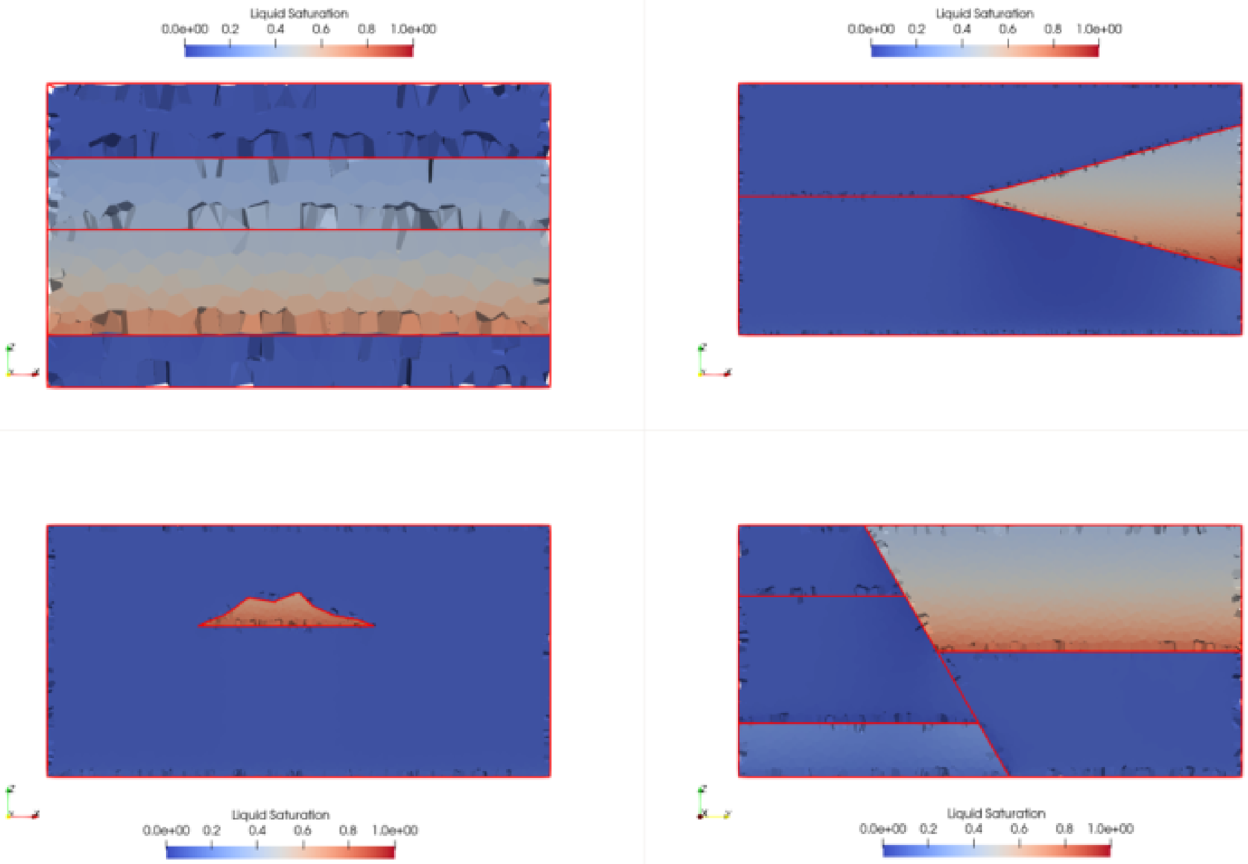




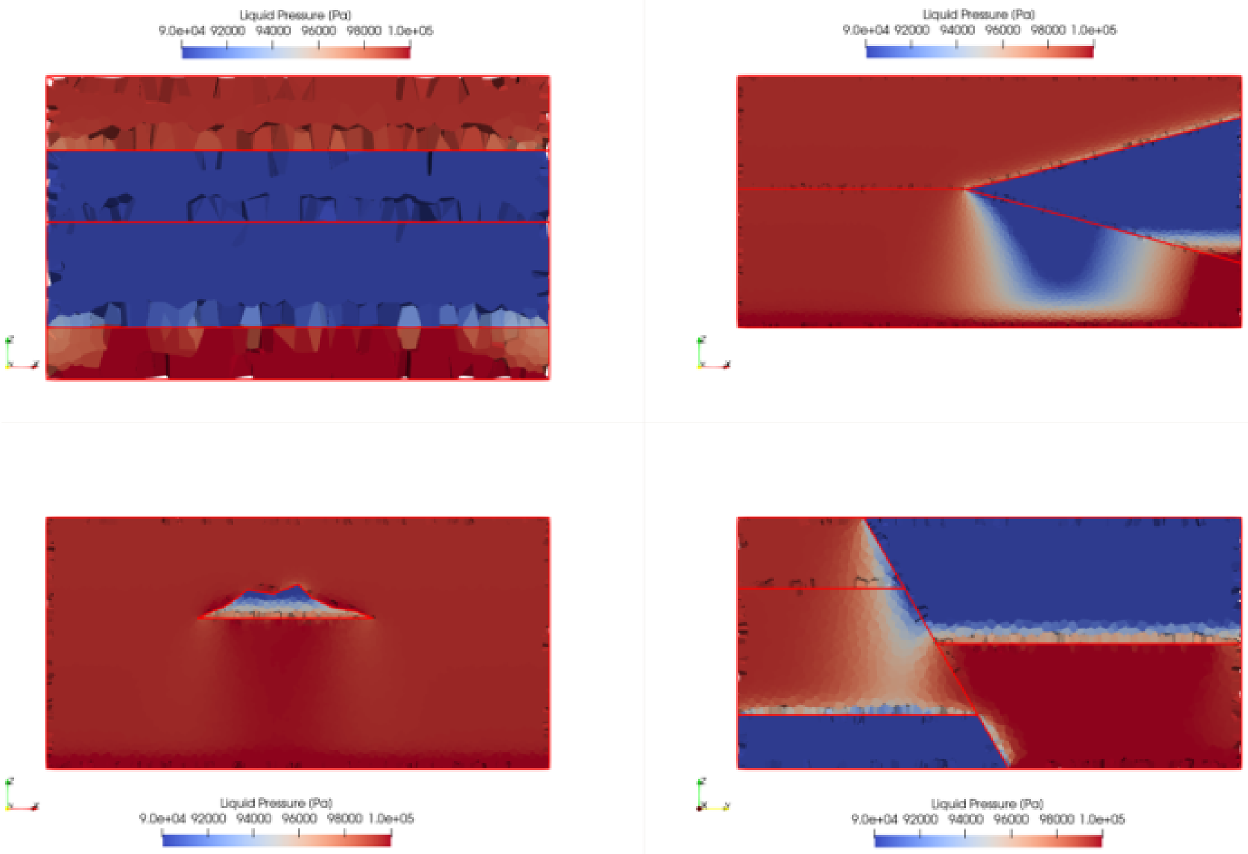
(LaForce et al., 2021b)

Test case 1.4-4.4 results

