Fully Coupled Geomechanics, Multi-Phase, Thermal and Equation of State Compositional Simulator

Jean H. Prévost, Lee Y. Chin*, Zhihua Weng

e-mail: prevost@princeton.edu
URL: http://www.princeton.edu/~prevost
URL: http://www.princeton.edu/~dynaflow
URL: http://denali.princeton.edu

collaborators: G. Scherer, R. Fuller, B. Huet

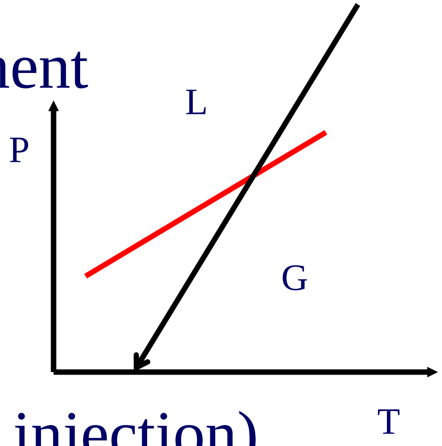
sponsors: BP, Ford

Department of Civil and Environmental Engineering
Princeton University

**ConocoPhillips, Bartlesville, Oklahoma*

Research Focus: CO_2 leaks

- Wells cement degradation / leakage paths:
  - Geochemical interaction with wells cement
    - » cement degradation; seal loss
  - Leakage:
    - » thru seepage across overburden
    - » via abandoned wells (damage due to injection)
  - Super-critical/sub-critical CO_2 flow; crossing saturation line; CO_2 bubbling/condensing
  - Thermal/heat transfer effects w/ rock



Dynaflow

- Fully Coupled Multiphysics Simulator
  - Geomechanics
  - Multi-Phase flow; Multi-components
  - Heat flow (including heat of reaction)
  - Flash via equation of state
- *Modular* flash and geochemistry
  - Transportable to other codes (e.g., Eclipse)
- Related models:

TOUGH2 (K. Pruess, LBL): similar flash capabilities but not modular; no coupled poromechanics; no cement geochemistry

NUFT (Nitao, Wolery, J. Johnson, LLNL): no extensive thermodynamic data base for cement geochemistry; no coupled poromechanics

FLOTRAN (Lichtner, J. Carey, LANL): reactive transport; no coupled poromechanics

ECLIPSE (Schlumberger), VIP (Halliburton),….: no accurate CO_2 flash; no cement geochemistry; no coupled poromechanics

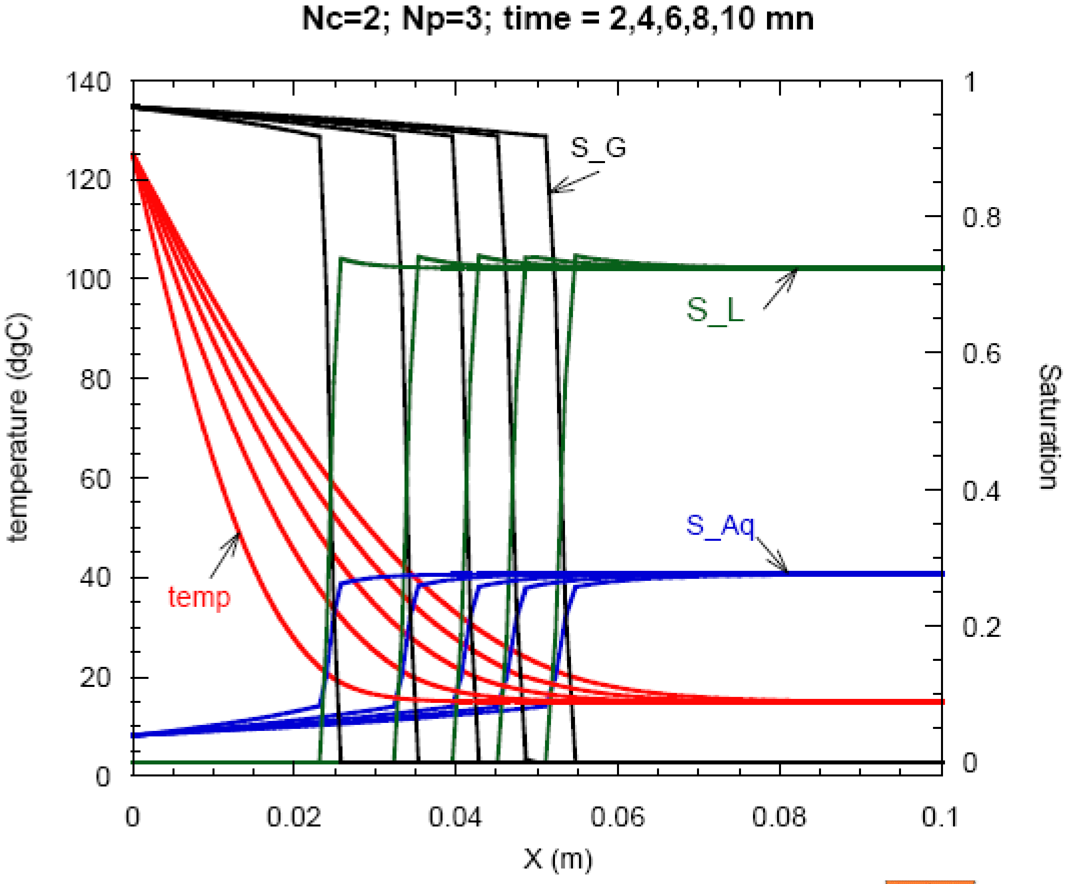
Dynaflow

- finite element based (arbitrary meshing)
  - » Galerkin, stabilized Galerkin (SUPG)
  - » Finite volume (cell centered; vertex centered)
- staggered implementation to allow flexible/versatile algorithmic options for integration of coupling effects
- multiphase flows
  - » compressible; incompressible flows
  - » miscible; immiscible flows
  - » heat transfers
- fluid flows fully coupled with geomechanics
- reactive transports capabilities for cement attack/degradation by CO_2 (B.H.)
- eos based flash (L.Y.C.)
- 1D/2D/3D capabilities
- parallel computing on shared and/or distributed memory/architectures (openMP/MPI)

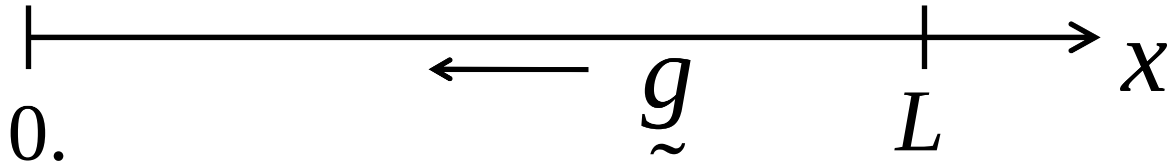
Modeling Leakage

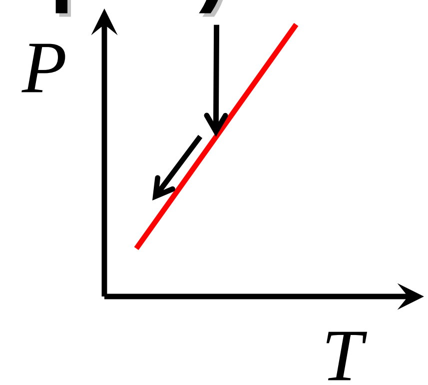
◆ If a gap exists, the escaping (super-critical) fluid will react with the cement, but it will also boil

- Simulation shows advance of boiling front (gas, aqueous phase and CO_2-rich liquid
- Other flash models are unable to handle this case



adiabatic CO2 leak (Nc=2, Np=3)





