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Coupled Multiphase Flow and Geomechanics for Analysis of Caprock Damage

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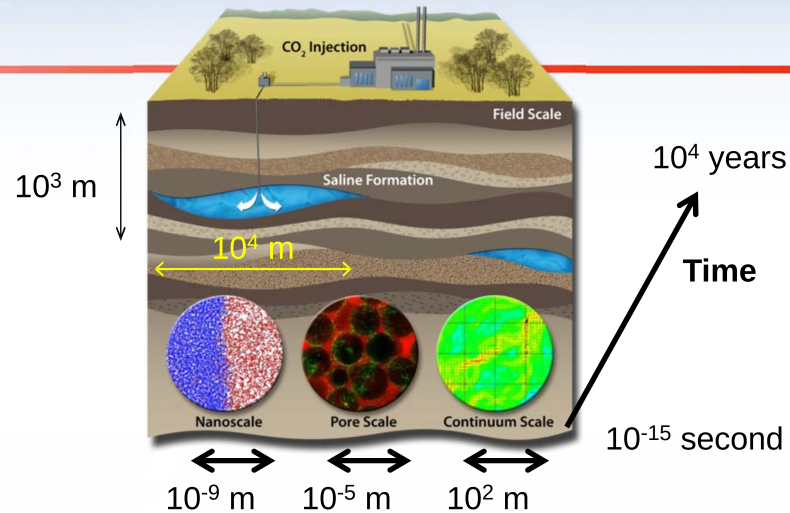
Outline

1. Technical Challenges for CO_2 Sequestration
2. Potential leakage paths
3. Goal of predictive assessment of caprock integrity
4. Coupled flow and geomechanics analyses
5. Future work
6. Summary

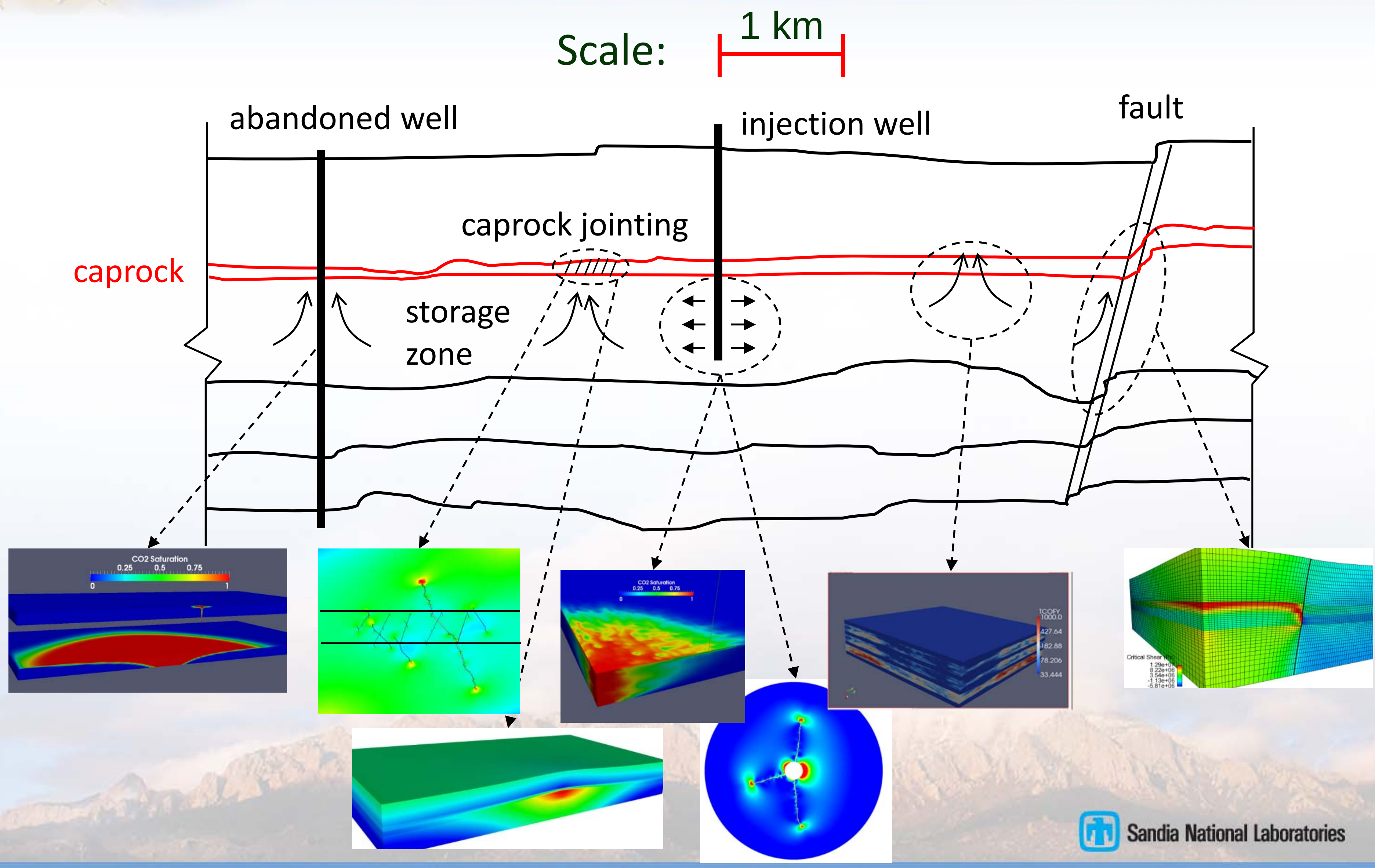
Technical Challenges for CO_2 Sequestration



1. Subsurface
   - uncertain materials
   - uncertain structures
2. Multiple scales
   - time, space
   - multi-scale analysis (e.g. homogenization) attempts to exploit any scale separation
   - may not have scale separation → scale embedding with 'mortars'
   - fracture is inherently multi-scale
3. Multiple physics
   - geomechanics, geochemistry, biology
   - solid mechanics, porous flow, chemical and biological reactions
   - phase changes, localization, fracture
4. Dynamic, highly nonlinear
   - instabilities, bifurcation phenomena, limit cycles, aperiodic behavior
   - emergent phenomena

Potential Leakage Paths for CO_2

Primary CO_2 trapping mechanism is structural.



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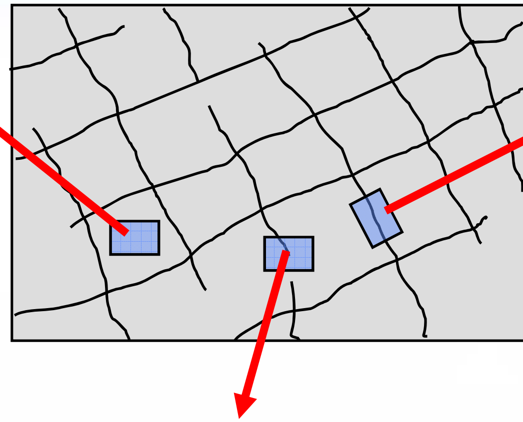
Goals

1. Predictive modeling capability for assessing caprock integrity
   - various field sites, general stratigraphy
   - assess injection scenarios
2. Assess potential leakage rate as a function of site characteristics and injection schedules
3. Assessment of mitigation scenarios
   - refine injection criteria

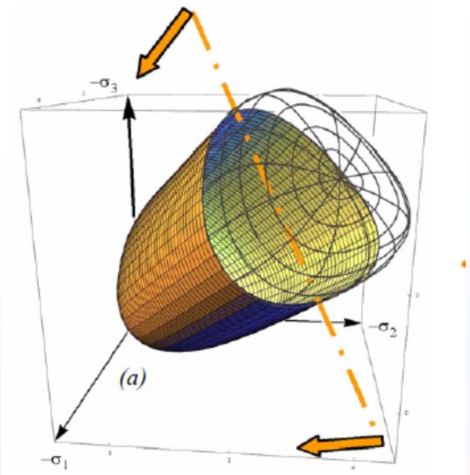
Hydromechanical Coupling in Fractured Rock

Fractured Caprock



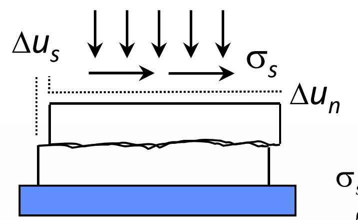
Bulk Constitutive Properties

- plasticity model
- limit surface
- effective stress, Biot coeff.

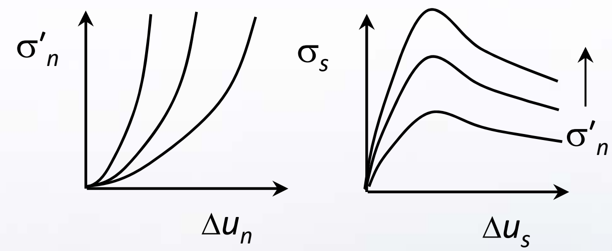


Fracture contact properties

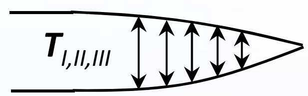
$$\sigma'_n = \sigma_n - p$$



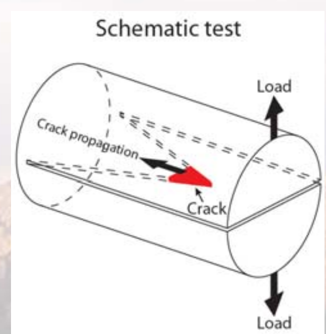
$$\sigma_s = \sigma_s\{\Delta u_s, \Delta u_n\}$$
$$\sigma'_n = \sigma'_n\{\Delta u_s, \Delta u_n\}$$



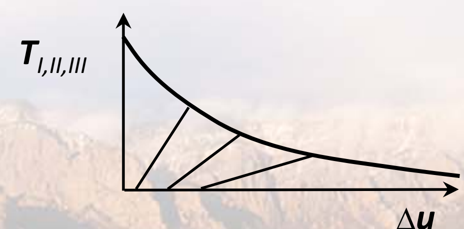
Crack-tip Properties



Fracture Toughness



Cohesive Properties



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Hydromechanical Coupling Scheme In Sierra Mechanics