Steady-state liquid saturation

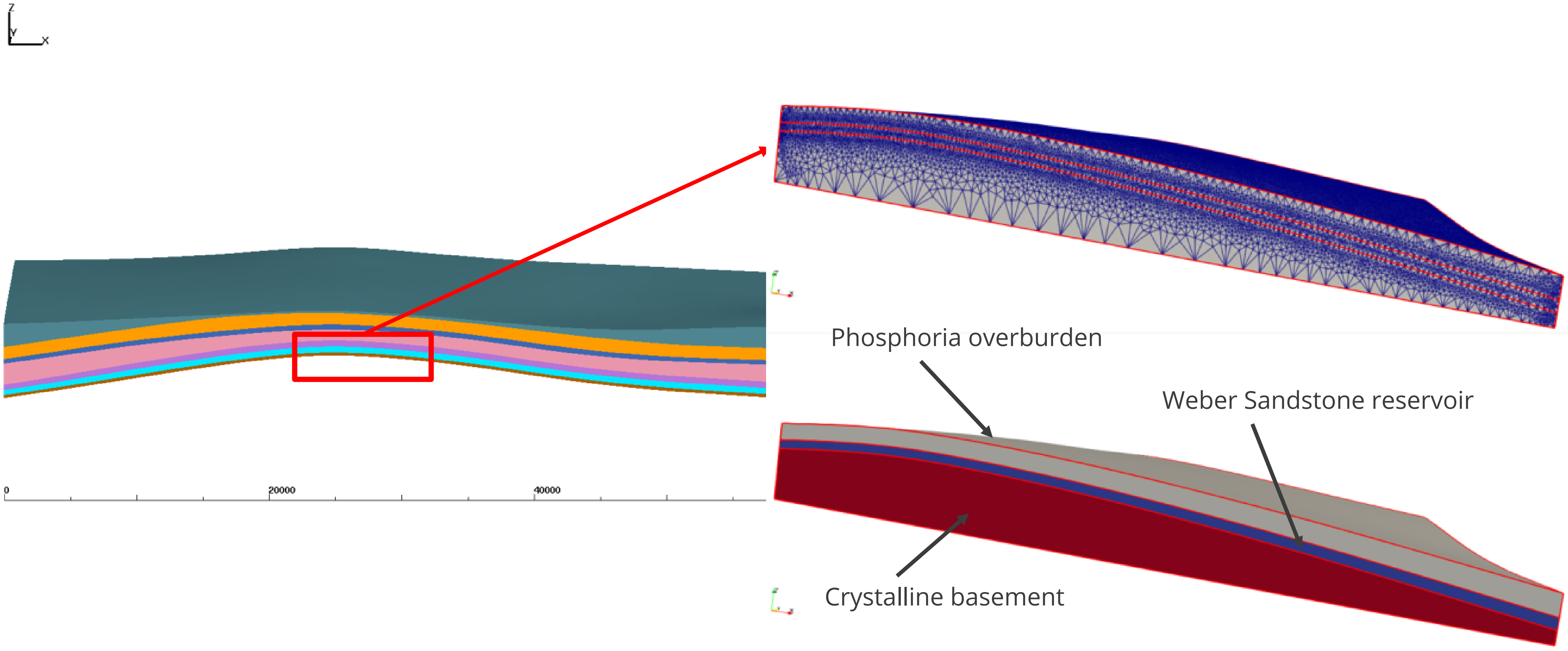


Steady-state liquid pressure



(LaForce et al., 2021b)

