Area of Interest 2, Geomechanics of CO_2 Reservoir Seals

DE-FE0023316

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National Energy Technology Laboratory
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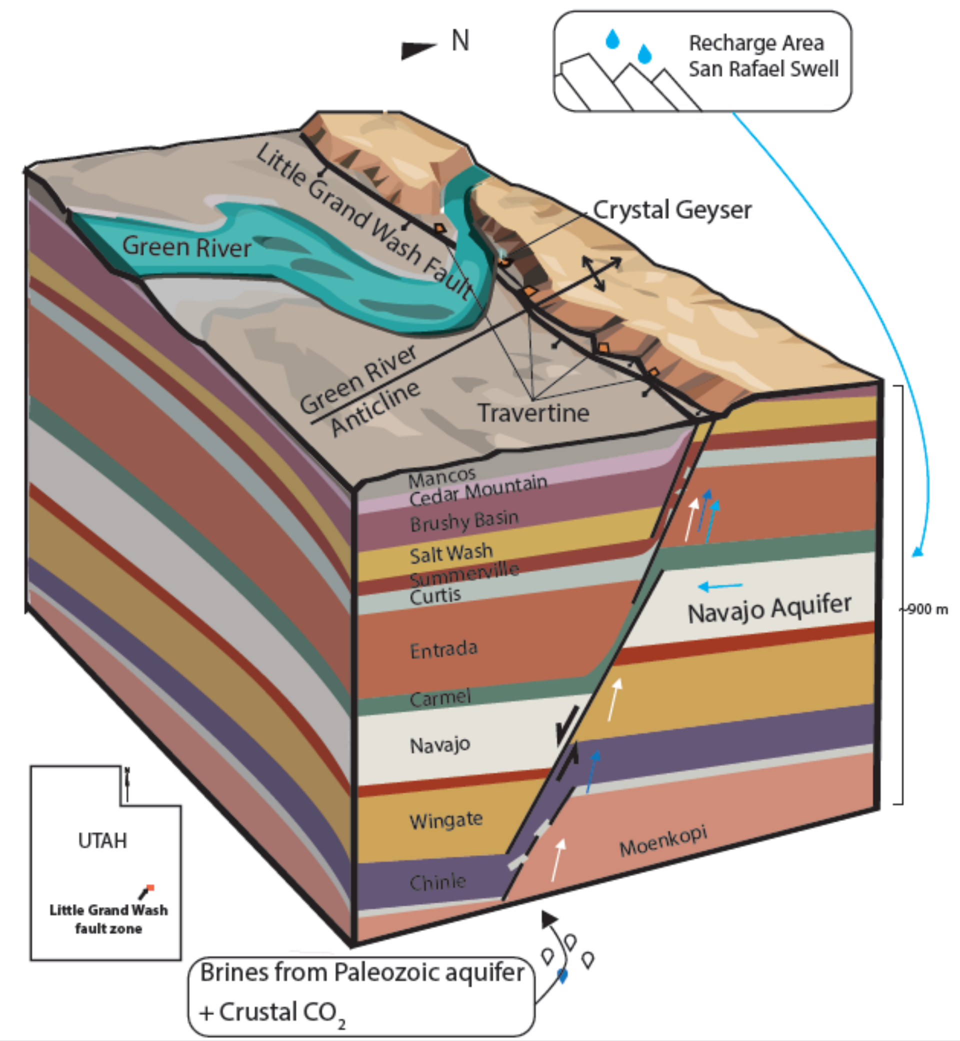
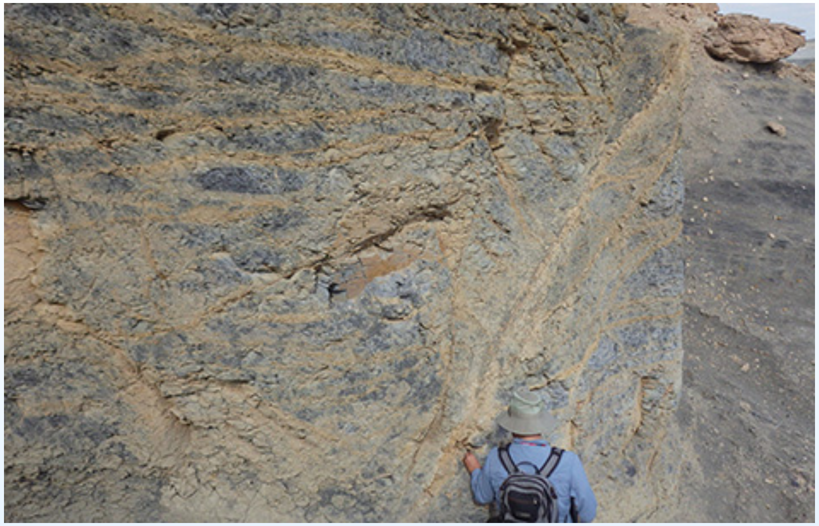
Problem Statement

- Sealing efficiency of CO_2 reservoirs has to exceed 99%.
- Design criteria are needed that establish the long term sealing capacity of CO_2 reservoirs and to model leakage risk.
- Top and fault seal risk assessment well established in oil & gas exploration, but:
- scCO$_2$ and CO_2 brine potentially interact *physically & chemically* with top seal.
- Seal risk assessment criteria taking these interactions into account are needed for CO_2 systems.

Fractures in CO_2 caprocks

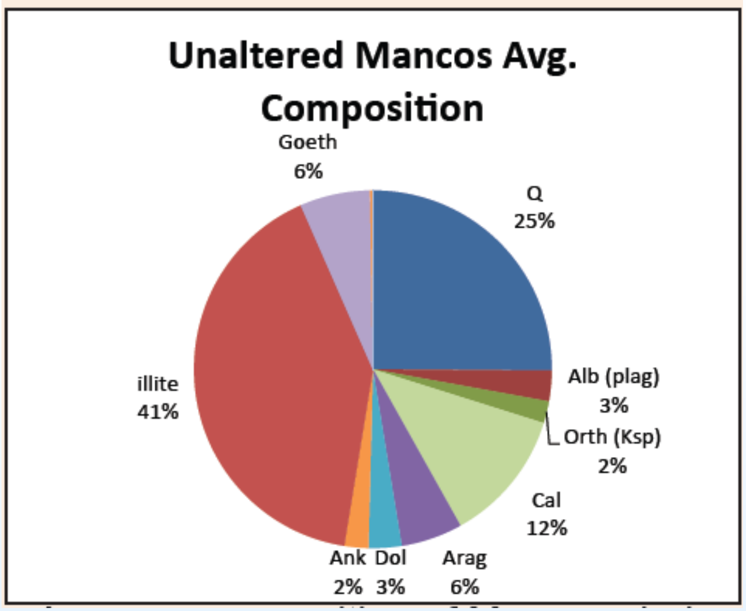
Crystal Geyser analog site

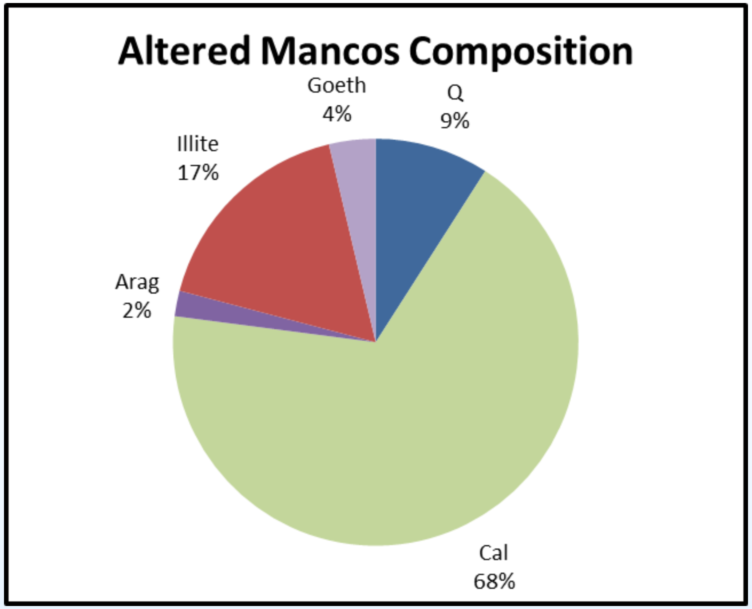




Active on 10^2 - 10^5 year time scales

Compositional changes of mudrock


Unaltered Mancos Avg. Composition


Altered Mancos Composition

Presentation Outline

- Benefit
- Project Overview
- Problem Statement
- Methodology
- Accomplishments to Date
  - Fracture mechanics experiments
  - Fracture & leakage modeling
- Summary

Benefit to the Program

- Program goals: Develop characterization tools, technologies, and/or methodologies that improve the ability to predict geologic storage capacity within ±30 %, improve the utilization of the reservoir by understanding how faults and fractures in a reservoir affect the flow of CO_2, and ensure storage permanence.
  - Area of Interest 2 – Fractured Reservoir and Seal Behavior: Develop tools and techniques to increase the accuracy and reduce the costs of assessing subsurface seal containment and the seal/reservoir interface, including the measurement of in-situ rock properties in order to develop a better understanding of seal behavior when CO_2 is injected into a reservoir.
- *Project is designed to*
  - *Provide calibrated and validated numerical predictive tools for long-term prediction of reservoir seal integrity beyond the engineering (injection) time scale.*
  - *Contribute toward technology ensuring 99% storage permanence in the injection zone for 1000 years.*

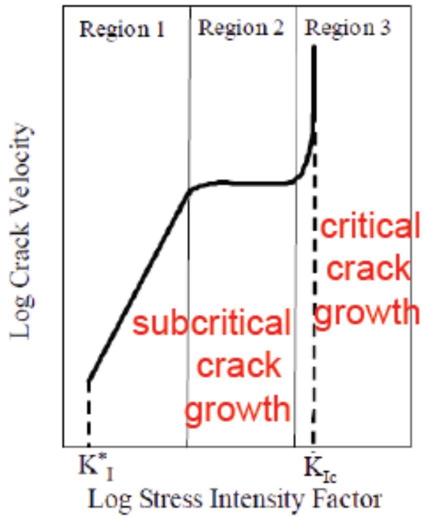
Project Overview:
Goals and Objectives

- ***Derive predictive and validated numerical models*** for fracture growth in chemically reactive environments relevant to CCUS top seal lithologies.
- ***Perform laboratory fracture testing*** to provide input parameters on fracture constitutive behavior, fracture rate and geometry, and deformation and transport processes involved in subcritical chemically assisted fracture growth for relevant top seal lithologies.
- ***Validate*** the laboratory observations **against microstructural and textural observations** on fractures from natural CO_2 seeps.
- ***Perform numerical simulations*** that are informed by field and lab results toward predictive tools ***for top seal integrity analysis***, top seal mechanical failure, and impact on CO_2 leakage in CCUS applications.
- ***Demonstrate*** a means ***to upscale*** discrete and network numerical models to continuum scale reservoir models coupling geomechanics with multiphase flow and leakage.

