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*

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Project Kickoff Meeting
Nov 19, 2010
Problem Statement

Ordovician strata (e.g., Arbuckle Group Saline Aquifer) extensively karsted worldwide

- Limited understanding of paleokarst heterogeneity & spatial distribution
- Karst features may be coincident with basement to surface fault systems
- Lateral and vertical transmissibility of karst features/boundaries - unknown
  - Identification of potentially conductive pathways critical to reducing risks related to CO₂ storage and permanence
Proposal to Test & Prototype a New Tool

- What is needed? – A cost-effective tool to image karst compartments in the Arbuckle Group Saline Aquifer
  - Volumetric Curvature (VC) Analysis
Volumetric Curvature (VC) Analysis

- **Curvature** – A measure of the bending of a surface (~2\textsuperscript{nd} derivative of the surface).

- **Most-positive and most-negative curvatures**, which measure the maximum positive and negative bending of the surface at a given point, are the most useful for delineating subtle faults, fractures, flexures, and folds.

\[ \text{Curvature (k)} = \frac{1}{R} \]

**2-D**
- Positive Curvature
- Zero Curvature
- Negative Curvature
- Anticline
- Dipping Plane
- Syncline

**3-D**
- May be computed at any azimuth about a point
- Generally computed normal to tangent plane
- Principal Curvatures ($k_{\text{max}}$ and $k_{\text{min}}$) can be combined to define other curvature attributes

**After Roberts, 2001**

**Sigismondi and Soldo, 2003**
Volumetric Curvature (VC) Analysis

Wellington Anson-Bates

V.C. used to infer:
- faults
- fracture swarms
- fracture sets
- flexures
- sags
- paleokarst

2-dimensionally volumetrically

3-dimensionally volumetrically

2-dimensionally

curvature map
Arbuckle Outcrop Analog
Ordovician Paleokarst Architecture & Heterogeneity

Nopah Range, CA

seismically image impedance contrast

cross-cuts reservoir bodies with different petrophysical properties

Collapse Doline
Solution Doline

Subsidence Doline
Subjacent Collapse Doline
Alluvial Streamsink Doline

Bed Dip: 60° ENE

vertical shaft

50 m
90 m
Evidence of Karst Compartments – DOE funded
Mississippian Carbonate Reservoir - Kansas

- Well produced openhole for 1 month
- Sudden stop of all fluid production
- Suspect collapse of karst fill in lateral
- Hole cleanup complicated by lost bit
Previous Application of VC Analysis – DOE funded
Smoky Creek Field, Cheyenne County, Colorado

Most +ve curvature

Significant production variability between adjacent wells

Top Spergen Subsea Depth (CI = 5 ft)

Interpreted positive curvature lineament

RFs – 40 acre spacing

C1 = 178.5%  C2 = 14.9%  C3 = 81.8%
C4 = 36.0%
H1X = 40.6%  H2 = 48.6%  KA4 = 50.5%
Previous Application of VC Analysis – DOE funded
Smoky Creek Field, Cheyenne County, Colorado
Previous Application of VC Analysis – DOE funded
Cheyenne Wells Field, Cheyenne County, Colorado

Positive curvature with interpreted lineaments superimposed. Blue = top Spenger below OWC.

CA 3 (full log suite, Cum oil 90 MBO from 1993)
CA 1 (Dphi only, Cum oil 150 MBO from 1973)
CA 2 (uncalibrated Neutron Phi, poor producer)

Interpreted lineaments in Red

Cheyenne County Well
Volumetric Curvature Application

- Simulation - 75% Confidence
- Simulation - 50% Confidence
- 5-month Avg (till Feb 2010)
Previous Application of VC Analysis – DOE funded
Wildcat Well (Albin 1-23), Gove County, Kansas

Mississipian Subsea, ft

Most –ve curvature map
Previous Application of VC Analysis – DOE funded
Wildcat Well (Albin 1-23), Gove County, Kansas
Volumetric Curvature Analysis - Workflow

Processed 3D data → Edge Preserving Smoothening → Geometric Multi-trace attributes