Rock Springs uplift
(Stauffer et al. 2009, Deng et al. 2012 and Harp et al. 2017)



(LaForce et al., 2021b)

Rock Springs uplift mesh

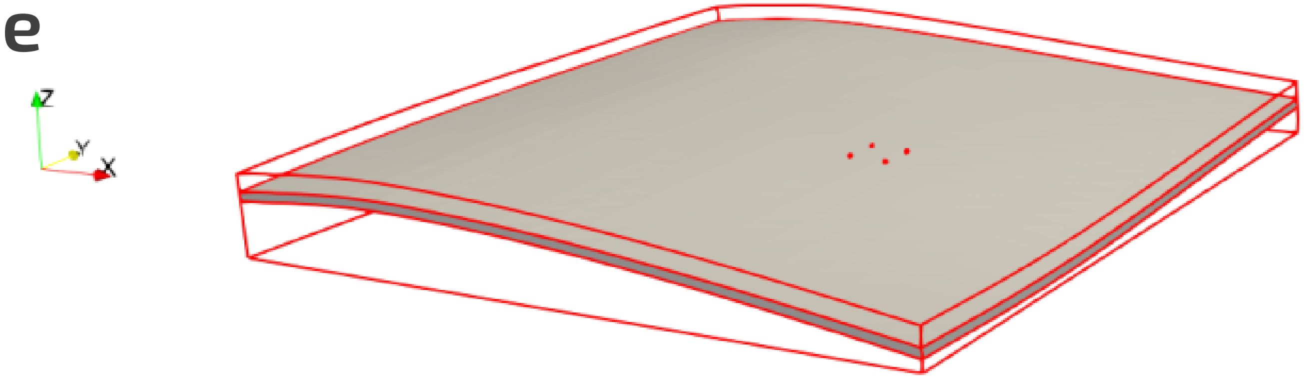
Using Los Alamos open-source software LaGriT excess layers are eliminated and mesh clipped to the region of interest.

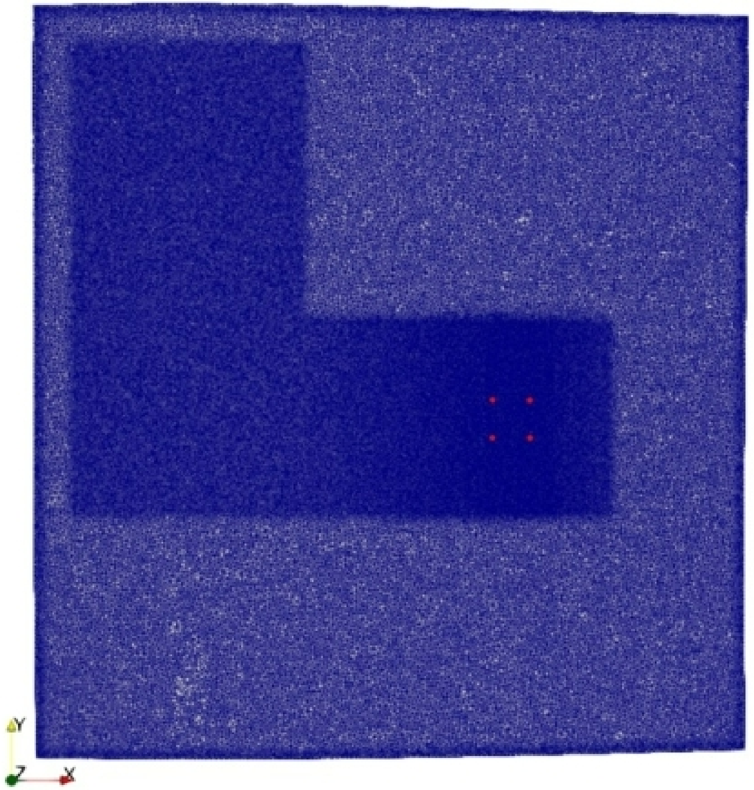
- 4 surfaces are preserved to represent formation of interest, overburden and underburden
- Real underburden layer is eliminated because it was too thin and a flat base is used
- Model is clipped to 20 x 20 km square encompassing one side of uplift and the top structure

