Fracture mechanics of shales under chemically reactive conditions

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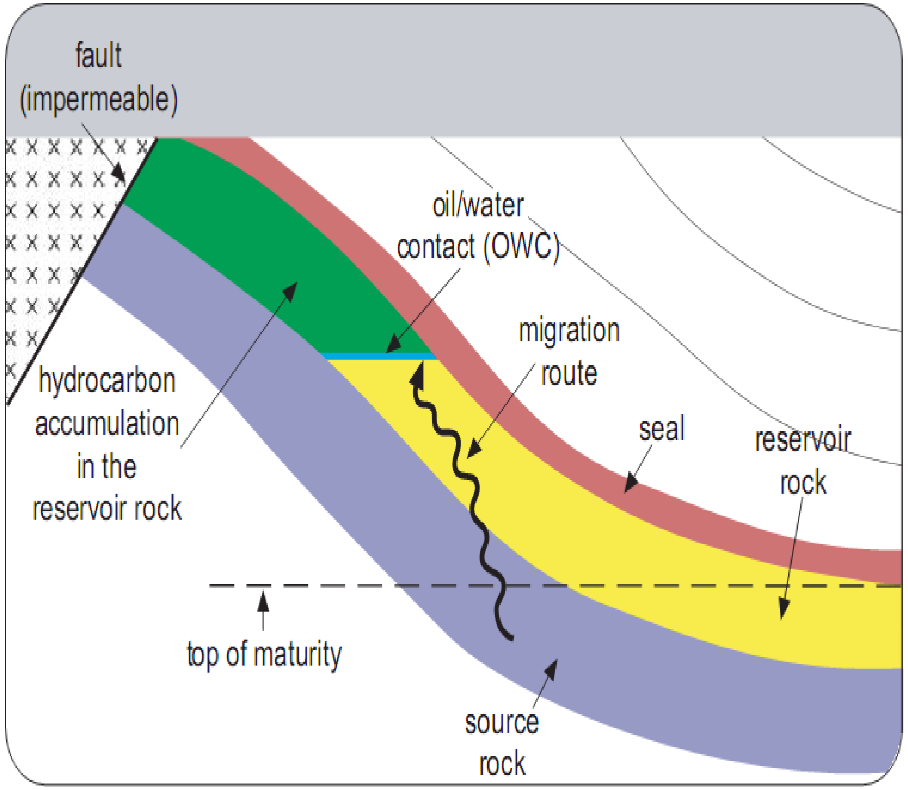
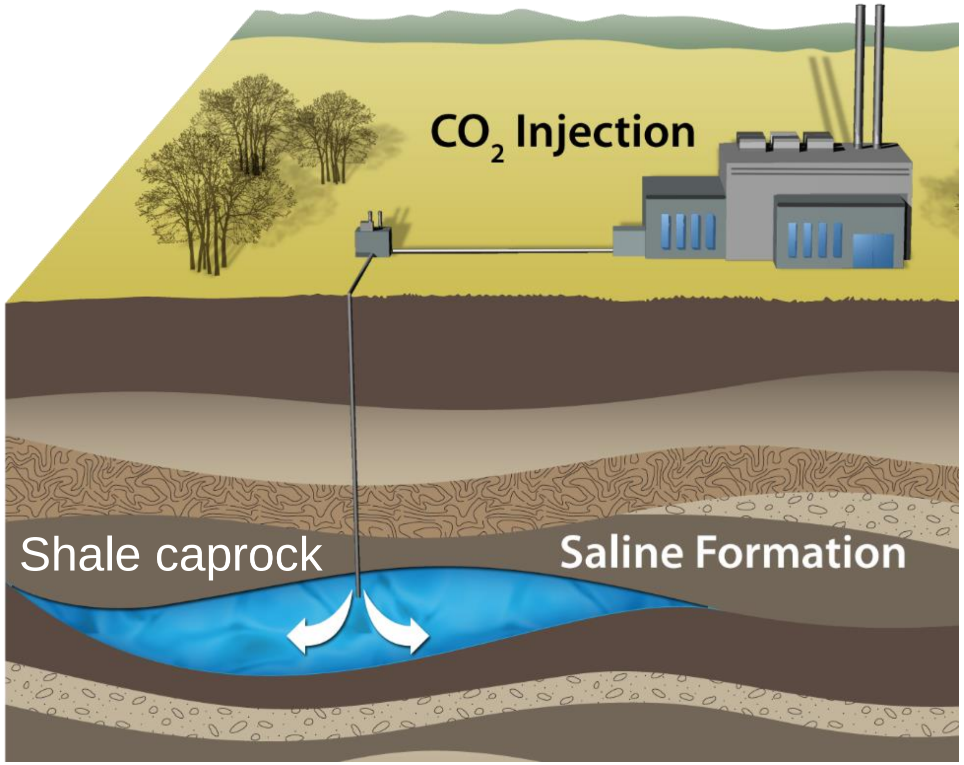
Motivation

Problem: **fracture growth under chemically reactive conditions**.

Fluid-rock interactions ⟷ **Fracture growth**.



