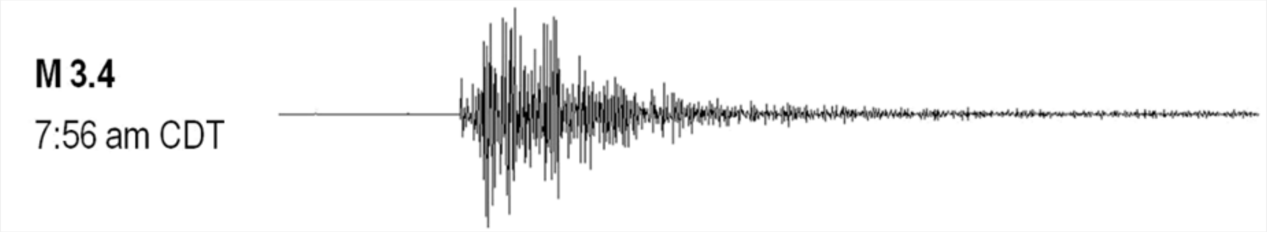
Earthquakes in the southern midcontinent: What we know and what we need to know - Current research at KU and the Kansas Geological Survey



W. Lynn Watney, Tandis S. Bidgoli, & Eugene Holubnyak

December 2, 2014

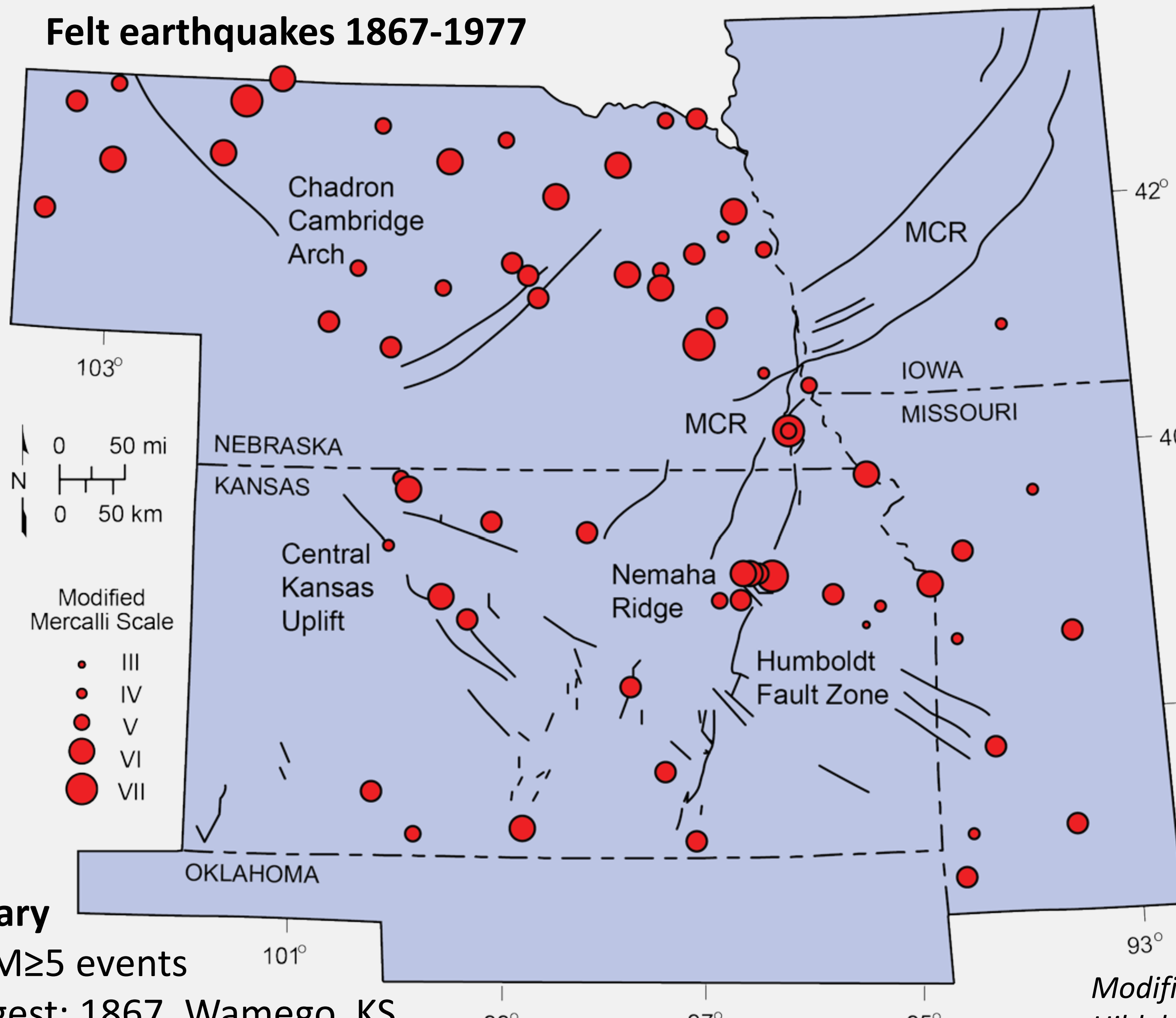
Kansas Geological Survey – University of Kansas

Outline

- Seismicity
  - Historical seismicity in Kansas
  - Earthquakes in southern Kansas
  - Trends from the CEUS
- Why care about seismicity?
- Mechanics of induced events
- Mississippian Lime Play
  - Geology
  - Production trends
  - Brine disposal
- Current research
  - Seismic monitoring
  - Fault mapping and stress field analysis
  - Geologic and simulation models
- Future research and need for collaboration

Historical seismicity in KS

Felt earthquakes 1867-1977



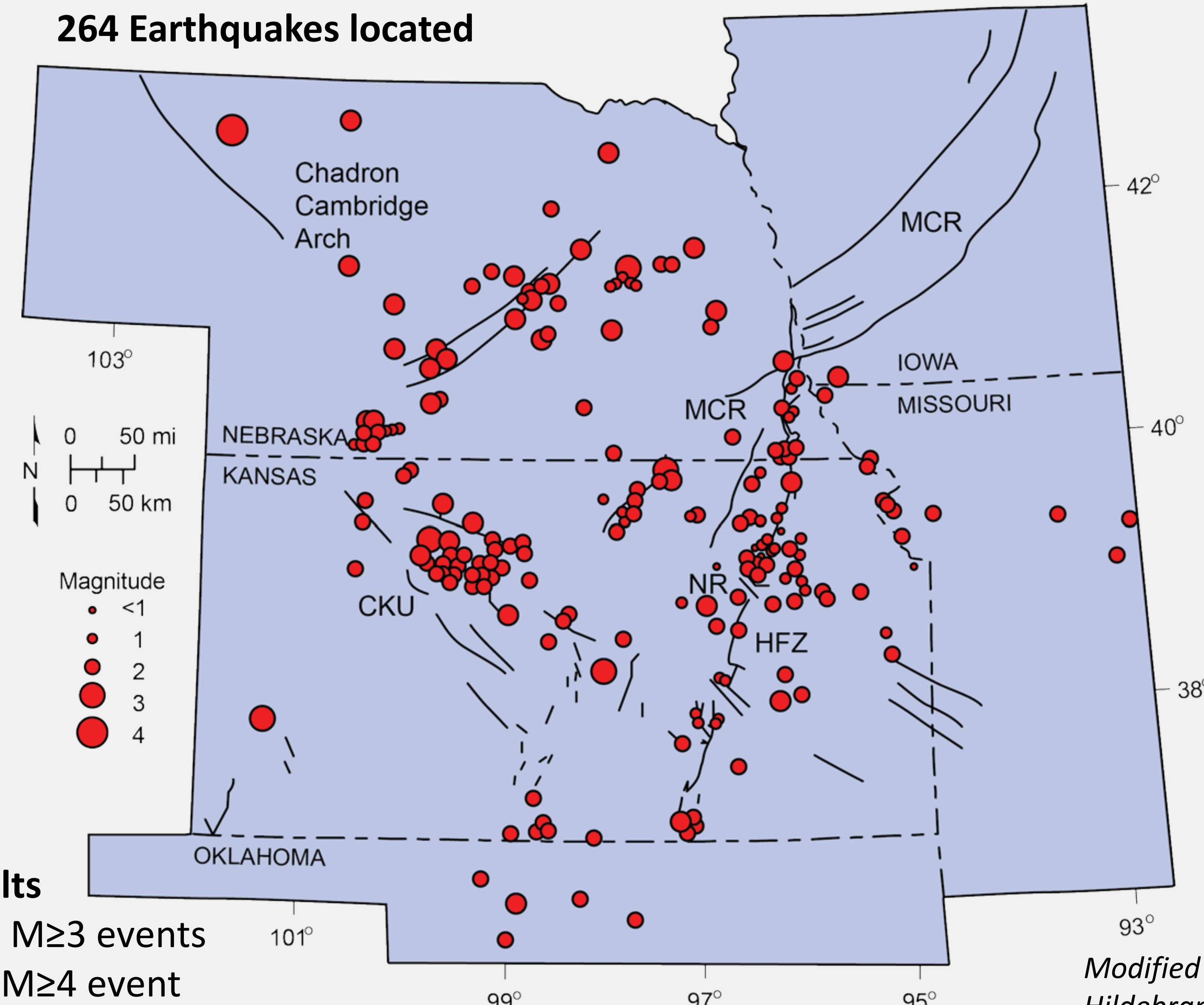
Summary

- 2 ~M≥5 events
- Largest: 1867, Wamego, KS

Modified from Hildebrand et al. (1988)

KS-NE Network, 1977-1989

264 Earthquakes located



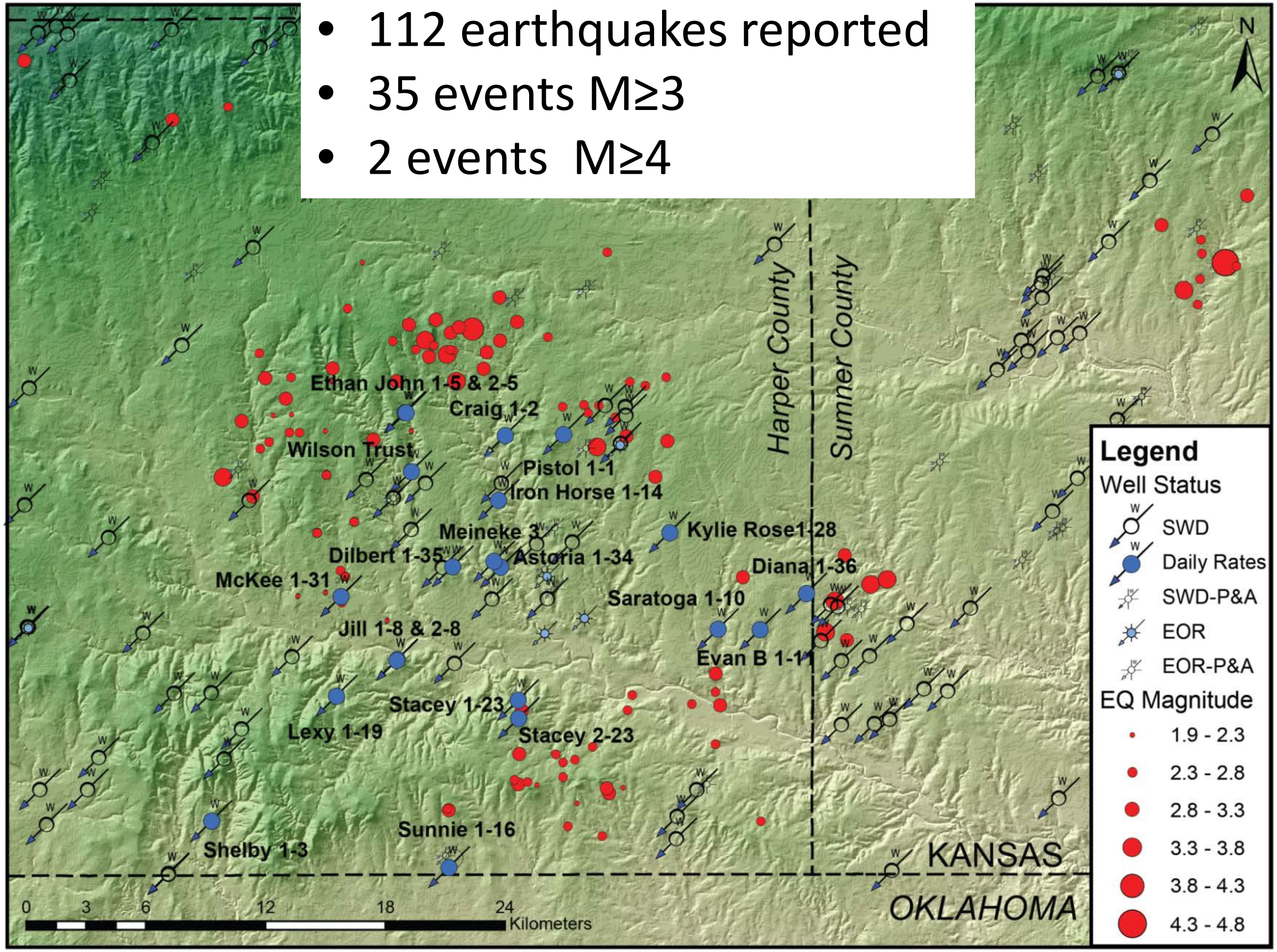
Results

- 2 M≥3 events
- 1 M≥4 event

Modified from Hildebrand et al. (1988)

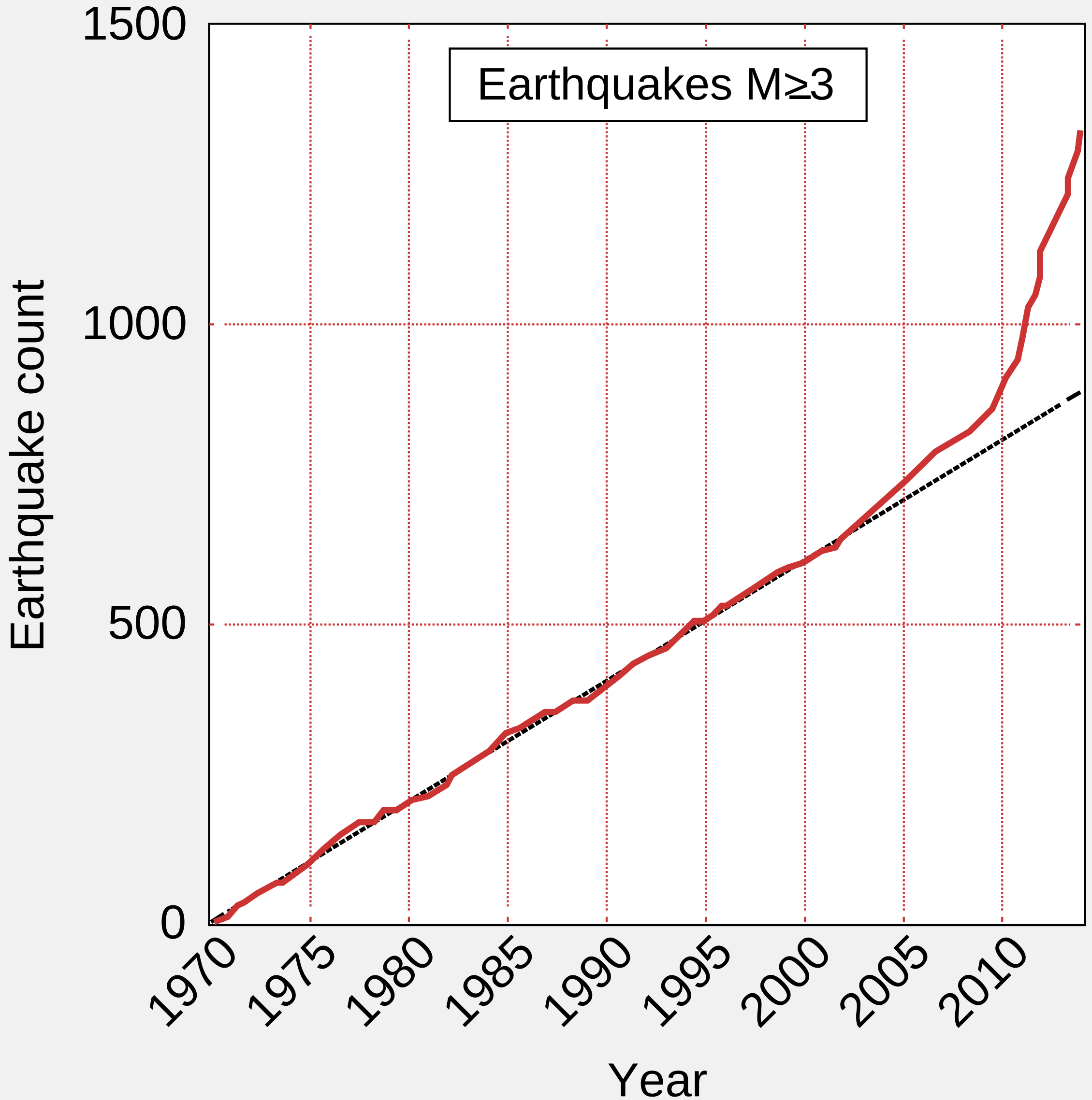
Seismicity in southern KS

- 112 earthquakes reported
- 35 events M≥3
- 2 events M≥4

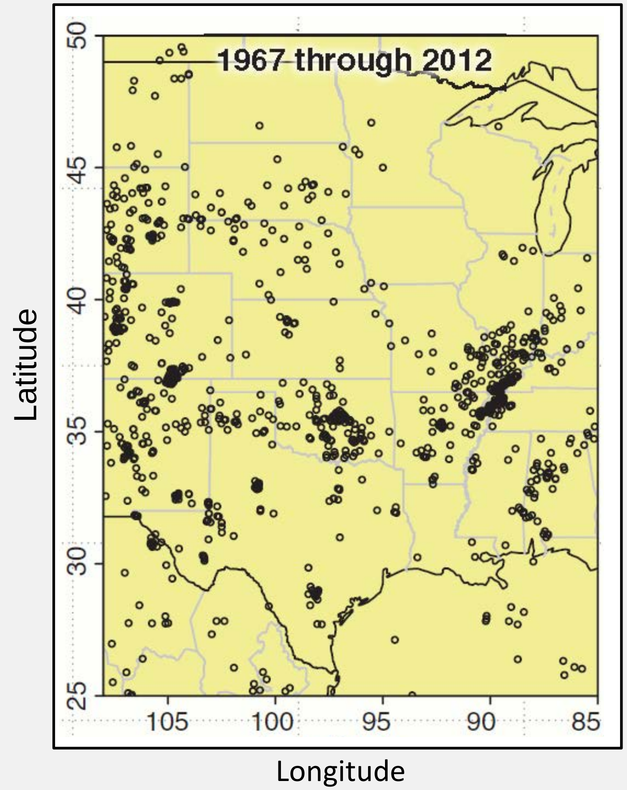


Source: USGS NEIC catalog (11/21/14)

Trends in the central & eastern US



Modified from Ellsworth (2013)



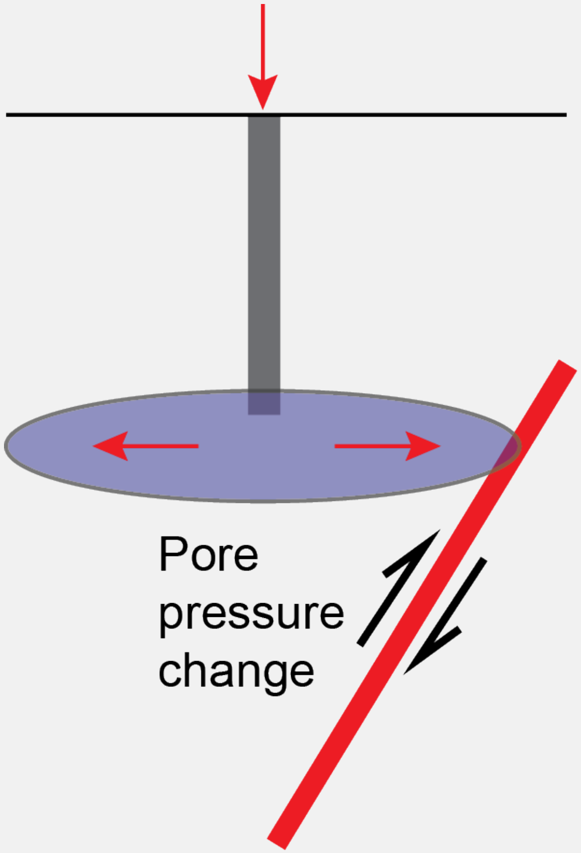
- Long-term average of 20 EQs/year
- Rapid increase since 2009

