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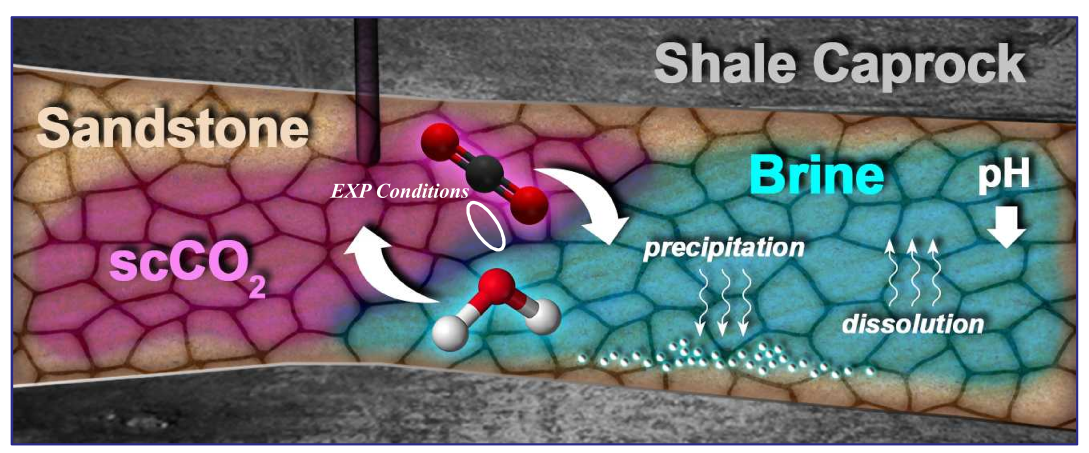
Chemically Induced Changes in Strength of Reservoir Sandstones at Carbon Sequestration Conditions

Charles Choens[1], Tom Dewers[1], Anastasia Ilgen[1], Nicolas Espinoza[2], Peter Eichhubl[2], Joshua Feldman[1]

1. Sandia National Laboratories, Albuquerque, NM. 2. University of Texas, Austin, TX

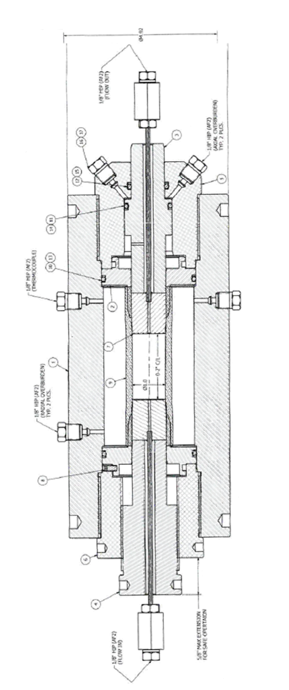
Introduction

Carbon Capture, Utilization, and Storage (CCUS) has been identified as a potential tool to offset anthropogenic emissions of carbon dioxide (CO_2) to help mitigate the effects of climate change. The goal is to capture CO_2 emissions from large emission single point sources and to inject the emissions in the ground. The injections can be used to enhance oil recovery, where some CO_2 would be produced with the oil, but some remain in the reservoir. CO_2 could also be stored long term in depleted oil and gas reservoirs, as well as saline aquifers. CO_2 would be injected as a supercritical fluid into the reservoir and allowed to migrate throughout the subsurface. Supercritical CO_2 is less dense than water, and would rise shallower from buoyant forces. The supercritical plume would be stored for the short term by trapping against an impermeable stratigraphic layer. Over longer time periods, CO_2 would be stored through dissolution and disassociation into the subsurface brine. CO_2 dissolved in brine would chemically react to dissolve and precipitate minerals for permanent storage.