Petroleum system

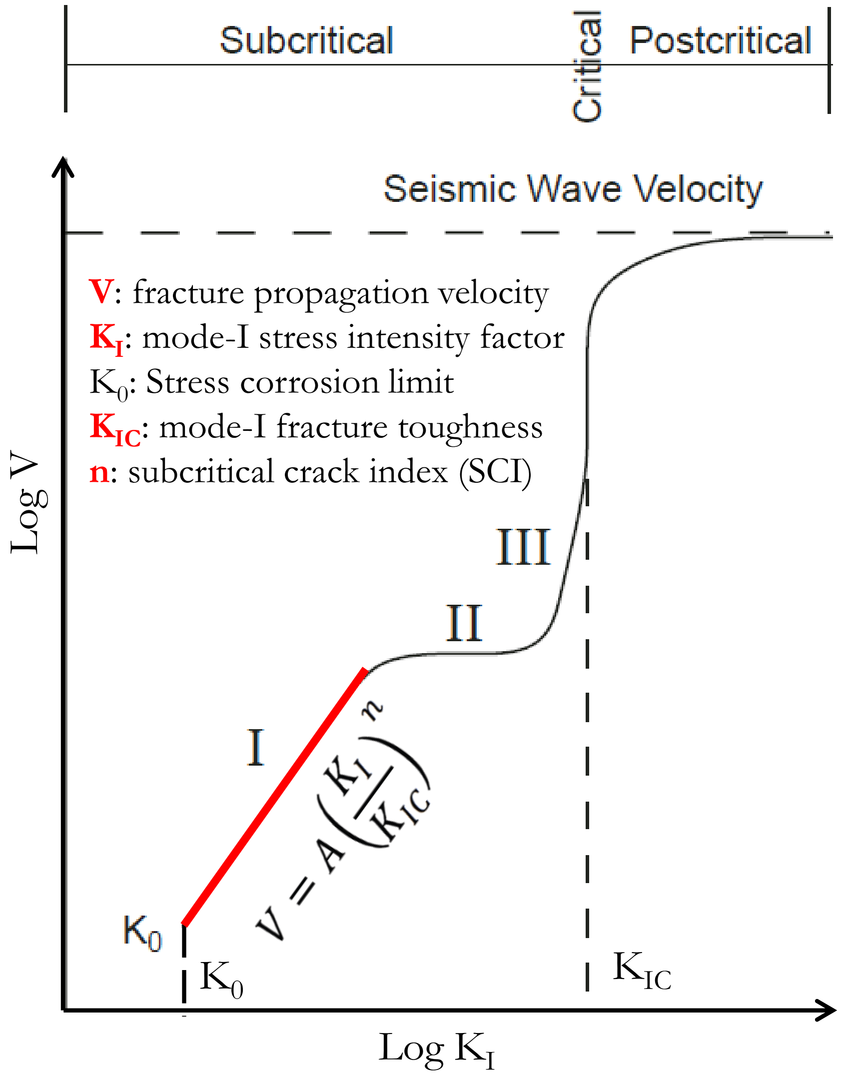


Carbon sequestration

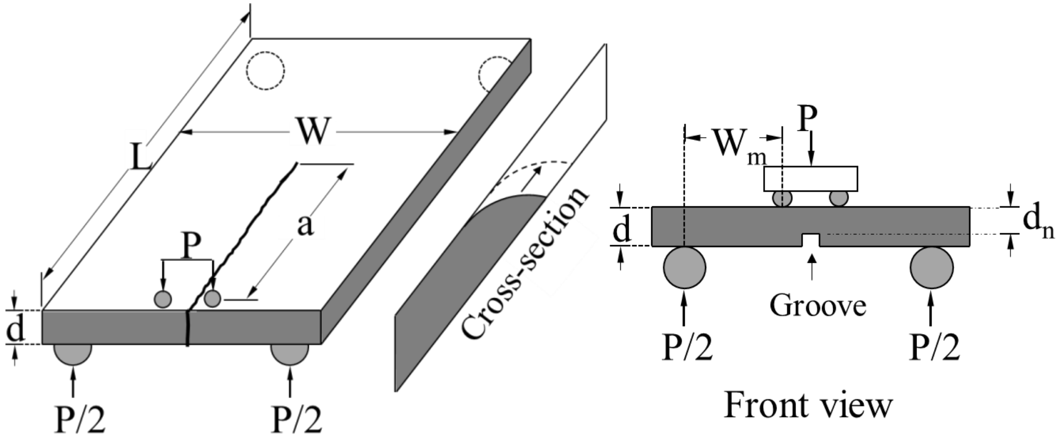
Approach: subcritical fracturing tests under chemically reactive conditions.