$$domain: \quad x = [0., L] \quad Area = [1 \times 1] \quad L = 600.\, m$$

$$g = -10.\, m/s^2 \quad \rightarrow T = T(x,t) \quad P = P(x,t)$$

- *initial conditions:*

$$T(x, t=0) = 15\,^0C$$

$$P(x=0, t=0) = 5.23 MPa, \quad P(x=L, t=0) = 0.1 MPa$$

$$Z^{CO_2}(x, t=0) = 0, \quad Z^{H_2O}(x, t=0) = 1.0$$

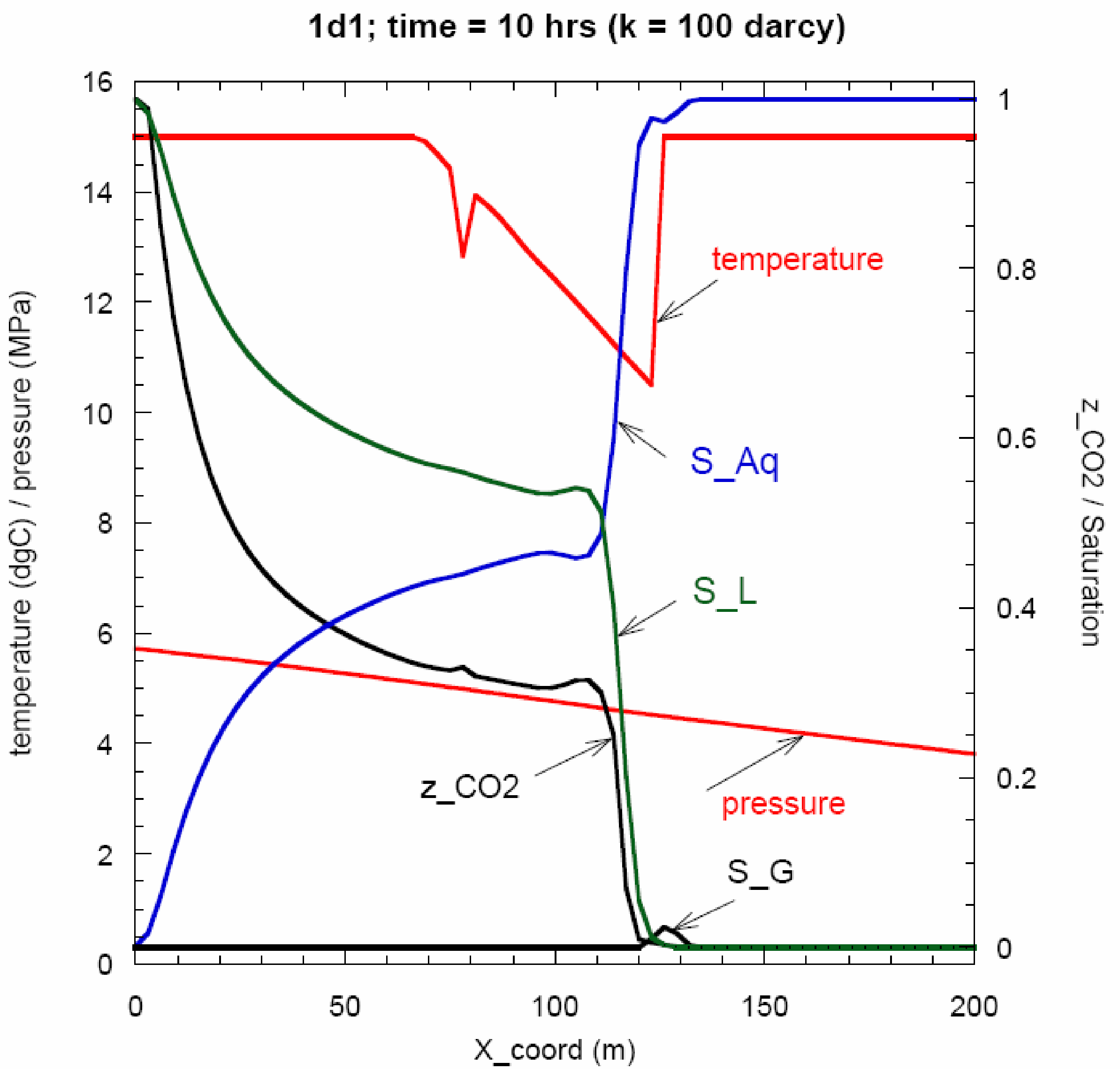
- *boundary conditions:*

$$T(x=0, t=0^+) = 15^0 C$$

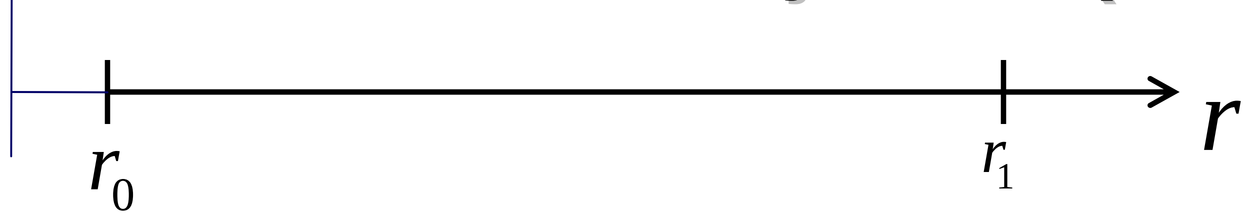
$$P(x=0, t=0^+) = 5.73 MPa, \quad \Delta P = 0.5 MPa, \quad P(x=L, t=0^+) = 0.1 MPa$$

$$Z^{CO_2}(x=0, t=0^+) = 1.0$$

adiabatic CO2 leak (Nc=2, Np=3)



Radial steam injection (Nc=3, Np=3)



