Double torsion fracture mechanics testing of CO_2 reservoir caprocks

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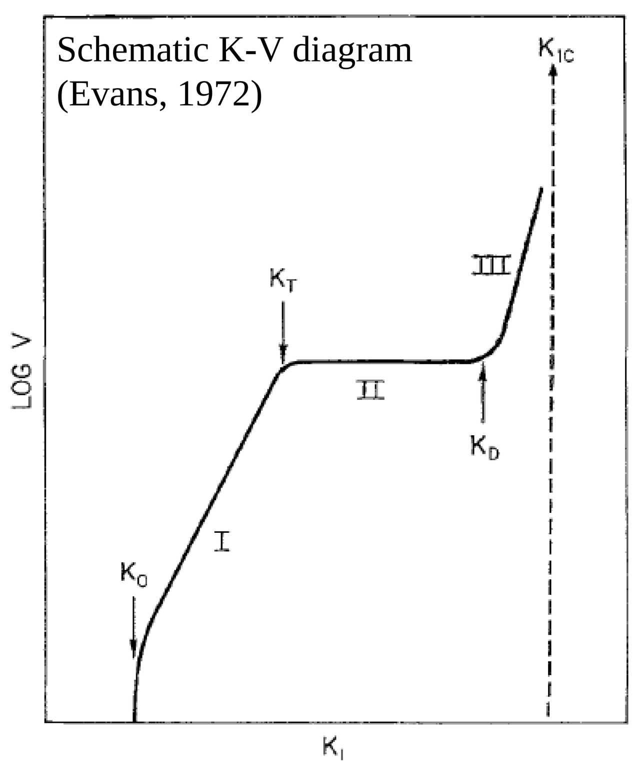
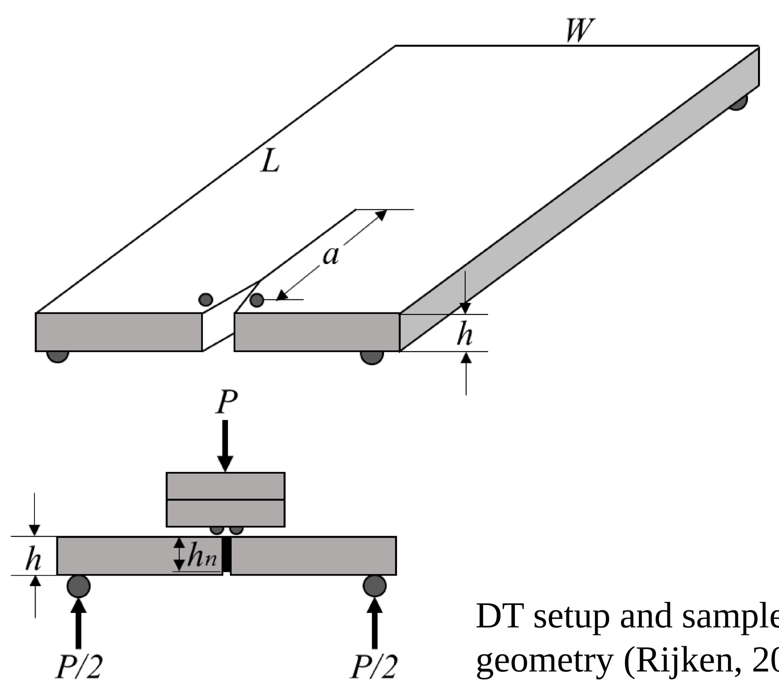
Introduction

One of the main issues for CO_2 sequestration is the risk of CO_2 leakage. Reservoir seal capacity is affected by short-term integrity during CO_2 injection, and long-term stability of the seal after injection. During injection, increased pore pressure may cause hydraulic fracturing of the caprock or triggering slip on pre-existing faults. Subcritical crack growth is the main concern for long-term seal integrity. Stress analysis and geomechanical tests such as leak-off and mini-frac tests are used to evaluate the hydraulic fracturing and fault reactivation potential, while fracture tests are used to study subcritical fracture growth.