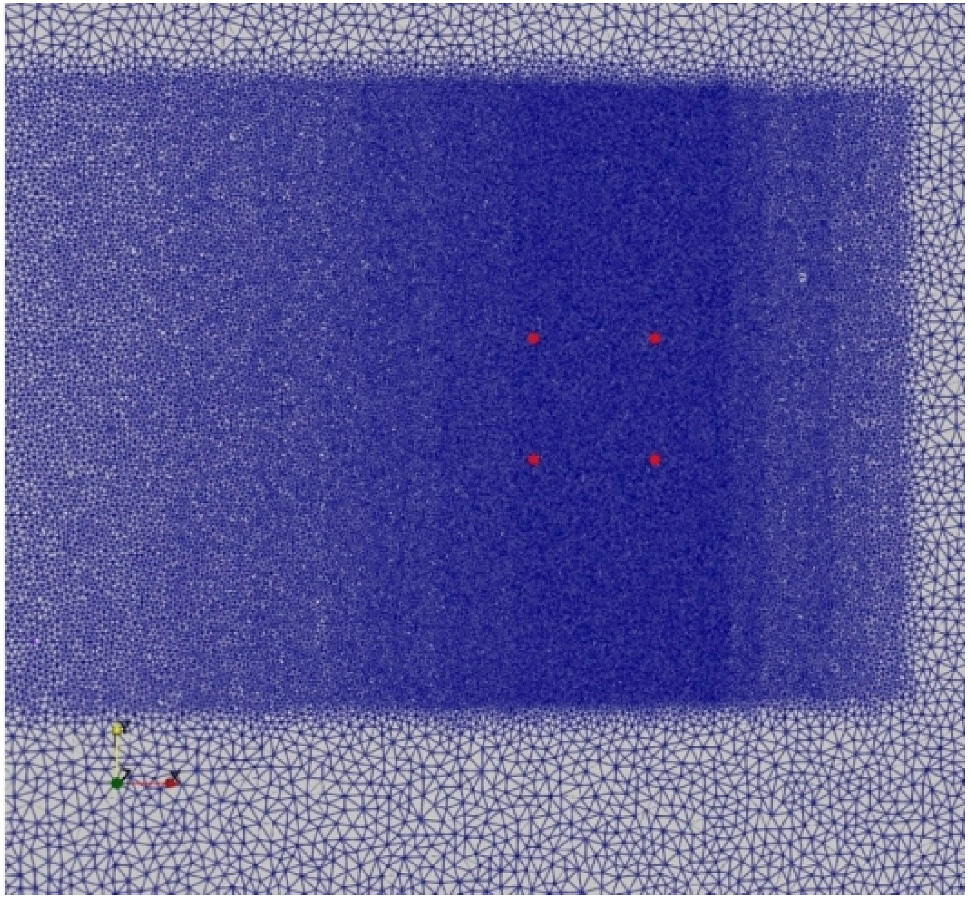
Using VoroCrust mesh refinement capability

- Volume near the 4 injection wells is refined to a maximum cell radius of 20 m
- Weber Sandstone updip and downdip of the wells is refined to maximum cell radius of 50 m
- Grid cell sizes in the rest of the mesh are automatically adapted to be the largest allowable for the geometry.

Top Weber Sandstone mesh







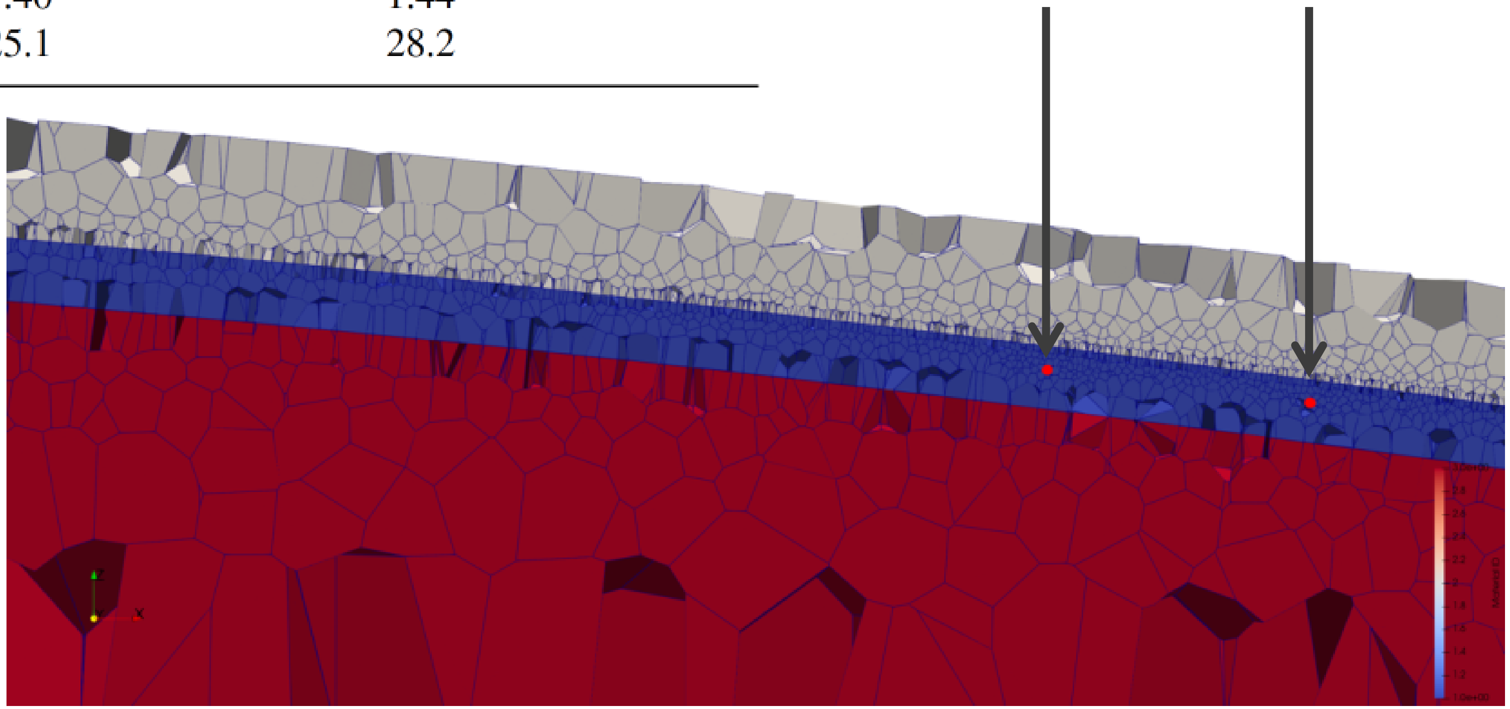
(LaForce et al., 2021b)

