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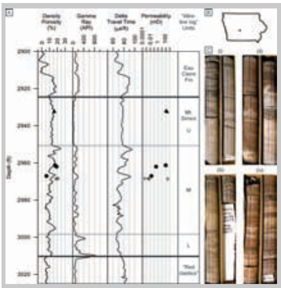

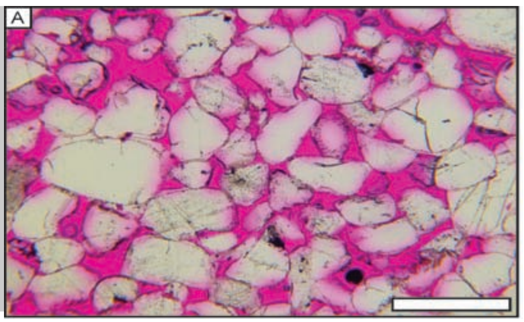

Sandia National Laboratories

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Geologic Carbon Storage and Fracture Fate: Chemistry, Heterogeneity, Models, and What to Do With It All

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

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[5]Department of Geological Sciences; [6]Bureau of Economic Geology; [7]The Institute for Computational Engineering and Sciences; [8]Institute for Geophysics; [9]Center for Petroleum and Geosystems Engineering, UT Austin;

CFSES Review, February 17, 2016

Austin, TX

U.S. DEPARTMENT OF ENERGY — NNSA National Nuclear Security Administration — TEXAS — Sandia National Laboratories

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Acknowledgements

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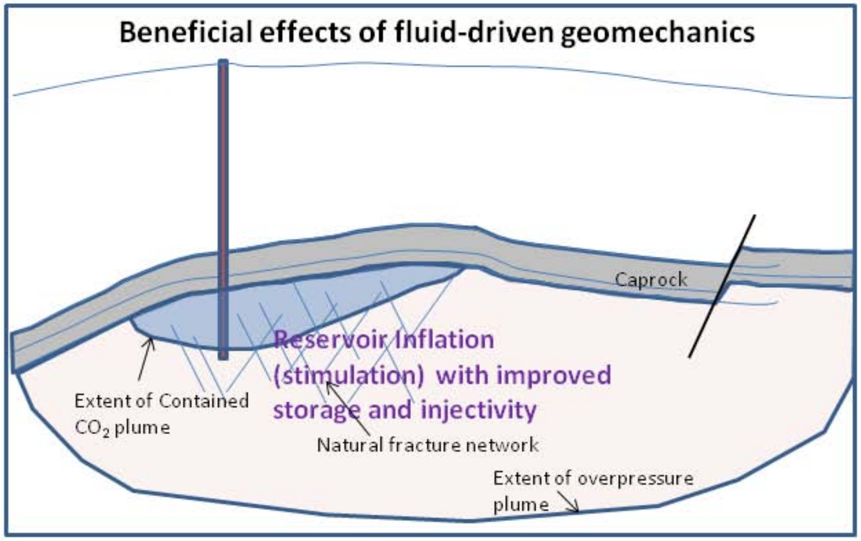
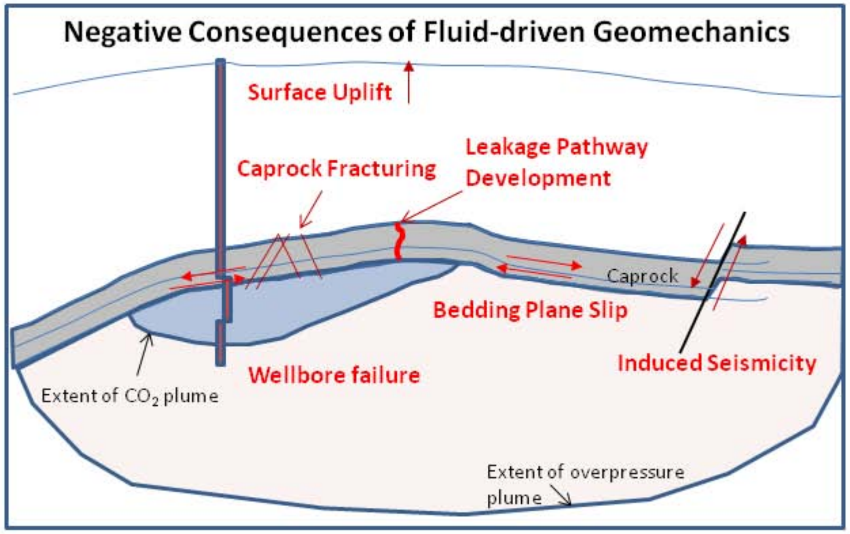
CFSES Research Challenges

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





Theme 1: Fluid-Assisted Geomechanics

Objectives

- Via experimental methods, understand mechanical consequences of CO_2 injection in reservoir and caprock lithologies
- Focus on chemo-mechanical short- and long-term impact
- Quantify behavior in advanced "constitutive laws"
- Advance lab-scale understanding to injection scenarios using next-generation coupled modeling
- Inform community, regulatory concerns, risk

Students and Post-Docs

Aman -
Choens – experimental rock mechanics, rock physics
Feldman – experimental rock mechanics, geochemistry
Lee – phase field fracture network modeling
Major – experimental fracture mechanics, structure
Mirabolghasemi -
Reber – experimental fracture, rheology (now at ISU)
Rinehart – rock physics (now at NMT)
Shafiei – continuum modeling

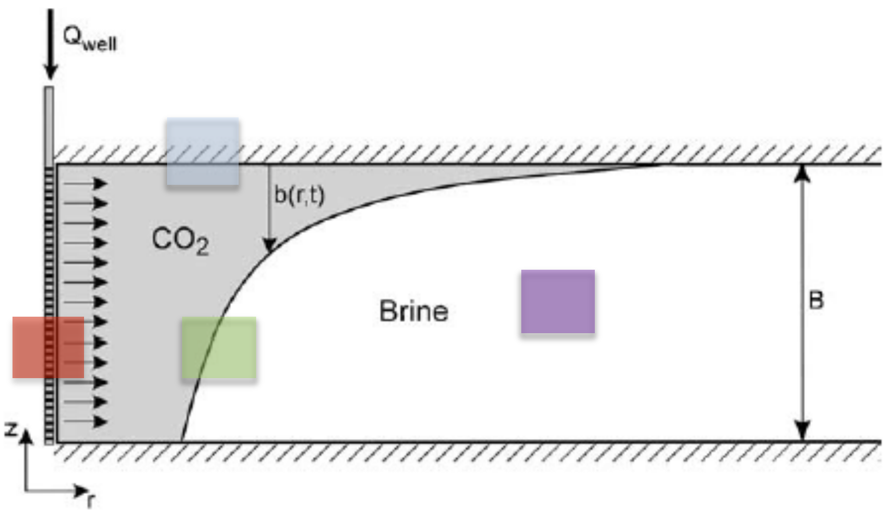
Senior Personnel

Balhoff – UT Theme lead; DEM; pore scale modeling
Dewers – SNL Theme lead, experimental mechanics
Eichhubl – experimental fracture mechanics, structural geol.
Ilgen – geochemistry, caprock integrity
Espinoza – experimental mechanics, caprock integrity
Ganis – continuum and fracture modeling
Hayman – experimental and theoretical fracture mechanics
Newell – constitutive modeling; fracture mechanics
Prodanovich – DEM modeling, petrophysics
Wheeler – continuum and fracture modeling

CFSES Organization

Theme 1 Tasks

1 Experimental Fracture Propagation
2 Reservoir Geomechanical Evolution
3 Caprock Chemical and Mechanical Integrity
4 Fracture Propagation Modeling
5 Constitutive and Continuum Modeling



From Nordbotten, Celia, and Bachu (2005)

Regions of Interest

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

Chemo-Mechanical Coupling

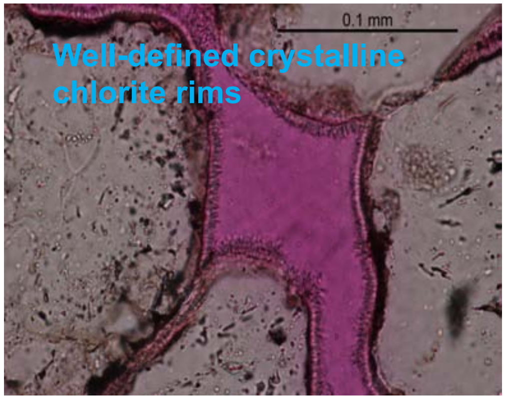
Near-Instantaneous

- Sub-Critical Fracture
- Water and other weakening
- CO_2-Enhanced creep
- Clay effects