Fracture growth is divided into three regimes based on the relationship between the stress intensity factor (K_I) and the crack velocity (V). At large K_I close to fracture toughness (K_{IC}), crack growth is controlled by mechanical rupture (region III); at intermediate K_I, the rate of transport of corrosive species controls crack growth (region II); at low K_I, the rate of the stress corrosion reaction near the crack tip controls crack growth (region I).

Considering the sensitivity of stress corrosion reactions, coupled chemical-mechanical interactions could significantly affect seal integrity during timescales of CO_2 storage in subsurface CO_2 reservoirs. Injection and subsequent dissolution of CO_2 into the aqueous pore fluid are likely to alter the natural water-rock system by accelerating chemical reactions, such as selective dissolution and solution-precipitation, that affect mechanical properties and lead to reduced seal integrity.





DT setup and sample geometry (Rijken, 2005)

Methods

We use the double torsion (DT) load relaxation technique to study subcritical fracture growth (Williams and Evans, 1973). The specimen is sliced into a thin rectangular shape (1.25" x 3" x 0.07") with a central groove to guide fracture growth. The specimen is supported with four ball bearings from below, and the load is applied by the ball bearings near the center of sample axis from above at a constant displacement rate by the step motor. The load and crosshead speed are continuously monitored. After the peak load is reached, the crosshead is then held at a fixed position by stopping the step motor. The load relaxes with time due to subcritical crack growth. The stress intensity factor (K) is proportional to the load (P), and the crack growth rate can be derived from the load relaxation P(t) by

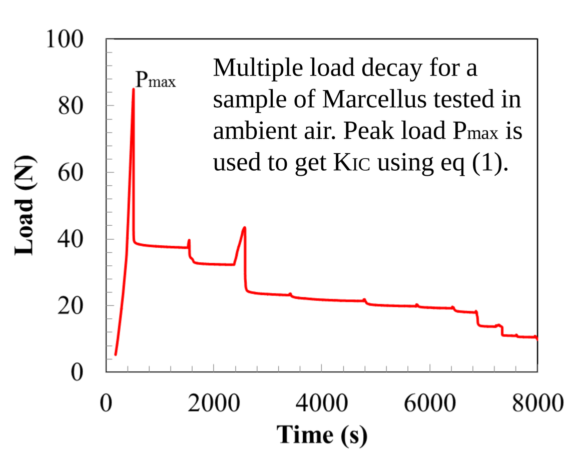
$$K_I = PW_m\sqrt{\frac{3(1+\nu)}{Wh^3h_n}} \qquad (1)$$

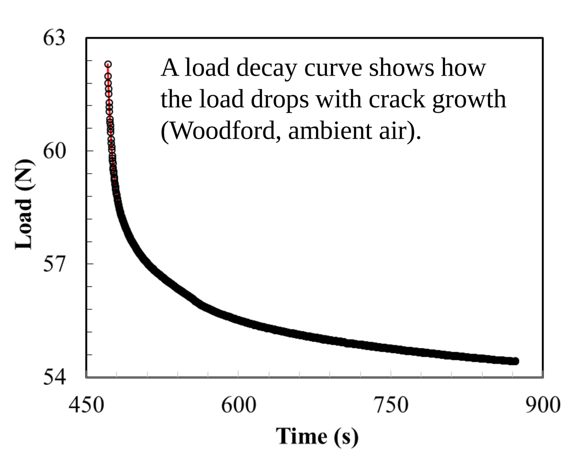
$$V = -\frac{a_iP_i}{P^2}\left(\frac{dP}{dt}\right) \qquad (2)$$