Documented examples

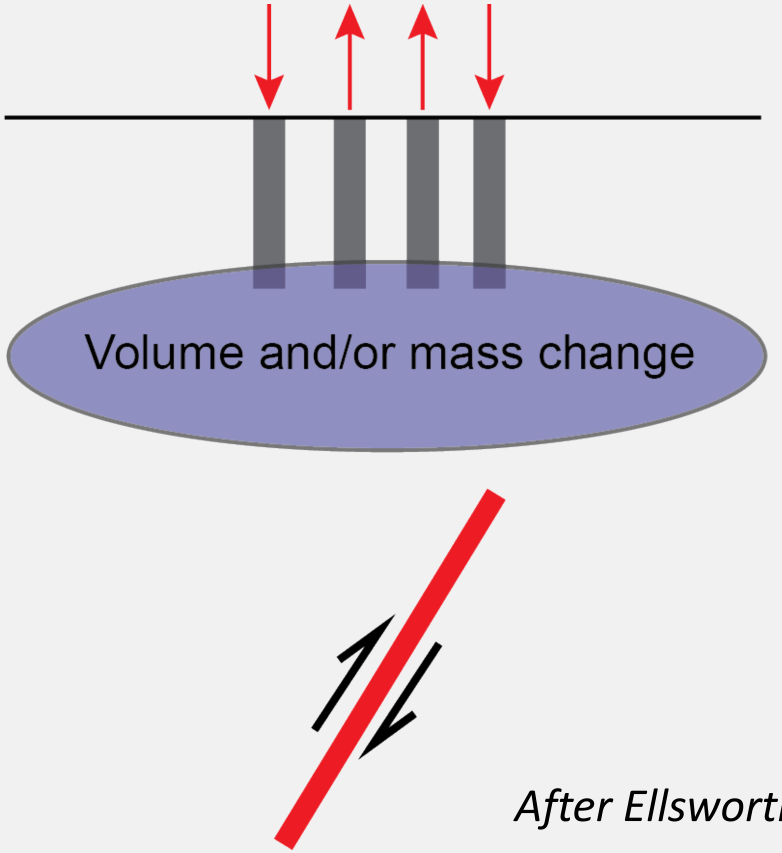
- RMA, CO, M 5.3, 1962-1968 (Healy et al.,1968)
- Paradox Valley, CO, M 4.3, 1996-2003 (Ake,2005)
- DFW, M 3.3, 2008-2011 (Frolich, 2013)
- Guy, AR, M 4.7, 2010-2011(Horton, 2012)
- Youngstown, OH, M 4.0, 2010-2011 (Kim, 2013)
- Raton Basin, CO/NM, M 5.3 2001-2011 (Rubenstein, 2014)

Mechanics of induced earthquakes

1. **Increase pore fluid pressure acting on a fault**
   - Brine disposal (e.g., Healy et al.,1968)
   - Fracking (e.g., Holland, 2011)
   - Hydraulic connection needed



2. **Change shear or normal stress acting on fault**
   - Reservoir depletion or repressurization (e.g., McGarr, 1991)
   - No direct connection to fault

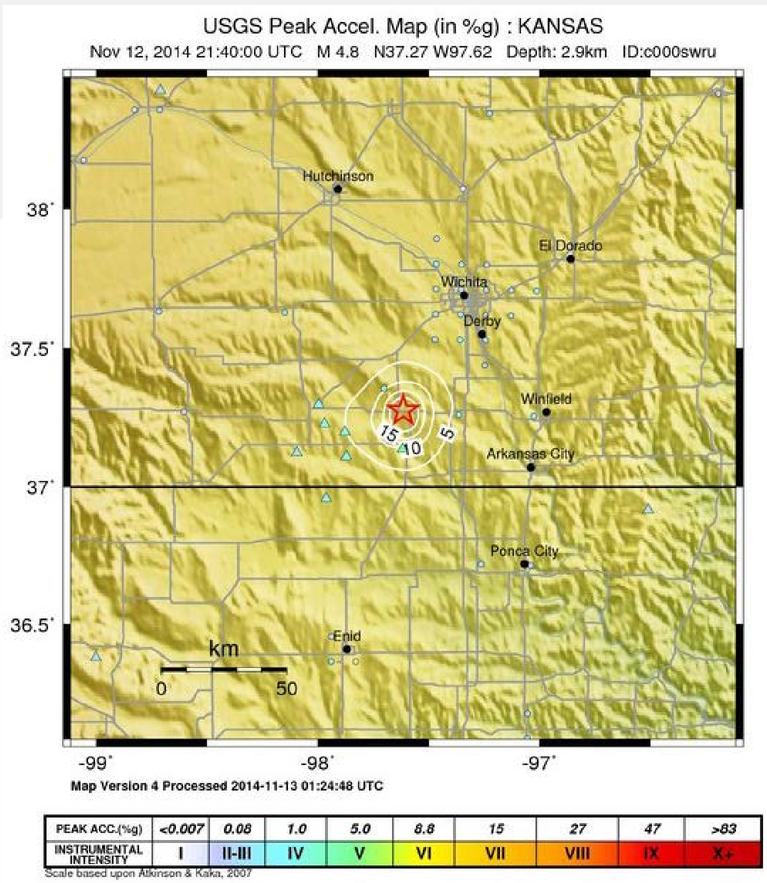


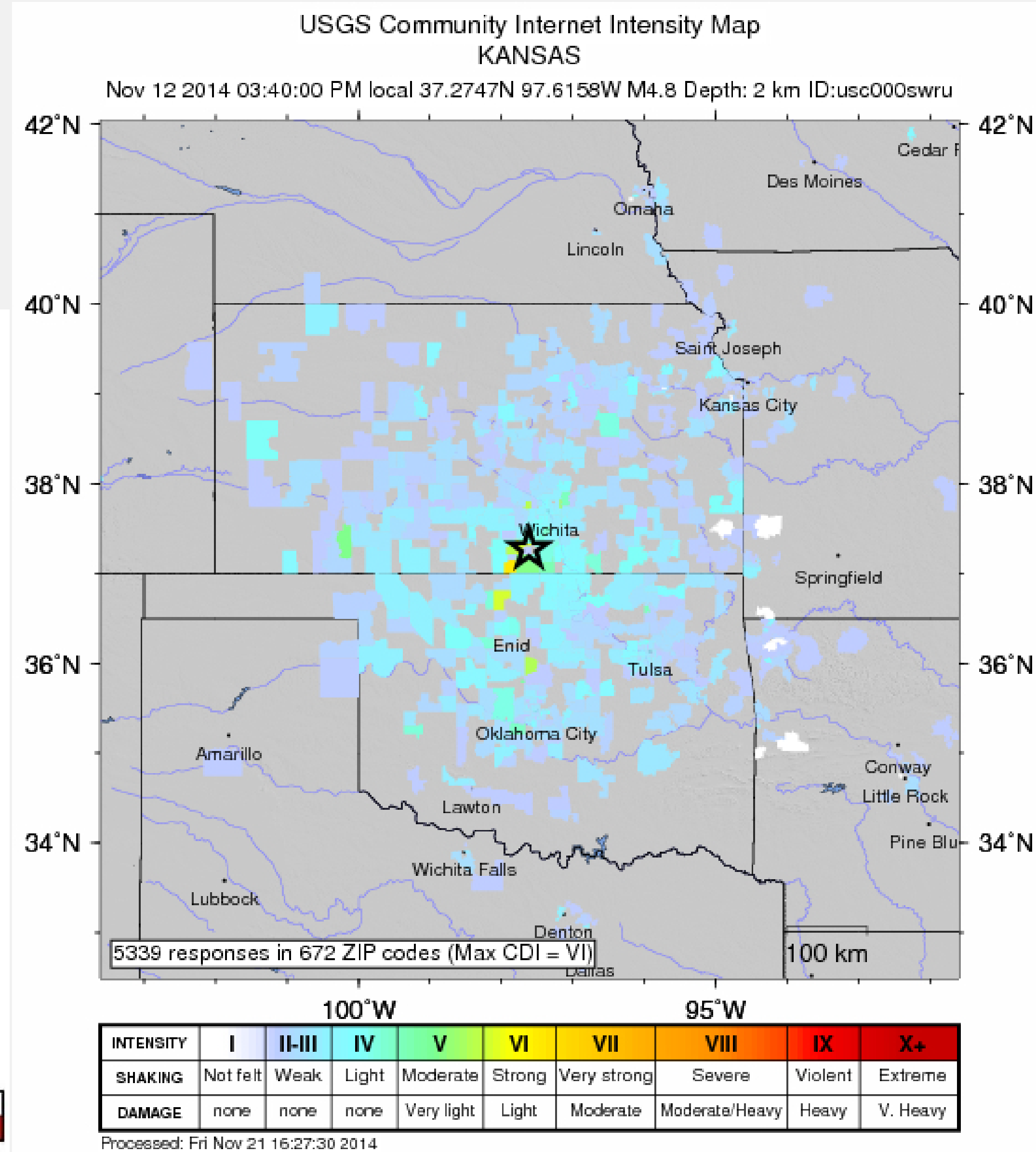
After Ellsworth, 2013

Why care about seismicity?

Surface hazard

- Injuries
- Property damage

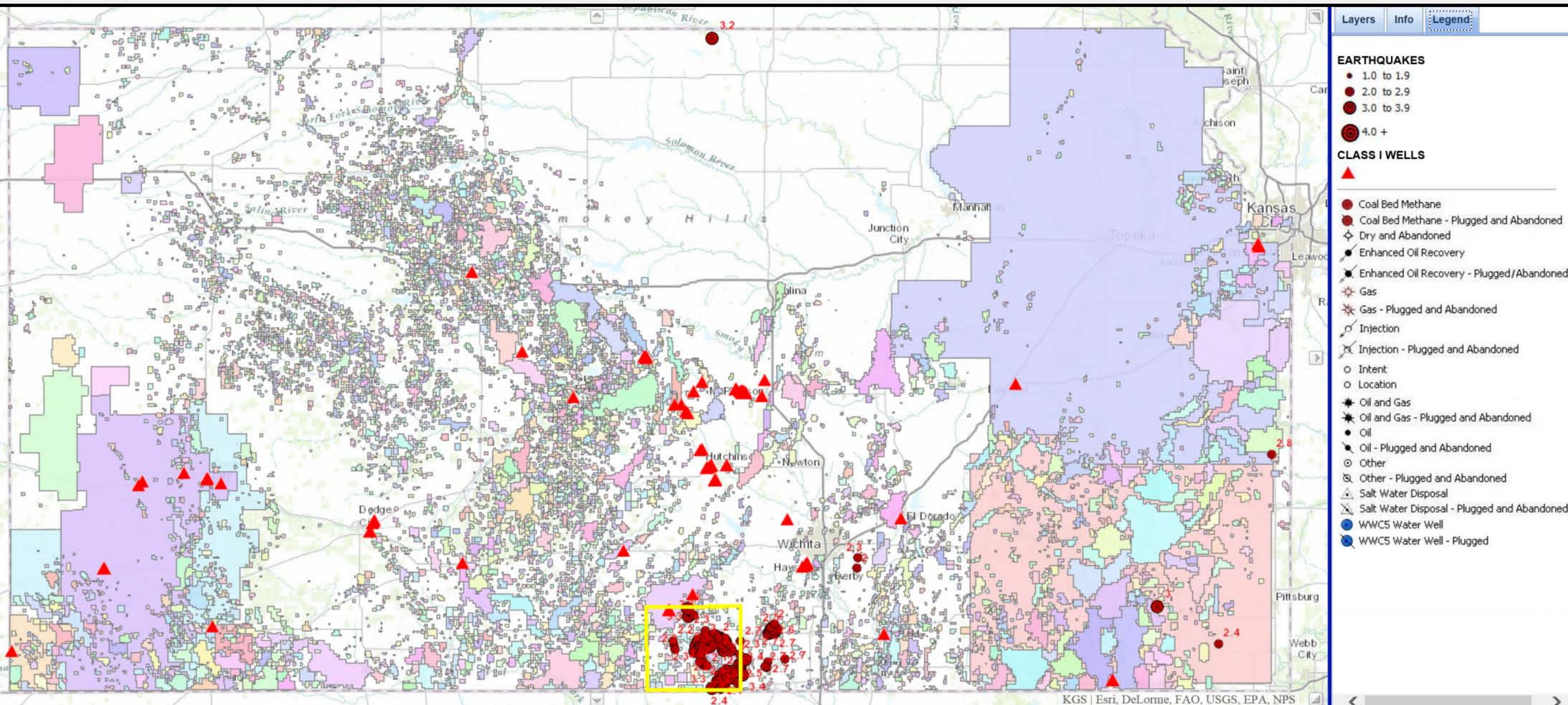




Subsurface hazard

47 active UIC Class I wells in state

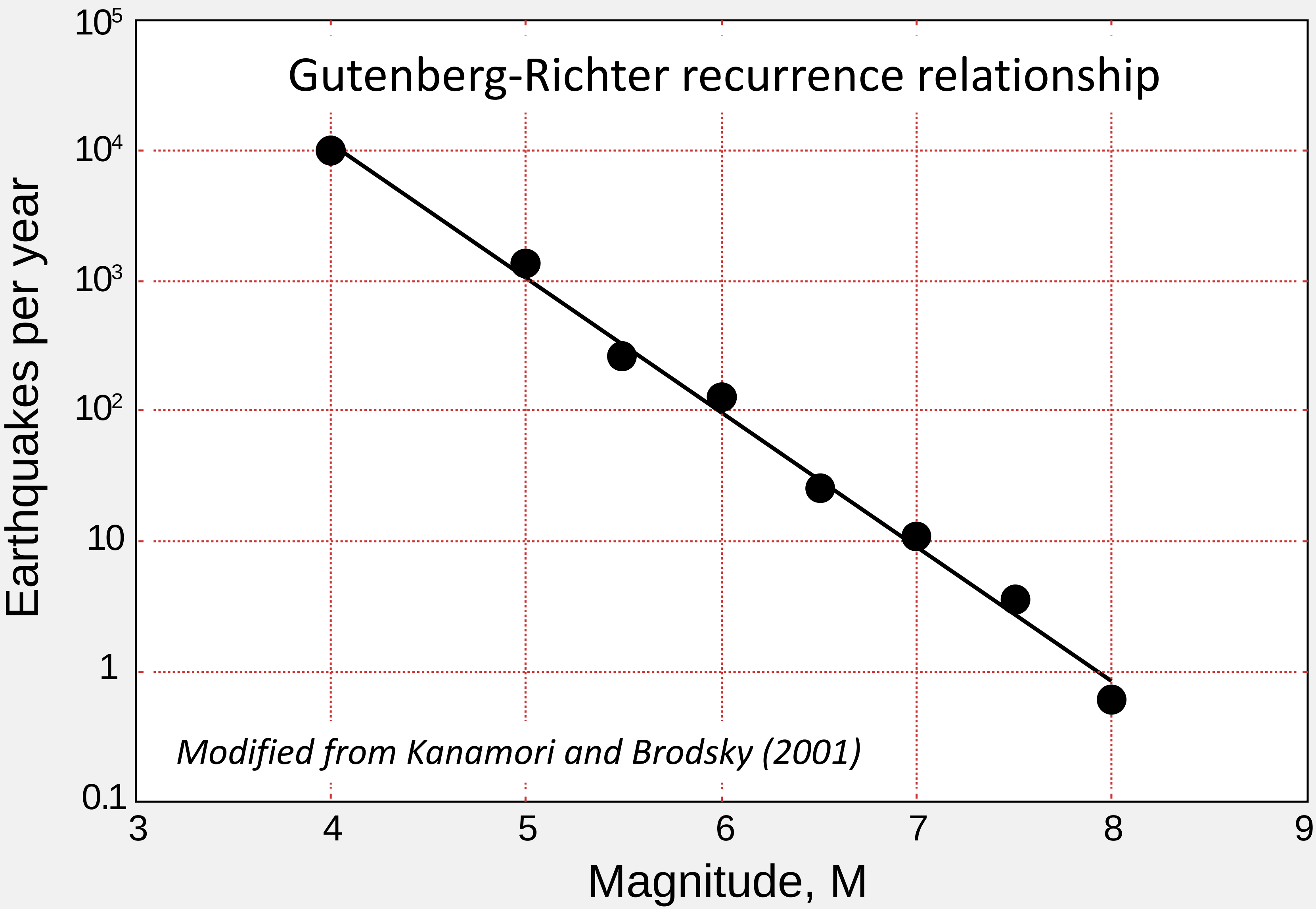
46 dispose of fluid within the Arbuckle



30 mi

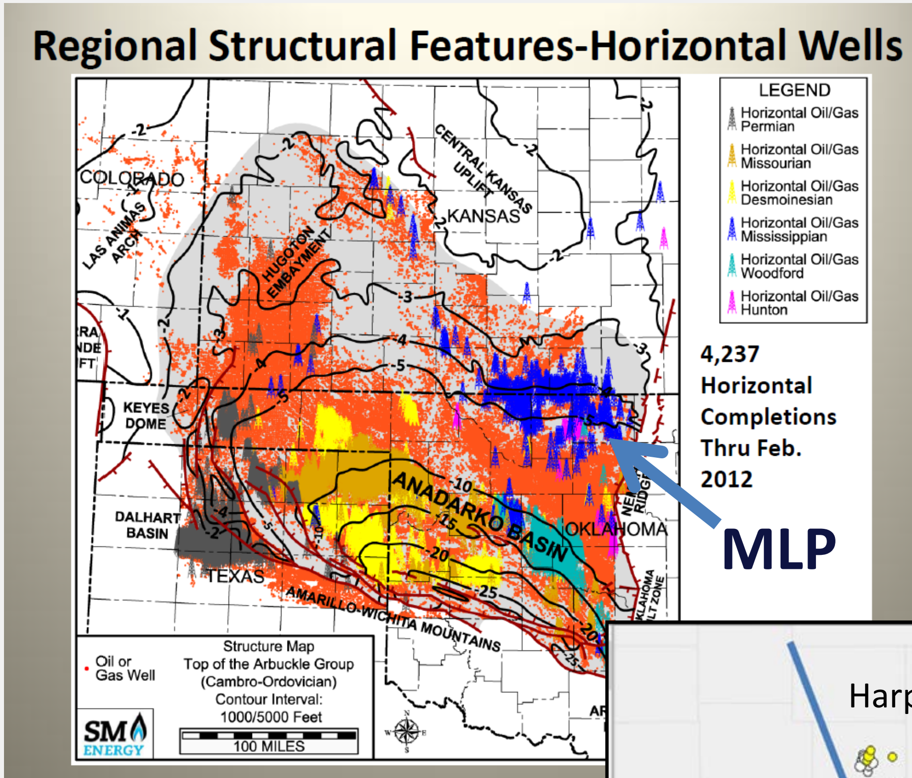
http://maps.kgs.ku.edu/co2/

Why care about seismicity?

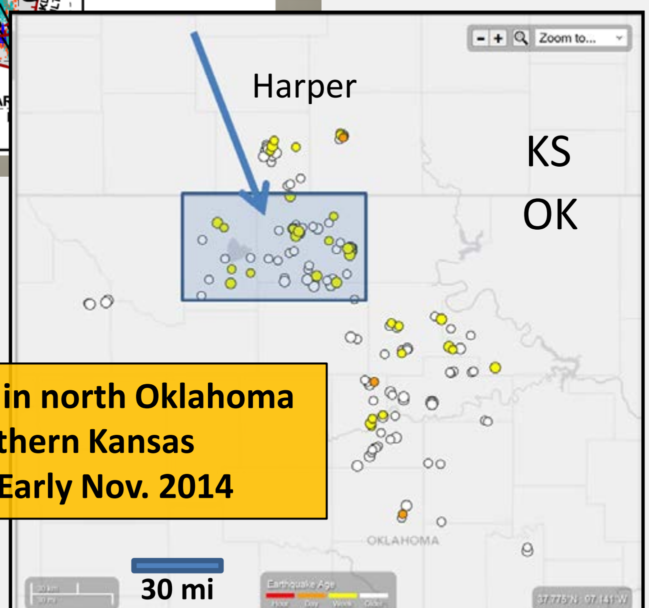


Mississippi Lime Play – Definition

-- on Anadarko Basin side of Nemaha Uplift



John Mitchell, retired
SM Energy Co.
Tulsa, Oklahoma
TGS, March 2012



Seismicity in north Oklahoma & southern Kansas
late Oct→Early Nov. 2014

Relevant structural elements of Arkoma and Anadarko Basin as basis for the MLP

- Concurrent and post Mississippian structural deformation
- Systematic reactivation of basement weaknesses defined by potential fields & basement terrain
- Inherited fracture systems
- Major wrench fault systems directed stress into craton during Late Paleozoic
- Major influence on regional/local maturation of organic matter, migration routes and trapping of oil and gas

