Area of Interest 2, Geomechanics of CO_2 Reservoir Seals

DE-FE0023316

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U.S. Department of Energy
National Energy Technology Laboratory
DE-FOA0001037 Kickoff Meeting
November 12-13, 2014

Presentation Outline

- Benefit
- Project Overview
- Methodology
- Expected Outcomes
- Project Management
- Deliverables
- Risk
- Schedule

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

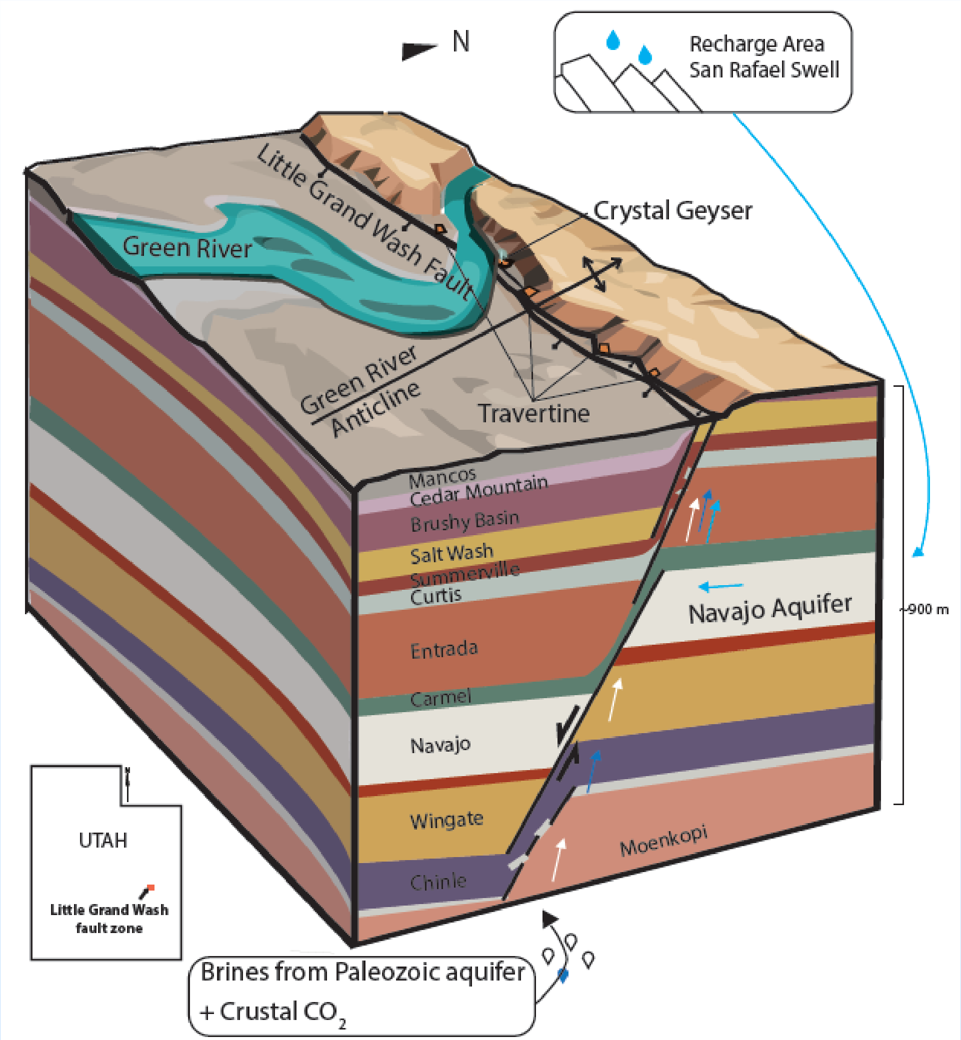
- ***Derive predictive and validated numerical models*** for fracture growth in chemically reactive environments relevant to CCUS top seal lithologies.
- ***Perform laboratory fracture testing*** to provide input parameters on fracture constitutive behavior, fracture rate and geometry, and deformation 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.

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.
- Currently no established seal risk assessment criteria for CO_2 systems.

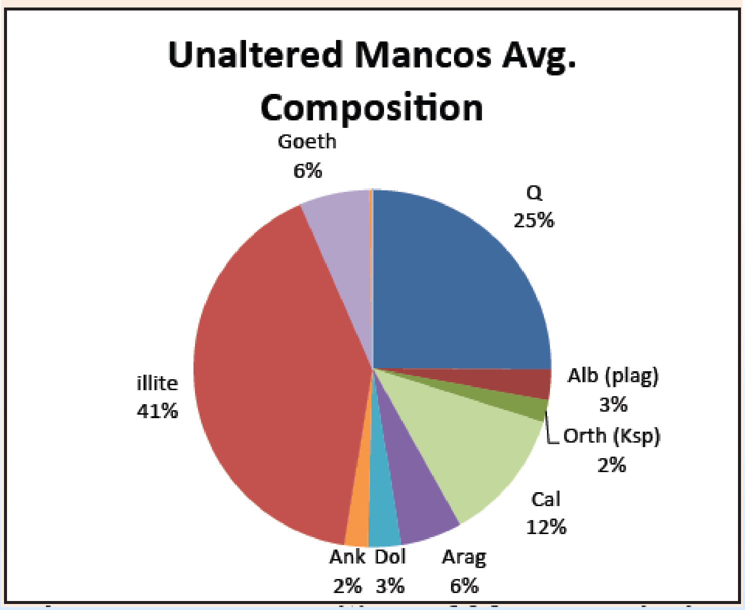
Fractures in CO_2 cap rocks

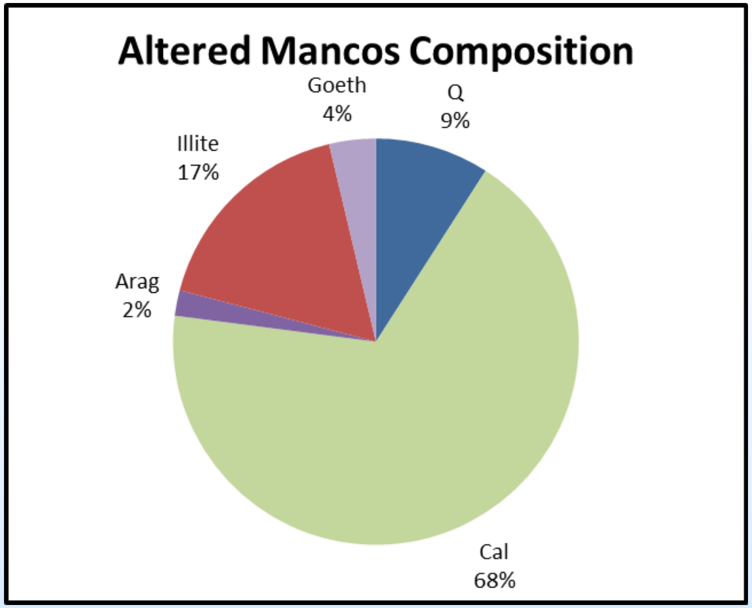
Crystal Geyser analog site



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

Compositional changes of mudrock





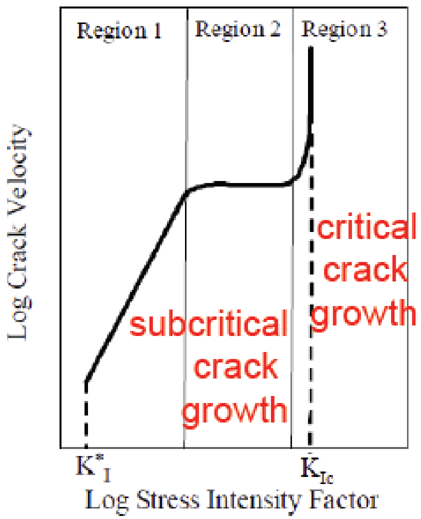
Questions being addressed

- What is the effect of CO_2 on
  - Top & fault seal properties?
  - Failure localization?
  - Capillary sealing capacity?
  - Fracture & cement morphology?
- Are CO_2 reactions rock weakening/ strengthening?
- What reactions are involved?
- Scale of CO_2 interaction (near tip, pervasive)?
- What are rates of seal failure & chemical reactions?

Methodology

- Experimental measurement of subcritical fracture propagation in analog top seals
  - Short-rod test
  - Double torsion test
- Textural and compositional fracture imaging
  - Fractures in natural CO_2 systems
  - Post-mortem analysis of lab test specimens
- Numerical modeling of fracture propagation in top seals
  - Discrete fracture modeling using cohesive zone models within Sierra Mechanics
  - Fracture network modeling using JOINTS
  - Upscaled modeling for top seal deformation using Kayenta and Sierra Mechanics

Subcritical fracture growth



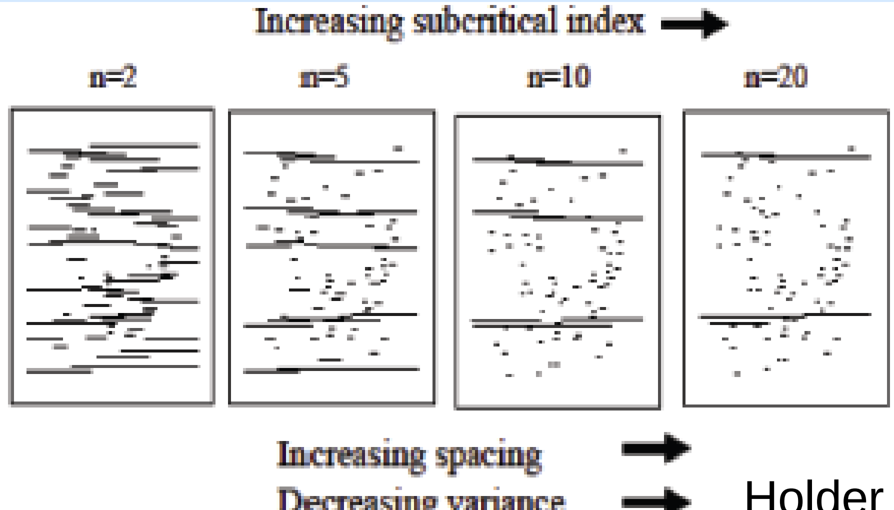
K^*_I = stress corrosion limit
K_{IC} = fracture toughness

