SAND2011-4899C

Coupled Flow and Mechanics in Porous and Fractured Media

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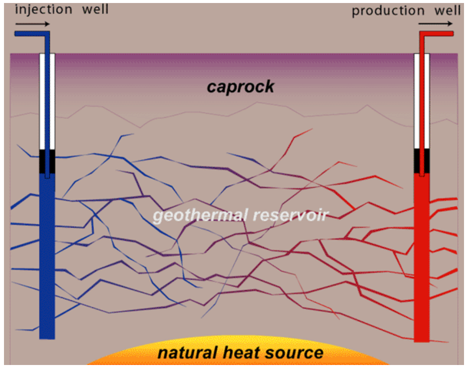
Outline

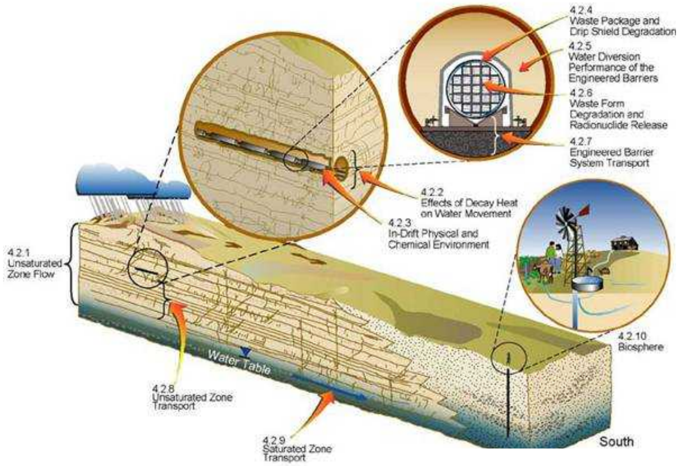
1. Motivation: Geosciences at Sandia National Laboratories
2. Sierra software system
   i. Geoscience capabilities
   ii. Examples
3. Multiphysics coupling in Sierra
4. Coupled flow and geomechanics: CO2 Sequestration
5. Hydromechanical modeling of discrete fracture networks

Geoscience Applications at SNL

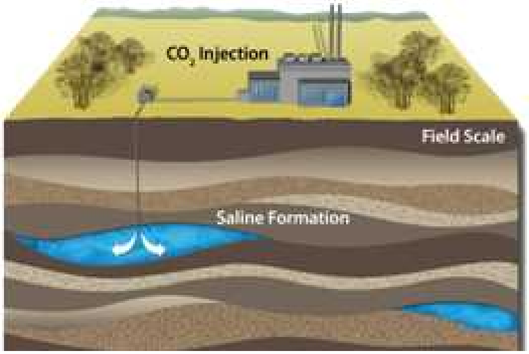
Engineered Geothermal



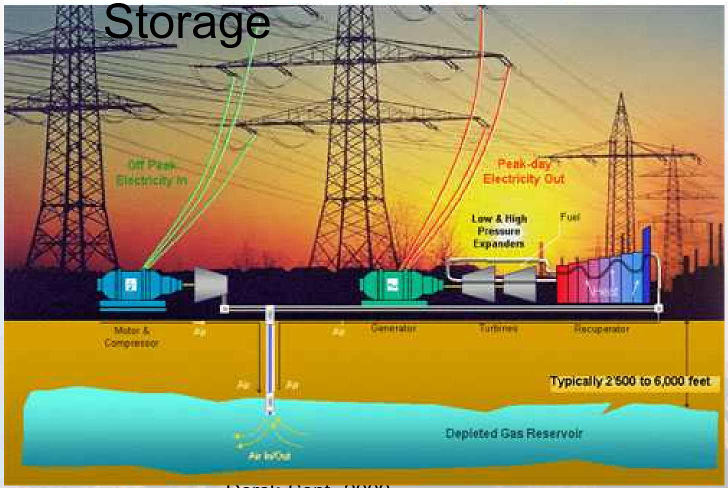
Nuclear Waste Isolation



CO_2 Sequestration

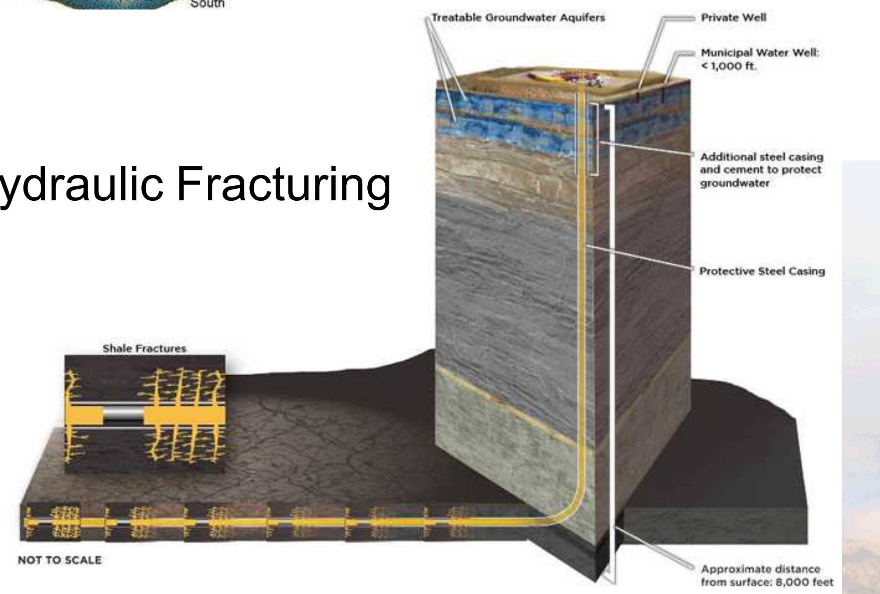


Compressed Air Energy Storage



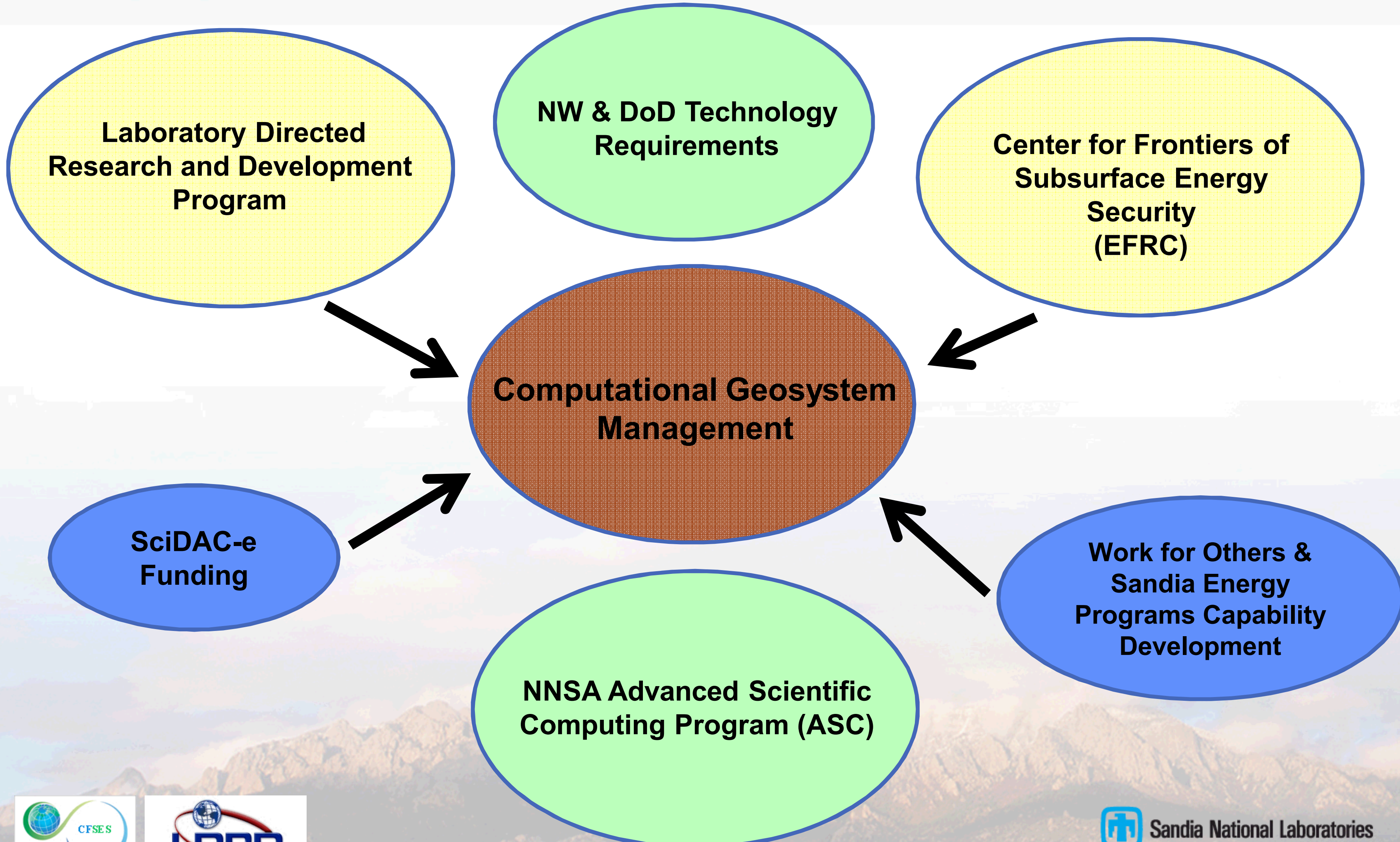
Derek Sept. 2009

Hydraulic Fracturing



http://www.hydraulicfracturing.com

Sandia Computational Geoscience Research and Subsurface Management Program



CFSES

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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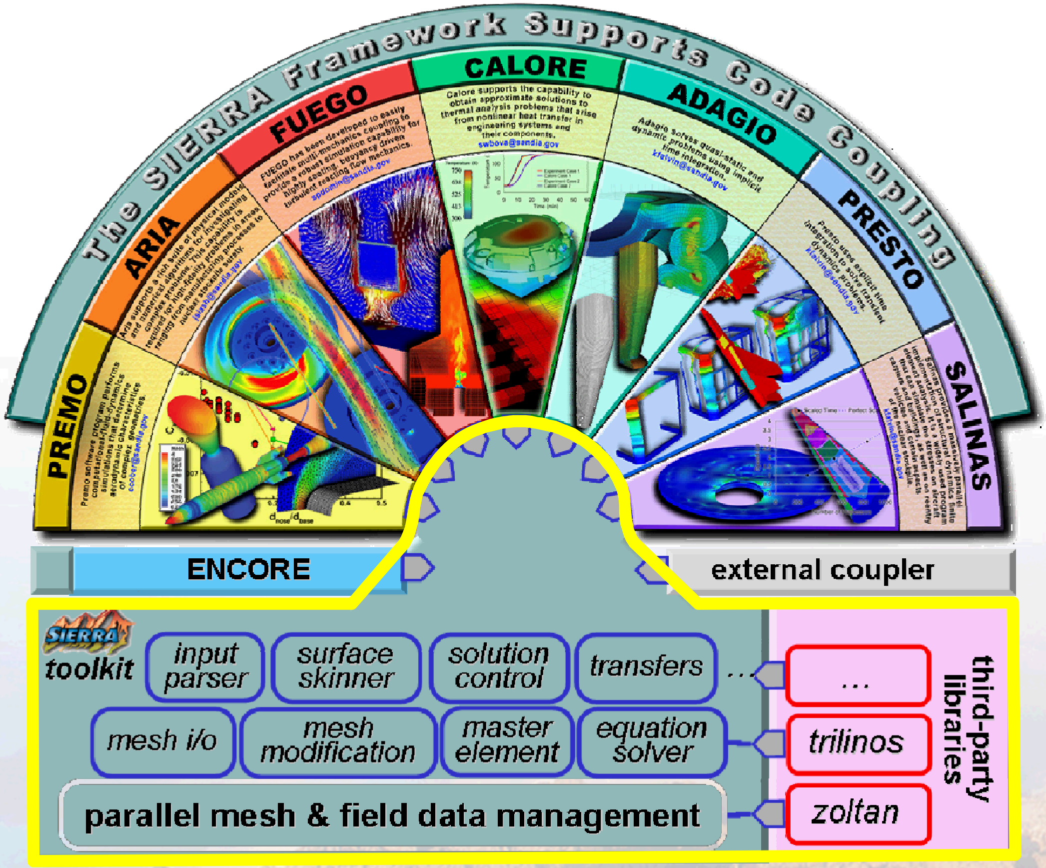
Subsurface simulation software leverages SIERRA Mechanics Foundation

SIERRA_toolkit
FE application code services



Services provided to mechanics applications:

- Mesh & field data management (parallel, distributed)
- Transfer operators for mapping field variables from one mechanics to another
- Solution controller for code coupling: Arpeggio
- Includes third party libraries (e.g. solver libraries, MPI communications package)
- Accommodates heterogeneity

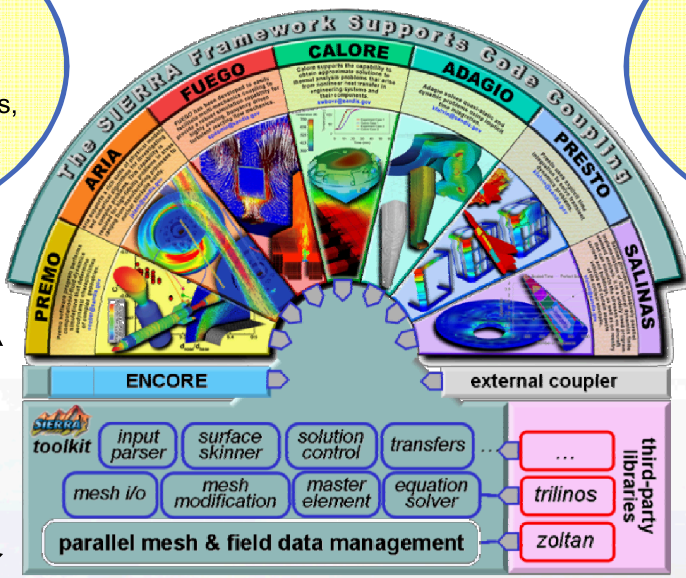
SIERRA Mechanics Represents Enabling Capability for Coupled Geoscience Multiphysics Simulation

•Large deformation, large strain mechanics
•Nonlinear constitutive behavior

Coupling: temperatures, pore pressures, saturations, capillary pressure

•Multiphase, multicomponent, noisothermal porous flow

Coupling: displacements, stresses, permeability, porosity



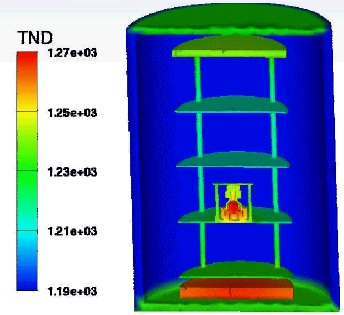
Heterogeneity
•Material
•Initial state

Coupled Algorithms

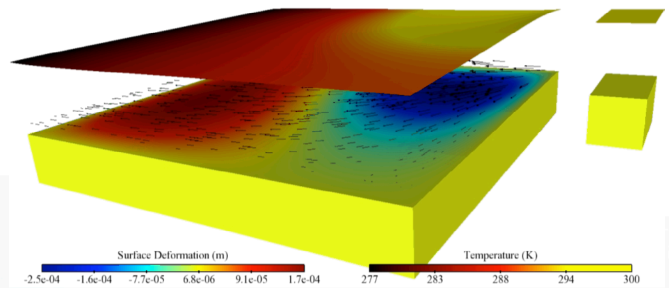
•Sorption
•Reaction-transport modeling
•Water/rock interaction kinetics
•Brine/CO2 reactions

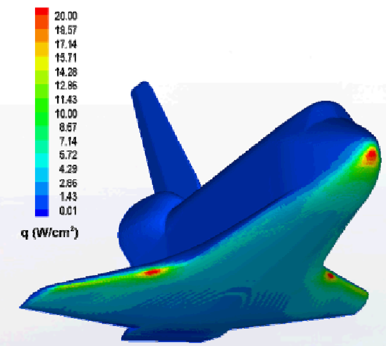
Coupling: temperature, porosity, Darcy velocity, permeability

SNL Thermal/Fluid Modeling Capabilities in Sierra Mechanics

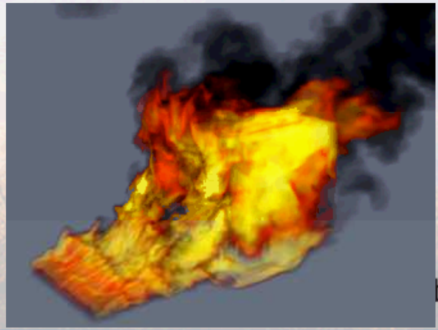


- **Aria** – Non-Newtonian, Multi-physics, and Free Surface Flows
  - Fully-Coupled, Galerkin FEM (GFEM)
  - Complex material response
  - Level sets for surface tracking
  - Flexible coupling schemes
- **Calore** – Heat Transfer, Enclosure Radiation and Chemistry
  - Galerkin FEM (GFEM)
  - Dynamic enclosures
  - Element birth death
  - Contact



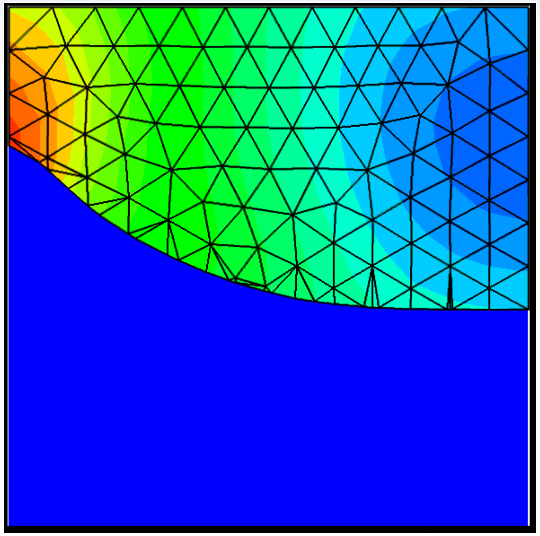


- **Premo** – Compressible Fluid Mechanics
  - Fully-Coupled, Edge-Based Finite Volume (node centered)
  - Subsonic through hypersonic
  - Laminar and turbulent
- **Fuego** – Low Speed, Variable Density, Chemically Reacting Flows (Fire)
  - Loosely-Coupled, Control Volume FEM (CVFEM)
  - Eddy dissipation and mixture fraction reaction models
  - RANS and LES based turbulence models
  - Pressurization models



