A Coupled Geomechanical, Acoustic, Transport and Sorption Study of Caprock Integrity in CO2 Sequestration

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Presentation Outline

• Benefit to the Program
• Goals and Objectives
• Technical Status
• Accomplishments to Date
• Synergy Opportunities
• Summary
• Appendix
Benefit to the Program

• Area of Interest 2: Fractured Reservoir and Seal Behavior
• Measured changes in permeability, sorption, mass transfer, and mechanical and seismic properties of seal rocks due to supercritical CO\textsubscript{2} will allow us to:
  – Understand CO\textsubscript{2} migration in caprocks
  – Provide tools to identify and monitor damaged caprocks
  – Determine CO\textsubscript{2} escape pathway through shale
• Outcome: Our methods will allow a better assessment of storage security and develop certainty for Carbon Storage Program effort to monitor and ensure 99% CO\textsubscript{2} retention and storage permanence
Project Overview:
Goals and Objectives

• **OBJECTIVE 1**: Determine the behavior of intact and fractured caprocks when exposed to supercritical CO\textsubscript{2} at elevated pressures.
  – **GOAL 1**: Assess the risk of CO\textsubscript{2} leakage arising from geomechanically damaged shale.

• **OBJECTIVE 2**: Characterize the physical, chemical and geomechanical processes associated with fluid flow and storage in caprocks
  – **GOAL 2**: Provide tools for monitoring and identifying damaged shale caprocks.
Technical Status

1. Direct-shear experiments on shale permeability
2. Sorption capacity of shale for hexane, CO$_2$, water vapor in dry and water-imbibed state
3. Changes in acoustic and NMR properties during CO$_2$ sorption
Methods and Materials

• Vapor adsorption isotherms: hexane, water, nitrogen
• BET apparent specific surface area (ASSA)
• Sample: Siltstone (no OM) and Organic-rich shales

Details on Kumar-Zhang’s poster

S: Siliceous Minerals
C: Carbonate Minerals
P: Pyrites
Results (from 2015)

- Cryogenic N₂ selectively blocked by nano-sized pores in OM*
- OM* pores are hydrophobic
- OM* pore development starts at the onset of oil window
- Presence of bitumen free OM* pores

*OM = organic matter

Details on Kumar-Zhang's poster
Preferential Sorption

- CO₂ sorption capacity in dry state
- CO₂ sorption capacity in water-imbibed state (imbibition at 4000 psi)

Samples used:
- Illite clay samples
- Organic-rich shales

Details on Kumar-Zhang’s poster
Sorption in shales with water

CO₂ Sorption at 50°C

- CO₂ sorption in dry rock: OM pores and Illite pores fill with CO₂
- CO₂ sorption after forced imbibition with water: Illite pores fill with water; OM pores fill with CO₂

Details on Kumar-Zhang’s poster
Rate of sorption is reduced substantially in the presence of water due to the much lower diffusion coefficient of CO$_2$ in liquid water than that of its gas state.
Fractional Uptake and Analytical Solution

![Graph showing fractional uptake and analytical solution](image)

<table>
<thead>
<tr>
<th></th>
<th>illite</th>
<th>4A zeolite</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure (psi)</td>
<td>2.77</td>
<td>1.64 - 1.45*</td>
</tr>
<tr>
<td>$D/R^2$ [s$^{-1}$]</td>
<td>$1 \times 10^{-4}$</td>
<td>0.067 - 2.9$ \times 10^{-3}$*</td>
</tr>
</tbody>
</table>

*Cejka et al.*
Method

- Ultrasonic p-wave measurements on water and hexane vapor sorbing clay aggregates
- Distinct flow and deformational properties of liquid and gas fluids in pores affect P-wave modulus differently
- Resonance frequency (FFT) used as proxy for attenuation

<table>
<thead>
<tr>
<th>Sample</th>
<th>Porosity, ϕ (%)</th>
<th>Bulk Density, ρ_d (g/cc)</th>
<th>Grain Density, ρ_d (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illite</td>
<td>17.66</td>
<td>2.21</td>
<td>2.68</td>
</tr>
<tr>
<td>Smectite</td>
<td>17.46</td>
<td>2.27</td>
<td>2.75</td>
</tr>
<tr>
<td>I-S Mixed Layer</td>
<td>20.95</td>
<td>2.11</td>
<td>2.67</td>
</tr>
</tbody>
</table>

Details on Kumar-Zhang’s poster
Vapor Adsorption in Clays

- Partial saturation for vapor phase adsorbed (*CUC) phase

- Saturation of adsorbed phase: 
  \[ S_{ads} = \frac{(Q_1 v_1)}{(\phi/\rho_g)} \]

*CUC: Confined undersaturated condensate

Details on Kumar-Zhang’s poster
Isotherms, Waveforms, Spectra

**Isotherms**
- Hexane: IMt-1
  - Q (mmol/g) vs. Relative Pressure (p/p₀)
  - S_{CTC}(%)

**Waveforms**
- Amplitude, V vs. Time, µs
- Frequency, kHz vs. Power, V²

**FFT Spectra**
- Power, V² vs. Frequency, kHz

Water: IMt-1
- Q (mmol/g) vs. Relative Pressure (p/p₀)
- S_{CTC}(%)

Graphs show the relationships and data for hexane and water in IMt-1 samples.
**P-wave Modulus**

- P-wave modulus ($M_{CUC}$) is unaffected by Hexane CUC in pores.
- Two regimes with water CUC in pores:
  - Initial slight rise in P-wave modulus up to 3-5% saturation.
  - Drastic drop in P-wave modulus with further increase in saturation.

Details on Kumar-Zhang’s poster.
NMR T2 Relaxation Times

NMR spectra in a combined Berea sandstone and a Niobrara mudstone sample.
Direct-Shear Experiments on Shale Perm

Carey, LANL
Effect of Confining Pressure (Depth)

Utica shale at 3.5 MPa  Utica shale at 22 MPa

Carey, LANL
Permeability Behavior and Depth

Permeability (mD) vs. Confining Pressure (MPa)

- Brittle/Transmissive
- Ductile/Non-transmissive

Carey, LANL
Accomplishments to Date

**Completed:**
- Experimental Setup
- Subcritical Adsorption on various fluids
- CO2 sorption in shales / clay
- Acoustic tests during sorption
- Permeability of shear fractures in Utica shale
- Leakage through damaged caprock is critically dependent on the interaction shale properties and depth

**Ongoing:**
- Acoustic Tests
- Equation of state calculations
- High pressure and temperature tests
- NMR experiment during CO2 injection
- Triaxial tests for strength and fracture permeability
Synergy Opportunities

Our work on changes in acoustic and NMR properties of caprocks with CO\textsubscript{2} has synergies with research on:

- Quantification of CO\textsubscript{2} storage from remote seismic surveys used to monitor, measure, and verify CO\textsubscript{2}
- Evaluation of storage capacity of CO\textsubscript{2} storage sites using well log analyses of NMR and acoustic logs
- Assess changes in geomechanical strength of caprocks after CO\textsubscript{2} injection
- Kinetics of supercritical CO\textsubscript{2} adsorption
Summary

– Key Findings:
  • Transition from transmissive to non-transmissive fracture systems (for Utica shale > 15 MPa)
  • Sorption dependent on sorptive and mineralogy
  • No CO2 sorption in clays in the presence of water

– Lessons Learned:
  • Sorption experiments should be conducted in presence of water

– Future Plans:
  • Acoustic tests with simultaneous measurements of storage capacity and acoustic properties
  • Acoustics, NMR, and permeability tests with more cap rocks