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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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology, Innovation, Partnerships and Collaboration:

Carbon Storage and Oil and Natural Gas Technologies Review Meeting

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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

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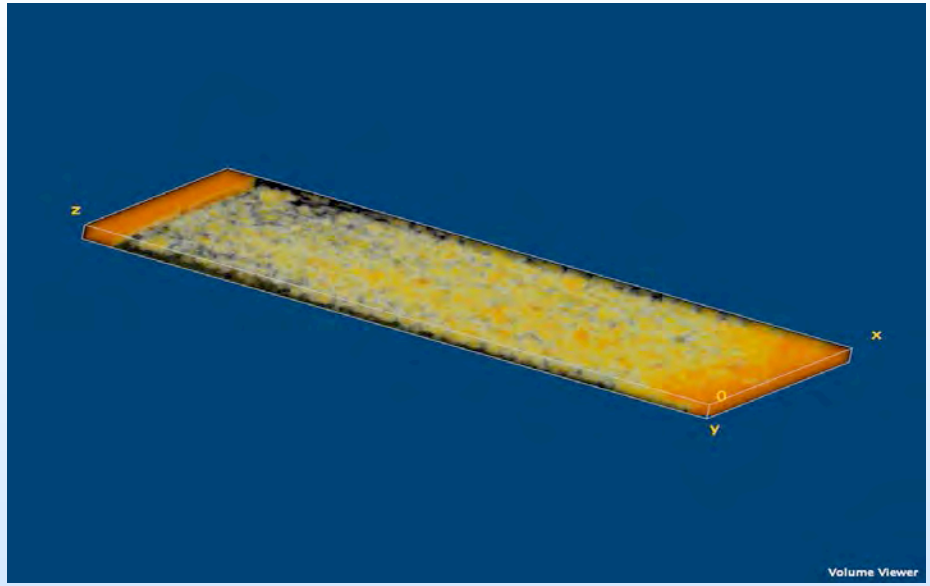
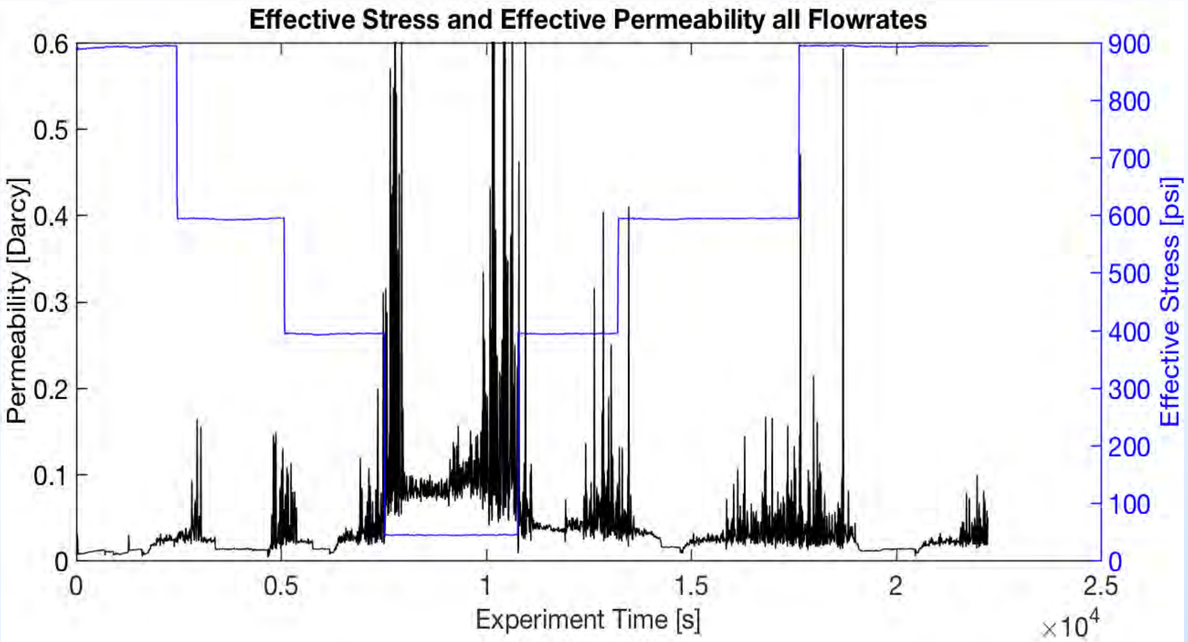
Permeability vs Effective Stress, I



