SAND2012-0198 C

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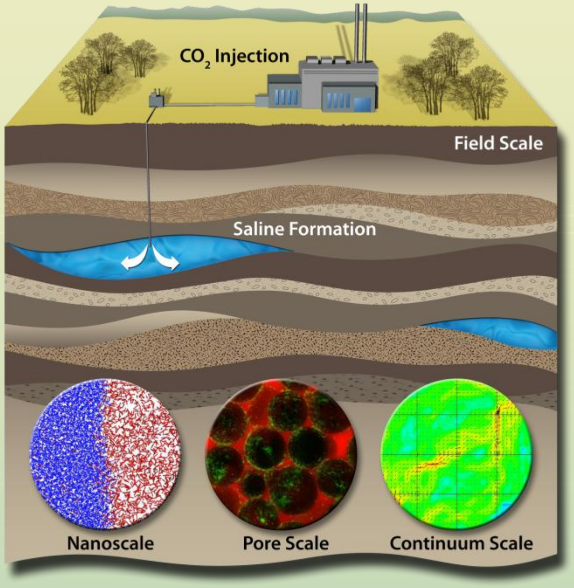
CFSES

Center for Frontiers of Subsurface Energy Security

CO_2 Sequestration Simulations Supporting the Caprock Integrity Assessment



Presenter: Joseph Bishop

Contributors: M. Martinez, P. Newell, T. Dewers, S. McKenna, T. Arbogast, M. Wheeler

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Denver, Colorado
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Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY Office of Science

TEXAS

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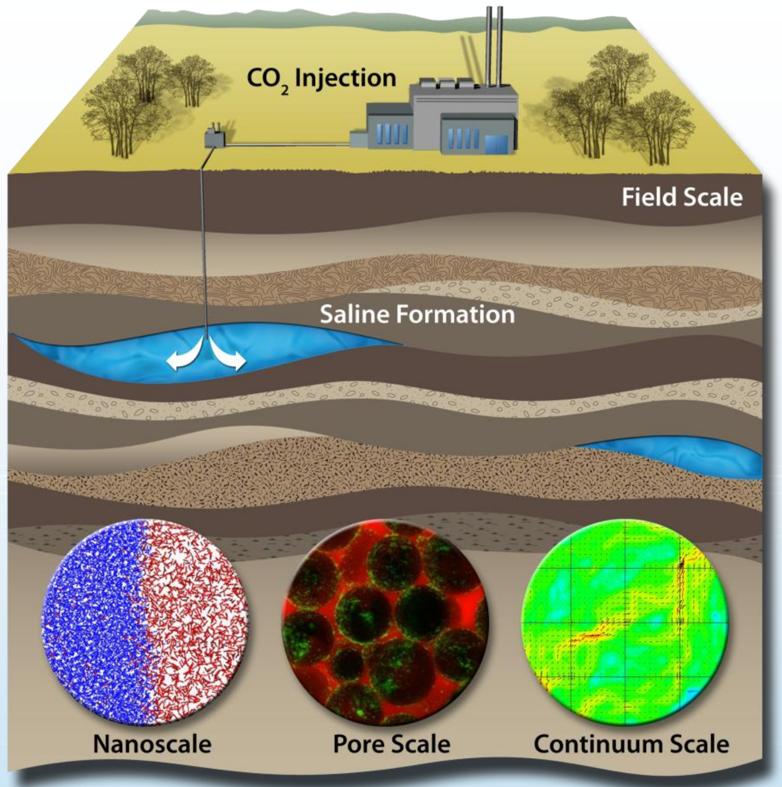
NNSA

Scales Range from Molecular to the Field and Femtoseconds to Millennia

CFSES



Time: 10^{-15} second → 10^{3} years (or more)

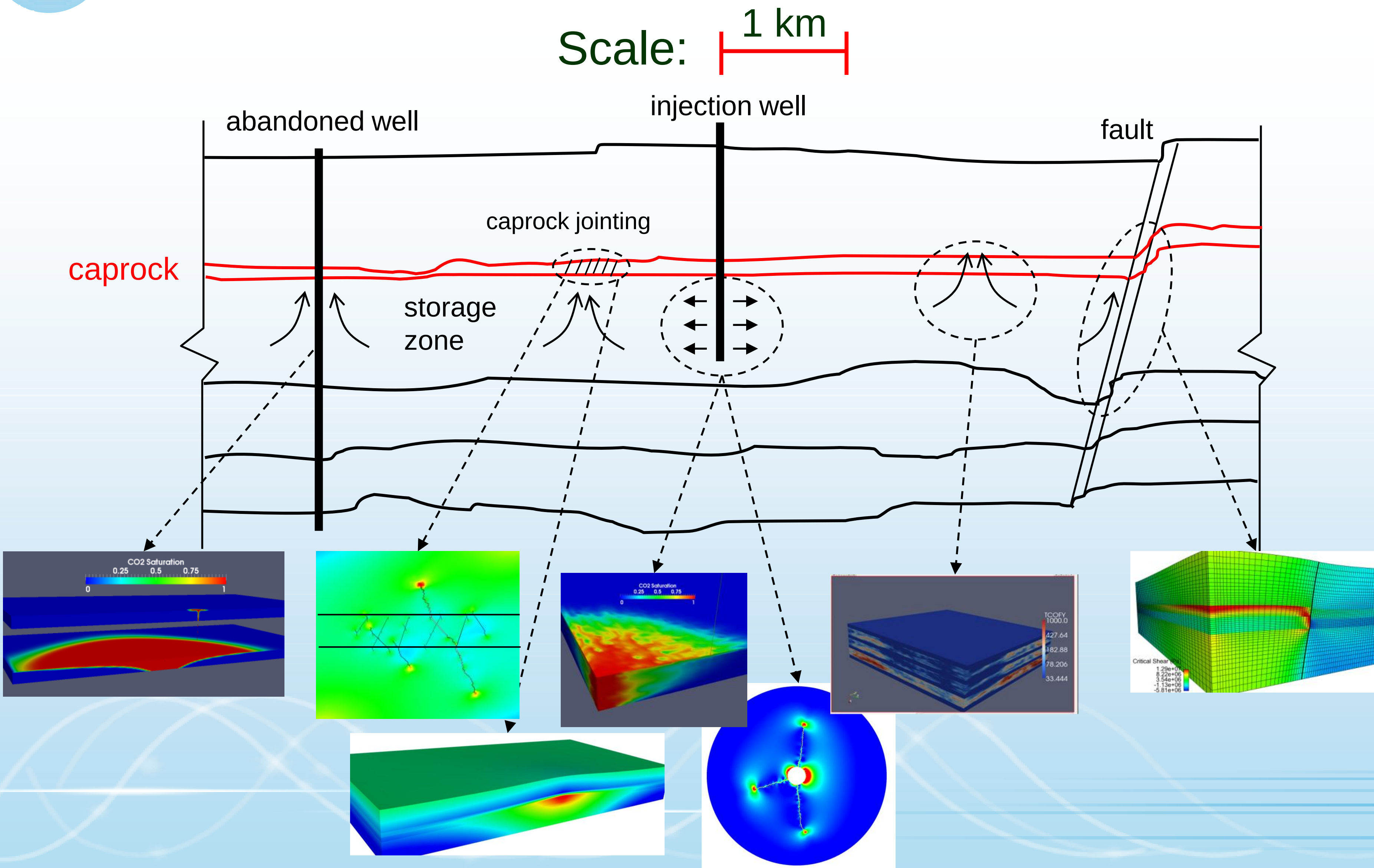
10^{-9} m	10^{-5} m	10^{-1} m	10^{2} m
Focus Area 1	Focus Area 2	Focus Area 3	Focus Area 4
Nanoscale	Pore Scale	Continuum Scale	Field Scale

Outline

1. Potential leakage paths
2. Goal of predictive assessment of caprock integrity
3. Why this is such a challenging scientific problem
4. Research and accomplishments to date
5. Future work
6. Summary

Potential Leakage Paths for CO_2

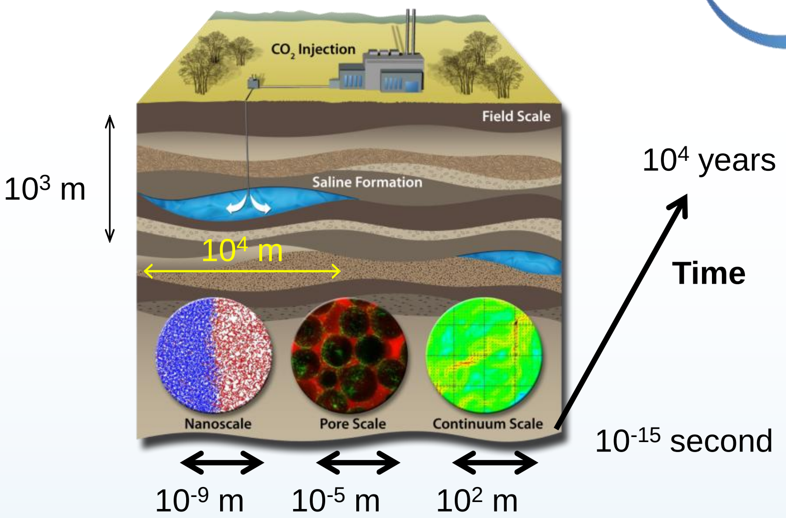
Primary CO_2 trapping mechanism is structural.



