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The Effect of Hydrous Supercritical Carbon Dioxide on the Mohr Coulomb Failure Envelope in Boise Sandstone

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Sustaining Injectivity

- Changes in rock strength could lead to development of fracture networks, creating high permeability pathways into the reservoir
- Reduction of bonding strength in granular rocks could lead to consolidation and reduced permeability

Storage Efficiency

- Induced fractures and dilatant deformation create additional porosity for storage and improved sweep
- Consolidation reduces porosity and decreases available storage space

Controlling Emergence

- Movement along induced fractures and faults could pierce overlying seal
- Consolidation of the reservoir induces deformation in overlying seal, jeopardizing integrity

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- Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
- Boise cores purchased from Kocurek Industries, Caldwell, Texas
- Anastasia Ilgen performed geochemical analysis, Josh Feldman assisted in sampling
- Michael Aman performed scratch test measurements under supervision of Nicolas Espinoza
- Tom Dewers provided insight and guidance

Introduction

- Atmospheric CO_2 levels are at their highest recorded levels for over 400,000 years; surface temperatures show a >0.85°C increase since 1880
- Renewable power sources are becoming increasingly competitive, but fossil fuels are still necessary, as well as other large CO_2 sources like cement and fertilizer production
- Geologic carbon storage (GCS) is a potential tool to decrease CO_2 emissions, mitigate climate change
- CO_2 is stripped from emissions and injected into depleted reservoirs and deep saline aquifers as a supercritical phase ($scCO_2$) for at least 10,000 years
- To make a significant impact, 3.5 billion tons of CO_2 needs to be sequestered

Field Trials

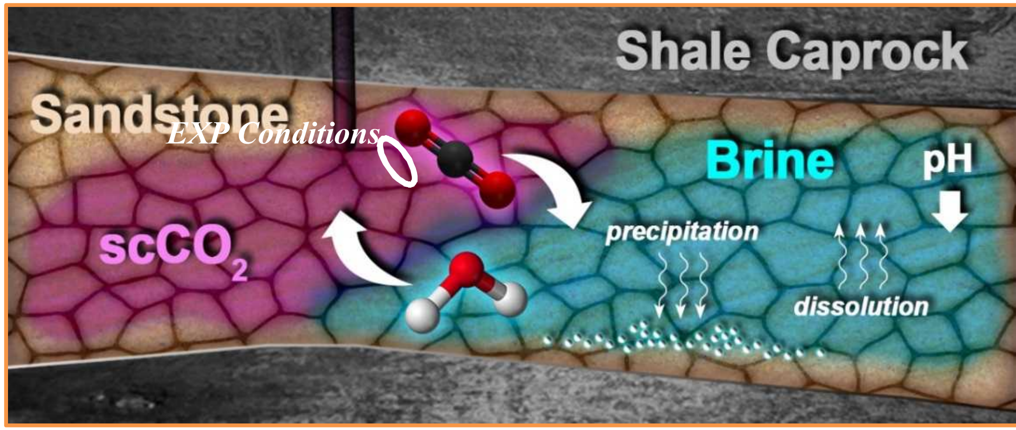
- Sleipner Field, offshore Norway
  - Best example of GCS. Stripping CO_2 from natural gas, reinjecting into overlying reservoir at rate of 1 megaton per year since 1996. Highly porous injection target, minimal pressure increases and pore space utilization.
- In Salah field, Algeria
  - CO_2 from natural gas production injected in fracture, tight sandstone reservoir. 4 megatonnes have been stored, 12 MPa pressure increase, 2 cm uplift and fault reactivation
- Weyburn field, Canada
  - CO_2 EOR transition to storage. Pressure had risen by 5 MPa and reactivated pre existing faults

Previous Experimental Work

- Crystal Geyser, natural analog for GCS
  - Reservoir rocks exposed to natural CO_2, flow channelized into fault and fracture networks
  - Fracture toughness, scratch toughness lower in bleached rocks exposed to $scCO_2$ than country rock
- Limestones and anhydrites
  - Reductions in failure strengths due to reactions caused by low p.H. CO_2 solution
- Artificial calcite cemented rocks
  - Low p.H. solutions dissolve cement and weaken rock
- Sandstones
  - Lacking reactive phases, no change in strength due to exposure to CO_2

Objectives

- Following Sleipner example, US has lots of potential targets in offshore Gulf of Mexico
- This study focuses on fluid rock interactions between $scCO_2$, water, and an analog for Tertiary, offshore Gulf of Mexico reservoir rocks, Boise sandstone
- During injection, $scCO_2$ forms a buoyant plume. At brine-plume interfaces, $scCO_2$ dissolves over time into the brine, water from the native brine can dissolve into the $scCO_2$ plume where it is present as humidity.
- Experiments are conducted to investigates the effect of hydrous $scCO_2$ on the shear failure of Boise sandstone.
- Decreases in failure strength injectivity, storage, and seal integrity