- Gray Berea - fractured core with spacers on left
- Initially brine filled, displaced by sc-CO_2
- Differential CT scan of $S_{sc\text{-}CO2}$ in aperture (brighter colors)
- Flow is from the right to left

Permeability vs Effective Stress,II



- $scCO_2$ effective permeability versus effective stress
- Various flow rates were used at each effective stress
- High variability occurs primarily for the lowest flow rates
- Noise - from sample, tubing, or back-pressure pump

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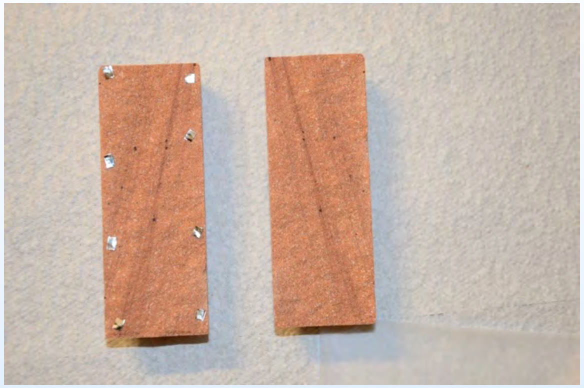
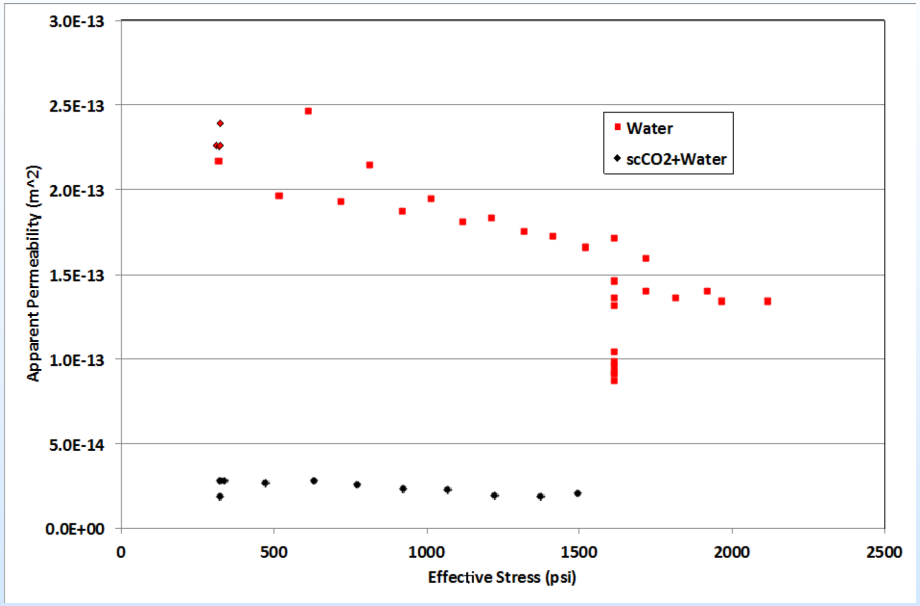
Permeability vs Effective Stress,III





- Sandstone - brine permeability, 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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Brine Injected into Concrete

- Six samples; 8 in cubes with 4.5 in borehole epoxied to 3.5 in
- 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

