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)

Jason Rush

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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 CO_2 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 CO_2 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 CO_2 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 CO_2 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

Petrel 2012
Shared earth–critical insight
Schlumberger

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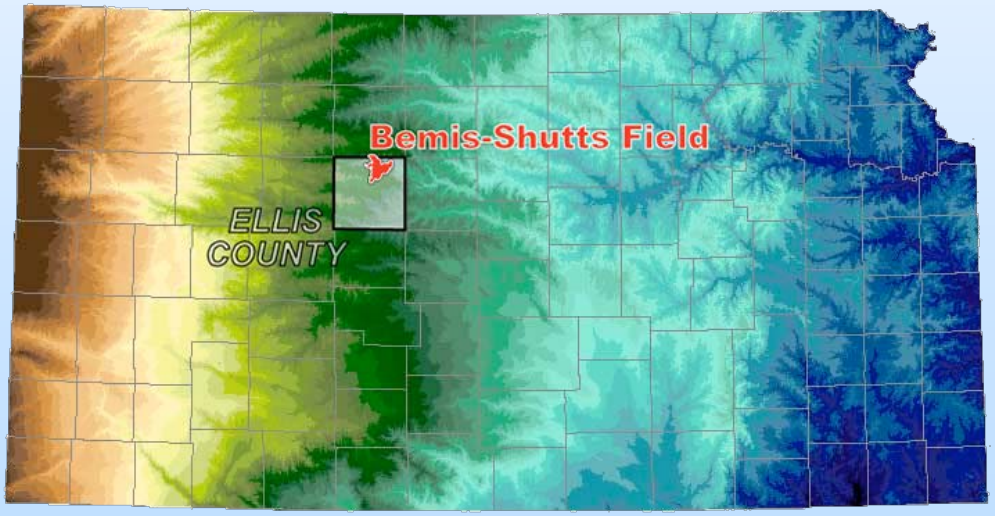
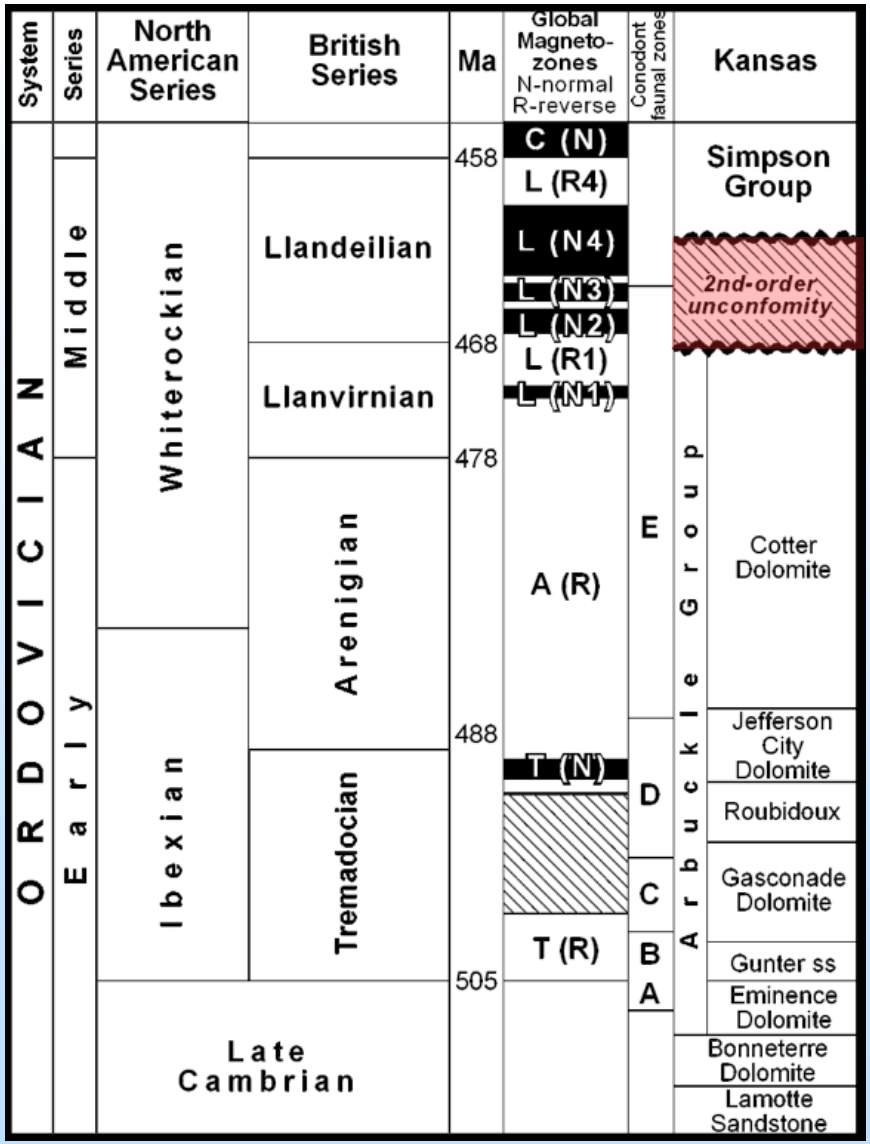
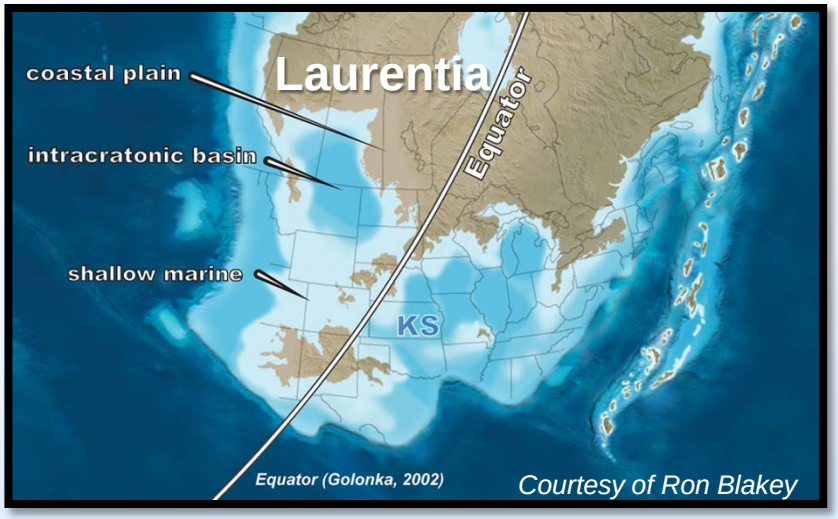
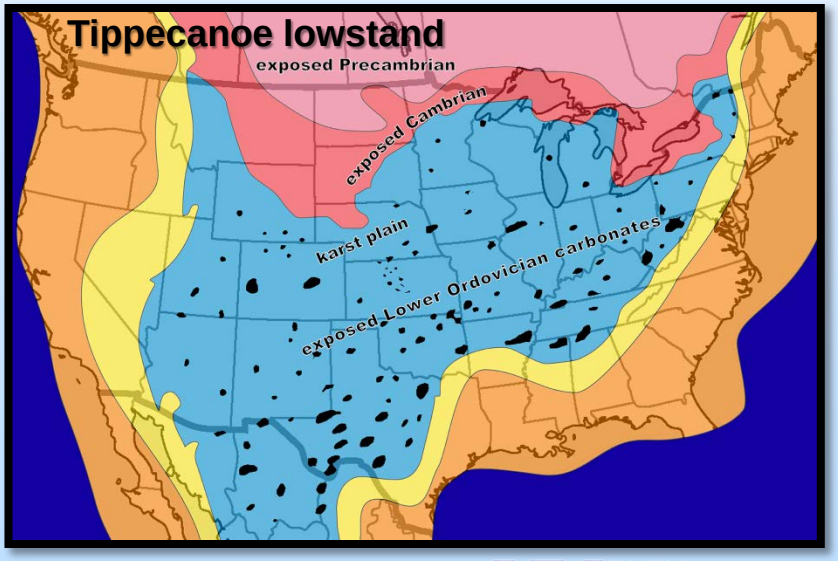


