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Geomechanical Alterations of reservoir and crystalline rocks under supercritical CO₂ Injection: insights for reservoir management and energy generation

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Abstract:

Injection of supercritical CO₂ into subsurface formations can alter coupled geochemical and geomechanical processes, thereby altering rock pore structure, mineral composition, and mechanical integrity, with implications for carbon capture, utilization, and storage (CCUS). This research study will focus on investigating the response of reservoir and crystalline rock to sCO₂-rich brine injected under controlled subsurface conditions. A setup experiment with laboratory testing for characterization analysis, including CT and micro-CT imaging, ultrasonic P- and S-wave velocity tests, Uniaxial Compressive Strength testing, and X-Ray diffraction analysis, was conducted before and after sCO₂-rich brine flooding to quantify the changes in microstructure, elastic properties, strength, and mineralogy. The results demonstrate that geomechanical changes are strongly dependent on lithology, with carbonate and sandstone rocks exhibiting greater chemical and mechanical modification than dolomite and crystalline rocks. The findings provide experimental constraints on rock integrity during supercritical CO₂ injection and help improve risk assessment, injection design, and long-term storage security for CCUS applications.

Keywords: Supercritical CO₂; CCUS; geomechanical alteration; reservoir integrity; sCO₂ brine rock interaction; rock mechanics

1 Introduction:

Carbon Capture, Utilization, and Storage (CCUS) involves injecting CO₂ into a subsurface formation where it usually exists in the supercritical phase and can interact with the formation fluid

and rock minerals. These sCO_2 interactions with brine and rock can drive mineral dissolution and precipitation, pore structure reorganization, fracture development, and changes in porosity and permeability, resulting in alterations in mechanical properties. Many studies before report that carbonates with rich calcite are particularly susceptible to chemical dissolution and mechanical weakening, whereas siliciclastic and crystalline rocks mostly exhibit more moderate changes dominated by cement alteration, microcracking, or stress redistribution. However, comparative experimental data evaluating multiple reservoir and crystalline lithologies under consistent sCO_2 conditions remain limited. This study addresses this gap by experimentally investigating the geochemical and geomechanical evolution of representative reservoir and crystalline rocks subjected to sCO_2 rich brine exposure, providing insights relevant to CCUS reservoir integrity and long-term storage security.

2 Methods:

A core flooding system operating at high pressure and high temperature was used to simulate the injection of supercritical CO_2 -rich brine under subsurface conditions. Using reservoir rock samples (Austin Chalk, Berea Sandstone, Bonne Terre Dolomite) were mounted in a core holder and flooded with CO_2 rich brine at a temperature of 80°C (176°F) and pore pressure of 1100 psi (76 bar). Confining pressure was maintained between 1200 and 1500 psi (82-103 bar) to ensure mechanical stability during injection. The injection fluid consisted of CO_2 -rich brine with a salinity of 3% and a constant flow rate of 0.05 ml/min (4.5×10^{-4} bbl/day) for an injection duration of 7 days. The system's condition remained within the supercritical CO_2 regime throughout the experiments. Due to the samples having low permeability, the crystalline rocks (Ultramafic and granite) were exposed to a sCO_2 -rich brine using a high-pressure vessel under the same temperature and pressure conditions.

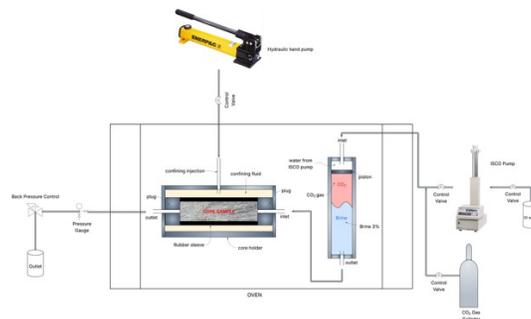


Figure 1 sCO_2 -rich Brine Core Flooding System

Characterization tests were conducted before and after sCO_2 -rich brine injection to quantify geochemical and geomechanical alterations. CT scanning was used to evaluate pore structure in reservoir rocks, while micro-CT was used to image tight crystalline rocks (ultramafic and granite). Ultrasonic P- and S-wave velocities were measured using a digital oscilloscope to assess elastic property changes, followed by uniaxial compressive strength testing to quantify strength and failure behavior. X-ray diffraction analysis was performed to identify mineralogical changes associated with sCO_2 brine interaction, providing an integrated assessment of microstructural, elastic, and mechanical responses.

3 Results:

3.1 Microstructural Evolution from CT and Micro CT Imaging



Table 1 Porosity Changes

Porosity (%)		
Rock Type	Before	After
Carbonate	24	20
sandstone	17.55	11
Dolomite	11	15
Ultramafic	5	3
Granite	0.1	0.1

Figure 2 CT Scan System

The results indicate that sCO₂-rich brine affects porosity changes after injection and shows that, depending on lithology, carbonate and sandstone experience significant decreases of around 16% and 37% in porosity compared with other rocks.