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Sample 40

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

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

CO_2 Injected into Concrete

- Twenty eight samples
- 8 in cubes with 4.5 in borehole epoxied to 3.5 in
- Various triaxial stresses: (1000<x<1500 psi), (1500<y<2250 psi), (1875<z<3000 psi),
- 10 and 40 ml/min the most common flow rates
- Samples, CO_2, preheated to desired temperature
- Injected CO_2 either gas, liquid or supercritical depending on borehole conditions

Sample 70

- Composite sample – low strength, high permeability concrete ball at core center
- Simplified version of injection into high permeability zone surrounded by low permeability sealing formation
- Initial stresses: 1250:1562:1875 psi
- Injection rate 40, raised to 100 around 900 sec
- P and S waves show delay and wave form change, indicating fracturing

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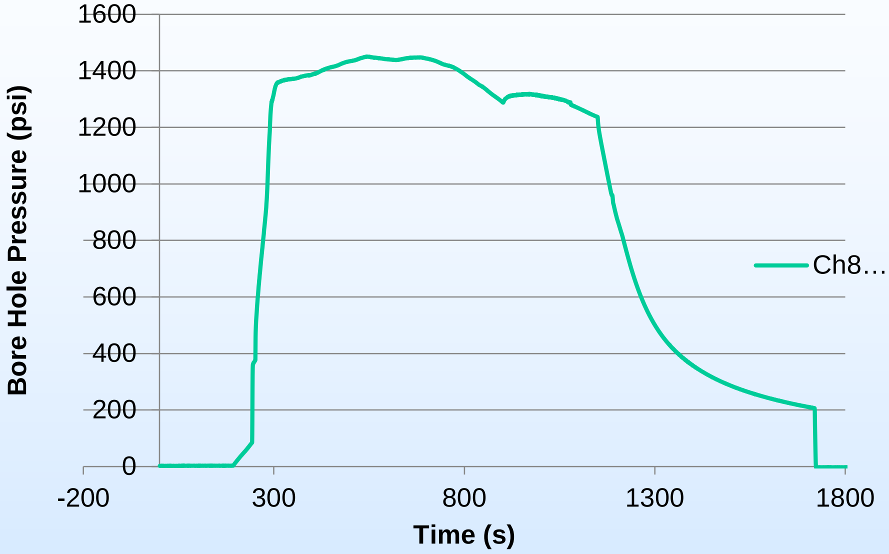
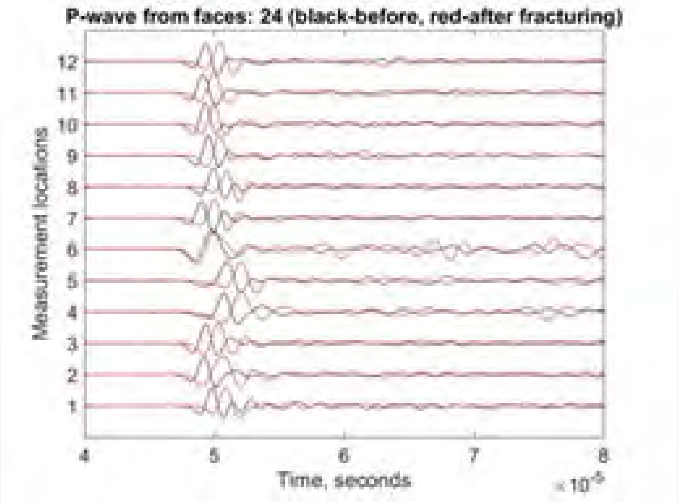
Sample 70





