Area of Interest 2, Geomechanics of CO_2 Reservoir Seals

DE-FE0023316

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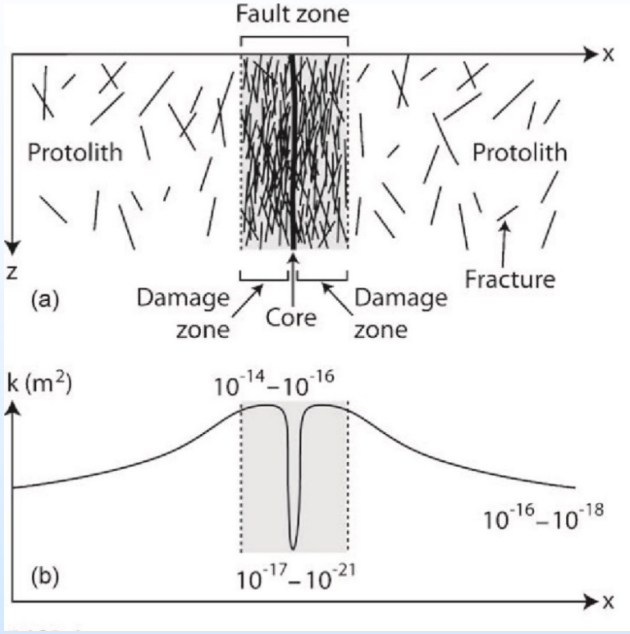
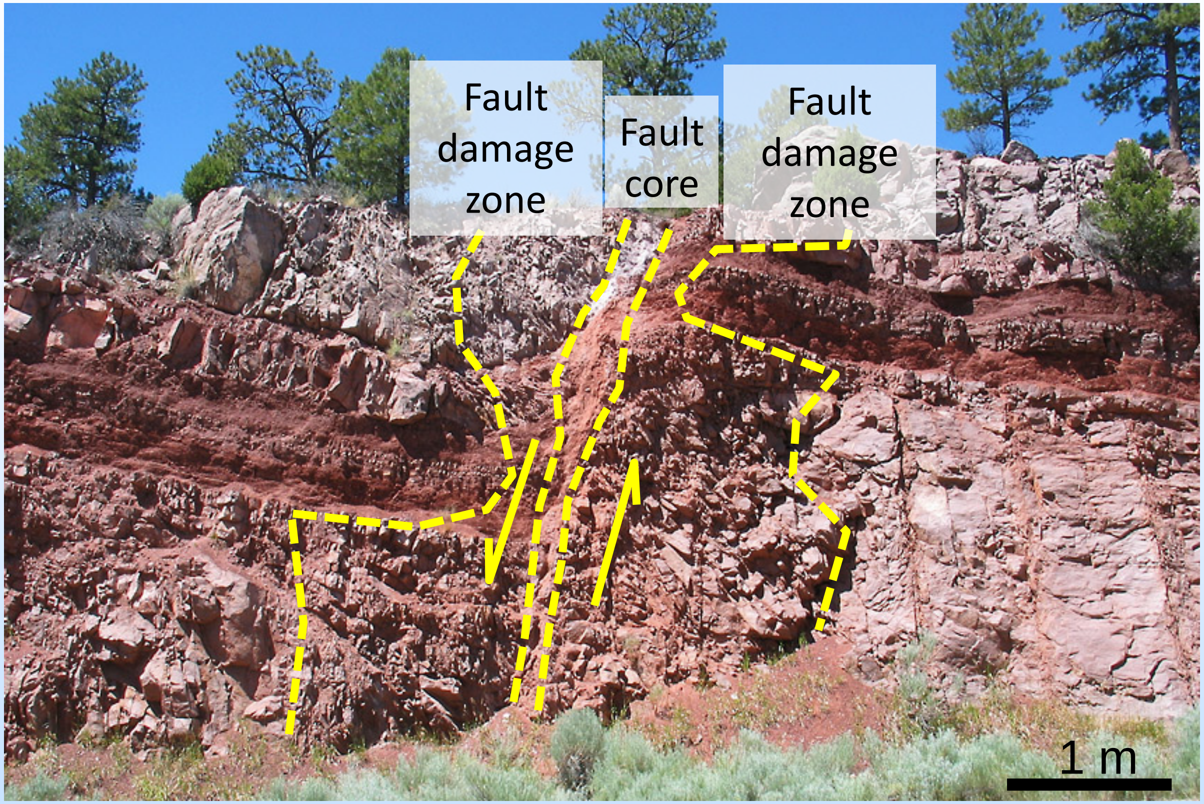
Problem Statement

- 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.

Permeability structure of conduit-barrier fault zone



Cappa and Rutqvist, 2011,
Chester et al., 1993

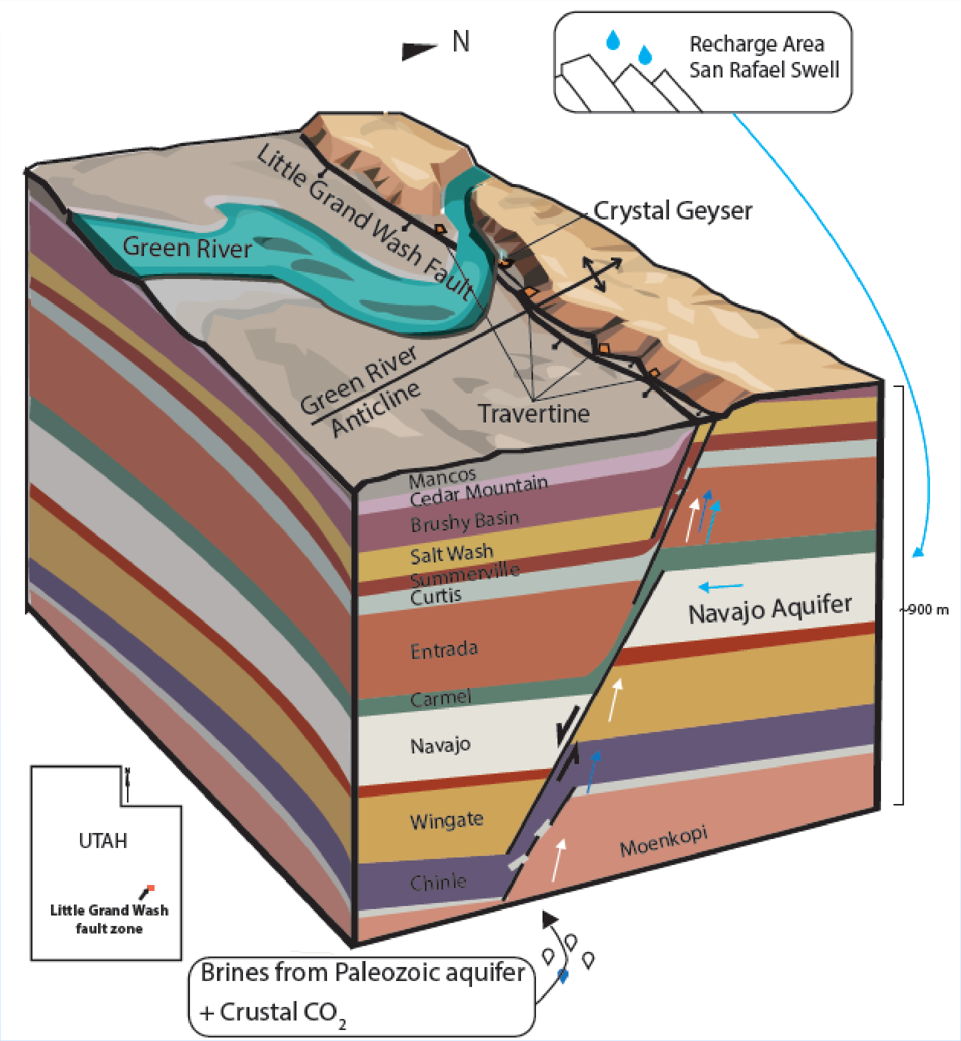


Normal fault in sandstone-siltstone sequence

Opening-mode & sheared opening-mode fractures control flow properties of conductive fault zones.

Slip surfaces control damage zone evolution.

