H43G-1730: Mode-I Fracture Toughness Testing and Coupled Cohesive Zone Modeling at In Situ P, T, and Chemical (H_2O-CO_2-NaCl) Conditions

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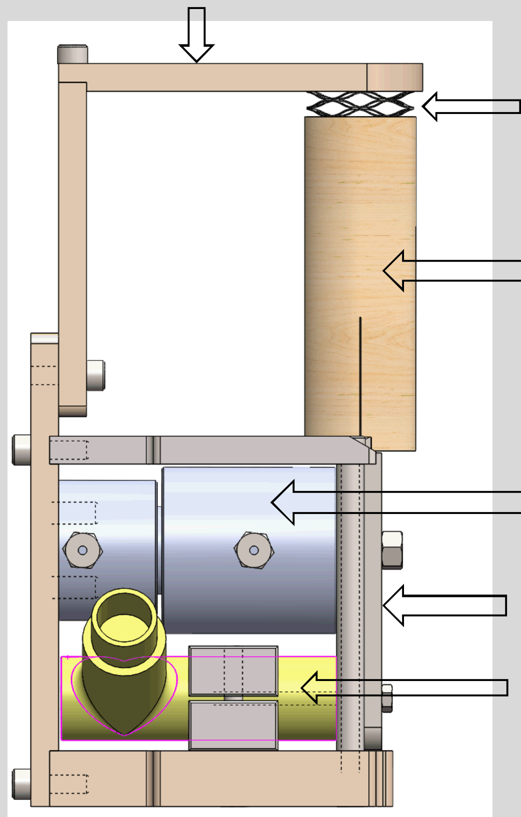
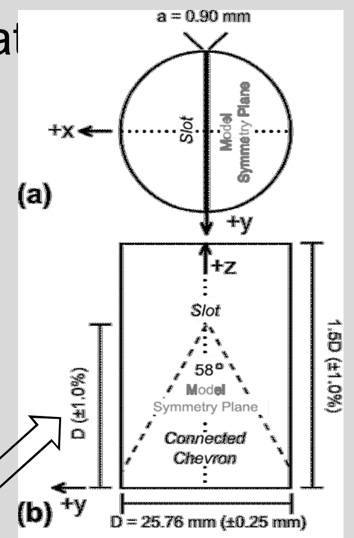
Introduction

Propagation of Mode I cracks is fundamental to subsurface engineering endeavors, but the majority of fracture toughness measurements are performed at ambient conditions. A novel testing apparatus was used to quantify the relationship between supercritical carbon dioxide ($scCO_2$), water vapor, and fracture toughness in analogs for reservoir rock and caprock lithologies at temperature and pressure conditions relevant to geologic carbon storage. Samples of Boise Sandstone and Marcellus Shale were subject to fracture propagation via a novel short rod fracture toughness tester composed of titanium and Hastelloy® and designed to fit inside a pressure vessel. The tester was controlled by a hydraulically-driven ram and instrumented with a LVDT to monitor displacement. We measured fracture toughness under conditions of dry supercritical CO_2 ($scCO_2$) and $scCO_2$-saturated H_2O, at 13.8 MPa and 70°C.

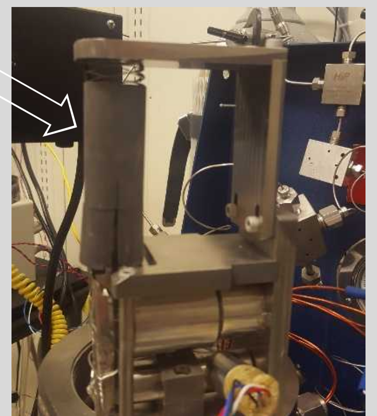
Design of Test Frame

- Uses "sub-sea" actuator and LVDT to deform materials inside a pressure vessel
- Composed of titanium and hastelloy
- Uses "short-rod" configuration to propagate mode-I fracture in cored specimens
- Good to 34.5 MPa, 150°C





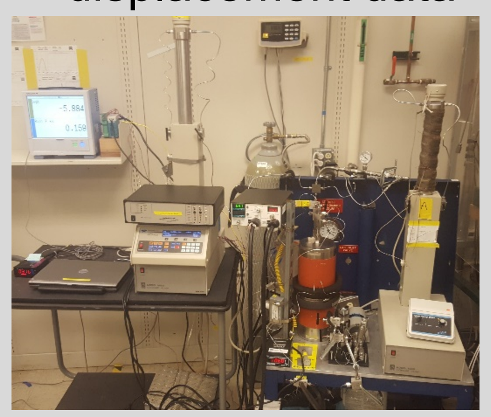
Short rod configuration (Rinehart et al., 2015 after Barker and Guest , 1978)