Goals

1. Predictive modeling capability for assessing caprock integrity
   - any field site, stratigraphy
   - any injection scenario
2. Quantitative prediction of leakage rate as a function of time through caprock
3. Injection schedule design
4. Assessment of mitigation scenarios

Why this is a Very Challenging Problem



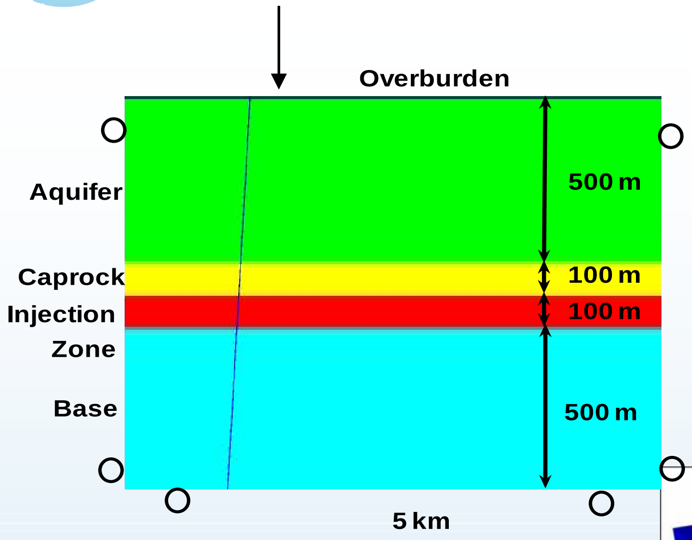
1. Subsurface
   - uncertain materials
   - uncertain structures
2. Multiple scales
   - time, space
   - multi-scale analysis (e.g. homogenization) attempts to exploit any scale separation
   - may not have scale separation → scale embedding with 'mortars'
   - fracture is inherently multi-scale
3. 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
   - emergent phenomena

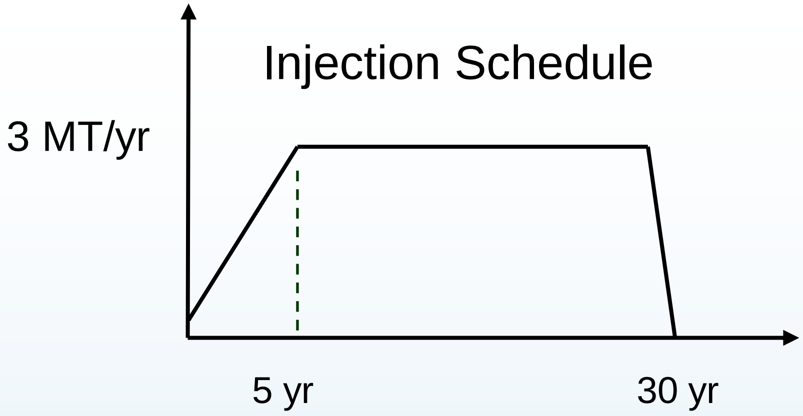
Outline

1. Potential leakage paths and scales
2. Goal of predictive assessment of caprock integrity
3. Why this is such a challenging scientific problem
4. Research and accomplishments to date
    - example field-scale simulation, coupled porous-flow/geomechanics
    - effects of caprock jointing on leakage
    - new methods for simulating injection-induced caprock damage
5. Future work
6. Summary

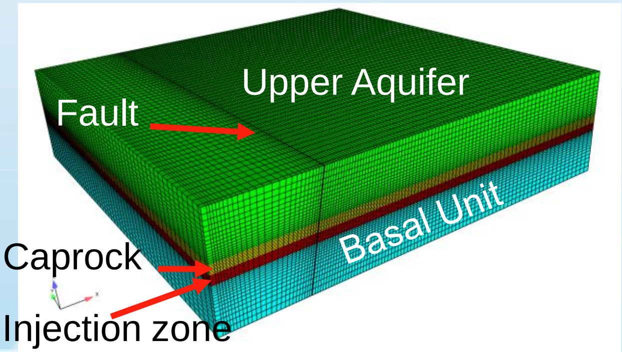
Coupled Flow and Geomechanics

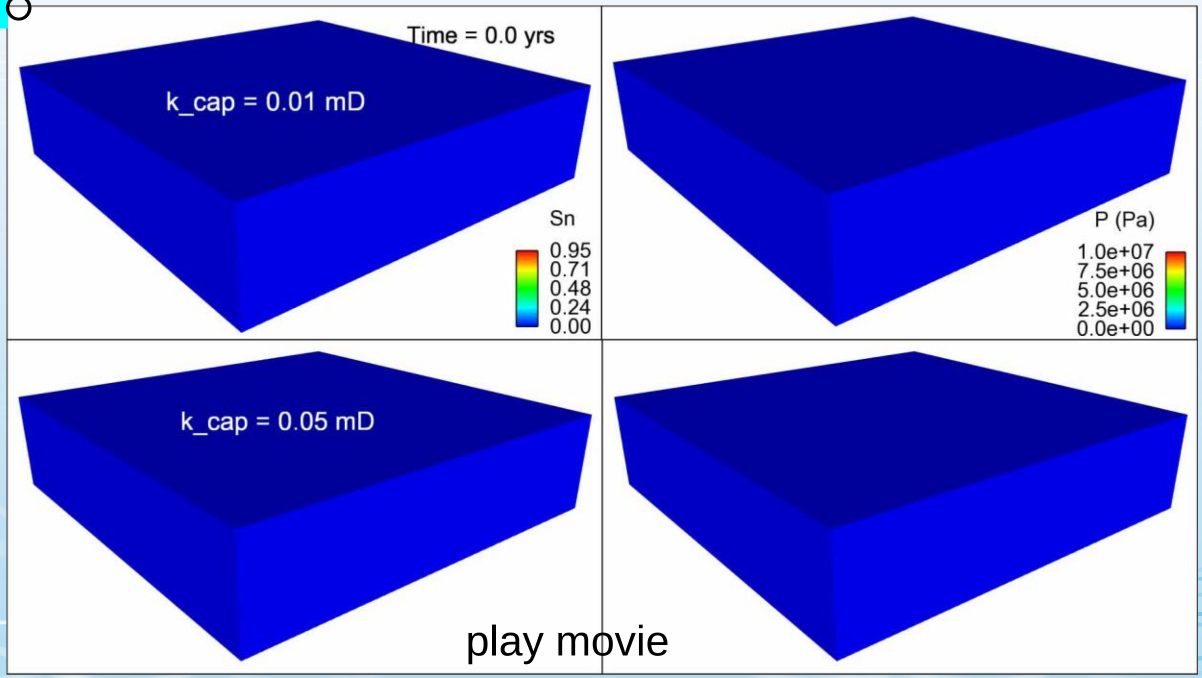
Injection into a Reservoir/Caprock System





Finite Element Model

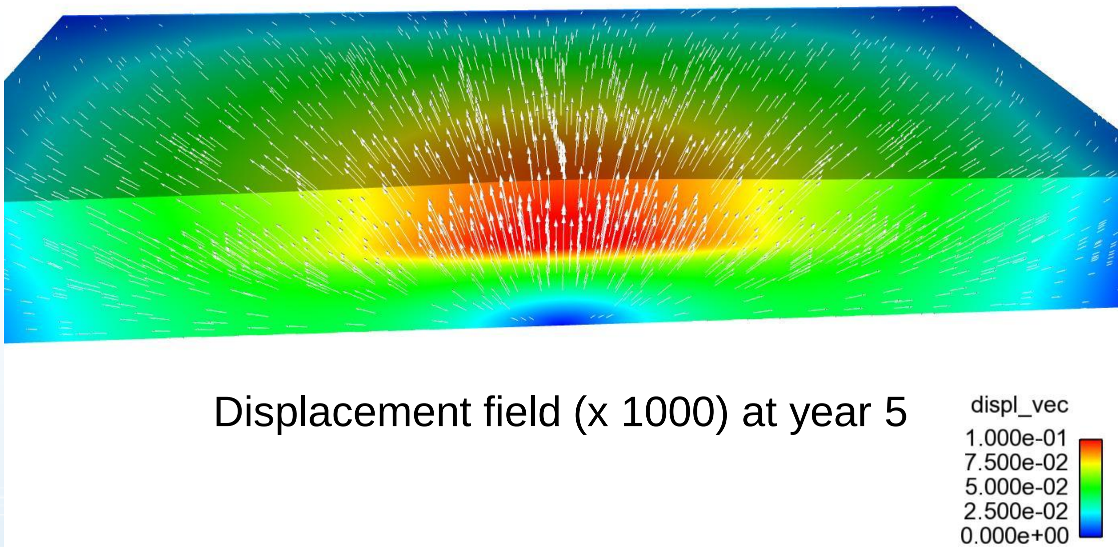




play movie

Injection Induced Uplift

5.32 years

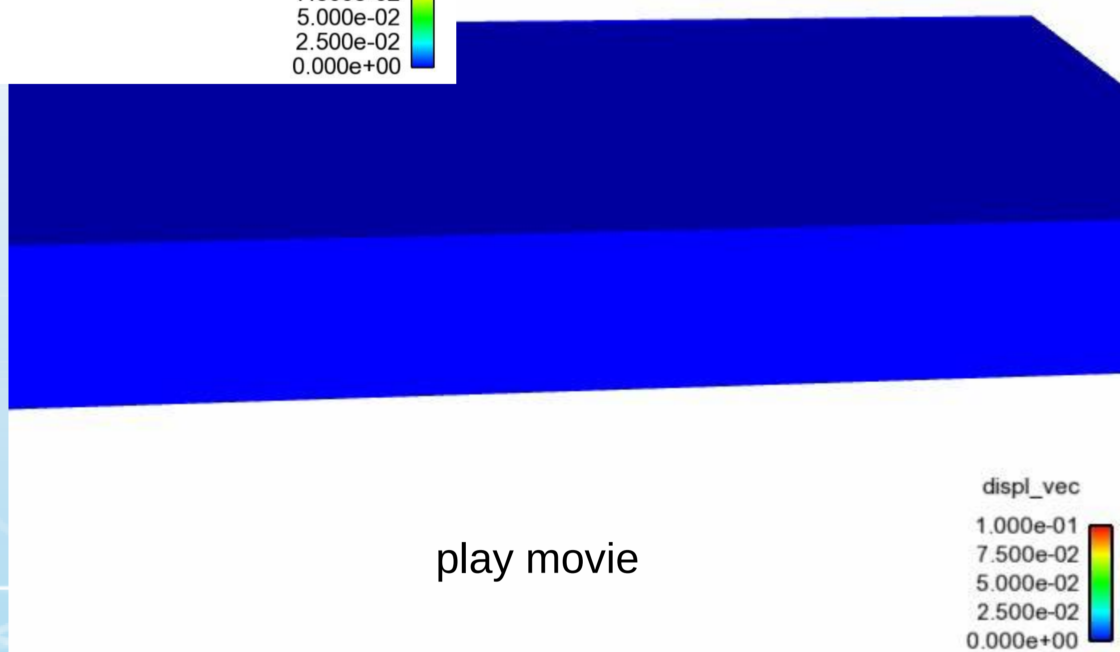


Displacement field (x 1000) at year 5

Note: 0.1 m uplift
(500 m above injection zone)

