Quantitative Characterization of Impacts of Coupled Geomechanics and Flow on Safe and Permanent Geological Storage of CO_2 in Fractured Aquifers

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Presentation Outline

- Technical Status
- Accomplishments to Date
- Lessons Learned
- Synergy Opportunities
- Project Summary
- Appendix

Technical Status

2) Laboratory studies of effects of geomechanics on CO_2 flow and transport properties in fractured rock

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Rock Property Tests

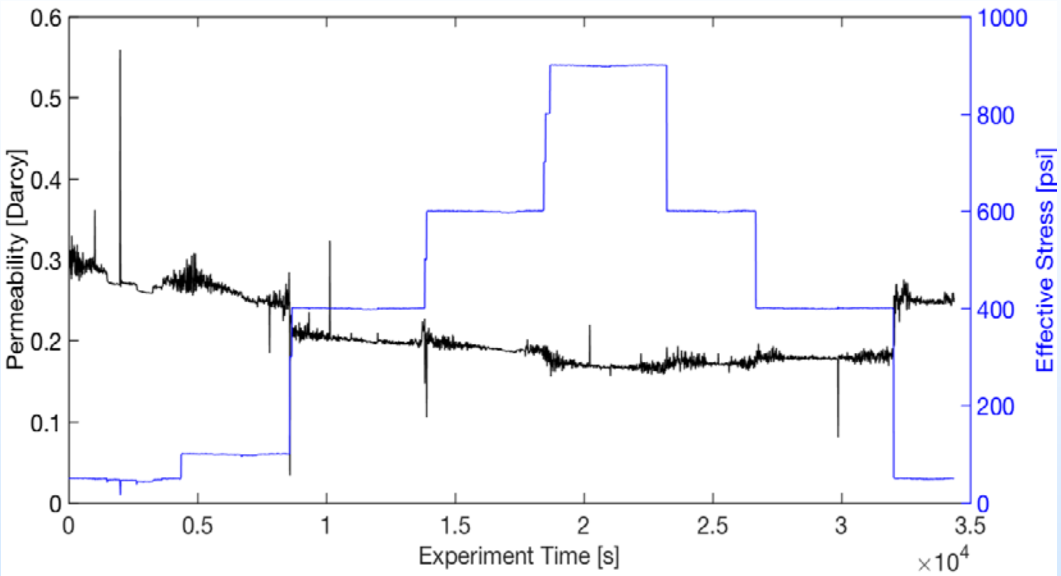
- Three different rock types: concrete, sandstone and shale
- Acoustic test, permeability and porosity, Brazilian test, uniaxial compression test, specific heat

	Concrete	Sandstone	Shale
Sample Origin	Type II Portland Cement	Williams Fork Outcrop,West CO	Niobrara Form. Boulder, CO
E, Gpa; υ	30.0; 0.243	118.3; 0.142	49.3; 0.268
Φ; k, mD	9.56; 0.009	11.47; 0.349	6.65; 0.001
Tensile Str., MPa	2.878	4.505	8.455
Uni-Comp Str, MPa	37.343	41.457	54.585
Sp. Heat, J/kg·K	891	857	990

Permeability vs Effective Stress

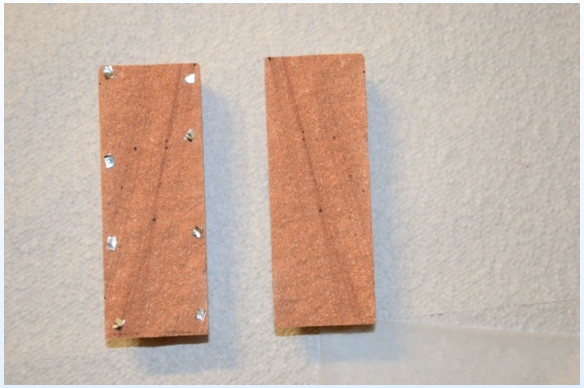
- Fractured sample (Brazilian test), place spacers at corners
- Reassemble core, wrap core in sleeves, place in core holder
- Confining pressure applied, fluid flows through sample at specific rates, measure differential pressure
- Compute permeability versus effective stress
- CT scan core at each flow rate shows change in fracture aperture