Methodology

- Experimental measurement of subcritical fracture propagation in analog top seals
  - Short-rod test
  - Double torsion test
- Textural and compositional characterization
  - Fractures & CO_2 alteration in natural systems
  - Post-mortem analysis of lab test specimens
- Numerical modeling of fracture propagation in top seals
  - Discrete fracture modeling using cohesive zone models (Poster by Borowski et al.)
  - Fracture network modeling using JOINTS
  - Upscaled modeling for top seal deformation using Sierra Mechanics

Subcritical fracture growth



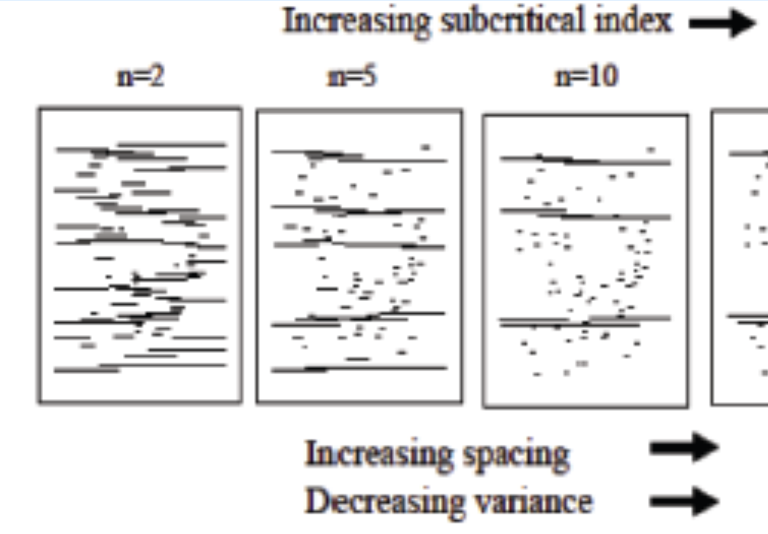
K^*_I = stress corrosion limit
K_{IC} = fracture toughness

After Atkinson, 1984

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

V: fracture propagation velocity
K_I: mode-I stress intensity factor,
K_{IC}: mode-I critical stress intensity factor (or fracture toughness)
A: a pre-exponential constant (Atkinson, 1984; Swanson 1984)
n: velocity exponent (SCI)

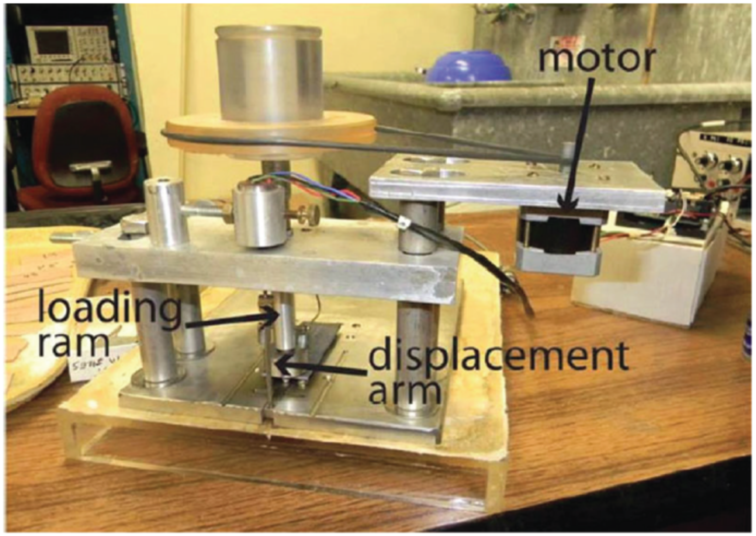
Results of subcritical crack growth affecting fracture network geometry



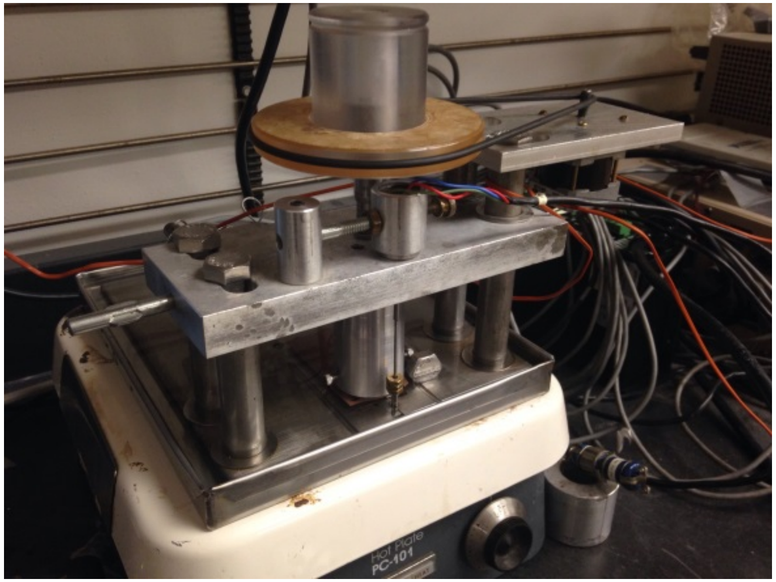
Holder et. al, 2001

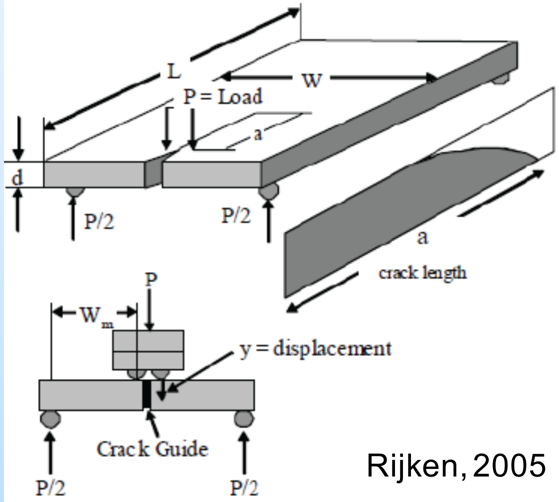
Double torsion fracture mechanics testing

DOUBLE TORSION (DT)