After Atkinson, 1984

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

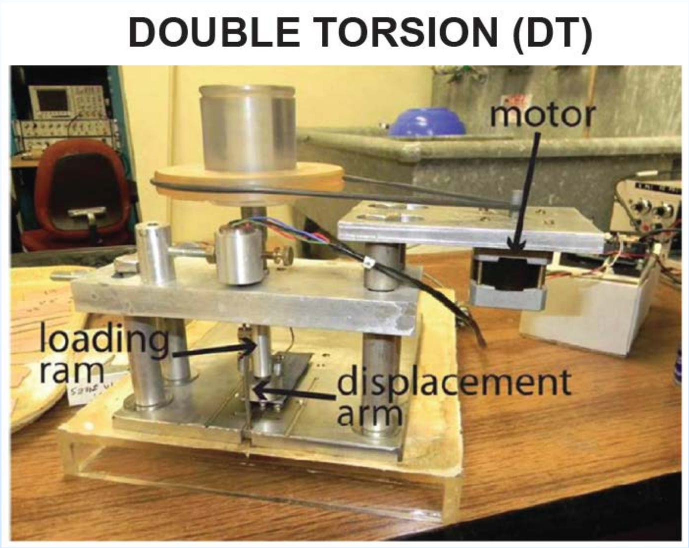
V: fracture propagation velocity
K_I: mode-I stress intensity factor,
K_{IC}: mode-I critical stress intensity factor (or fracture toughness)
A: a pre-exponential constant (Atkinson, 1984; Swanson 1984)
n: velocity exponent

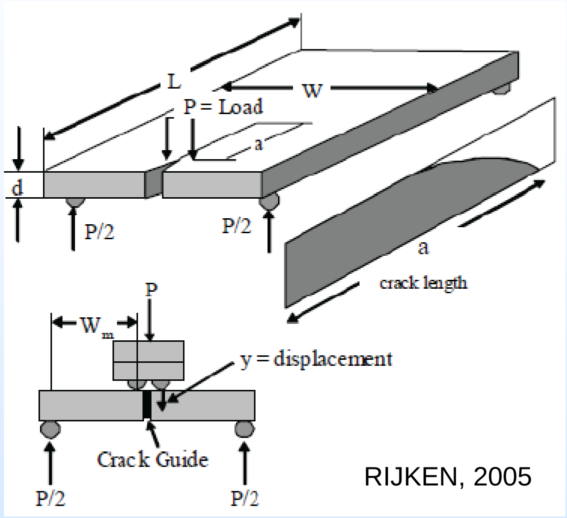
Results of subcritical crack growth affecting fracture network geometry