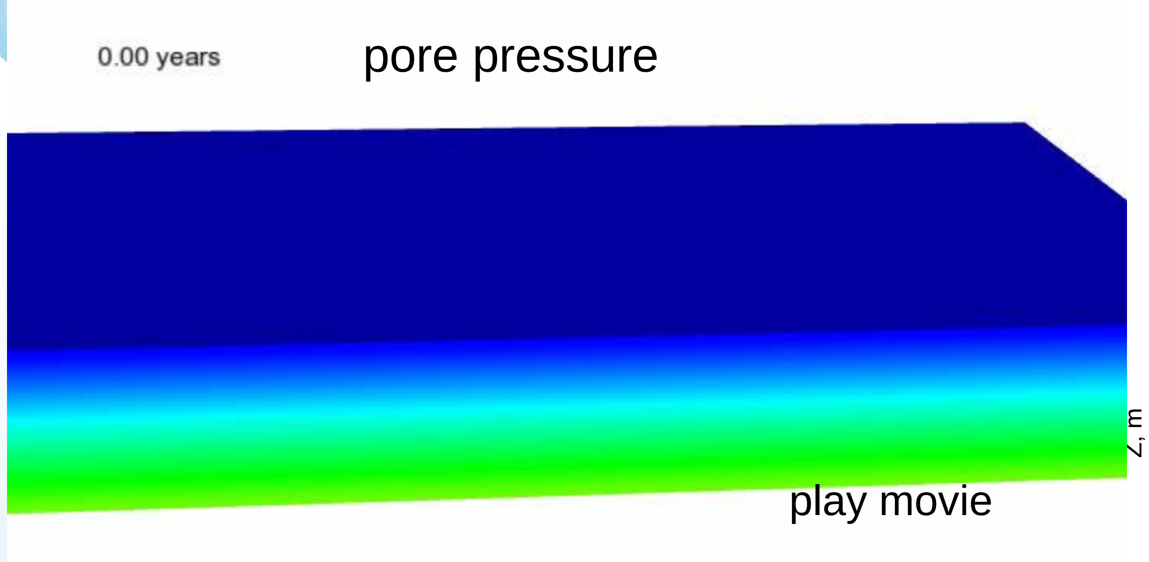
This injection-induced deformation can cause:

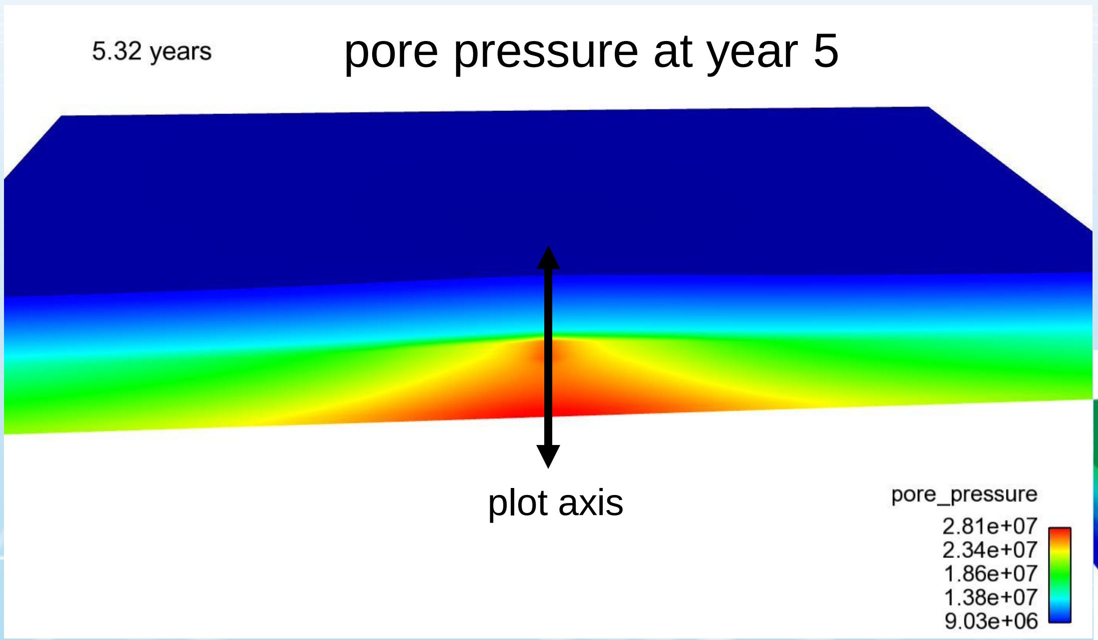
- stress-redistribuion in the caprock
- opening of caprock joints
- caprock fracturing