Bore hole pressure of Sample 70

P-wave signatures measured from Faces 2 & 4 of Sample 70

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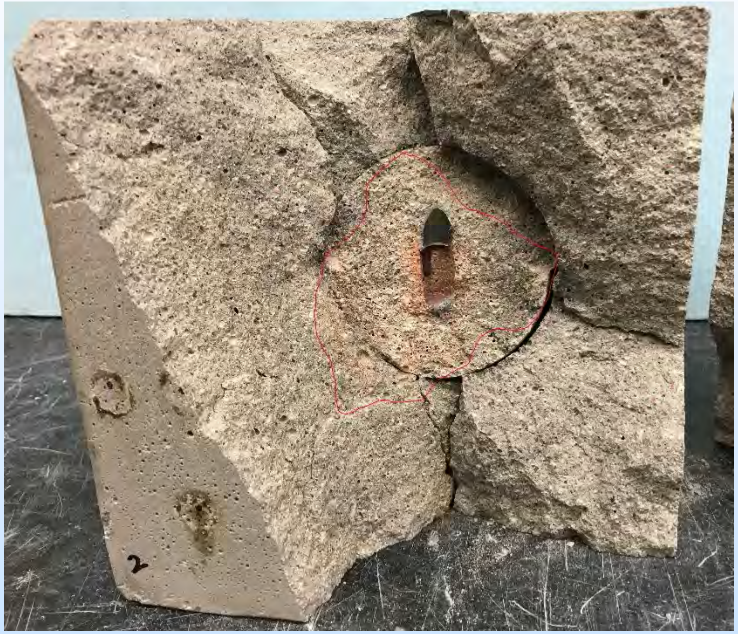
Internal Cross Section



Fracture profile inside sample with high permeability zone apparent.

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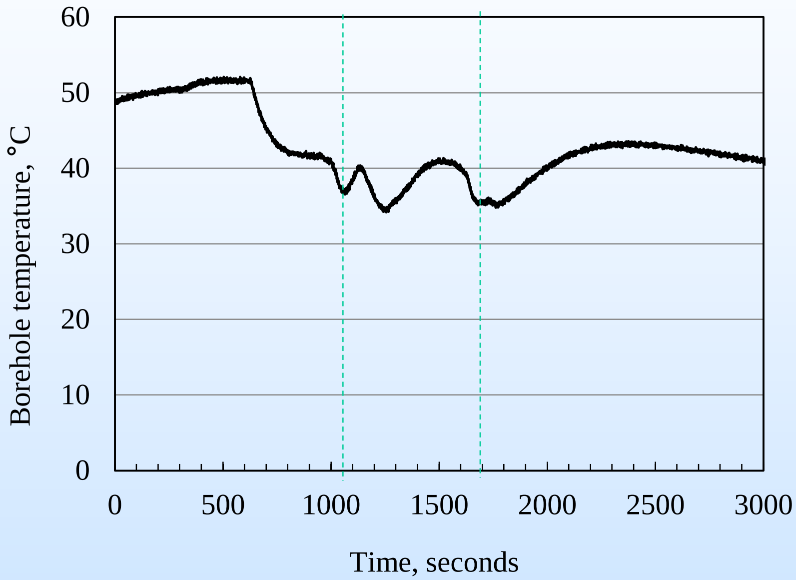
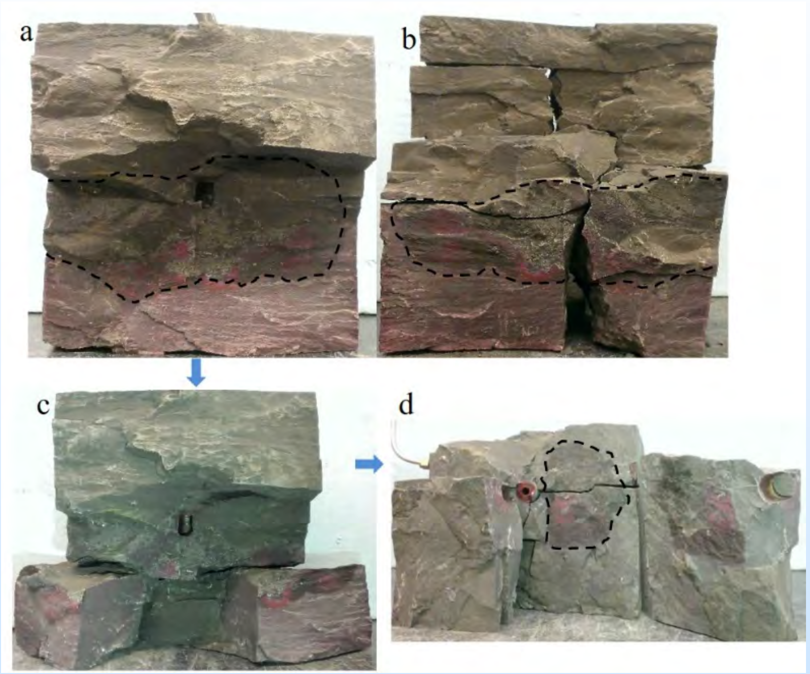
Shale Experiments

