Area of Interest 2, Geomechanics of CO_2 Reservoir Seals

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Carbon Storage and Oil and Natural Gas Technologies Review Meeting
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Presentation Outline

- Benefit
- Problem Statement
- Project Overview
- 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.*

Problem Statement

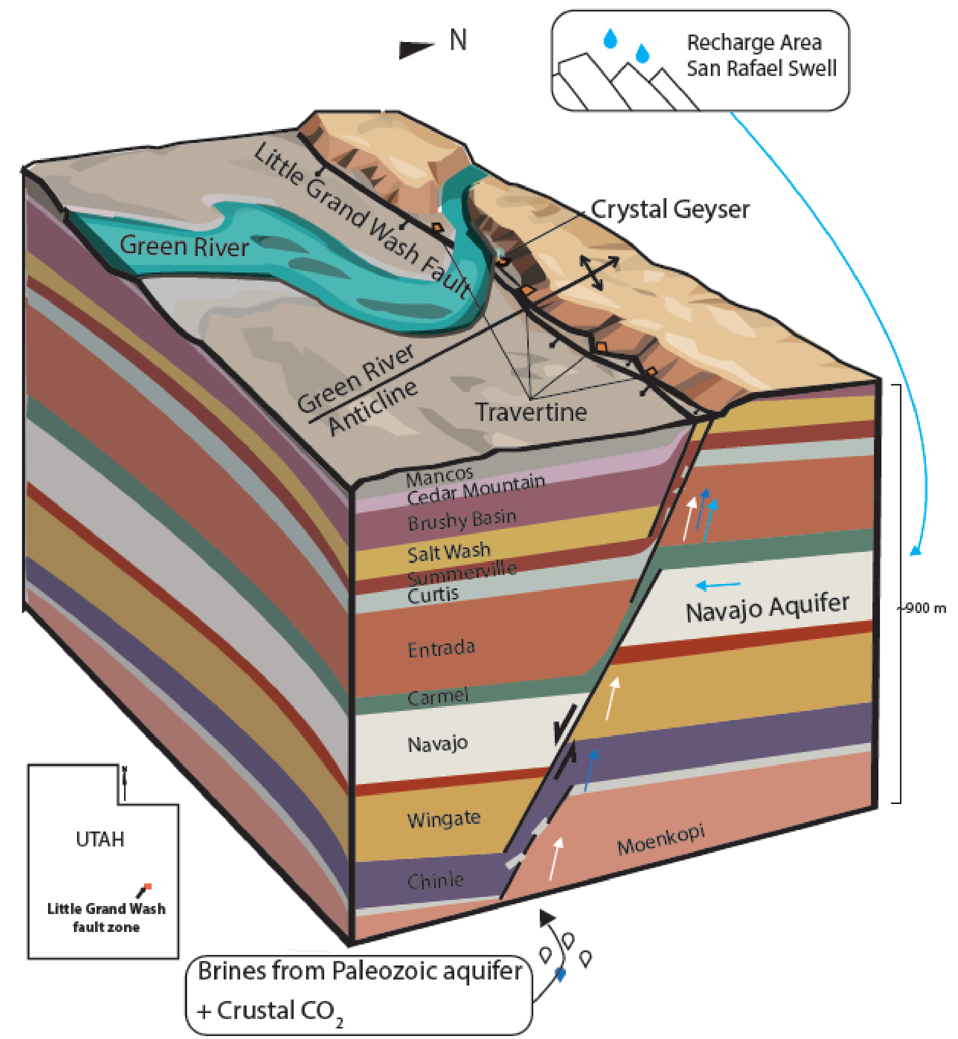
- Sealing efficiency of CO_2 reservoirs has to exceed 99%.
- Design criteria are needed that establish the long term sealing capacity of CO_2 reservoirs and to model leakage risk.
- Top and fault seal risk assessment well established in oil & gas exploration, but:
- $scCO_2$ and CO_2 brine potentially interact *physically & chemically* with top seal.
- Seal risk assessment criteria taking these interactions into account are needed for CO_2 systems.

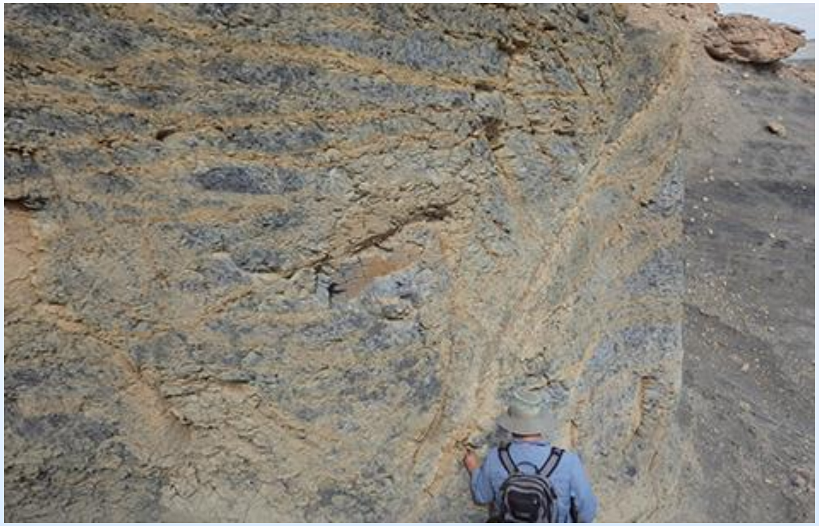
Project Overview: Goals and Objectives

- ***Perform laboratory fracture mechanics testing*** to
  - gain fundamental understanding into fracture processes in chemically reactive systems and 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.
- ***Derive predictive and validated numerical models*** for fracture growth in chemically reactive environments relevant to CCUS top seal lithologies.
- ***Validate*** numerical & laboratory observations **against microstructural and textural observations** on fractures from natural CO_2 seeps.
- ***Perform upscaled 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.