Rock Springs uplift simulation

Realization	mesh 1	mesh 2	mesh 3
Grid cells	763,607	763,769	762,763
Maximum connections	36	36	37
Average connections	11	11	11
Minimum connections	4	4	4
Injector 1 (x,y,z)	(18500, 8500, -1390)	(18500, 8550, -1390)	(18500, 8500, -1390)
Injector 2 (x,y,z)	(18500, 9500, -1390)	(18500, 9550, -1390)	(18500, 9500, -1390)
Injector 3 (x,y,z)	(19500, 8500, -1515)	(19500, 8550, -1515)	(19500, 8500, -1515)
Injector 4 (x,y,z)	(19500, 9500, -1515)	(19500, 9550, -1515)	(19500, 9500, -1515)
Mesh generation time (hr)	1.87	1.40	1.44
Simulation time (hr)	24.7	25.1	28.2

Slice through two of the wells at y = 9500 m.

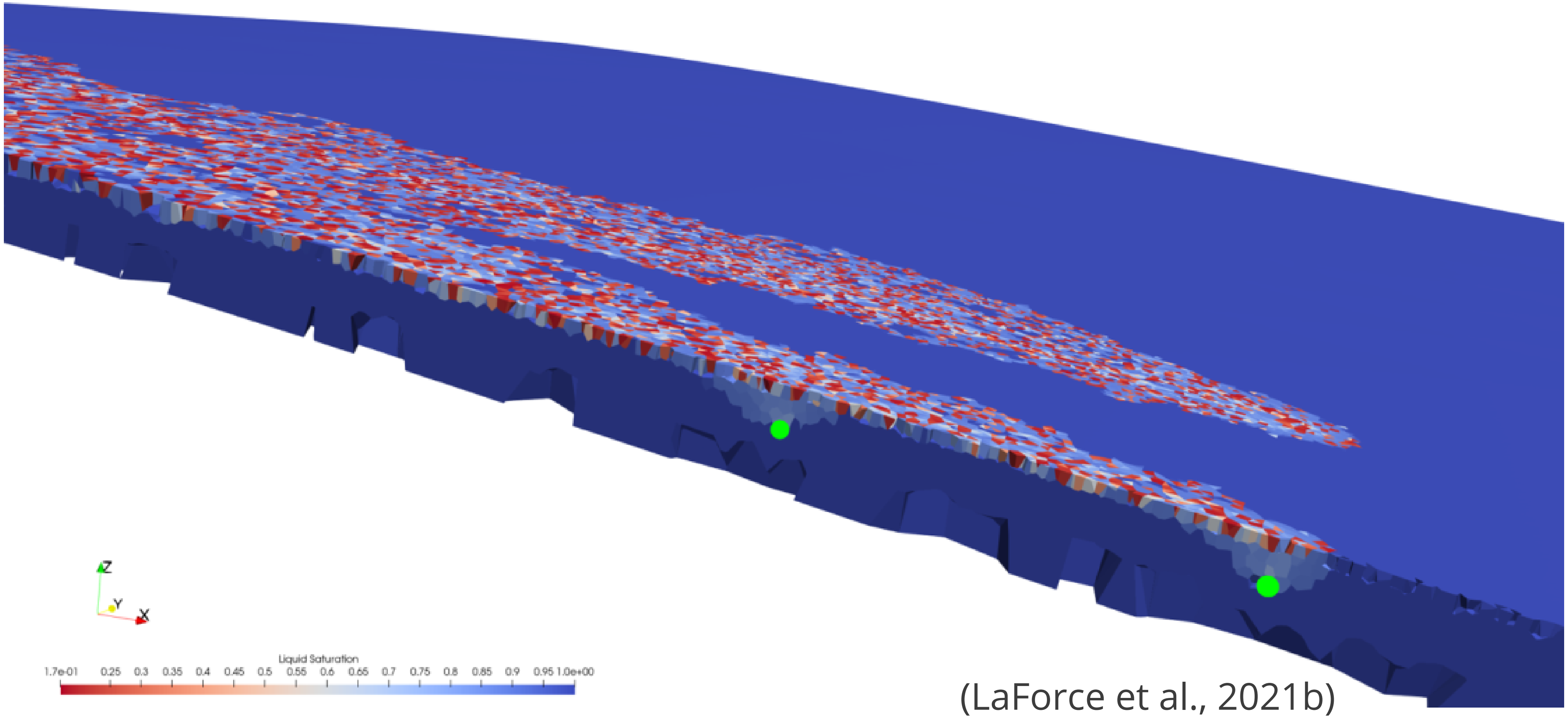
Injection for 100 years at
1 million tons per year