Age & Regional Setting

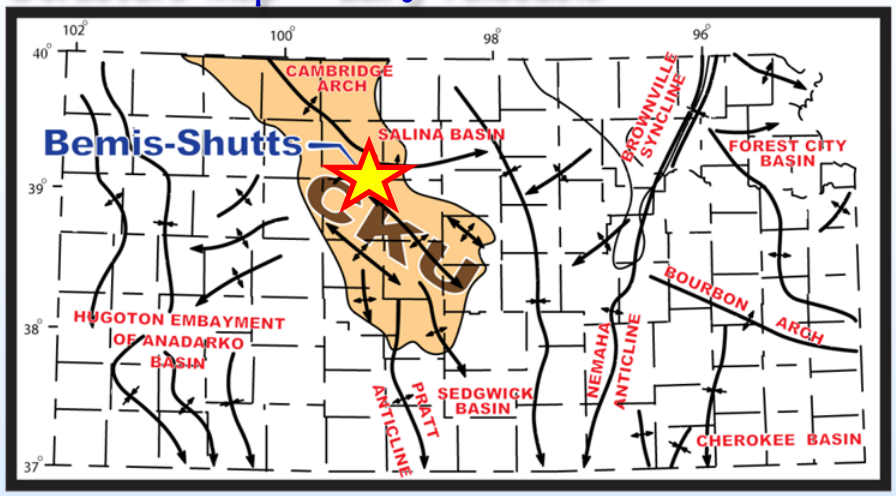




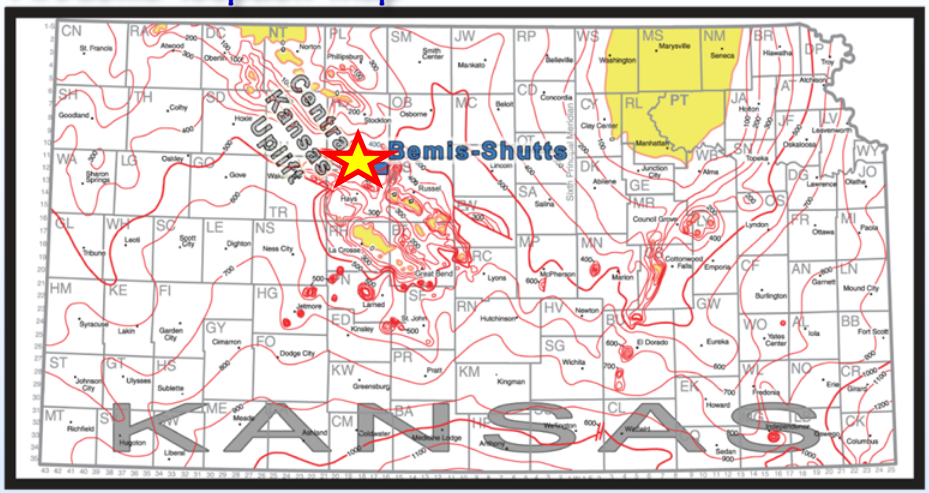


Kansas Setting

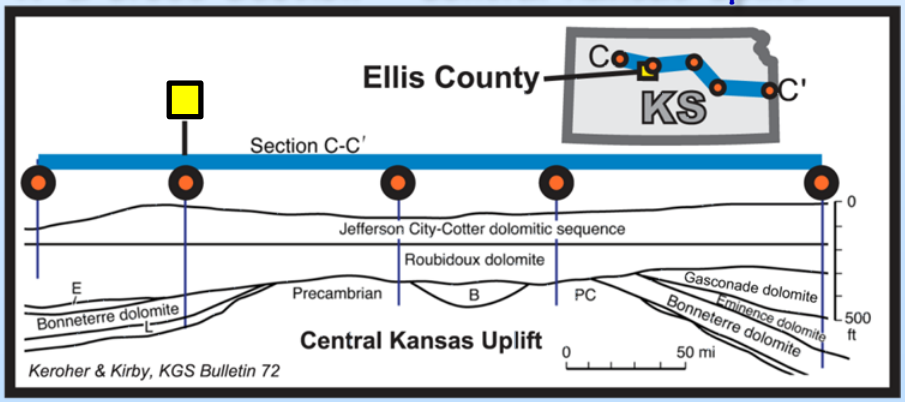
Structure Map — Early Paleozoic



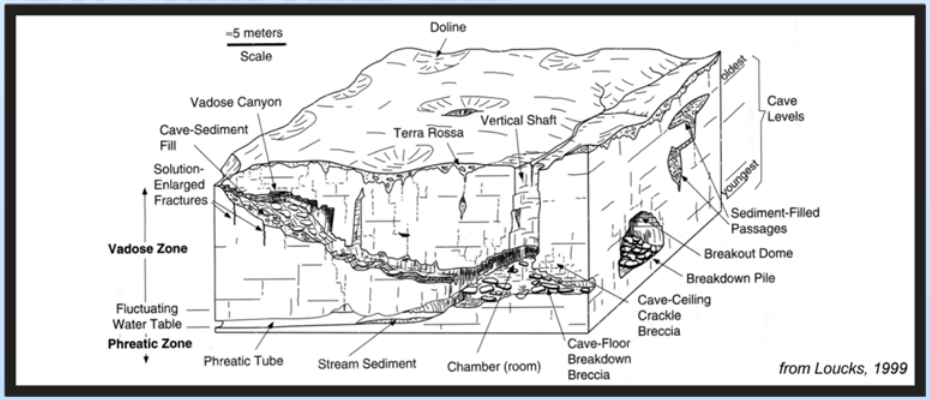
Arbuckle Isopach Map



W–E Cross Section — Central Kansas Uplift

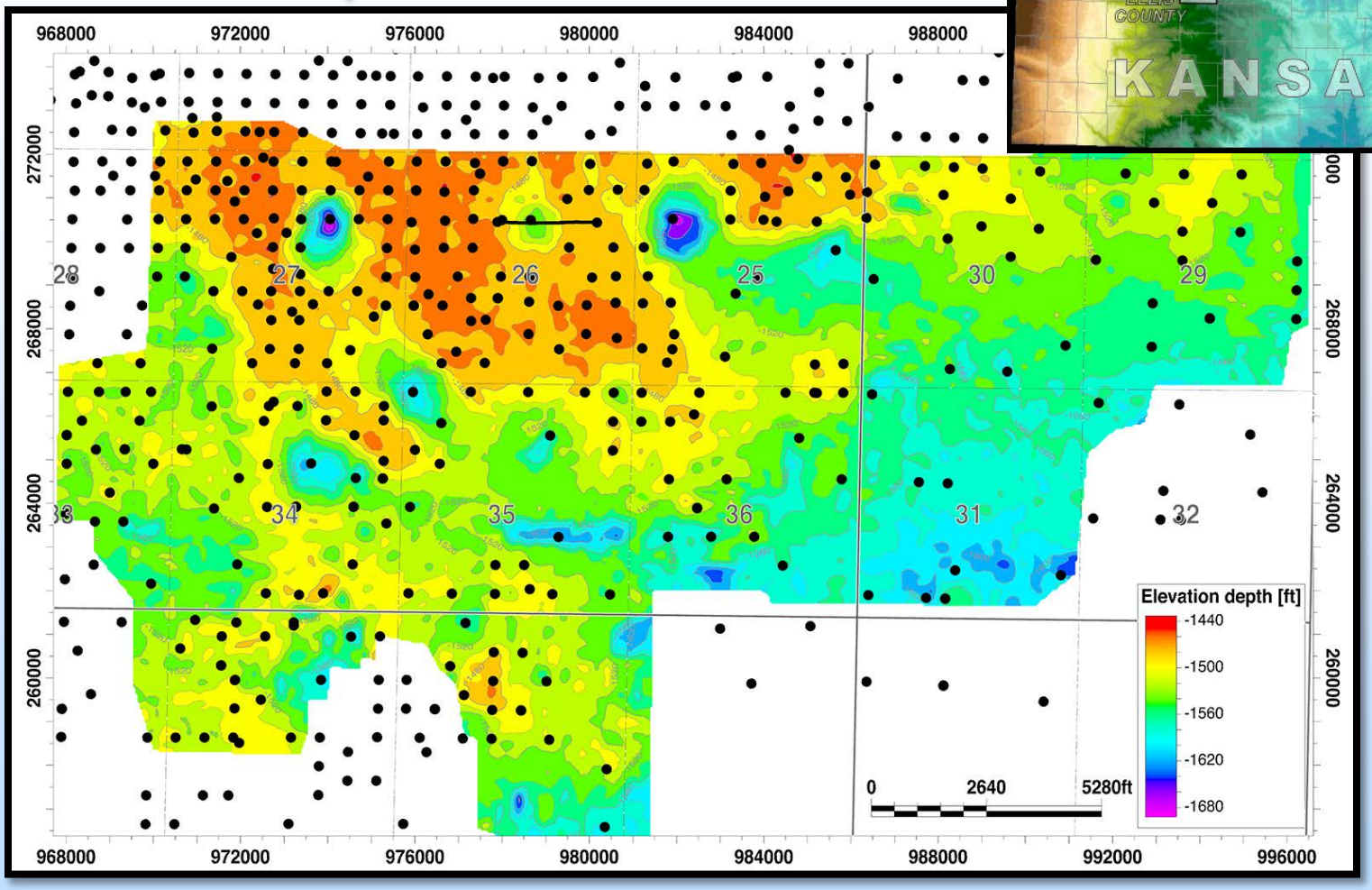


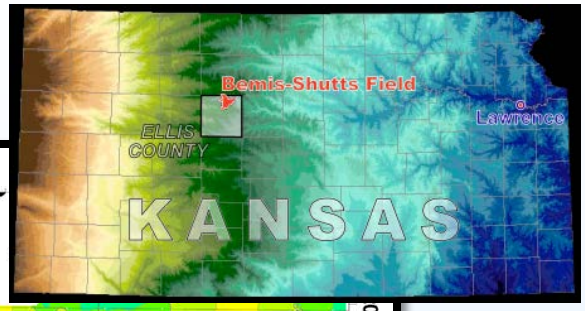
Karst Process-Based Model



Study Area — Bemis Shutts Field

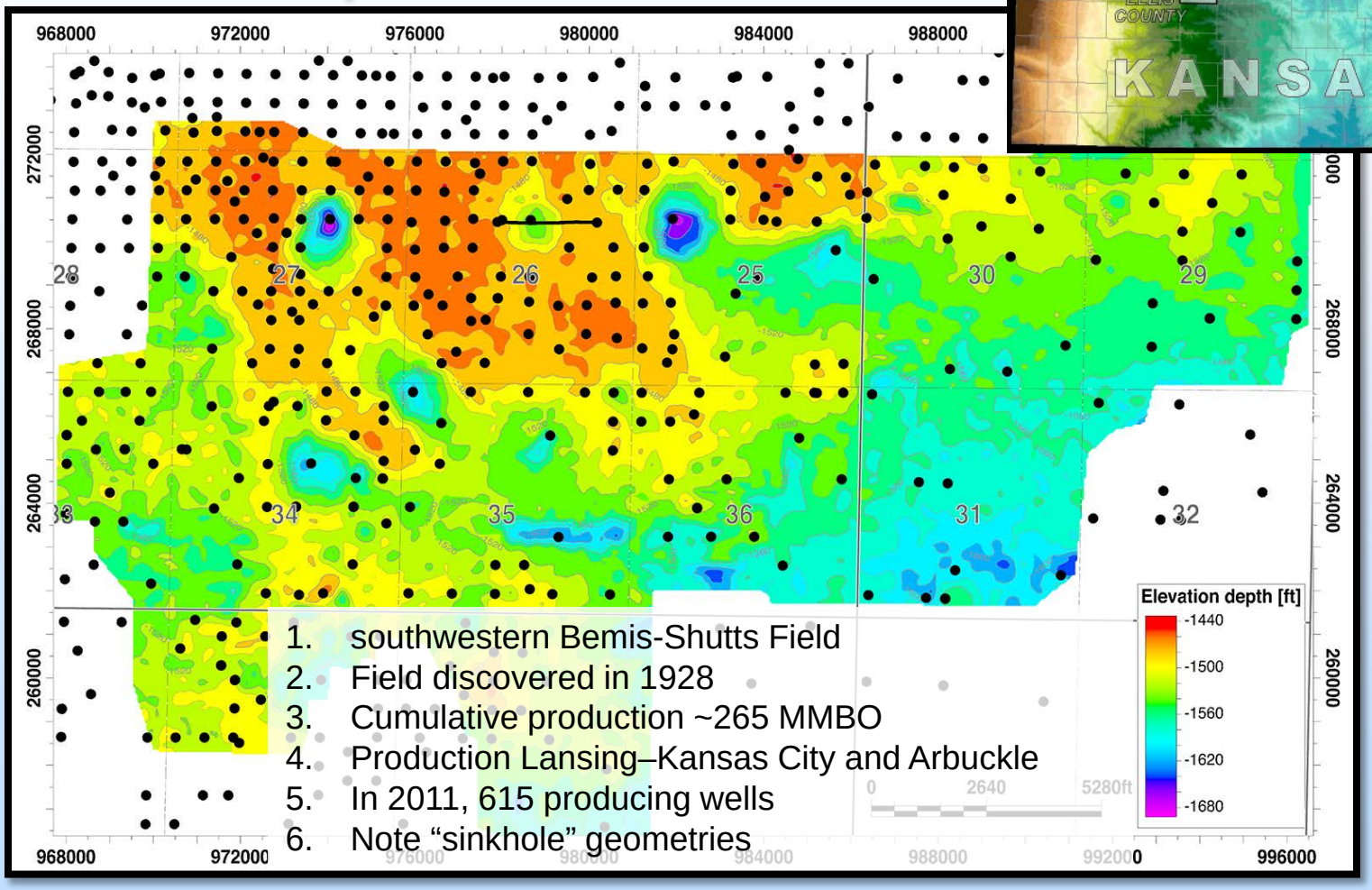
Structure Map

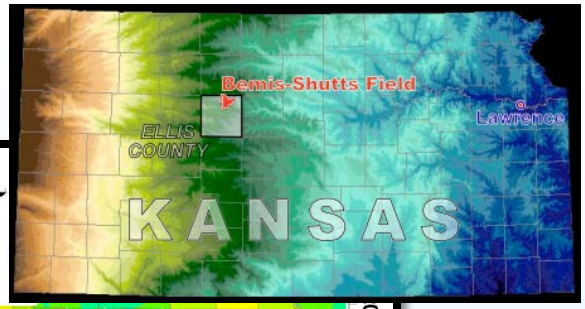




Study Area — Bemis Shutts Field

Structure Map

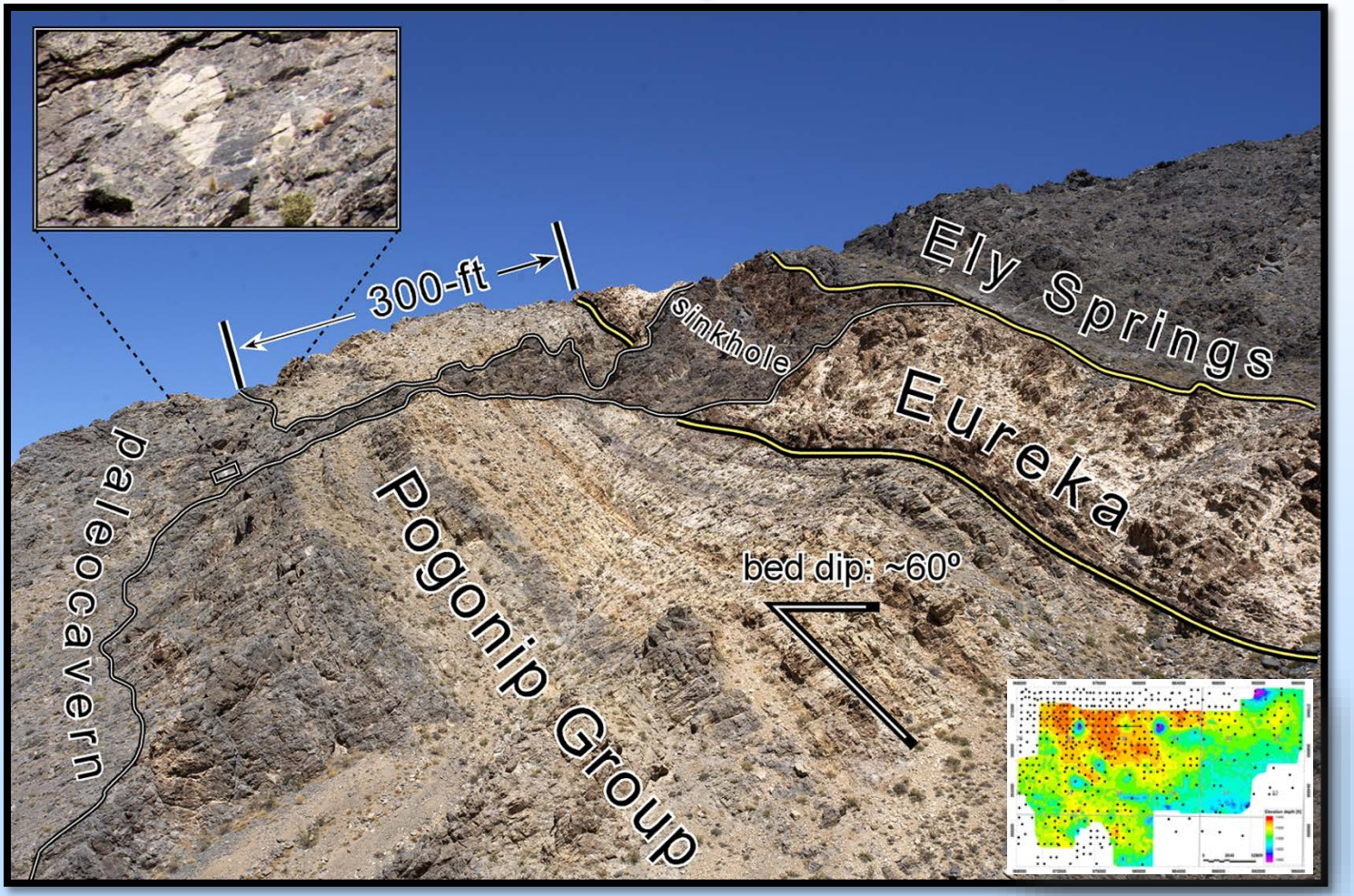




1. southwestern Bemis-Shutts Field
2. Field discovered in 1928
3. Cumulative production ~265 MMBO
4. Production Lansing–Kansas City and Arbuckle
5. In 2011, 615 producing wells
6. Note “sinkhole” geometries

Arbuckle Analog

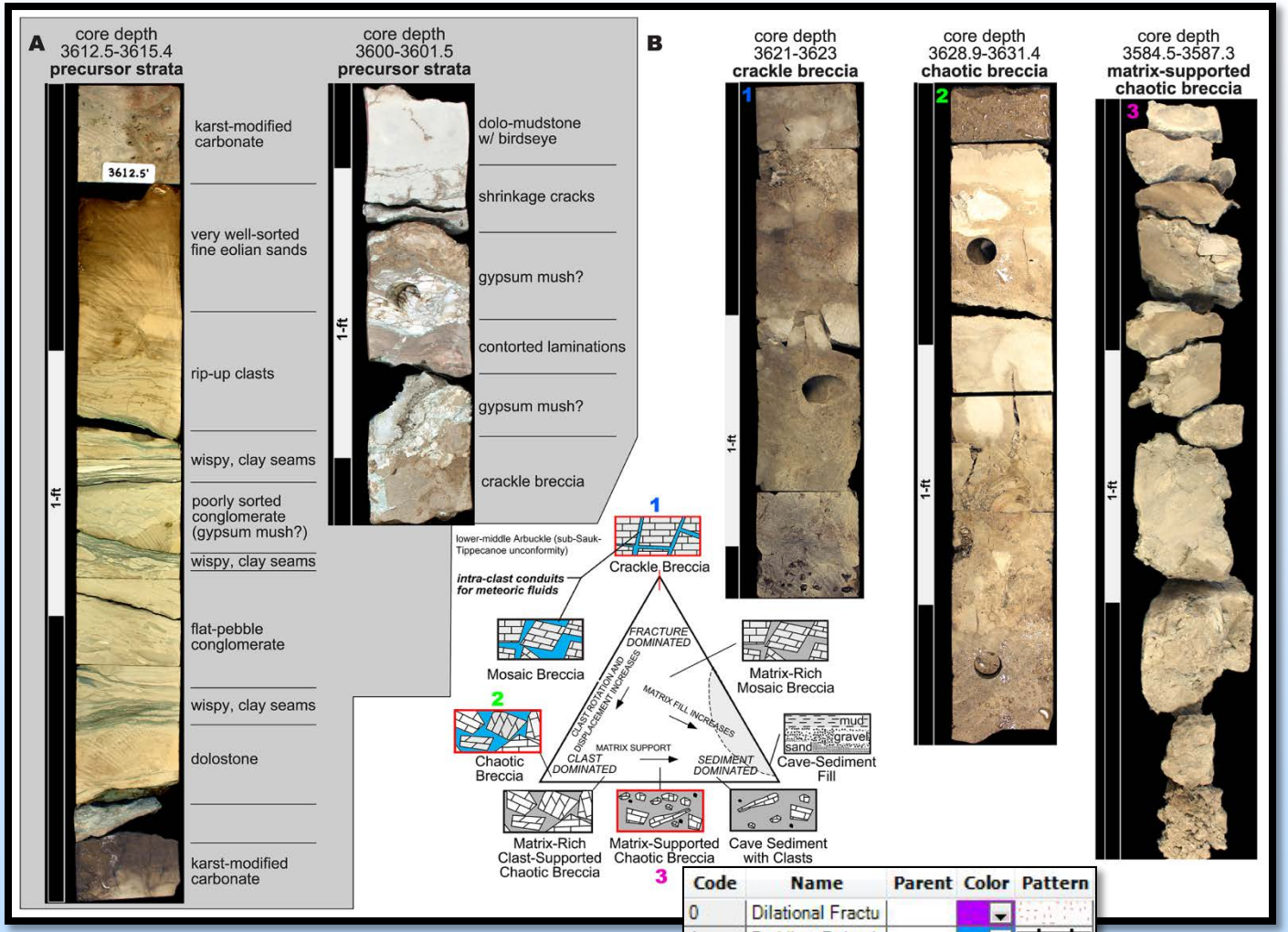
Whiterockian Paleokarst Outcrop Analog — Nopah Range, CA



Field Setting

Precursor Strata

Paleokarst Rock Fabrics



KANSAS GEOLOGICAL SURVEY
The University of Kansas

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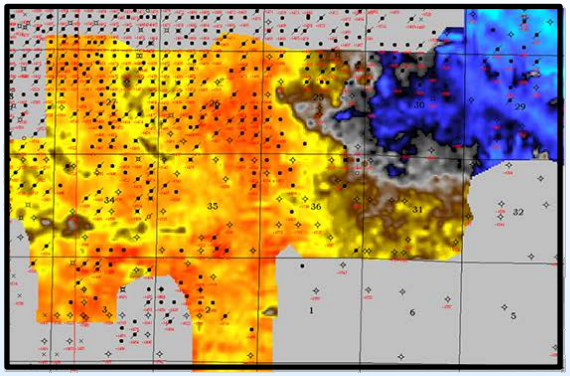
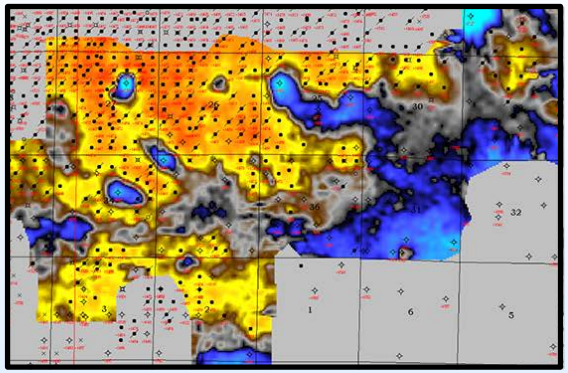
Time & Depth Migration

