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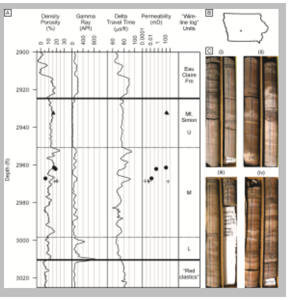

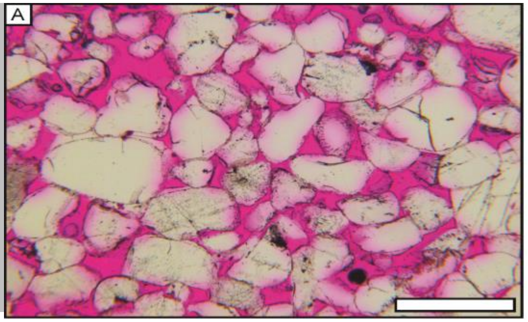

GEOMECHANICS AND RESEARCH CHALLENGES FOR GEOLOGIC CARBON STORAGE

Thomas Dewers[1], Alex Rinehart[4], Jon Major[5,6], Sanghyun Lee[7], Jacqueline Reber[8], Peter Eichhubl[6], Mary Wheeler[7], Nick Hayman[8], Anastasia Ilgen[2], Joseph Bishop[3], Matt Balhoff[9], Nicolas Espinoza[9], Mario Martinez[3], Hongkyu Yoon[1]

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EFRC PI Meeting, October 26-27, 2015
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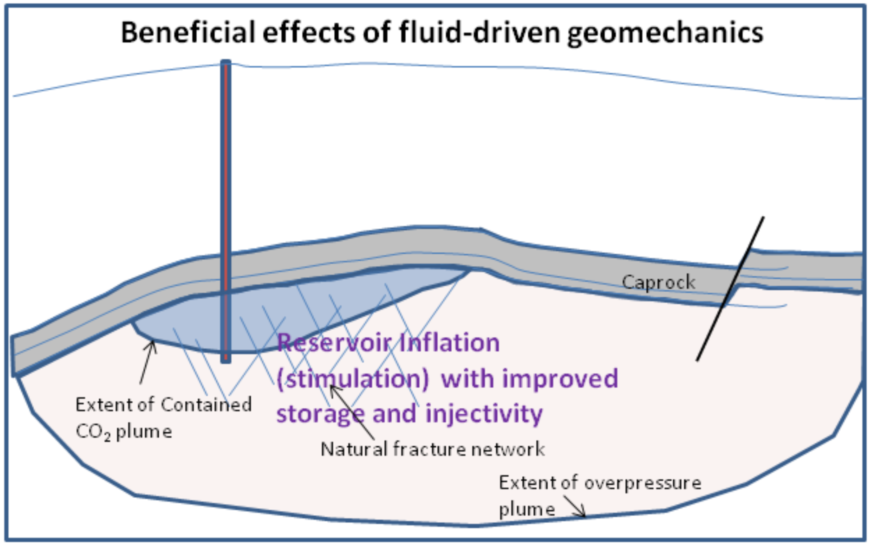
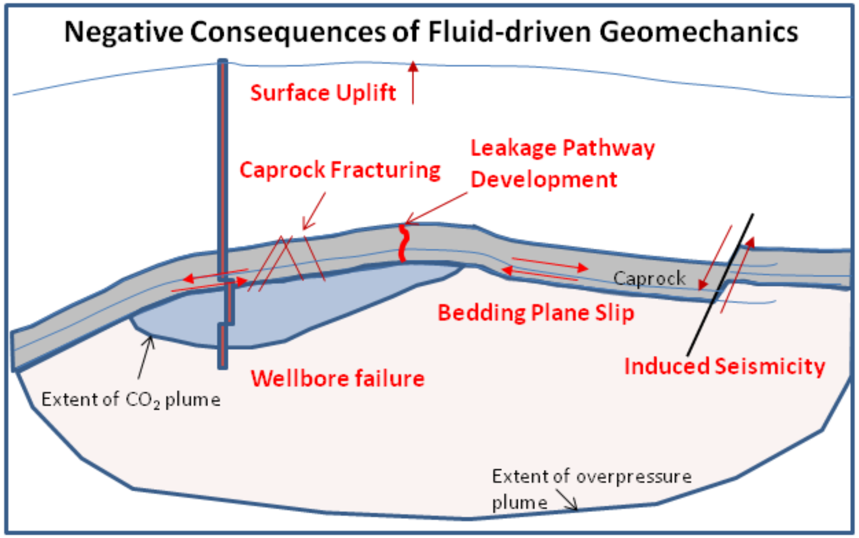
CFSES Research Challenges

- **Sustaining Injectivity and Storage Rates**
- **Using Pore Space With Unprecedented Efficiency**
- **Controlling Undesired or Unexpected (Emergent) Behavior**