$$domain: \quad r = [r_0, r_1] \qquad r_0 = 0.1m \quad r_1 = 250.\,m$$

$$\rightarrow T = T(r,t) \quad P = P(r,t)$$

- *initial conditions:*

$$T(r,t=0) = 65\,^0C$$

$$P(r,t=0) = 6.0MPa$$

$$Z^{C3}(r,t=0) = 0.4, \quad Z^{C16}(r,t=0) = 0.4, \quad Z^{H_2O}(r,t=0) = 0.2$$

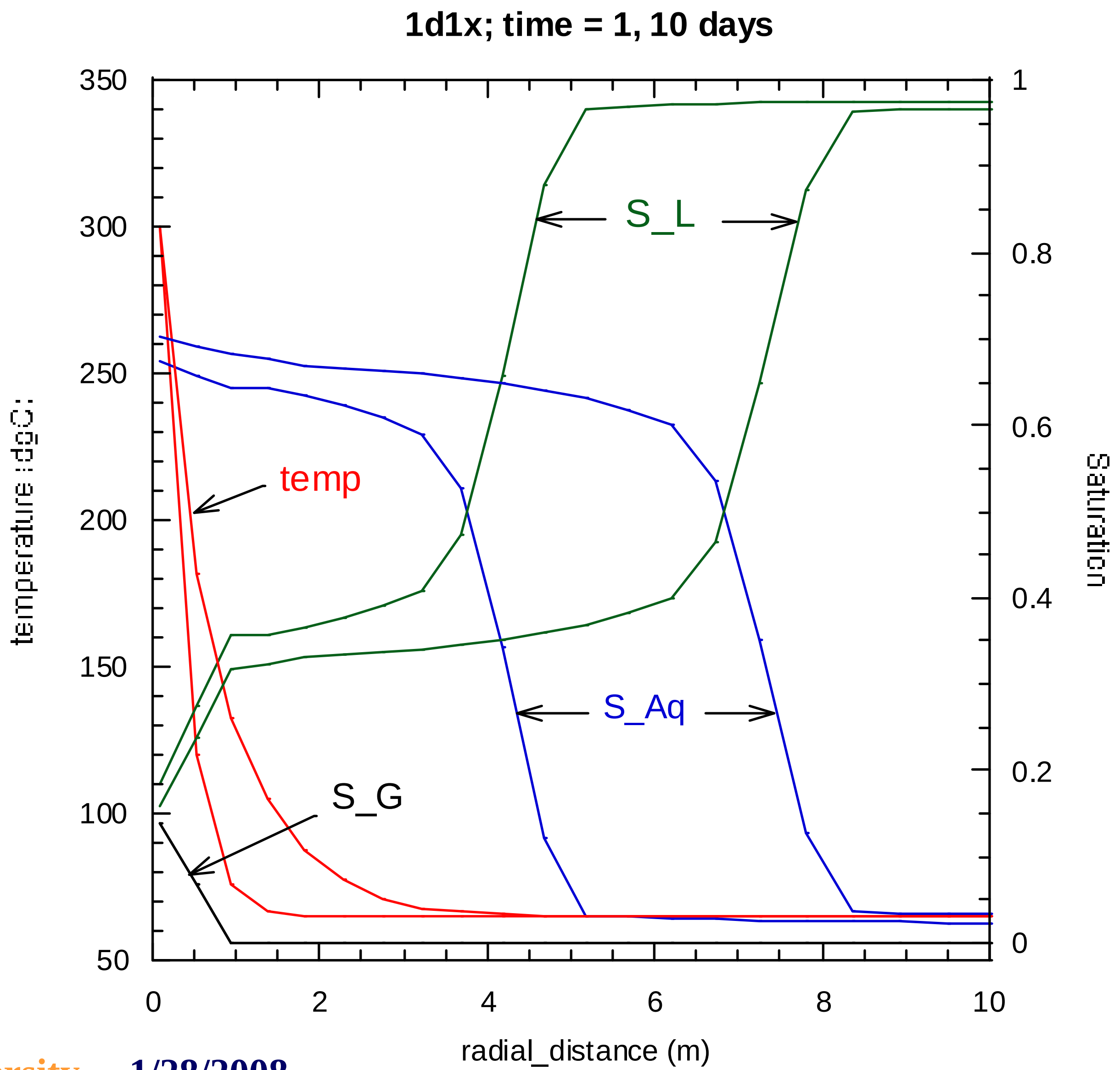
- *boundary conditions:*

$$T(r=r_0, t=0^+) = 300^0C$$

$$P(r=r_0, t=0^+) = 7.0MPa, \quad \Delta P = 1.0MPa$$

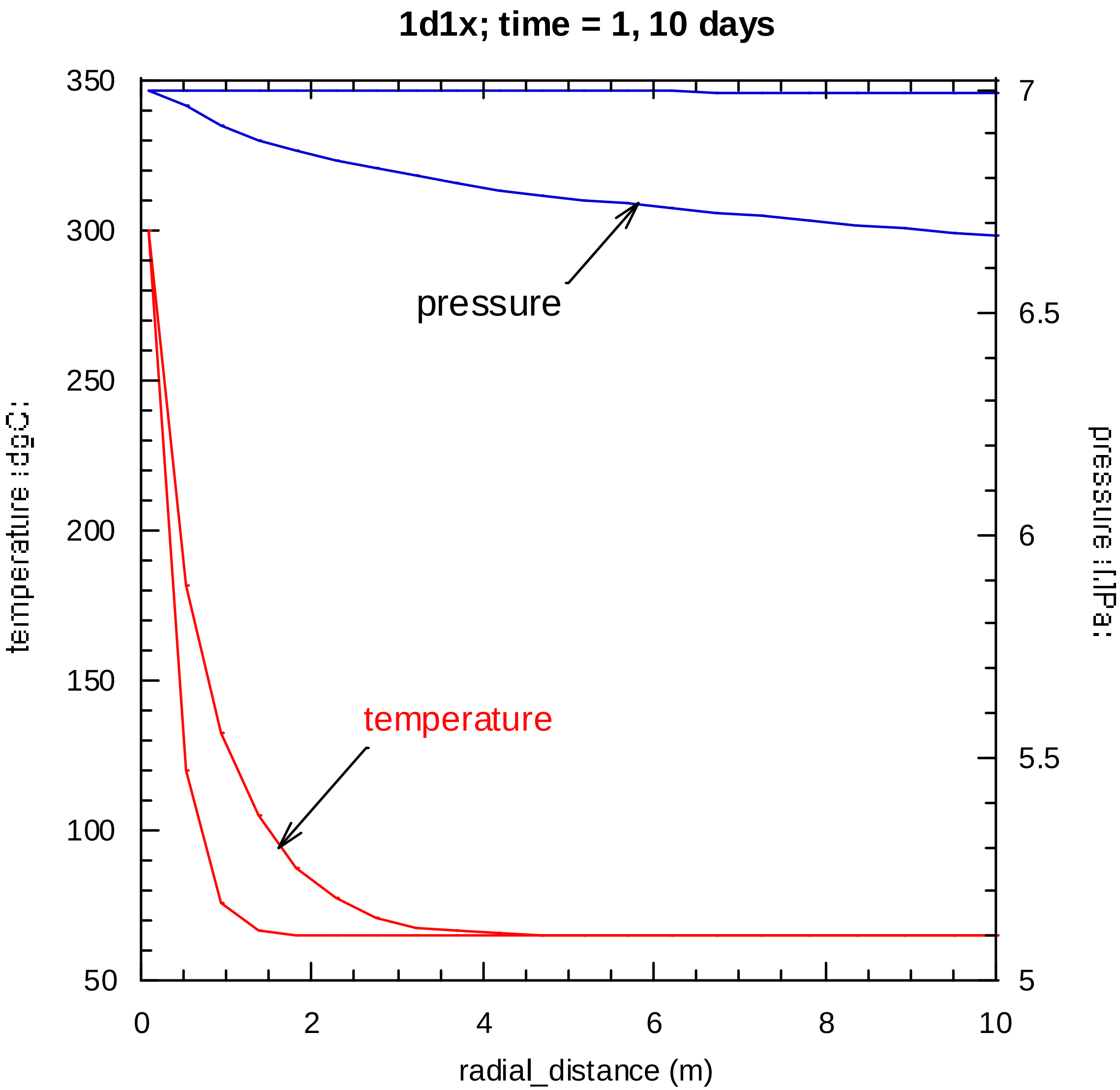
$$Z^{H_2O}(r=r_0, t=0^+) = 1.0$$

Radial steam injection (Nc=3, Np=3)



Radial steam injection (Nc=3, Np=3)

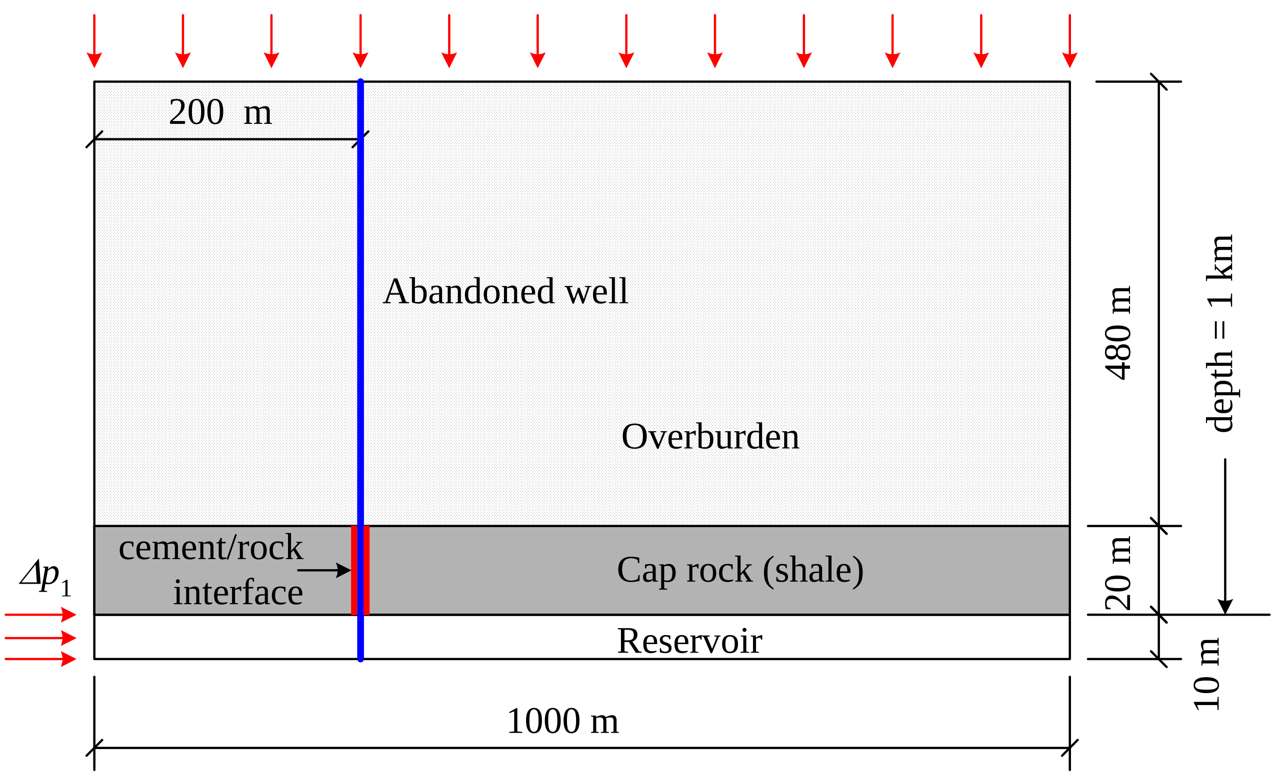
Loss of injectivity

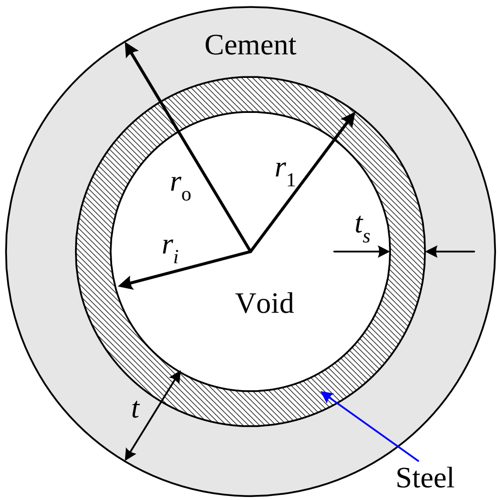


Geomechanics and Well Leakage

- Pressure created by injection of CO_2 deforms overburden
- Simulation investigates stresses from bending of cap rock and shear of cement relative to cap rock

$$\sigma'_{H,reservoir} = 10.4\,MPa$$

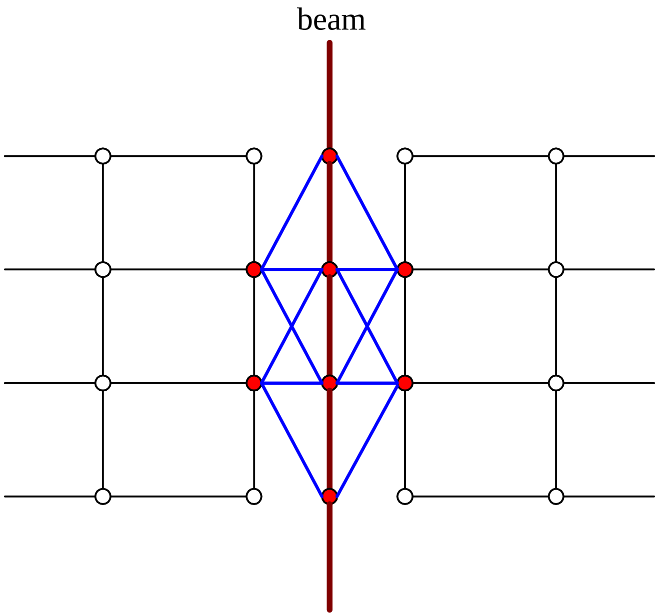




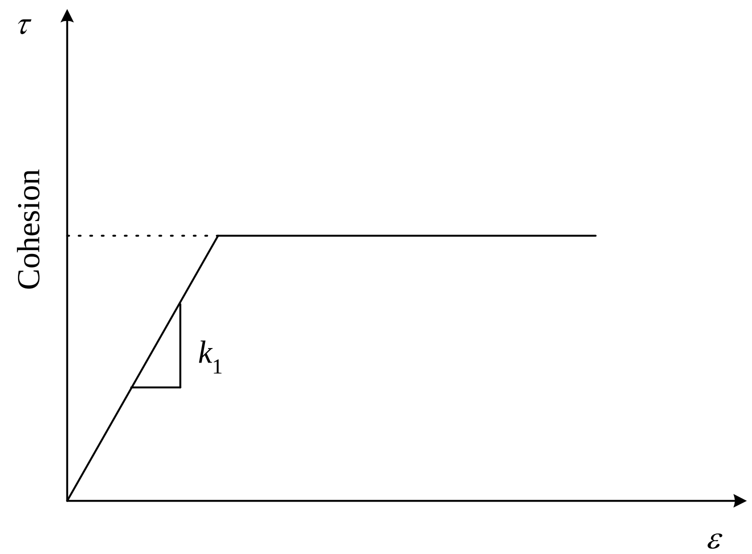
Not to scale!!!

interface (slide-line) elements

- Modeling the well (cement)-rock interface



Schematic of interface element



Tangential constitutive relation for interface elements

Material properties

- Geological layers

	Young's Modulus	Poisson's ratio	Density	Permeability
	E (Pa)	υ	ρ (kg/m^3)	κ (m^2)
Overburden	3.45E+09	0.35	2.50E+03	1.0E-15 (1 mD)
Reservoir	2.00E+09	0.40	2.60E+03	1.0E-13 (100 mD)
Shale	1.00E+10	0.35	2.50E+3	1.0E-17 (10 μD)