- Dip
- Curvature
- Most +ve
- Most -ve
- Azimuth
- Coherence

Uses many "Black Box" parameters

- Wavelength of curvature
- Fractional derivative power

Companies that generate curvature attributes – GeoTexture, Resolve etc.
Bemis-Shutts Field
- Arbuckle production
- Compartmentalized
  - Variable production from adjacent wells
  - Offsetting dry holes – water production
- Seismic geometries - evidence of paleokarst
- Industry partner - Vess-Murfin (MVP LLC)
- Seismic donation : 9.8 mi²
  - cost match: $

Stafford County Lease
- Mississippi production
- Seismic geometries - evidence of paleokarst
- Industry partner - Murfin
- Seismic donation: 10 mi²
  - cost match: $

Study Area

- Bemis-Shutts Field (Ellis County)
- Stafford County Lease
- Regional KGS-DOE Sequestration Assessment
- Southern Bemis-Shutts
Study Area 1 - Bemis-Shutts Field

Seismic Geomorphology, Cores, & Production consistent with Paleokarst

re-entrants, internal sags, and breccias indicate paleokarst
Arbuckle Model – Bemis-Shutts Field

Proposed test boring concept

- "triple combo"
- drill-stem test
- image log
- pressure test
- sidewall cores

~200 miles
Proposed Well Placement – Using Wellington VC Analysis

Paleokarst compartments identified from volumetric curvature (VC) analysis
Pre-Spud Evaluation
Oct 2010 to Apr 2011

• Reprocess seismic
• Seismic interpretation
• Generate volumetric curvature
  – Identify karst compartments
• Build initial geocellular model
• Simulate & history match - performance of existing wells located in identified compartments
• Locate test boring
Drilling Program
May 2011 to Sep 2011

- Permit well
- Drill & set intermediate casing
- Drill vertical pilot hole to Arbuckle
- Log (“triple combo” & sonic)
- Drill-stem test
- Set plug
- Kick-off – depth dependent on VC interpretation
- Land well uppermost 40’ Arbuckle - directional tools
- Case to landing point
- Drill horizontal lateral (<1500-ft) - directional tools
- Condition hole for logging
Wireline Logging Program

• Vertical pilot (free-fall wireline)
  – “triple combo”- GR, resistivity, neutron-density
  – full-wave sonic – for synthetic seismic & vuggy porosity

• Horizontal lateral (tool-push wireline)
  – “triple combo”
  – image logging
  – pressure tester & fluid sampler
    • within and across the karst compartment boundary
  – rotary sidewall coring
    • within and across the karst compartment boundary
Validate Karst Compartment Boundary
Oct 2011 to Sep 2012

• Explore what geological feature is being imaged by VC analysis – is it a FLOW/NO-FLOW boundary?
  – Image analysis
  – Pressure analysis
  – Fluid chemistry
  – Sidewall cores
Validate and Optimize VC Model
Nov 2011 to Feb 2012

• Reprocessing
• Time-to-depth processing
• Horizon mapping
• Impedance inversion
• Synthetics
• Attribute analysis
  – Curvature analysis
  – Single & multi-trace
• Fault mapping
• Generate curvature volumes
Revise Geocellular Model
Feb 2012 to Sep 2012

- **Structural**
  - Import seismic data & interpretations
  - Fault model
  - DFN
  - Transmissibility of karst compartment boundary – lateral and vertical

- **Facies**
  - Rock fabric (capillary pressure-specific)
  - Stratigraphic (zones & layering)
  - SIS, facies-based, with 3D property trends
  - Paleokarst facies model
    - Overprint facies model

- **Analyze and identify possible leakage pathways**
  - Fault offset and seal juxtaposition
  - Shale gouge ratio
Reservoir Simulation Studies
Oct 2012 to Sep 2013

• Incorporate petrophysical properties of karst fill (compartment boundary)
  – Horizontal & vertical permeability
  – Capillary pressure curves
  – Relative permeability including hysterisis end-points

• Evaluate CO₂ sequestration potential in Arbuckle Group Saline Aquifer
  – Long-term effectiveness of cap rock
  – Tonnage of CO₂ sequestered in brine (solution)
  – Tonnage of CO₂ sequestered as residual gas
  – Tonnage of CO₂ sequestered by mineralization

• Simulate permanence of CO₂ sequestered in Arbuckle Group Saline Aquifer
  – Plume leakage/containment at karst compartment boundary
  – Plume growth and migration – near- and long-term
    • Plume attenuation with time