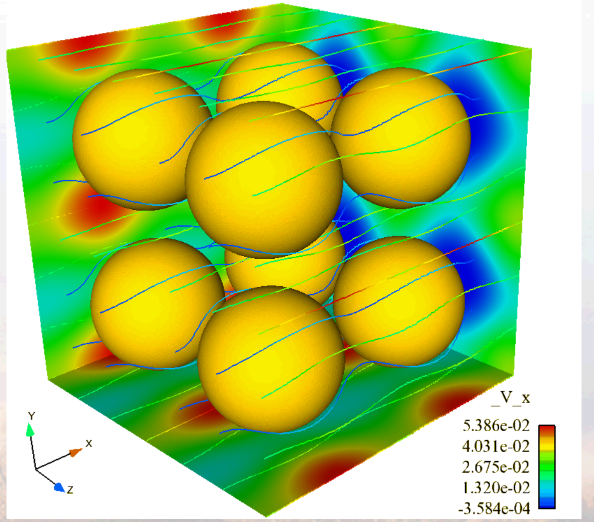
CDFEM Capability Development Status

Objective:
Implement CDFEM capability in Sierra Mechanics to track moving interfaces and capture interfacial physics between multiple materials or phases



Approach:
- Use level set technology to capture implicit interfaces
- Decompose non-conformal elements into conformal ones and obtain solution on conformal elements
- Use ALE technology to handle nodes that change phase

Accomplishments:
- Implemented CDFEM for steady state and transient interface problems
- Capability verified to scale well in parallel
- Tested on air-water capillary flows, solid suspension flows, and thermal phase change problems
- Verified accuracy of CDFEM to be 2nd order for potential flow, conduction, two fluid viscous flow, and blunt body flow problems

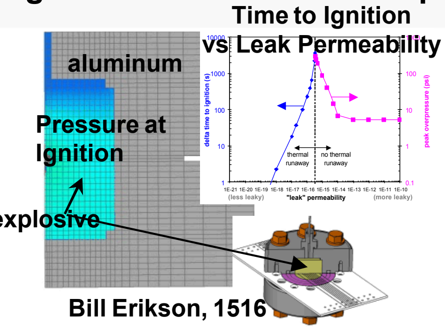


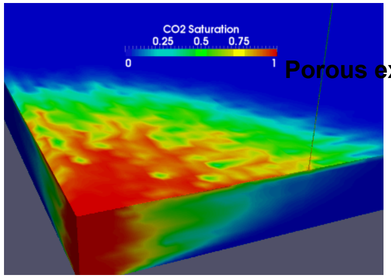
Status:
- Extending scheme to track interface based on various interfacial physics including reactions, phase change, and thermal degradation
- Extending capability to multiple phases (more than two)

Overview of Porous Flow in Aria

- **Leveraged development under LDRD & EFRC**
  - Targets SNL activities in energy security, conventional munitions, thermal batteries, heat pipes, …
- **Current capabilities**
  - Single phase heat and reactive mass flow
  - Immiscible two-phase flow
  - Two-phase, two-component (air & water) evaporating/condensing thermal model
  - Chemically reactive flows (e.g. calcite mineralization)
  - Spatially heterogeneous material and transport properties
  - Couples with mechanics and other Sierra physics modules
- **Capability under development**
  - Nonisothermal two-phase CO2-H2O-NACL EOS with general phase behavior
  - Advanced discretization schemes (UT technology)

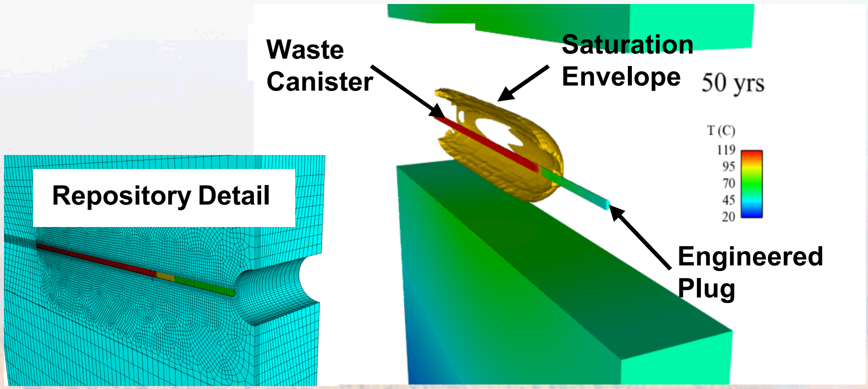
Modeling Cook-Off in Granular Explosives





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

Heat-Generating Waste Disposal



Development of a confining saturation envelope in ultra-low permeability clays, trapping gases within.

Boundary and Initial Conditions

- Initial Conditions
  - Element block dependent
  - Function of coordinates
    - Linear, quadratic built-in
  - Output file from a previous solution
  - User Plug-in
- Dirichlet BCs (nodeset, sideset)
  - f(*t*,x,soln_vector,expression)
    - Many built-in forms
  - Plug-in
- Flux BCs (sidesets)
  - f(*t*,x,soln_vector,expression)
  - Many built-in forms
    - Third-type BCs
  - Outflow (e.g. wells)
  - Periodic
  - XFER – values set from a transfer
  - Encore function
  - Plug-in
- Distinguishing Condition (constraint)
  - Replaces original equation
  - Implemented in weak form
  - E.g. Kinematic BC with deforming mesh (ALE):

$$R^i = \int_S \left(\mathbf{n} \bullet (\mathbf{v} - \dot{\mathbf{x}}) - v_{leak} \right) N^i \, dS = 0$$

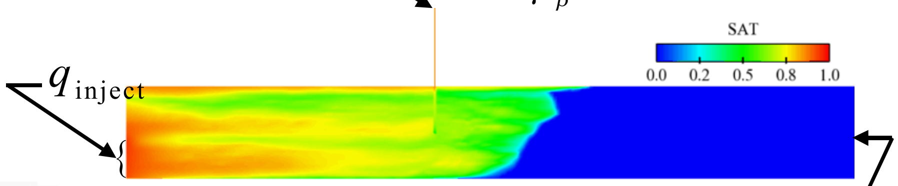
Fingering of CO_2 Injected into a Heterogeneous Aquifer with Leaky Well

Hydrostatic IC

$$p(z) = p_{ref} - \rho g z$$

Outflow BC

$$q_\beta = \rho_\beta \frac{k_{r\beta}}{\mu_\beta} k(PI)\left(p_\beta - p_{ref}\right)$$



Hydrostatic BC

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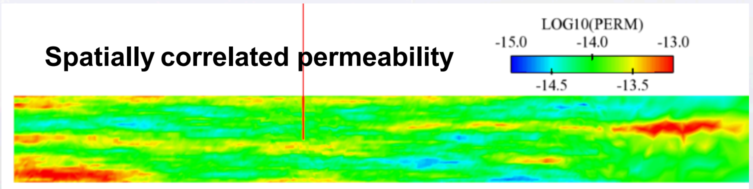

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Aria Multiphase Porous Flow Physics

Two-Phase Two-Component Non-Isothermal Model (water, air, energy)

- Water - steam tables, equilibrium thermodynamic phase partitioning
- Air - ideal gas, Henry's Law partitioning
- Energy - conduction, latent and sensible energy transfer, including binary diffusion of heat
- Evaporating/condensing flows
- Phase appearance/disappearance via persistent variables approach
- General specification of transport property dependence on solution vector (e.g., densities, viscosities, diffusion coeffs. depend on T, P, phase volume fraction)
- Capillary pressure, relative permeability models
- Specification of heterogeneous property fields (e.g. permeability, porosity, GSLIB linkage)
- Other EOS under development

Aria Porous Flow Physics

Two-Phase Heat and Mass Flow

Mathematical Model

- **Two-Phase Component Mass and Energy Balances:**

$$\frac{\partial}{\partial t}\begin{bmatrix}\phi\left(S_l\rho_l^w + S_g\rho_g^w\right)\\ \phi\left(S_l\rho_l^a + S_g\rho_g^a\right)\\ (1-\phi)\rho_s e_s + \phi\left(\rho_l S_l e_l + \rho_g S_g e_g\right)\end{bmatrix} + \nabla\bullet\begin{bmatrix}\mathbf{F}_l^w + \mathbf{F}_g^w\\ \mathbf{F}_l^a + \mathbf{F}_g^a\\ \mathbf{q}_e\end{bmatrix} + \begin{bmatrix}Q_w\\ Q_a\\ Q_e\end{bmatrix} \quad \begin{matrix}\text{water}\\ \text{air}\\ \text{energy}\end{matrix}$$

- **Net Mass Flux:**

$$\mathbf{F}_\beta^\alpha = Y_\beta^\alpha \rho_\beta \mathbf{v}_\beta + \mathbf{J}_\beta^\alpha$$

$$\alpha = \text{component}$$

$$\beta = \text{phase}$$

- **Darcy Velocity:**

$$\mathbf{v}_\beta = -\frac{k_{r\beta}}{\mu_\beta}\mathbf{k}\bullet\left(\nabla P_\beta - \rho_\beta \mathbf{g}\right)$$

- **Binary Diffusion (gas phase):**

$$\mathbf{J}_g^\alpha = -\rho_g D_g^\alpha \nabla Y_g^\alpha$$

Aria Porous Flow Physics

Two-Phase Heat and Mass Flow

Mathematical Model (cont.)

- Total Energy Flux (heat conduction, convection, binary diffusion):

$$\mathbf{q}_e = -\lambda_T \nabla T + \sum_{\beta} \rho_\beta \mathbf{v}_\beta h_\beta + \sum_{\alpha} h_g^\alpha \mathbf{J}_g^\alpha$$

- Saturation Constraint: $S_l + S_g = 1$

- Mixing Rules: $\sum_{\beta=l,g} Y_\beta^\alpha = 1, \qquad \alpha = w\,(\text{water}),\ a\,(\text{air})$

- Capillary Pressure: $P_g - P_l = P_c(S_l)$

- Relative Permebility: $k_{r,\beta} = f(S_l, T, \ldots)$

Spatial Discretization

- **Unstructured Grid Finite Element-Based Discretization**
- **Finite-dimensional basis representation:** $f(x,u) = \sum_J N_J(x) f_J(u)$
- **Residual-based implicit weak formulation:**

$$\begin{bmatrix} R_{w,I} \\ R_{a,I} \\ R_{e,I} \end{bmatrix} = \int_\Omega N_I \sum_J N_J \begin{bmatrix} \dot{d}_{w,J} \\ \dot{d}_{w,J} \\ \dot{e}_J \end{bmatrix} d\Omega - \int_\Omega \nabla N_I \bullet \begin{bmatrix} \mathbf{F}_w \\ \mathbf{F}_a \\ \mathbf{q}_e \end{bmatrix} d\Omega - \int_\Omega N_I \begin{bmatrix} Q_w \\ Q_a \\ Q_e \end{bmatrix} d\Omega + \int_\Gamma N_I \begin{bmatrix} \mathbf{F}_w \bullet \mathbf{n} \\ \mathbf{F}_a \bullet \mathbf{n} \\ \mathbf{q}_e \bullet \mathbf{n} \end{bmatrix} d\Gamma$$

Hybrid Features:

- **Mass lumping for multiphase systems**
- **Control-volume finite element upwind scheme for convective terms**
  - **Supports tensor permeability**

Nonlinear Solution Procedures

Discretization leads to nonlinear system:

$$\mathbf{R}(\mathbf{u}) = (\mathbf{R}_w, \mathbf{R}_a, \mathbf{R}_e)^T = \mathbf{0}$$

Nonlinear Solve:

– **Newton Iteration**

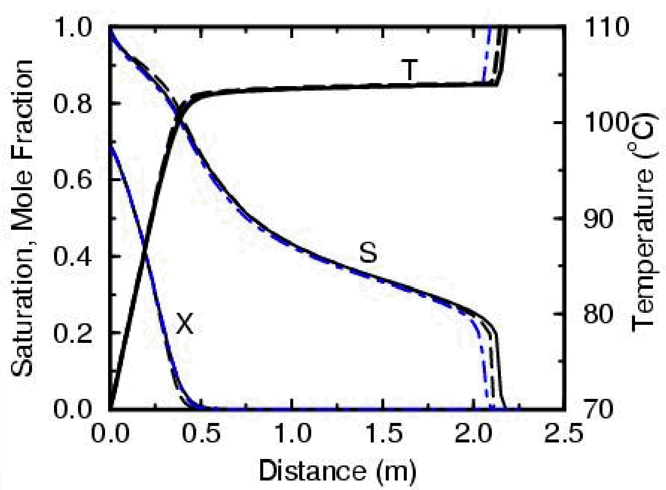
$$\mathbf{J}(\mathbf{u}^q)\delta\mathbf{u}^{q+1} = -\mathbf{R}(\mathbf{u}^q)$$

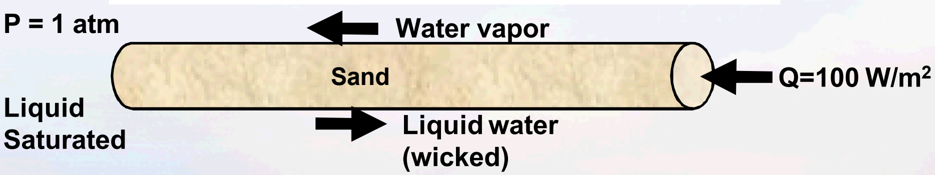
$$\mathbf{u}^{q+1} = \mathbf{u}^q + \delta\mathbf{u}^{q+1}$$

Coupled Mass and Heat Flow Examples

Porous Heat Pipe with Non-Condensible Gas

(solid – PorSalsa/upwind, dashed – TOUGH2/upwind, dash-dot – Aria/gfem)

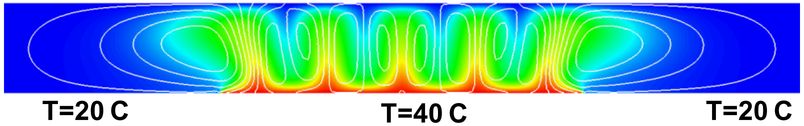




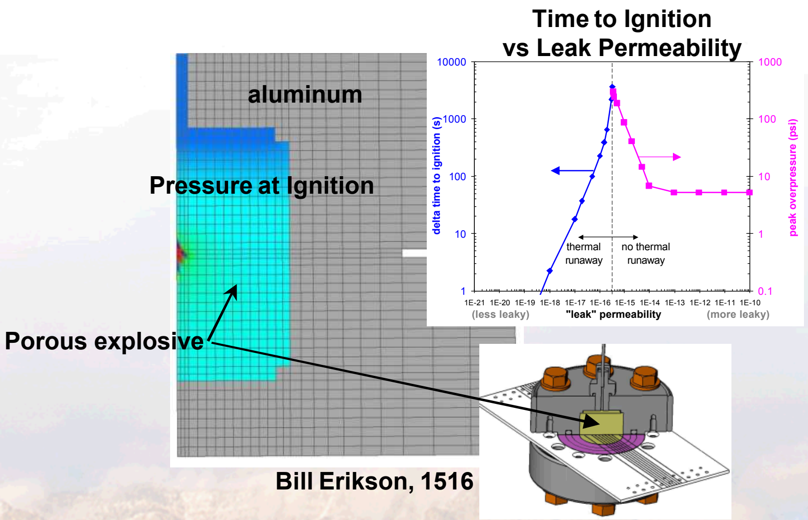
Elder Problem

Buoyant Convection in a Porous Layer

Ra = 150



Modeling Cook-Off in Granular Explosives



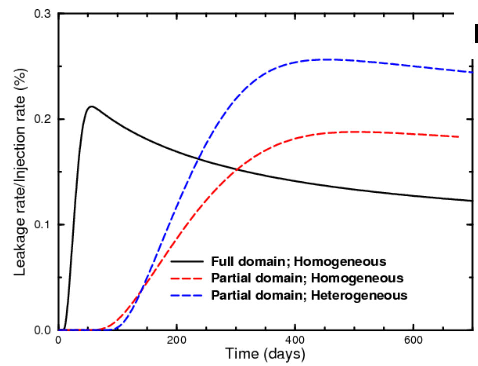
CO_2 Leakage Through an Abandoned Well

Reference Problem Description:
- 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
- 500 k elements, 1200 day injection

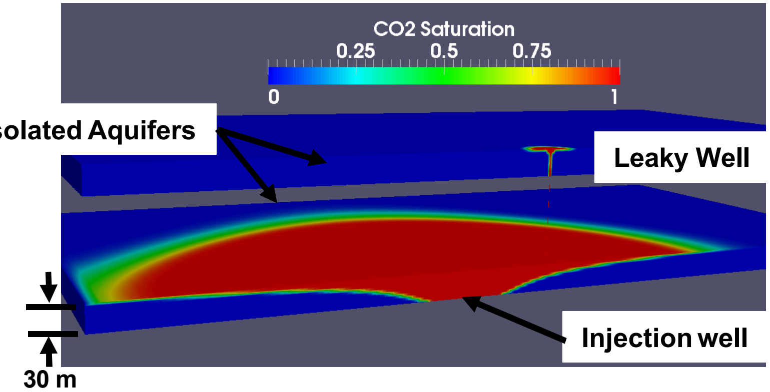
Assumptions:
- Isothermal injection process
- CO_2 and brine immiscible phases
- Isotropic formation
- Neglect capillary pressure

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

Leakage Rate (%)



CO_2 Distribution at 200 days

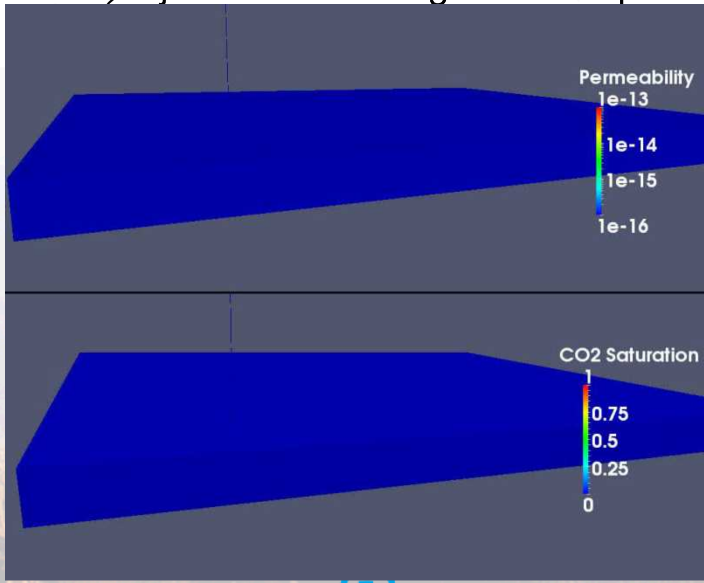


Effects of Heterogeneous Permeability:
- Geologic aquifers are highly heterogeneous
- Truncated domain allows multiple realizations
- Lognormal distribution of permeability, normal distribution of porosity
- Highly non-uniform (fingering) injection in the presence of heterogeneity
- Lognormal permeability increases the leakage rate