Solid Mechanics (Sierra/Adagio)

Large strain finite element nonlinear elastic/plastic solid mechanics; Sandia GeoModel

Effective stress

$\sigma'_n = \sigma_n - \lambda p$

•Displacement field
•Effective permeability

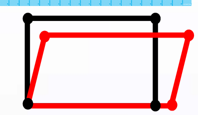
Transfer Function

•Pore pressure field

Fluid Mechanics (Sierra/Aria)

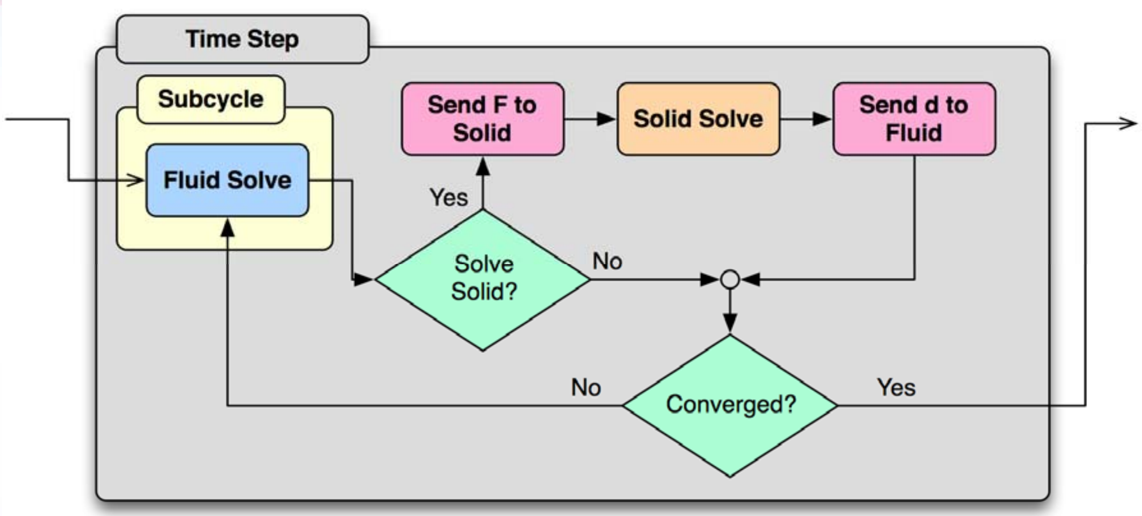
Vertex-centered control volume method for multiphase flows in heterogeneous porous media

$k_{eff}(\sigma_n)$
$\phi(\det F)$



- Transfer function facilitates data movement between Sierra modules
- Sierra modules can use different grids
- Both solve on deforming grid systems

Conditional Loose Coupling with Nonlinear Iteration and Subcycling




```
Begin System Main
  Use Initialize MyInit
  Begin Transient MyTransient
    Begin Nonlinear MyNonlinearLoop
      Begin Subcycle MySubcycle
         Advance AriaRegion
      End
      Transfer ForceAriaForceAdagio when "Solve_Solid()"
      Advance AdagioRegion when "Solve_Solid()"
      Transfer DispAdagioDispAria when "Solve_Solid()"
    End
  End
End
```

CO_2 Leakage Through an Abandoned Well

Flow Benchmark Problem

<u>Reference Problem Description</u>:

- **3D model of leakage during supercritical CO2 injection into a brine aquifer**
- **Single CO_2 injection well**
- **Two aquifers separated by an aquitard**
- **One leaky well, 100 m from injection well**
- **1200 day injection**

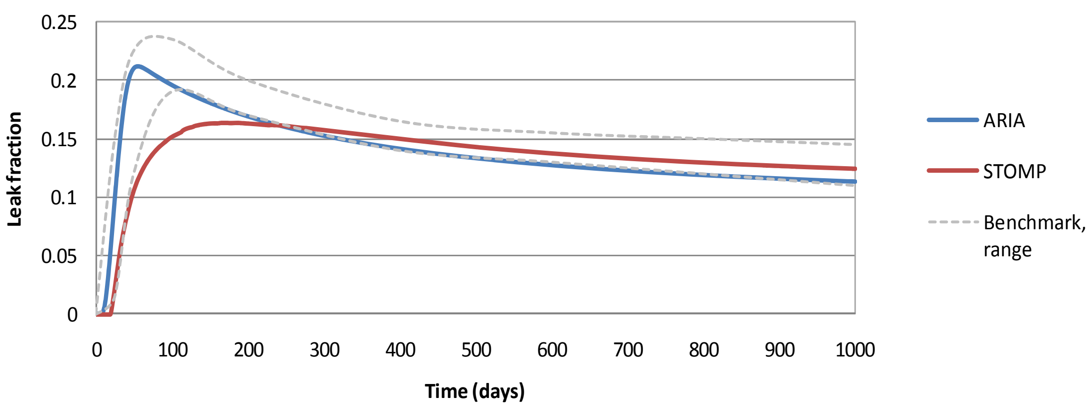
Assumptions:

- **Isothermal injection process**
- **CO_2 and brine immiscible phases**
- **Isotropic formation**
- **Neglect capillary pressure**

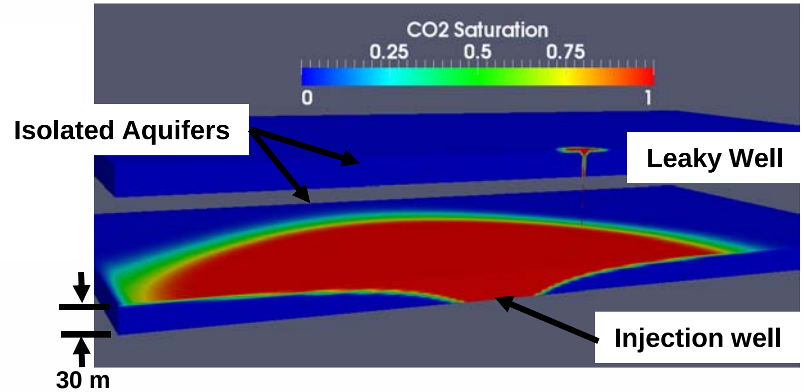
Results:

- **Computed leakage rate and arrival times compare well with benchmark study:**

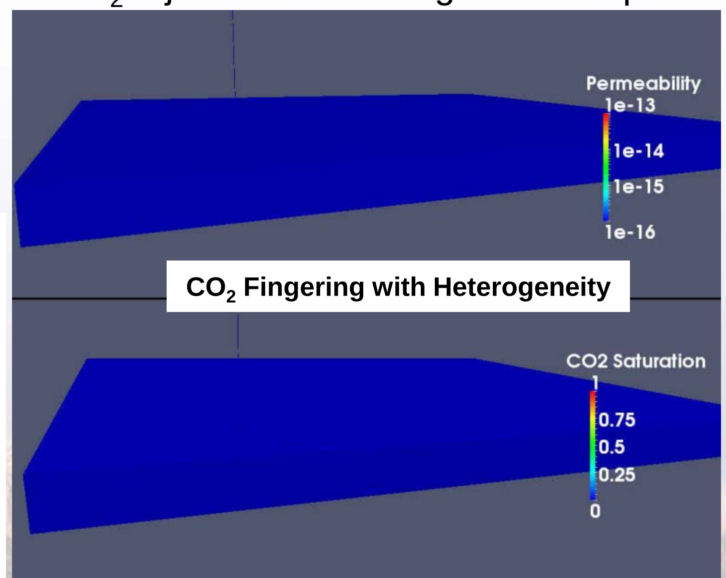
•Max leakage: 0.214% at 56 days
•Leakage at1000 days: 0.116%
•Arrival time: 11.5 days



CO_2 Distribution at 200 days



CO_2 Injection in Heterogeneous Aquifer



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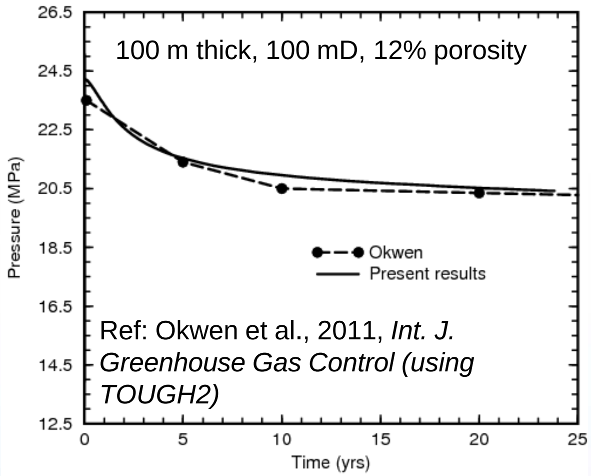
Verification Problems

CO2 Injection into a Confined Saline Aquifer

Near-Wellbore Pressure

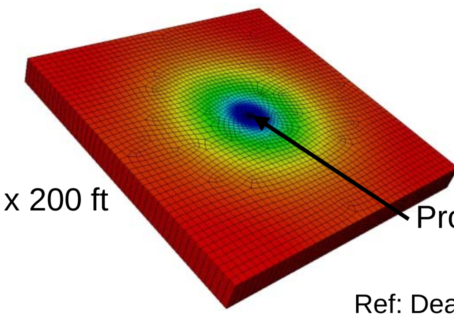


Features:
- fluid properties @ 45C (Okwen: TOUGH2)
- 100 kg/s (3.16 MMT/yr)
- Cap. Pressure: van Genuchten P_0=19.6 kPa
- krl: Van Genuchten, Slr=0.3, lambda = 0.457
- krg: cubic Slr=0.3 (Okwen: Brooks-Corey)