Fractures in CO_2 caprocks

Crystal Geyser field analog site



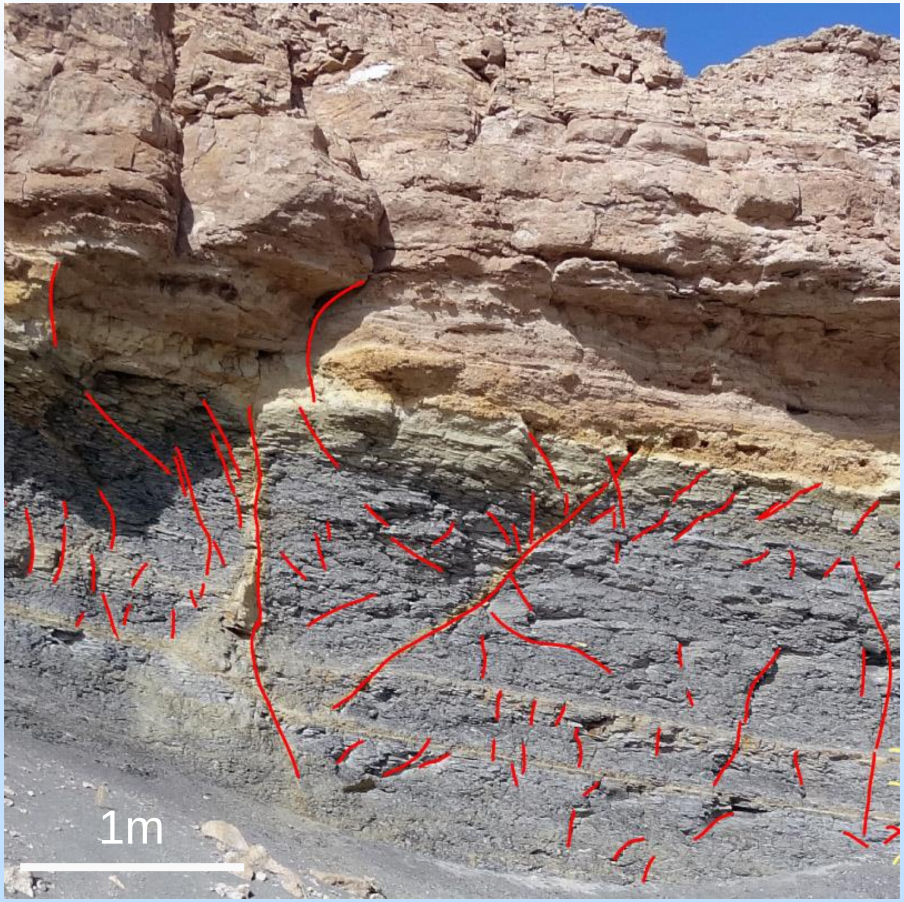


Active on 10^2 - 10^5 year time scales

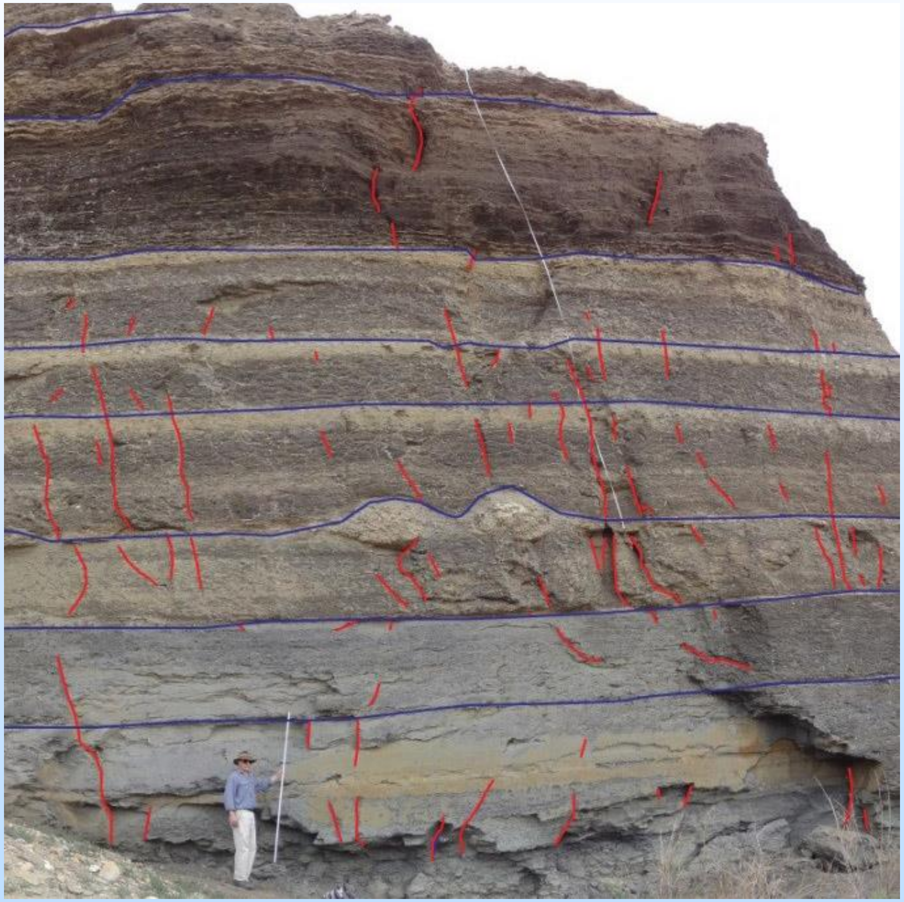
Natural fracture networks

Mancos Shale at Crystal Geyser

10 m from CO_2 conduit



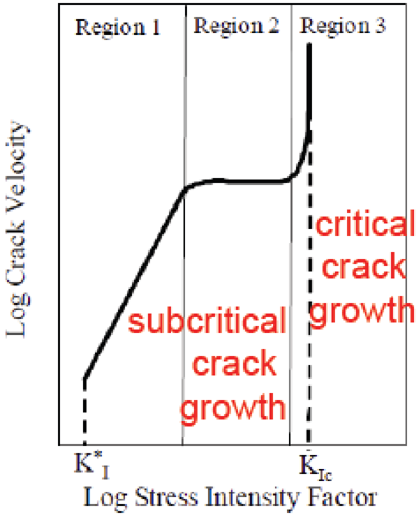
> 300 m away from CO_2 conduit



Methodology

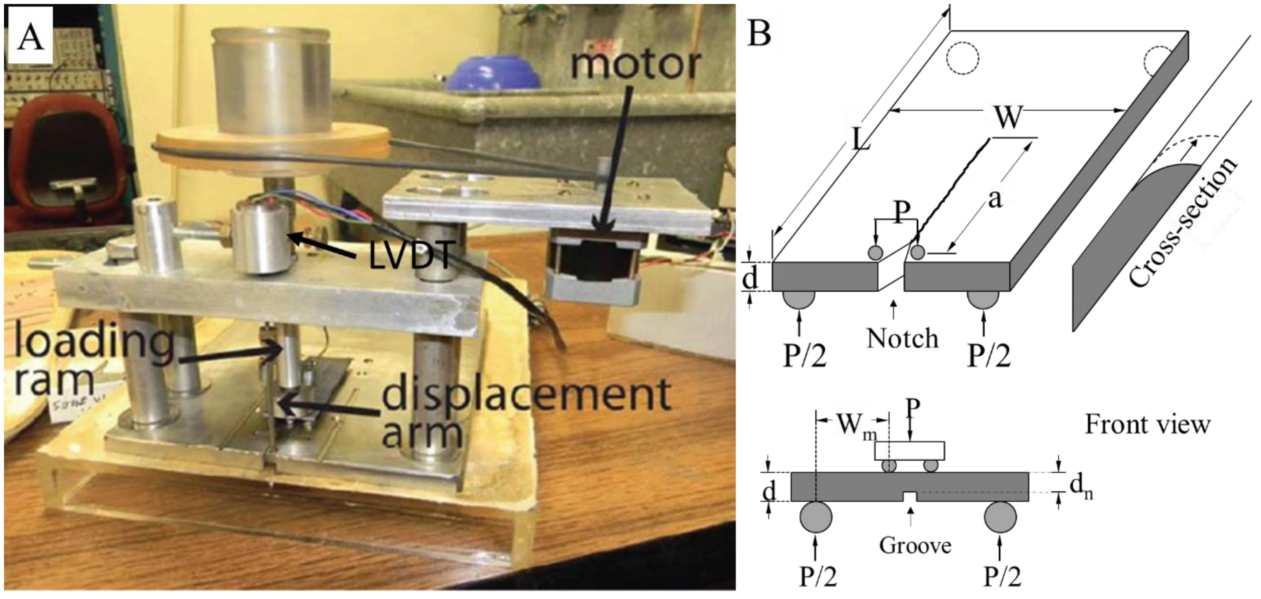
- Experimental measurement of subcritical fracture propagation in various shale lithologies
  - Double torsion test, unconfined conditions
  - Short-rod test, confined conditions (scCO_2)
- Textural and compositional characterization
  - Shale material used for fracture testing
  - Fractures & CO_2 alteration in natural systems
  - Post-mortem analysis of lab test specimens
- Numerical modeling of fracture propagation in top seals
  - Fracture network modeling using JOINTS
  - Upscaled modeling for top seal deformation using Sierra Mechanics

Double torsion fracture mechanics testing



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

After Atkinson, 1984



Rijken, 2005

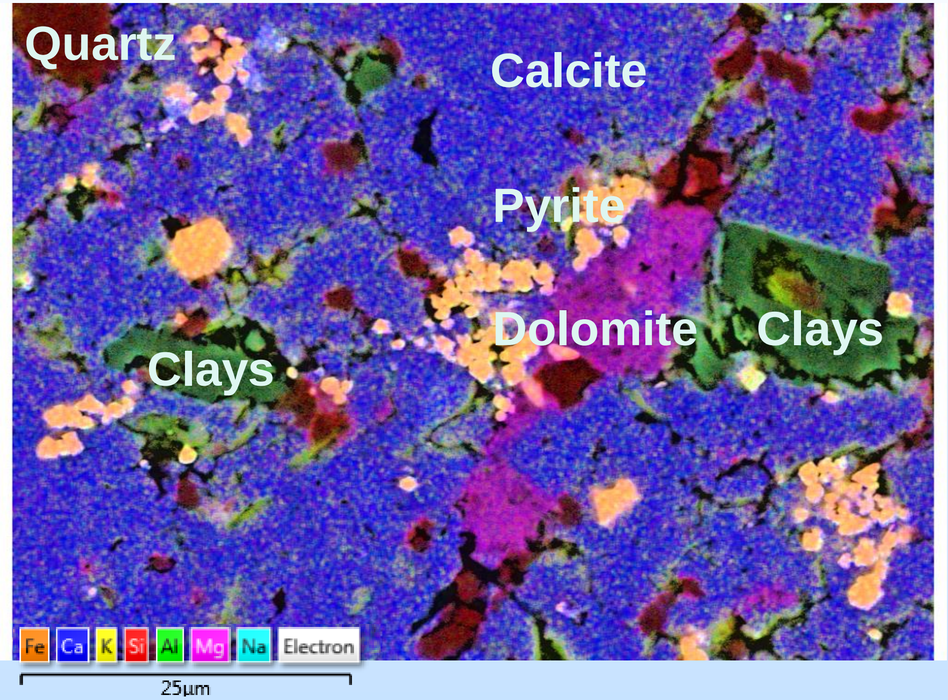
$$V = A\left(\frac{K_I}{K_{IC}}\right)^n$$

V: fracture propagation velocity
K_I: mode-I stress intensity factor
K_{IC}: mode-I fracture toughness
A: pre-exponential constant
n: velocity exponent, subcritical crack index (SCI)

Sample geometry

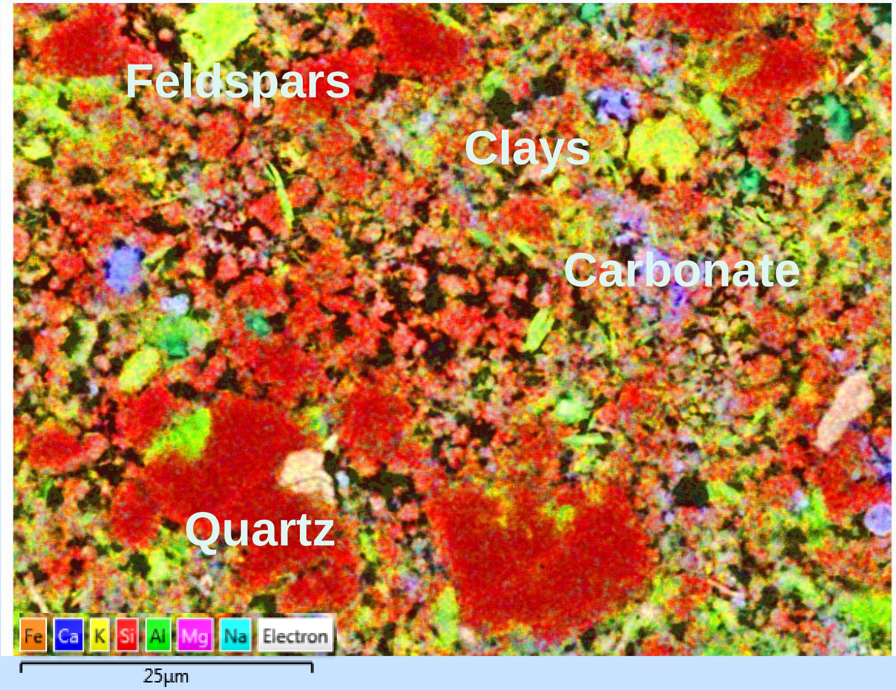
Material characterization

Marcellus Shale (carbonate-rich)