(LaForce et al., 2021b)

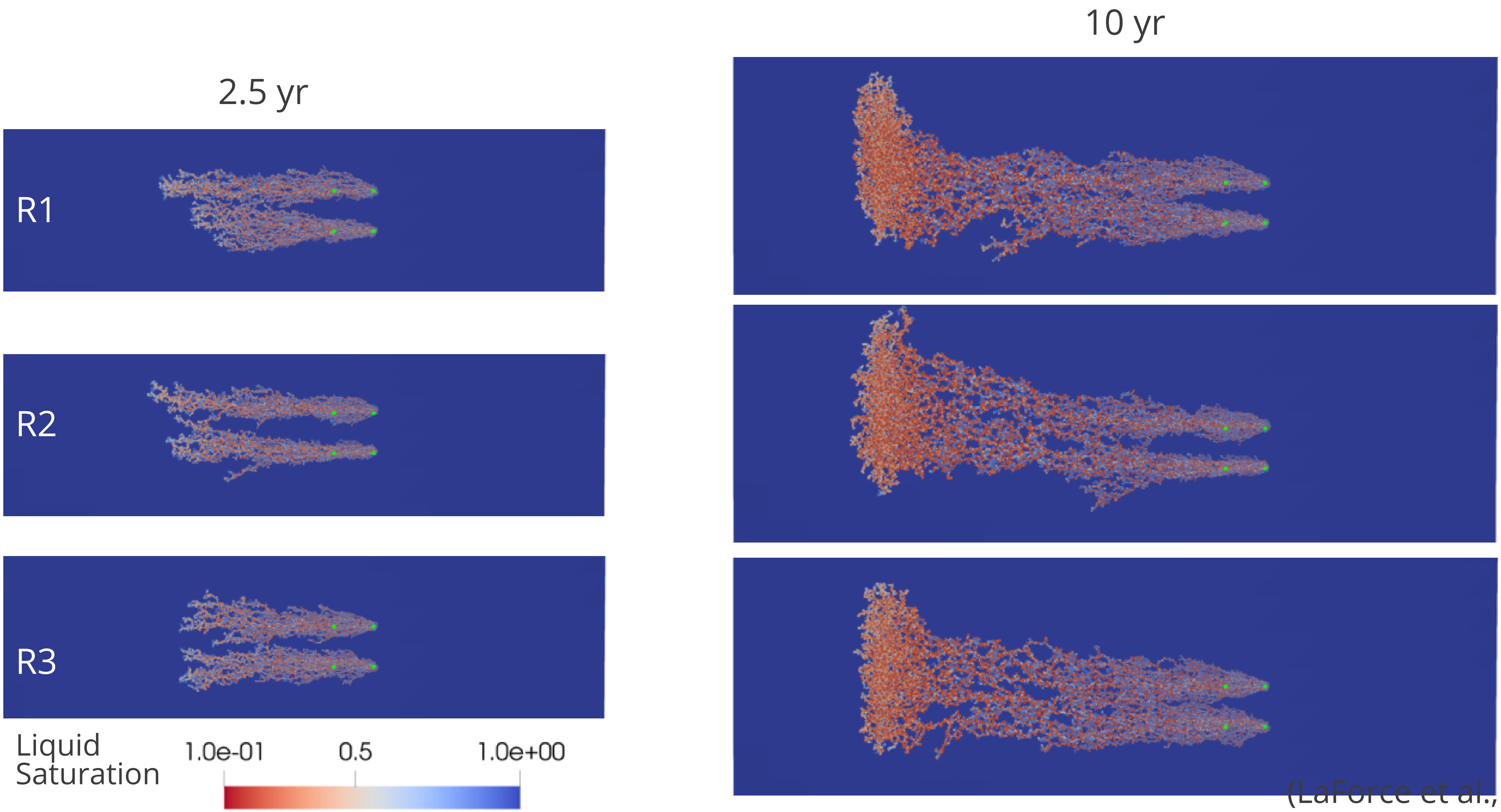
Rock Springs uplift

Weber sandstone slice through two of the wells at y = 8500 m. Time = 10 yr



(LaForce et al., 2021b)