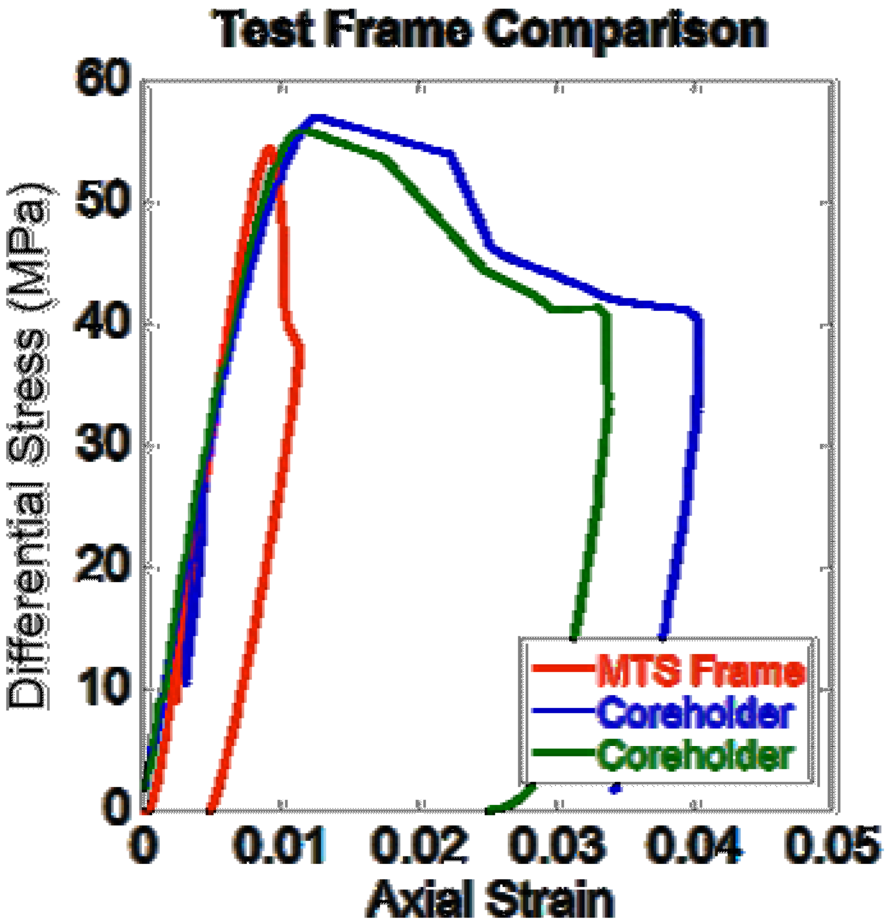


Methods

- Experiments were conducted using partial humidity and fully saturated $scCO_2$ on analog reservoir rock, Boise SS
  - 29% porosity; quartz, albite, microcline, illite-smectite, and calcite
  - Water present as a vapor phase in $scCO_2$
- Long term changes in strength due to chemical reactions
- Hydrous $scCO_2$ generated using pressure vessel, recirculating pump, at 70C and 2000PSI
- Partial humidity $scCO_2$, water added in 5mL increments via Rheodyne injector valve, 0-40 mL total
- Boise samples in separate vessel at 70C and 2250PSI
  - Cylindrical core and thin disc stacked together
- $scCO_2$ recirculated through sample for 24 hours
- After depressurization, samples removed for triaxial testing, scratch testing
  - Remaining fluids that condensed from hydrous $scCO_2$ chemically analyzed in ICPMS
- Triaxial experiments conducted at 500, 1000, and 1500 PSI confining pressure
  - Experiments performed in CoreLabs Coreholder, MTS servo-hydraulic load frame
  - Room temperature, dry
- Scratch testing performed at UT

Load Frame Comparison

- Two different load frames used
  - MTS servo-hydraulic 220 kn frame
  - CoreLabs “Temco” triaxial core holder
- Core holder initially used for corrosion resistance
  - Jacket permeable to $scCO_2$
- MTS frame incompatible with acidic fluids
  - Dry tests
- Stiffnesses different, strengths same



1000 PSI P_C

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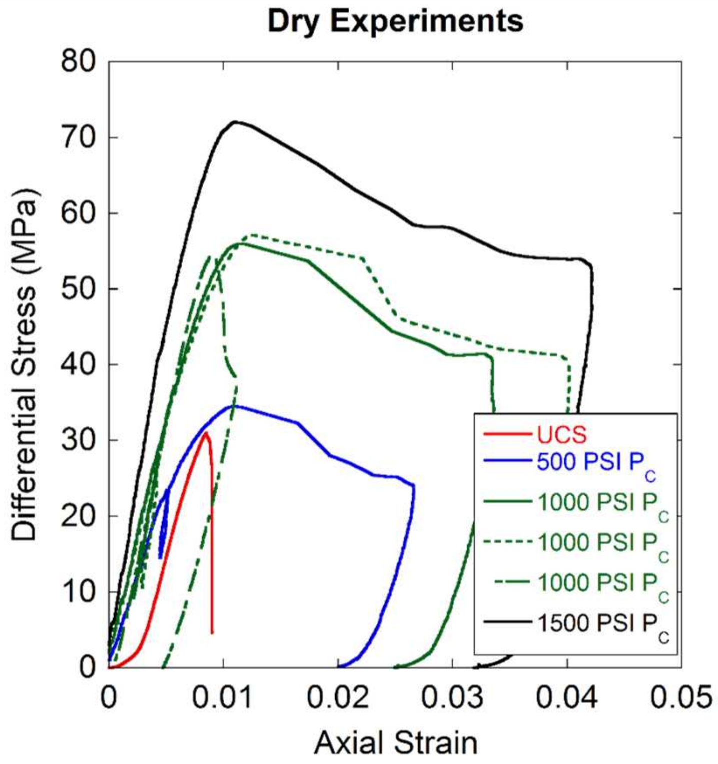
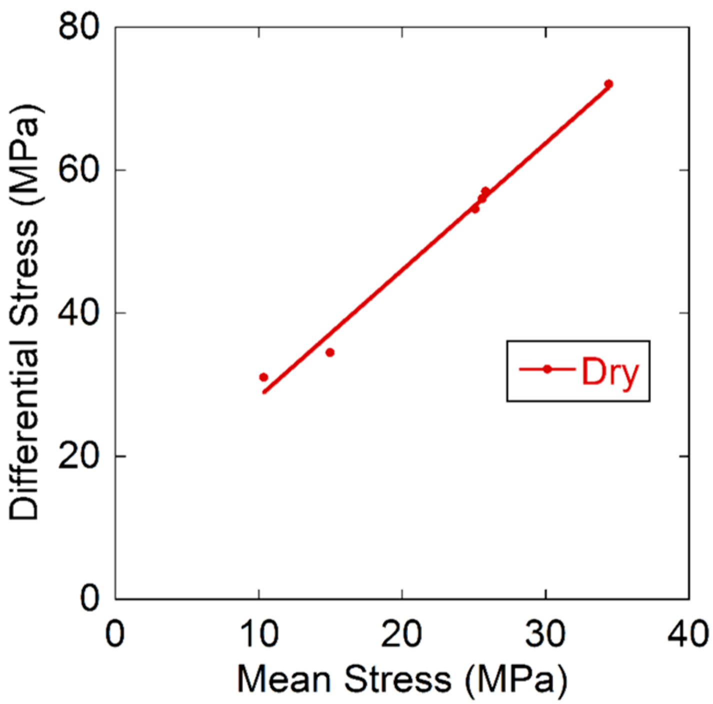
Dry Experiments