3.2 Elastic Properties Changes from Ultrasonic Wave Velocities Analysis

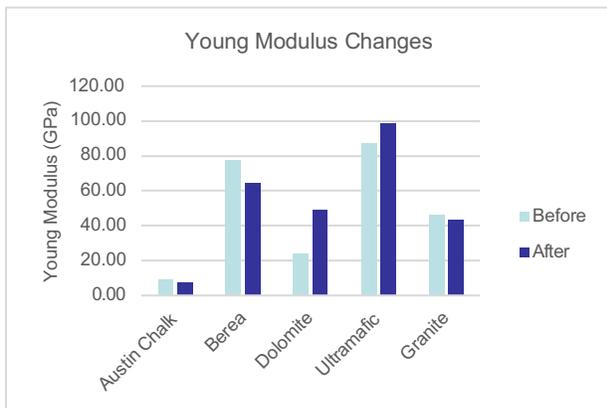


Figure 3a Young's Modulus Changes

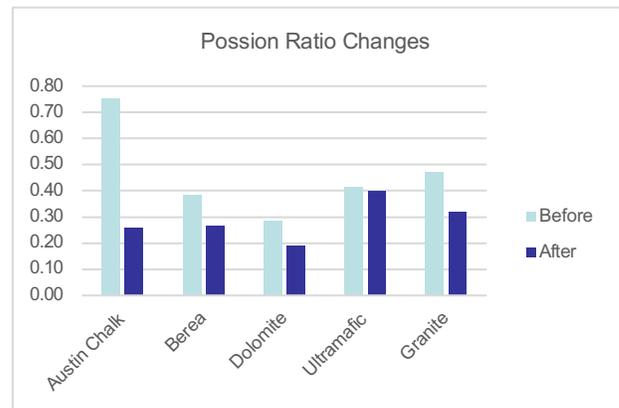


Figure 3b Poisson's Ratio Changes

Among all the lithologies, the Poisson's ratio results show a reduction after exposure, whereas Young's modulus shows different changes after exposure, indicating that some rocks experience elastic degradation compared with other rocks.

3.3 Mechanical Strength Response from UCS Testing

The UCS after sCO₂-rich brine injection for Carbonate Austin Chalk and Berea Sandstone show a 10-20% reduction, while dolomite shows the opposite results, with a slight strength increase, and ultramafic and granite show minimal changes in elastic values monitored from velocity tests.

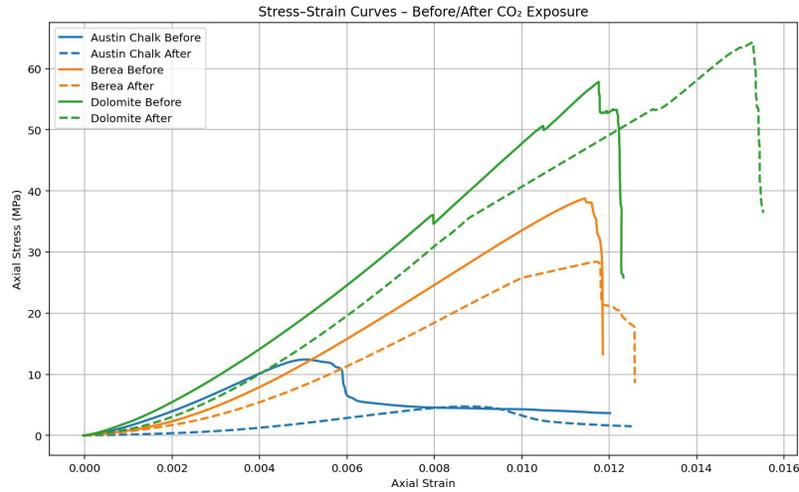


Figure 4 UCS testing

3.4 Mineralogical Evolution after scCO₂ Exposure

XRD analysis shows a reduction in carbonate mineral content after scCO₂-rich brine exposure, with calcite content in Austin Chalk decreasing by approximately 15–25 wt.%,

Table 2 XRD Results

Rock Type	Condition	Dominant Minerals	Mineral Percentage (%)
Austin Chalk	Before CO ₂ (B-AC)	Calcite (CaCO ₃)	97.3
		Illite	2.7
Berea Sandstone	Before CO ₂ (B-BR)	Illite	4.4
		Quartz (SiO ₂)	41
	Fe-phosphate/hydroxide phase	59	
After CO ₂ (T-BR)	Quartz (SiO ₂)	100	
Dolomite	Before CO ₂ (B-DL)	Dolomite (CaMg(CO ₃) ₂)	31
		Fe-Si-P phase	68.2
		Mg-calcite	0.8
	After CO ₂ (T-DL)	Dolomite (CaMg(CO ₃) ₂)	91.5
		Fe-bearing dolomite	7.3
Mg-calcite	1.2		

4 Discussion

The observation of porosity decrease and mechanical weakening after injection in carbonate and sandstone indicates that carbonic acid from scCO₂-rich brine formed and interacted with rock minerals. The carbonic acid (CO₂ + H₂O → H₂CO₃) which can cause mineral dissolution when it reacts with calcite, leading to pore enlargement, loss of grain contacts, and reduction in strength and elastic properties, is similar to sandstone when dissolution of cement occurs and has minor feldspar alteration, weakening the grain framework and contributing to microcrack development. In contrast, dolomite has slower dissolution kinetics and potential reprecipitation, resulting in minimal changes in porosity and strength. While granite and ultramafic monitored from velocity tests show minimal to moderate increases in elastic properties, the response is through microcracking rather than bulk chemical dissolution, reflecting the relative stability of silicate minerals to carbonic acid. These results help demonstrate that carbonic acid reaction products are the primary control on geomechanical alteration during and after scCO₂ injection and must be

considered when assessing reservoir integrity and CCUS storage security.

5 Conclusion

Supercritical CO₂ rich brine injection induces coupled geochemical and geomechanical alterations that are strongly controlled by rock mineralogy. Carbonate and sandstone rocks experience greater porosity decrease, elastic degradation, and strength reduction due to carbonic-acid-driven dissolution, whereas dolomite and crystalline rocks exhibit greater mechanical stability with limited mineralogical change. These findings highlight the importance of lithology-specific characterization for evaluating reservoir integrity, injection strategy, and long-term storage security in CCUS applications.

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