Rock Springs uplift: CO_2 at top of Weber Sandstone



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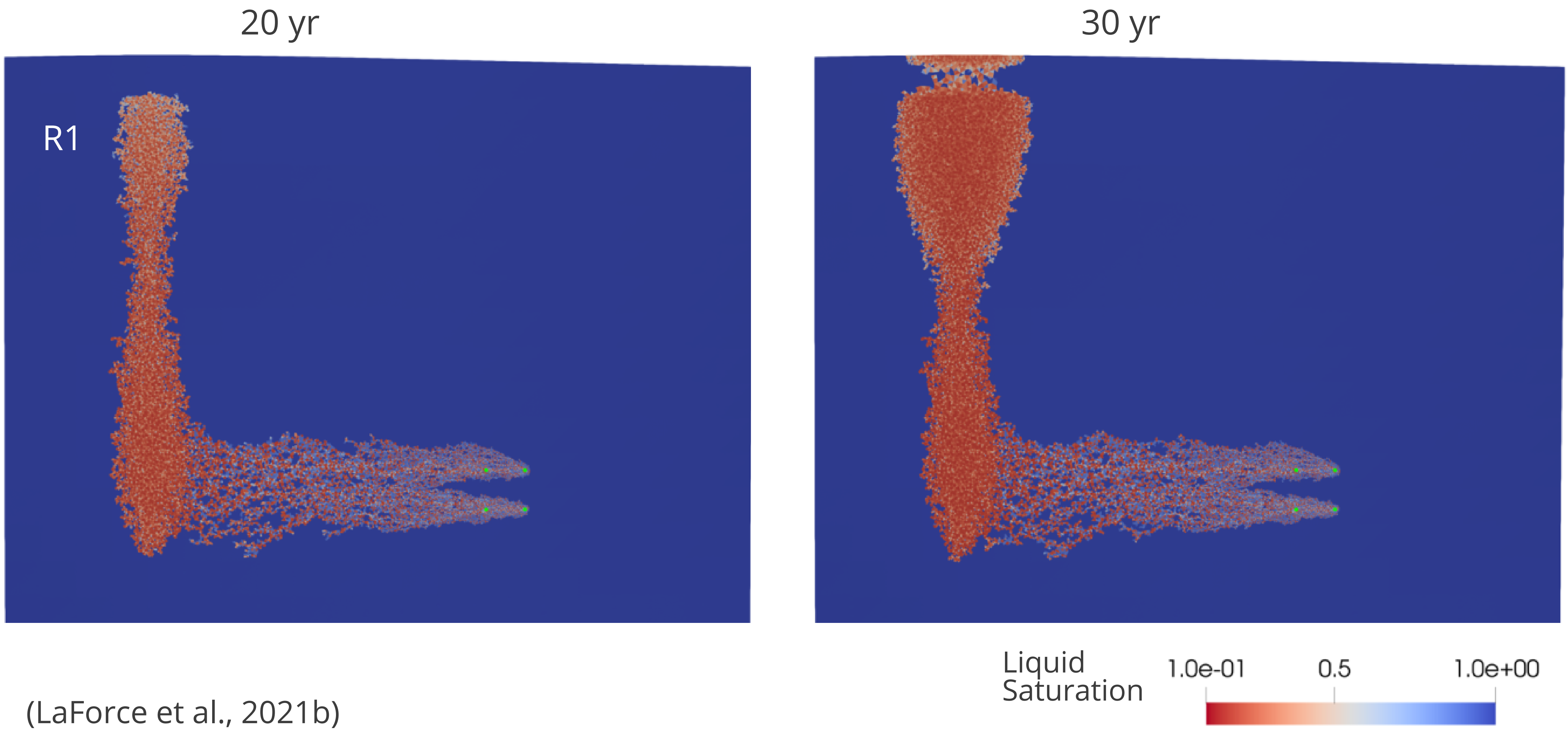
Rock Springs uplift: CO_2 at top of Weber Sandstone



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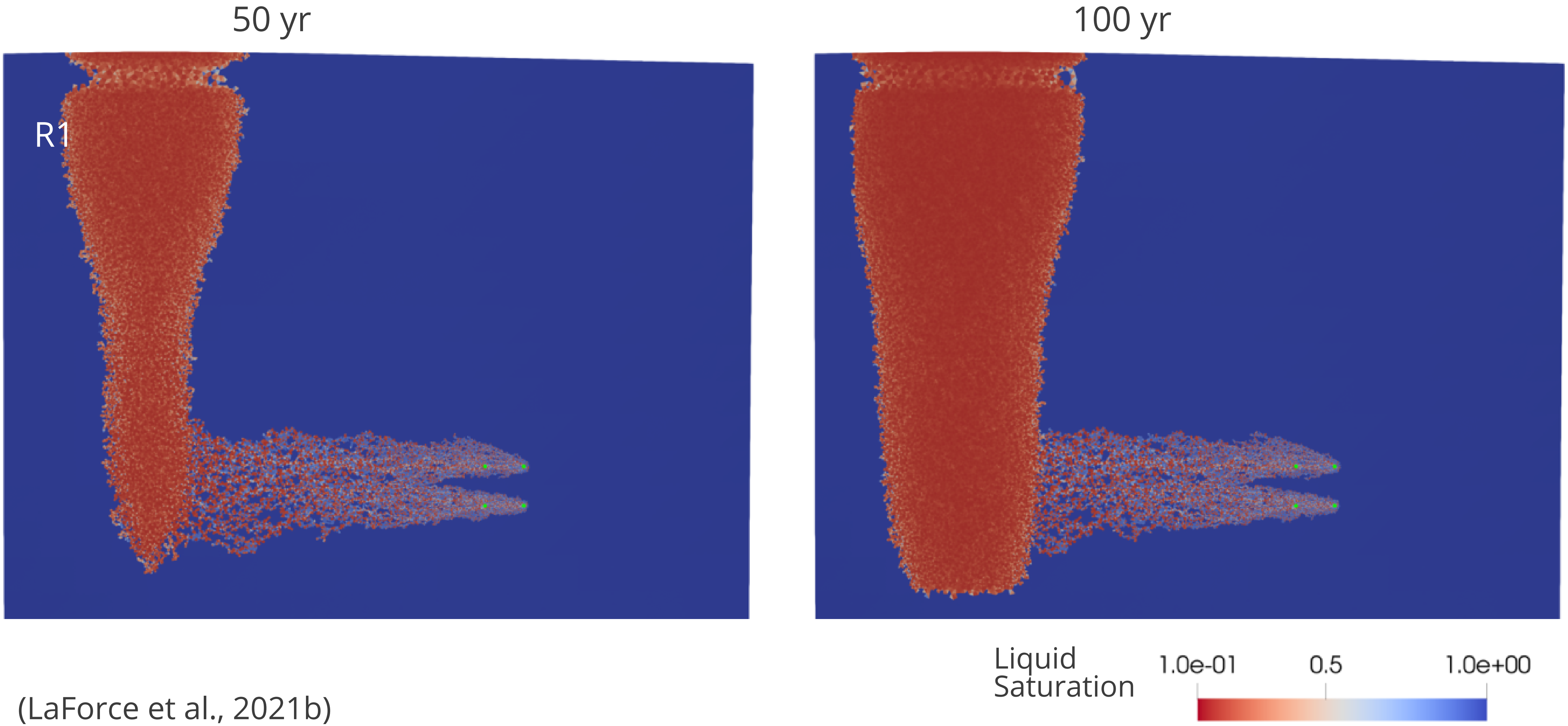
Rock Springs uplift: CO_2 at top of Weber Sandstone