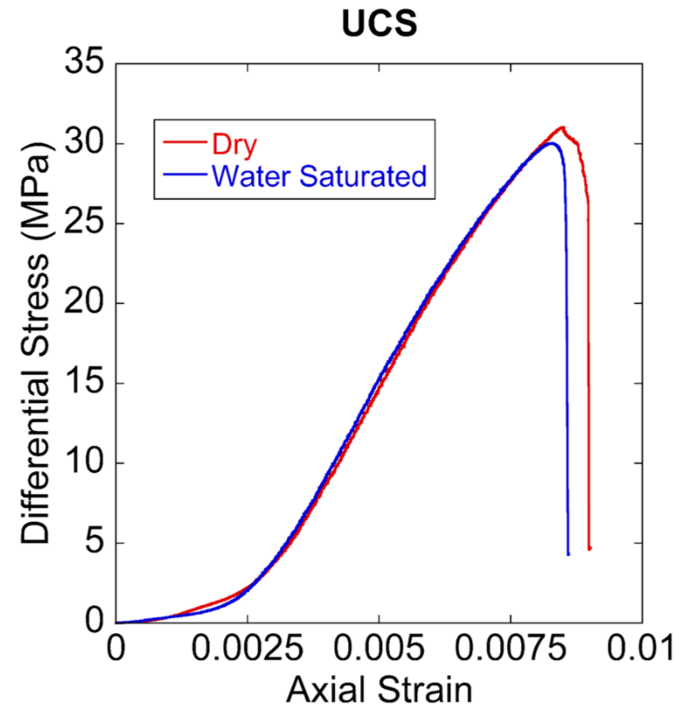


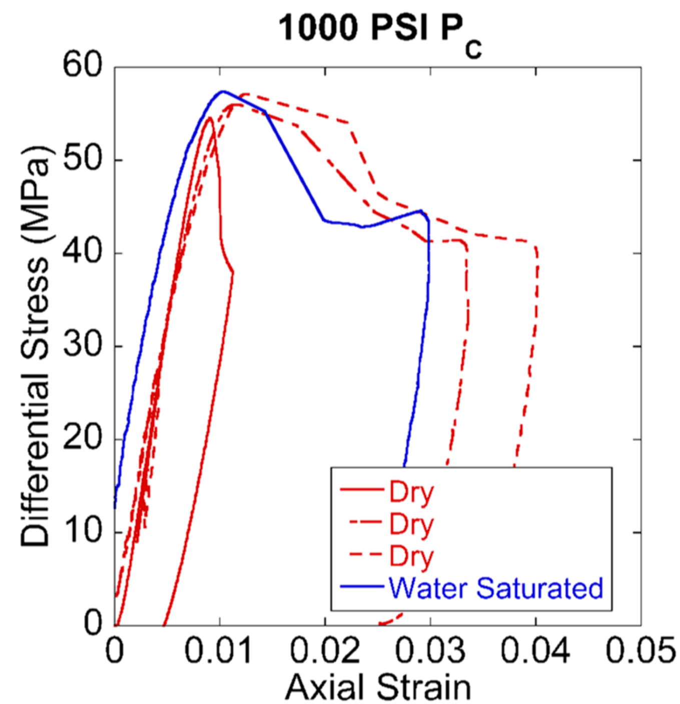


- Triaxial experiments performed on room dry samples
- Increasing strength with increasing confining pressure
- Increasing stiffness with increasing confining pressure
- Linear failure envelope