CFSES Organization

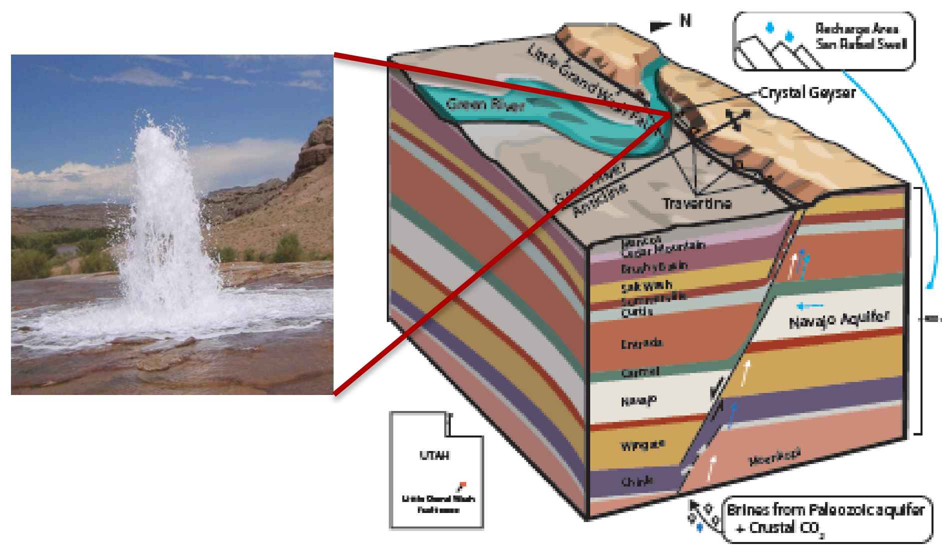
Theme 1: Fluid Assisted Geomechanics

Theme 2: Multifluid Geochemistry

Theme 3: Buoyancy-Driven Multiphase Flow

Link with NETL Partnership InjectionProjects

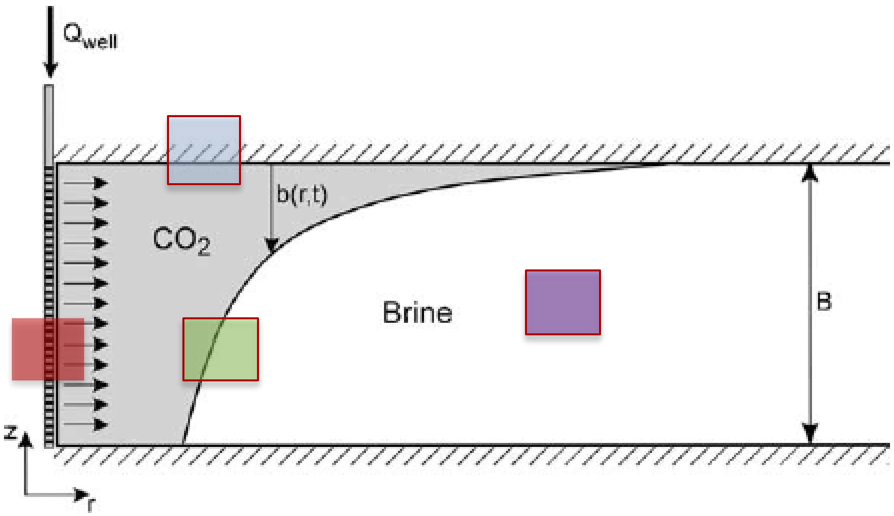
Natural Analogues (e.g. Crystal Geyser)



CFSES Organization

Theme 1 Tasks

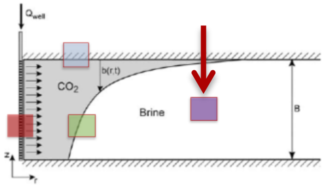
- Experimental Fracture Propagation
- Reservoir Geomechanical Evolution
- Caprock Chemical and Mechanical Integrity
- Fracture Propagation Modeling
- Constitutive and Continuum Modeling



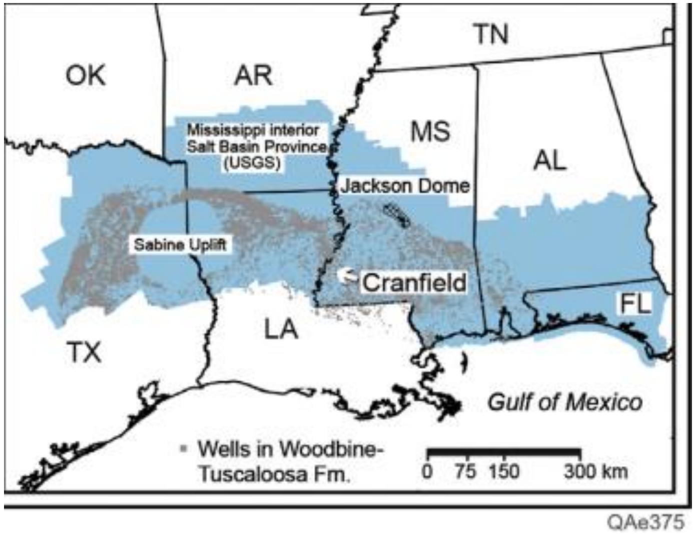
From Nordbotten, Celia, and Bachu (2005)

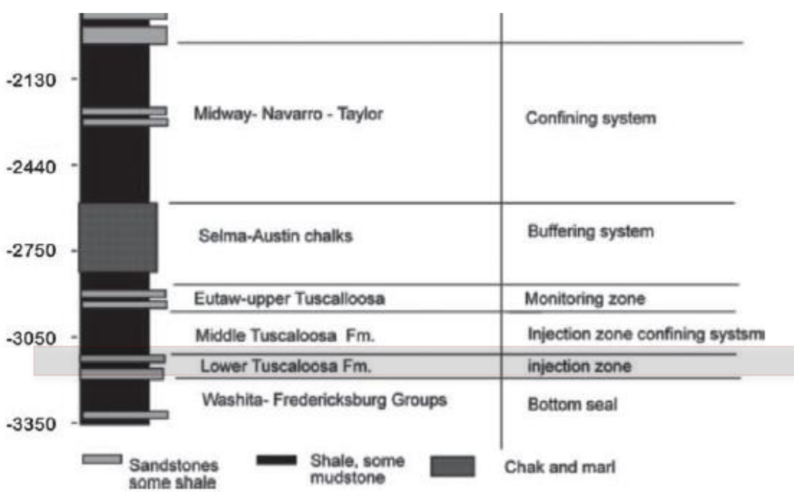
<u>Regions of Interest</u>

- Near wellbore
- Caprock and Caprock-Reservoir Interface
- Reservoir CO2 Interface
- Reservoir Brine

