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
(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 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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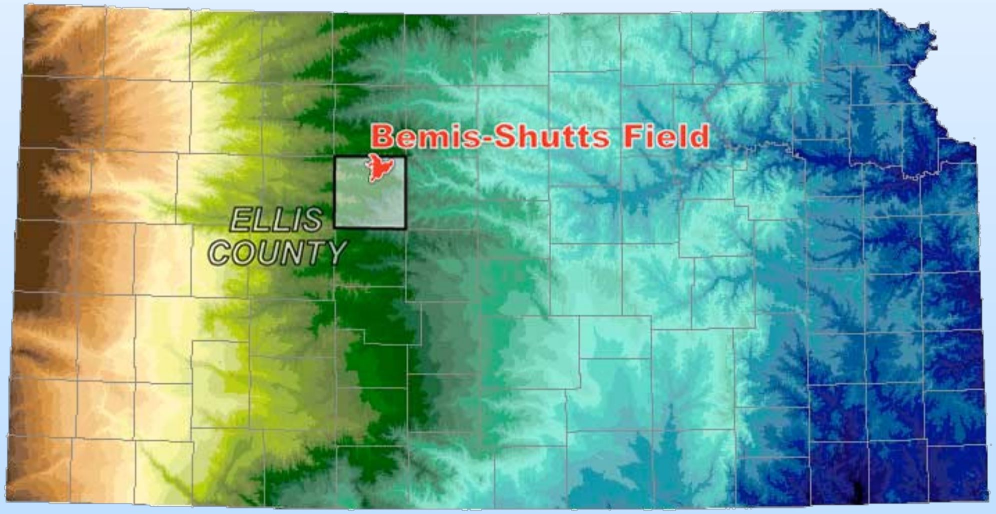
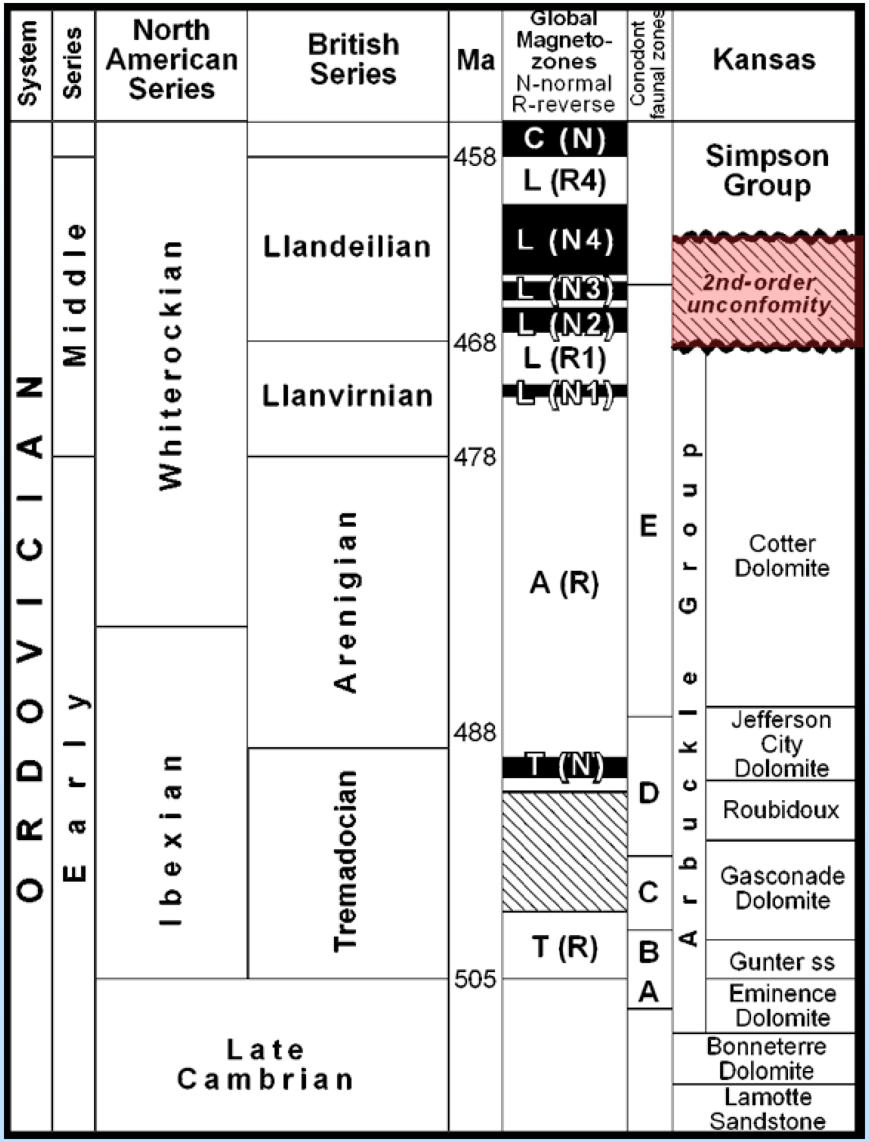
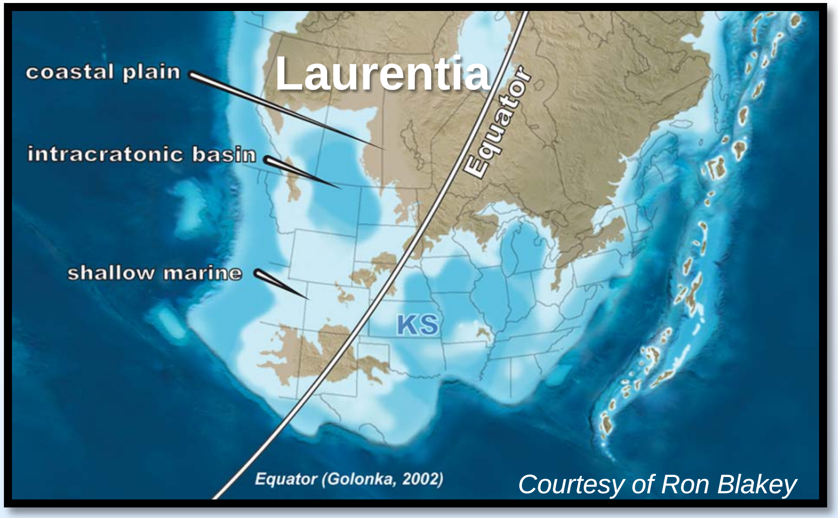
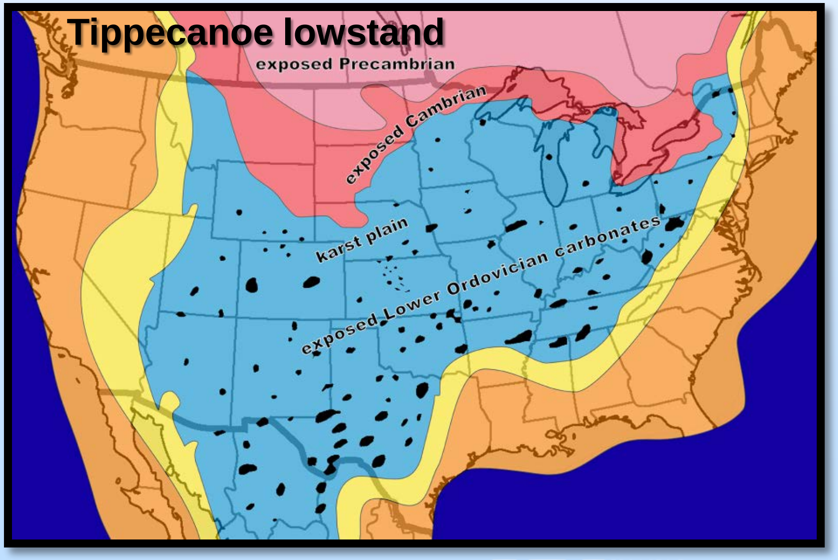