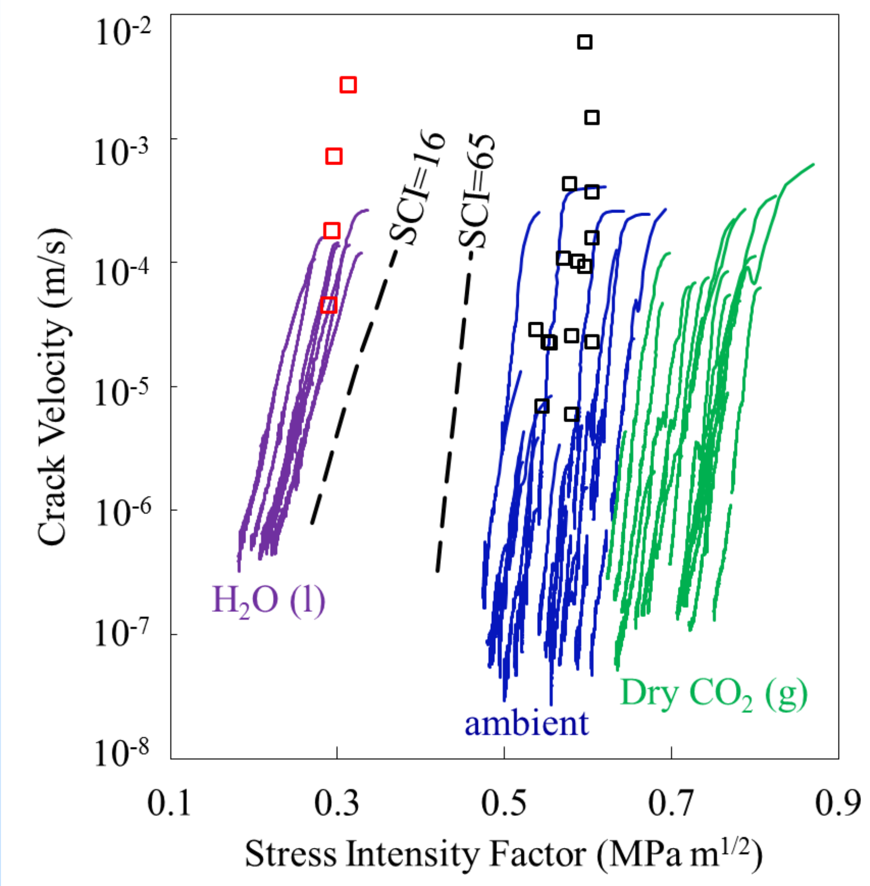
- Carbonate & clay
- Minor amounts of quartz and pyrite

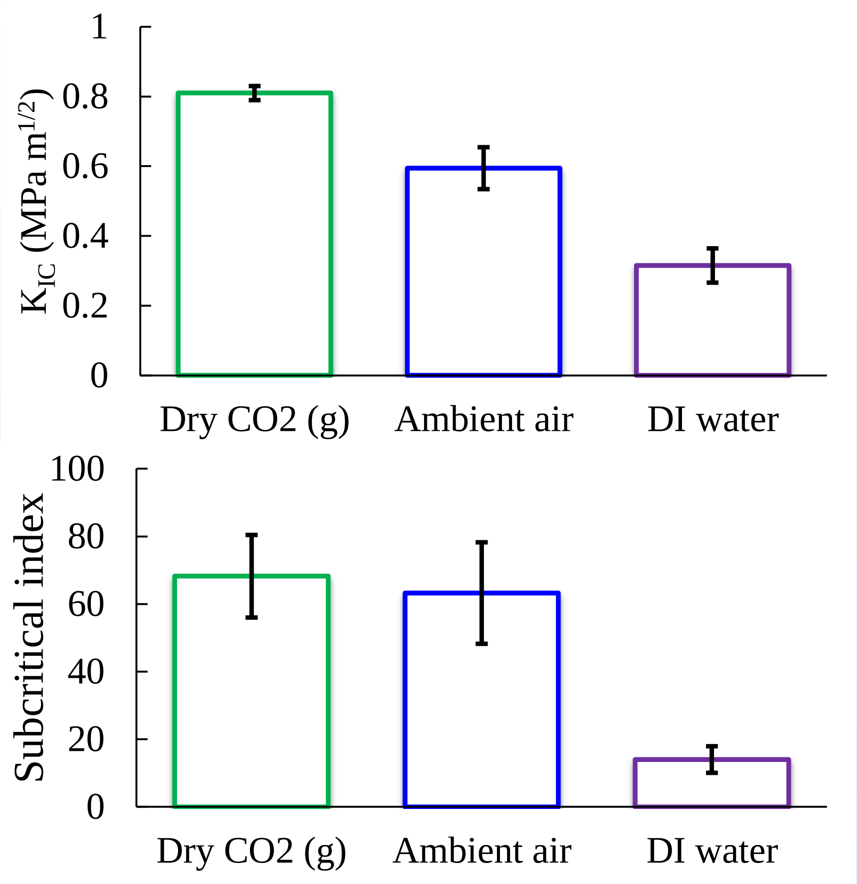
Woodford Shale



- Quartz & clay
- Minor amounts of carbonate and feldspar

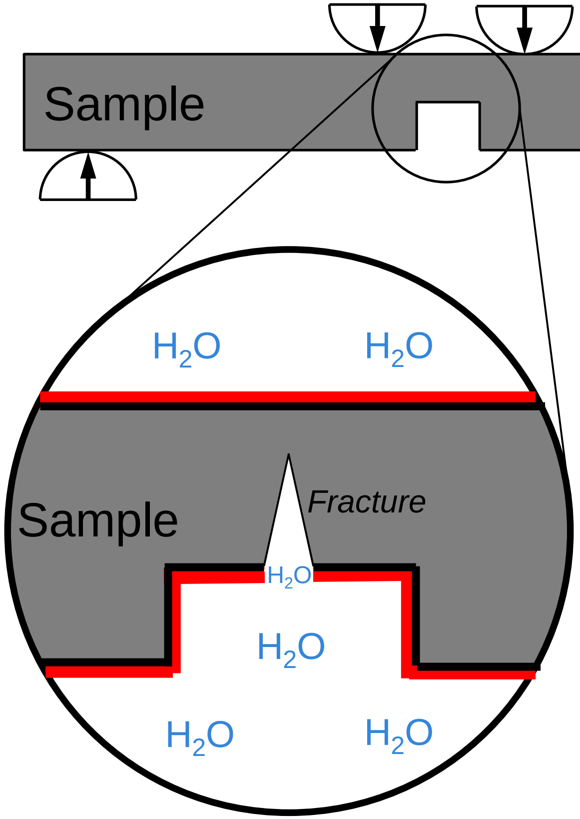
Woodford: dry-air-water

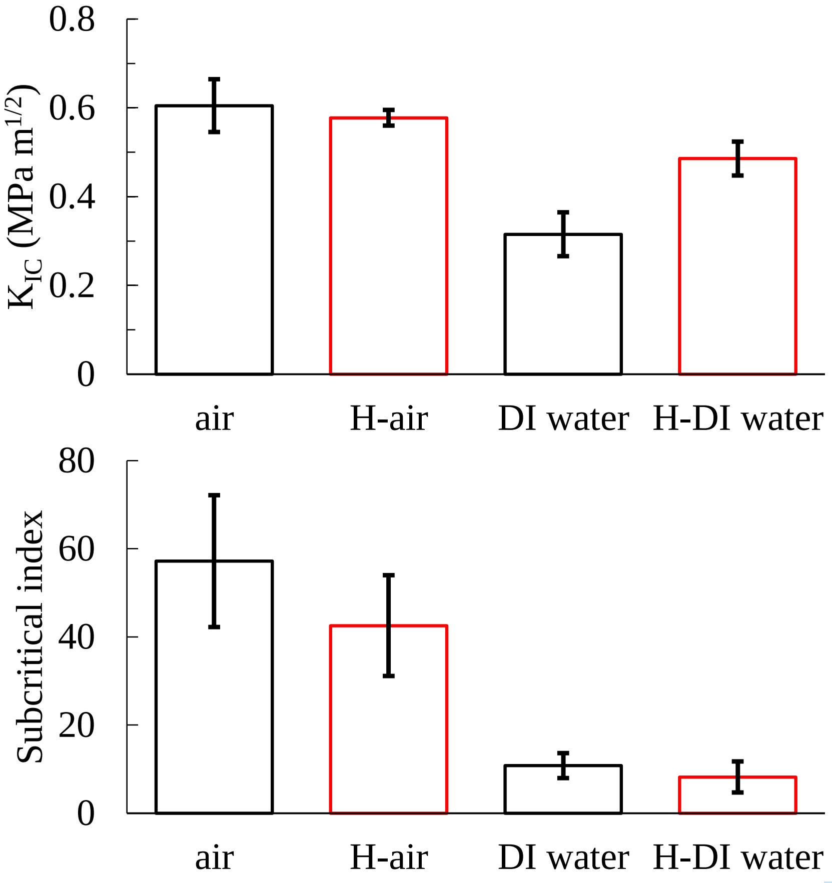




- Strong reduction of K_{IC} (48%) and SCI (75%) from ambient air to DI water
- Fracturing strongly facilitated in H_2O saturated conditions
- K-V curves obey power-law, indicating fracturing @ stress-corrosion regime (I)
- Load relaxation technique (lines) match constant loading rate method (squares)