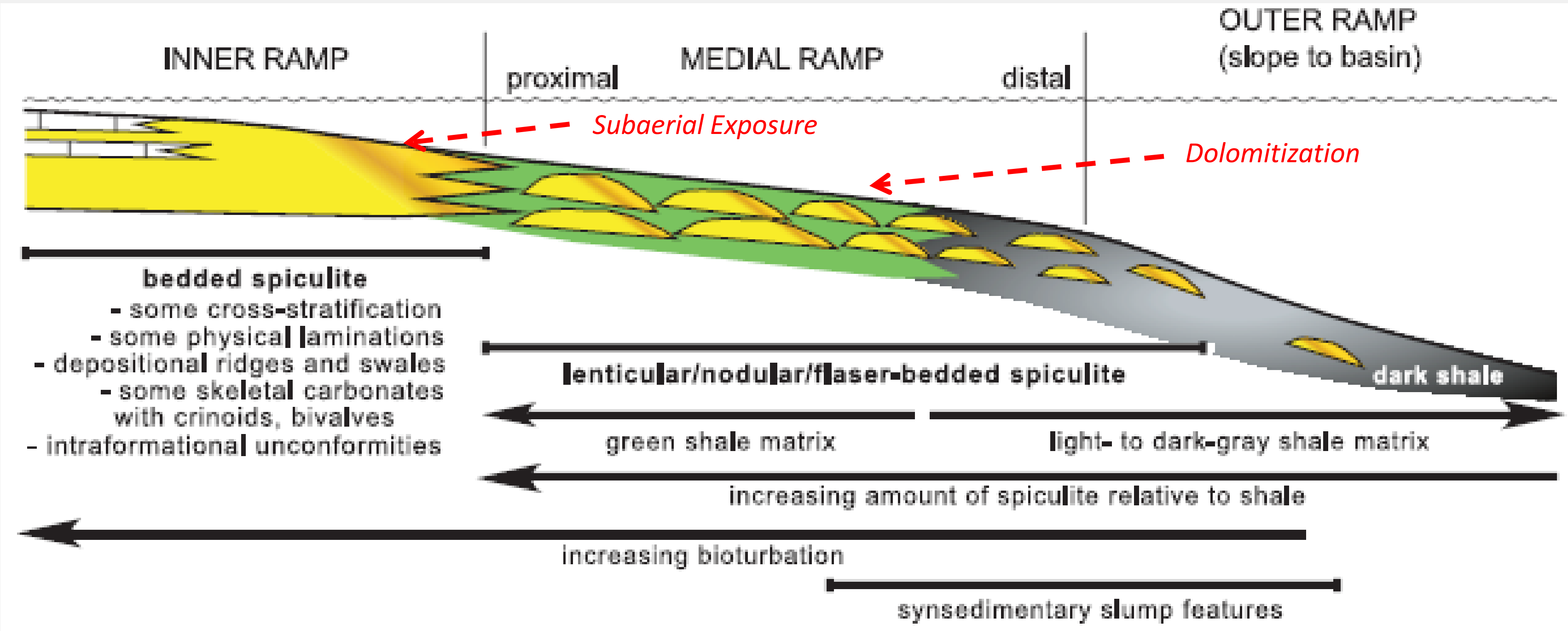
Spectrum of potential reservoir lithofacies

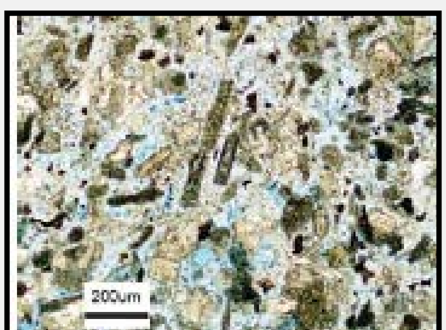
Inner Ramp Tripolite to Outer Ramp Basinal Shale Depositional Model

North

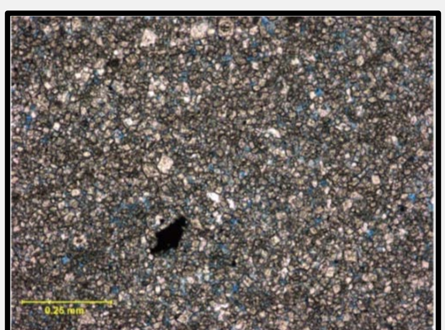
Modified from S. J. Mazzullo, Brian W. Wilhite, and I. Wayne Woolsey (2009)

South

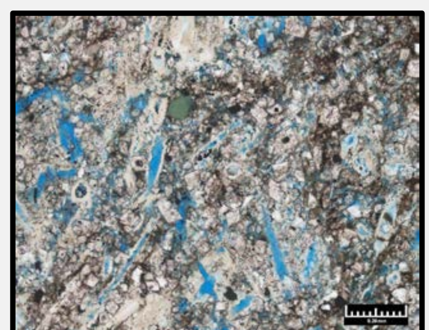




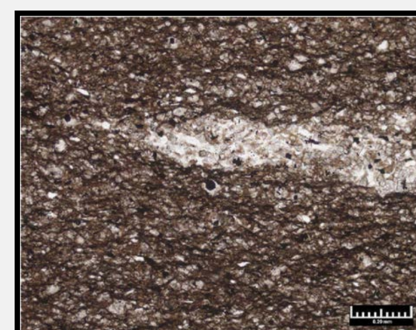
tripolite



cherty dolomite



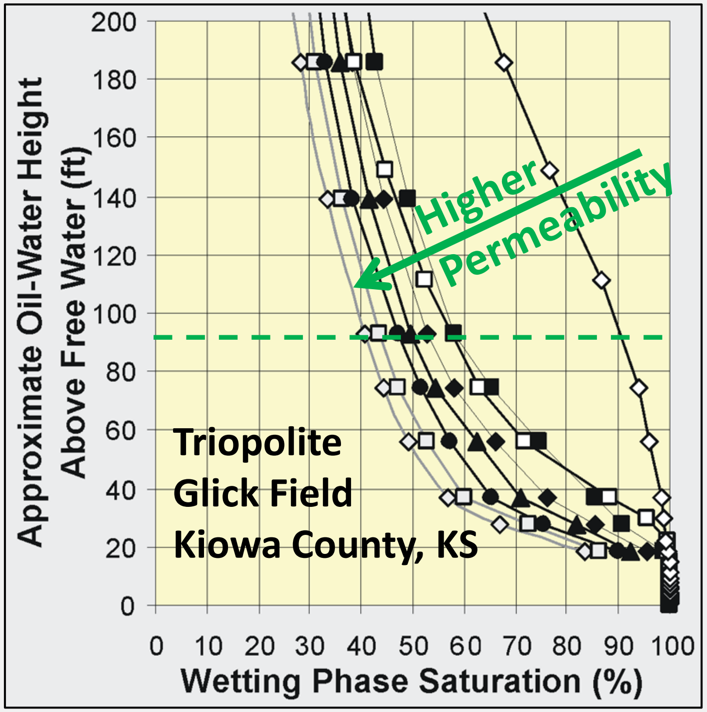
dolomitic spiculite

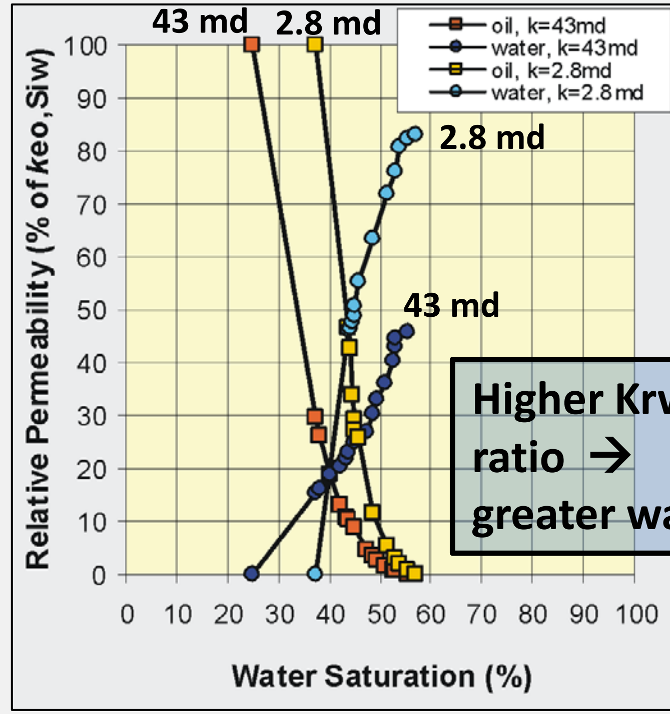


argillaceous, organic dolomitic siltstone

MLP reservoirs

More permeable chert reservoir and greater distance above free water level → *lower water cut*

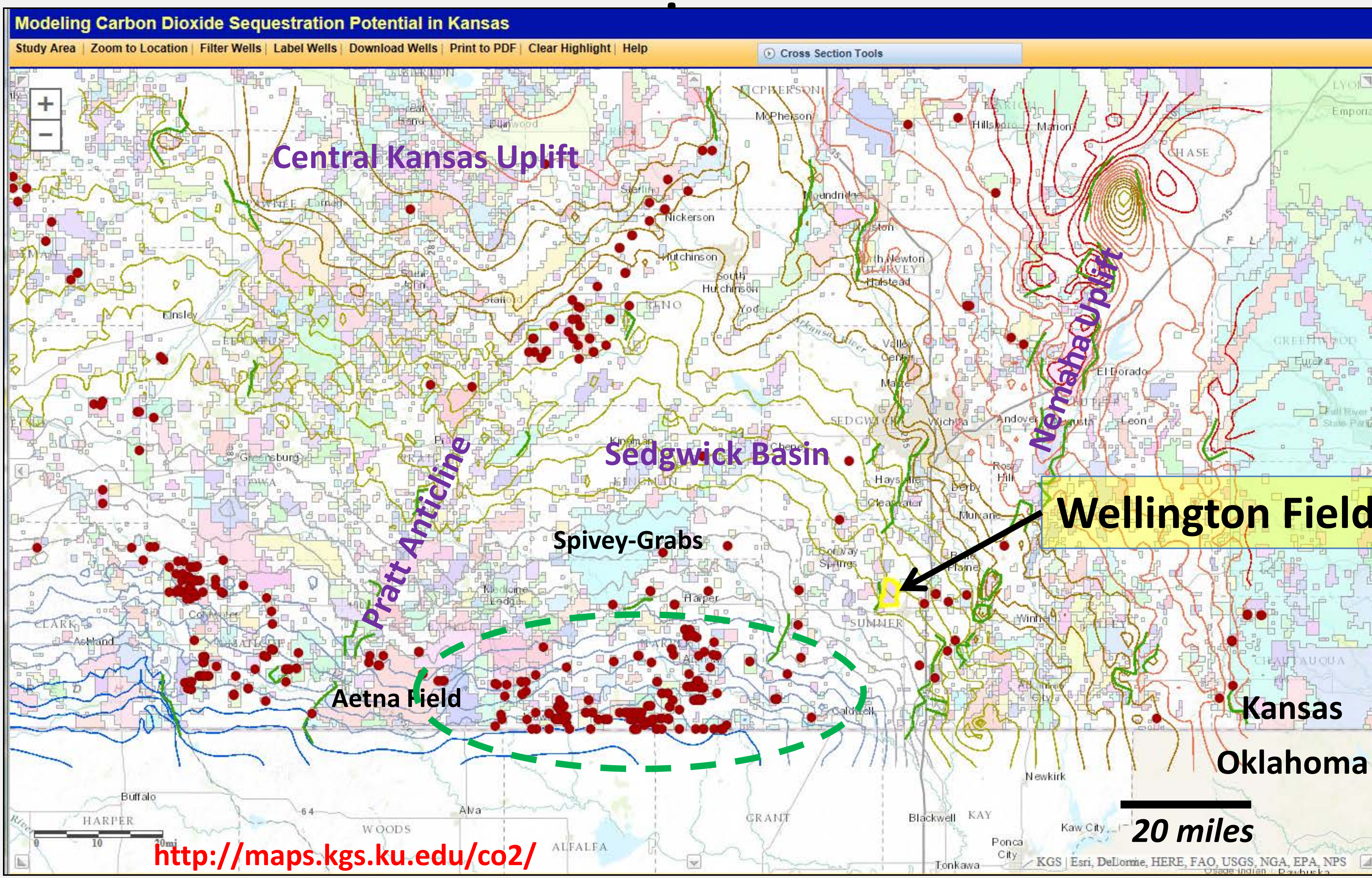




Higher Krw/Kro ratio → greater water cut

"High bound water saturations in the tripolitic chert have led to difficulty in estimating reserves and determining producible zones. This problem in water saturations is further complicated by difficulty in establishing free water level. While some fields exhibit apparent structural closure greater than 200 feet, the presence of nearly isolated blocks of production within these fields surrounded by nonproductive areas may indicate that there is not a continuous hydrocarbon column and that free water level is independently established for each block". -- Watney, Guy, Byrnes (2001)

Focus of MLP in Sedgwick Basin in south-central Kansas

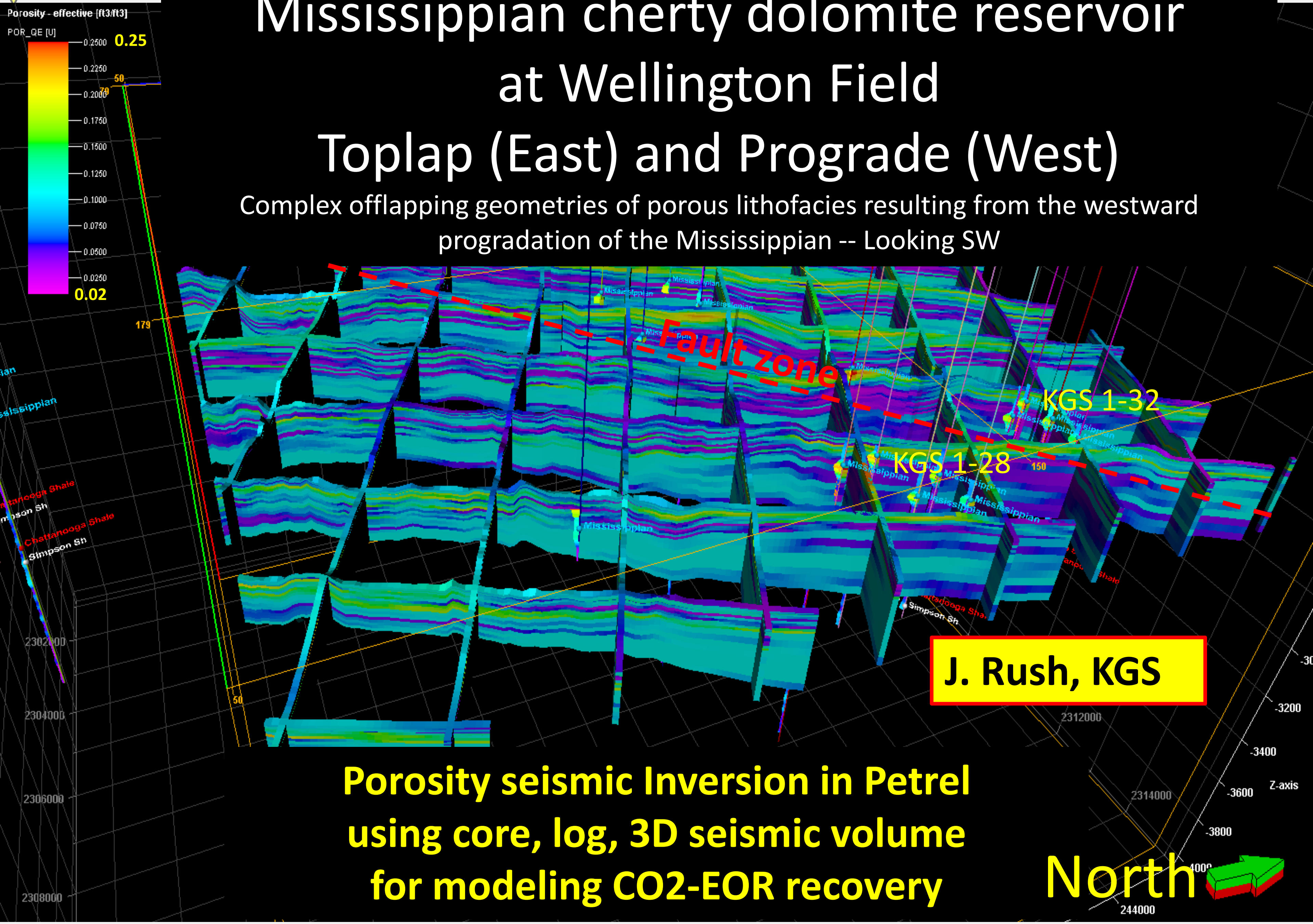


Horizontal wells drilled since January 2011

Mississippian structure (450 ft C.I.) and notable faults (green lines)

Mississippian cherty dolomite reservoir at Wellington Field
Toplap (East) and Prograde (West)

Complex offlapping geometries of porous lithofacies resulting from the westward progradation of the Mississippian -- Looking SW

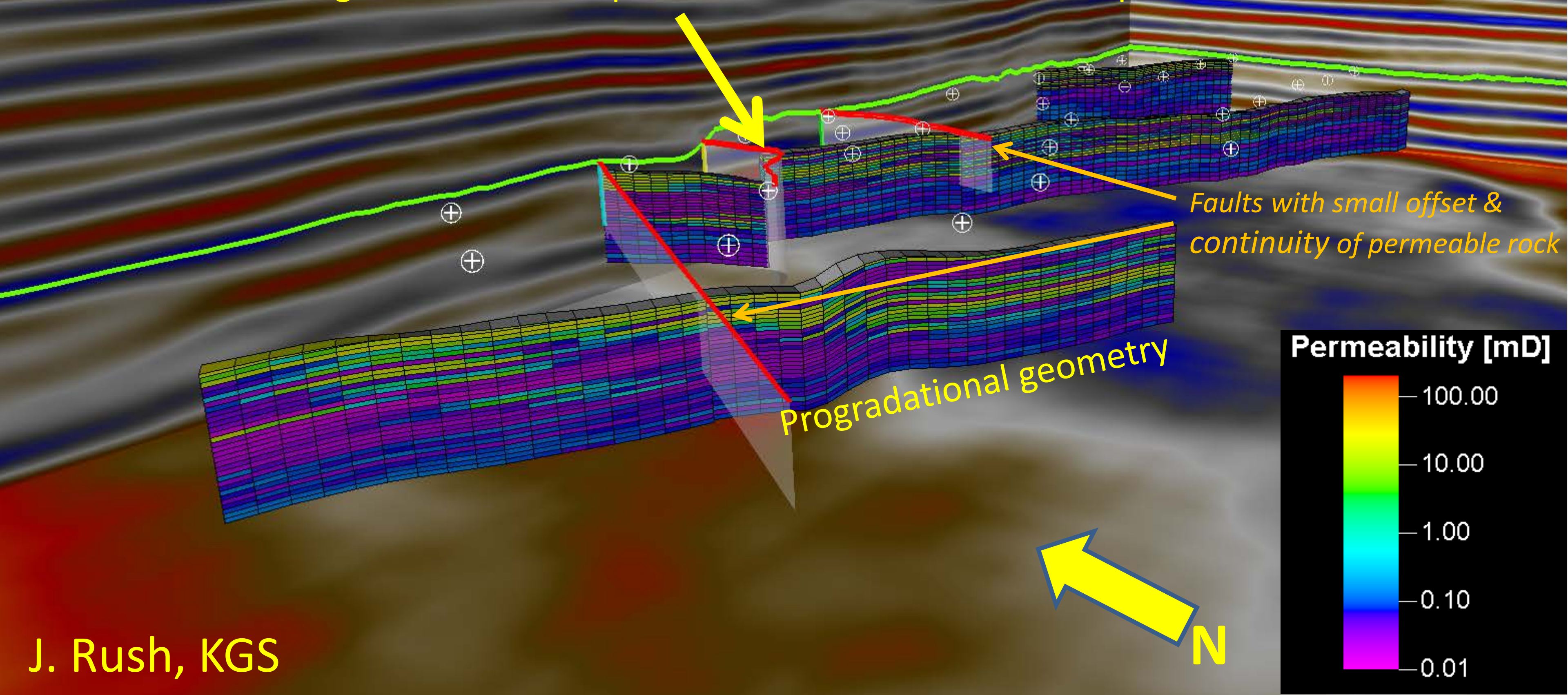


Porosity seismic Inversion in Petrel using core, log, 3D seismic volume for modeling CO2-EOR recovery

Permeability fence diagram of Mississippian oil reservoir within 3D seismic, Wellington Field

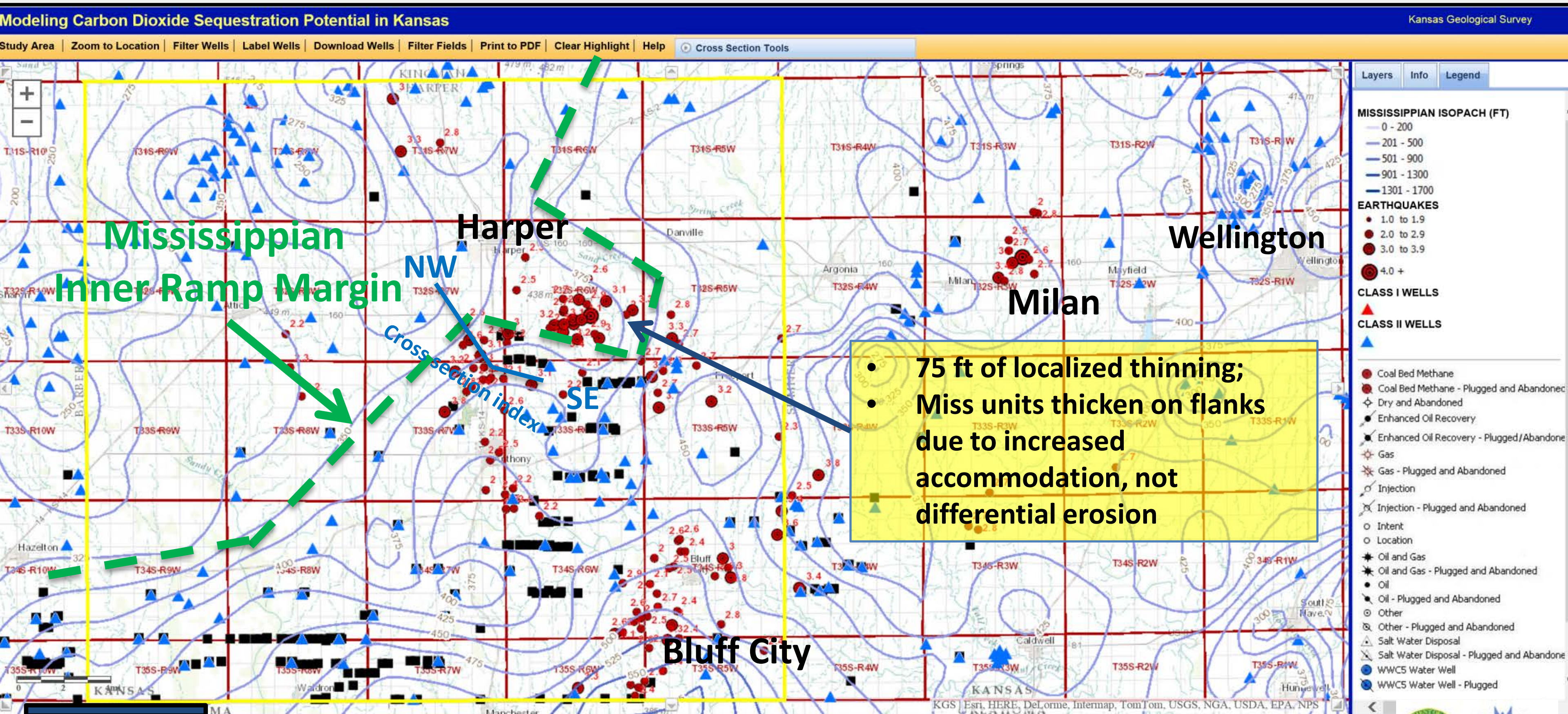
--Small faults that tip out above the top of the Mississippian reservoir