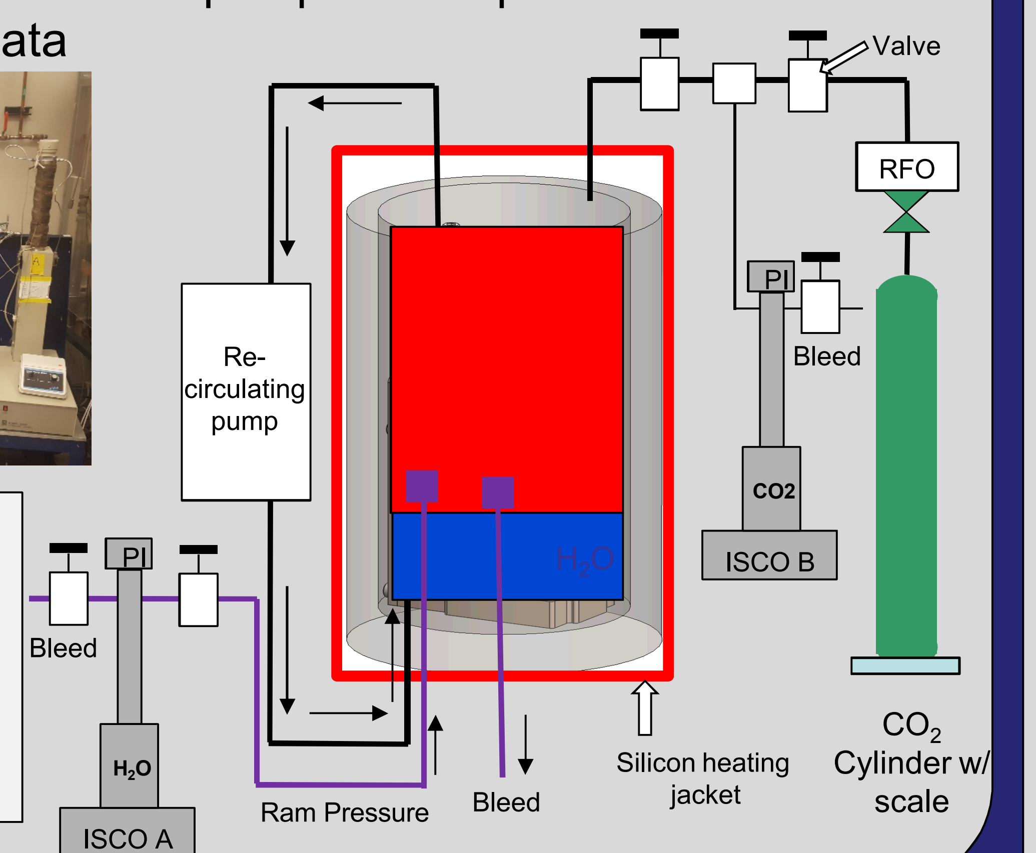


Sample of Marcellus Shale, post-testing in wet $scCO_2$

Experimental Methods

- 1"x3" core sample cut and notched with diamond blade
- Test frame & sample placed in Ti pressure vessel
- Vessel brought to P &T with ISCO A pump and silicon heater
- For "wet" $scCO_2$ atmosphere, use bubbler configuration and transfer pump to equilibrate H_2O and CO_2 phases
- Advance ram with ISCO pump and acquire force vs displacement data

