Prototyping and testing a new volumetric curvature tool for modeling reservoir compartments and leakage pathways in the Arbuckle saline aquifer: reducing uncertainty in CO₂ storage and permanence

Project Number (DE-FE0004566)

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University of Kansas Center for Research
Kansas Geological Survey

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO₂ Storage
August 12-14, 2014
Presentation Outline

• Benefits, objectives, overview
• Methods
• Background & setting
• Technical status
• Accomplishments
• Summary
Benefit to the Program

• Program goal addressed:

  Develop technologies that will support the industries’ ability to predict CO₂ storage capacity in geologic formations to within ± 30 percent.

• Program goal addressed:

  This project will confirm — via a horizontal test boring — whether fracture attributes derived from 3-D seismic PSDM Volumetric Curvature (VC) processing are real. If validated, a new fracture characterization tool could be used to predict CO₂ storage capacity and containment, especially within paleokarst reservoirs.
Project Overview:
Goals and Objectives

Evaluate effectiveness of VC to identify the presence, extent, and impact of paleokarst heterogeneity on CO₂ sequestration within Arbuckle strata

– Develop technologies that demonstrate 99% storage permanence and estimate capacity within ±30%.
  • Predict plume migration...within fractured paleokarst strata using seismic VC
  • Predict storage capacity...within fractured paleokarst strata using seismic VC
  • Predict seal integrity...within fractured paleokarst strata using seismic VC

– Success criteria
  • Merged & reprocessed PSTM volume reveals probable paleokarst
  • Within budget after landing horizontal test boring
  • VC-identified compartment boundaries confirmed by horizontal test boring
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Methods

- Merge, reprocess, interpret PSDM 3-D seismic
- PSTM & PSDM VC-processing (Geo-Texture)
  - Pre-processing: Raw, Basic PCA, Enhanced PCA, Robust PCA
  - Lateral wavelength resolutions: high (~50-ft), medium (~150-ft), long (~500-ft)
- Build pre-spud fault & geocellular property models
- Locate, permit, drill, and log horizontal test boring
- KO & lateral, slimhole & hostile, logging program with Compact Well Shuttle™
  - Triple combo
  - Full-wave sonic
  - Borehole micro-imager [Weatherford]
- Formation evaluation & image interpretation
- Seismic inversion, variance & ant track
- Construct discrete fracture network (DFN) Model
- Revise fault, facies, and property models
- Simulate & history match
Presentation Outline

- Benefits, objectives, overview
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Age & Regional Setting

### North American Series

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<th>System</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
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<td>458</td>
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Laurentia

Coastal plain

Intracratonic basin

Shallow marine

Equator (Golonka, 2002)

Courtesy of Ron Blakey

KU GEOLOGICAL SURVEY
The University of Kansas
Kansas Setting

Structure Map — Early Paleozoic

Arbuckle Isopach Map

W-E Cross Section — Central Kansas Uplift

Karst Process-Based Model
Study Area — Bemis Shutts Field

1. southwestern Bemis-Shutts Field
2. Field discovered in 1928
3. Cumulative production ~265 MMBO
4. Production Lansing–Kansas City and Arbuckle
5. In 2011, 615 producing wells
6. Note “sinkhole” geometries
Arbuckle Analog

Whiterockian Paleokarst Outcrop Analog — Nopah Range, CA
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Time & Depth Migration

Arbuckle PSTM

Arbuckle PSDM

Average Velocity to Arbuckle

Arbuckle Velocity & Well Control
Volumetric Curvature

- A measure of reflector shape:
  - Most-positive: anticlinal bending
  - Most-negative: synclinal bending

- Multi-trace geometric attribute calculated directly from the 3-D seismic volume

- Calculated using multiple seismic traces and a small vertical window

- The analysis box moves throughout the entire volume

- VC attributes can be output as a 3-D volume

- Provides *quantitative* information about lateral variations

*Al-Dossary & Marfurt, 2006*
PSDM VC Processing Results

VC-processing by Geo-Texture Technologies
Arbuckle PSDM VC Horizon-Extraction

area shown on next slide
Proposed Lateral to Test VC Attributes

Objectives:
- Land well outside paleocavern
- Drill through paleocavern
- TD in “flat-lying” host strata
- Run Triple, Sonic, Image tools

no mud losses!
Image Log  Facies — Facies Model

Crackle  Bedding  Dilational Fracture  Dilational Fracture

Crackle Breccia  Bedding  Open Fracture  Open Fracture

Bedding  Dilational Fracture  Matrix-Supported  Chaotic

Bedding  Open Fracture  Matrix-Supported Breccia  Chaotic Breccia

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<td>4</td>
<td>Chaotic Breccia</td>
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VC-indicated Compartments
Consistent with Log Interpretations
Formation Evaluation

Lithology

Sonic S-vug
Res. Svug
New Field-Wide Fault/Fracture Model

~201 Faults...thanks to Rock Deformation Research plug-in
VC-Faults *Match* Seismic Faults
Probability Maps for Conditioning Geocellular Models

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- **Dilational Fractures**
- **Crackle & Chaotic Breccia**
- **Peritidal Dolostone & Matrix-Supported Breccia**

