Acknowledgments

• The Midwest Geological Sequestration Consortium (MGSC) is funded by the U.S. Department of Energy through the National Energy Technology Laboratory (NETL) via the Regional Carbon Sequestration Partnership Program (contract number DE-FC26-05NT42588) and by a cost share agreement with the Illinois Department of Commerce and Economic Opportunity, Office of Coal Development through the Illinois Clean Coal Institute.

• The MGSC is a collaboration led by the state geological surveys of Illinois, Indiana, and Kentucky.

• Through a university grant program, Landmark Software was used for the reservoir and geologic modeling.
Presentation Outline

• Project benefit to CO$_2$ program
• Project goals and objectives
• Project approach
• Outcomes
• Accomplishments to date
• Summary
Benefit to the Program

CARBON STORAGE PROGRAM MAJOR GOALS

- Support industry’s ability to predict CO₂ storage capacity in geologic formations to within ±30 percent.
- Develop and validate technologies to ensure 99 percent storage permanence.
- Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.

BENEFITS STATEMENT

This project will address Area of Interest 3, Field Methods to Optimize Capacity and Ensure Storage Containment. The identification of field techniques to improve storage efficiency above the baseline CO₂ storage efficiency in specific geologic formation classes of different depositional environments identified by DOE as promising storage formations will provide better regional assessment estimates and site screening criteria. The research will contribute to the program’s effort of estimating CO₂ storage capacity in geologic formations.
Project Overview:

Goals

• Quantify storage efficiency for different depositional systems;
  • DOE’s “High” and “Medium” storage potential ratings

• Identify methods to
  • Improve $E$;
  • Control CO$_2$ plume footprint
Project Overview: Objectives

- Select Illinois Basin (ILB) formations representing different depositional systems
- Develop rigorous geologic and geostatistical models of selected formations
- Conduct numerical simulations
  - Estimate $E$
  - Depict CO$_2$ plume distribution within formation flow units
  - Determine depositional system-based strategies to improve $E$
Background

- CO₂ storage potential Matrix (NETL, 2010)
- Large Scale, Small Scale and Characterization are DOE defined groups

<table>
<thead>
<tr>
<th>Depositional Environment</th>
<th>High Potential</th>
<th>Medium Potential</th>
<th>Low or Unknown Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deltaic</td>
<td>Shelf Clastic</td>
<td>Shelf Carbonate</td>
</tr>
<tr>
<td>Large Scale</td>
<td>–</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>Small Scale</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Characterization</td>
<td>1</td>
<td>–</td>
<td>8</td>
</tr>
</tbody>
</table>
Approach for each depositional environment

- Pre-selection of ILB Formations
- Conceptual Geologic Model
- Geocellular or Static Models
- Reservoir Simulations
- Storage Efficiency Calculations
- Interpretation of Results

Validate
# Depositional Environments

<table>
<thead>
<tr>
<th>Depositional Environment</th>
<th>Storage Potential (DOE’s Rating)</th>
<th>ILB Formation</th>
<th>Other US Basin formations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deltaic</td>
<td>High</td>
<td>Benoist</td>
<td>Frontier Formation (Rocky Mountain basins)</td>
</tr>
<tr>
<td>Shelf Clastic</td>
<td>High</td>
<td>Cypress</td>
<td>Tapeats Sandstone (Colorado Plateau); Hamilton and Martinez (Sacramento Valley Basin)</td>
</tr>
<tr>
<td>Shelf Carbonate</td>
<td>High</td>
<td>Ste. Genevieve</td>
<td>Naco and Martin (Colorado Plateau); Knox (Illinois and Michigan Basins); Arbuckle (Ozark Plateau)</td>
</tr>
<tr>
<td>Strandplain</td>
<td>High</td>
<td>Upper Mt. Simon</td>
<td>Fleming Group (Gulf of Mexico Basin); Pottsville, Parkwood, and Hartselle (Black Warrior Basin)</td>
</tr>
<tr>
<td>Reef</td>
<td>High</td>
<td>Racine</td>
<td>Cisco-Canyon (Permian Basin)</td>
</tr>
<tr>
<td>Fluvial Deltaic</td>
<td>Medium</td>
<td>Bridgeport</td>
<td>Domengine (Sacramento Valley Basin); Fleming Group</td>
</tr>
<tr>
<td>Fluvial &amp; Alluvial</td>
<td>Medium</td>
<td>Lower Mt. Simon</td>
<td>Tuscaloosa (Gulf Coast Basin); Stockton and Passaic (Newark Basin)</td>
</tr>
<tr>
<td>Turbidite</td>
<td>Medium</td>
<td>Carper</td>
<td>Puente (Los Angeles Basin)</td>
</tr>
</tbody>
</table>
Conceptual and Geocellular Models

• Conduct geologic mapping
  • Available Data
    • Logs: spontaneous potential, neutron-density, openhole, and casedhole
    • Core
    • Outcrops

• Results
  • Cross sections
  • Isopach maps
  • Structure maps
  • Block diagram of the depositional environment

• Software: Geographix and Petra
Conceptual and Geocellular Models (cont.)