- Five shale samples from Niobrara shale outcrop
- 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

Shale Sample 3



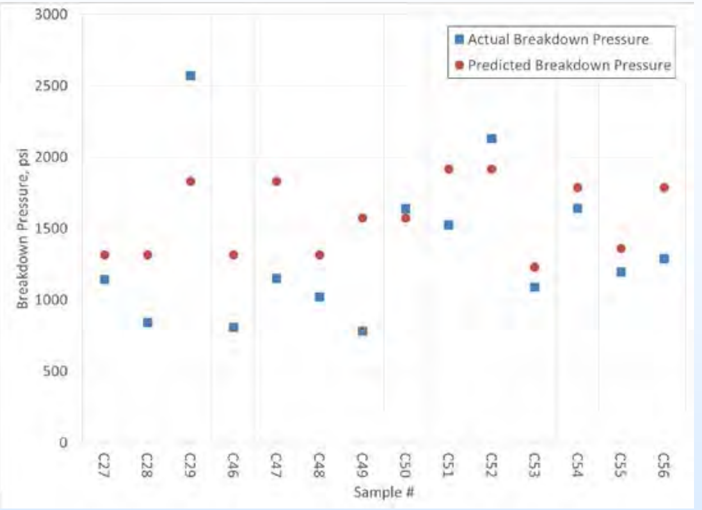


Borehole temperature profile during CO_2 injection into Shale Sample 3.

CO_2 injection induced fracture planes in Shale Sample 3.

Failure Analysis

- Concrete samples 27-29,46-56
- Actual breakdown pressure > predicted bp then tensile failure; otherwise shear failure



- Mogi-Coulomb shear failure: linear shear envelope, stress tensor invariants I1, $I2^{.5}$

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

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TOUGH2-CSM

Geomechanics

- Mean stress equation, form geomechanical equations for thermo-multi-poroelastic media, functions of P, T, mean stress
- Stress tensor component equations, P,T,MS,Sij
- Geomechanical equations added to TOUGH2 fluid and heat flow formulation
- Similar form to Darcy flow equations
- Fully implicit finite difference formulation

Caprock Failure

- Mohr-Coulomb failure – shear failure of fault or randomly fractured caprock
- Hydraulic fracturing due to pore pressure greater than minimum principal stress; also hydraulic fracture growth and extension
- Fractured media – fracture aperture correlated to permeability
- Permeability and porosity correlated to stress

Finite Difference Formulation, I

- Reservoirs conceptualized as rock strata with constant properties (E,υ,α,β) – composite media

- Solutions to transport problems in composite media obtained from:

  - ➢ Constant property solution in each composite
  - ➢ Fluxes, primary variables continuous at interfaces