Fractures in CO_2 caprock
Crystal Geyser field analog site

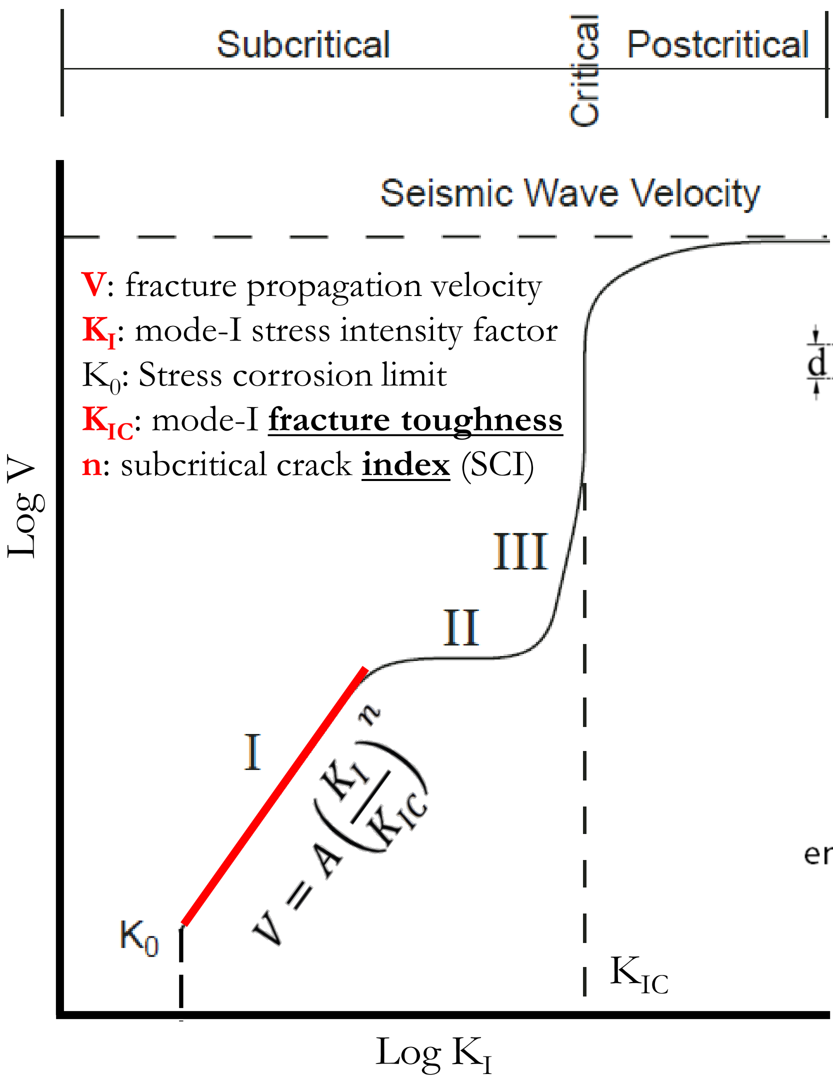


Active on 10^2 - 10^5 year time scales

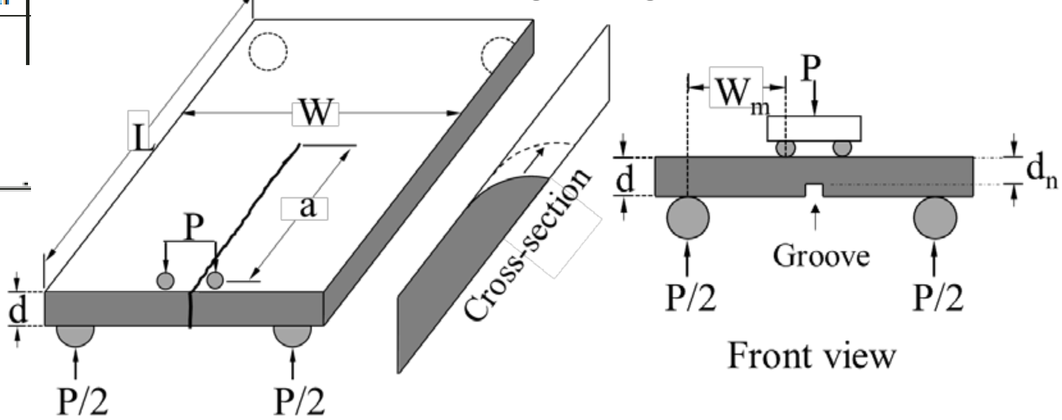
Methodology

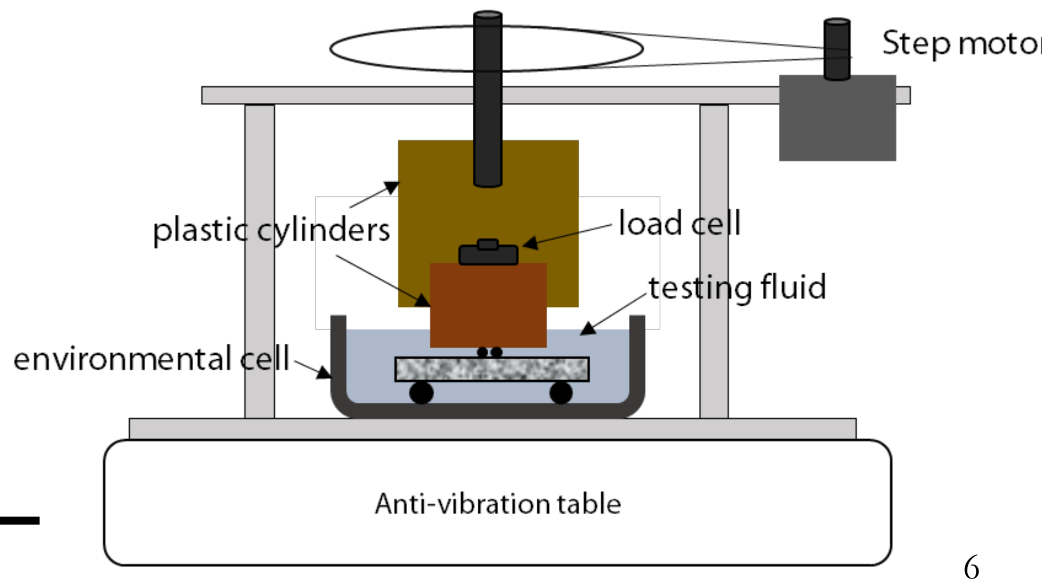
- Experimental measurement of subcritical fracture propagation in various shale lithologies
  - Double torsion test, unconfined conditions
  - Short-rod test, confined conditions ($scCO_2$)
- Textural and compositional characterization
  - Shale material used for fracture testing
  - Post-mortem analysis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

Mode-I fracture testing



Loading configuration



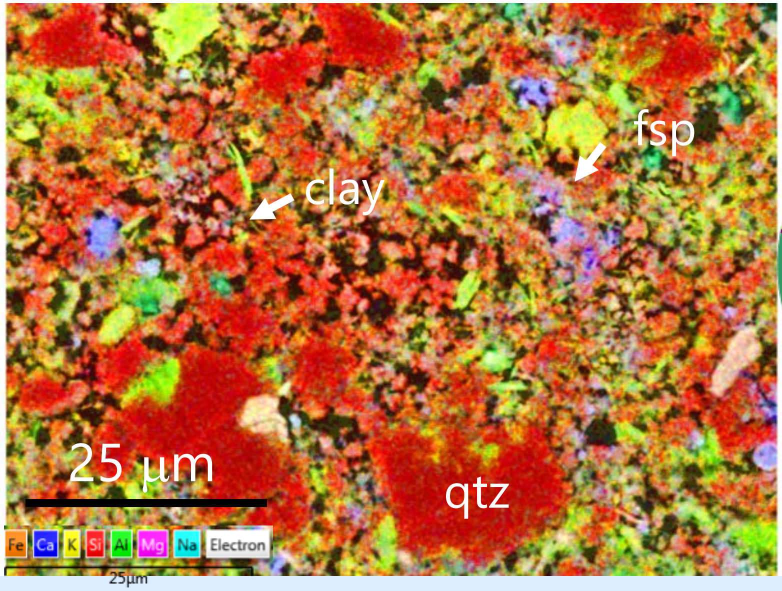


Experimental setup

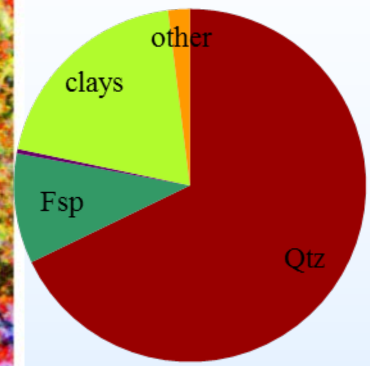
Testing protocol

- Three shale types
  - Woodford, Mancos, Marcellus
  - Also sandstones for comparison/integration
- Room dry, CO_{2gas}, DI water
- Varying salinity, NaCl, KCl
- Varying pH
- Room temperature, 65°C
- Some samples coated with hydrophobic agent to limit fluid/rock interaction to fracture tip