- Conduct geostatistical analyses using
  - Conceptual geologic model
  - Digitized logs
  - Core data
  - Surface maps
- Build geocellular model (4 distributions)
  - Porosity
  - Permeability
  - Thickness
  - Facies
- Flat, no structure
- Software: Isatis
Example: Shelf Carbonate

Model Permeability distribution (0.1–1000 mD)
Example: Deltaic

- Permeability distribution (5–300 mD)
- Model area covers isopach map (Seyler et al., 2012)
Reservoir Simulations

Input and initial conditions

- Reservoir and PVT properties
- End-point saturations and relative permeabilities
- Initial conditions
  \[ P_{\text{res}} > P_{\text{CO}_2,\text{crit}} : 1100 \text{ psi} \]
  \[ T_{\text{res}} > T_{\text{CO}_2,\text{crit}} : 90 \degree \text{F} \]
- Injection rate:
  \[ 18,854 \text{ Mscf/d (1 tonne/d)} \]
- No pressure constraint

- Software: Landmark Nexus

End-point saturations & rel. permeability

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sandstone</th>
<th>Limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_{wr} )</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>( k_{rw,\text{max}} )</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>( S_{g,c} )</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>( k_{rg, \text{max}} )</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>( m )</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>( n )</td>
<td>3.00</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Fig.: Sandstone relatively curve
Reservoir Simulations, cont.

Storage Efficiency (E)

\[ E = \frac{V_{CO_2}}{V_p} \]

- \( V_{CO_2} \): reservoir pore volume contacted by \( CO_2 \).
- \( V_p \): pore volume available for storage

Warmer colors indicate higher \( CO_2 \) saturation and blue indicates water.
Reservoir Simulations

• Sensitivity studies
  • Infinite acting aquifer (analytical vs. numerical model)
    • Wellblock permeability
    • Aquifer permeability averaging method
    • Water influx vs outflux
Aquifer permeability averaging method

Aquifer strength on BHP

- Average reservoir $k$ closely exhibit infinite-acting aquifer behavior.

Fluid outflux vs. influx

- Outflux-Influx ratio approaches 1.0 over time.
Reservoir Simulations

• Sensitivity studies (continued)
  
  • End-point saturations and relative permeabilities
    
    • $S_{wirr}$ : irreducible brine saturation
    
    • $S_{gc,}$ : critical CO$_2$ saturation
    
    • $k_{rg,max}$ : maximum CO$_2$ relative permeability
End-point Saturations and relative permeability Effects

- $E$ declines as $S_{\text{swirr}}$ or $K_{\text{rg, max}}$ increase
- $E$ increases with $S_{\text{gc}}$

Illinois State Geological Survey
www.CO2efficiency.org
Example: Storage Efficiency profile

Strandplain

- Vertical Well
- Horizontal Well
Example: shelf carbonate

- Cells: 1,209,748

CO₂ plume distribution (3 years)
Example: Fluvial Deltaic

- Channel System
- Cells: 127,500, $k_{av}$: 100 md

$\text{CO}_2$ plume distribution ($0$ year)

Porosity cutoff: 2%
# of gridcells: 106,000
Av. permeability: 100 md

Porosity cutoff: 0%
# of gridcells: 1,100,000
Normalize baseline efficiencies

- Normalize for effect of relative permeability and end-point saturations

\[ (1) \quad E_v = \frac{E}{S_g} \]

\[ (2) \quad E_v = \frac{E}{S_g} k_r g (\bar{S}_g) \]

\[ (3) \quad E_v = \frac{E (1-S_{wirr})}{\bar{S}_g} \]

\[ (4) \quad E_v = \frac{E (1-S_{wirr}-S_{gc})}{\bar{S}_g} \]

\[ (5) \quad E_v = \frac{E (1-\bar{S}_g)}{S_g} \]