- Apply above to geomechanical formulation

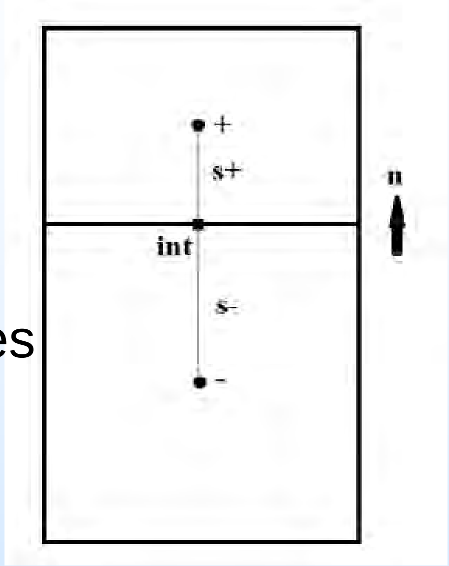
Finite Difference Formulation, II

- Geomechanical equation form: $\nabla \cdot \Psi_k = 0; k = m, zz, xz, \ldots$

$$\Psi_m = \frac{3(1-\upsilon)}{1+\upsilon}\nabla\tau_m + \bar{F}_b - \frac{2(1-2\upsilon)}{1+\upsilon}\nabla h(\bar{P},\bar{T})$$

- Associate primary variables with grid block interface
- Equal fluxes at interface, from node and interface quantities

$$\Psi_k \cdot \hat{n} = \Psi_{k,+} \cdot \hat{n} = \Psi_{k,-} \cdot \hat{n}$$



- Solve for flux and interface primary variable

$$\Psi_m \cdot \hat{n} = \frac{\tau_{m,+} - \tau_{m,-} + \Gamma_1(\nu_+, s_+)\bar{F}_{b,+}\cdot\hat{n} + \Gamma_2(\nu_-, s_-)\bar{F}_{b,-}\cdot\hat{n} - \Upsilon_1(\nu_+)\left(h(\bar{P},\bar{T})_+ - h(\bar{P},\bar{T})_{+,int}\right) - \Upsilon_1(\nu_-)\left(h(\bar{P},\bar{T})_{-,int} - h(\bar{P},\bar{T})_-\right)}{\Gamma_1(\nu_+, s_+) + \Gamma_2(\nu_-, s_-)}$$

$$\Gamma_1(\nu_i, s_i) = \frac{(1+\upsilon_i)s_i}{3(1-\upsilon_i)}; \qquad \Upsilon_1(\nu_i) = \frac{2(1-2\upsilon_i)}{3(1-\upsilon_i)}$$

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.

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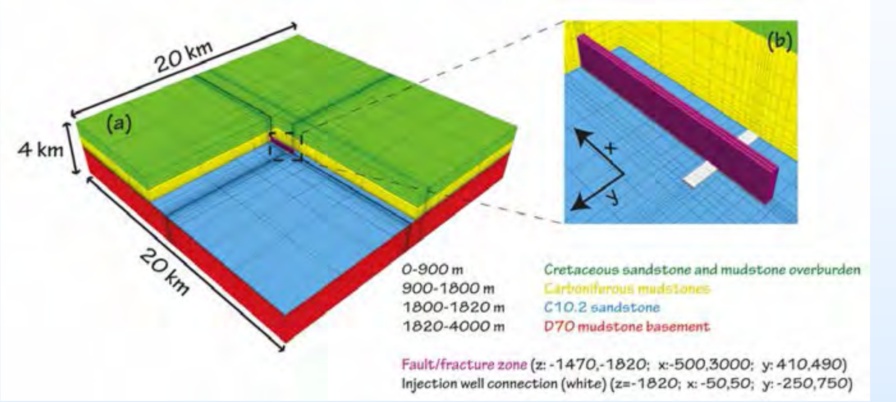
6) Concept and flow-mechanics coupled model validation using field data of stress measurement and/or land surface uprise

Rinaldi and Rutqvist (2013)

- In Salah well KB-502 double-lobe uplift pattern
- Measured using Interferometric Satellite Aperture Radar (InSAR)
- Explained from presence of a deep vertical fracture



- Four geologic layers, plus sublayers; 1 km horizontal injection well; 80 m wide vertical fracture
- Time-dependent permeability for fracture and aquifer layer to match observed pressure data
- Anisotropic geomechanical properties (fracture) approximated as isotropic in TOUGH2-CSM

