Integrated characterization of CO$_2$ storage reservoirs on the Rock Springs Uplift combining geomechanics, geochemistry, and flow modeling

DE-FE0023328

John Kaszuba
University of Wyoming
Presentation Outline

• Benefits and overview
• Technical status
• Accomplishments to date
• Synergy opportunities
• Summary
Benefit to the Program

• Program goals addressed
  – Develop and validate technologies to ensure 99% storage permanence
  – Develop Best Practice Manuals (BPMs) for monitoring, verification, accounting (MVA), and assessment; site screening, selection, and initial characterization; public outreach; well management activities; and risk analysis and simulation.
The project will conduct research under Area of Interest 1, Geomechanical Research, by developing a new protocol and workflow to predict the post-injection evolution of porosity, permeability and rock mechanics, relevant to estimate rock failure events, uplift and subsidence, and saturation distributions, and how these changes might affect geomechanical parameters, and consequently reservoir responses. The ability to predict geomechanical behavior in response to CO$_2$ injection, if successful, could increase the accuracy of subsurface models that predict the integrity of the storage reservoir.
Project Overview:
Goals and Objectives

Overall Objective

Improve understanding of the effects of CO$_2$ injection and storage on geomechanical, petrophysical, and other reservoir properties.

• Combines integrated, interdisciplinary methodology using existing data sets (Rock Springs Uplift in Wyoming)
• Culminates in integrated workflow for potential CO$_2$ storage operations
Project Overview: Goals and Objectives

Specific Objectives

1) Test new facies and mechanical stratigraphy classification techniques on the existing RSU dataset

2) Determine lithologic and geochemical changes resulting from interaction among CO$_2$, formation waters, and reservoir rocks in laboratory experiments

3) Determine the effect(s) of CO$_2$-water-reservoir rock interaction on rock strength properties; this will be accomplished by performing triaxial strength tests on reservoir rock reacted in Objective #2 and comparing the results to preexisting triaxial data available for reservoir rocks
Project Overview:
Goals and Objectives

Specific Objectives (continued)

4) Identify changes in rock properties pre- and post-CO$_2$ injection

5) Identify the parameters with the greatest variation that would have the most effect on a reservoir model

6) Make connections between elastic, petro-elastic, and geomechanical properties

7) Develop ways to build a reservoir model based on post-CO$_2$-injection rock properties

8) Build a workflow that can be applied to other sequestration characterization sites, to allow for faster, less expensive, and more accurate site characterization and plume modeling.
Project Overview:
Goals and Objectives

Relationship to DOE program goals

Our approach can be adapted to other sites to guide site characterization and design of surveillance and monitoring techniques to meet the goal of 99% safe storage, reach ±30% model accuracy, contribute to the BPM, and reduce time and cost of site characterization.
Technical status

Interdisciplinary Team

- Vladimir Alvarado: Reservoir Engineer
- Erin Campbell-Stone: Structural Geology, Geomechanics, Wyoming Geology
- Dario Grana: Rock Physics
- Kam Ng: Geomechanics
- John Kaszuba: PI, Geochemistry

Today’s results predominantly work of D. Grana.
Rocks Spring Uplift, WY
## Stratigraphy

<table>
<thead>
<tr>
<th>JURASSIC</th>
<th>Stump Sandstone</th>
<th>Morrison Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>Preuss Formation</td>
<td>Entrada Sandstone</td>
</tr>
<tr>
<td>Middle</td>
<td>Twin Creek Limestone</td>
<td>Carmel Formation</td>
</tr>
<tr>
<td>Lower</td>
<td>Nugget Sandstone</td>
<td></td>
</tr>
</tbody>
</table>

**TRIASSIC**

- Ankareh Formation
- Thaynes Limestone
- Woodside Formation
  - Dinwoody Formation

**PERMIAN**

- Phosphoria Formation

**PENNOSYLVANIAN**

- Tensleep Sandstone
- Weber Sandstone
- Amsden Formation
- Morgan Formation
- Darwin Sandstone
- Madison Limestone

**MISSISSIPPIAN**

**DEVONIAN**

- Upper
  - Three Forks Formation
  - Jefferson Formation
  - Darby Formation

**SILURIAN**

**ORDOVICIAN**

- Bighorn Dolomite

**CAMBRIAN**

- Upper
  - Gallatin Limestone
- Middle
  - Gros Ventre Formation
- Lower
  - Flathead Sandstone