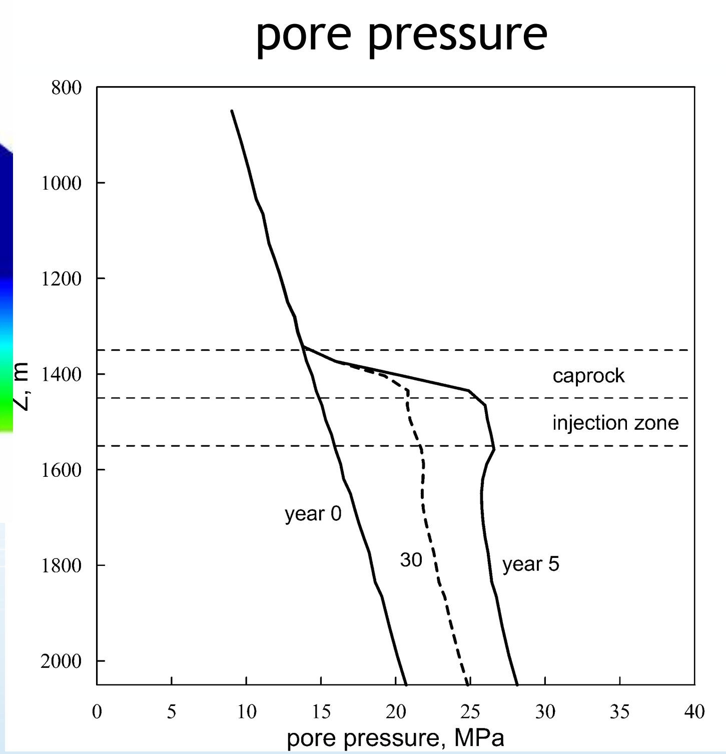


play movie

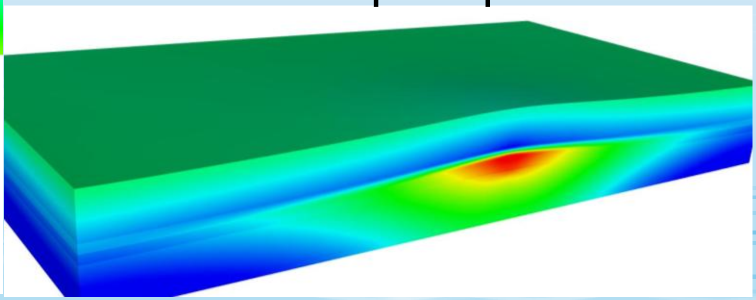
Pore Pressure



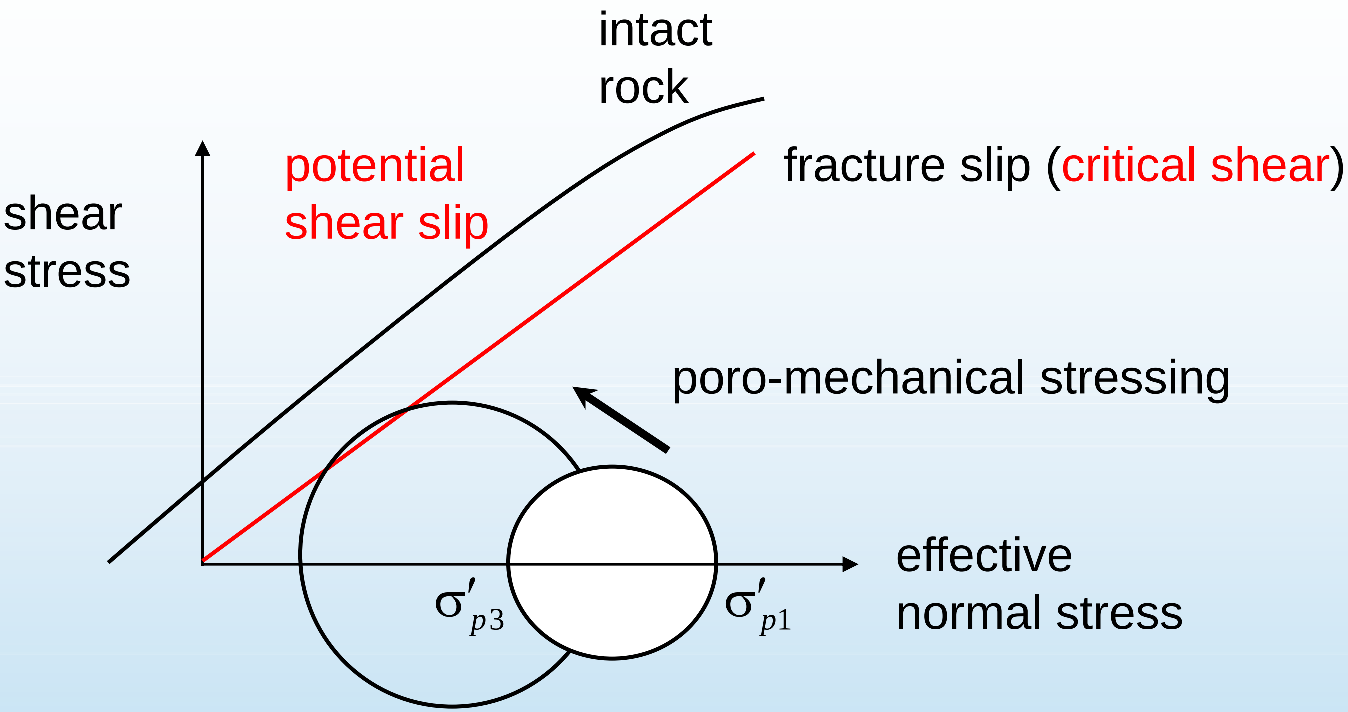




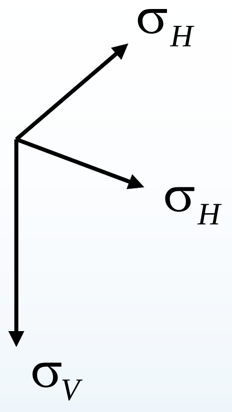
deviatoric pore pressure



Mohr-Coulomb

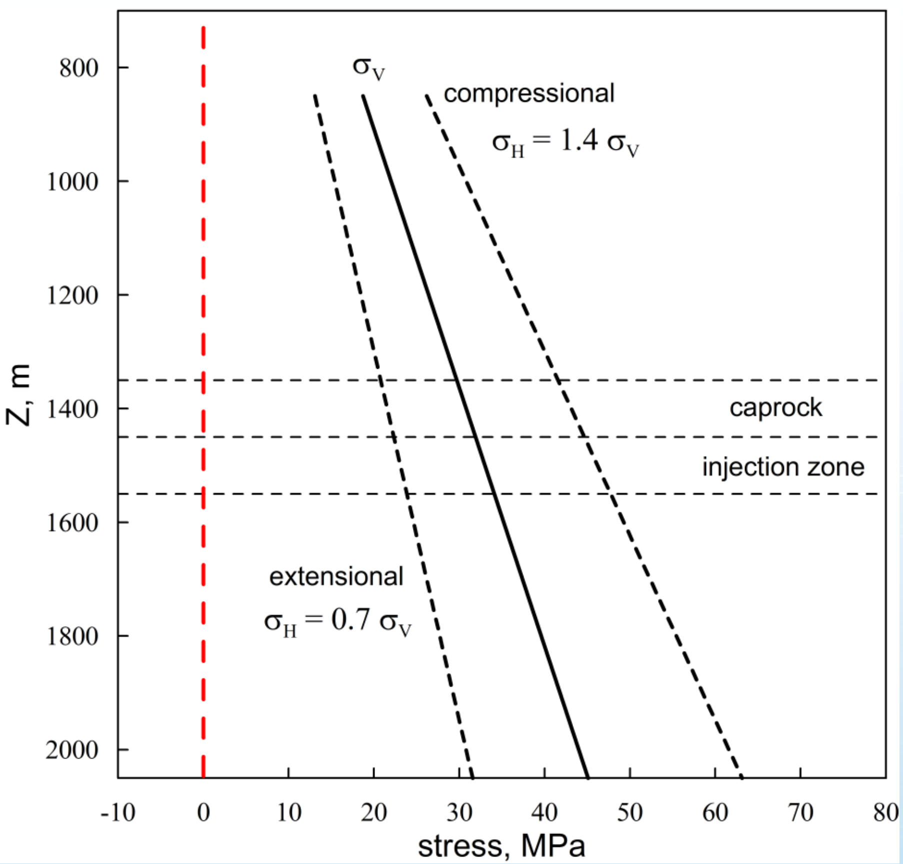


Initial Stress State

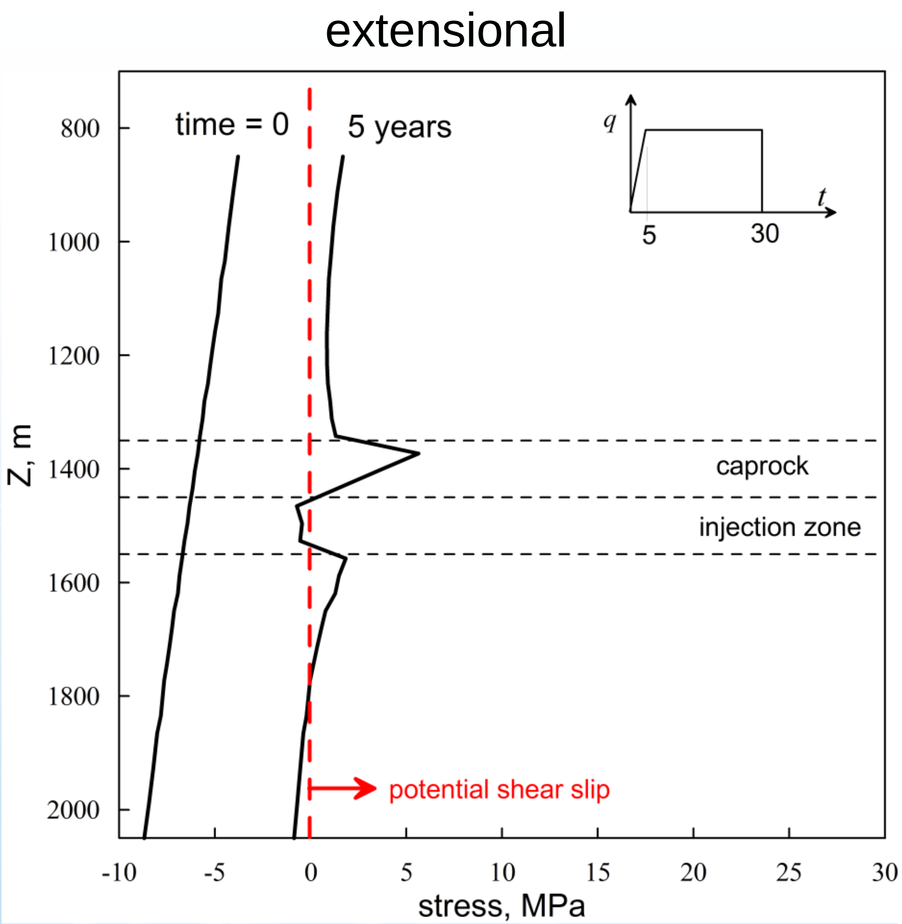


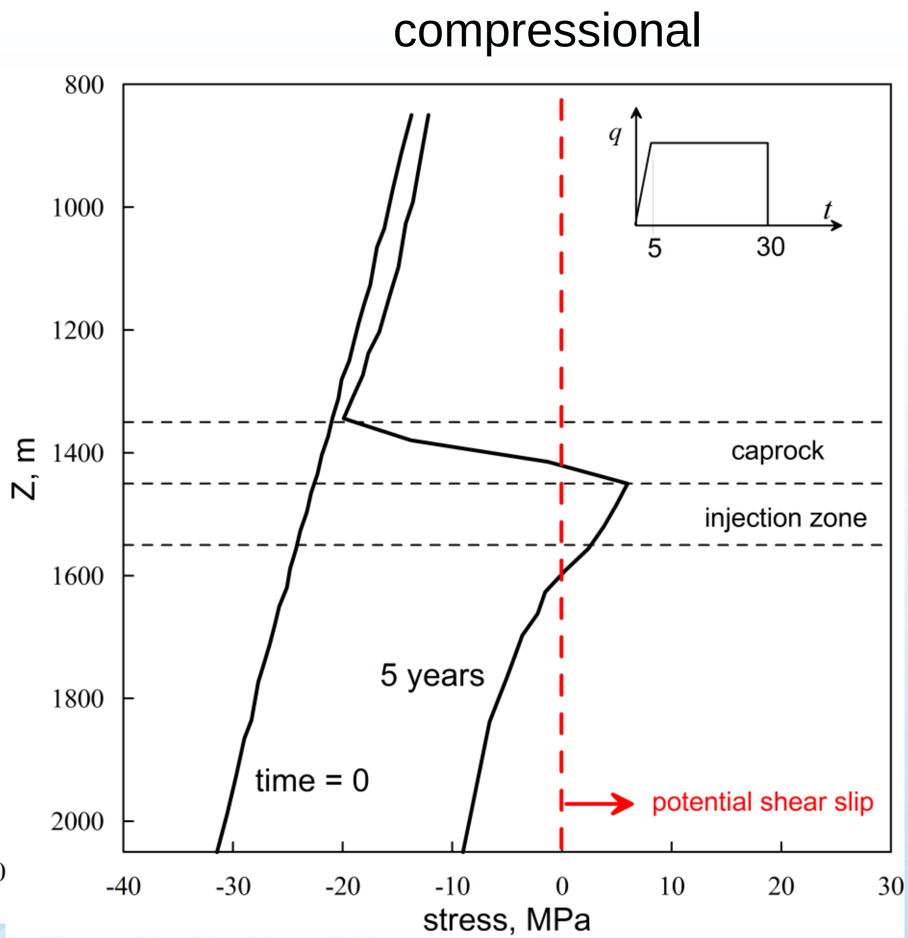
Consider two initial stress regimes

1. extensional $\sigma_H < \sigma_V$
2. compressional $\sigma_H > \sigma_V$



Critical Shear-Stress Comparison



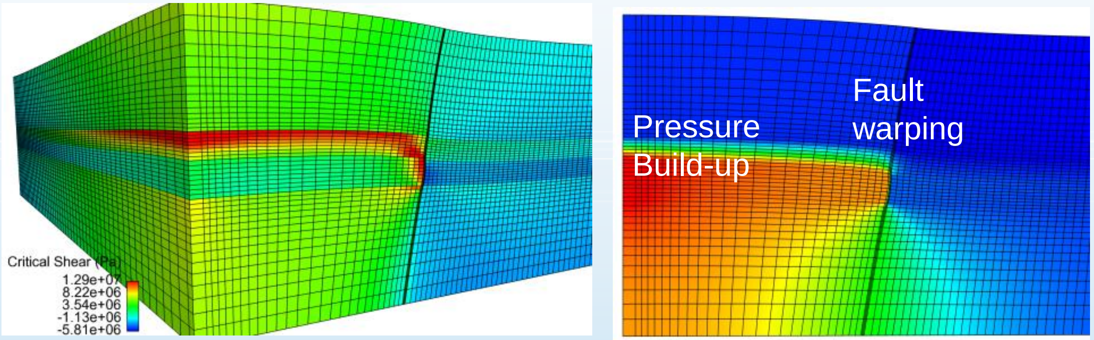


Need to quantify uncertainty in initial stress state.

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.

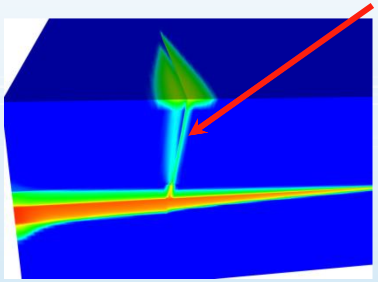