Shale sample composition

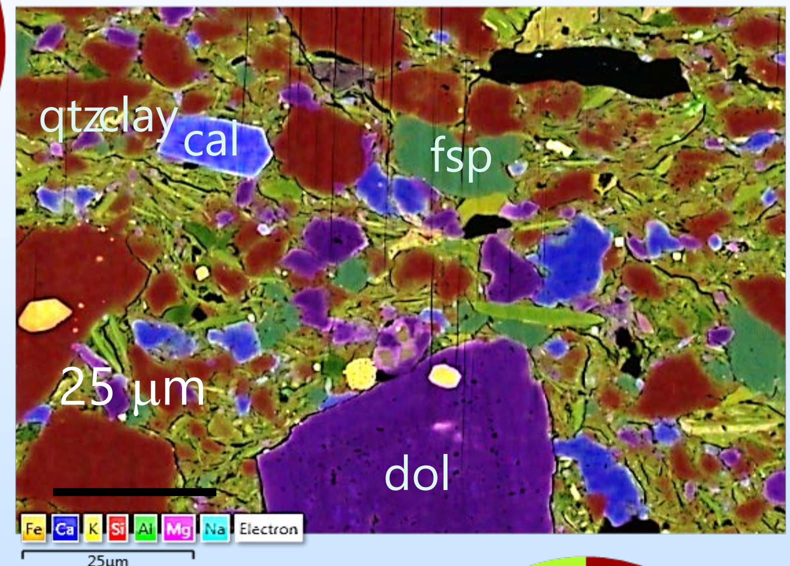


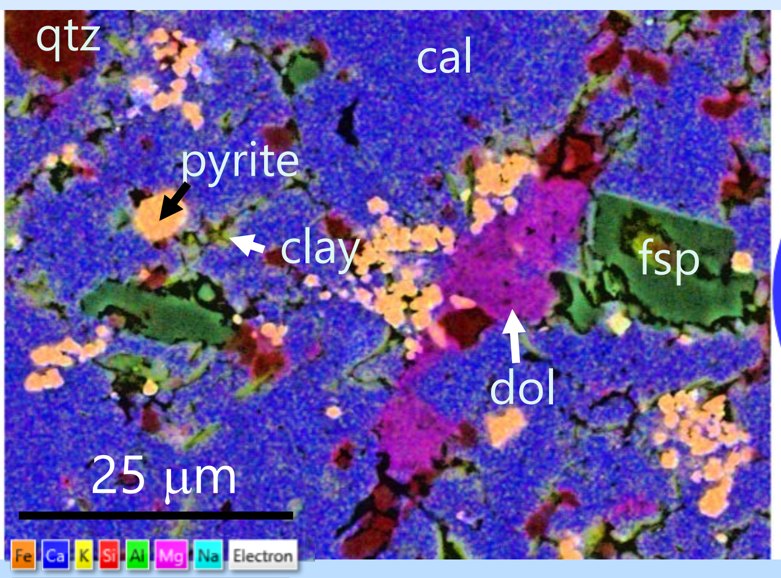
Woodford shale



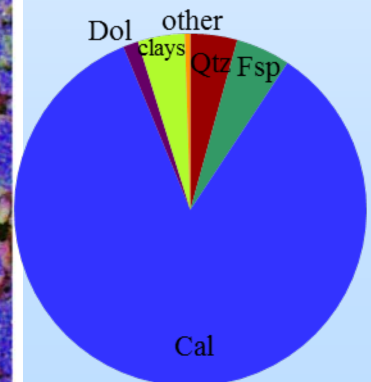
Qtz, clays, fsp

Mancos shale

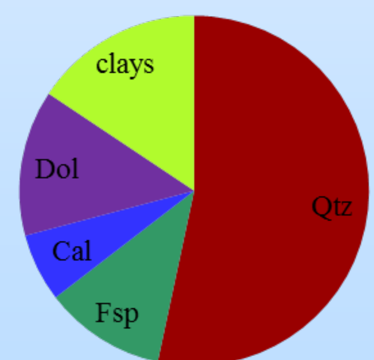




Marcellus shale



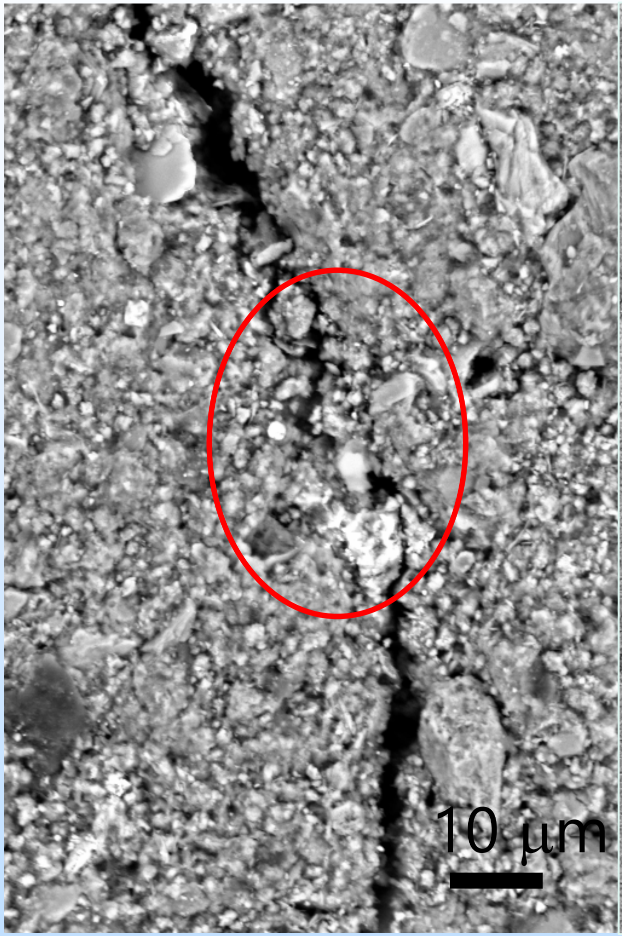
Calcite



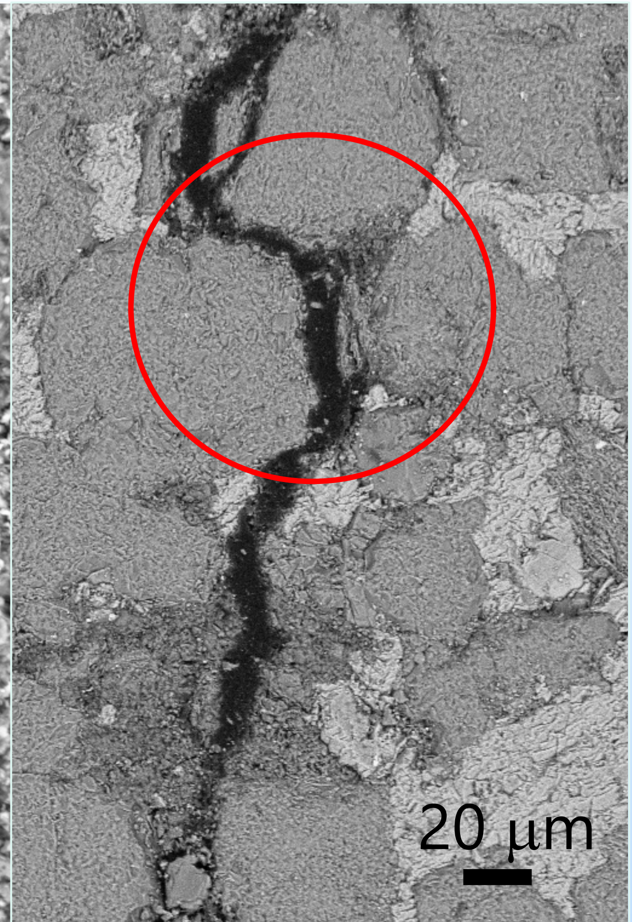
Qtz, clays, carbonate

Fracture trace imaging

Woodford



Mancos

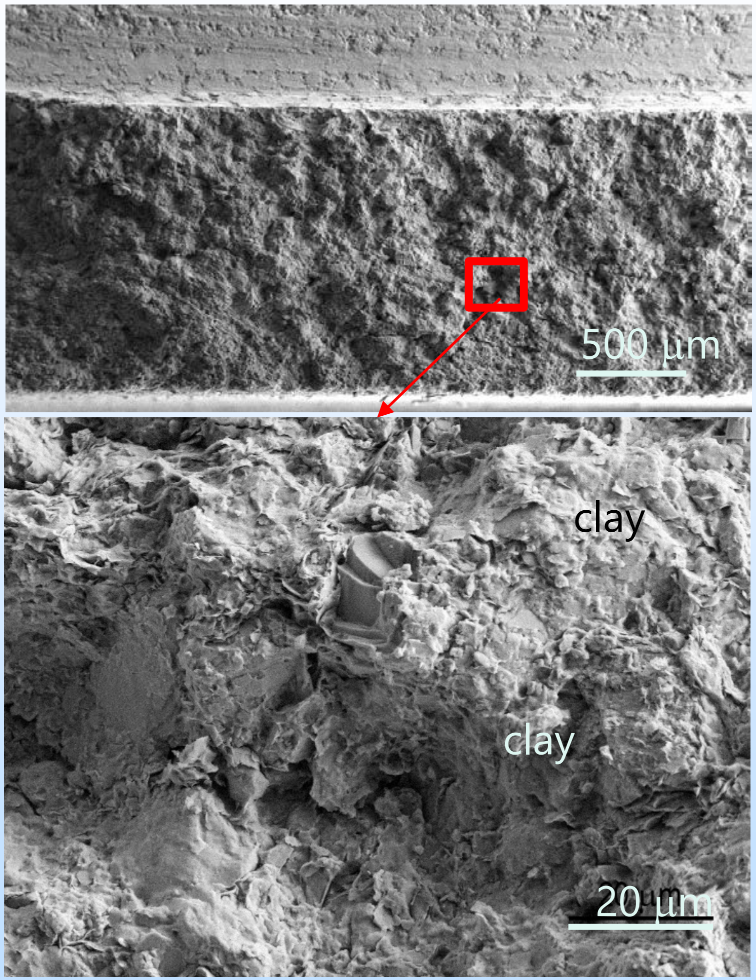


Marcellus

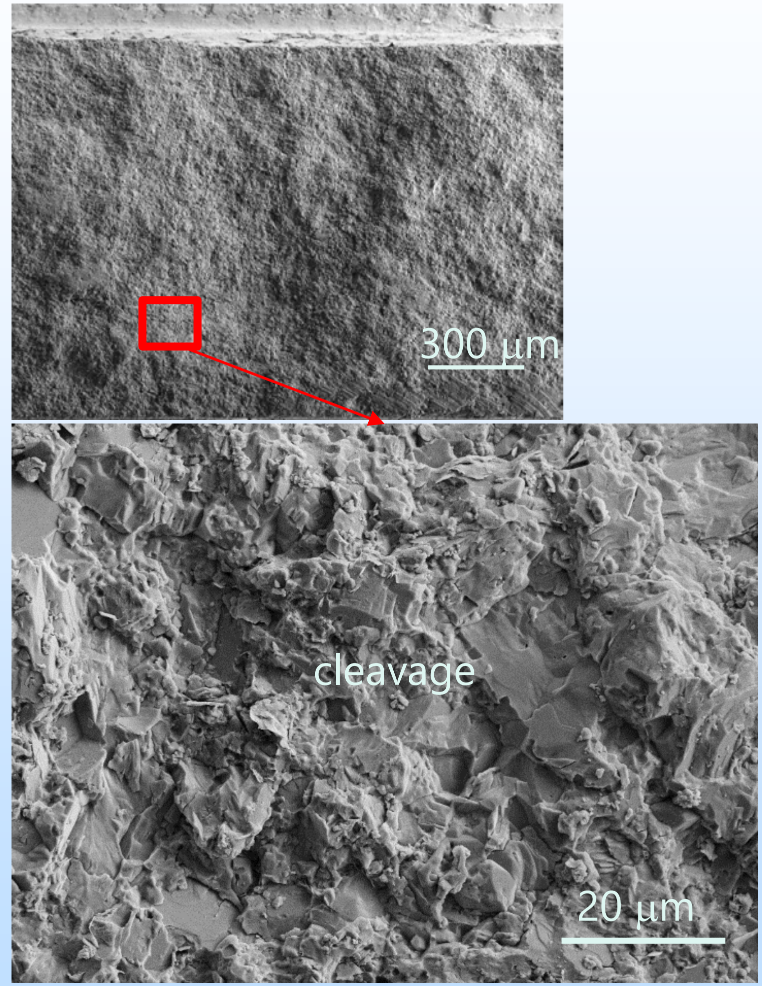
Woodford, Mancos: intergranular (clay matrix)
Marcellus: intragranular (cleavage)