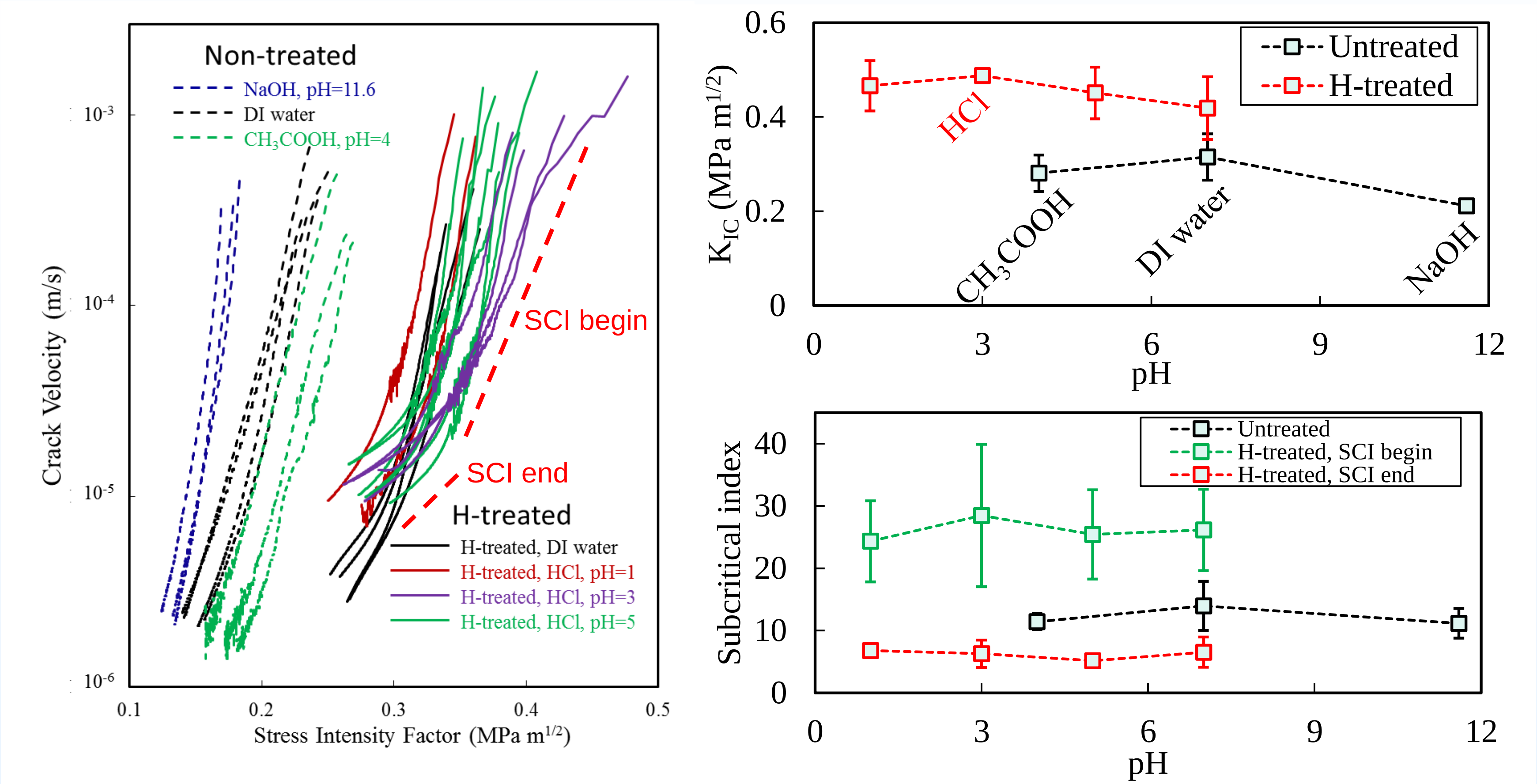
Woodford: hydrophobic treatment





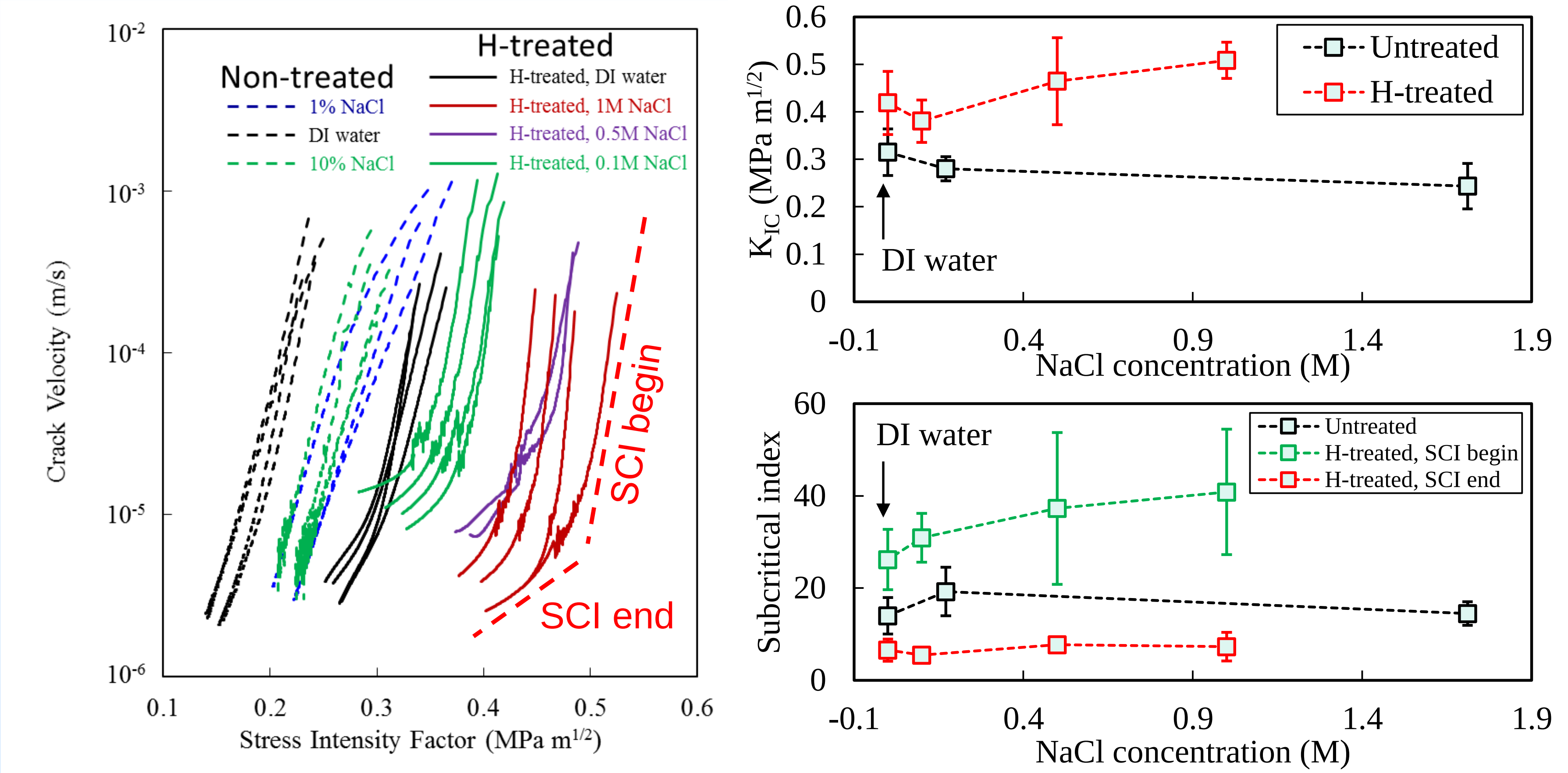
- H-treatment restricts water-sample interaction to the fracture tip
- H-treatment protects K_{IC} from large weakening in DI water
- H-treatment has little effect on long-term SCI both in ambient air and DI water

Woodford: effect of pH



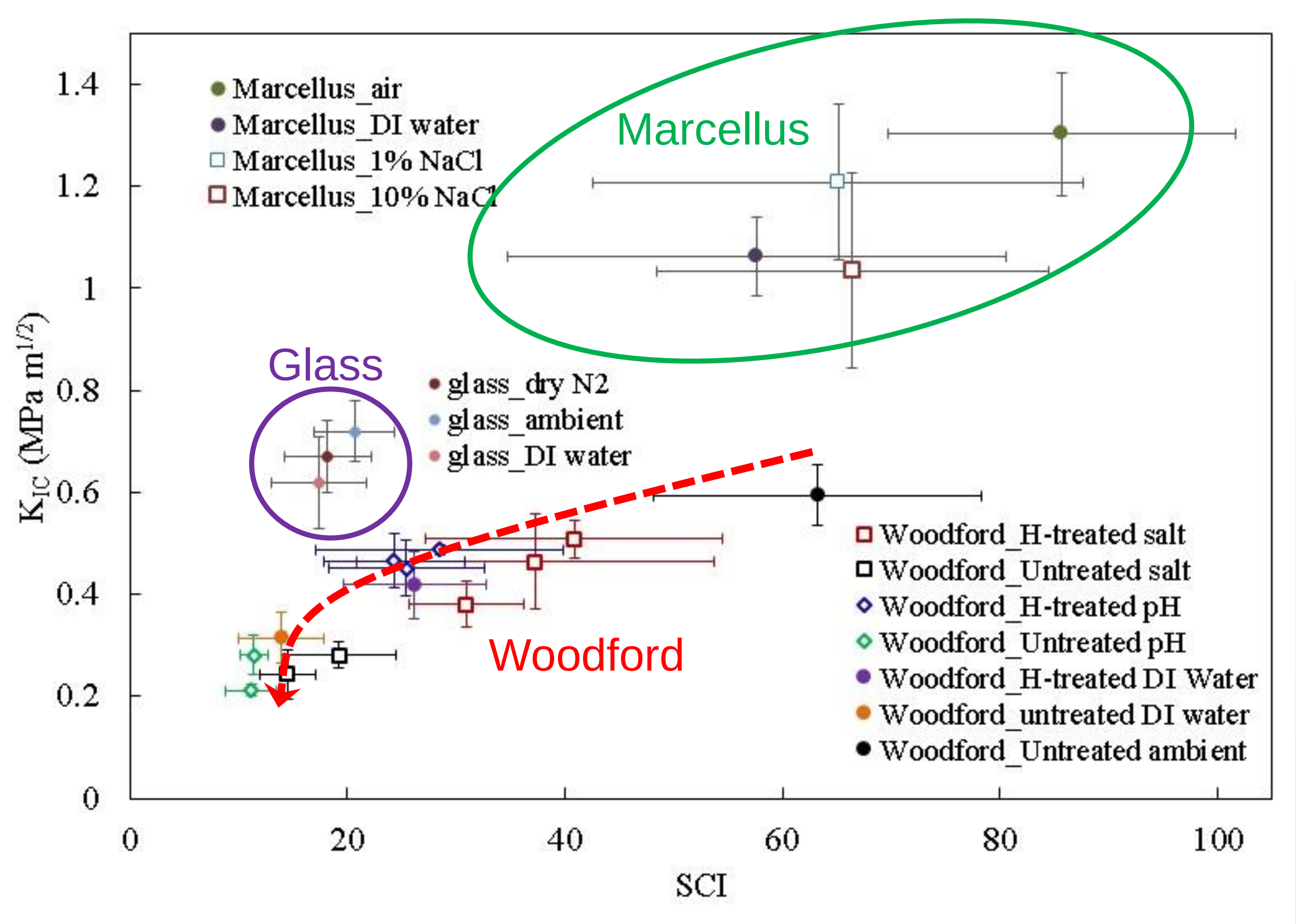
- K_{IC} , SCI not obviously dependent on pH
- Non-power-law K-V curves for H-treated sample
- SCI begin > SCI Untreated > SCI end
- H-treatment protects K_{IC} from strong weakening

Woodford: effect of salinity



- K_{IC} dependency on salinity: Untreated: K_{IC} ↓ as salinity ↑.
  H-treated: K_{IC} ↑ as salinity ↑.
- Non-power-law K-V curves for H-treated samples.
- SCI begin > SCI Untreated > SCI end.