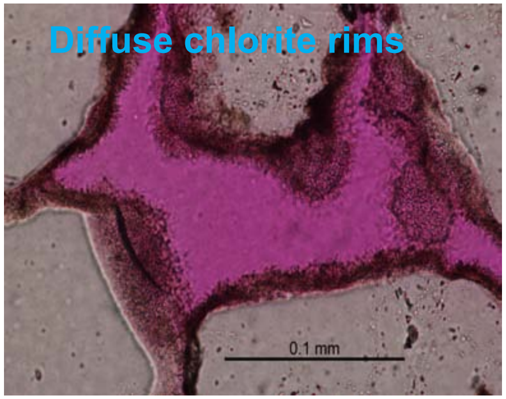
Long Term

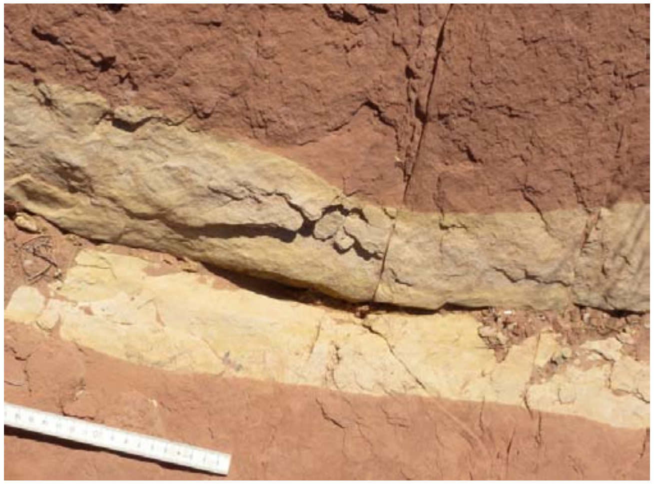
- Cement Degradation
- Mineral Alteration
- Dry-Out & Salt Effects

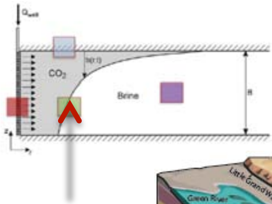
Untested



24-hr exposure to CO2 Brine

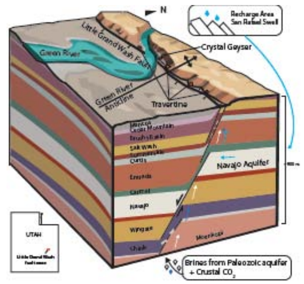


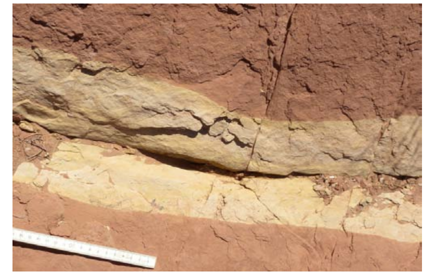


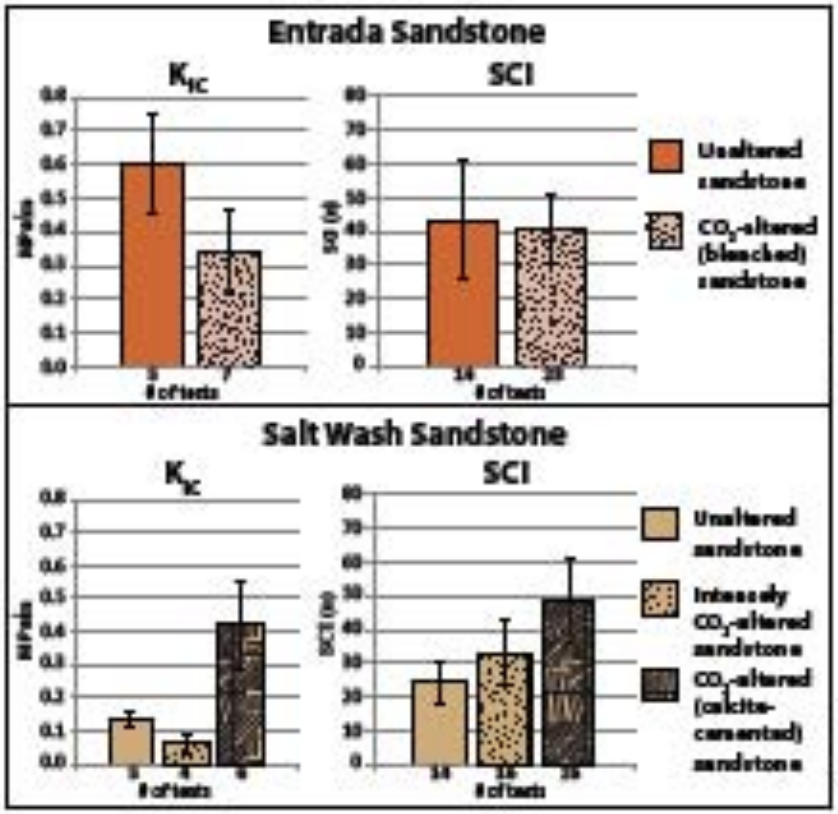


1 Fracture Propagation

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

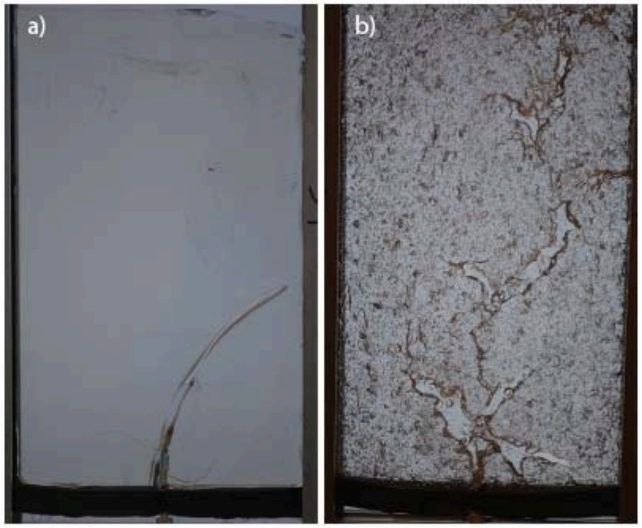




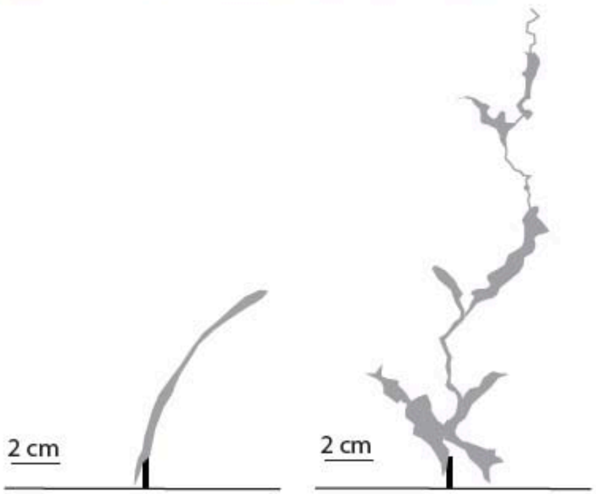


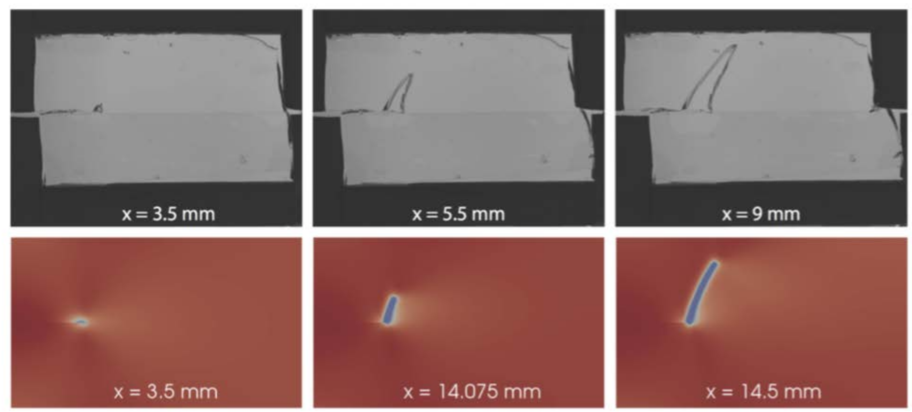
- •Double Torsion and Short-rod testing of lithologies from Crystal Geyser, UT
- •Iron Oxide alteration shows a weakening or lowering of fracture toughness relative to unaltered samples.
- •Increase in calcite cementation that has strengthened or increased fracture toughness relative to unaltered samples.