Hot plate & tray for temperature and fluid control





Rijken, 2005

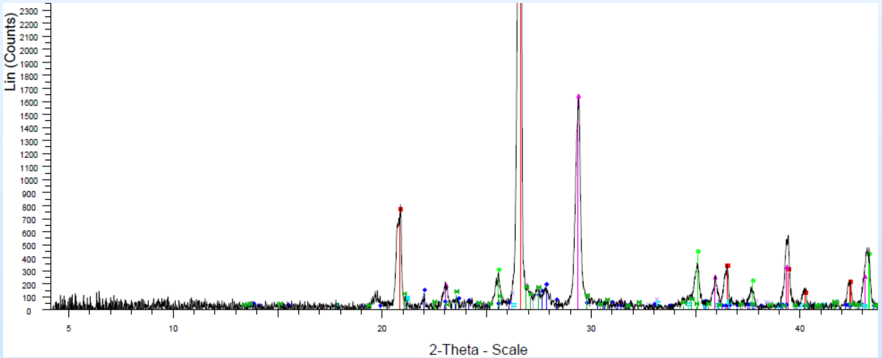
Sample geometry

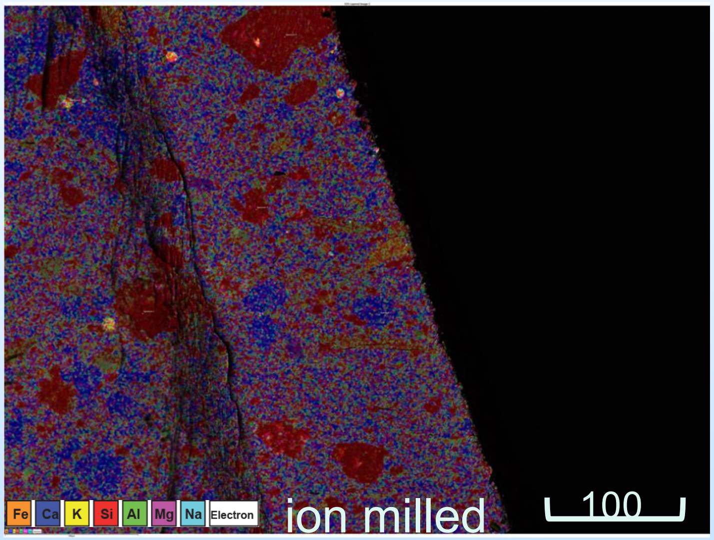
Characterization of samples

OUTCROP

HAND SAMPLE

XRD analysis

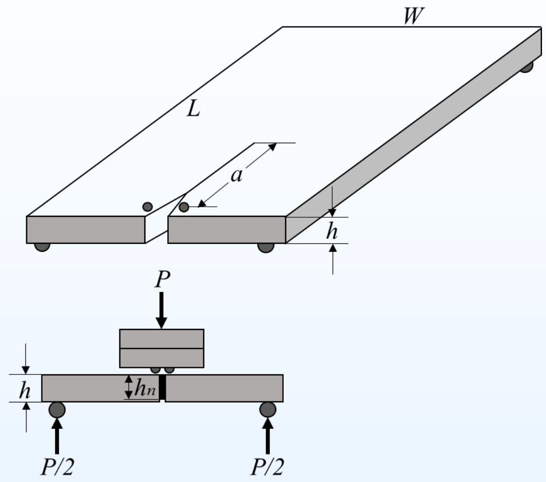




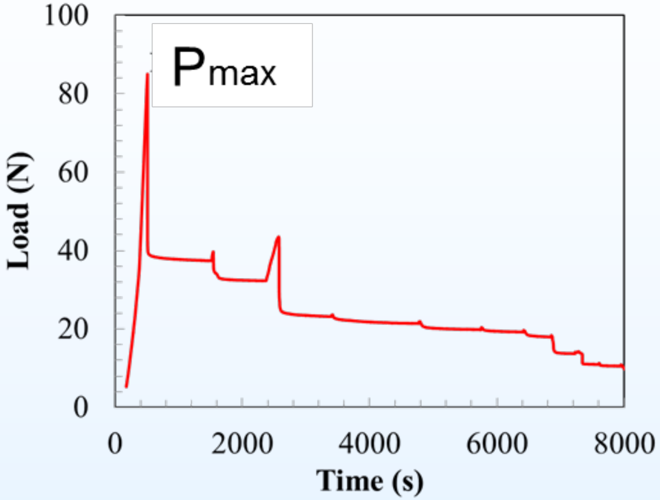
SEM-EDS imaging

Double torsion experiments

1) Sample preparation



2) Load decay experiments

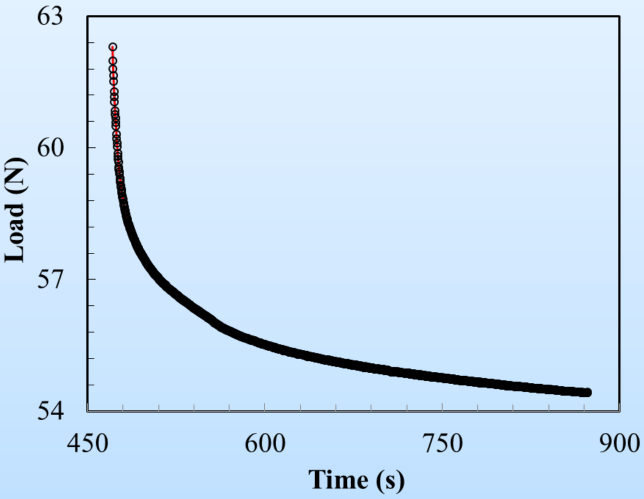


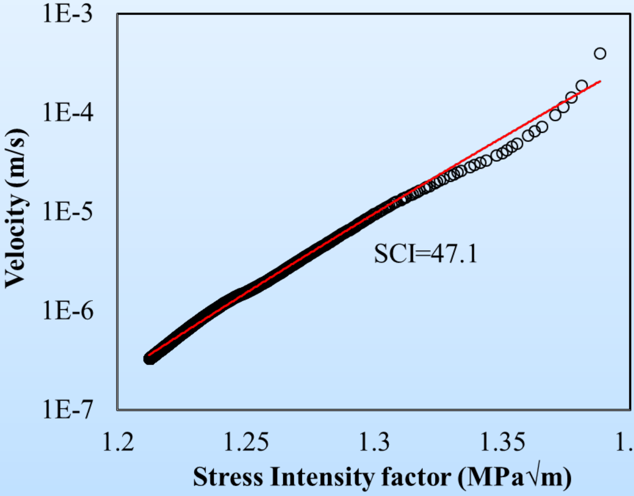
3) Determine K_{IC}, SCI, and K-V curve

$$K_I = P W_m \sqrt{\frac{3(1+\nu)}{W h^3 h_n}}$$

$$V = -\frac{a_i P_i}{P^2}\left(\frac{dP}{dt}\right)$$

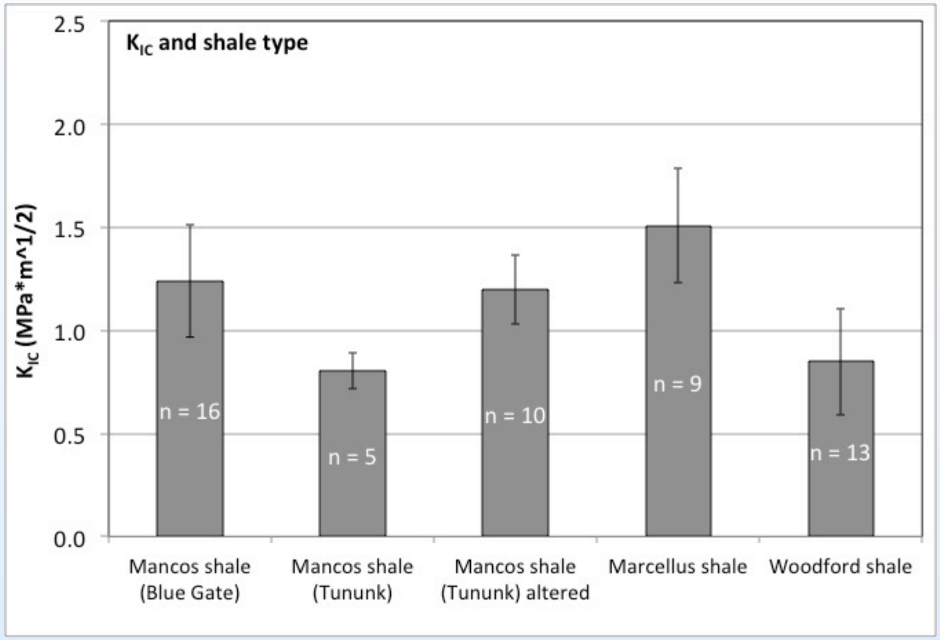
$$V = A \cdot K_I^n$$



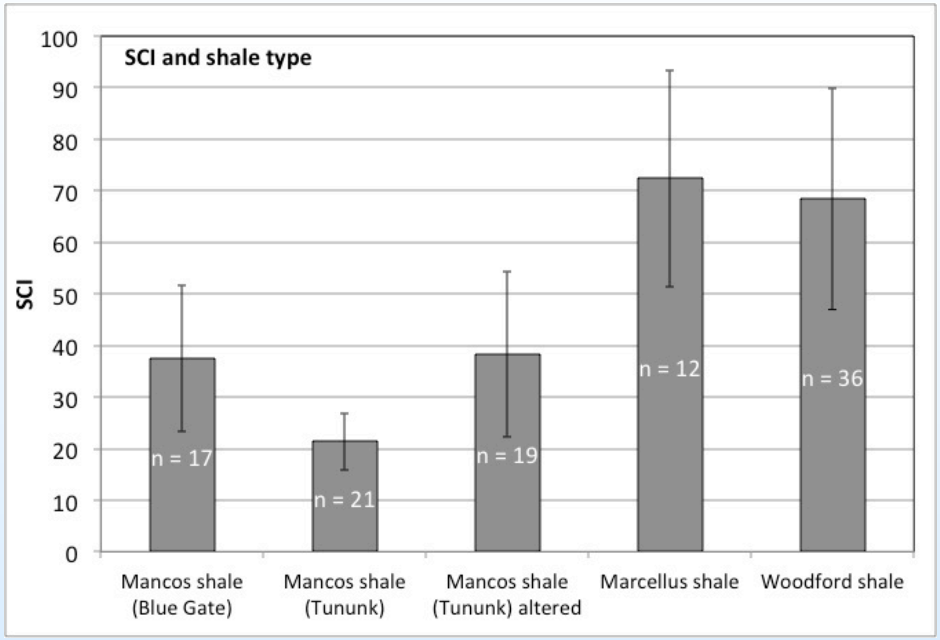


K_{Ic}/SCI across shale formations

Fracture toughness (air)

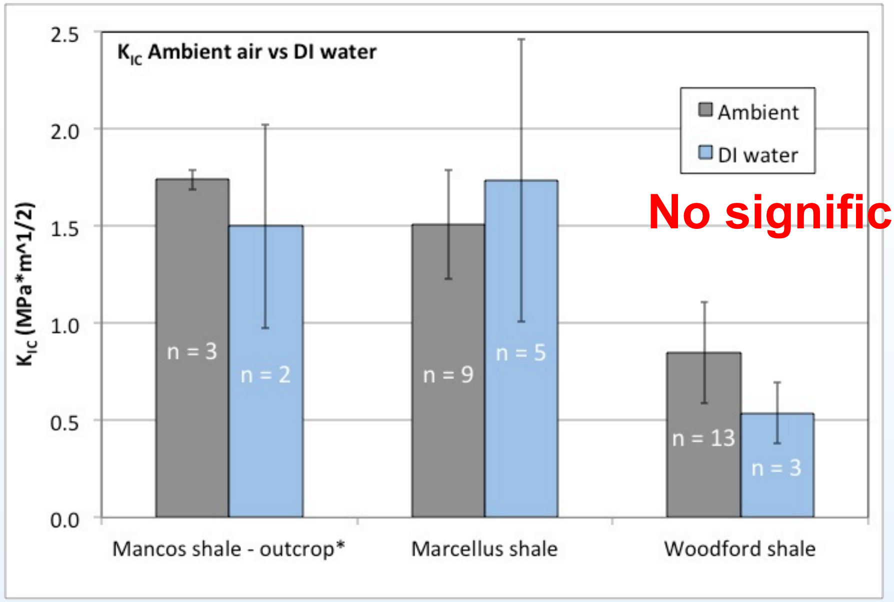


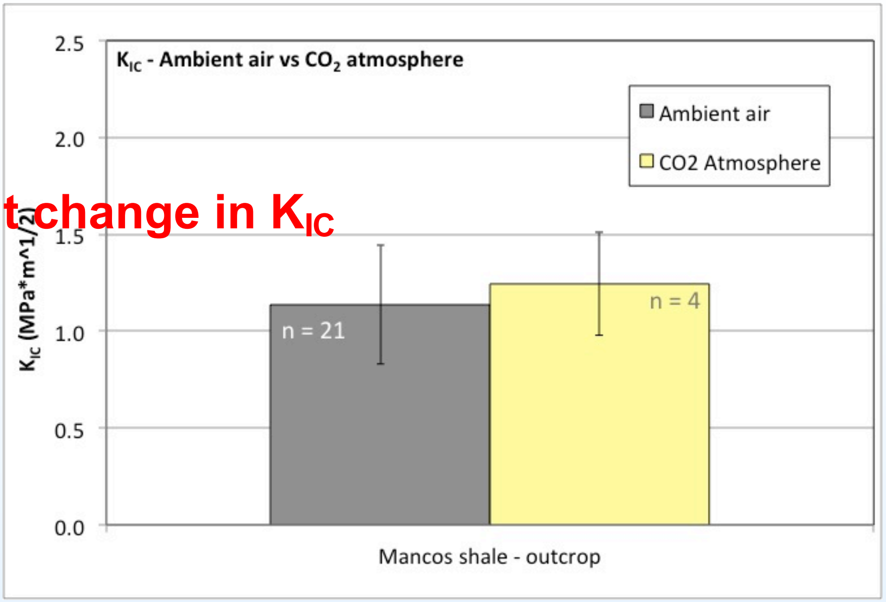
Subcritical index SCI (air)



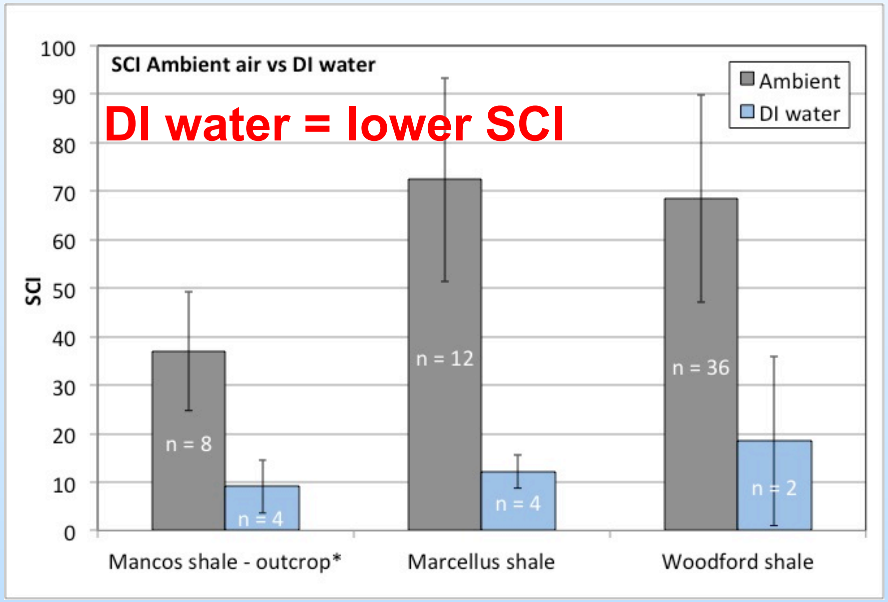
- Significant variation among shale formations.
- n = number of samples
- Measured at ambient atmospheric conditions (~24° C)