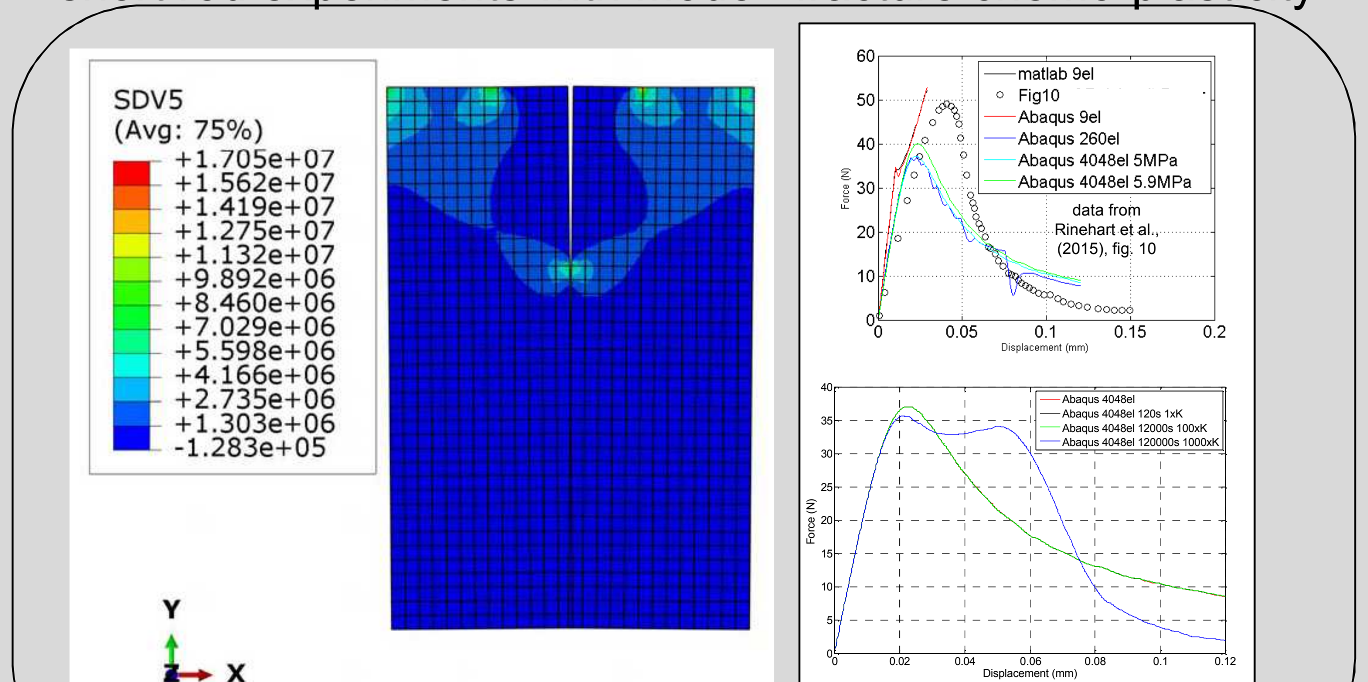




(Above) Testing system. (Right) Schematic of fracture test frame immersed in brine and scCO2 inside pressure vessel. Recirculating pump aids in equilibrating CO_2 and H_2O phases.

Cohesive SE Modeling

- 2D plane strain bulk and cohesive surface element (CSE) model developed in Abaqus UEL with CSE chemical weakening after Hu and Hueckel (2013)
- Calibrating model against three-point-bend experimental data showing weakening in presence of brine
- Will extend 2D poromechanical to 3D CSE for modeling short rod experiments with Mode I fracture chemo-plasticity

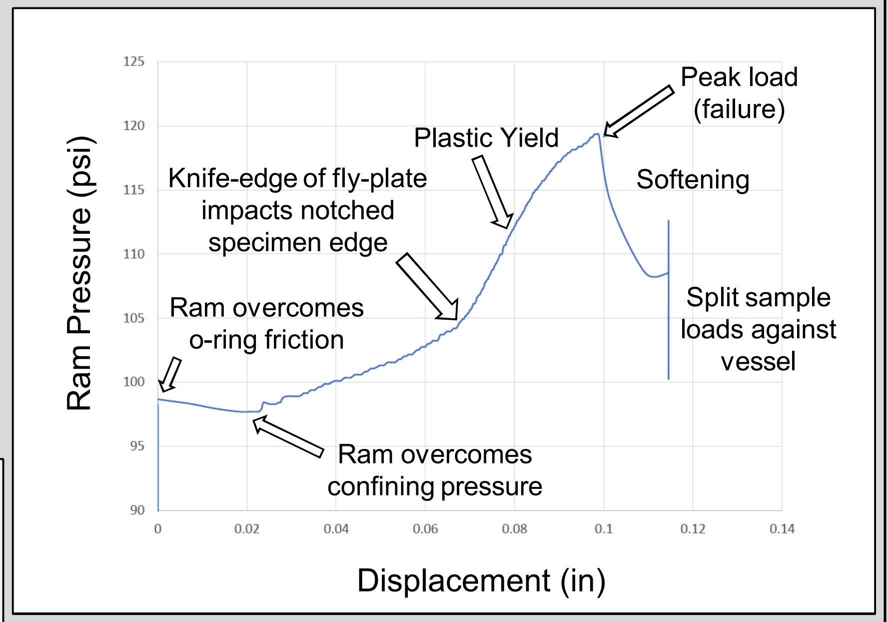


Single fracture cohesive zone modeling coupled with chemistry and calibrated to three-point-bend experimental data