Fracture surface imaging

Mancos shale

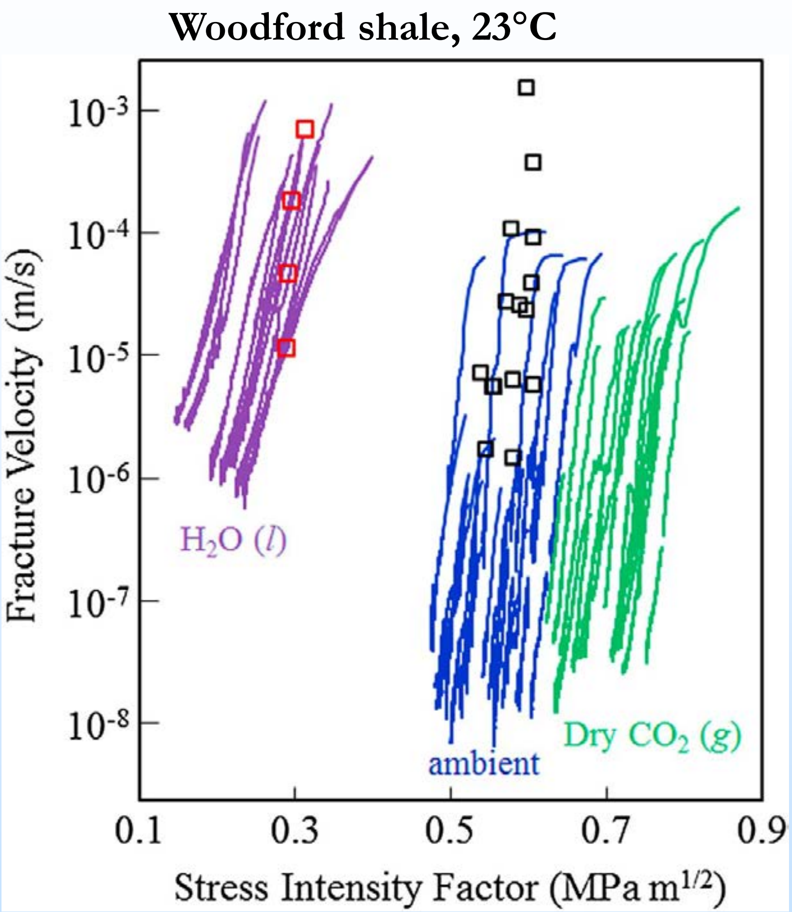


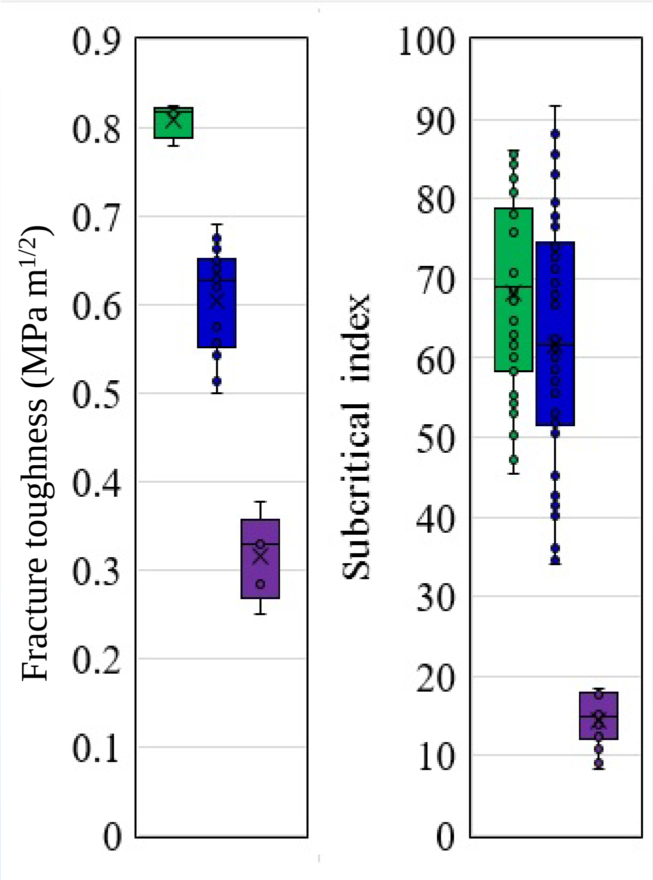
Marcellus shale



Roughness variation, but no plumose structure
Grain boundary breakage vs transgranular breakage

Water content



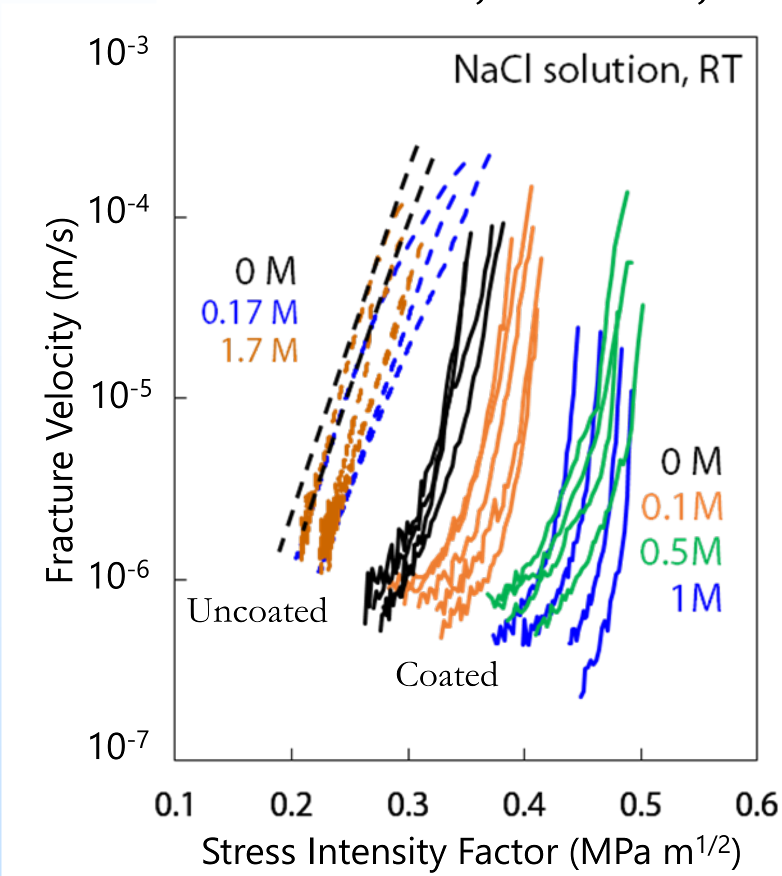


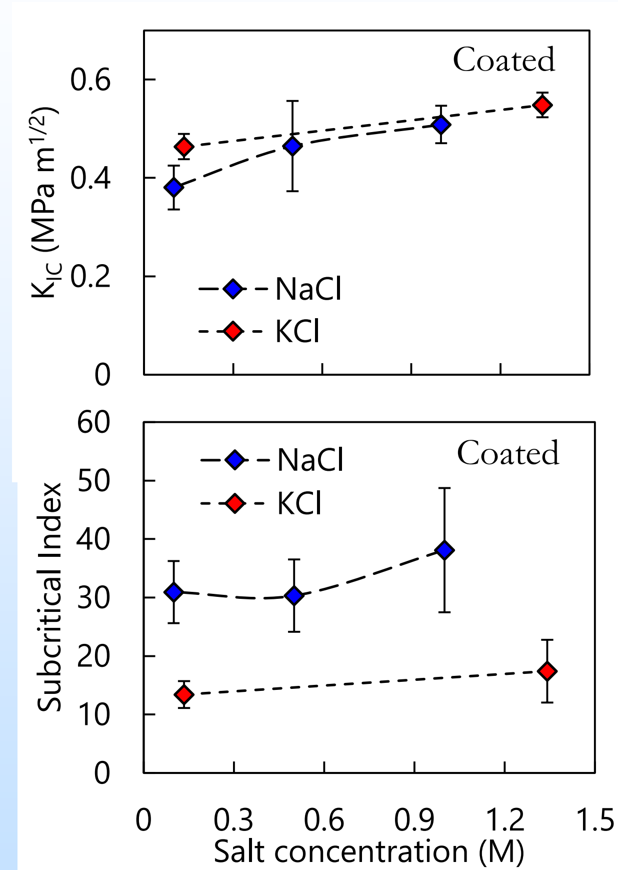
<u>Water enhances subcritical fracturing for clay-rich shales</u>

- Strong reduction of K_{IC} (48%) and SCI (75%) with increasing water content
- K-V curves obey power-law, indicating fracturing in stress-corrosion regime (I)
- Load relaxation technique (lines) matches constant loading rate method (squares)