Age & Regional Setting



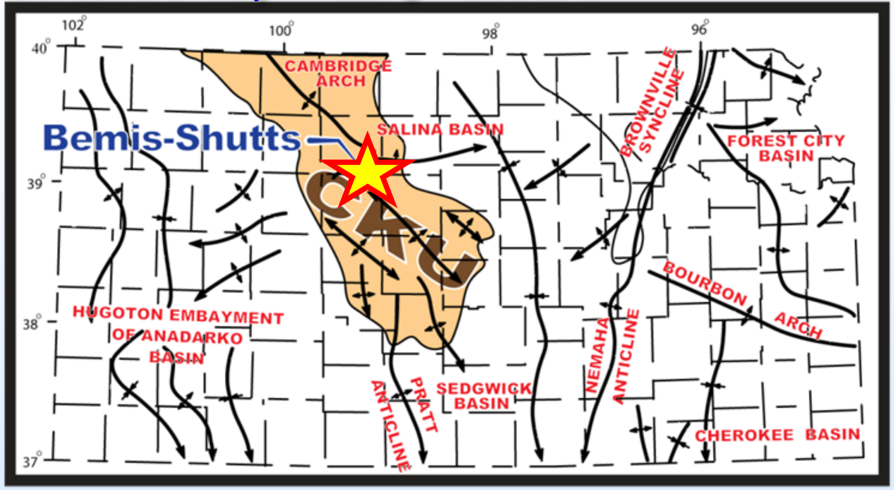


Courtesy of Ron Blakey

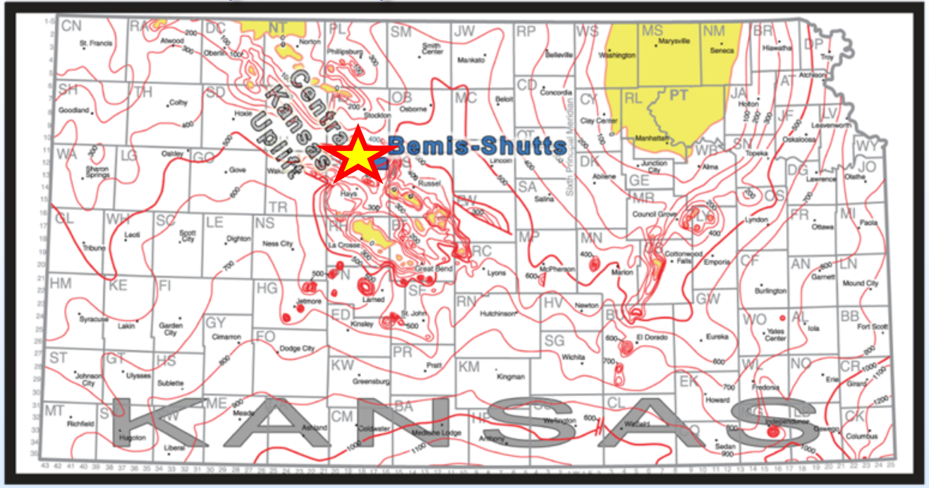


Kansas Setting

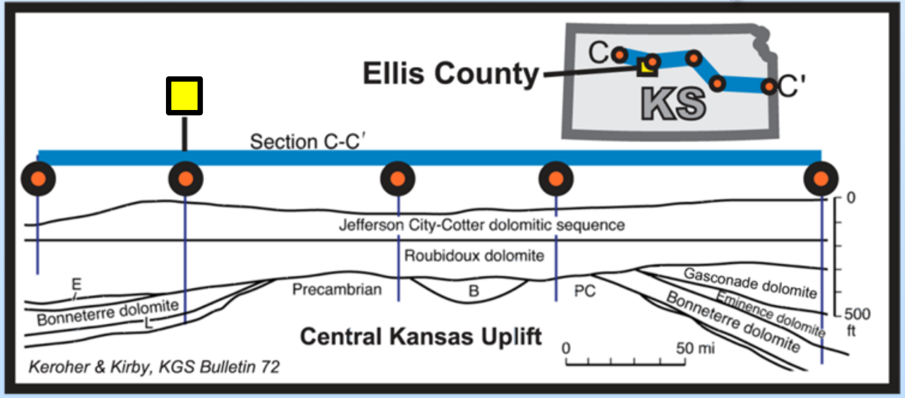
Structure Map — Early Paleozoic



Arbuckle Isopach Map

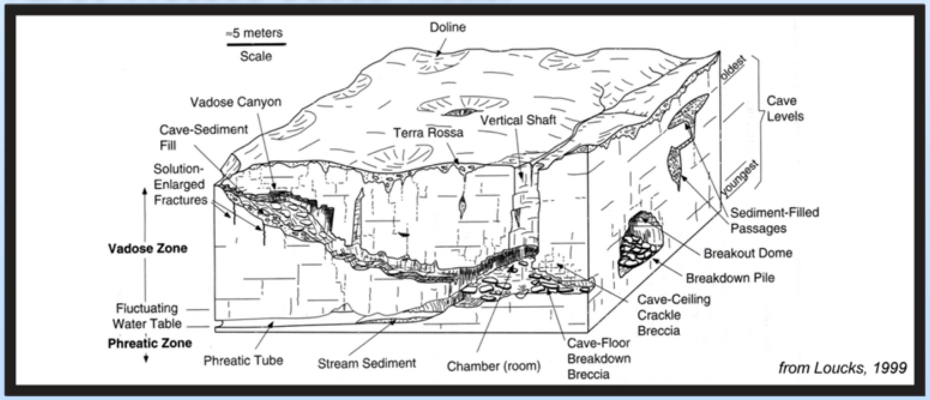


W-E Cross Section — Central Kansas Uplift



Keroher & Kirby, KGS Bulletin 72

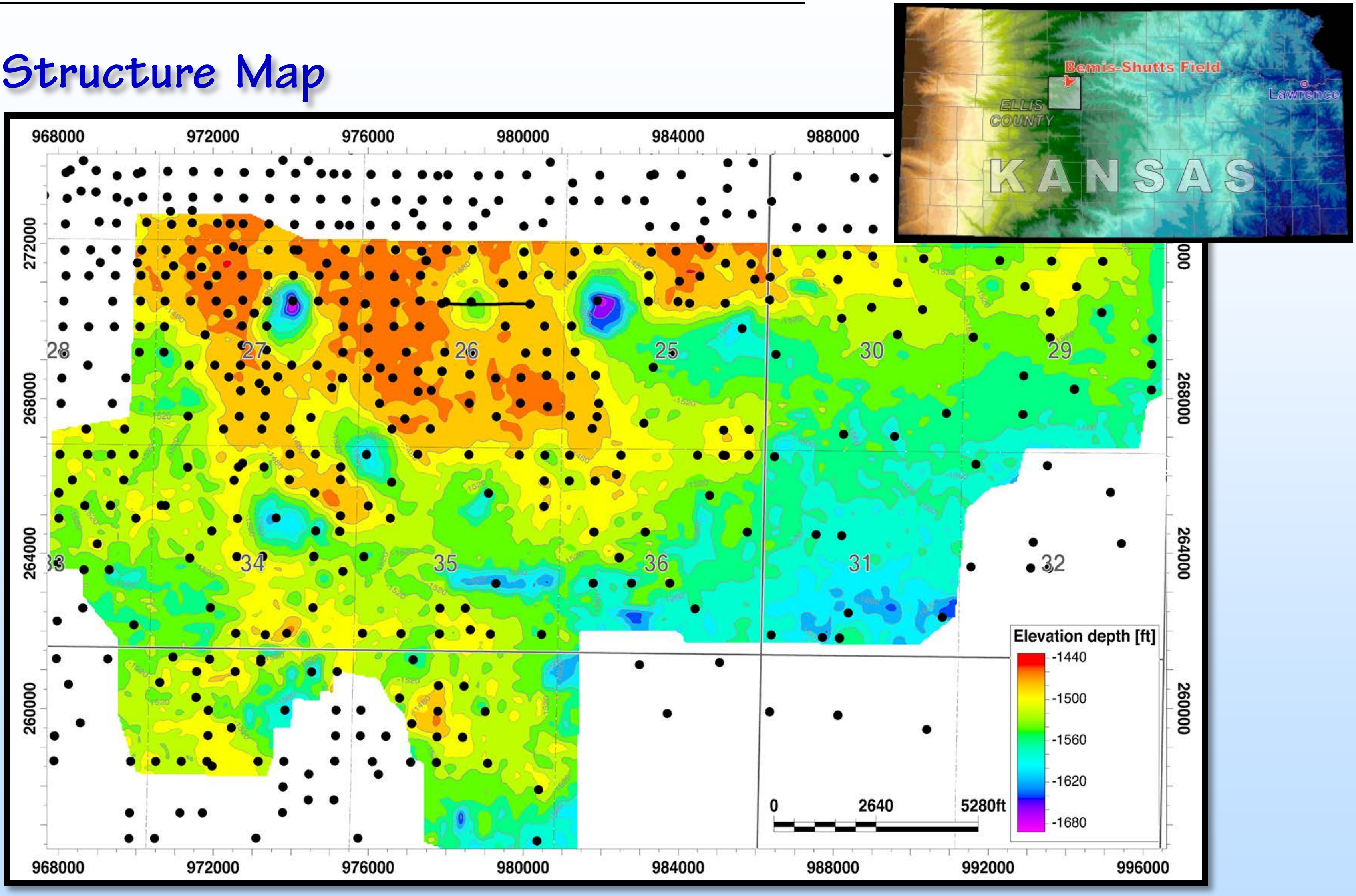
Karst Process-Based Model



from Loucks, 1999

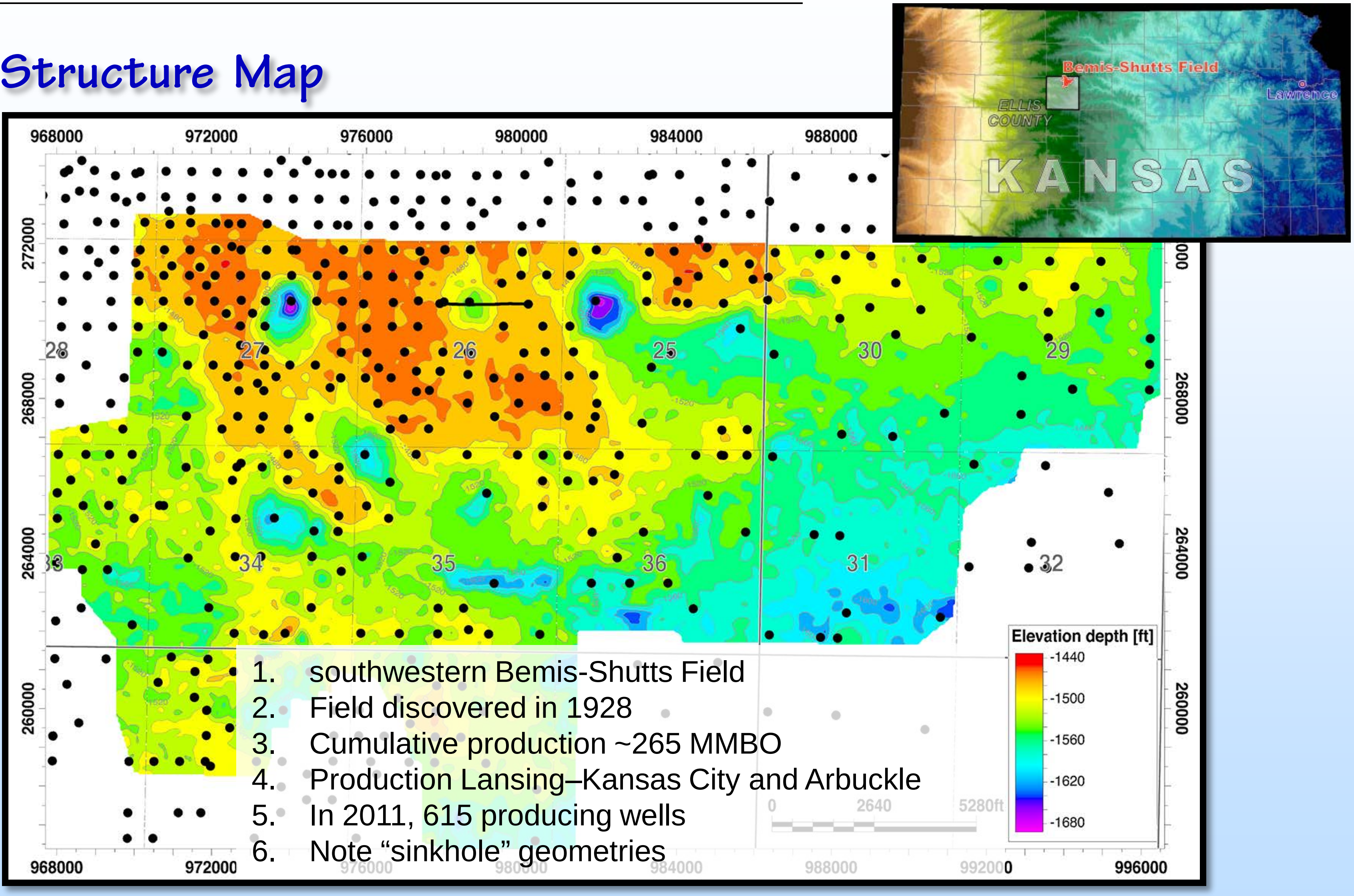
Study Area — Bemis Shutts Field

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

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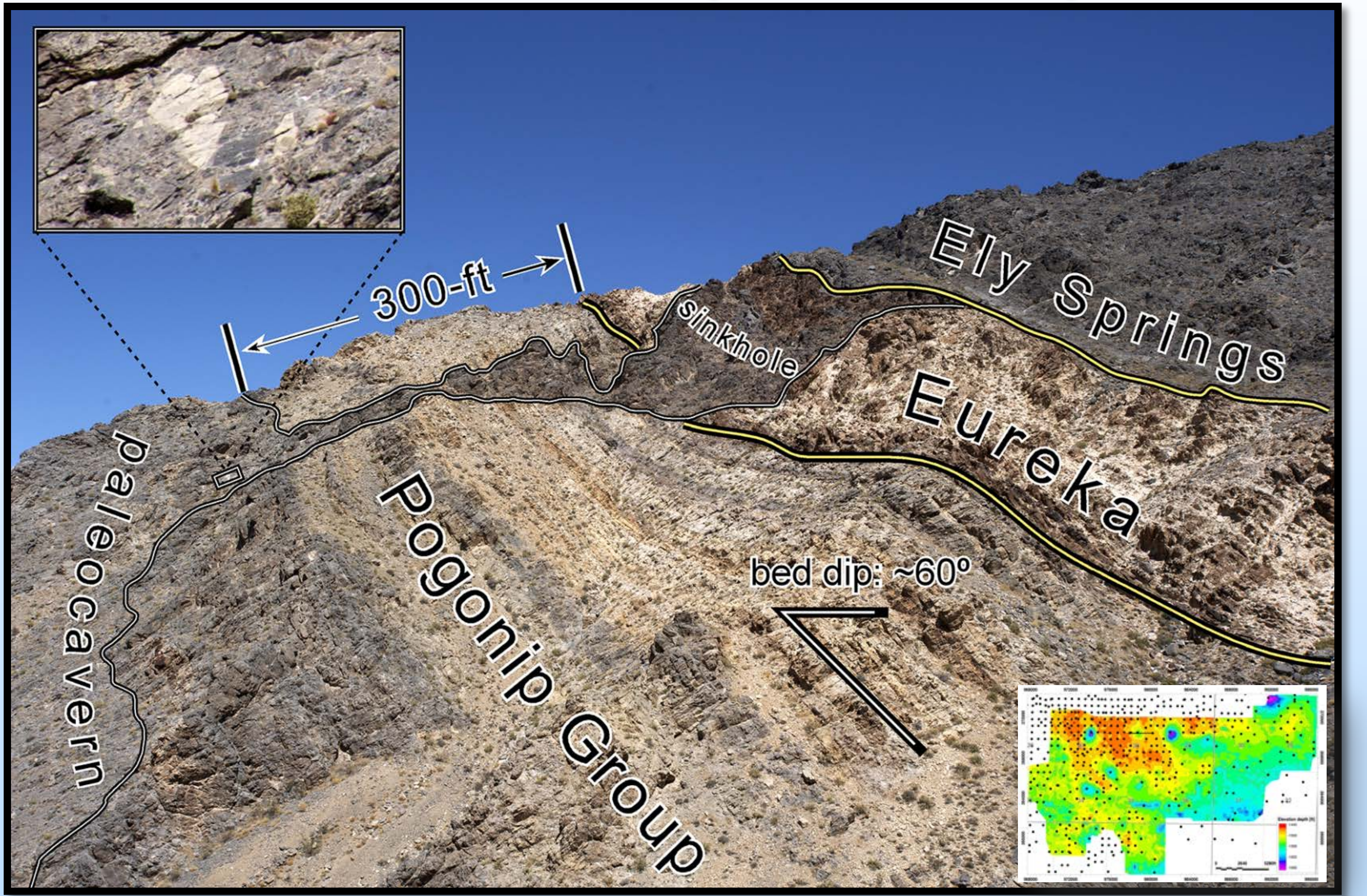
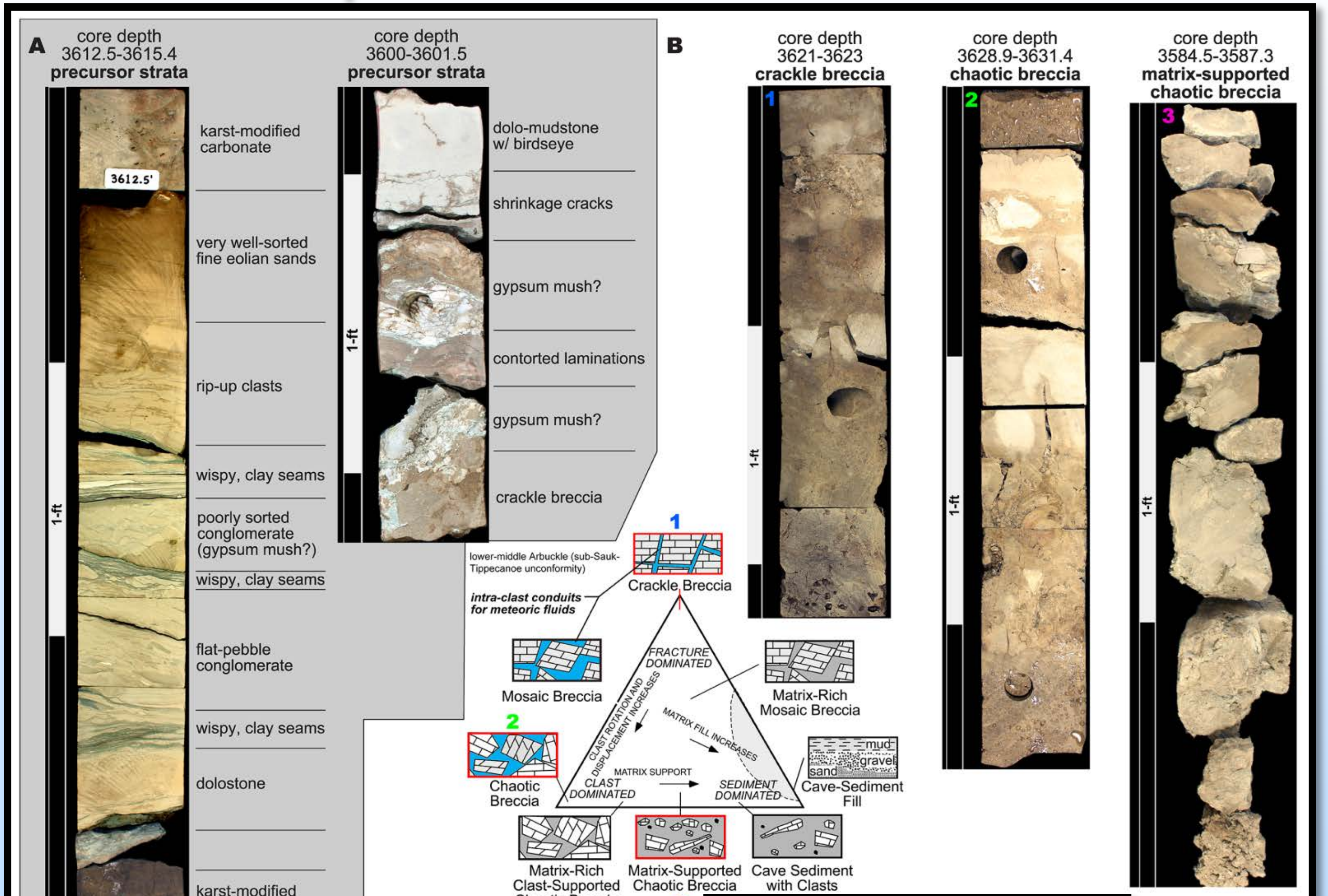
Arbuckle Analog

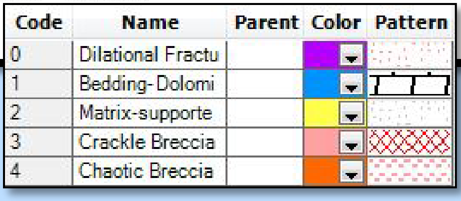
Whiterockian Paleokarst Outcrop Analog — Nopah Range, CA



Field Setting

Core Description — Paleokarst Rock Fabrics





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1	Bedding-Dolomi		🟦	▨
2	Matrix-supporte		🟨	▨
3	Crackle Breccia		🟥	▨
4	Chaotic Breccia		🟧	▨

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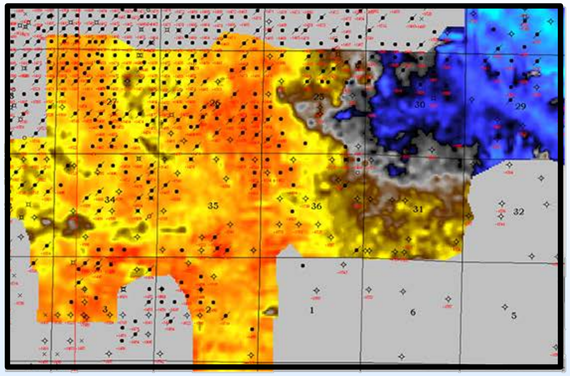
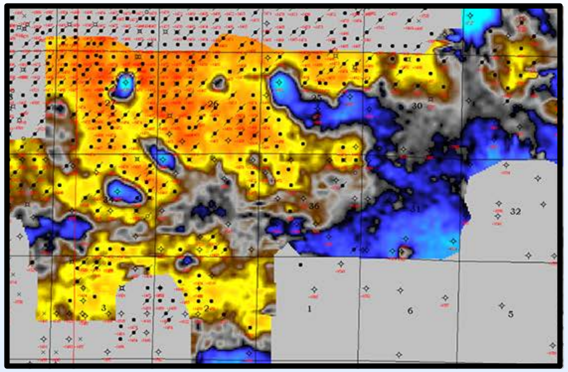
Time & Depth Migration

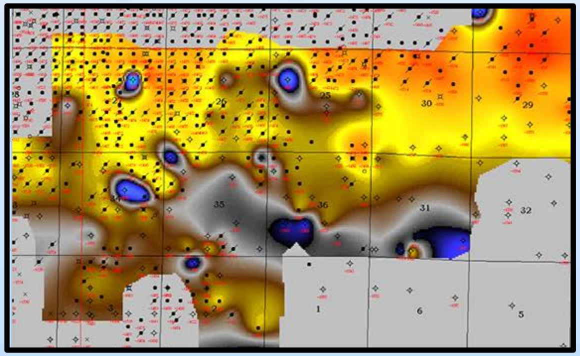
Arbuckle PSTM



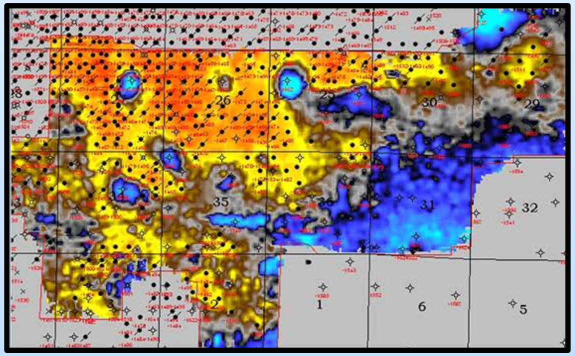
Arbuckle PSDM



Average Velocity to Arbuckle



Arbuckle Velocity & Well Control



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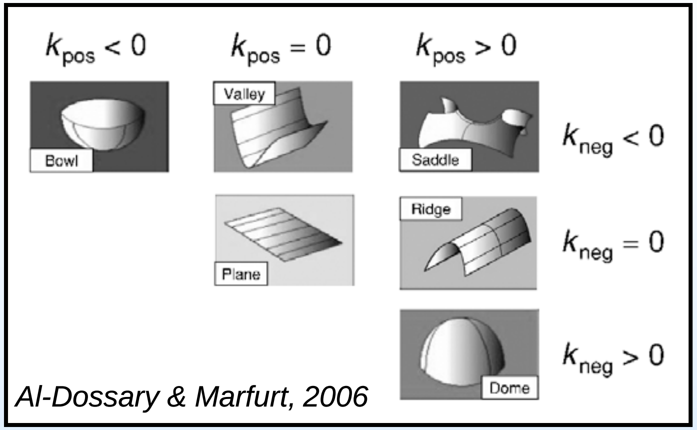
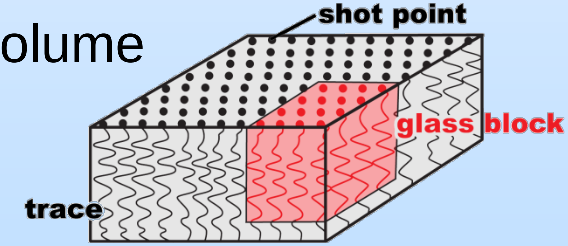
Volumetric Curvature

