Interdisciplinary investigation of CO$_2$ sequestration in depleted shale gas formations

Sander Hol
Mark D. Zoback, Jennifer Wilcox, Anthony R. Kovscek
Stanford University

DE-FE-0004731

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Infrastructure for CCS
August 20-22, 2013
Presentation Outline

• Research Objectives and Benefits to the Program
• Technical Status
  – Transport
  – Storage
  – Geomechanics
• Summary / Accomplishments
Research Objectives and Benefits to the Program

• Spectacular development of shale gas plays in the US offers a massive opportunity for CCS applications in the near future.

• Effective CO$_2$ sequestration strategies rely on solid understanding of local fluid/rock properties under in-situ post-production conditions.

• Our work integrates laboratory and theoretical studies and aims at developing a realistic description of multi-scale transport, storage mechanisms and geomechanical behavior of gas shales.
Technical Status

Transport
- free/adsorbed CO$_2$
- permeability anisotropy
- role of fractures
- pore connectivity

Storage
- free/adsorbed CO$_2$
- pore size distribution
- pore shape

Geo-mechanics
- free/adsorbed CO$_2$
- instantaneous vs. time-dependent response
Adsorption

- Adsorption related to TOC, H₂O and clay content
- CO₂ adsorption sometimes significant
- Coupling between adsorption, transport and mechanical behavior in shales unclear

Chareonsuppanimit et al., 2012

Gasparik et al., 2012
Transport

• Experimental work using pulse-decay method
  – Horizontal (“high”) permeability versus vertical (“low”) permeability
  – Separate rock permeability($k_\infty$), slippage effect, and adsorption

• Simulations
  – Comparing Brace (1968), Jones (1976) and history-match methods based on pulse-decay data
  – Non-equilibrium molecular dynamics 3D carbon network
  – Incorporate direct effect of adsorption
Simultaneous porosity, permeability, and sorption measurement

HORIZONTAL SAMPLES!

very little adsorption…
Horizontal permeability when exposed to N$_2$, CH$_4$, and CO$_2$

**Barnett Shale**

- $P_f = 182$ psia
- Effective Stress = 333 psi
- $K (\text{MD})$: N$_2$ = 4.02, CH$_4$ = 2.41, CO$_2$ = 0.009

**Eagle Ford Shale**

- No adsorption effect
- $k_w = 12.5$ $\mu$D
- $b_{slip} = 208.36$ psi
- $R^2 = 0.9664$
- $k_w = 13.1$ $\mu$D
- $b_{slip} = 203.13$
- $R^2 = 0.9595$

Stanford University
Transport

Simulations based on pulse-decay data on horizontal cores

Eagle Ford Shale

- History Match Method
- Jones Method
- Brace Method

Permeability, μD

Pore Pressure, psi
Transport

VERTICAL SAMPLES!

Eagle Ford Shale disc

Stanford University
Transport

Vertical permeability when exposed to He and CO₂
Transport

• $k_{\text{hor}} >> k_{\text{vert}}$ (orders of magnitude)
• related to fractures versus pores (refer to CT work reported previously)
• CO$_2$ adsorption causes direct and indirect reduction in $k$, i.e. ”blocking” versus “swelling”
• Strongly sample-dependent
Transport / Storage

Storage and transport of fluids in porous materials influenced by morphology -> pore connectivity, pore shape, size, and surface characteristics

Realistic descriptions of local pore characteristics can be achieved by modeling of the solid material itself, and understanding pore structure including pore-size distribution, and pore-network connectivity.

Stanford University
Storage

• Low pressure $N_2$ adsorption isotherms
  – Quantachrome Autosorb iQ2

• Sample: Eagle Ford shale
  – Pore size distributions
  – Create framework for modeling efforts
  – Link pore scale to fracture scale
Improper outgassing can:
- Suggest heterogeneity in samples that may not exist
- Decrease apparent pore volume
- Lead to isotherms unsuitable for further analysis
Storage

Eagle Ford Shale

\[ \text{Pore Diameter (nm)} \]

\[ \text{dV/dn} \text{ (cm}^3\text{ / nm/g)} \]

- Sample 1
- Sample 2
- Sample 3

Volume @ STP (cm$^3$ g$^{-1}$)

\[ \frac{P}{P_0} \]