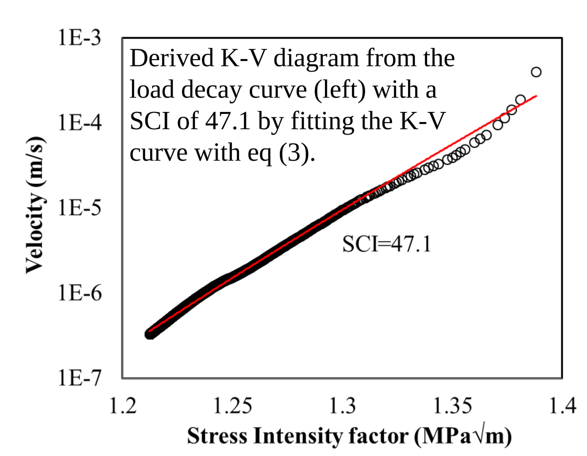
Maximum load is used to determine the fracture toughness (equation 1). Multiple stress intensity factor vs crack growth rate curves (K-V curves) can be obtained from a single specimen from load decay relationships. Cracking velocity is related to stress intensity factor by

$$V = A\cdot K_I^n \qquad (3)$$

with n the subcritical index (SCI, Atkinson, 1987). The subcritical crack growth index can be found by fitting the K-V curves with a power law relationship.