Salinity

Woodford shale, NaCl brine, 23°C

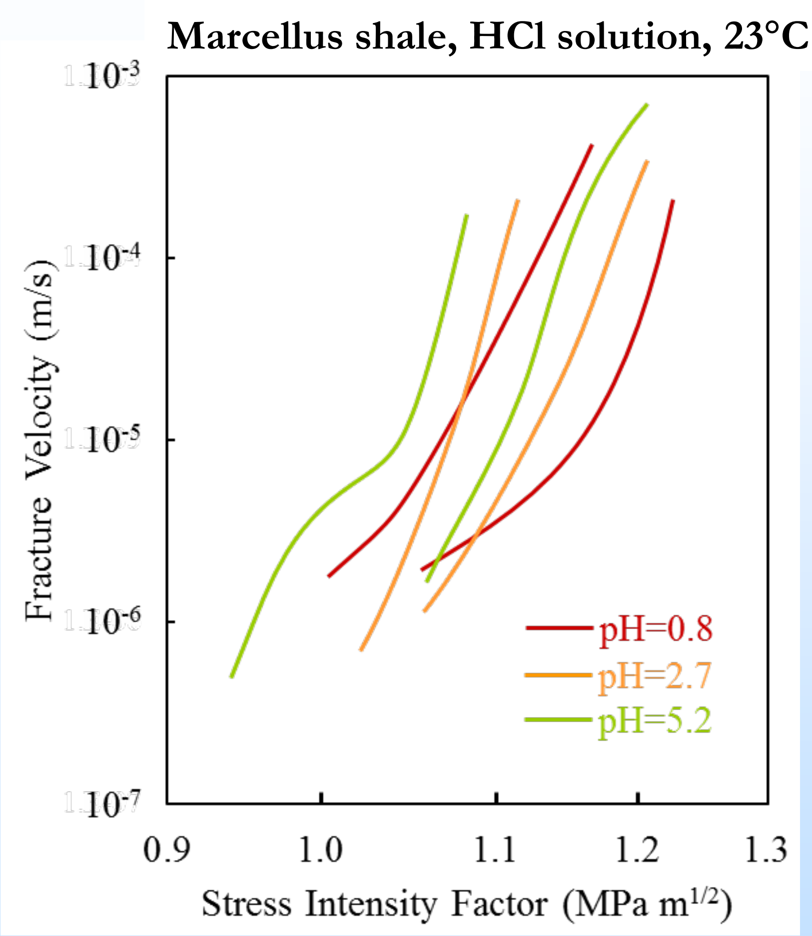


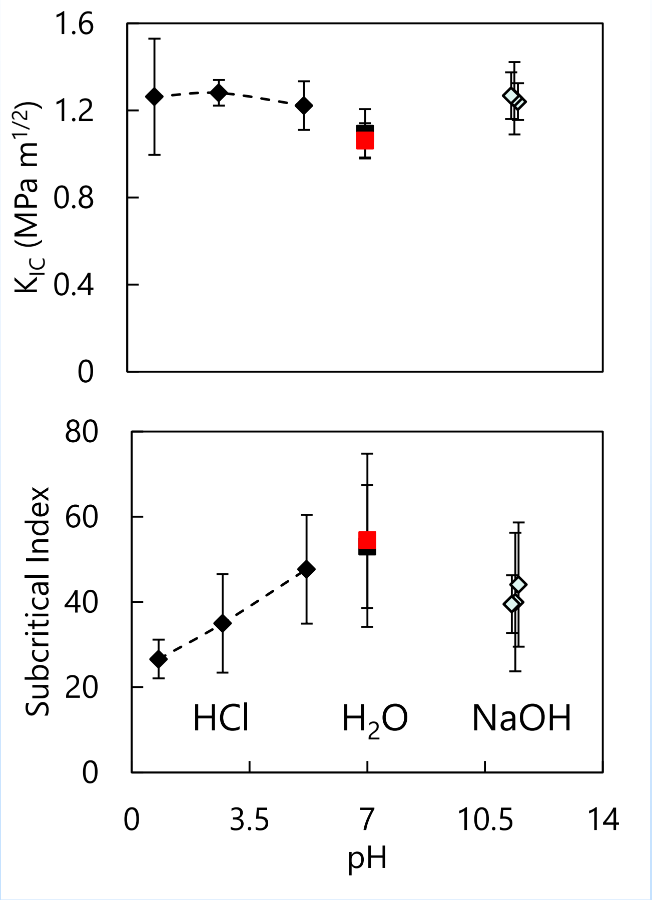


Increase of fluid salinity increases K_{IC} and SCI in clay-rich Woodford and Mancos shales

- Less weakening in KCl brine than in NaCl brine
- Clay swelling

pH

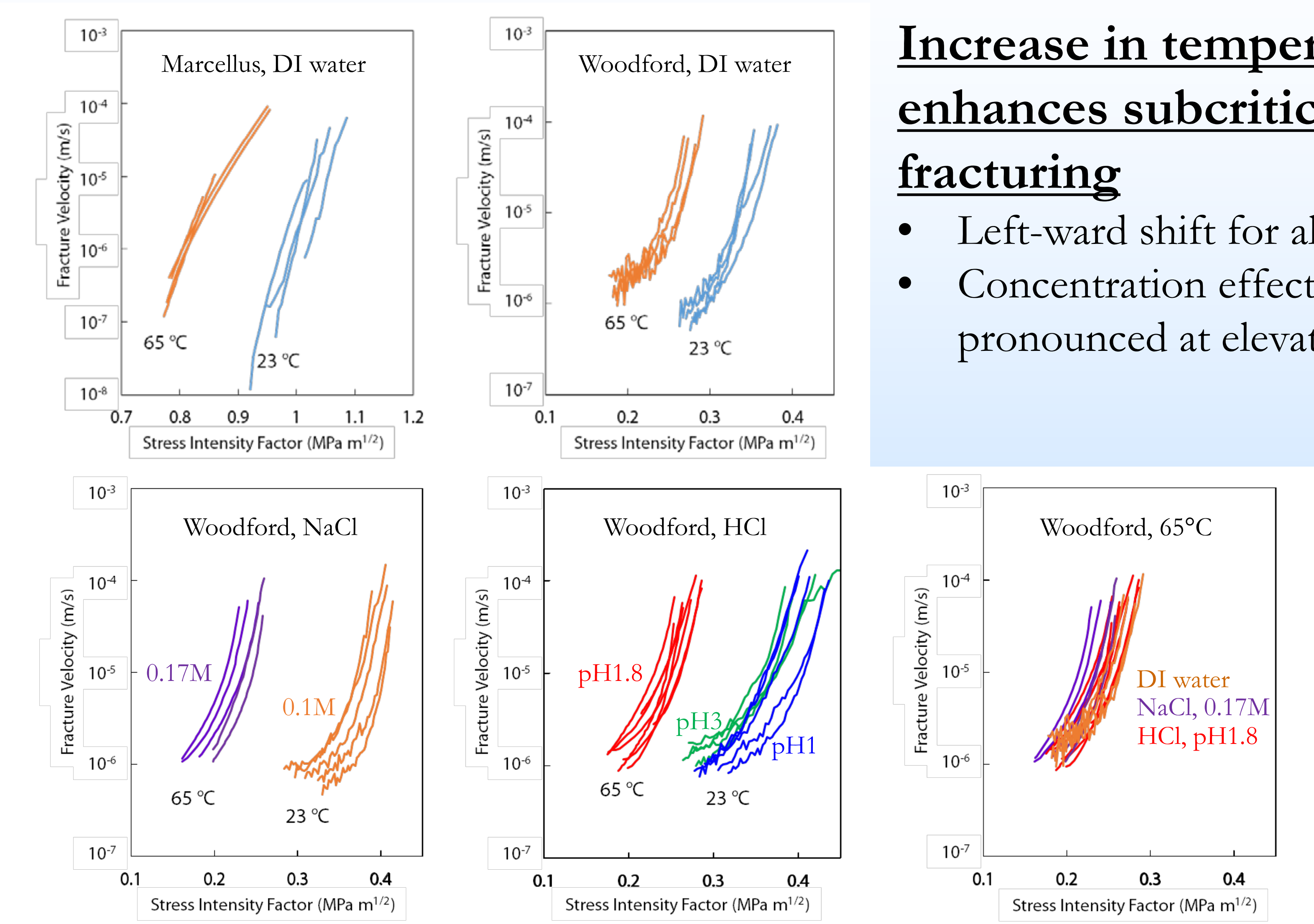




<u>SCI decreases with decreasing pH for carbonate-rich Marcellus shale</u>

- K_{IC} is independent of pH
- SCI effect opposite to that in glass and quartzite
- Calcite dissolution