K_{Ic}/SCI ambient vs water

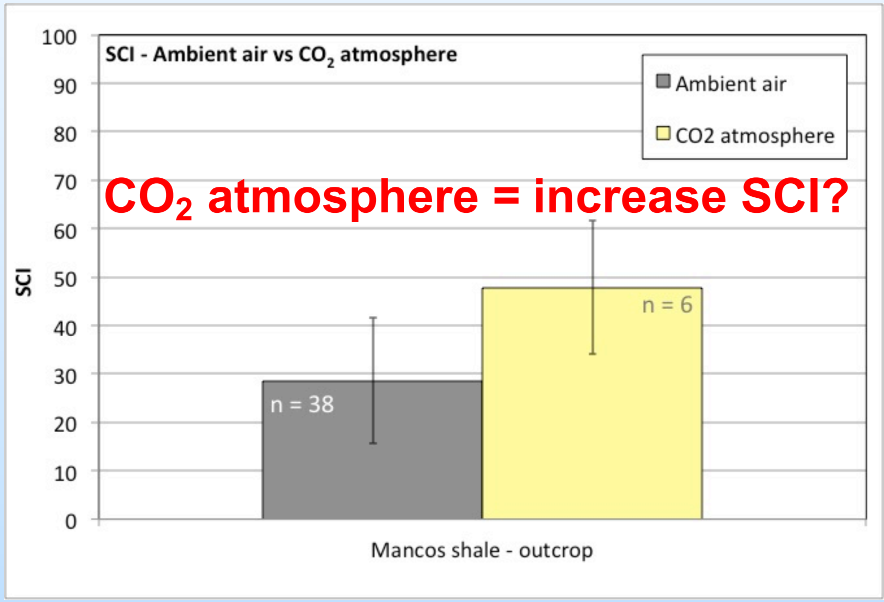




No significant change in K_{IC}

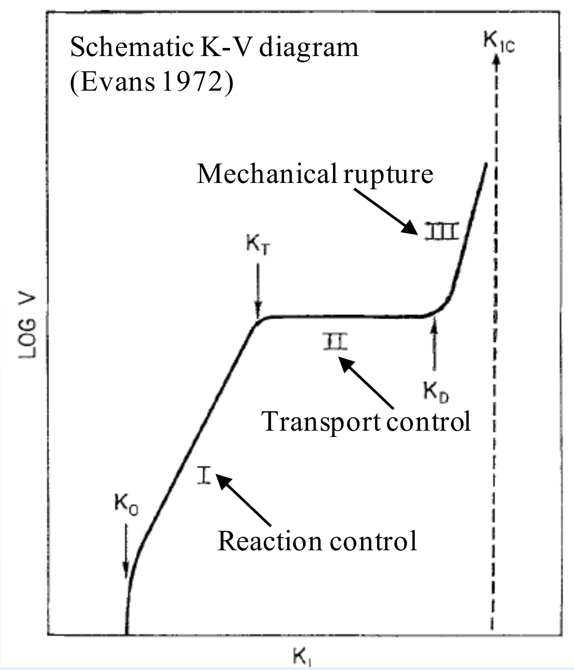


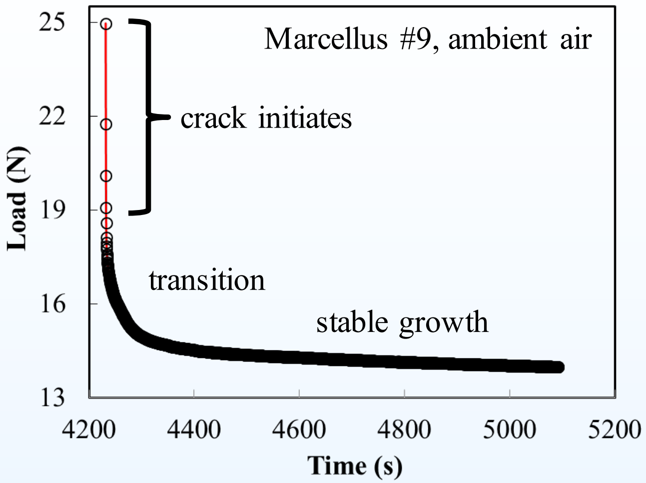
DI water = lower SCI

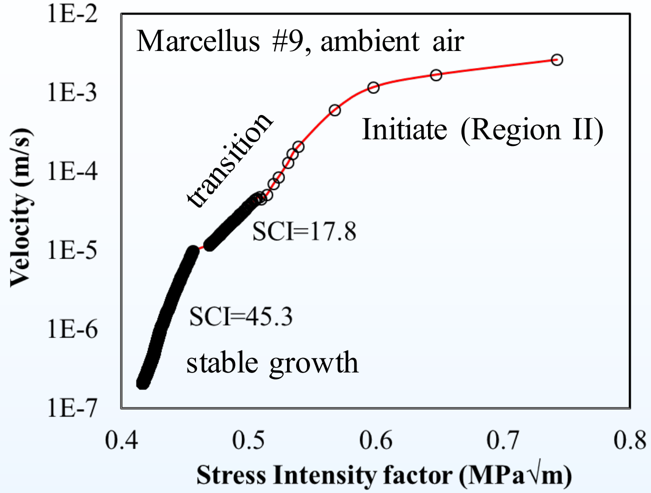


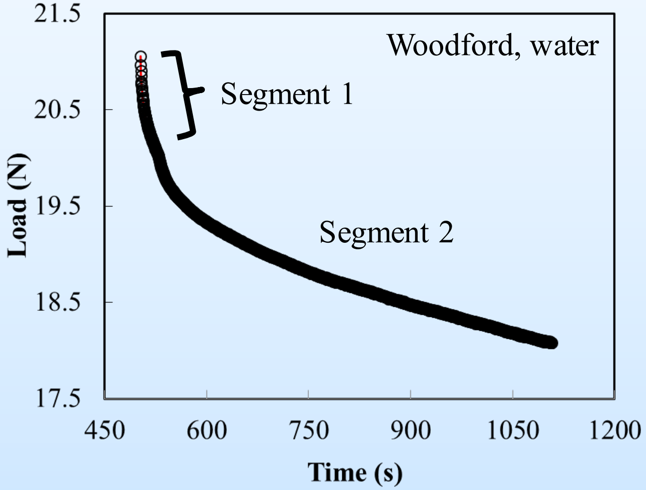
CO_2 atmosphere = increase SCI?

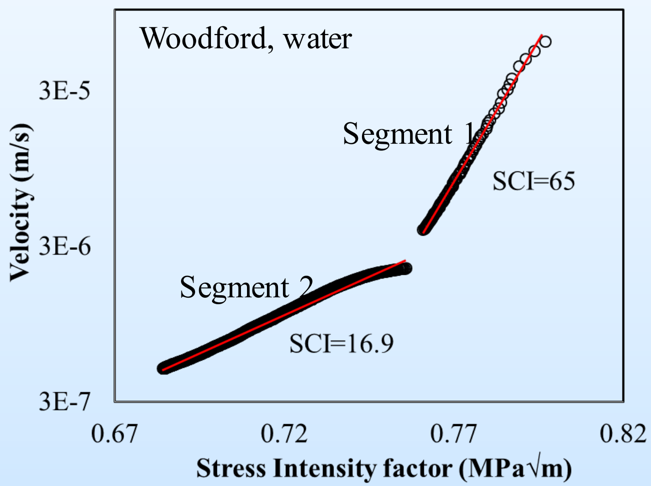
K-V curve characteristics











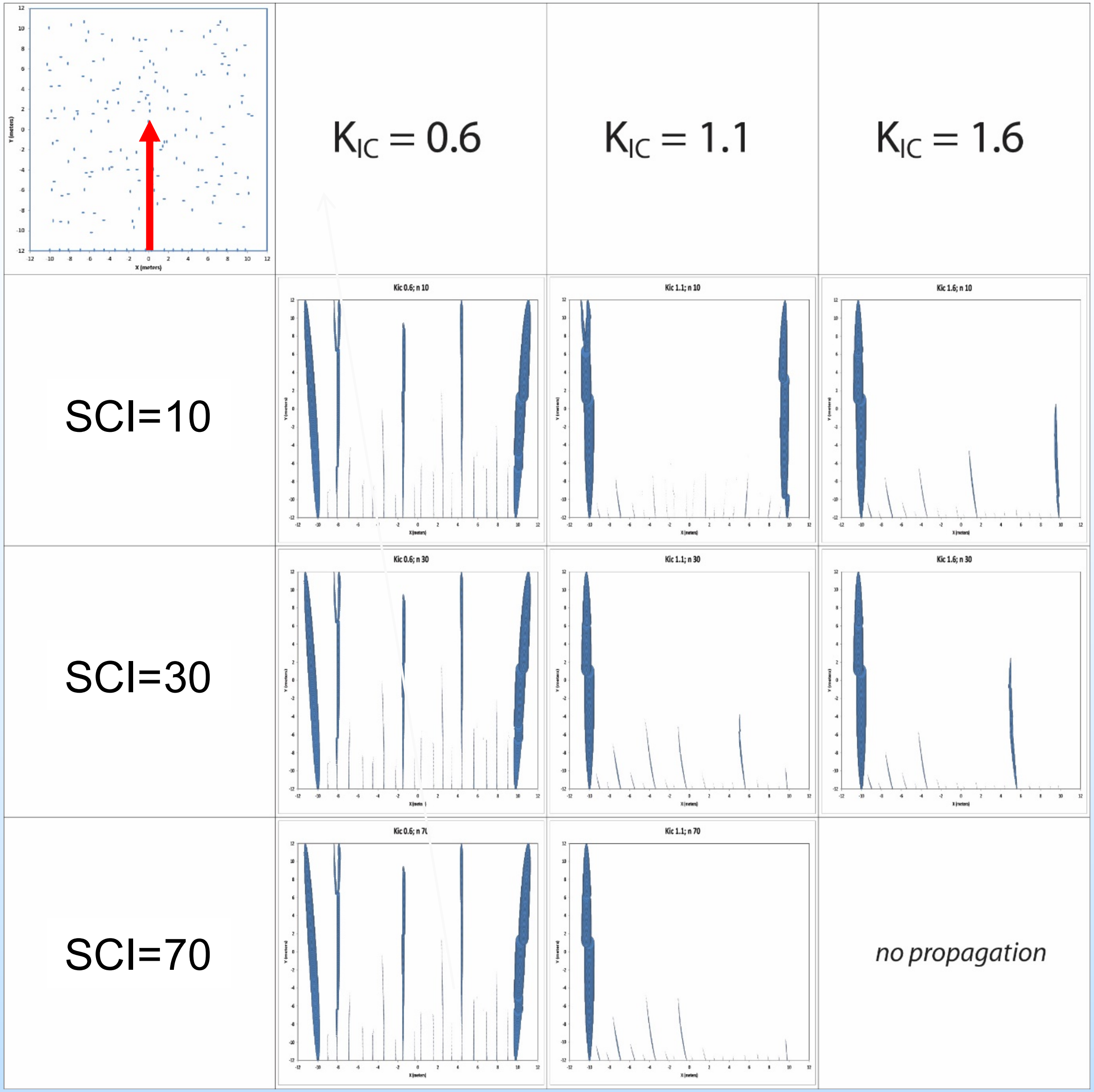
- DT tests represent Region I behavior ---- related to chemical reactions

JOINTS fracture network model

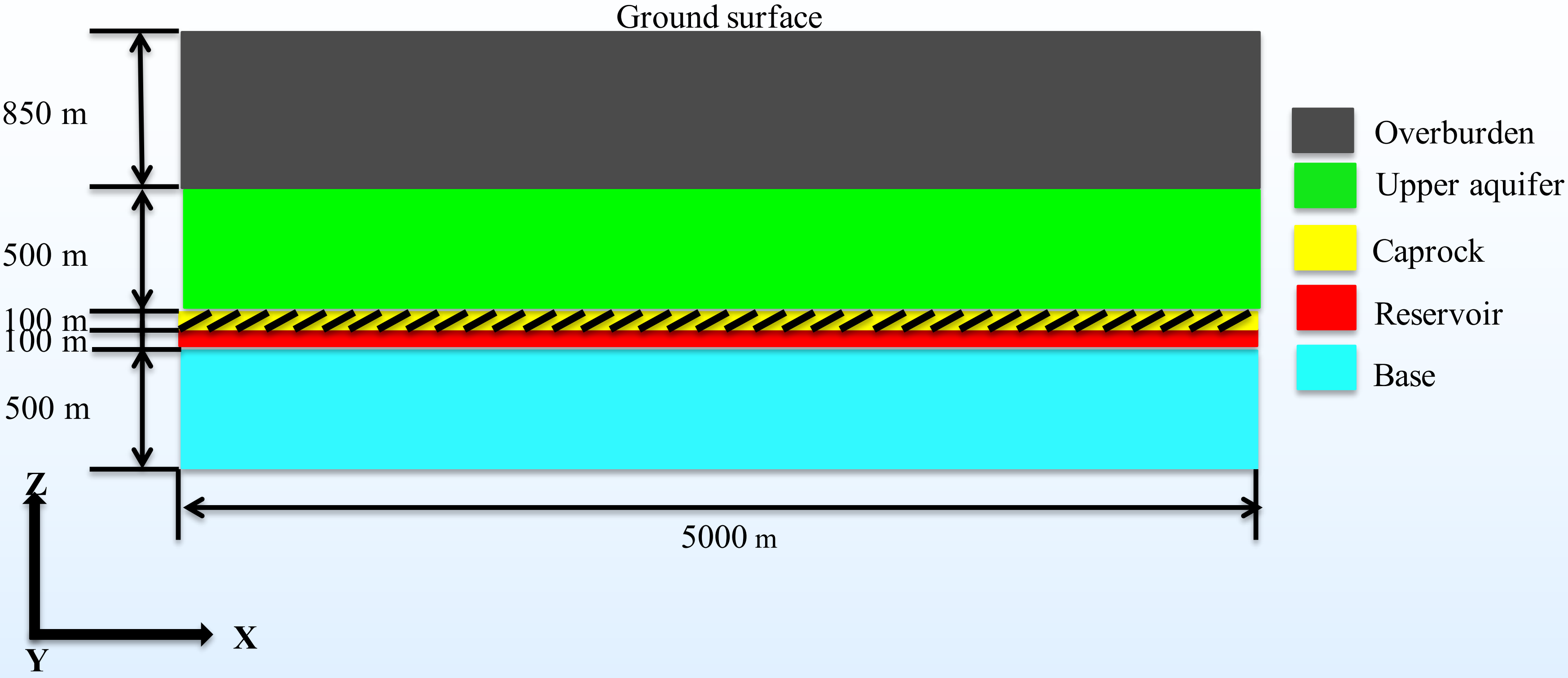
- Boundary element code
- Linear elastic
- Pseudo-3D, accounts for elastic interaction
  - Opening-mode and mixed-mode fracture propagation
- Allows simulation of subcritical fracture propagation as function of
  - Subcritical index SCI
  - Elastic material properties
  - Distribution of nucleation sites (seed fractures)
  - For applied displacement or stress boundary conditions