CO_2 Injection in Heterogeneous Aquifer

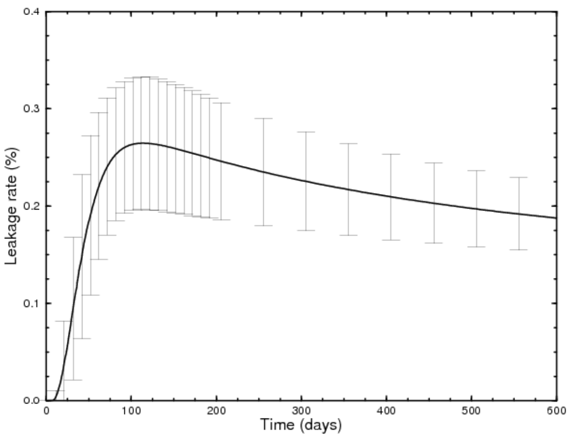
Lognormal Permeability

CO_2 Fingering with Heterogeneity



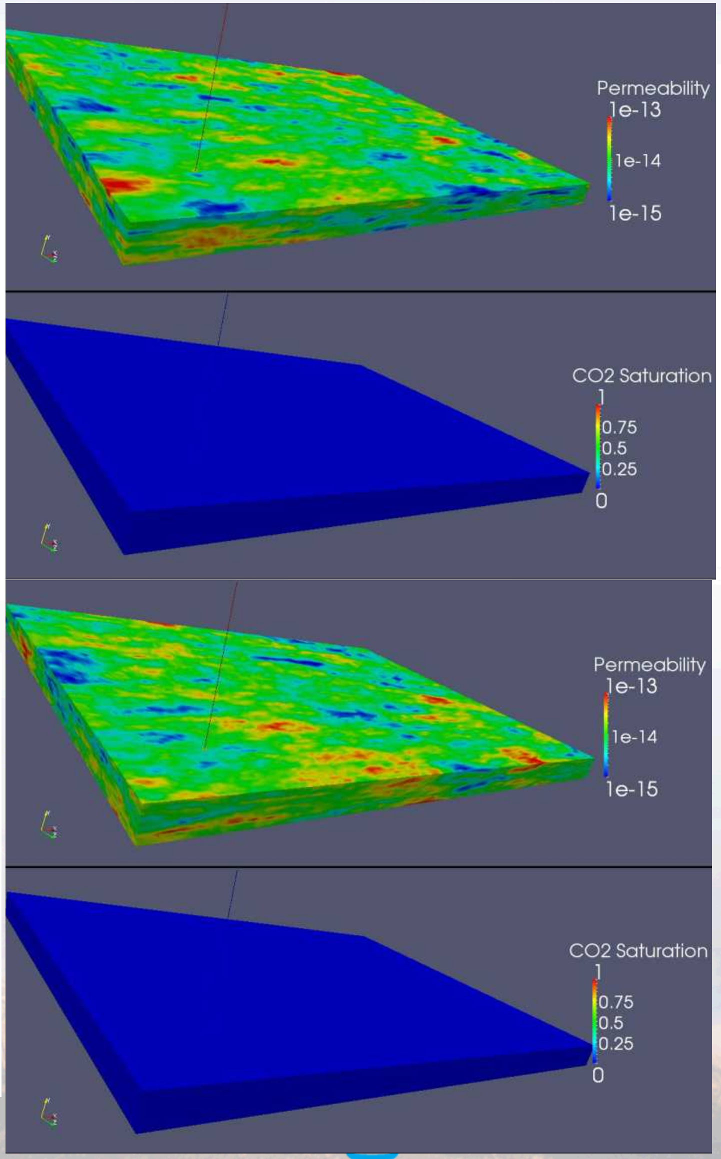
CO2 Leakage Through an Abandoned Well
Effects of Heterogeneity

Average Leakage Rate and Std. Dev.

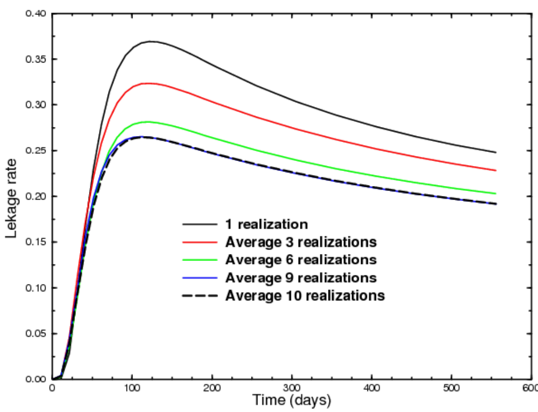


Some Results
(10 realizations)

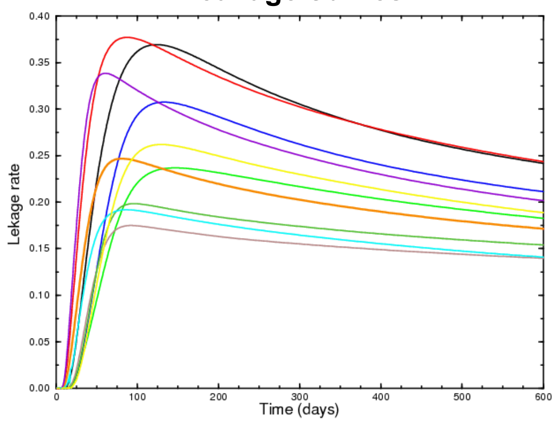
- Correlation between fast paths and permeability distribution is evident
- Leakage, arrival time are heavily dependent on permeability distribution
- Standard deviations are substantial
- Appears useful results can be obtained from a few realizations



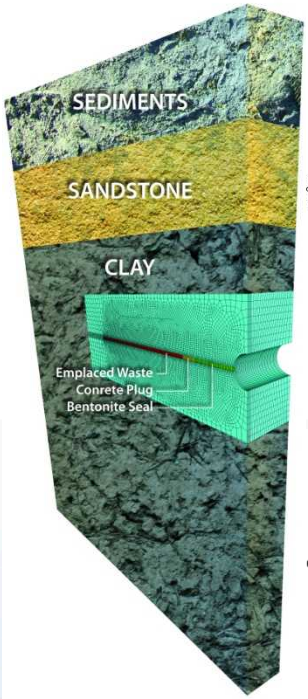
Leakage Rate: Running Average



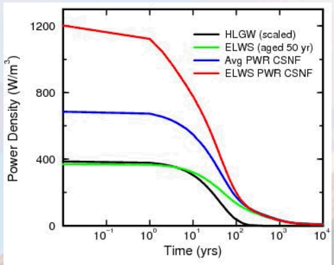
Leakage Curves



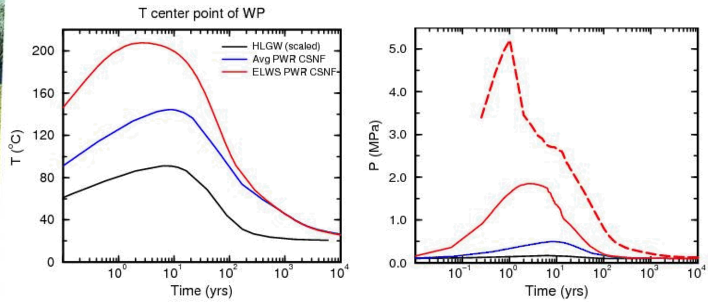
High Level Waste Disposal in Clay
Thermo-Hydrologic Features



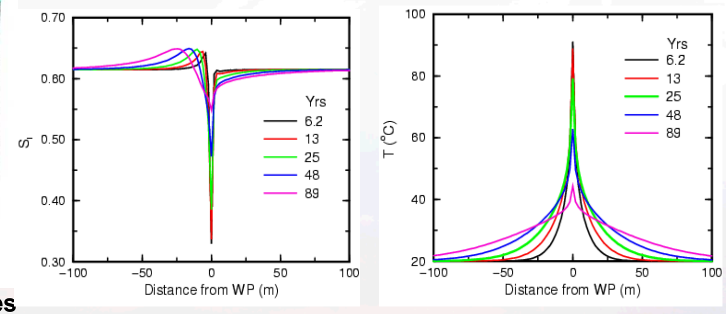
Sample Power Densities



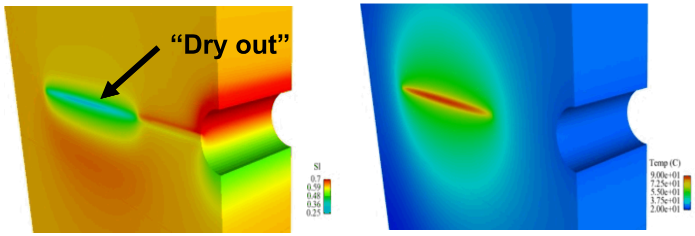
Repository Temperature and Pressure

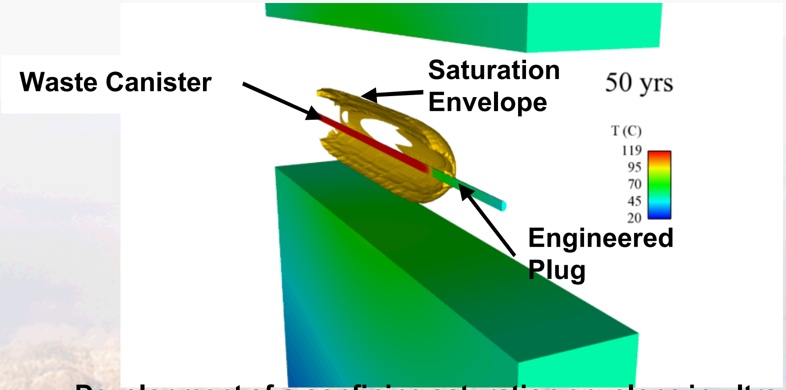


Spatial Variation of Temperature and Pressure



High decay powers in ultra-low permeability clays can result in dry out regions and saturation envelopes.





Development of a confining saturation envelope in ultra-low permeability clays, trapping gases within.

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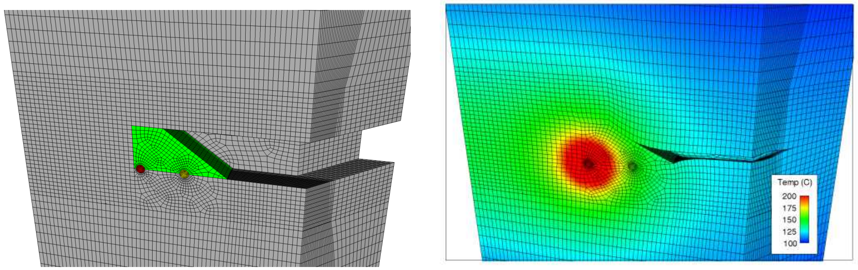
Overview of Geomechanics in Adagio

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

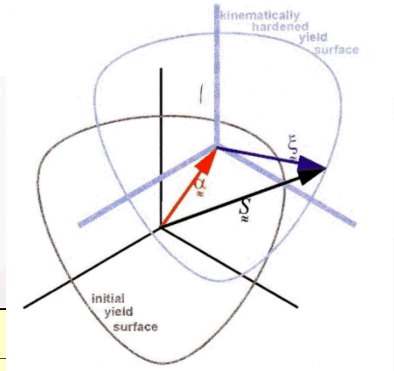
Thermally Enhanced Creep Closure

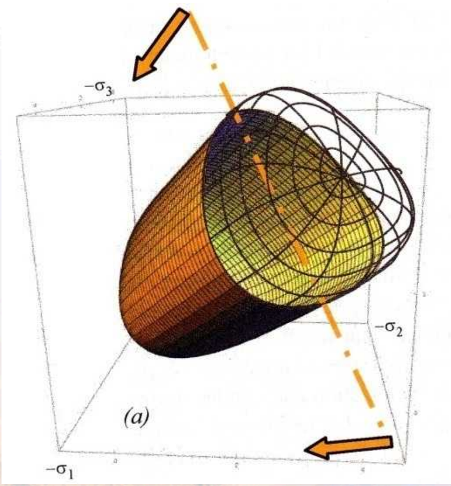


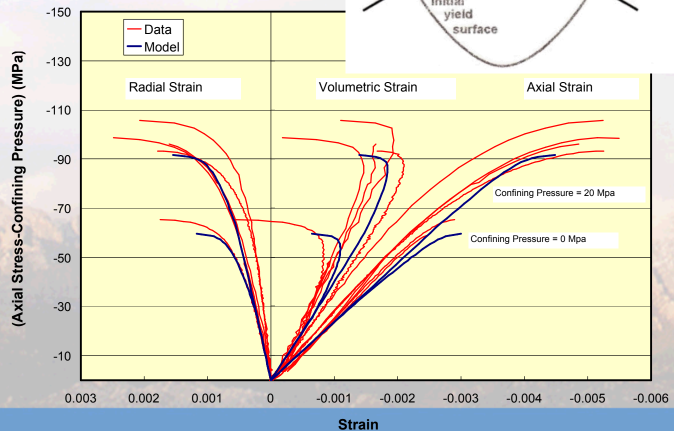
Undeformed and Deformed Storage Tunnels in a Heated Salt Repository

Models for Geomechanics:

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







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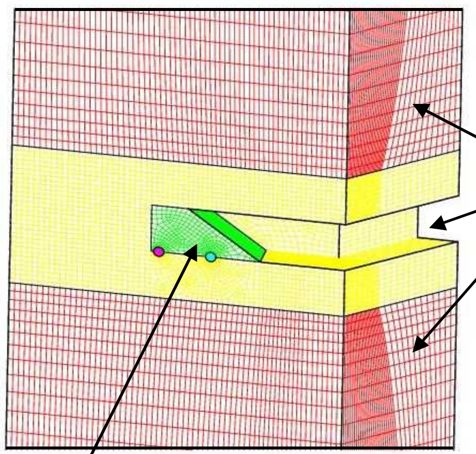
Sierra Mechanics Simulation of Salt Repository



- Three-dimensional fully coupled thermal/mechanical analysis
- Massively Parallel Calculation - 96 processors
- Dissimilar meshes and domains for thermal and structural mechanics
- Contact surfaces used for both thermal and structural problems

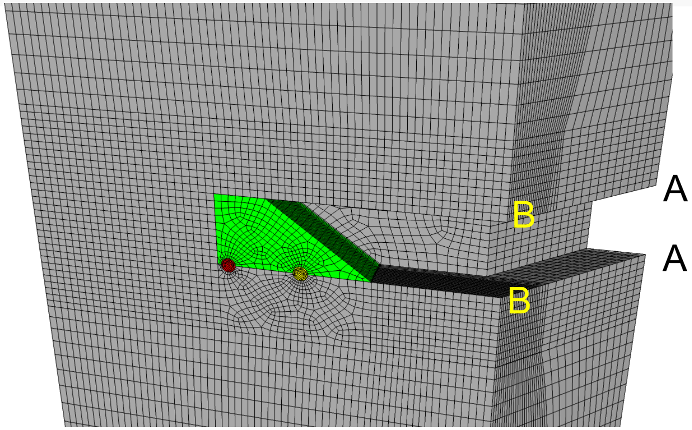
Thermal Analysis Features:

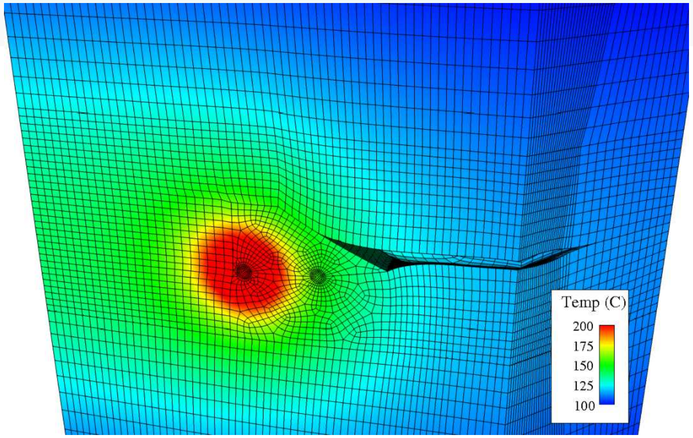
- 904736 nodes / 864927 elements
- Contact surfaces used to accommodate heat conduction between contacting surfaces (alcove and haulage way)
- Re-computation of radiation view factors for deforming heated room surfaces

Structural Analysis Features:

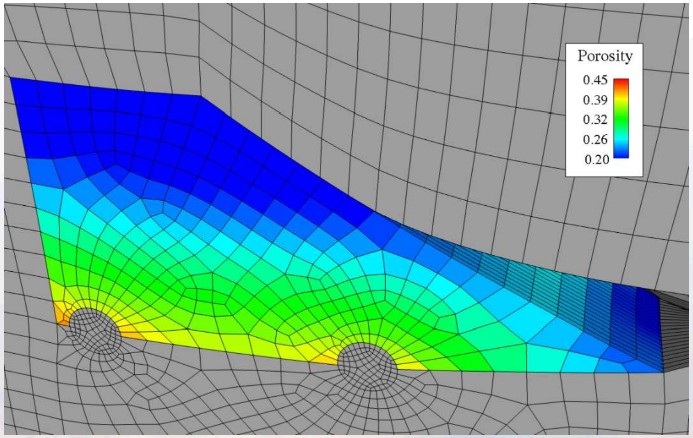
- Quasistatic analysis with 294698 nodes / 279537 elements
- Large deformation, large strain formulation
- Nonlinear power law secondary creep model for salt
- Volumetric compaction model for the crushed salt
- Contact surfaces defined to allow arbitrary roof, rib, and floor contact
- Temperature dependent material properties

Generic Salt Repository Closure Details





Generic salt repository final deformed state



Corresponding porosity in crushed salt backfill

Cross-section A-A

Cross-section B-B

Solving Multiphysics Problems
Trade-offs in Coupling Strategies

Full Coupling

- Provides a consistent solution
- Known convergence properties
- Expensive to solve
- Requires compatible algorithms among physics