Subsidence due to Fluid Withdrawal

Coupled Flow and Geomechanics

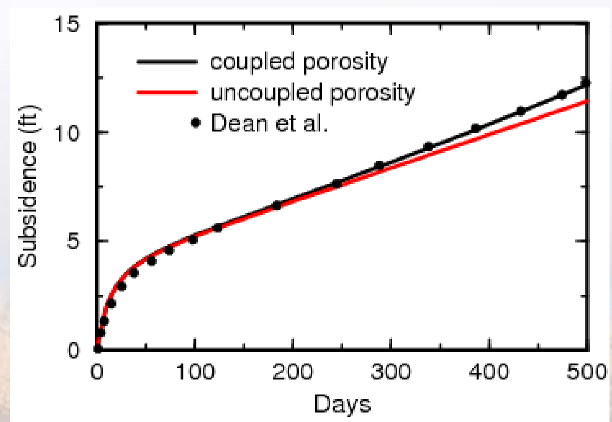
2200 x 2200 x 200 ft reservoir



Producing Well

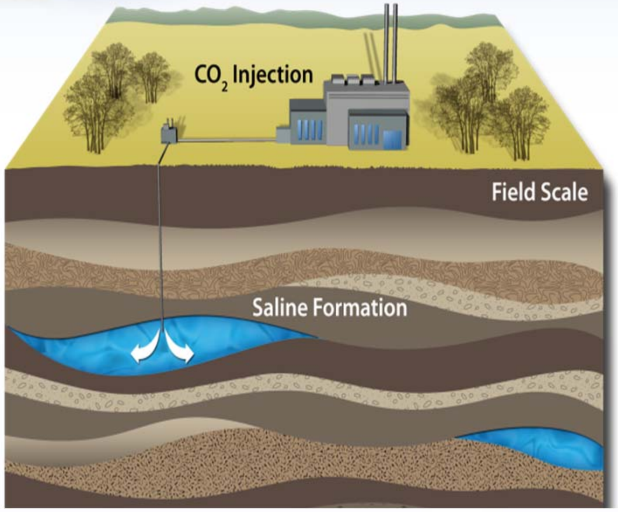
Ref: Dean et al., 2003, *SPE -79709*

Subsidence & Porosity Distribution



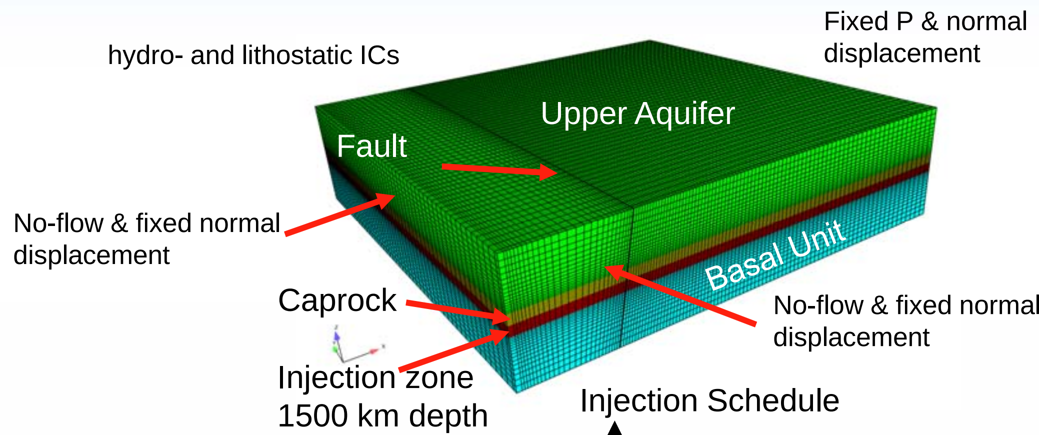
Flow and Geomechanics in Jointed Rock

Model Problem

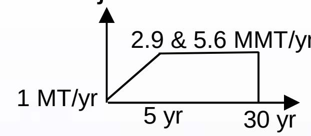


Model problem definition showing conceptual stratigraphy (left), and model problem geometry.

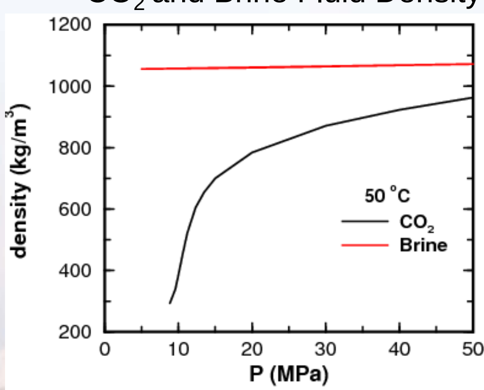
Discrete Geologic Model



Injection Schedule



CO_2 and Brine Fluid Density



Overburden

	ϕ	k (mD)	E (GPa)	ν	Thickness
Upper Aquifer	0.15	20-100	20	0.20	500 m
Caprock	0.05	0.001	50	0.12	100 m
Injection Zone	0.15	20-100	20	0.20	100 m
Base	0.1	0.01	50	0.12	500 m

15 km

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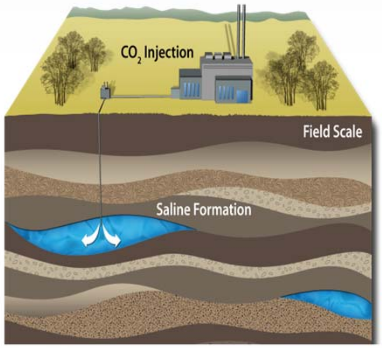
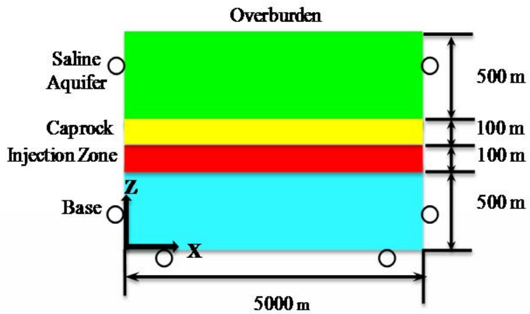
Coupled Flow and Geomechanics

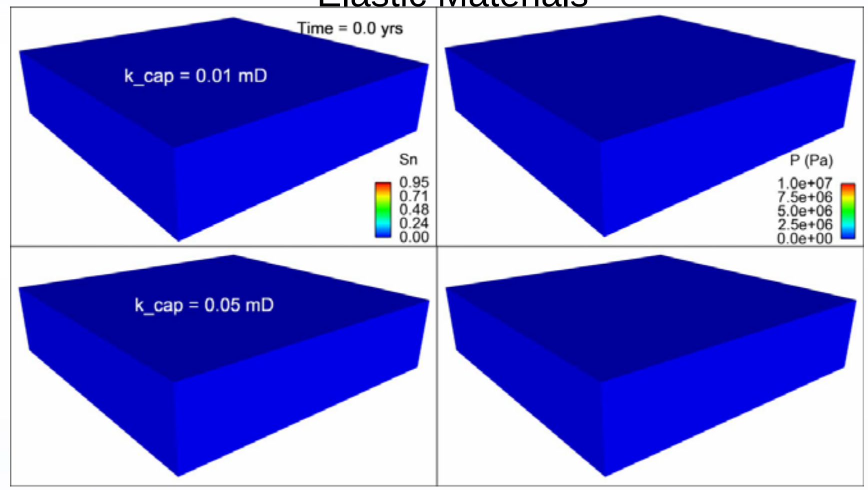
Flow, CO2 Transport and Deformation

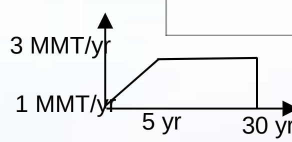




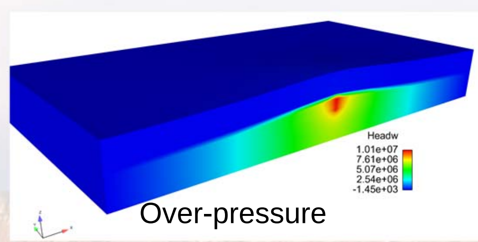
Model problem definition showing conceptual stratigraphy (left), and model problem geometry (right, not to scale).

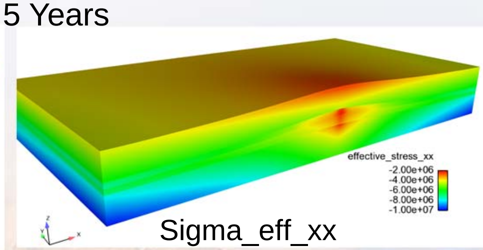
CO_2 saturation, Overpressure & Displacement
Elastic Materials