JOINTS models of caprock failure

- Vertical section in shale caprock
- Fractures initiate at base
- Low K_{IC}, fractures propagate critically (SCI does not change pattern)
- High K_{IC}, high SCI, no fracture growth



Sierra Mechanics model of caprock failure



Failure modeled as zone of fractures across caprock (fractures modeled implicitly)

Two-phase flow

Normal-faulting stress regime σH = 0.7σv

Solid BCs: Sides and the bottom are fixed against normal displacement.

Fluid Bcs: The two adjacent vertical planes, the y–z plane x = 0 and x–z plane y = 0 are no-flow boundaries, the opposite vertical planes (x = 5 km and y = 5 km) are constant pressure boundaries corresponding to the initial hydrostatic state.

Properties

Solid

Property	Aquifer	Caprock	Injection zone	Base	Units
Density	2100	2100	2100	2100	Kg/m^3
Biot's coefficient	1	1	1	1	
Young's modulus	20	50	20	50	GPa
Poisson's ratio	0.2	0.12	0.2	0.12	

Fluid

Property	Aquifer	Caprock	Injection zone	Base	Units
Initial porosity	0.15	0.05	0.15	0.10	
Intrinsic permeability	2×10^{-14}	1×10^{-18}	2×10^{-14}	1×10^{-16}	m^2

Fracture

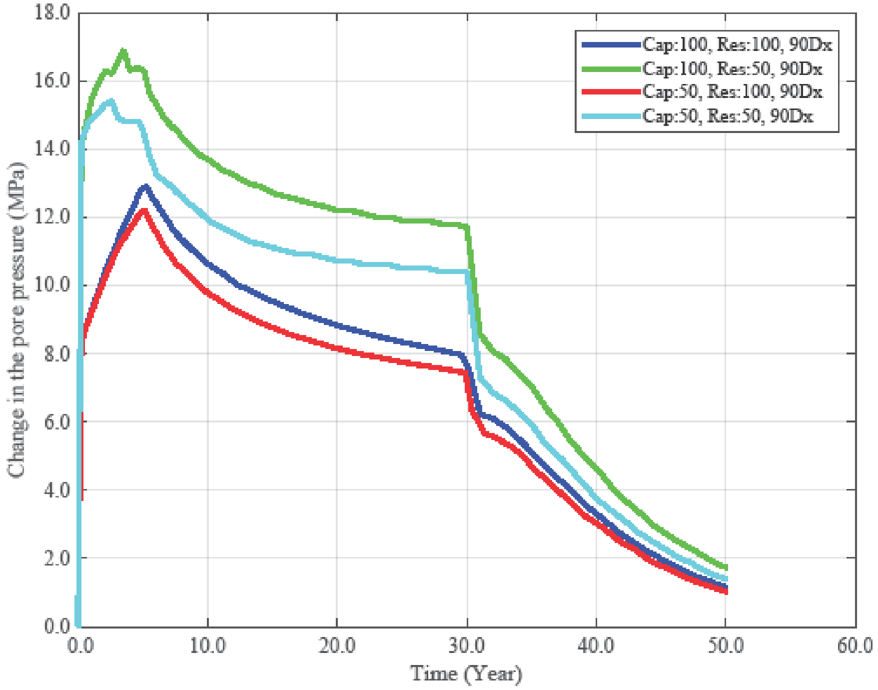
Stiffness	Spacing
K_{ni} (Pa)	S (m)
$1.5 \times 10^{+10}$	1.00

Different scenarios

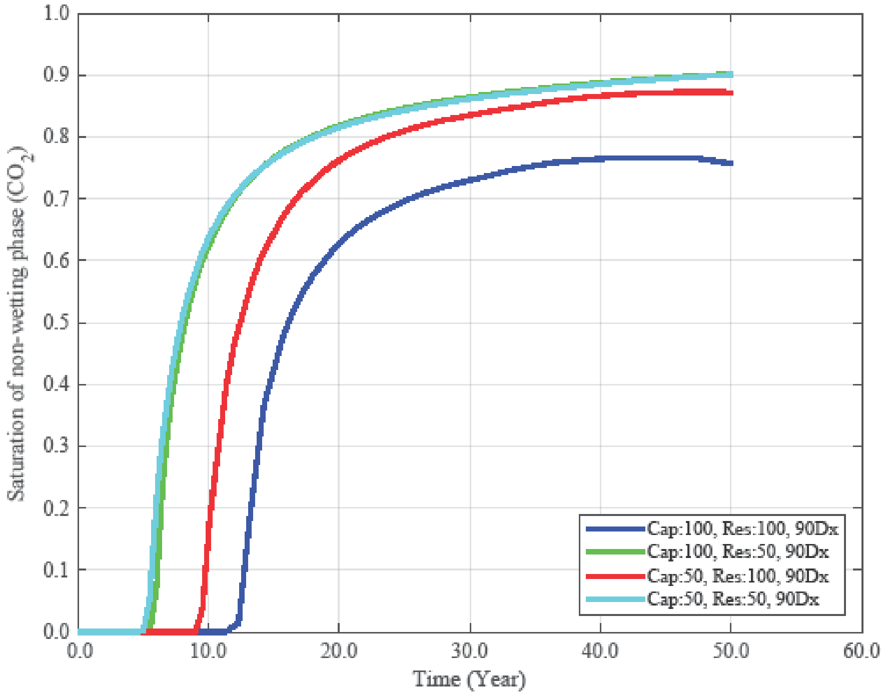
	Case	**Reservoir thickness (m)**	**Caprock thickness (m)**	**Fracture orientation (Degree)**
Base case	1	100	100	Without joint
Geometry	2	100	100	90
	3	100	50	90
	4	50	100	90
	5	50	50	90
Fracture orientation	6	100	100	30
	7	100	100	45
	8	100	100	60

Leakage scenarios using Sierra Mechanics: Effect of layer thickness

Change in pore pressure



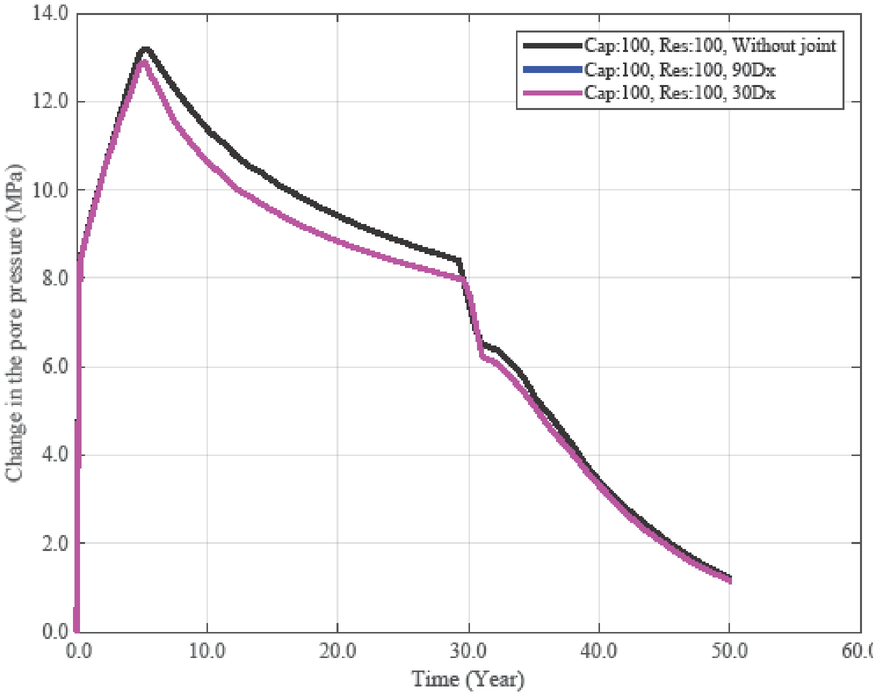
Saturation of CO$_2$ at top of upper aquifer



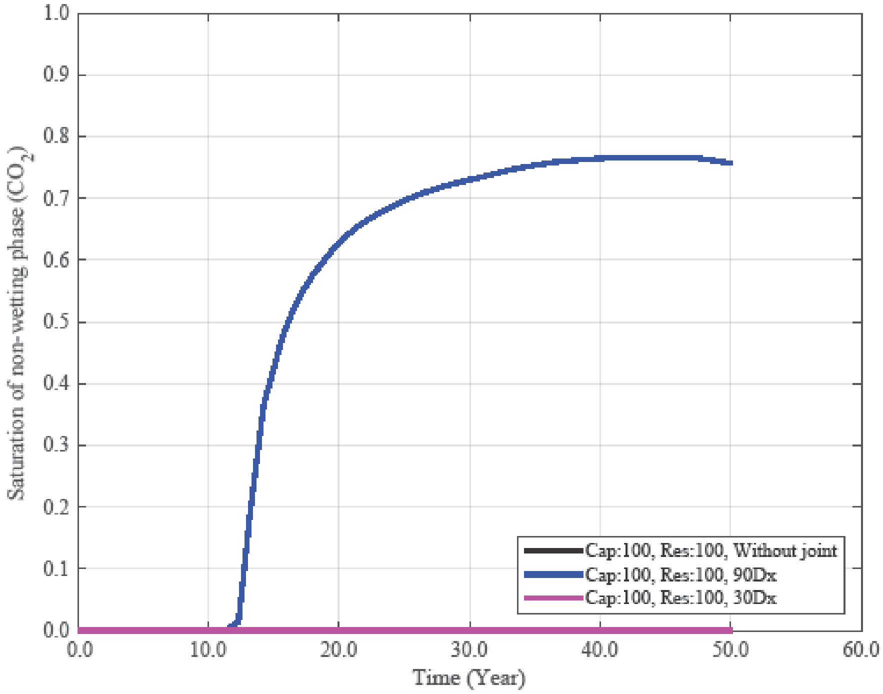
- Thinner reservoir, thicker caprock → higher pore pressure
- Thinner reservoir, thinner caprock → higher leakage of CO$_2$