- View looks to the northeast
- Fault juxtaposes reservoir and non reservoir facies (at arrow tip)
- Fault offset ~30 ft and laterally discontinuous
- Faults serve as potential barriers to flow or redirect CO_2 plume depending on fault damage and juxtaposed rocks
- Faults aligned SW-NE oblique to maximum horizontal compressive stress



J. Rush, KGS

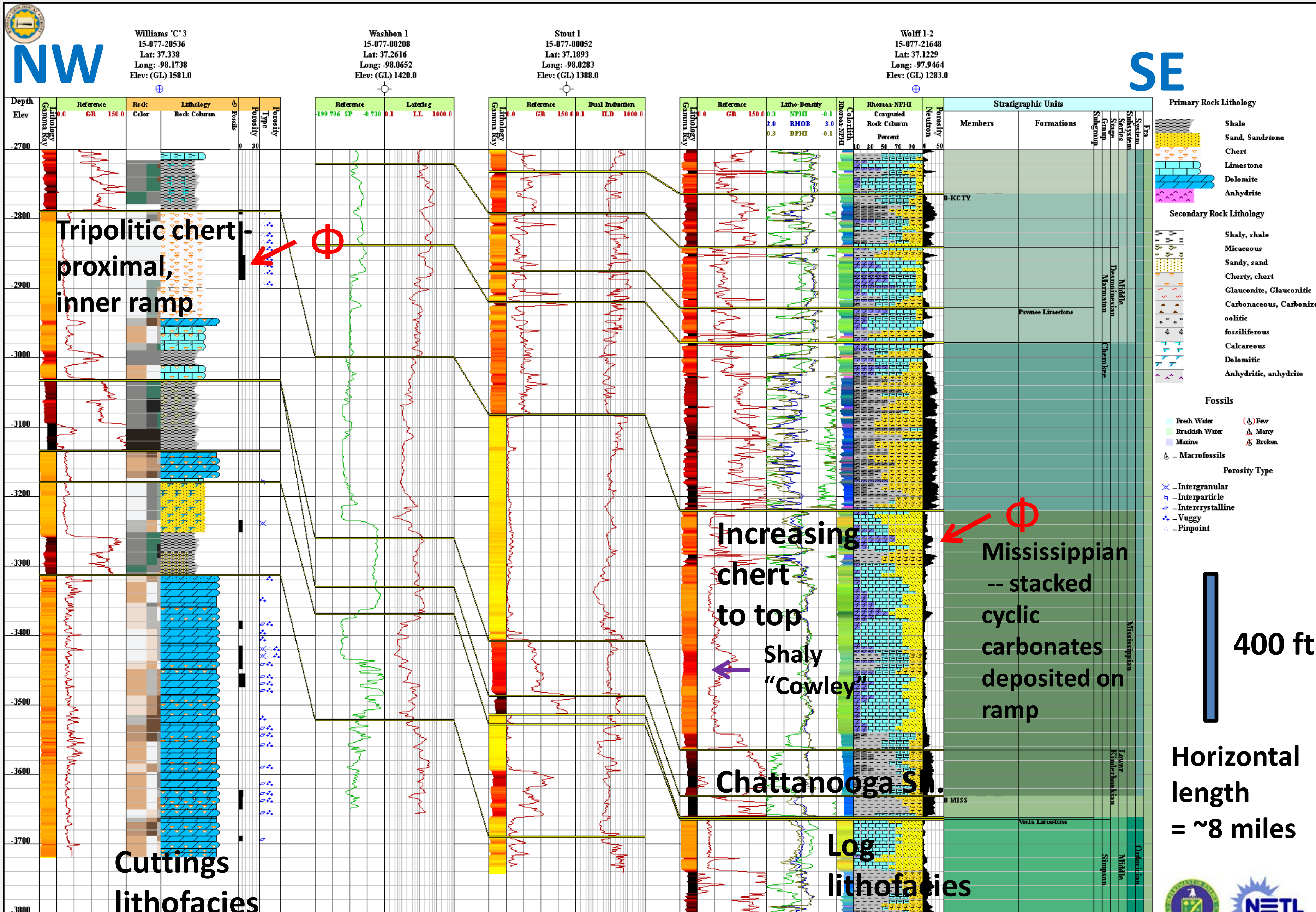
Mississippian isopachous map with horizontal (■) and Class II wells (▲)



Stratigraphic correlations and mapping by Gerlach and Nicholson, DOE-CO2

Earthquakes and magnitude 2.2

NW-SE structural cross section across updip edge of Miss ramp

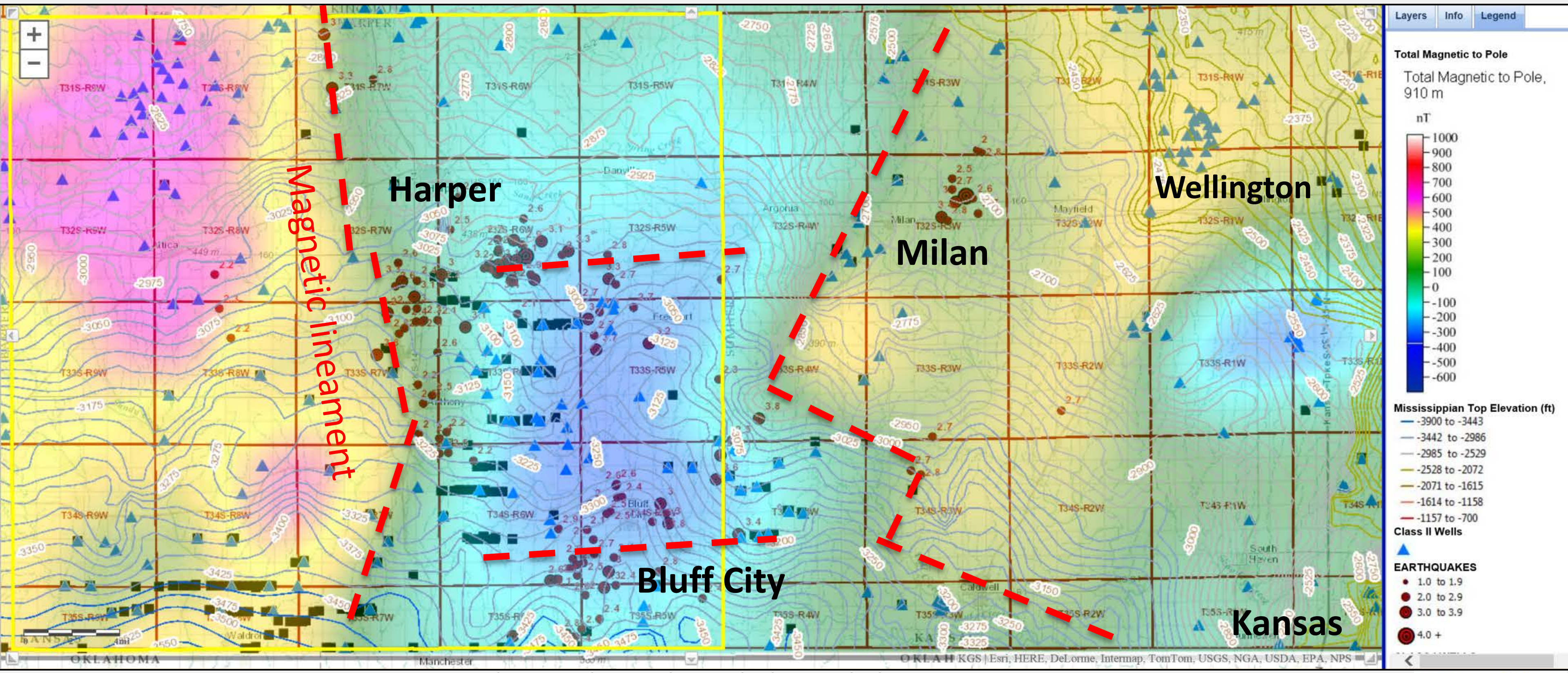


Stratigraphic correlations by Gerlach & Nicholson – DOE-CO2

Heart of MLP in the core of the southern extension of the Midcontinent Rift System (*magnetic low*)

Total magnetic field intensity reduced to pole 910 m + top Mississippian structure

Harper County (yellow outline)



5 mi

Stratigraphic correlations by Gerlach & Nicholson – DOE-CO2
http://maps.kgs.ku.edu/co2/

Oklahoma

Earthquakes along edges of magnetic lineaments

-- Suggest link of earthquakes to basement structure

Production trends

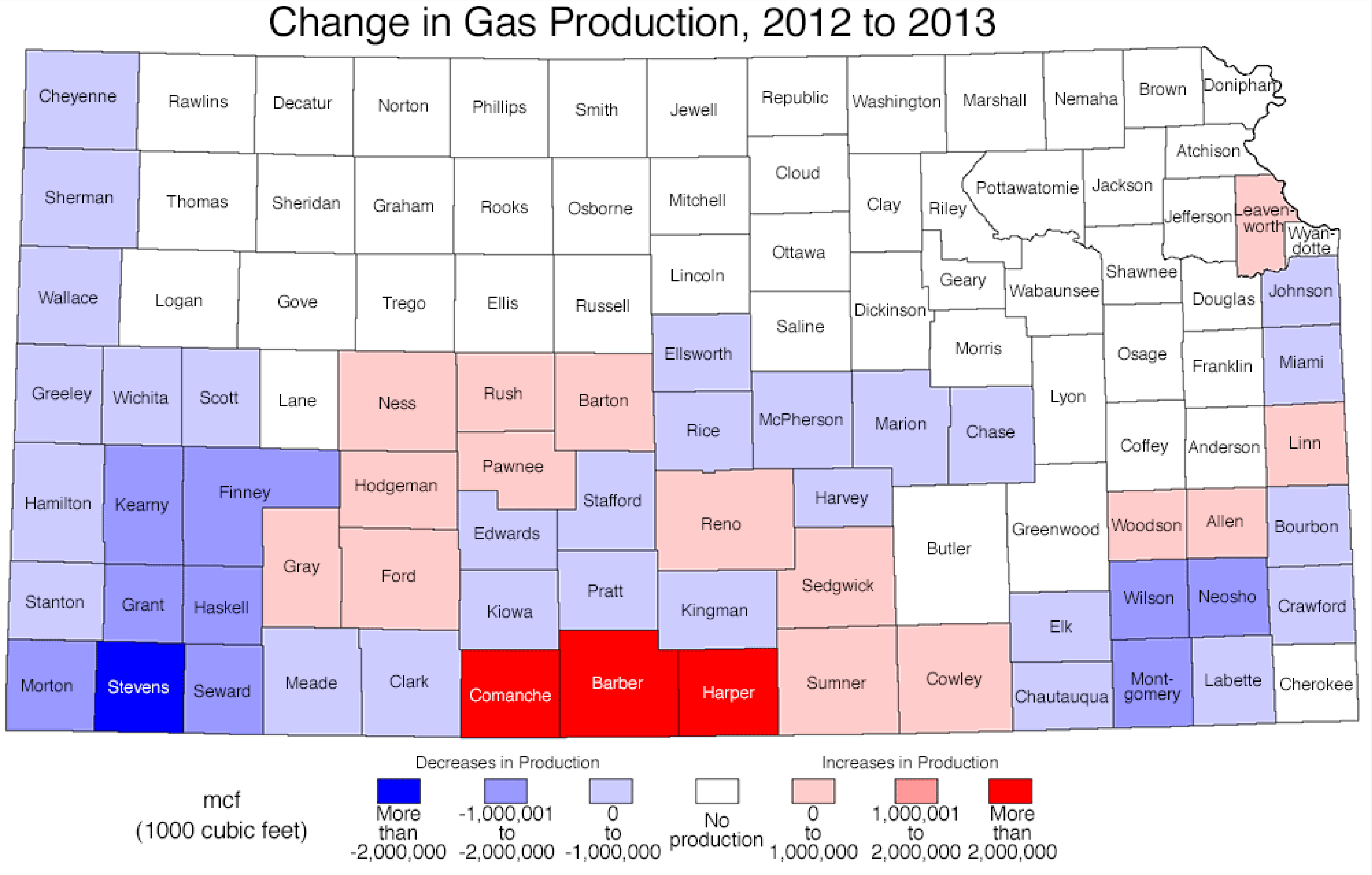


Figure courtesy of D. Adkins-Heljeson (KGS)

Production trends

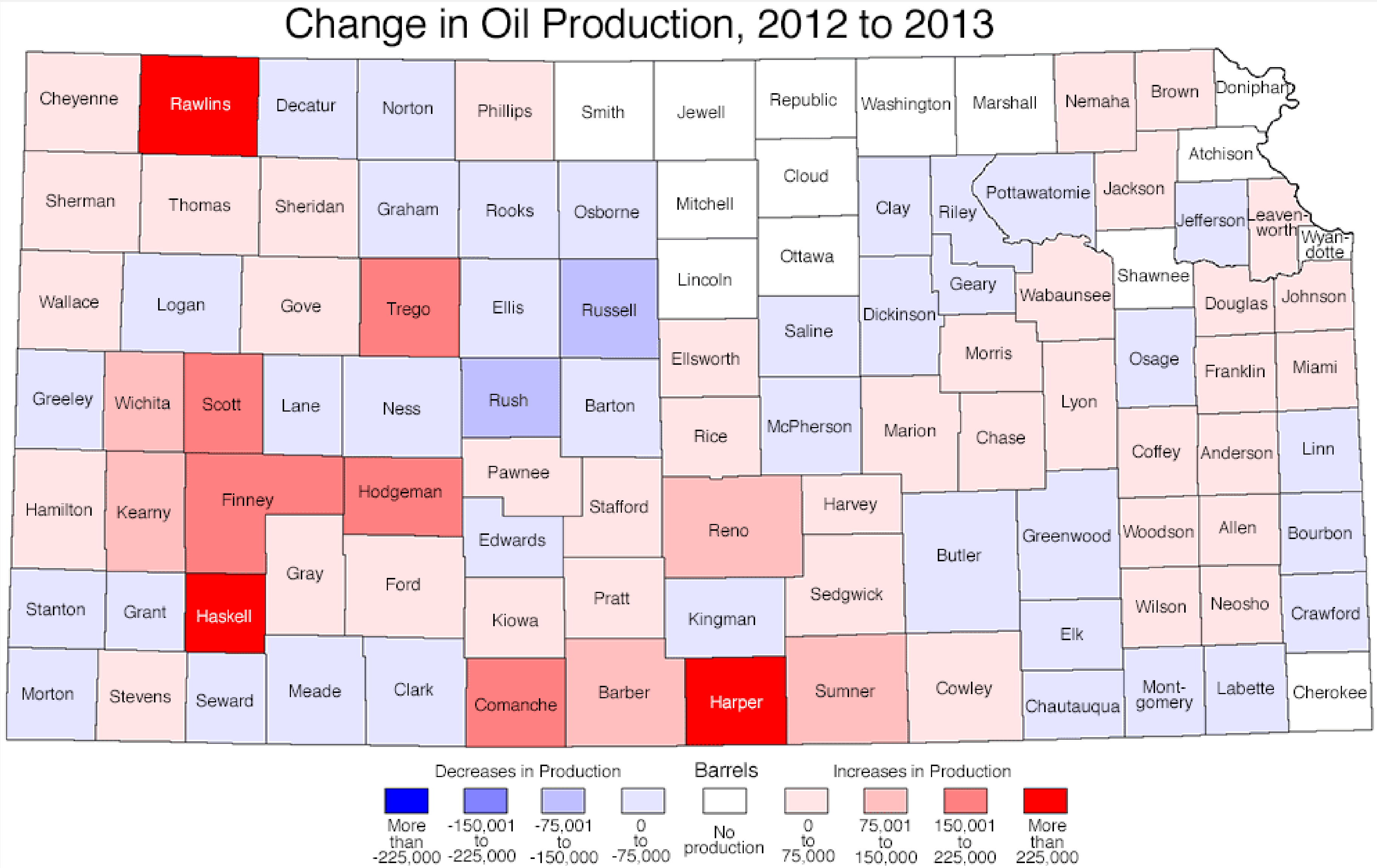
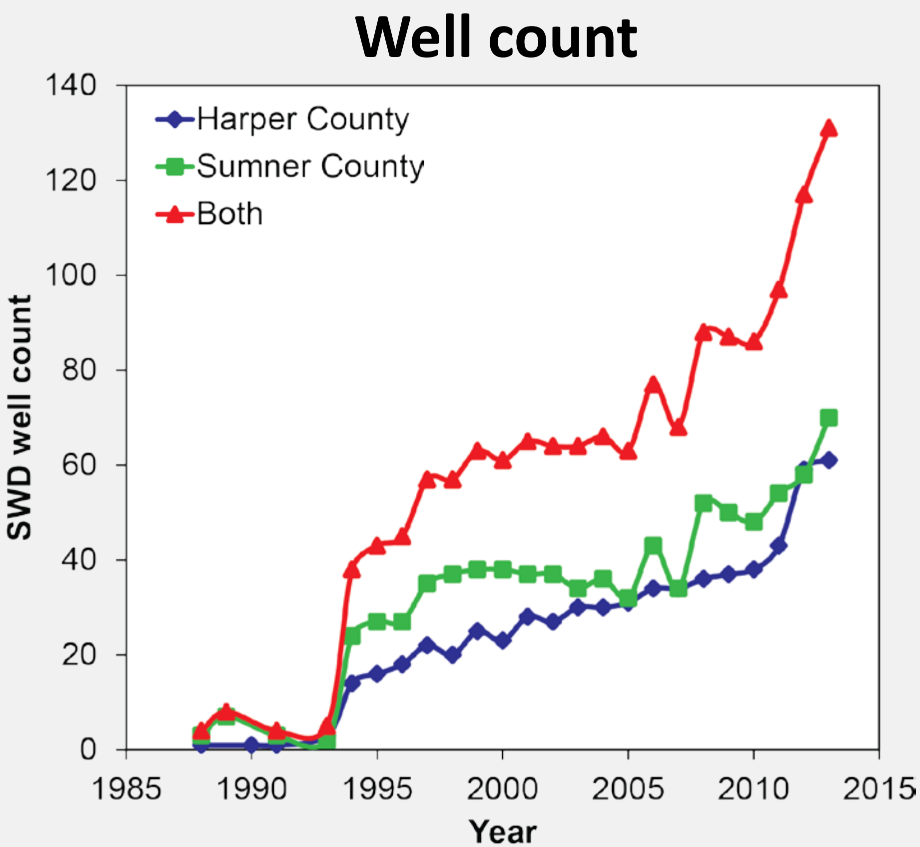
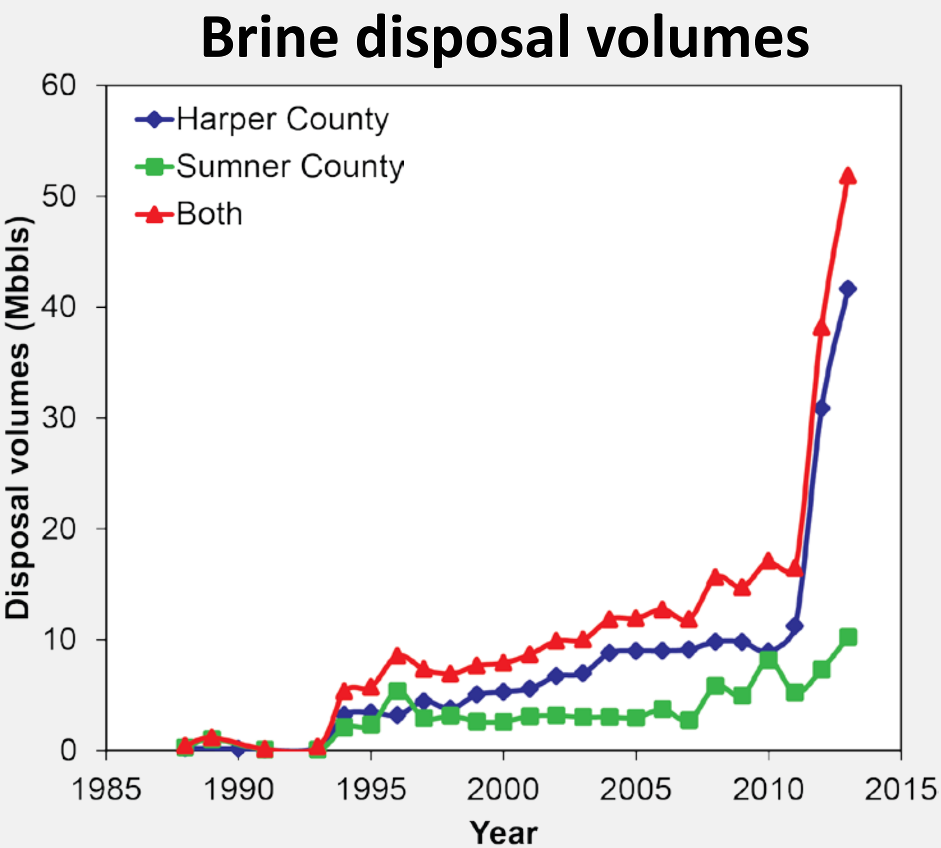