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3400 – 3600 m (11150 – 11800 ft)

3725 – 3855 m (12225 – 12650 ft)

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Shafer 2013
Madison Ls
Existing Well Logs

After Surdam et al., 2013
Petrophysical Data

(a) Porosity vs. Depth
(b) Volume of sandstone vs. Depth
(c) Volume of shale vs. Depth
(d) Volume of limestone vs. Depth
(e) Volume of dolomite vs. Depth

Depth (m)

Madison Ls
Weber Ss
Permeability

Measured permeability from Surdam et al., 2013

Calculated permeability (Kozeny-Carman):

$$\kappa = \frac{\rho g}{\mu} f_k(n) c_{f_i}^2$$
Facies Classification

- Weber Ss
- Amsden Fm
- Do, n>10%
- Do, n<10%

+Shale (dark blue)
Rock Physics Analysis

- Ss
- Do
- Ls
- Shale
- Do, n<10%
Bayesian Facies Classification

(a) Predicted elastic facies (four facies)
(b) Predicted seismic facies (four facies)
(c) Predicted elastic facies (five facies)
(d) Predicted seismic facies (five facies)

Ss
Shale
Ls
Do, n>10%
Do, n<10%
# Frequency Table

<table>
<thead>
<tr>
<th>Petrofacies</th>
<th>Classified Elastic Facies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shale</td>
</tr>
<tr>
<td>Shale</td>
<td>0.900</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.178</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0.047</td>
</tr>
<tr>
<td>Dolomite</td>
<td>0.231</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Petrofacies</th>
<th>Classified Elastic Facies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shale</td>
</tr>
<tr>
<td>Shale</td>
<td>0.733</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.117</td>
</tr>
<tr>
<td>Sand</td>
<td>0.038</td>
</tr>
<tr>
<td>Dolomite ((\varphi &lt; 0.1))</td>
<td>0.068</td>
</tr>
<tr>
<td>Dolomite ((\varphi &gt; 0.1))</td>
<td>0.110</td>
</tr>
</tbody>
</table>
Rock Physics & Geomechanics
Experiments - Sample Selection, Preparation, and Workflow
### Geomechanics Lab

Interpreted in-situ stress conditions (Shafer 2013)

<table>
<thead>
<tr>
<th>Geomechanical Parameter</th>
<th>Weber (@11,365 ft)</th>
<th>Madison (@12,512 ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Stress</td>
<td>12250 psi</td>
<td>13380 psi</td>
</tr>
<tr>
<td>Pore Pressure</td>
<td>4914.55 psi</td>
<td>5380.15 psi</td>
</tr>
<tr>
<td>$S_{h\text{min}}$ magnitude range</td>
<td>6841 – 7268 psi</td>
<td>8240 – 9895 psi</td>
</tr>
<tr>
<td>$S_{H\text{max}}$ magnitude range</td>
<td>9645 – 12,290 psi</td>
<td>10600 – 19,810 psi</td>
</tr>
</tbody>
</table>

### Selected geomechanical test conditions

<table>
<thead>
<tr>
<th>Geomechanical Parameter</th>
<th>Weber</th>
<th>Madison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Confining Pressure</td>
<td>6000 psi, 9000 psi, 13,000 psi</td>
<td>6000 psi, 9000 psi, 13,000 psi</td>
</tr>
<tr>
<td>Pore Pressure (brine)</td>
<td>5300 psi</td>
<td>5750 psi</td>
</tr>
<tr>
<td>Temperature</td>
<td>200 F</td>
<td>215 F</td>
</tr>
<tr>
<td>Ultrasonic Frequency (Vs and Vp)</td>
<td>200 KHz</td>
<td>200 KHz</td>
</tr>
</tbody>
</table>
Accomplishments to date