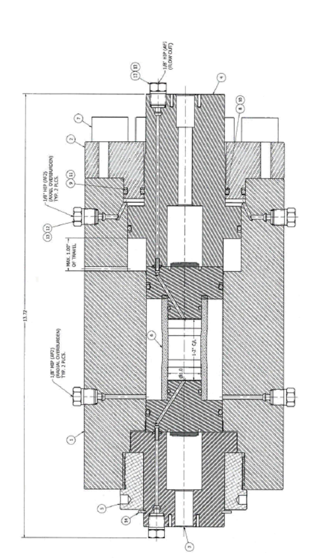
The goal of this project is to study the changes in strength of a reservoir sandstone due to the presence of supercritical CO_2. As the plume of supercritical CO_2 interacts with the in situ brine, it changes the chemical equilibrium and can cause chemical reactions that change the strength of the reservoir. The sandstone used in this study is Boise sandstone, an analog for Tertiary sandstones in the Gulf of Mexico. Depleted offshore reservoirs represent a potentially large volume for storage with proven sealing capabilities. The pressure and temperature conditions for pore fluids utilized in these experiments, 70°C and 2000 PSI are chosen to ensure supercritical CO_2. Different humidities are used in the experiments, from 0% to 100%. This is designed to simulate the conditions at the edge of the supercritical CO_2 plume as it interacts with in situ brine. Samples will be reacted with the fluids for 24 hours and then deformed to quantify changes in strength due to chemical reactions

Laboratory Facilities



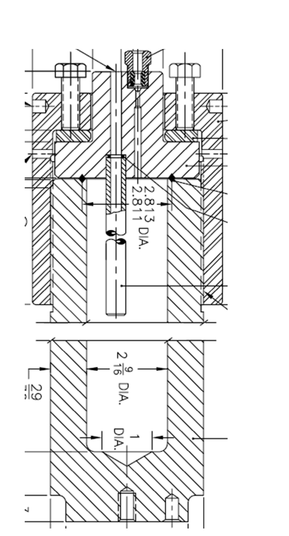
TEMCO Division of Core Laboratories

Triaxial Core Holder: Capable of independent axial, confining, and pore pressure. Capable of flow through. Rated to 15000 PSI. Elevated temperature provided by external heaters



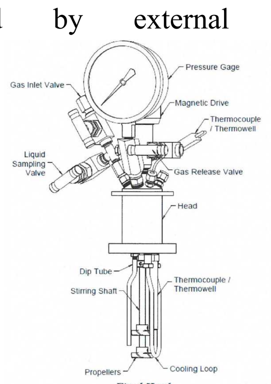
TEMCO Division of Core Laboratories

Ultrasonic Core Holder: Capable of independent axial, confining, and pore pressure. Capable of flow through. Ultrasonic transducers measure P and S velocities. Elevated temperature provided by external heaters



Newport Scientific, Inc.

Hydrostatic Reactor: Capable of independent confining and pore pressure. Capable of flow through. Elevated temperature provided by external heaters. Highest heat and pressure ratings.

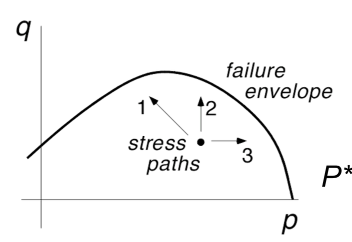


Parr Instrument Company

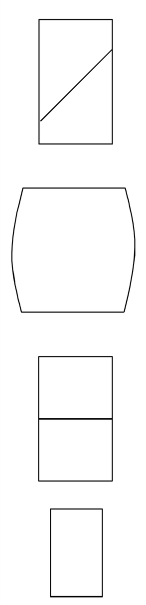
Parr Reactor: Stirred reactor for mixing of fluids at elevated temperature and pressure. Elevated temperatures provided by external heaters.

Also used in this study: XRF, ICPMS, Load press

Failure of Porous Rock



Reservoir production and injection causes changes in stress, resulting in poroelastic response. Changes in pore fluid pressure (Pp) can change the effective pressure (Pe) in the reservoir even though the far field vertical and horizontal stresses remain unchanged. The effective pressure is the pore pressure subtracted from the far field stresses. For experiments, effective pressure is the difference between confining pressure (Pc) and pore fluid pressure. Effective axial stress (σ_a') is the difference between the axial stress (σ_a) and the pore fluid pressure.