CO_2 Leakage in Jointed Caprock
5 Years

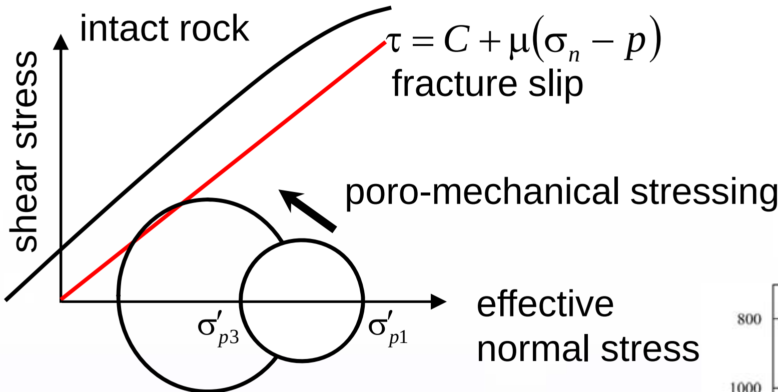




Coupled Flow and Geomechanics

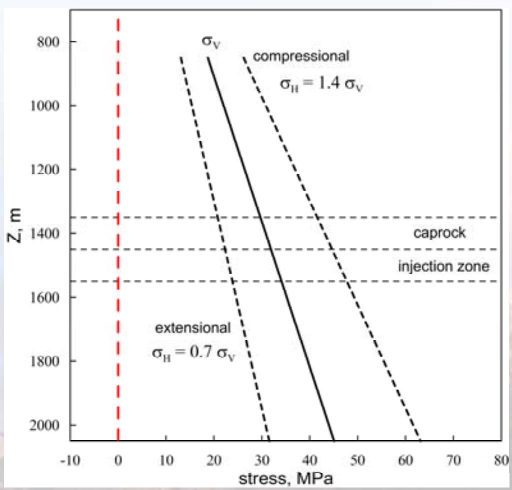
Effect of Regional Stress State

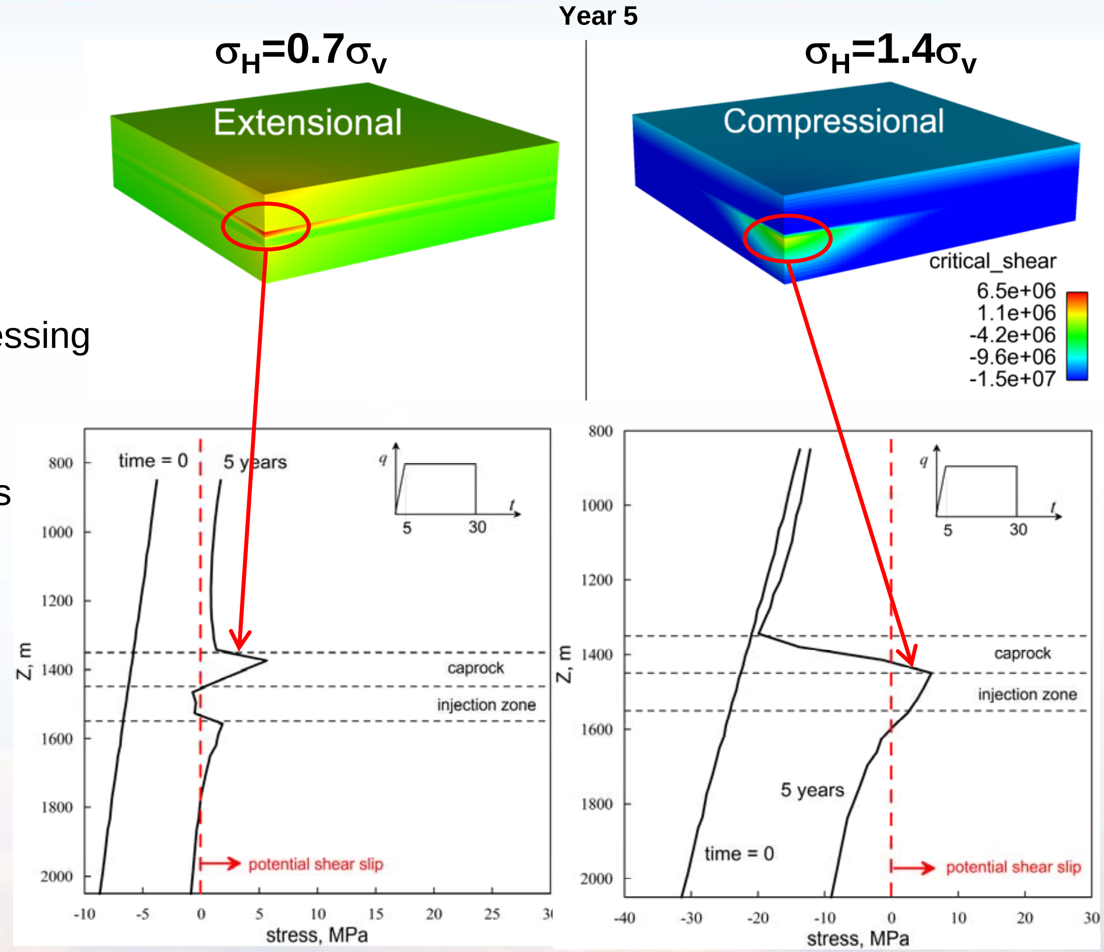
Linear Mohr-Coulomb



Critical Shear

$$\sigma'_{p1} - 3\sigma'_{p3} > 0$$





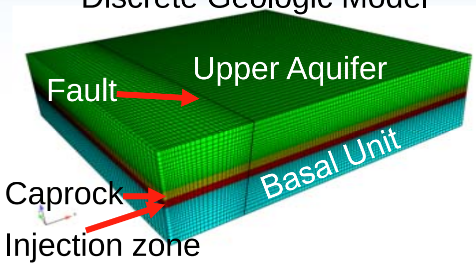
Extensional regional stresses are more dangerous to caprock integrity

Coupled Flow and Geomechanics

Hydromechanical Effects of Faults

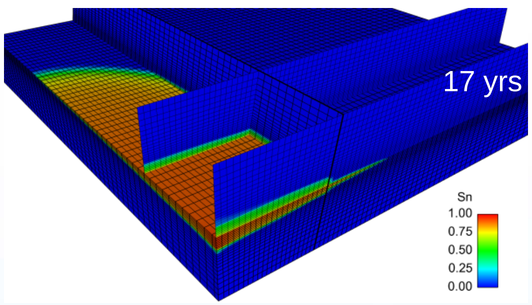
Some faults could go undetected and may pose a risk to sequestration of CO_2 by reactivation due to injection pressures. This study considers possible hydromechanical effects due to a low and high permeability fault.

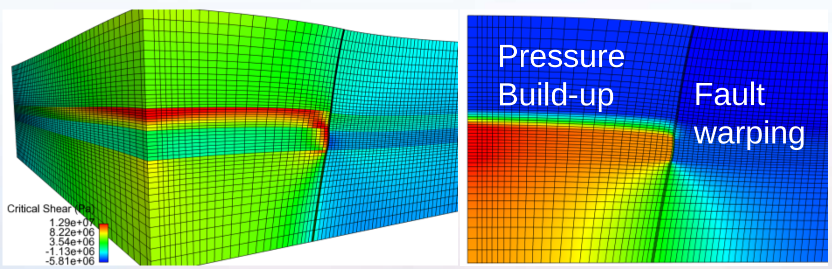
Discrete Geologic Model



Low Permeability Fault

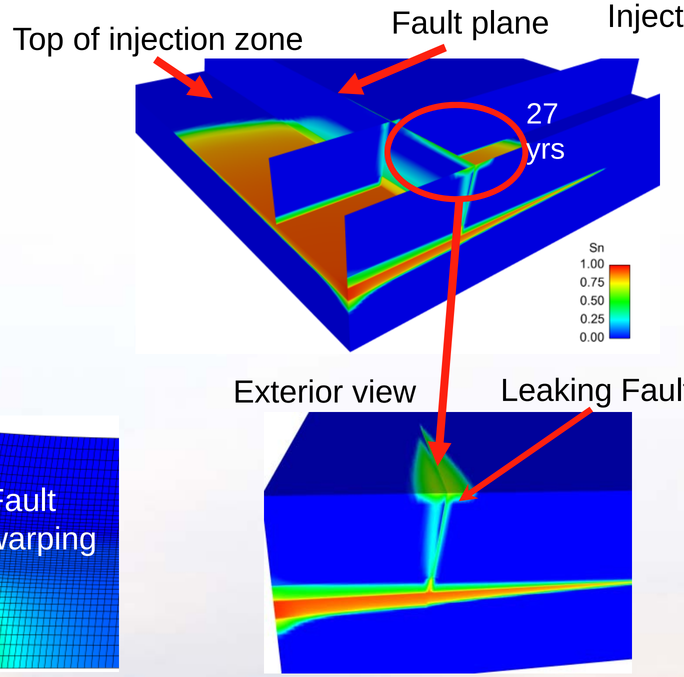
Interior view of CO_2 Saturation





Low permeability fault impedes CO_2 injection, diverts flow along fault and builds pressure behind the fault, thereby shearing/warping the fault and inducing critical shear failure in both the caprock and fault.

High Permeability Fault



High permeability fault creates a pathway for leakage of CO_2 through the caprock, ultimately pooling at the top of the upper aquifer, which is capped by an impermeable boundary.

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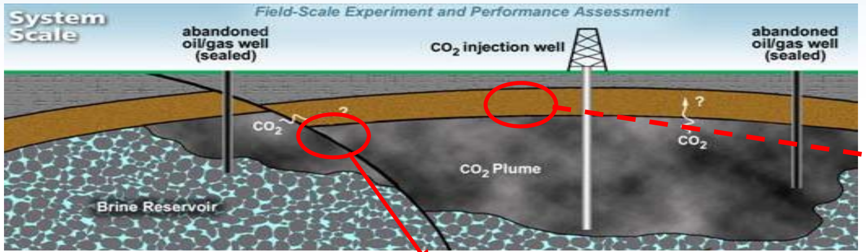
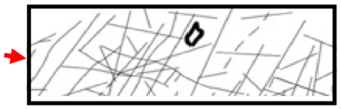
Deformation Dependent Caprock Permeability due to Jointing

Change in joint aperture due to CO_2 injection causes a change in caprock permeability (anistropic).