1 Fracture Propagation



- “Sandbox” experiments serve as analogs for fracture development
- Rheology influences fracture development; compare gelatin (far left) with Carbopol (right)
- Model validation (below) using Phase Field Method





1 Fracture Propagation

Quartz Crystal Microbalance (QCM)

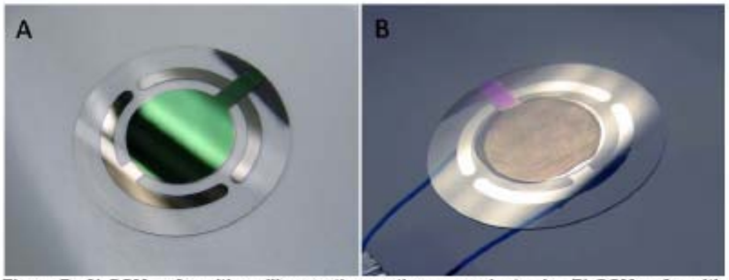
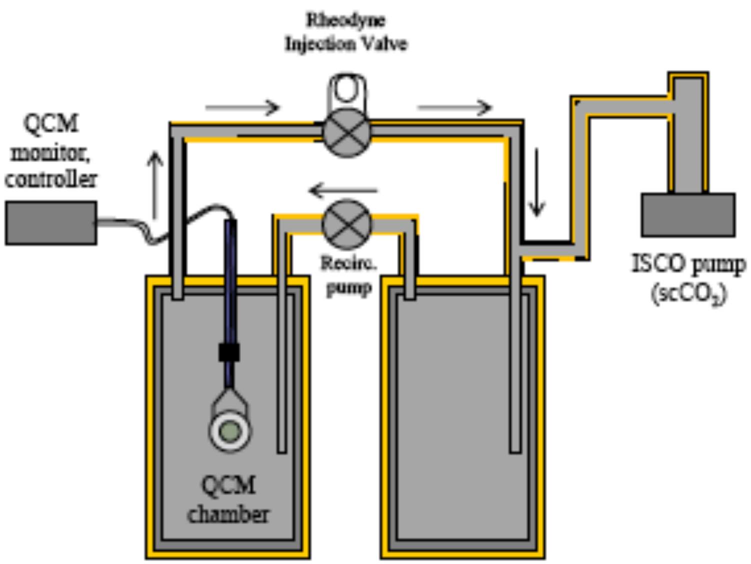
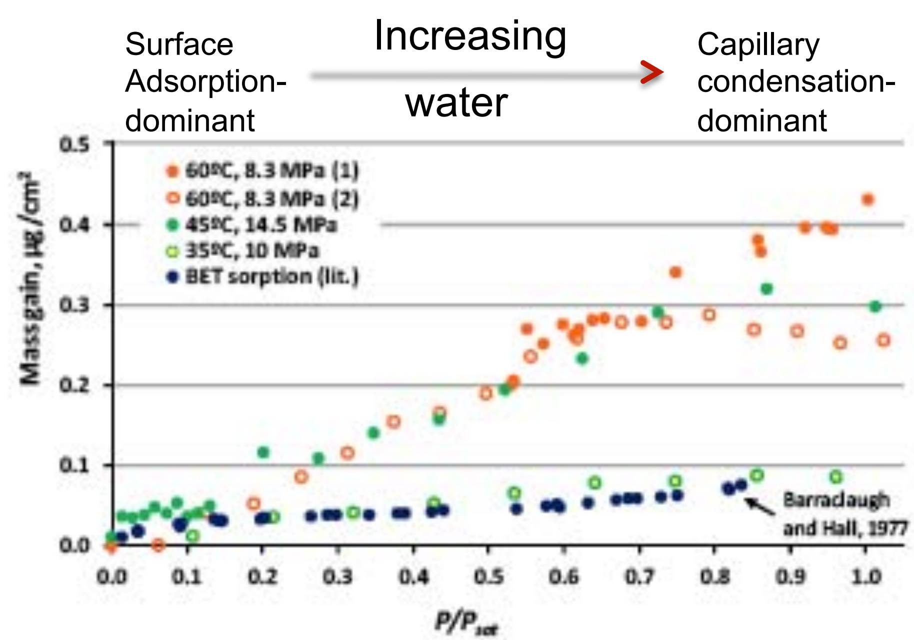


Figure 7. A) QCM wafer with a silica coating on the upper electrode. B) QCM wafer with a smectite clay film deposited on the crystal.

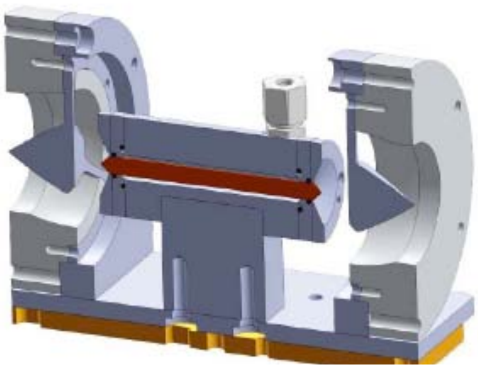


- QCM tests in humid $scCO_2$ show progressive development of water films
- Sorption isotherms match literature BET values
- Can measure water uptake by clays; much less in $scCO_2$ than in air