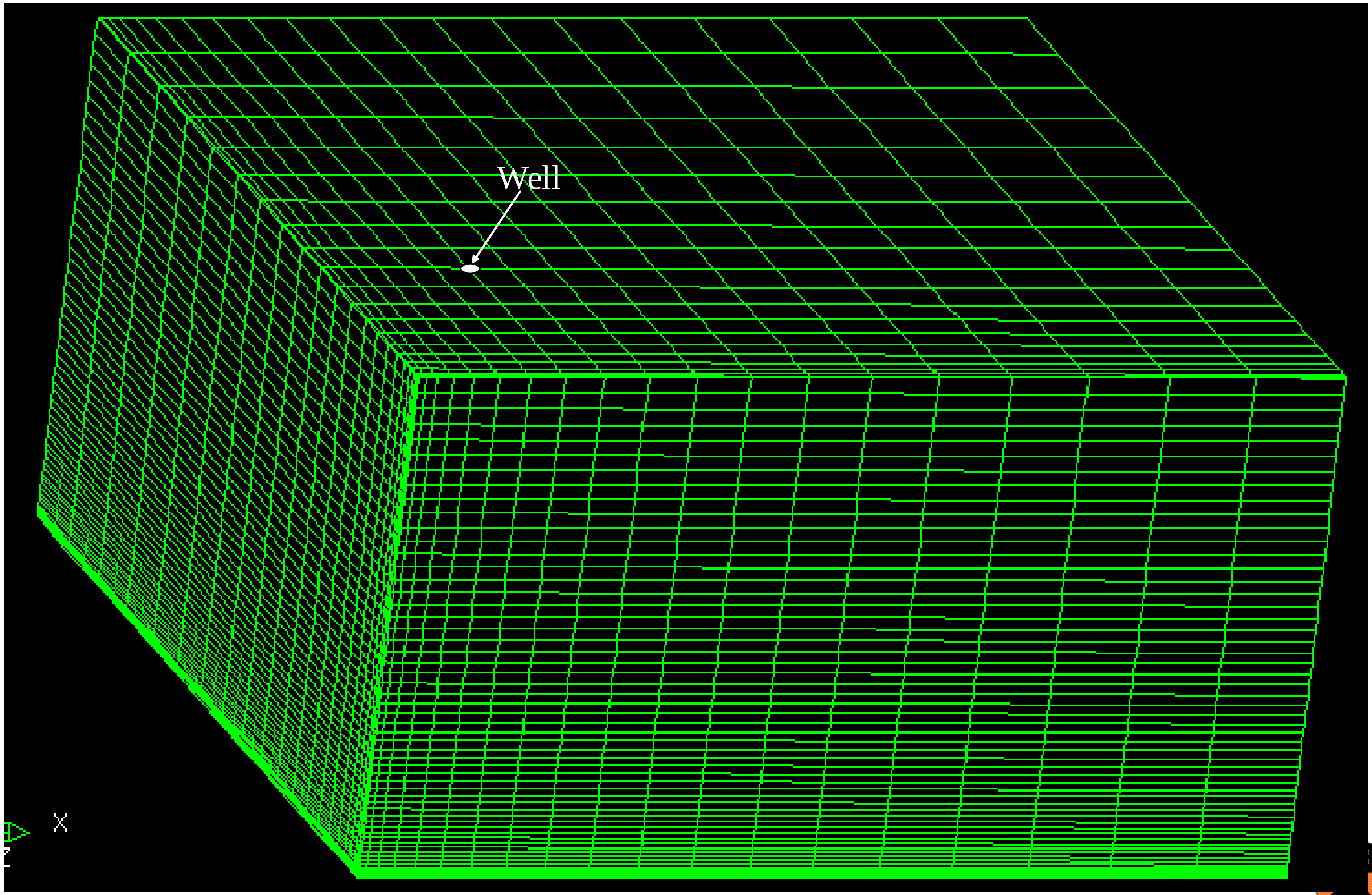
Material properties

- Geological layers

	Parameters	Value
Materials	Young's Modulus of cement E_c (Pa)	6.90E+09
	Poisson's ratio of cement υ_c	0.2
	Young's Modulus of steel E_s (Pa)	2.07E+11
	Poisson's ratio of steel υ_s	0.28
	Young's Modulus of composite beam E (Pa)	5.15E+10
Dimensions	Inner radius r_i (m)	7.74E-02
	Outer radius c or r_o (m)	1.21E-01
	Beam thickness t (m)	4.33E-02
	Steel layer thickness t_s (m)	1.15E-02
	Solid section area, A (m^2)	2.69E-02
	Bending inertia, I (m^4)	5.53E-04
	S, I/c (m^3)	4.58E-03
	EI ($N.m^2$)	2.85E+07
Rock-cement interface	Tangential stiffness k_1 (Pa)	3.00E+09
	Normal stiffness k_2 (Pa)	2.00E+12
	Cohesion (Pa)	4.00E+05