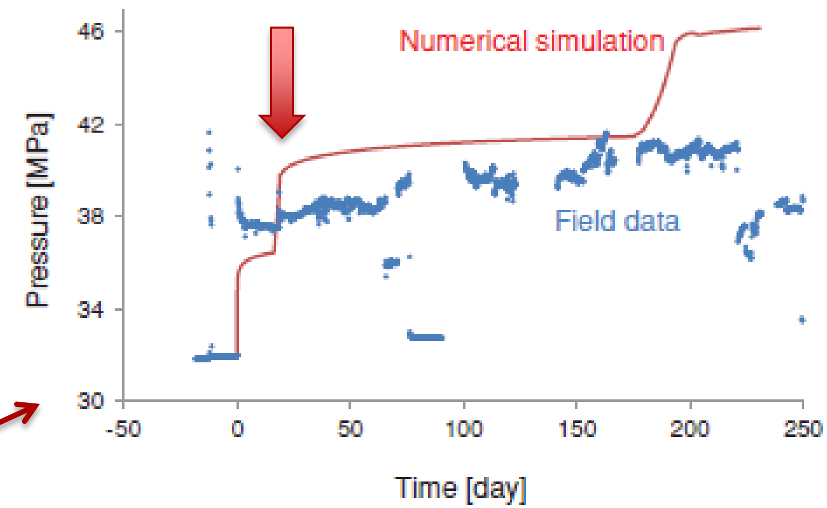


Reservoir Chemo-Mechanical Evolution

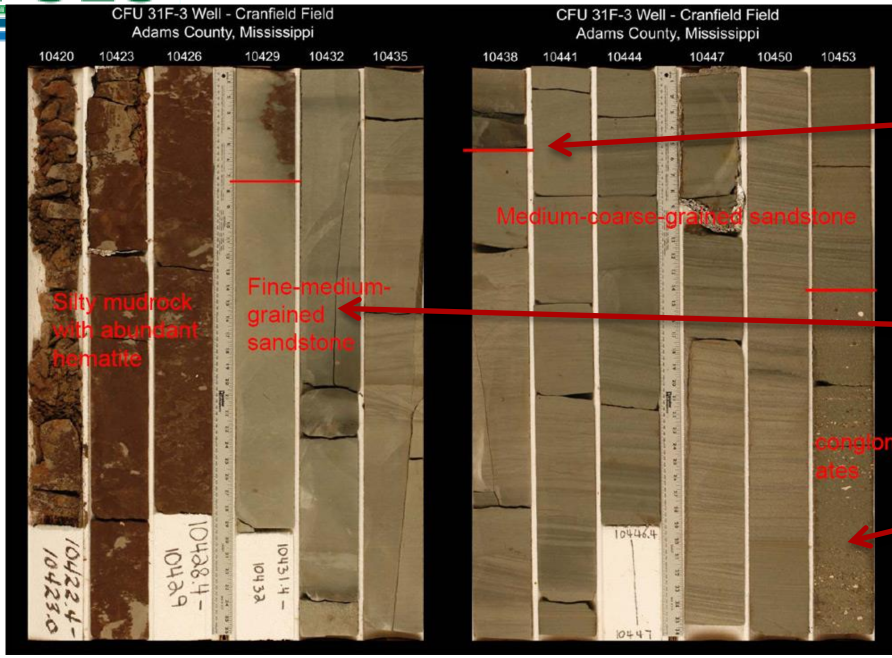




- Pressure response during injection suggests a "geomechanical event"
- Tracer studies show increase in permeability with "event"



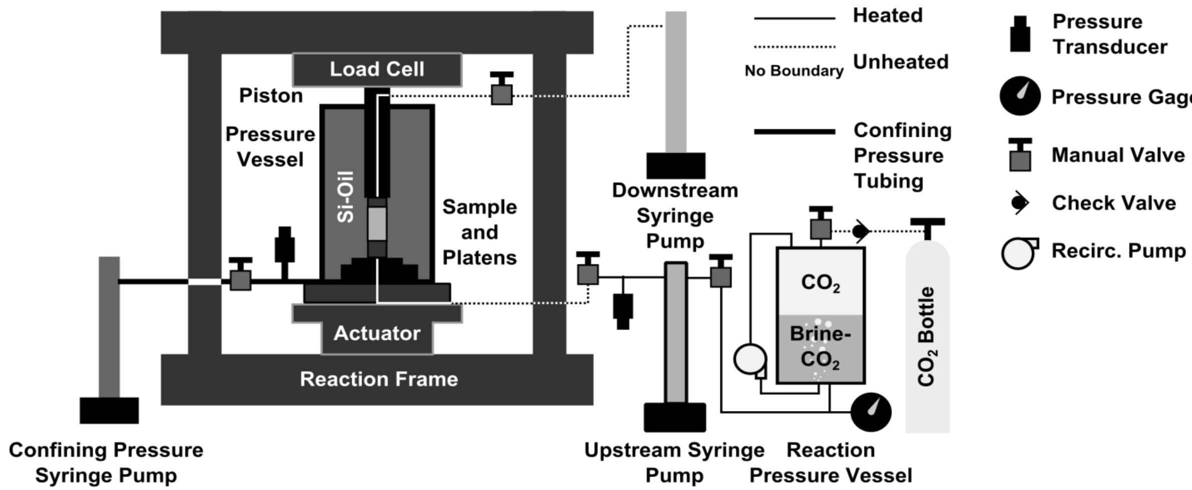
Field and simulated pressure response at Cranfield injection zone (Kim and Hosseini, 2013)



- Mixed chlorite- and quartz-cemented muddy cross-bedded fine sandstone (Facies B);
- Quartz-cemented tabular very fine sandstone (Facies C)
- Chlorite-cemented conglomeratic sandstone (Facies A);

Geomechanical Testing

- T, P and major ion fluid chemistry
- UCS, hydrostatic and triaxial stress paths
- Pore fluid equilibrated with scCO2



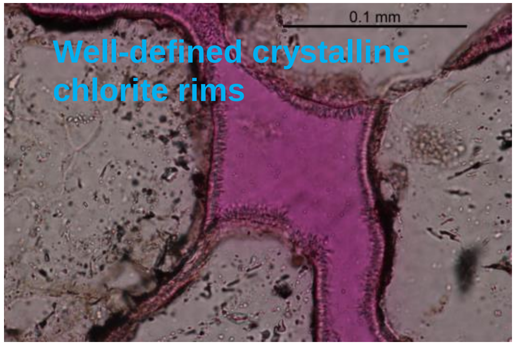
Compression Test System **Brine-CO_2 Equilibration System**

Rinehart et al., submmitted

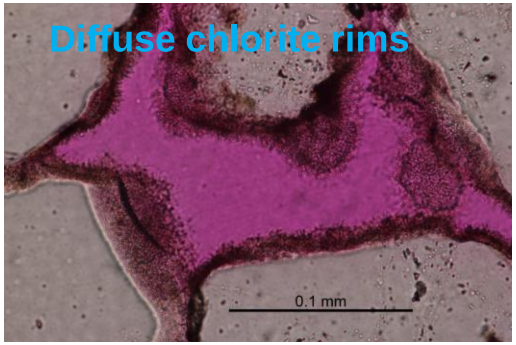
Chemical effects may have caused "Geomechanical Event"

- Accelerated creep at low stresses consistent with stress corrosion model (pH-activated?)
- Failure of chlorite facies below in situ stresses
- Grain-coating chlorite delamination (pH activated?)