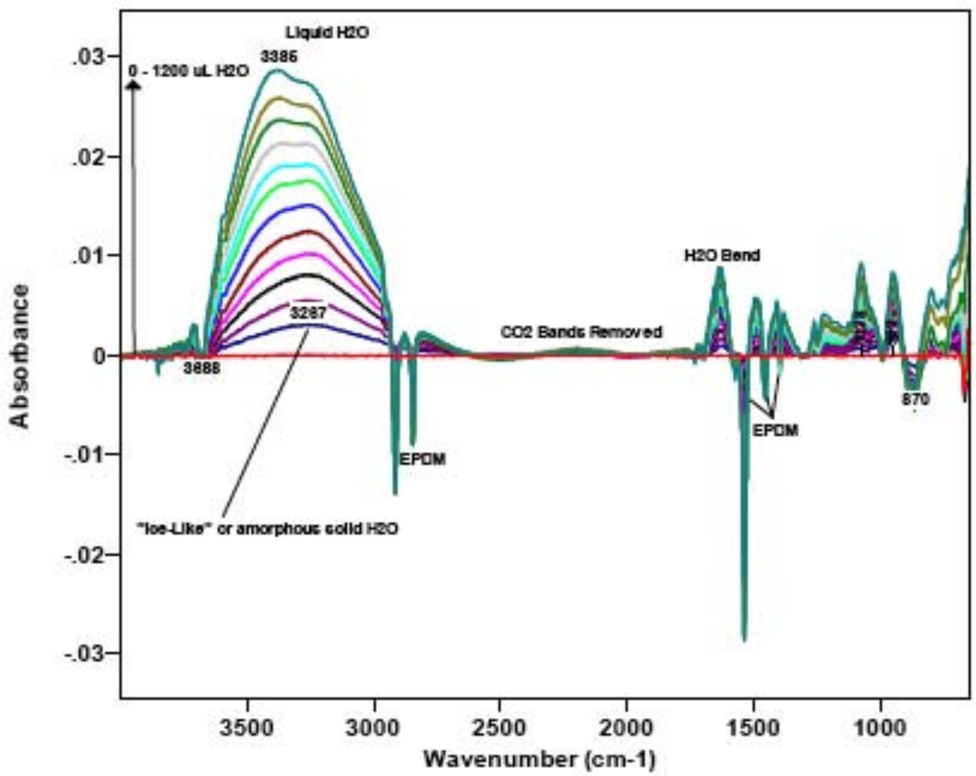
Water uptake by silica in scCO2

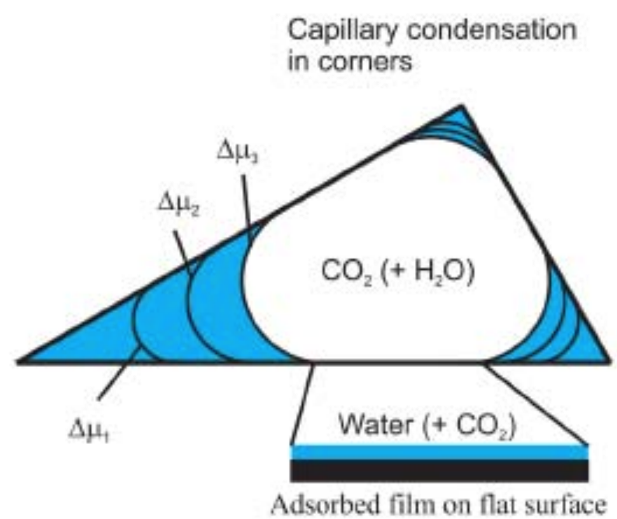
1 Fracture Propagation



•High Pressure FTIR experiments using silica-coated ZnSe crystal show development of liquid water films in scCO2 as humidity is increased (capillary condensation)

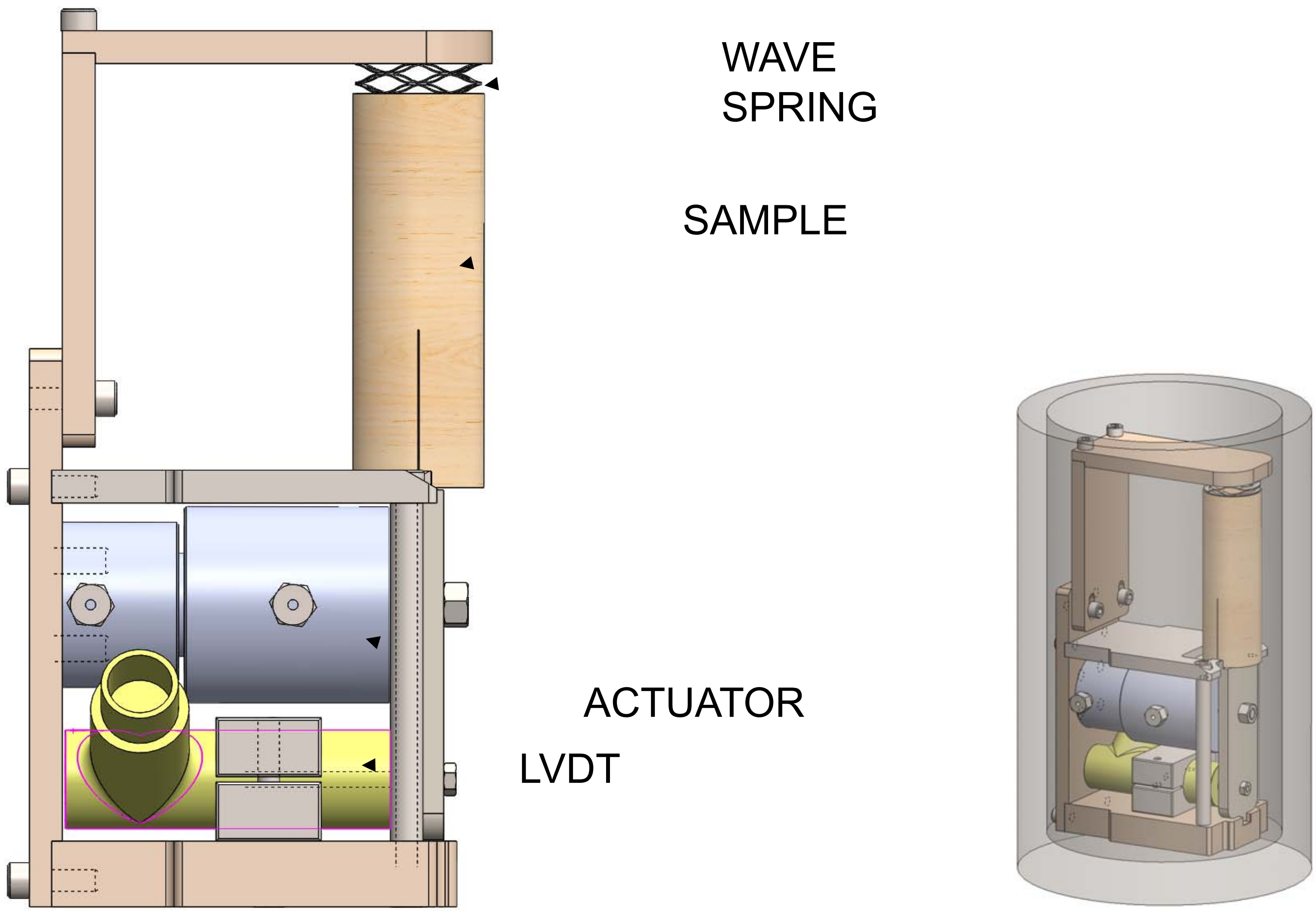
•Complex structure of + and – pointing spectra is attributed to attachment of hydroxyl molecules to silica tetrahedra, converting bridging Si-O-Si bonds to silanols

