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Sandia National Laboratories

A comparison study of density-driven flow in fractured porous media

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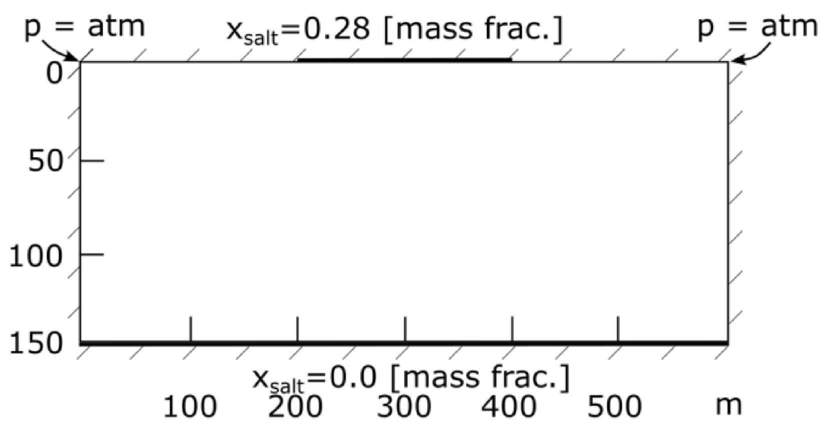
Introduction: Density-driven flow

Density-driven flow occurs in many geologic settings, including seawater intrusion into a freshwater aquifer, carbon sequestration in deep sediments, and glacial cycles altering the salinity in fractured crystalline bedrock. A problem commonly used to benchmark density-driven flow simulations is the Elder problem. We extend the Elder problem to three dimensions, and investigate the effect of varied fracture networks on density-driven flow. To examine the bounds of these effects, we compare the results reached by two flow and reactive transport simulators: FEHM and PFLOTRAN. FEHM is a groundwater flow and transport simulator that uses a control volume finite element approach to ensure conservation of mass. PFLOTRAN is a massively parallel flow and transport simulator that solves a coupled system of equations using a finite volume discretization. The fracture network is discretized using dfnWorks, a parallelized computational suite capable of generating stochastic fracture networks in three dimensions.

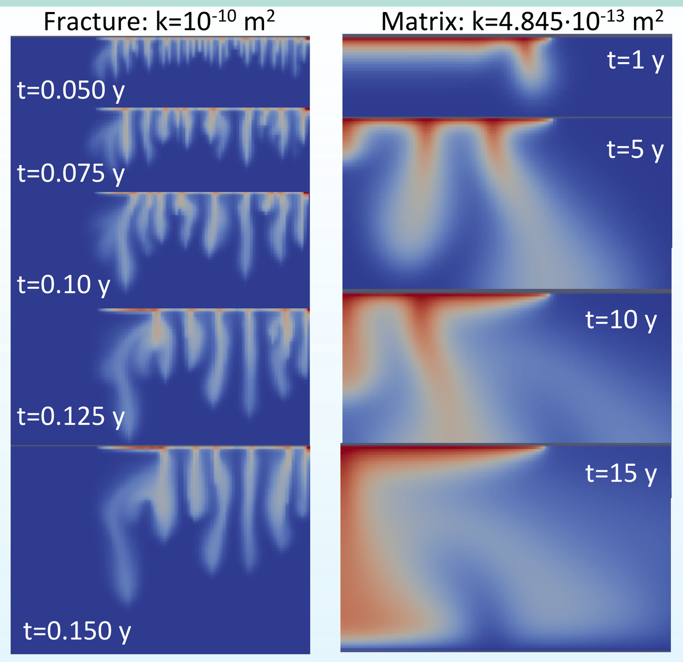
Elder problem

The Elder problem originated in the 1960s as a buoyant flow experiment where convection was initiated by heating the bottom of a water-filled, rectangular Hele-Shaw cell. To benchmark porous media flow and transport simulators, the Elder problem was modified in the 1980s to use density changes that drive convection arising from variations in solute concentration rather than variations of temperature. The modern Elder problem is set in a rectangular domain with zero-flux boundaries on all sides, where density-driven convection is initiated by an elevated, constant salt concentration along its upper boundary.