Correlation between K_{IC} & SCI



- Woodford: large drop of K_{IC} and SCI between ambient to aqueous solutions.
- Glass and Marcellus: less change in K_{IC} and SCI.

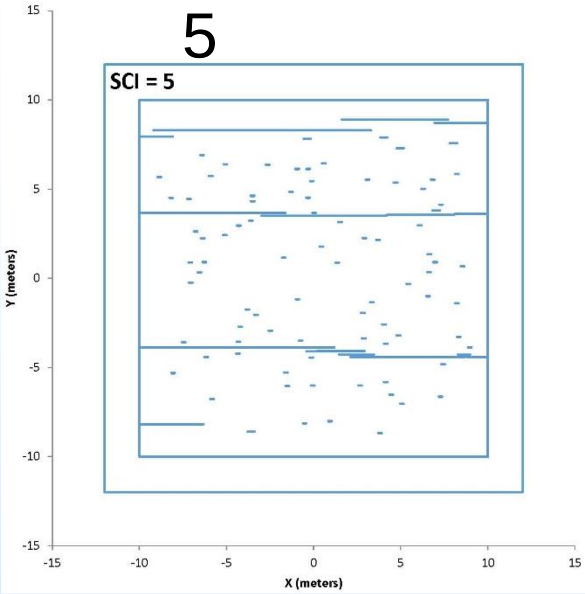
Results fracture mechanics testing

- K_{ic} and SCI lower in water compared to dry tests
  - Dry tests of limited applicability for aqueous subsurface systems
  - Dry tests potentially applicable to $scCO_2$ systems
- Effect of varying water chemistry minor in current tests
- Dry-out by $scCO_2$ injection could strengthen caprock
- Water increases inelastic behavior, impedes fracture growth
  - Decreased inleastic behavior under dry CO2 conditions could favor fracture growth

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

Effect of var SCI, constant K_{Ic} = 1 MPa·$m^{1/2}$



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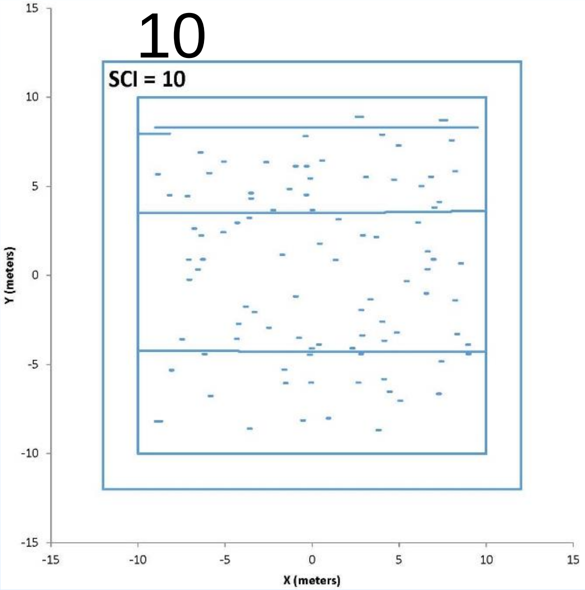

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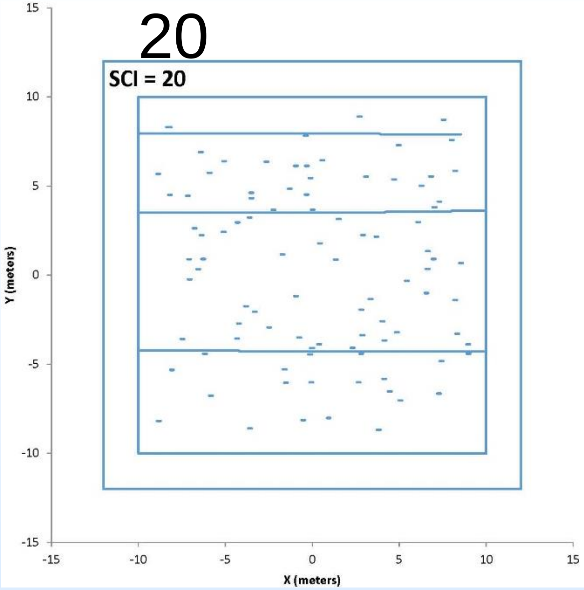

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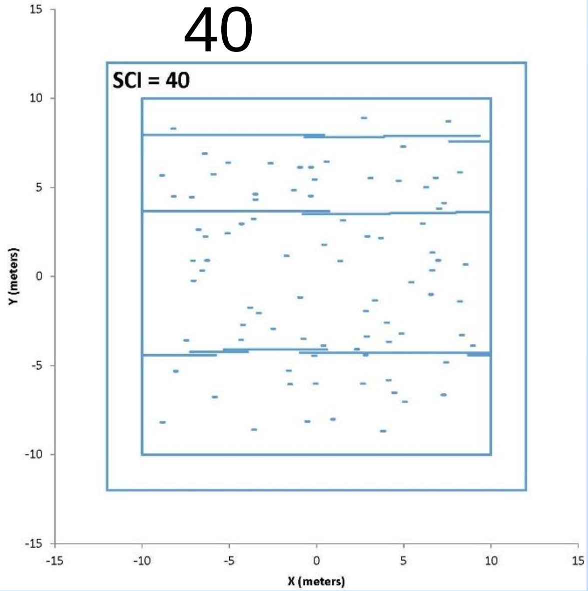

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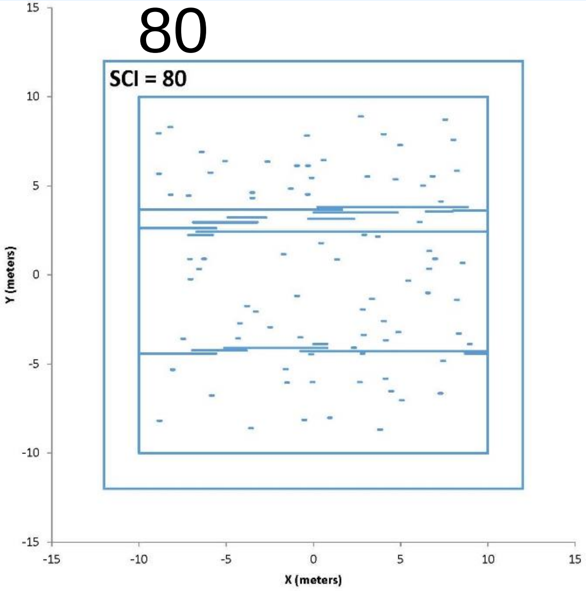

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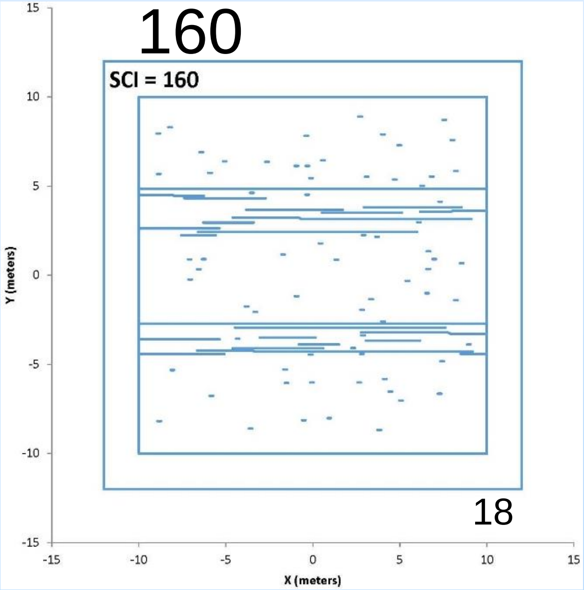

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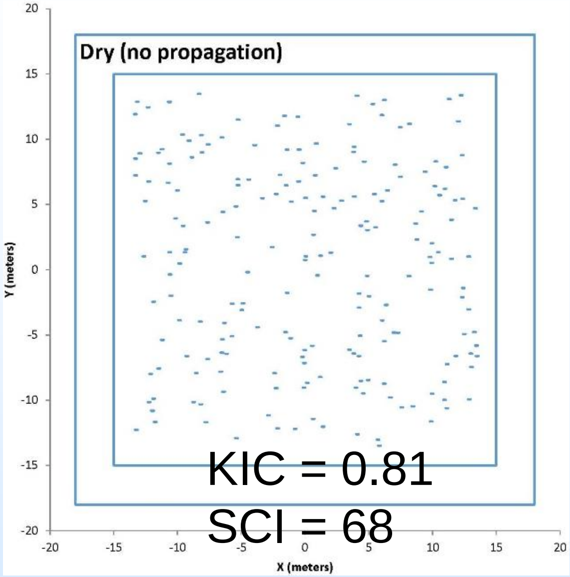
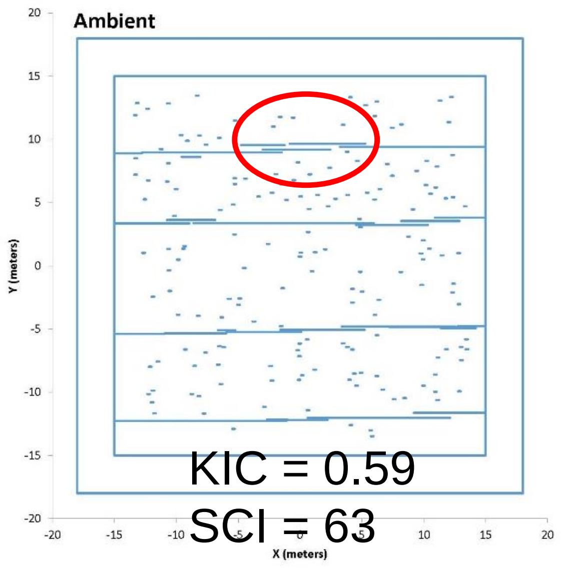
JOINTS models for Woodford