Low Permeability Fault



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.

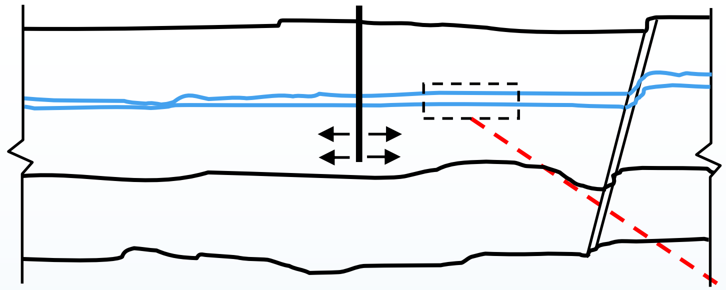
High Permeability Fault

Leaking Fault

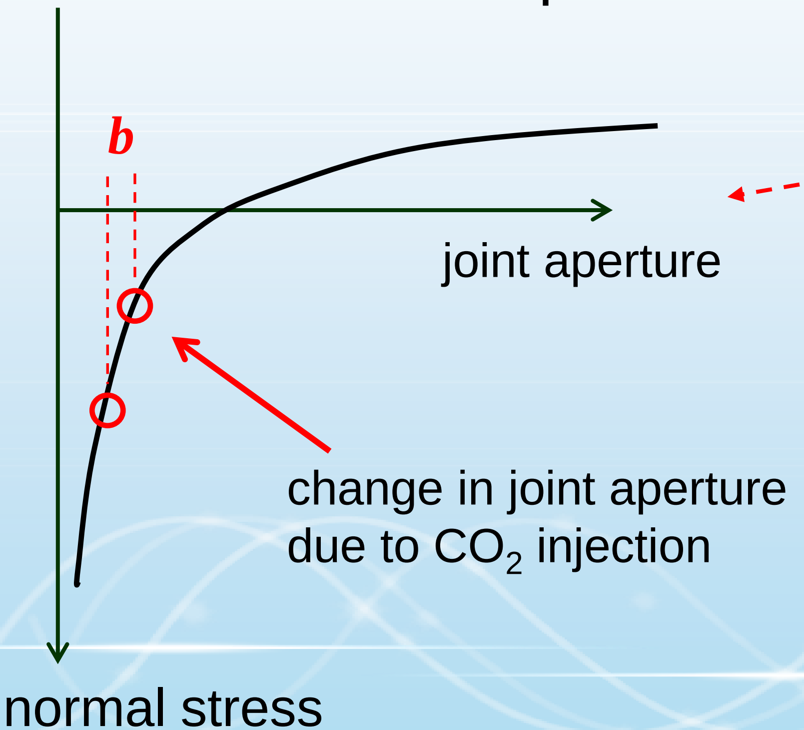


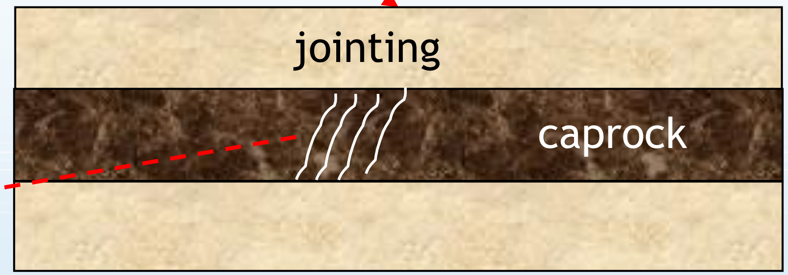
High permeability fault creates a pathway for leakage of CO_2 through the caprock

Deformation Dependent Caprock Permeability due to Jointing



Stress vs. Joint aperture

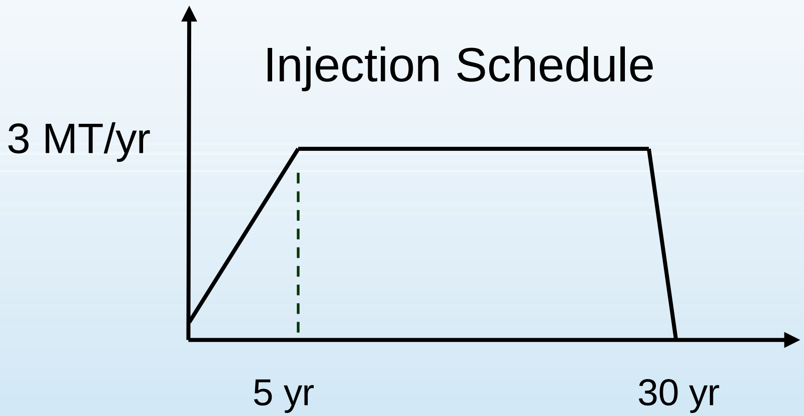




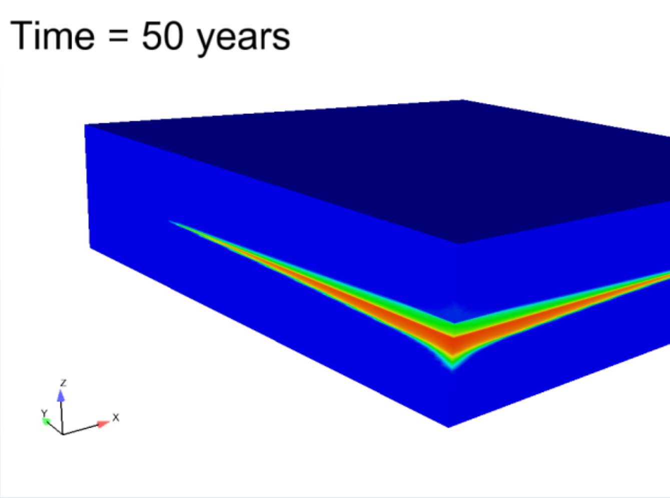
Change in joint aperture due to CO_2 injection causes a change in caprock permeability (anistropic).

Caprock Leakage due to Jointing

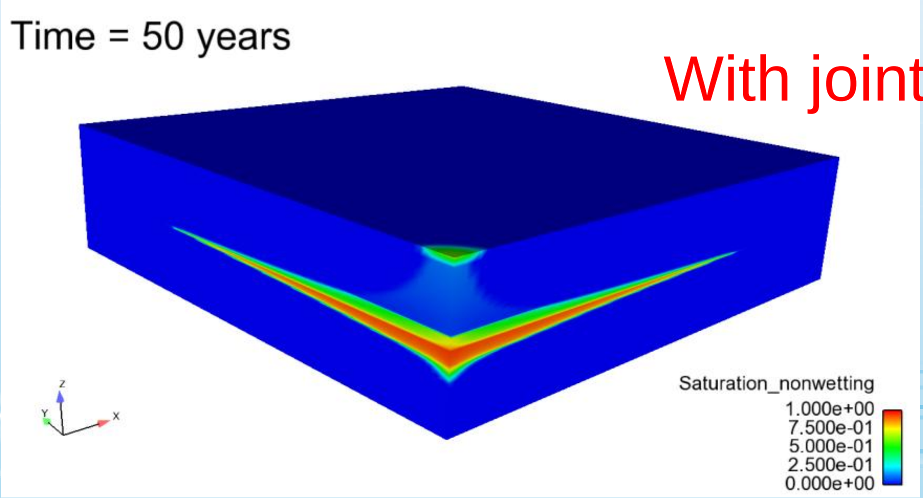
from PostDoctoral Researcher, Pania Newell