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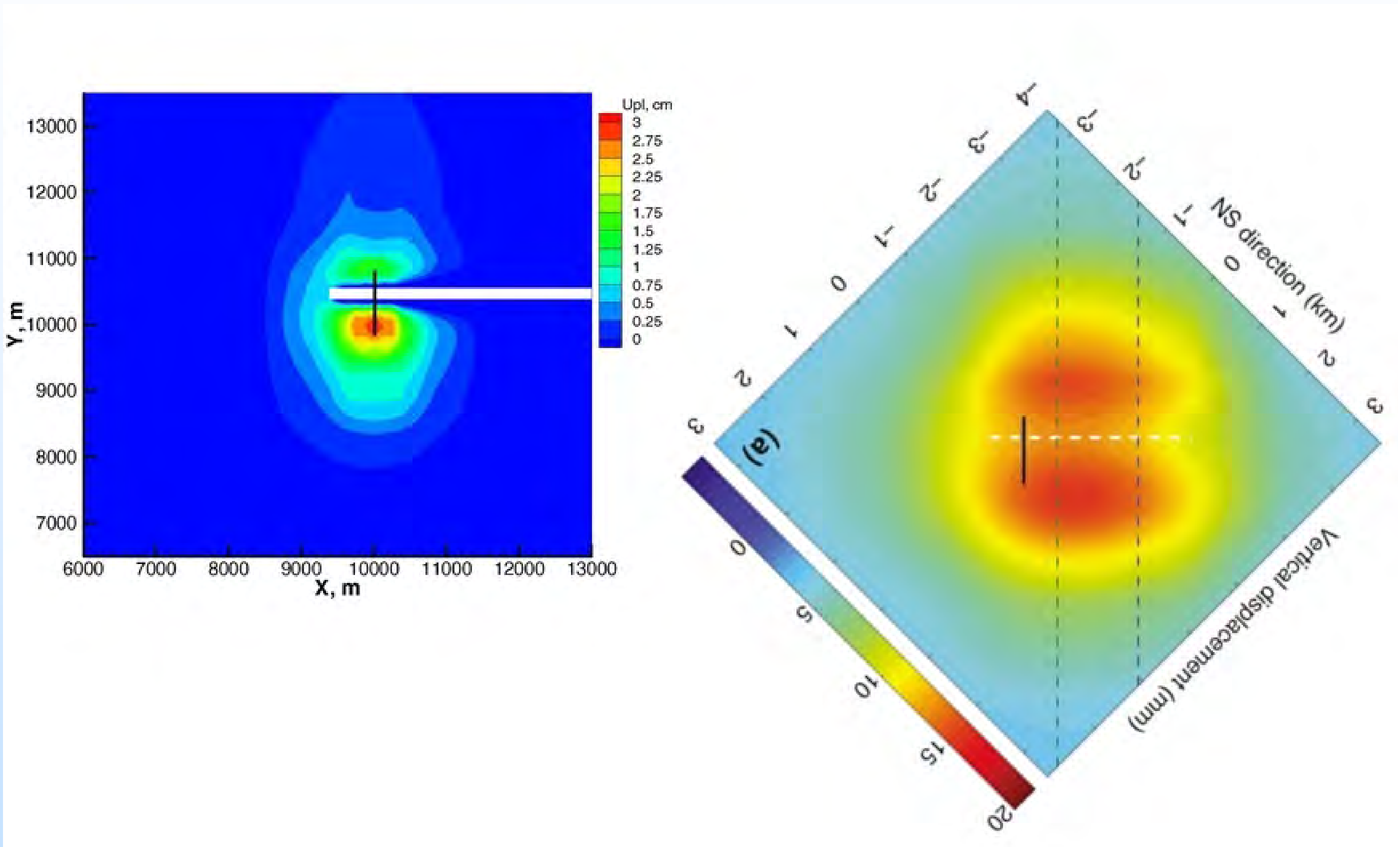
Uplift Comparison



Surface uplift for Rinaldi and Rutqvist (2013) (right) and TOUGH2-CSM (left).

Solid black lines are wells and white lines are fracture.