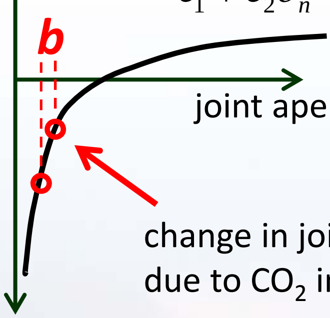
faulting

Caprock jointing



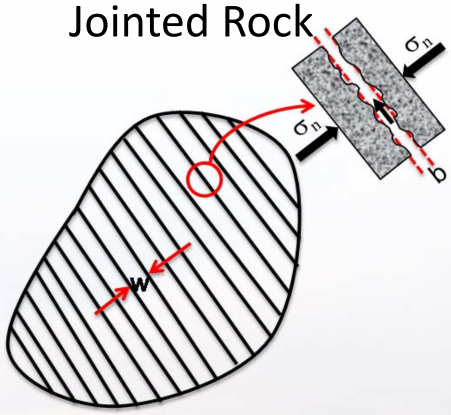
Stress vs. Joint aperture

$$\sigma_n^{eff} = \frac{\delta_n}{c_1 + c_2 \delta_n}$$



$$\mathbf{k}_{eff} = k\mathbf{I} + \frac{b^3}{12W}\left(\mathbf{I} - \mathbf{n} \otimes \mathbf{n}\right)$$

Conceptual Model of Jointed Rock



Multiple joints sets can be modeled

Change in effective stress with CO_2 injection causes a change in caprock stiffness, normal to fracture plane.

$$K_n = K_{ni}\left(1 - \frac{\sigma_n^{eff}}{K_{ni} V_m}\right)^2$$

$$\dot{\boldsymbol{\varepsilon}}^{\text{joint}} = \frac{1}{W\,K_n}\mathbf{P} \bullet \dot{\boldsymbol{\sigma}} \bullet \mathbf{P}$$

$$\mathbf{P} = \mathbf{n} \otimes \mathbf{n}$$

CO_2 Injection with a Jointed Caprock

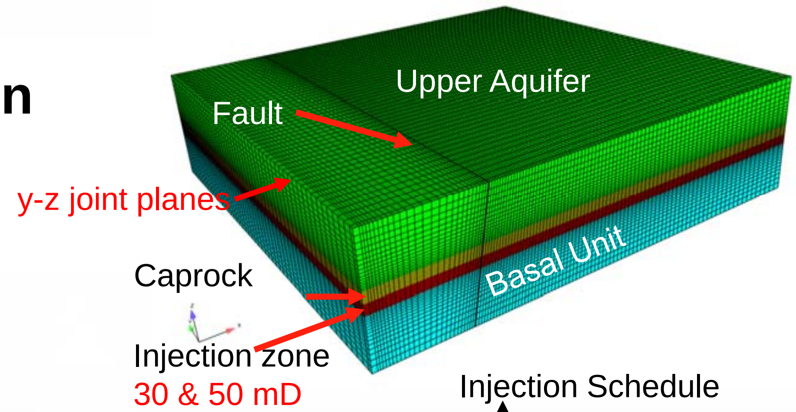
Effect of injection rate and permeability

Investigate the relationship between injection zone permeability and injection rate

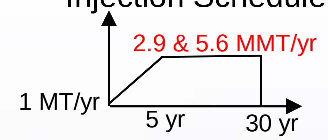
- single joint set (vertical joints in y-z plane)
- two injection rates: 2.85 & 5.6 MMT/yr
- two injection zone permeabilities:
  - 30 and 50 mD

- Van Genuchten capillary pressure
  - P_{entry} = 5kPa all layers
- Cubic relative permeability

Discrete Geologic Model



Injection Schedule



Overburden

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15 km

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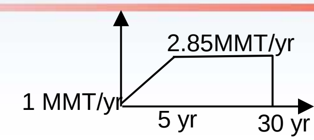
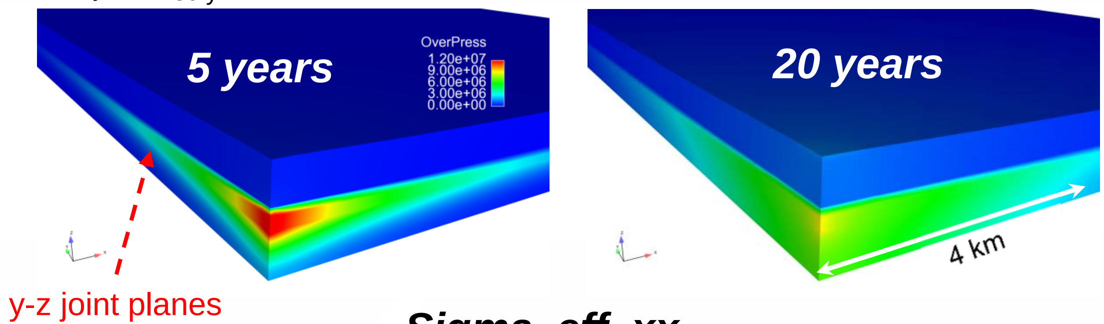
Simulation Results
Joint Activation Case

<u>Features</u>:

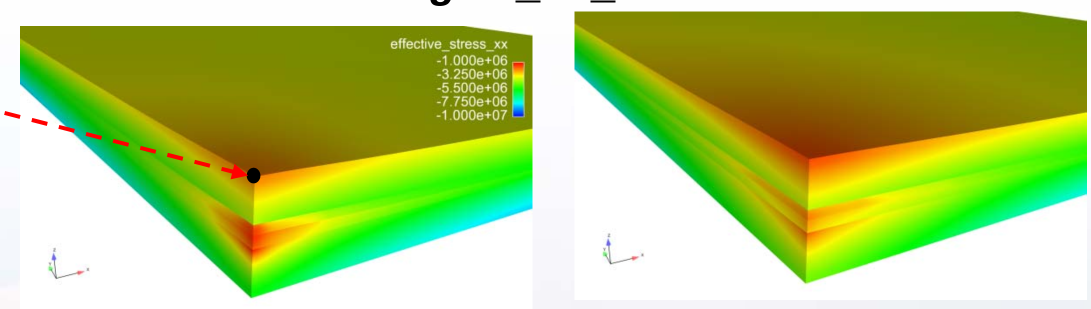
- Single joint set in y-z plane
  - K_n=15 Gpa, W = 1 m
- Injection zone perm: 30 mD
- Max. injection rate: 2.85 MMT/yr

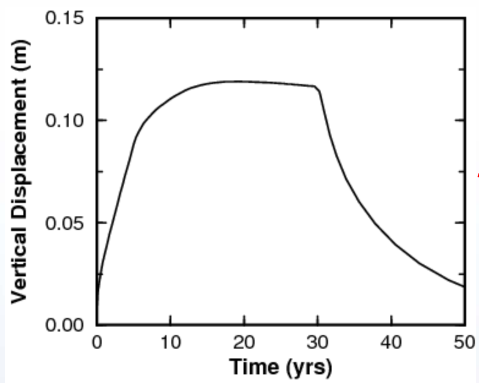


Over-Pressure

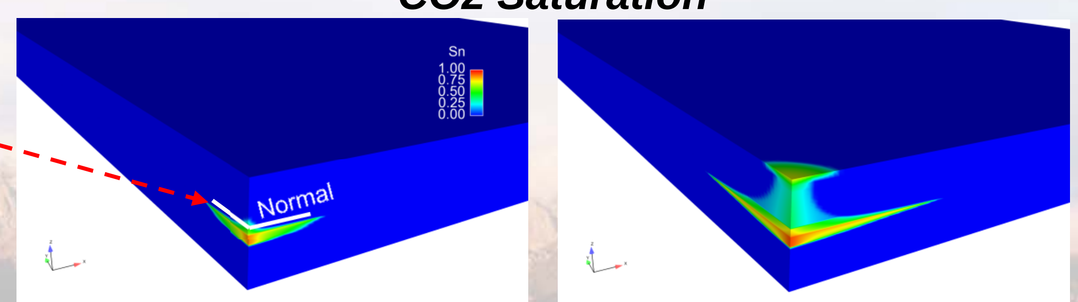


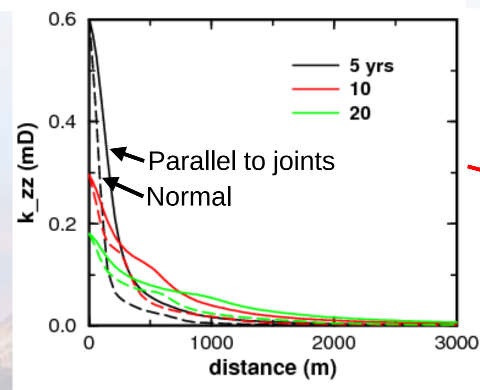
Sigma_eff_xx





CO2 Saturation





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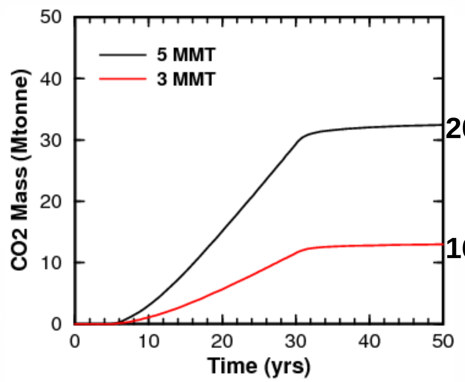
Pressure, Mass Budget and Leakage