Mode I fracture testing

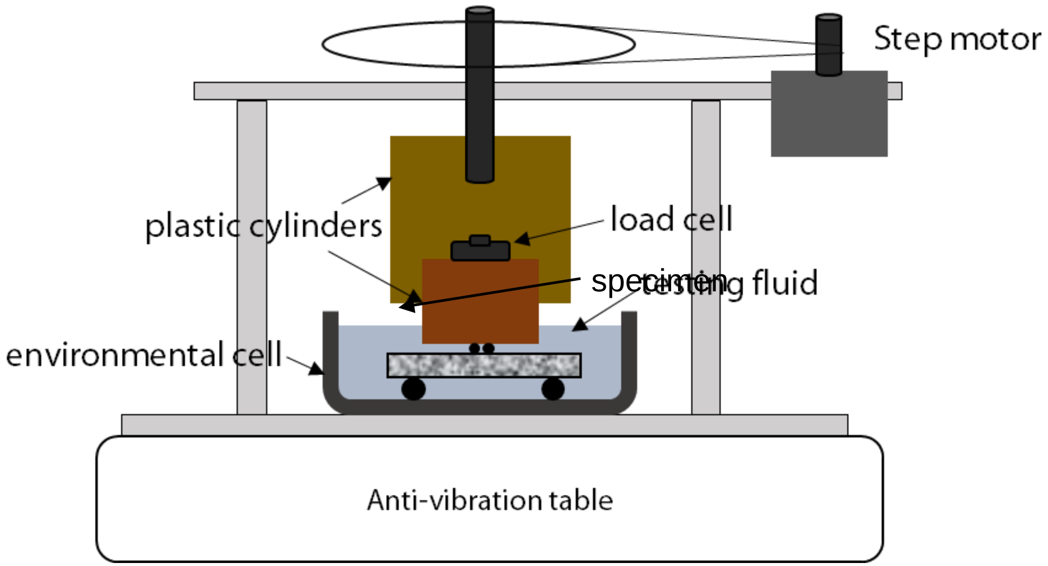
K-V curve



Specimen configuration

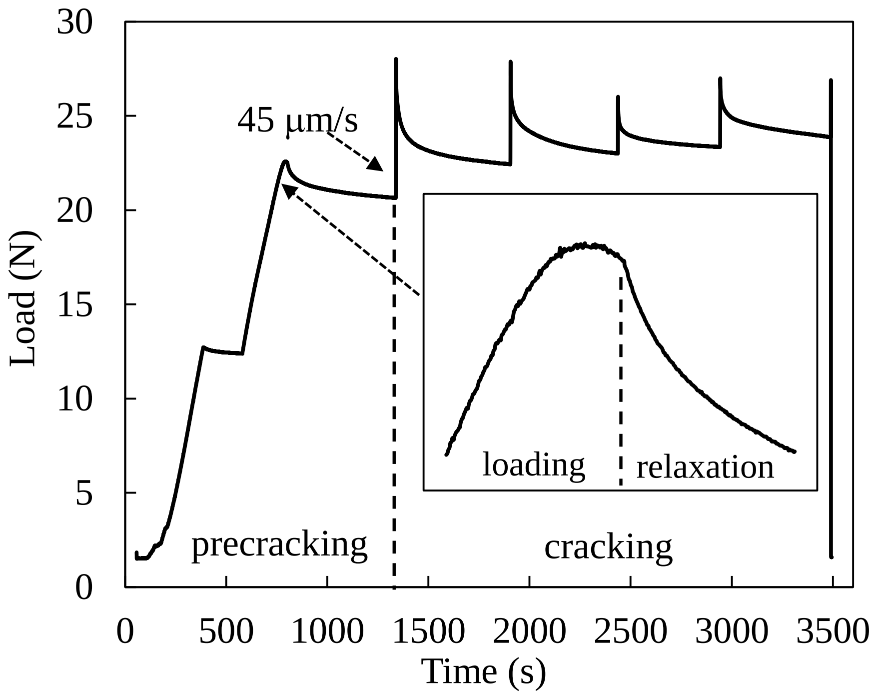


Experimental setup

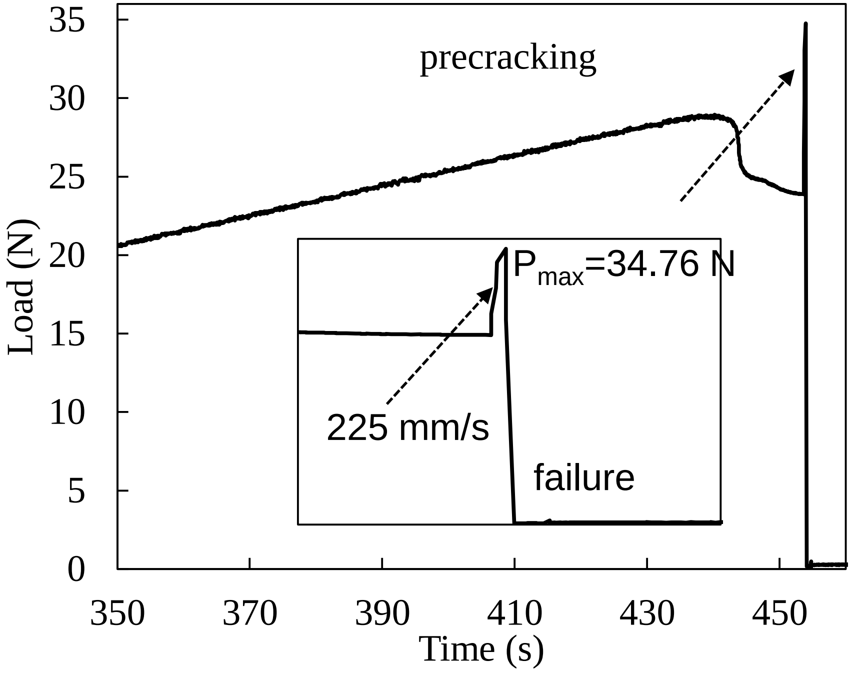


Mode-I fracture testing

Load relaxation: SCI and K-V curves



Critical failure: K_{IC}

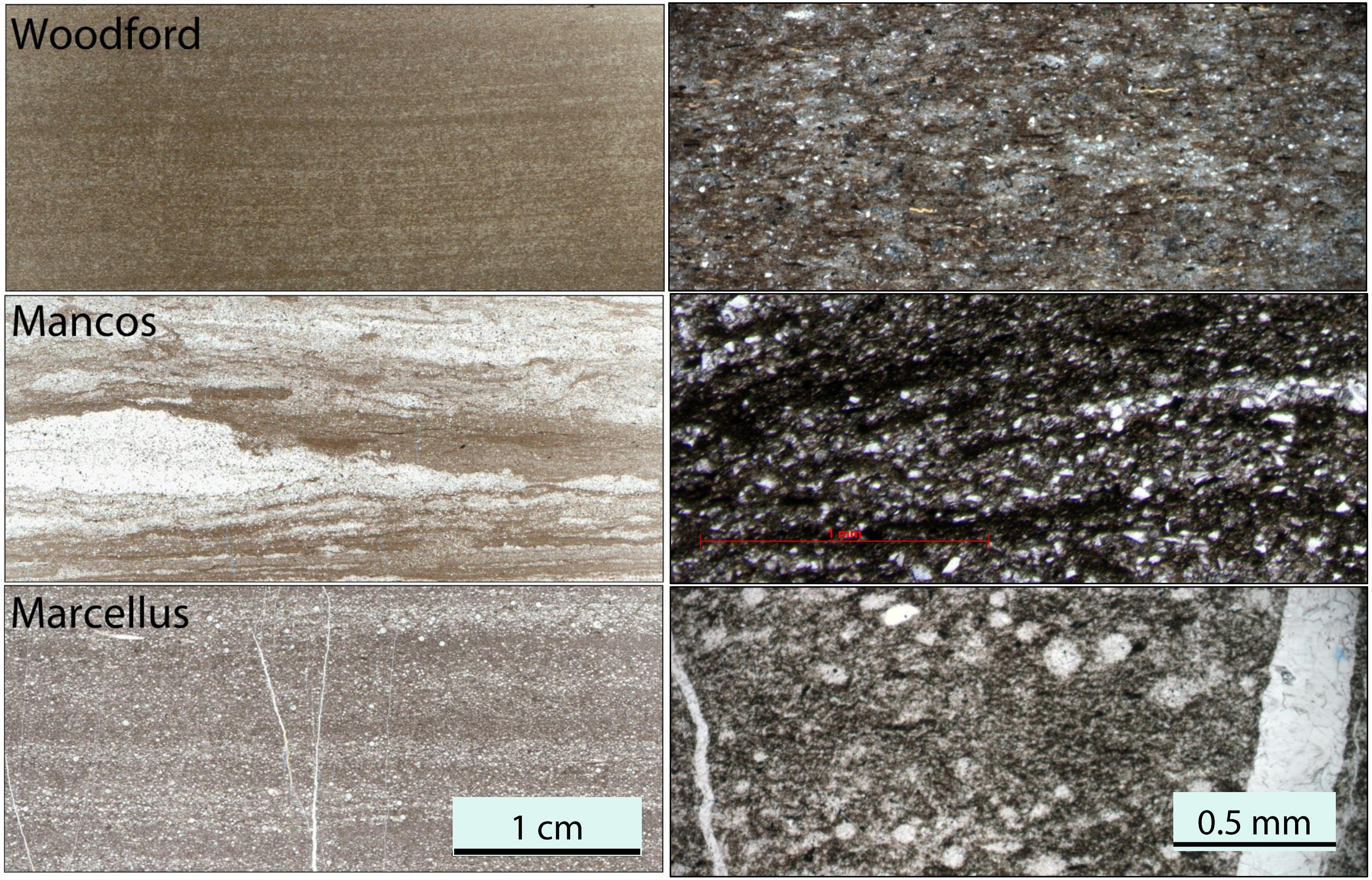


$$K = PW_m \left[\frac{3(1+\nu)}{Wd^3 d_n \psi}\right]^{1/2} \qquad V = -\phi \frac{P_0 a_0}{P^2}\frac{dP}{dt}$$