Plan view; Fractures initiate internally



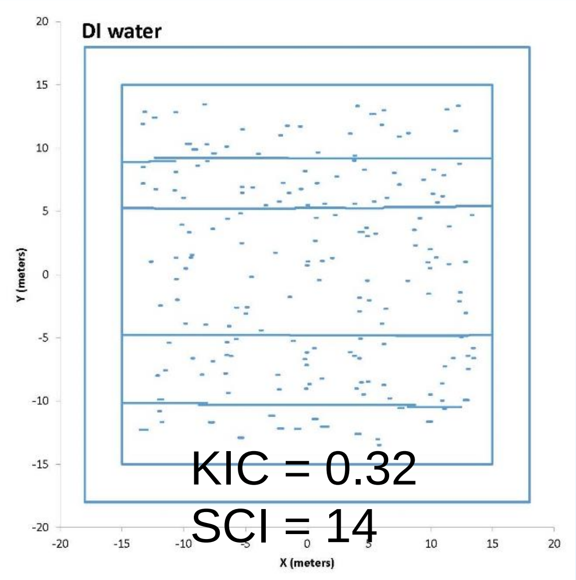
KIC = 0.81

SCI = 68



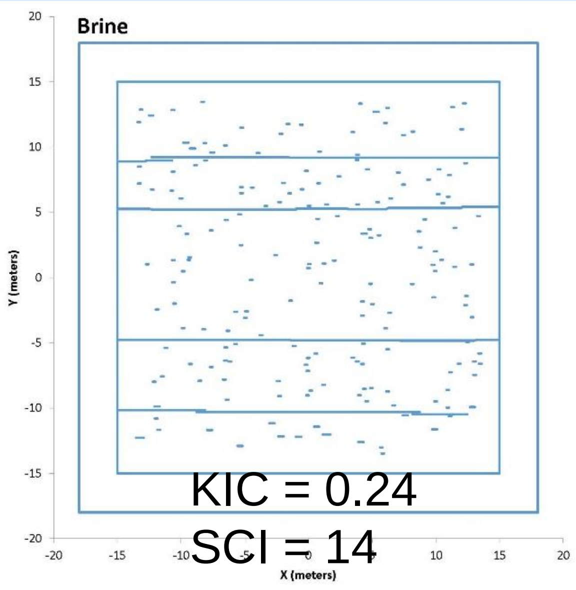
KIC = 0.59

SCI = 63



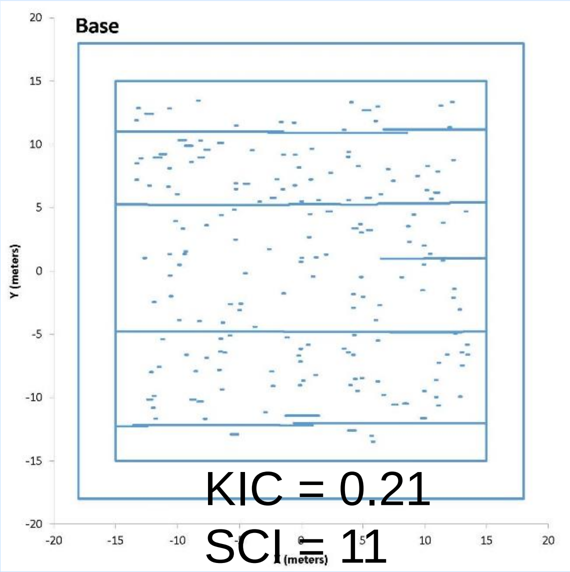
KIC = 0.32

SCI = 14



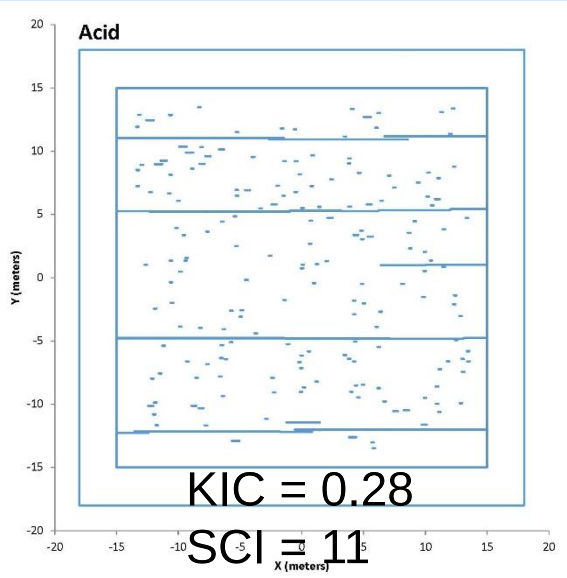
KIC = 0.24

SCI = 14



KIC = 0.21

SCI = 11

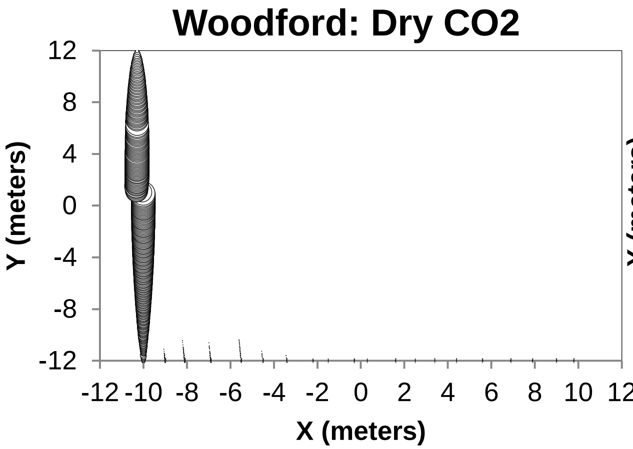


KIC = 0.28

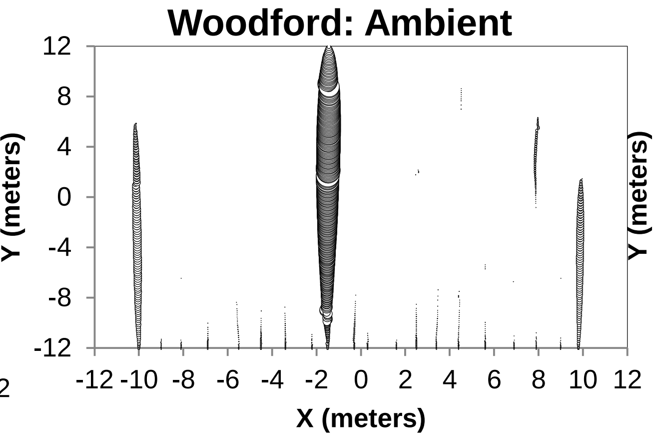
SCI = 11

JOINTS models of caprock failure

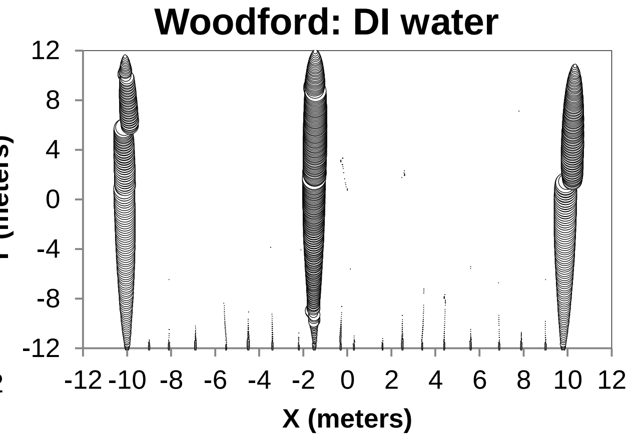
- Vertical section in shale caprock
- Fractures initiate at base
- Best fracture connectivity with DI water
- Decreased fracture connectivity in dry CO_{2gas}



KIC = 0.81
SCI = 68



KIC = 0.59
SCI = 63



KIC = 0.32
SCI = 14

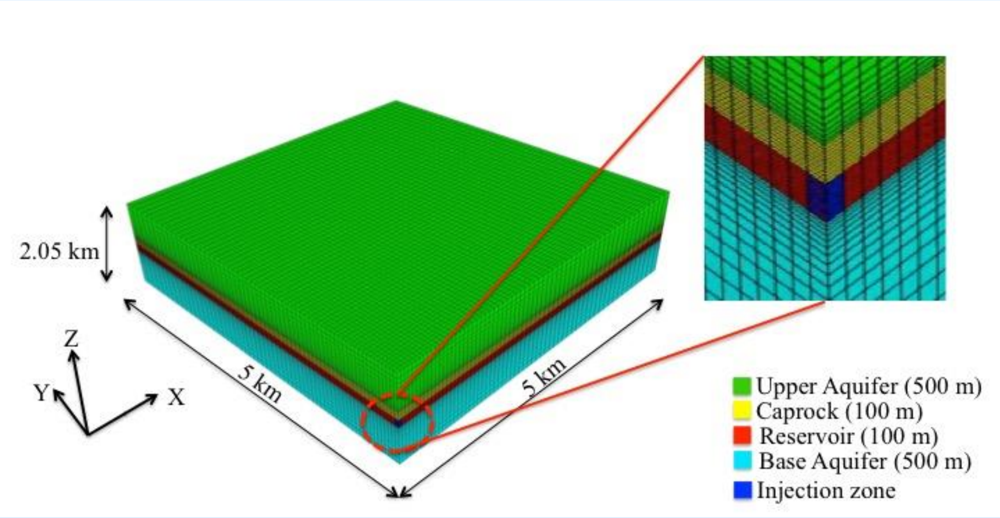
Caprock Integrity Sierra Mechanics

P. Newell, M. J. Martinez, P. Eichhubl, 2016, Impact of layer thickness and well orientation on caprock integrity for geologic carbon storage, Journal of Petroleum Engineering [*http://doi:10.1016/j.petrol.2016.07.032*](http://doi:10.1016/j.petrol.2016.07.032)