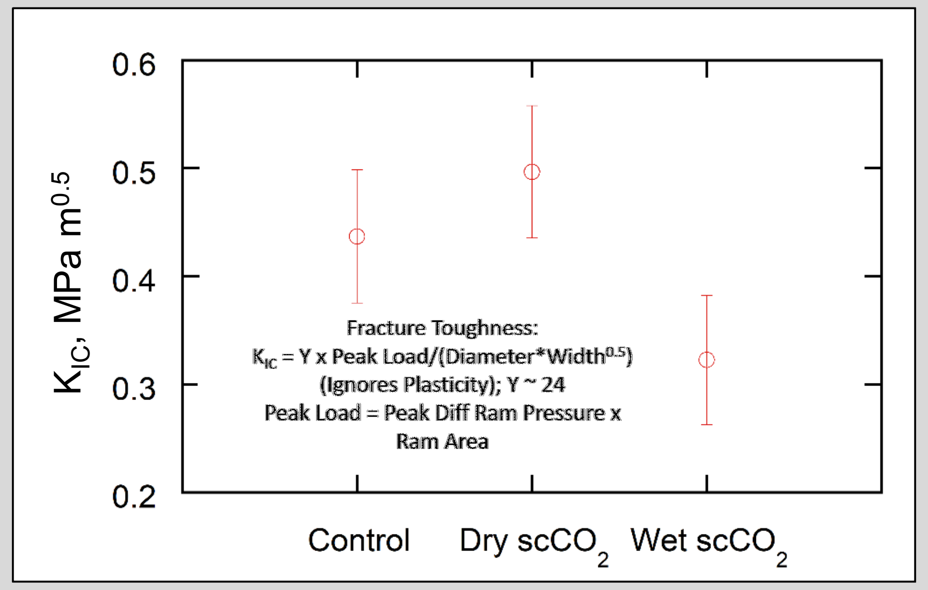
Experimental Results

Boise Sandstone

- Control at room T and humidity
- Dry $scCO_2$ at 13.8 MPa and 70°C
- H_2O-Saturated $scCO_2$ at 13.8 MPa and 70°C



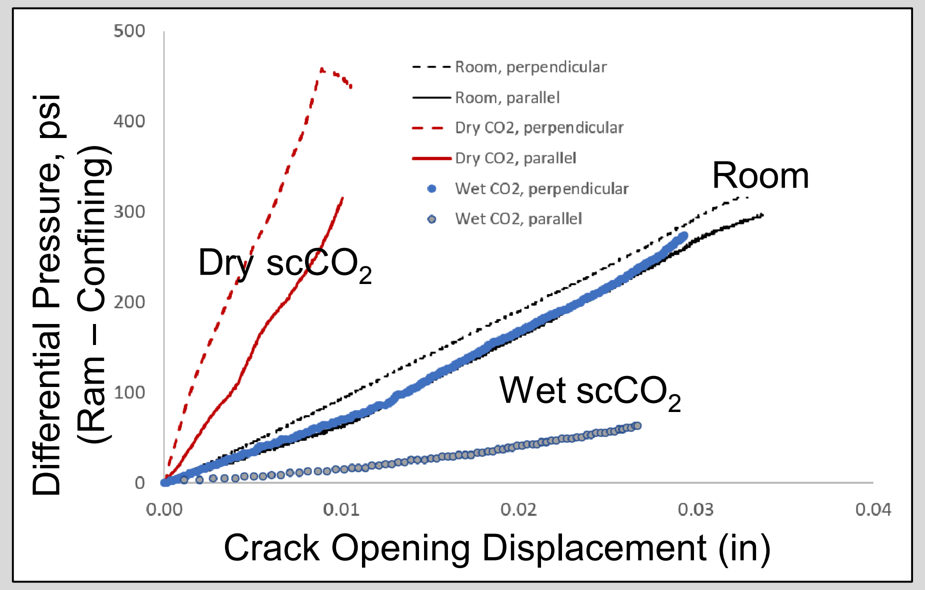
(Right) Example of raw ram pressure versus displacement data, "dry CO_2" experiment