Parameter	Value
Permeability	$4.845 \cdot 10^{-13}$ m^2
Porosity	10%
Fluid viscosity	$1 \cdot 10^{-3}$ Pa·s
Grid dx,dy	2.14 m
L/h	600/150 m/m
Initial solute conc.	0.0
Upper boundary solute concentration	0.28



Density-driven flow in fractures

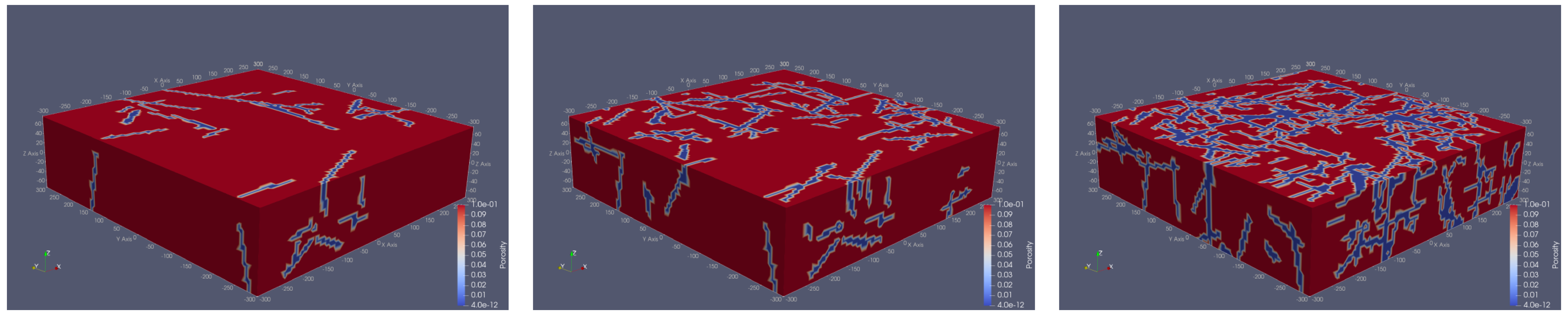


- Fracture permeability is very high (10^{-10} m^2) compared with the matrix permeability (10^{-13} m^2)
- Heightened permeability the increases the Rayleigh number, which lowers the $\Delta\rho$ required to initiate convection
- Convection initiates faster, shorter spacing between fingers

$$Ra = \frac{buoyancy/gravitation}{diffusion/dispersion} = \frac{gk\beta(C_{max} - C_{min})H}{\phi\left(\frac{\mu}{\rho}\right)D}$$

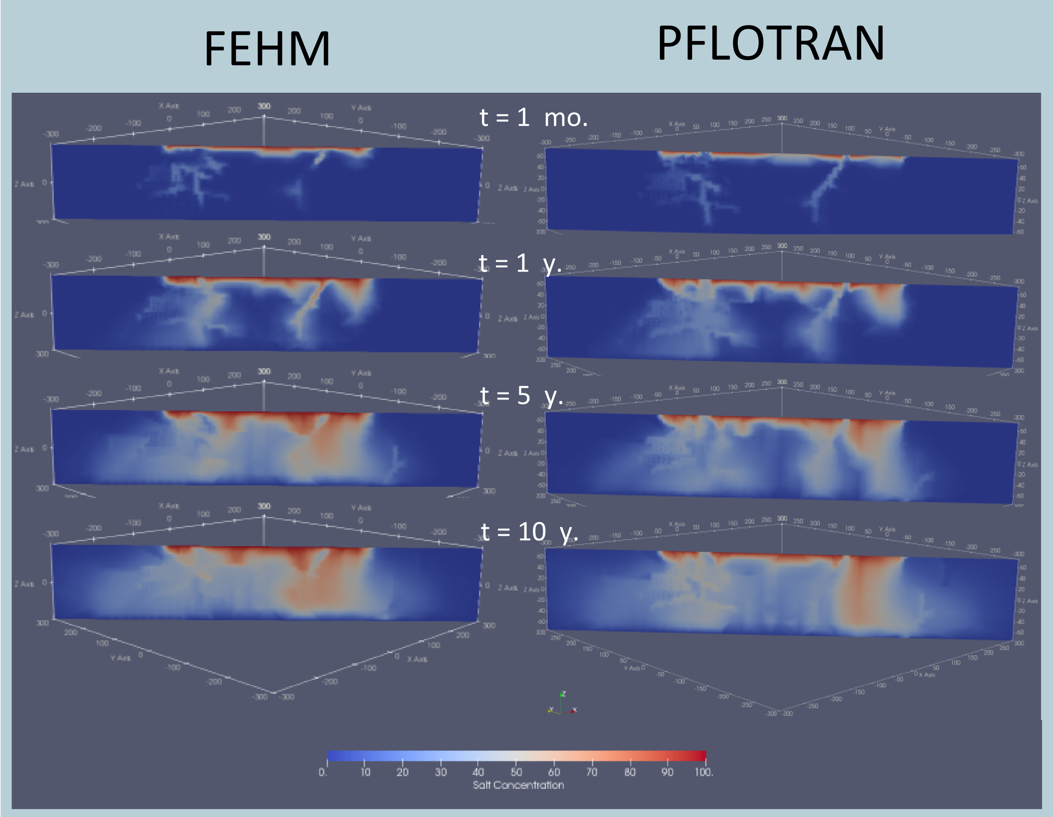
3D fractured problem: dfnWorks

The fracture network is composed of three fracture families whose radii follow a truncated power law distribution (exponent: 1.6, minimum radius: 10 m, maximum radius: 100m). The fractures are represented as squares. The primary orientations of the families are aligned with the principal Cartesian axes. The fracture centers are uniformly distributed throughout the domain. We consider three fracture intensities, defined using P32 (fracture surface area per unit volume), of 0.03 m^{-1}, 0.06 m^{-1}, and 0.12 m^{-1}, with equal contribution from each family.