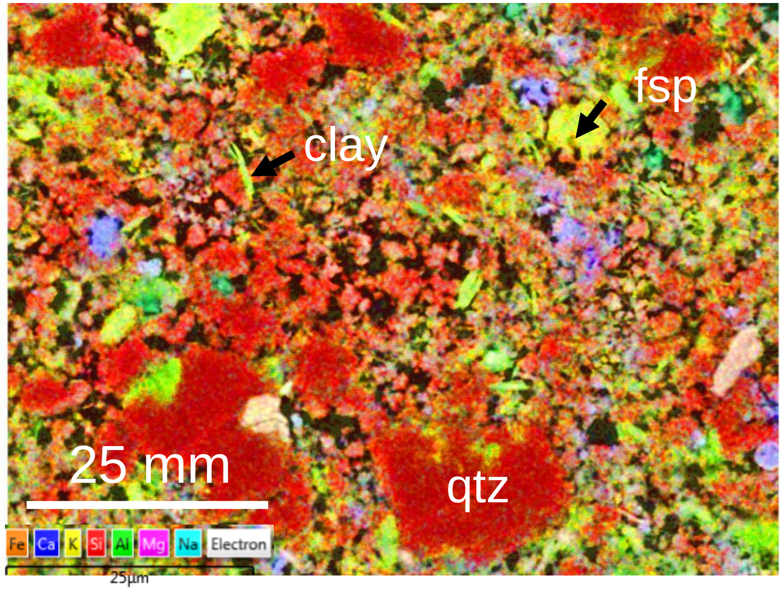
Testing protocol

- 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

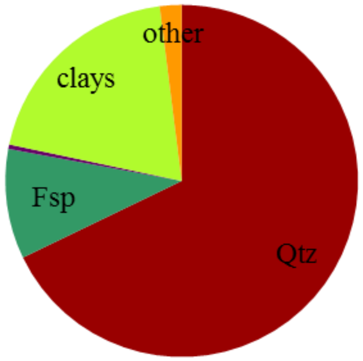
Three shale lithologies



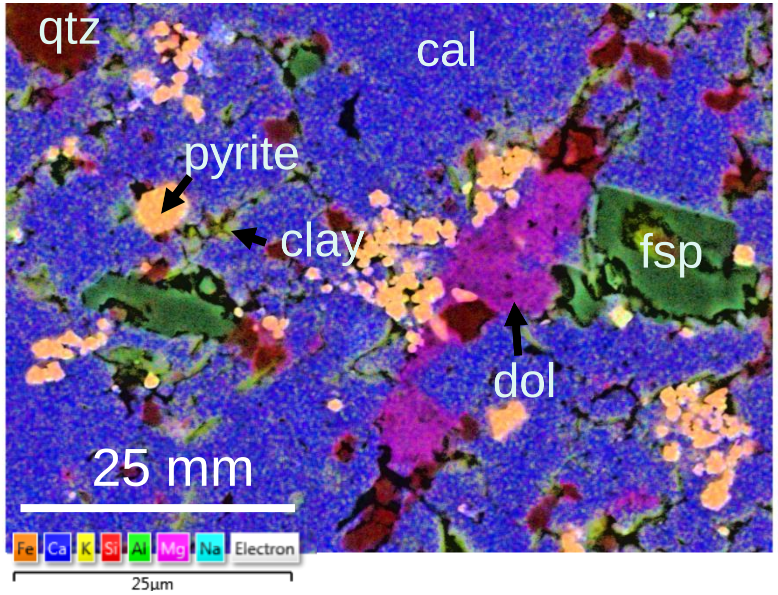
Shale sample composition



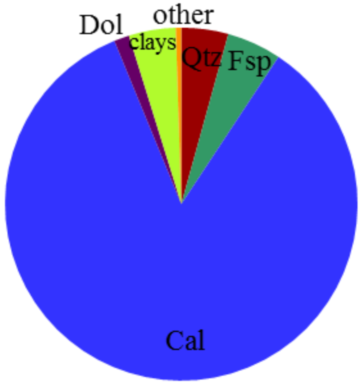
Woodford shale



Quartz, clays, fsp

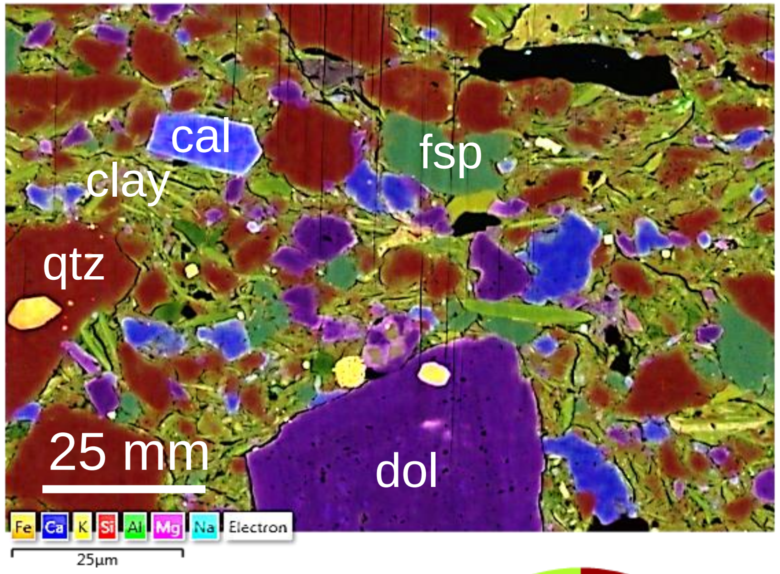


Marcellus shale

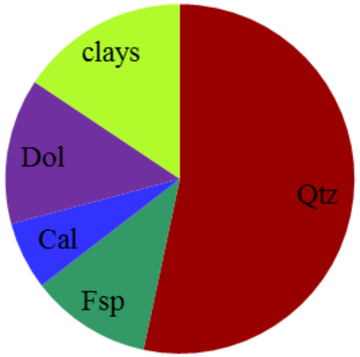


Calcite

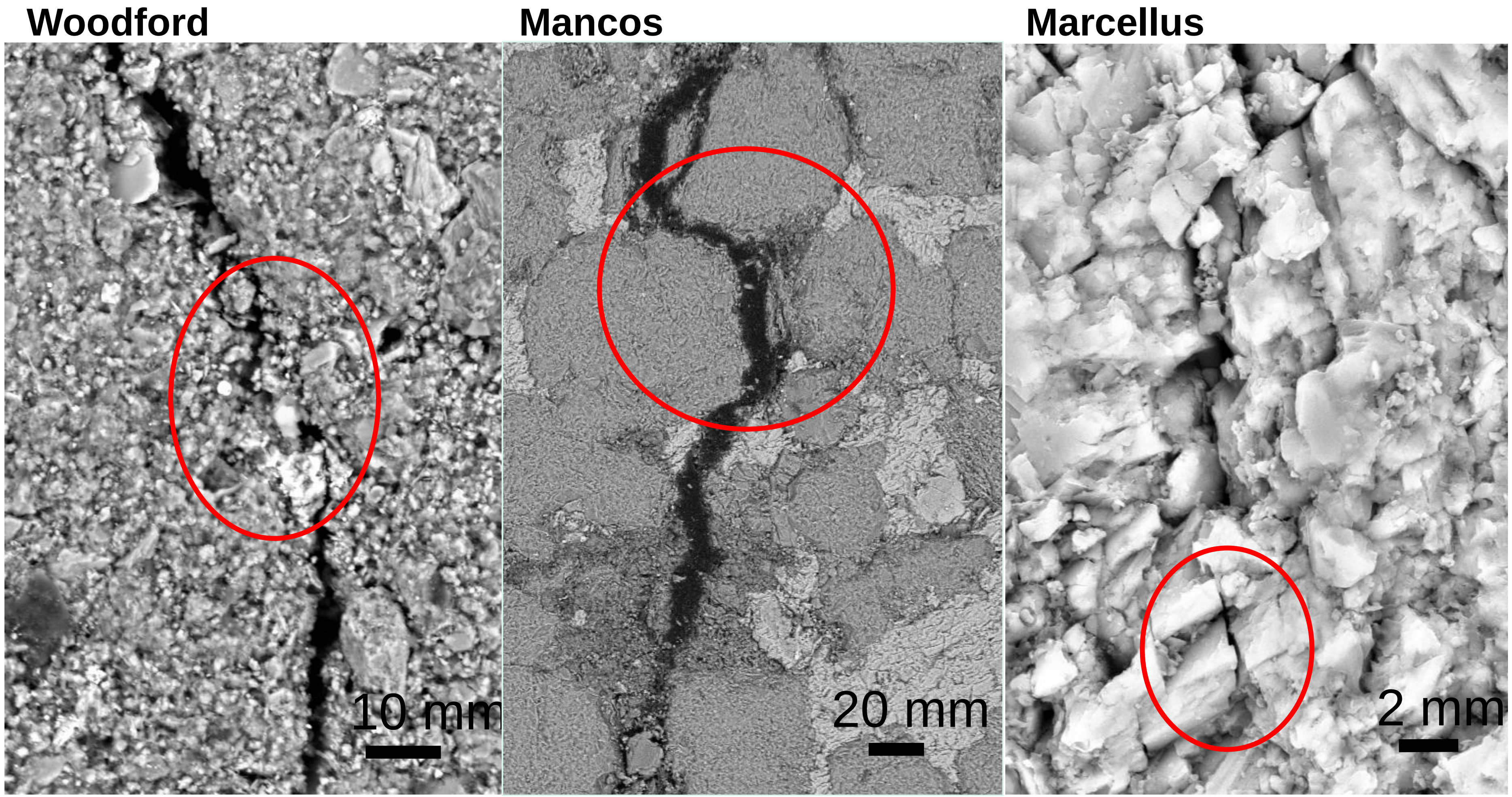
Mancos shale



Quartz, clays, carbonate