Figure courtesy of D. Adkins-Heljeson (KGS)

Brine disposal trends



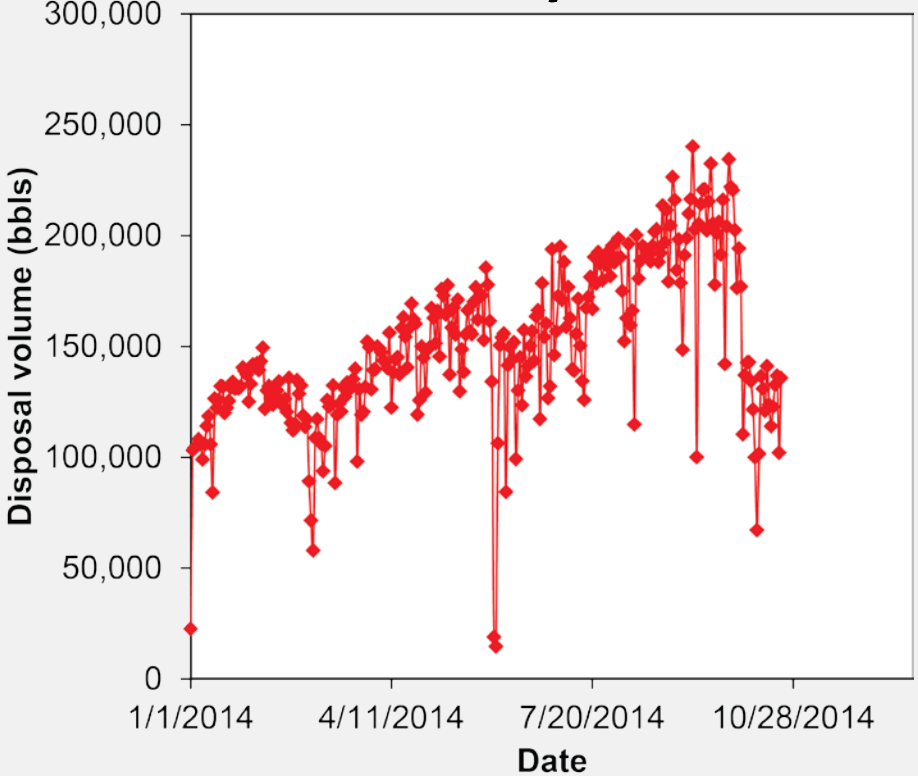


- Well count has doubled since 2005
- 6-fold increase in yearly disposal volumes since mid-1990s
- Yearly volumes have tripled since 2011

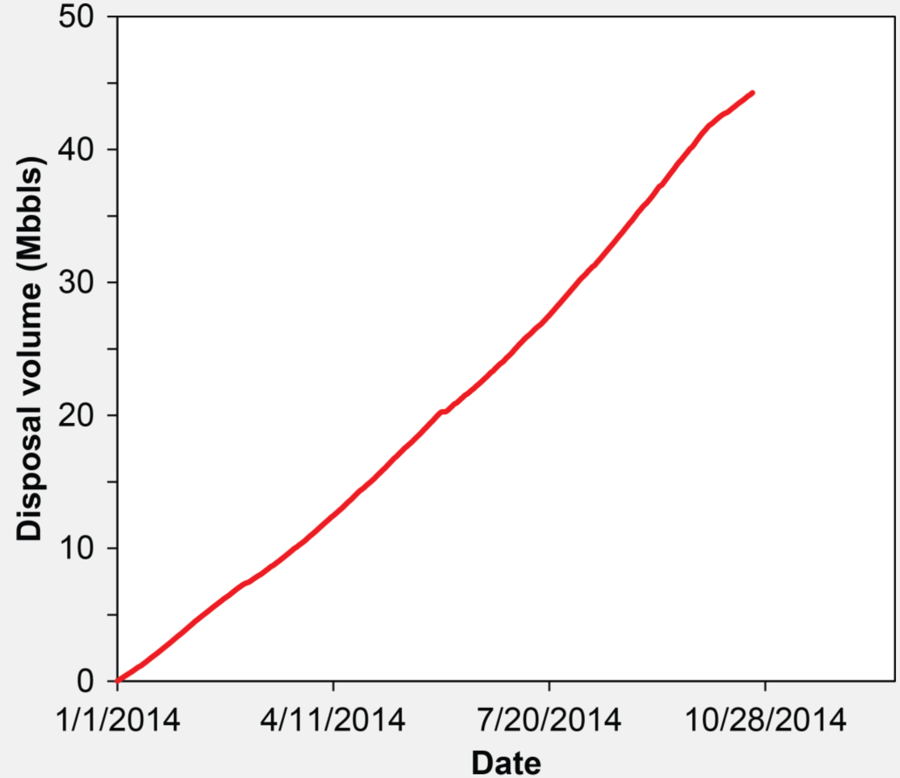
Data courtesy of the KCC

Brine disposal trends

2014 Daily volumes



2014 cumulative volume



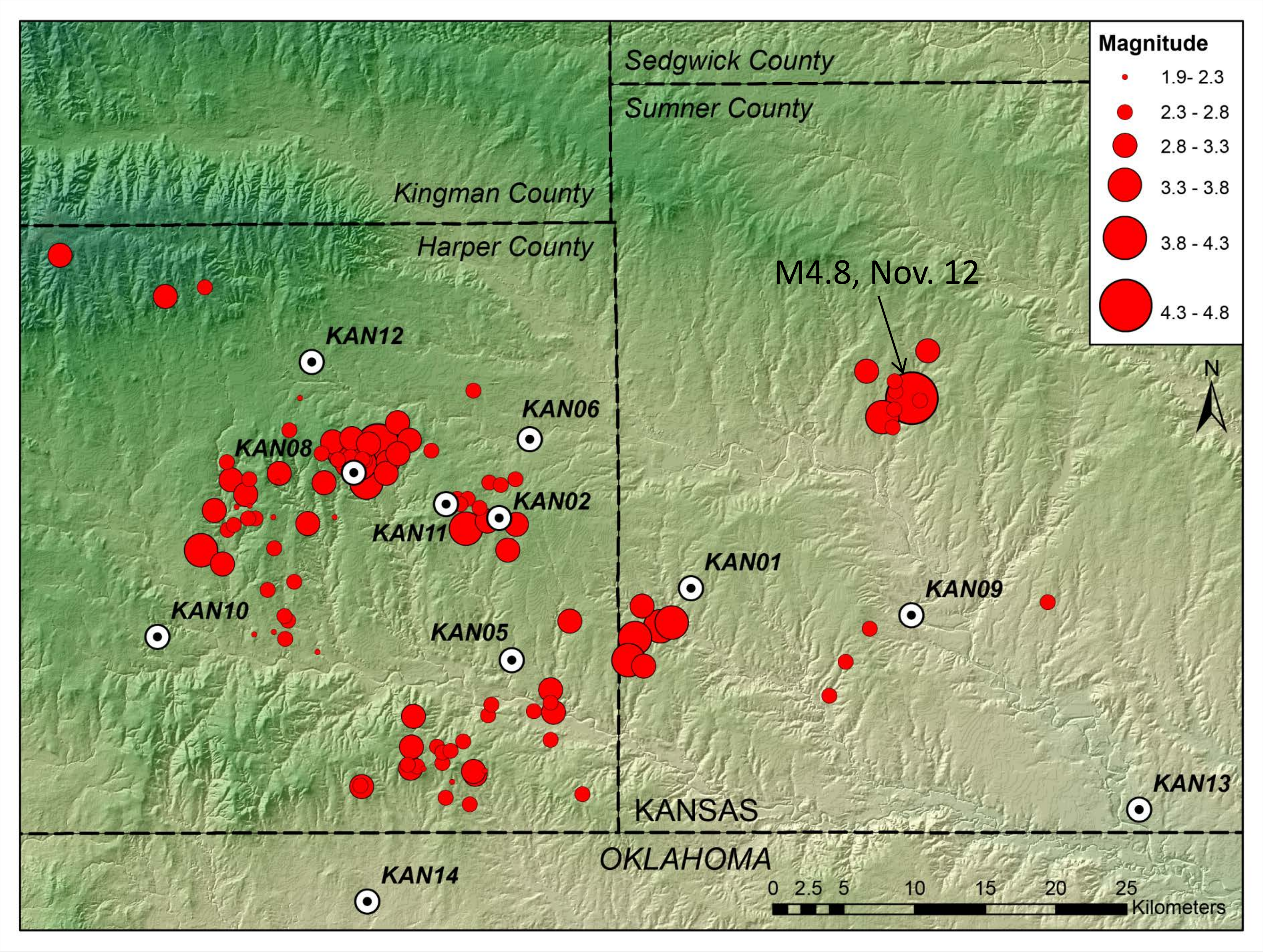
- Daily disposal data from 22 of 131 SWD wells
- Expect large increase between 2013 and 2014

Data courtesy of the KCC

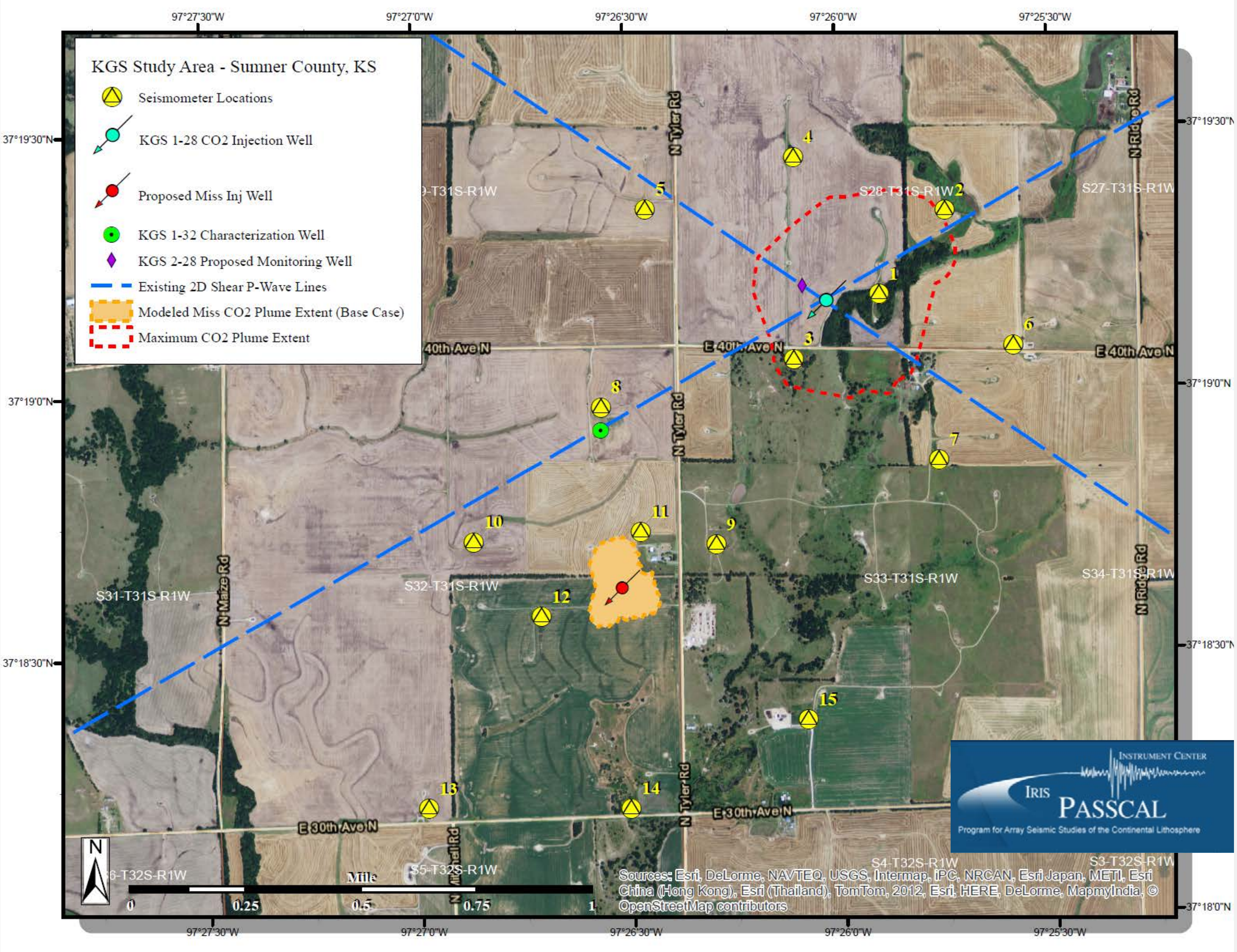
Current research

1. Where are faults or potential hazards located?
   - Seismic monitoring
   - Lineament and fault mapping
2. What are the pressures or stress changes needed to trigger or reactivate those faults?
   - *In situ* stress field analysis
   - Reservoir-geomechanical modeling of fluid injection

Seismic monitoring: USGS



Seismic monitoring: Wellington Field



Wellington seismic network

Courtesy of R. Miller and S. Petrie, KGS

Seismic monitoring: KGS network

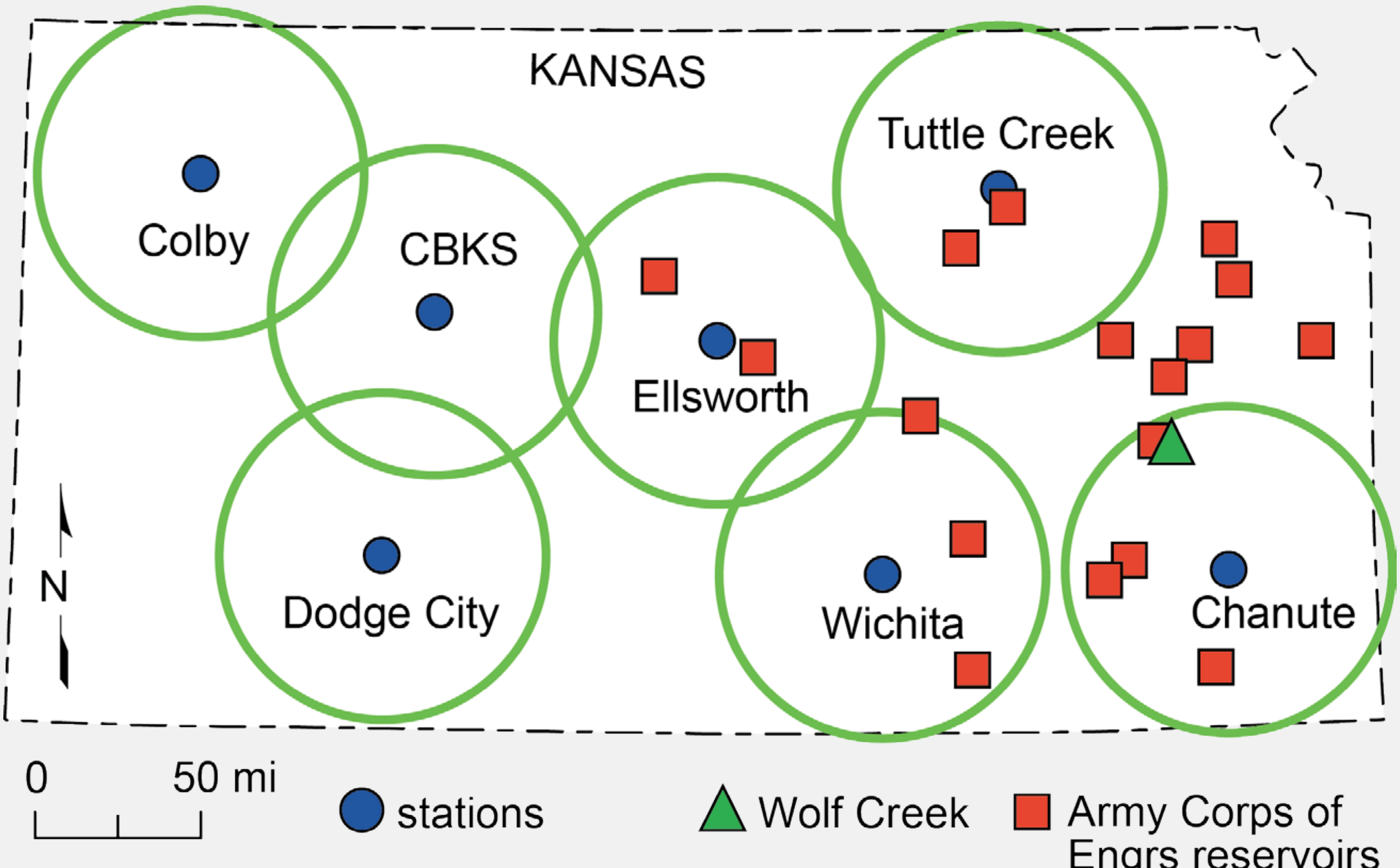
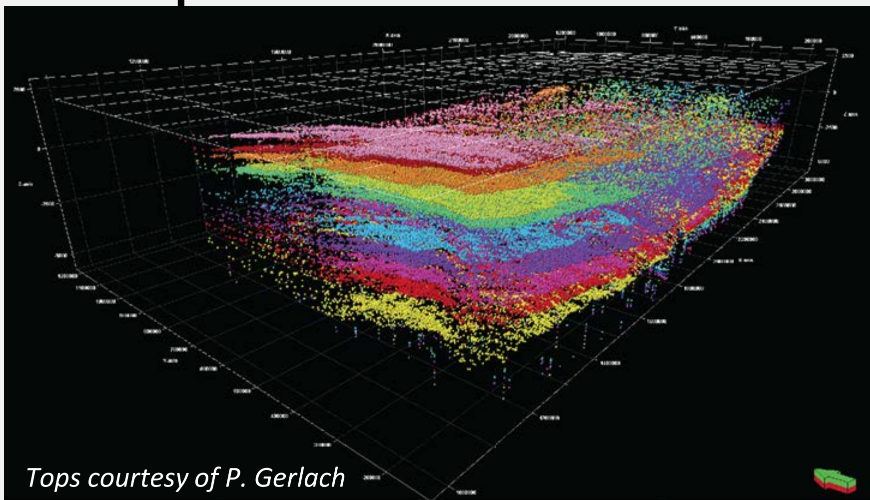


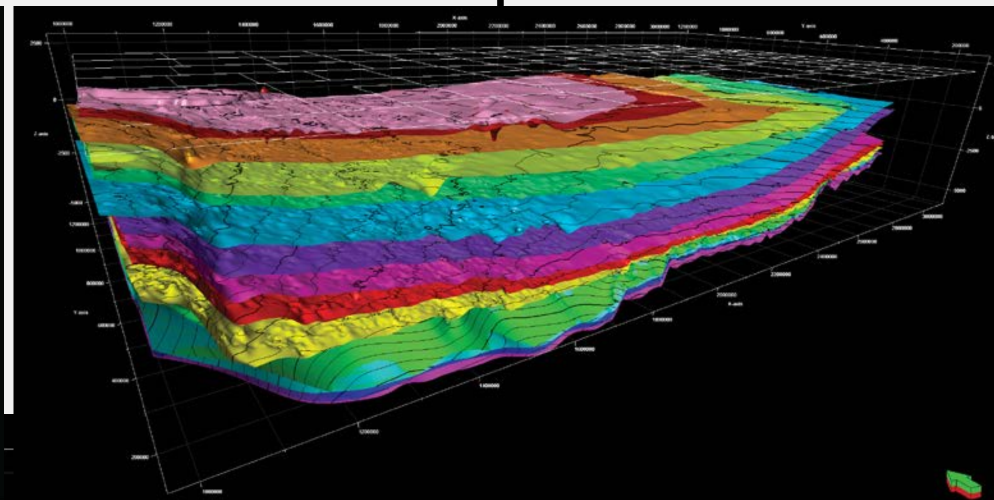
Figure courtesy of R. Miller (KGS)