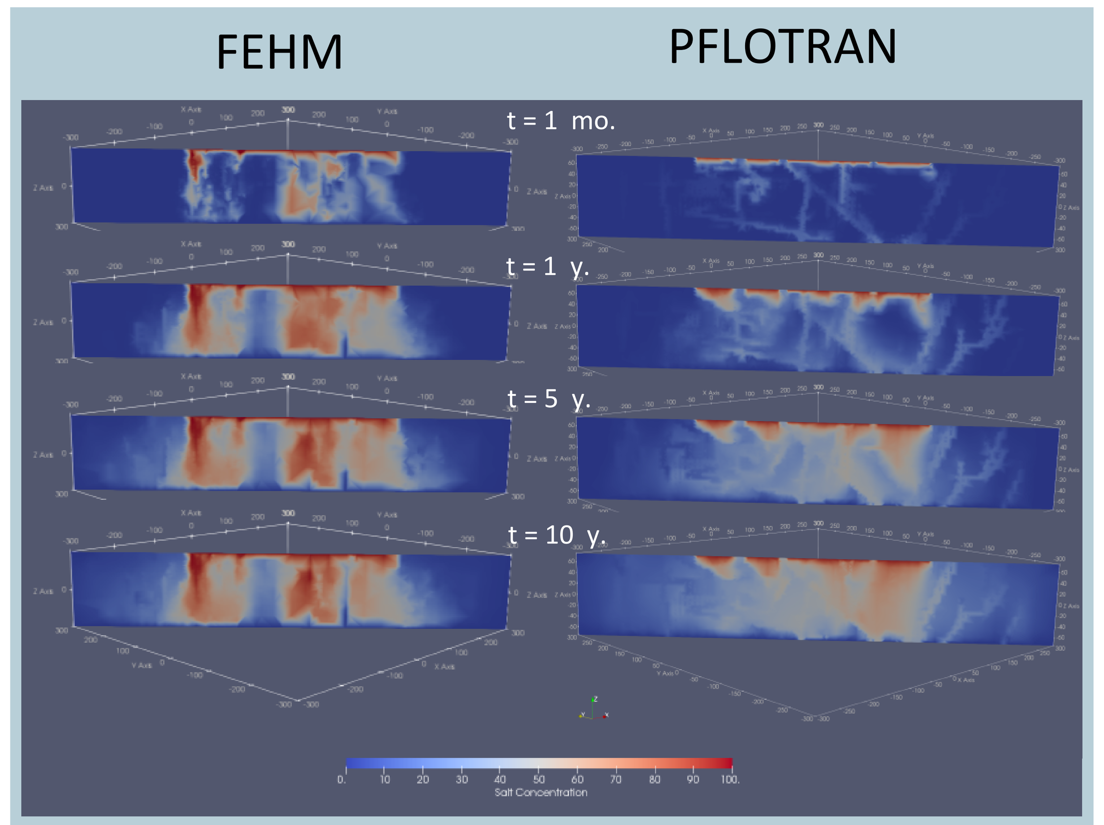


3D fractured system: FEHM and PFLOTRAN

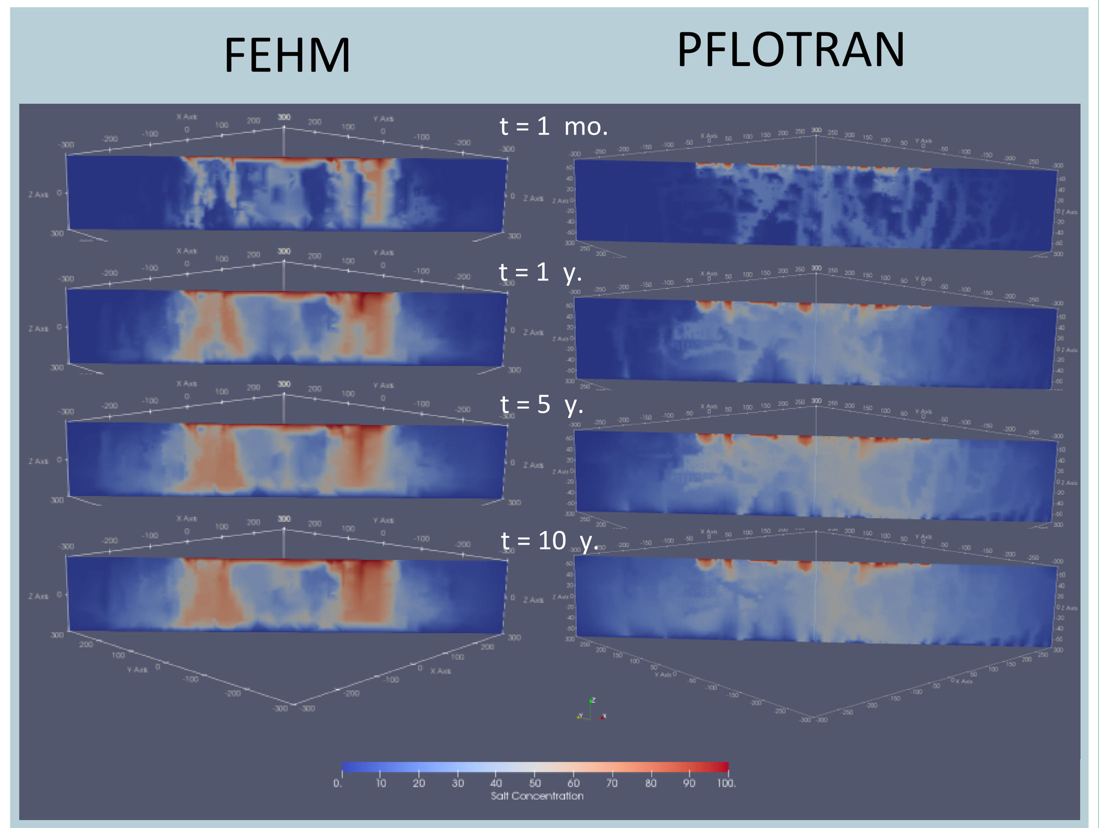
- FEHM uses a control volume finite element approach to solve the fractured Elder problem.
- PFLOTRAN uses the Richards flow mode sequentially coupled with solute transport.



- Good agreement between FEHM and PFLOTRAN at high fracture spacing
- Initial solute transport through the fractures
- Instabilities appear between fractures