Control Experiments

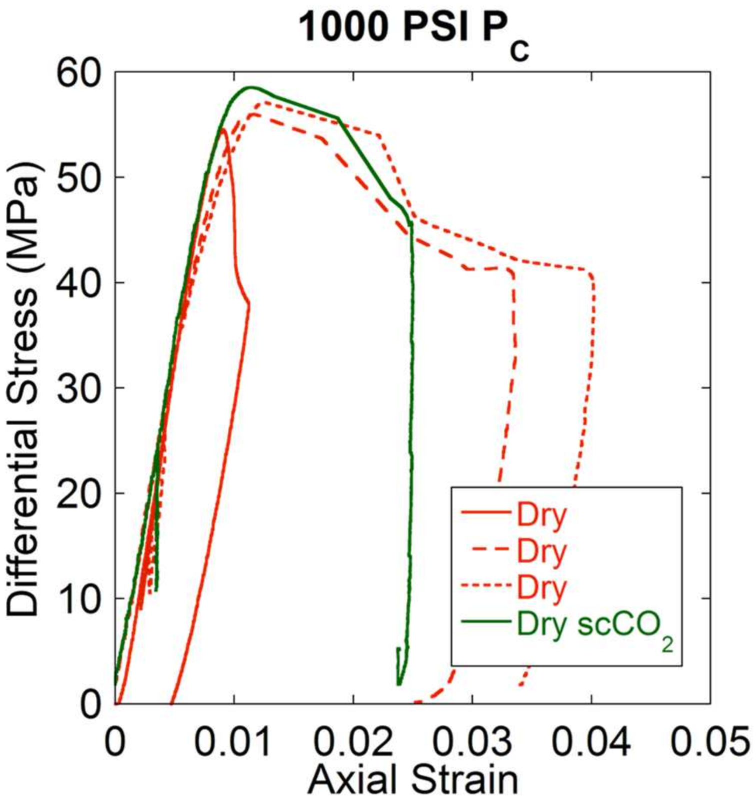
- Triaxial experiments performed on room dry and wet samples
  - UCS test saturated
  - 1000 PSI P_C test flowing at 0.2 mL/min, heated at 70°C
- Strength agrees within natural variability of the rock
- Water does not have an effect on strength
- Temperature does not affect strength
- Any variations in strength due to exposure to $scCO_2$



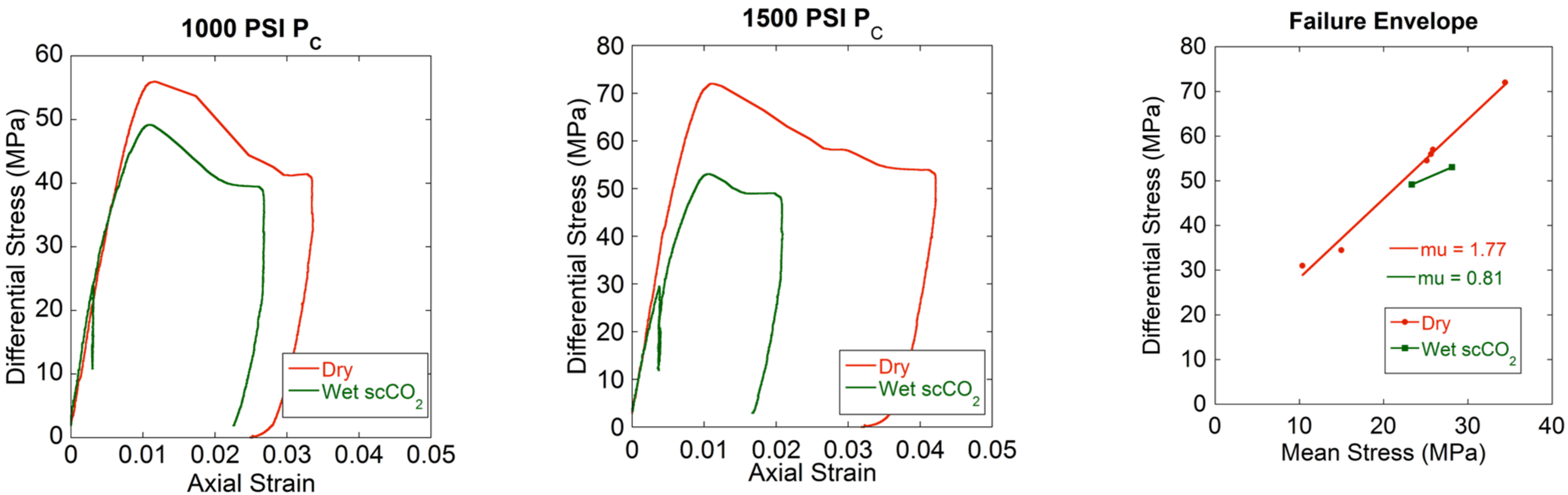


Dry $scCO_2$

- $scCO_2$ generated in 2.5L pressure vessel, heated to 70°C, pressurized to 2000 PSI
- Core in jacketed and pressurized in separate pressure vessel at 2250 PSI and 70°C
- $scCO_2$ recirculated through core for 24 hours, allowed to depressurize and cool overnight
- Tested separately at dry, room temperature conditions
- No effect from $scCO_2$