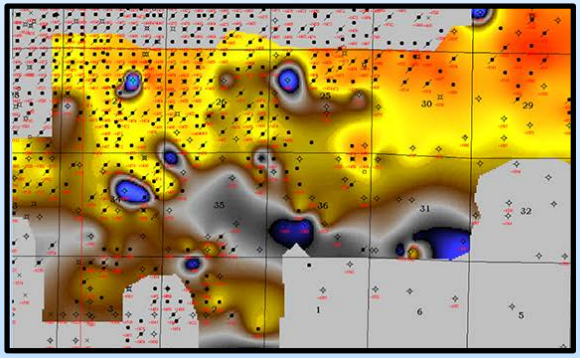
Arbuckle PSTM



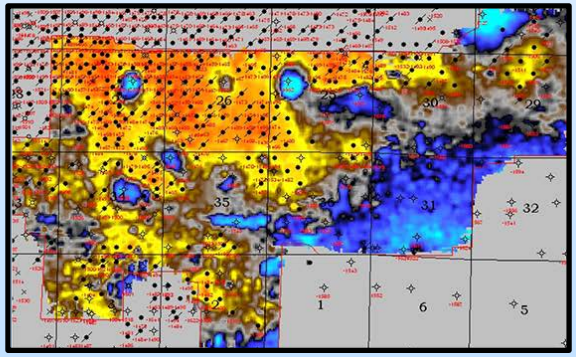
Arbuckle PSDM



Average Velocity to Arbuckle

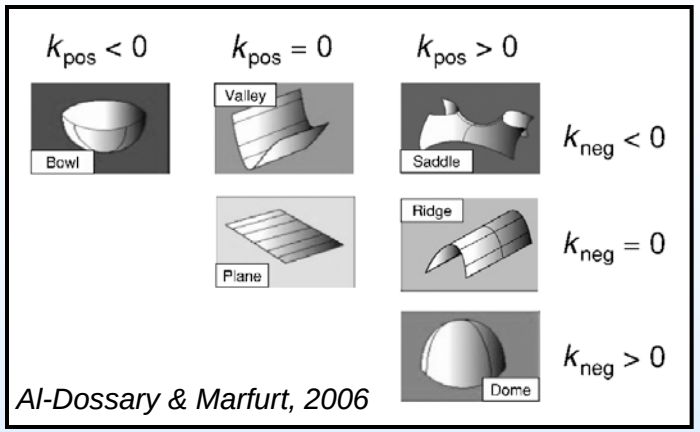


Arbuckle Velocity & Well Control



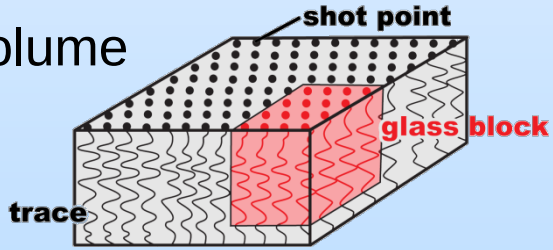
Volumetric Curvature

- 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



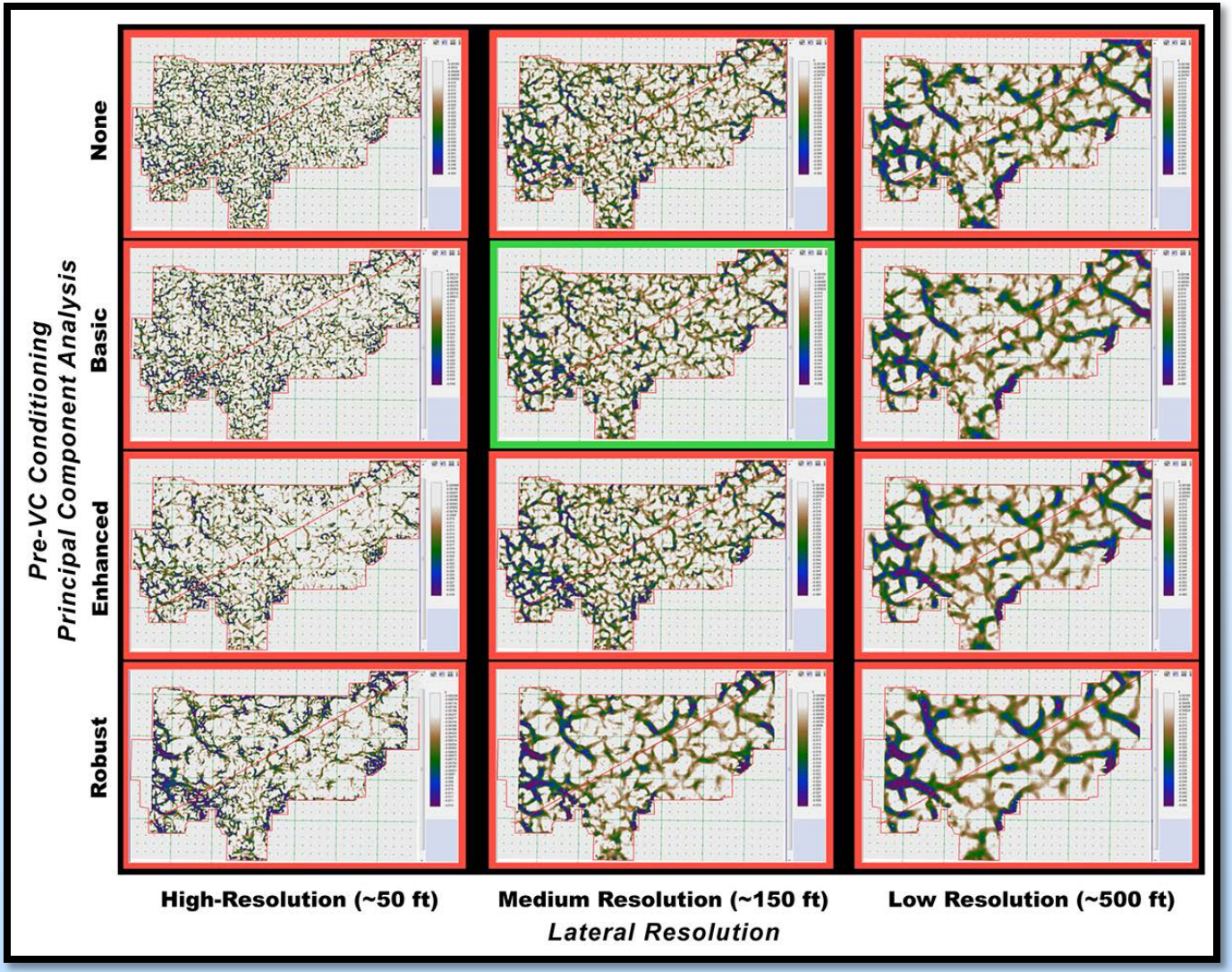
Al-Dossary & Marfurt, 2006

- 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

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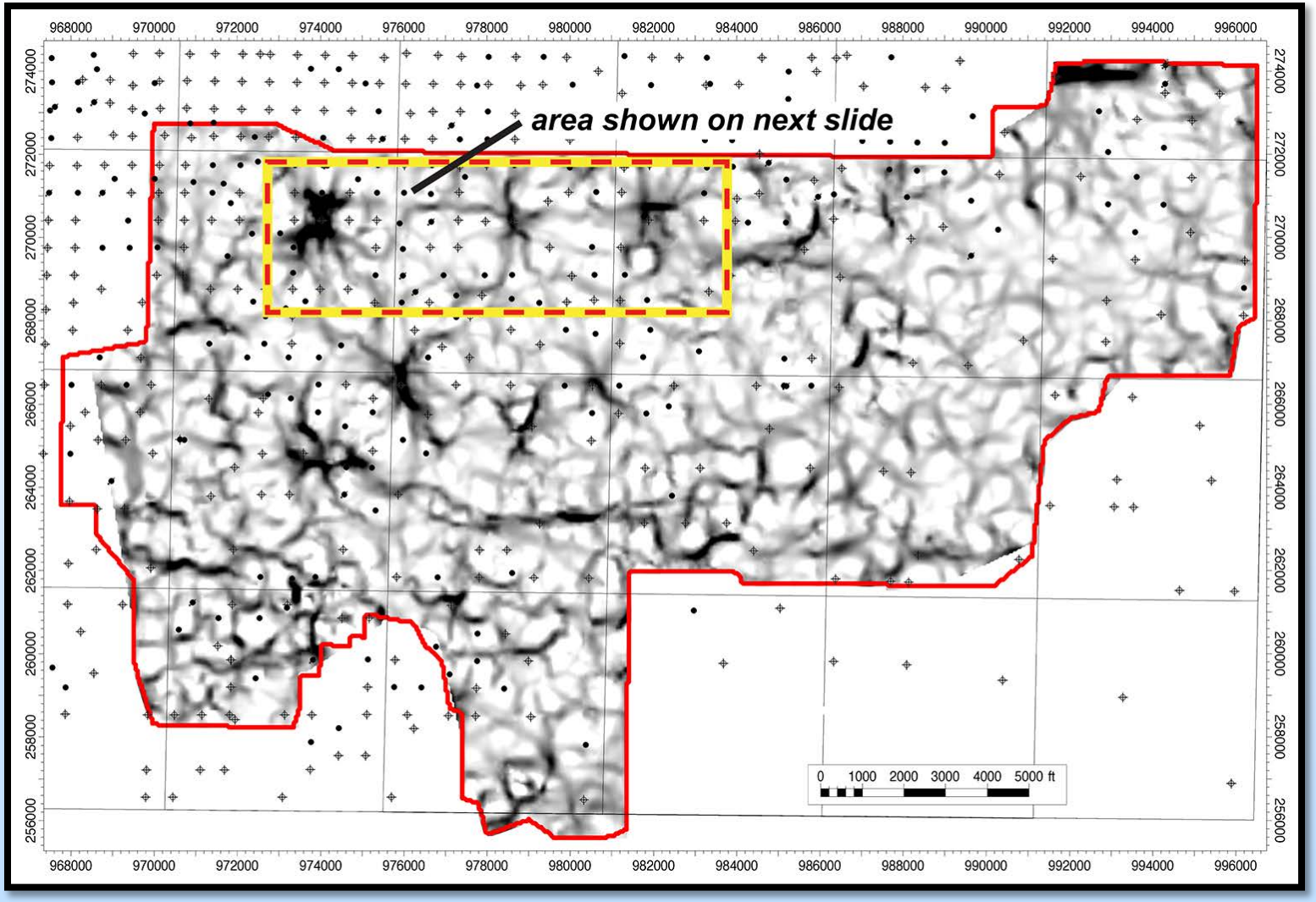
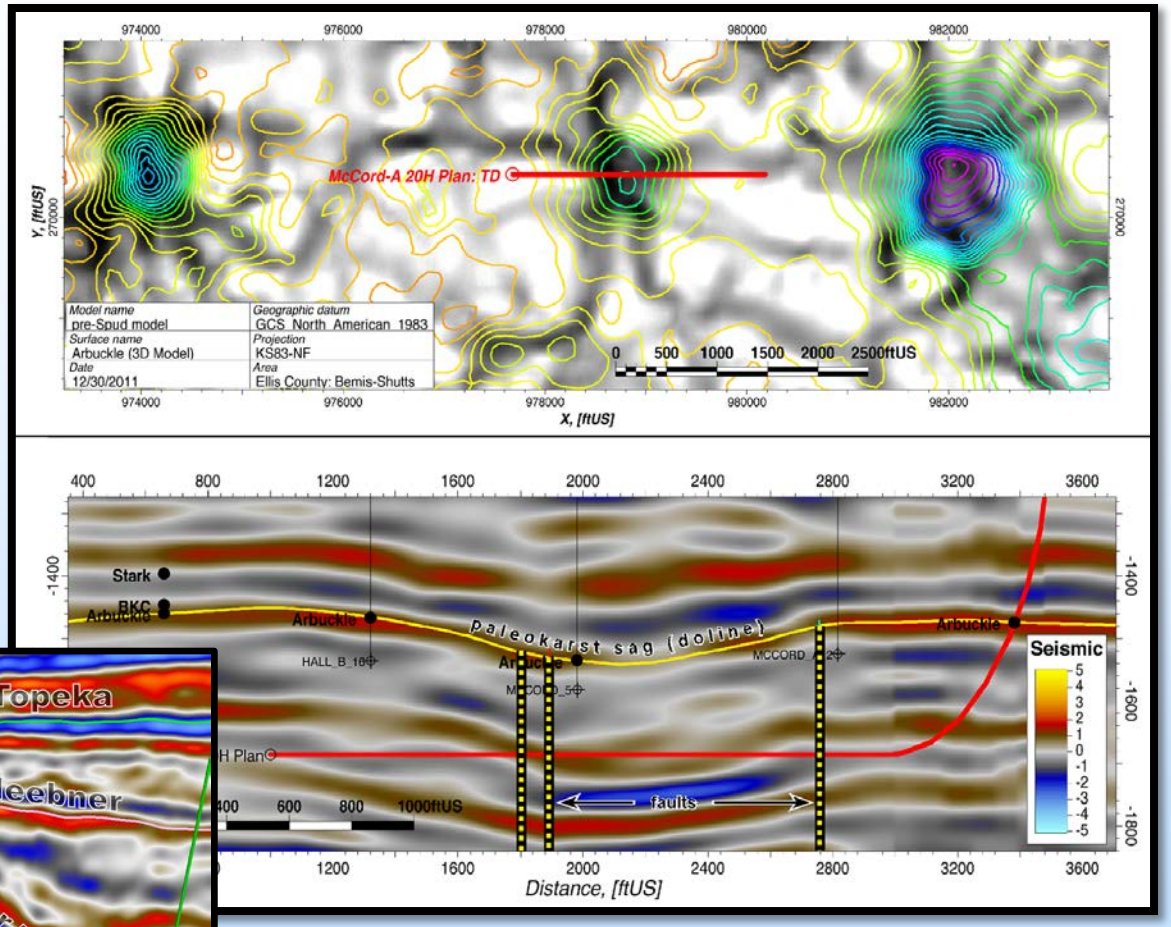
Arbuckle PSDM VC Horizon-Extraction



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

Unanticipated results:
- *Strataform breccias outside dolines*
- *no mud losses!*



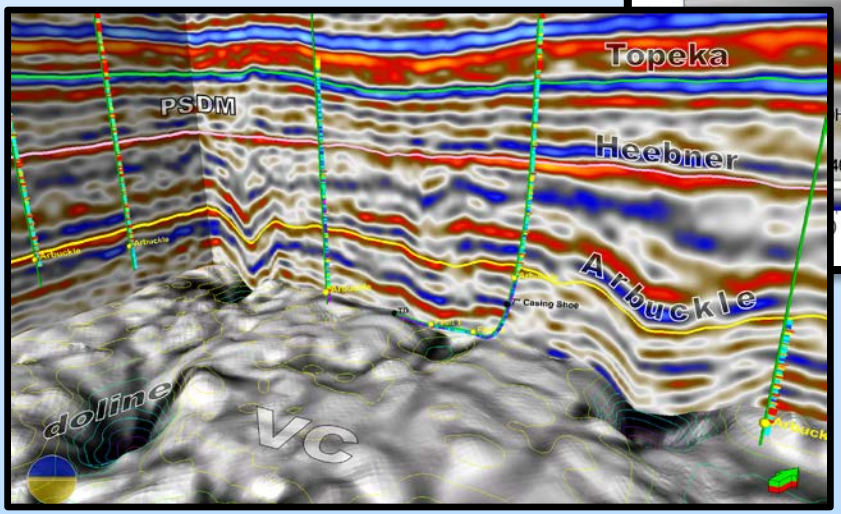
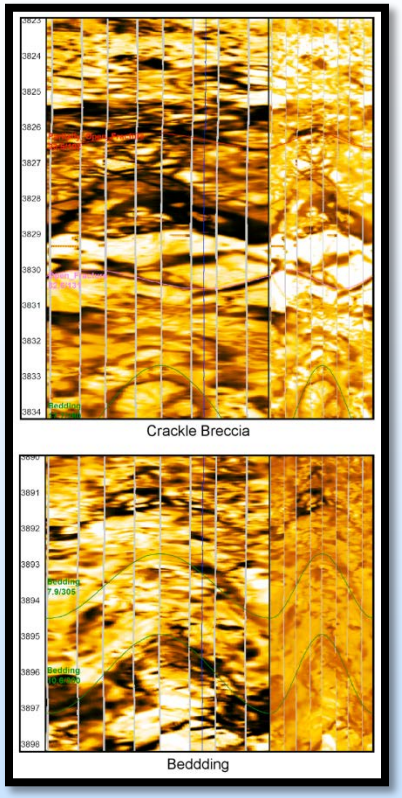
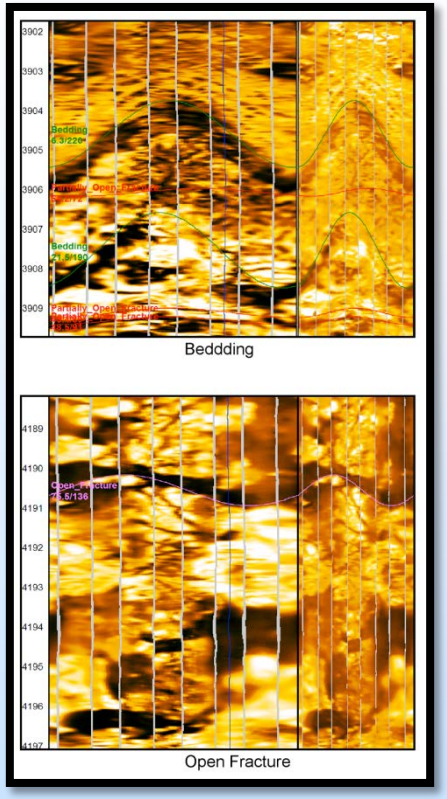