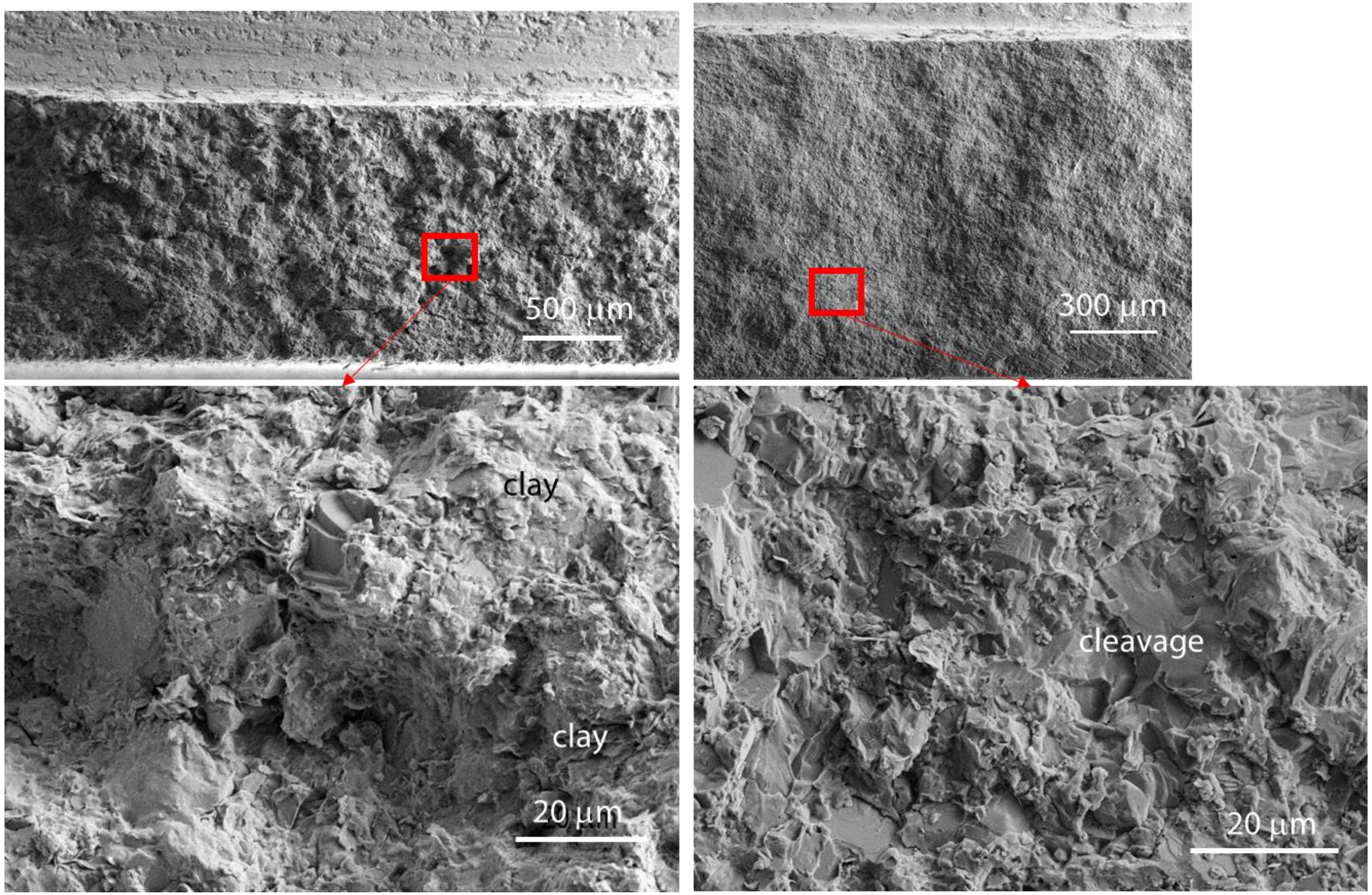
Fracture trace imaging



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

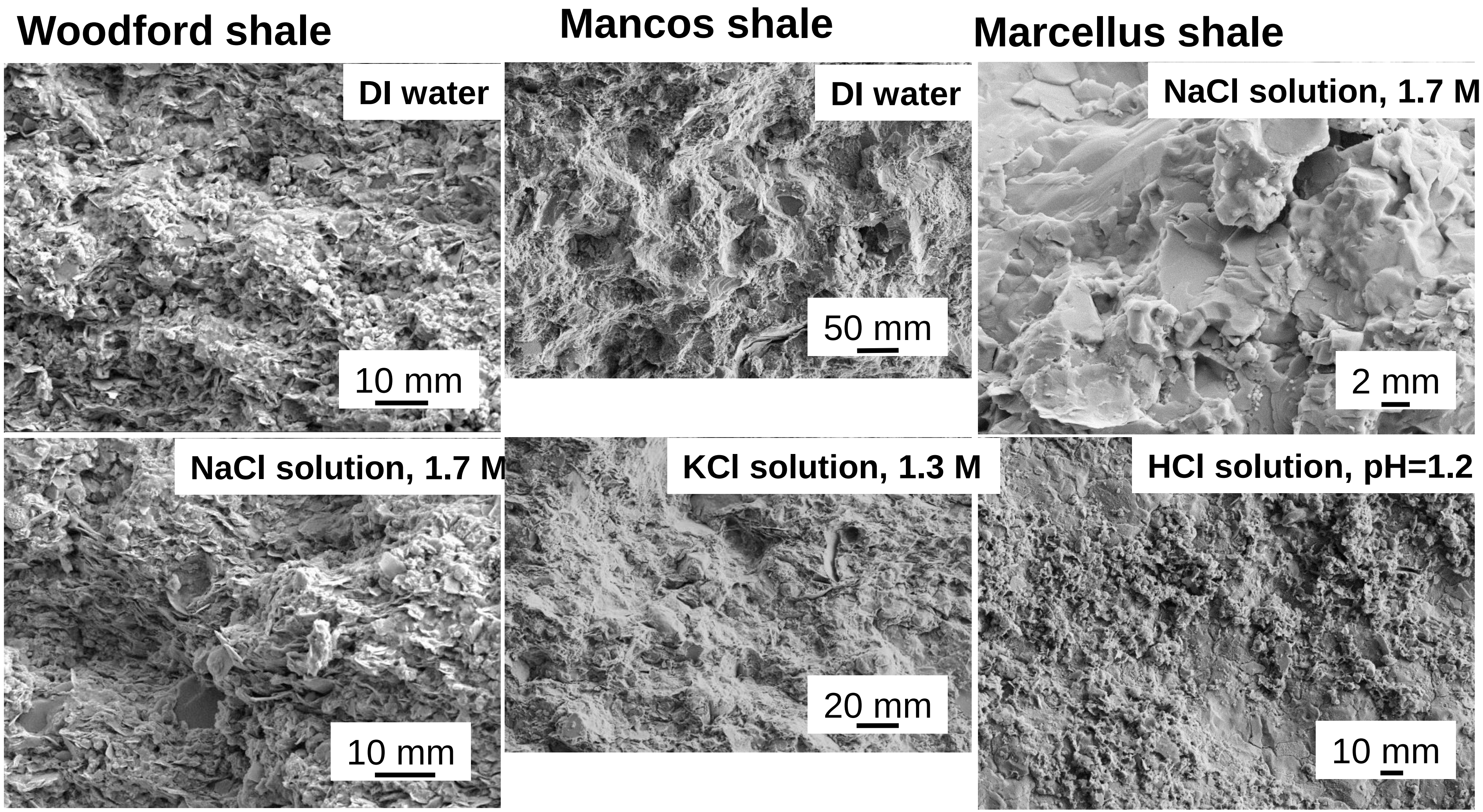
Fracture surface imaging

Mancos shale **Marcellus shale**



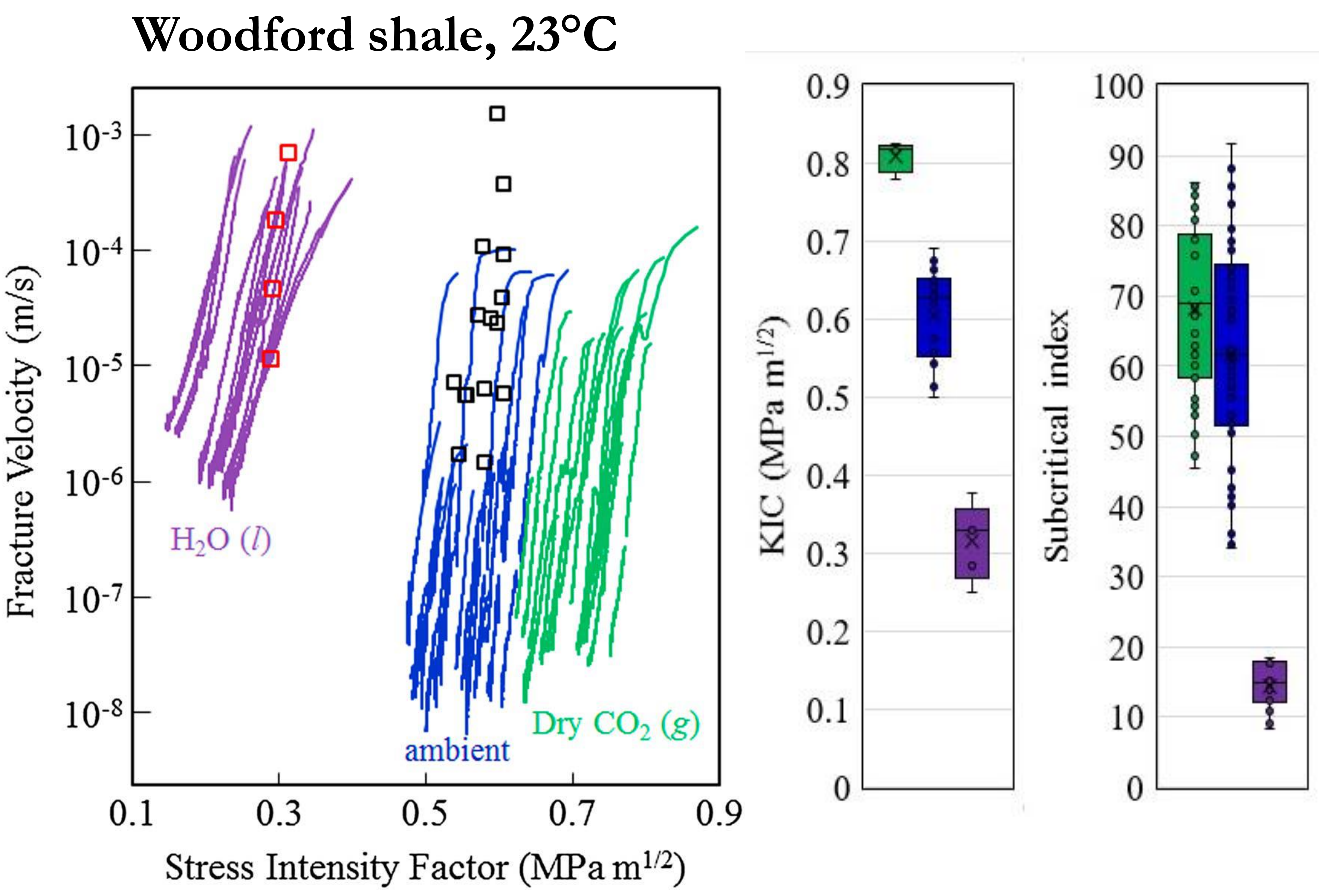
- Roughness variation, but no plumose structure
- Grain boundary breakage vs transgranular breakage

Fracture surface imaging



Fracture surface features invariable with fluids conditions, indicating similar subcritical fracturing process.