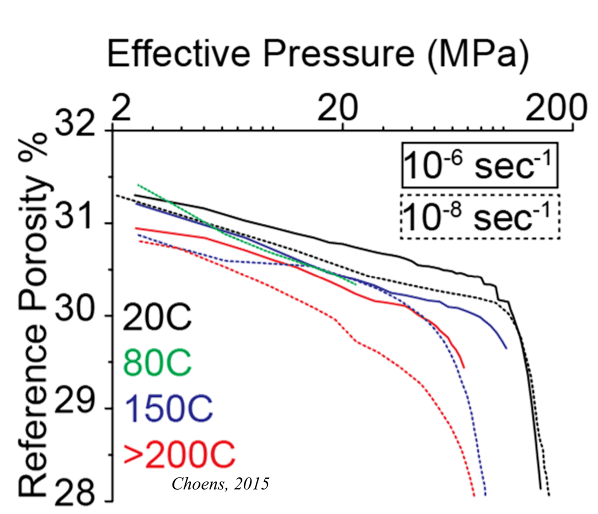


The behavior of porous, granular rocks is pressure dependent.

- Low Pe regime: Localized, dilatant shear fracture described by Mohr-Coulomb envelope. Increasing failure strength with increasing Pe.
  - Intergranular cracking, breaking cemented boundaries, grain boundary sliding and grain rotation
- High Pe regime: Distributed, compactional cataclastic flow described by elliptical CAP. Decreasing failure strength with increasing Pe.
  - Fracturing of grains initiating at Hertzian contacts, porosity collapse, and grain rearrangement
- Transitional regime: Combined distributed deformation and localized deformation bands. Failure strength roughly constant with increasing Pe.
  - Mix of low and high Pe mechanisms of damage
- Hydrostatic Consolidation: Porous granular material can deform by hydrostatic pressure alone for distributed deformation.
  - Fracturing of grains initiating at Hertzian contacts, porosity collapse, and grain rearrangement

Differential stress (q) and mean stress (p) vary with position and time. Injection into a reservoir increases the pore fluid pressure, decreasing the effective pressure. Differential stresses are unaffected by changes in pore fluid pressure, so the resulting stress path is a horizontal line. The stress path for the reservoir would move towards lower pressures, and could possibly intersect the failure envelope, most likely in the low effective pressure regime..

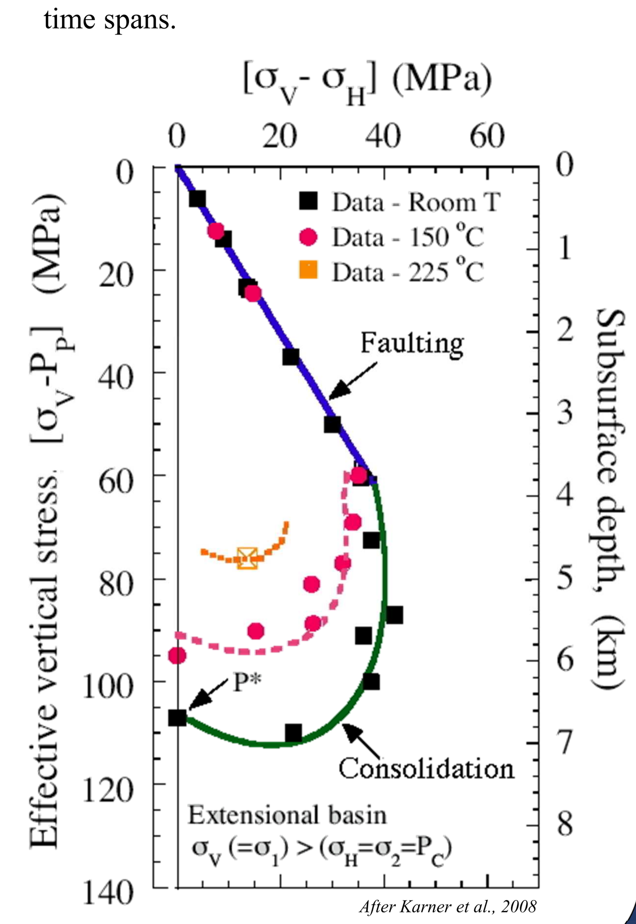
One concern for CCUS is that the chemical reactions between the reservoir rock and the injected CO_2 could change the failure envelope. Weakening reactions could cause the failure envelope to collapse, causing failure at in situ pore pressures. Failure is most likely in the high effective pressure regime, causing compactional behavior that could induce subsidence and could disturb the stability of the caprock.