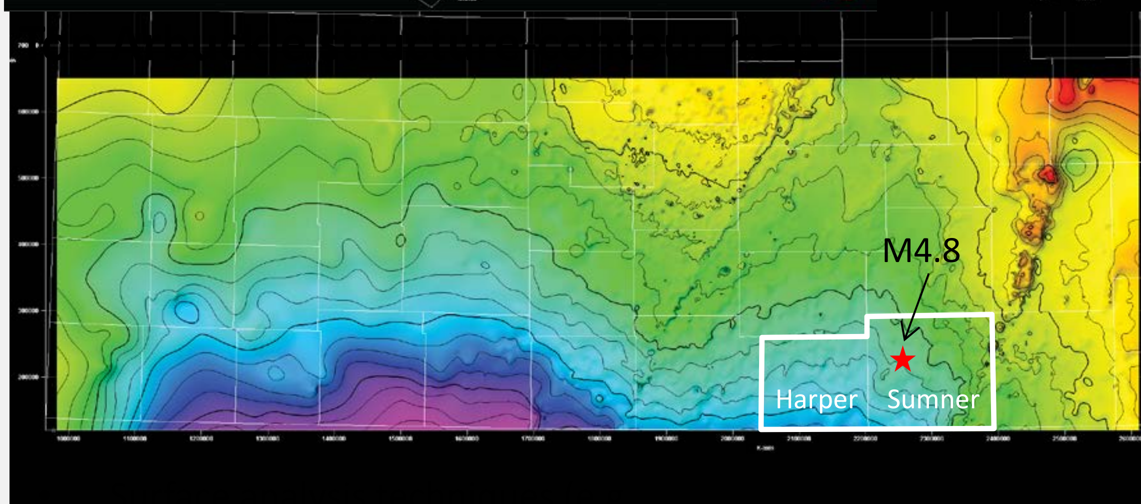
Subsurface lineaments

Well tops database

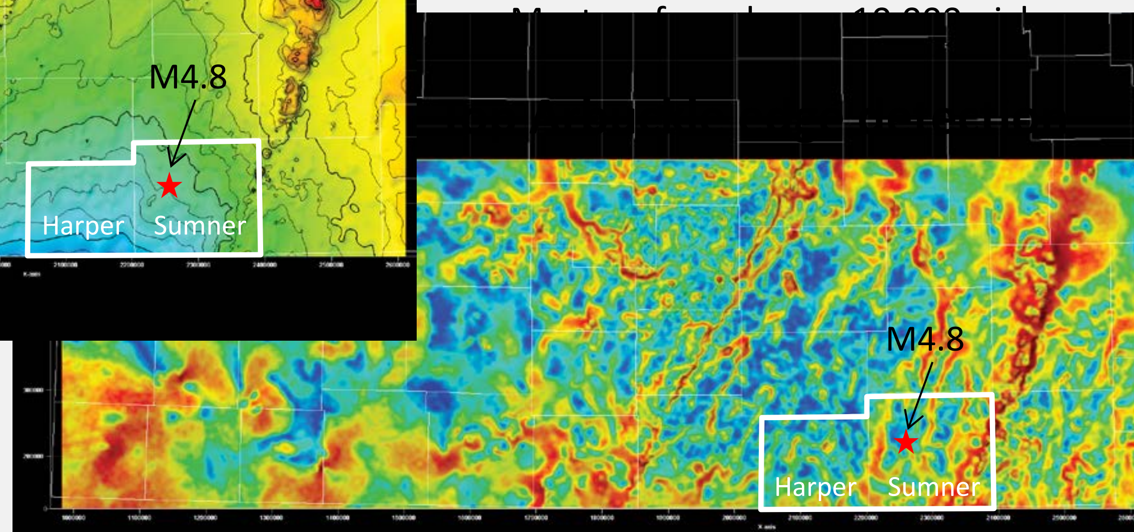


Structure contour maps





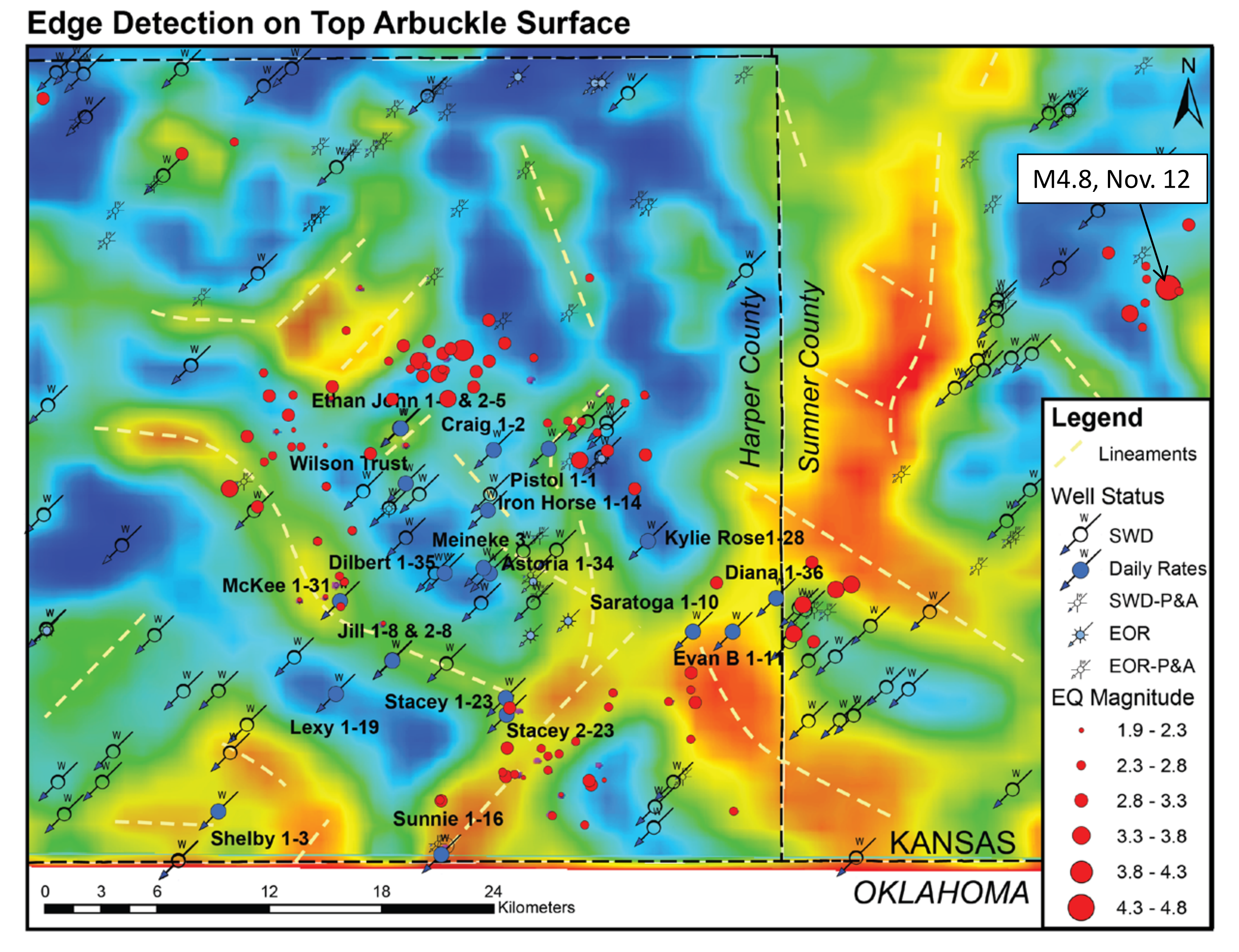
- Well tops from 18 regional stratigraphic surfaces



slope, curvature, residual analysis, etc.)

- Compare to surface lineaments and potential field discontinuities

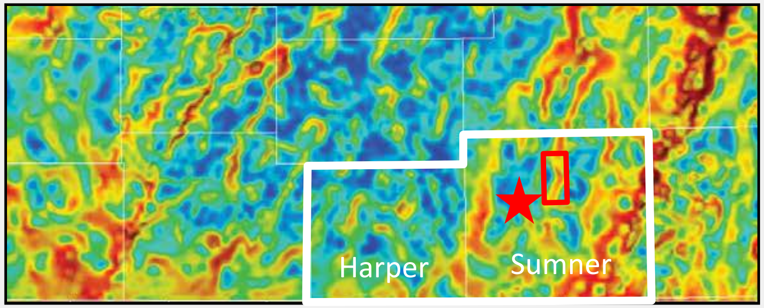
Fault mapping: Subsurface lineaments

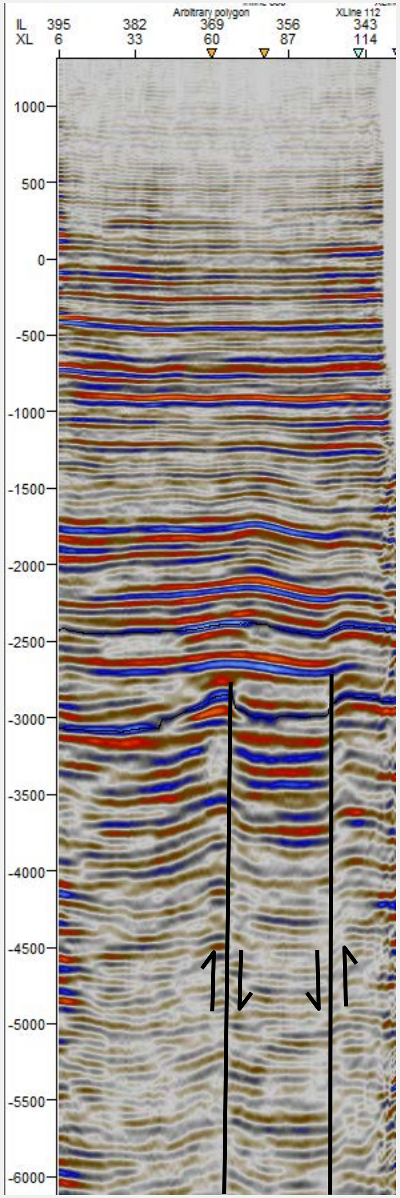


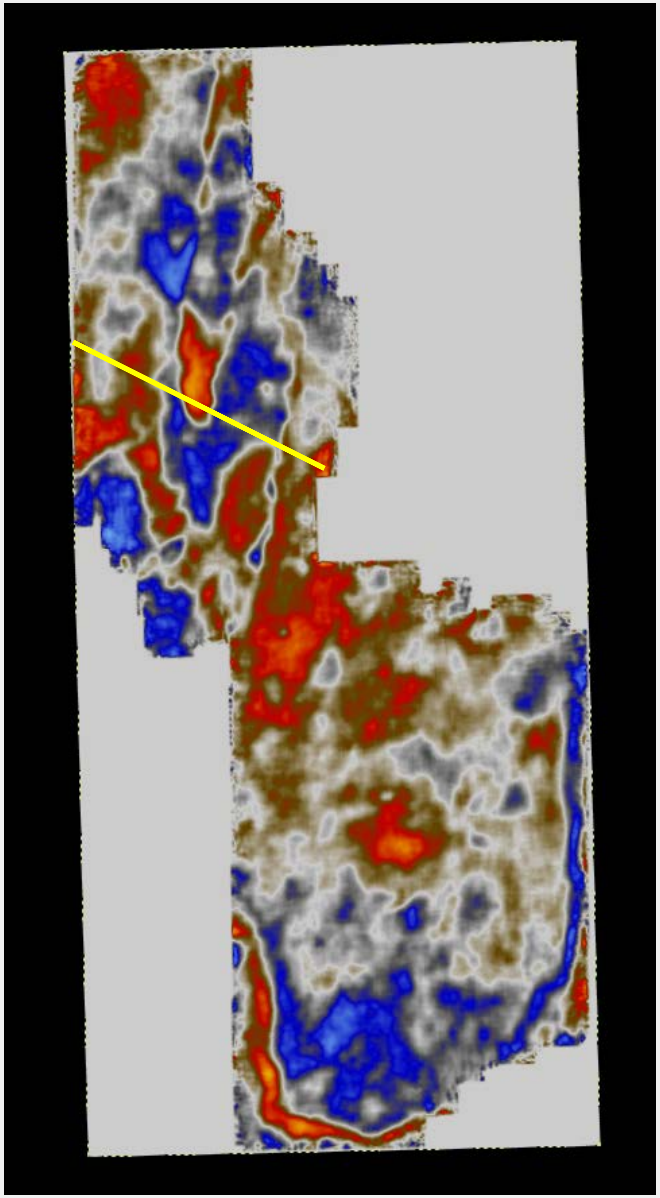
Fault mapping: Wellington area

- Map fault orientations and geometries
- Evaluate slip and dilation tendency
- 3D stress state

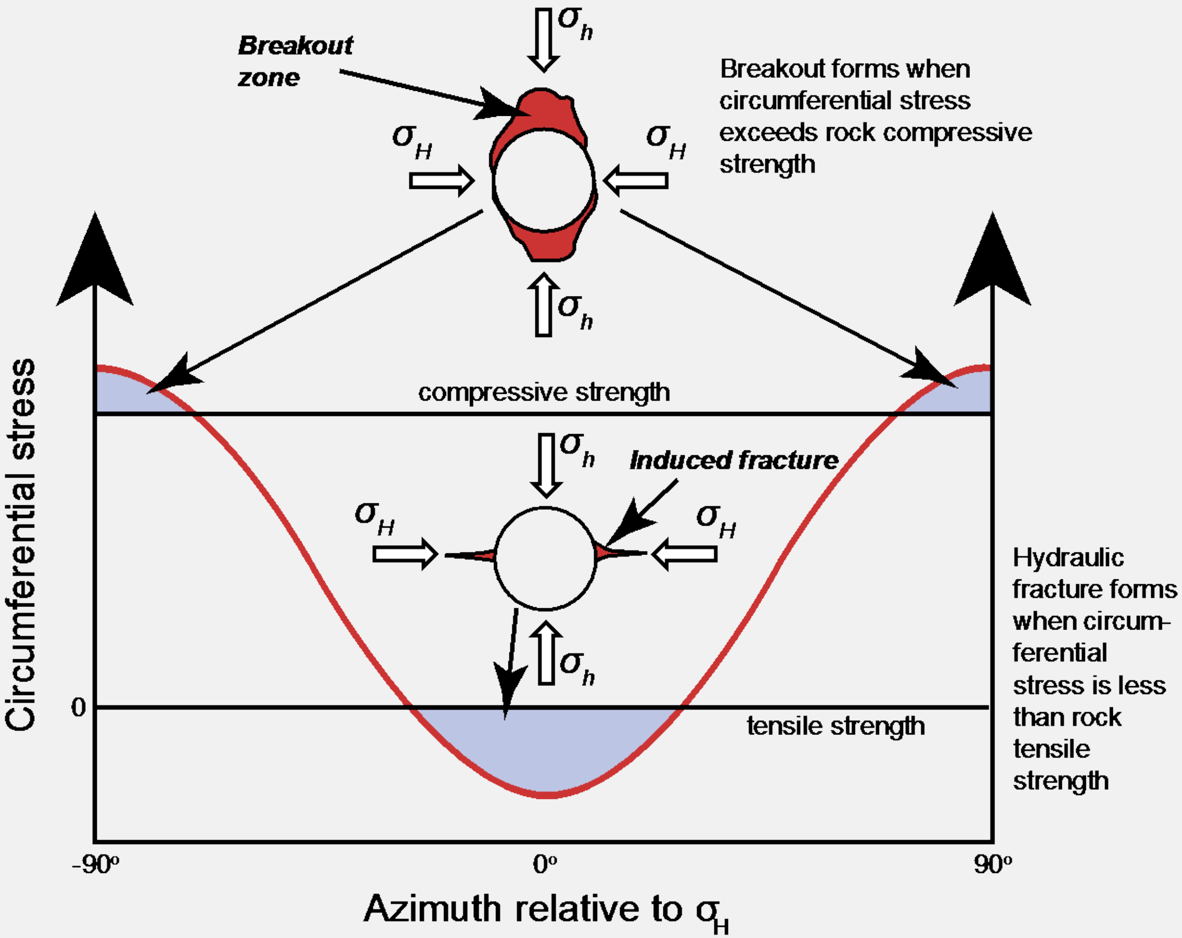
Arbuckle edge detection





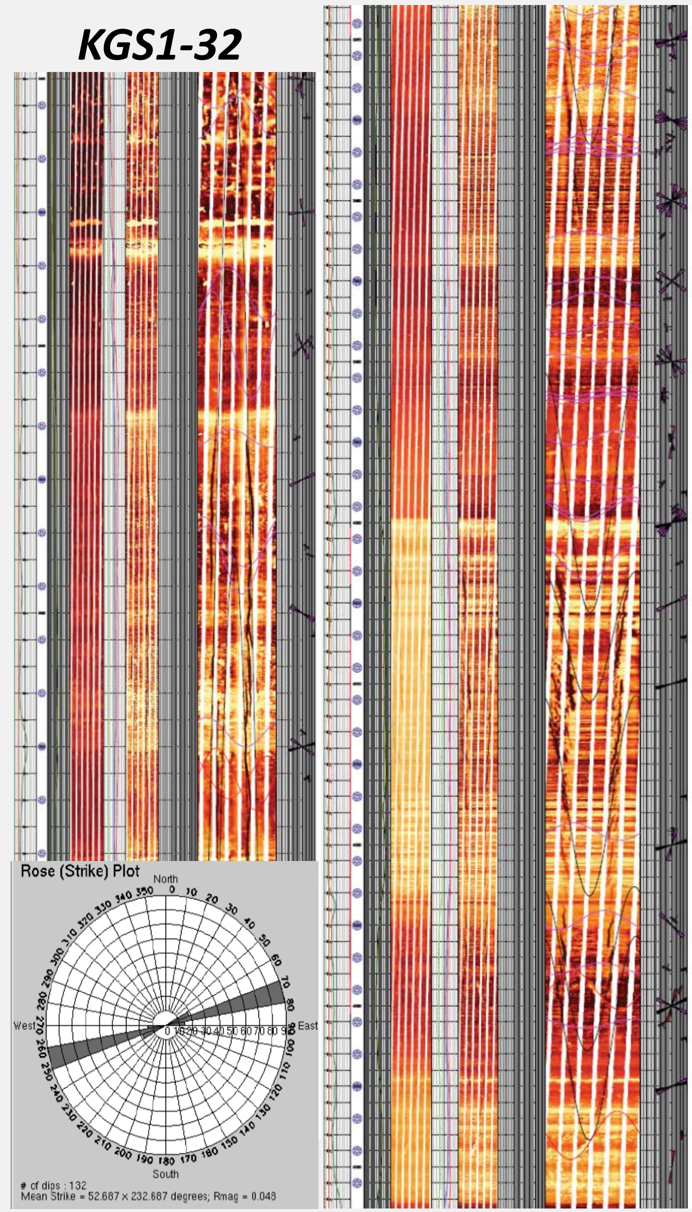


Stress field analysis: Orientation



KGS1-32

KGS1-28



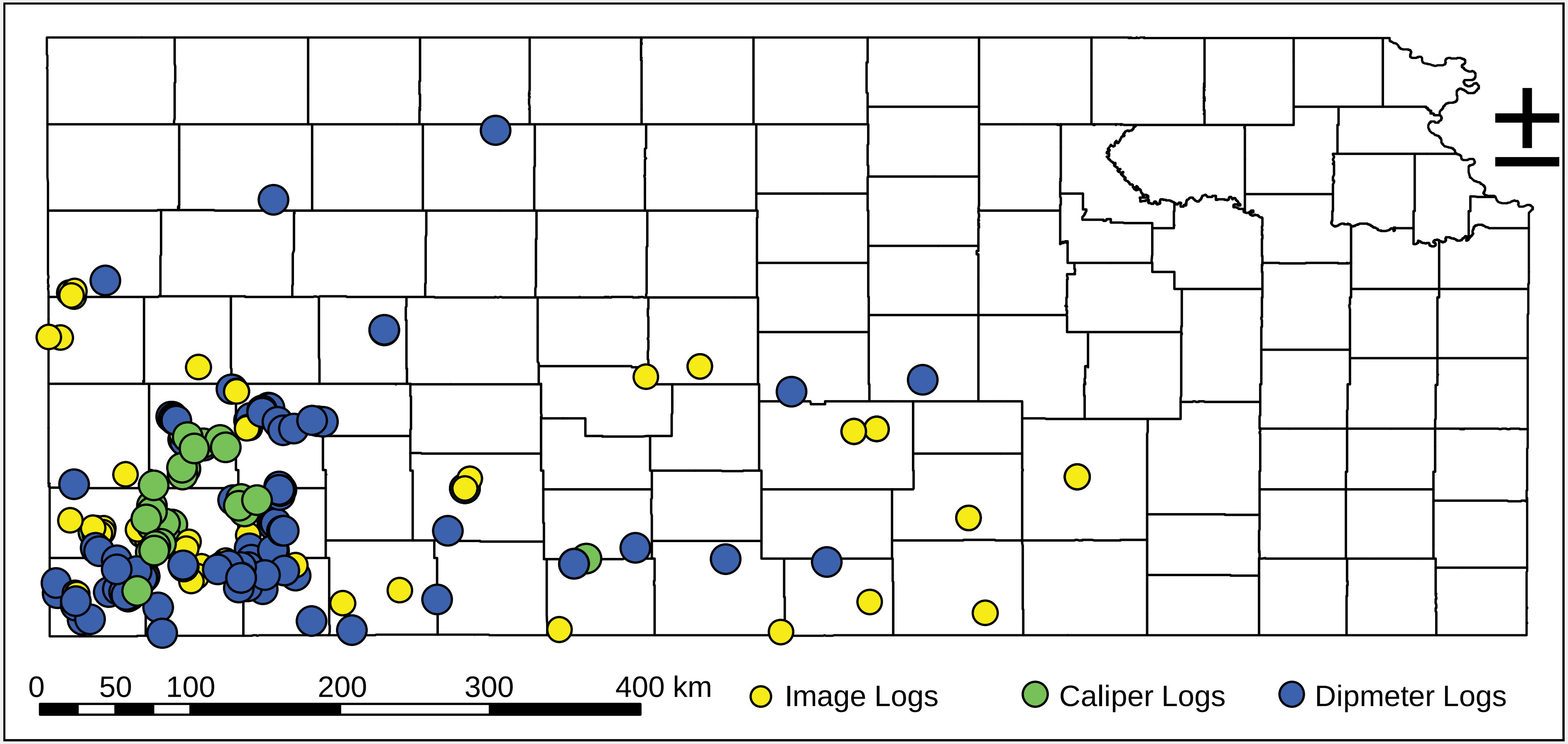
Modified from Tingay et al. (2008)