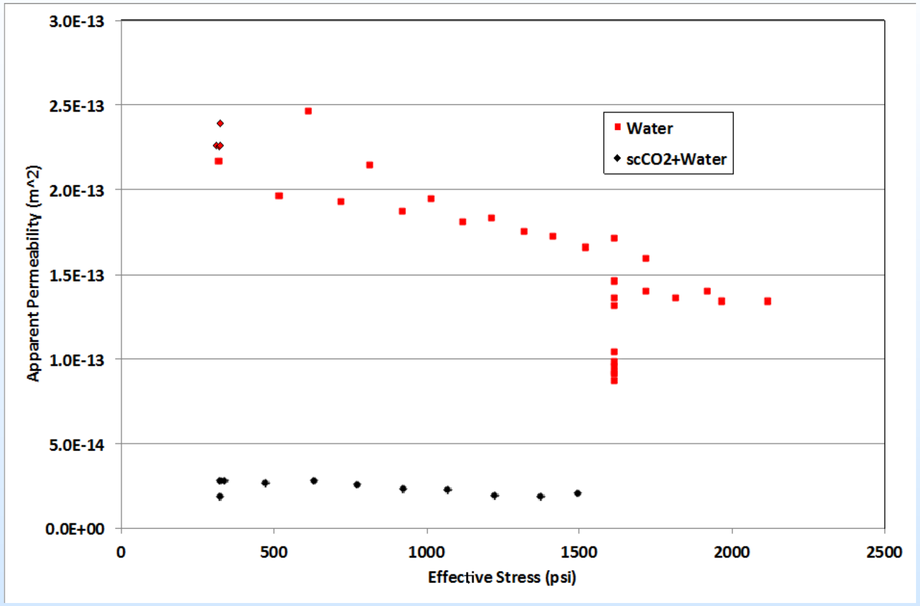
Gray Berea Permeability



- Fractured core with spacers on left
- 3 M potassium iodide brine (provides X-ray contrast)
- Permeability vs flow rate for each effective stress
- Lowest measured permeability ~ unfractured permeability

Nugget Sandstone Permeability





- Brine permeability measured, then $scCO_2$ permeability
- Apparent permeability decreased by 10 for sc-CO_2 flow
- $scCO_2$ expected to be non-wetting fluid
- CT images – $scCO_2$ is only in fracture at low effective stress

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3) Laboratory studies of CO_2 and brine injection induced fracturing

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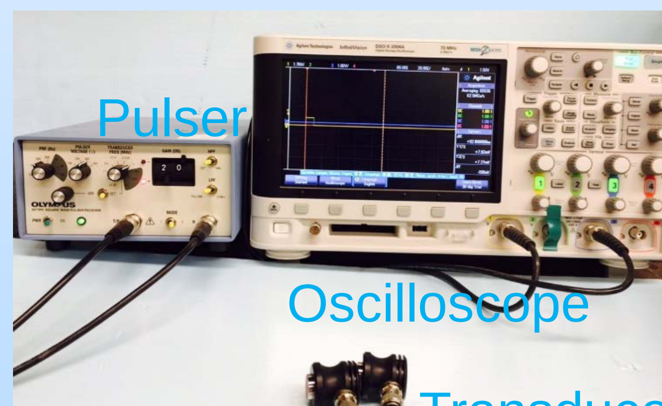
Equipment

- Tri-axial loading system: three pistons - two horizontal, one vertical
- Injection pump - Teledyne ISCO 500HPx; ideal for brine and sc-CO_2
- Data acquisition devices - Type T thermocouples; pressure transducers;
- Acoustic measurement devices - Olympus pulser, two Olympus transducers and an Agilent DSO-X 2004A digital oscilloscope