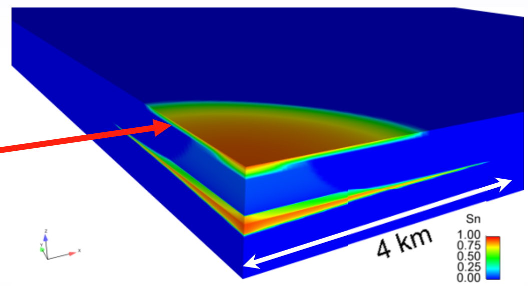
Cumulative CO_2 Leaked



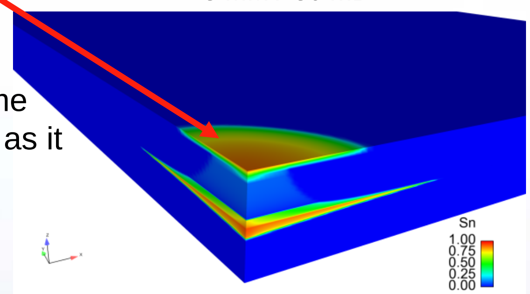
20%

16%

5 MMT 50 mD

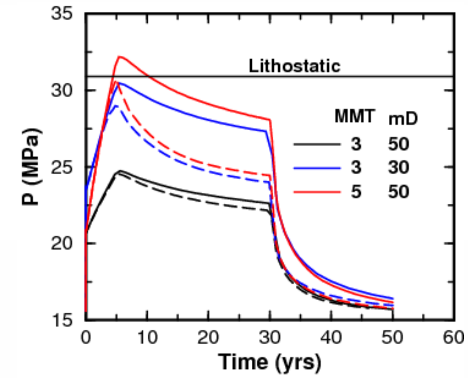


3 MMT 30 mD



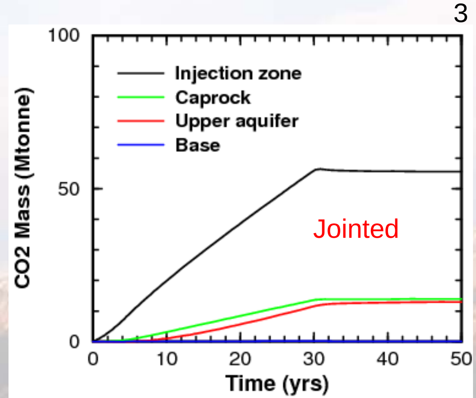
CO_2 volume increases as it rises

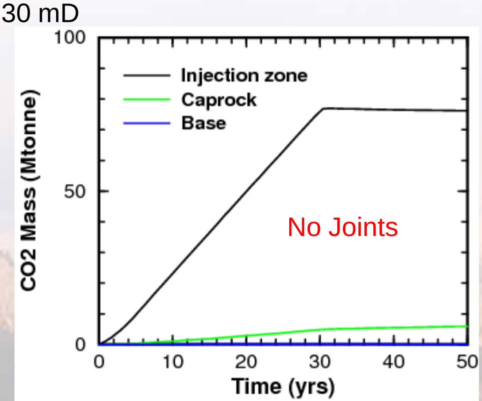
Near-Wellbore Pressure



- Joints activated near the tension limit
- Joint activation relieves pressure

CO_2 Mass Budget
3 MMT 30 mD





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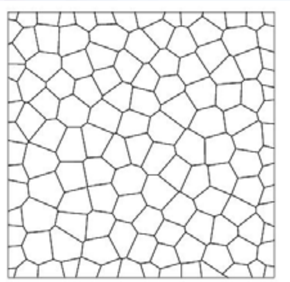
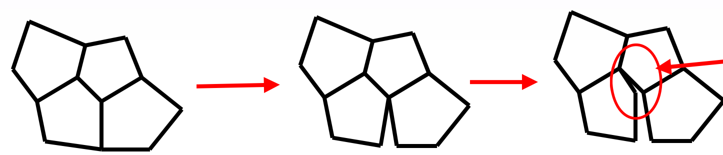
Future Directions: Methods for Modeling Fracture Growth in Disordered Materials

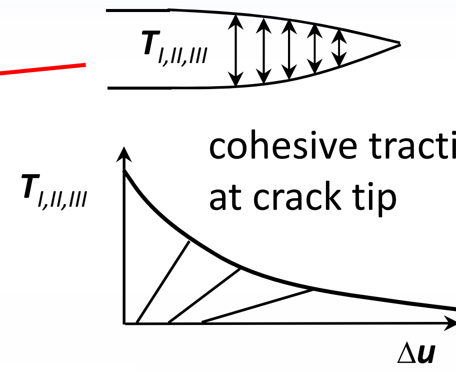
(JE Bishop)



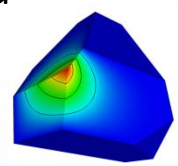
randomly closed packed Voronoi mesh



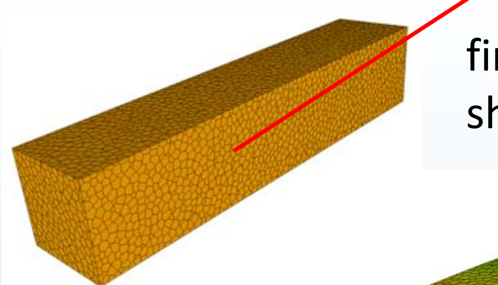
changing mesh connectivity

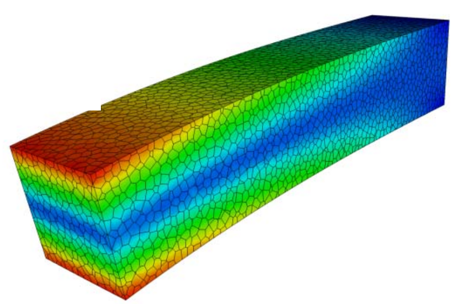


cohesive tractions at crack tip

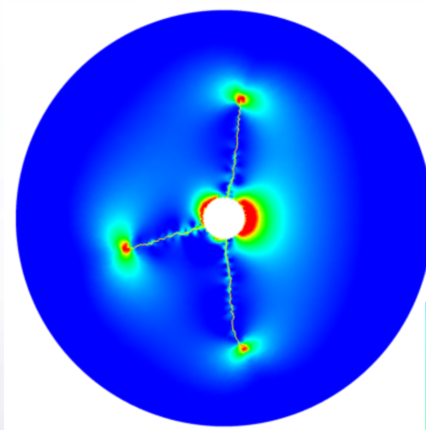


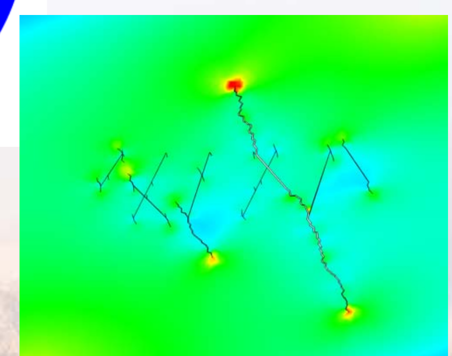
finite-element shape function





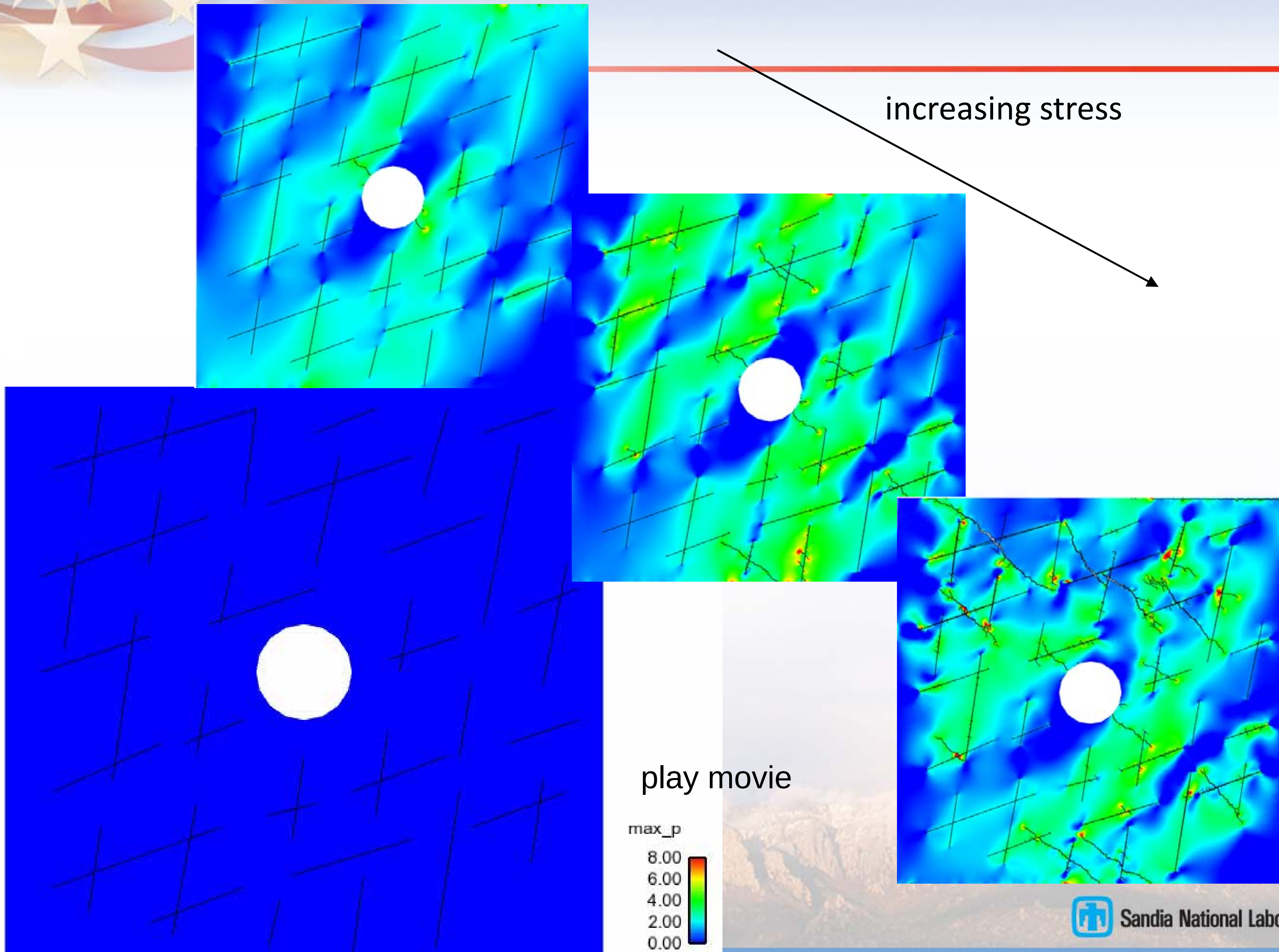
beam-bending verification problem





fluid-induced fracture simulations

Dynamic Fracture Growth in Disordered Materials



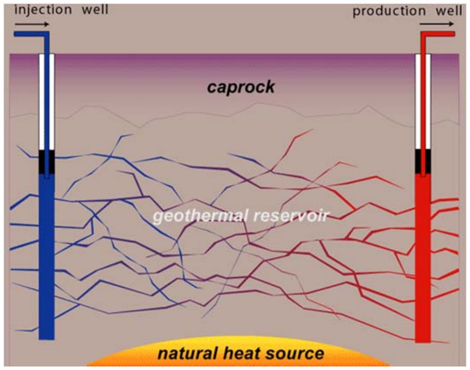
Summary

1. An important scientific research question for the feasibility of CO_2 sequestration is assessment of the integrity of the caprock.
2. Problem is inherently multi-physics and multi-scale (space and time). Fluid-structure interaction is important, both at the field scale and micro-scale. Requires a multi-disciplinary team of researchers.
3. A number of new numerical methods are under development for modeling fracture activation, nucleation and propagation in heterogeneous media with coupled fluid flow for continuum and/or discrete representations of fractures.