Fracture response: Water content

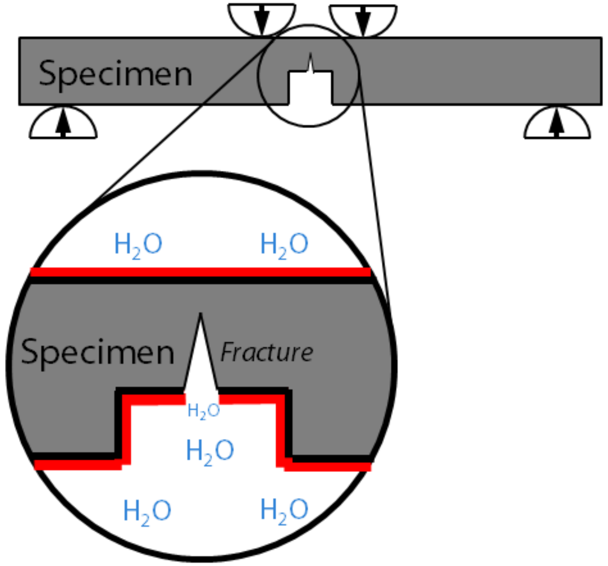


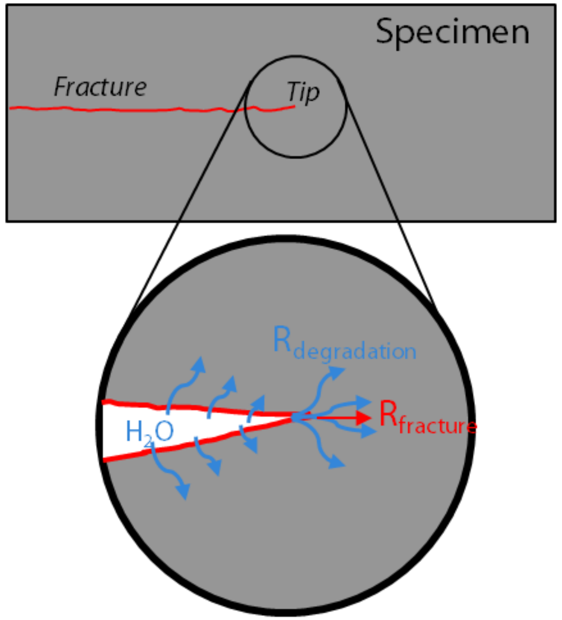
Water enhances subcritical fracturing for clay-rich shales

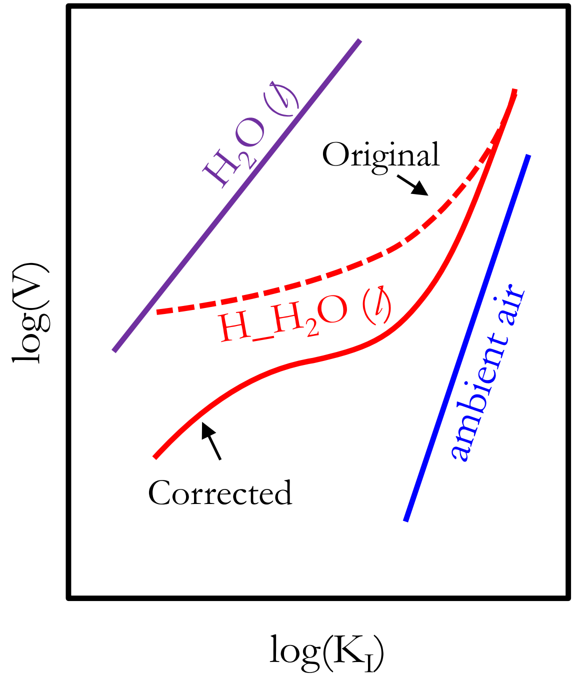
- Strong reduction of K_{IC} (48%) and SCI (75%) with increasing water content
- K-V curves obey power-law, indicating fracturing in stress-corrosion regime (I)
- Load relaxation technique (lines) matches constant loading rate method (squares)

Transient weakening response: Coated samples

- Hydrophobic coating restricts water-sample interaction to the fracture tip
- Coating temporarily protects specimens from weakening except at fracture tip
- Transient K-V curves.
  - ❑ Only for clay-rich Woodford and Mancos shales
  - ❑ Competition between **<u>fracture growth</u>** and **<u>rock degradation</u>** by H_2O-rock interaction