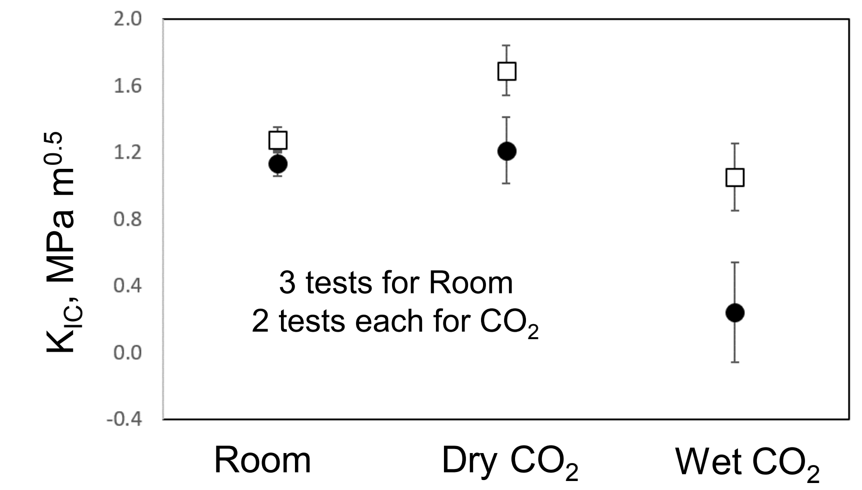


- Much sample variability (3 tests each per condition)
- Discernable weakening in "wet" CO_2
- Slight strengthening in "dry" CO_2

Marcellus Shale

- Sample prep difficult (!)
- Chevrons cut both parallel and perpendicular to bedding
- Testing same as Boise; Dry and H_2O-Saturated $scCO_2$ at 13.8 MPa and 70°C





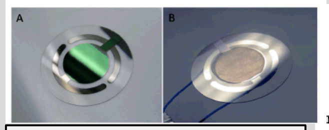
- Similar to Boise, with weakening in "wet" CO_2
- Different elastic behavior in tension and compression; environment dependent

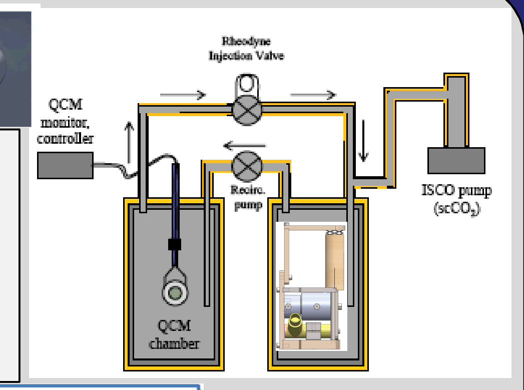
Conclusions

Dry CO_2 has a negligible to slight strengthening effect compared to a control, however hydrous $scCO_2$ can decrease fracture toughness, and the effect should increase with humidity, which we hypothesize is due to capillary condensation of reactive water films at nascent crack tips and associated subcritical weakening. A 2D poromechanical finite element model with cohesive surface elements (CSEs) and a chemo-plasticity phenomenology is being developed to describe the chemical weakening/softening effects observed in the testing. The reductions in fracture toughness seen in this study could be important in considerations of borehole stability, in situ stress measurements, changes in fracture gradient, and reservoir caprock integrity during CO_2 injection and storage.

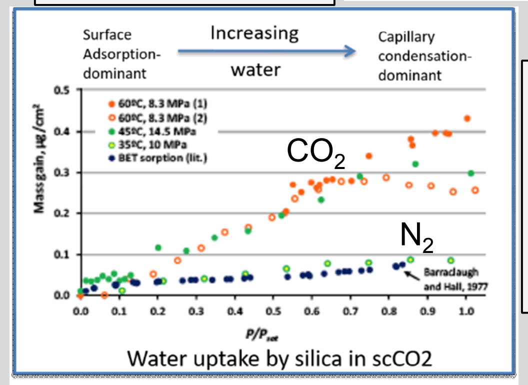
Future Work

- Run suite of tests controlling humidity of $scCO_2$ within vessel
- Quartz crystal microbalance (QCM) used to measure humidity and capillary condensation
- Model capillary condensation in nascent crack tips (Heath et al., 2014) and relate to weakening with CSE models





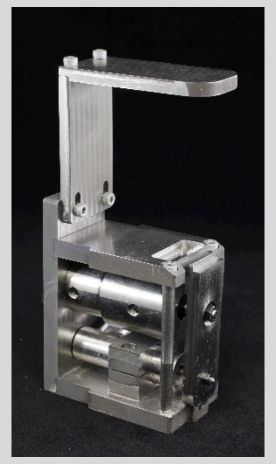
(Above) QCM with silica and clay coating (Right) QCM in pressure vessel in line with fracture testing



From Bryan et al., 2013

(Left) Water uptake as function of humidity in N_2 and $scCO_2$ environments

Acknowledgements



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