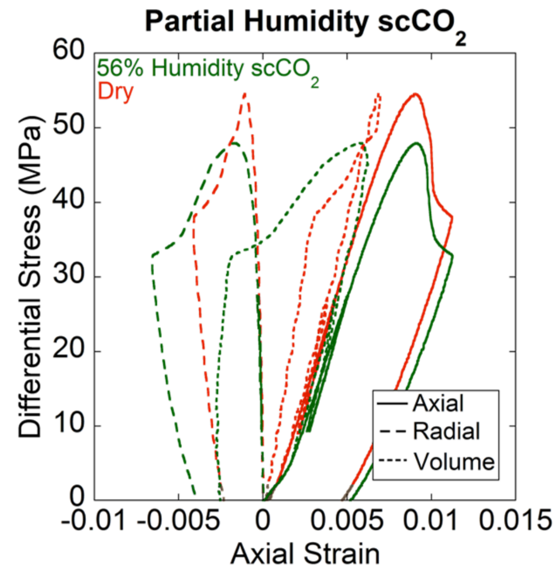
Fully Saturated $scCO_2$

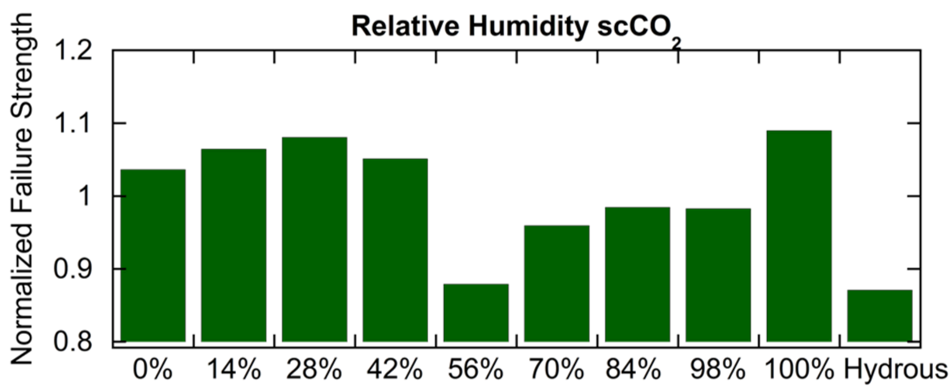


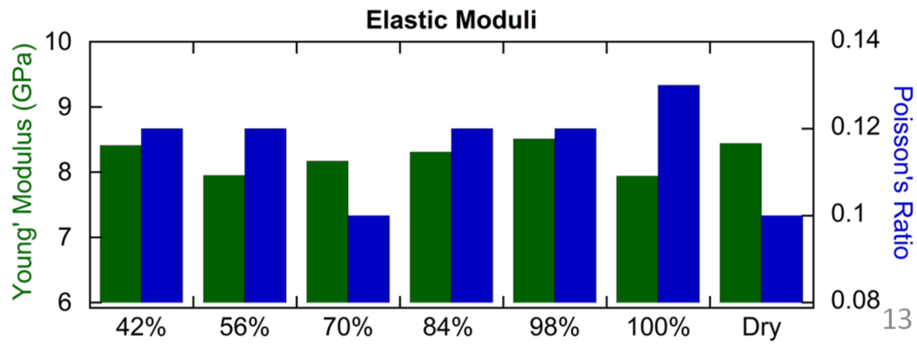
- Preliminary experiments added 500mL of water to hydrous $scCO_2$ generator prior to pressurization
- Samples deformed experimentally post reaction at 500, 1000, and 1500 PSI confining pressure
- Fully saturated $scCO_2$ reduces failure strength, exacerbated at higher confining pressure tested
- Reduction in failure envelope due to exposure to hydrated $scCO_2$
  - Water, temperature, and dry $scCO_2$ don't have an effect
  - Chemical reactions caused by low p.H. solutions condensing at grain contacts

Parital Saturation

- Partial humidity $scCO_2$ prepared with 5mL increments of water, up to 40mL total
  - Added via Rheodyne injector valves after achieving supercritical state
  - Fully saturated ~ 38mL water
- Samples deformed experimentally post reaction at 1000 PSI confining pressure
- No clear trend in failure strength with partial humidity
  - Don't observe same decrease at full saturation as preliminary tests
- No variation in elastic moduli
- One sample showed weakening
  - Slightly reduced Young's modulus, elevated Poisson's ratio
- Fluid remaining in supercritical $scCO_2$ generator analyzed on ICP-MS for ion concentrations