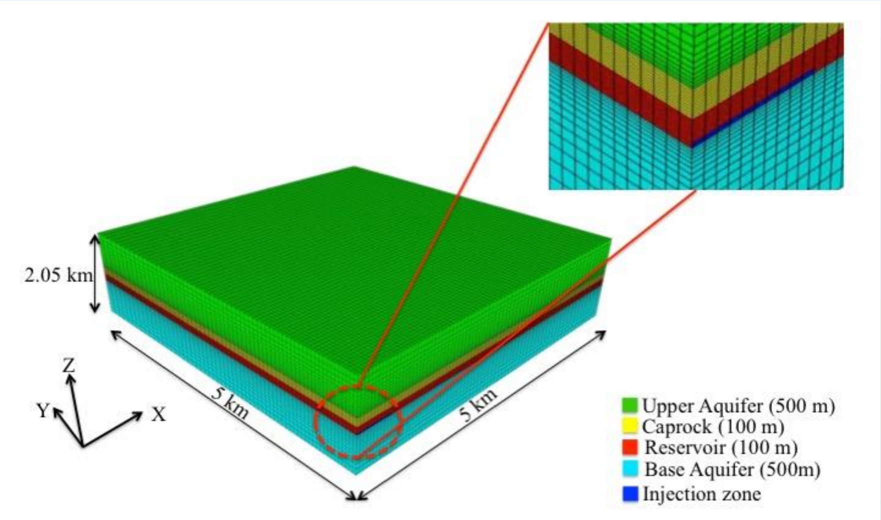
Test for effect of:

- wellbore orientation: vertical, horizontal
- injection rate: 3 Mt/yr, 5 Mt/yr for 30 years
- caprock/reservoir thickness: 50 m, 100 m, 200 m

on leakage across caprock with/without pre-existing fractures (implicit continuum scale)



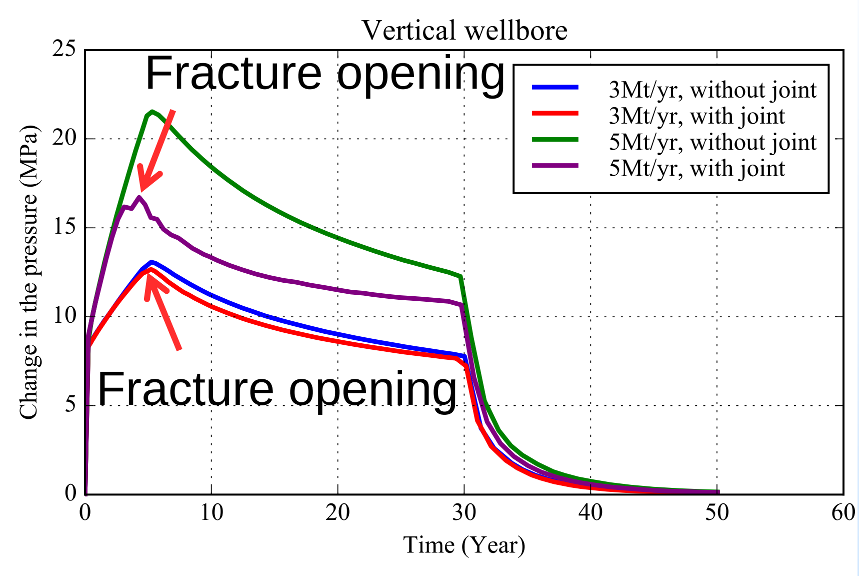
Vertical wellbore



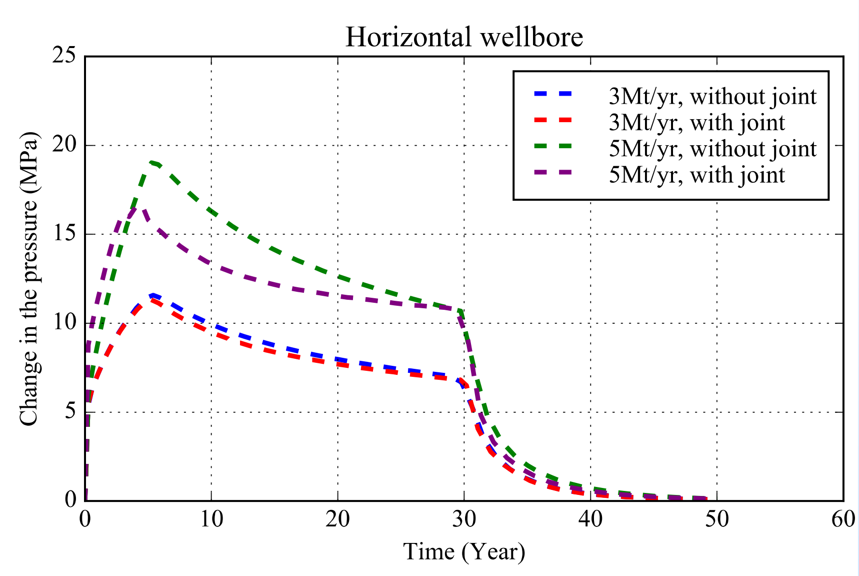
Horizontal wellbore

Pore pressure within reservoir

Vertical well



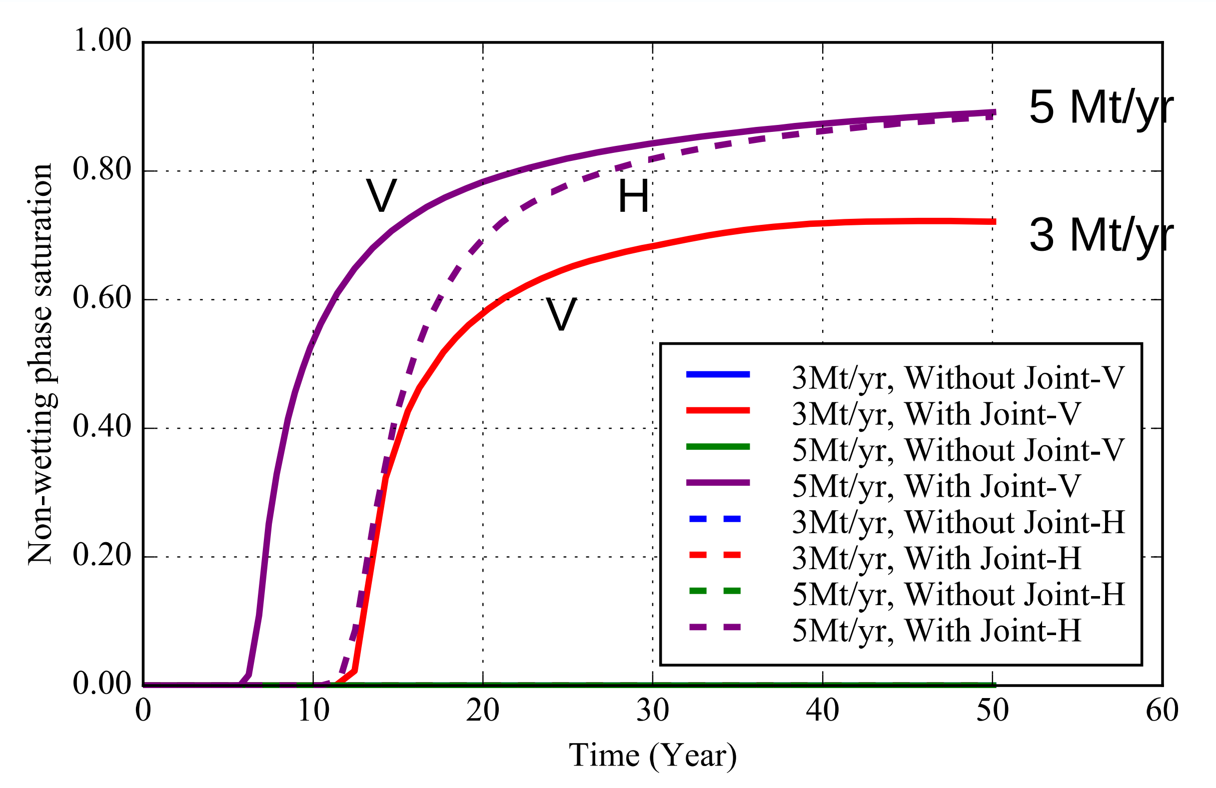
Horizontal well



- Lower pressure in horizontal wellbore cases
- Even for horizontal well, fractures can be reactivated causing leakage

Reservoir, cap: 100 m

Maximum saturation of CO_2 on top of seal

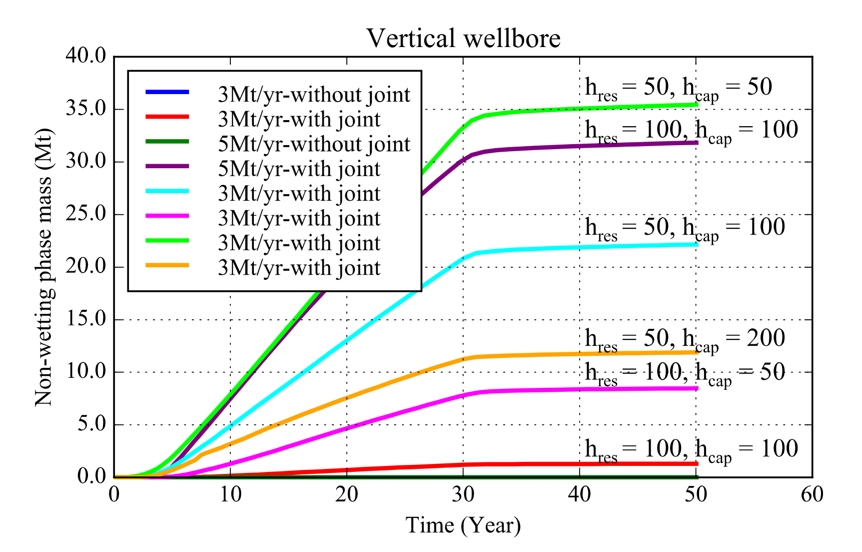


- Leakage for higher injection rates even in horizontal wellbore
- Long-term: same leakage for horizontal & vertical well @ 5 Mt/yr; later onset of leakage for horizontal well