- 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

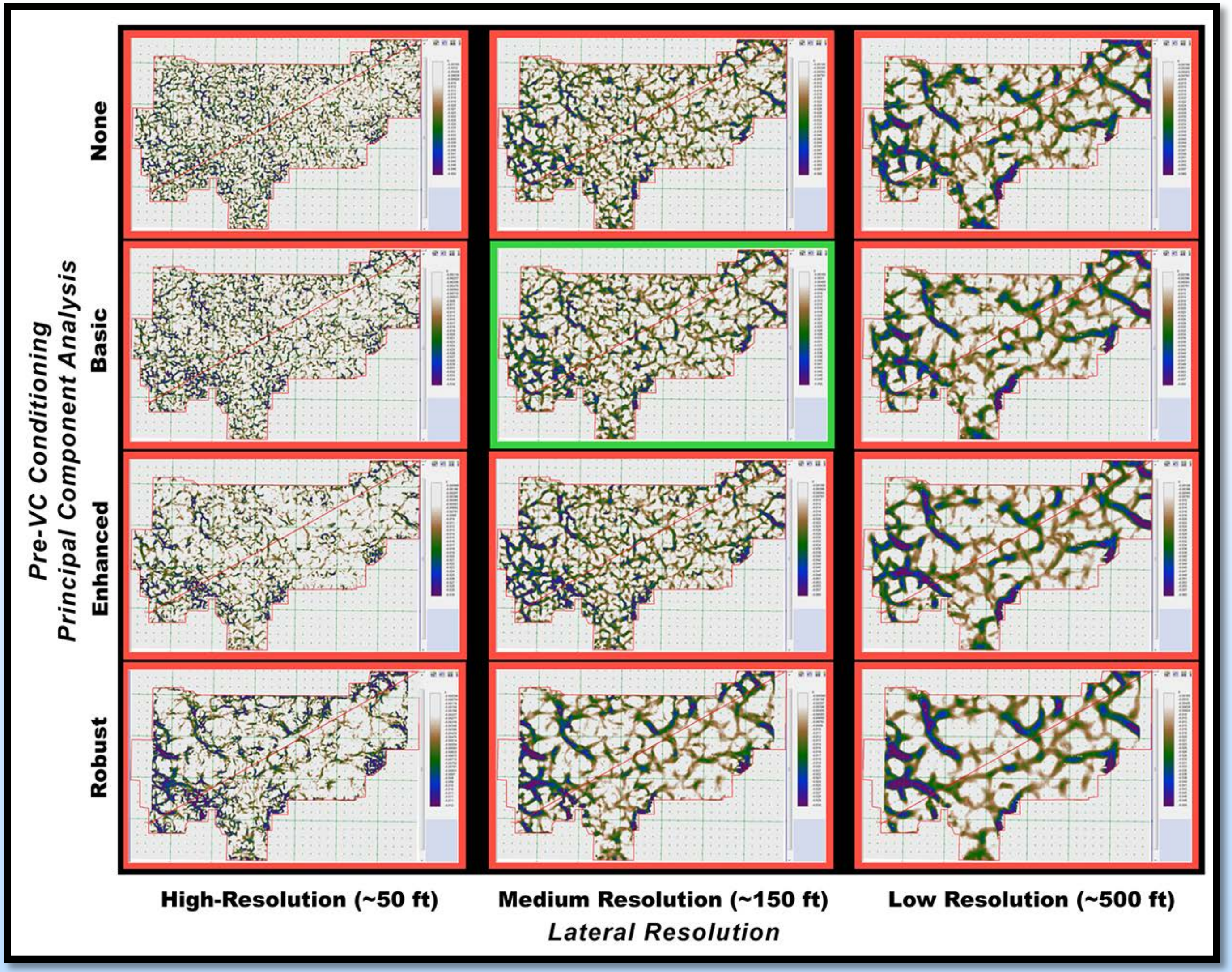


Al-Dossary & Marfurt, 2006

- 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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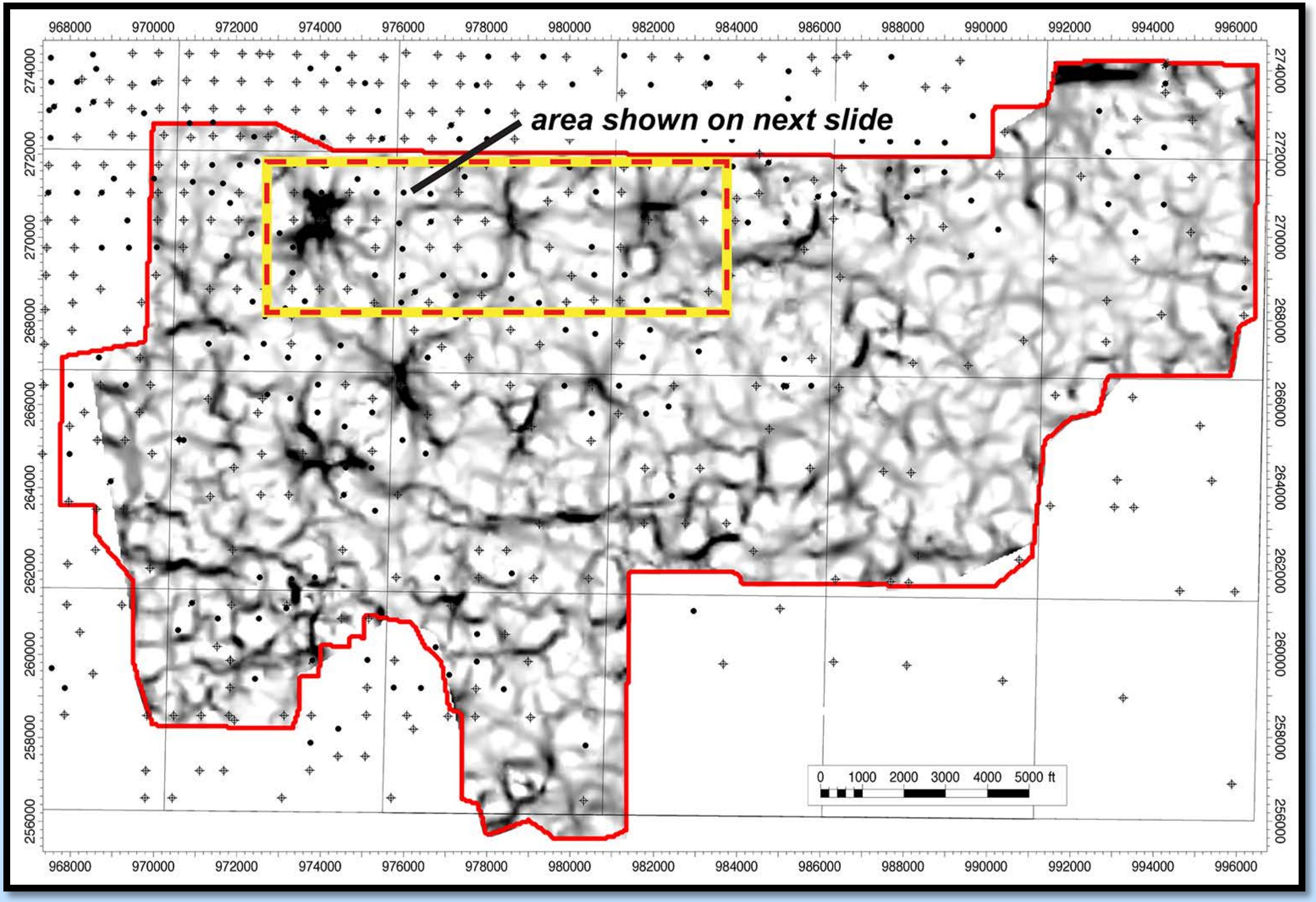
Arbuckle PSDM VC Horizon-Extraction



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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!

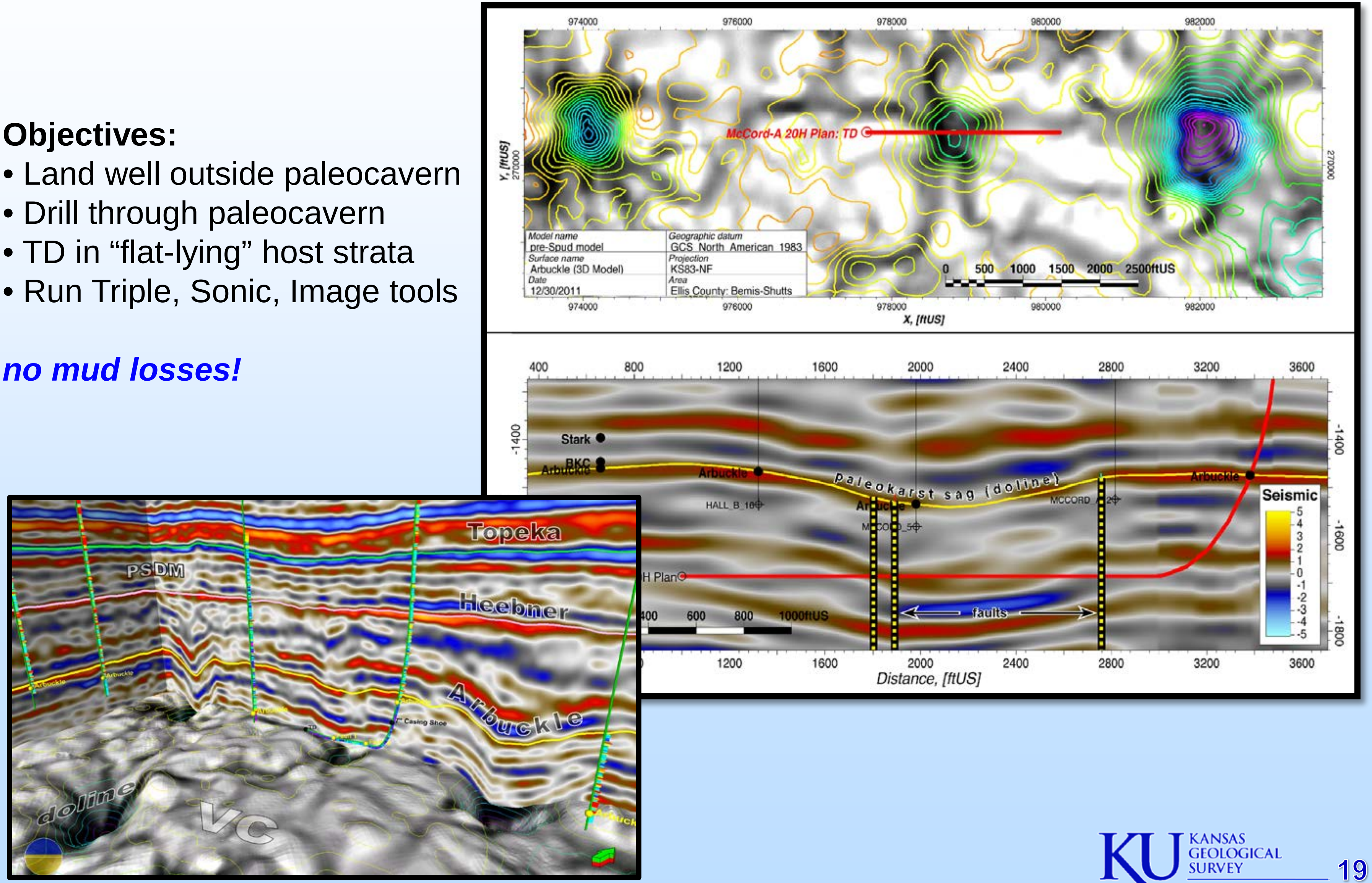
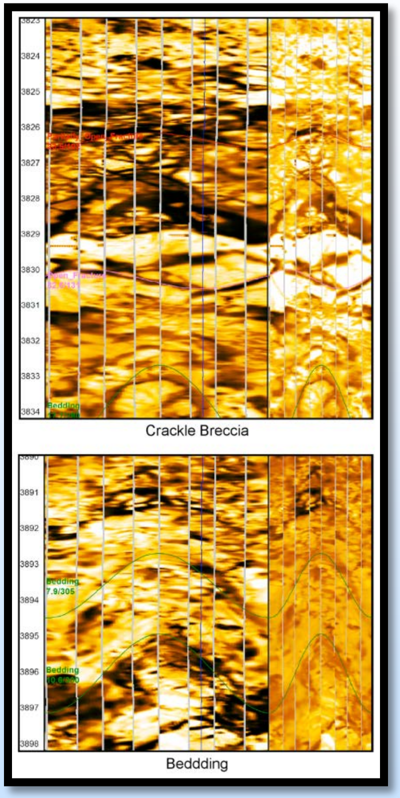


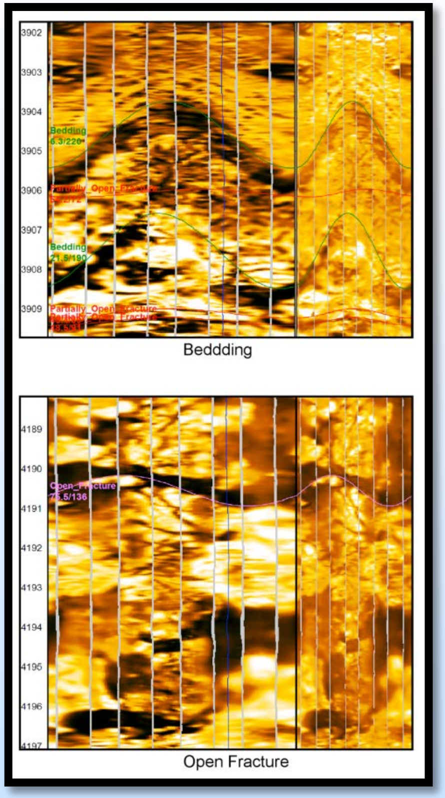
Image Log Facies — Facies Model

Crackle



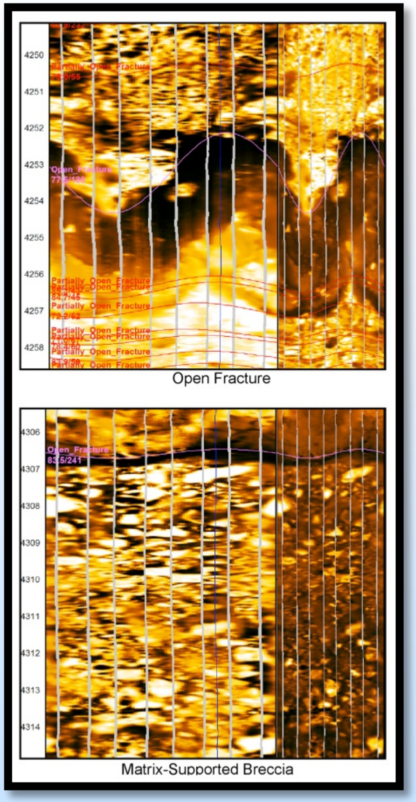
Bedding

Bedding



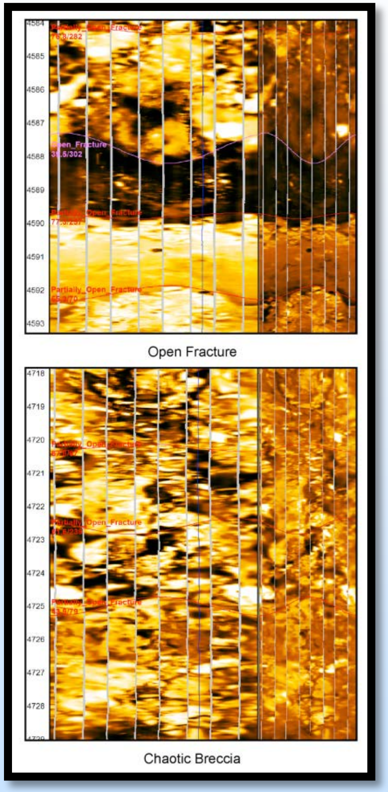
Dilational Fracture

Dilational Fracture

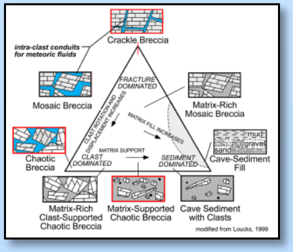


Matrix-Supported

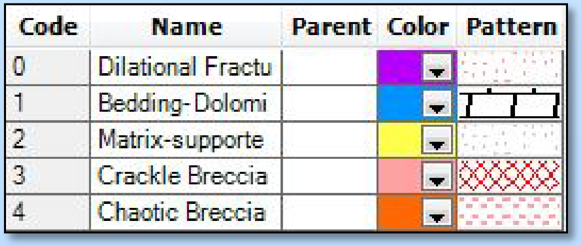
Dilational Fracture



Chaotic



modified from Loucks, 1999



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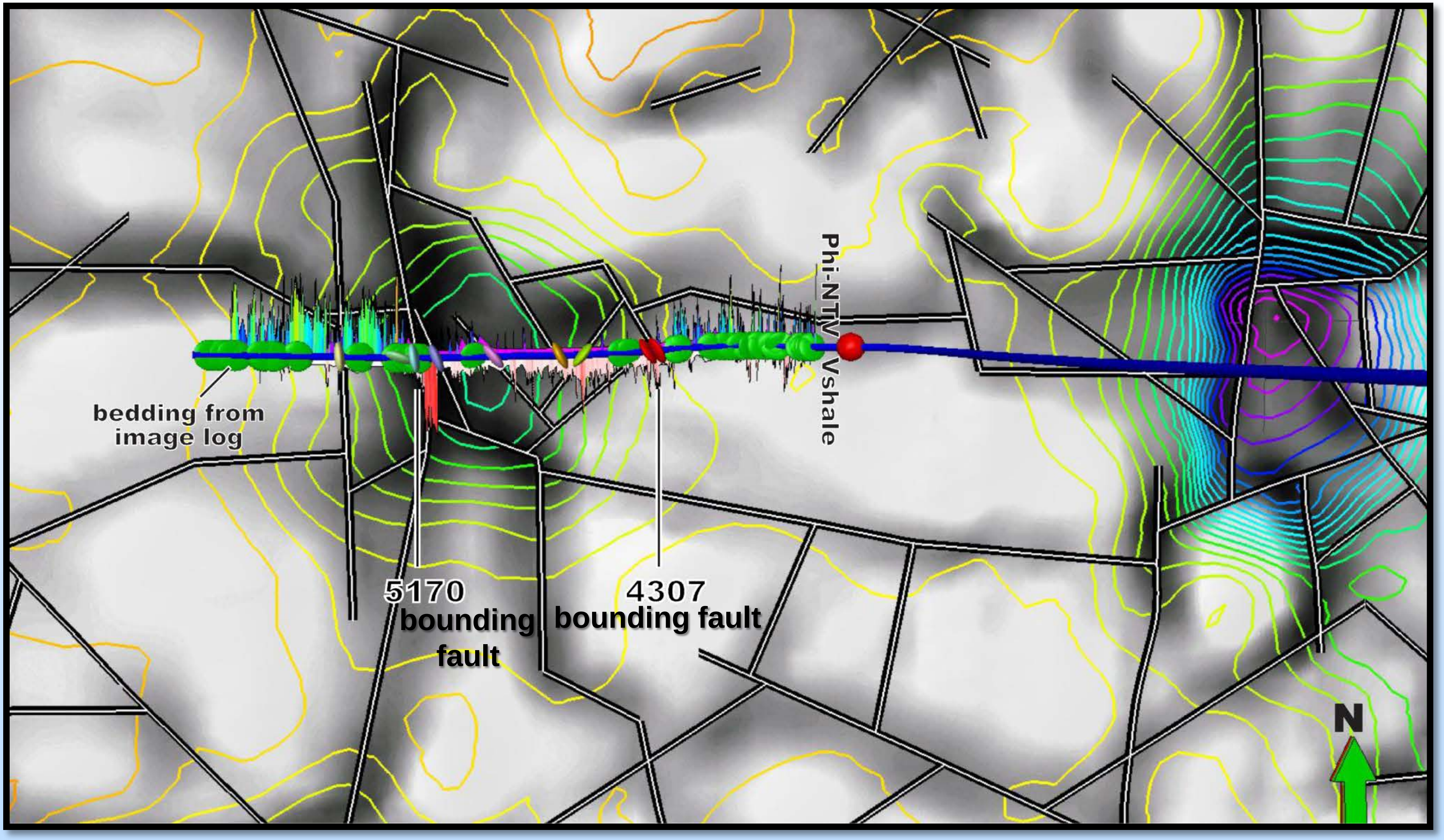
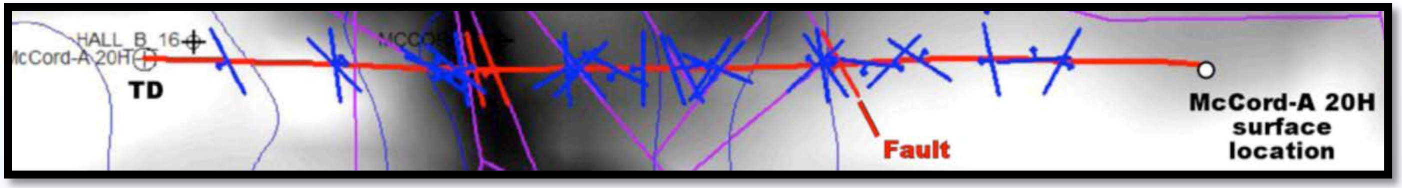
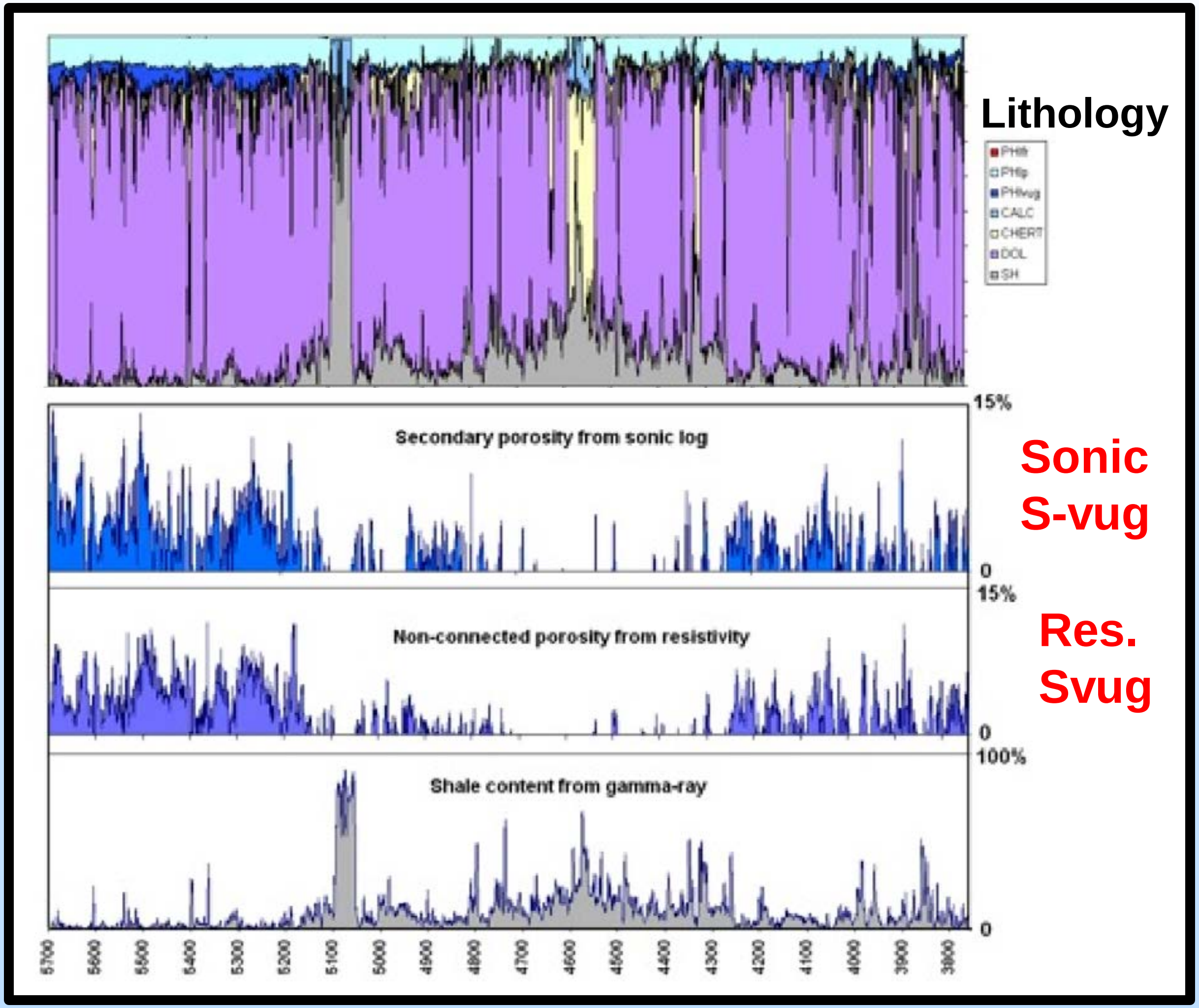
2	Matrix-supporte		🟨	▨
3	Crackle Breccia		🟥	▨
4	Chaotic Breccia		🟧	▨