- evaporite karst in host strata
  - strata-bound breccia
  - anhydrite-filled molds
  - geochemistry-sulfates
Discrete Fracture Network Modeling
3-D Volumetric Curvature Volume

VC muted
Reflectors flat

faults identified from remote sensing analysis

anhydrite

Chase Group

Topeka Heebner

Arbuckle

McCord-A 20H
Filtered 3-D VC Geocellular Model

VC cells absent
Seismic Attributes: Coherence vs VC

1 mile
Seismic Attributes: Coherence vs VC

1 mile
Seismic Attributes: Coherence vs VC

1 mile
Geologic Findings & Interpretations

- Fault-bounded doline confirmed
- Dolines coincident with VC-identified radial lineaments
- Interior drainage
- Headward-eroding escarpment
- Disappearing streams/springs/fluvial plains
Dynamic Modeling Objectives

Explore the effect of fault transmissibility on:
– CO$_2$ Injectivity
– Storage capacity
– Vertical and horizontal CO$_2$ movement

*simulation studies performed by Eugene Holubnyak (KGS)*
## Dynamic Simulations

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<th>Value</th>
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<tr>
<td>Temperature Gradient</td>
<td>0.008 °C/ft</td>
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<tr>
<td>Pressure</td>
<td>2093 psi</td>
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<tr>
<td>Pressure Gradient</td>
<td>0.42 psi/ft</td>
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<td>Reservoir Depth</td>
<td>4,500 – 4,900 ft</td>
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<tr>
<td>Perforation Zone</td>
<td>4,750 – 4,850 ft</td>
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<tr>
<td>Perforation Length</td>
<td>100 ft</td>
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<tr>
<td>Injection Period</td>
<td>10 years</td>
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<tr>
<td>Injection Rate</td>
<td>300, 200, 200, 150 tones/day</td>
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<tr>
<td>Total CO2 injected</td>
<td>3M tones</td>
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<td>Reservoir CO₂ Density</td>
<td>580 kg/m³</td>
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<td>Fault Transmissibility</td>
<td>1, 0, &amp; 0.5</td>
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<td>Fault Count</td>
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CO$_2$ Injection

Permeability I (md) 2015-01-01  K layer: 49

CO$_2$ Injection

CO$_2$inj1 – 300 tones/day
CO$_2$inj2 – 200 tones/day
CO$_2$inj3 – 200 tones/day
CO$_2$inj4 – 150 tones/day
CO₂ Injection

Permeability (md) 2015-01-01  K layer: 49

Boundary: Carter-Tracy aquifer, infinite extent
CO₂ Injection

Permeability I (md) 2015-01-01  J layer: 71

Top of Arbukle, 4,440 ft

Mid. Arbukle Low Permeability Zone

Injection Zone 4,760 - 4,960 ft

Bottom of Arbukle, 4,950 ft
Fault Transmissibility Multiplier 1 vs. 0

Injectivity Profile

Well Bottom-hole Pressure

![Graph showing injectivity profile with two different lines representing Fault Transmissibility Multiplier 1 and 0.](image-url)
CO$_2$ Extent and Movement
Fault Trans. Multiplier set to 1

Gas Saturation 2117-01-31  J layer: 80
CO₂ Extent and Movement
Fault Trans. Multiplier set to 0

Gas Saturation 2119-12-31  J layer: 80

matrix permeability
sharp edge at fault
CO$_2$ Extent and Movement
Fault Trans. Multiplier set to 1
CO₂ Extent and Movement
Fault Trans. Multiplier set to 0
Delta Pressure and Movement
Fault Trans. Multiplier set to 1
Delta Pressure and Movement
Fault Trans. Multiplier set to 0
Simulation Findings to Date

Key Findings
Fault transmissibility effects for Arbukle Formation:
  Injectivity and storage capacity are reduced
  CO₂ movement is impacted by faults, but matrix control is dominant

Future Plans
  Analyze uncertainty of **flux between blocks**
  History match new models
  Ways to estimate fault transmissibility
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Accomplishments to Date

- Merged & reprocessed seismic
- PSTM & PSDM VC processing
- Built pre-spud model
- Drilled ~1800-ft lateral to test VC
- Ran extensive logging program
- Formation evaluation
- Simulated pre-spud model

- Inversion & genetic inversion
- Probability maps & property modeling
- ASME Peer Review (addressed recommendations)
- DFN modeling
- Contrast with other techniques
- Simulations fault
- Publication-ready figures
Presentation Outline

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Summary

• Key Findings
  – Direct **confirmation** of VC-identified, fault-bound, paleokarst doline
  – **PSDM VC attribute** consistent with structure maps and facies distribution (providing converging lines-of-evidence)
  – **VC cost-effective**
    • Multi-component 3D seismic acquisition costly
    • Shear-wave processing (i.e., Anisotropy volumes) costly

• Lessons Learned
  – **VC attributes fractal**, requires some constraints
  – **Lost-in-hole tool insurance** can overwhelm budget

• Future Plans
  – Analyze uncertainty of **flux between blocks**
  – **History** match and forecasting
  – Technology transfer — publish results
Bibliography

List peer reviewed publications generated from project per the format of the examples below

- **Journal, one author:**

- **Journal, multiple authors:**

- **Publication:**