Image Log Facies — Facies Model

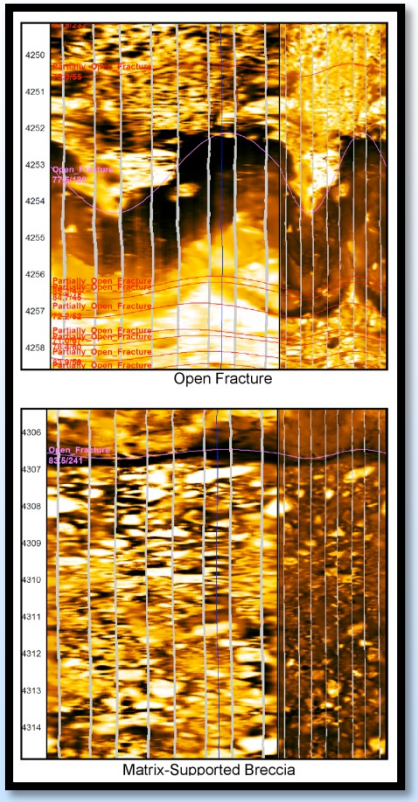
Crackle



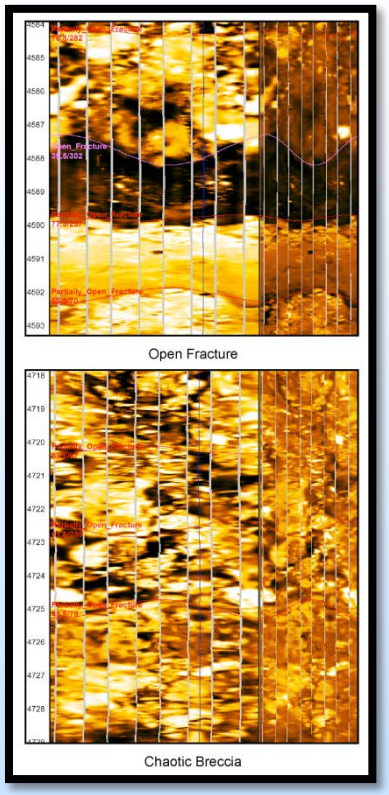
Bedding



Dilational Fracture



Dilational Fracture

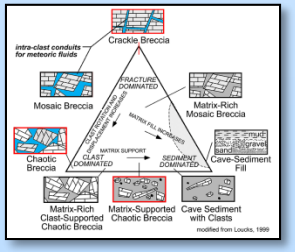


Bedding

Dilational Fracture

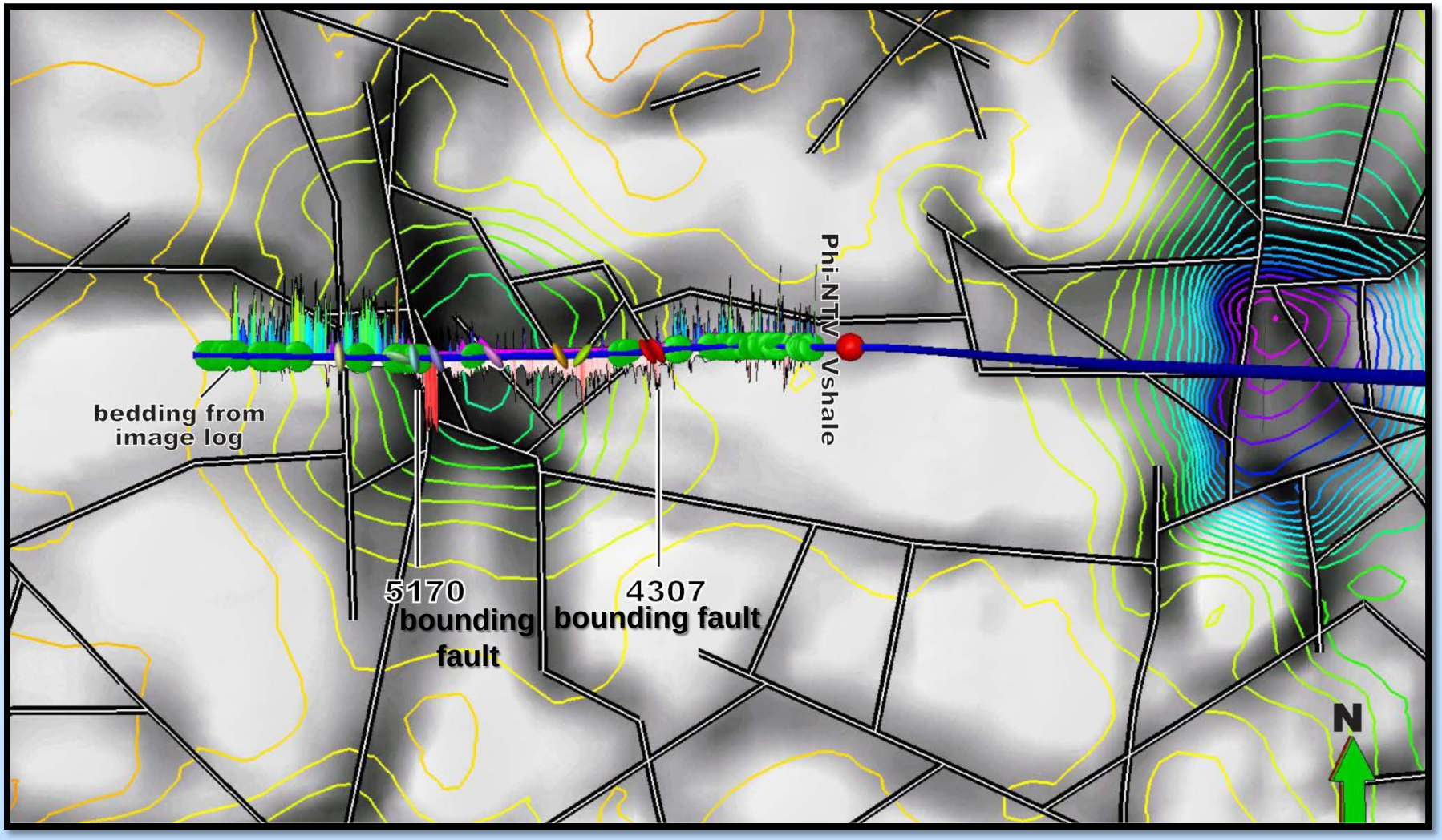
Matrix-Supported

Chaotic

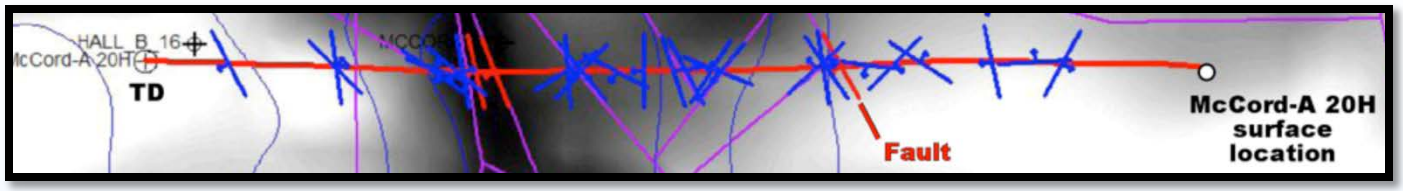


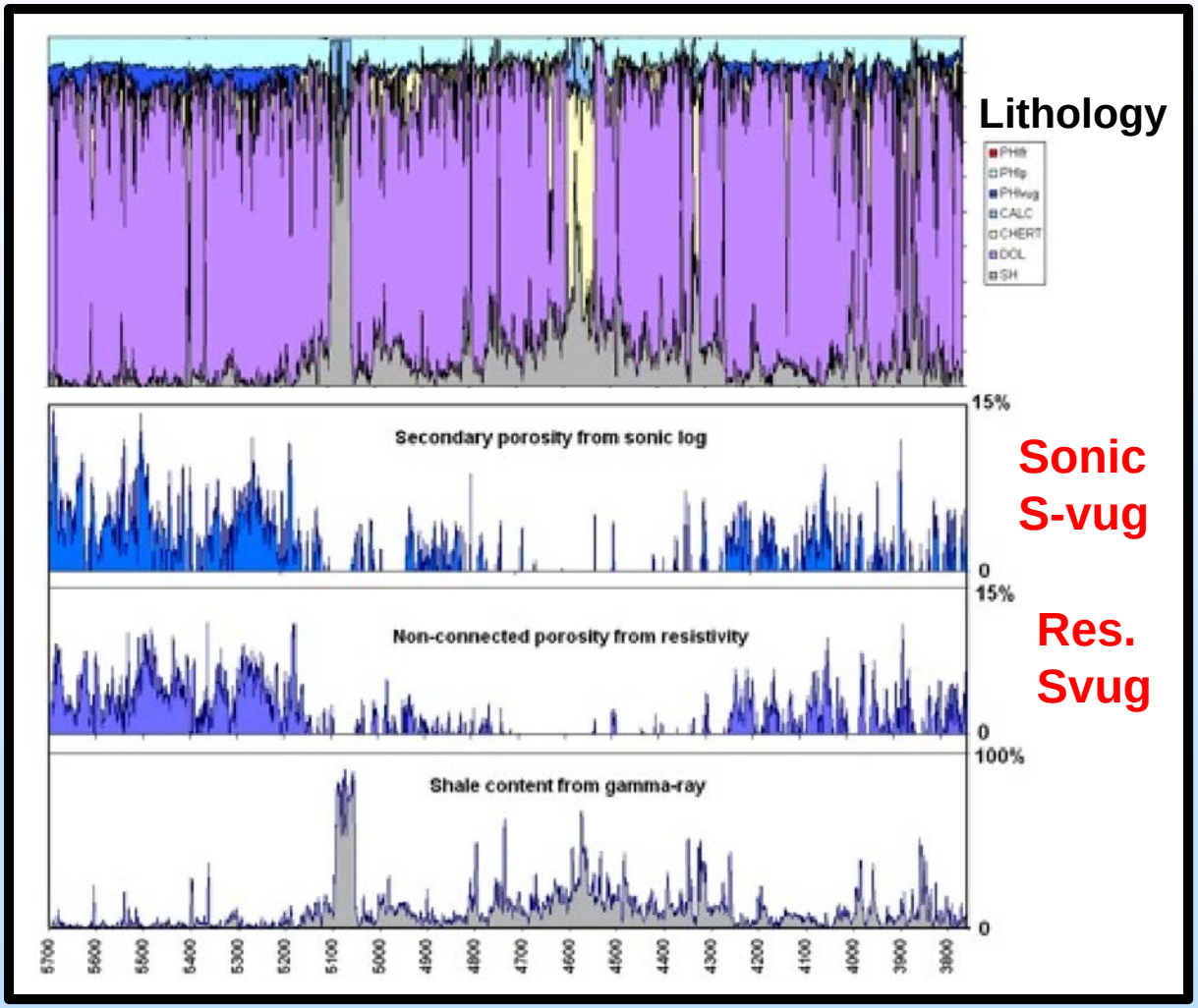
Code	Name	Parent	Color	Pattern
0	Dilational Fractu			
1	Bedding-Dolomi			
2	Matrix-supporte			
3	Crackle Breccia			
4	Chaotic Breccia			

VC-indicated Compartments Consistent with Log Interpretations

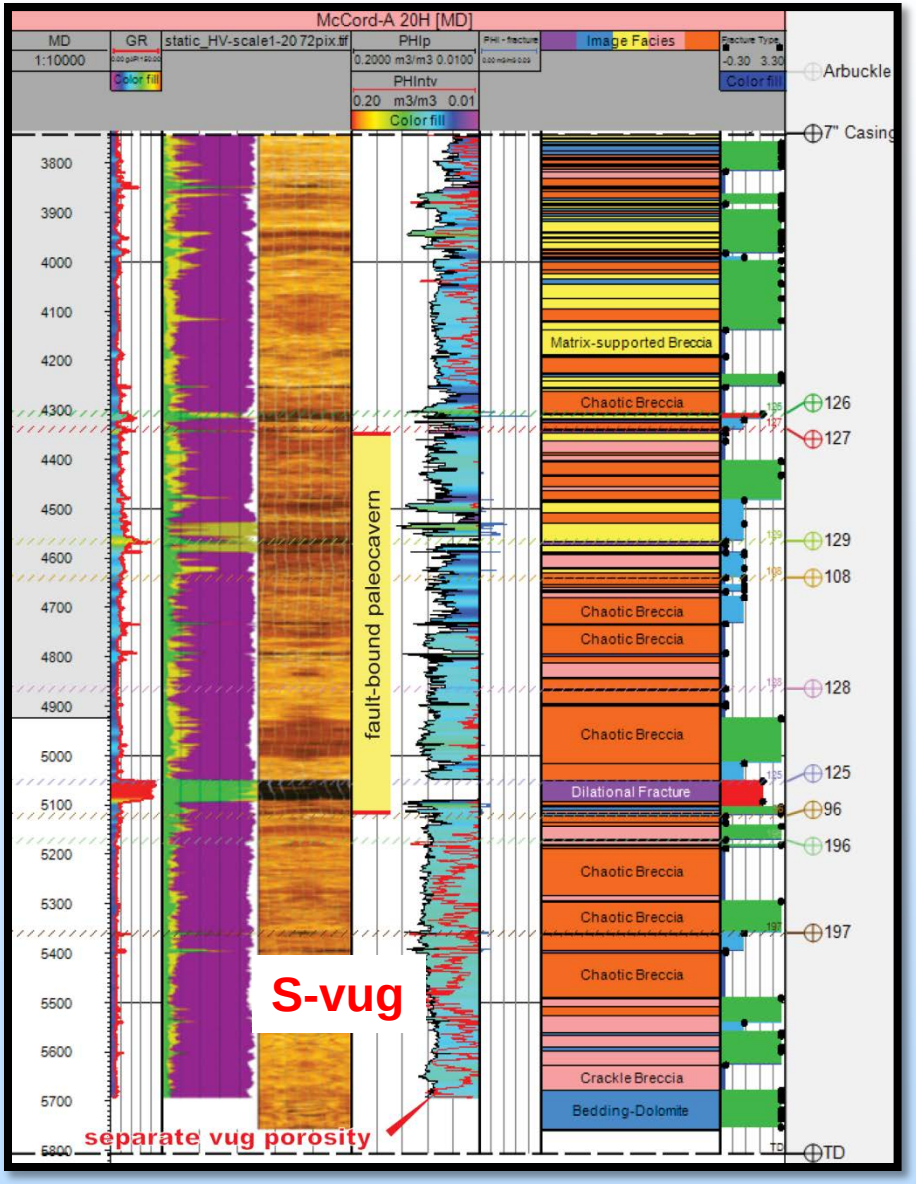


Formation Evaluation

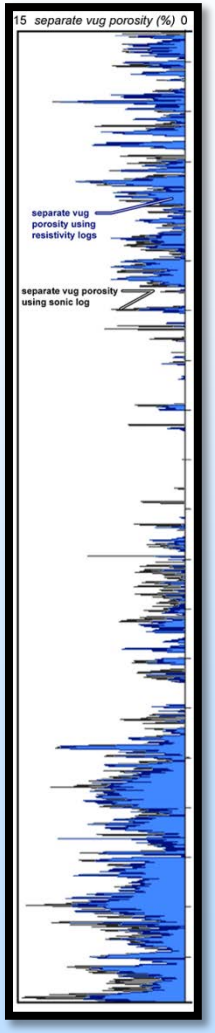


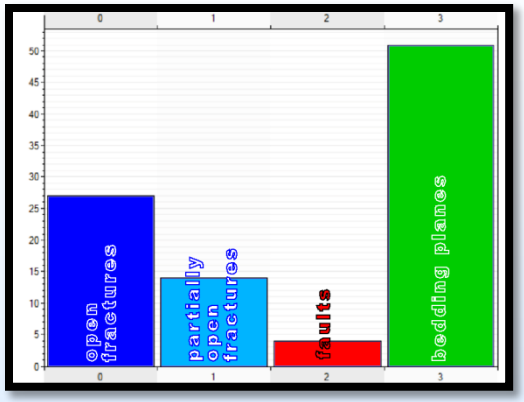


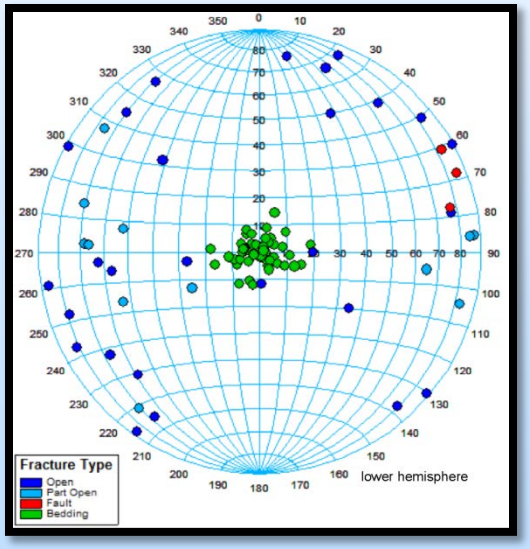
Formation Evaluation



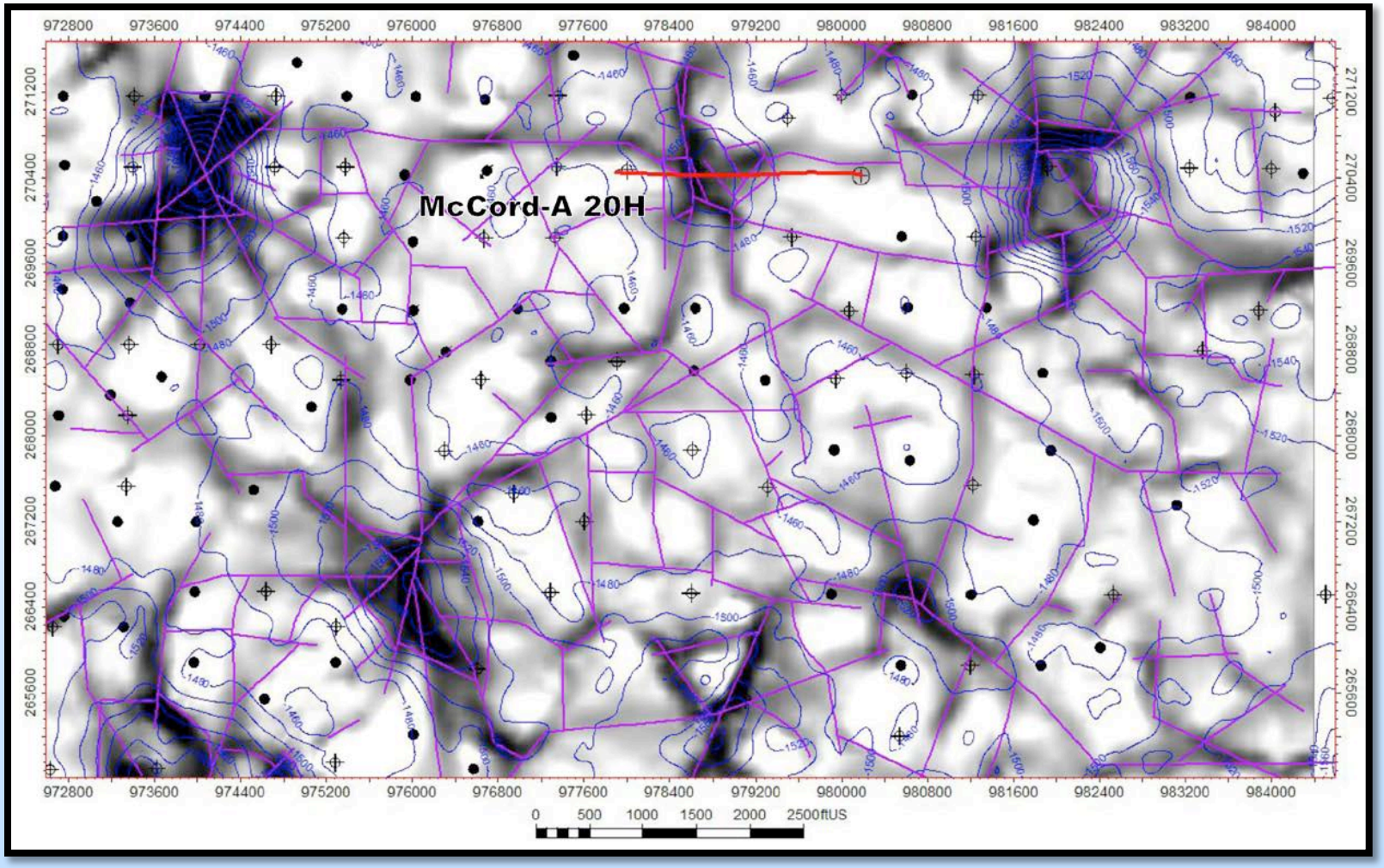
Svug %





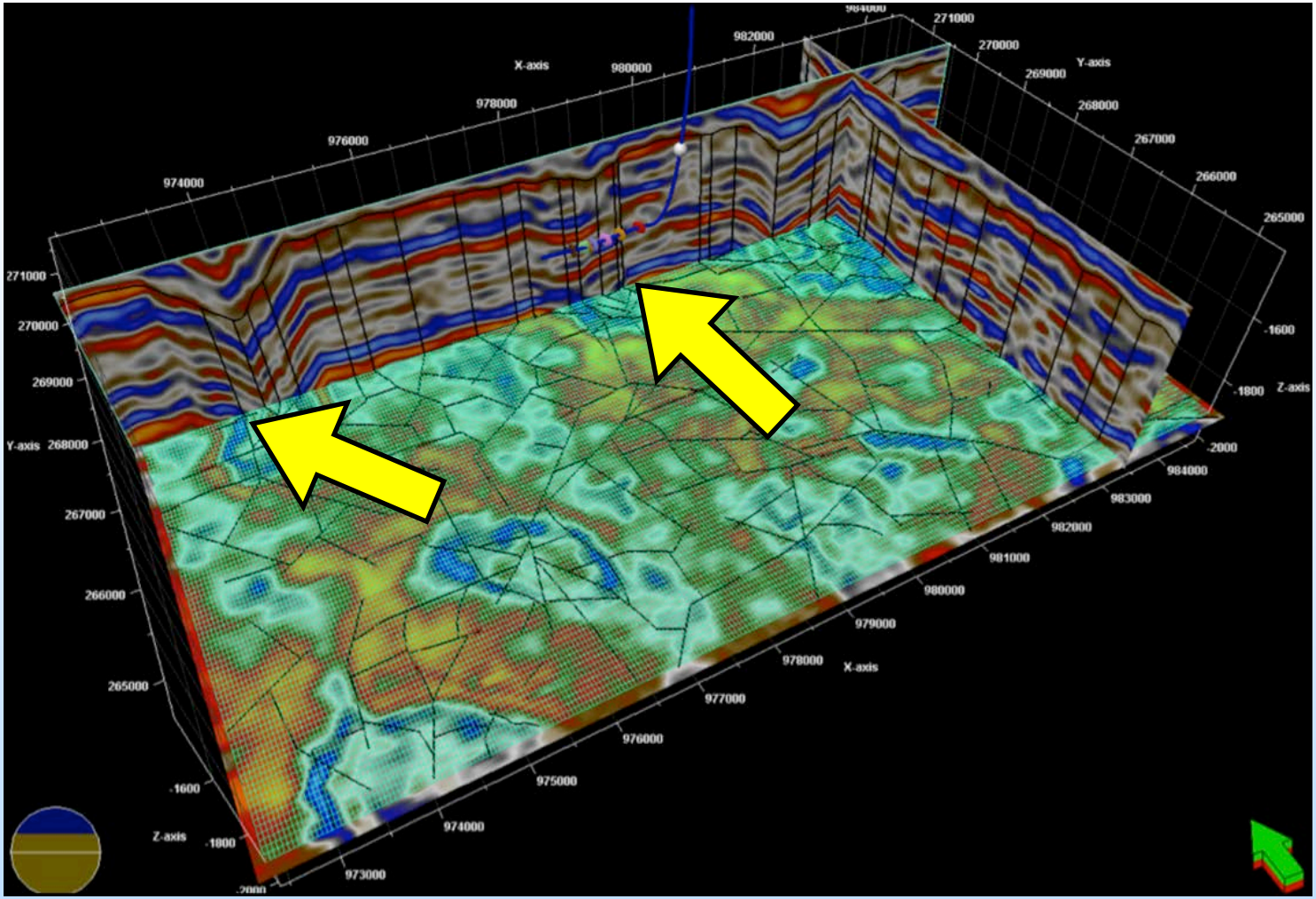


New Field-Wide Fault/Fracture Model



~201 Faults...thanks to Rock Deformation Research plug-in

VC-Faults ***Match*** Seismic Faults



Probability Maps for Conditioning Geocellular Models

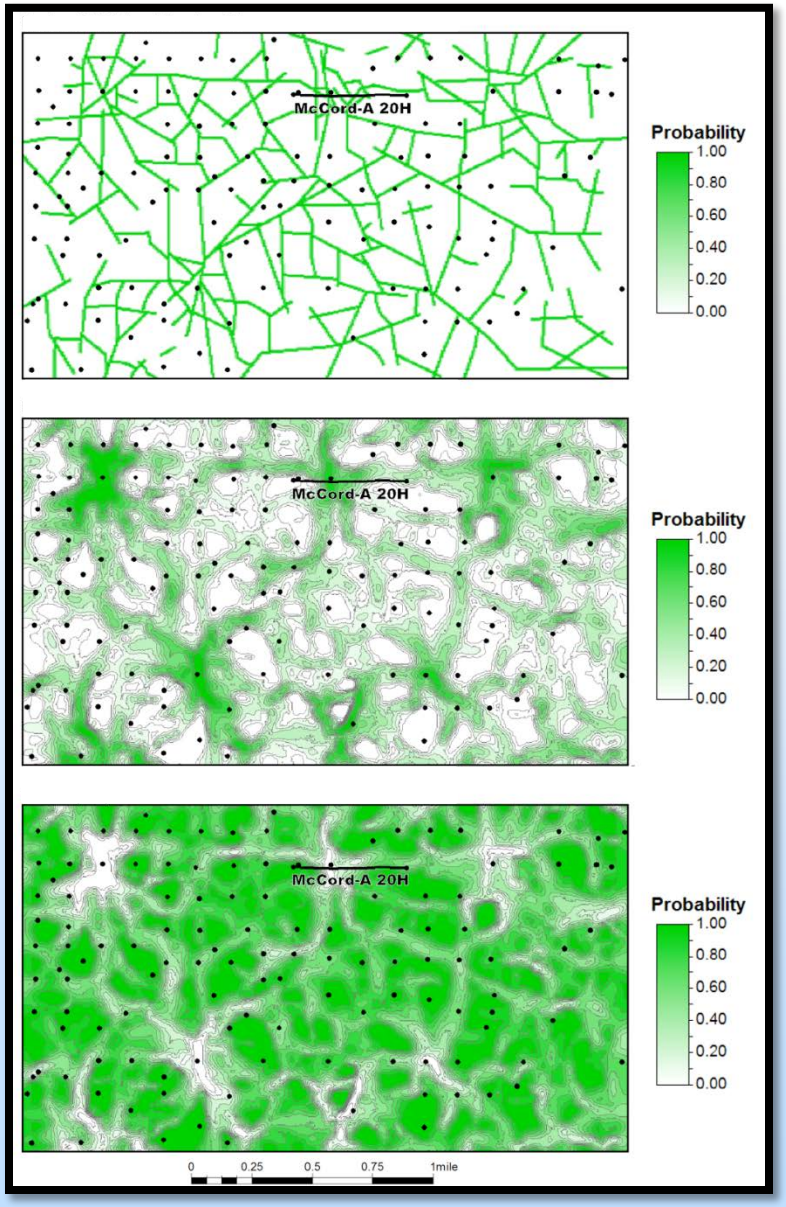
Facies

Code	Name	Parent	Color	Pattern
0	Dilational Fractu			
1	Bedding-Dolomi			
2	Matrix-supporte			
3	Crackle Breccia			
4	Chaotic Breccia			