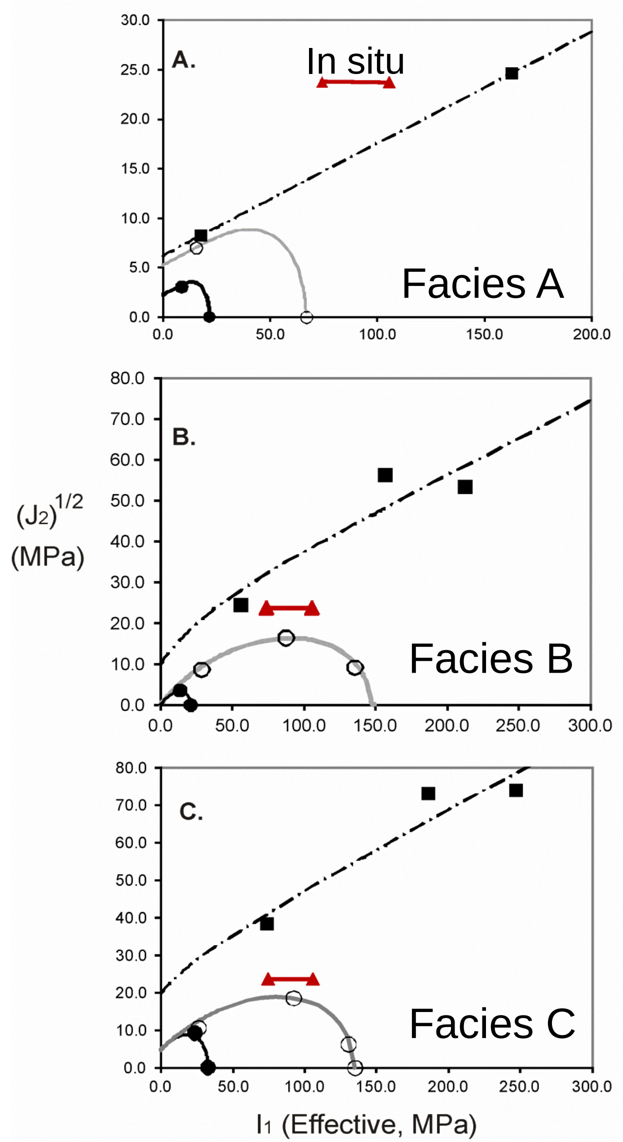
Untested



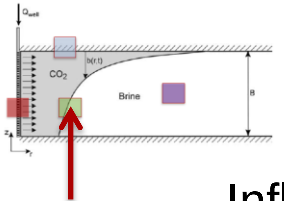
24-hr exposure to CO2 Brine



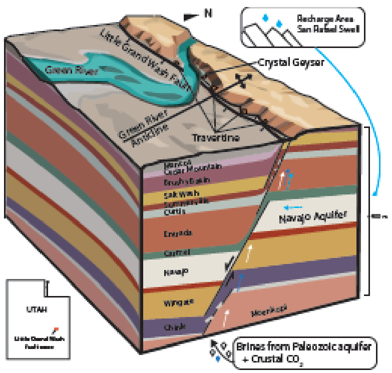
Yield and Failure Surfaces



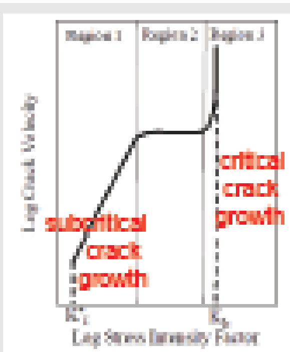
Fracture Growth Experiments



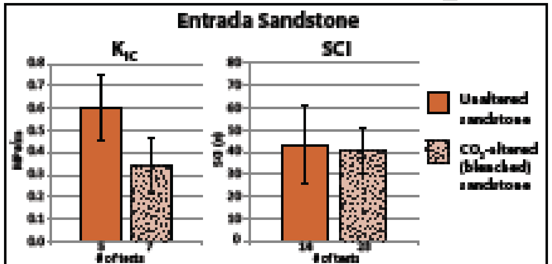
Influence of CO_2 Alteration on Fracture Toughness

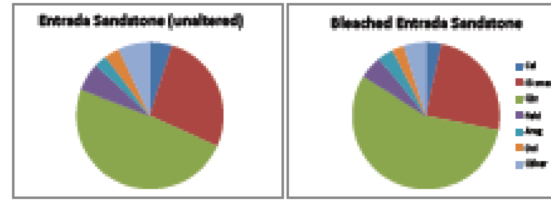


$$V = A\left(\frac{K_I}{K_{IC}}\right)^n$$

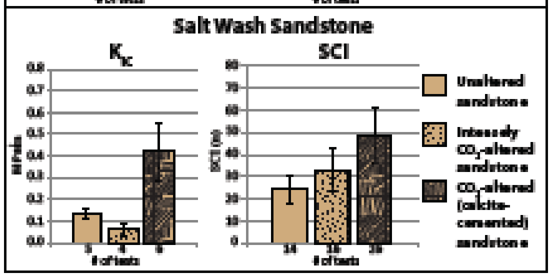


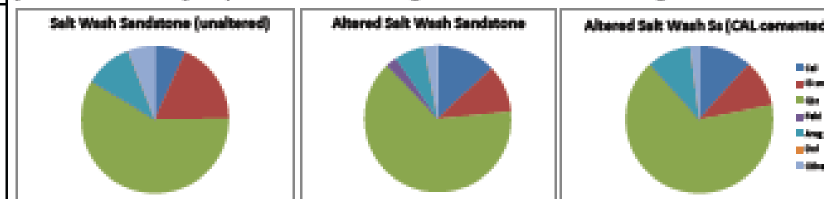
K'_I = stress corrosion limit
K_{IC} = fracture toughness



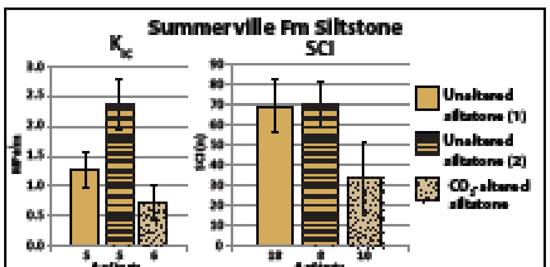


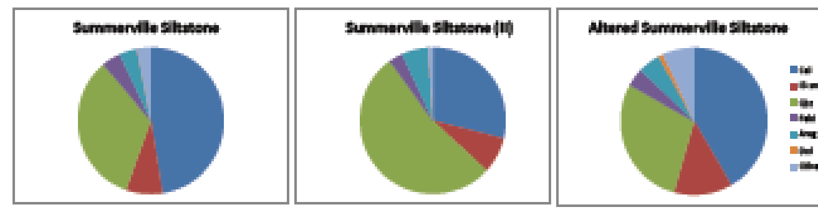
CO_2-related bleaching of Entrada sandstone slightly altered bulk mineralogy, yet it measurably impacts fracture toughness. Field shot on right.