Stress field analysis: Magnitudes

- Principle stresses at depth:
  - S_v - Overburden (density logs)
  - S_{hmin} - Minimum horizontal stress (LOTs, SRTs, stimulation pressures)
  - S_{Hmax} - Maximum horizontal stress (dipole sonic logs)
- Other parameters:
  - Pp - Pore fluid pressure
  - Poisson’s ratio, Young’s modulus (sonic data; lab tests)

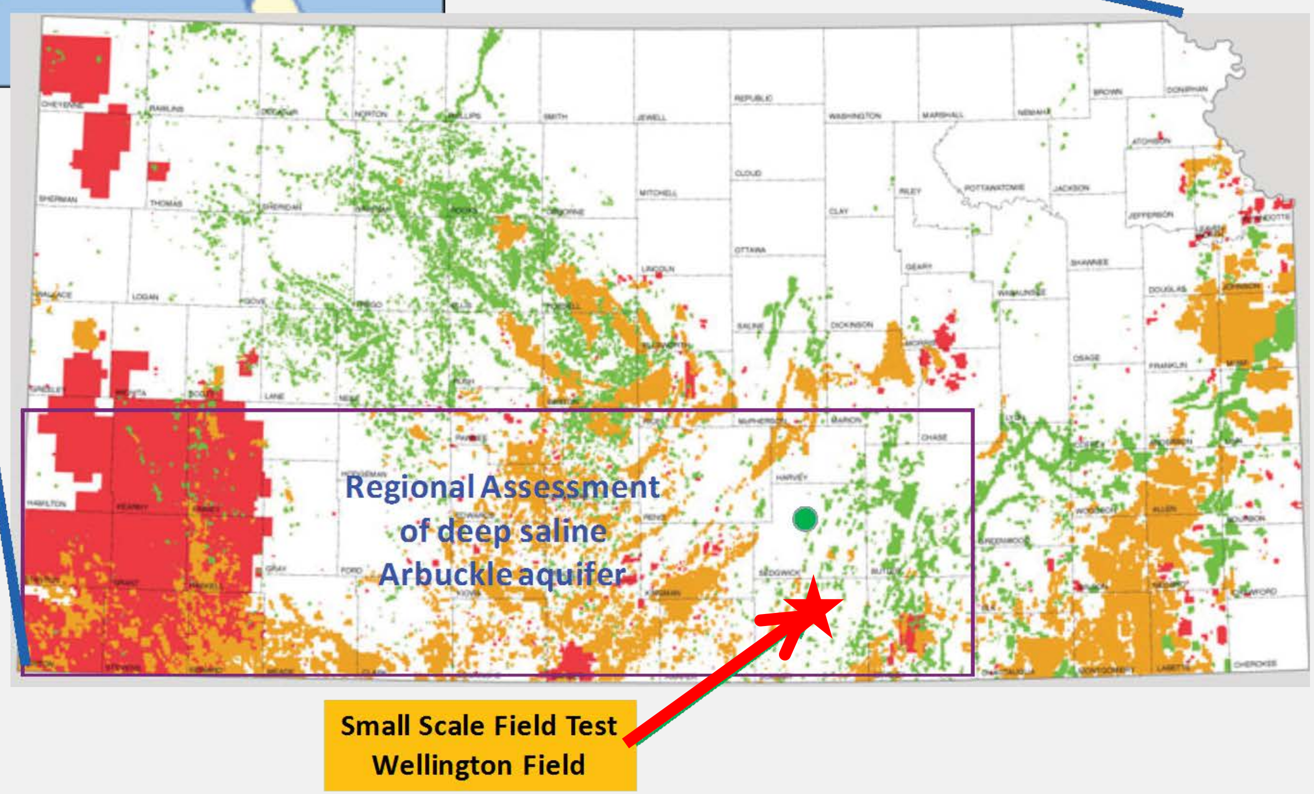
Stress field analysis: Statewide

240 well logs available in Kansas



- 109 are scanned
- 131 in paper form

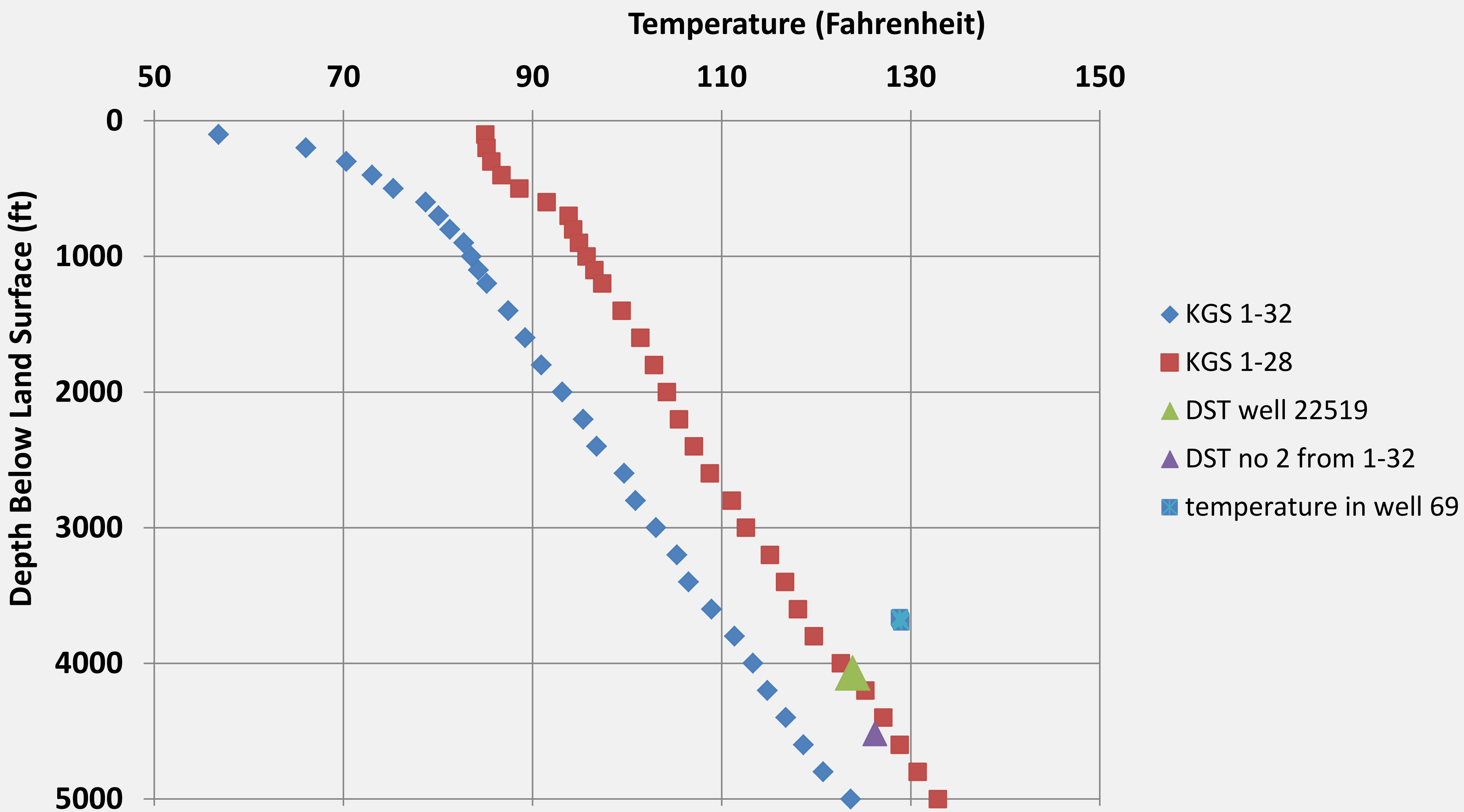
Project Location: Wellington Field, Sumner County, KS



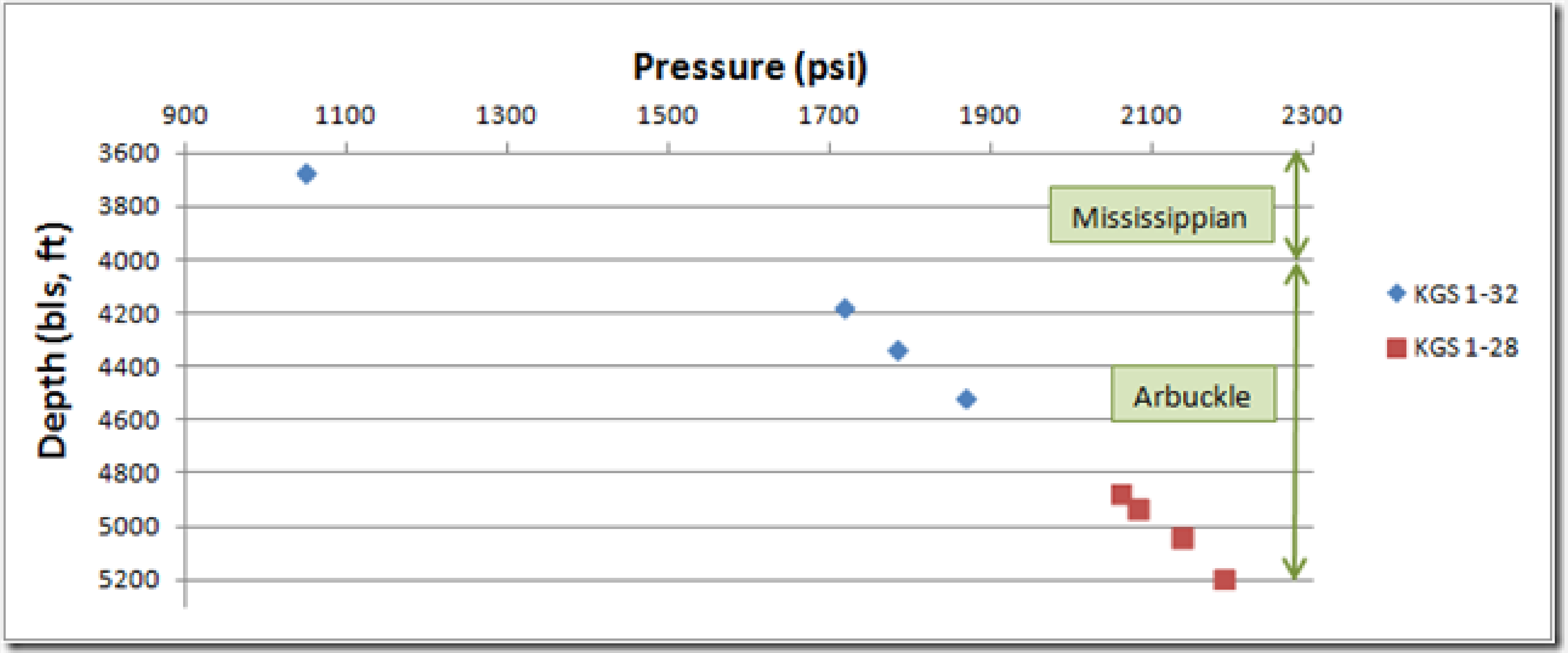
Reservoir characterization data

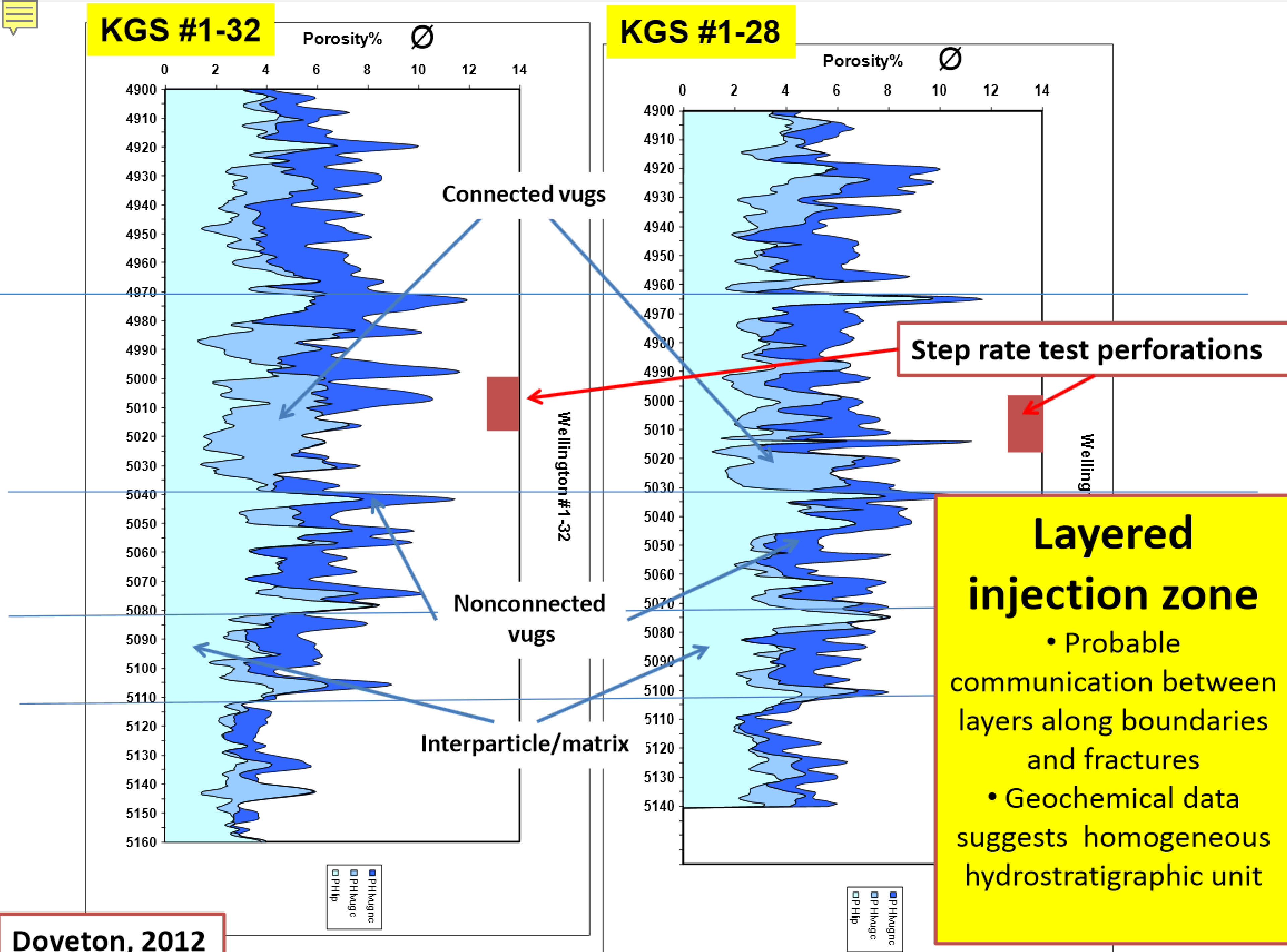
- What we know about Arbuckle reservoir we have learned from the CO_2 characterization study
- 2 wells were drilled into Arbuckle Fm
- Core was obtained form well KGS 1-32
- Whole set of modern logs for both wells
- 3D and 2D Seismic data
- Geochemical data
  - Water samples
  - Mineral composition
- Step Rate and Drill Stem tests

Reservoir temperature



Reservoir pore pressure



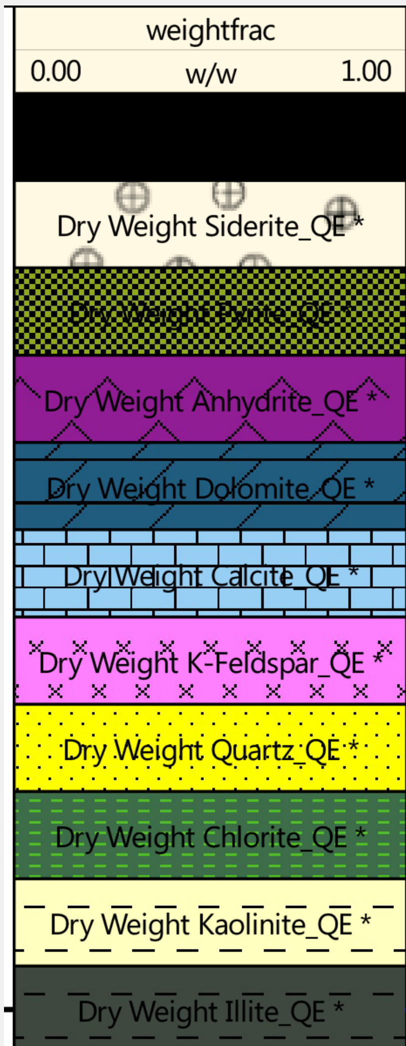


Layered injection zone

- Probable communication between layers along boundaries and fractures
- Geochemical data suggests homogeneous hydrostratigraphic unit

Doveton, 2012

Well KGS 1-32



weightfrac
0.00
w/w
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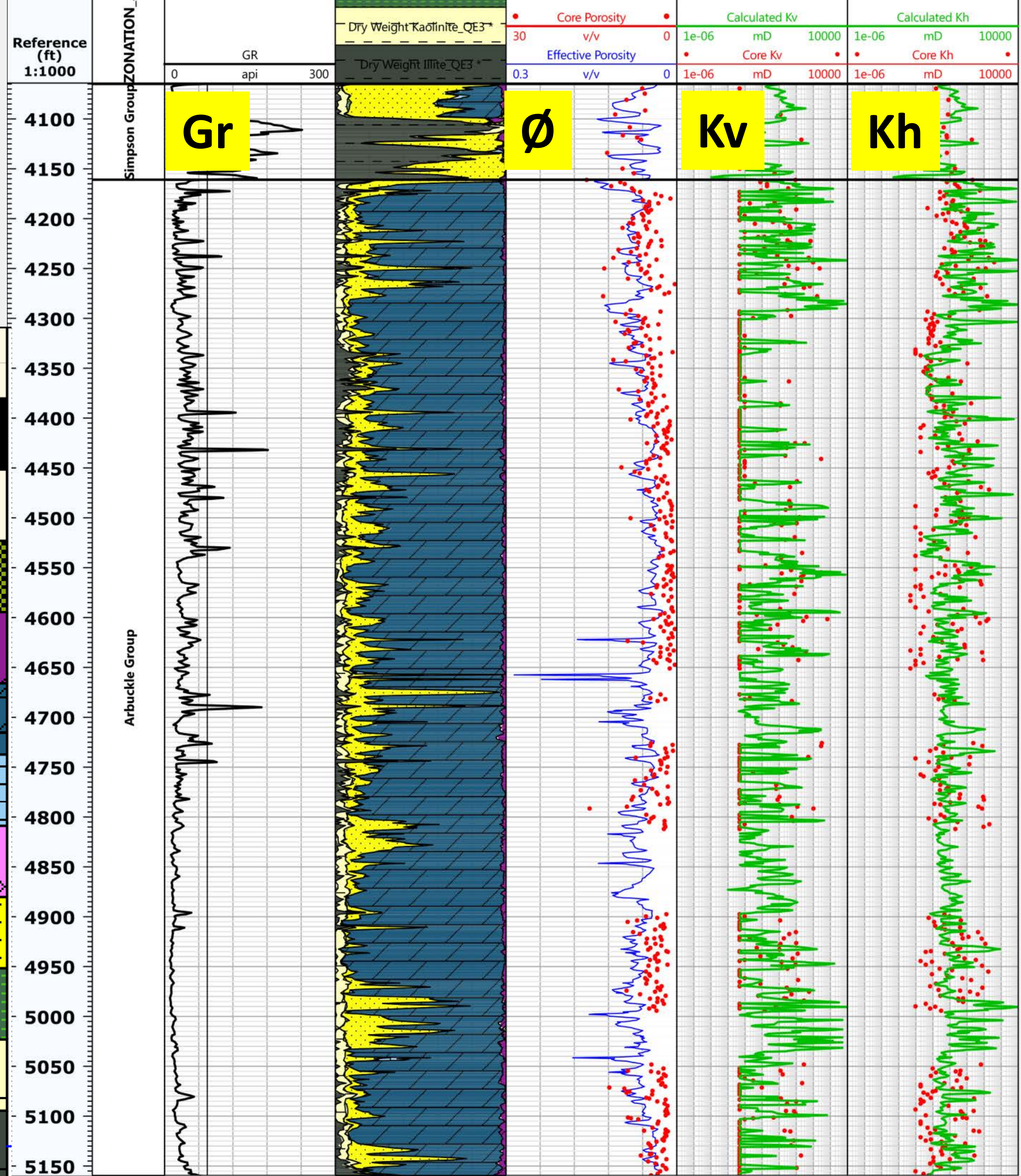
Dry Weight Siderite_QE *
Dry Weight Pyrite_QE *
Dry Weight Anhydrite_QE *
Dry Weight Dolomite_QE *
Dry Weight Calcite_QE *
Dry Weight K-Feldspar_QE *
Dry Weight Quartz_QE *
Dry Weight Chlorite_QE *
Dry Weight Kaolinite_QE *
Dry Weight Illite_QE *