Dilational Fractures

Crackle & Chaotic Breccia

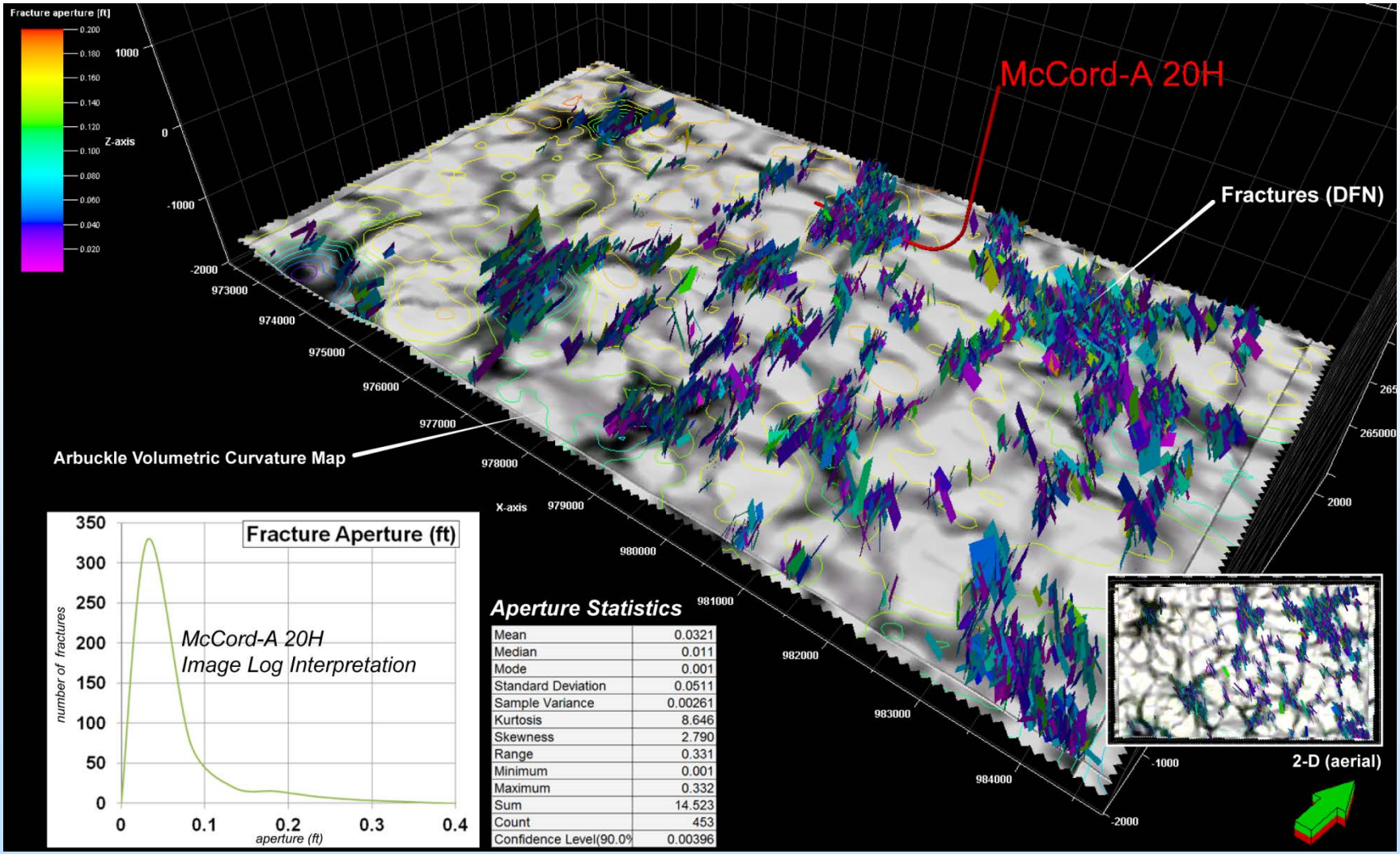
Peritidal Dolostone & Matrix-Supported Breccia



evaporite karst in host strata

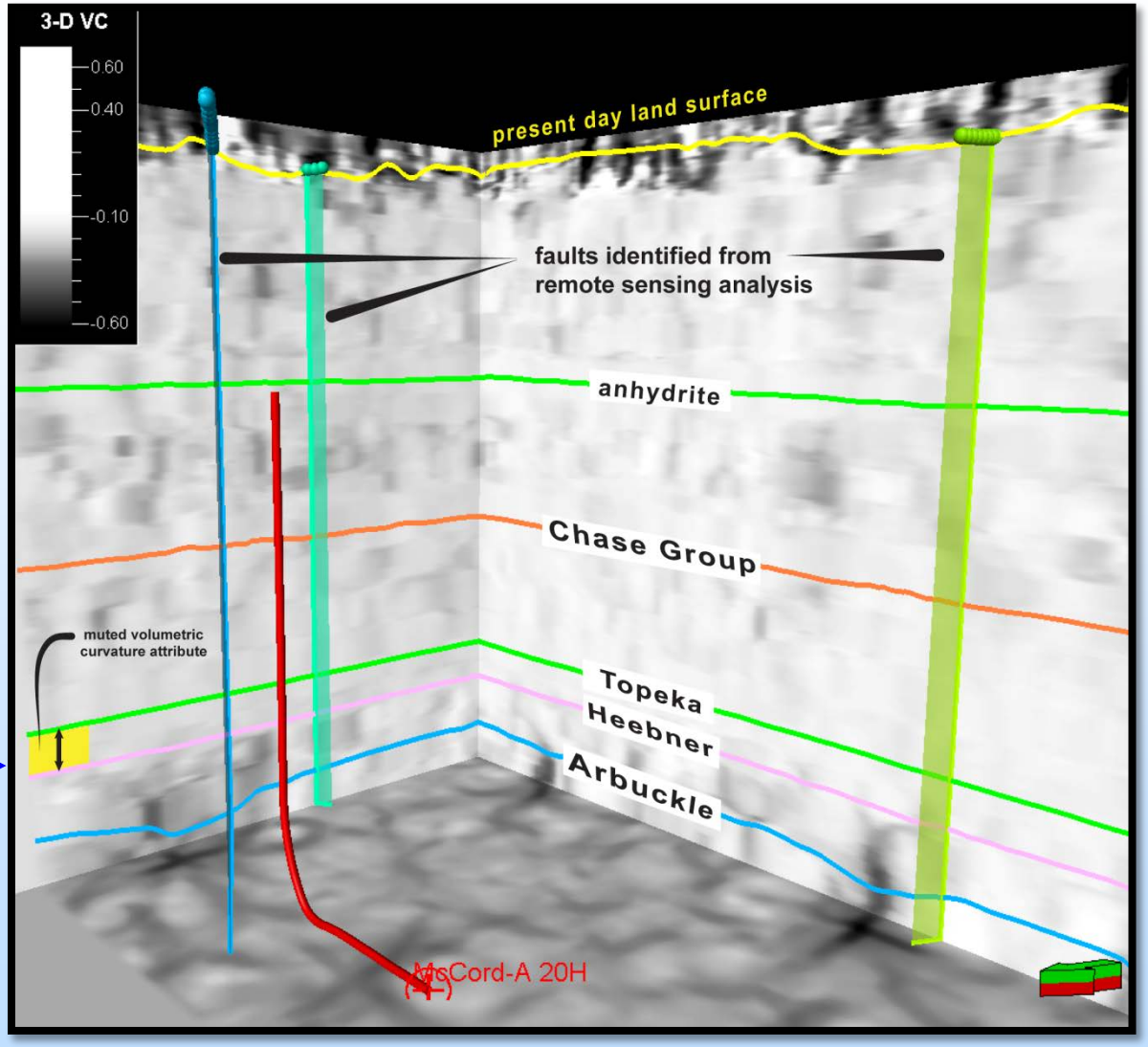
- strata-bound breccia
- anhydrite-filled molds
- geochemistry-sulfates