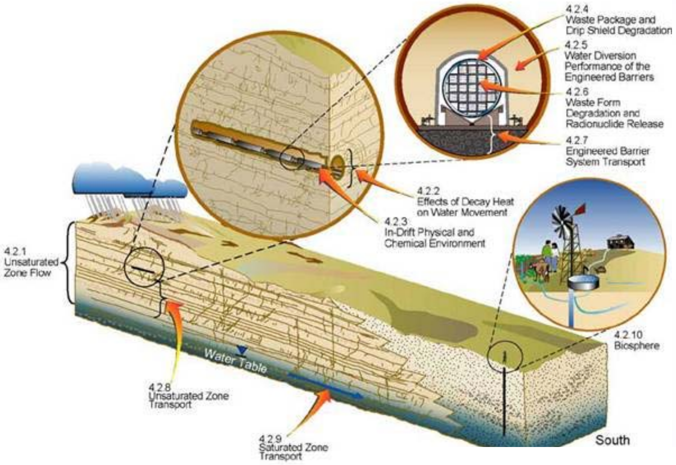
Backup Slides

Geoscience Applications at SNL

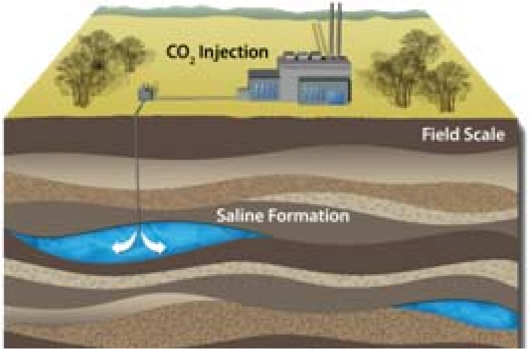
Engineered Geothermal



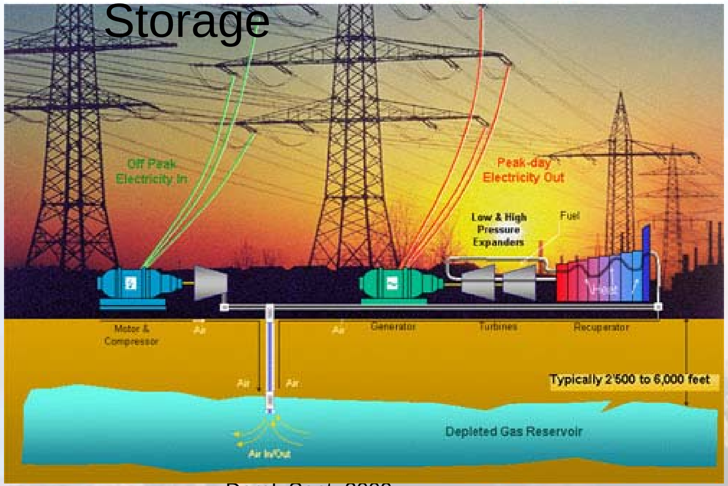
Nuclear Waste Isolation



CO_2 Sequestration

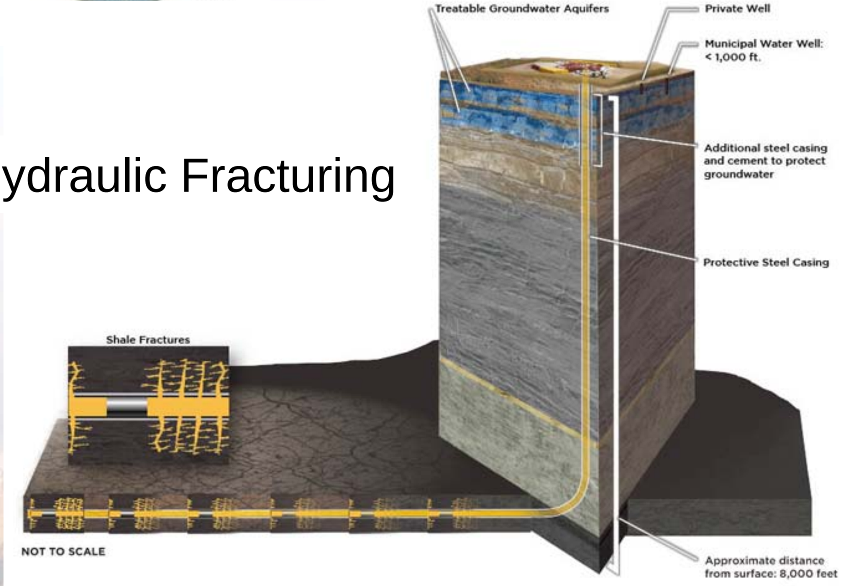


Compressed Air Energy Storage



Derek Sept. 2009

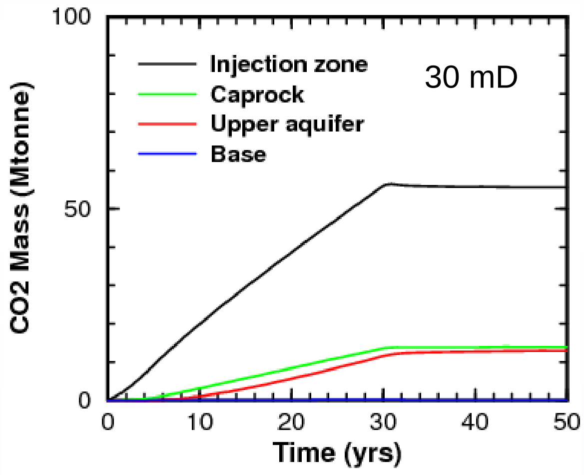
Hydraulic Fracturing

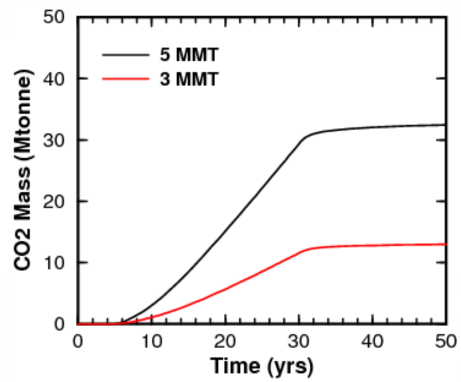


http://www.hydraulicfracturing.com

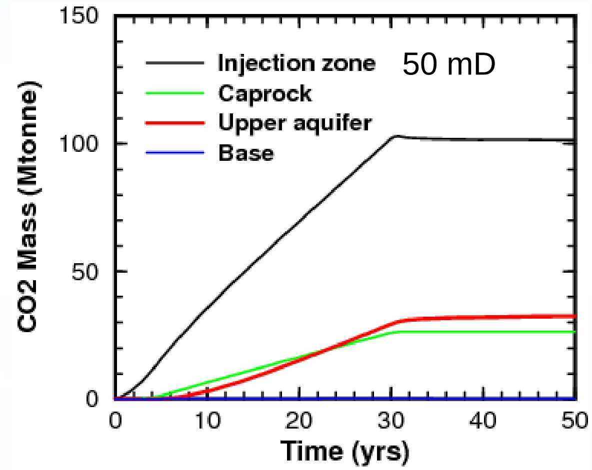
Mass Budget and Leakage

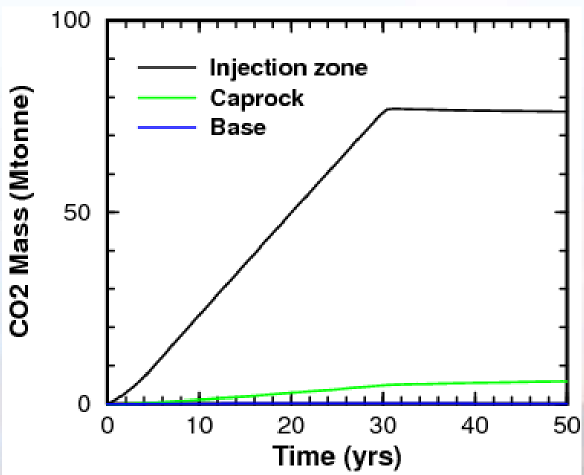
3.1 MMT/yr



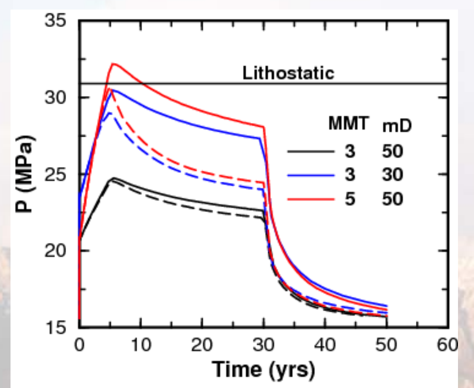


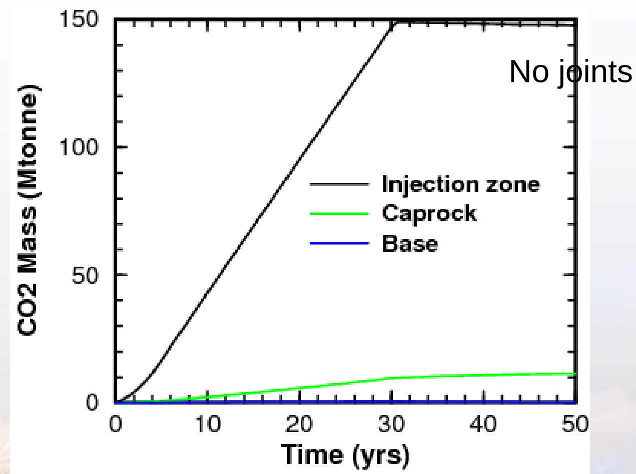
5.6 MMT/yr





No joints





Aria Porous Flow Physics

Immiscible Flow

Mathematical Model

- **Two-Phase Immiscible Mass Balances:**

$$\frac{\partial\left(\rho_w \phi S_w\right)}{\partial t} = \nabla \bullet \left(\rho_w \frac{k_{rw}}{\mu_w} \mathbf{k} \bullet \left(\nabla p - \rho_w \mathbf{g} \right) \right) + Q_w$$

$$\frac{\partial\left(\rho_n \phi S_n\right)}{\partial t} = \nabla \bullet \left(\rho_n \frac{k_{rn}}{\mu_n} \mathbf{k} \bullet \left(\nabla p + \nabla p_c - \rho_n \mathbf{g} \right) \right) + Q_n$$