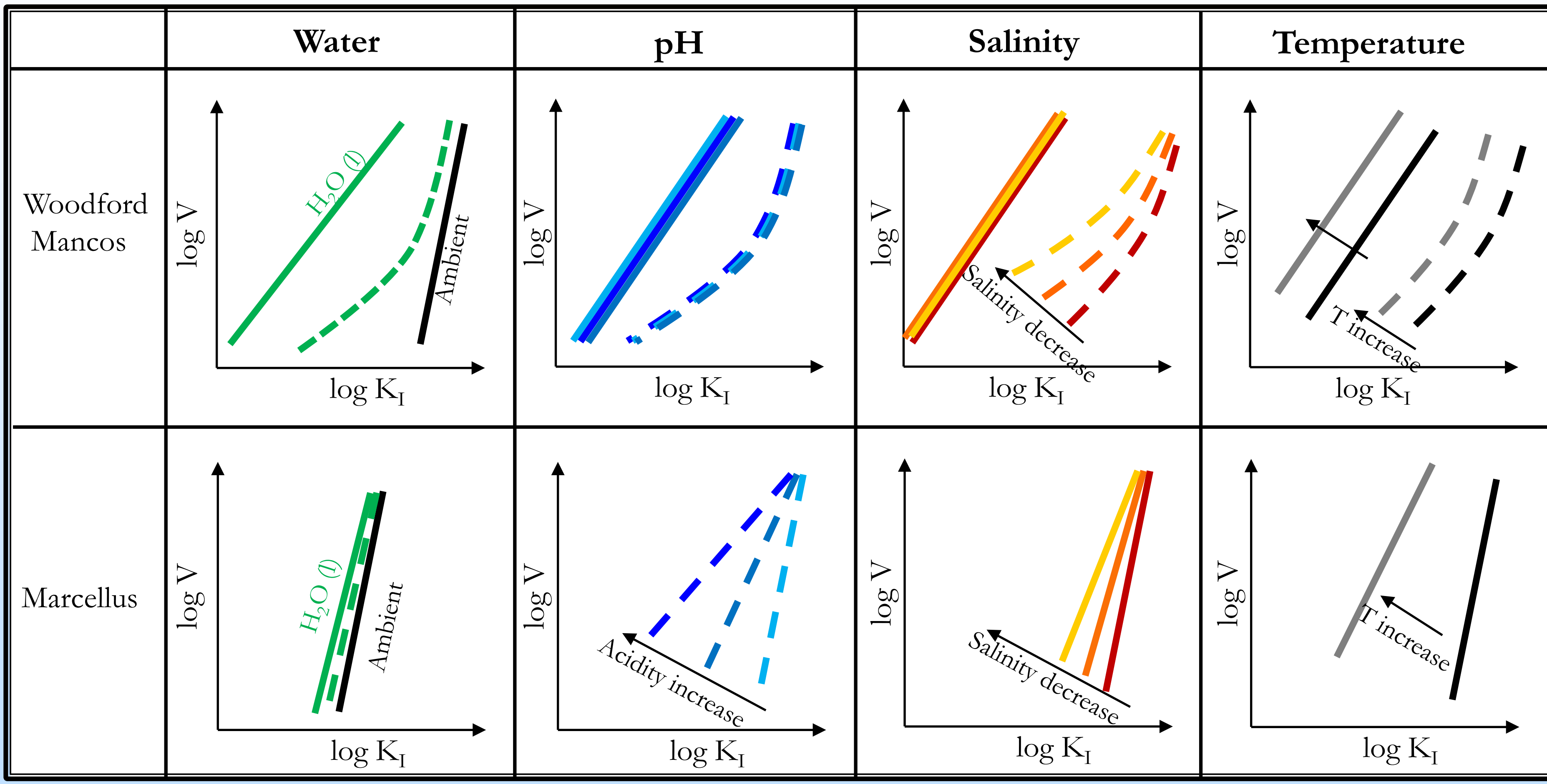
Temperature



<u>Increase in temperature enhances subcritical fracturing</u>

- Left-ward shift for all shales
- Concentration effects less pronounced at elevated T

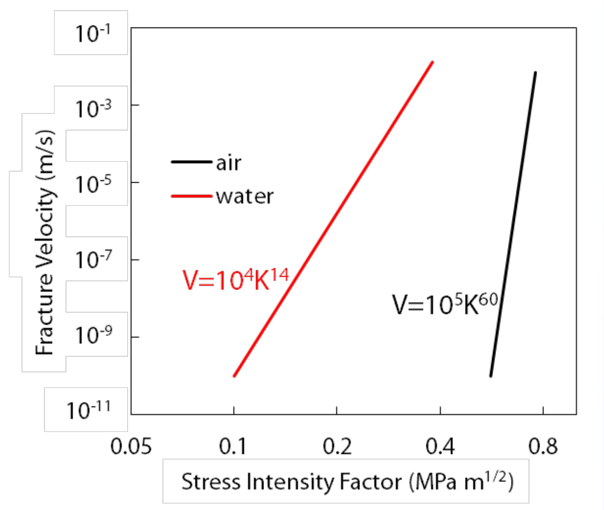
Summary of K-V relations



Uncoated

Coated

Time-to-failure analysis

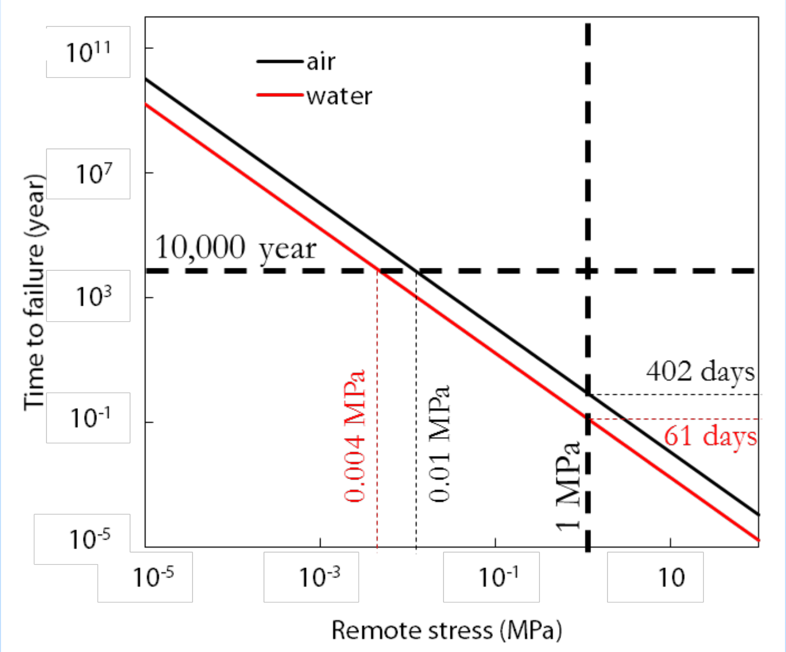


Constant stress loading:

$$\left.\begin{array}{l} K = \sigma Y \sqrt{a} \\ V = A K^n \end{array}\right\} \Rightarrow t_f = \int dt = \int_{a_0}^{a_f} \frac{da}{V} = \frac{2}{\sigma^2 Y^2} \int_{K_0}^{K_{IC}} \frac{K}{V} dK$$

$$\Rightarrow t_f = \frac{2}{(2-n) A \sigma^2 Y^2} \left({K_{IC}}^{2-n} - {K_0}^{2-n} \right)$$

Evans (1972) & Nara et al. (2015)

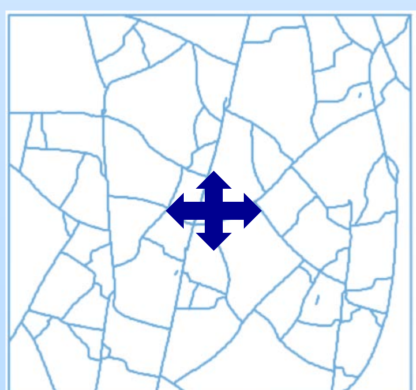


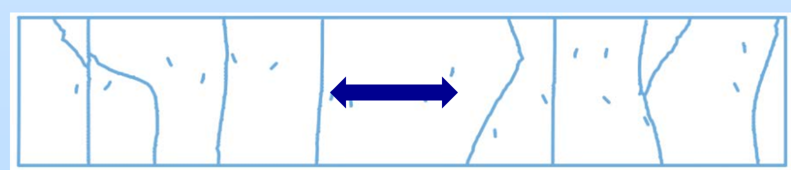
Assume subcritical crack growth limit @ 10^{-10} m/s:

- To meet safe storage time>10^4 years, σ<0.004 MPa for wet, σ<0.01 MPa for dry conditions.
- Under σ=1 MPa, failure occurs at 61 days for wet, 402 days for dry.

JOINTS modeling

- Linear elastic, Boundary element code
- Pseudo-3D, accounts for elastic interaction
  - Opening- and mixed-mode fracture propagation
- Allows simulation of fracture network development as function of
  - Subcritical index (SCI) and K_{IC}
  - Elastic material properties
  - Distribution of nucleation sites (seed fractures)