No joints

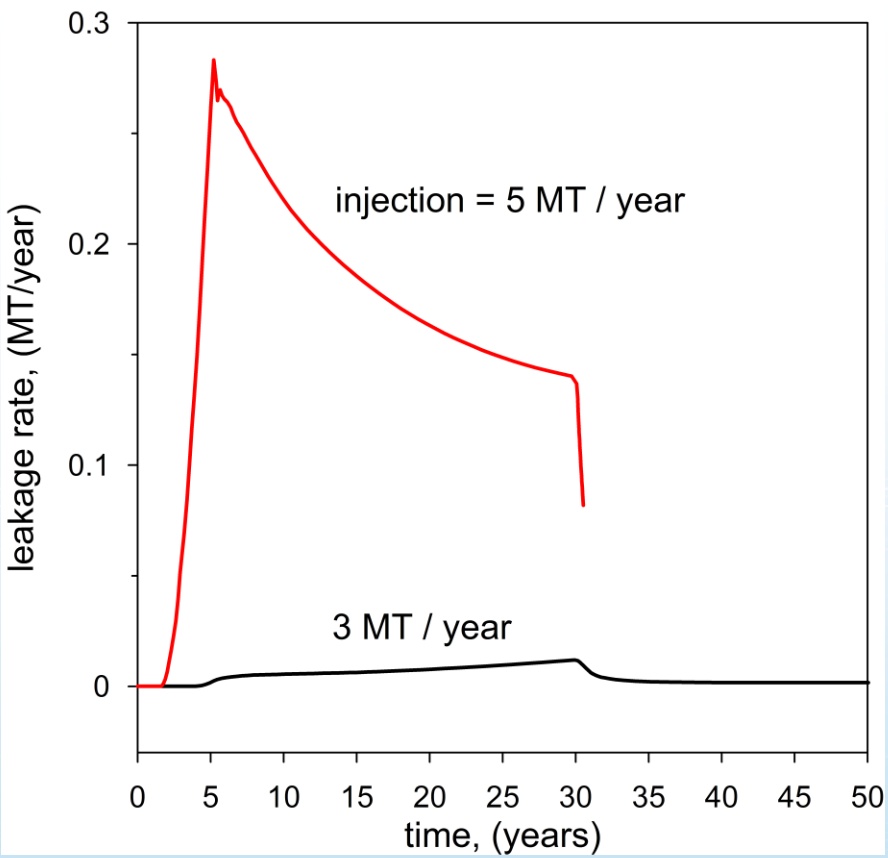


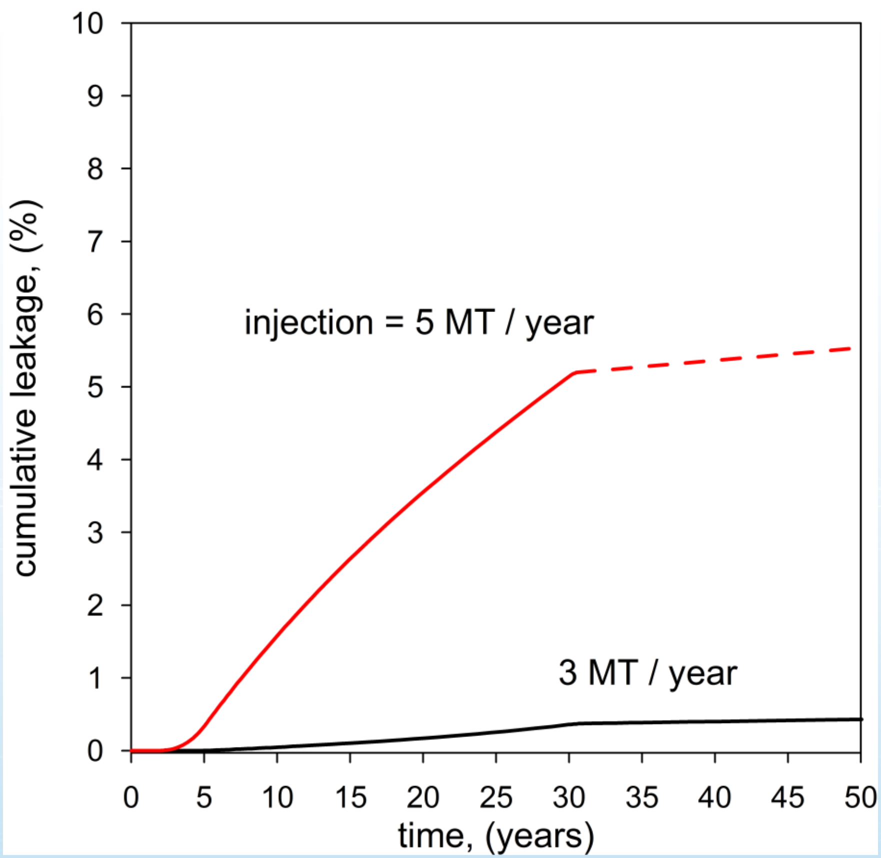
With joints



Caprock Leakage due to Jointing

from PostDoctoral Researcher, Pania Newell

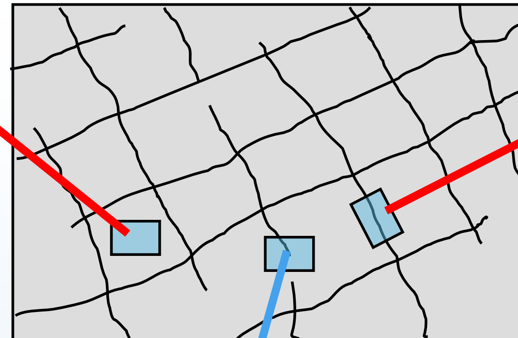




- optimal injection schedule to minimize leakage?
- optimal well spacing to minimize leakage?

Hydromechanical Coupling in Fractured Rock

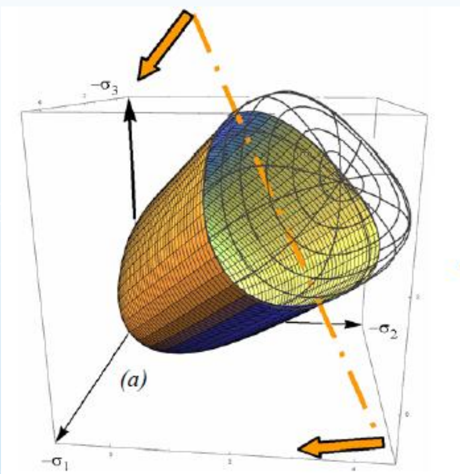
Fractured Caprock



Bulk Constitutive Properties

(from Focus Area 2)

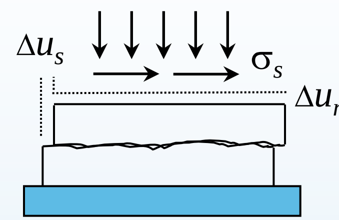
- plasticity model
- limit surface
- effective stress, Biot coeff.



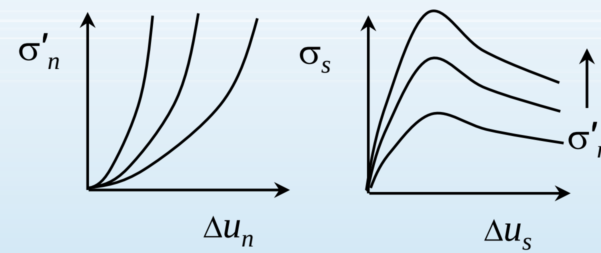
Fracture contact properties

(from Focus Area 2)

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

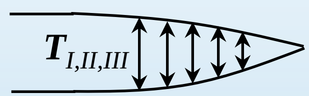


$$\sigma_s = \sigma_s\{\Delta u_s, \Delta u_n\}$$
$$\sigma'_n = \sigma'_n\{\Delta u_s, \Delta u_n\}$$

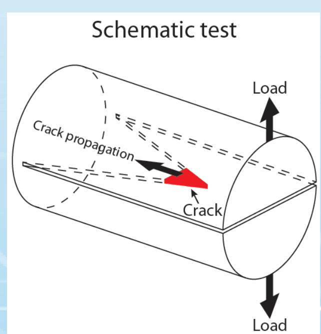


Crack-tip Properties

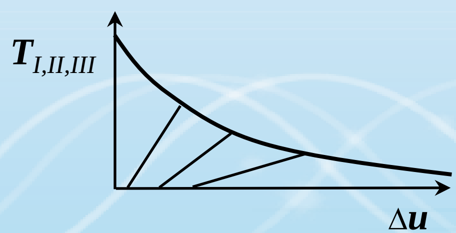
(from Focus Area 2)



Fracture Toughness

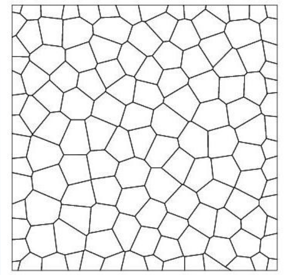


Cohesive Properties

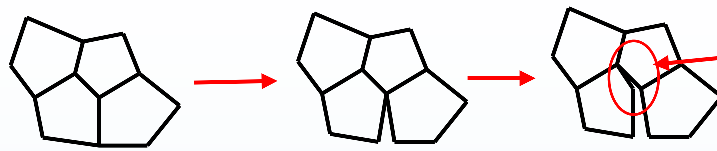


How do these properties change in the presence of sCO_2?