\[ (6) \quad E_v = \frac{E (1-S_{wirr})}{S_g - S_{gc}} \]
## Outcomes

Normalize baseline efficiencies

<table>
<thead>
<tr>
<th>Depositional Environment</th>
<th>Baseline $E_v$ (%)</th>
<th>% Change (effect of geologic structure)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ILB formation</td>
<td>Stratigraphic</td>
</tr>
<tr>
<td>Deltaic</td>
<td>Sandstone</td>
<td>23 — 41</td>
</tr>
<tr>
<td>Shelf clastic</td>
<td>Sandstone</td>
<td>17 — 41</td>
</tr>
<tr>
<td>Shelf carbonate</td>
<td>Limestone</td>
<td>9.5 — 26</td>
</tr>
<tr>
<td></td>
<td>Dolomite</td>
<td>7.5 — 19</td>
</tr>
<tr>
<td>Fluvial deltaic</td>
<td>Sandstone</td>
<td>36 — 52</td>
</tr>
<tr>
<td>Strandplain</td>
<td>Sandstone</td>
<td>16 — 32</td>
</tr>
<tr>
<td>Reef</td>
<td>Limestone</td>
<td>14 — 53</td>
</tr>
<tr>
<td>Fluvial and alluvial</td>
<td>Sandstone</td>
<td>11 — 52</td>
</tr>
</tbody>
</table>

*Large structure, low dip angle and thick reservoir

E and $E_v$ increase with size of geologic structure.

Min: Median: Max
0% : 7.4% : 88%
### CO₂ storage potential Matrix (NETL, 2010)

<table>
<thead>
<tr>
<th>Geologic Formation Classes</th>
<th>High Potential</th>
<th>Medium Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Deltaic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shelf Clastic</td>
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<td>Strandplain</td>
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<td></td>
<td>Reef</td>
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<tr>
<td></td>
<td></td>
<td>Fluvial Deltaic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eolian</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fluvial &amp; Alluvial</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turbidite</td>
</tr>
<tr>
<td>Ranking</td>
<td>1</td>
<td>2</td>
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<td></td>
<td>3</td>
<td>4</td>
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<td>7</td>
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<td>9</td>
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### CO₂ storage Efficiency Matrix

<table>
<thead>
<tr>
<th>Geologic Formation Classes</th>
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<th>Medium Potential</th>
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<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td>Turbidite</td>
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<tr>
<td>Ranking</td>
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<td>4</td>
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<td>7</td>
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<td></td>
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<td>3</td>
</tr>
</tbody>
</table>

Classification is based on $E_v$ of simulation using stratigraphic geologic models

**Note:** High $E \neq$ high storage capacity (potential).
Summary

• Key Findings
  • Formations studied exhibit a mixture of depositional environments with one having a dominating presence.
  • Depositional systems in cratonic and non-cratonic US Basins exhibit similar characteristics but differ in scale of geologic features.

• Lessons Learned
  • Effect of geologic structure on storage efficiency is dependent on:
    • Size
    • Dip angle
    • Reservoir thickness

• Future Plans
  • Developed database tool to estimate $E$ from simulation data.
ISGS Staff

- **Reservoir Engineers:**
  - Roland Okwen
  - Scott Frailey

- **Sub-contractor (Schlumberger):**
  - John Grube
  - Beverly Seyler

- **Database specialist**
  - Damon Garner

- **Geologists:**
  - Hannes Leetaru
  - Yaghoob Lasemi
  - Nathan Webb
  - James Damico
  - Charles Monson

- **Editor:**
  - Dan Klen
Appendix

- These slides will not be discussed during the presentation, but are mandatory
Team Organization and Structure

U.S. Department of Energy
DOE Project Officer
Darin Damiani

ISGS
Scott Fralley
Task 1

ISGS
Roland Okoven
P.I.
Task 1

ISGS
Hannes Leetaru
Task 1

Task 2
Geologic Screening
Hannes Leetaru

B. Huff
J. Grube
Y. Lasemi
H. Leetaru
B. Seyler
N. Webb
R. Okoven
S. Fraley
Deadline: 02/28/13

Task 3
Geologic Modeling
John Grube

Data
J. Damico
D. Garner
B. Huff
V. Lasemi
H. Leetaru
C. Monson
B. Seyler
C. Stohr
N. Webb
RO
SF
RE

Modeling
J. Damico
D. Garner
B. Huff
V. Lasemi
H. Leetaru
C. Monson
B. Seyler
C. Stohr
N. Webb
RE

Geostatistics
J. Grube
B. Huff
C. Monson
B. Seyler
N. Webb
Task 3.3
Deadline: 12/31/13