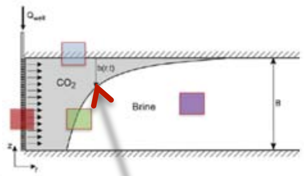




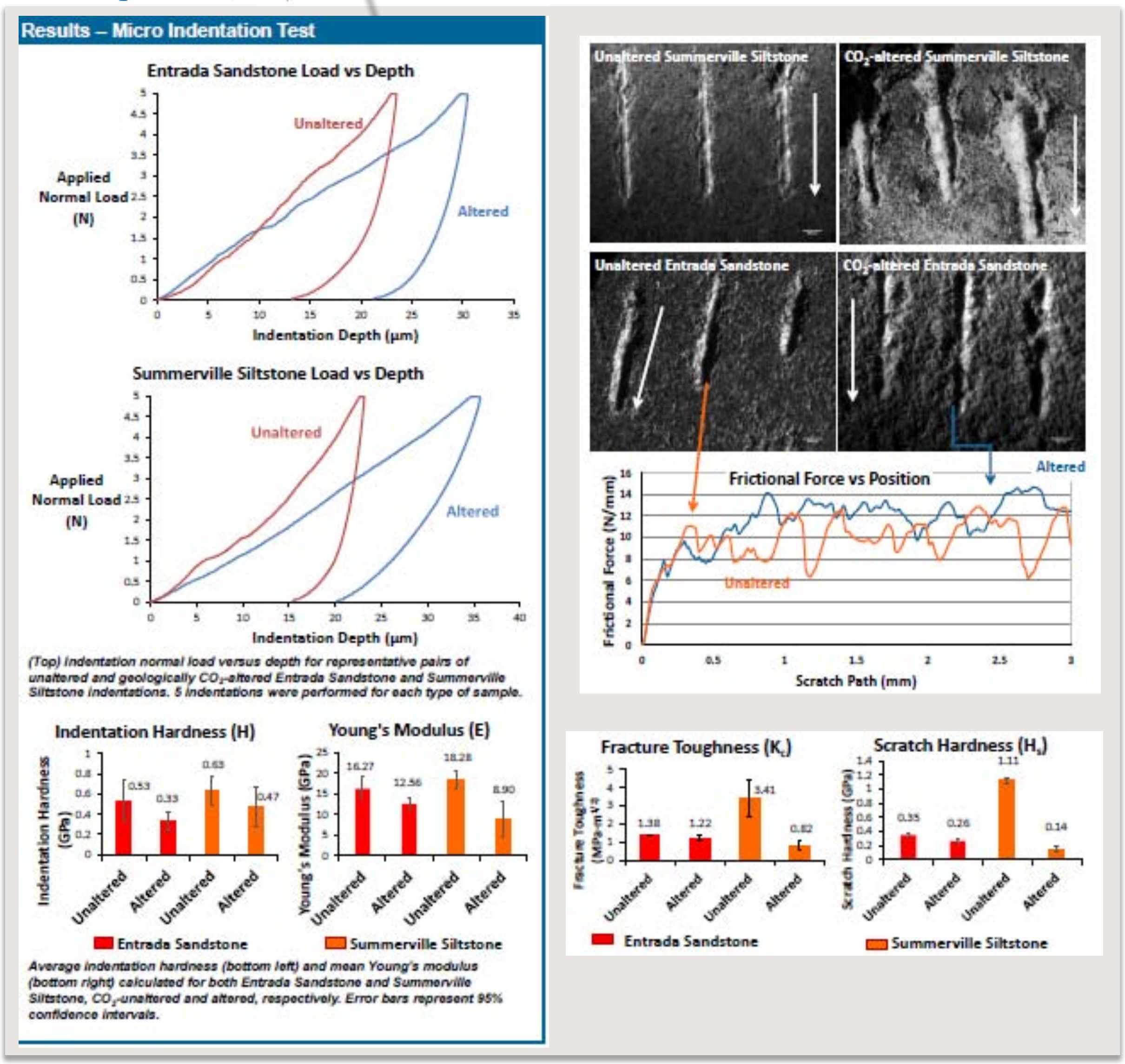
1 Fracture Propagation

In Situ Fracture Tester



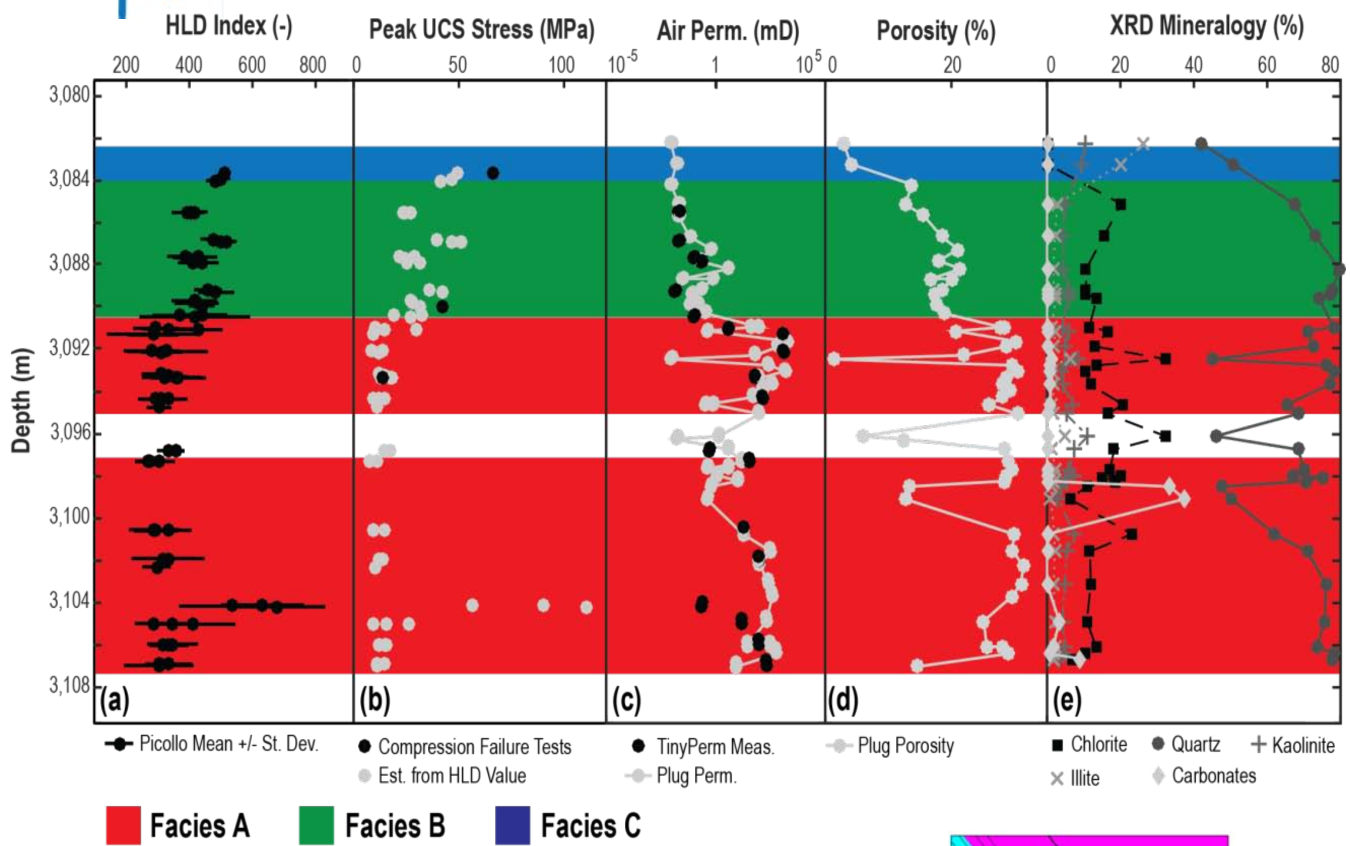


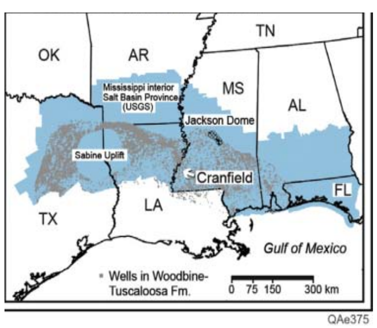
2 Reservoir Behavior

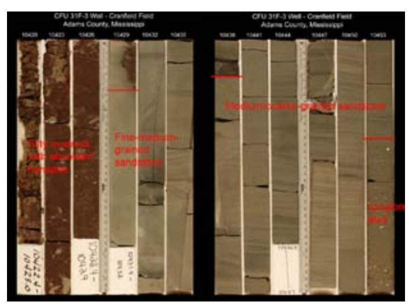


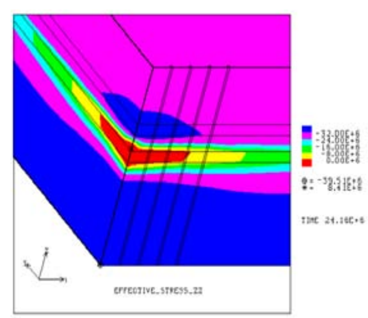
- Nanoindentation and micro-scratch tests permit a micro-scale characterization of heterogeneity in terms of strength, elastic moduli, and fracture toughness
- Similar to macro fracture testing, altered samples show a weakening relative to unaltered samples

2 Reservoir Behavior









- •Cranfield reservoir heterogeneity captured with three major llithofacies
- •“Bambino” hammer testing correlates with UCS estimates from ASC testing
- •“TinyPerm” air perm estimates agree with core tests
- •Used in borehole and reservoir coupled modeling

Proposed work: The effect of CO_2 injection on deformation and grain crushing

Mirabolghasemi and Prodanović

Problem statement:

- Grain crushing is enhanced at the presence CO_2; grain bonds weaken
- Mechanical and flow properties of the rock change after mechanical failure

Research plan:

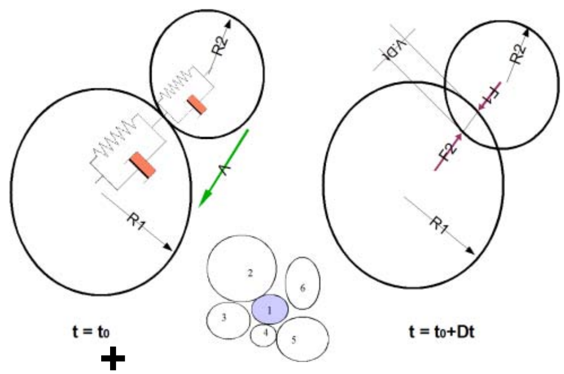
- Analyze grain size change (grain crushing extent) under various loads and formation fluid acidity
- Quantify petrophysical properties of the changed sample