Tight / Loose Coupling

- Can be efficient to solve (smaller, nicer matrices)
- Allows separate meshes, time steps, discretizations
- Best de-coupling may be unknown
- May be more expensive in the long run

Building Blocks for Coupled Equations

Region: a mesh and set of fields

- One or more equations, constraints, etc.
- Aria: implicitly solved equations in a single matrix
  - Newton (Analytic + AD + FD)
  - Newton Finite Difference
  - Trilinos::NOX

Multiple Regions can be coupled with "transfers"

- Fields are copied/interpolated between Regions
- Entire mesh or select blocks, sidesets, etc.
- Can have different discretizations (Q1 ←→ P0)
- Sequencing is user defined

Solving Multiphysics Problems
Solution Control Building Blocks

- Blocks you can use
  - `INITIALIZE` - Defines initialization sequence, including transfers
  - `SEQUENTIAL` - Once through pass (direct-to-steady-state)
  - `TRANSIENT` - Time iterative loop, all members at same time step size
  - `SUBCYCLE` - Sub-cycling within a transient block
  - `NONLINEAR` - Nonlinear iteration of members

- Lines you'll see in blocks
  - `ADVANCE` - Think of this as "move one step forward"
  - `TRANSFER` - Copy/interpolation fields from one Region to another
  - `EVENT` - Custom functions defined by different Sierra components
  - Others, like `INDICATE`, `MARK`, `ADAPT`, …

- When clauses:
  - Allow conditional execution of lines, e.g.,

    ```
    Advance Aria_Region when "CURRENT_STEP % 10 == 0"
    ```
  - Custom functions can be created and plugged in

Input File Structure Reveals Execution Hierarchy

Domain →

```
Begin Sierra job_name
   Define Materials
   Define "Finite Element Model":
      Mesh & Materials
   Define Linear Solvers
   Begin Procedure procedure_name
      Define Solution Control
         (e.g., time stepping)

      Begin Aria Region region_name
         Nonlinear Solver Settings
         Equation Definitions
         Boundary Conditions
         Sources
         Post-processors
         Output File Definition

      End
   End
End
```

Procedure → Begin Procedure

Region → Begin Aria Region

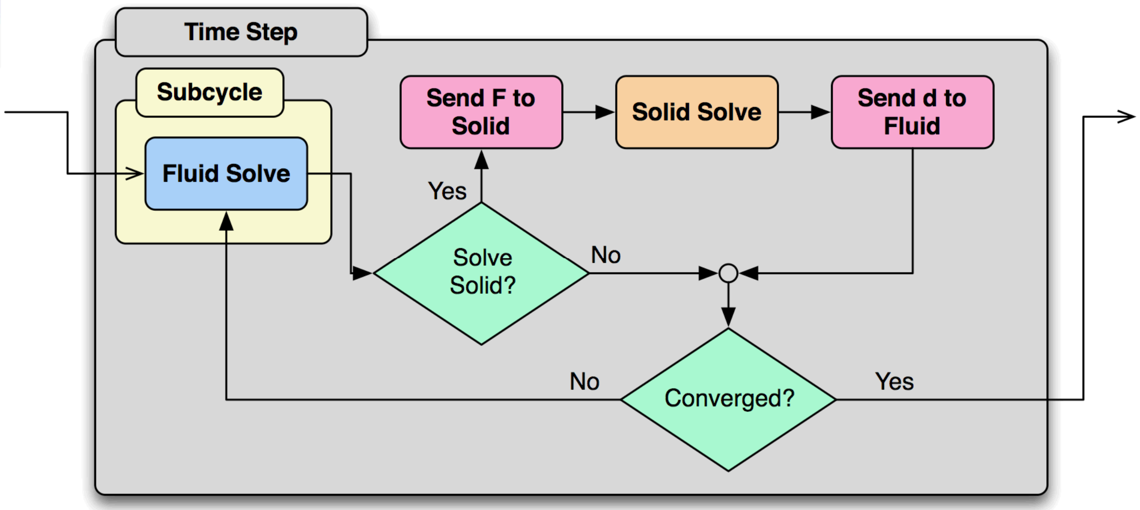
Procedure: solution control instructions