VC-indicated Compartments Consistent with Log Interpretations



Formation Evaluation





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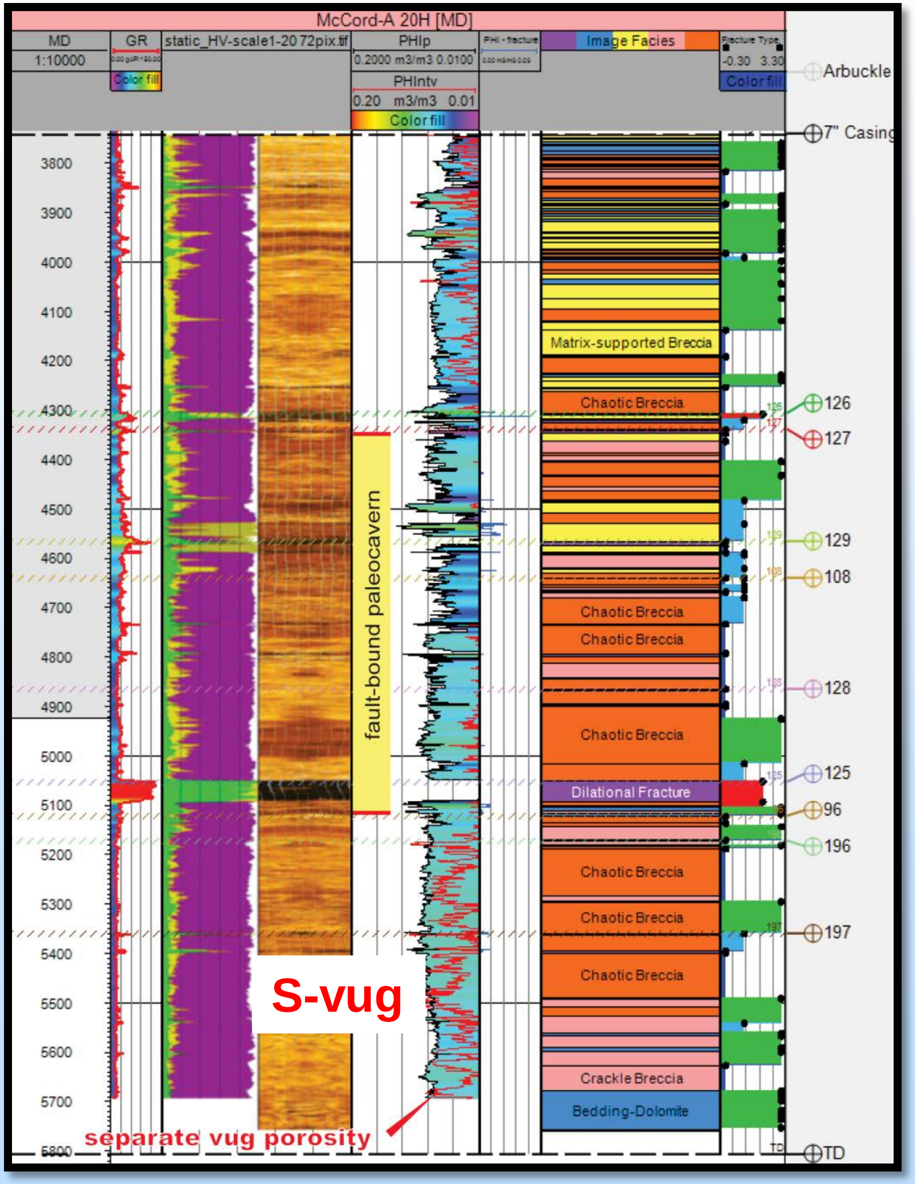
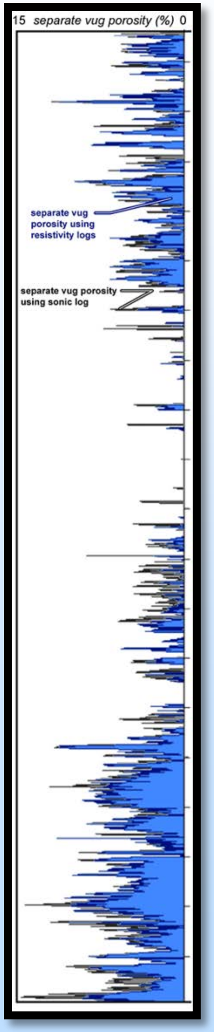
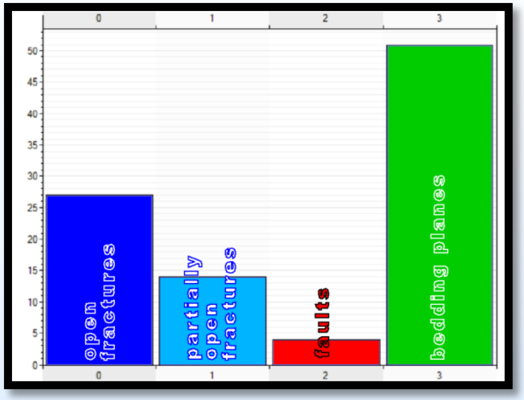
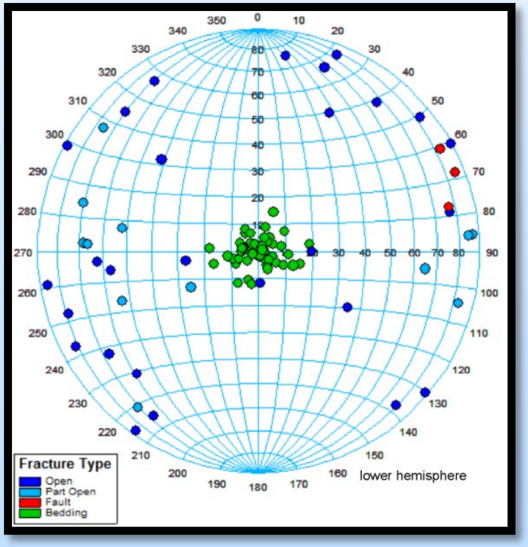
Formation Evaluation



Svug %







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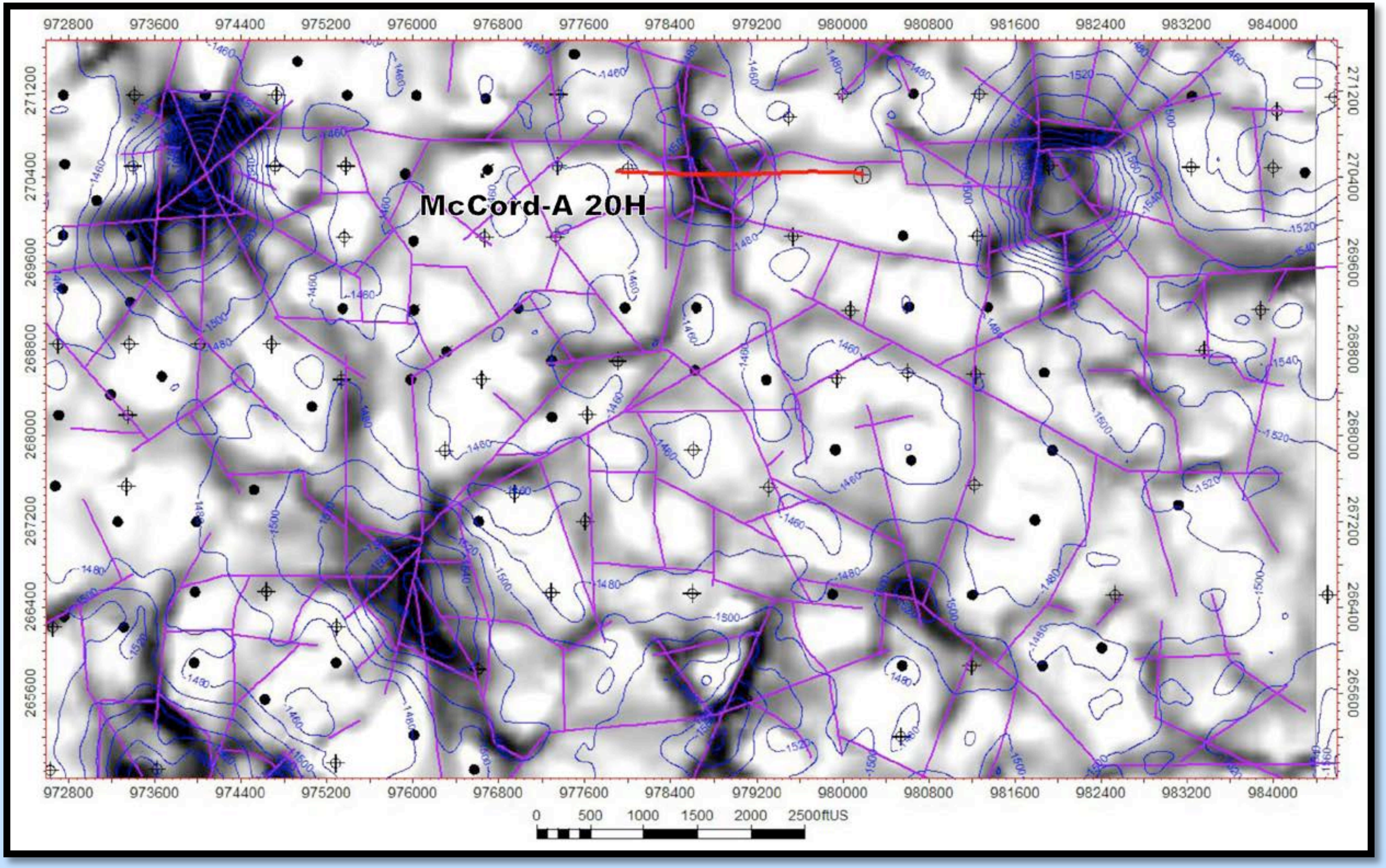
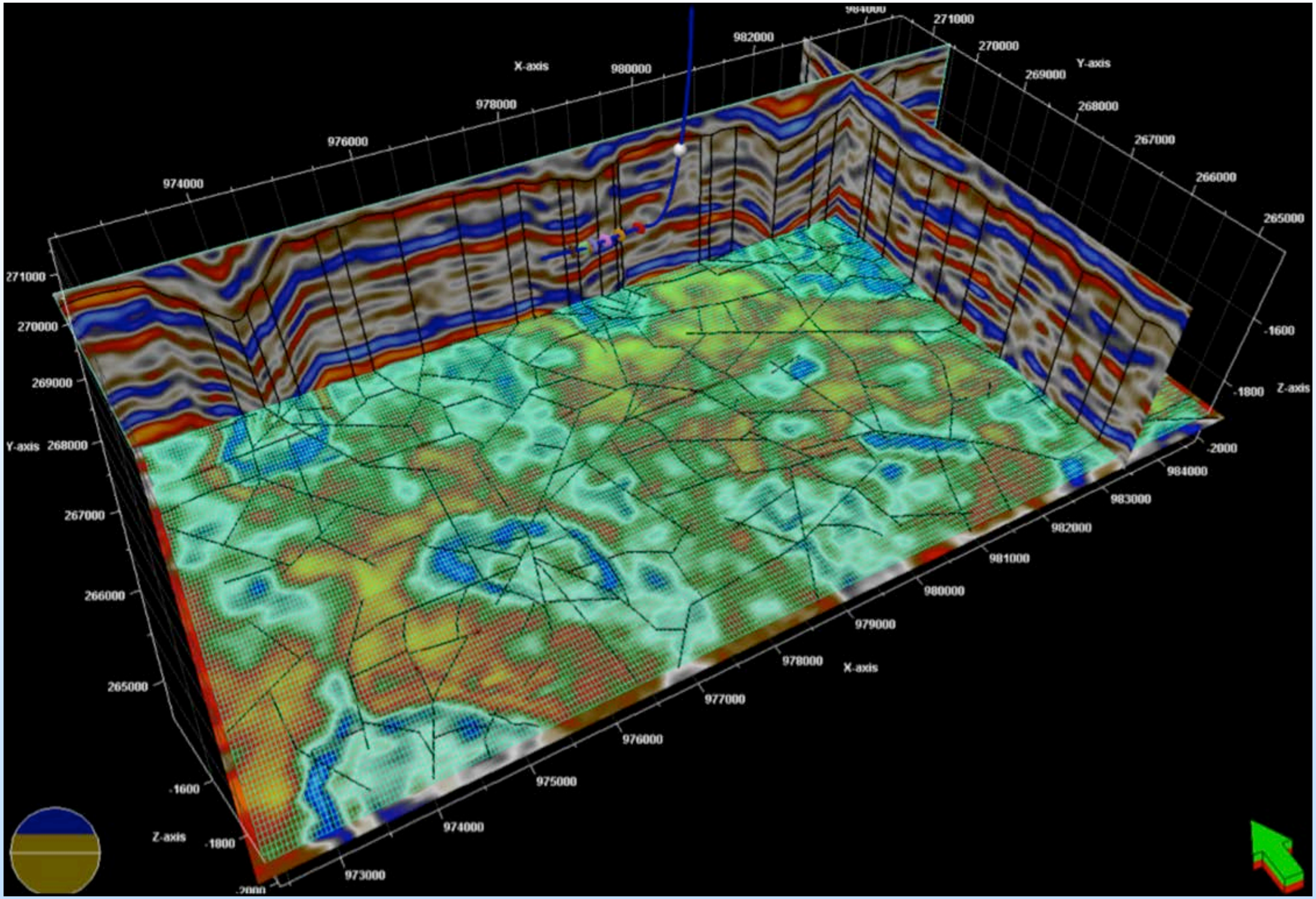
New Field-Wide Fault/Fracture Model



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

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



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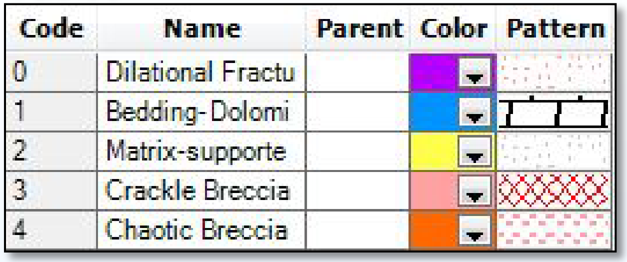
Probability Maps for Conditioning Geocellular Models