• Establish infrastructure and culture of communication among disciplines
  – Grounded by knowledge of geologic reservoir conditions
  – 2 PhD students hired, co-advised by coPIs
  – Graduate course in reservoir geomechanics taught Spring 2015 by coPI; PI and grad student participated
• Review results from previous study
• Select/machine samples from core
• Calibrate facies-dependent rock physics models (in sandstone, dolomite and limestone)
• Apply joint rock physics model for the estimation of elastic and electrical properties (velocity and resistivity)
• Implement statistical approach to facies classification and rock physics modeling for uncertainty quantification
• Finalize integrated geochemical-geomechanical test plan/workflow
• Begin initial geochemical tests
• Prepare labs for coreflood and geomechanical tests
  – Update triaxial equipment (ultrasonic, temperature control system, and high temperature load cell)
Synergy opportunities

To be determined
Summary –
Key Findings/Lessons Learned

• Four main rock types: sand, shale, limestone and dolomite. For each rock type in each formation, we determined a rock physics model to link rock and fluid properties, such as porosity, lithology and fluid saturations, with elastic and geomechanical properties.

• Four probabilistic approaches to quantify uncertainty in facies classification (Expectation Maximization, Bayesian classification, Gaussian mixture classification, and k-means clustering) provided similar results.

• Use Bayesian classification, which is also the most popular in the oil industry.
Summary – Key Findings/Lessons Learned

- Distinguish sandstone from other lithologies using elastic properties, but large overlap between limestone and dolomite.
- Uncertainty increases if facies classification is performed at resolution of seismic data rather than the well log scale.
- Geomechanical properties determined for facies
Summary – Future Plans

• Continue geochemical tests
• Begin coreflood tests
• Begin geomechanical tests (unreacted samples)
• Revisit rock physics models
  – Re-evaluate inversion of seismic data to improve resolution
  – Incorporate results of impending geomechanical tests into rock physics model
  – Extend Rock Physics models to 3D static model of the reservoir
Organizational Chart and Communication Plan

John Kaszuba
Principal Investigator
Dept. of Geology and Geophysics
School of Energy Resources
Task 1.0 – Project management and planning
Task 3.0 – CO$_2$-water-rock experiments
Task 8.0 – Integrate results to generate workflow

Vladimir Alvarado
Petroleum Engineer
Dept. of Chemical and Petroleum Engineering
Adjunct in Dept. of Geology and Geophysics
Task 3.0 – CO$_2$-water-rock experiments
Task 7.0 – Fluid flow simulation
Task 8.0 – Integrate results to generate workflow

Dario Grana
Rock Physicist
Dept. of Geology and Geophysics
Dept. of Chemical and Petroleum Engineering
School of Energy Resources
Task 2.0 – Construction of advanced static model
Task 5.0 – Statistical rock physics

Erin Campbell-Stone
Structural Geologist
Dept. of Geology and Geophysics
Task 6.0 – Build initial static model

Kam Ng
Civil Engineer
Dept. of Civil and Architectural Engineering
Task 4.0 – Geomechanical experiments

Ph.D. Student No. 1
CO$_2$-H$_2$O-rock experiments and modeling
Co-advised by Alvarado and Kaszuba
Years 1–3

Postdoctoral Research Scientist
Geomechanical modeling/Rock physics
Advised by Grana
Years 2–3

Ph.D. Student No. 2
Geomechanical experiments
Co-advised by Campbell-Stone and Ng
Years 1–3