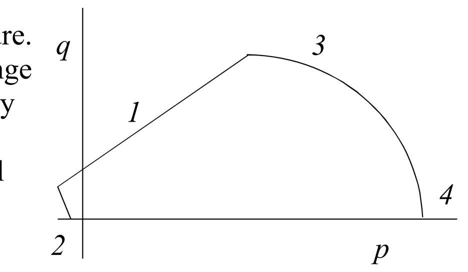
Previous work on the hydrostatic consolidation of quartz sand has demonstrated that grain crushing behavior is highly dependent on temperature and strain rate. Changes in either temperature or strain rate have small effects in reducing the pressure necessary to induce grain crushing, but changes in both temperature and strain rate have pronounced effects. These are important consideration for extrapolating laboratory experiments to predict stability at geologic time spans.

Previous work on the triaxial compression of quartz sand has demonstrated that the temperature dependence is pressure dependent. At high effective pressures, the behavior is dependent on temperature, where increasing temperature causes decreases in failure strength. At low effective pressure, the behavior is independent of temperature.

Processes involving grain cracking are temperature and strain rate dependent, and increases in temperature and decreases in strain rate magnify the effect because of the greater contribution of sub-critical crack growth. Processes involving slip between grains are independent of strain rate and temperature because frictional processes are generally insensitive to these variables.



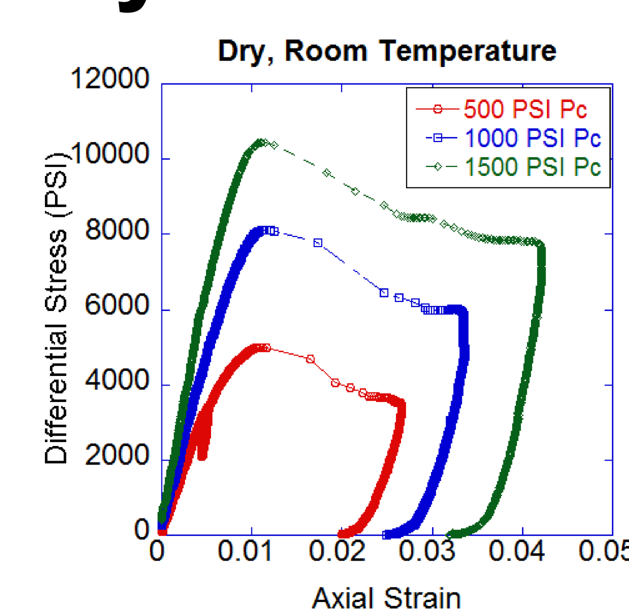
Experimental Plan



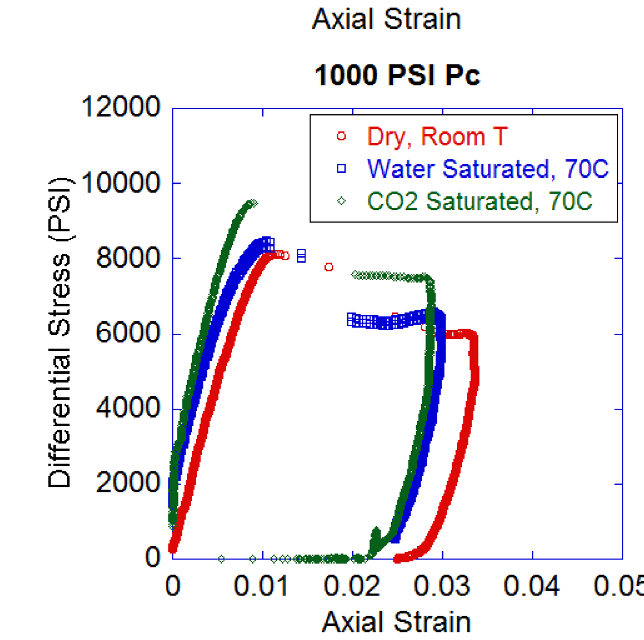
1. The effect of humidity of supercritical CO_2 on shear fracture. Samples will be deformed in triaxial compression at a range of low confining pressures. Samples will be deformed dry at room temperature to establish the Mohr-Coulomb envelope. Samples will then be reacted with supercritical CO_2 at different humidities for 24 hours at 70C and 2000 PSI . Samples will be deformed in triaxial compression.
2. The effect of supercritical CO_2 saturated water on tensile strength. Discs of Boise Sandstone will be reacted with water and CO_2 at 2000 PSI and 70 C for 5 days in a stirred reactor. Water samples will be sampled throughout the reaction to monitor changes in fluid due to chemical reactions. After the experiment, the reacted discs will be used for Brazilian tension tests to compare against unreacted tensile strength.
3. The effect of humidity of supercritical CO_2 on compaction band formation. Samples will be deformed in triaxial compression at a range of high confining pressures. Samples will be deformed dry at room temperature to establish the elliptical CAP. Samples will then be reacted with supercritical CO_2 at different humidities for 24 hours at 70C and 2000 PSI . Samples will be deformed in triaxial compression. Acoustic velocities will be measured throughout the experiment to monitor chemical reactions and damage development.
4. The effect of supercritical CO_2 on hydrostatic consolidation. Samples will be deformed at hydrostatic pressure and elevated pressure. Samples will be held at a set hydrostatic pressure and allowed to creep. Samples will be initially dry, then different fluids will be flowed through the sample and allowed to creep to steady state.