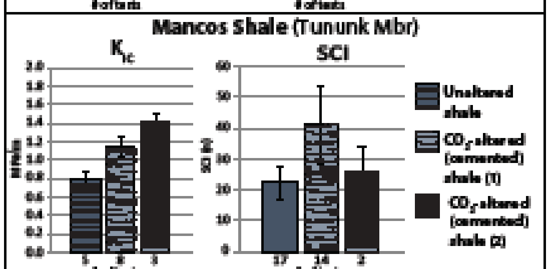


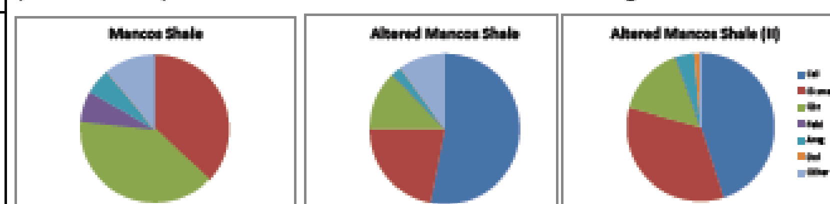
CO_2-related alteration characterized by slight increases in calcite, which increases fracture toughness. The most intensely altered sample is weakest.





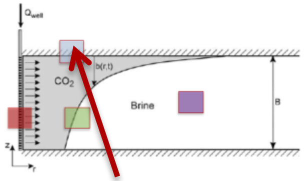
CO_2 alteration in siltstone characterized by increase in amount of clays (illite-smectite). This alteration also decreases fracture toughness.



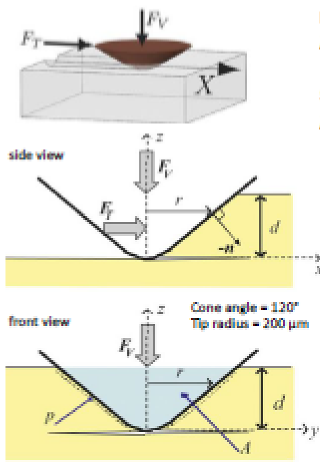


CO_2-alteration characterized by large increases in calcite content, which helps increase fracture toughness.

Caprock Chemical and Mechanical Integrity



Methods - Micro Scratch Test



Fracture Toughness (K_c):

$$K_c = \frac{F_T}{\sqrt{2pA}}, \text{[Mpa*m}^{1/2}\text{]}$$

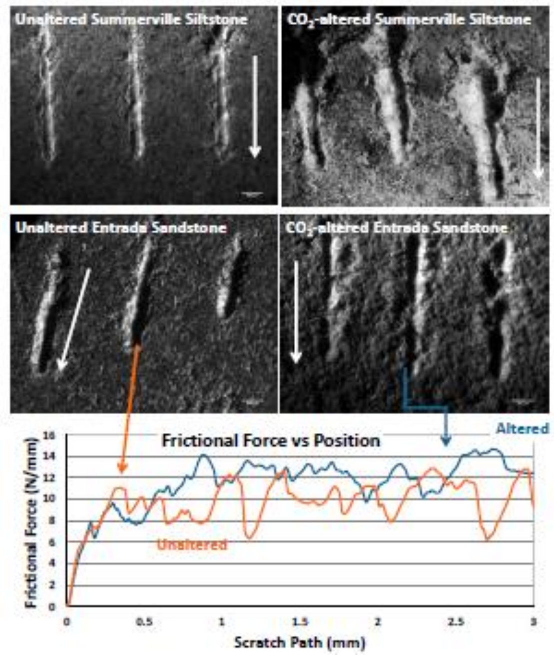
Scratch Hardness ($H_{scratch}$):

$$H_{scratch} = \frac{kF_V}{w^2}, \text{[GPa]}$$

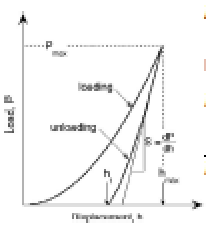
Variables:

- F_T: Horizontal force
- F_V: Vertical force (constant)
- p: Stylus perimeter
- A : Projected horizontal load bearing contact area
- k: Geometric constant
- w: Scratch width
- v: Translation velocity (constant)

(Top) Diagram of scratch test showing translation direction. (Middle) Side view and (Bottom) front view of loaded axisymmetric stylus with relevant parameters. [Figures, equations from Akono et al., 2012, ASTM G171]



Methods – Micro Indentation Test



Indentation Hardness (H):

$$H = \frac{P_{max}}{A_c}, \text{[GPa]}$$

Elastic Modulus (E):

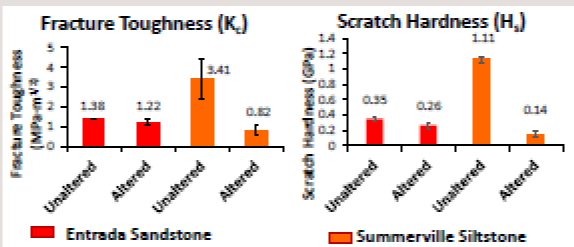
$$E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A_c}}$$

$$\frac{1}{E_r} = \frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i}$$

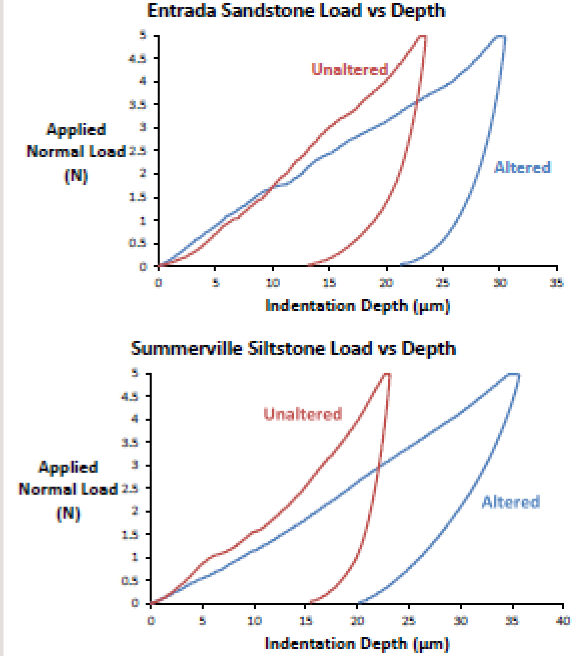
Variables:

- P_{max}: Maximum applied load
- A_c: Contact area
- E_r: Reduced elastic modulus
- E_i: Indenter elastic modulus
- ν_i: Indenter Poisson's ratio
- S: Elastic unloading stiffness

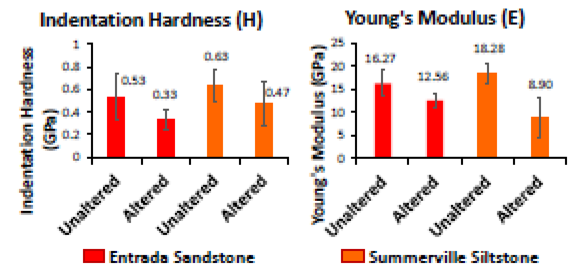
(Top) Indentation load displacement data showing important parameters. Measurements are taken on the unloading cycle [Oliver and Pharr 2004]. (Right) Diagram of penetrating indentation stylus.