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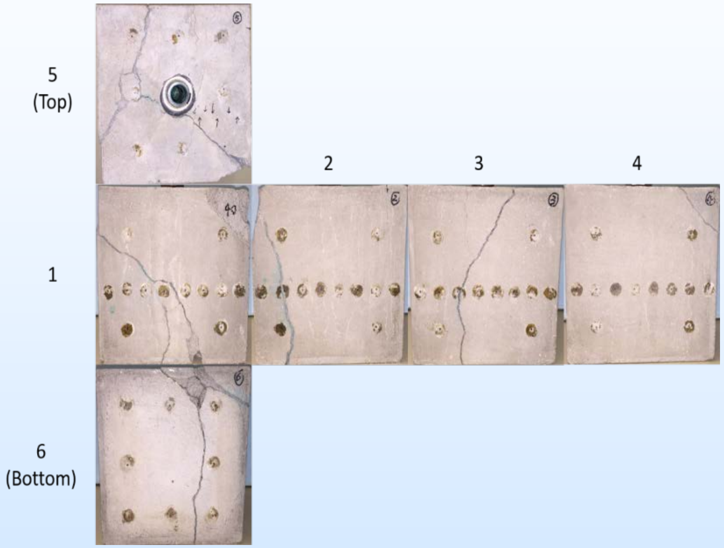
Brine Injected into Concrete

- Six samples
- Triaxial stresses were (500,750,1000 psi) or (1000,1500,2000 psi)
- Various flow rates, with 40 ml/min the most common
- Peak pressure (fracturing first occurs) - lower at higher injection rates, incr. along with triaxial stress
- Fracture patterns, acoustic signatures before and after injection obtained

Sample 40



Surfaces of Sample 40 after dye and gas break-down.

Internal fracture morphology of Sample 40 after dyeing and gas breakdown.

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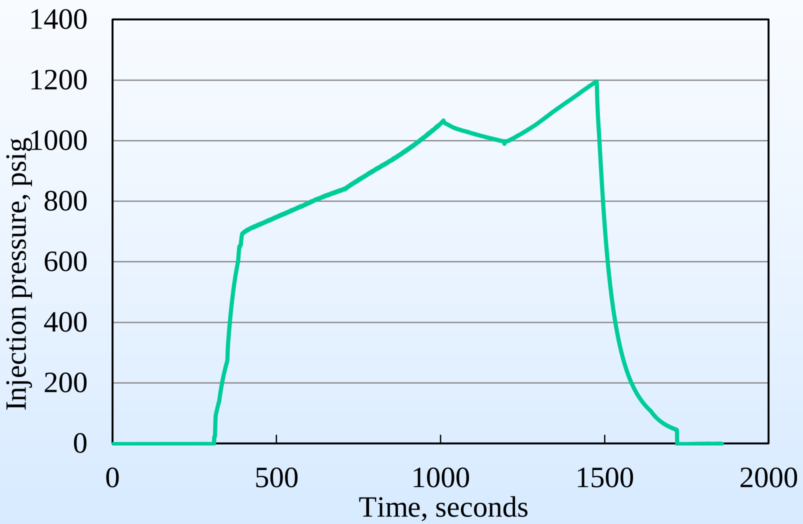
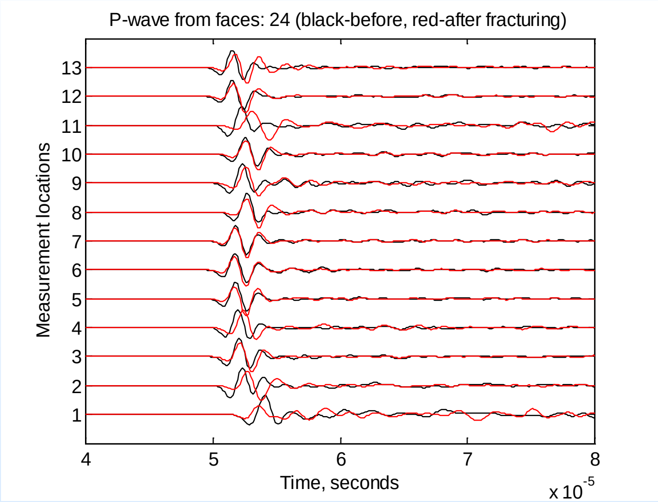
CO_2 Injected into Concrete

- Twenty five samples
- Various triaxial stresses: ($1000<x<1500$ psi), ($1500<y<2250$ psi), ($2000<z<3000$ psi),
- Various flow rates, with 40 ml/min the most common
- Samples, CO_2, preheated to desired temperature
- Injected CO_2 either gas, liquid or supercritical depending on borehole conditions

Sample 55





CO_2 injection pressure of Sample 55.

P-wave signatures measured from Faces 2 & 4 of Sample 55.