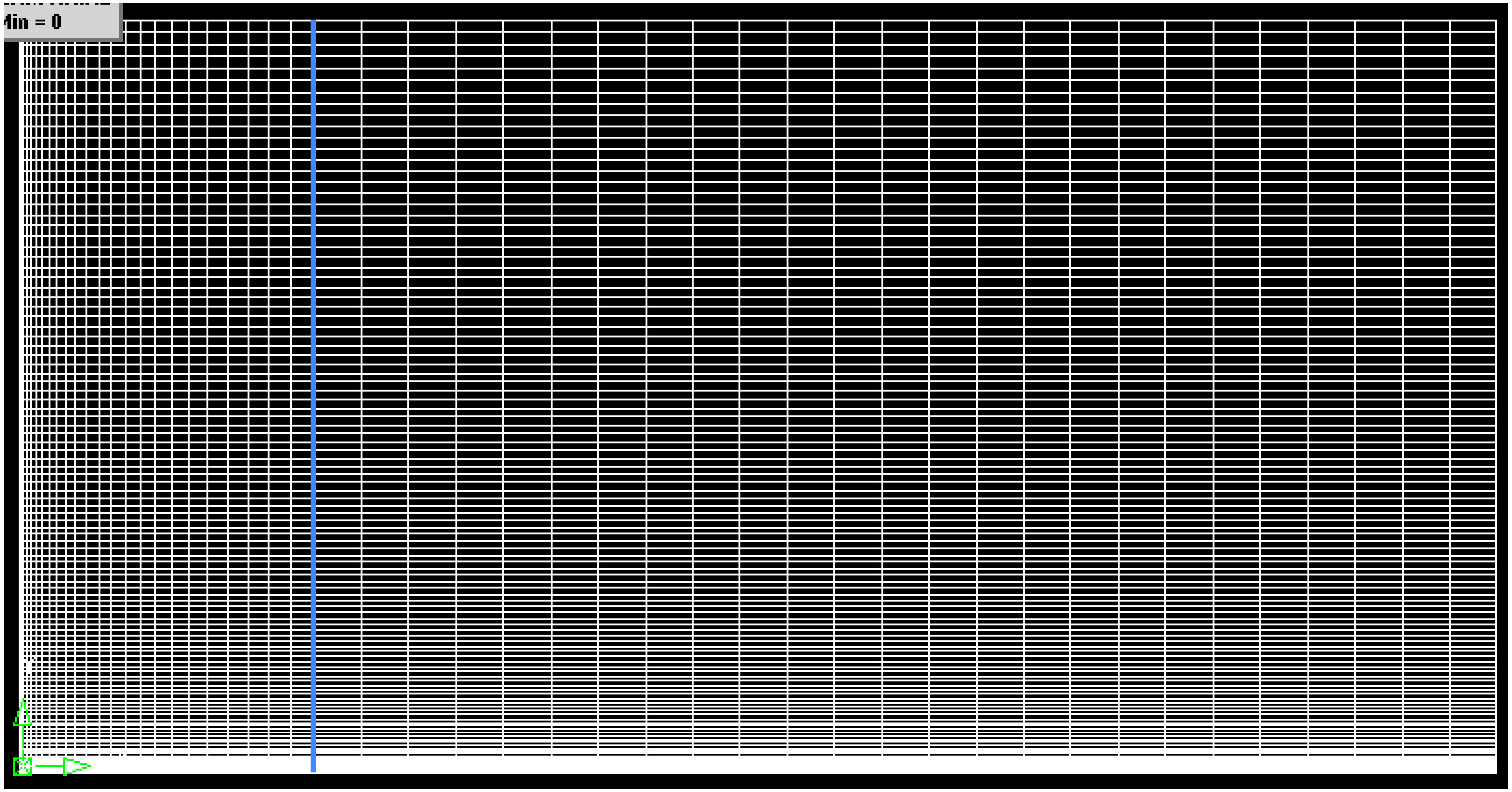
Finite element mesh

- 3D

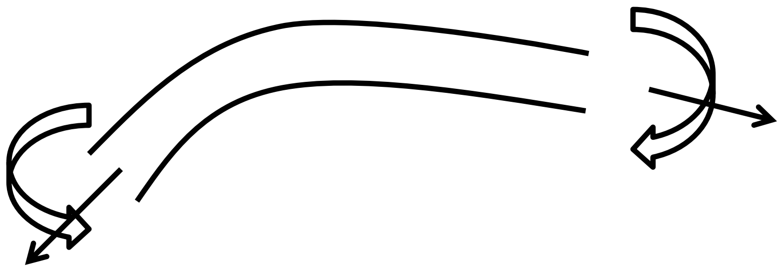


Finite element mesh

- 2D axisymmetric

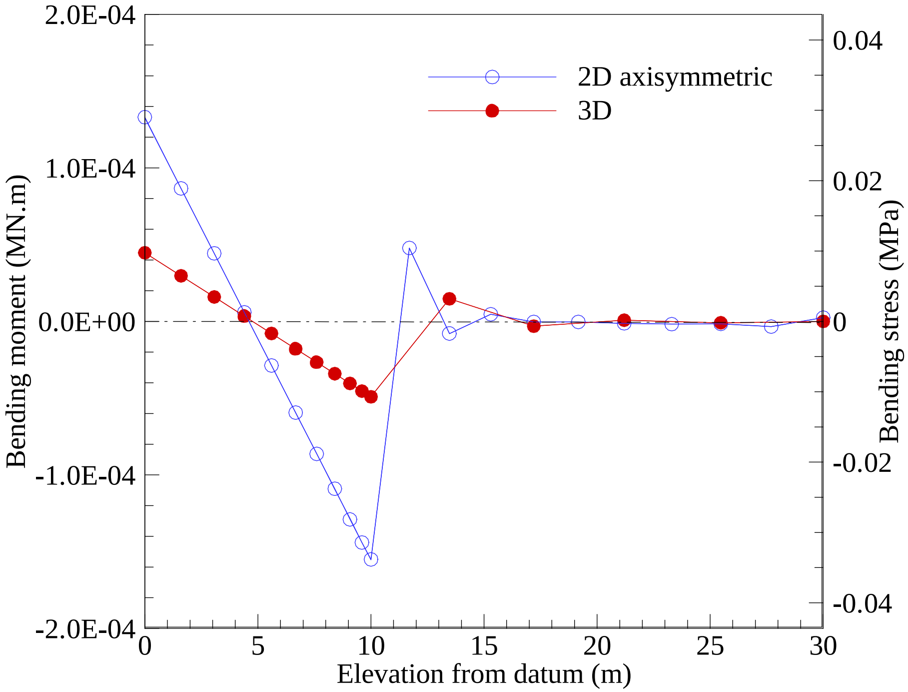


Beam bending: 3-layer formation (w/ shale)



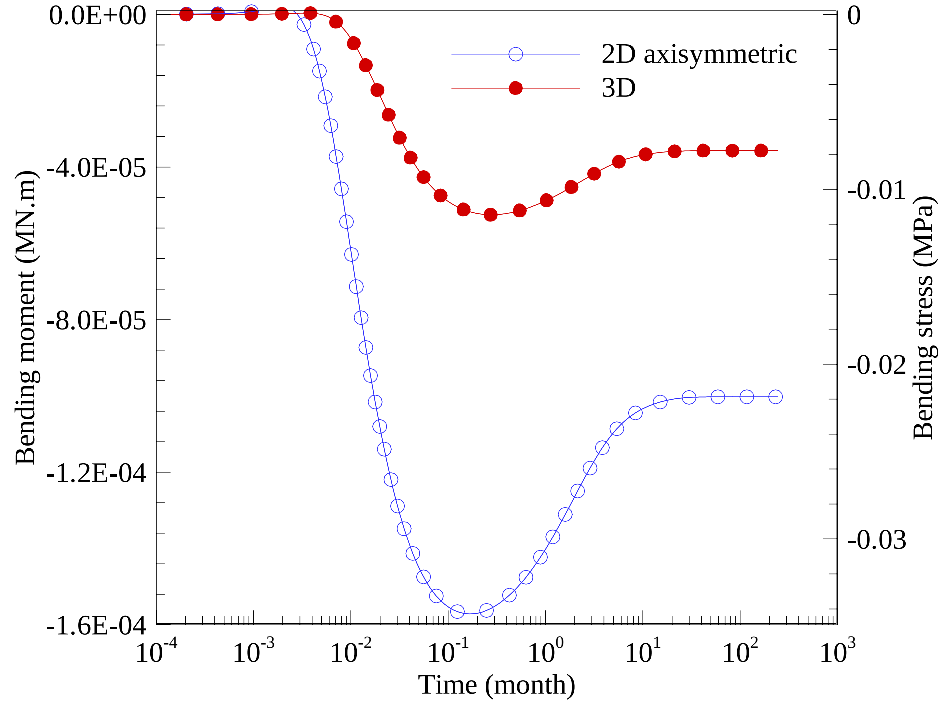
$$\sigma_{bending} = N / A + M / S$$

$$\sigma_{bending} \square \ 3MPa$$



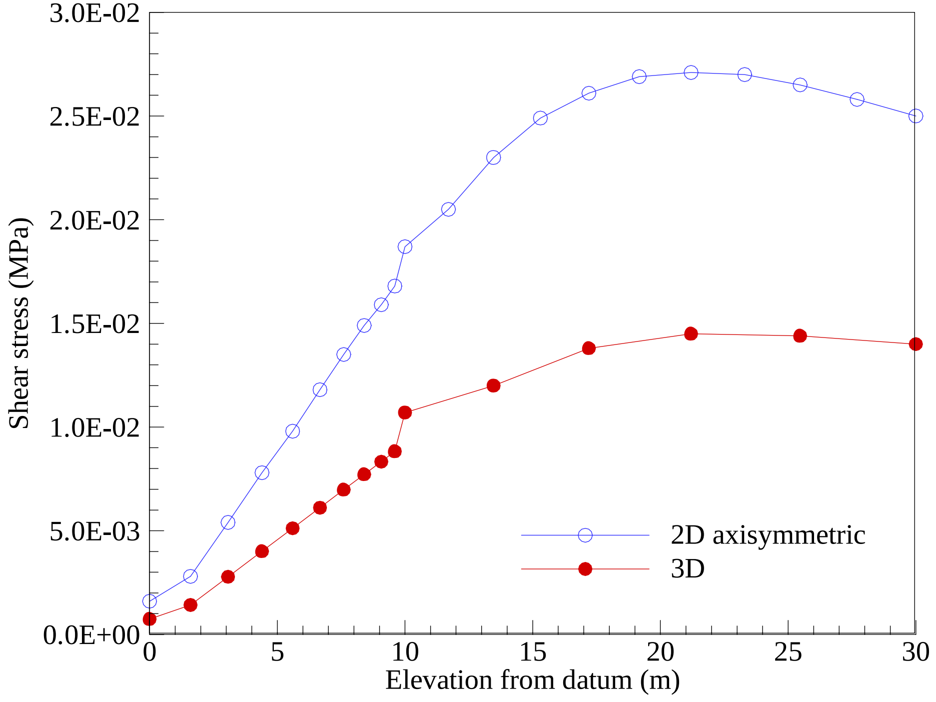
Spatial distribution of bending moment/stress