Figure 1. Organizational chart.
<table>
<thead>
<tr>
<th>Task/Subtask</th>
<th>Milestone ID/Description</th>
<th>Planned Completion</th>
<th>Verification Method*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>A. Updated Project Management Plan</td>
<td>11/07/2014</td>
<td>Project Management Plan file</td>
</tr>
<tr>
<td>1.0</td>
<td>B. Kickoff Meeting</td>
<td>11/30/2014</td>
<td>Presentation file</td>
</tr>
<tr>
<td>2.0/2.5</td>
<td>C. Summary of the activities and results from Task 2.0 for the advanced rock property model</td>
<td>8/31/2015</td>
<td>Quick-look report</td>
</tr>
<tr>
<td>3.0/3.1</td>
<td>D. List of rock samples selected-obtained for CO2-Water-Rock experiments to include pertinent sample properties (formation, lithology, depth, facies)</td>
<td>03/06/2015</td>
<td>List</td>
</tr>
<tr>
<td>3.0/3.3</td>
<td>E. Plan that describes the details of the geochemical-mineralogic experiments to be performed</td>
<td>04/30/2015</td>
<td>Quick-look report with plan</td>
</tr>
<tr>
<td>3.0/3.4</td>
<td>F. Initiate CO2-Water-Rock experiments</td>
<td>05/30/2015</td>
<td>Email to FPM describing initiation</td>
</tr>
<tr>
<td>3.0/3.5</td>
<td>G. Plan for coreflood experiments</td>
<td>10/01/2015</td>
<td>Interim report to FPM with plan for coreflood experiments</td>
</tr>
<tr>
<td>3.0/3.7</td>
<td>H. Report of analyses and results studied in the CO2-Water-Rock experiments</td>
<td>04/14/2017</td>
<td>Quick-look report</td>
</tr>
<tr>
<td>4.0/4.1</td>
<td>I. Initiate geomechanical experiments</td>
<td>10/01/2015</td>
<td>Email to FPM describing initiation</td>
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<tr>
<td>4.0/4.1</td>
<td>J. Report of baseline geomechanical experiment results</td>
<td>03/21/2016</td>
<td>Interim report to FPM with results of baseline geomechanical experiments</td>
</tr>
<tr>
<td>4.0/4.3</td>
<td>K. Report of results and analyses of the geomechanical experiments</td>
<td>02/28/2017</td>
<td>Quick-look report</td>
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<tr>
<td>5.0</td>
<td>L. Summary of the activities and results performed in the rock physics model development and analyses in Task 5.0</td>
<td>10/31/2016</td>
<td>Quick-look report</td>
</tr>
<tr>
<td>6.0/6.1</td>
<td>M. Report of Subtask 6.1 seismic reservoir characterization</td>
<td>08/30/2016</td>
<td>Interim report to FPM describing seismic reservoir characterization</td>
</tr>
<tr>
<td>6.0/6.2</td>
<td>N. Summary of the activities and results performed in development and analyses of the initial static model, and the modeled petrophysical, geomechanical, and elastic response and implications for monitoring, performed in Task 6.0</td>
<td>12/29/2016</td>
<td>Quick-look Report</td>
</tr>
<tr>
<td>7.1</td>
<td>O. Initiate Simulations</td>
<td>10/31/2015</td>
<td>Email to FPM describing initiation</td>
</tr>
<tr>
<td>7.2</td>
<td>P. Report summarizing the activities and results performed in the simulations in Task 7.0</td>
<td>08/31/2017</td>
<td>Quick-look Report</td>
</tr>
<tr>
<td>8.0</td>
<td>Q. Report summarizing the workflow, accompanying documentation, and activities and results performed in Task 8.0 for the workflow definition and accompanying documentation.</td>
<td>08/31/2017</td>
<td>Quick-look Report</td>
</tr>
</tbody>
</table>
### Proposed Schedule

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>Start Date</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Subtask 1.2 - Project Meetings</td>
<td>3/14/2014</td>
<td>3/17/2014</td>
</tr>
<tr>
<td>4</td>
<td>Milestone B: Kickoff Meeting</td>
<td>3/14/2014</td>
<td>3/17/2014</td>
</tr>
<tr>
<td>5</td>
<td>Milestone C: Project Approval</td>
<td>3/14/2014</td>
<td>3/17/2014</td>
</tr>
<tr>
<td>8</td>
<td>Subtask 2.2 - Conduct Geophysical Modeling Experiments</td>
<td>3/14/2014</td>
<td>3/17/2014</td>
</tr>
<tr>
<td>15</td>
<td>Task 5.0 - Geotechnical Data Analysis</td>
<td>3/14/2014</td>
<td>3/17/2014</td>
</tr>
<tr>
<td>16</td>
<td>Subtask 5.1 - Data Analysis</td>
<td>3/14/2014</td>
<td>3/17/2014</td>
</tr>
<tr>
<td>17</td>
<td>Subtask 5.2 - Conduct Geotechnical Data Analysis</td>
<td>3/14/2014</td>
<td>3/17/2014</td>
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<tr>
<td>24</td>
<td>Task 8.0 - Geotechnical Model Validation</td>
<td>3/14/2014</td>
<td>3/17/2014</td>
</tr>
</tbody>
</table>

*Note: Dates are illustrative and may vary.*
Bibliography

No peer reviewed publications to date