Discrete Fracture Network Modeling

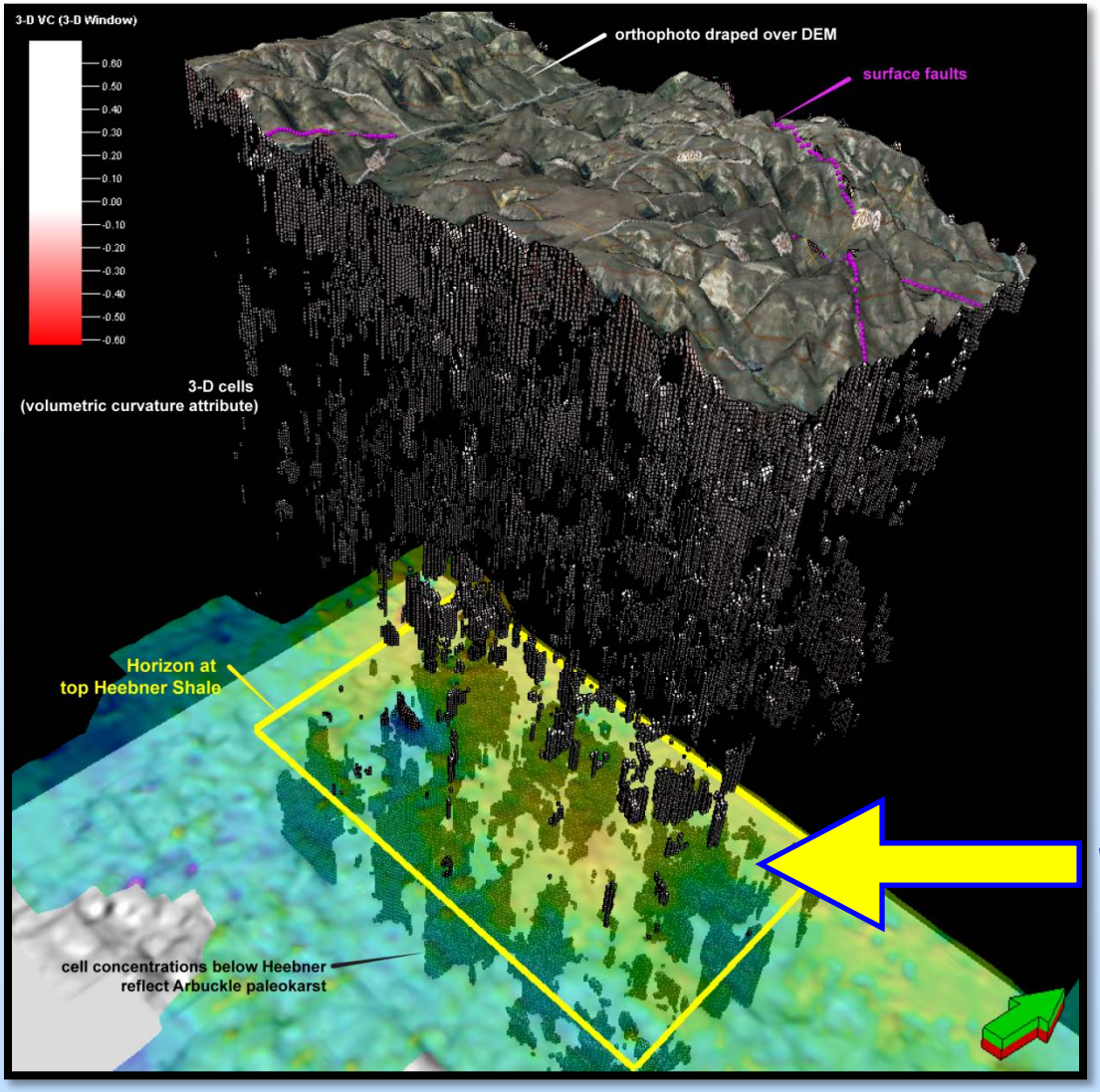


3-D Volumetric Curvature Volume

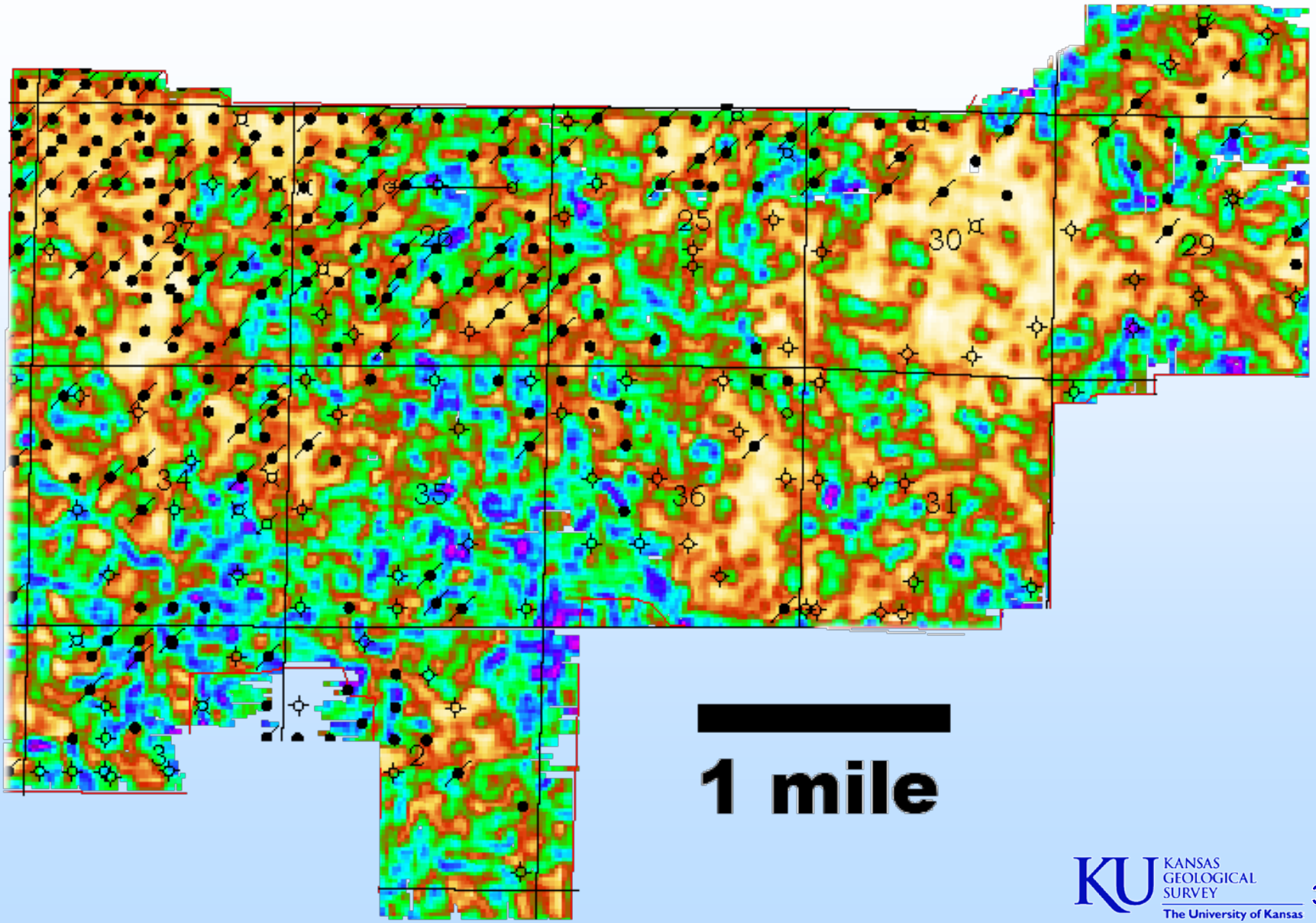
VC muted
Reflectors flat



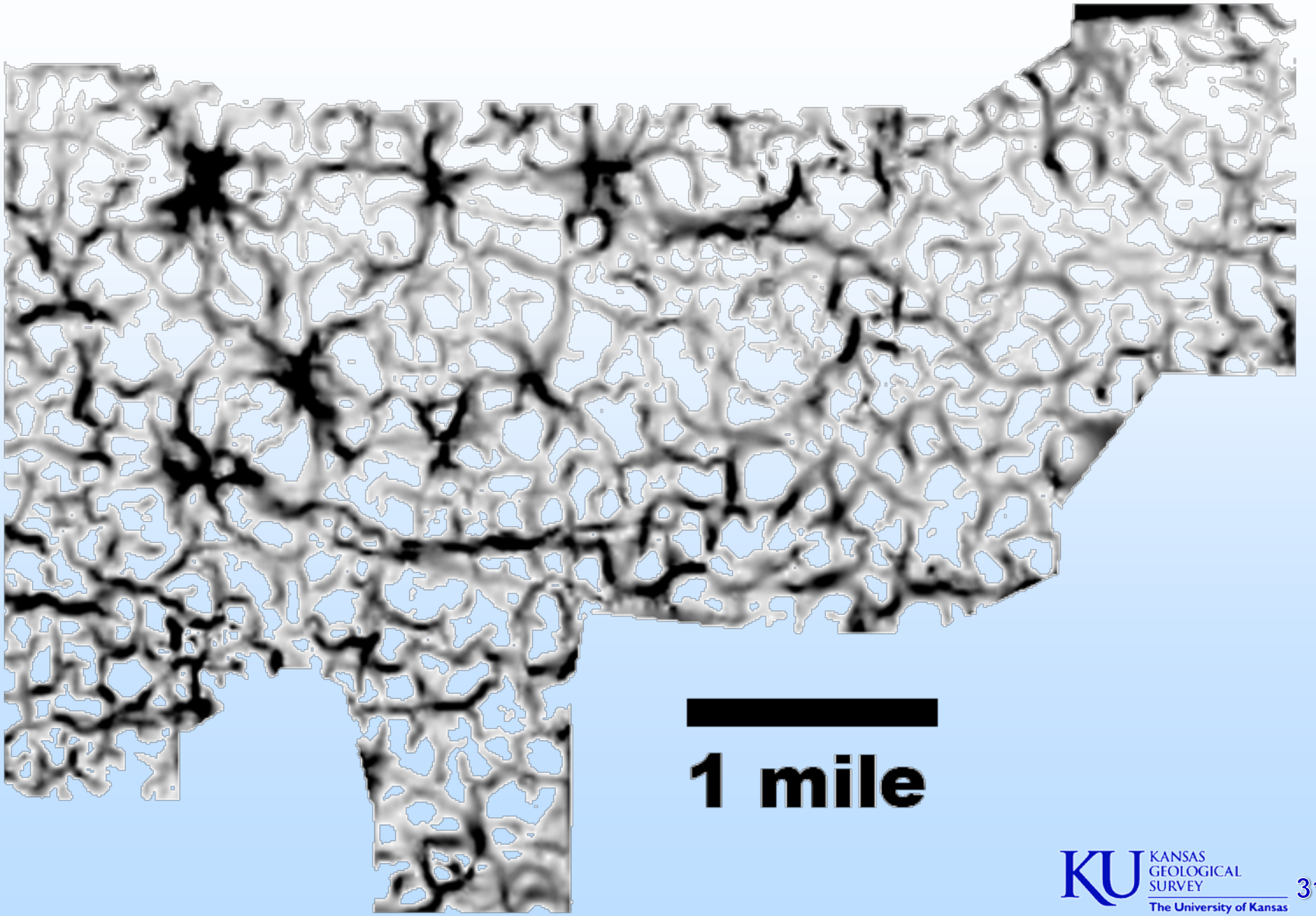
Filtered 3-D VC Geocellular Model



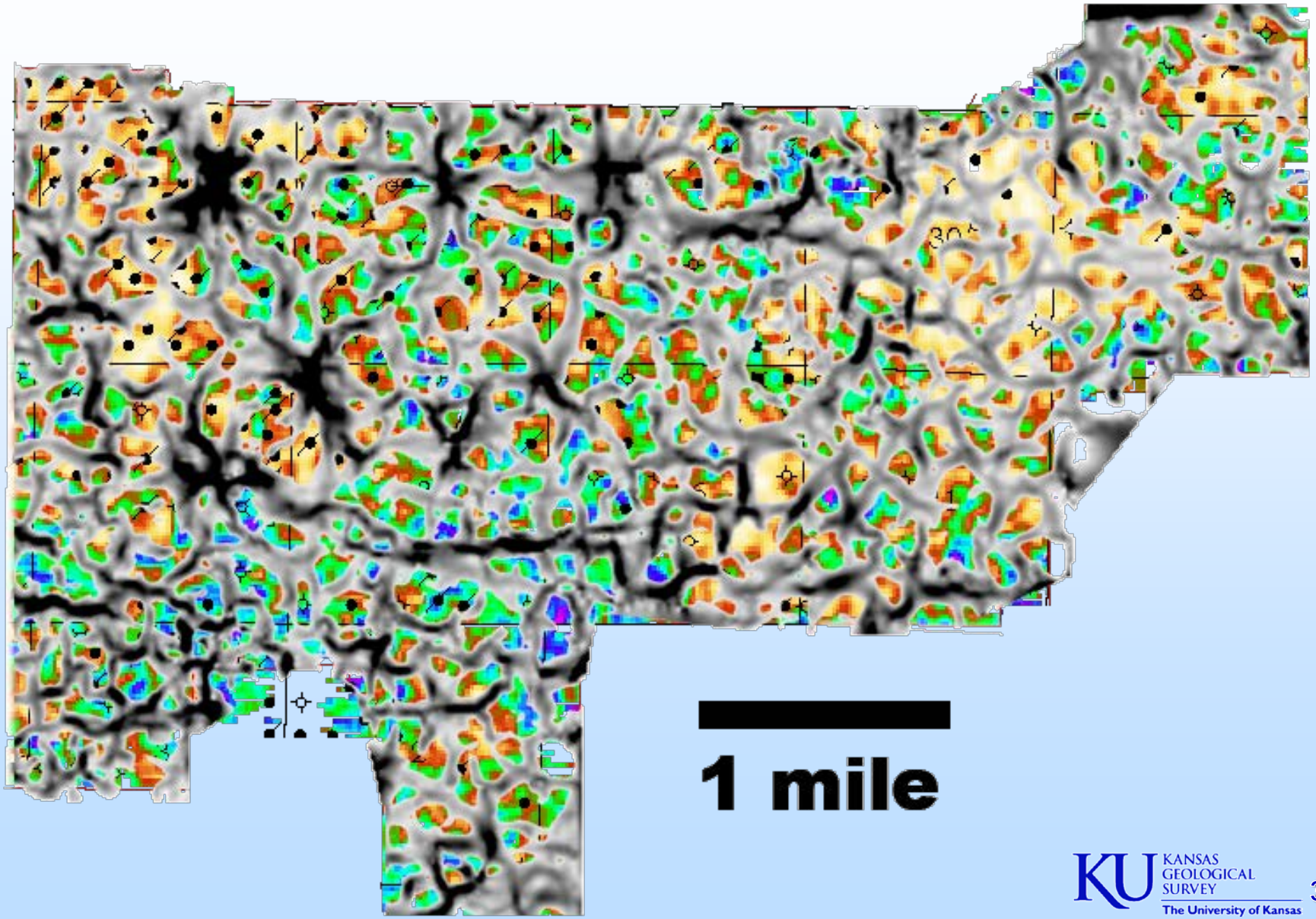
Other Seismic Attributes: **Semblance** vs VC



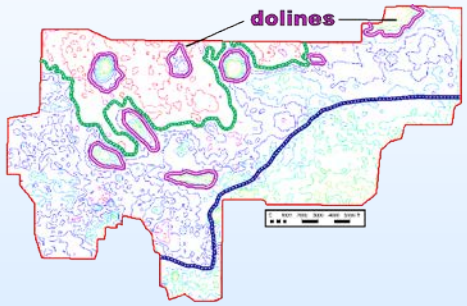
Seismic Attributes: Coherence vs **VC**

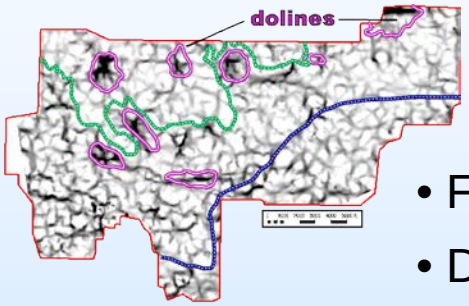


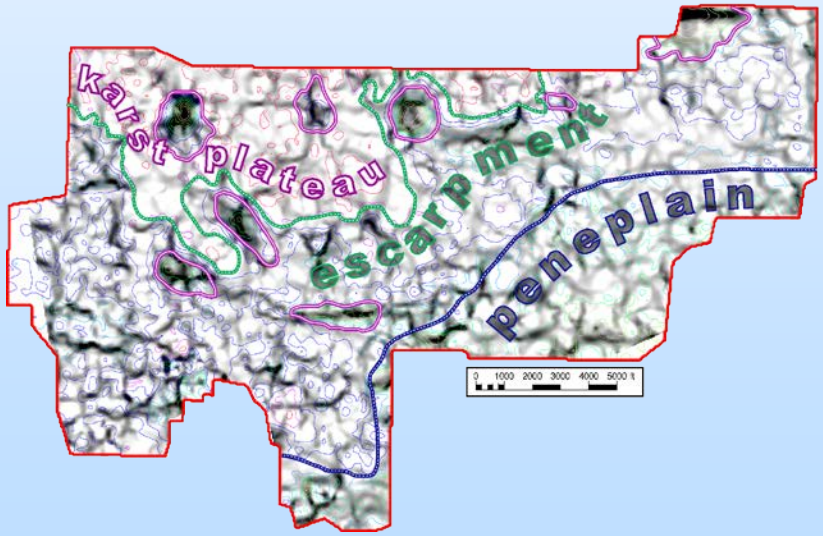
Seismic Attributes: **Coherence vs VC**

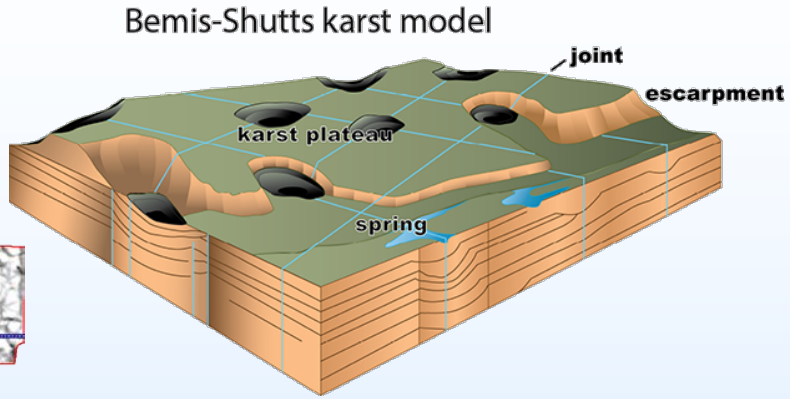


Geologic Findings & Interpretations









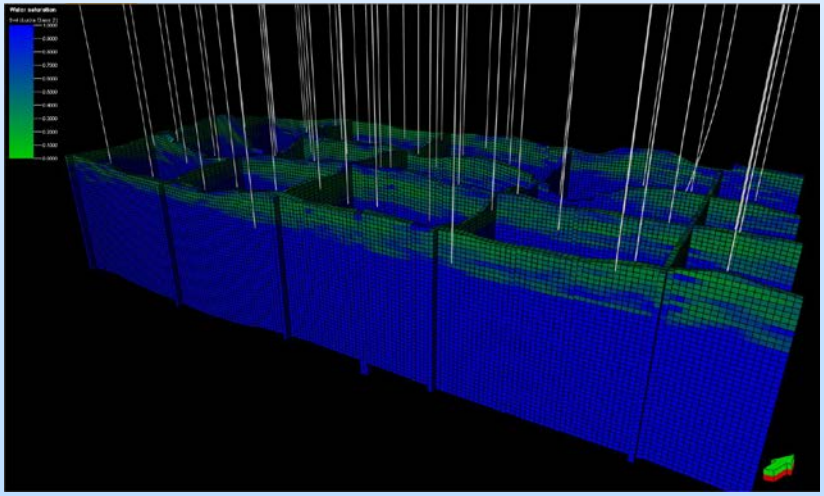
- Fault-bounded doline confirmed
- Dolines coincident with VC-identified radial lineaments
- Interior drainage
- Headward-eroding escarpment
- Disappearing streams/springs/ fluvial plains

Dynamic Modeling Objectives

Explore the effect of fault transmissibility on:

- CO_2 Injectivity
- Storage capacity
- Vertical and horizontal CO_2 movement

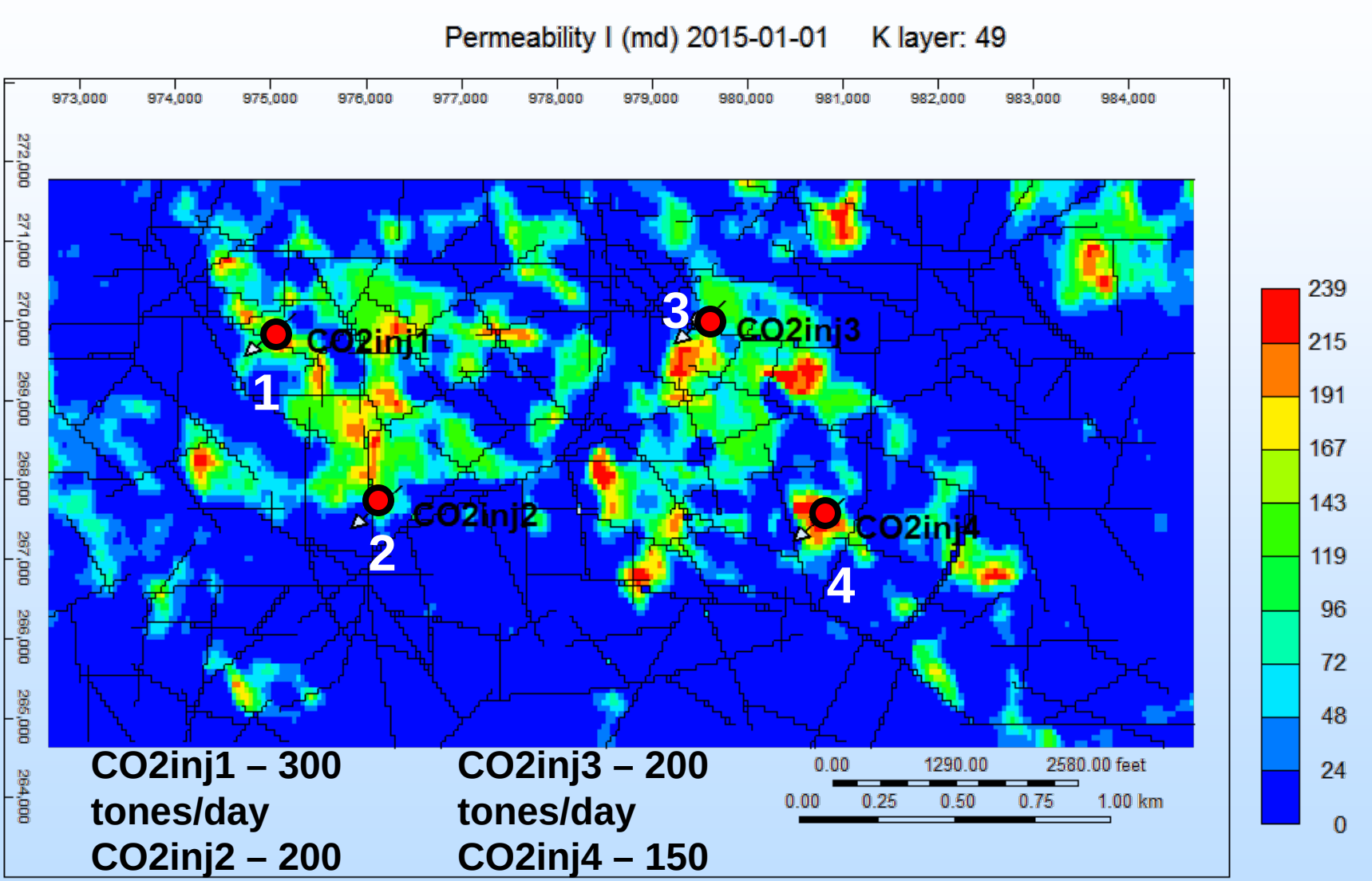
*simulation studies performed by **Eugene Holubnyak (KGS)***



Dynamic Simulation Parameters

Temperature	122 °F
Temperature Gradient	0.008 °C/ft
Pressure	2093 psi
Pressure Gradient	0.42 psi/ft
Reservoir Depth	4,500 – 4,900 ft
Perforation Zone	4,750 – 4,850 ft
Perforation Length	100 ft
Injection Period	10 years
Injection Rate	300, 200, 200, 150 tones/day
Total CO2 injected	3M tones
Reservoir CO_2 Density	580 kg/m^3
Fault Transmissibility	1, 0, & 0.5
Fault Count	201