Preliminary Results

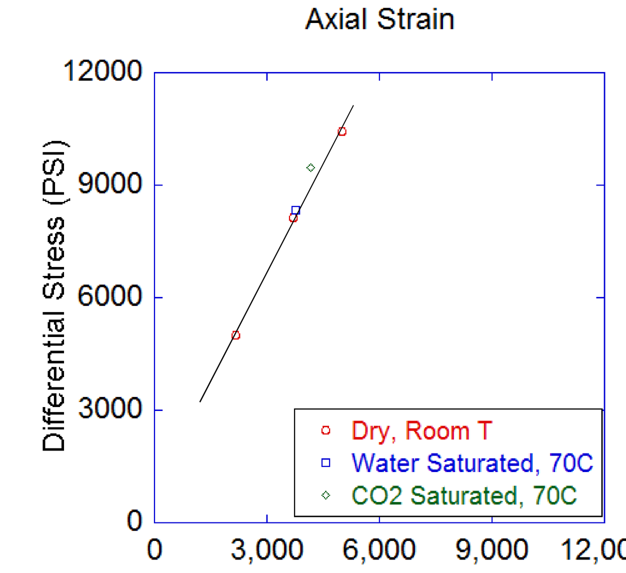
Sample of Boise sandstone were deformed dry at room temperature conditions at confining pressures of 500, 1000, and 1500 PSI. Sample strength increases with increasing confining pressure. The stress and strain failure is consistent with published values.



Sample of Boise sandstone were deformed at 1000 PSI effective pressure at three different conditions: dry at room temperature, saturated with deionized water pressurized to 2000 PSI at 70°C, and flowing CO_2 at 2000 PSI at 70°C. There is little strength difference between the water saturated sample and the dry sample. The CO_2 sample is noticeably stronger.



The failure strengths for the three dry experiments form a linear line between mean stress and differential stress. The water saturated sample agrees with this relationship. The CO_2 saturated sample follows this relationship as well.



Collaborations

- After the Brazilian tests have been performed on reacted and unreacted rocks, the samples will be sent to Nicolas Espinoza for further mechanical testing.
- Results will be used to verify elasto-plasticity of IPARS simulator of Mary Wheeler

Conclusions

1. Preliminary results from experiments demonstrate the expected behavior for the low effective pressure regime. The dry experiments at three different confining pressures form a linear relationship as expected for the Mohr Coulomb regime.
2. The experimental apparatuses used in the study have shown to produce reliable and reproducible results. Repeats at the same confining pressure have shown similar failure strengths. This holds true for results between the two triaxial core holders.
3. Water saturation and elevated temperature does not change the strength of Boise sandstone. As expected from previous work on quartz sand packs, failure in the Mohr Coulomb regime is independent of temperature. Furthermore, the fast strain rate used in the experiments also make it unlikely to see changes in strength in the absence of chemical reactions
4. At this early stage, it is unclear if the increase in strength from supercritical CO_2 saturation is real. It could be the result of dilatancy hardening, or incompatibilities of the jacket material with CO_2.

Imminent work

1. T. Dewers has begun measuring ultrasonic waves of Boise sandstone during loading and failure at dry conditions.
2. The chemical reaction experiment has been completed and the fluid samples and the analysis will be performed by A. Ilgen when new equipment is installed in March. The reacted discs will be deformed by the end of March.
3. Testing the effect of different relative humidities of water in supercritical CO_2 will start at the beginning of March.

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