Reservoir, cap: 100 m

Effect of layer thickness

Vertical well

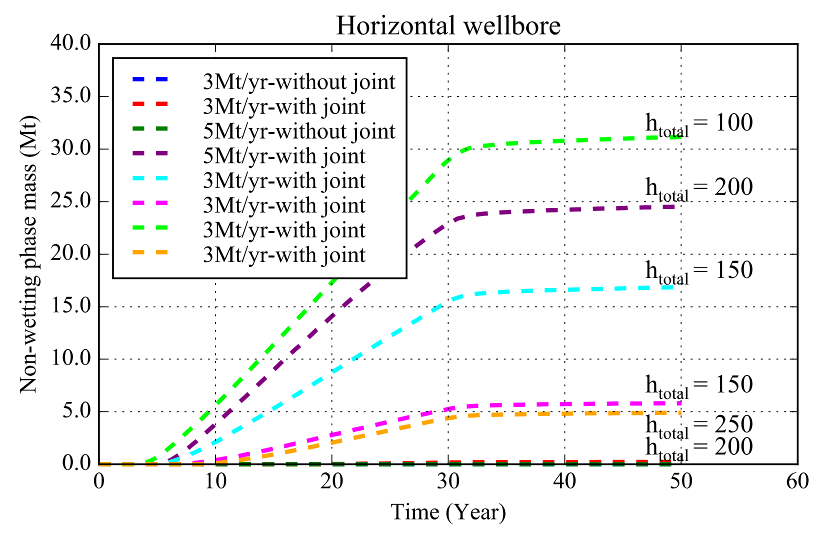


Thick reservoir is safer

For given reservoir thickness, thicker caprock is safer

Reservoir thickness is more important than caprock thickness

Horizontal well



Combined reservoir & caprock thickness (h_{total}) controls leakage amount of to the top layer

High total thickness is safer

Summary

- Wide range in fracture properties for different caprock lithologies
- Distinct stress corrosion effect observed in DT tests in water w/ varying composition
- Shale less fracture prone in dry CO_{2gas} environment
- Fractures most transmissive at intermediate SCI
- Horizontal wells, thick reservoir & seal favor caprock integrity
  - Vertical well: Reservoir thickness most important

Accomplishments to Date

- Fracture mechanics testing on caprock lithologies in dry & aqueous environments of varying composition
- Conducted numerical simulations on fracture network evolution by chemically aided fracture growth
- Simulated caprock leakage behavior using in Sierra Mechanics continuum models for varying well/reservoir/caprock geometry

Next steps

- DT and short-rod fracture testing under
  - varying temperature
  - water composition
  - pressure
  - $scCO_2$
- Integration of continuum & fracture network modeling
  - Effects of varying K_{ic} & SCI included into Sierra Mechanics
- Validation of fracture network models with field fracture network observations

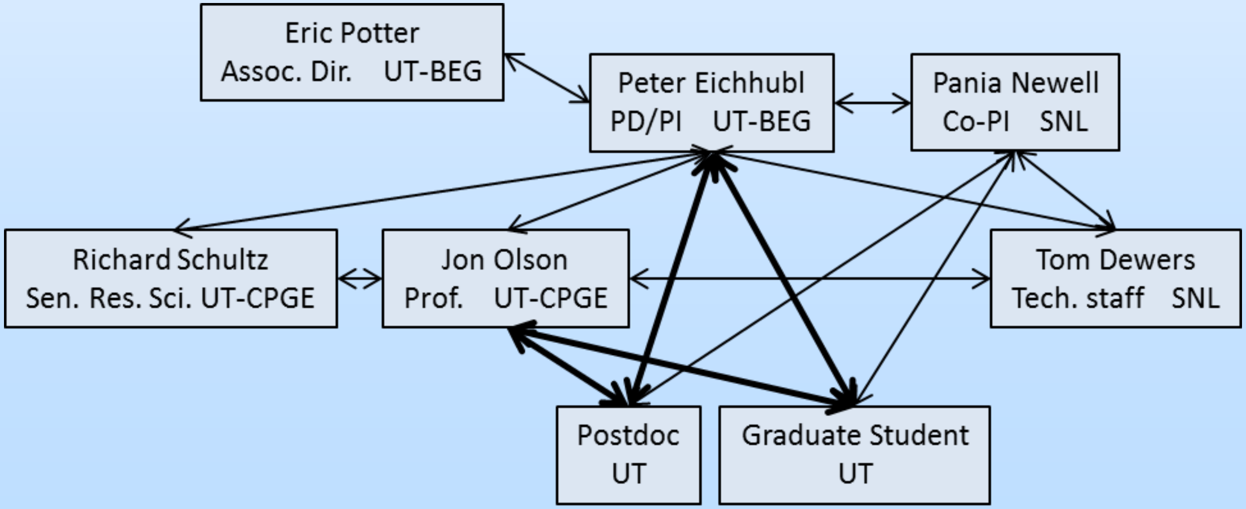
Synergy Opportunities

- Fracture mechanics analysis of Cranfield and FutureGen II core material
- Coordination with EFRC research on reservoir rock geomechanics
- Integration of lab results with fracture network modeling (phase-field, cohesive end-zone, peridynamics)
- Integration with hydraulic fracture research

Appendix

Organization Chart/ Communication Plan

- Established Sandia-UT collaboration
  - Olson – Schultz – Eichhubl on joint industry projects
  - Dewers – Newell –Eichhubl on joint EFRC



Team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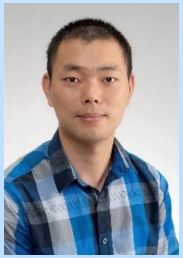
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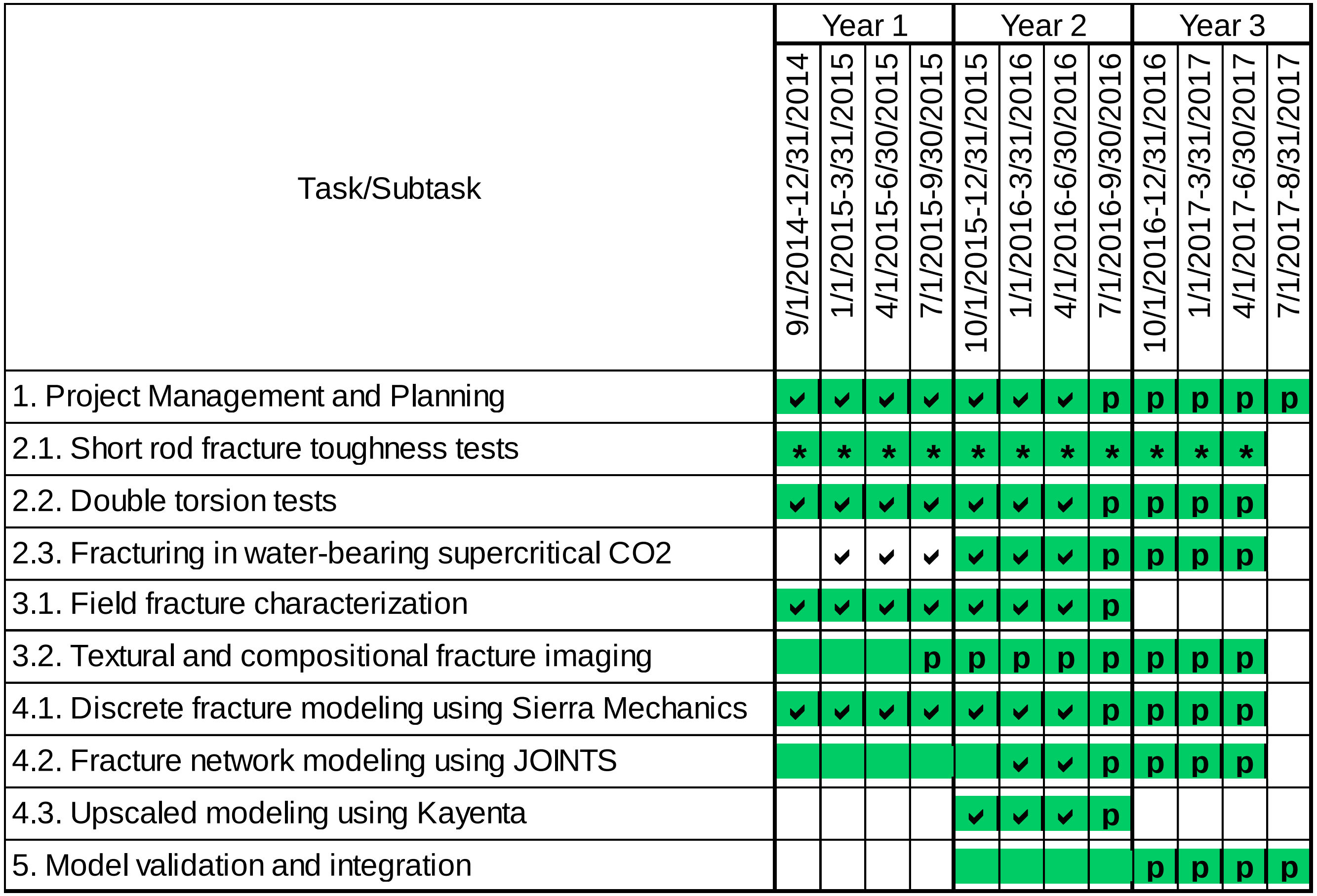
Chen
UT BEG


Jon Major
UT BEG


Owen
Callahan
UT BEG


Erick Wright
UT BEG

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	
2.3. Fracturing in water-bearing supercritical CO2		✓	✓	✓	✓	✓	✓	p	p	p	p	
3.1. Field fracture characterization	✓	✓	✓	✓	✓	✓	✓	p				
3.2. Textural and compositional fracture imaging	🟩	🟩	🟩	p	p	p	p	p	p	p	p	
4.1. Discrete fracture modeling using Sierra Mechanics	✓	✓	✓	✓	✓	✓	✓	p	p	p	p	
4.2. Fracture network modeling using JOINTS	🟩	🟩	🟩	🟩	🟩	✓	✓	p	p	p	p	
4.3. Upscaled modeling using Kayenta					✓	✓	✓	p				
5. Model validation and integration					🟩	🟩	🟩	🟩	p	p	p	p

*** Short rod tests (task 2.1) are being performed under task 2.3 under confined conditions.**

Bibliography

- <u>Journal, multiple authors:</u>
  - P. Newell, M. J. Martinez, P. Eichhubl, 2016, Impact of layer thickness and well orientation on caprock integrity for geologic carbon storage, Journal of Petroleum Science and Engineering, available at: http://doi:10.1016/j.petrol.2016.07.032