Shale Experiments

- Five shale samples from Niobrara shale outcrop, (CEMEX Lyons cement plant)
- Shale has natural fractures; epoxy injected into fractures through the borehole to seal them
- Fluids injected: slickwater, gaseous CO_2, and sc-CO_2
- Triaxial stress values: (1100,1600,2100), (1200,2100,3000), and (1600,2100,2600)
- Pump rates: 40 or 80 ml/min for CO_2; 1 ml/min for slickwater

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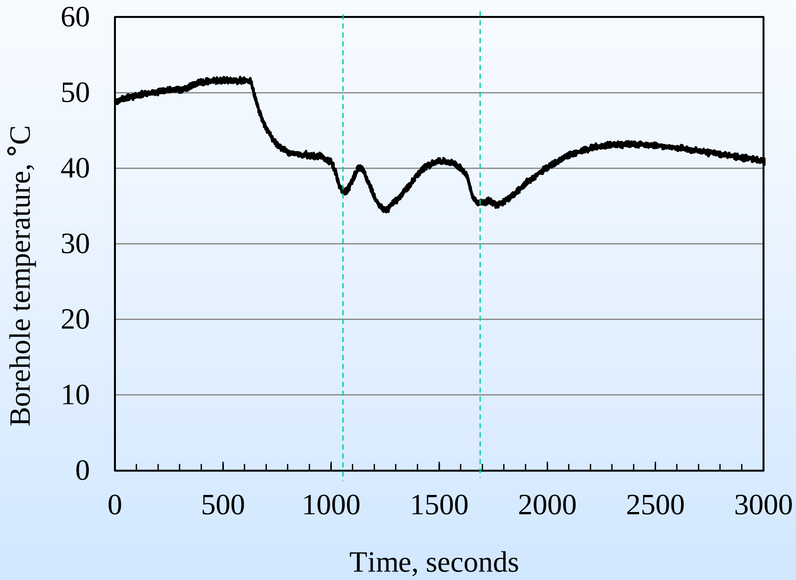
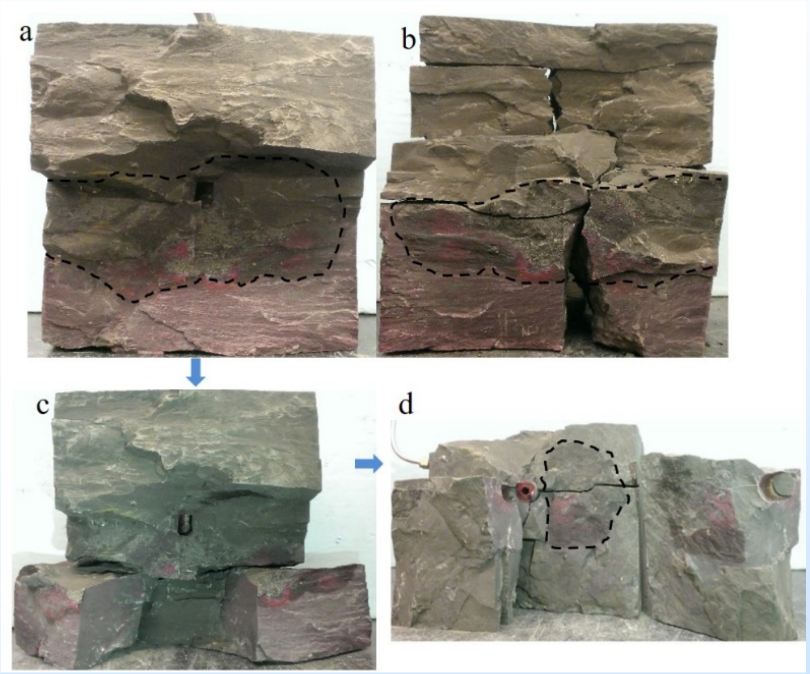
Shale Sample 3



Borehole temperature profile during CO_2 injection into Shale Sample 3.



CO_2 injection induced fracture planes in Shale Sample 3.