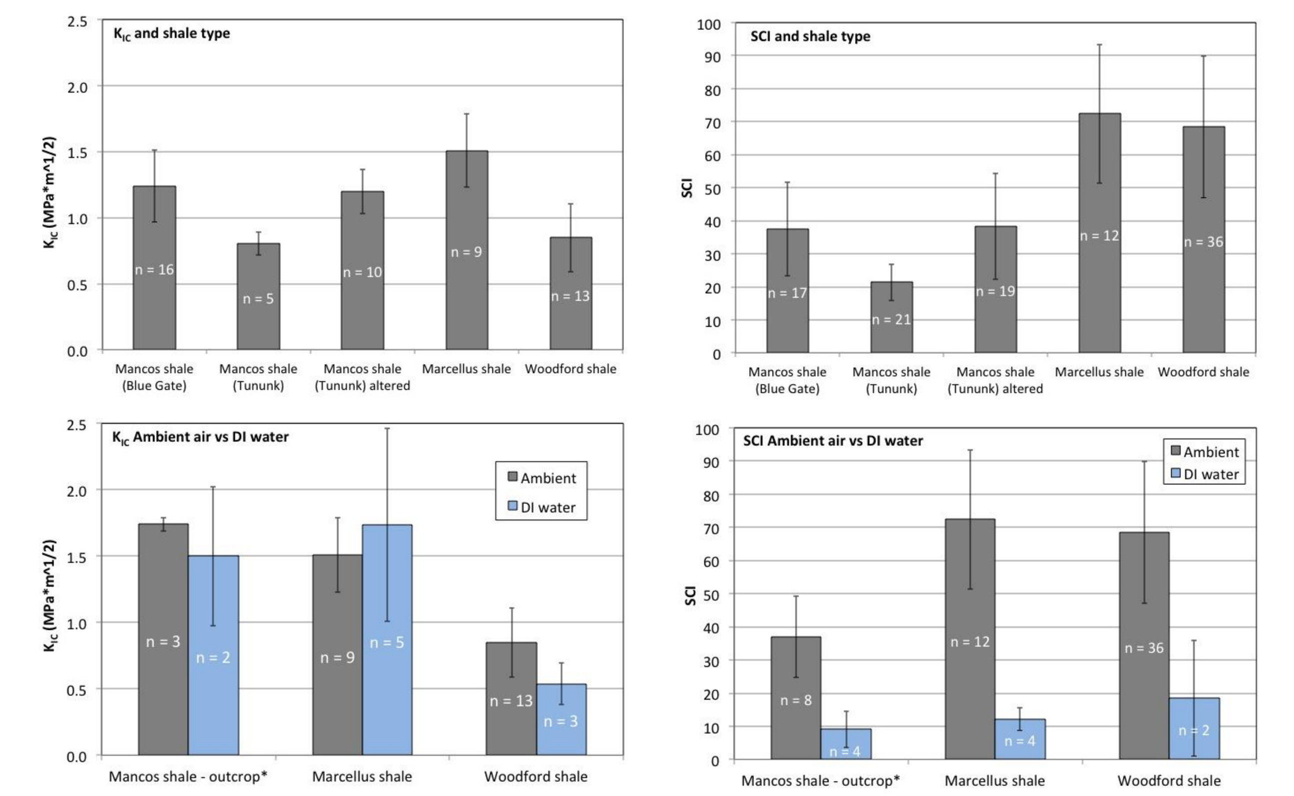


Materials

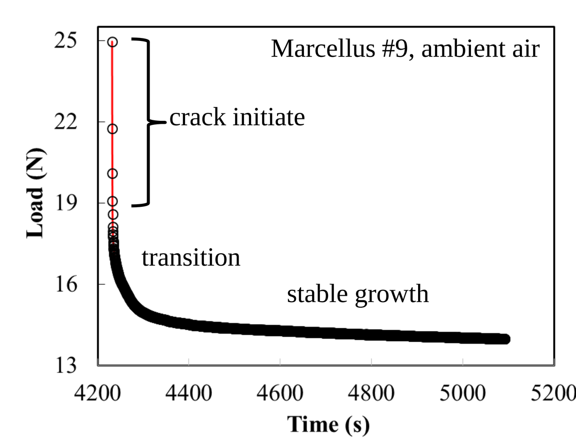
The materials tested here include Woodford shale purchased from TerraTec Schlumberger, Marcellus shale cored from the Appalachian Basin, and Mancos shale from outcrop near Crystal Geyser, UT.

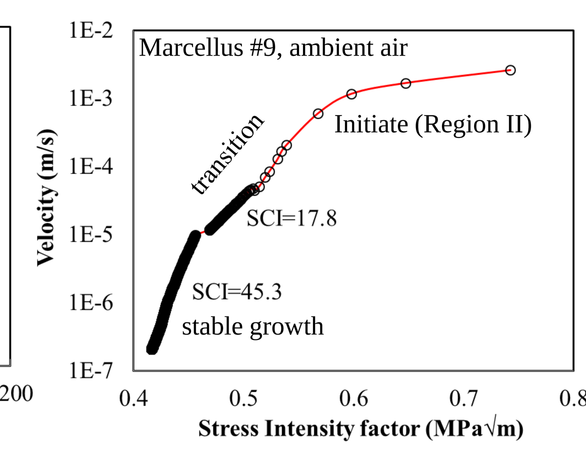
Results

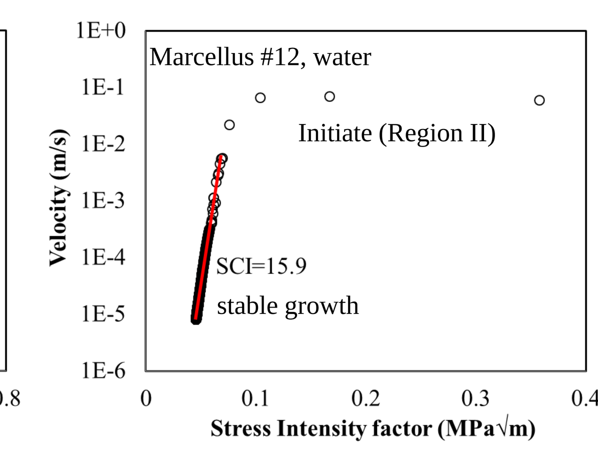
- **Fracture toughness**:
  - ❑ Measured K_{IC} values: 1.51±0.32 MPa·$\sqrt{m}$ for Marcellus, 0.85±0.25 MPa·$\sqrt{m}$ for Woodford, 1.08±0.17 MPa·$\sqrt{m}$ for Mancos shale at ambient air conditions.
  - ❑ K_{IC} slightly varied with changing of environmental conditions. Tests under water showed slight variation of K_{IC} compared to ambient air condition. K_{IC} is also sensitive to CO_2 atmosphere and hydrophobic agent surface treatment for Mancos shale.