Facies



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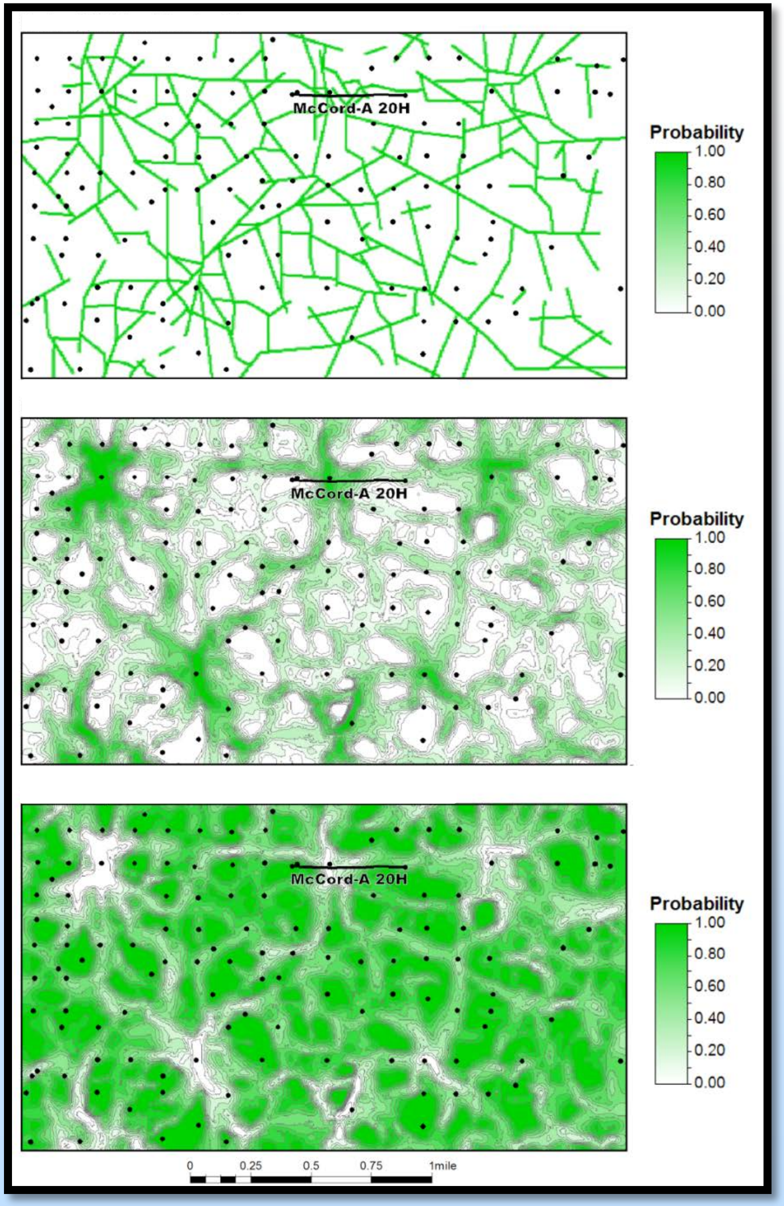
2	Matrix-supporte		🟨	▨
3	Crackle Breccia		🟥	▨
4	Chaotic Breccia		🟧	▨



Dilational Fractures

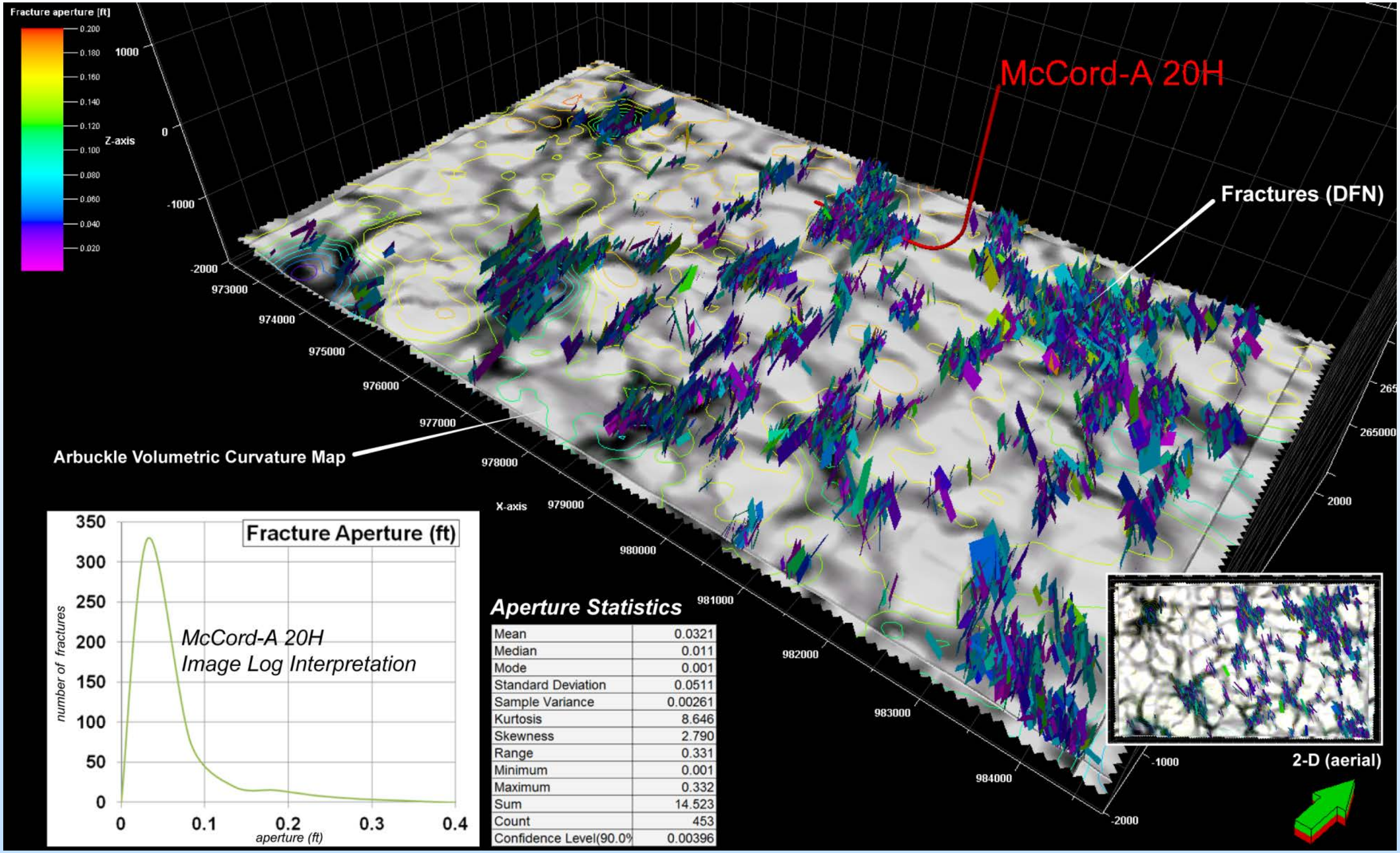
Crackle & Chaotic Breccia

Peritidal Dolostone & Matrix-Supported Breccia

evaporite karst in host strata

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

Discrete Fracture Network Modeling

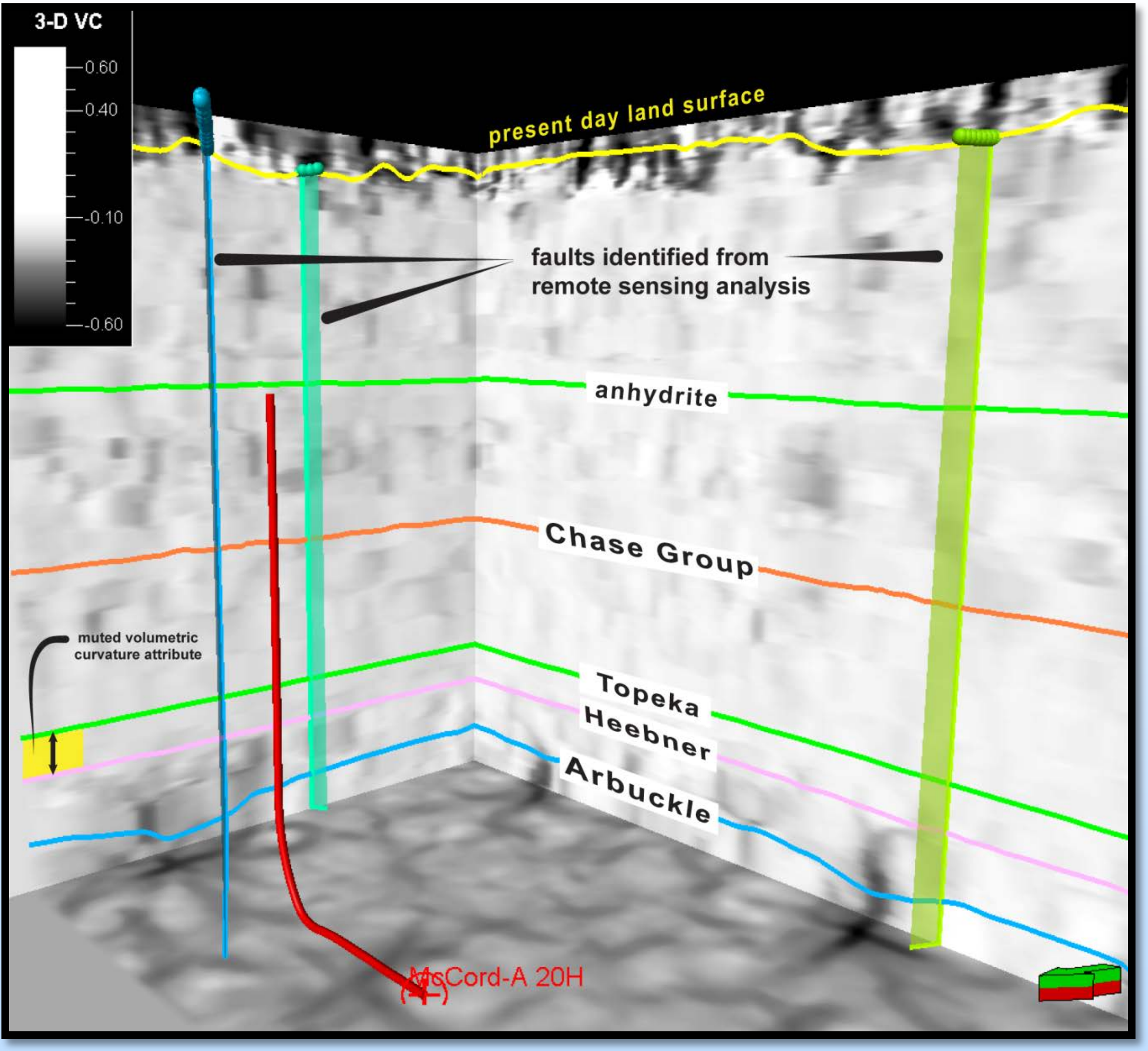


Aperture Statistics

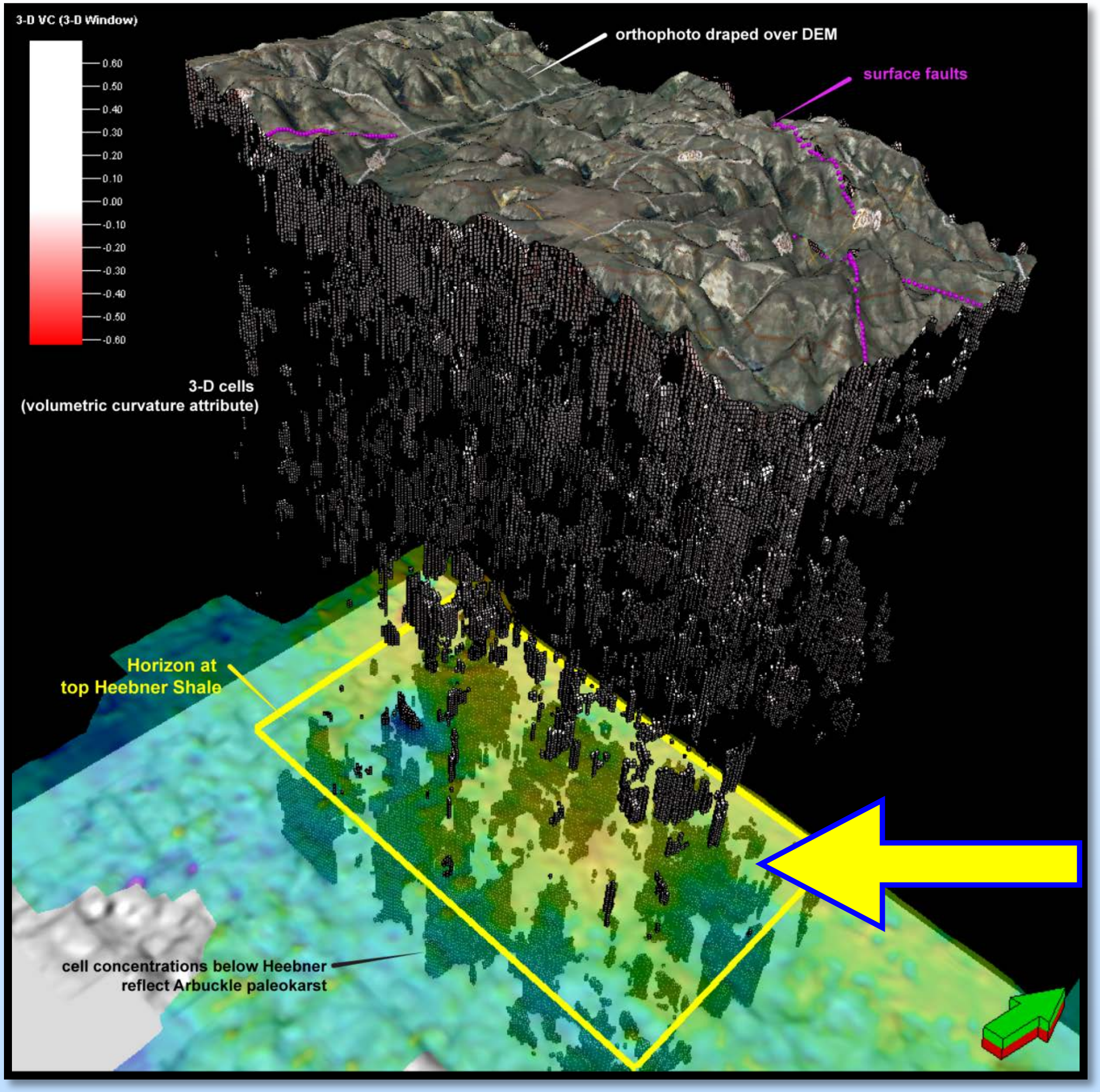
Mean	0.0321
Median	0.011
Mode	0.001
Standard Deviation	0.0511
Sample Variance	0.00261
Kurtosis	8.646
Skewness	2.790
Range	0.331
Minimum	0.001
Maximum	0.332
Sum	14.523
Count	453
Confidence Level(90.0%	0.00396

3-D Volumetric Curvature Volume

VC muted
Reflectors flat



Filtered 3-D VC Geocellular Model



VC cells absent

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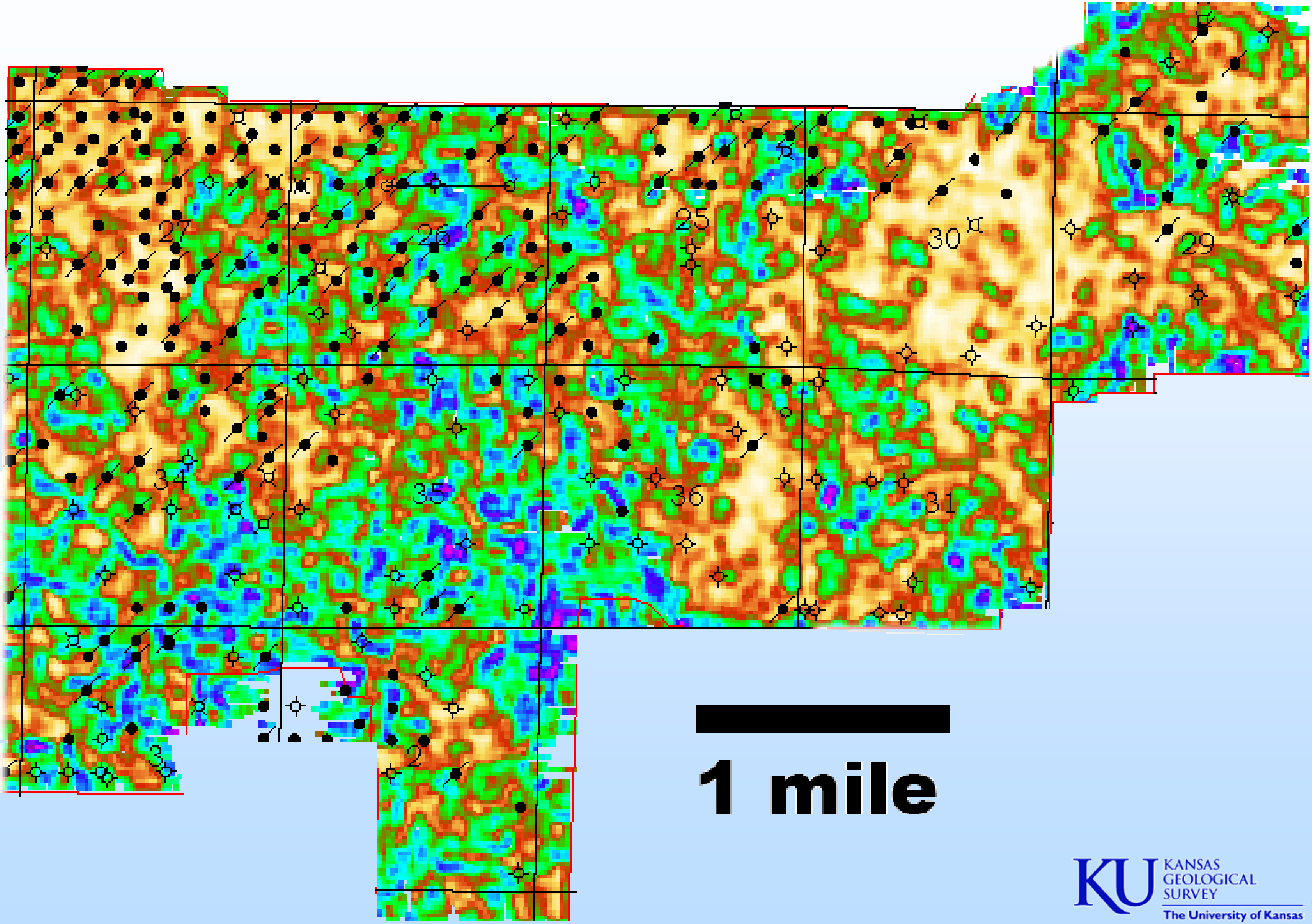
Seismic Attributes: Coherence vs VC