Holder et. al, 2001

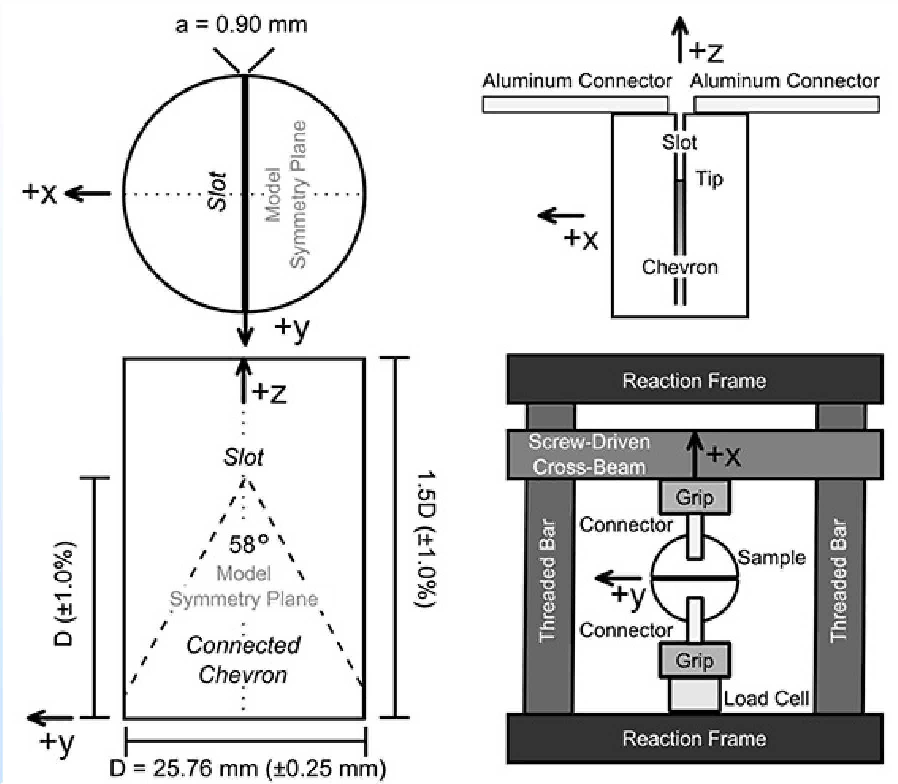
Double torsion testing geometry



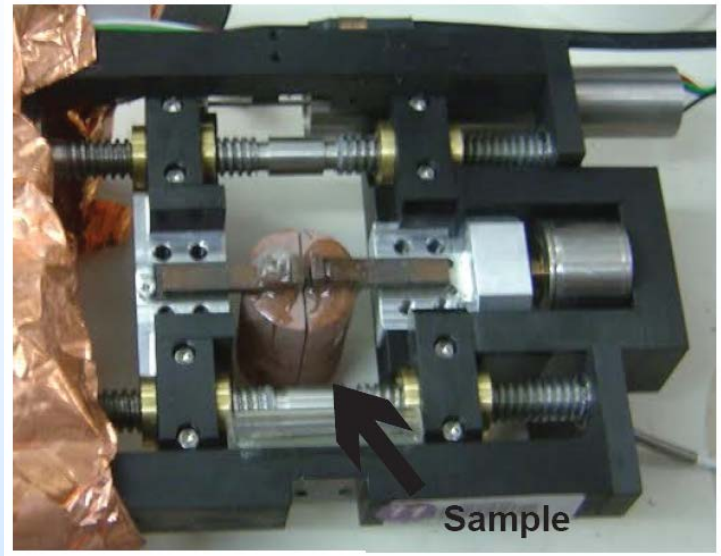


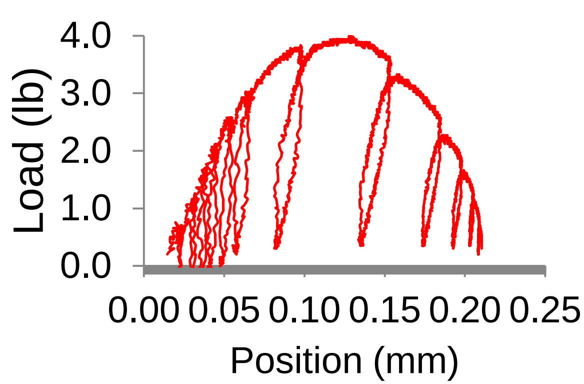
Sample geometry

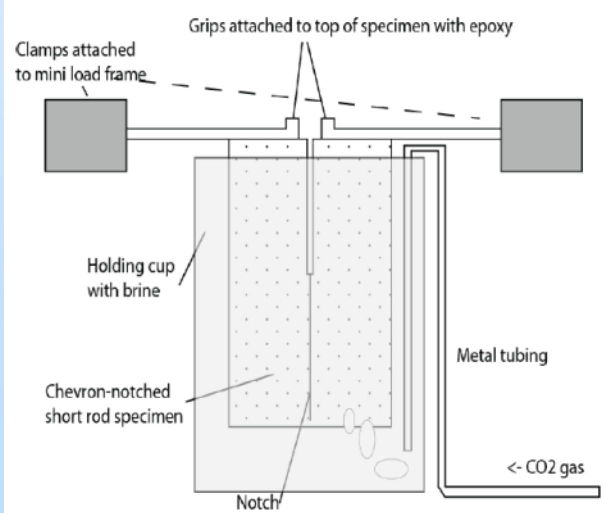
Short-rod testing geometry



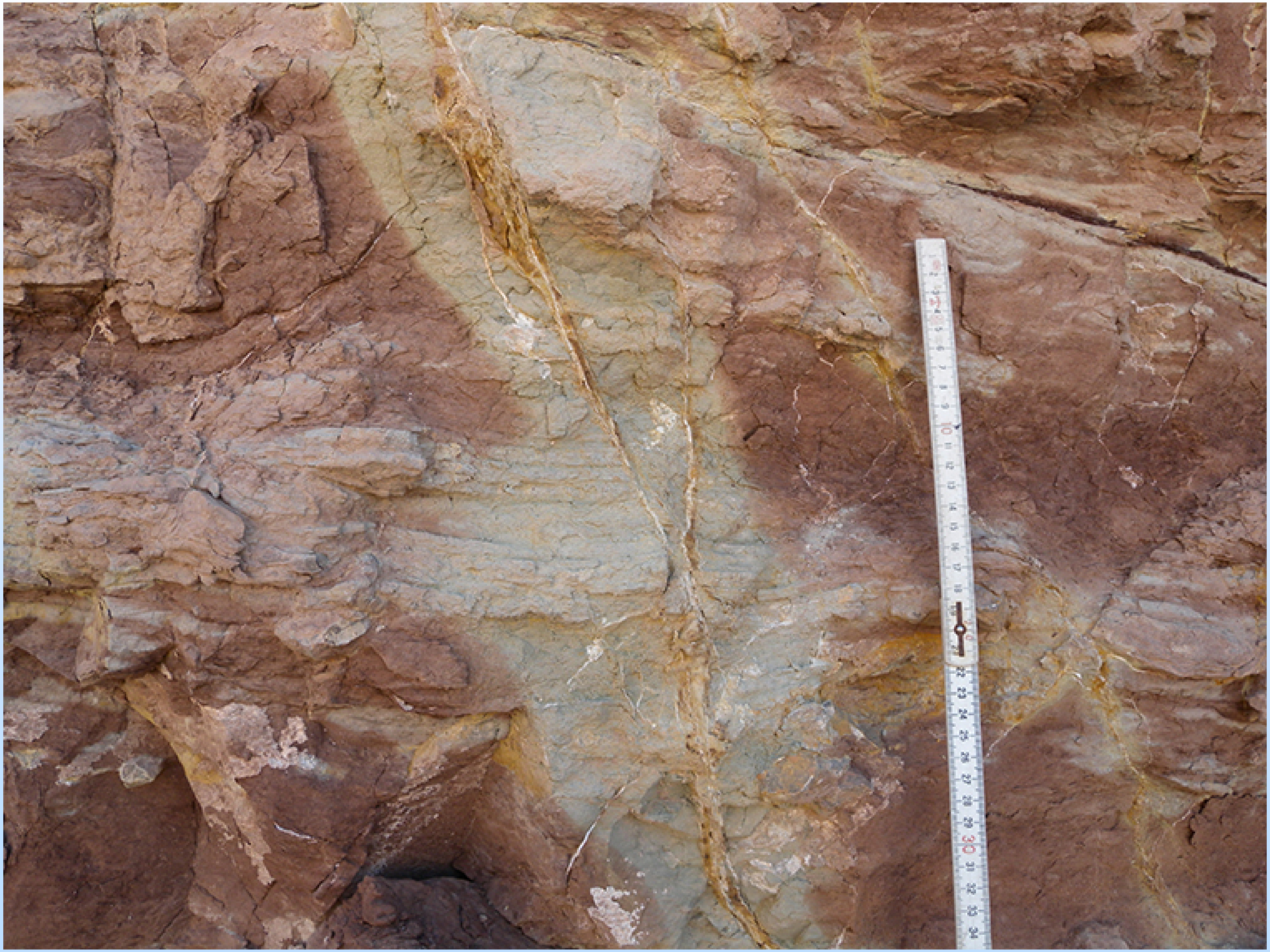
SHORT ROD (SR)





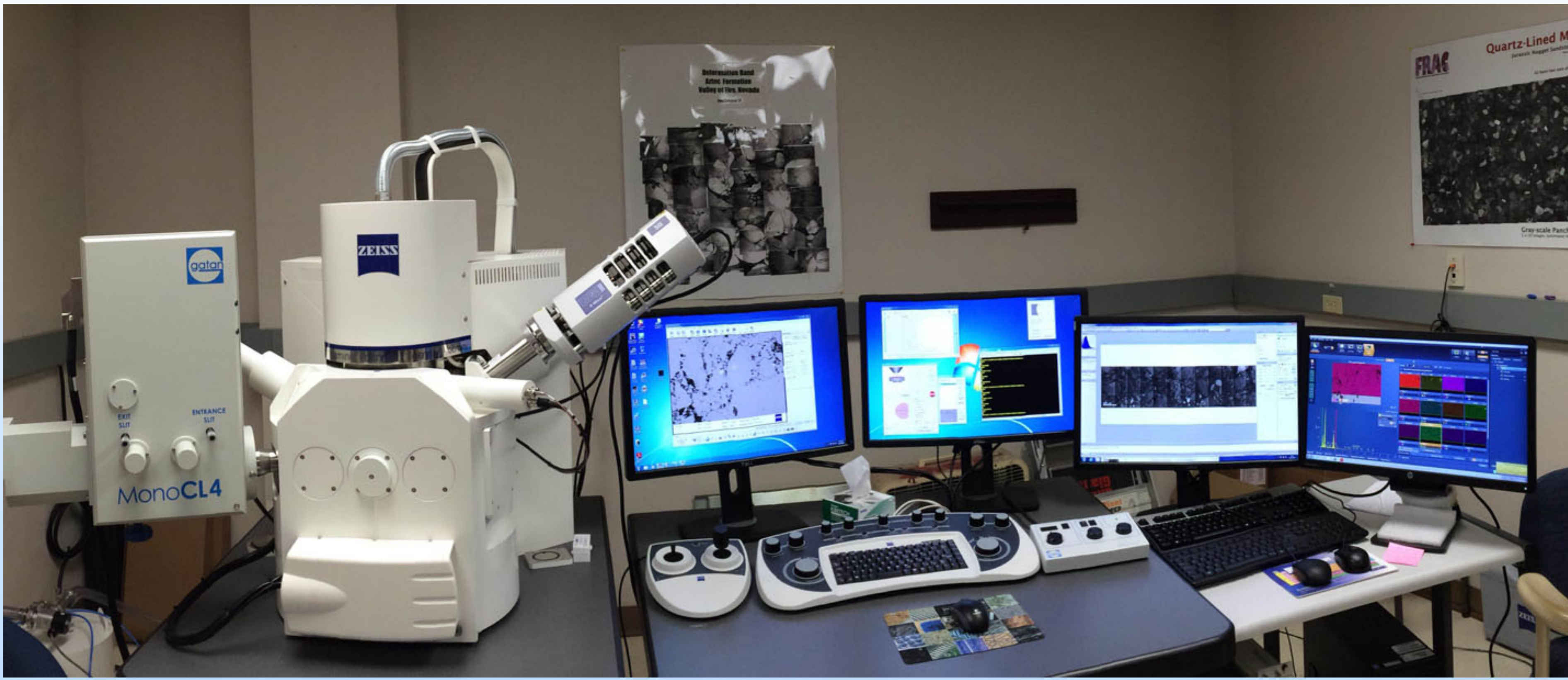


Field fracture characterization in natural CO_2 systems



Field & lab fracture imaging

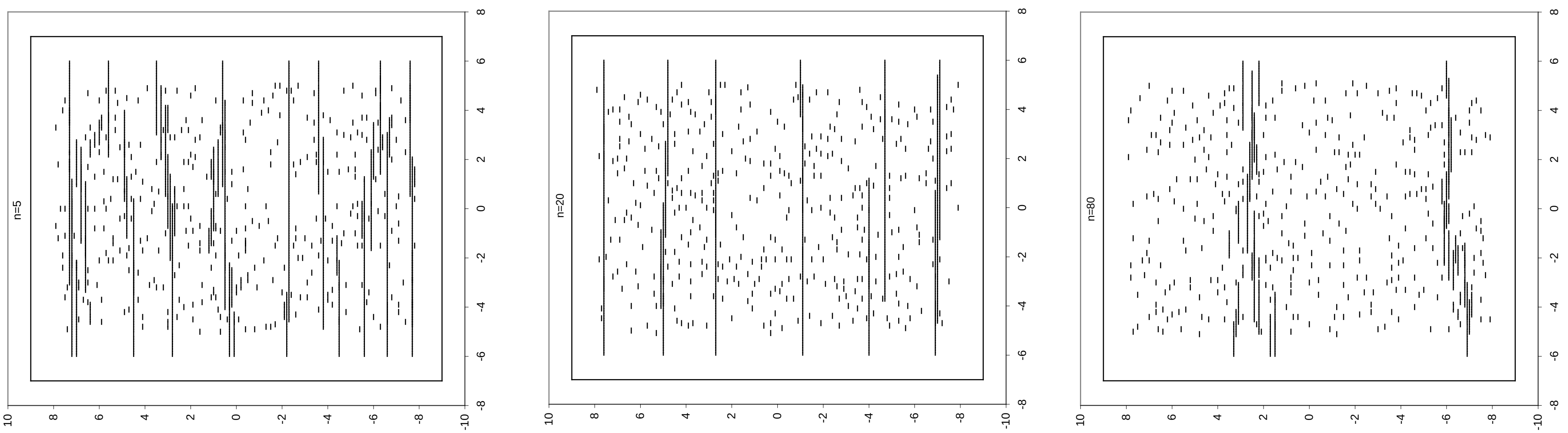
Fracture tip morphology & alteration in field & lab fracture specimens



Zeiss Sigma Field Emission SEM with Gatan MonoCL4 & Oxford EDS for large-area high-resolution textural imaging.
Installed at UT-BEG September 2014