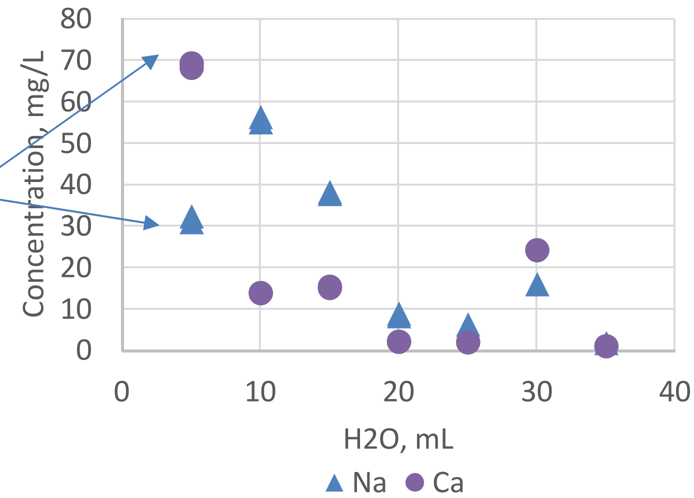


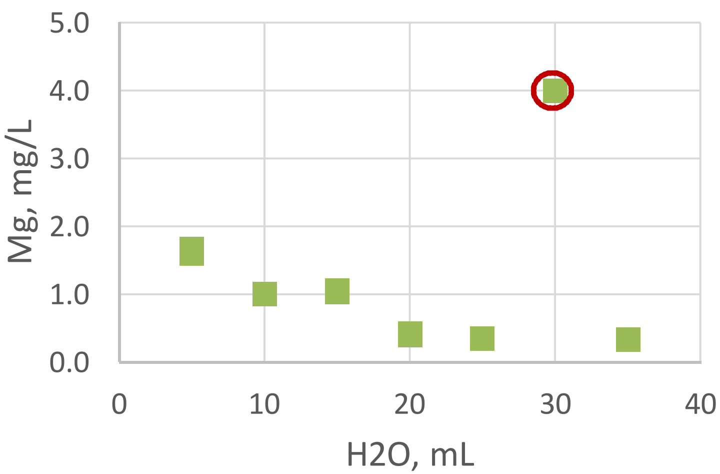


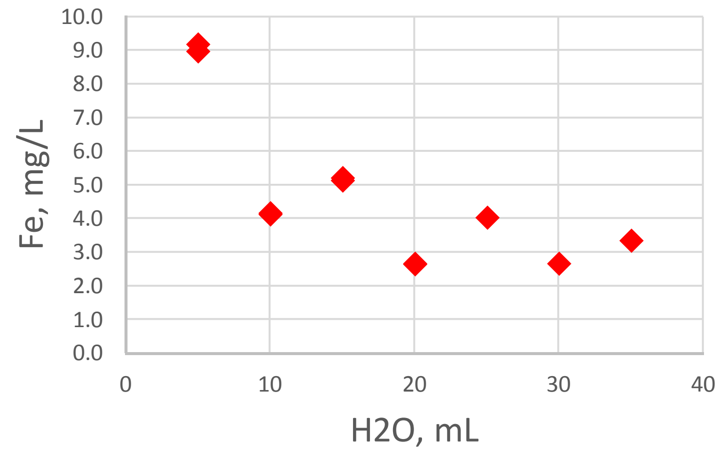
Aqueous chemistry data

Minerals
Quartz **Si**O_2
Albite **NaAlSi**$_3O_8$
K-feldspar **KAlSi**$_3O_8$
Calcite **Ca**CO_3
Illite
(**K**,H_3O)(**Al**,**Mg**,**Fe**)$_2$(**Si**,**Al**)$_4O_{10}$[$(OH)_2$,(H_2O)]

ΔG(hydr):
Ca^{2+} = -1553 kJ mol^{-1}
Na^{+} = -371 kJ mol^{-1}

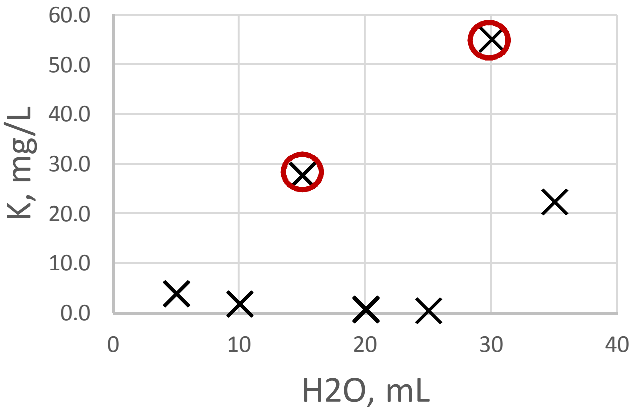


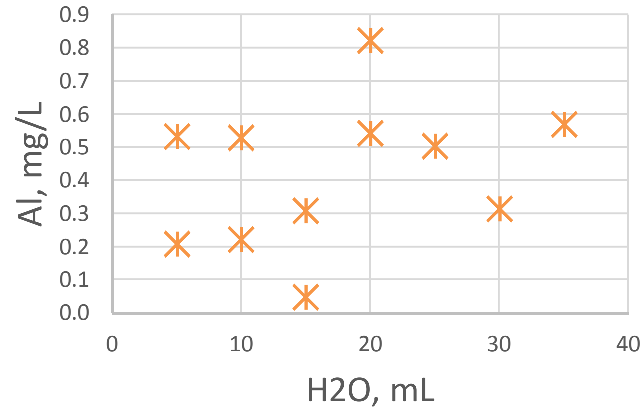


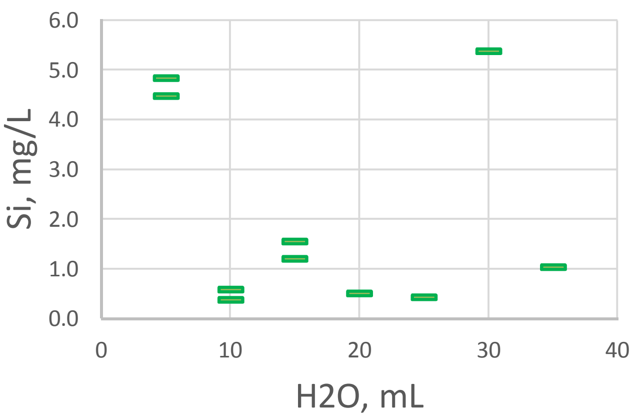


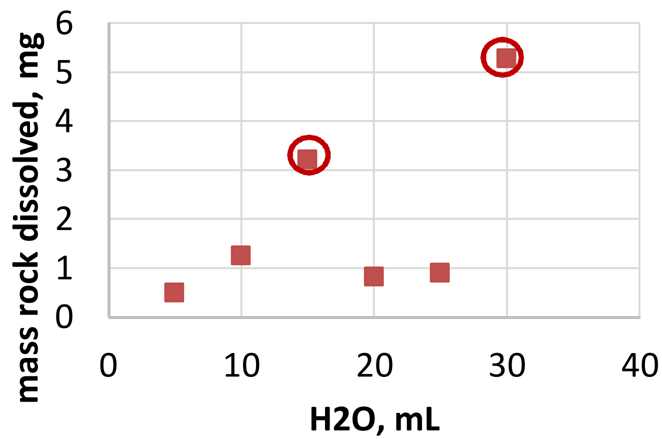
- Detectable movement of ions, carried by humidity
- Observable trend of decreasing concentration as fluid volume increases
- Flip between sodium and calcium at low fluid volumes
  - Calcium outcompetes
- Outlier in measurements