4) Development of CO_2 flow and geomechanics-coupled models for modeling fracturing growth

TOUGH2-CSM

Mean Stress Equation

- Hooke's law for a thermo-multi-poroelastic medium + stress equilibrium equation + strain tensor definition = Navier equation, then take divergence

$$\nabla \cdot \left[\frac{3(1-\upsilon)}{1+\upsilon} \nabla \tau_m + \mathbf{F}_b - \frac{2(1-2\upsilon)}{1+\upsilon} \nabla \left(\sum_j \left(\alpha_j P_j + 3\beta K \omega_j T_j \right) \right) \right] = 0$$

- Trace of Hooke's law: volumetric strain equation

$$K\varepsilon_v = \tau_m - \sum_j \left(\alpha_j P_j + 3\beta K \omega_j \left(T_j - T_{ref} \right) \right)$$

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Stress Tensor Components

- Derivatives of thermo-multi-poroelastic Navier equation vector components are zero:

- Normal stresses:

$$\frac{\partial^2}{\partial x^2}\left[h\left(\mathbf{P},\mathbf{T}\right)\right]+\frac{3}{2\left(1+\upsilon\right)}\frac{\partial^2}{\partial x^2}\left[\tau_m-h\left(\mathbf{P},\mathbf{T}\right)\right]+$$
$$\frac{1}{2}\nabla^2\left[\tau_{xx}-h\left(\mathbf{P},\mathbf{T}\right)-\frac{3\upsilon}{1+\upsilon}\left(\tau_m-h\left(\mathbf{P},\mathbf{T}\right)\right)\right]+\frac{\partial F_{b,\mathrm{x}}}{\partial x}=0$$

- Shear stresses:

$$\frac{\partial^2}{\partial x\partial y}\left[h\left(\mathbf{P},\mathbf{T}\right)\right]+\frac{3}{2\left(1+\upsilon\right)}\frac{\partial^2}{\partial x\partial y}\left[\tau_m-h\left(\mathbf{P},\mathbf{T}\right)\right]+\frac{1}{2}\nabla^2\tau_{xy}+$$
$$\frac{1}{2}\left(\frac{\partial F_{b,\mathrm{y}}}{\partial x}+\frac{\partial F_{b,\mathrm{x}}}{\partial y}\right)=0$$

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Rock Failure Modes

- Mohr-Coulomb failure – shear failure of fault $$\tau > \mu\sigma' + C_0$$
- Mohr-Coulomb failure – shear failure of randomly fractured caprock $$\sigma_1' > 3\sigma_3'$$
- Hydraulic fracturing due to pore pressure greater than minimum principal stress $$P > \sigma_{\min} + \sigma_{tens}$$

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Post Rock Failure

- Permeability and porosity correlated to stress for faults
- Fractured media – fracture aperture correlated to permeability:

$$k_f = \frac{b_f^2}{12\mu} \qquad b_f = b_f\left(\boldsymbol{\tau}'\right) \qquad \phi_f = \phi_f\left(\boldsymbol{\tau}'\right)$$

- Fracture growth and extension (stress intensity factor):

$$K_I > K_{IC} \qquad d \approx \left(\frac{K_I - K_{IC}}{K_{IC}}\right)^n$$

2D Cylindrical Coordinates

- r,θ stress component equations cumbersome
- zz- stress calculated as before
- Sum of strains:

$$\varepsilon_{rr} + \varepsilon_{\theta\theta} = \varepsilon_v - \varepsilon_{zz} = \frac{\partial u_r}{\partial r} + \frac{u_r}{r} = \frac{1}{r}\frac{\partial}{\partial r}(r u_r)$$

- Solve for displacement r-vector component:

$$u_r(r,z) = \frac{1}{r}\int_{r_0}^{r} \xi\left(\varepsilon_v(\xi,z) - \varepsilon_{zz}(\xi,z)\right) d\xi$$

- Strains: $\varepsilon_{\theta\theta} = \frac{u_r}{r}$; $\varepsilon_{rr} = \varepsilon_v - \varepsilon_{zz} - \varepsilon_{\theta\theta}$
- rθ shear stress also

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Example rz Problem

- Yamamoto et al. (2013)
- 100 m aquifer, 1000 m caprock above, 500 m below
- Outer radius of 4100 m
- Equilibrium stress and pressure fields initially
- Mohr-Coulomb failure in upper caprock
- 50 kg/sec CO_2 injected into aquifer at center, 500 days