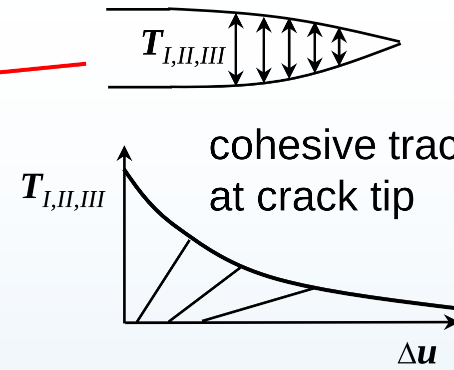
A Finite-Element Method for Modeling Fracture Growth in Disordered Materials



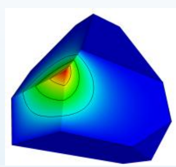
randomly closed packed Voronoi mesh



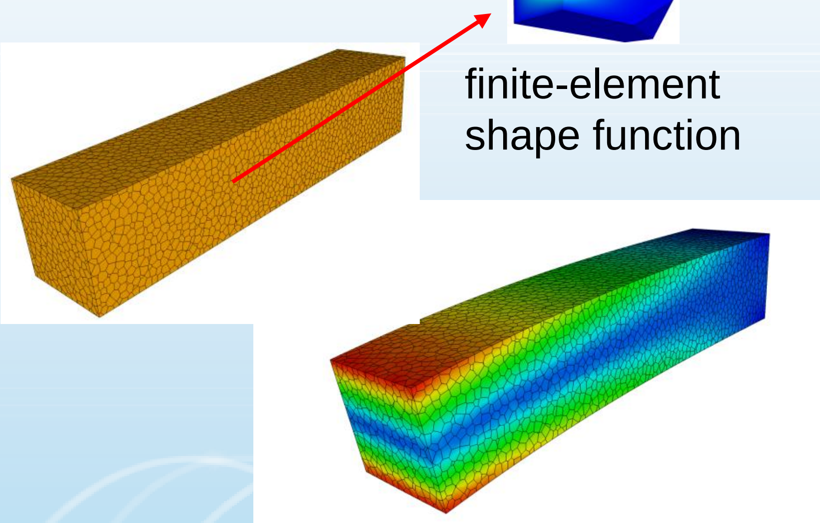
changing mesh connectivity



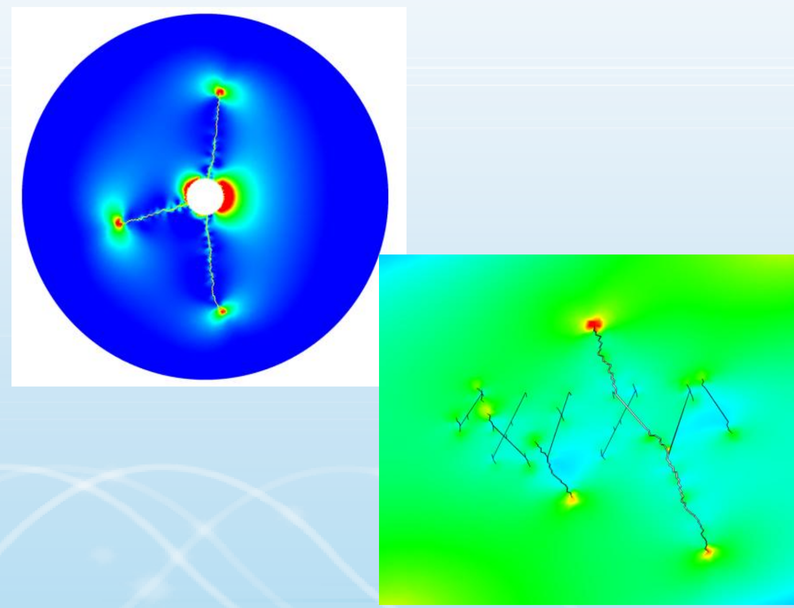
cohesive tractions at crack tip



finite-element shape function

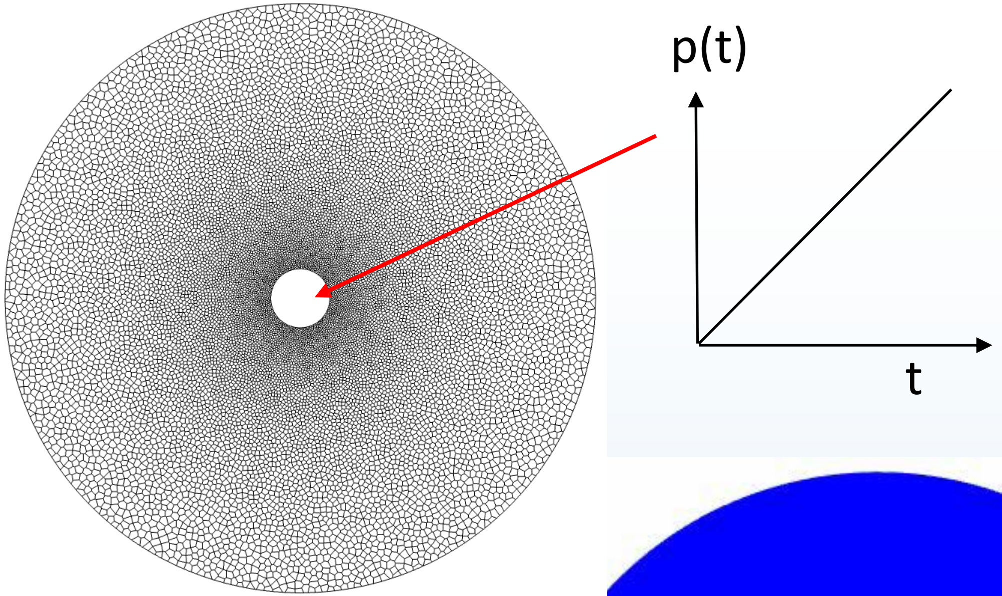


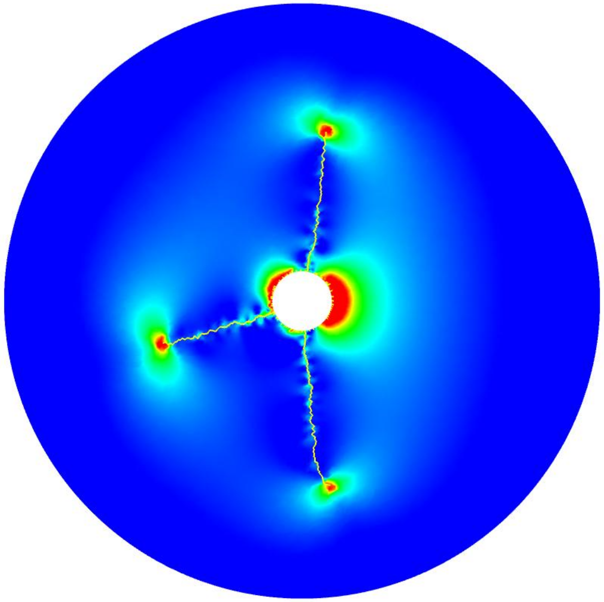
beam-bending verification problem

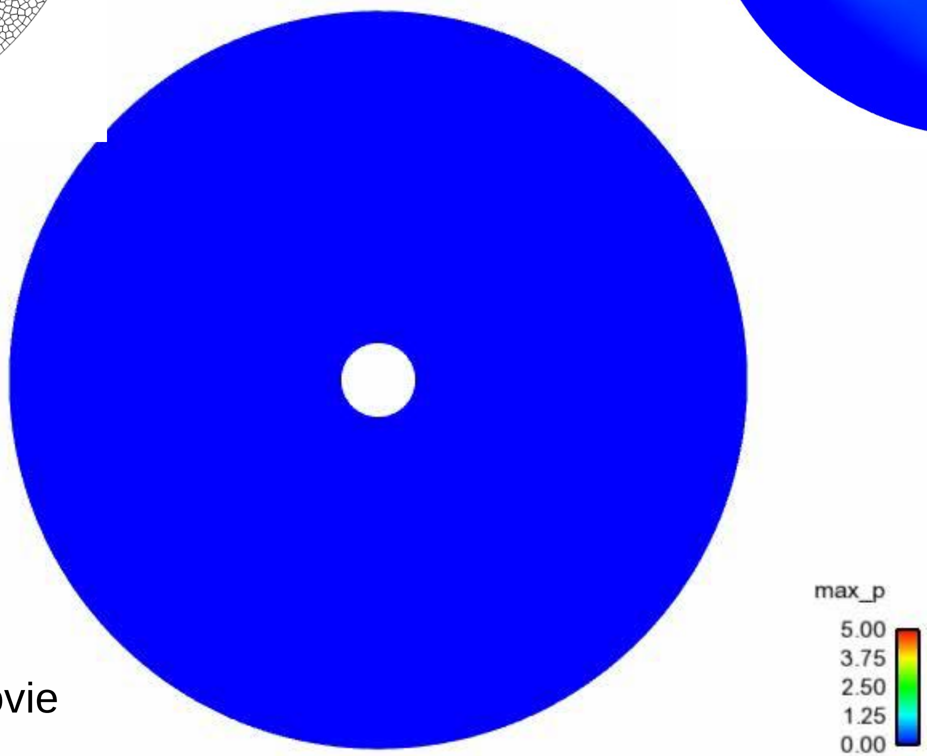


fluid-induced fracture simulations

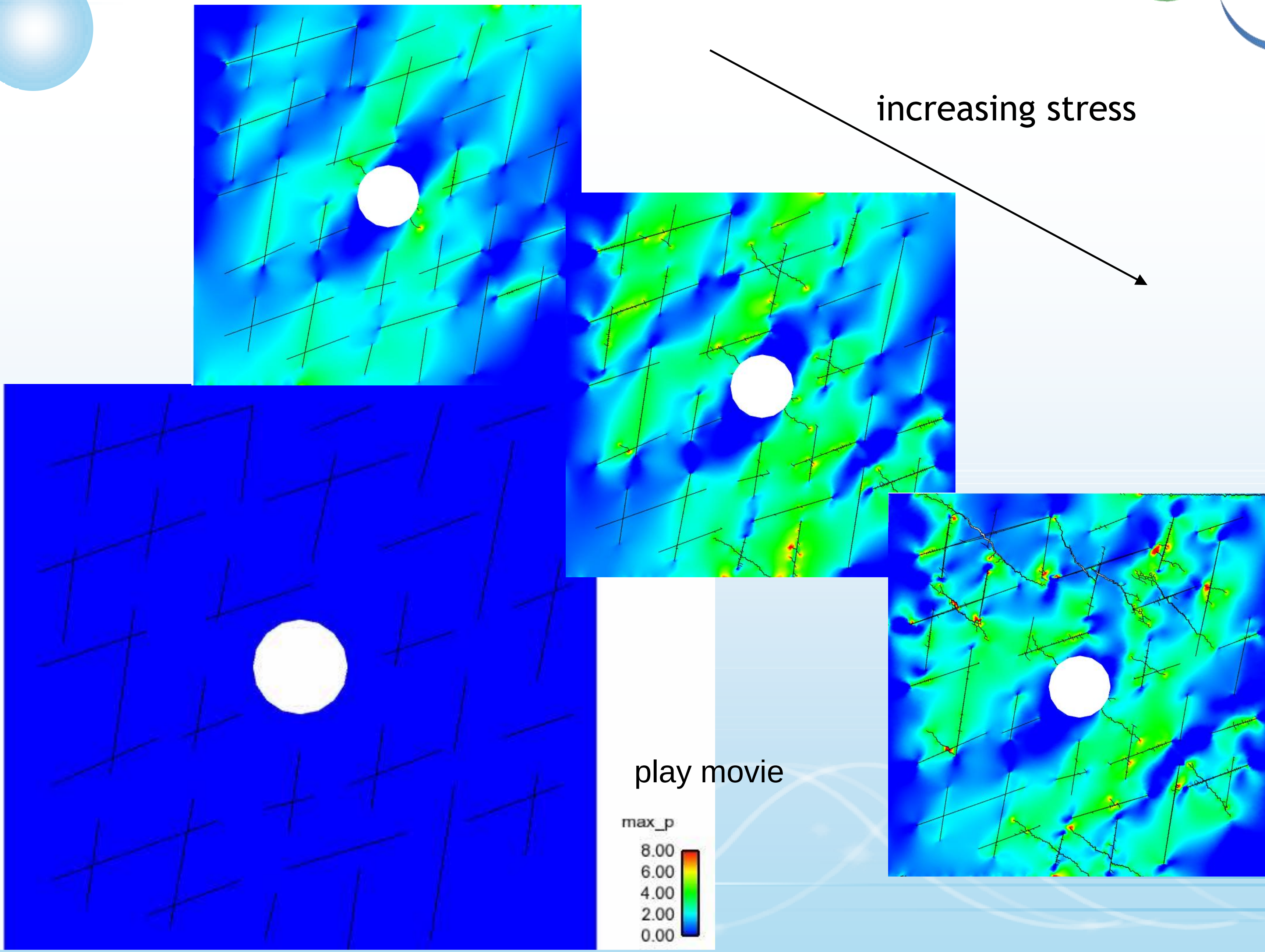
Hydraulic Fracture Simulation







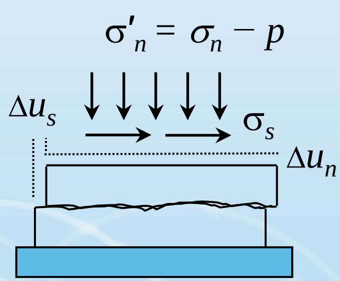
play movie


increasing stress
play movie
max_p
8.00
6.00
4.00
2.00
0.00

Future Work

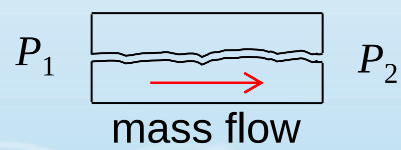
1. Continue development of computational models for modeling injection induced fractures and fluid flow within the fractures
   - work with FA2 to develop cohesive models for fracture growth and initiation for various caprock materials, e.g. mudstones, clay-shales.
   - work with FA2 to develop shear-normal-displacement models for fully open fractures and joints for various caprock materials, e.g. mudstones, clay-shales.
   - work with FA1 and FA2 to develop precipitation, dissolution models for flows in fractures
   - work with FA1, FA2, FA3, to develop scale dependent fracture-flow models

solid mechanics



highly coupled

fluid mechanics



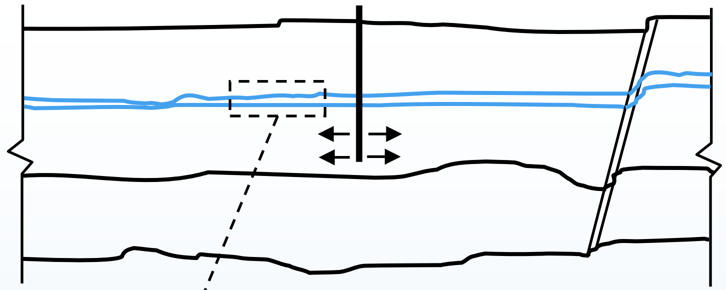
- bioclogging?
- precipitation?