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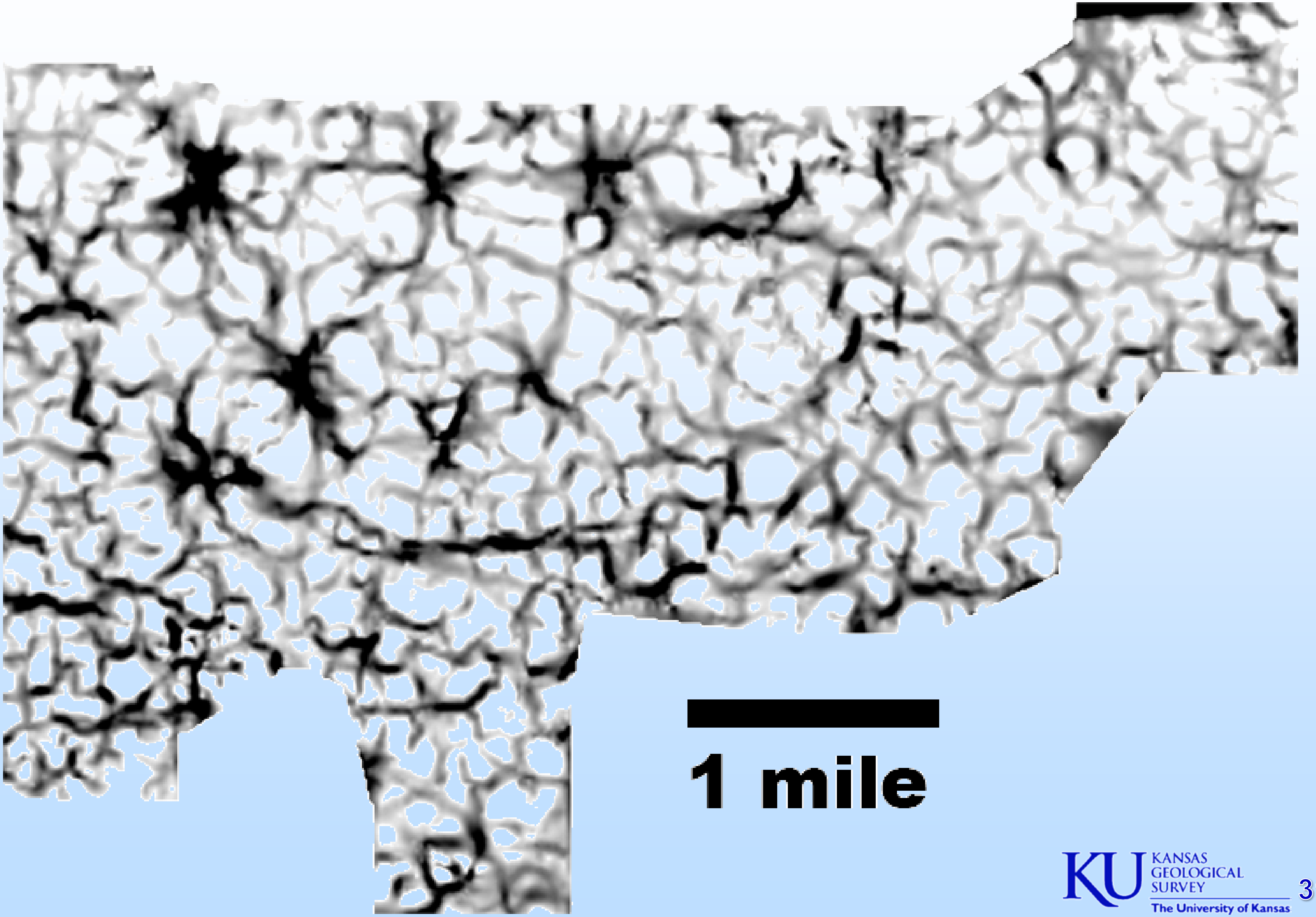
Seismic Attributes: Coherence vs VC



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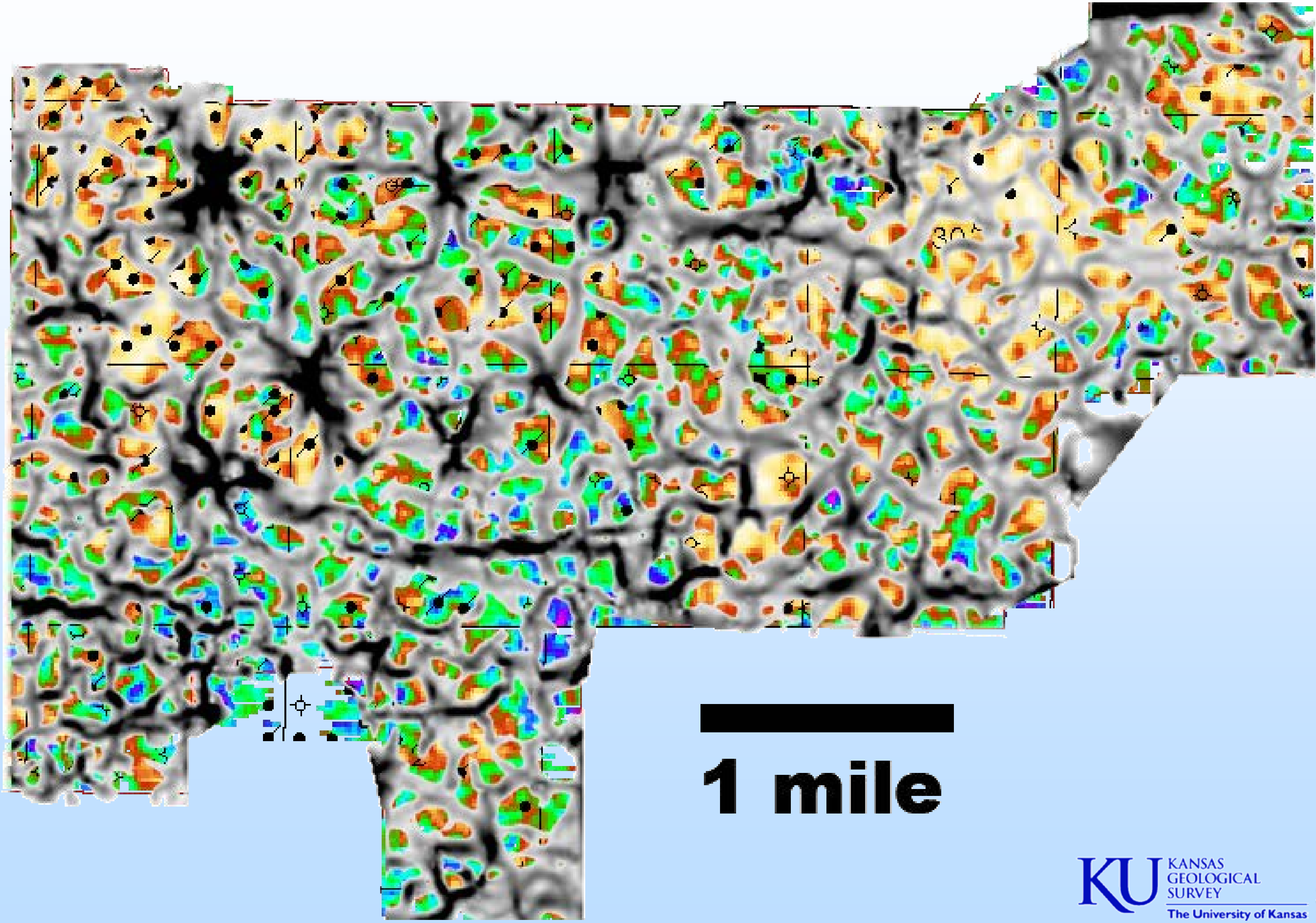
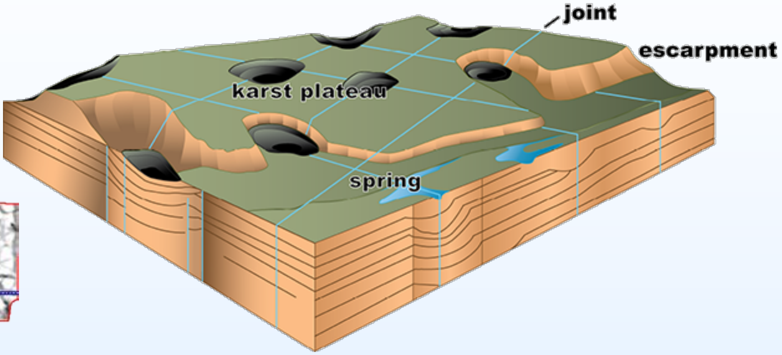
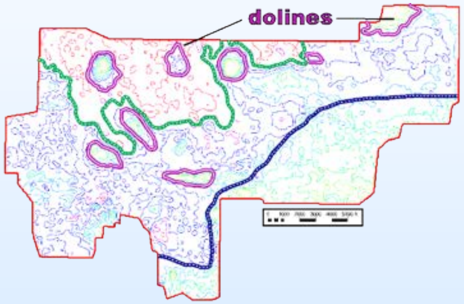
Seismic Attributes: Coherence vs VC

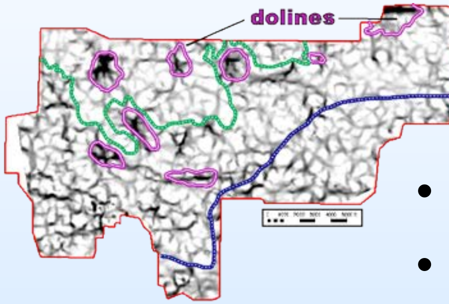


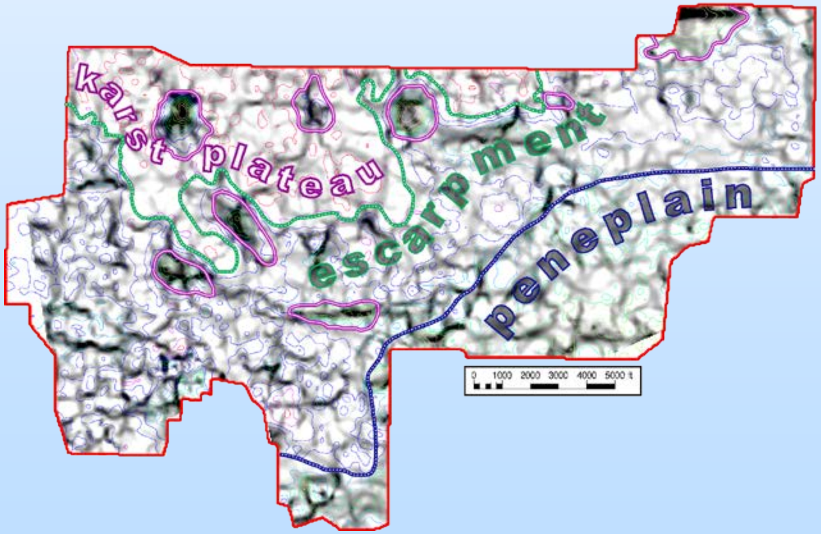
Geologic Findings & Interpretations

Bemis-Shutts karst model









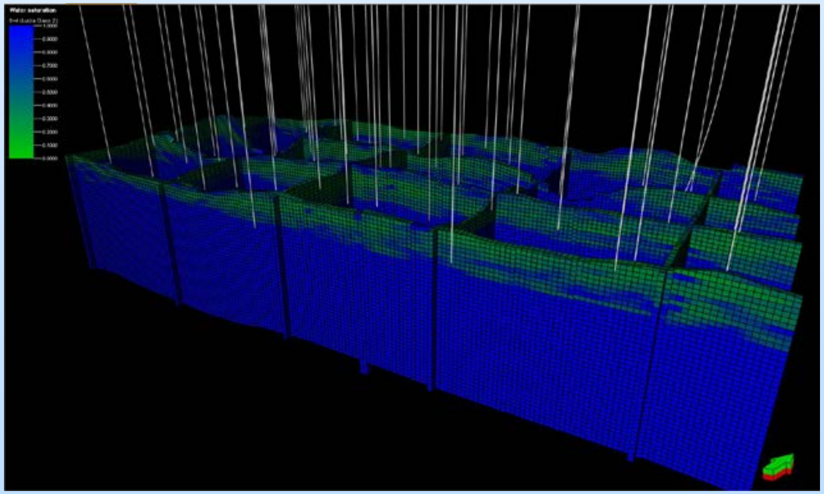
- Fault-bounded doline confirmed
- Dolines coincident with VC-identified radial lineaments
- Interior drainage
- Headward-eroding escarpment
- Disappearing streams/springs/ fluvial plains

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

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

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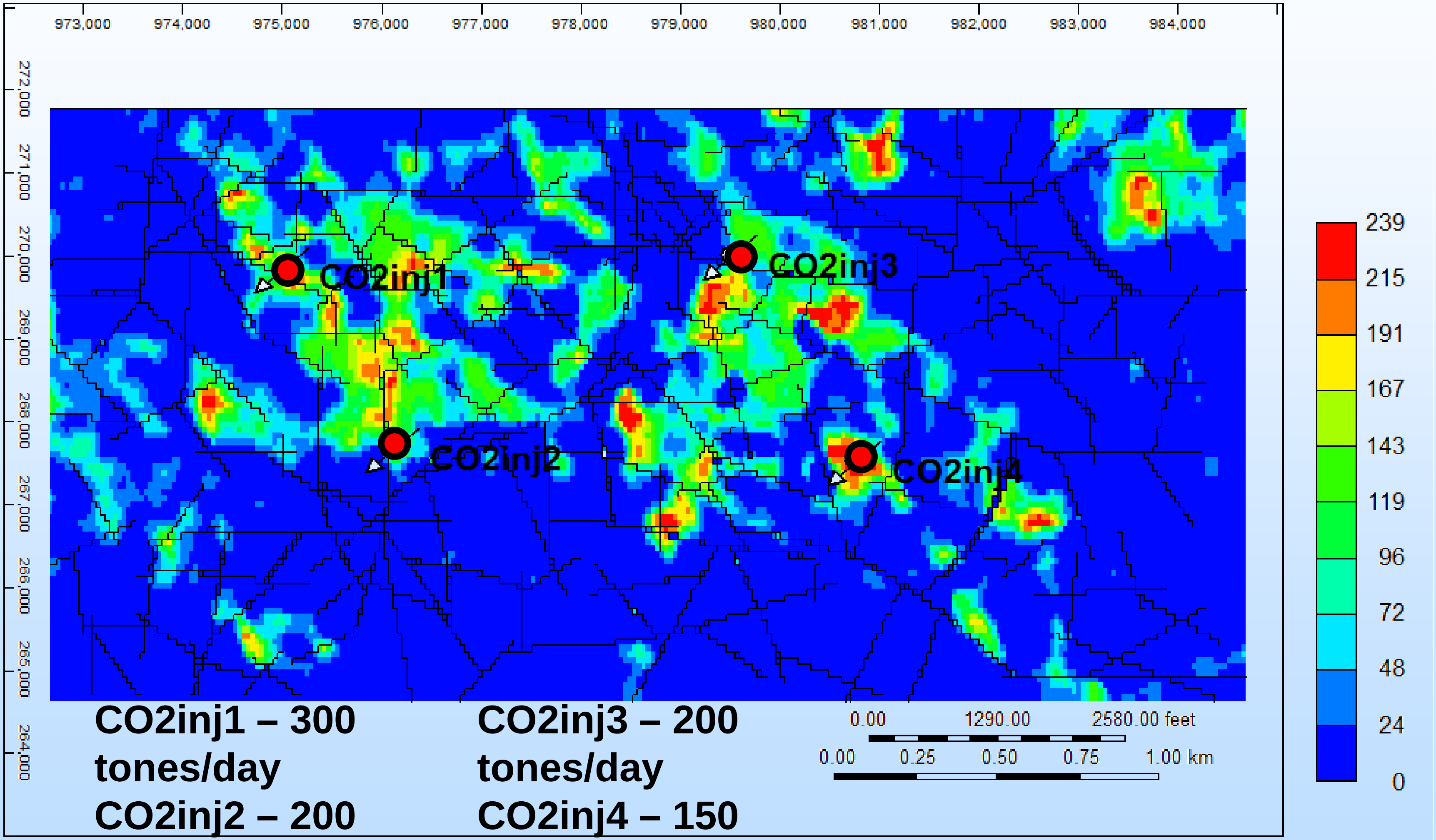
CO$_2$ Injection