Task 4
Geocellular Modeling
James Damico

Interpretation
J. Damico
S. Fraley
B. Huff
Y. Lasemi
H. Leetaru
C. Monson
B. Seyler
C. Stohr
N. Webb
Task 4.3
Deadline: 04/30/2014

Task 5
Reservoir Modeling
R. Okoven

Reservoir Analysis
S. Fraley
D. Garner
C. Monson
N. Webb
Reservoir Engr
Task 5.2, 5.3
Deadline: 05/30/2014

Task 6
Storage Efficiency Analysis
S. Fraley

Baseline
D. Garner
C. Monson
R. Okoven
N. Webb
Task 6.1
Deadline: 09/30/2014

Task 6.2
Deadline: 09/30/2014
Gantt Chart

Task Name

1. Task 1 – Project Management, Planning, and Reporting
   Start: Mon 10/11
   Finish: Wed 12/31
   % Complete: 55%

2. Task 2 – Geologic Formation Screening
   Start: Mon 10/11
   Finish: Thu 2/28
   % Complete: 100%

53. Milestone: Formation List to NETL Capacity Team for Review
   Start: Thu 2/28
   Finish: Thu 2/28
   % Complete: 100%

54. Deliverable: Task 2 Report
   Start: Fri 3/1
   Finish: Fri 3/1
   % Complete: 100%

55. Task 3 - Geology and Geologic Modeling
   Start: Mon 10/11
   Finish: Tue 12/31
   % Complete: 80%

56. Deliverable: Task 3 Report
   Start: Tue 12/31
   Finish: Tue 12/31
   % Complete: 0%

57. Task 4 – Geostatistical Analyses and Geocellular Modeling
   Start: Mon 10/11
   Finish: Wed 4/3
   % Complete: 60%

58. Deliverable: Task 4 Report
   Start: Wed 4/3
   Finish: Wed 4/3
   % Complete: 0%

59. Task 5 – Reservoir Flow Modeling
   Start: Mon 10/11
   Finish: Mon 3/1
   % Complete: 20%

60. Deliverable: Task 5 Report
   Start: Mon 3/1
   Finish: Mon 3/1
   % Complete: 0%

61. Task 6 – Interpretation and Analyses of Modeling Results
   Start: Tue 3/1
   Finish: Tue 9/30
   % Complete: 10%

   Start: Tue 9/30
   Finish: Tue 9/30
   % Complete: 0%

Milestone: Finalize estimates of storage efficiency by geologic classification

Illinois State Geological Survey
www.CO2efficiency.org


4) Okwen, R., C. Monson, Y. Lasemi, and N. Grigsby, accepted (in prep), Quantifying CO₂ storage efficiencies of geologic depositional environments: poster to be presented at the 42nd annual AAPG Eastern Section meeting, London, ON, September 27–October 1, 2014.


## Outcomes

### Baseline Storage efficiencies

\[
E = \frac{V_{CO_2}}{V_p}
\]

<table>
<thead>
<tr>
<th>Depositional Environment</th>
<th>Lithology</th>
<th>Baseline E (%)</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Stratigraphic</td>
<td>Structural</td>
</tr>
<tr>
<td>Deltaic</td>
<td>Sandstone</td>
<td>9.5 — 18</td>
<td>10 — 20</td>
</tr>
<tr>
<td>Shelf clastic</td>
<td>Sandstone</td>
<td>5.6 — 15</td>
<td>6.6 — 19</td>
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<tr>
<td>Shelf carbonate</td>
<td>Limestone</td>
<td>3.1 — 9.0</td>
<td>3.3 — 9.9</td>
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<tr>
<td></td>
<td>Dolomite</td>
<td>3.0 — 8.2</td>
<td>3.8 — 7.5</td>
</tr>
<tr>
<td>Fluvial deltaic</td>
<td>Sandstone</td>
<td>13 — 22</td>
<td>15 — 22</td>
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<tr>
<td>Strandplain</td>
<td>Sandstone</td>
<td>6.1 — 13</td>
<td>11 — 17</td>
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<tr>
<td>Reef</td>
<td>Limestone</td>
<td>4.8 — 19.7</td>
<td>4.7 — 21.3</td>
</tr>
<tr>
<td>Fluvial and alluvial</td>
<td>Sandstone</td>
<td>8.0 — 19</td>
<td>9.9 — 22</td>
</tr>
<tr>
<td>Turbidite</td>
<td>Fine Sandstone</td>
<td>6.5 — 24</td>
<td>7.0 — 25</td>
</tr>
</tbody>
</table>

*Large structure