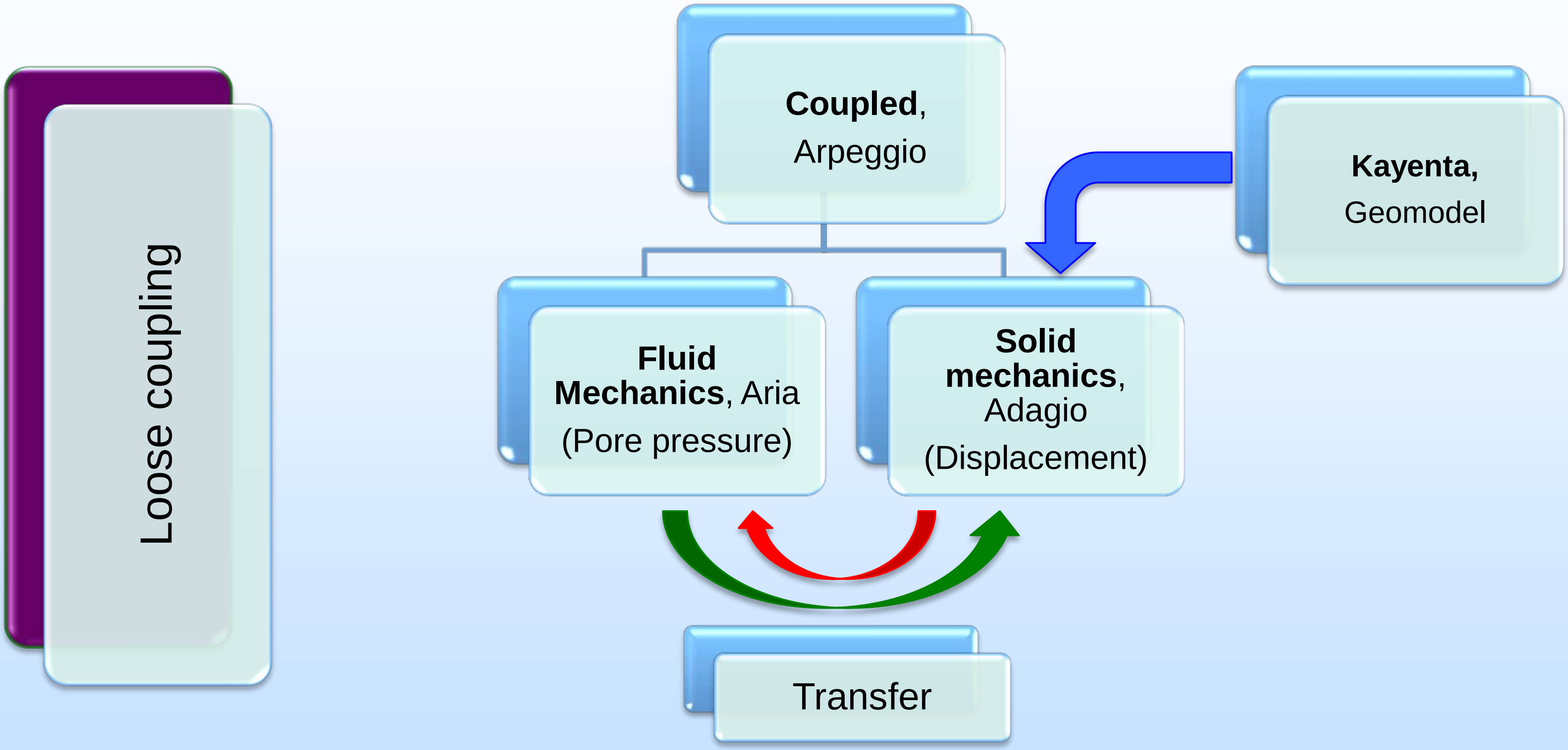
JOINTS fracture network model

- Boundary element code
- Pseudo-3D, accounts for elastic interaction
- Allows simulation of subcritical fracture propagation as function of subcritical index n



Holder et. al, 2001

Sierra Mechanics

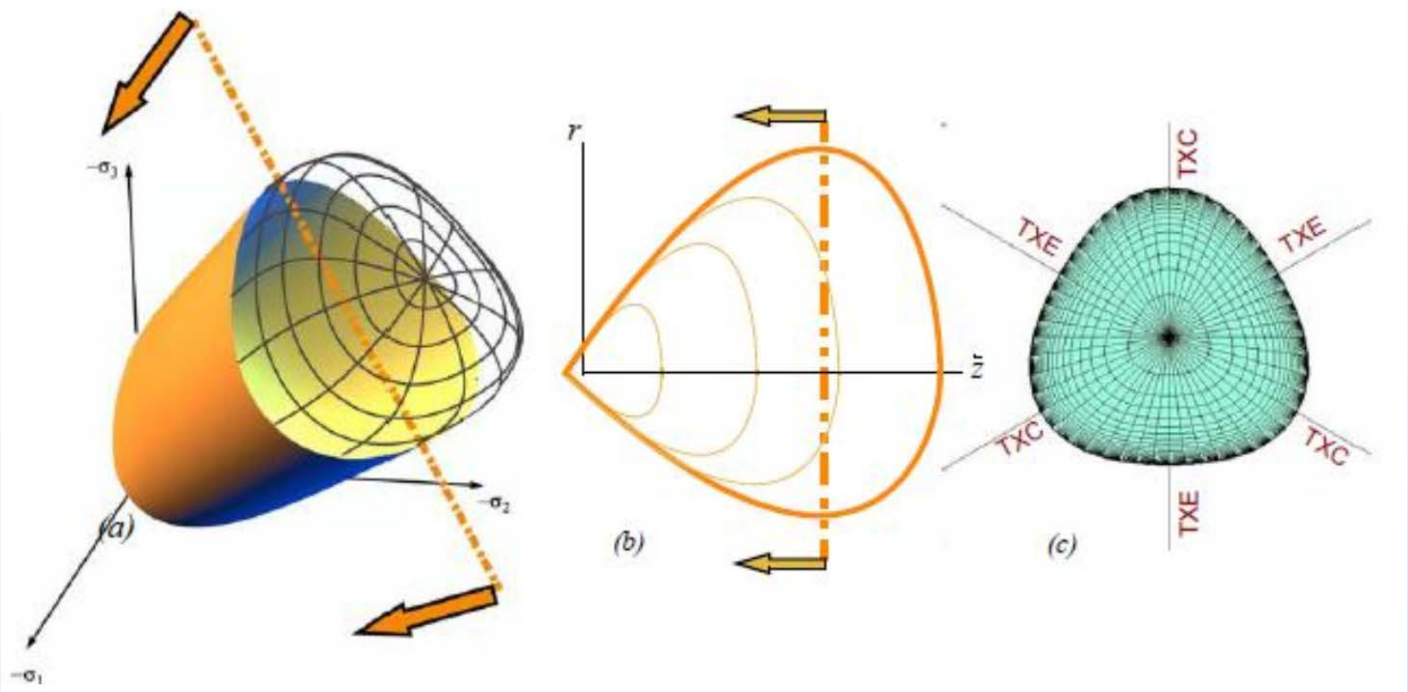


Aria: Galerkin FE program for coupled-physics problems described by systems of coupled PDEs
Adagio: 3-D, implicit, nonlinear Quasi-Statics; dynamics code
Arpeggio: Couples the Adagio, Aria, BEM, Calore and Premo Sierra Mechanics modules

Features of Kayenta

- Kayenta is a phenomenological and semi-empirical model
- 3 invariant, mixed hardening, continuous surface cap plasticity
- Pressure and shear dependent compaction of pores
- Strain-rate independent or strain-rate sensitive yield surface
- Nonlinear elasticity
- Hardening functions, which account for dilation (from microcracks) and compaction (from pore collapse)

Kayenta material model

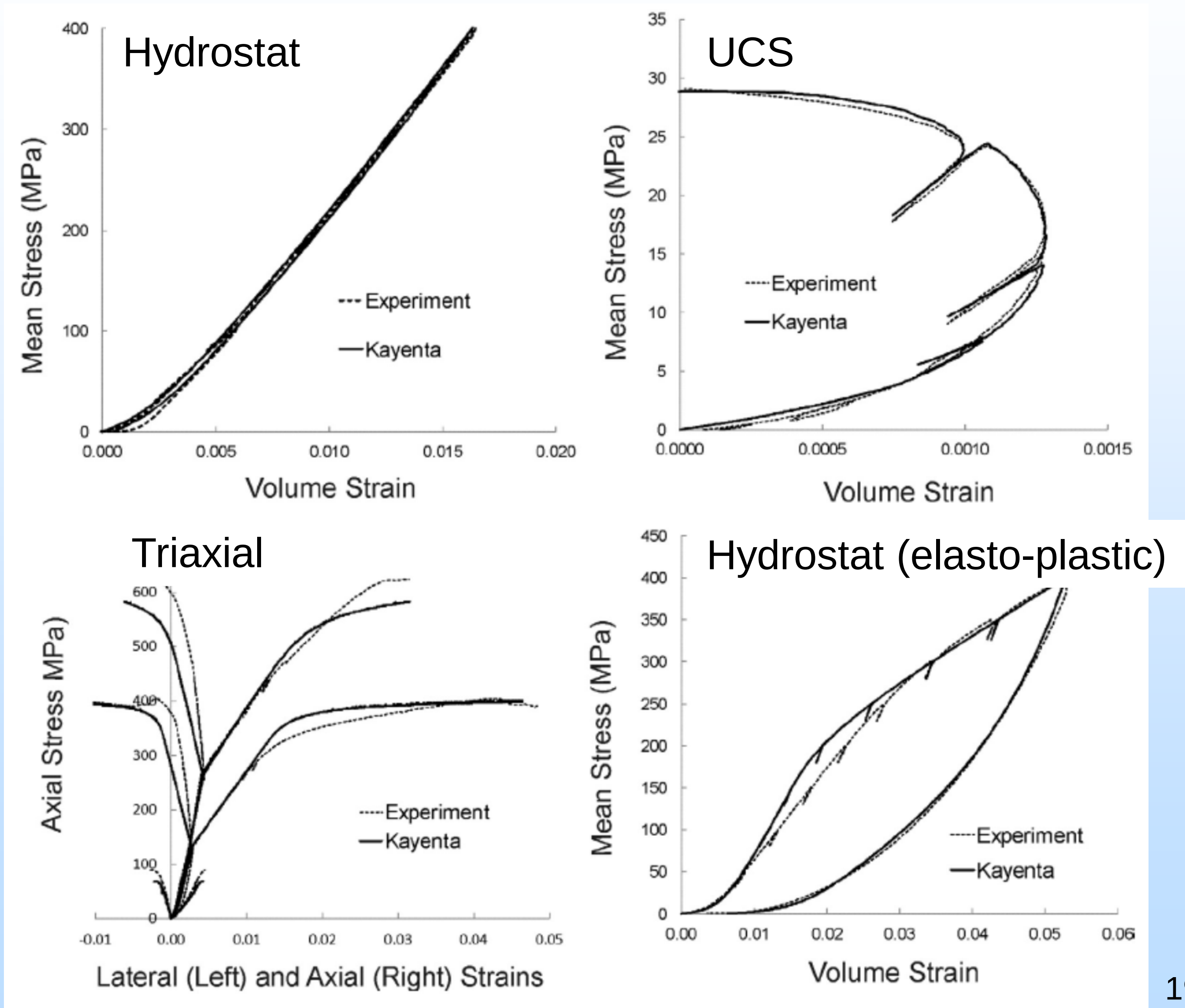


- Kayenta continuous yield surface
  - (a) 3D view: Principal stress space with the high pressure “cap”
  - (b) Side view: Using cylindrical coordinate system
  - (c) The Octahedral view: Looking down at the hydro stat