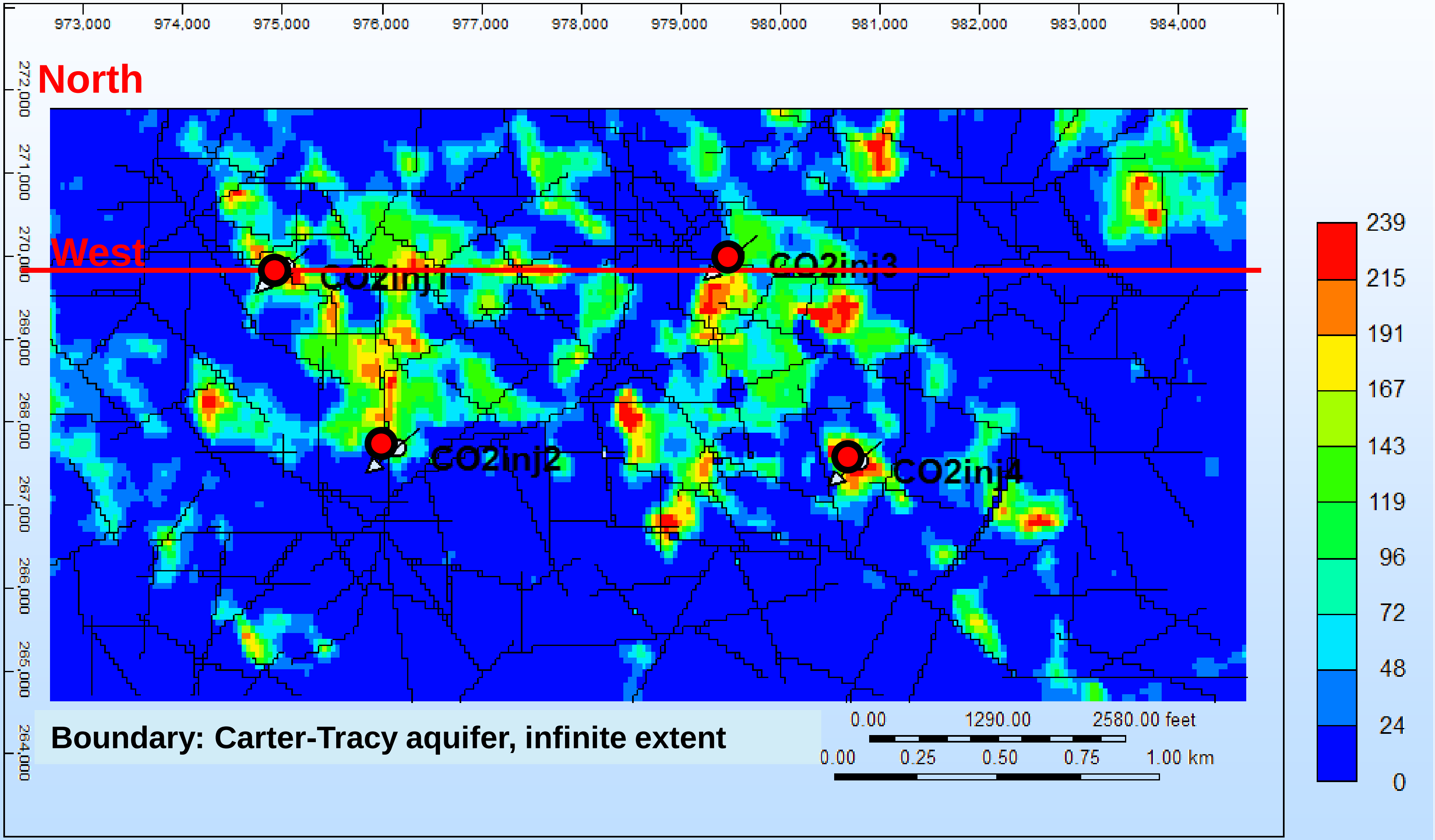

Permeability I (md) 2015-01-01 K layer: 49

CO2inj1 – 300 tones/day
CO2inj2 – 200 tones/day

CO2inj3 – 200 tones/day
CO2inj4 – 150 tones/day

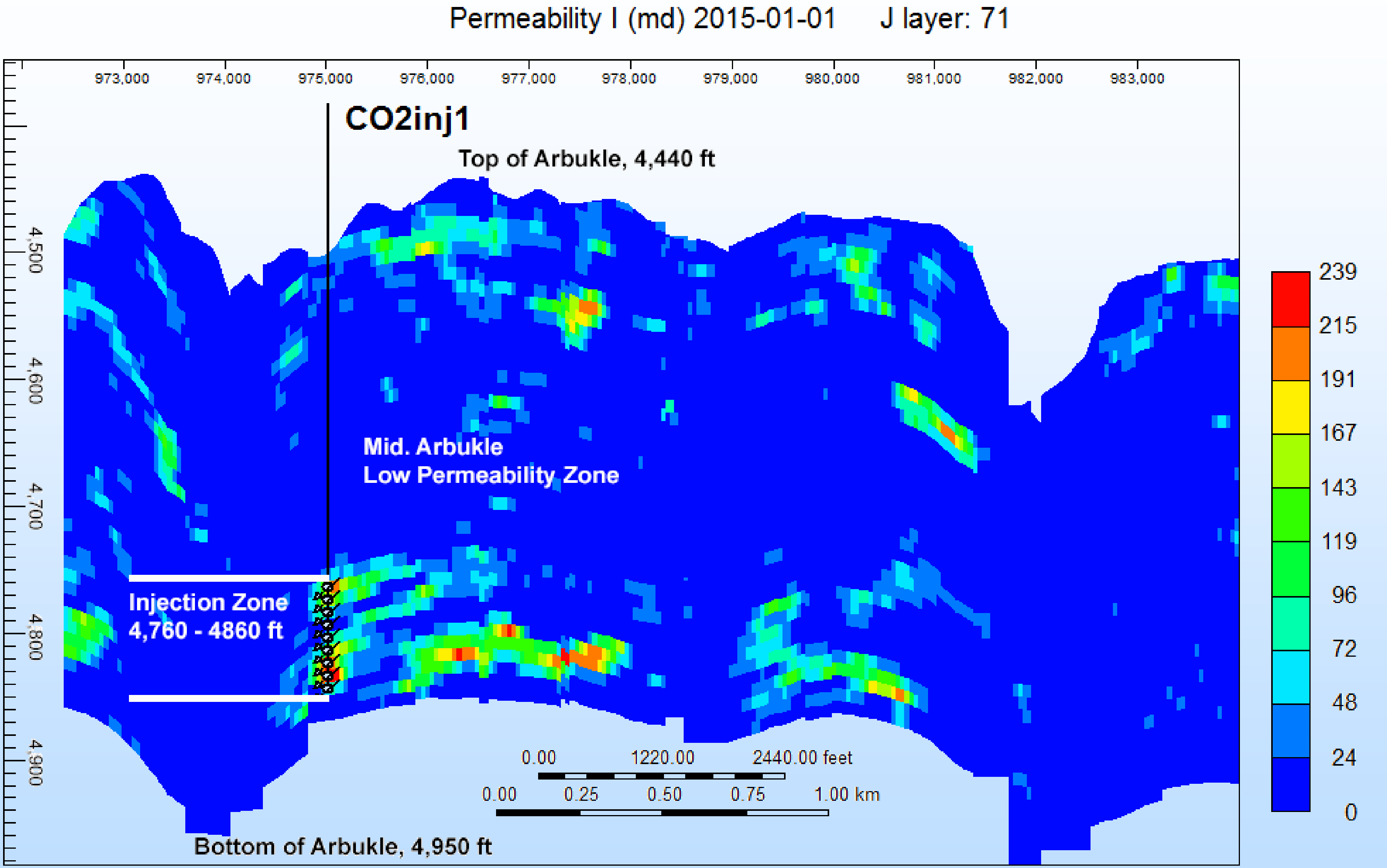
CO_2 Injection

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



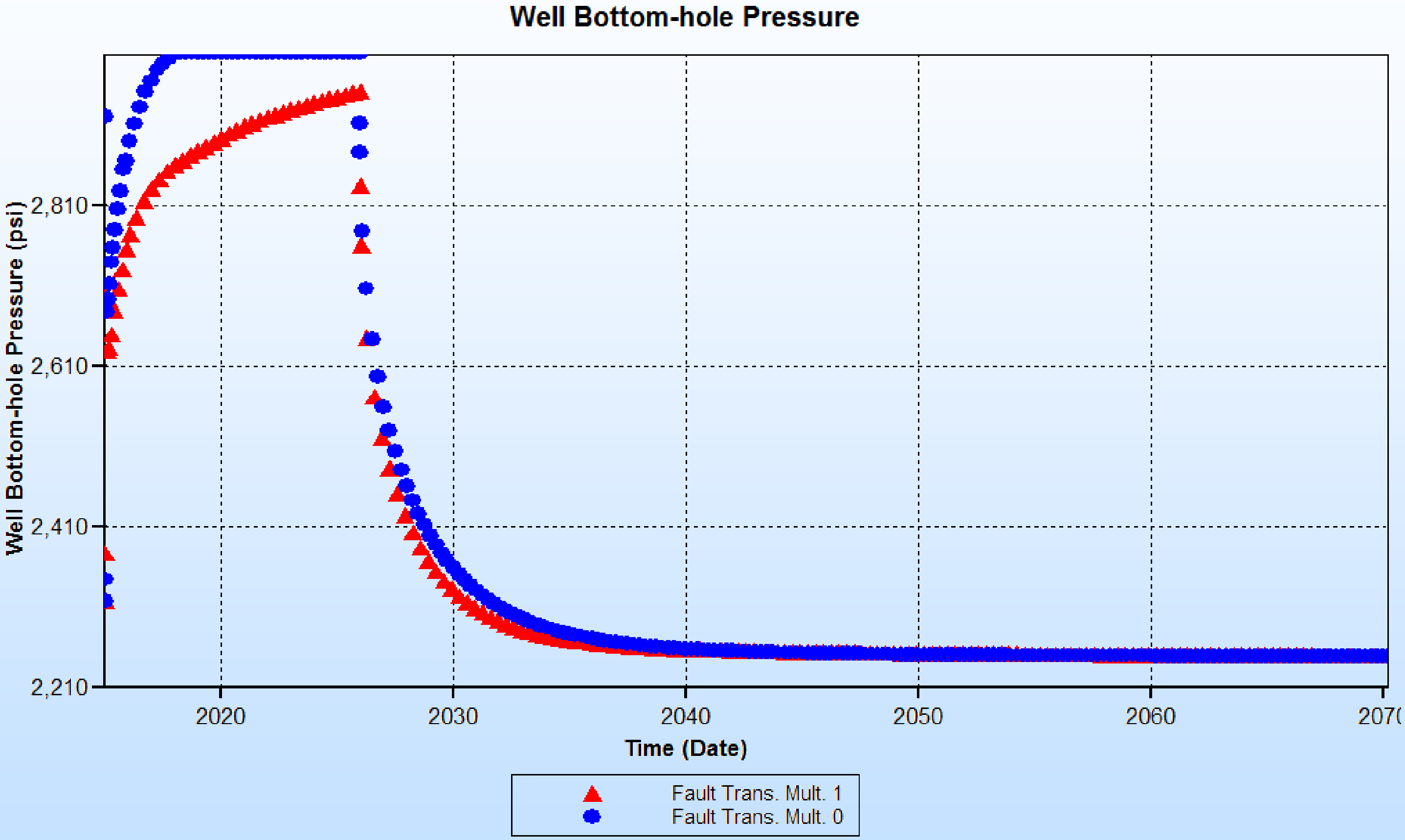
Boundary: Carter-Tracy aquifer, infinite extent

CO_2 Injection



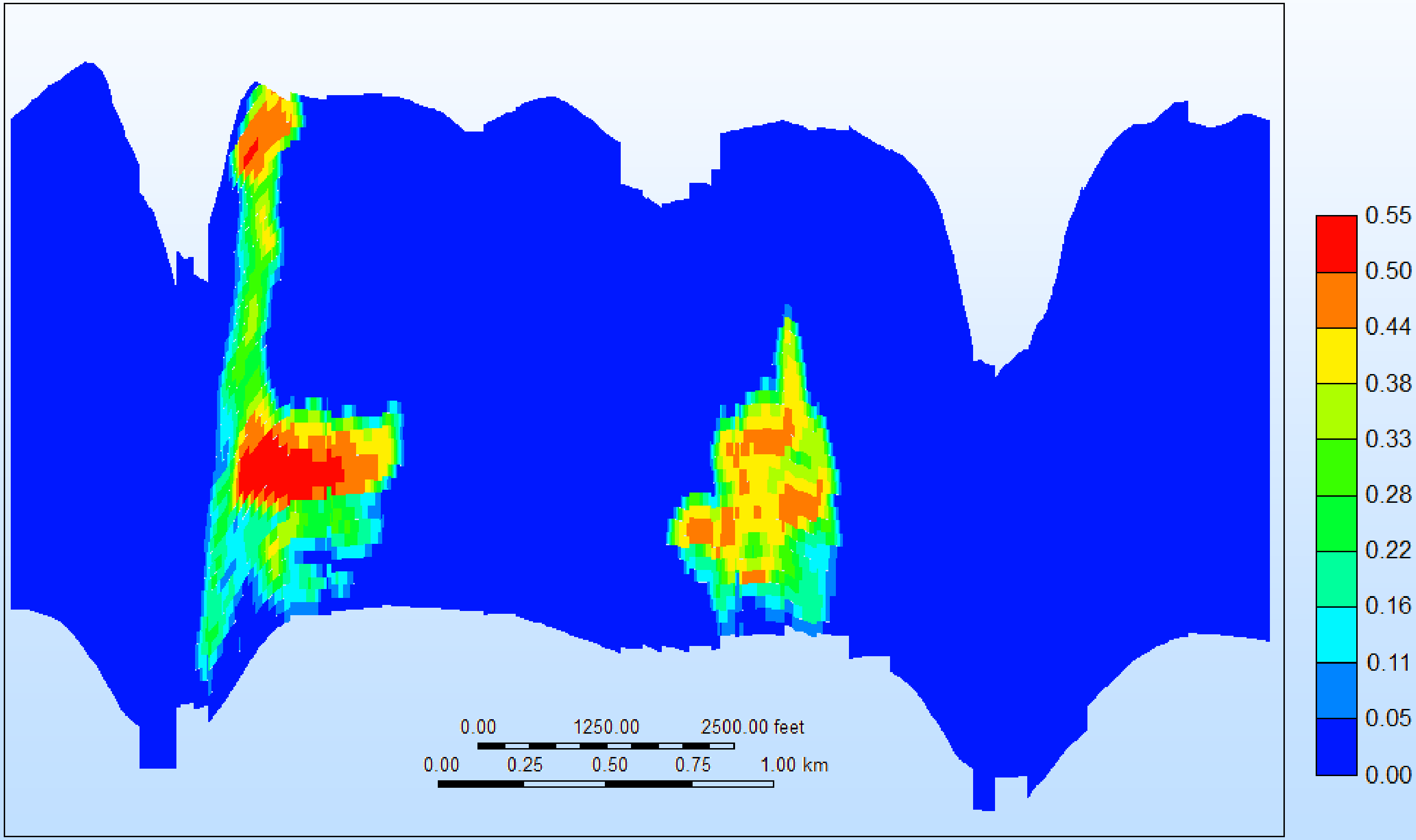
Fault Transmissibility Multiplier 1 vs. 0

Injectivity Profile



CO$_2$ Extent and Movement Fault Trans. Multiplier set to 1

Gas Saturation 2117-01-31 J layer: 80



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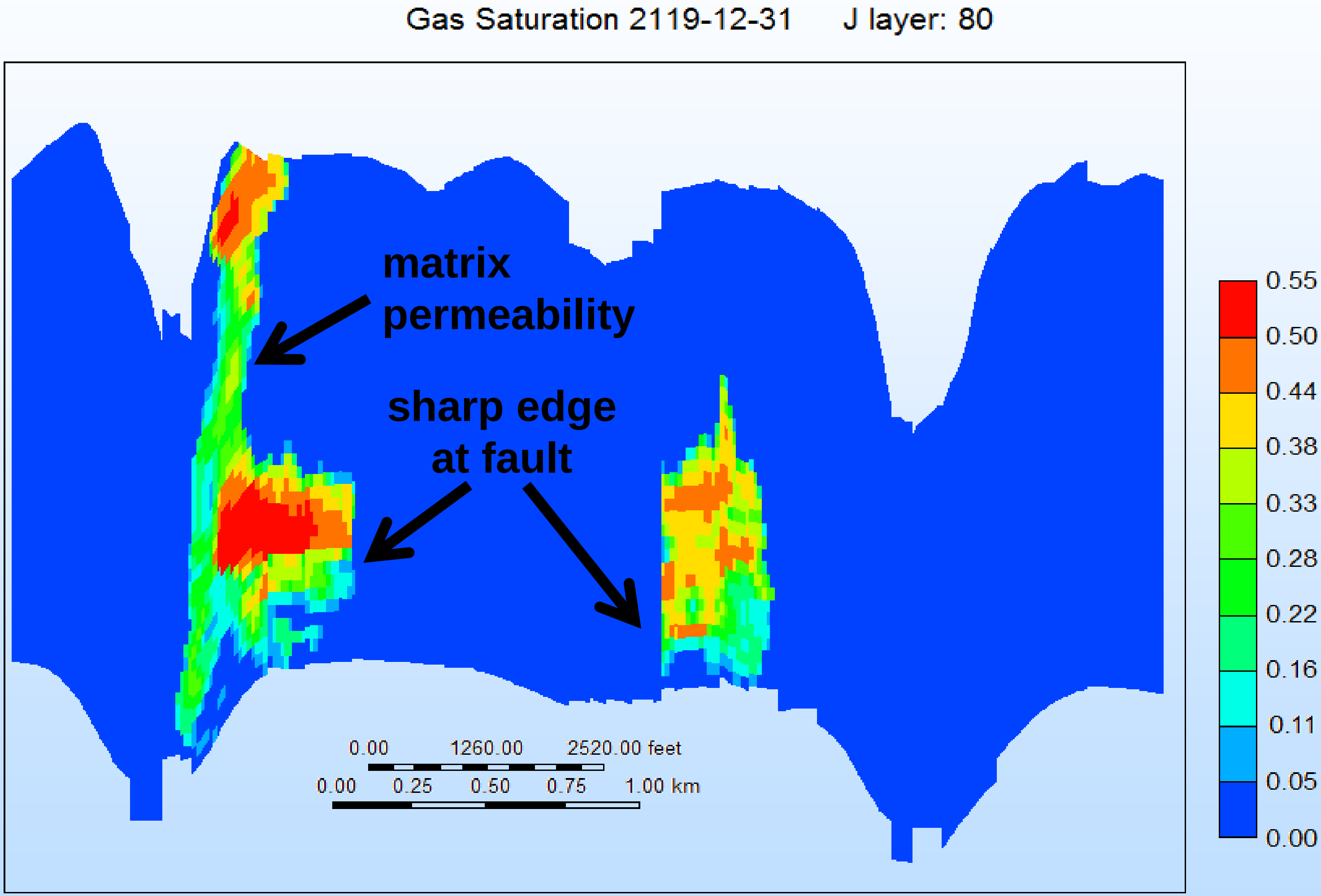
CO_2 Extent and Movement Fault Trans. Multiplier set to 0