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Accomplishments to Date

- Performed rock property measurements on cores made from concrete, sandstone and shale
- Measured permeability versus effective stress for fractured gray Berea and sandstone
- Performed many fracturing experiments on concrete and shale samples
- Extended TOUGH2-CSM code to calculate rock failure scenarios; modified TOUGH2-FLAC to simulate fracture initiation and growth
- Verified TOUGH2-CSM code using InSalah uplift simulation

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Lessons Learned

- 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.
- Mathematical derivations that include physical principles perform better than those based on mathematics alone.

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
- We are completing the remaining work, namely the experiments, model validation, and application to the field

Appendix

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

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

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												
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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												

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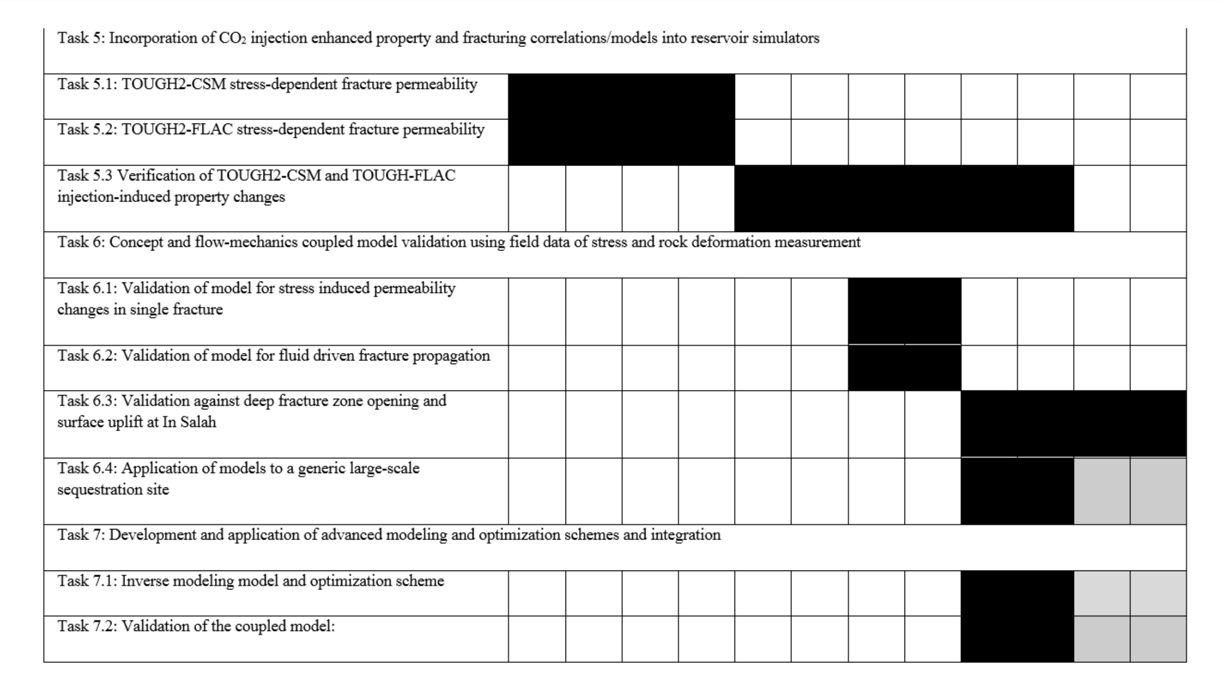
Gantt Chart, continued



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- P. H. Winterfeld and Yu-S. Wu, 2017. Coupled Reservoir-Geomechanical Simulation of Caprock Failure and Fault Reactivation during CO2 Sequestration in Deep Saline Aquifers, SPE 182605-MS, presented at SPE Reservoir Simulation Conference, 20-22 February, 2017 in Montgomery, TX.

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– Winterfeld, P. H. and Wu Y.-S., 2018. Simulation of Coupled Thermal-Hydrological-Mechanical Phenomena in Heterogeneous and Radial Systems, to be presented at TOUGH Symposium 2018, Berkeley, CA, October 8-10, 2018.

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