Leakage scenarios using Sierra Mechanics: Effect of fractures

Change in pore pressure



Saturation of CO_2 at top of upper aquifer



- Vertical fractures → highest leakage
- 30° dip fractures → pressure similar to case with no fractures

Accomplishments to Date

- Initiated rigorous fracture mechanics testing on caprock lithologies in aqueous environments relevant to CO_2 sequestration
- Performed initial numerical simulations on fracture network evolution by chemically aided fracture growth and caprock failure
- Performed coupled fluid flow-geomechanics simulations of caprock leakage using in Sierra Mechanics continuum models

Synergy Opportunities

- Share samples of caprock material with M. Prasad (School of Mines)
- Fracture mechanics analysis of Cranfield and FutureGen II core material
- Coordination with EFRC research on reservoir rock geomechanics

Summary

- Findings
  - Wide range in fracture properties for different caprock lithologies
  - Distinct stress corrosion effect observed in DT experiments in water
  - Subcritical fracture most significant for rocks of intermediate toughness
  - Effect of reservoir/caprock geometry on CO_2 leakage
- Next steps
  - Fracture testing under varying temperature, water composition, pressure
  - Integration of testing & fracture modeling

Acknowledgement

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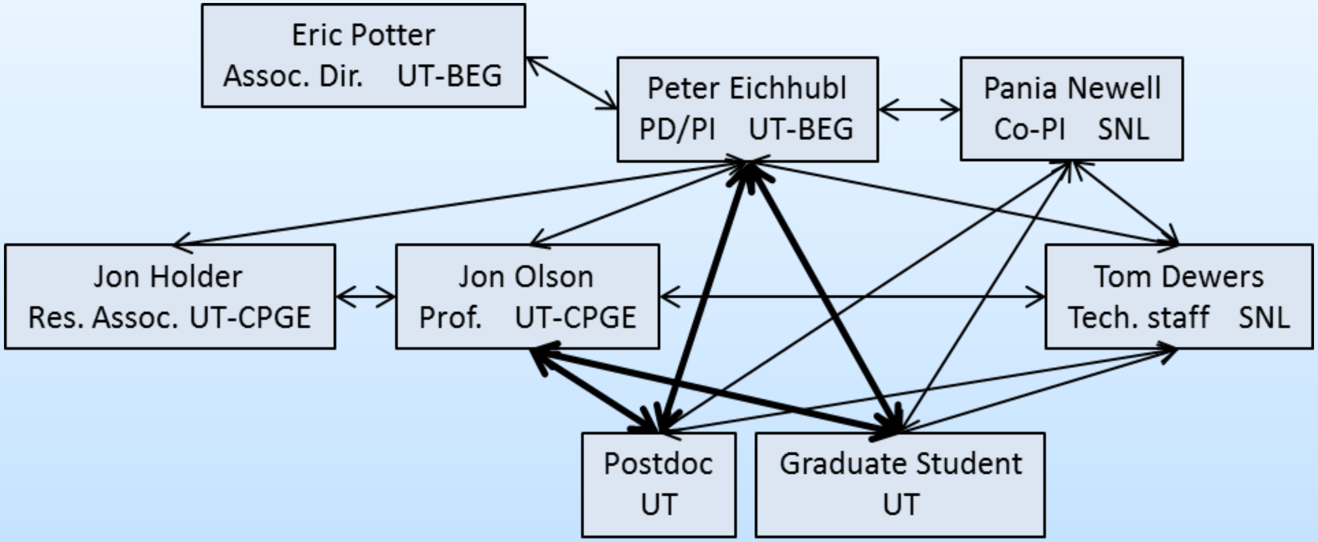
Appendix

Organization Chart/ Communication Plan

- Established Sandia-UT collaboration
  - Olson – Holder – Eichhubl on joint industry & DOE/RPSEA projects
  - Dewers – Newell –Eichhubl on joint EFRC



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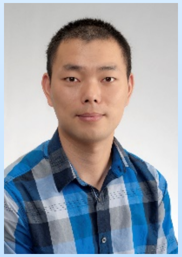

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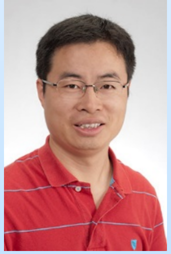

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Gantt Chart

Task/Subtask	Year 1				Year 2				Year 3			
	9/1/2014-12/31/2014	1/1/2015-3/31/2015	4/1/2015-6/30/2015	7/1/2015-9/30/2015	10/1/2015-12/31/2015	1/1/2016-3/31/2016	4/1/2016-6/30/2016	7/1/2016-9/30/2016	10/1/2016-12/31/2016	1/1/2017-3/31/2017	4/1/2017-6/30/2017	7/1/2017-8/31/2017
1. Project Management and Planning	🟩 ✓	🟩 ✓	🟩 ✓	🟩 p	🟩 p	🟩 p	🟩 p	🟩 p	🟩	🟩	🟩	🟩
2.1. Short rod fracture toughness tests	🟩 *	🟩 *	🟩 *	🟩 *	🟩 *	🟩 *	🟩 *	🟩 *	🟩	🟩	🟩	
2.2. Double torsion tests	🟩 ✓	🟩 ✓	🟩 ✓	🟩 p	🟩 p	🟩 p	🟩 p	🟩 p	🟩	🟩	🟩	
2.3. Fracturing in water-bearing supercritical CO2		✓	✓	p	🟩 p	🟩 p	🟩 p	🟩 p	🟩	🟩	🟩	
3.1. Field fracture characterization	🟩 ✓	🟩 ✓	🟩 ✓	🟩 p	🟩 p	🟩 p	🟩 p	🟩 p				
3.2. Textural and compositional fracture imaging	🟩	🟩	🟩	🟩 p	🟩 p	🟩 p	🟩 p	🟩 p	🟩	🟩		
4.1. Discrete fracture modeling using Sierra Mechanics	🟩 ✓	🟩 ✓	🟩 ✓	🟩 p	🟩 p	🟩 p	🟩 p	🟩 p	🟩	🟩	🟩	
4.2. Fracture network modeling using JOINTS	🟩	🟩	🟩	🟩 p	🟩 p	🟩 p	🟩 p	🟩 p	🟩	🟩	🟩	
4.3. Upscaled modeling using Kayenta					🟩 p	🟩 p	🟩 p	🟩 p				
5. Model validation and integration					🟩 p	🟩 p	🟩 p	🟩 p	🟩	🟩	🟩	🟩

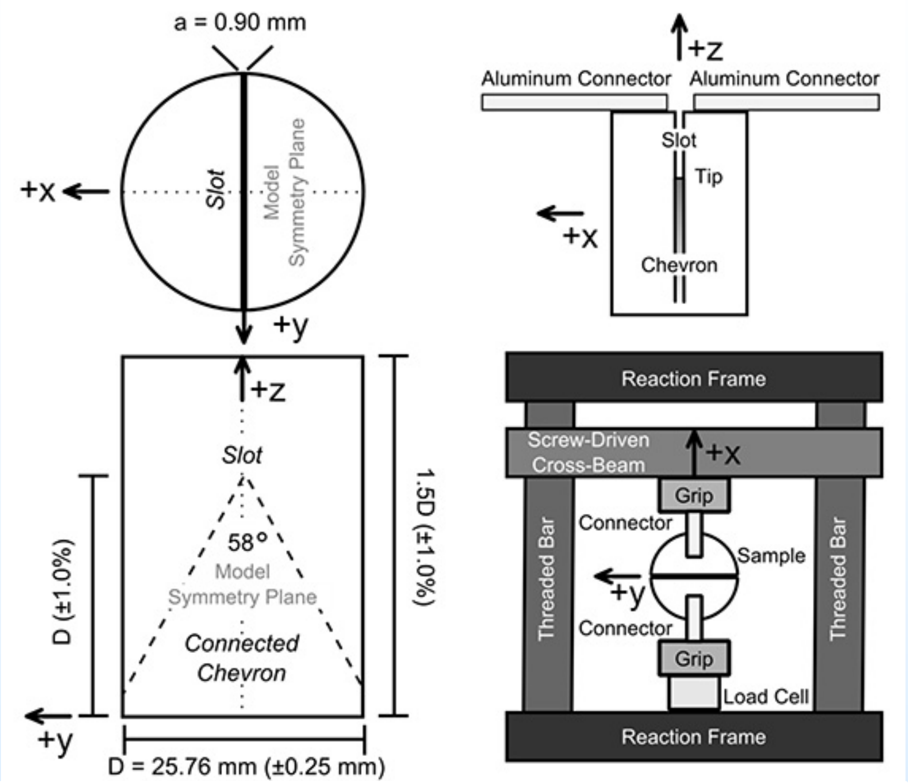
Bibliography

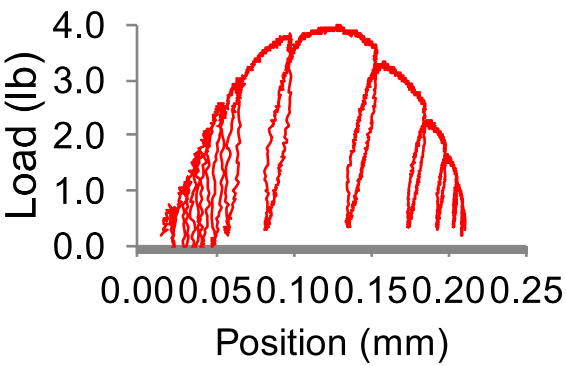
List peer reviewed publications generated from the project per the format of the examples below