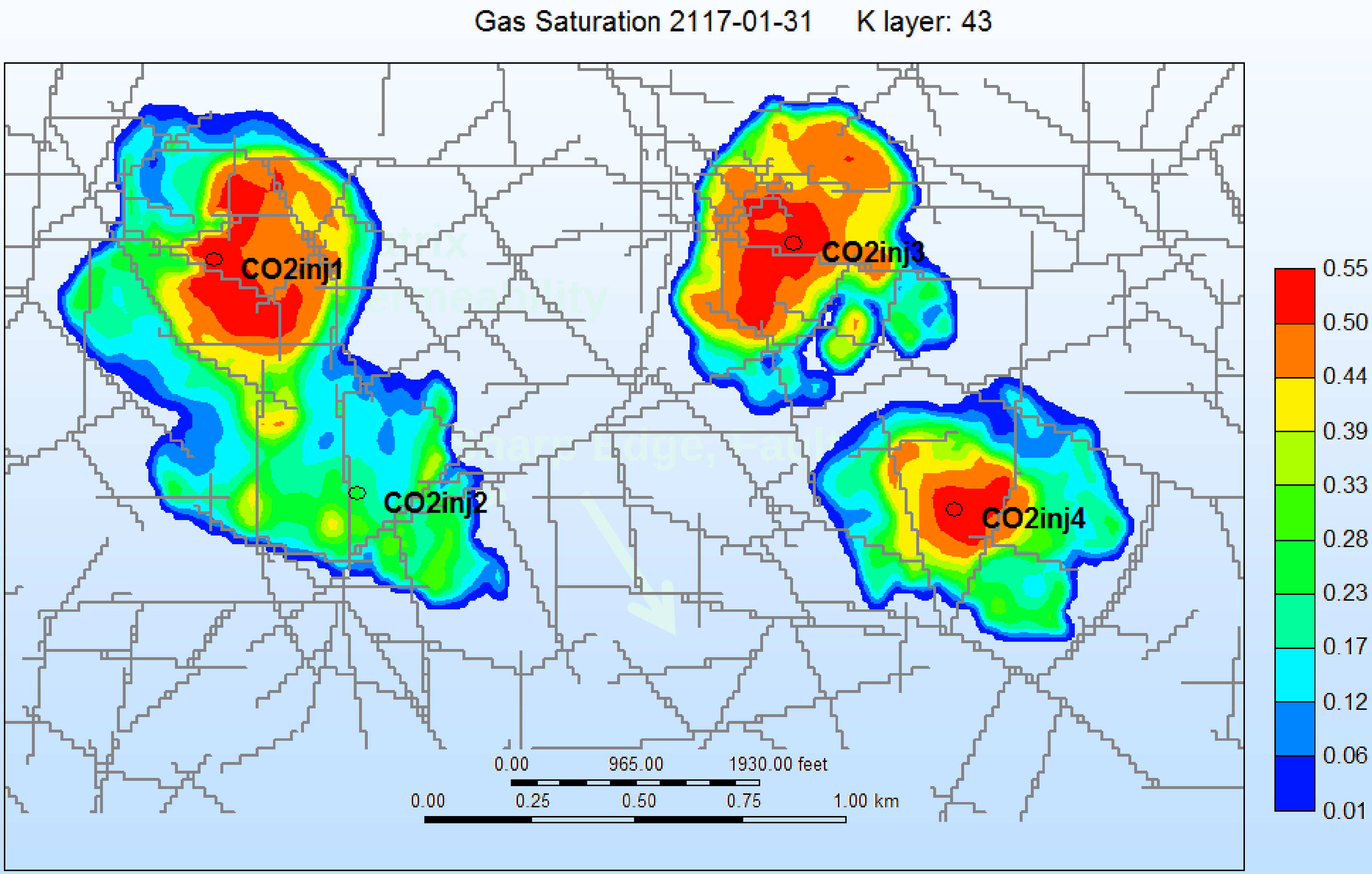


Gas Saturation 2119-12-31 J layer: 80

matrix permeability

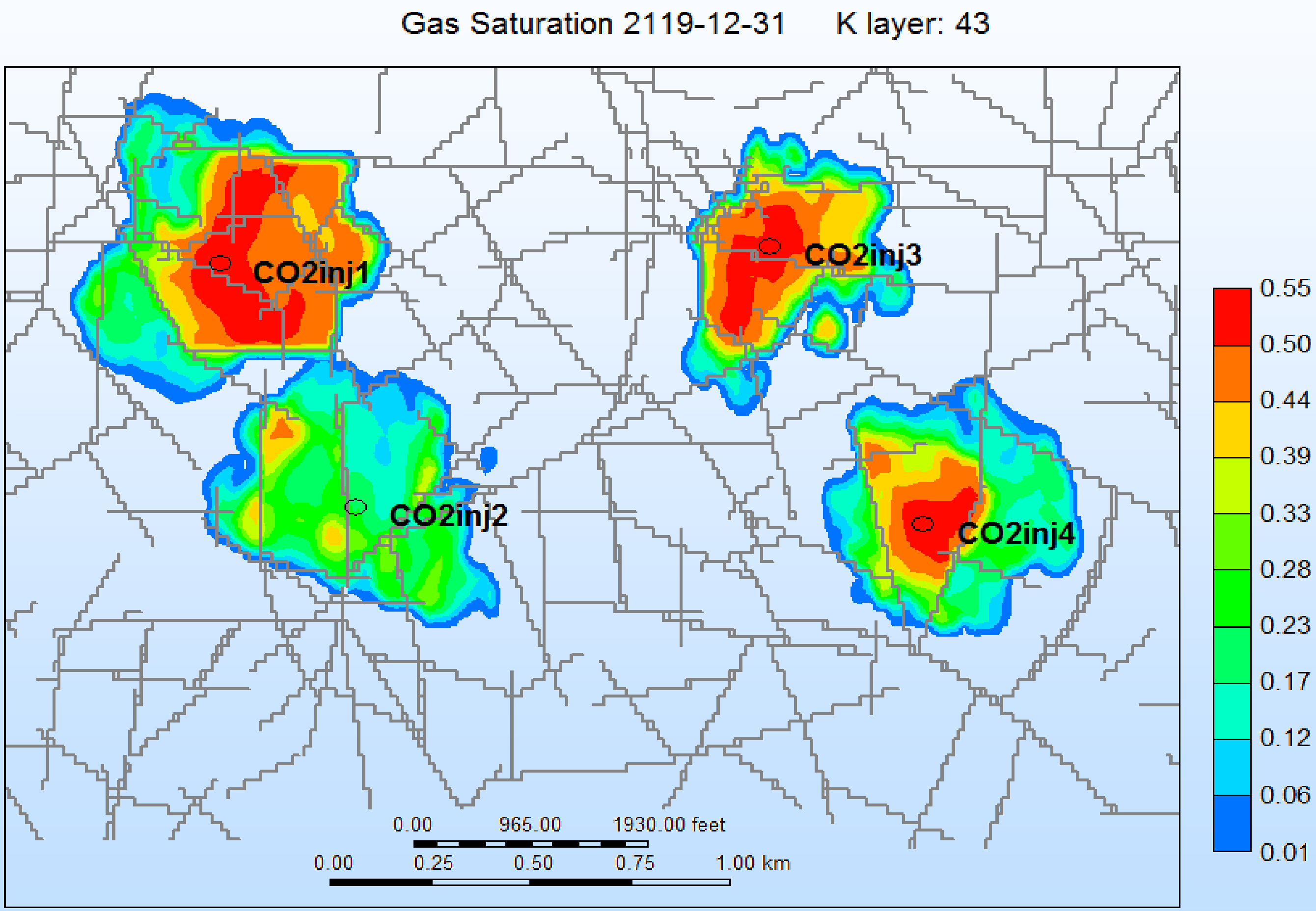
sharp edge at fault

CO_2 Extent and Movement
Fault Trans. Multiplier set to 1



Gas Saturation 2117-01-31 K layer: 43

CO_2 Extent and Movement
Fault Trans. Multiplier set to 0



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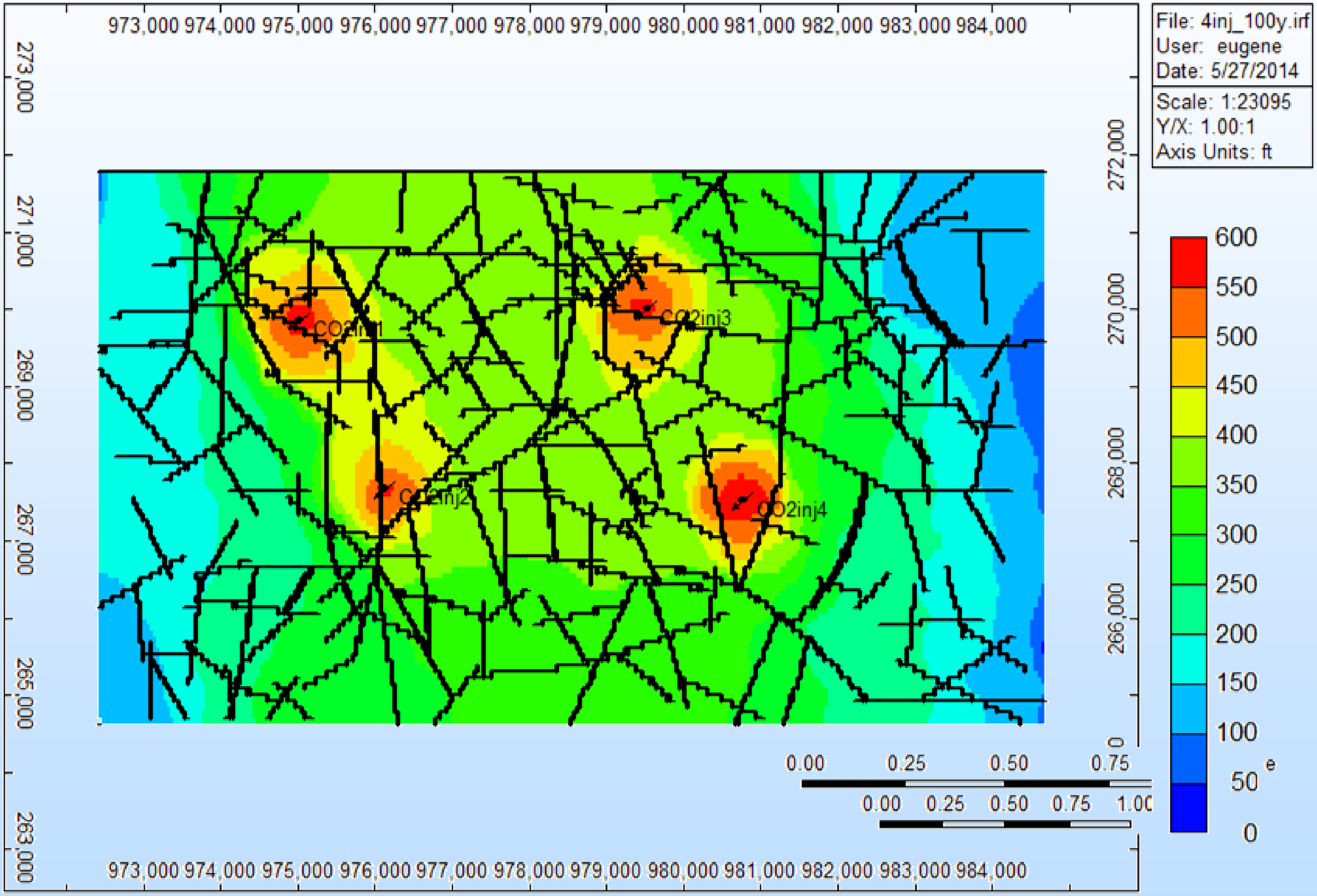
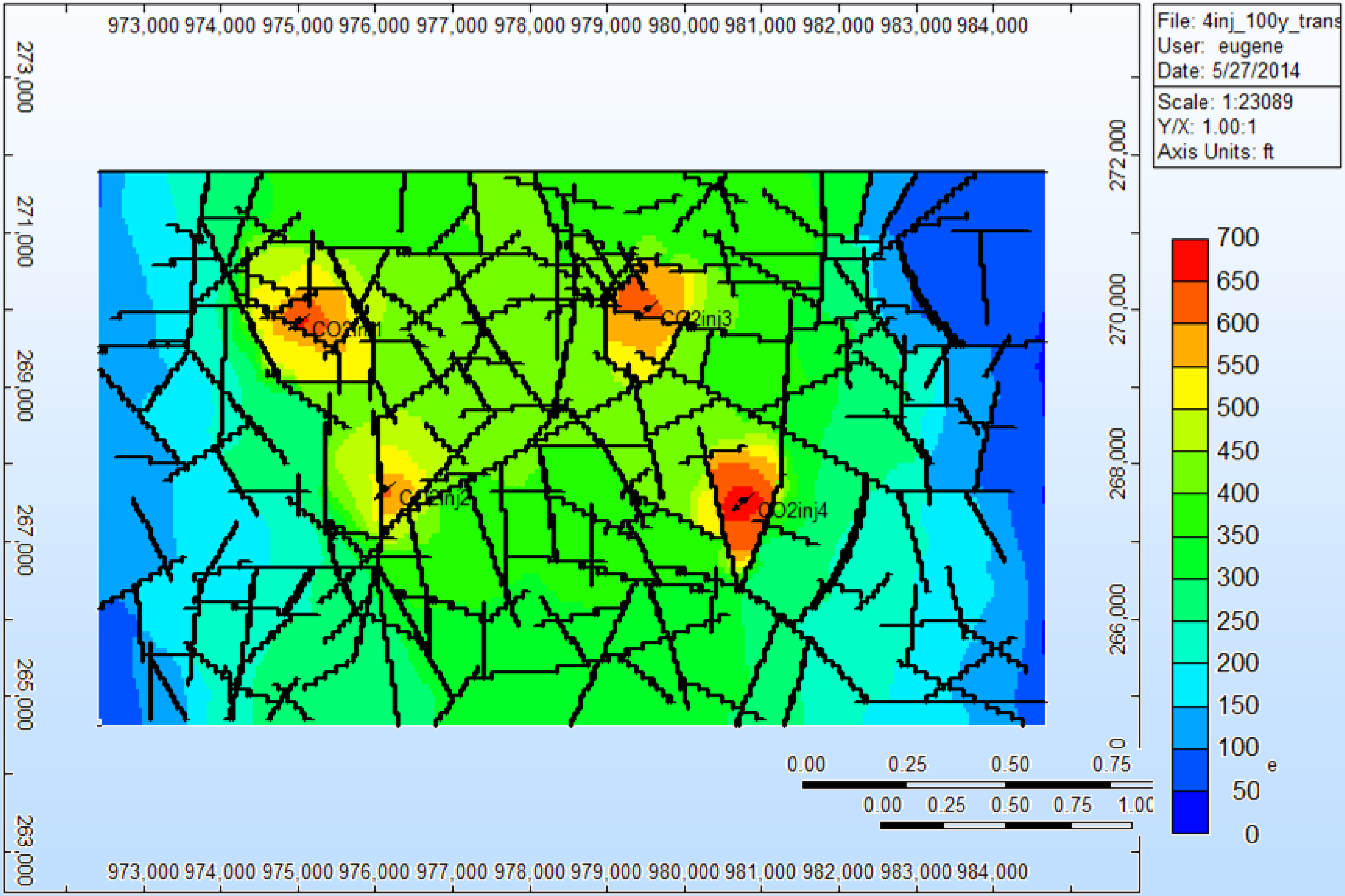
Delta Pressure and Movement Fault Trans. Multiplier set to 1



File: 4inj_100y.irf
User: eugene
Date: 5/27/2014
Scale: 1:23095
Y/X: 1.00:1
Axis Units: ft

Delta Pressure and Movement Fault Trans. Multiplier set to 0



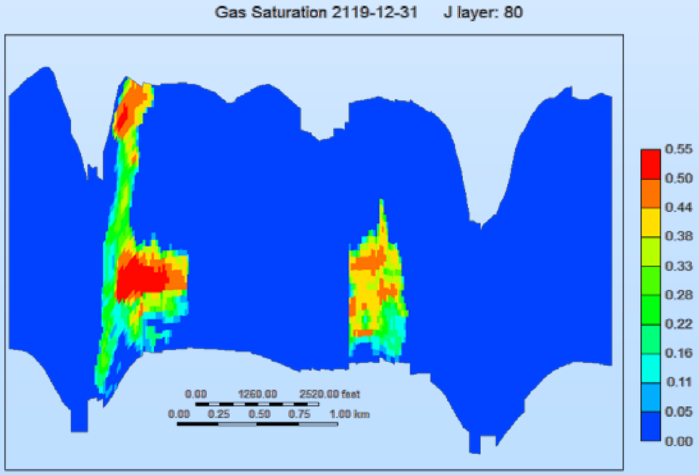
Simulation Findings to Date

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

Future Plans

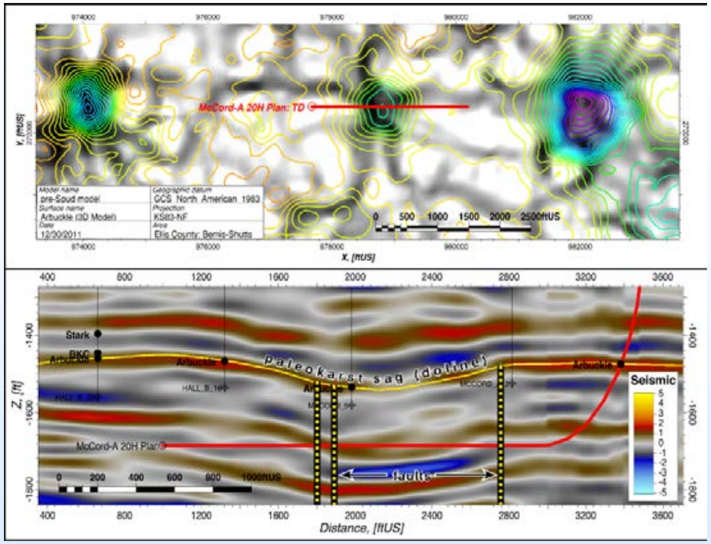
- Analyze uncertainty of ***flux between blocks***
- History match new models
- Ways to estimate fault transmissibility



Presentation Outline

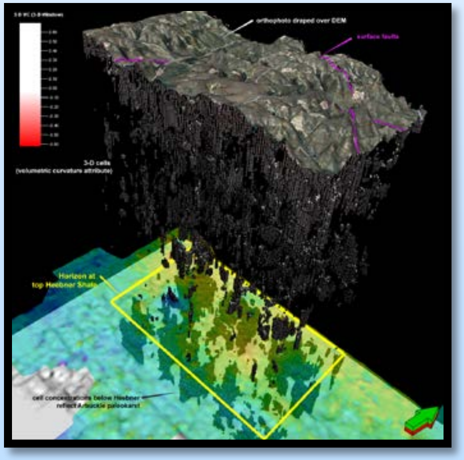
- Benefits, objectives, overview
- Methods
- Background & setting
- Technical status
- Accomplishments
- Summary

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
- Simulations fault
- Publication-ready figures



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Presentation Outline

- Benefits, objectives, overview
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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.