Modeling tools

Discrete Element Method (DEM)
for mechanical behavior using LIGGGHTS

$$m_i \ddot{\mathbf{x}}_i = \sum_j \mathbf{F}_{ij}$$

$$\mathbf{I}_i \ddot{\boldsymbol{\theta}}_i = \sum_j \mathbf{M}_{ij}$$



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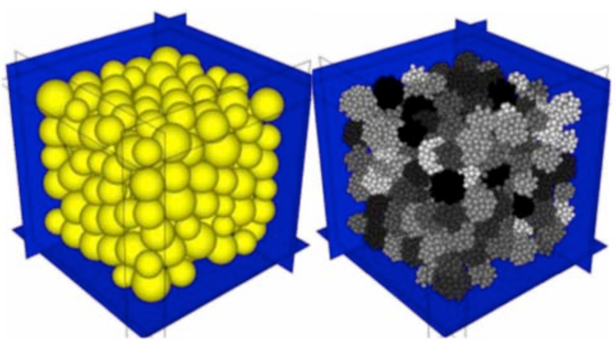
Computational fluid dynamics
(OpenFOAM software) for permeability estimates

Each grain consists of bonded subparticles



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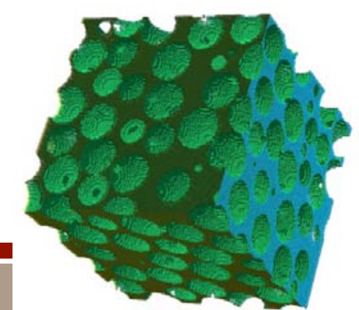

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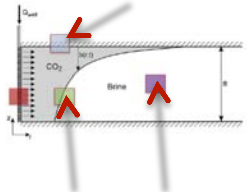
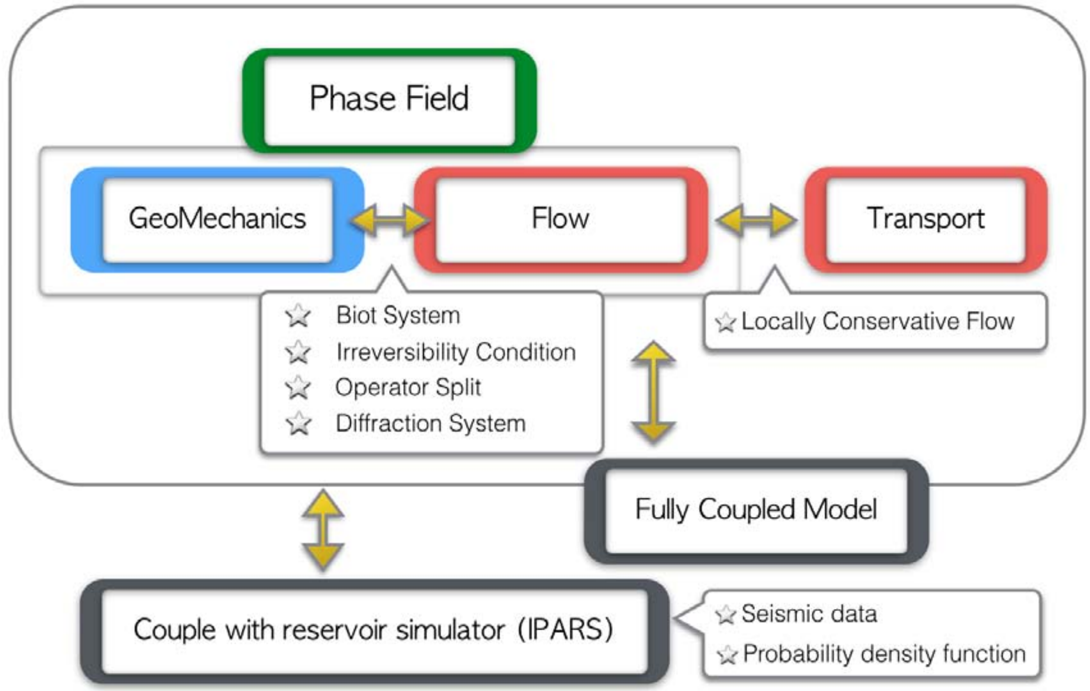
quantify petrophysical prop's after grain crushing

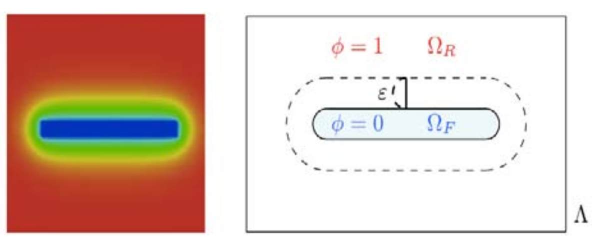
4 Fracture Propagation Modeling



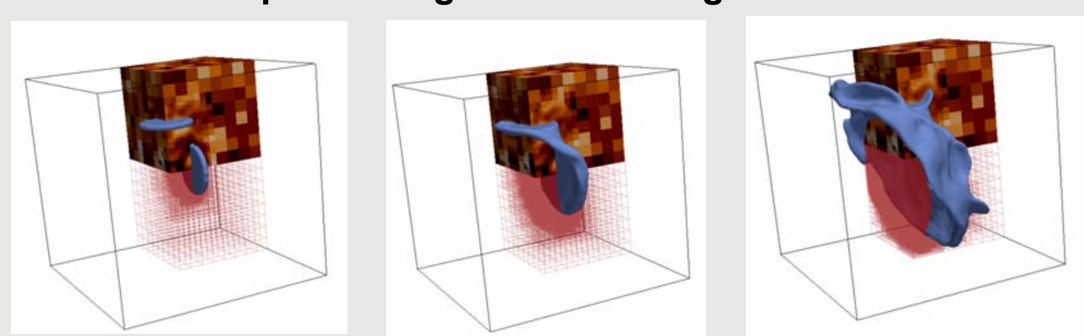
Phase Field Method

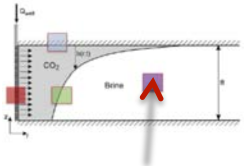
- Phase Field method interpolates between fractured and unfractured states
- Variational method based on energy minimization
- Crack advances when energy release rate exceeds threshold
- Nucleation, propagation, and path are automatically determined



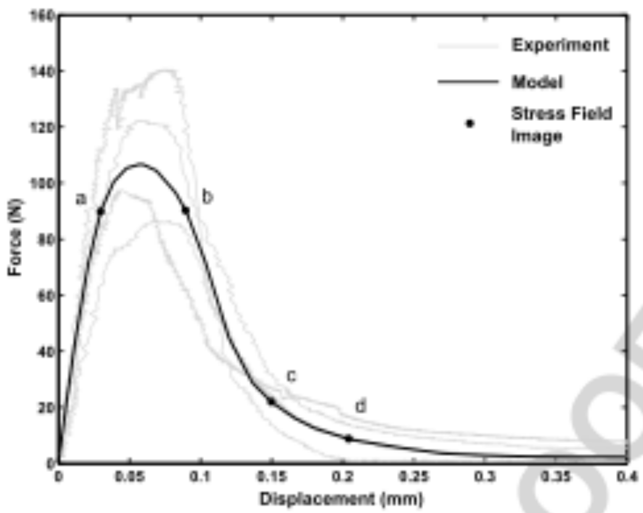


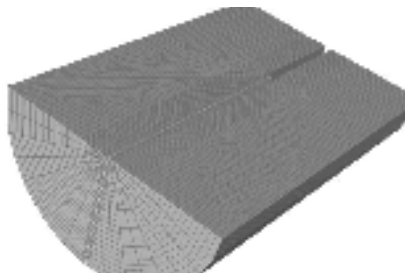
Multiple Joining and Branching Fractures