(LaForce et al., 2021b)

Conclusions

Automated meshing allows us to overcome many of the ‘usual issues’ with Voronoi meshing

- Meshes are genuinely Voronoi and honor arbitrary interior surfaces
- Meshing is automated and requires little human or computer time
- Easy to change refinement locally or globally
- Easy to generate a new realization of the mesh

Benchmark simulation on Voronoi mesh is accurate against analytical solution and not prohibitively slow

Generating meshes and running simulations on the four test structures was successful and simulations are accurate

Field-scale CO_2 storage simulation of gas flow on multiple realizations of the mesh

Future work

Immediate future:

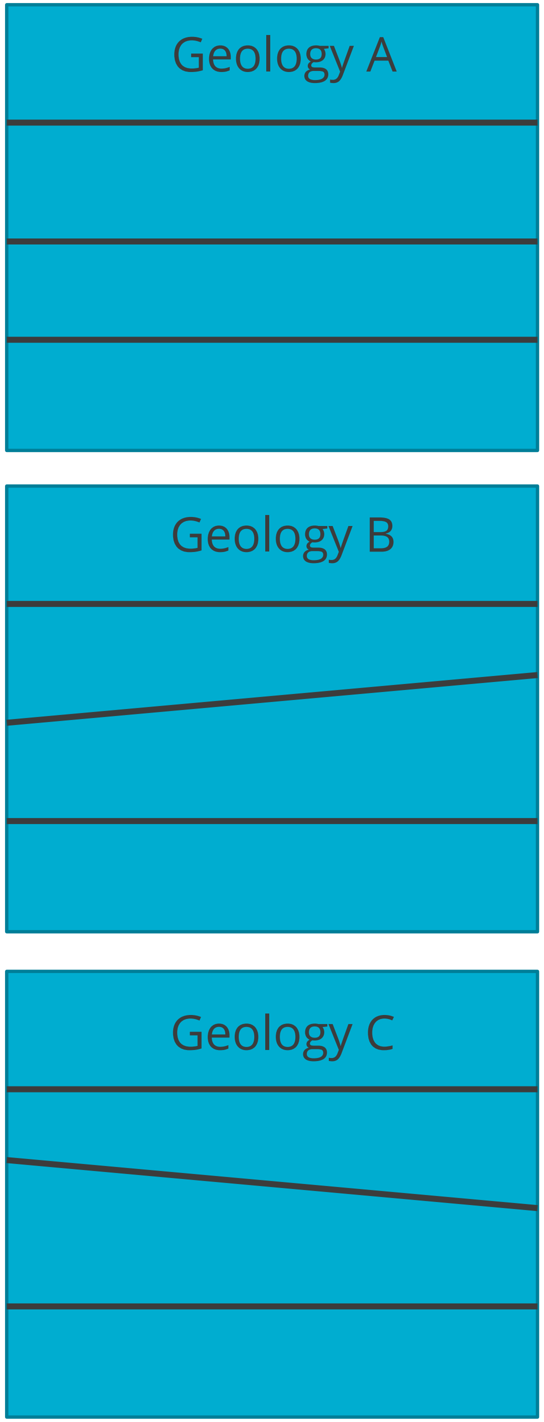
- Investigate Voronoi meshes for simulations with known grid orientation effects

Medium term:

- Open-source version of the meshing software
- Add to uncertainty quantification and sensitivity analysis:
  - Impact of mesh realization
  - Introduce geological uncertainty

Longer term:

- Mesh faults that terminate within the model
- Anisotropic meshing to reduce element numbers



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