Stanford University
Geomechanics

• Storage: free phase in large pores/fractures and adsorption in nanoscale pores
• How do these phases affect long-term geomechanics? -> direct and indirect coupling
• Conduct creep experiments on samples equilibrated with CO₂
Geomechanics
Pre-consolidation Stress

Time

Pore Pressure

Evacuate

Helium

Carbon Dioxide

Time

Stanford University
Evacuation and exposure to CO₂ at 3 MPa

Sample 6 clay-poor

Sample 10 clay-rich

Geomechanics

<table>
<thead>
<tr>
<th>SampleID</th>
<th>Depth (m)</th>
<th>TOC</th>
<th>QTZ</th>
<th>CARB</th>
<th>CLAY</th>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3781</td>
<td>0.79</td>
<td>31.65</td>
<td>51.19</td>
<td>10.32</td>
<td>6.35</td>
</tr>
<tr>
<td>6</td>
<td>3816</td>
<td>2.11</td>
<td>3.72</td>
<td>86.05</td>
<td>7.44</td>
<td>0.59</td>
</tr>
<tr>
<td>10</td>
<td>3884</td>
<td>5.32</td>
<td>17.80</td>
<td>45.54</td>
<td>24.43</td>
<td>6.44</td>
</tr>
</tbody>
</table>
Mechanical response:
- Elastic (biggest effect)
- Viscoelastic (significant effect – clay rich)
- Fluid migration effect (up to 15% effect)
Summary / Accomplishments

• Transport
  – Insights into separating rock permeability from slip flow and adsorption effects, plus composition-dependence and effects of scale.
  – Further understanding of basis of permeability anisotropy, and relation to direct and indirect effects of adsorption and rock fabric.

• Storage
  – Practical constraints on determination of PSD by N₂ adsorption techniques – effects of outgassing / role of residual fluids.

• Geomechanics
Appendix

– Organizational Chart
– Gantt Chart
– Bibliography
Stanford University, School of Earth Sciences

- **PI:** Professor **Mark D. Zoback**, Department of Geophysics,
  - Dr. Sander Hol (Postdoctoral Scholar), Dr. Julia Reece (Postdoctoral Scholar), Rob Heller (PhD student)

- **Co-PI:** Professor **Anthony R. Kovscek**, Energy Resources Engineering Department,
  - Bolivia Vega (Research Assistant), Dr. Cindy Ross (Research Associate), Hamza Aljamaan (PhD student) and Khalid Alnoaimi (PhD student)

- **Co-PI:** Assistant Professor **Jennifer Wilcox**, Energy Resources Engineering Department,
  - Dr. Mahnaz Firouzi (Postdoctoral Scholar), Dr. Dawn Geatches (Postdoctoral Scholar), and Dr. Erik Rupp (Research Associate)
<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>Quarters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Project Management and Planning</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
</tr>
<tr>
<td>1.1</td>
<td>Project management plan</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>Planning and reporting</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Physical and Chemical Aspects of CO₂/Shale Interactions</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
</tr>
<tr>
<td>2.1</td>
<td>Obtain gas shale samples</td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>Gas shale surface characterization experiments</td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>Gas shale bulk characterization experiments</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>Development of model systems for adsorption/transport</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>Adsorption simulations using Monte Carlo</td>
<td></td>
</tr>
<tr>
<td>2.6</td>
<td>Physical property measurements</td>
<td></td>
</tr>
<tr>
<td>2.7</td>
<td>Shale swelling due to adsorption</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Transport and Mobility of CO₂ in Fractures and Pores</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
</tr>
<tr>
<td>3.1</td>
<td>Transport simulations and permeability predictions</td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>In-situ imaging of gas transport pathways</td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>Shale permeability to CO₂</td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>Gas diffusivity within shale</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Groundwater and Stored CO₂ Interactions</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
</tr>
<tr>
<td>4.1</td>
<td>Model gas-water-CO₂ interactions with clay</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Trap and Seal Analysis of CO₂ in Shale Gas Reservoirs</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
</tr>
<tr>
<td>5.1</td>
<td>Examine evolution of fractures and seal properties</td>
<td></td>
</tr>
</tbody>
</table>
Bibliography


Heller, R.J. and Zoback, M.D., “Experimental Investigation of Matrix Permeability of Gas Shales”, AAPG Bulletin, Accepted Manuscript