Simulation Results

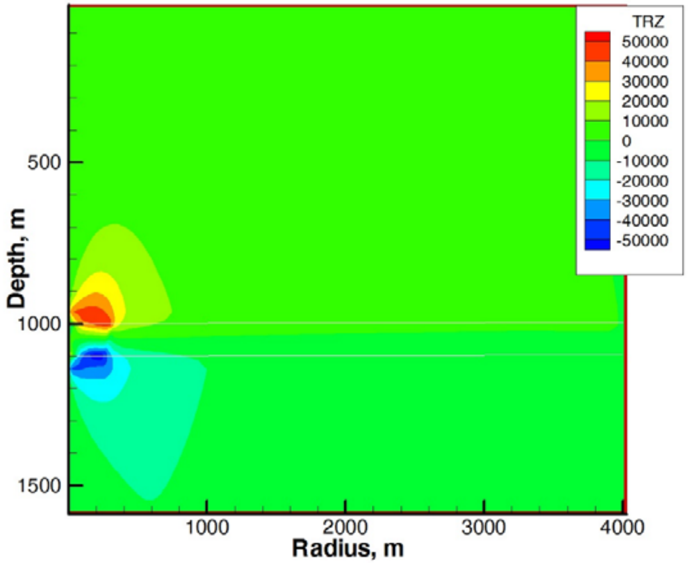


Figure 4.2. Shear stress rz-component after 500 days injection.

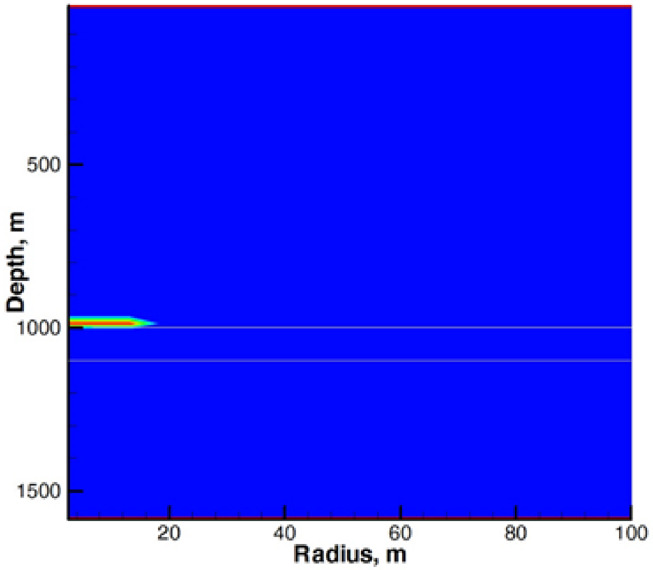


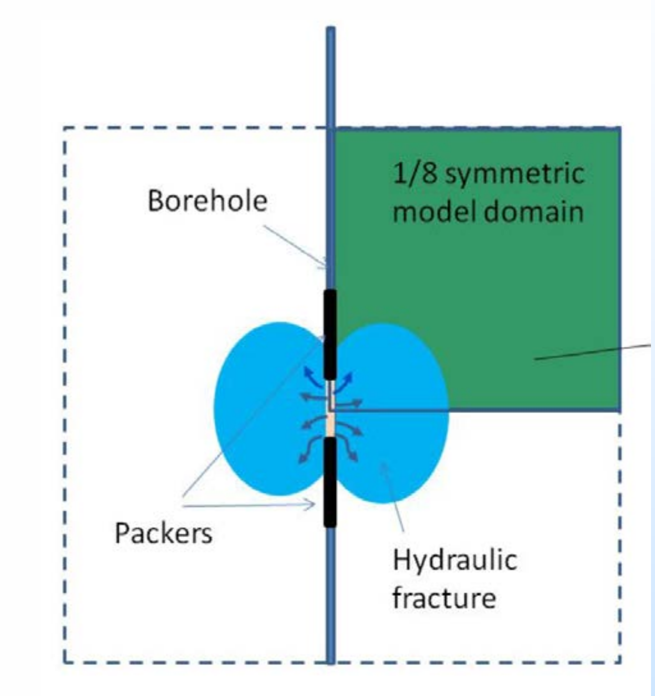
Figure 4.3. Region of caprock failure, just above the aquifer

TOUGH2-FLAC

Fracture Initiation and Growth

- Strain softening tensile behavior and softening of modulus
- Brittle to more ductile fracture behavior can be simulated by changing the strain softening characteristics
- Aperture changes with fracture propagation are related to the tensile strain normal to the fracture plane
- Permeability - cubic relation between fracture transmissivity and fracture aperture.