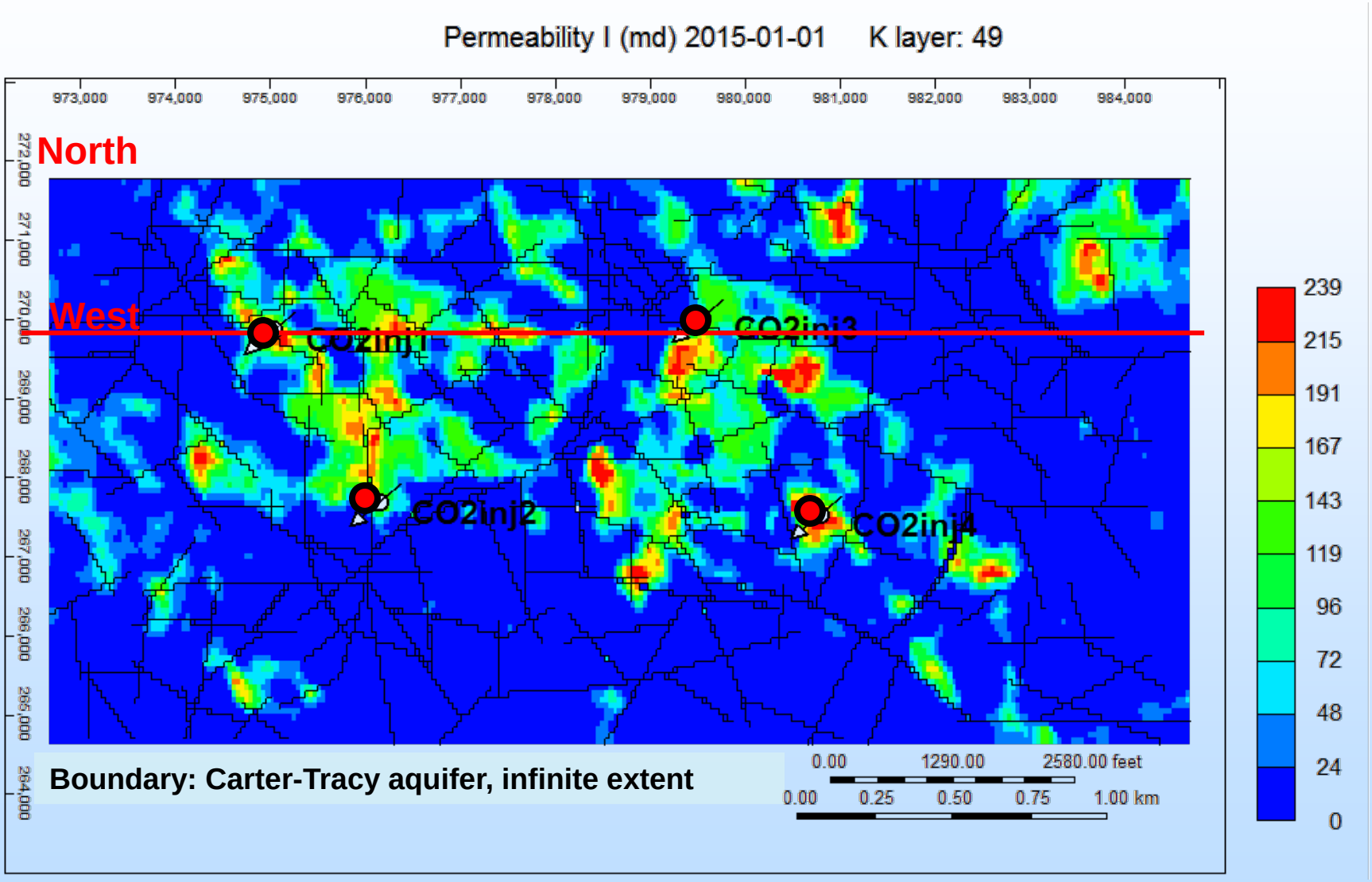
CO_2 Injection



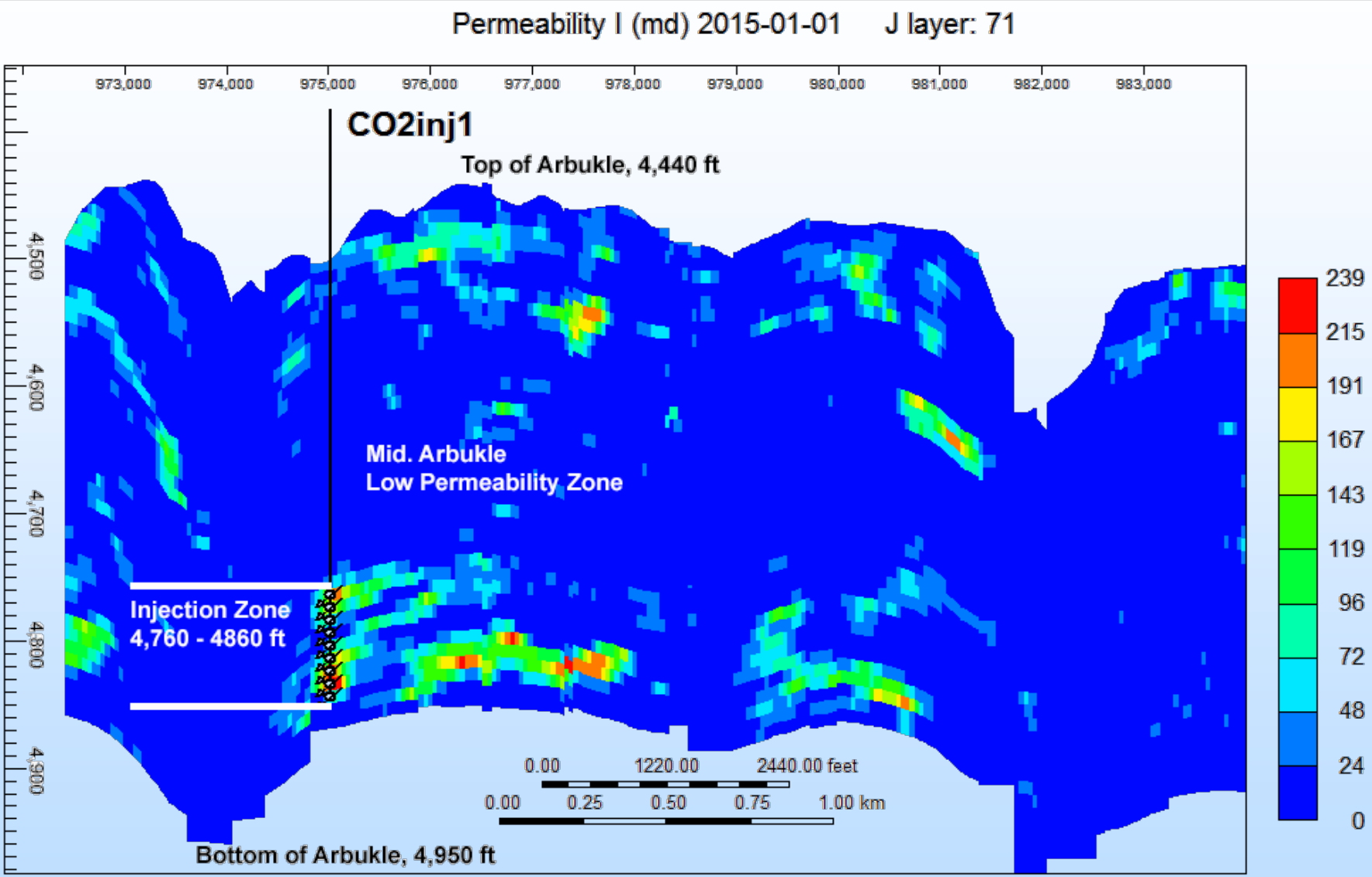
CO2inj1 – 300 tones/day
CO2inj2 – 200 tones/day
CO2inj3 – 200 tones/day
CO2inj4 – 150 tones/day

KANSAS GEOLOGICAL SURVEY
The University of Kansas

CO_2 Injection at Year 2015



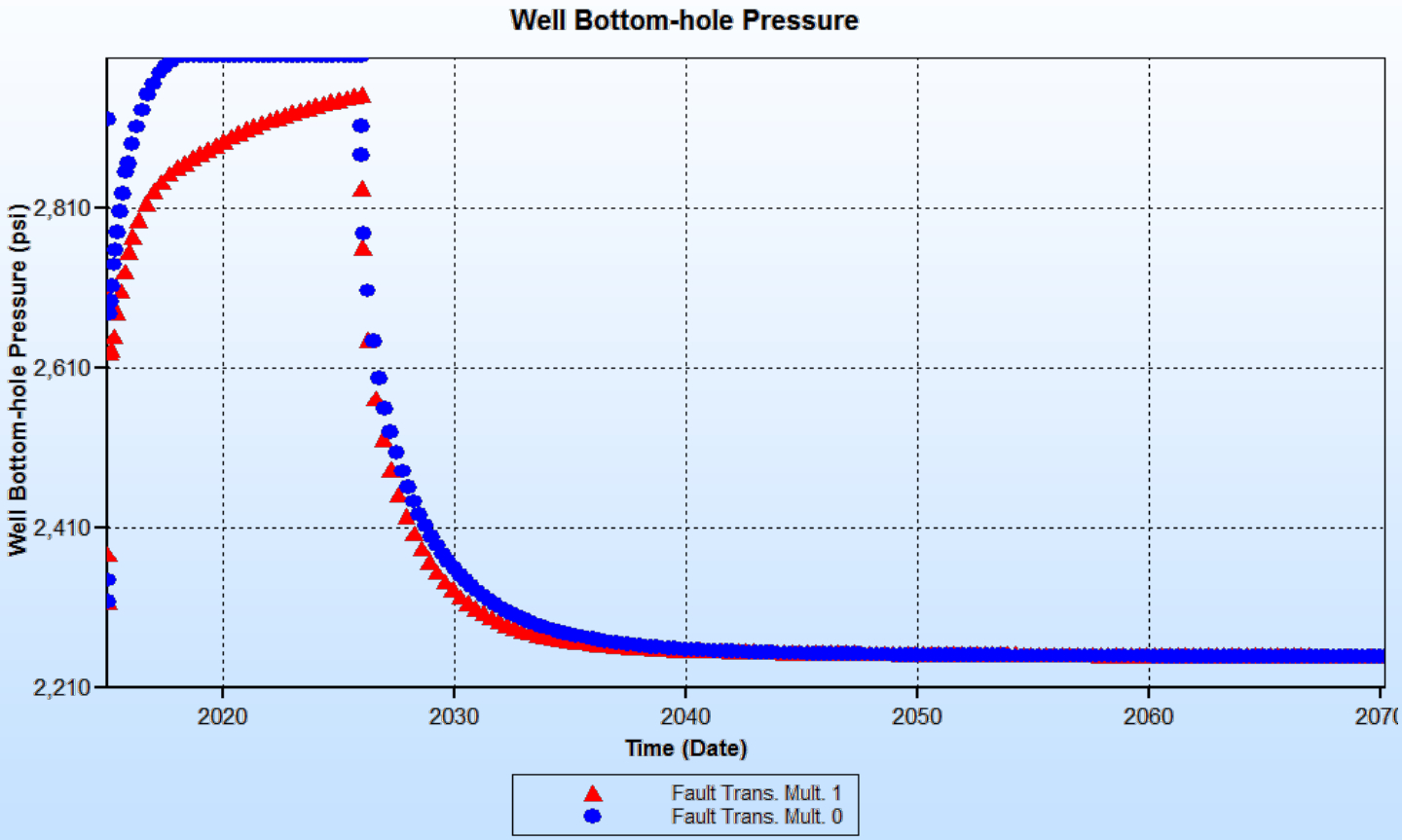
CO_2 Injection at Year 2015



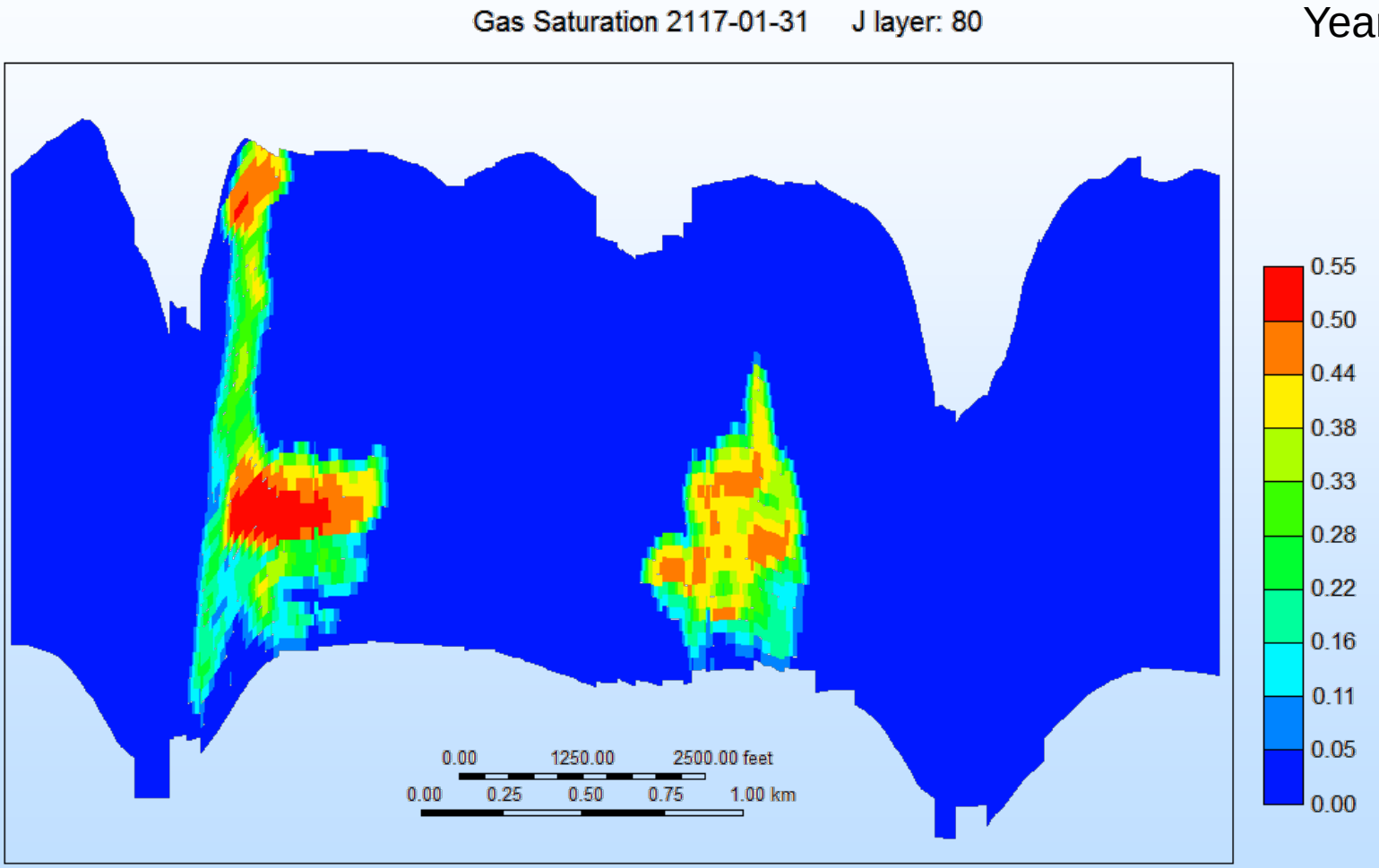
KANSAS GEOLOGICAL SURVEY
The University of Kansas