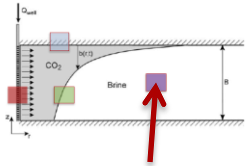
Results – Micro Indentation Test



(Top) Indentation normal load versus depth for representative pairs of unaltered and geologically CO_2-altered Entrada Sandstone and Summerville Siltstone indentations. 5 indentations were performed for each type of sample.



Average indentation hardness (bottom left) and mean Young's modulus (bottom right) calculated for both Entrada Sandstone and Summerville Siltstone, CO_2-unaltered and altered, respectively. Error bars represent 95% confidence intervals.

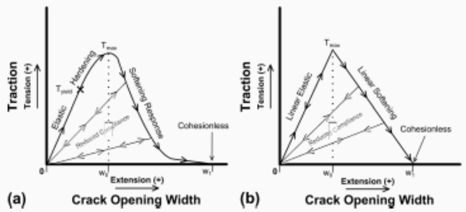


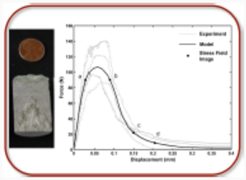
Fracture Propagation Modeling

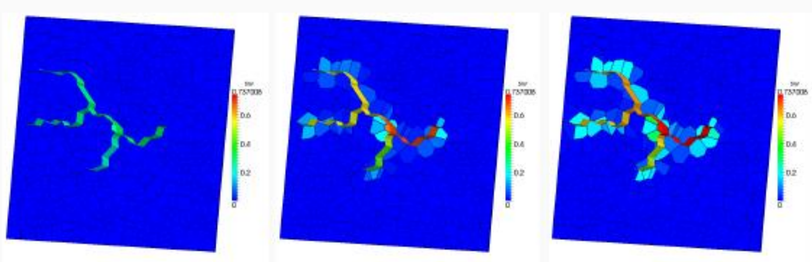
Cohesive Fracture Modeling

Cohesive Fracture Models (CFM) lump the inelastic processes occurring during fracture propagation into a thin zone between elastic subdomains. CFM assumes that the cohesive zone initially deforms elastically to a maximum tensile stress and then softens linearly from the crack opening width to zero stress at a critical crack opening width [6].

$$\nabla \cdot \mathrm{P} + \rho \mathrm{g} = 0$$



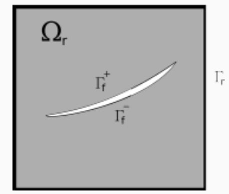


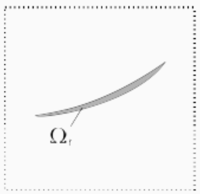


Multiphase flow solutions through fracture network embedded in a Voronoi mesh using the MFD method.

Mimetic Finite Differences

The Mimetic Finite Difference method [4] solves flow problems over a general set of polyhedral elements, which includes Voronoi grids.
For fracture flow calculations, the problem is divided over two separate domains, one for the fracture and one for the matrix. The two problems are then coupled using boundary conditions and source terms [1]:



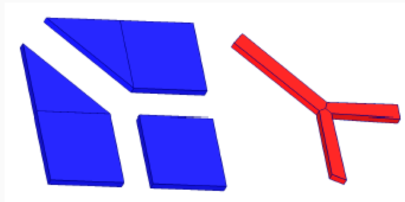


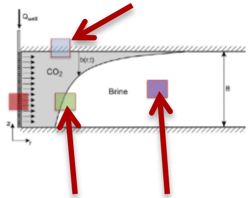
$$-\nabla \cdot K_r \nabla p_r = f \quad \text{in } \Omega_r$$
$$p_r = p_f \quad \text{on } \Gamma_f^{\{+,-\}}$$

$$-\nabla \cdot K_f \nabla p_f = Q_l - Q_L \quad \text{in } \Omega_f$$
$$K_f \nabla p_f \cdot n = 0 \quad \text{on } \partial\Omega_f$$

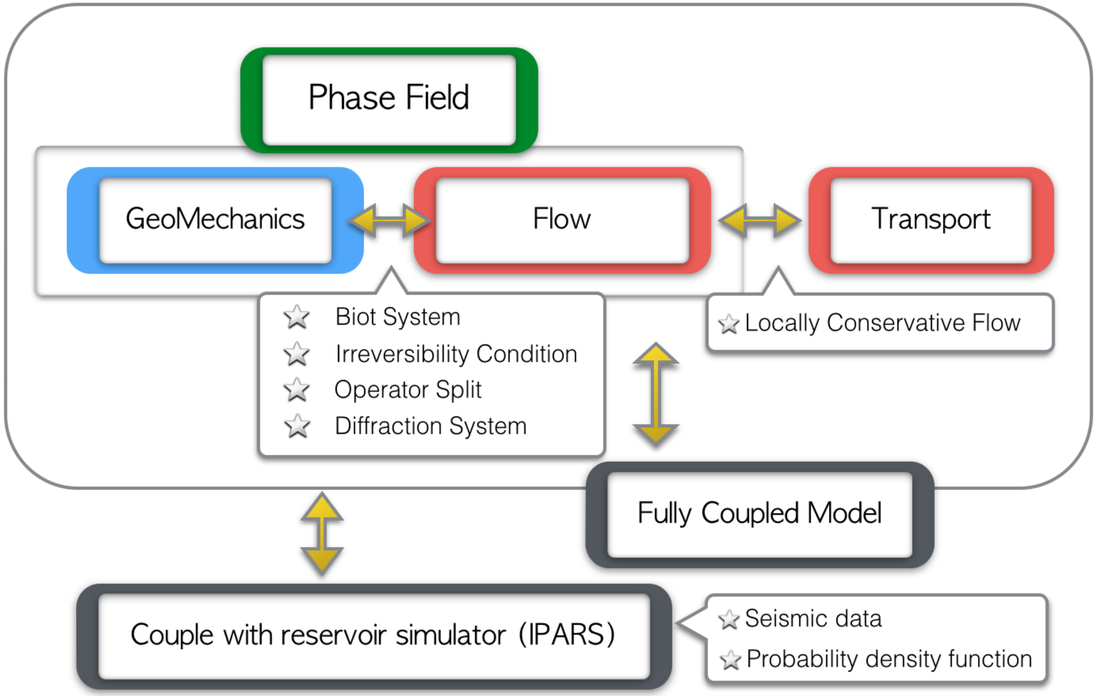
Unlike other methods that define the fracture problem over a lower-dimensional manifold, we represent the fracture domain in the same dimension as the matrix domain. Doing so has some important advantages:

- Code reusability: we are using the exact same code for the both the fracture and matrix solution.
- Simple intersections: intersecting fractures are naturally represented in the full dimensional space.
- Fracture geometry: we can fully represent fracture aperture and curvature directly using the mesh.