Model Verification



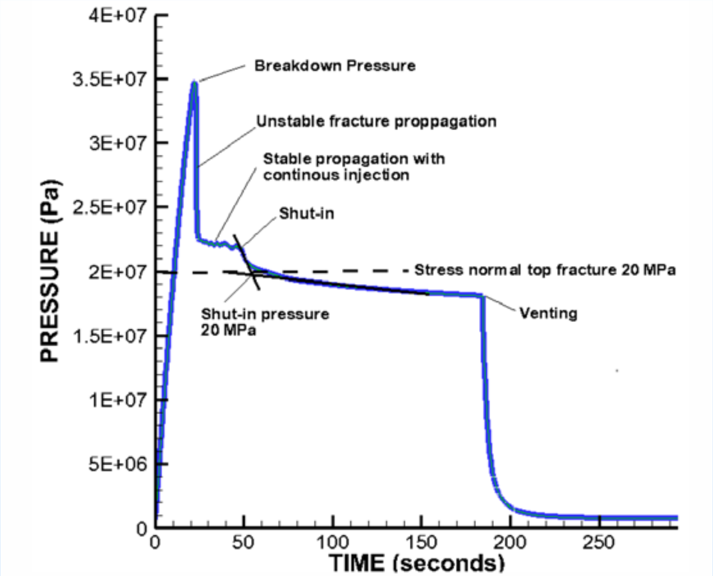


Figure 4-2. Borehole pressure evolution during simulated hydraulic fracturing stress measurement operation showing the first break-down cycle with shut-in and venting.

- Simulation of injection induced fracturing around a well
- Water injection at a constant rate, then shut in
- Pressure profile close to theoretical value
- Fracture propagates into formation

Accomplishments to Date, I

- Set up laboratory apparatuses for measuring rock properties
- Performed five rock property measurements on cores made from concrete, sandstone and shale
- Measured permeability versus effective stress for fractured gray Berea and sandstone
- Set up laboratory apparatuses for brine and CO_2 induced fracturing
- Performed fracturing experiments on concrete and shale samples using brine and CO_2

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Accomplishments to Date, II

- Extended TOUGH2-CSM code to calculate stress tensor components and rock failure scenarios
- Modified TOUGH2-FLAC to simulate fracture initiation and growth

Lessons Learned

- Laboratory results versus theoretical models – reconciling the two can be difficult - the conditions under which the two operate can be different
- Using a polyimide film between the sample and sleeve helped protect the sleeve from the sc-CO_2 and allowed a longer test to be performed.

Synergy Opportunities

- Project entails laboratory studies of rock deformation and fracturing and development of coupled geomechanical models for rock deformation and fracturing
- Rock property data obtained elsewhere can enhance our research efforts; rock property data obtained here could enhance other research efforts
- Our geomechanical models could be applied to other research efforts; other geoemechanical models could suggest enhancements of ours

Project Summary

- We have a large amount of results from the experimental portion of the project
- We have modified our numerical models to simulate injection induced property changes
- The remaining work in this project will be centered on model validation and application to the field

Appendix

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Benefit to the Program

- Laboratory studies of rock deformation, fracturing with coupled geomechanical modeling to quantify effects of geomechanics and flow on safe and permanent geological storage of CO_2

- Understanding of geomechanical effects on CO_2 flow and storage in fractured reservoirs; develop modeling tools for assessment of CO_2 geo-storage systems

- Technology developed in project will contribute to our ability to predict CO_2 storage capacity in geologic formations to within $\pm$30 percent

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Project Overview:
Goals and Objectives

- Understanding and correlations for injection pressure induced geomechanical effects (rock deformation, fracturing) on CO_2 storage systems, through lab experiments
- Incorporate above into simulators (TOUGH2-CSM and TOUGH-FLAC) to model CO_2 injection induced rock mechanical processes associated with CO_2 storage in reservoirs
- Quantify flow, storage, and potential leakage pathways; develop remediation measures when needed