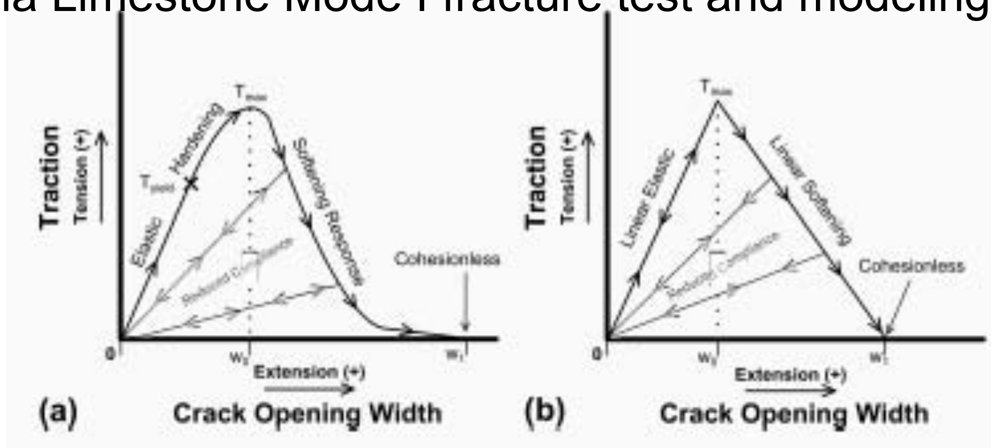


4 Fracture Propagation Modeling



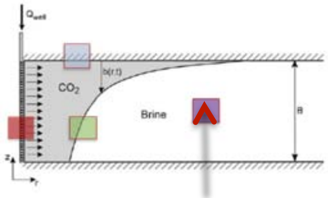


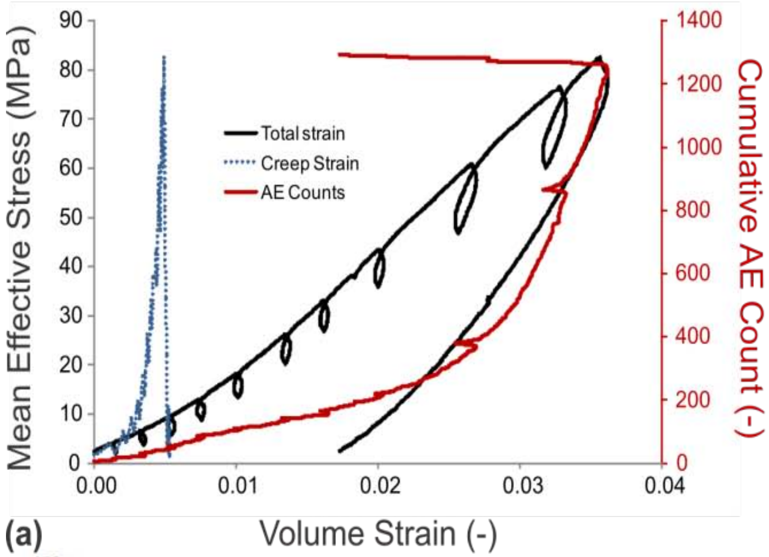
Indiana Limestone Mode I fracture test and modeling

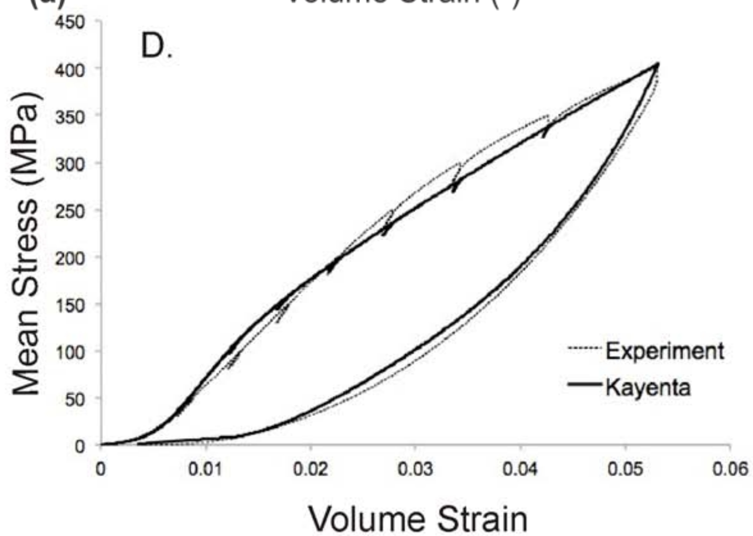


- Cohesive Fracture Models (CFM) lump inelastic behavior into a thin zone between elastic sub-domains
- Validated using aluminum and Indiana Limestone
- Different elastic properties in tension vs compression
- Linkage to local chemical environment (collaboration with Prof Rich Reguiro & post-doc at UC Boulder)

5 Constitutive Modeling

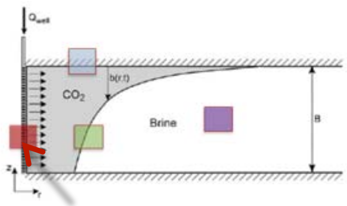






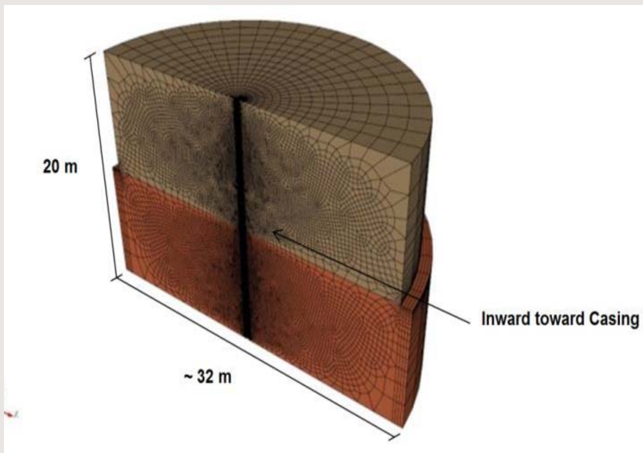
- Mechanics testing of reservoir rocks from NETL partnerships shows acoustic emission (AE), modulus degradation; heightened creep and reduced peak strength associated with CO_2
- Elasto-plastic and visco-elastic modeling captures experimental behavior in the form of constitutive laws for reservoir-scale modeling

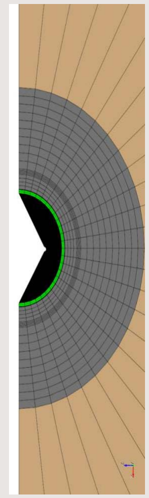
Dewers et al., IJGHGC, 2014

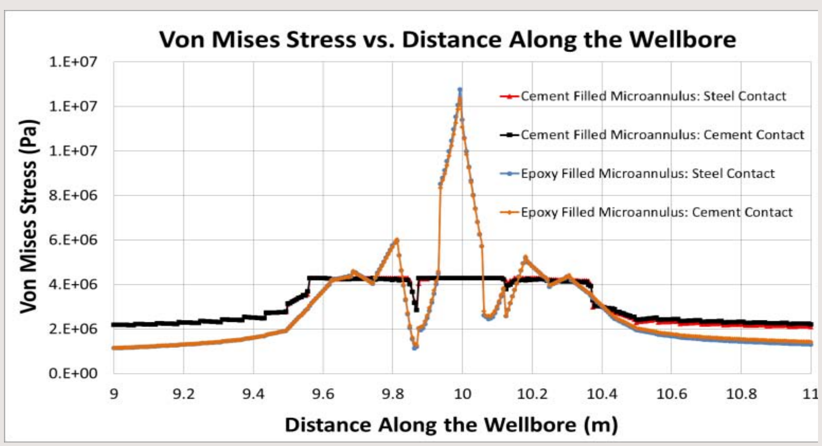


5 Continuum Modeling

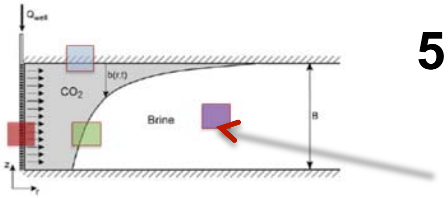
Modeling Effects of Injection on Wellbore Integrity







- Finite element modeling of Cranfield interfaces show localized wellbore deformation
- Can lead to casing failures in some cases
- Used to examine repair materials including nanocomposites (partnered with UNM)
- Quantitative basis for “frac” gradient; could be used to inform regulatory constraints in injection