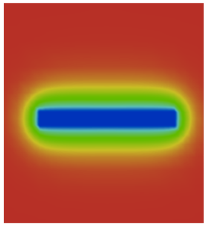


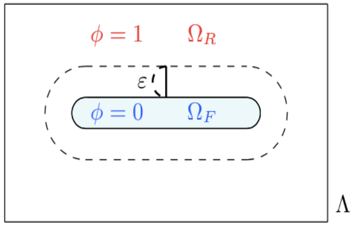
Fracture Propagation Modeling



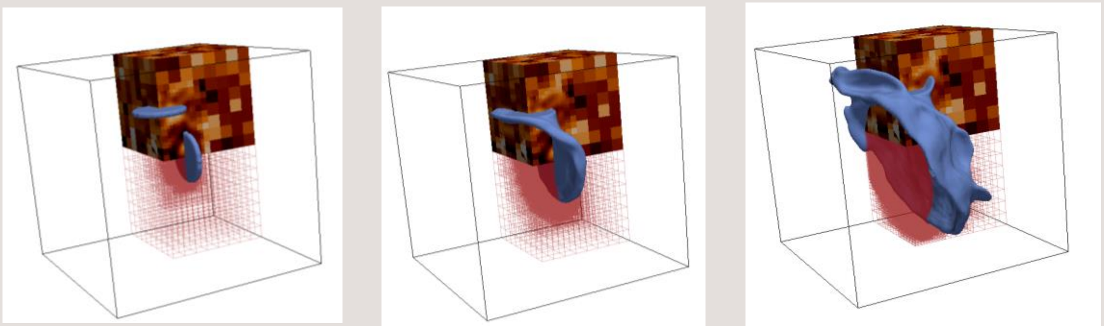
Phase Field Method

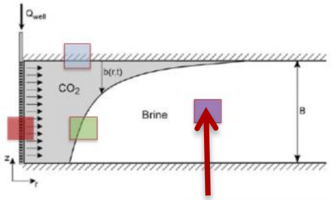
- Phase Field method interpolates between fractured and unfractured states
- Variational method based on energy minimization
- Crack advances when energy release rate exceeds threshold
- Nucleation, propagation, and path are automatically determined





Multiple Joining and Branching Fractures





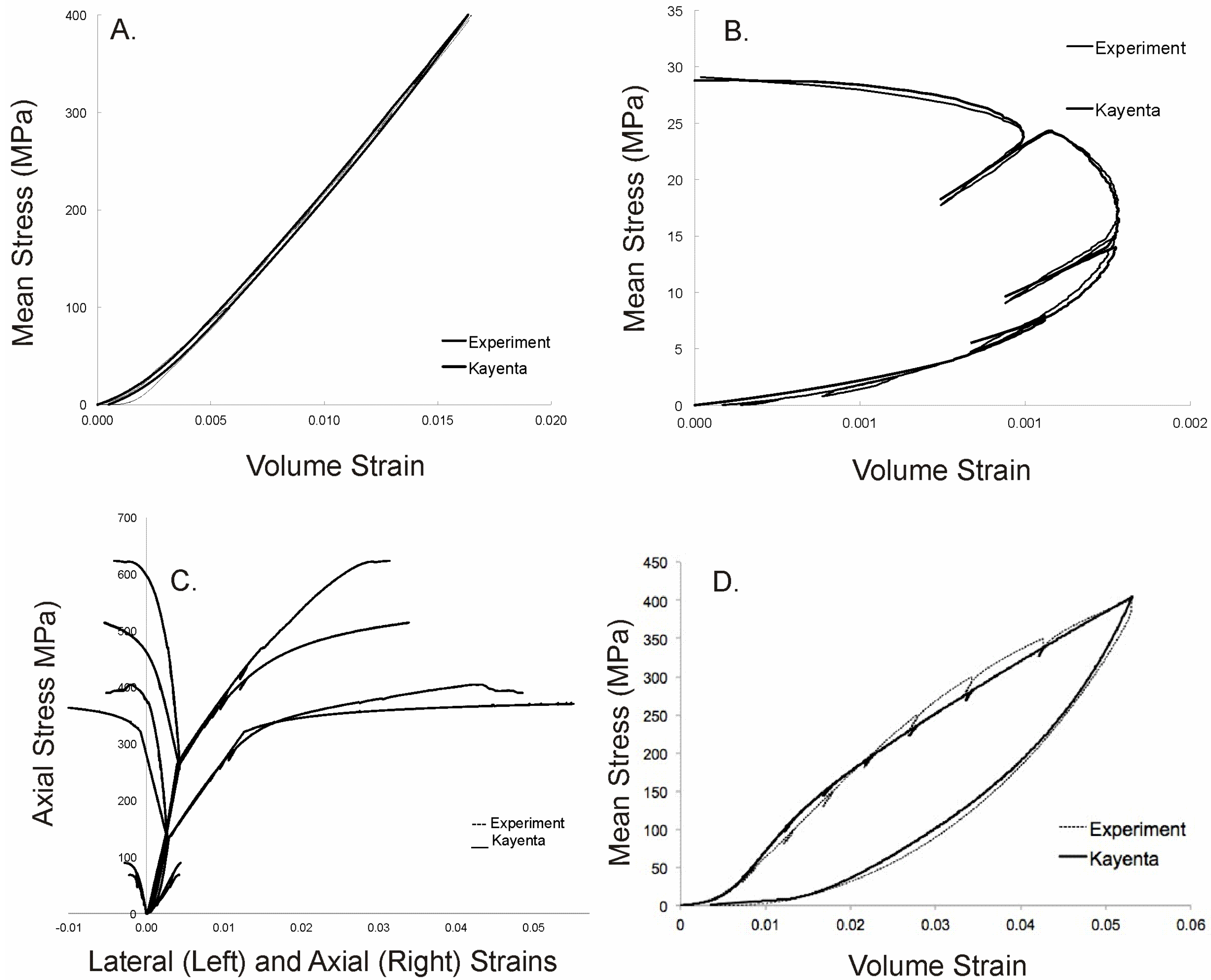
Constitutive Modeling

Mt. Simon Sandstone

Kayenta* Includes:

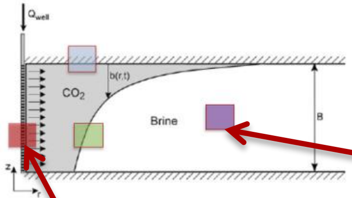
- •Non-Associative Plasticity
- •Stress Invariant Dep. Failure
- •Elliptical Cap Surface
- •Kinematic Hardening
- •Isotropic Hardening
- •Nonlinear Elasticity
- •Elastic-Plastic Coupling

*Developed by Brannon et al. 2009

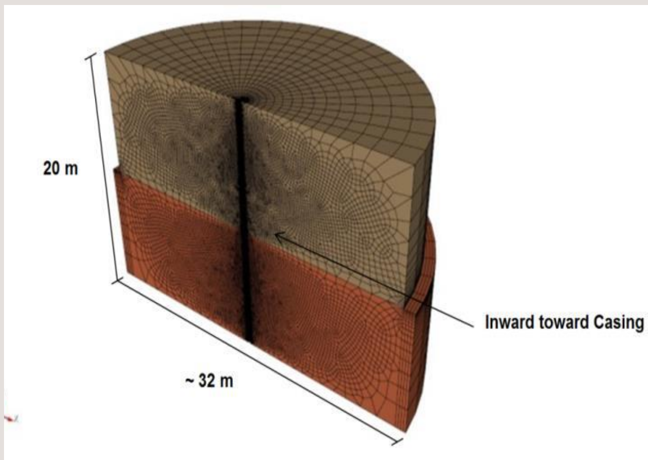


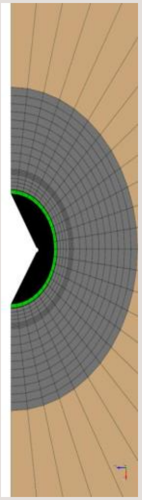
Dewers et al., IJGHGC, 2014

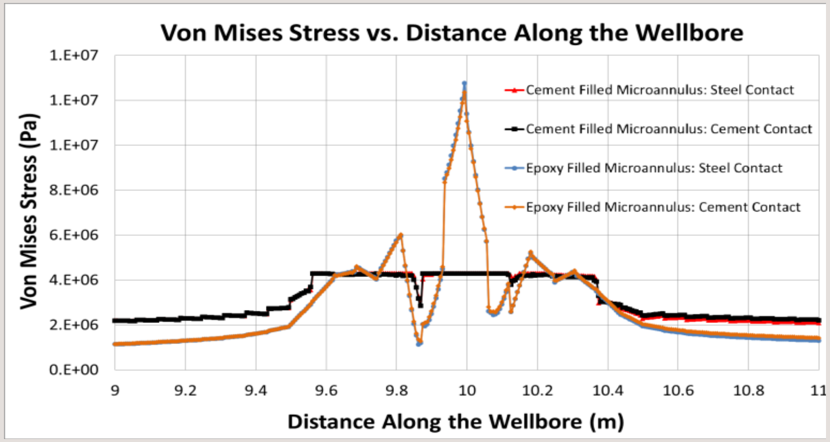
Continuum Modeling

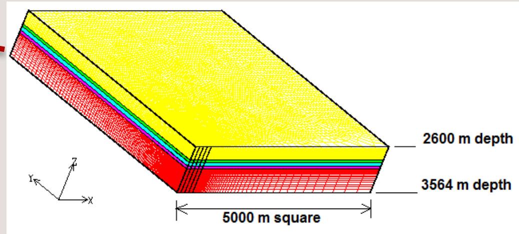


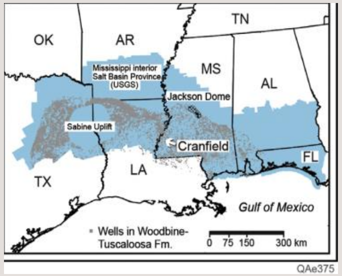
Modeling Effects of Injection on Wellbore Integrity



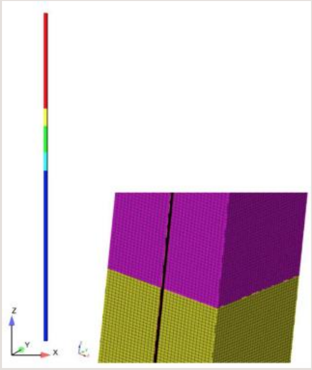




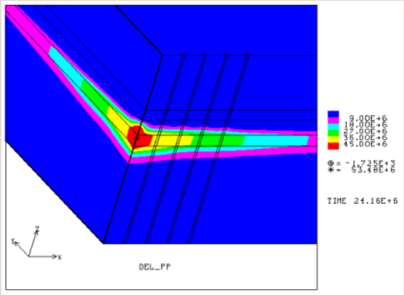




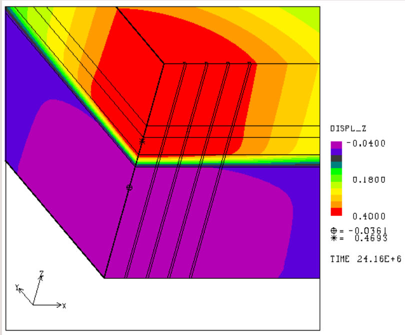
Cranfield Site



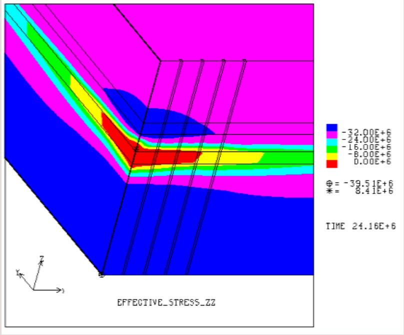
Computational Meshes



Pore Pressure, 280 d



Z-displacement, 280 d



Effective Vertical Stress

Putting It All Together: CFSES Research Challenges and Efforts

Sustaining Injectivity

Experimentally validated geomechanics models can show where wellbore failure could occur during injection, and efficiency of repair methods

Chemo-mechanical models of near-wellbore damage can inform regulatory constraints on injectivity (i.e. “frac” gradient) and withdrawal (borehole shear failure).

Storage Efficiency

Experiments suggest that chemo-mechanical stimulation of reservoirs may improve sweep efficiency

State-of-the-art and experimentally validated constitutive models predict the extent of damage and deformation associated with pore pressure hazards in reservoirs

Controlling Emergence

Experiments and models of fracture propagation can predict timing and location of networks and cascades of fractures and could be used to prevent unwanted fracturing

Caprock alteration experiments are showing potential for understanding and controlling leakage pathway development and flow self-focusing of CO_2 plumes