at t = 3 days

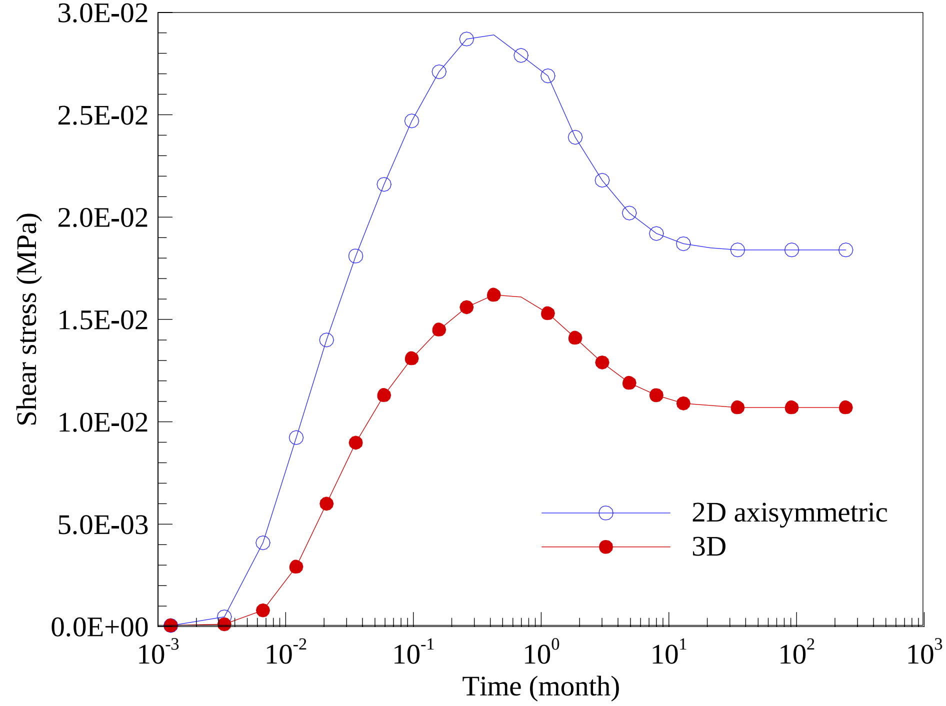


Time history for maximum bending moment/stress

shear stress in formation

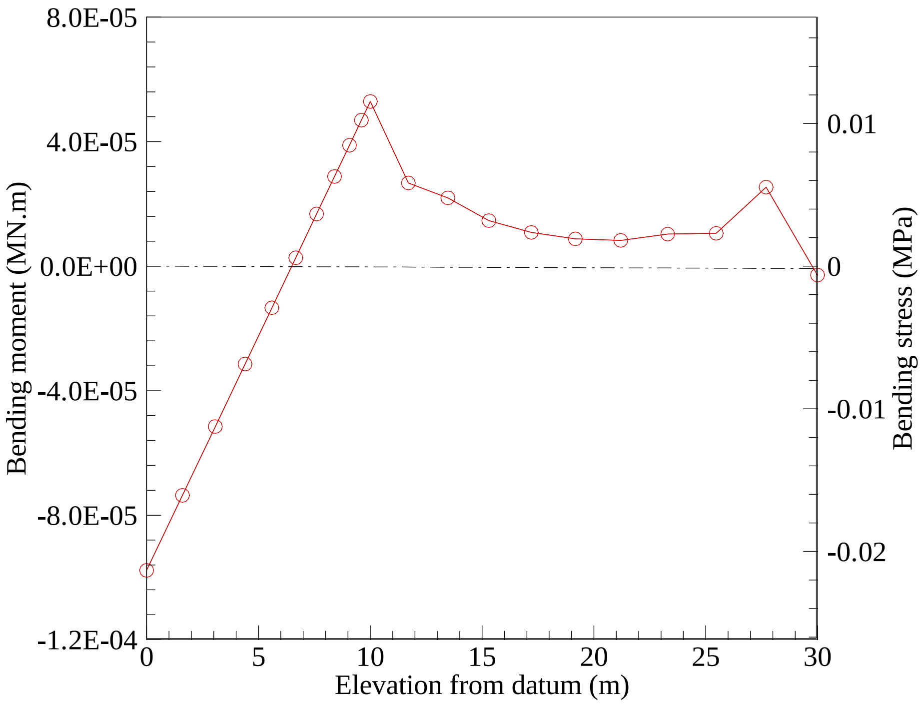


Spatial distribution of shear stress t = 5 days

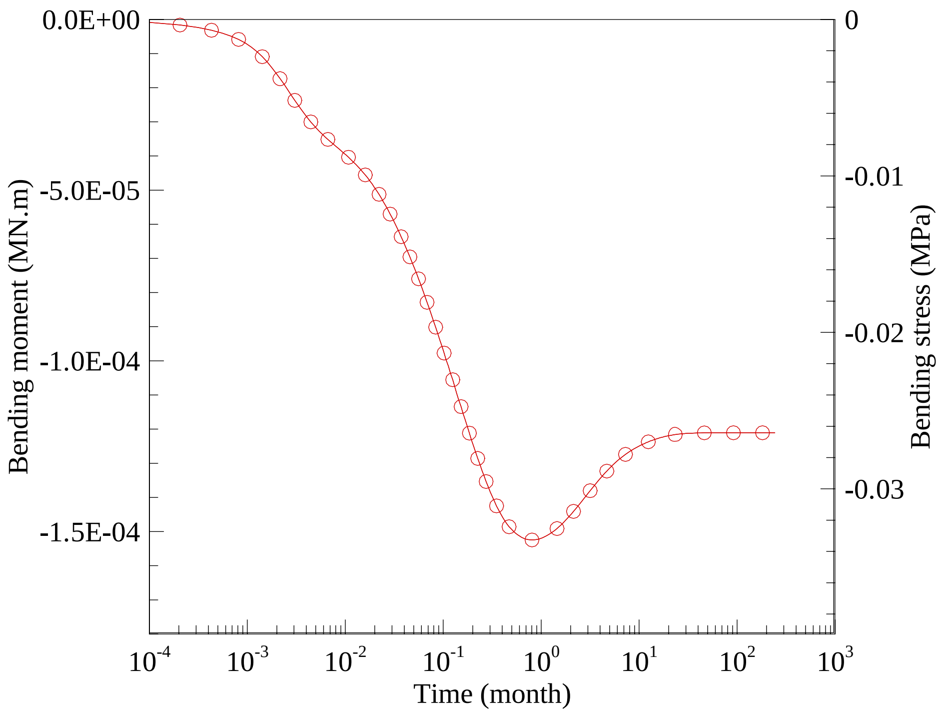


Time history for maximum shear stress

w/ slip at rock-cement interface

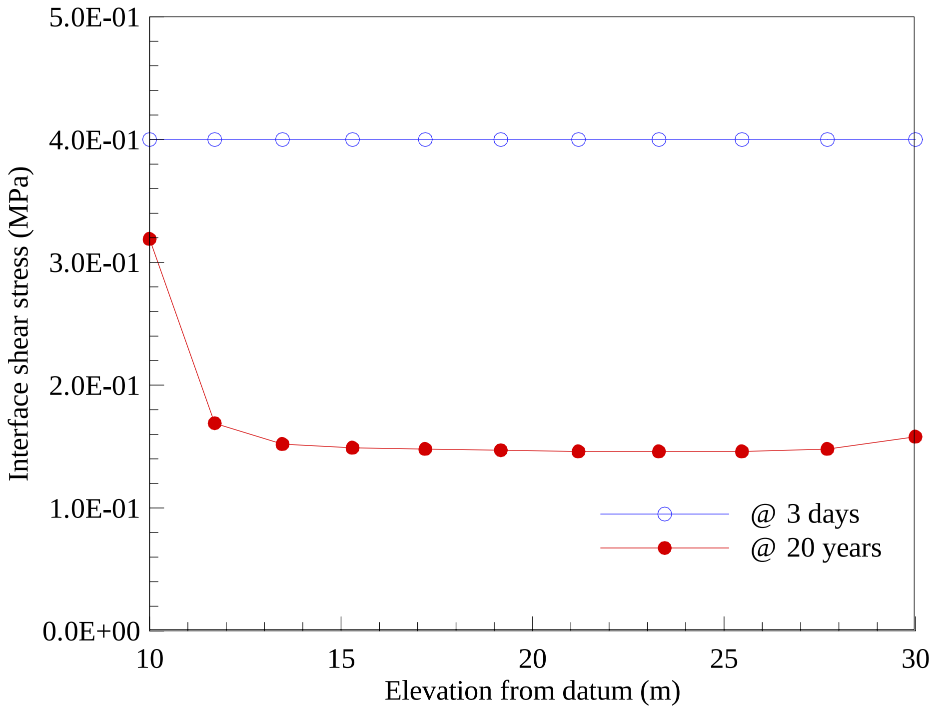


Spatial distribution of bending moment/stress at t = 3 days



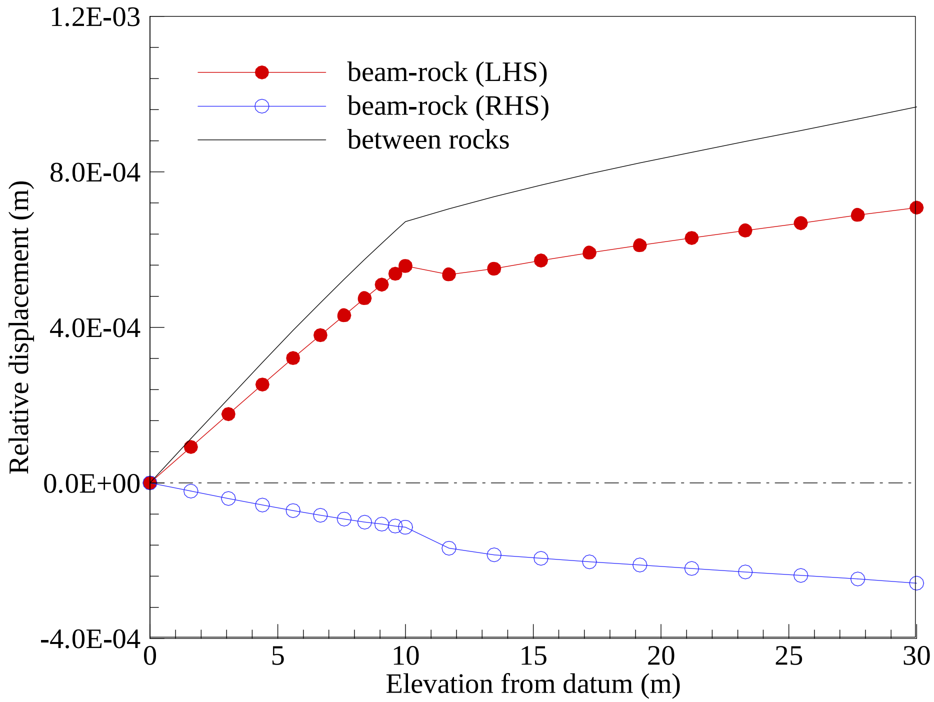
Time history for maximum bending moment/stress