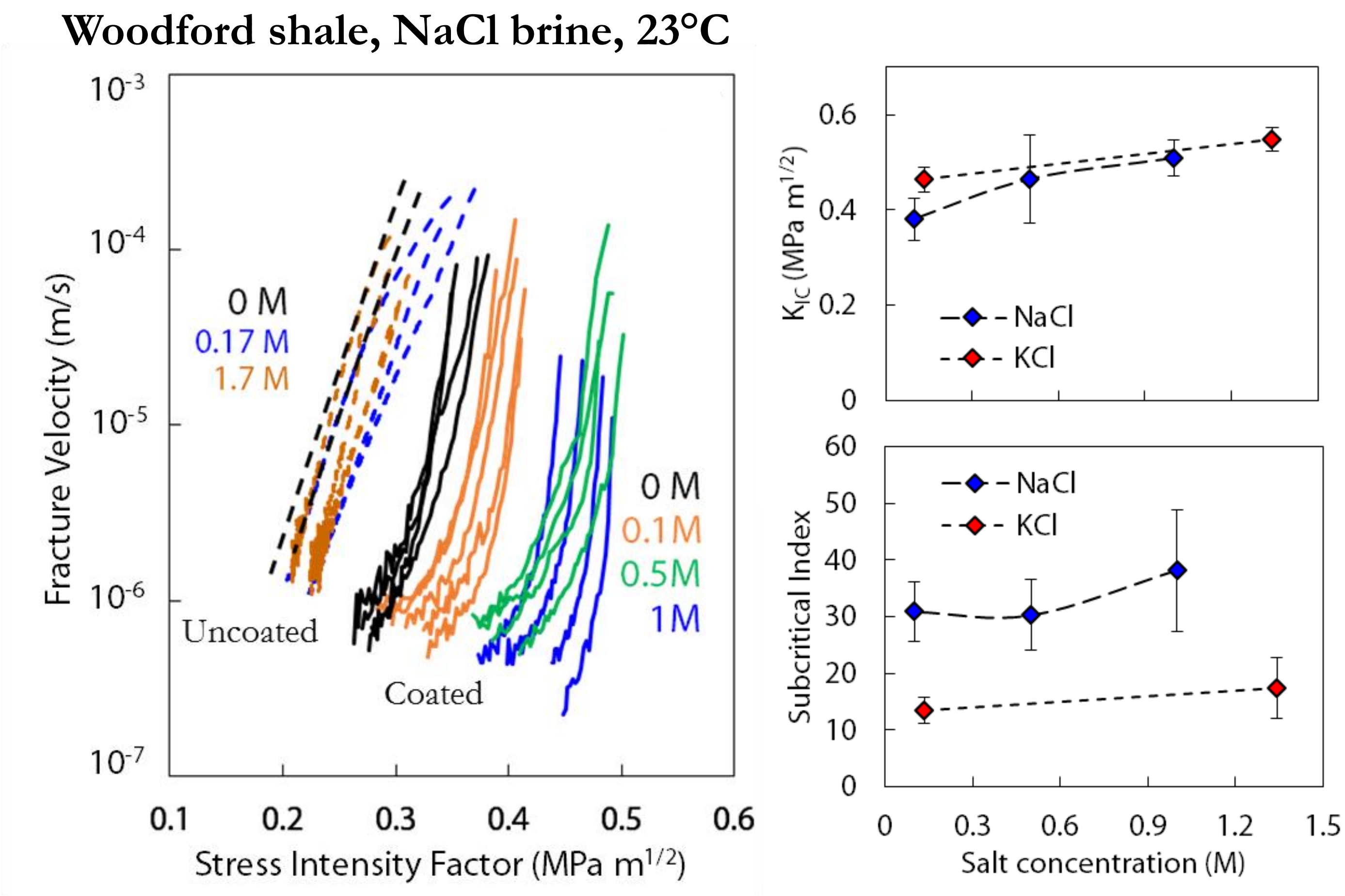






Chen et al., JGR 2017

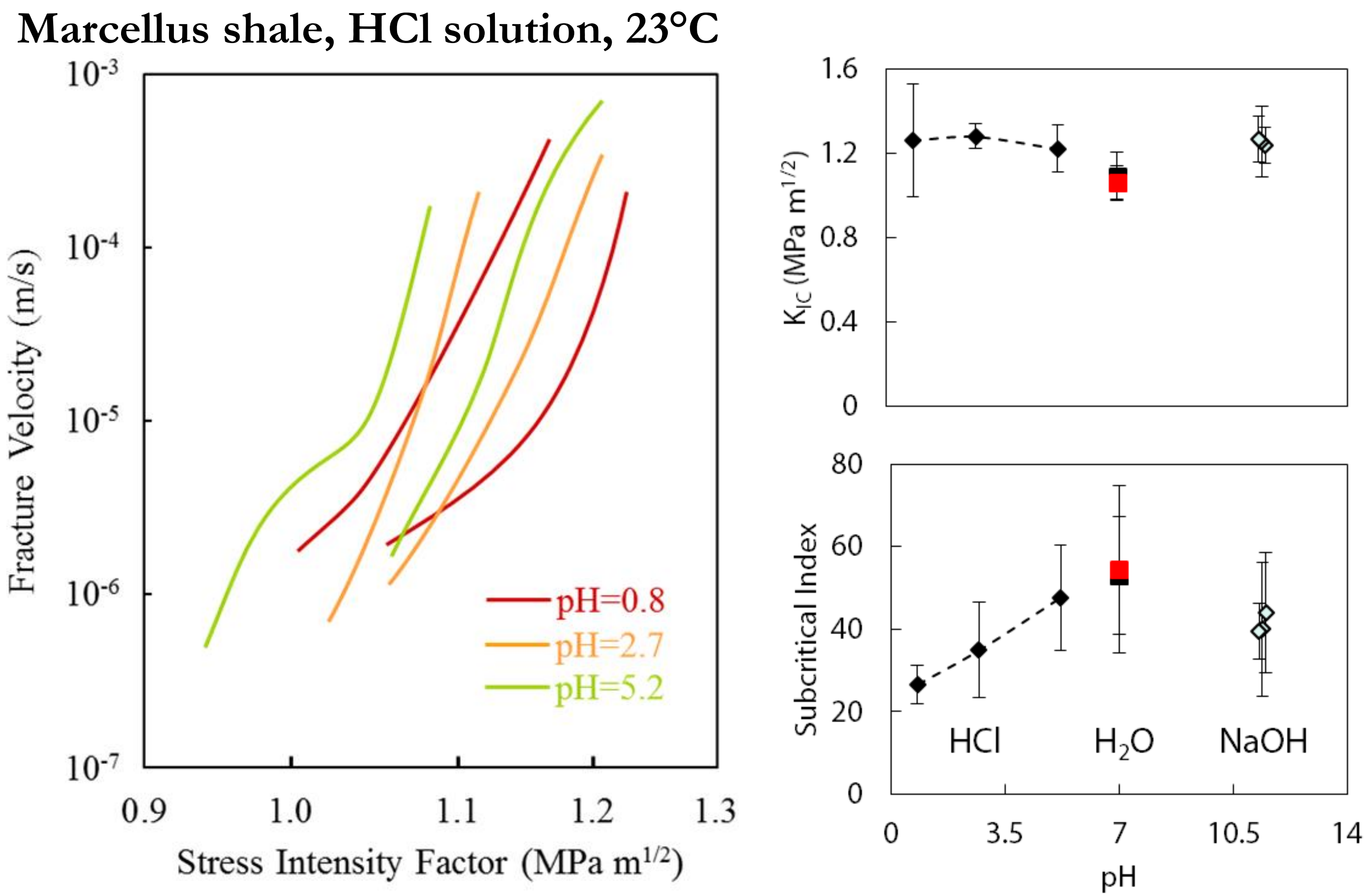
Fracture response: Salinity



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

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

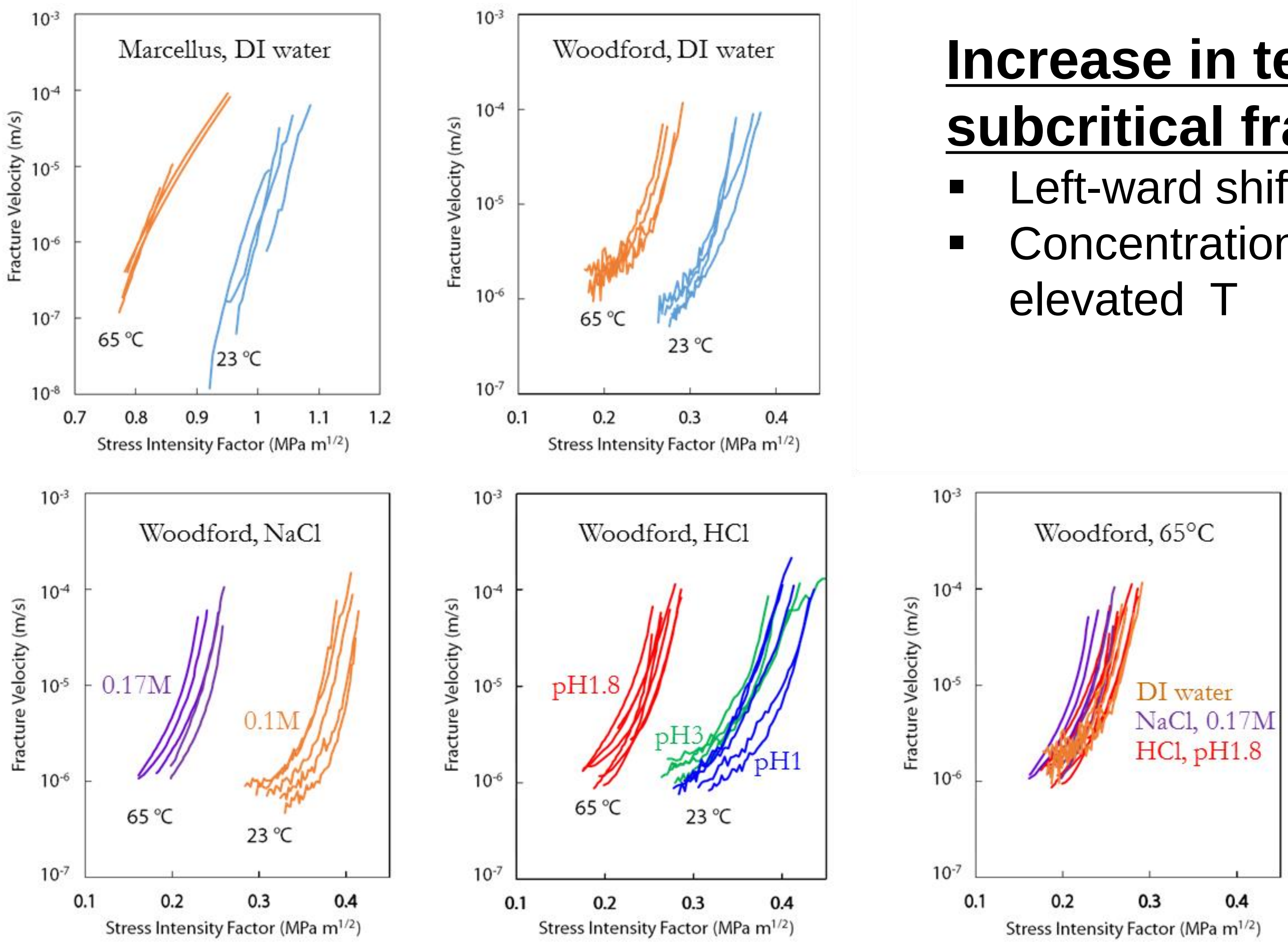
Fracture response: pH



SCI decreases with decreasing pH for carbonate-rich Marcellus shale

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

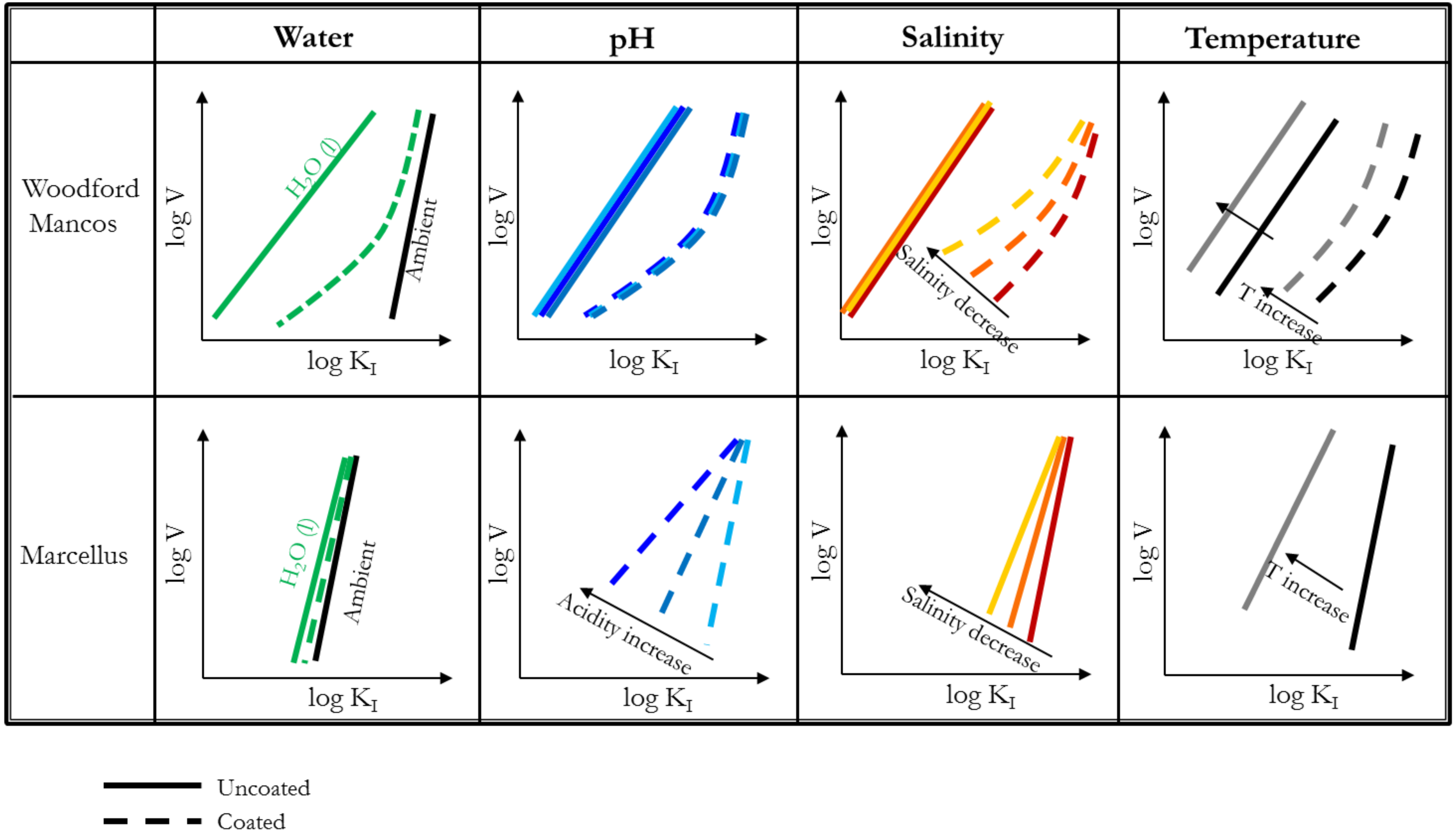
Fracture response: Temperature



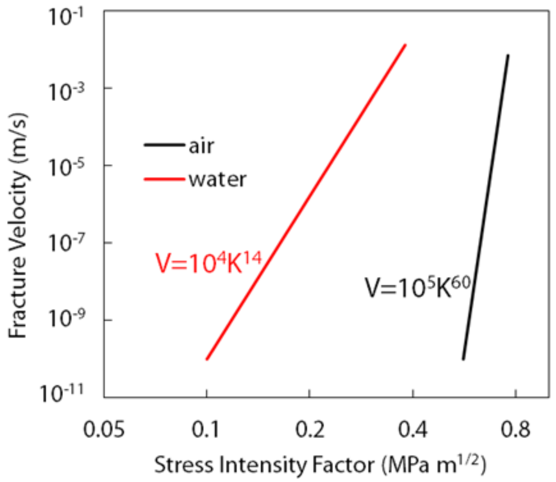
<u>Increase in temperature enhances subcritical fracturing</u>

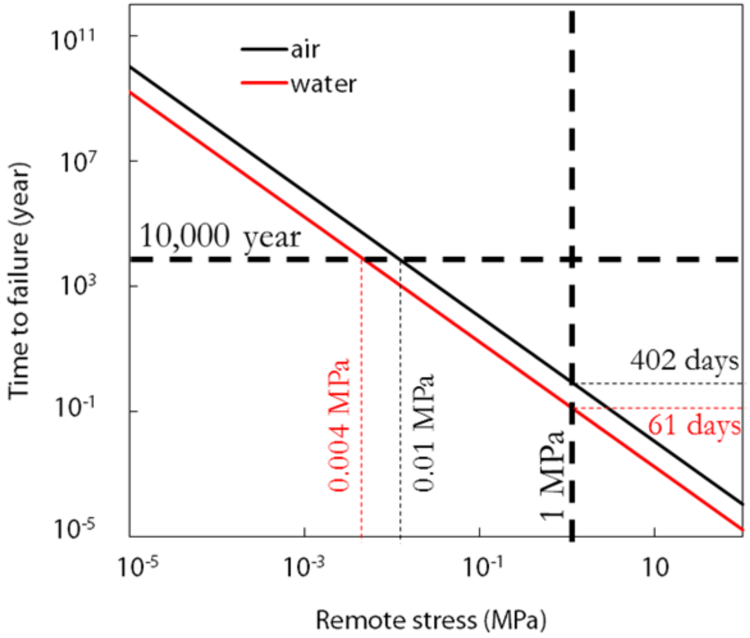
- Left-ward shift for all shales
- Concentration effects less pronounced at elevated T

Environmental effects on K-V behavior



Time-to-failure analysis





Constant stress loading:

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

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

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.

Summary

- Chemical environments , rock mineralogy, and temperature influence shale fracture properties.
- Stronger 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-fluid interaction
  - K_{IC} 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

- Fracture growth strongly affected by *water content* variations
  - Natural fractures: lithification, diagenesis, oil-water system, gas charging
  - Engineered systems: hydraulic fracturing, EOR, CO_2 sequestration
- Higher *temperature* systems have higher propensity for subcritical fracture growth.
- *Clay-rich* rocks:
  - more sensitive to water-weakening.
  - high salinity suppresses water-weakening.
  - higher risk for seal failure with subcritical fracture growth.
- *Carbonate-rich* rocks:
  - more prone to subcritical fracture by pH decrease (CO_2 EOR, CO_2 sequestration, organic acids).