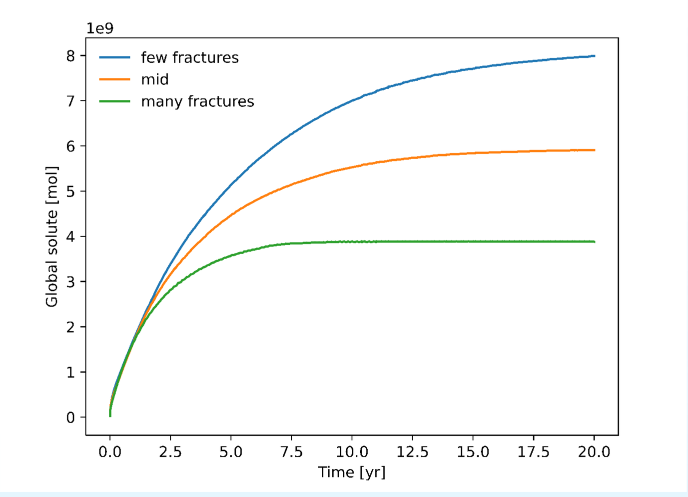


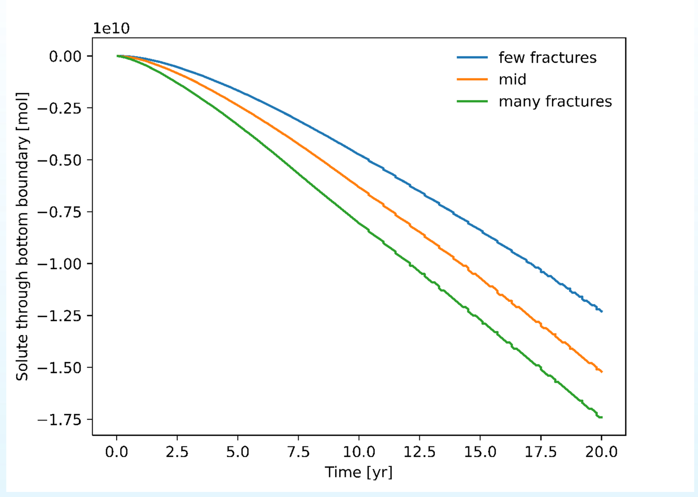
- Fingers appear in FEHM, with more solute transport in the matrix in FEHM than PFLOTRAN
- PFLOTRAN prioritizes fracture transport



- Higher fracture density increases solute flux out of the domain
- Lower solute concentration throughout domain
- Little agreement between FEHM and PFLOTRAN

Effect of fracture spacing on solute transport





Acknowledgements

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