Fault Transmissibility Multiplier 1 vs. 0

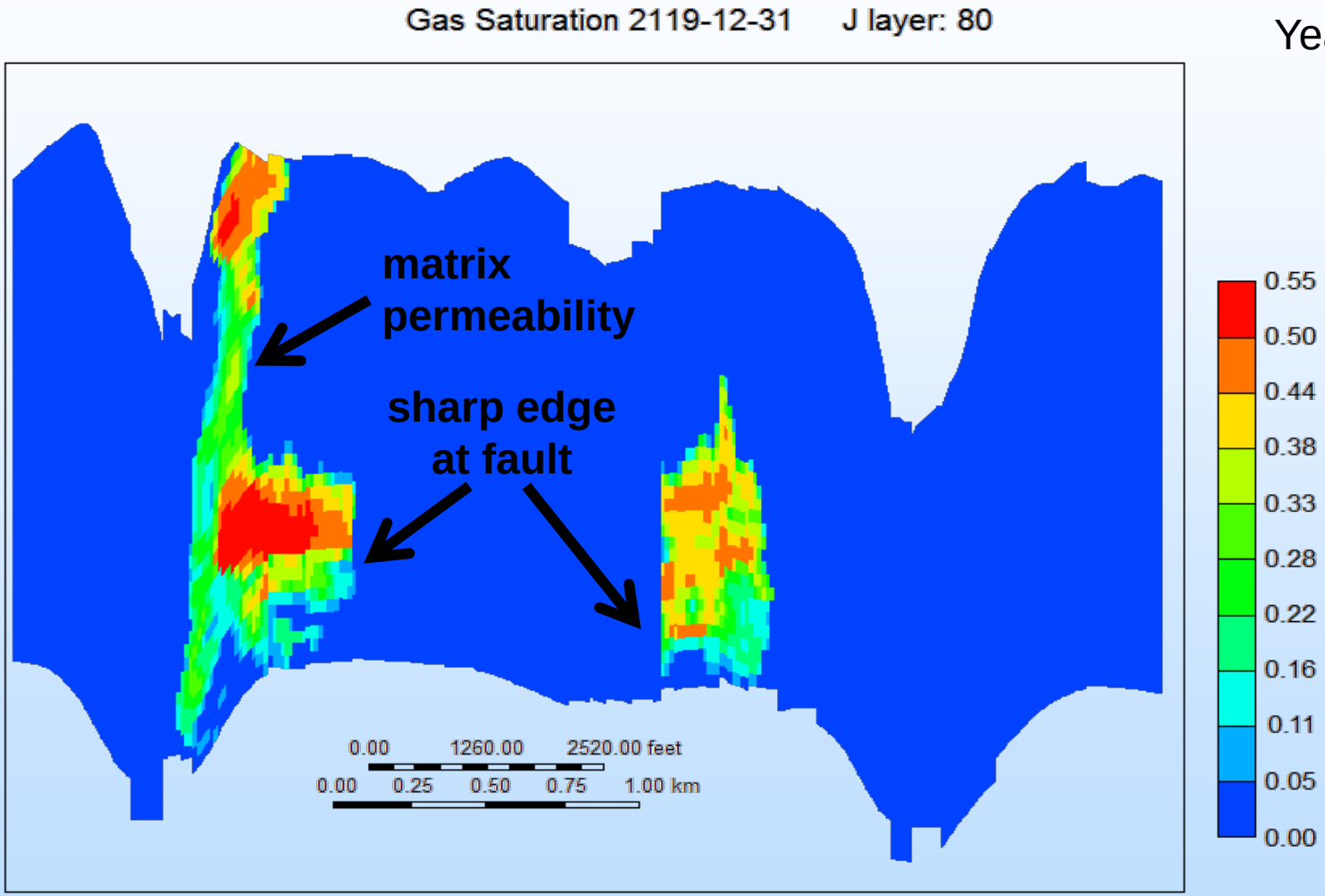
Injectivity Profile



CO_2 Extent and Movement
Fault Trans. Multiplier set to 1

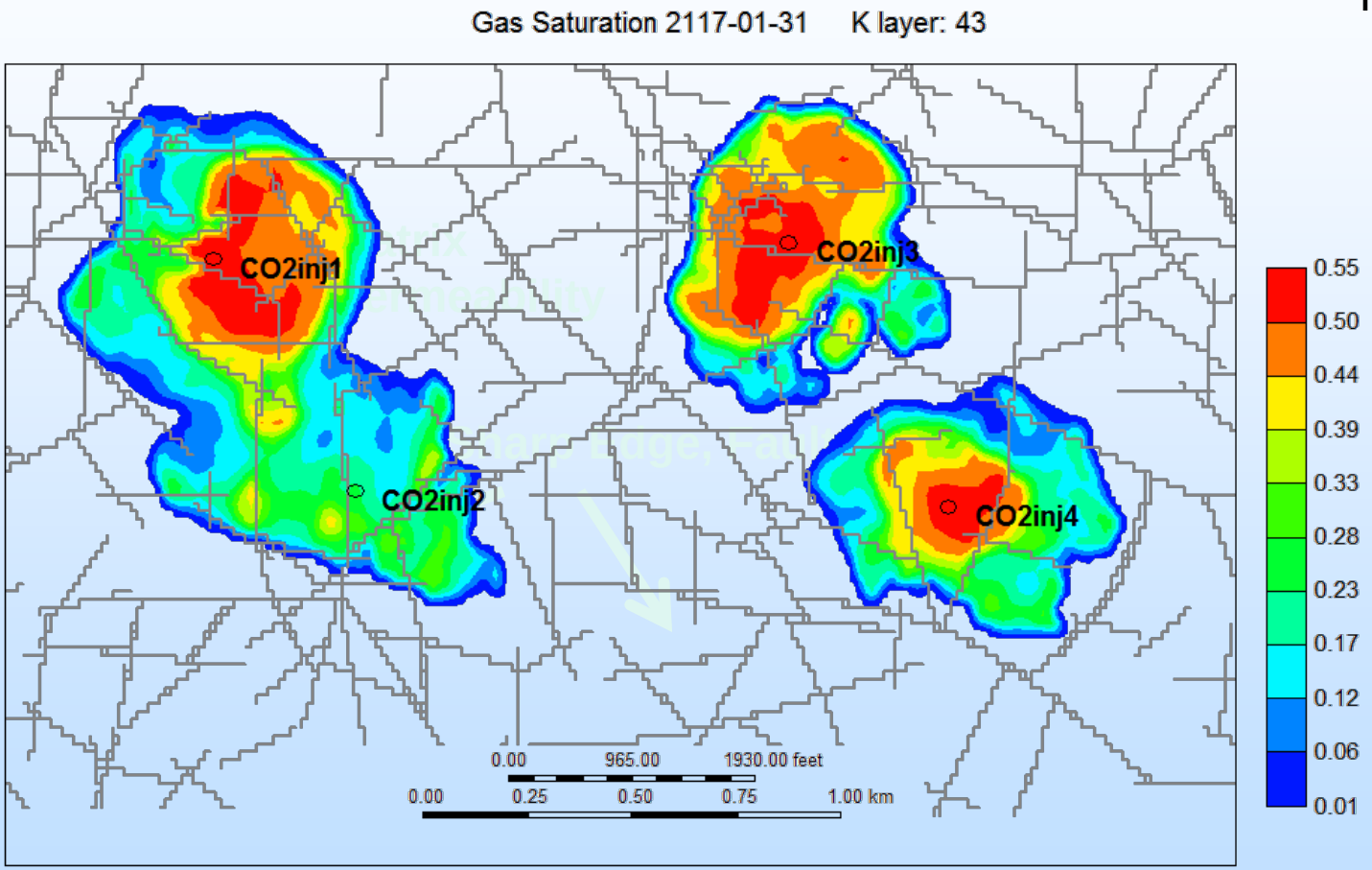


CO_2 Extent and Movement
Fault Trans. Multiplier set to 0



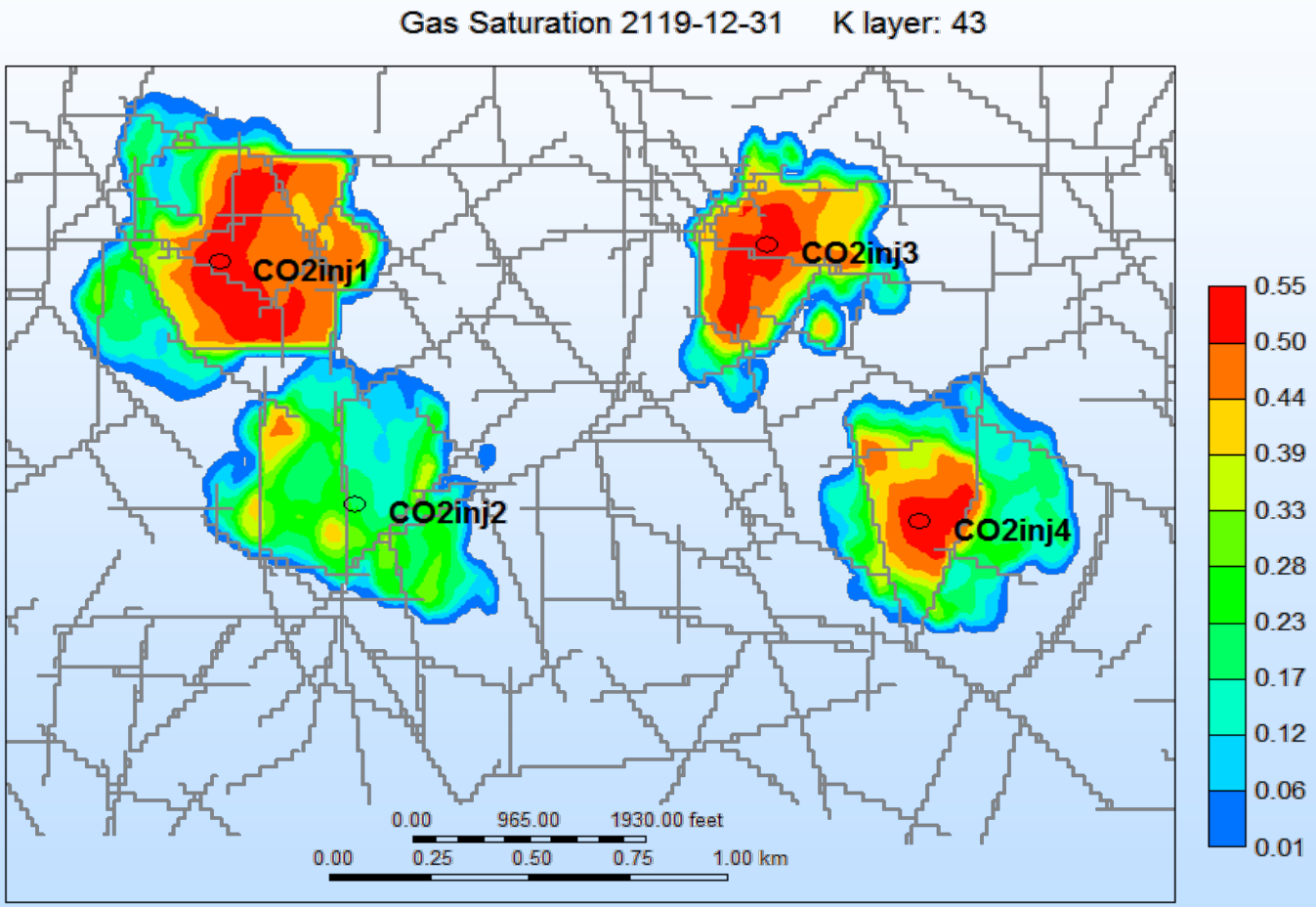
CO_2 Extent and Movement
Fault Trans. Multiplier set to 1

Year 2117

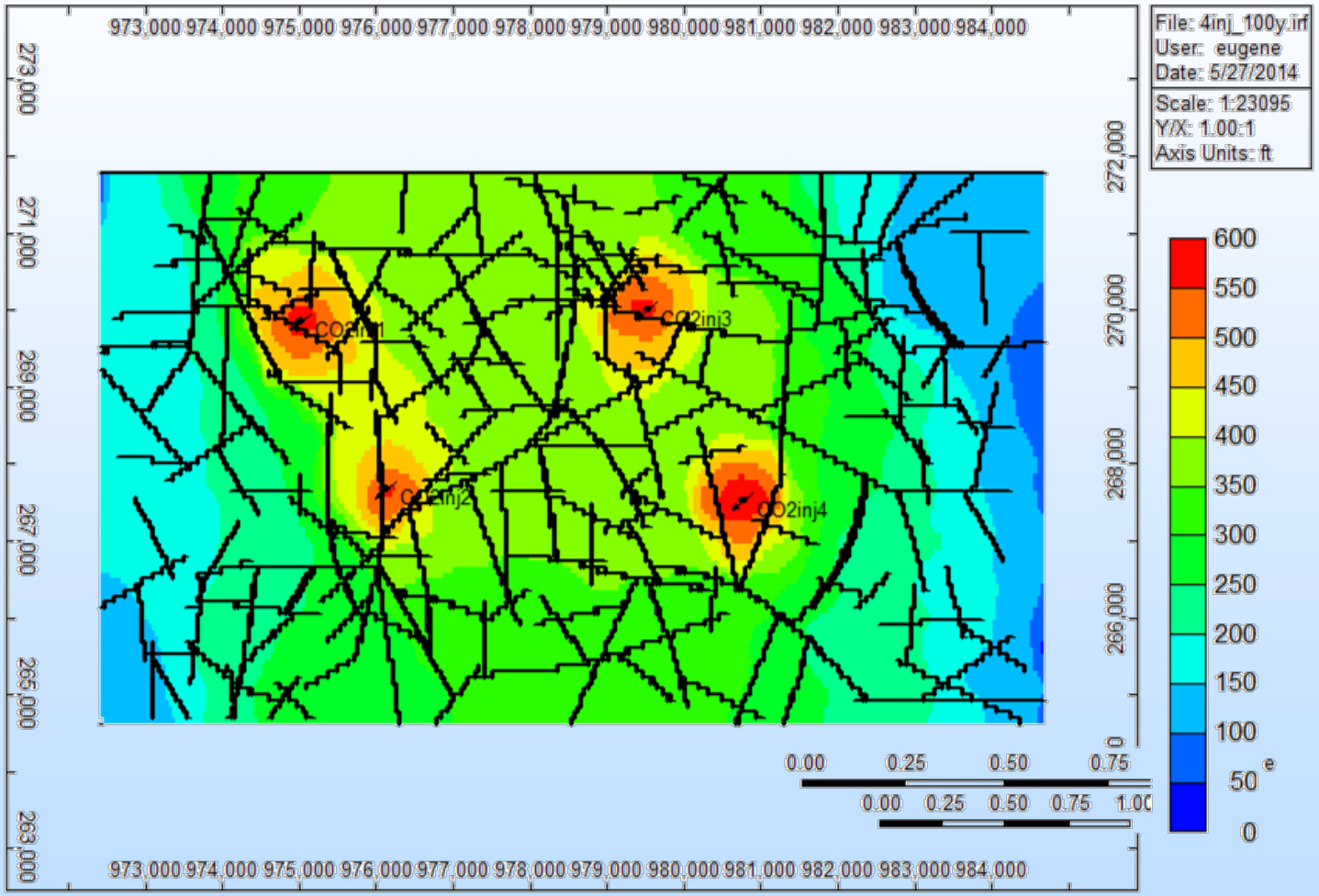


CO_2 Extent and Movement
Fault Trans. Multiplier set to 0

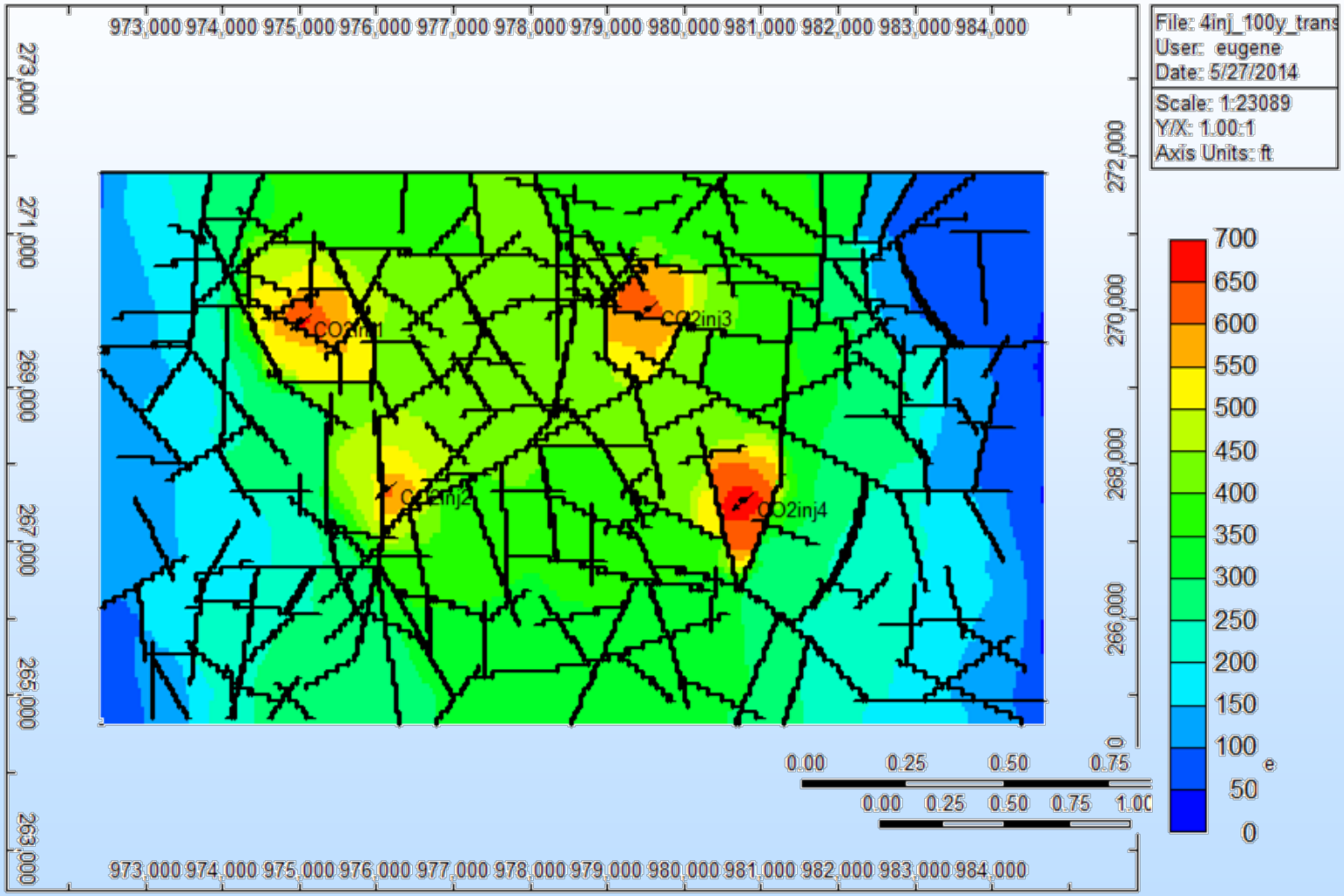
Year 2119



Delta Pressure and Movement Fault Trans. Multiplier set to 1



Delta Pressure and Movement
Fault Trans. Multiplier set to 0



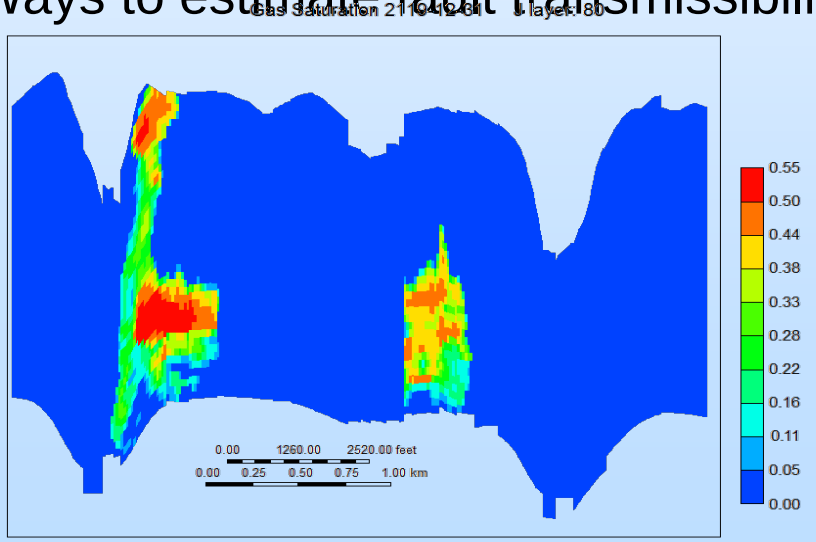
Simulation Findings to Date

Key Findings

- Fault transmissibility effects for Arbukle Formation:
  - Injectivity and storage capacity are reduced
  - CO_2 movement is impacted by faults, but matrix control is dominant
  - Fingering occurs next to faults with similar vertical K

Future Plans

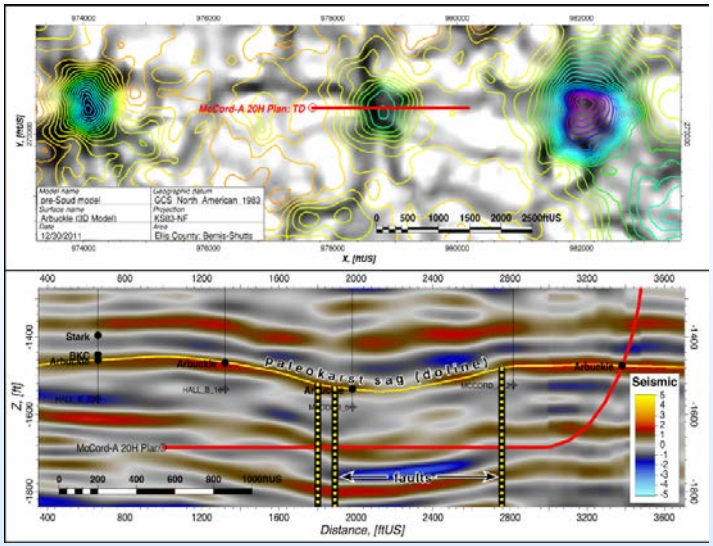
- Analyze uncertainty of ***flux between blocks***
- History match new models
- Ways to estimate fault transmissibility



Presentation Outline

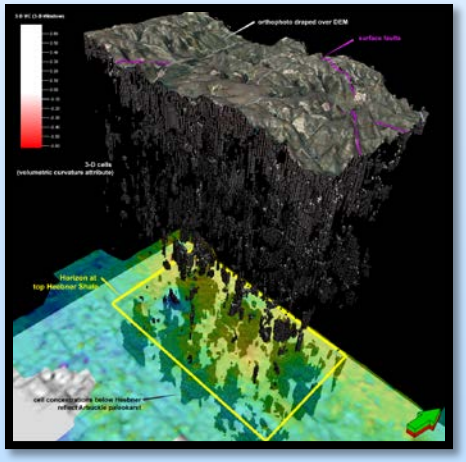
- Benefits, objectives, overview
- Methods
- Background & setting
- Technical status
- Accomplishments
- Summary

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
- Successful simulation of complex fault models
- 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***
  - ***H***istory 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:
  - Gaus, I., 2010, Role and impact of CO2-rock interactions during CO2 storage in sedimentary rocks: International Journal of Greenhouse Gas Control, v. 4, p. 73-89, available at: XXXXXXX.com.
- Journal, multiple authors:
  - MacQuarrie, K., and Mayer, K.U., 2005, Reactive transport modeling in fractured rock: A state-of-the-science review. Earth Science Reviews, v. 72, p. 189-227, available at: XXXXXXX.com.
- Publication:
  - Bethke, C.M., 1996, Geochemical reaction modeling, concepts and applications: New York, Oxford University Press, 397 p.