- None to report at this time

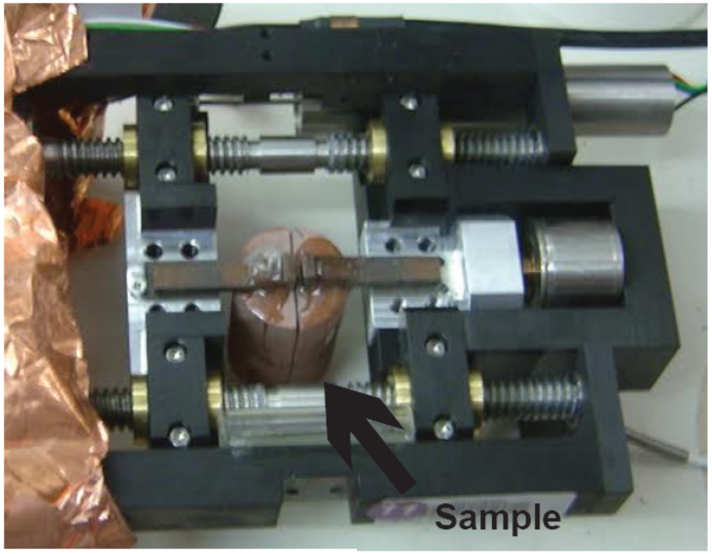
Extra slides

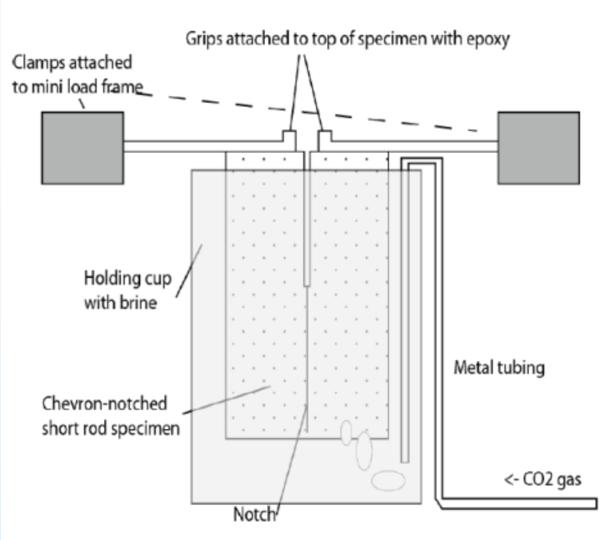
Short-rod testing geometry



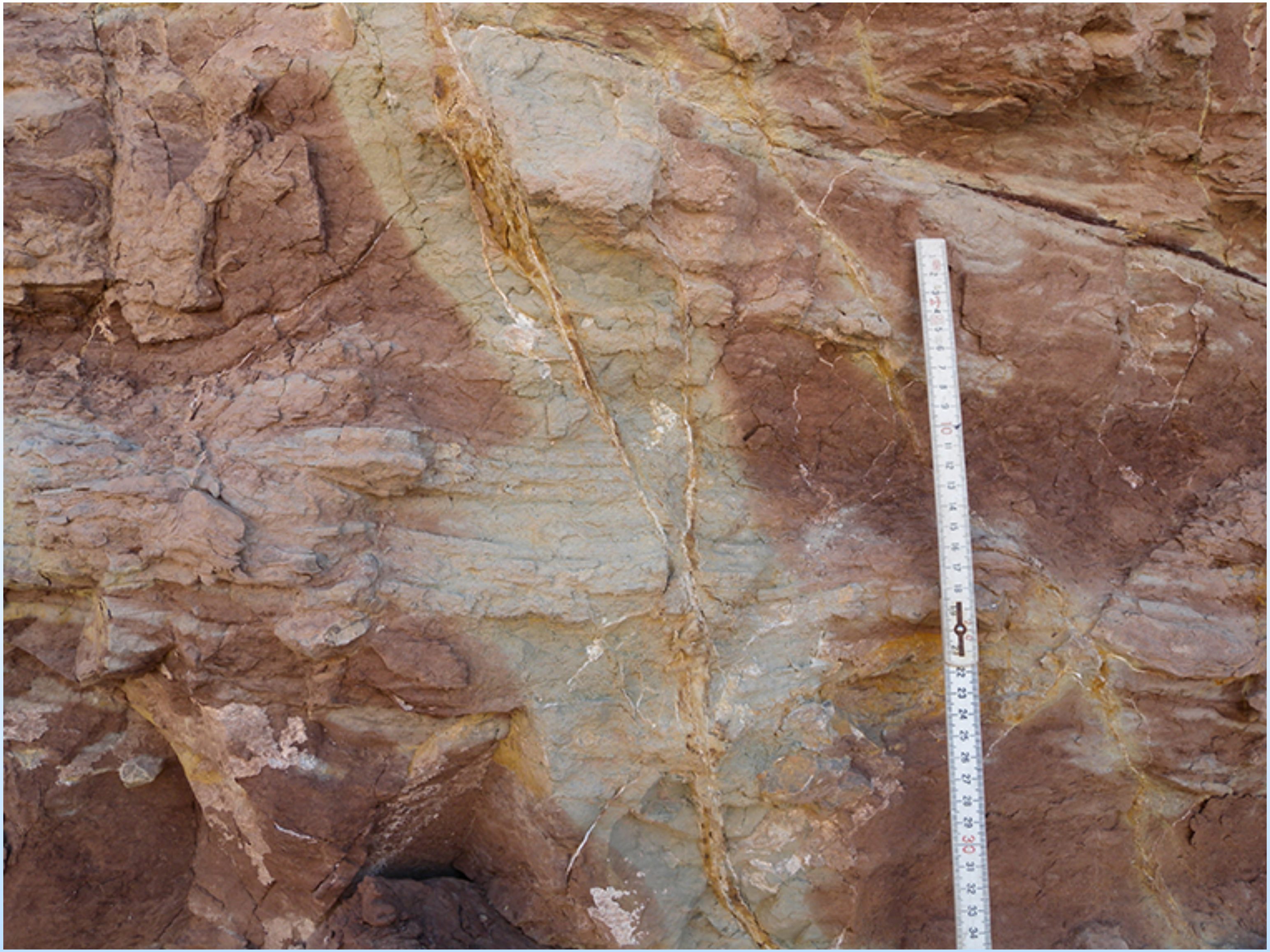


SHORT ROD (SR)





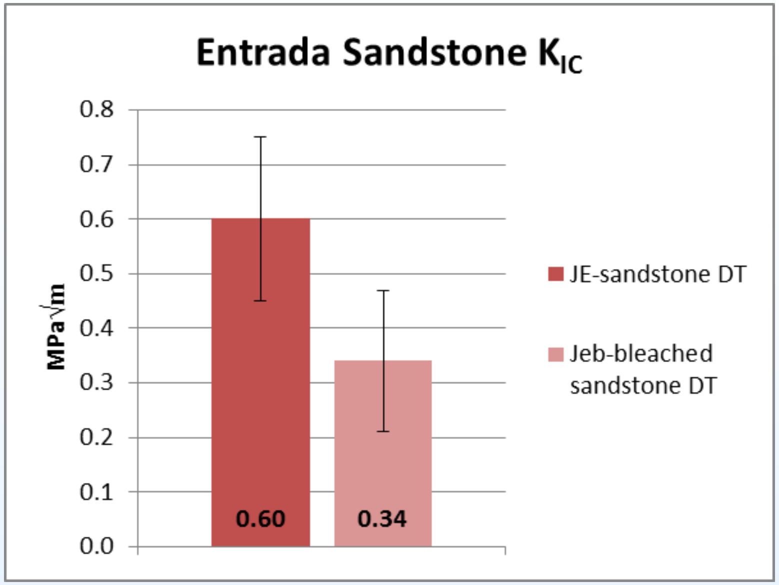
Field fracture characterization in natural CO_2 systems

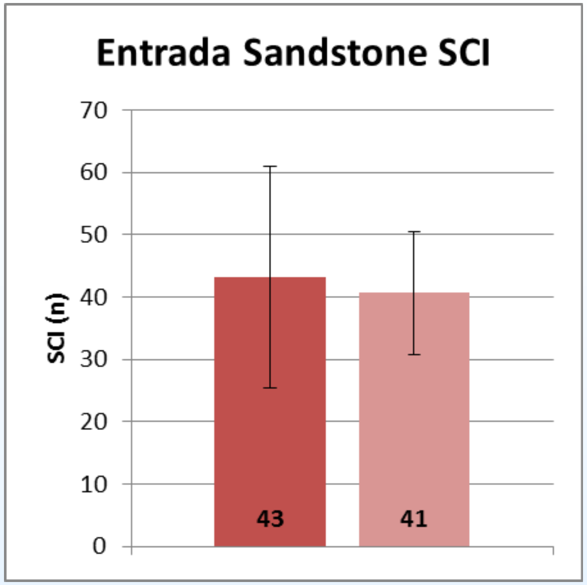


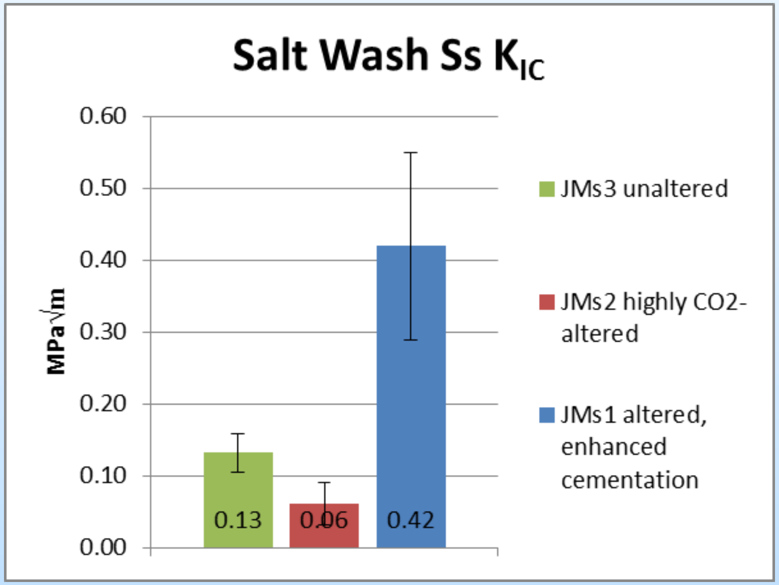
Task/Subtask Breakdown

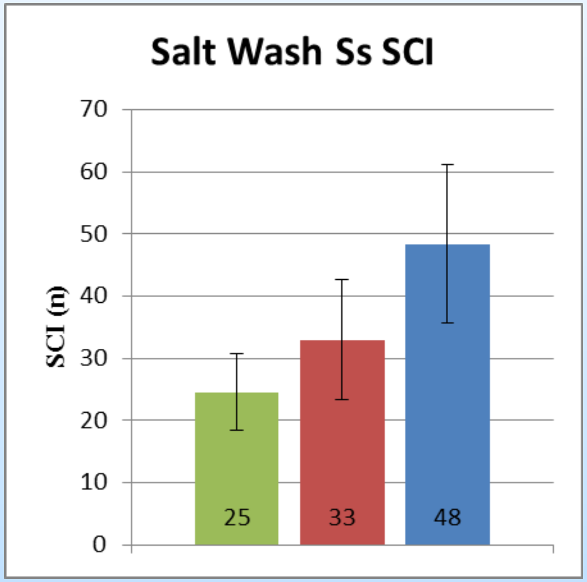
1. Project Management and Planning
2. Measure Subcritical Crack Propagation in Analog Top Seals
    1. Perform short rod fracture toughness tests
    2. Perform double-torsion test
    3. Evaluate fracturing in water-bearing supercritical CO_2 at reservoir conditions
3. Characterize Fracture Processes in Natural CO_2 Systems
    1. Characterize field fractures
    2. Perform textural and compositional fracture imaging
4. Numerical Modeling of Fracture Propagation in Caprock
    1. Develop and validate discrete fracture numerical model
    2. Develop and validate fracture network numerical model
    3. Upscale discrete behavior for reservoir and caprock deformation modeling
5. Model Validation and Integration

CO_2-altered vs unaltered sandstone (reservoir)