Brannon et al., 2009

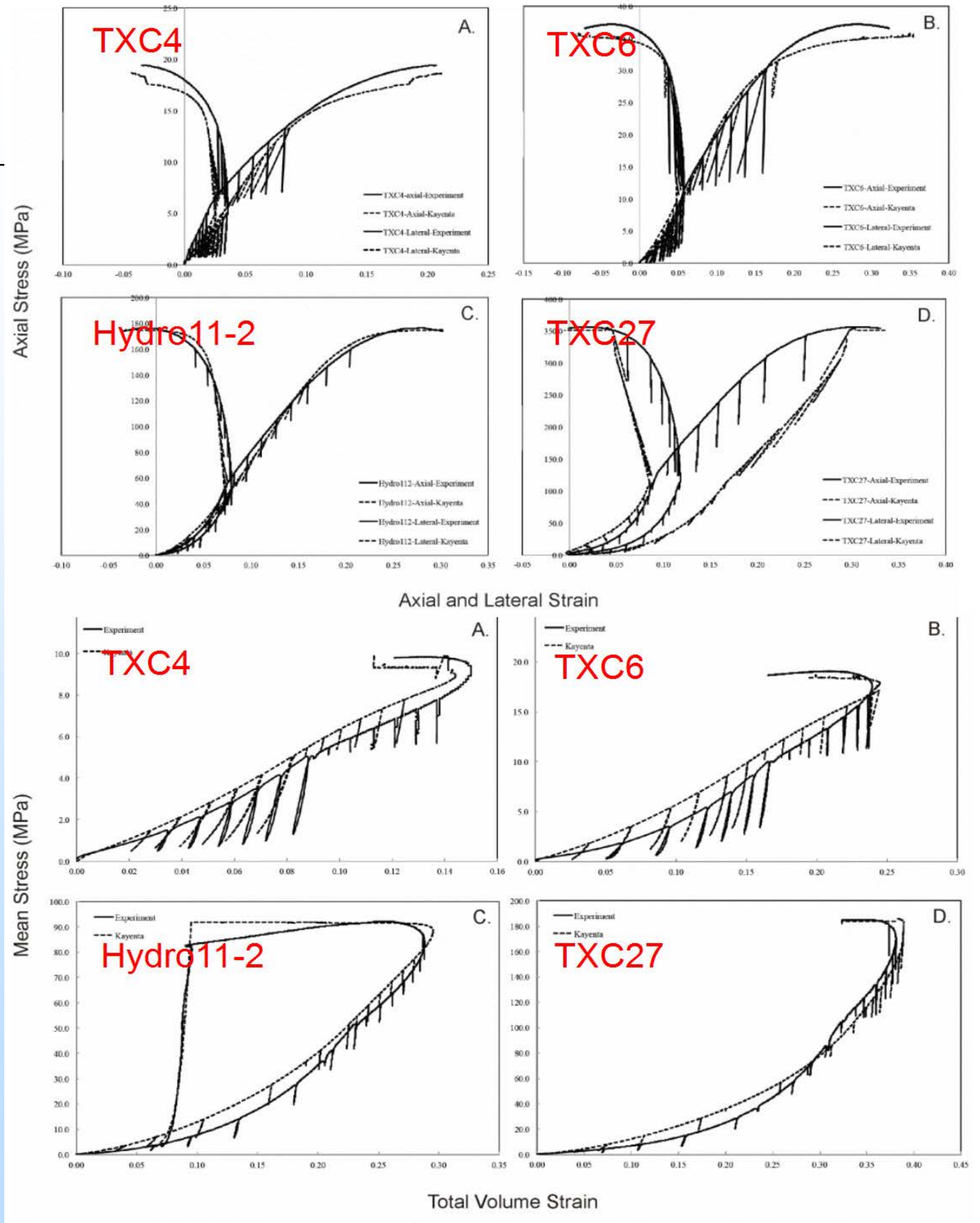
Kayenta example

Mt. Simon (Dewers et al., 2014)

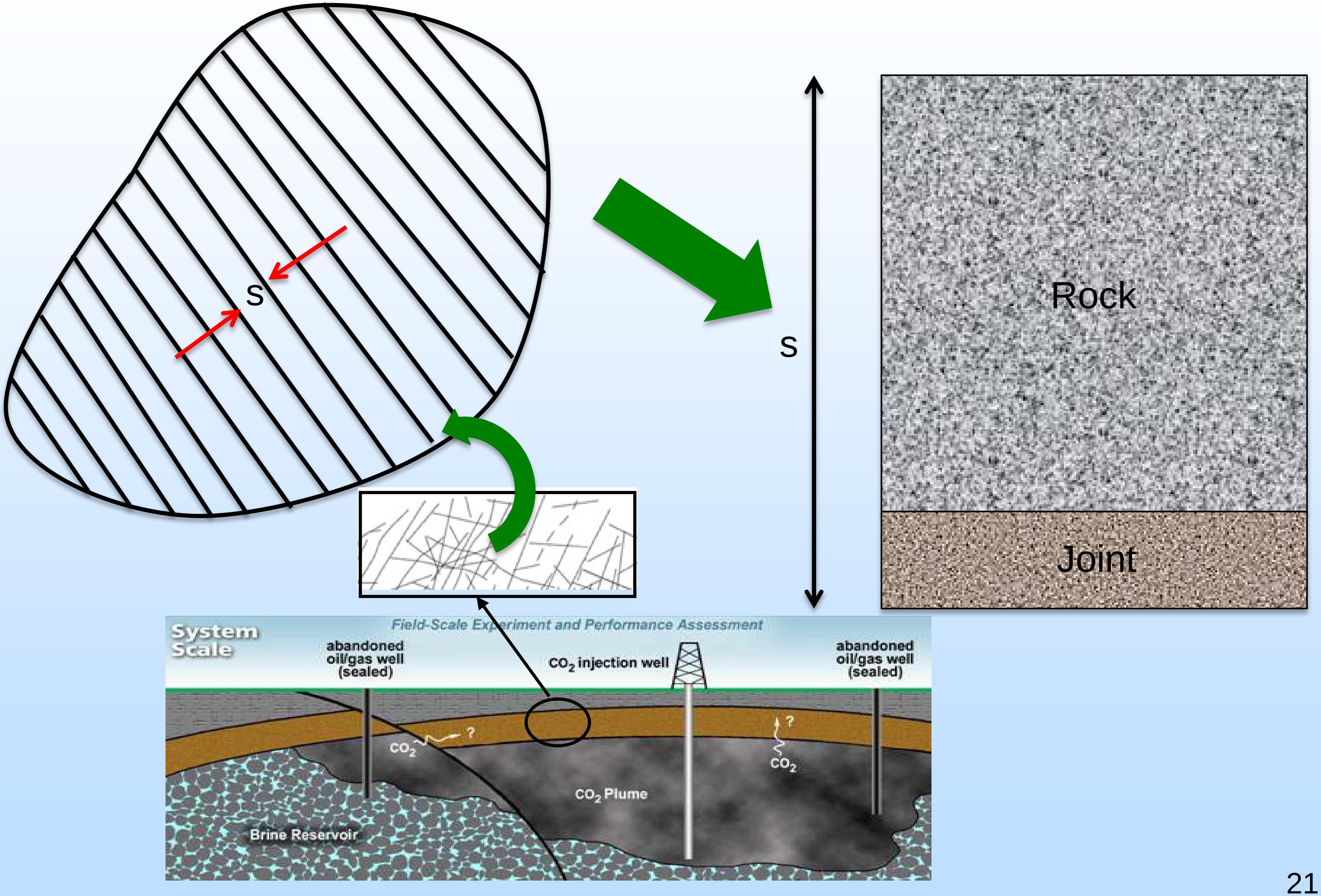


Kayenta

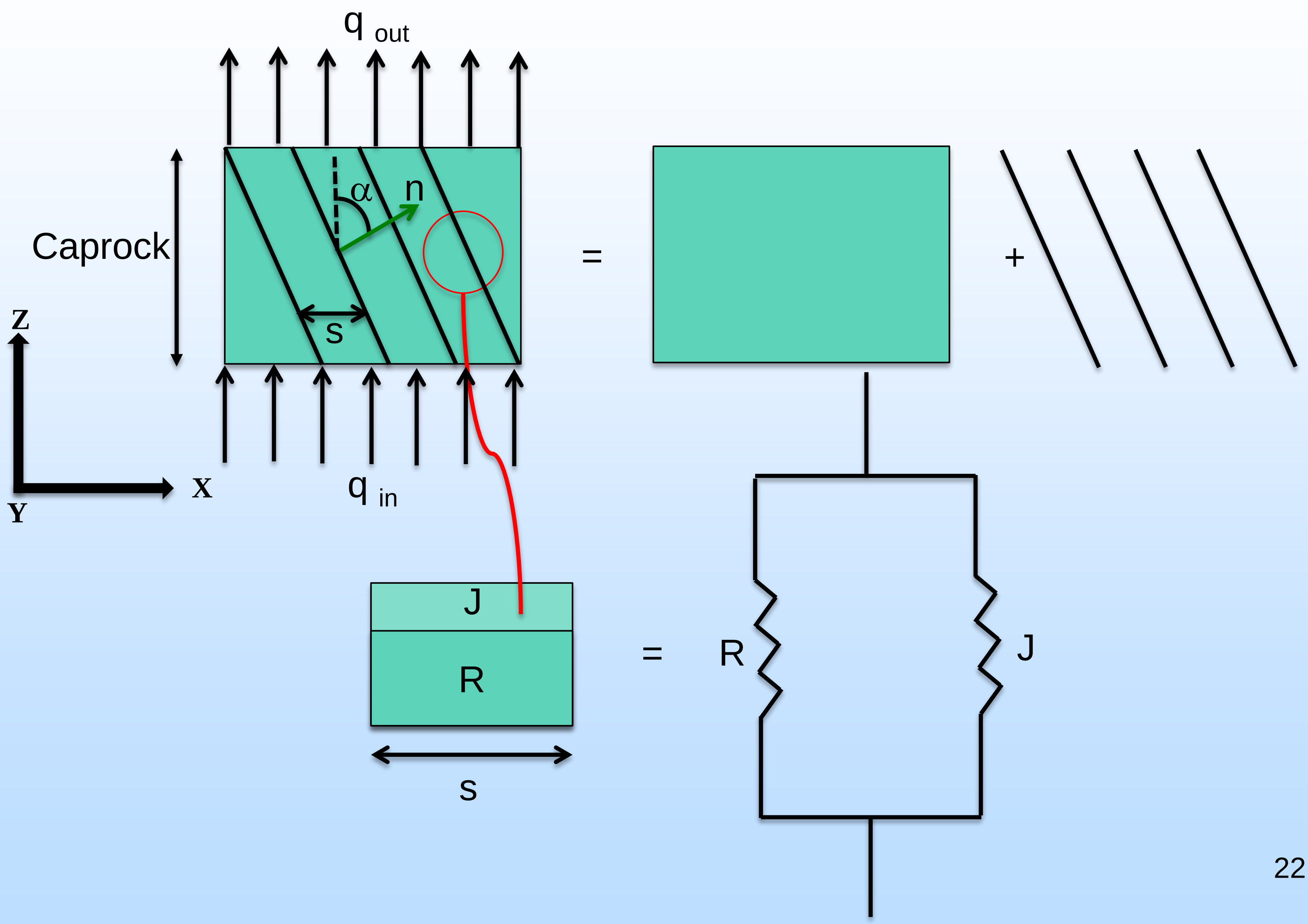
- Unconsolidated target soil impact verification
- Excellent match to the experimental data over a wide range of stress field
- Describes dilatation (microcracking) and compaction to dilatation “Turn around”