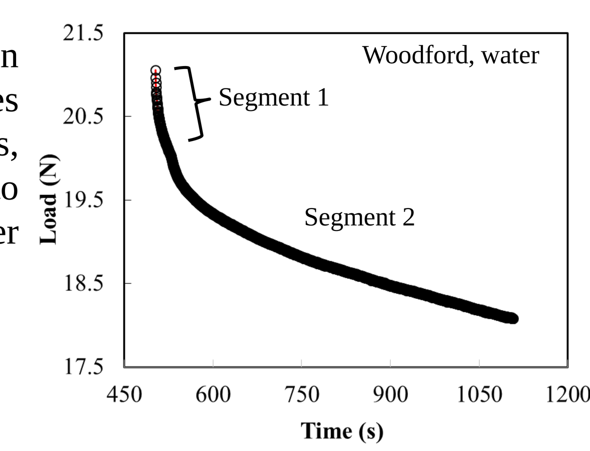
- **Subcritical index**:
  - ❑ Measured SCI values: between 40 and 80 at ambient air conditions.
  - ❑ Tests conducted in water result in 70-85% reduction in SCI compared to air condition.
- **K-V curves**:
  - ❑ K-V curves for rocks typically represent the stress corrosion region (Region I) of crack growth in which SCI is related to chemical reaction rates.
  - ❑ Transport-controlled region (Region II) could be captured with increased sampling rate. Crack growth in this region lasts for less than one second, with a characteristic velocity of 10^{-3} to 10^{-1} m/s.

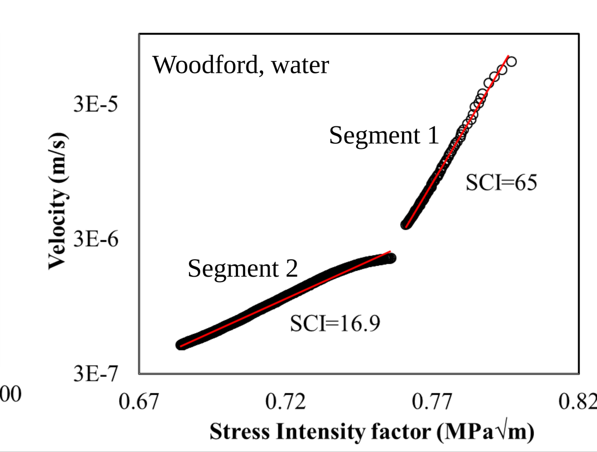




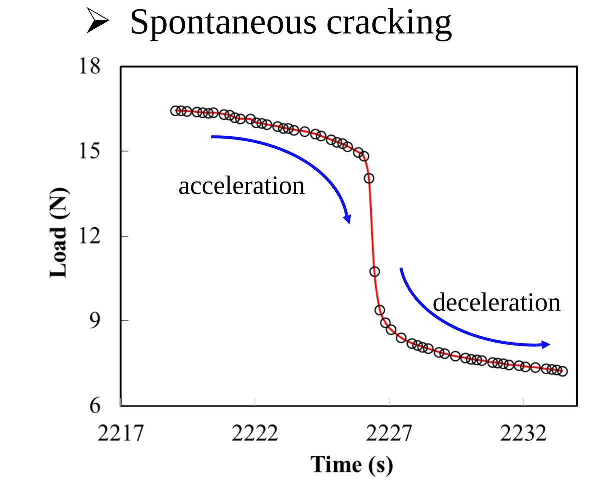


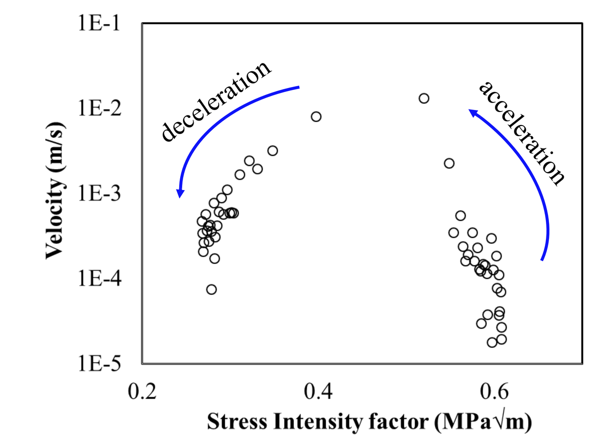
- ❑ Tests under water result in an initial cracking with SCI values comparable to ambient air tests, then gradually transition into stable but significantly lower SCI values of 10-20.



