Prototyping and testing a new volumetric curvature tool for modeling reservoir compartments and leakage pathways in the Arbuckle saline aquifer: reducing uncertainty in CO$_2$ storage and permanence

Project Number (DE-FE0004566)

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(W. Lynn Watney, Joint PI)

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 CO$_2$ Storage
August 20-22, 2013
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
• 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

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Age & Regional Setting

### System Series
- **North American Series**
- **British Series**

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<th>Ordovician</th>
<th>Early</th>
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### Maps
- **Laurentia**
- **Tippecanoe lowstand**
- **Coastal plain**
- **Intracratonic basin**
- **Shallow marine**

**Laurentia**
- **Equator**
  - Equator (Golenka, 2002)

**Tippecanoe lowstand**
- Exposed Precambrian
- Exposed Lower Ordovician carbonates

**Map courtesy of Ron Blakey**
Kansas Setting

Structure Map — Early Paleozoic

Arbuckle Isopach Map

W–E Cross Section — Central Kansas Uplift

Karst Process-Based Model
Presentation Outline

• Benefits, objectives, overview
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Study Area — Bemis Shutts Field

Structure Map
Study Area — Bemis Shutts Field

Structure Map

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
Common Morphologies

A. Modern karst zone
   - Paleocavern fill
   - Collapsed slabs
   - Tilted and folded disturbed host rock

B. Phase 1: Modern Cave System
   - Active Cave Systems
   - Subaerial Exposure Surface (Unconformity)

C. Phase 2: Multiple Near-Surface Cave Systems Developed at Composite Unconformity
   - Long-term Exposure
   - Composite Subaerial Exposure Surface (Composite Unconformity)
   - Relict Cave Systems

D. Phase 3: Paleocave System Collapses and Coalesces
   - Suprastratal Deformation
   - Burial and Collapse
   - PALEOCAVE EXPLORATION TARGETS

E. Type of Recharge
   - Via Karst Depressions
   - Diffuse
   - Hydrogenic

F. Dominant Type of Porosity
   - Angular Porous
   - Fissures
   - Intergranular
   - Radial Pasages
   - Anomalous Anhydrous Wases
   - Profile

G. VC

Sources:
- Loucks et al., 2004
- Palmer, 1997
- Loucks et al., 2004

KU Kansas Geological Survey
Field Setting

Core Description — Paleokarst Rock

A

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Time & Depth Migration

Arbuckle PSTM

Arbuckle PSDM

Average Velocity to

Arbuckle Velocity & Well
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
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

wow...no mud losses
Image Log  Facies — Facies Model

Chaotic

Bedding

Dilational Fracture

Dilational Fracture

Chaklic Breccia

Bedding

Open Fracture

Matrix-Supported Breccia

Chaotic Breccia

Bedding

Dilational Fracture

Matrix-Supported Breccia

Chaotic

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VC-indicated Compartments
Consistent with Log Interpretations
Formation Evaluation
Formation Evaluation

- Svug %

Other diagrams and data elements related to formation evaluation, including fault-bound paleocaverns and separate vug porosity.
New Field-Wide Fault Model

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

Geocellular Models

**Facies**

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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
Facies Model
3-D PSDM Seismic Porosity Attribute

Petrel’s™ genetic inversion tool
Porosity Model

averaged vertically
Permeability Model
Discrete Fracture Network Modeling

Fracture Aperture (ft)

McCord-A 20H Image Log Interpretation

Aperture Statistics

- Mean: 0.0321
- Median: 0.011
- Mode: 0.001
- Standard Deviation: 0.0511
- Sample Variance: 0.00261
- Kurtosis: 8.646
- Skewness: 2.790
- Range: 0.331
- Minimum: 0.000
- Maximum: 0.332
- Sum: 14.523
- Count: 453
- Confidence Level (50.0%): 0.00396
3-D Volumetric Curvature Volume

VC muted
Reflector flat
Filtered 3-D VC Geocellular Model

- orthophoto draped over DEM
- surface faults
- 3-D cells (volumetric curvature attribute)
- Horizon at top Heebner Shale
- Cell concentrations below Heebner reflect Arbuckle paleokarst
- VC cells absent
Key Findings & Interpretations to Date

- Fault-bounded doline confirmed
- Dolines coincident with VC-identified radial lineaments
- Interior drainage
- Headward-eroding escarpment
- Disappearing streams/springs/fluvial plains
- Fracture system O-age
  - reduces seal risk?
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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
- DFN modeling
Presentation Outline

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Summary

• Key Findings
  – Direct **confirmation** of VC-identified, fault-bound, paleokarst doline
  – **3-D VC PSDM** for complex structural settings
  – Pre-spud history-match **non-unique solution**
  – **VC-filtering** reveals vertical extent of faults

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

• Future Plans
  – **Cost analysis** vs other seismic attributes or interp. methods
  – Analyze uncertainty of **flux between blocks**
  – **Simulate** & history match new models