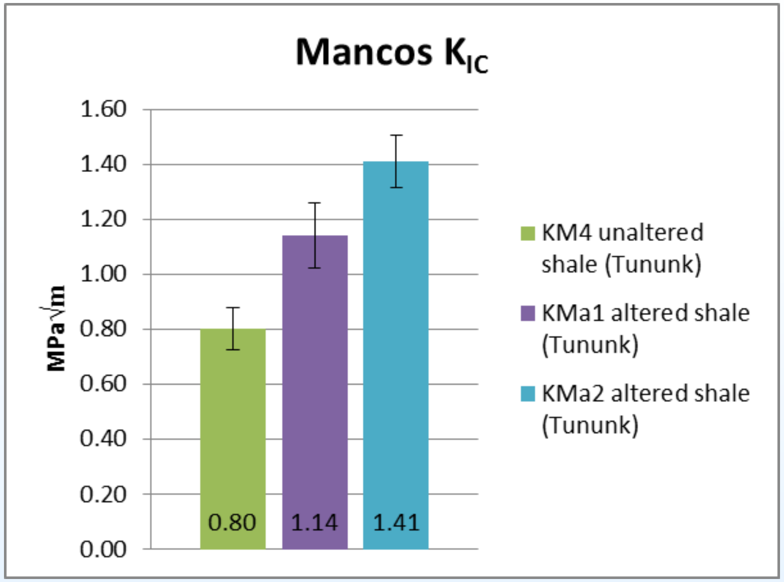


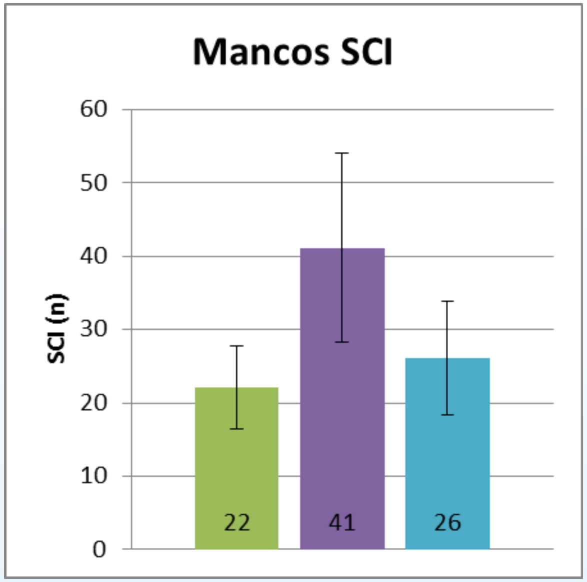


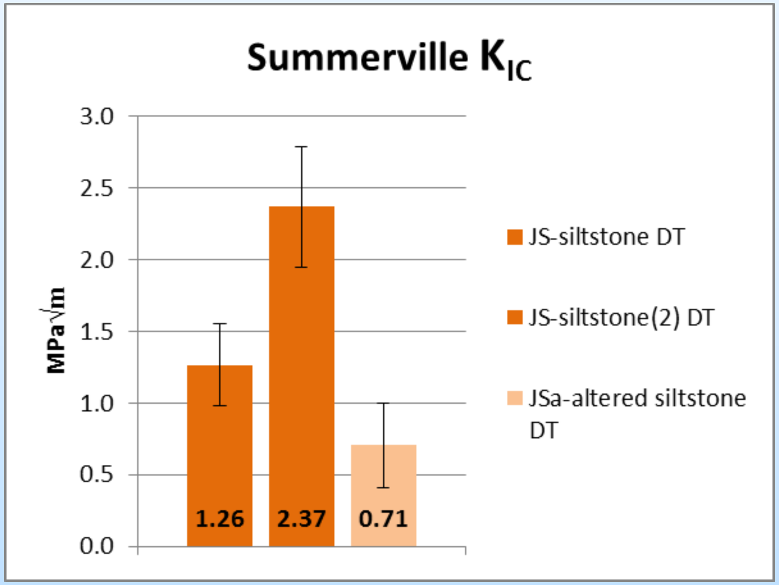


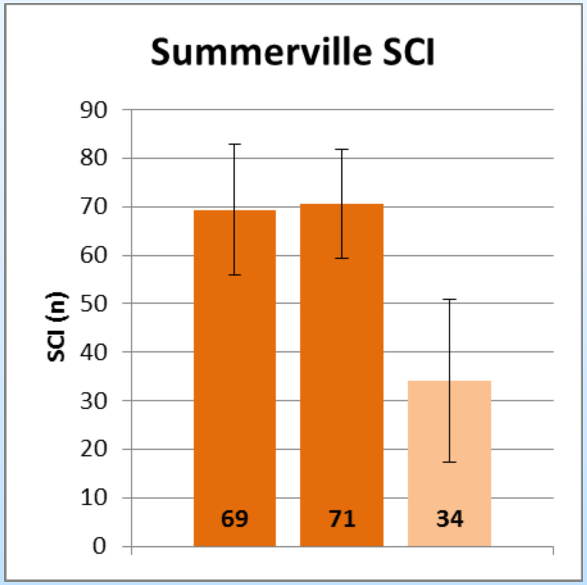


Double torsion testing: Fracture toughness, subcritical crack index n (SCI)









Field & lab fracture imaging

Fracture tip morphology & alteration in field & lab fracture specimens

Zeiss Sigma Field Emission SEM with Gatan MonoCL4 & Oxford EDS for large-area high-resolution textural imaging.

Installed at UT-BEG September 2014

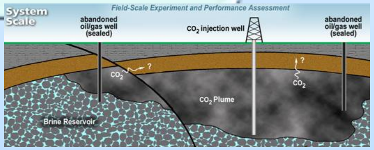
Numerical Modeling of Fracture Propagation in Caprock

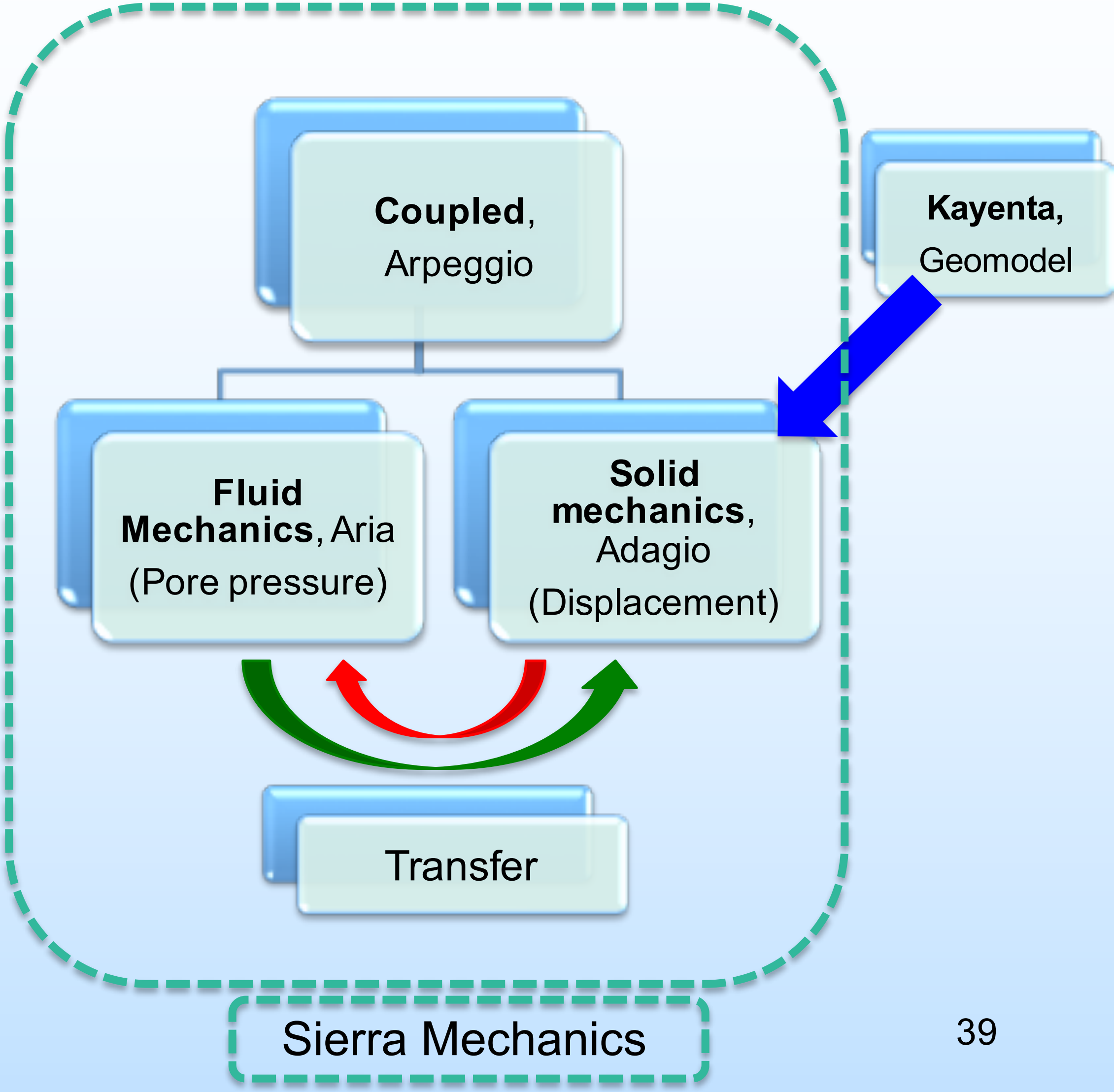
Safe and Secure storage systems

Experimental investigation
- Short rod
- Double torsion

Numerical investigation
- Joints

- Sierra Mechanics using Kayenta





Coupled, Arpeggio

Kayenta, Geomodel

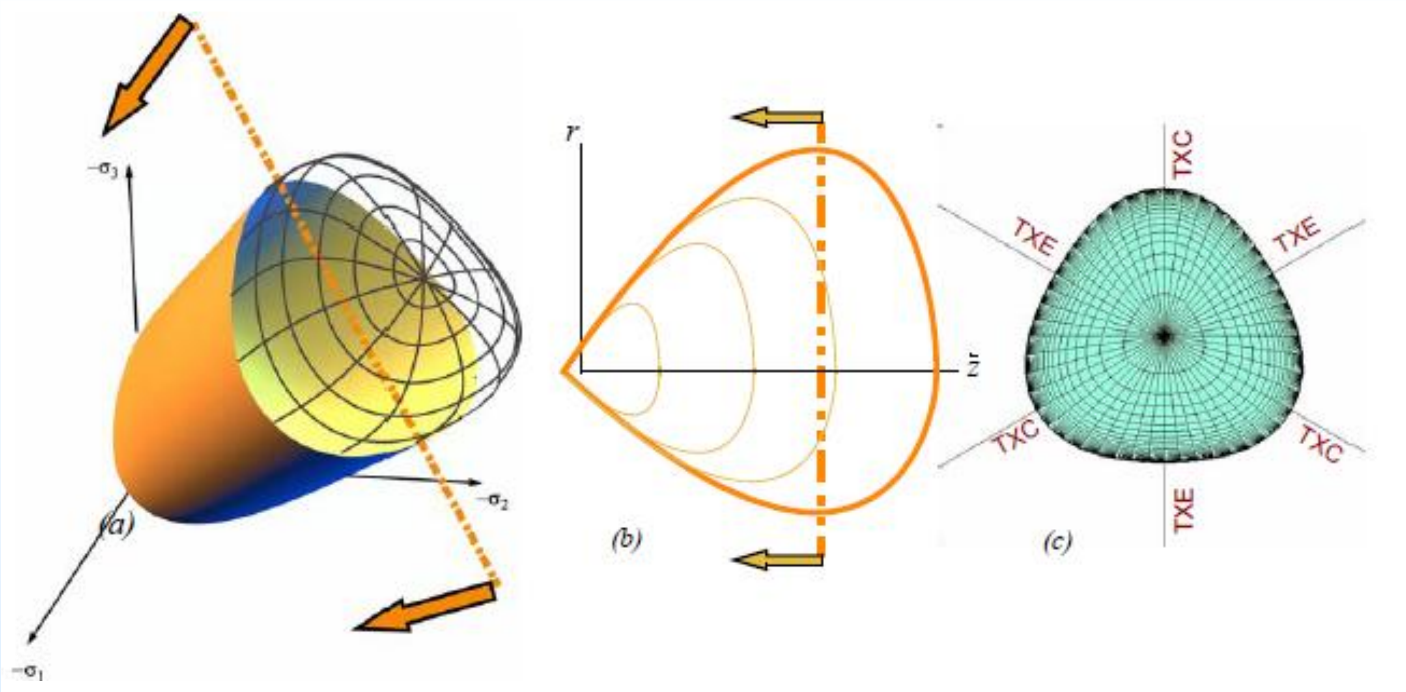
Fluid Mechanics, Aria (Pore pressure)

Solid mechanics, Adagio (Displacement)

Transfer

Sierra Mechanics

Kayenta material model



- Continuous yield surface
  - (a) 3D view: Principal stress space with the high pressure “cap”
  - (b) Side view: Using cylindrical coordinate system
  - (c) Octahedral view: Looking down at the hydrostat