Aqueous chemistry data









Minerals

Quartz SiO_2

Albite $NaAlSi_3O_8$

K-feldspar $KAlSi_3O_8$

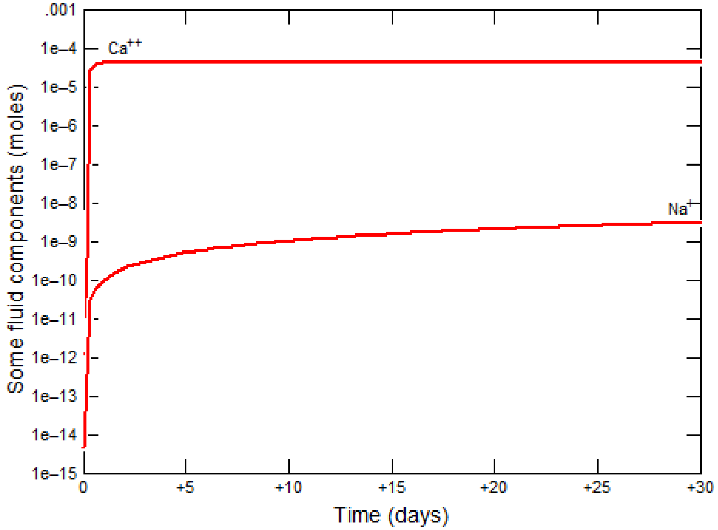
Calcite $CaCO_3$

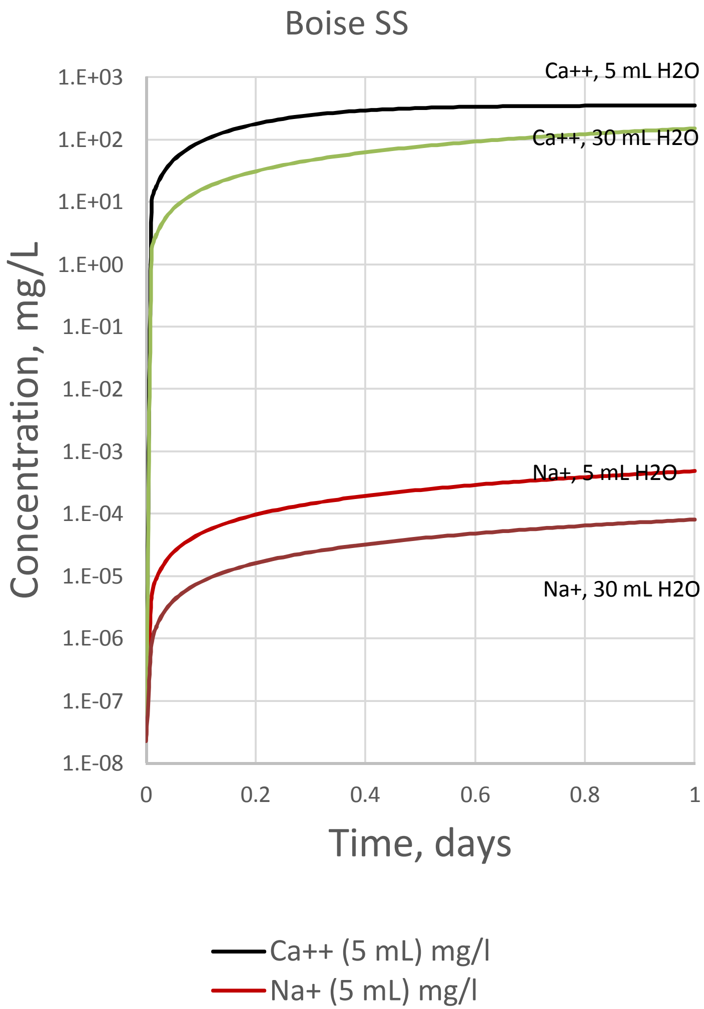
Illite

$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$

- Si – close or at the detection limit;
- Al is under detection level
- Outliers – 15 and 30 mL H2O
- Dissolved rock constant across humidity levels