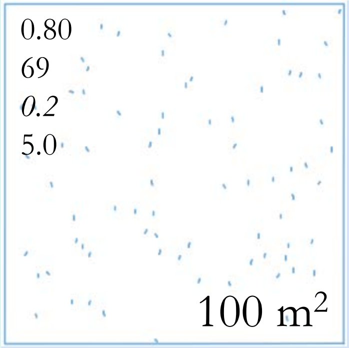
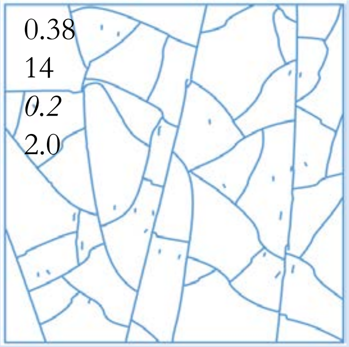
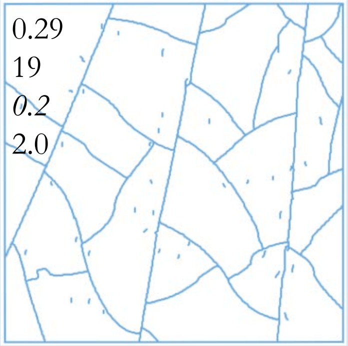
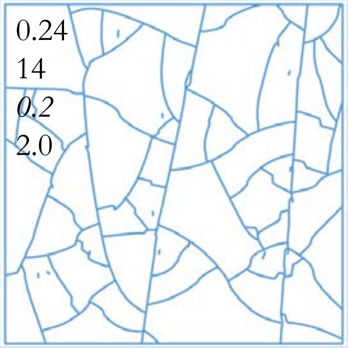
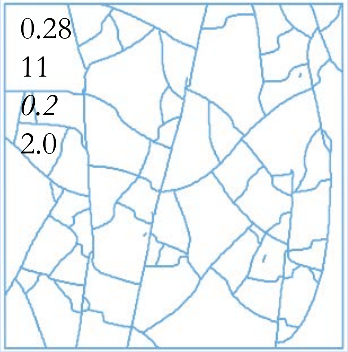
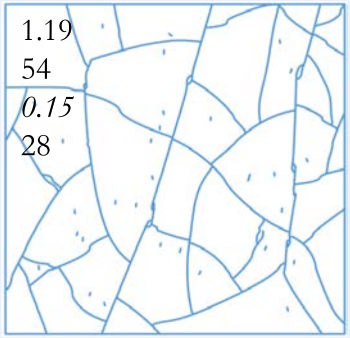
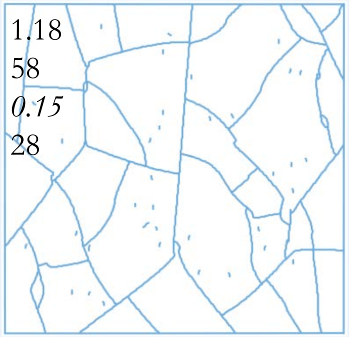
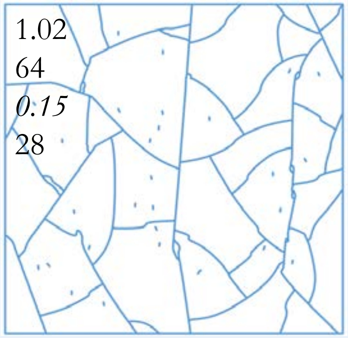
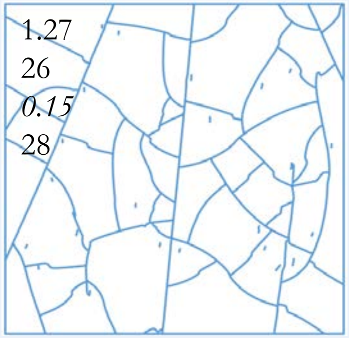


Plan and cross-section realizations

JOINTS plan view

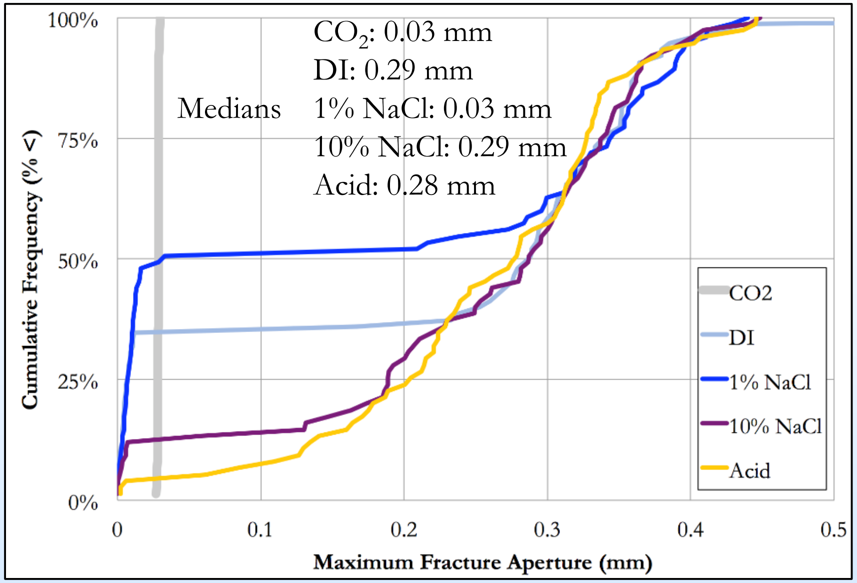
Qualitative differences in fracture network geometry in different chemical environments

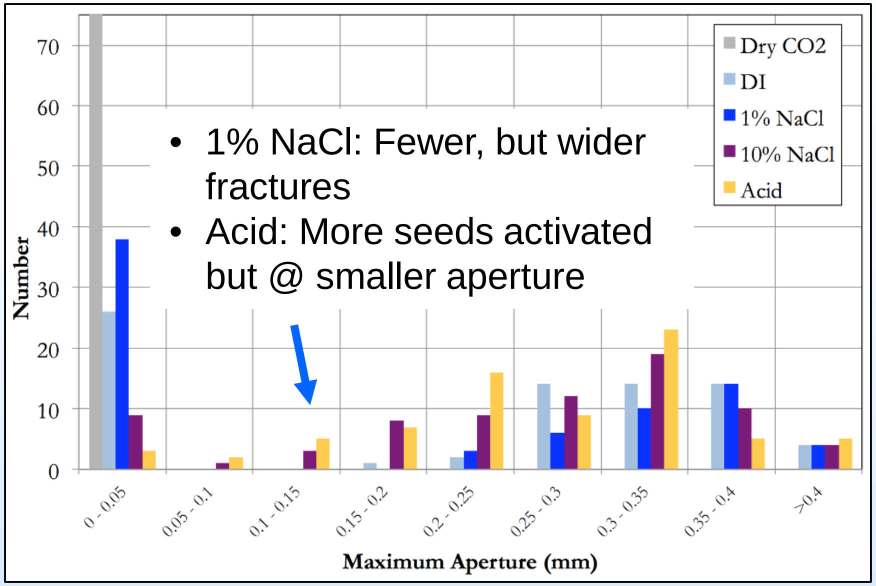
- Number of fractures, branching behavior, curvature

	Dry CO_2	DI water	1% NaCl	10% NaCl	Acid
Woodford	0.80 69 *0.2* 5.0  100 m^2	0.38 14 *0.2* 2.0 	0.29 19 *0.2* 2.0 	0.24 14 *0.2* 2.0 	0.28 11 *0.2* 2.0 
Marcellus	K_{IC} (MPa√m) SCI ν E (GPa)	1.19 54 *0.15* 28 	1.18 58 *0.15* 28 	1.02 64 *0.15* 28 	1.27 26 *0.15* 28 

Fracture aperture distribution

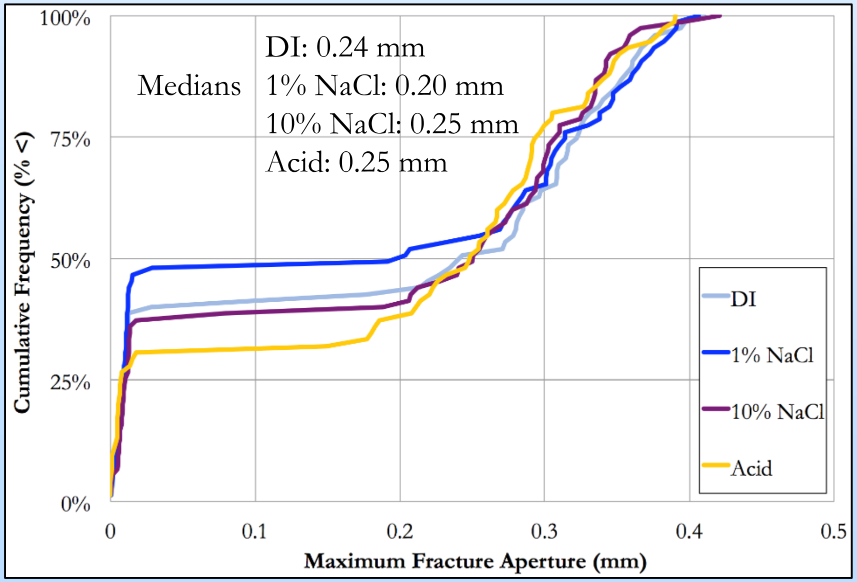
Woodford

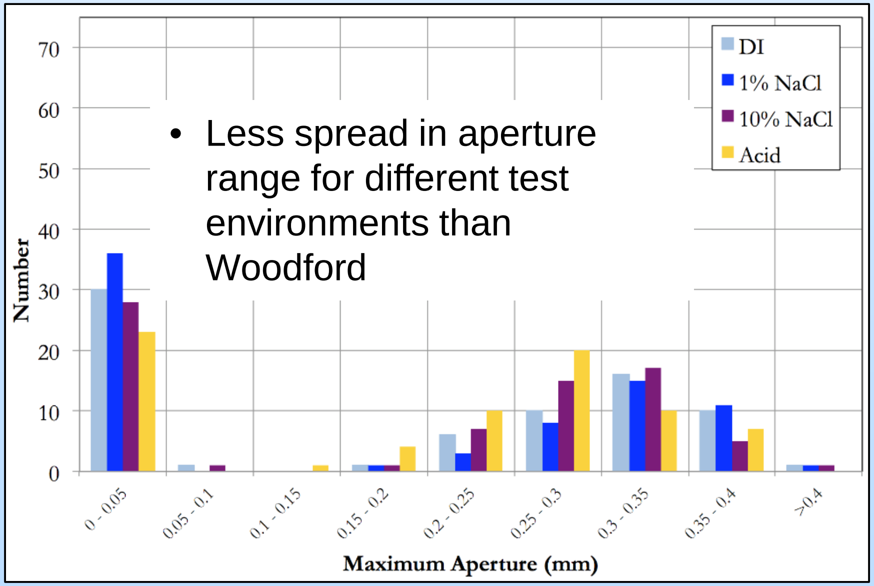




- 1% NaCl: Fewer, but wider fractures
- Acid: More seeds activated but @ smaller aperture