•multiple procedures allowed within a doman

Region: a mesh and set of fields

• multiple regions allowed within a procedure

Conditional Loose Coupling with Nonlinear Iteration and Subcycling

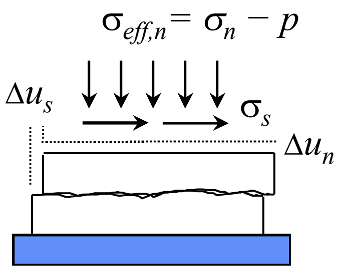



```
Begin System Main
  Use Initialize MyInit
  Begin Transient MyTransient
    Begin Nonlinear MyNonlinearLoop
      Begin Subcycle MySubcycle
         Advance AriaRegion
      End
      Transfer ForceAriaForceAdagio when "Solve_Solid()"
      Advance AdagioRegion when "Solve_Solid()"
      Transfer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

Coupling Multiphase Flow and Geomechanics

Effective stress principle: $\bar{\sigma}_{eff} = \sigma^{T} + \alpha p_{eff}$ e.g., $p_{eff} = p_w S_w + p_n S_n$

- effective stress is used the constitutive models
- equilibrium is based on total stress – balance of external forces



Porosity maps from deformation gradient: $\dfrac{1-\phi_0}{1-\phi} = \det \mathbf{F}(\mathbf{u})$

- deforming grids in flow and mechanics
- permeability models can depend on porosity or other damage criteria

Coupled Flow and Geomechanics

Injection into an Reservoir/Caprock System

Motivation

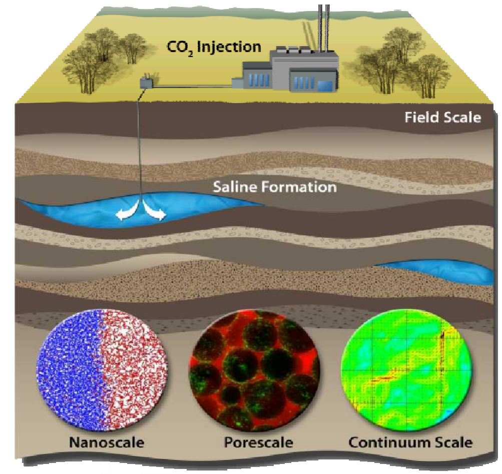
Global consumption of fossil fuels has significantly increased levels of atmospheric CO_2, a greenhouse gas. Carbon capture and storage (CCS) is a promising mitigation strategy. CCS consists of capturing and sequestering CO_2 emissions from large "point sources", for example, coal-fired power plants.

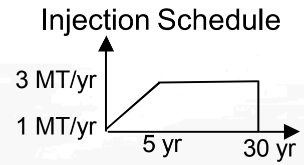
We are developing multiscale multiphysics simulation tools for investigating both the short and long term coupled chemical and mechanical processes encountered during subsurface CO_2 sequestration.

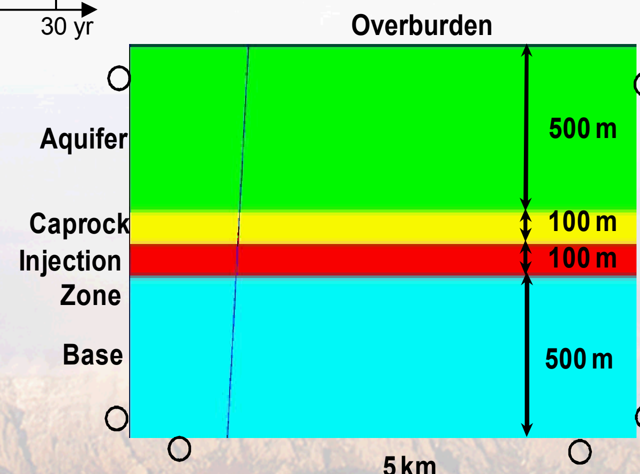
Problem Features and Goals

- Injection of large volumes of supercritical CO2 into a layered brine reservoir-caprock system at greater than 1km depth.
- High pressures can damage either the injection reservoir (e.g. plastic deformation), or the confining caprock (fracture generation or activation)
- We use a coupled multiphase flow and geomechanics numerical models to determine conditions for failure of the caprock due to injection pressures, flow rates, permeabilities, thus determining operation limits for design of safe CO_2 injection.

Problem Schematic







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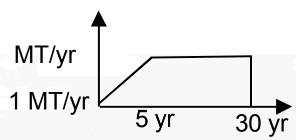
Coupled Flow and Geomechanics

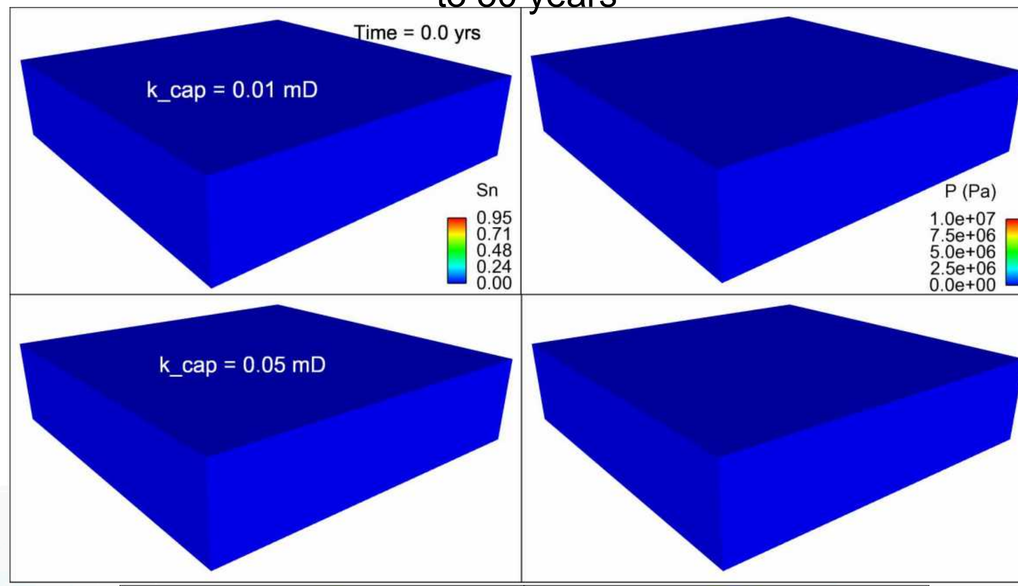
Flow, CO_2 transport and Deformation

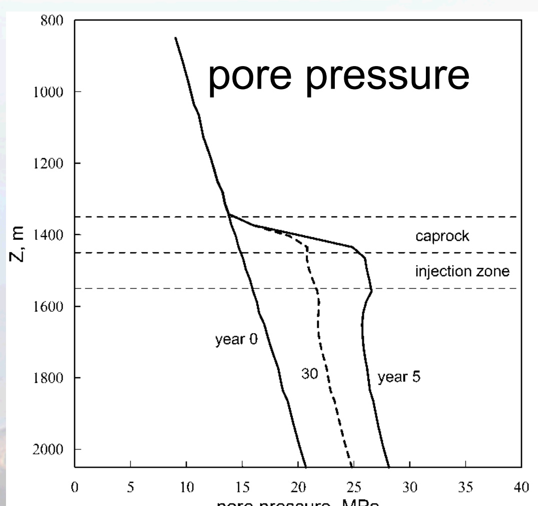
Results

- "gravity-override" for injected lighter, less viscous CO2
- higher overpressure, further penetration with low permeability caprock
- 50 μD caprock leaks during injection. Buoyant leaked CO2 rises and pools at the upper impermeable surface

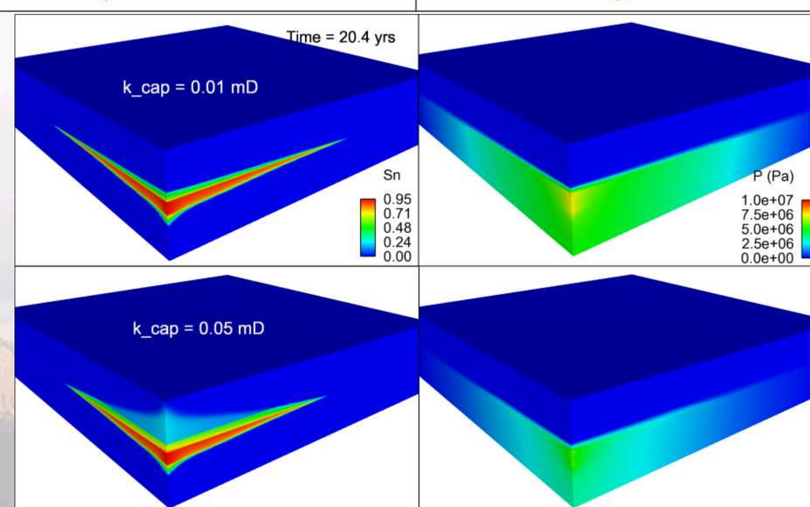