Equivalent continuum model-Geo model



Fracture modeling



Formulation

Coupling

$$K_{eff} = K_R + \sum_{J=1}^{n} K_J$$

$$n_1 = \sin\alpha \sin\beta$$

$$n_2 = \sin\alpha \cos\beta$$

$$n_3 = \cos\alpha$$

Fracture opening

$$K_J = \frac{b^3}{12d}\begin{bmatrix} 1-n_1^2 & -n_1 n_2 & -n_1 n_3 \\ -n_1 n_2 & 1-n_2^2 & -n_2 n_3 \\ -n_1 n_3 & -n_2 n_3 & 1-n_3^2 \end{bmatrix}$$

Fracture spacing

Kayenta (Geo-material model)
- Joint opening

Adagio (Solid mechanics)
- K_J

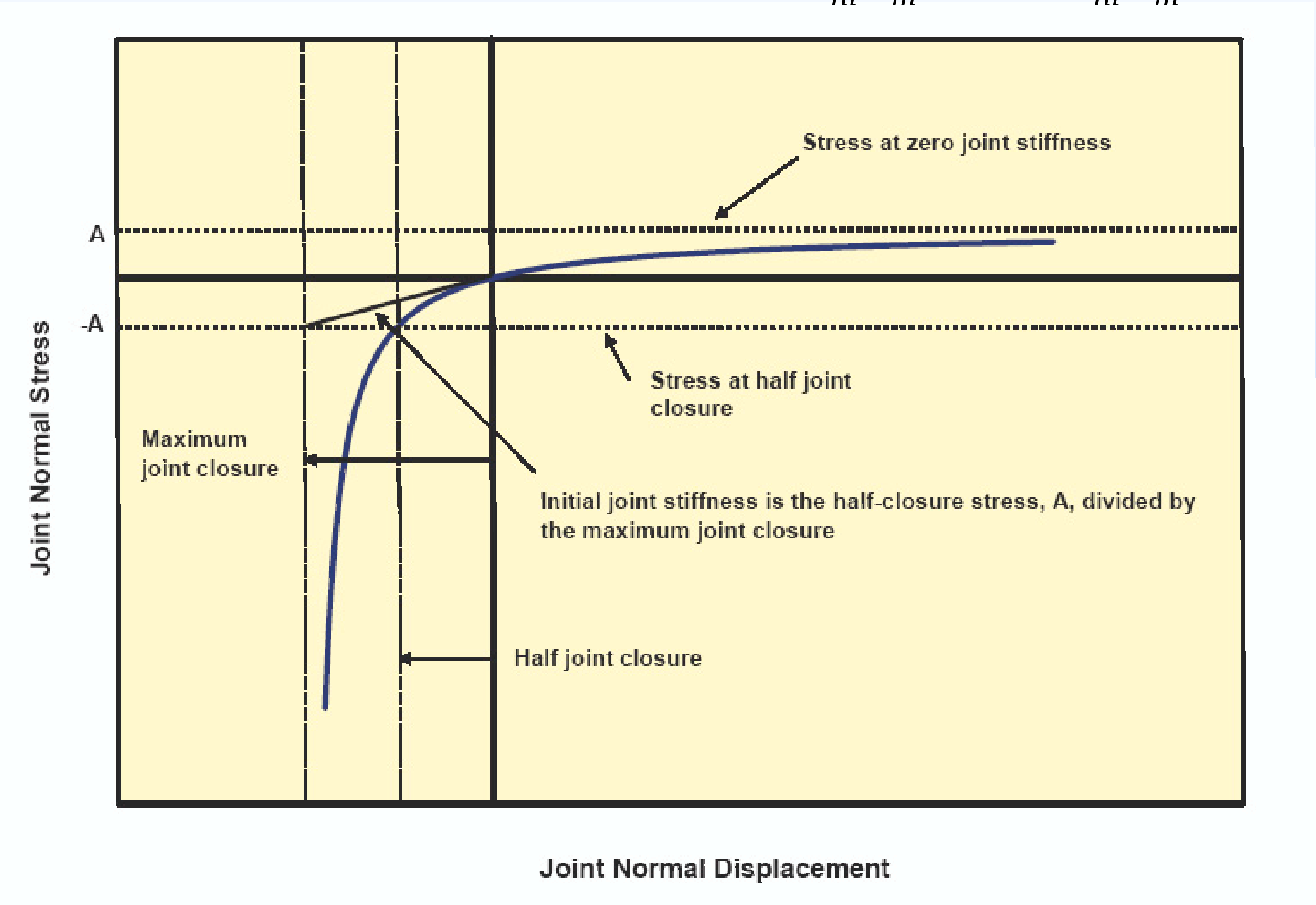
Aria (Fluid mechanics)
- K_R

Effective permeability
- K_{eff}

Formulation

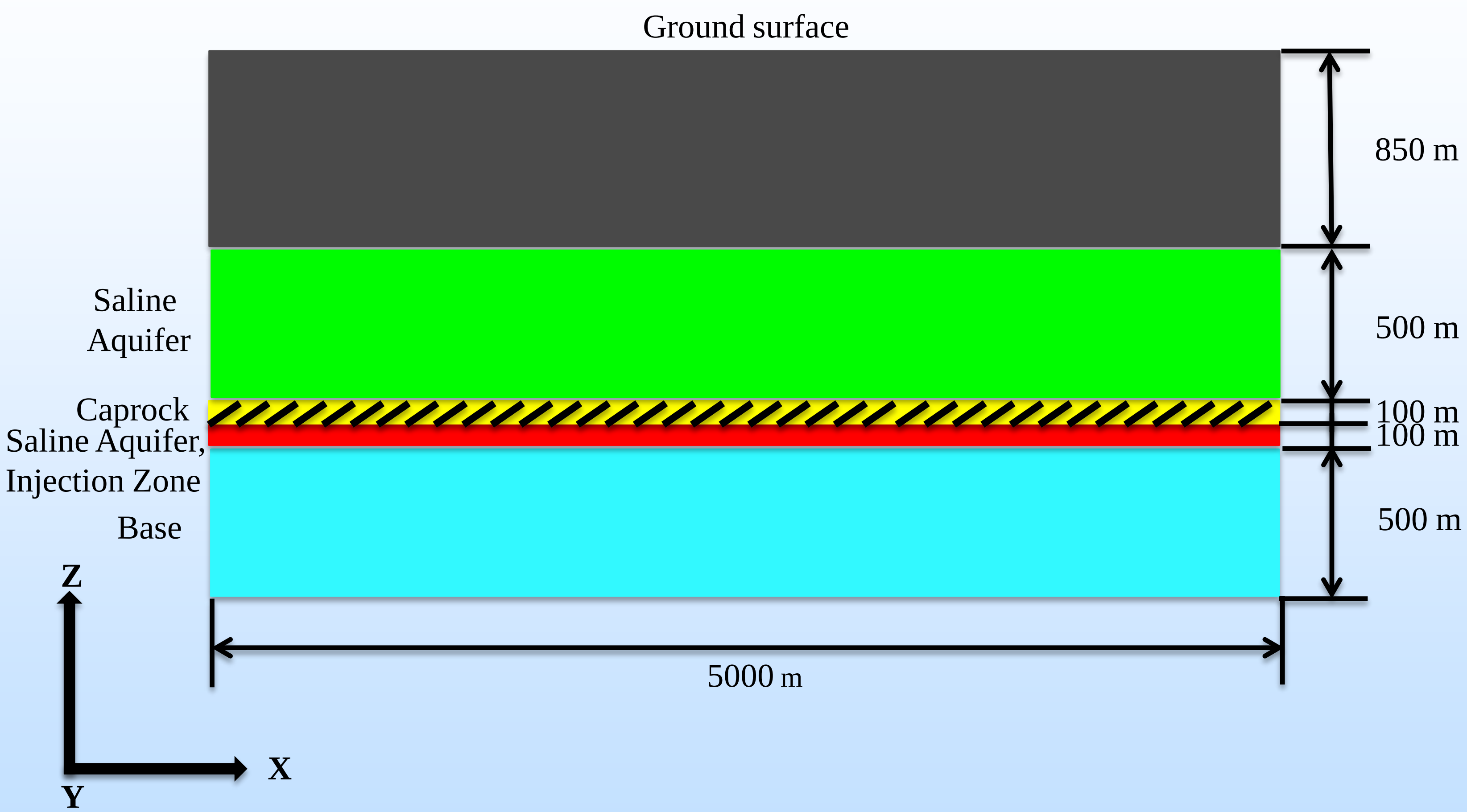
$$k_n = \frac{\partial \sigma_n}{\partial U_n} \Rightarrow k_n = k_{ni}\left(1 - \frac{\sigma_n}{k_{ni}V_m}\right)^2$$

$$b = \frac{V_m}{1 - \frac{\sigma_n}{k_{ni}V_m}} - \frac{V_m}{1 - \frac{\sigma_{ni}}{k_{ni}V_m}}$$