- **Thermophysical property models (new models are easily incorporated):**

$$\rho_w = \rho_{w.0}\left(1 + \kappa_{Tw}(p - p_o)\right)$$

$$\rho_n = \rho_{n.0}\left(1 + \kappa_{Tn}(p_n - p_{n,o})\right)$$

$$p_n = p + p_c(S_w)$$

$$S_w = 1 - S_n$$

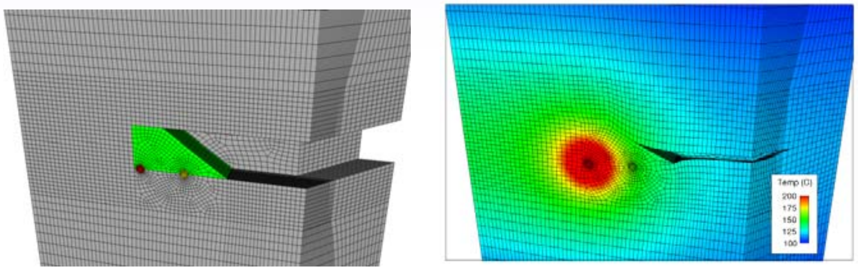
$$\phi = \phi_0\left(1 + C_r(p - p_0)\right)$$

Overview of Geomechanics in Adagio

Features:

- Large deformation, large strain kinematics
- Robust contact algorithms (both detection and application)
- Based on iterative (matrix-free) solvers with low order hourglass stabilized 8-node hexahedron element
- Efficient constitutive model implementations

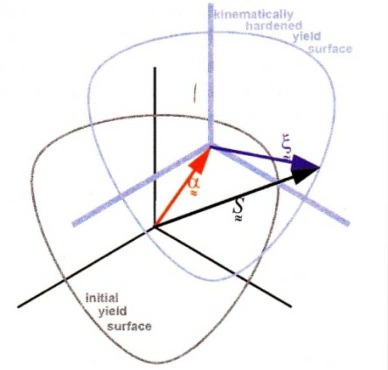
Thermally Enhanced Creep Closure

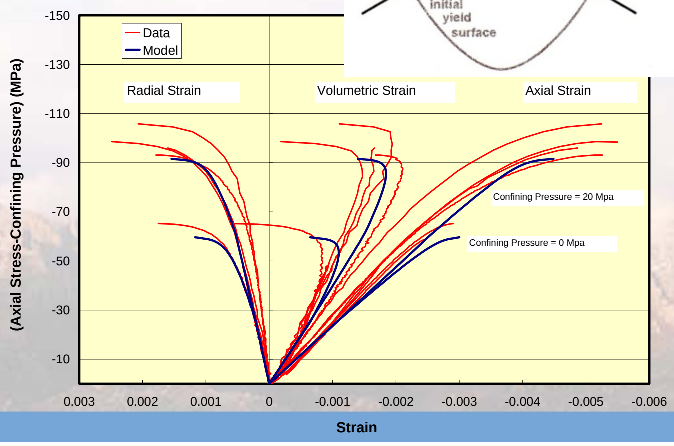


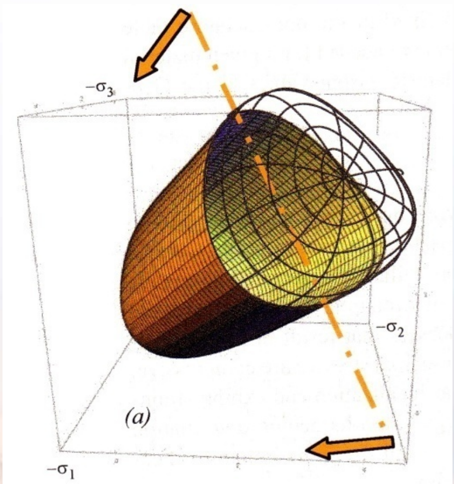
Undeformed and Deformed Storage Tunnels in a Heated Salt Repository

Models for Geomechanics:

- Elastic
- Elastic/Plastic
- Soil Foam
- Power Law Creep
- MD Creep Model
- Crushed Salt Creep Model
- Clay
- GeoModel

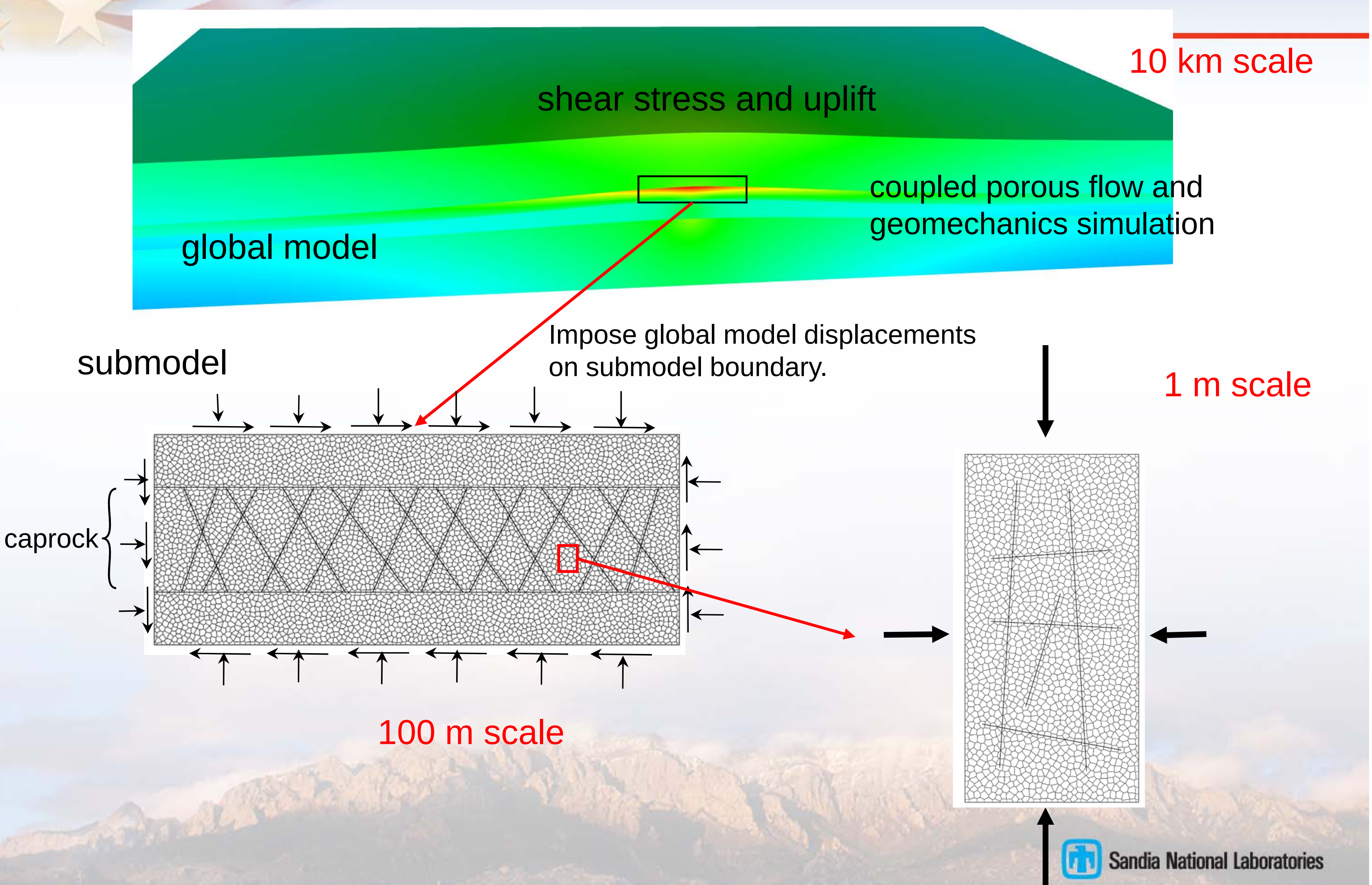






Sandia National Laboratories

Multiscale analysis of caprock integrity during CO2 injection



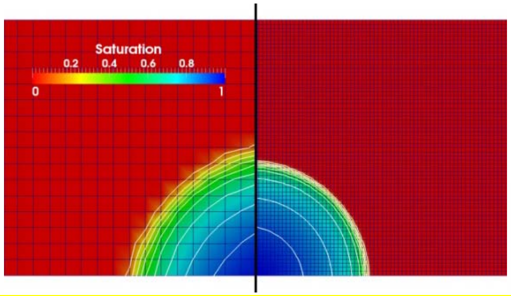
Sandia National Laboratories

Aria Multiphase Porous Flow Physics

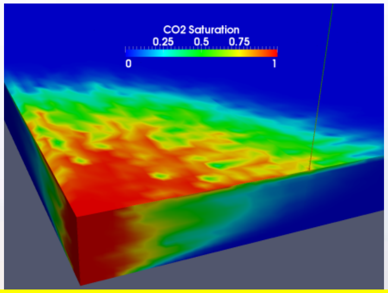
Two-Phase Immiscible Flow

- Compressible (fluids and/or formation), buoyancy effects
- General dependence of thermophysical and transport properties on solution vector
- Capillary pressure (optional)
- Relative permeability
- Specification of heterogeneous transport property fields (e.g. permeability, porosity)
- Can be coupled to energy equation

<u>Benchmark Problem</u>
Displacement of oil by water flood without capillary pressure or gravitational effects.



Grid effects using upwind CVFEM scheme



Injected CO_2 saturation levels in a brine filled reservoir represented with heterogeneous permeability