CO_2 saturation, Overpressure & Displacement to 50 years





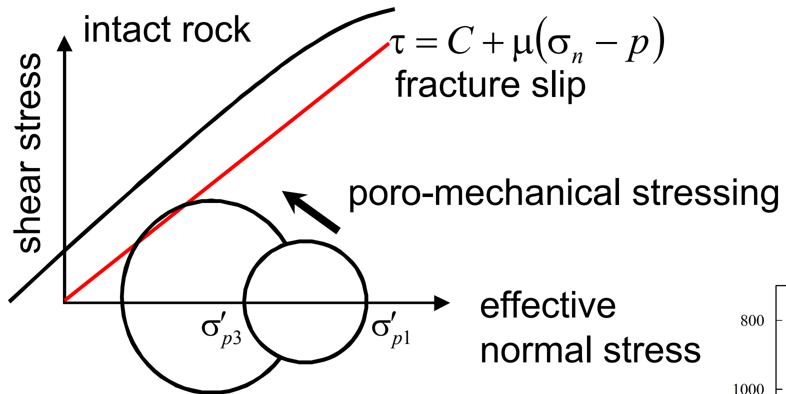
20 yrs



Coupled Flow and Geomechanics

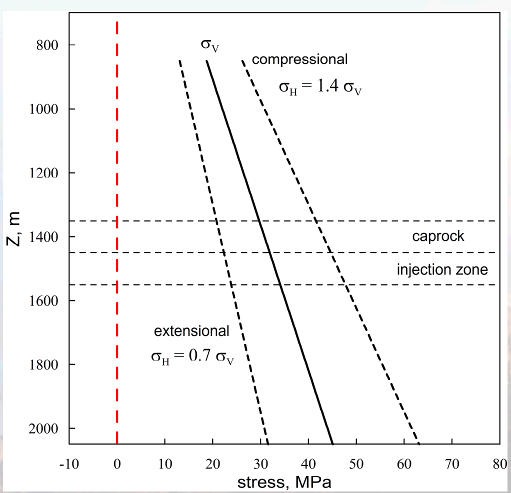
Effect of Regional Stress State

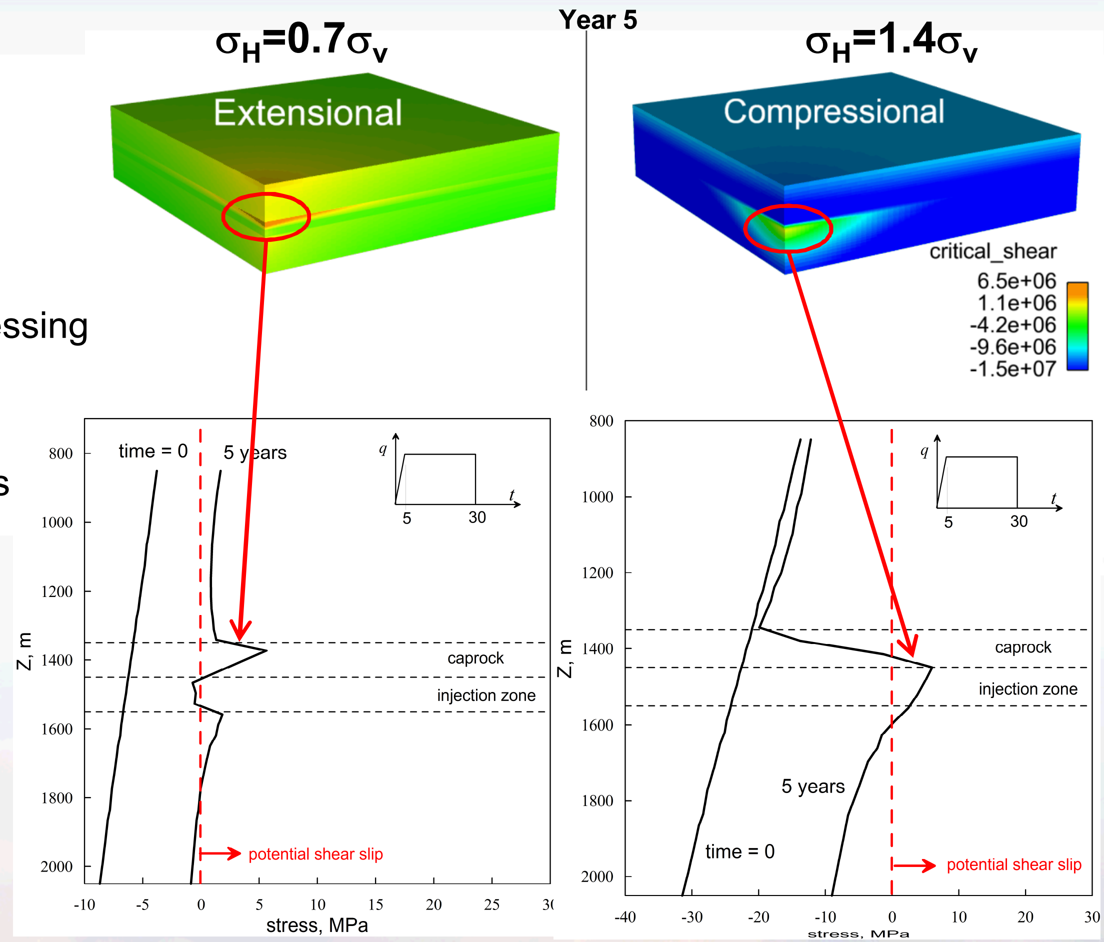
Linear Mohr-Coulomb



Critical Shear

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





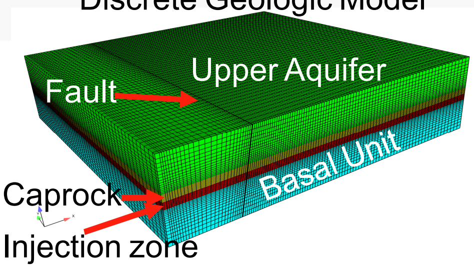
Extensional regional stresses are more dangerous to caprock integrity

Coupled Flow and Geomechanics

Hydromechanical Effects of Faults

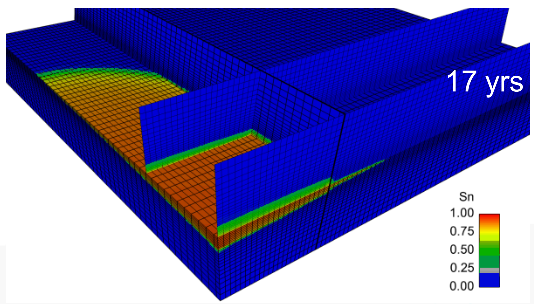
Some faults could go undetected and may pose a risk to sequestration of CO_2 by reactivation due to injection pressures. This study considers possible hydromechanical effects due to a low and high permeability fault.

Discrete Geologic Model

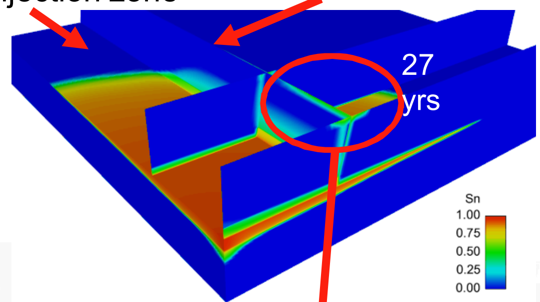


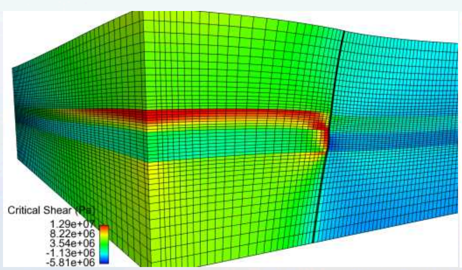
Low Permeability Fault

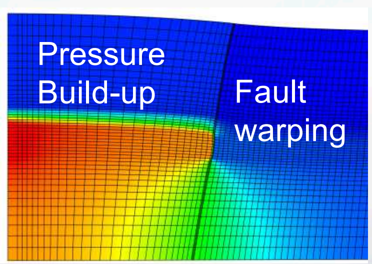
Interior view of CO_2 Saturation



High Permeability Fault

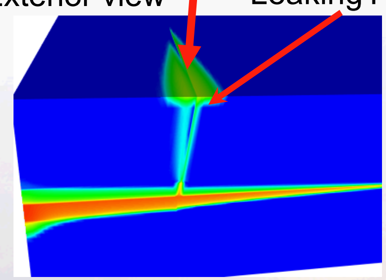






Exterior view

Leaking Fault

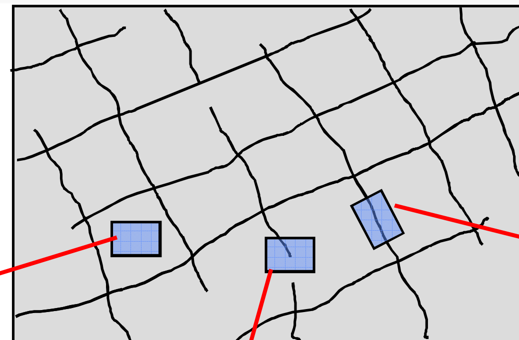


Low permeability fault impedes CO_2 injection, diverts flow along fault and builds pressure behind the fault, thereby shearing/warping the fault and inducing critical shear failure in both the caprock and fault.

High permeability fault 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.

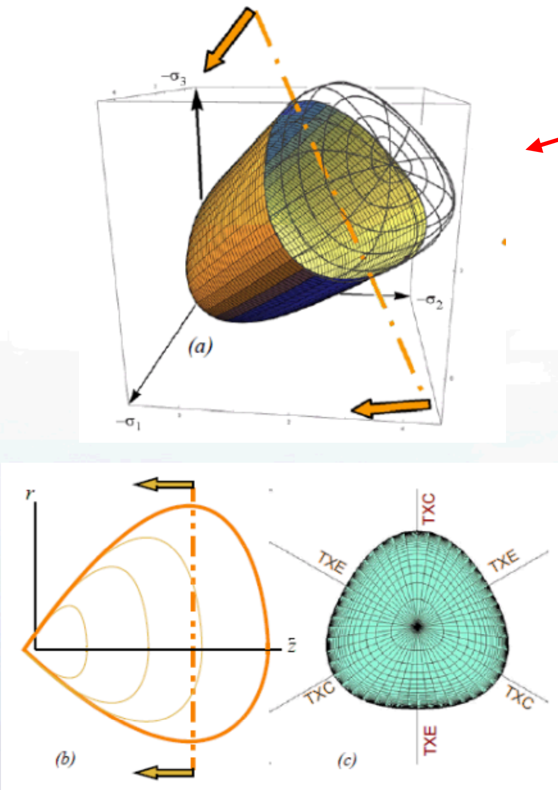
Hydromechanical Coupling in Fractured Rock

Fractured Porous Rock



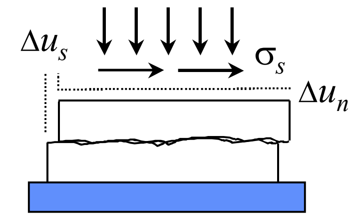
bulk constitutive properties

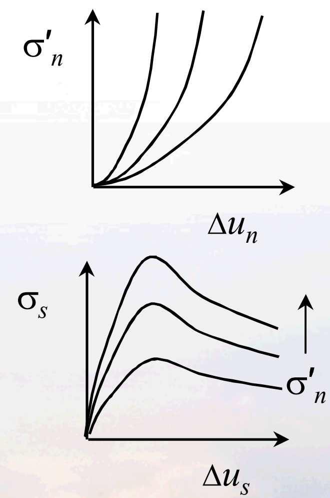
(Sandia GeoModel
Fossum & Brannon, 2004)



fracture contact properties

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

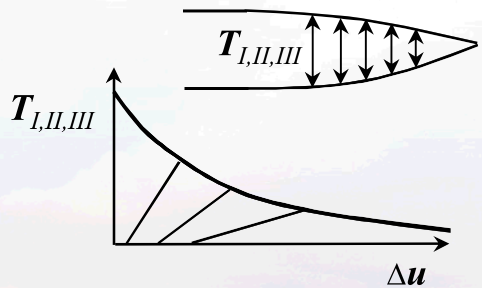




$$\sigma_s = \sigma_s\{\Delta u_s, \Delta u_n\}$$

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

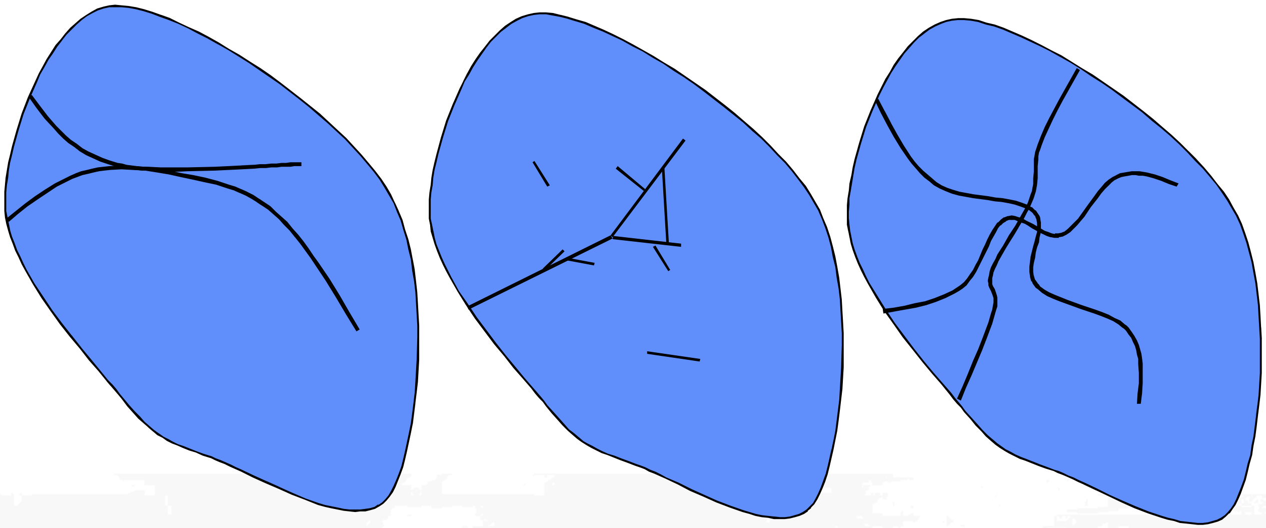
crack-tip cohesive properties



additional challenges

- scale dependence
- history dependence
- precipitation
- dissolution

Computational Challenges to Allowing Cracks to Grow Arbitrarily

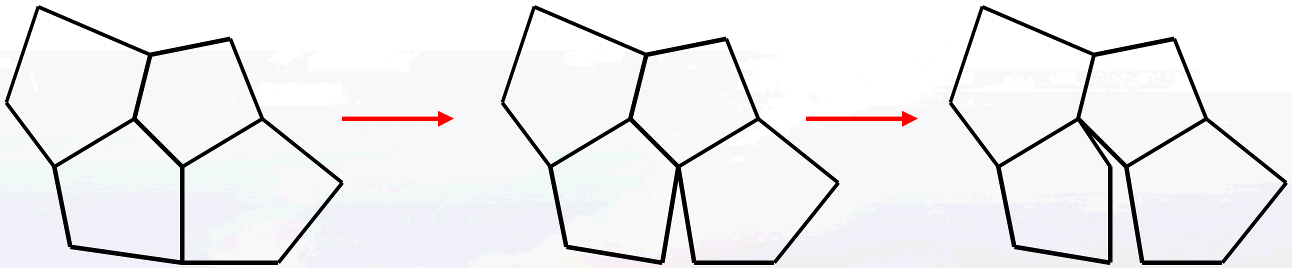


- Do we restrict branching?
- Do we restrict initiation?
  - from surface only?
  - from crack tips only?
  - from existing cracks only?
- Constraints on turning angles?
- Constraints on crossing angles?
- Constraints on minimum fragment size?

What about 3D?

Computational Approach

- Random Voronoi tessellation (mesh)
- Polyhedral finite-elements
- Fracture only allowed at element edges.
- *Dynamic* mesh connnectivity
- Insert cohesive tractions on new fracture surfaces.

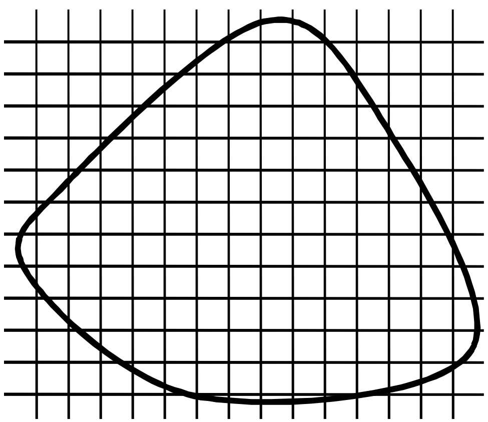


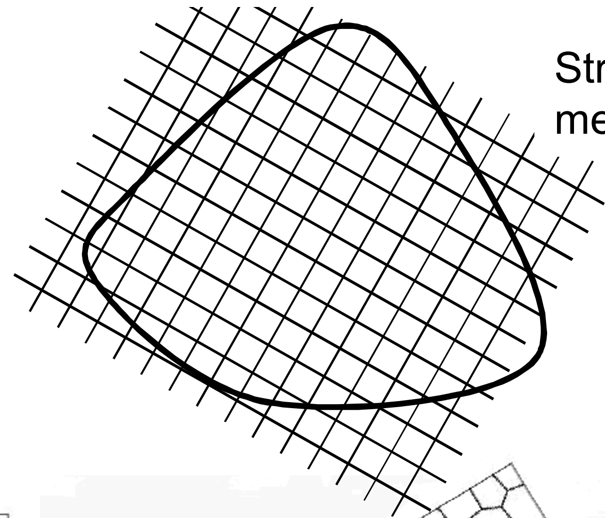
dynamic insertion of cohesive tractions based on . . .