w/ slip at rock-cement interface



Spatial distribution of interface shear stress

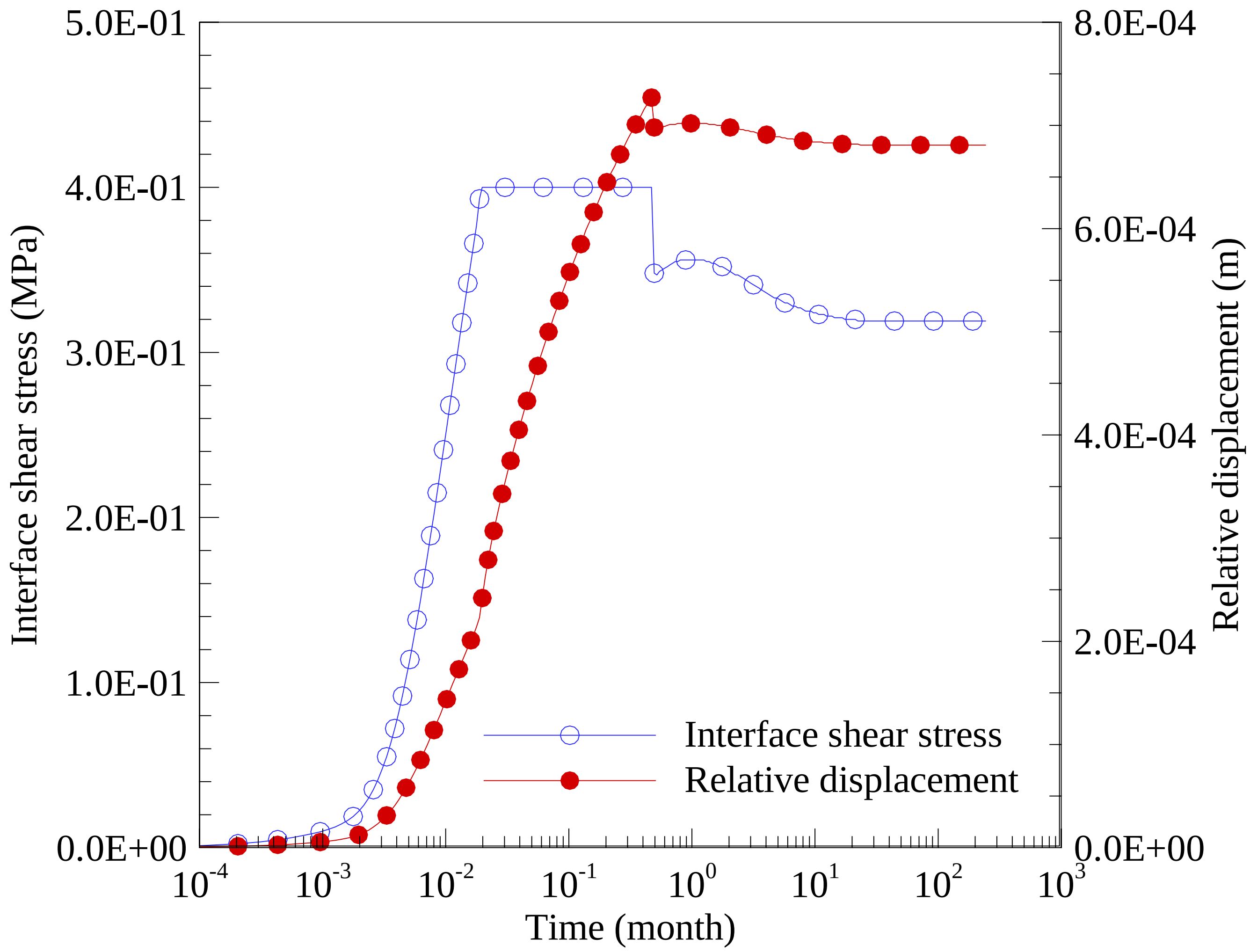
t = 3 days



Spatial distribution of interface shear displacement

t = 3 days

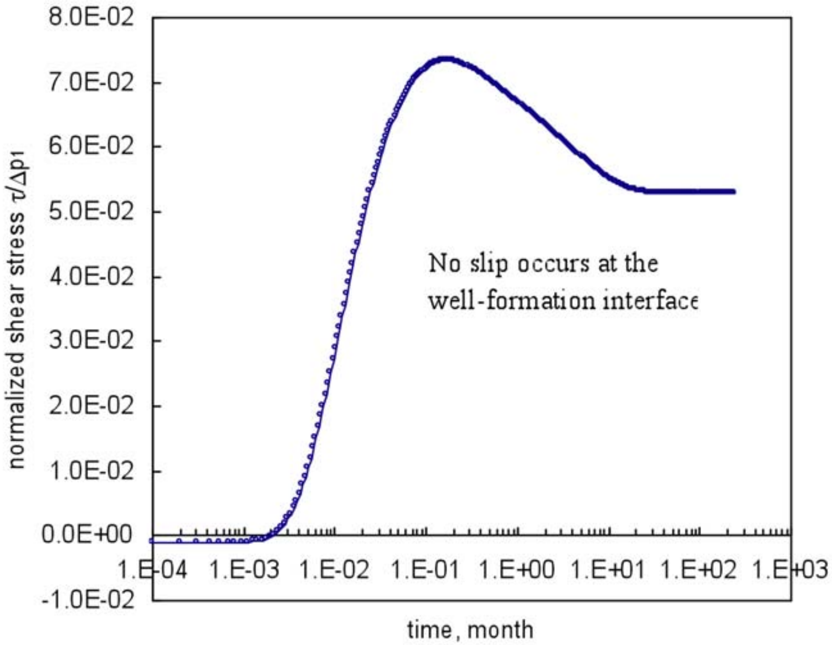
w/ slip at rock-cement interface

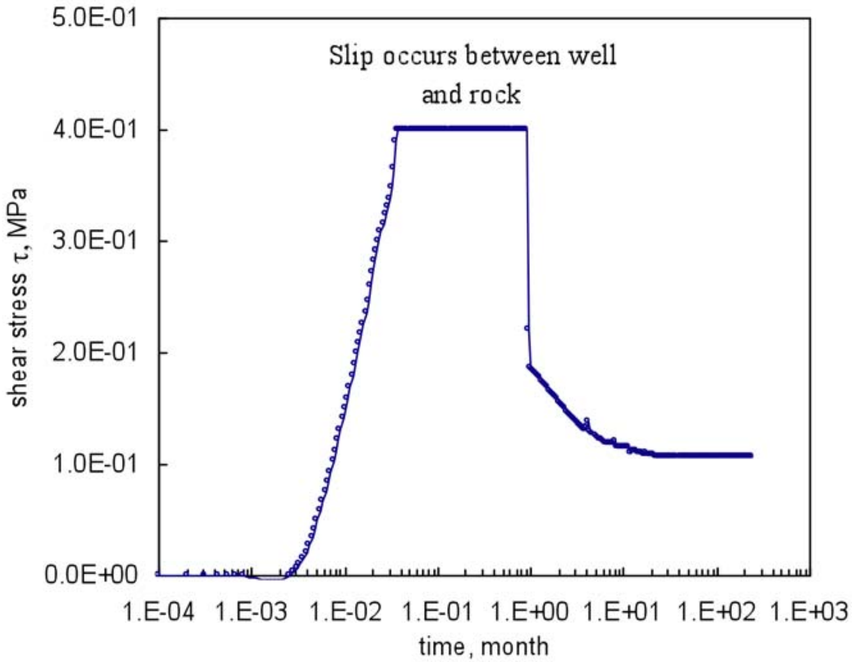


Time history for shear and relative displacement

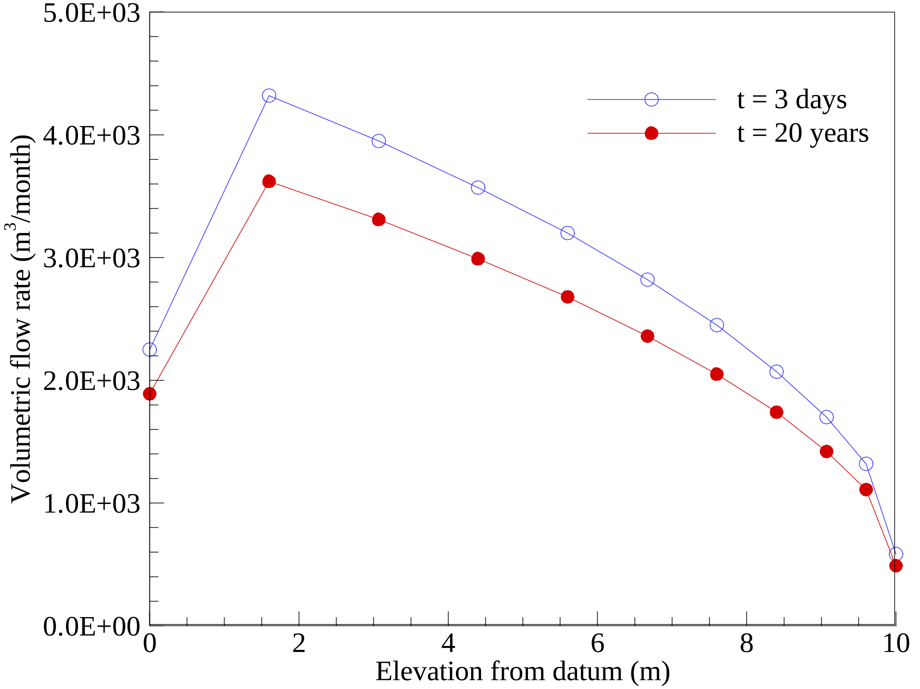
Geomechanics and Well Leakage

- Pressure created by injection of CO2 deforms overlying formation
- Simulation investigates stresses from bending of cap rock (found to be negligible) and shear of cement relative to cap rock (causing sliding, and possibly leakage???)