- dissolution?

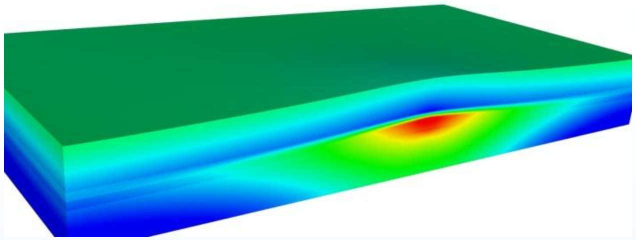
Future Work

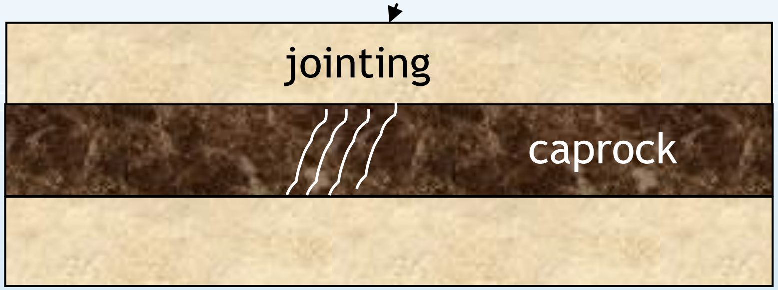
2. Continue development of multi-scale multi-physics numerical methods in collaboration with Univ. Texas (ICES)
   - explore possibility of using UT FA4 mortar methods for caprock integrity simulations, e.g. by allowing fractures to cross mortar boundaries
   - explore possibility of using UT FA2 pore-network models in a fracture context

3. Develop experiments to validate fracture/joint mechanical and flow models using FA1,2,3 lab experiments and site specific data (e.g. Crystal Geyser).

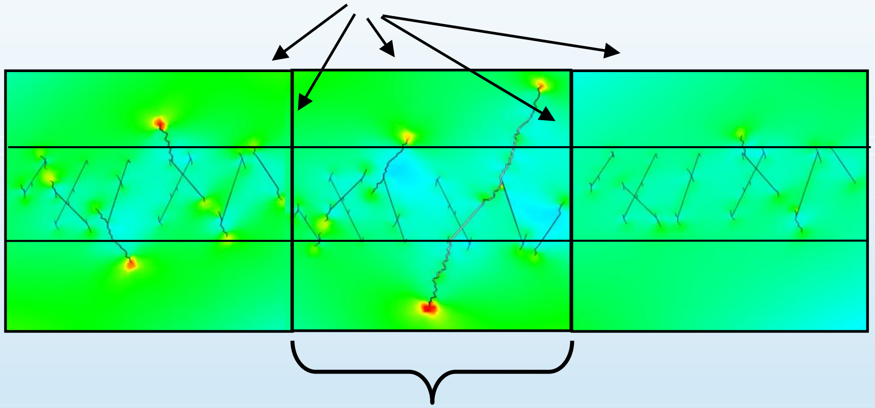
Adaptation of Multiscale Mortar Methods from UT FA4 for Fracture Modeling



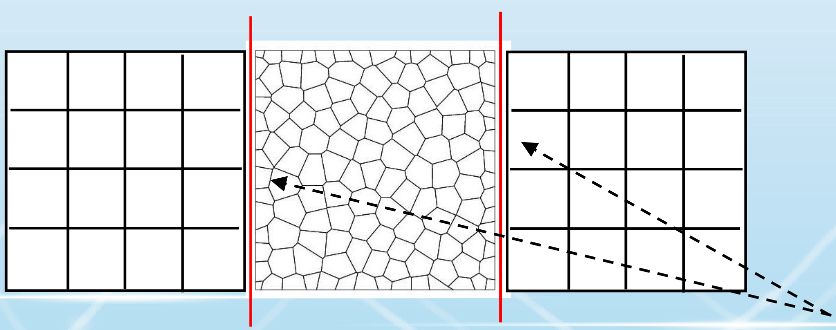




Multiscale mortar methods from UT FA4



Coupled fluid flow / fracture mechanics from Sandia



Multi-scale multi-physics mortars for coupling both fluid-flow and solid-mechanics across disparate finite-element formulations and scales.

Summary

1. A major scientific research question for the feasibility of CO_2 sequestration is the assessment of the integrity of the caprock.
2. Problem is inherently multi-physics and multi-scale (space and time). Fluid-structure interaction is paramount, both at the field scale and micro-scale. Requires a multi-institution, multi-disciplinary team of researchers.
3. A number of new numerical methods are under development for modeling fracture nucleation and propagation in heterogeneous media with subsequent fluid flow on fracture surfaces.