Pandolfi, A. and Ortiz, M. (2002) 'An efficient adaptive procedure for three-dimensional fragmentation simulations,' *Engineering with computers*, 18, 148-159.

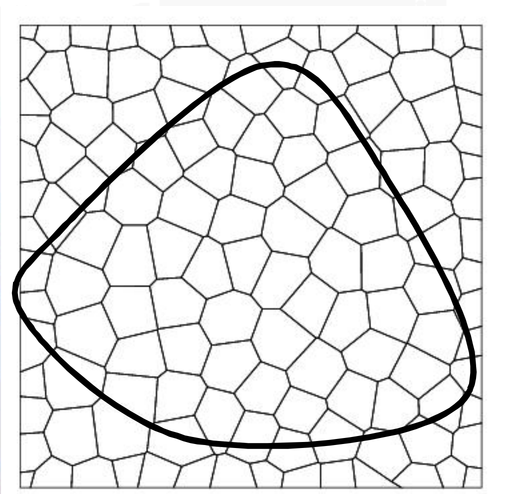
Eliminating Mesh Induced Crack Bias

If cracks can grow only at element edges, then need to eliminate any directional bias in crack growth.

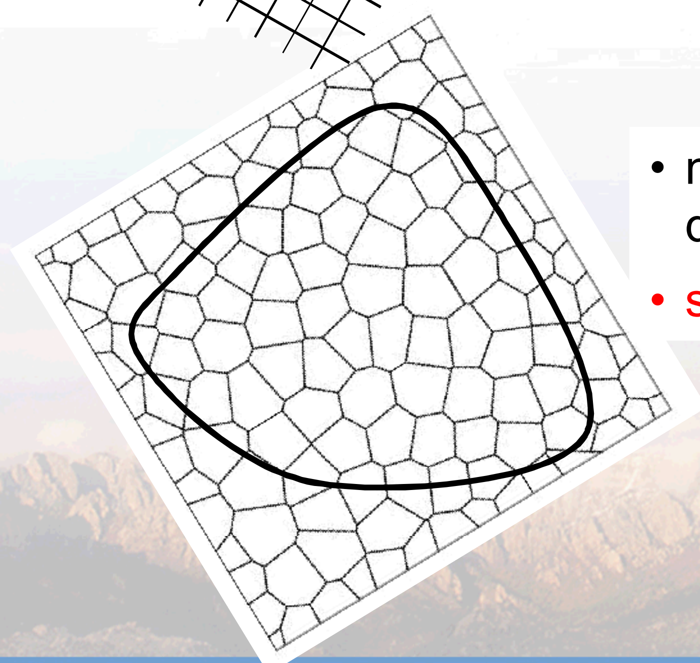




Structured grids can result in strong mesh induced bias (nonobjective).

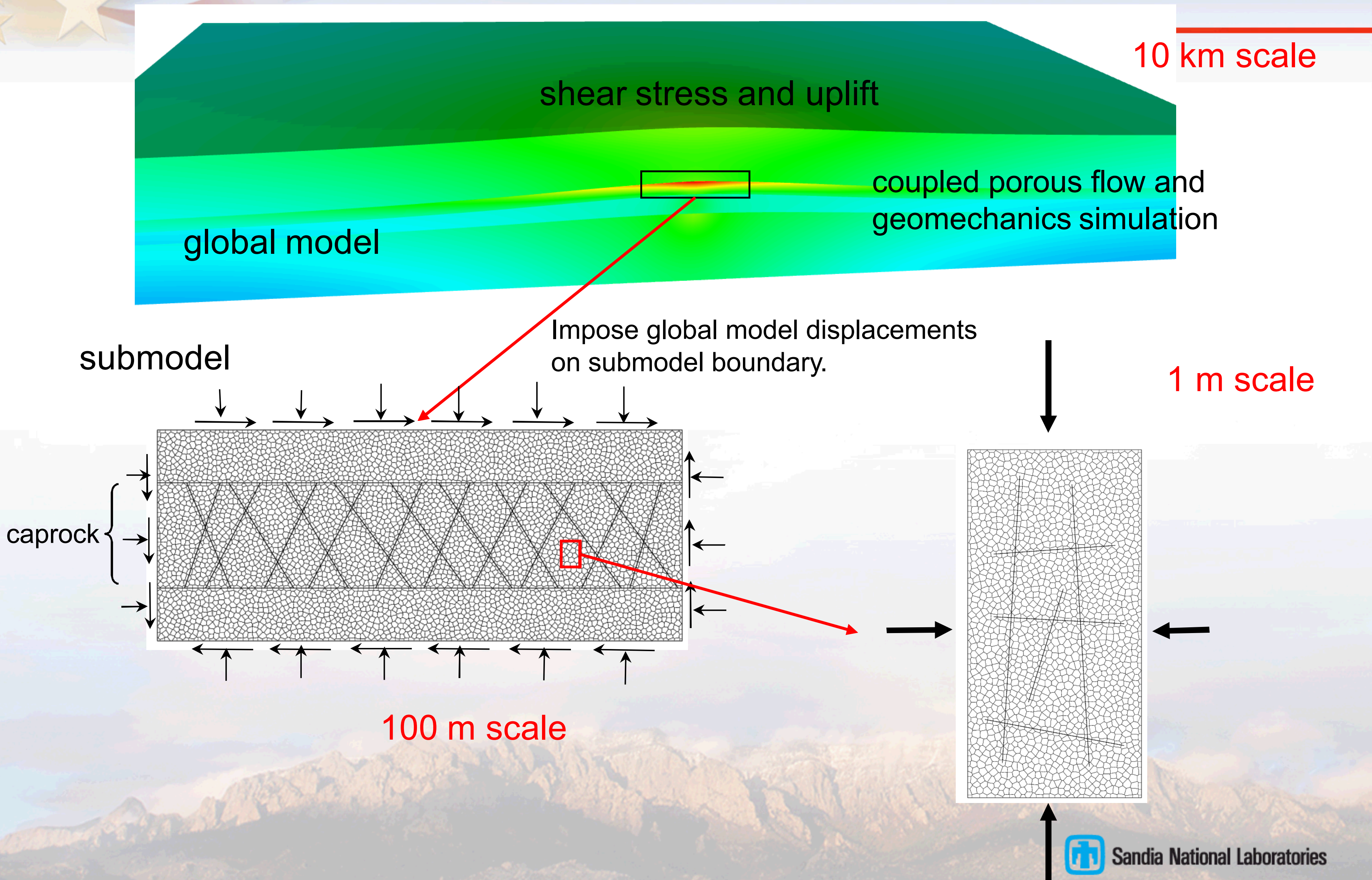


Voronoi tesselation of with random seeding



- need to use ‘random’ discretizations
- statistically isotropic

Multiscale analysis of caprock integrity during CO2 injection



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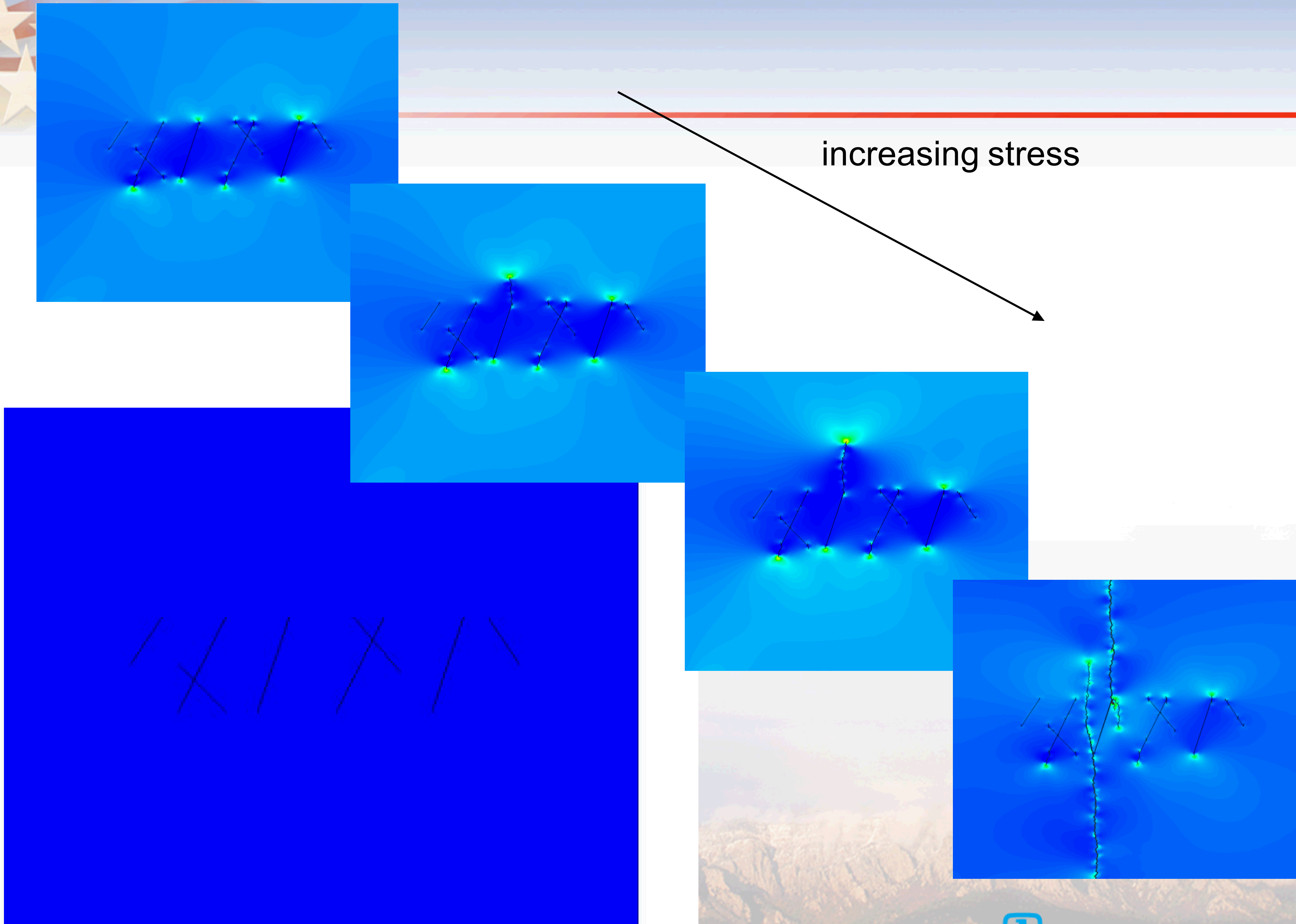
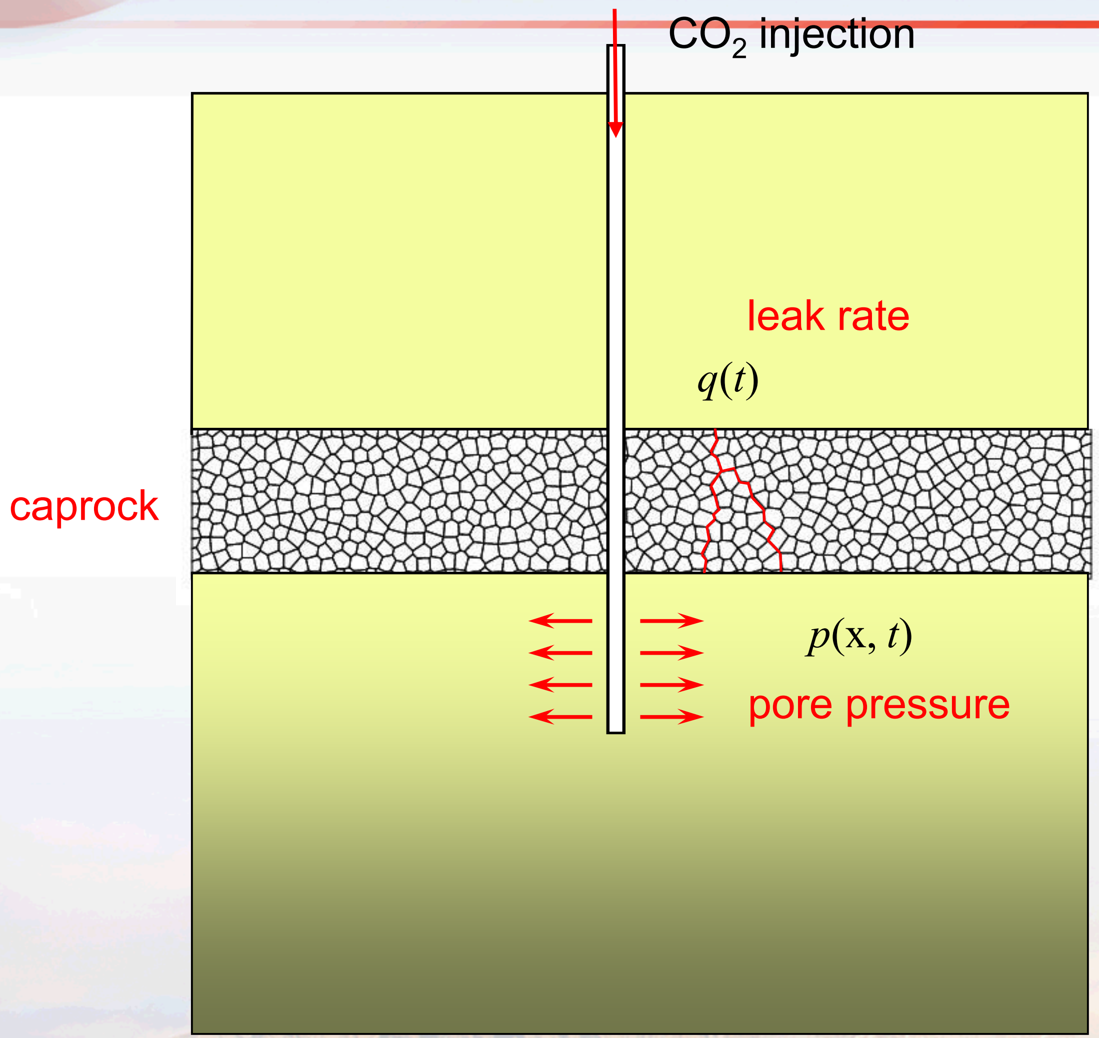
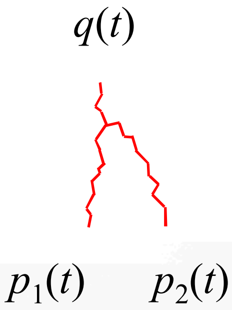

increasing stress

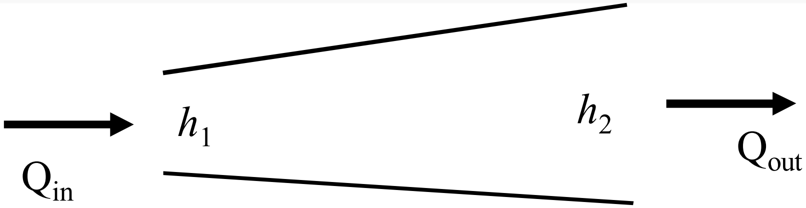
Fluid Flow in 2D Discrete Fracture Networks

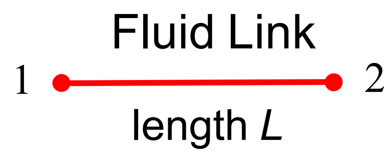




Fluid Flow in 2D Discrete Fracture Networks

Solve fluid network to get nodal pressures and flow rates.





$$\begin{Bmatrix} Q_1 \\ Q_2 \end{Bmatrix} = \frac{T}{\mu} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} P_1 \\ P_2 \end{Bmatrix}$$

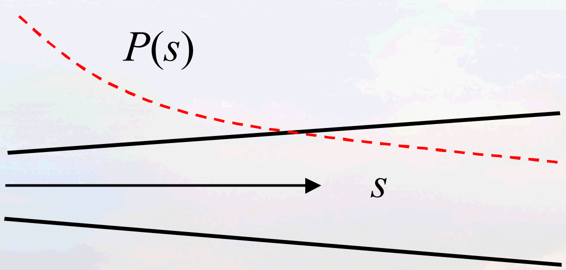
$$T = \frac{h_1^2 h_2^2}{6L} \frac{1}{h_1 + h_2}$$

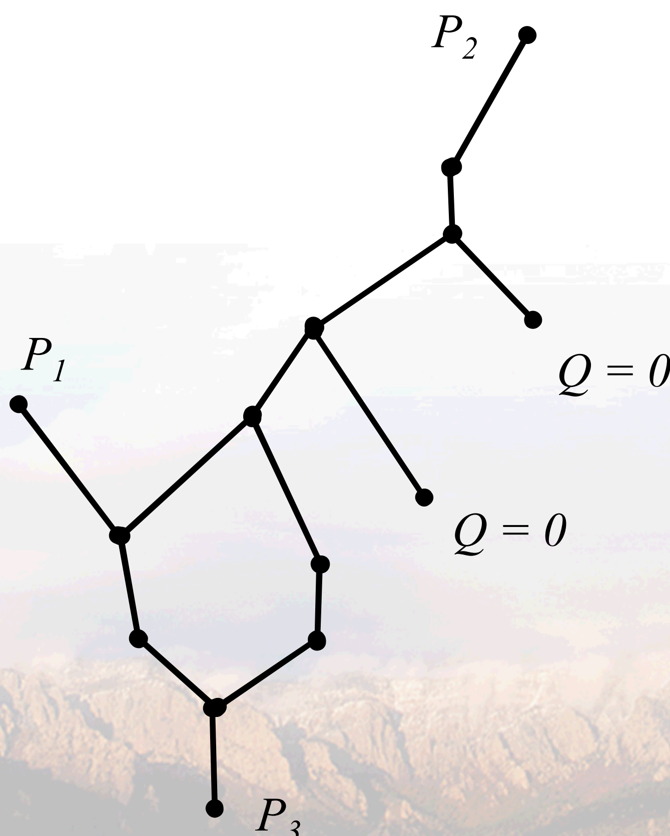
Q = flow rate
P = pressure
μ = viscosity
T = transmissibility

Reynold's lubrication equation

$$\nabla(\rho \mathbf{Q}) = 0$$

$$\mathbf{Q} = -\frac{h^3}{12\mu}(\nabla p - \rho g h)$$





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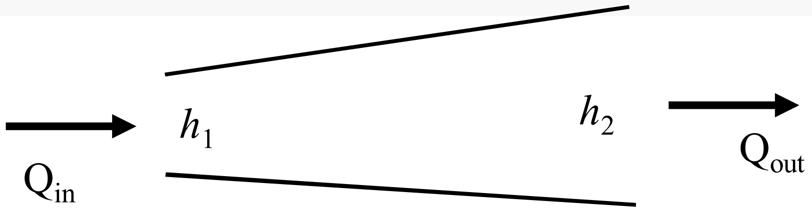
Fluid Flow in Discrete Fracture Networks



Reynold's lubrication equation

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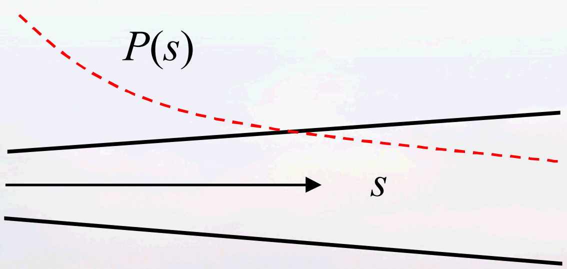
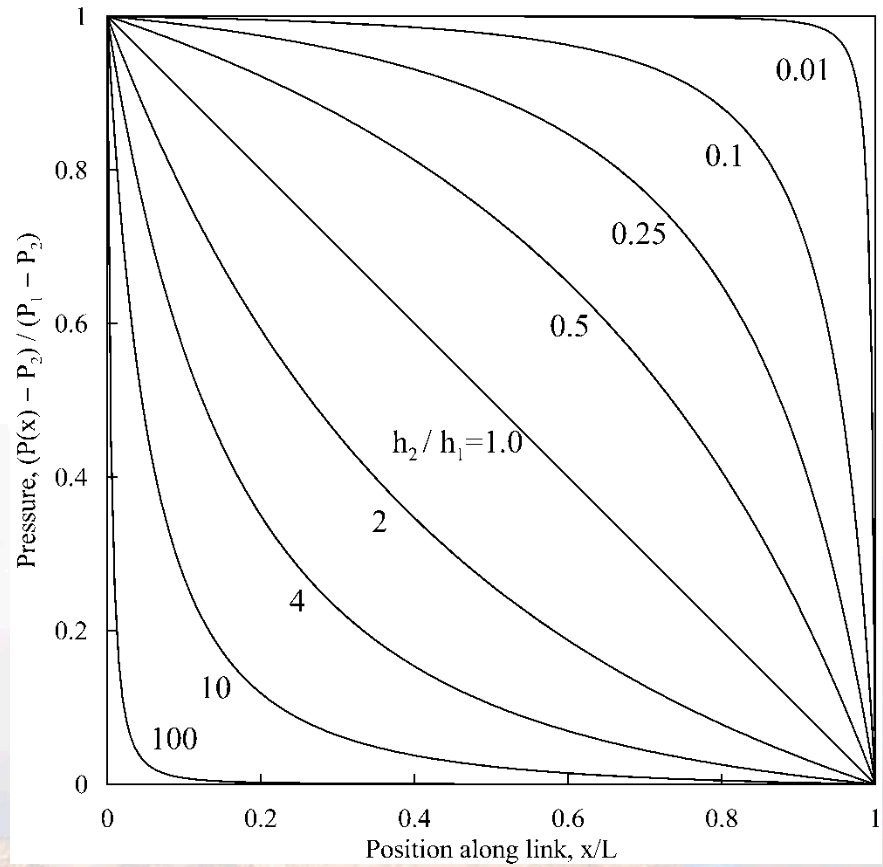
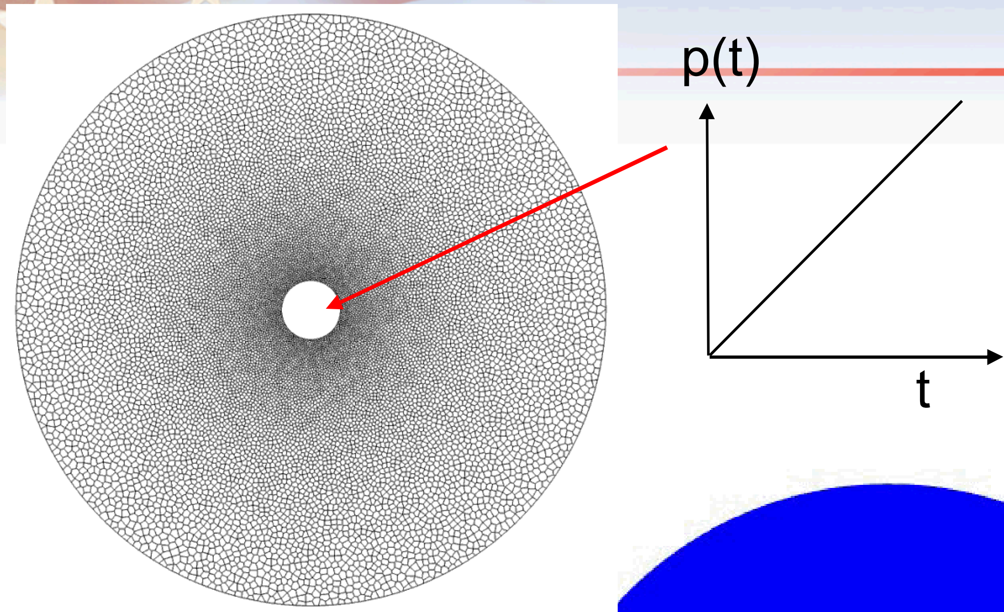
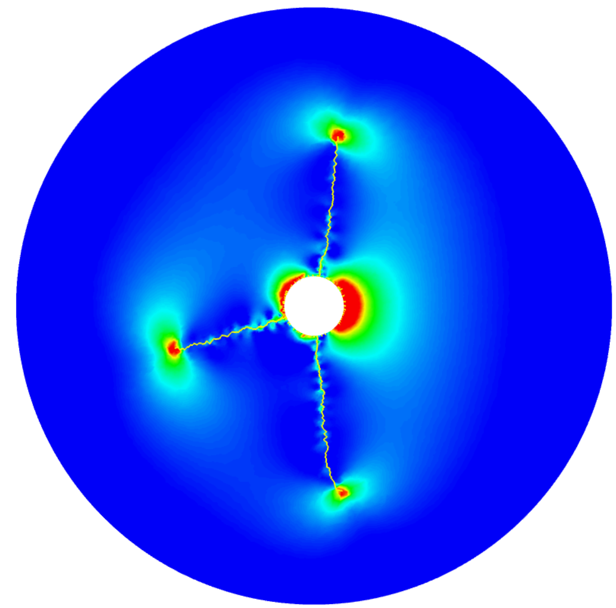
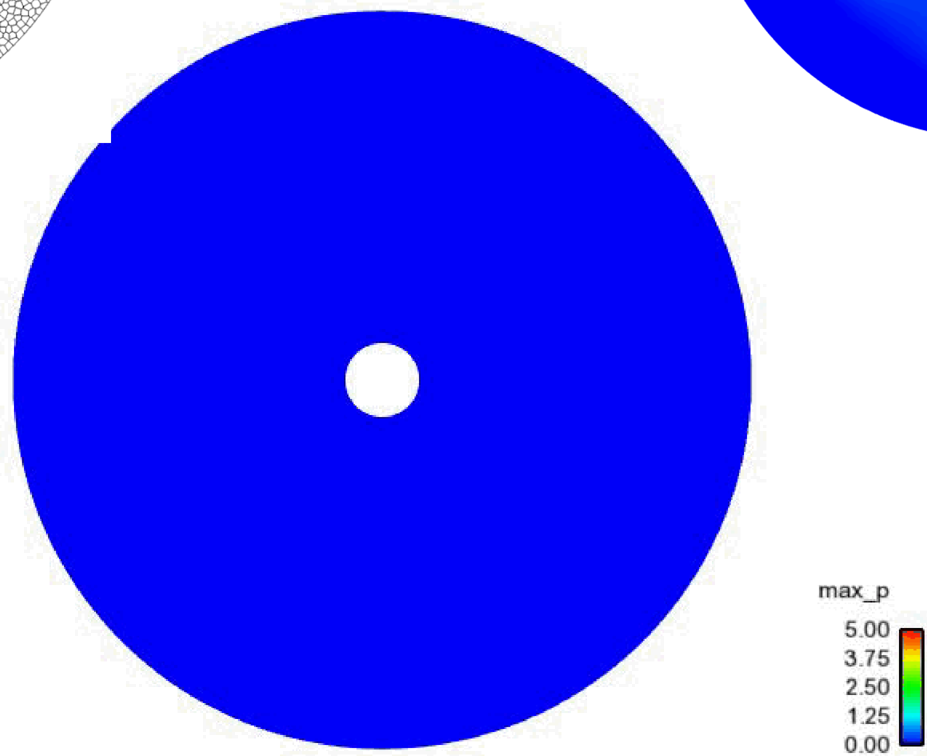




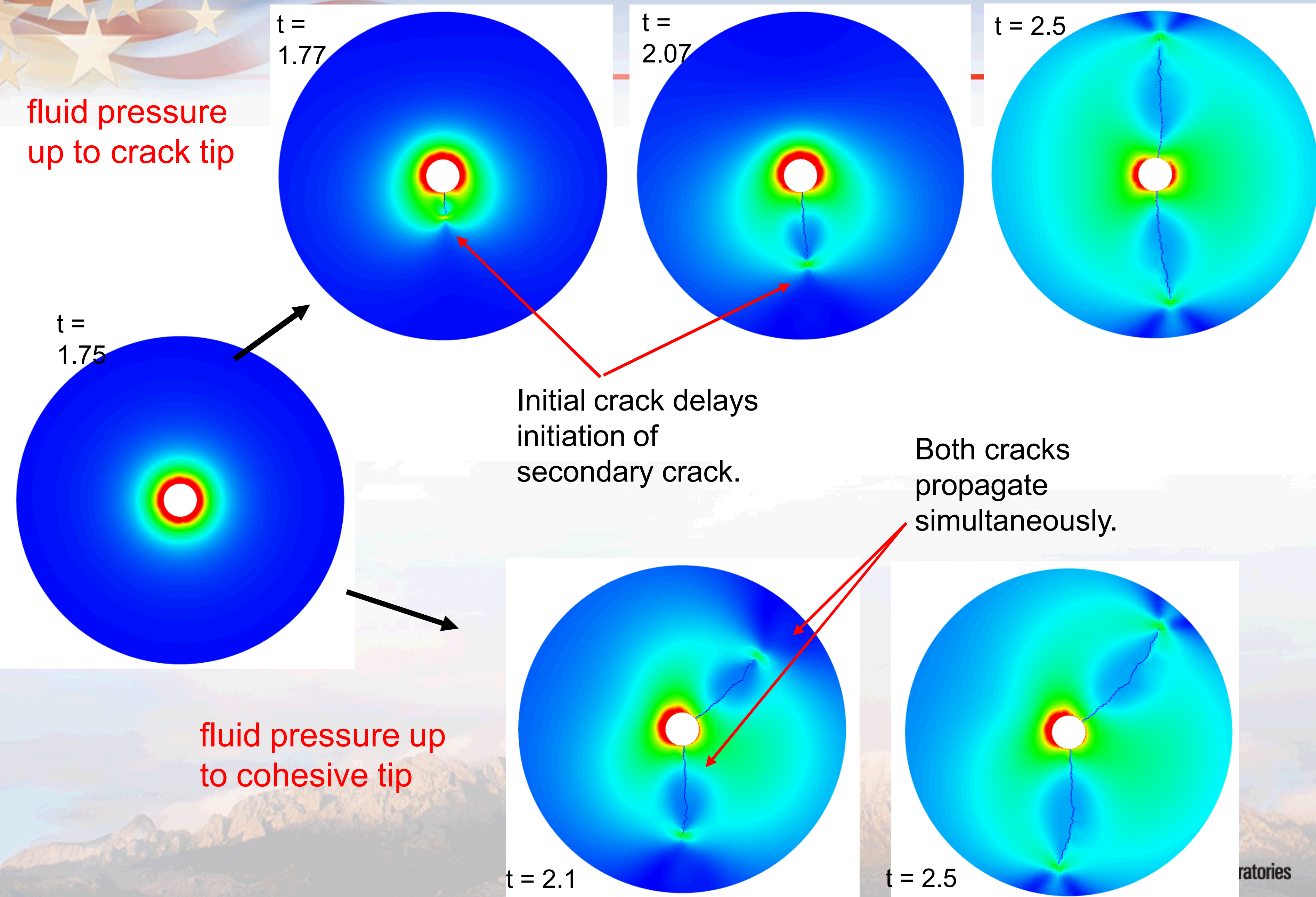
Hydraulic Fracture Simulation





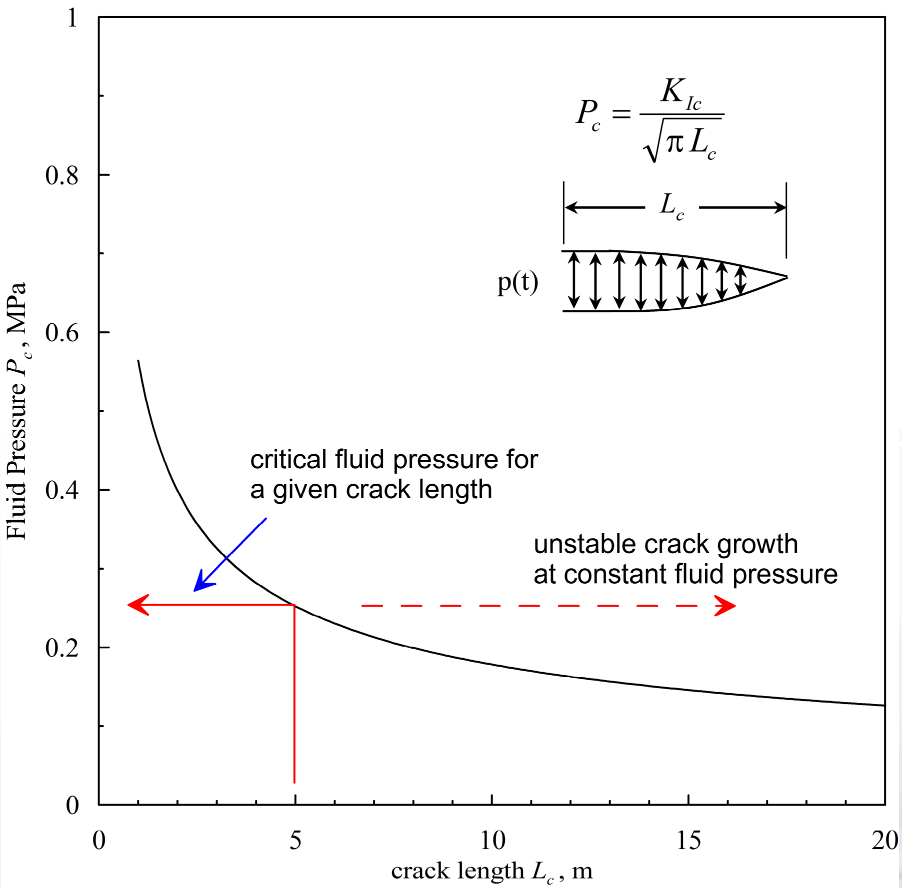


Hydraulic Fracture Simulation

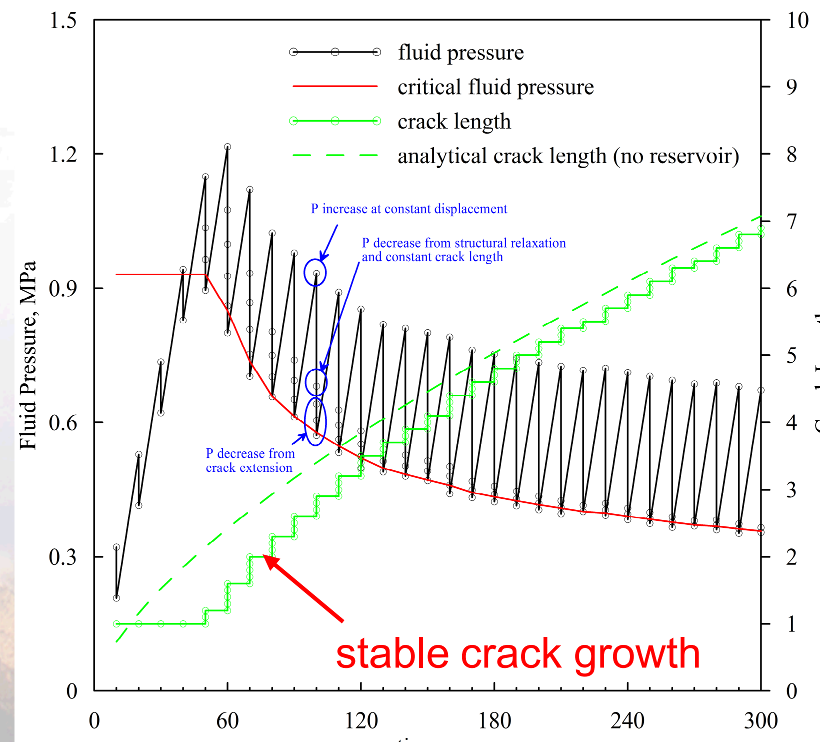


Hydraulic Fracture Simulation

- Constant fluid pressure causes unstable crack growth.
- Use fluid-mass control.



do
  increment fluid mass, Δm
  equilibrate at constanct crack length, a.
  while ($K_I > K_{Ic}$)
    increment crack length, Δa.
    equilibrate at constant crack length, $a + \Delta a$.
  end while
end do



Future Directions

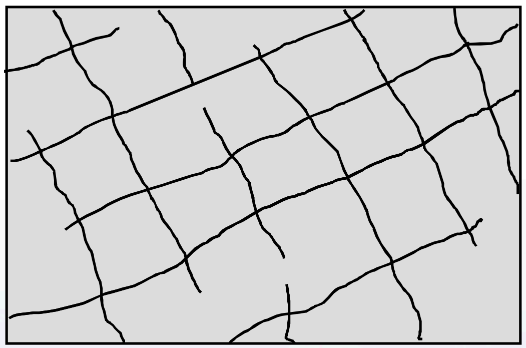
- Models of perm(stress, porosity, damage)
- Multiphysics coupling of dynamic discrete fracture network generation
  - One-way coupled (continuum → discrete) dynamic discrete fracture
  - Flow physics on shells
  - 3D Vornoi mesh in Sierra
- Thermal CO_2-NACL-H_2O phase behavior
- Geochemistry

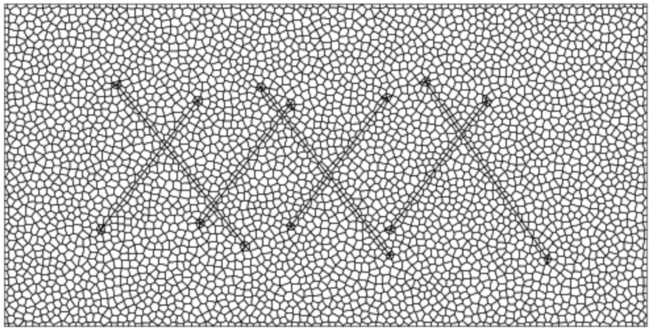
Backup Slides

MeshingGenie (Trilinos)