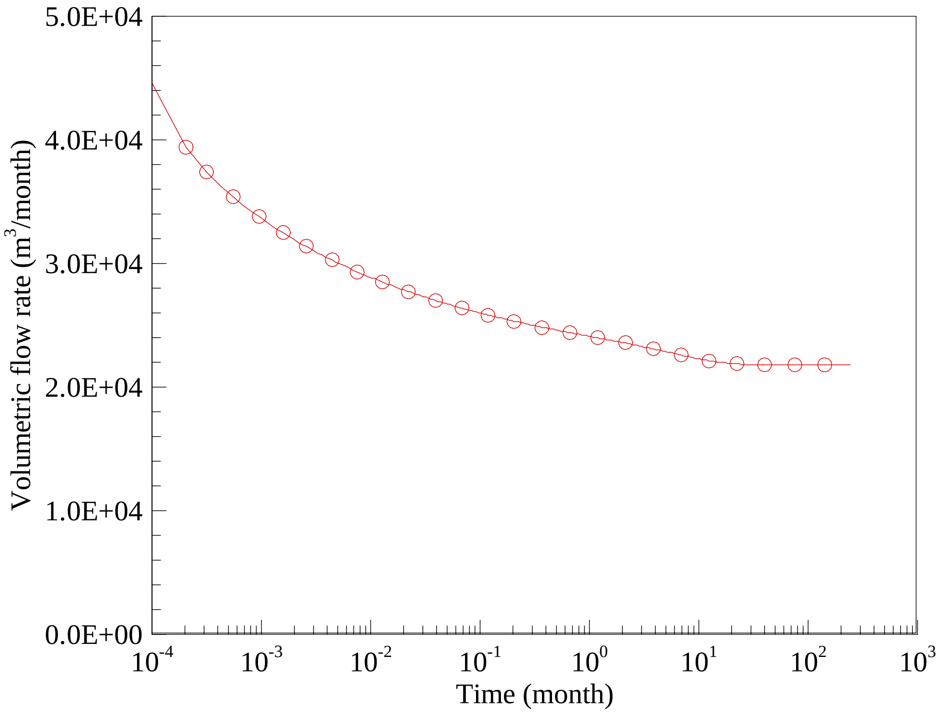




Volumetric flow rate at injection site

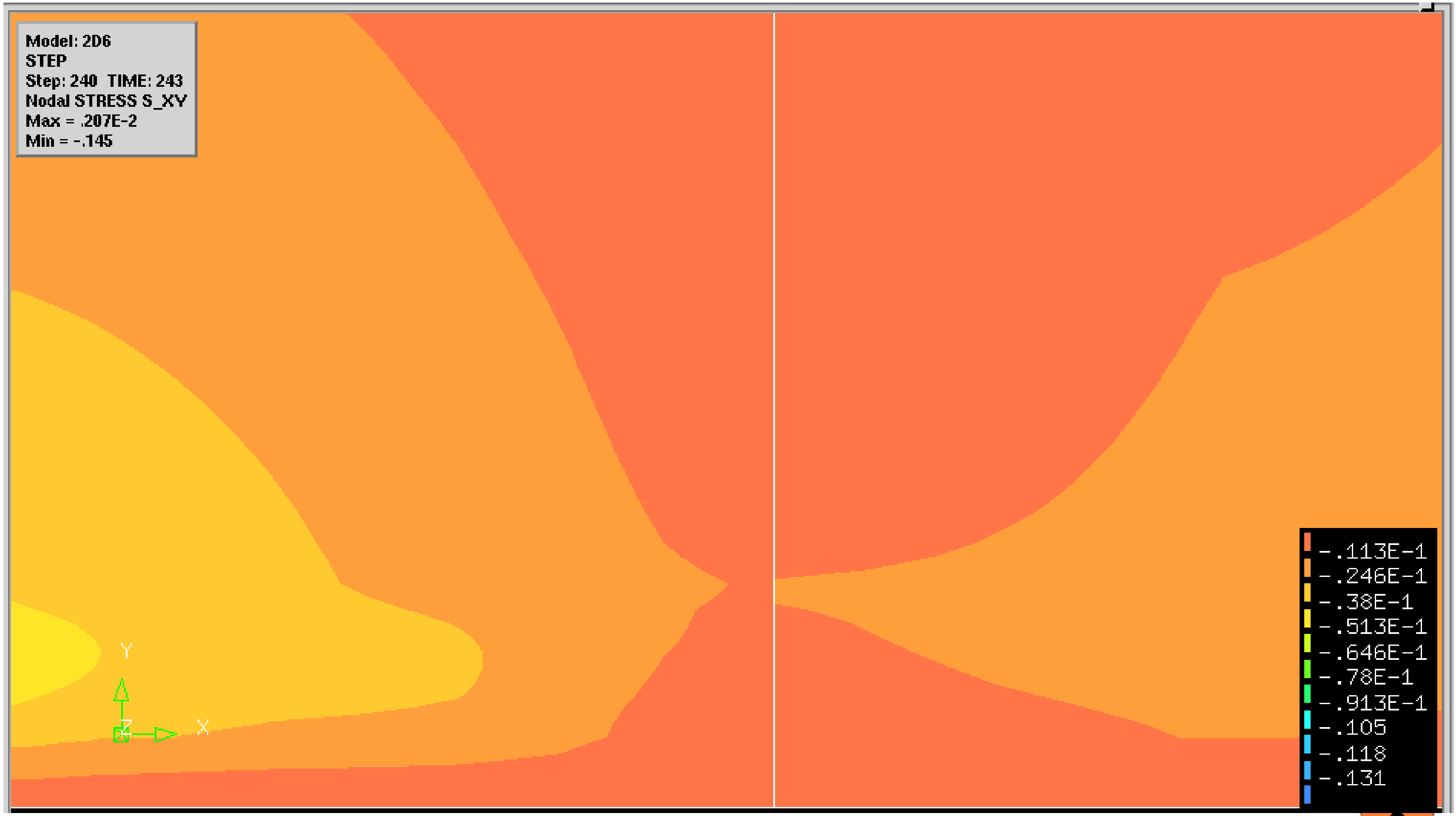


Spatial distribution of volumetric flow rate



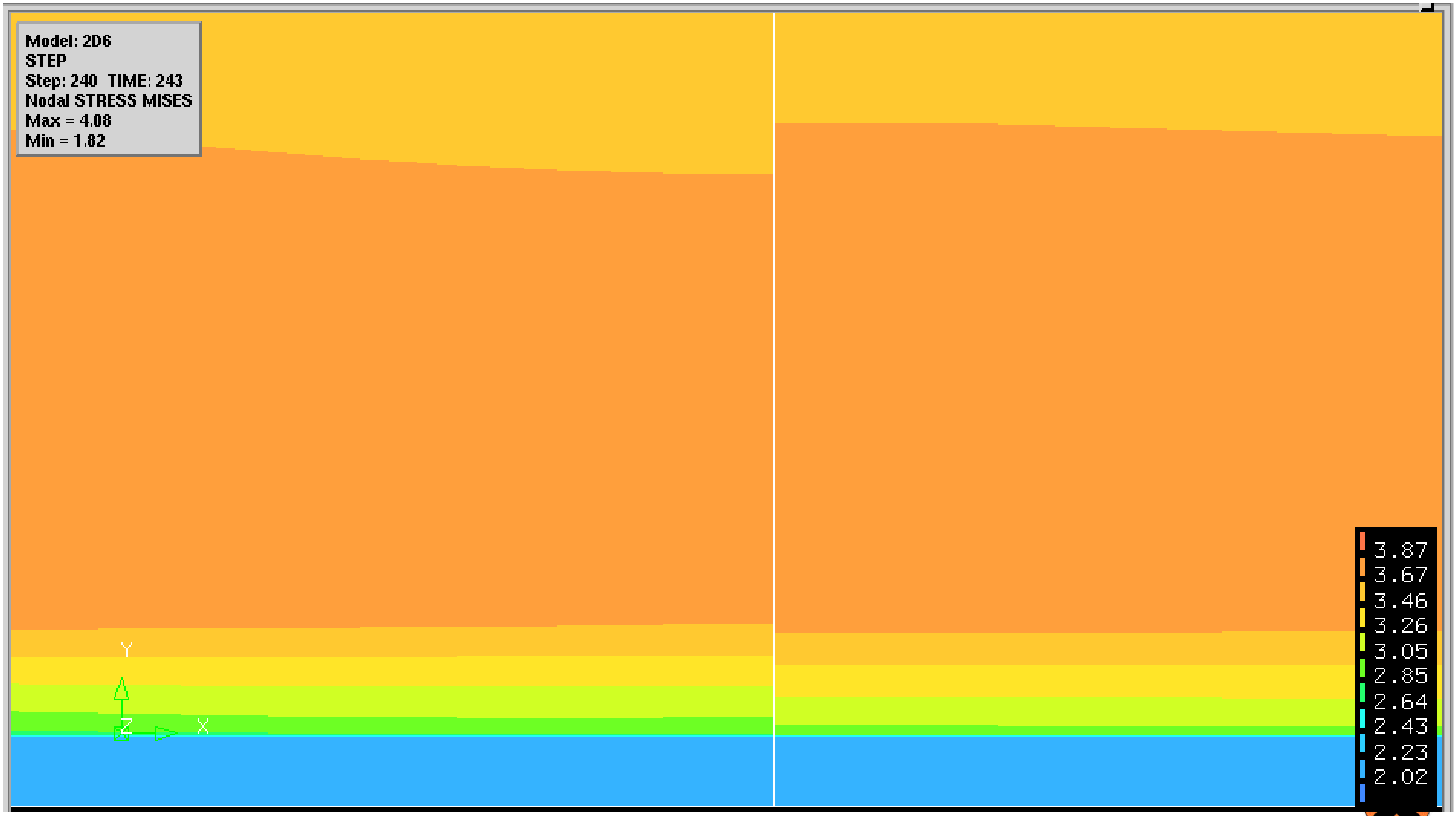
Time history for total flow rate

Numerical results: Shear stress τ_{xy}



Numerical results: Mises stress, Caprock failure?

$$mobilized\ \varphi \approx 17^0 \quad shear\ stress\ \tau \geq 3\ MPa$$



Future work

- Stabilize flash (Nc=2, Np=3)
- Investigate failure in cap rock
- Incorporate interface in 3D model
- Parametric studies
- "Detailed " leak simulation: viz., fluid (P,T, composition) – cement exposure vs depth

Hydrogeologic parameters

- $permeability: \quad K = 10^{-13} m^2 = 100\ mdarcy$
- $porosity: \quad \varphi = 0.15 \qquad pore\ compressibility: \quad C_m = 0.$
- $relative\ permeability: \quad Stone's\ first\ 3-phase\ method$

$a: Aqueous\ phase:$

$$k_{rAq} = \left[\frac{S_{Aq} - S_{ar}}{1 - S_{ar}}\right]^n \qquad S_{ar} = 0.15 \qquad n = 3$$

$b: Liquid\ phase:$

$$k_{rL} = \left[\frac{\hat{S} - S_{Aq}}{\hat{S} - S_{ar}}\right]\left[\frac{1 - S_{ar} - S_{lr}}{1 - S_{Aq} - S_{lr}}\right]\left[\frac{(\hat{S} - S_{ar})(1 - S_{Aq})}{1 - S_{ar}}\right]^n$$

$$\hat{S} = 1 - S_G - S_{lr} \qquad S_{lr} = 0.05 \qquad n = 3$$

$c: Gas\ phase:$

$$k_{rG} = \left[\frac{S_G - S_{gr}}{1 - S_{ar}}\right]^n \qquad S_{gr} = 0.01 \qquad n = 3$$

- $thermal\ parameters:$

$thermal\ conductivity: \quad K_T = 2.00\ W/m\ {}^0C$

$rock\ specific\ heat: \quad c_R = 1000\ J/kg\ {}^0C$

$rock\ density: \quad \rho_R = 2600\ kg/m^3$