Preliminary geochemical models



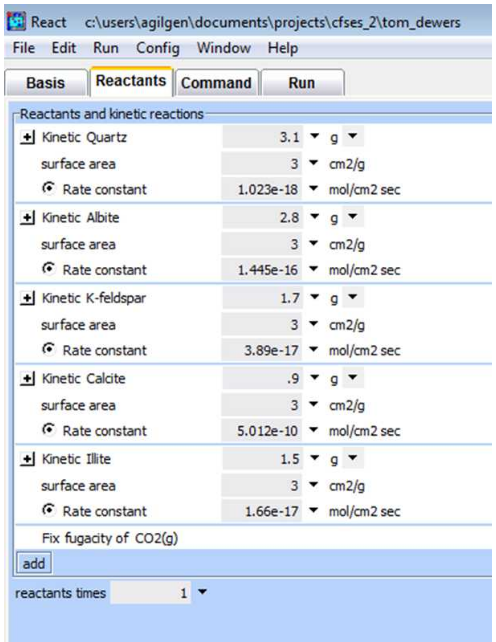


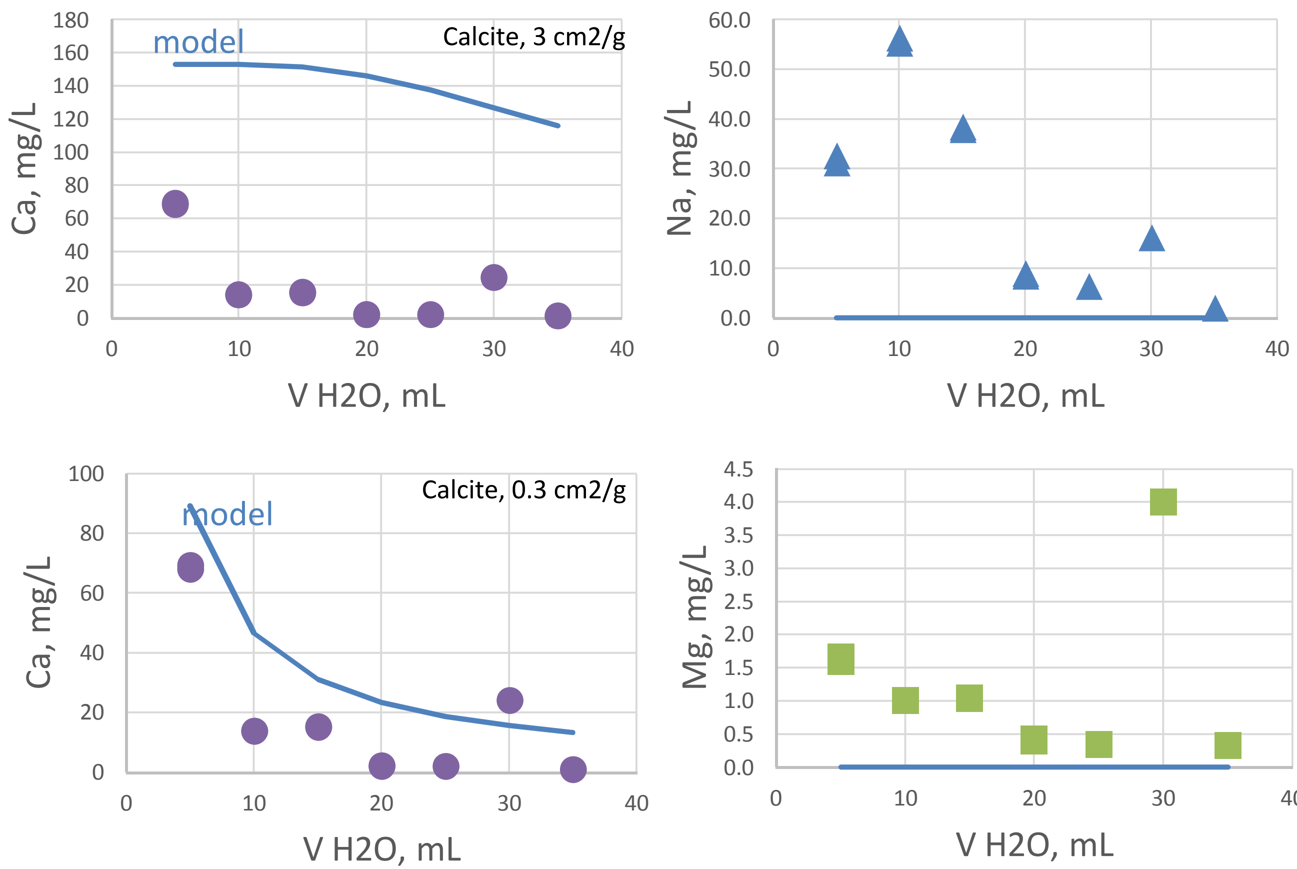
- Model predicts higher Ca++, compared to Na+
- Model predicts decrease in Ca++ and Na+ concentrations with increasing volume H2O

(t = 25C, V H2O=V exper, fugacity of CO_2=1 atm)

Model Comparison

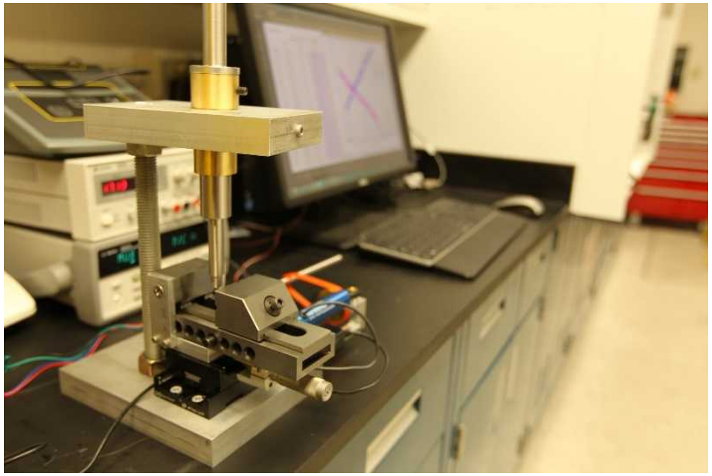
Kinetic parameters





- Model does not match observed concentrations
- Calcium matches depending on available surface area

Scratch Testing



Conclusions

- Boise sandstone is generally insensitive to water, dry $scCO_2$
- Fully saturated $scCO_2$ causes weakening in Boise sandstone that is exacerbated at higher confining pressures, leading to a decrease in the slope of the failure envelope
- Partial humidities of $scCO_2$ do not show clear weakening or strengthening trends
- Water present as humidity in $scCO_2$ does transport ions, is reactive
- Total amount of water available in partially saturated $scCO_2$ is very small, not enough to drive significant chemical reactions; but if there is sufficient amount of water available, chemical reactions can cause significant changes in strength.

Planned Manuscripts

The Effect of Hydrous $scCO_2$ on the Mohr-Coulomb Failure Envelope in Boise Sandstone
Choens, Dewers, Ilgen, Espinoza, Aman, Wheeler, Ganis

The Effect of Hydrous scCO2 on Deformation Band Development in Boise Sandstone
Choens, Dewers, Wheeler, Ganis

The Effect of Hydrous scCO2 on the Consolidation of Boise Sandstone
Choens, Dewers, Prodanović, Mirabolghasemi

The Effect of Hydrous scCO2 on the Fracture Toughness of Boise Sandstone
Choens, Dewers, Eichubl, Majors, Espinoza, Aman

Reservoir Response Induced by the presence of Hydrous scCO2
Choens, Dewers