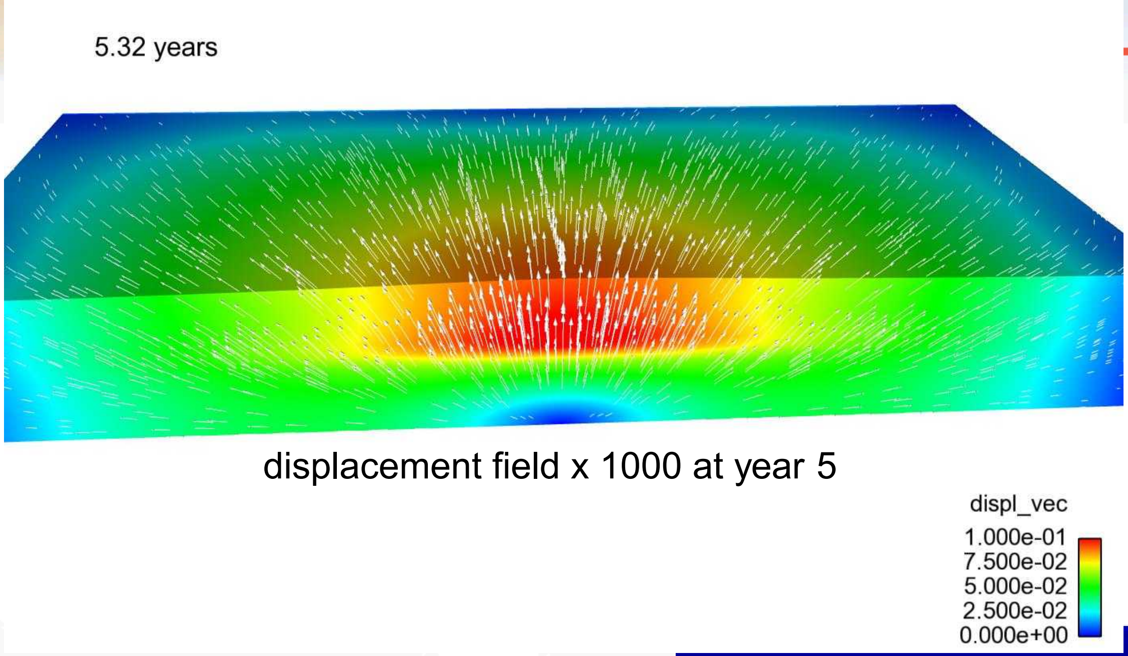
(Ebeida, M., Knupp, P., Vitus Leung, Sandia National Laboratories)

Fractured Rock

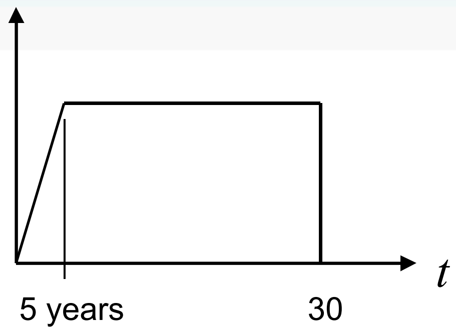


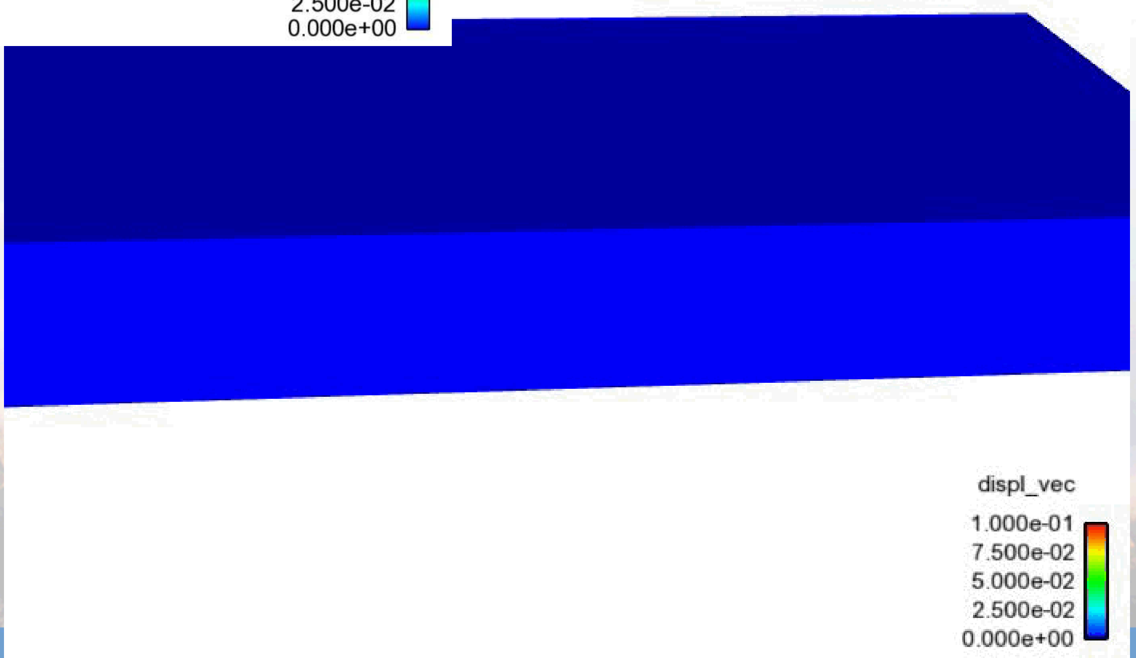


Injection Induced Uplift

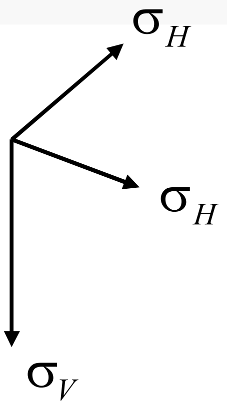


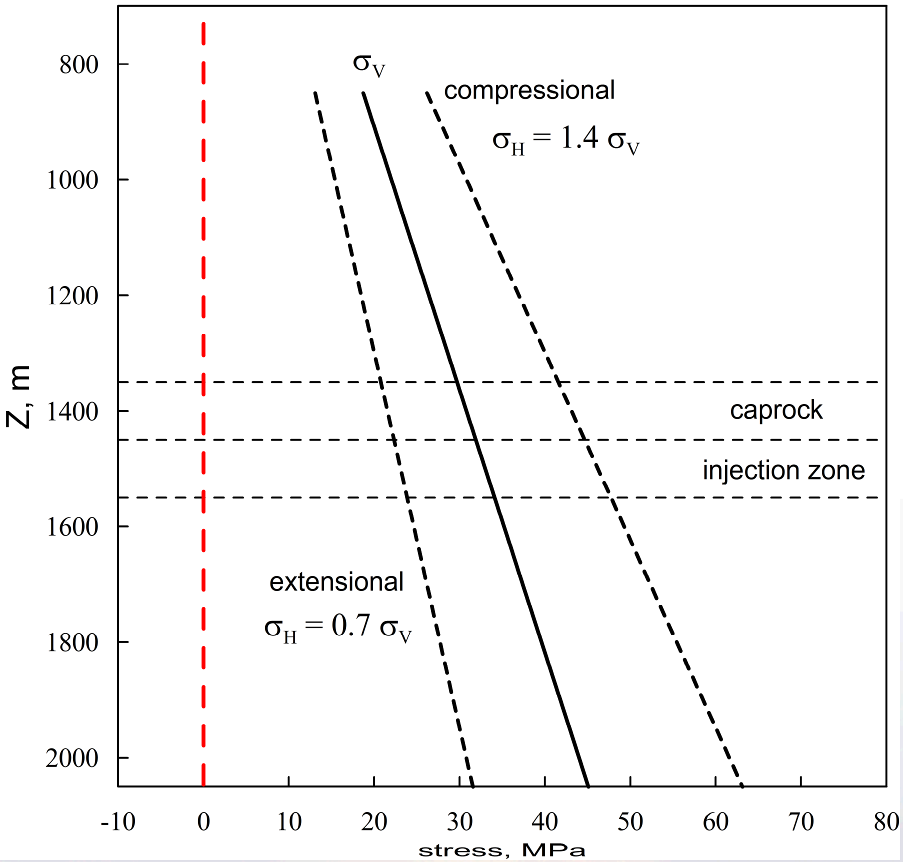
displacement field x 1000 at year 5





Initial Stress State



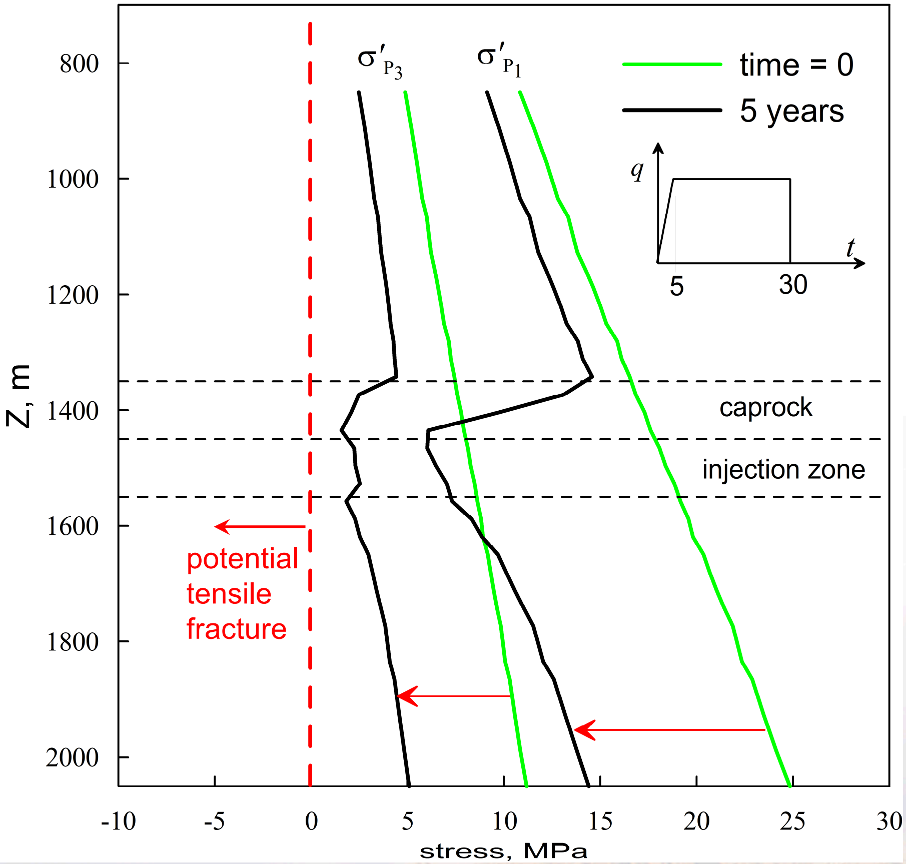


Look at two initial stress regimes

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

Extensional Initial Stress

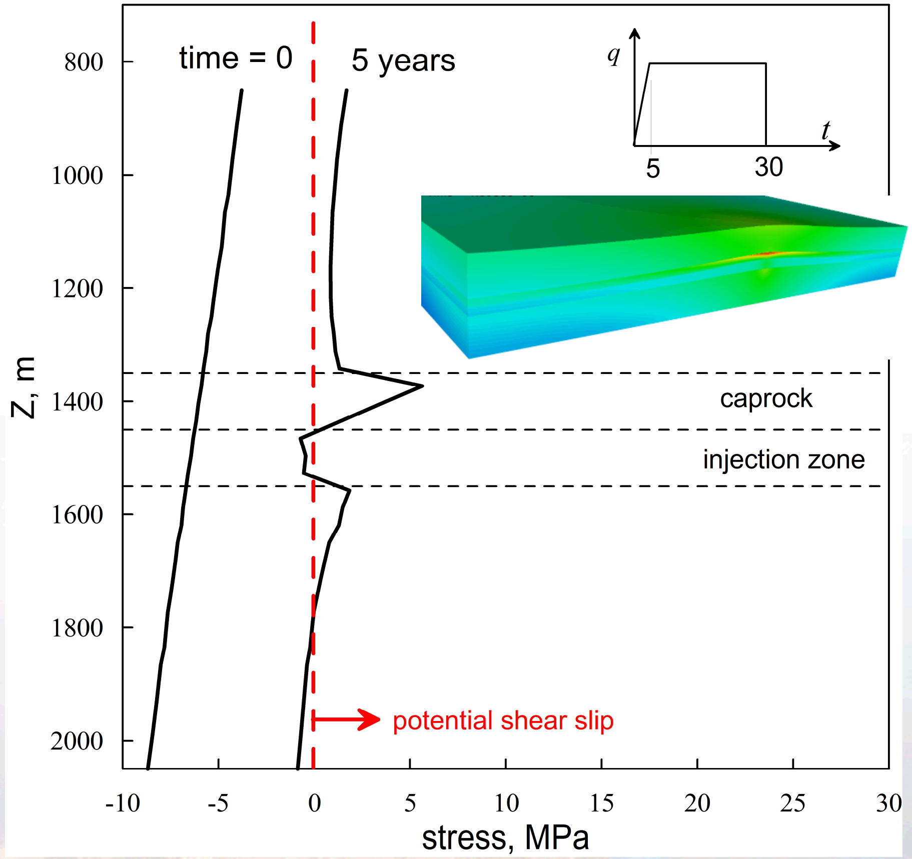
effective principal stresses



effective principal stress

critical shear

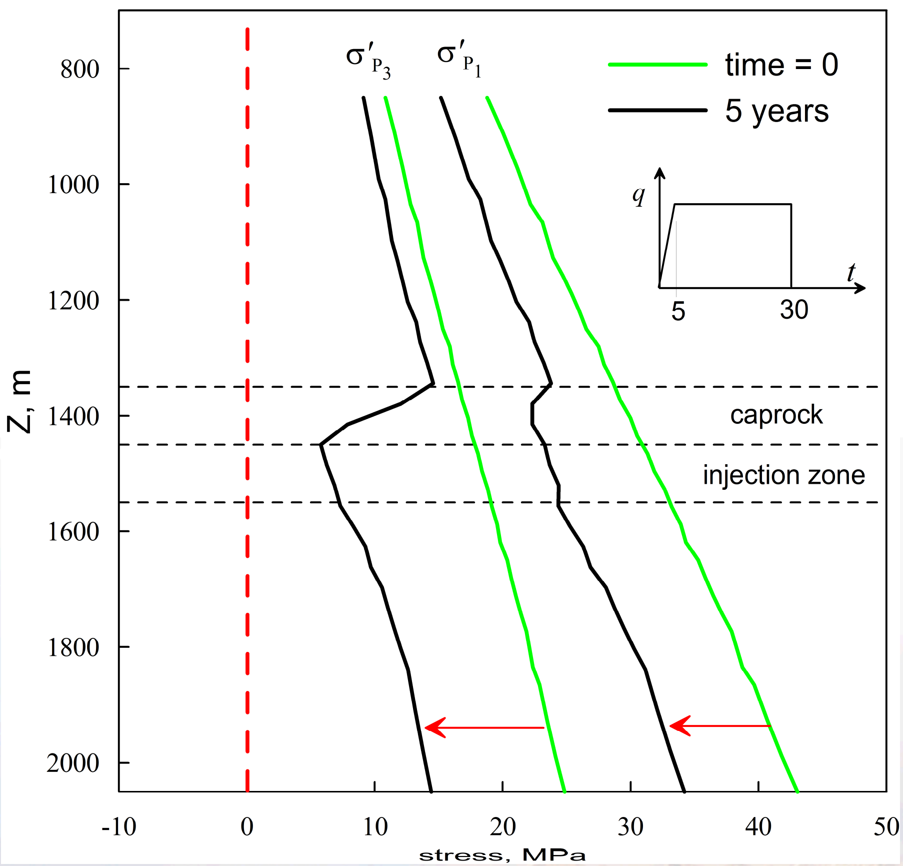
$$\sigma'_{p1} - 3\sigma'_{p3} > 0$$



critical shear stress

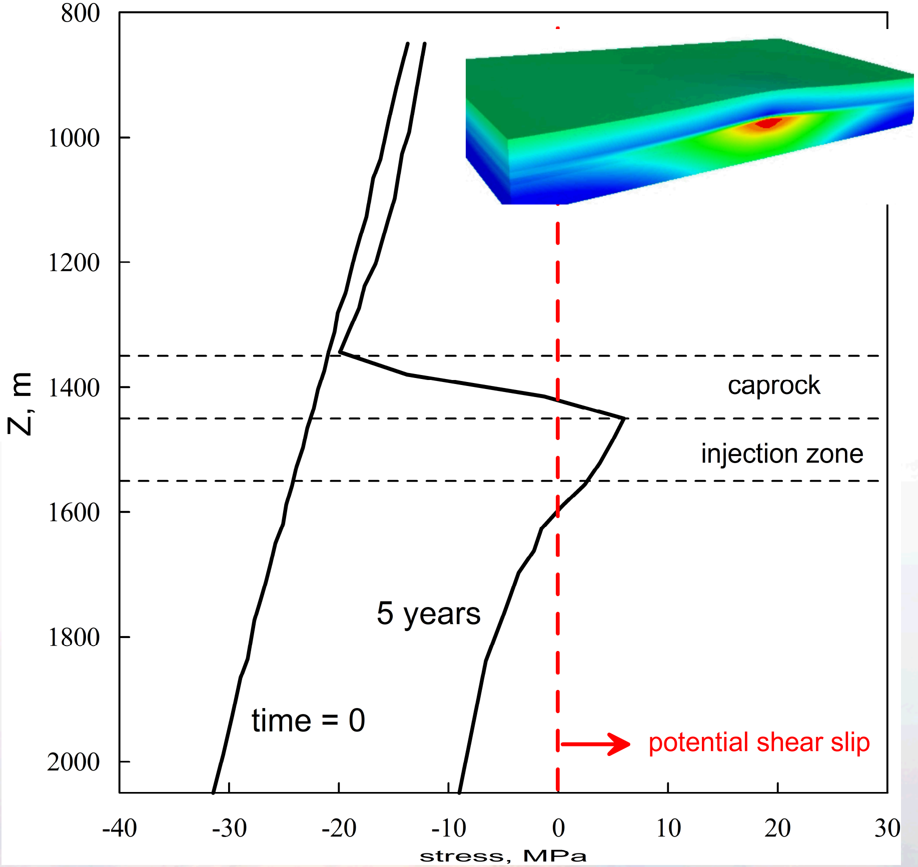
Compressional Initial Stress

effective principal stresses



critical shear

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



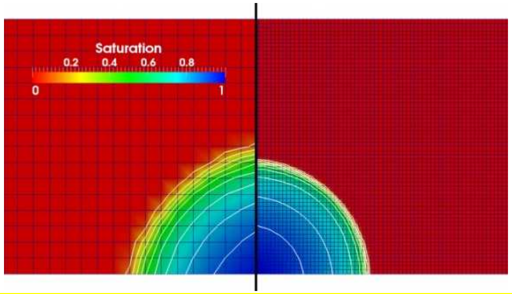
Aria Multiphase Porous Flow Physics

Two-Phase Immiscible Flow

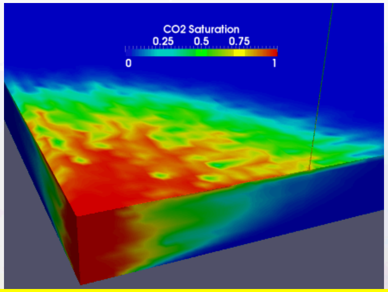
- Compressible (fluids and/or formation), buoyancy effects
- General dependence of thermophysical and transport properties on solution vector
- Capillary pressure (optional)
- Relative permeability
- Specification of heterogeneous transport property fields (e.g. permeability, porosity)
- Can be coupled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

Benchmark Problem

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

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):**

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

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

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

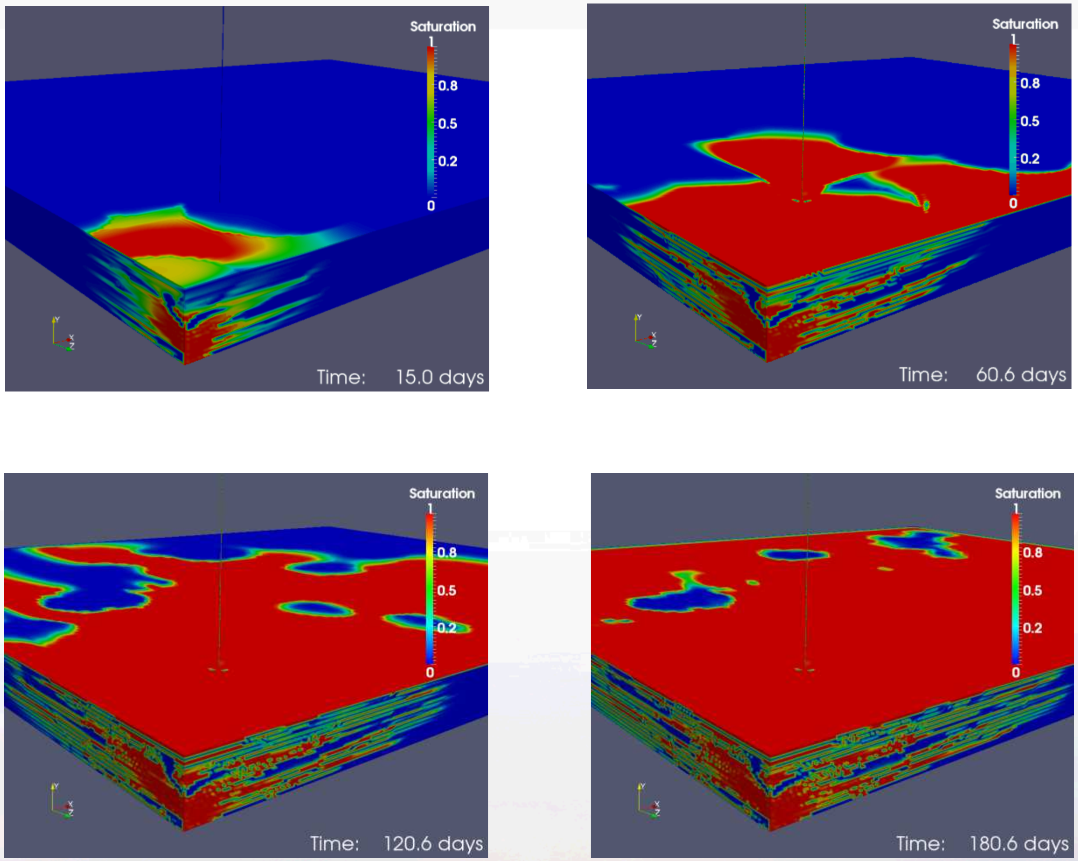
$$S_w = 1 - S_n$$

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

CO2 Leakage Through an Abandoned Well Heterogeneous Layered Media

Some Results
(10 realizations)

- Correlation between fast paths and permeability distribution is evident
- Leakage, arrival time are heavily dependent on permeability distribution
- Heterogeneous layer media results in similar leakage rates.



Contact Algorithm

A node-face contact capability is implemented with a two-part strategy:

1. **A search algorithm to define contact constraints which**
   - **operates on the current configuration**
   - **produces a list of interactions**
2. **An enforcement algorithm to enforce the contact constraints**
   - **Includes the physics, i.e. friction model**

The enforcement algorithm satisfies equilibrium across the contact interface and also enforces frictional sliding based on the following slip condition:

$$\Phi := \|\mathrm{t}_T\| - \mu t_N \leq 0$$ no slip due to shear

$$\Phi := \|\mathrm{t}_T\| - \mu t_N \succ 0$$ slip will occur due to shear

3D disposal room closure behavior in salt at different locations along drift