Brannon et al., 2009

Schematic of the fractured caprock



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 modulus	20	50	20	50	GPa
Poisson's ratio	0.2	0.12	0.2	0.12	

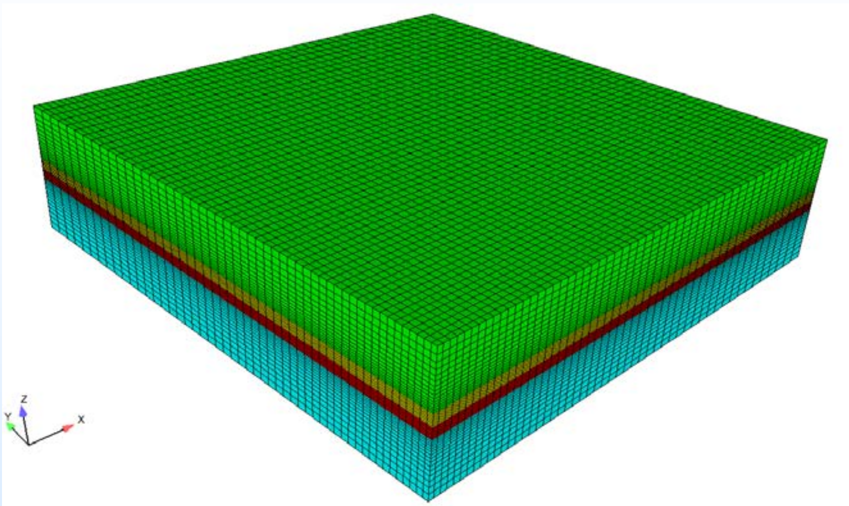
Fluid

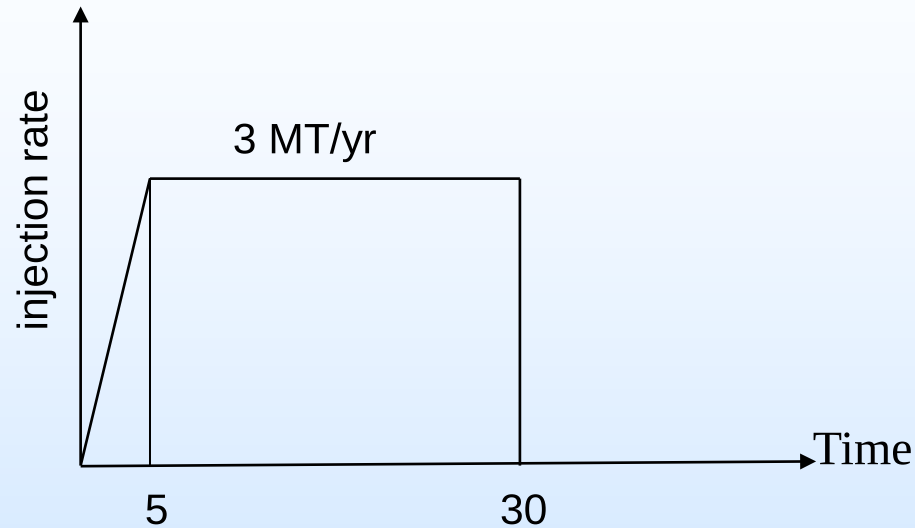
Property	Aquifer	Caprock	Injection zone	Base	Units
Initial porosity	0.15	0.05	0.15	0.10	
Intrinsic permeability	$2x10^{-14}$	$1x10^{-18}$	$2x10^{-14}$	$1x10^{-16}$	m^2

Fracture

Joint		
K_{ni} (Pa)	V_{max} (m)	S (m)
$1.5x10^{+10}$	$7.5x10^{-5}$	1.00

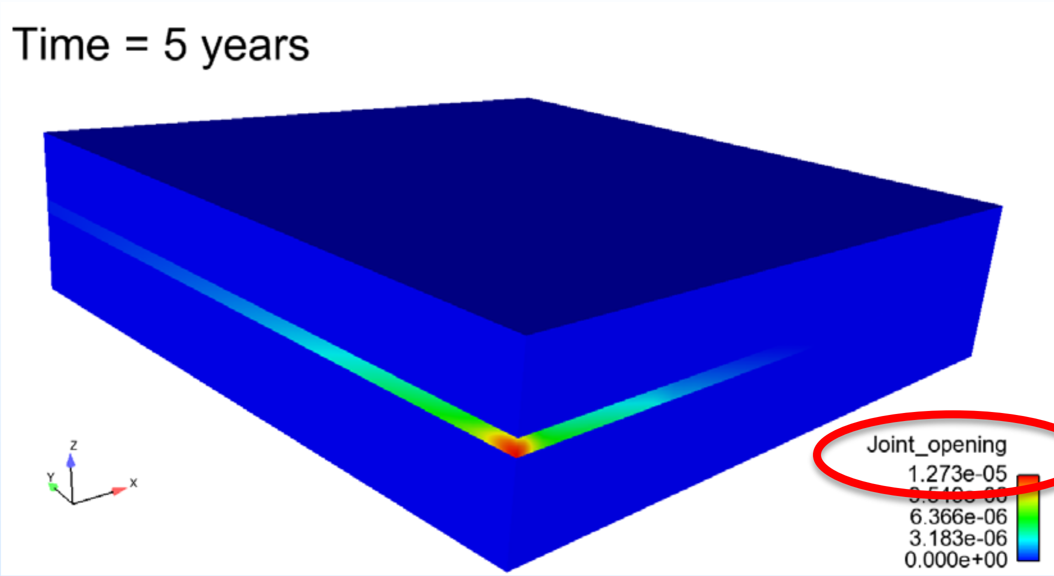
Model info



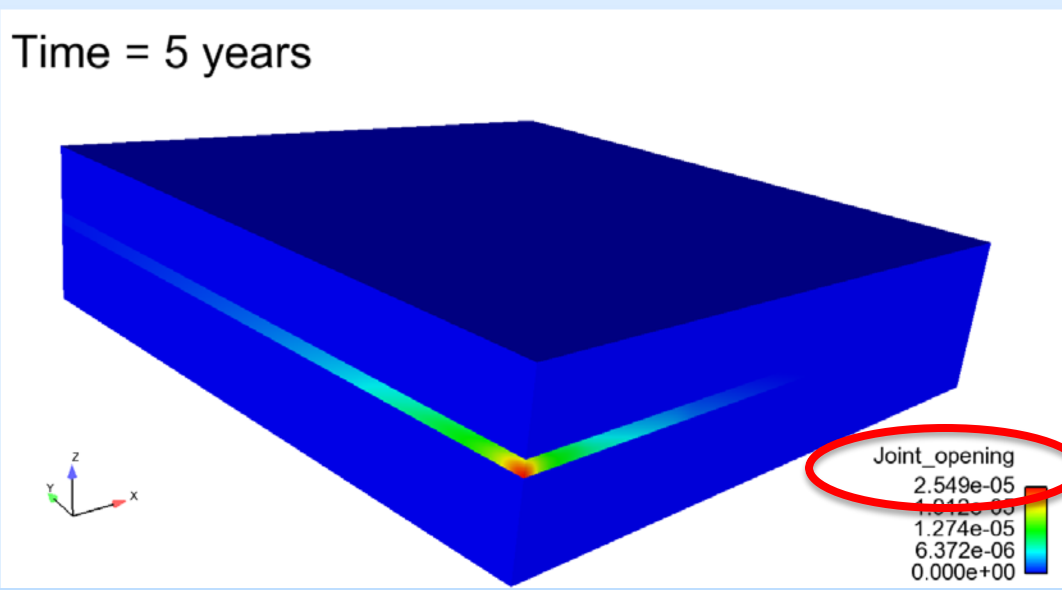


Mesh	Number of elements	Number of unknowns
1	120 K	600 K

Results

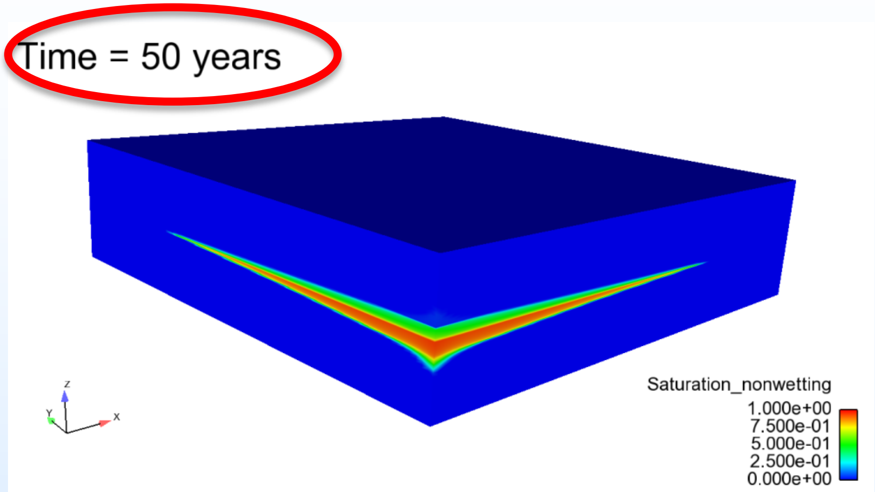


The fracture opening through top seal for case with fracture-3 Mt/yr, at 5 years of injection.