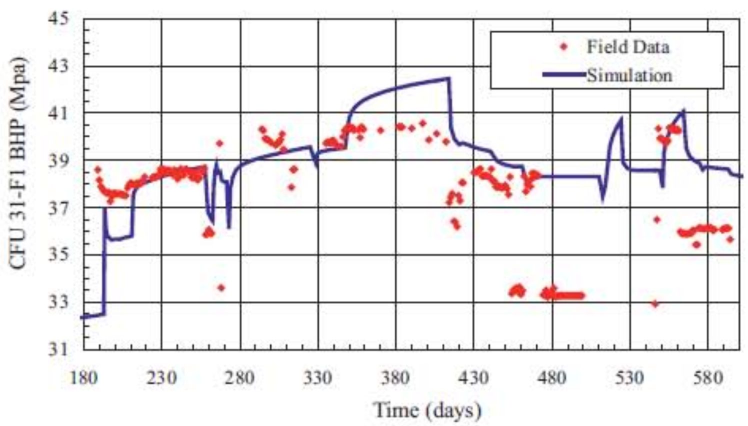
5 Continuum Modeling

Simulation of Drucker-Prager Plasticity Coupled with Fluid Flow for Modeling CO2 Sequestration at Cranfield

Ruijie Liu[2], Deandra White[1], Ben Ganis[1], Mohamad Jammoul[1], Mary Wheeler[1], Thomas Dewers[3]

[1] UT Austin, [2] UT San Antonio, [3] Sandia

- Previous compositional simulations had trouble matching injection BHP, suggesting geomechanical effects occurred near wellbore.
- History matching studies concluded development of high permeability channels.
- Goal: model geomechanical effects deterministically with Drucker-Prager plasticity.



$$\frac{\partial(\rho(\phi_0 + \alpha\varepsilon_v + \frac{1}{M}(p - p_0)))}{\partial t} + \nabla \cdot \left(\rho \frac{K}{\mu}(\nabla p - \rho g \nabla h)\right) - q = 0$$ **Fluid Flow**

$$\nabla \cdot (\sigma'' + \sigma_o - \alpha(p - p_0)I) + f = 0$$ **Stress Equilibrium**

Plastic Strain Evolution

$$\dot{\varepsilon}^p = \lambda \frac{\partial F(\sigma'')}{\partial \sigma''}, \quad \text{at } Y(\sigma'') = 0$$

$$\dot{\varepsilon}^p = 0, \quad \text{at } Y(\sigma'') < 0$$

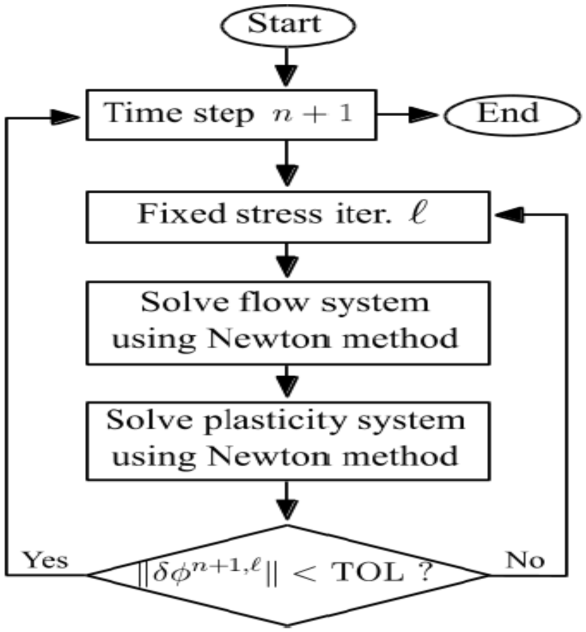
Yield and Flow Functions

$$Y = q + \theta\sigma_m - \tau_0$$

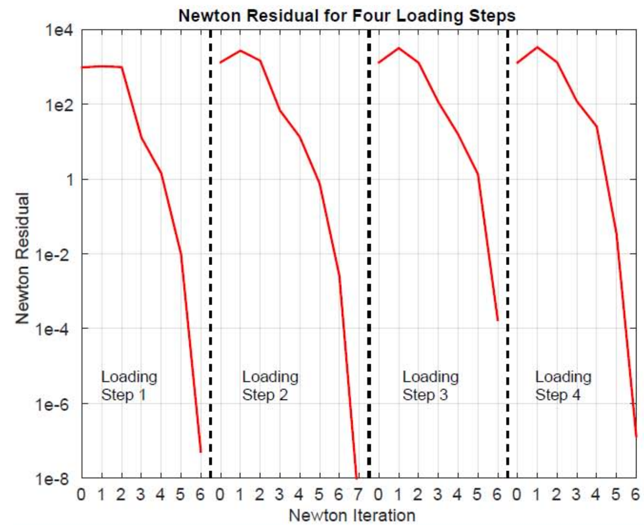
$$F = q + \gamma\sigma_m - \tau_0$$

Recent Progress and Future Directions

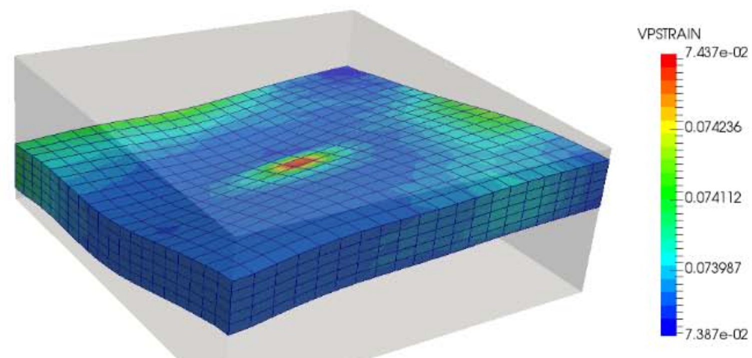
Fixed Stress Iterative Coupling Algorithm for Poroelastoplasticity



Improved convergence with incremental loading steps



Added overburden and underburden layers

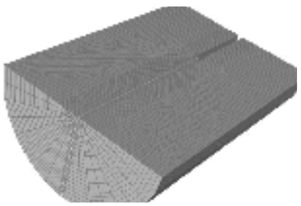


Volumetric Plastic Strain

Future Directions

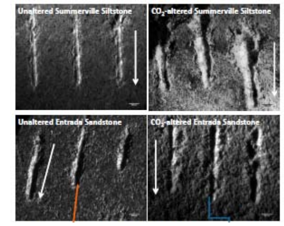
- **Use iterative solver for mechanics to allow for larger domain.**
- **Utilize compositional model for fluid flow for Cranfield.**

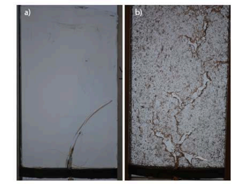
Summary: Year I Accomplishments

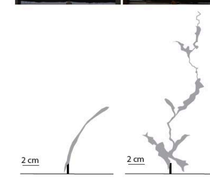


Experiment

- Double Torsion and Short-Rod Fracture Testing
- Analog Mode I and Shear Fracture Interaction in Carbopol
- New Equipment Acquisition at UT and SNL
- Design and Construction of In Situ Fracture Testing Apparatus
- Application of FTIR and QCM to Water Film Development
- Experiments Begun Examining Influence of Water Weakening

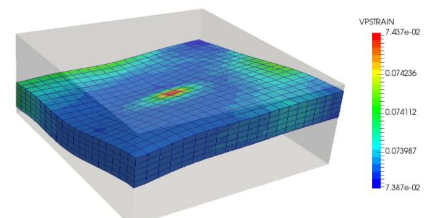


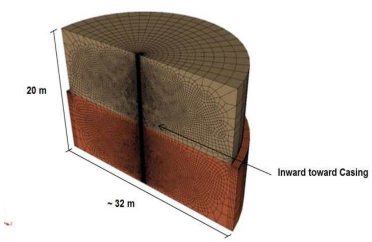




Modeling

- Implementation of Phase Field
- IPARS Coupling with Plasticity
- Kayenta Constitutive Modeling
- Cohesive Zone Modeling
- Discrete Element Methods





Publications

Rinehart et al., 2015
Rinehart et al., 2016 (to appear)
Rinehart et al., 2016 (in review)

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