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Organization Chart

Colorado School of Mines

Philip Winterfeld, Research Associate Professor, Petroleum Eng.
Yu-Shu Wu, Prof. and CMG Reservoir Modeling Chair, Pet. Eng.
Xiaolong Yin, Assistant Professor, Petroleum Engineering

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Computer Modeling Group (CMG)

Industry sponsor

↕

Lawrence Berkeley National Laboratory
(Hydrogeology Department)

Tim Kneafsey, Staff Scientist and Head

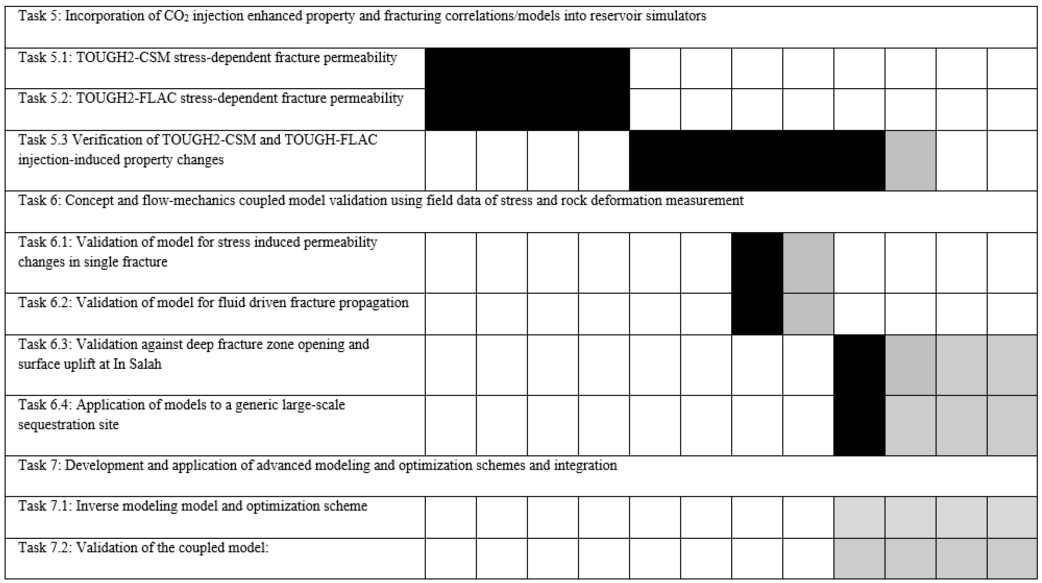
Jonny Rutqvist, Staff Scientist

Gantt Chart

Table 1. Baseline Schedule/Timeline – degree of task completion is shown in black.

	Year 1				Year 2				Year 3			
Quarter	1	2	3	4	1	2	3	4	1	2	3	4
Task 1: Management and Planning												
Task 1: Management and Planning	■	■	■	■	■	■	■	■	■	░	░	░
Task 2: Development of correlations of CO_2 injection induced rock property variation by experiments												
Task 2.1: Obtaining rock cores and rock preparation	■	■	■	■								
Task 2.2: Permeability versus effective stress					■	■	■	■				
Task 2.3: $scCO_2$ fracture permeability versus stress									■	░	░	░
Task 3: Development of understanding and correlations of CO_2 injection inducing fractures by experiments												
Task 3.1: Fracture initiation using brine	■	■	■	■								
Task 3.2: Fracture initiation using CO_2					■	■	■	■				
Task 3.3: Fracture propagation									■	░	░	░
Task 4: Development of CO_2 flow and geomechanics-coupled models for modeling fracturing growth												
Task 4.1: Constitutive correlations for fracture initiation	■	■										
Task 4.2: Calculate stress tensor components			■	■								
Task 4.3: Simulate fracture initiation and growth (TOUGH2-CSM)					■	■	■	■				
Task 4.4: Simulate fracture initiation and growth (TOUGH2-FLAC)					■	■	■	■				
Task 4.5: Verification of TOUGH2-CSM and TOUGH-FLAC for fracturing modeling									■	░		

Gantt Chart, continued



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- Winterfeld, P. H. and Wu Y.-S., 2015 A Coupled Flow and Geomechanics Simulator for CO2 Storage in Fractured Reservoirs, presented at the TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, CA, September 28-30, 2015
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