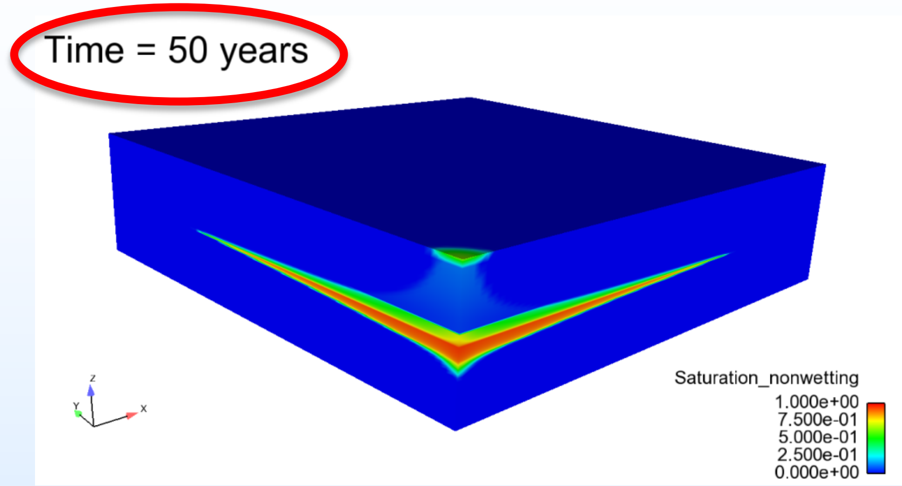


The fracture opening through caprock layer for case with joint-5 Mt/yr, at 5 years of injection.

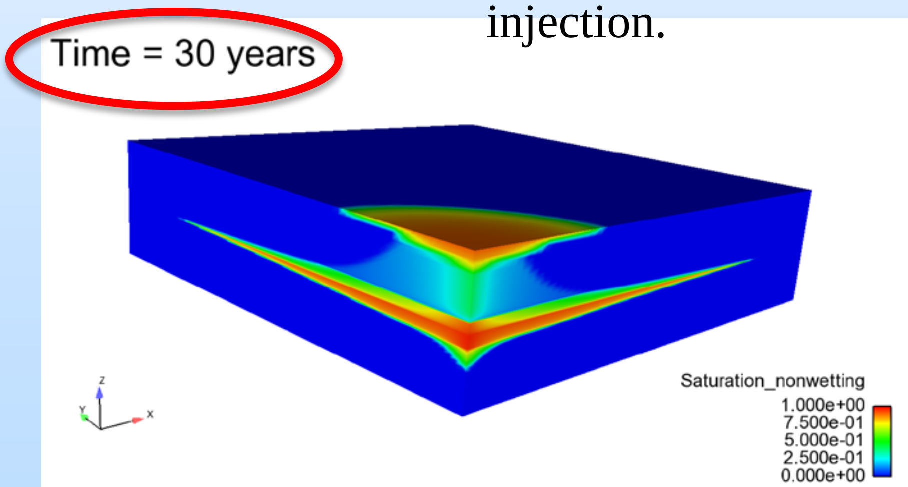
Results



The saturation of nonwetting phase for case without fracture - 3 Mt/yr, after 50 years of injection.



The saturation of nonwetting phase for case with fracture - 3 Mt/yr, after 50 years of injection.



The saturation of nonwetting phase for case with fracture - 5 Mt/yr, after 30 years of injection.

Expected Outcomes

- Quantification of chemical fluid-rock interaction on fracture processes & fracture network geometry;
  - Fundamental processes of fracture growth in chemically reactive environments
- Database of fracture toughness values & subcritical indices (variable lithology, stress loading conditions, fluid composition, temperature, pressure);
- Numerical workflow designed to assess caprock leakage of CO_2 as a function of stress loading conditions, rock fracture mechanics properties, and fluid chemical conditions;
- Proposed strategies for field implementation of this numerical workflow into leakage risk analysis by top seal failure in CCUS.

Success criteria

- Accuracy and precision of the rock fracture mechanics measurements to be performed.
- Ability of linking novel laboratory experiments on critical and subcritical fracture growth in CO_2 crack tip chemical environments, with state-of-the-art modeling efforts.
- Ability of including lab and field observations into upscaled models for inclusion in reservoir-scale modeling codes in terms of constitutive response and hydrological consequences of fracture development.
- Ability to cast results as a portion of a probabilistic risk assessment, which we expect to emerge as a critical tool to be used by operators and regulatory agencies.

Organization Chart/ Communication Plan

Peter Eichhubl
UT BEG

Pania Newell
Sandia

Tom Dewers
Sandia

Jon Olson
UT PGE

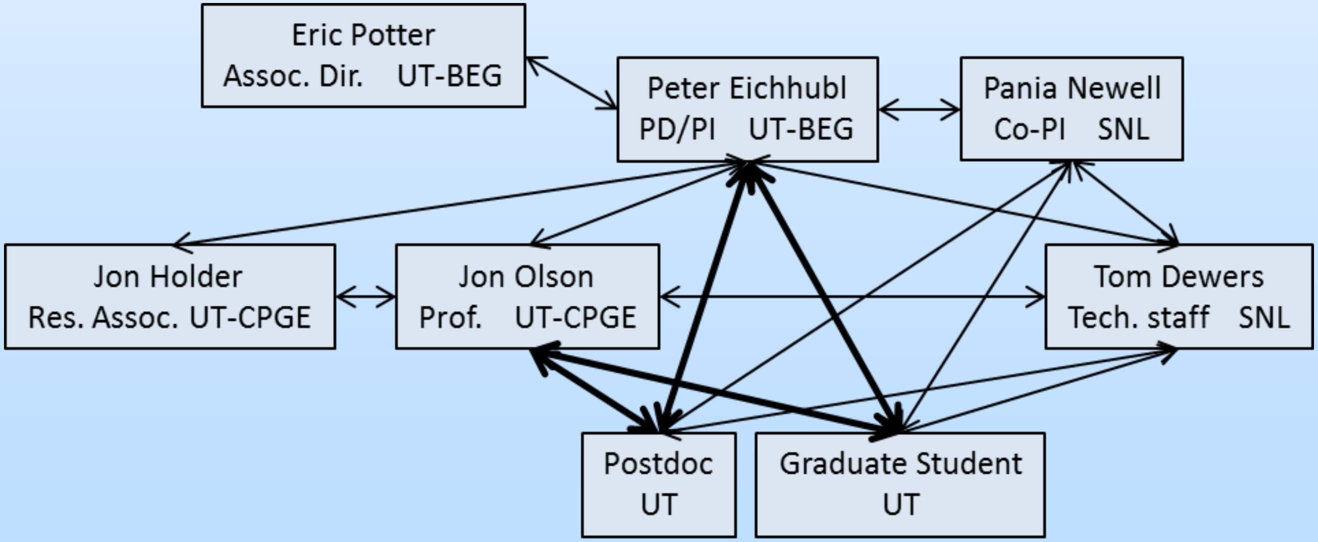
Jon Holder
UT PGE

Owen
Callahan
UT BEG

Postdoc TBA
UT BEG

Organization Chart/ Communication Plan

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



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

Deliverables

- Database of fracture toughness values & subcritical indices (variable lithology, stress loading conditions, fluid composition, temperature, pressure);
- Numerical workflow designed to assess caprock leakage of CO_2 as a function of stress loading conditions, rock fracture mechanics properties, and fluid chemical conditions;
- Proposed strategies for field implementation of this numerical workflow into leakage risk analysis by top seal failure in CCUS;
- Final report, publications, and presentations at conferences;
- Numerical data in NETL Energy Data eXchange.

Milestones

- Continuation to Budget Period 2 is contingent on verified completion of at least 10 fracture growth experiments.
- Continuation to Budget Period 3 is contingent on verified completion of Task 2.
- Continuation to Budget Period 2 is contingent on verified completion of at least 1 sampling trip from which a required number of viable samples are obtained for initiating characterization of field fractures (subtask 3.1) and textural and compositional fracture imaging (subtask 3.2).

Risk Matrix

- Technical difficulties
  - Equipment: experienced staff, established testing routines
  - Sample specific, e.g. problems with sample preparation: problems anticipated, taken into consideration during sample selection; staff experience dealing with geomaterials
- Resource availability
  - Lab and modeling resources in place; use of existing numerical code
- Environmental, health, or safety: established protocols for risk minimization
- Site access for field work: locations & access identified
- Management issues: experienced team with established research collaboration & communication
- Research outcomes: intrinsic to study of natural systems
  - Variability of testing and field outcomes too large: narrow scope of models in scale/time
  - Unanticipated physics of fracture growth: simplify physics in numerical models, “all models are wrong”

Proposed Schedule

Task/Subtask	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. Project Management and Planning	■	■	■	■	■	■	■	■	■	■	■	■
2.1. Short rod fracture toughness tests	■	■	■	■	■	■	■	■				
2.2. Double torsion tests	■	■	■	■	■	■	■	■				
2.3. Fracturing in water-bearing supercritical CO2					■	■	■	■				
3.1. Field fracture characterization	■	■	■	■	■	■	■	■				
3.2. Textural and compositional fracture imaging	■	■	■	■	■	■	■	■	■	■		
4.1. Discrete fracture modeling using Sierra Mechanics	■	■	■	■	■	■	■	■	■	■	■	
4.2. Fracture network modeling using JOINTS	■	■	■	■	■	■	■	■	■	■	■	
4.3. Upscaled modeling using Kayenta					■	■	■	■				
5. Model validation and integration					■	■	■	■	■	■	■	■

Summary

- Derive predictive and validated numerical models for fracture growth in chemically reactive environments relevant to CCUS top seal lithologies.
- Multidisciplinary approach toward top seal integrity analysis, combining
  - fracture mechanics testing,
  - natural fracture characterization, and
  - fracture modeling.
- Validation of numerical models against lab and field observations.