Marcellus





- Less spread in aperture range for different test environments than Woodford

JOINTS cross sections

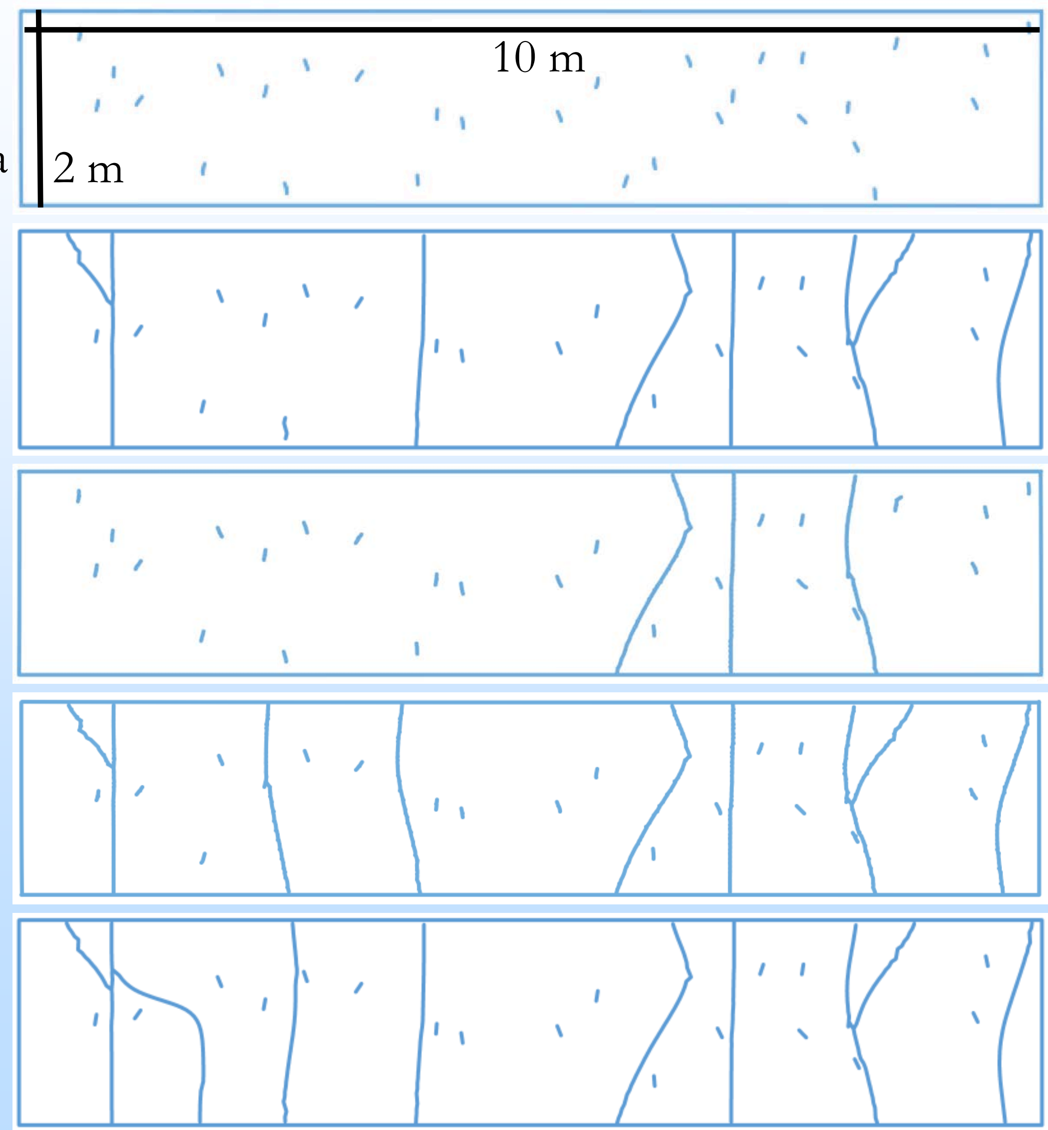
Woodford, **dry CO_2**
0.80 MPa√m, 69, 5.0 GPa

Woodford, **DI water**
0.38 MPa√m, 14, 2.0 GPa

Woodford, **1% NaCl**
0.29 MPa√m, 19, 2.0 GPa

Woodford, **10% NaCl**
0.24 MPa√m, 14, 2.0 GPa

Woodford, **acid**
0.28 MPa√m, 11, 2.0 GPa



Summary

- Chemical environments, rock mineralogy, and temperature influence shale fracture properties.
- Larger wet-dry differences in clay-rich shales (Woodford and Mancos) than in carbonate-rich shale (Marcellus).
  - "Wet" fracture growth rate faster by one-order of magnitude
- Increasing temperature enhances subcritical fracturing.
- Carbonate-rich Marcellus: carbonate dissolution
  - SCI sensitive to acidic pH
  - K_{IC} independent of chemical environment
- Woodford & Mancos: clay-water interaction
  - KIC and SCI sensitive to water content and salinity.
  - Water-weakening enhances subcritical fracturing
- Environmental effects controlled by competition between fracture growth rate and rate of rock degradation by fluid-rock interactions.

Implications for CO_2 seal integrity

- Dry tests potentially applicable to dry scCO_2 systems
  - Dry-out by CO_2 injection expected to strengthen caprock
- Increasing caprock failure risk with increasing temperature
- Clay-rich caprocks:
  - More pronounced dry-out effect
  - Lower risk for seal failure by subcritical fracture growth in scCO_2 system
  - High salinity strengthens caprock
- Carbonate-rich caprocks:
  - More prone to subcritical fracture by pH decrease through dissolution of CO_2 in brine

Accomplishments to Date

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

Next steps (in progress)

- Short-rod fracture testing under confinement with $scCO_2$
- Upscaled seal failure & leakage simulations
  - Integration of continuum & fracture network modeling

Synergy Opportunities

- Fracture mechanics analysis of Cranfield and FutureGen II core material
- Integration with tests of frictional behavior under chemically reactive conditions
- Integration of results with fracture network modeling (phase-field, cohesive end-zone, peridynamics)
- Integration with hydraulic fracture research

Appendix

Benefit to the Program

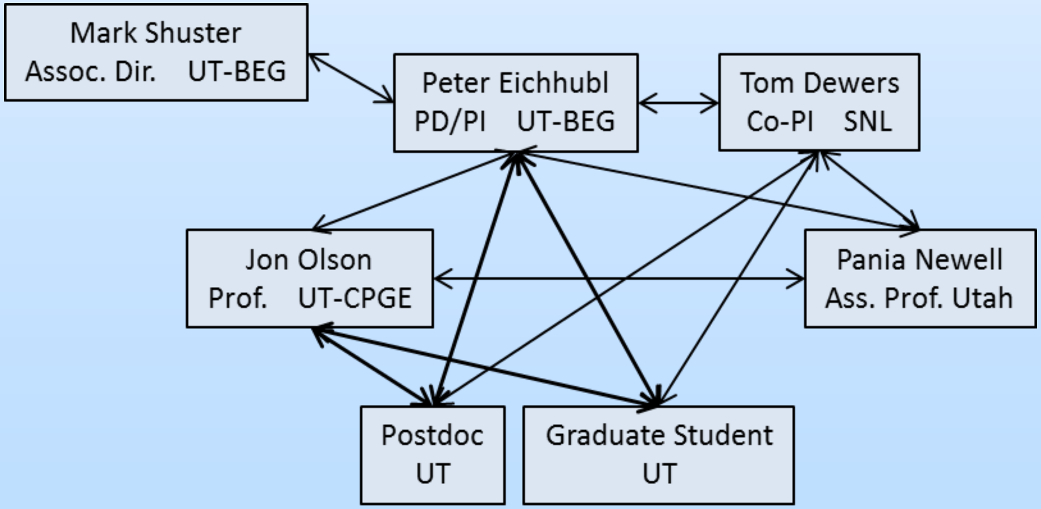
- Program goals: Develop characterization tools, technologies, and/or methodologies that improve the ability to predict geologic storage capacity within ±30 %, improve the utilization of the reservoir by understanding how faults and fractures in a reservoir affect the flow of CO_2, and ensure storage 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

- ***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.

Organization Chart/ Communication Plan

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



Gantt Chart

Task/Subtask	Year 1				Year 2				Year 3				Year 4**			
	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	10/1/2017-12/31/2017	1/1/2018-2/31/2018		
1. Project Management and Planning	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	p	p	p		
2.1. Short rod fracture toughness tests	*	*	*	*	*	*	*	*	*	*	*	*				
2.2. Double torsion tests	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	p	p			
2.3. Fracturing in water-bearing supercritical CO2		✓	✓	✓	✓	✓	✓	✓				p	p			
3.1. Field fracture characterization	✓	✓	✓	✓	✓	✓	✓	✓								
3.2. Textural and compositional fracture imaging				✓	✓	✓	✓	✓	✓	✓	✓					
4.1. Discrete fracture modeling using Sierra Mechanics	✓	✓	✓	✓	✓	✓	✓					p	p	p		
4.2. Fracture network modeling using JOINTS						✓	✓	✓	✓	✓	✓	p	p	p		
4.3. Upscaled modeling using Kayenta					✓	✓	✓									
5. Model validation and integration									✓	✓	✓	p	p	p		

*** Short-rod tests (task 2.1) are being performed under task 2.3 under confined conditions.**
**** No-cost extension pending following discontinuity of funding for Sandia in PY 17.**

Bibliography

- Journal, multiple authors:

  - 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
  - Chen, X., Eichhubl, P., Olson, J. E., 2017, Effect of water on critical and subcritical fracture properties of Woodford shale, Journal of Geophysical Research-Solid Earth, v. 122, http://dx.doi.org/10.1002/2016JB013708