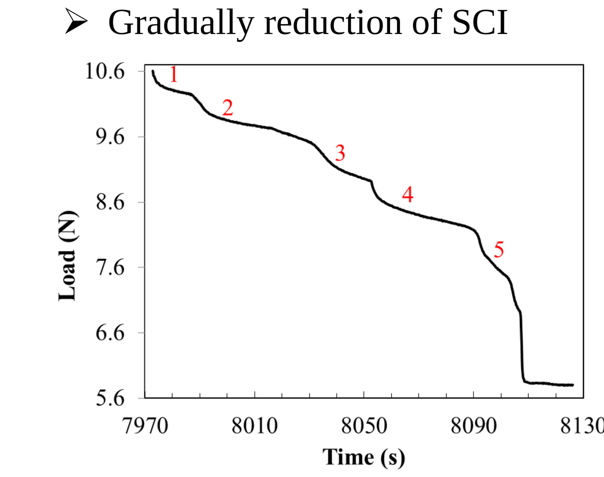


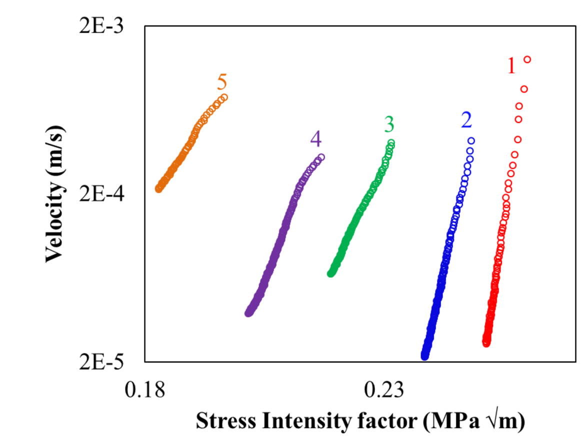
- ❑ Multiple cracking events within one load decay period.
  - ➢ Spontaneous cracking





  - ➢ Gradually reduction of SCI





Discussion and conclusions

- Materials with higher K_{IC} tend to be more resistant to fracture growth. Our data show Marcellus shale is the toughest, while Woodford shale is the least resistant to fracture growth.
- SCI is more sensitive to changing of environmental conditions than K_{IC}.
- In aqueous tests, initially high SCI numbers transition to lower numbers during the course of the testing. This suggests a reaction controlled behavior (Wiederhorn and Johnson, 1973; Wiederhorn, 1978). At high crack velocities, the rate of transport is the limiting factor since transport cannot keep pace with reaction (Region II). Based on the ion exchange model, the chemical composition of new crack surfaces is controlling crack growth at high velocities, when the transport of chemicals from fluid to crack tip cannot keep pace with the exposure of new reactive ions in the fresh crack surface. At low crack velocities subcritical growth is controlled by chemical diffusion rates in the bulk fluid.
- Low matrix permeability of shales may contribute to low transport efficiency from bulk fluid to crack tip.
- Spontaneous cracking acceleration and deceleration indicate spontaneous fracture growth, which might be related to interaction of crack tip with existing flaws or the mechanisms of subcritical crack growth, e.g., ion exchange induced local tension on fracture tip (Wiederhorn, 1978), and competition between disolution and precipitation.
- SCI values can be used to estimate crack velocity (equation 3). With a stress intensity factor drop of 10%, crack velocity will drop 79% for wet condition and 99.82% under dry conditions. The lower the K, the larger the difference between crack velocities from wet to dry conditions.
- Fracture growth rate estimation. Assume fracture velocity at K_{IC} is 10^{-3} m/s, threshold K below which fracture stops is 50% of K_{IC}. The velocity at Kth can be used as an approximation of fracture growth rate. For wet conditions $V = 0.5^{15}\times10^{-3} \approx 1\ m/year$, and for ambient conditions $V = 0.5^{60}\times10^{-3} \approx 0.03\ \mu m/Myr$.

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Acknowledgments

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