Reference (ft) 1:1000
ZONATION_
GR
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api
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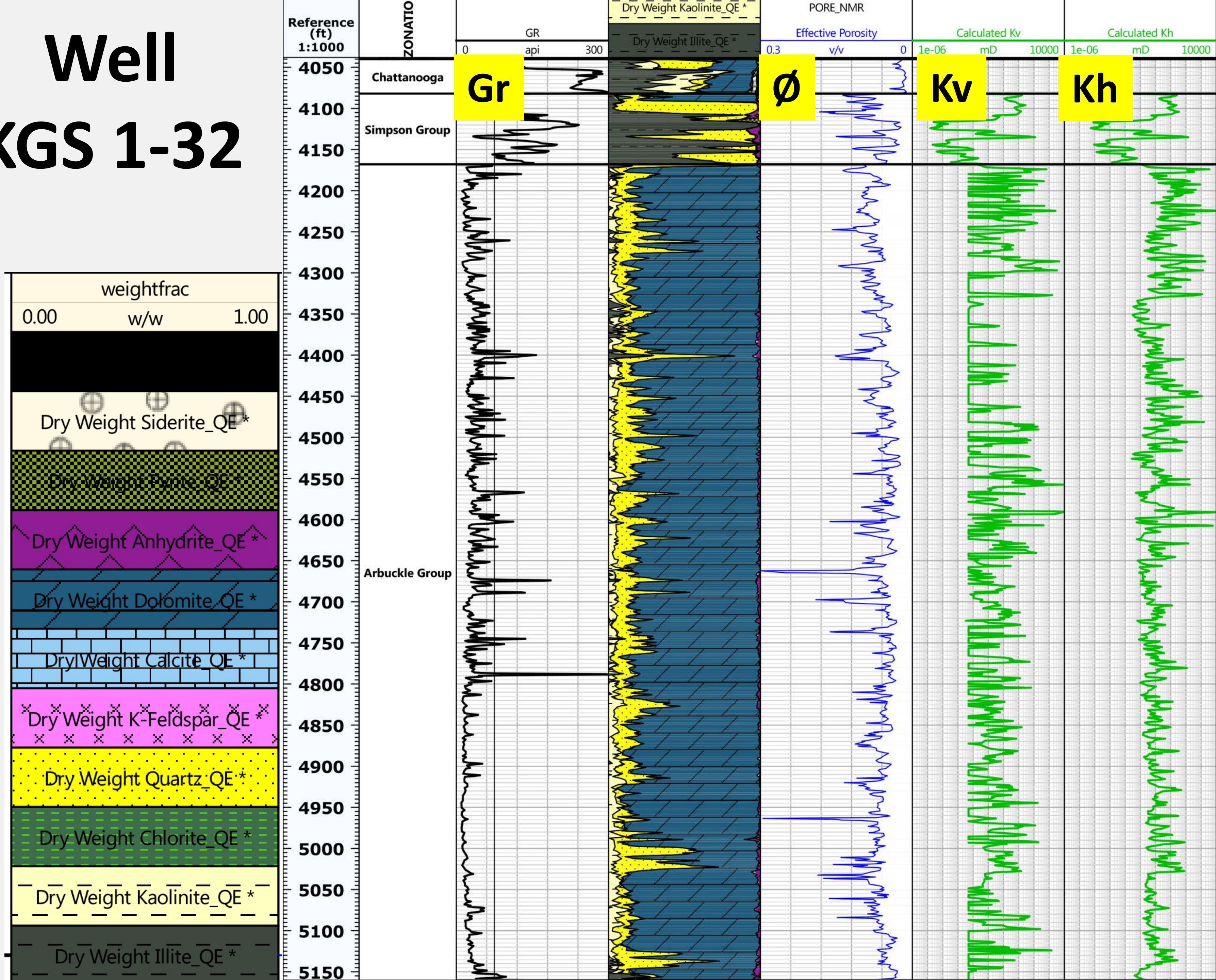
Dry Weight Kaolinite_QE3 *
Dry Weight Illite_QE3 *
Core Porosity
30
v/v
0
Effective Porosity
0.3
v/v
0
Calculated Kv
1e-06
mD
10000
Core Kv
1e-06
mD
10000
Calculated Kh
1e-06
mD
10000
Core Kh
1e-06
mD
10000
Simpson Group
Arbuckle Group
Gr
Ø
Kv
Kh
4100
4150
4200
4250
4300
4350
4400
4450
4500
4550
4600
4650
4700
4750
4800
4850
4900
4950
5000
5050
5100
5150

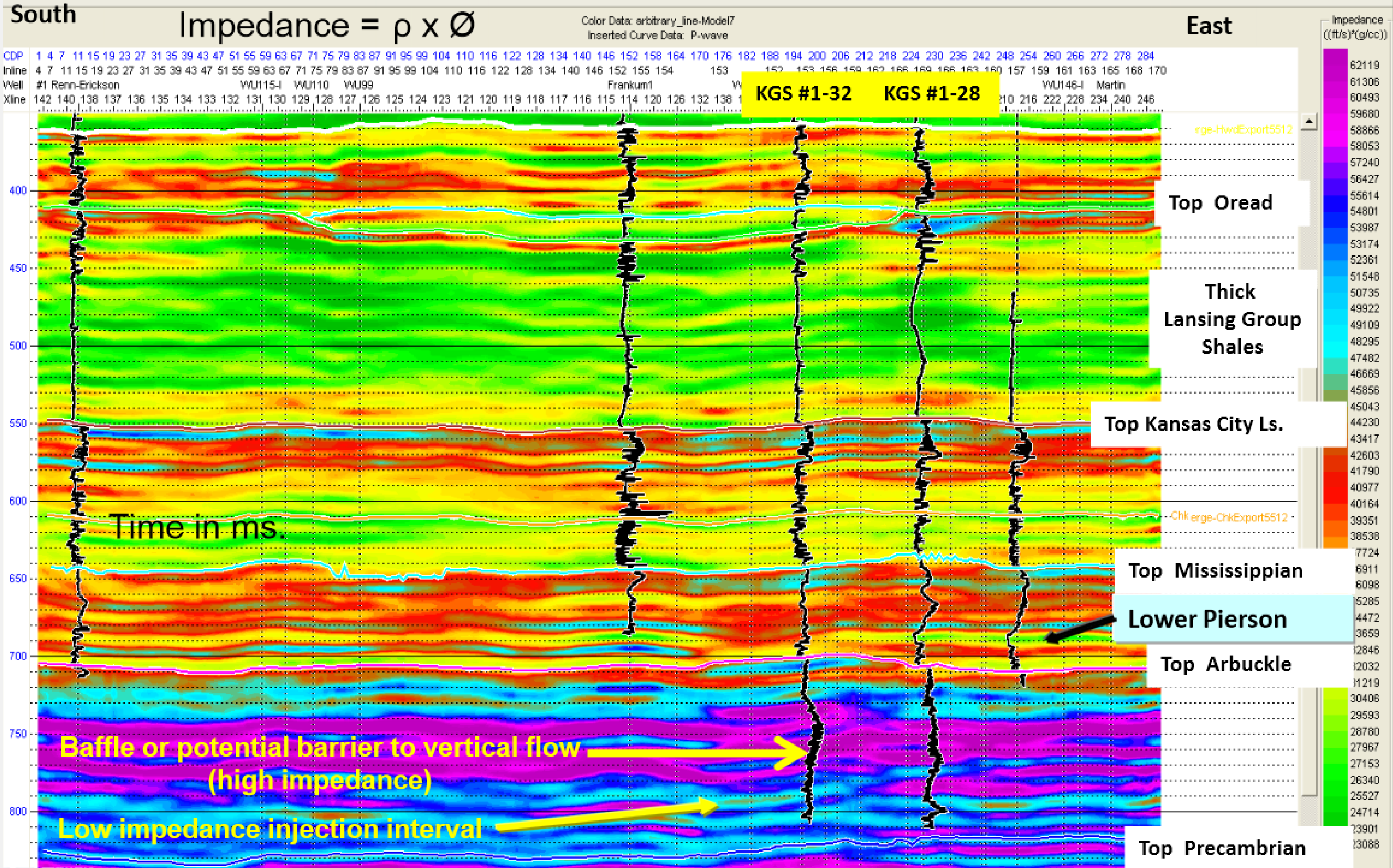
Well KGS 1-32



Reference (ft) 1:1000
ZONATIO
GR
0 api 300
Dry Weight Kaolinite_QE *
Dry Weight Illite_QE *
PORE_NMR
Effective Porosity
0.3 v/v 0
Calculated Kv
1e-06 mD 10000
Calculated Kh
1e-06 mD 10000
Gr
Ø
Kv
Kh
Chattanooga
Simpson Group
Arbuckle Group
4050
4100
4150
4200
4250
4300
4350
4400
4450
4500
4550
4600
4650
4700
4750
4800
4850
4900
4950
5000
5050
5100
5150
weightfrac
0.00 w/w 1.00
Dry Weight Siderite_QE *
Dry Weight Pyrite_QE *
Dry Weight Anhydrite_QE *
Dry Weight Dolomite_QE *
Dry Weight Calcite_QE *
Dry Weight K-Feldspar_QE *
Dry Weight Quartz_QE *
Dry Weight Chlorite_QE *
Dry Weight Kaolinite_QE *
Dry Weight Illite_QE *

Arbitrary seismic impedance profile – Wellington Field

distinct caprock, mid-Arbuckle tight, lower Arbuckle injection zone



Hedke – DOE/CO2

KU KANSAS GEOLOGICAL SURVEY The University of Kansas

Step-rate test results in 1-32

- Gauge depth: 4869’
- Test interval: 4995-5020’
- k = 113 mD based on Lorenz plot
- Vertical barriers above and below
- Compare to log k = 74mD

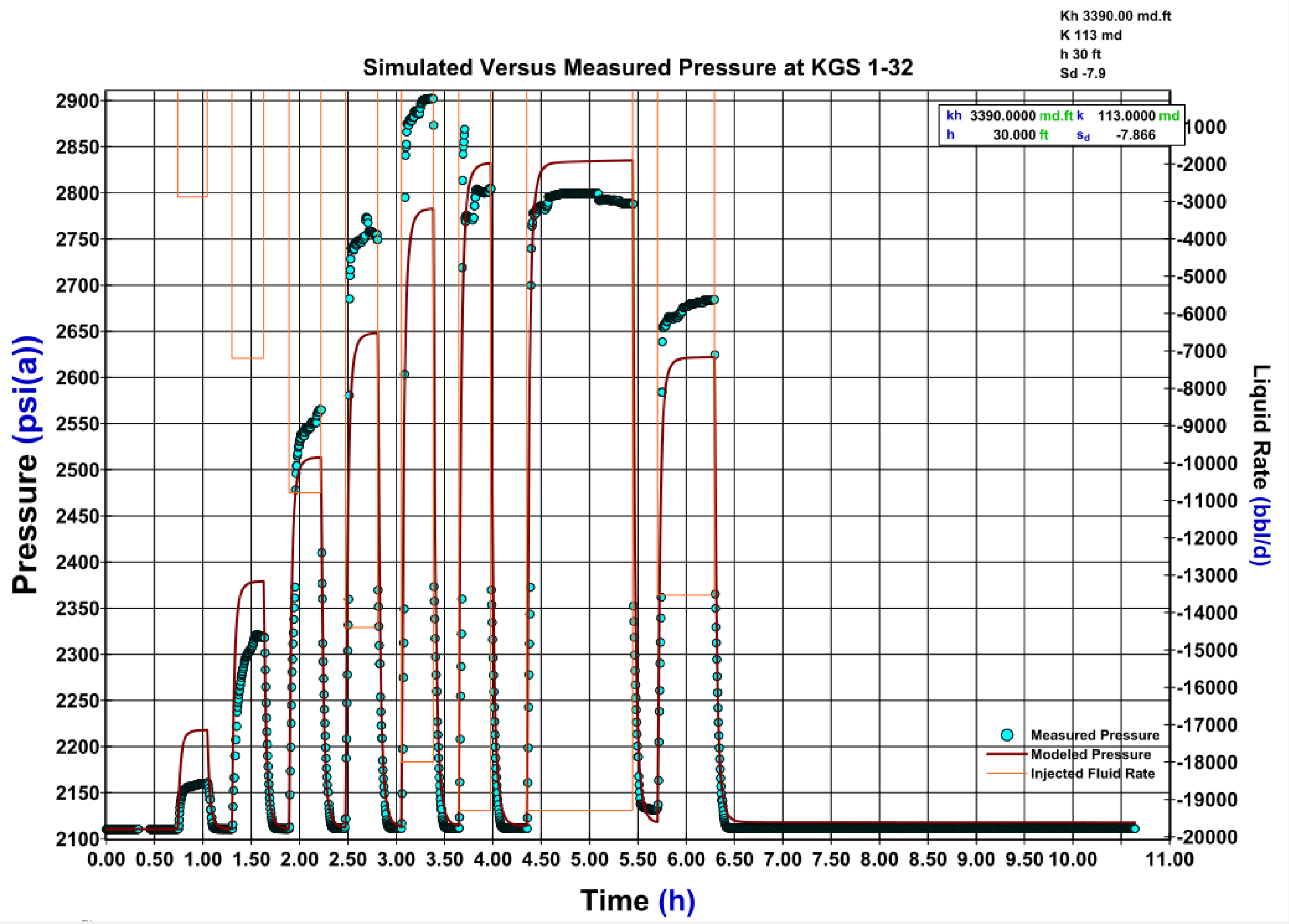
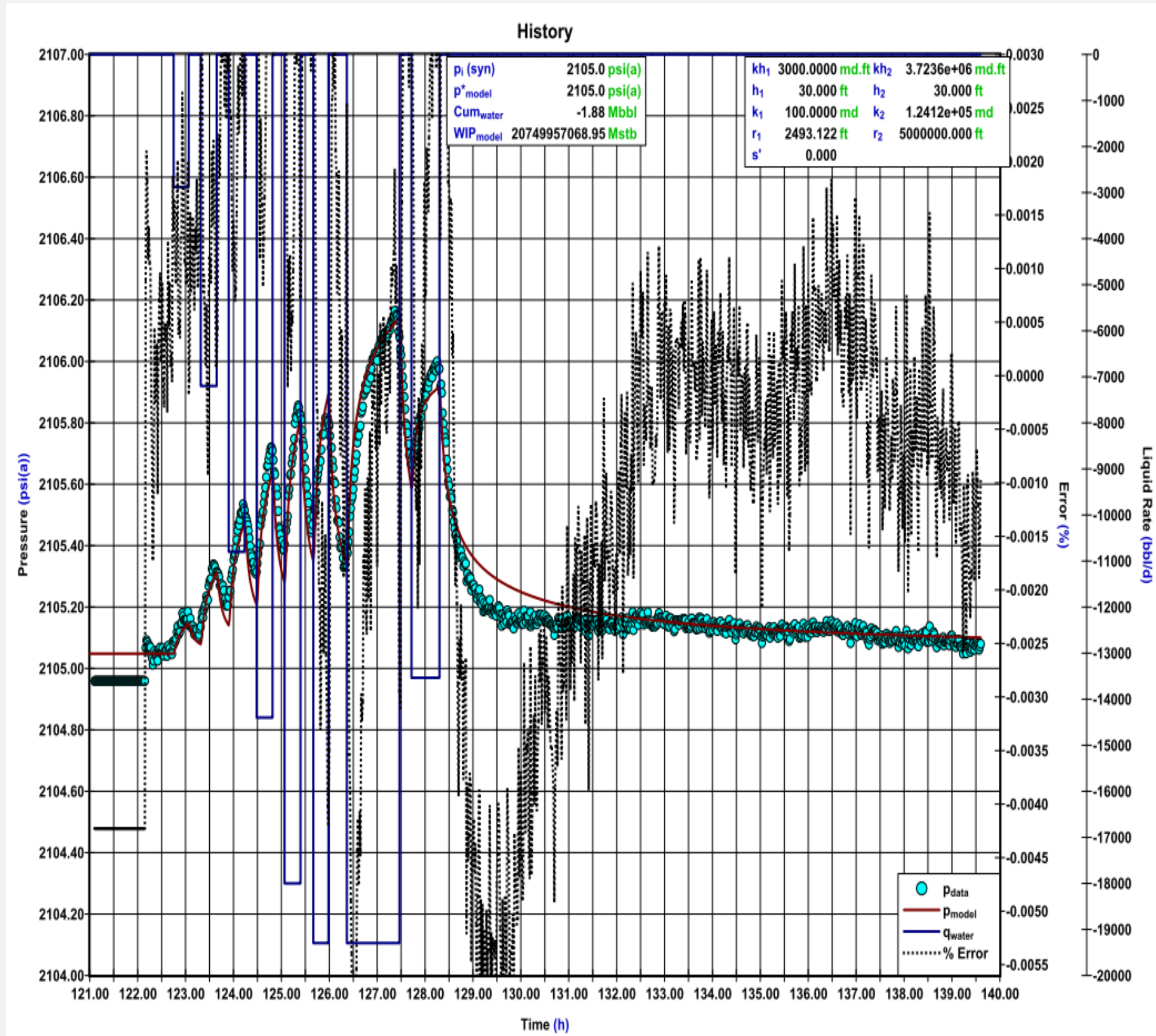


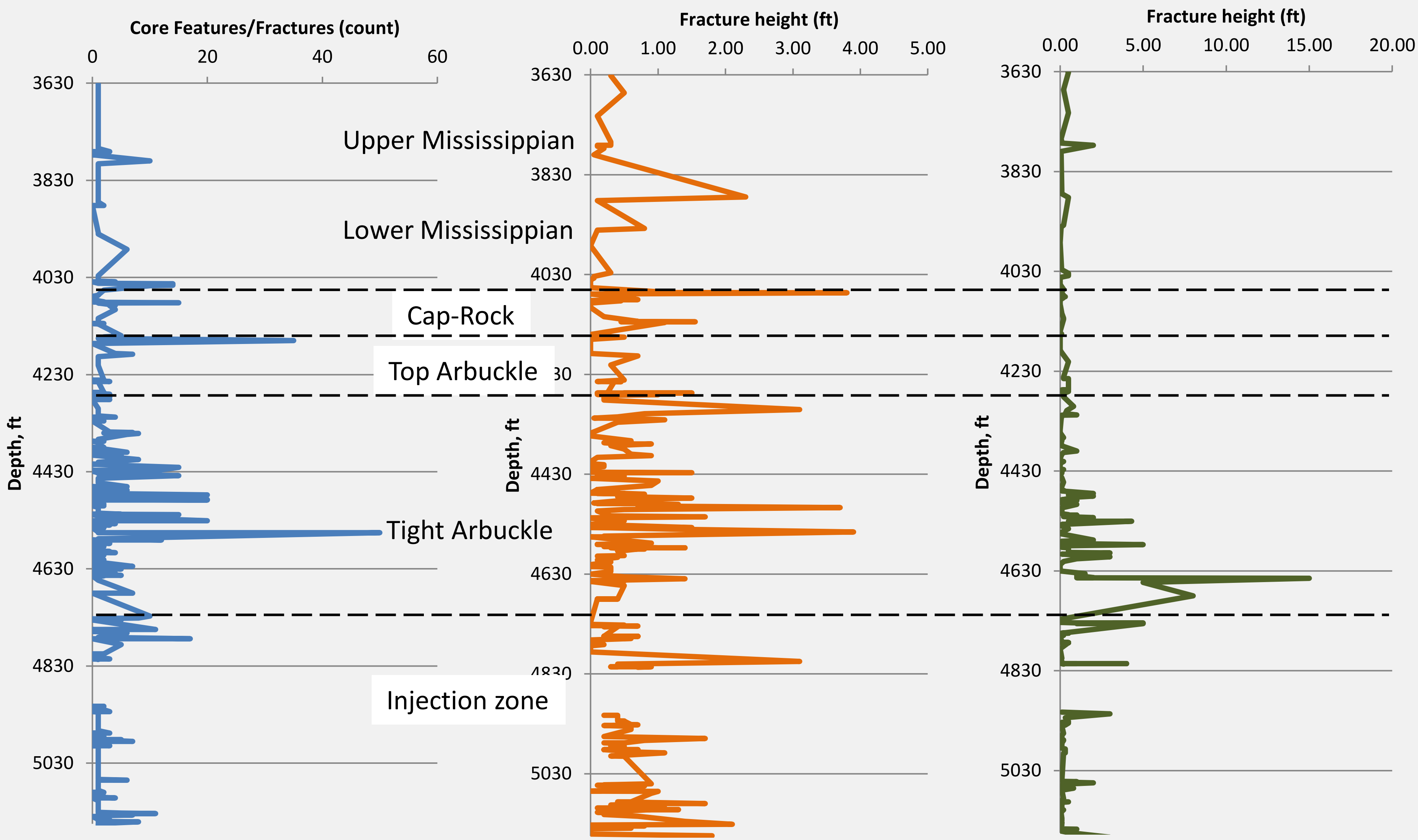
Figure from FazelAlavi (KGS)

Interference test results in 1-32 with 1-28 as an observation well

- Distance between 1-32 and 1-28 is 3500ft
- Composite model with dual porosity-permeability
- k around well 1-28 to a radius of 2493 ft (region 1) has a lower value (100 mD)
- k in the zone 2 is 124 D (2493ft).
- Permeability for the farther radius can be associated with fault/fracture between wells.

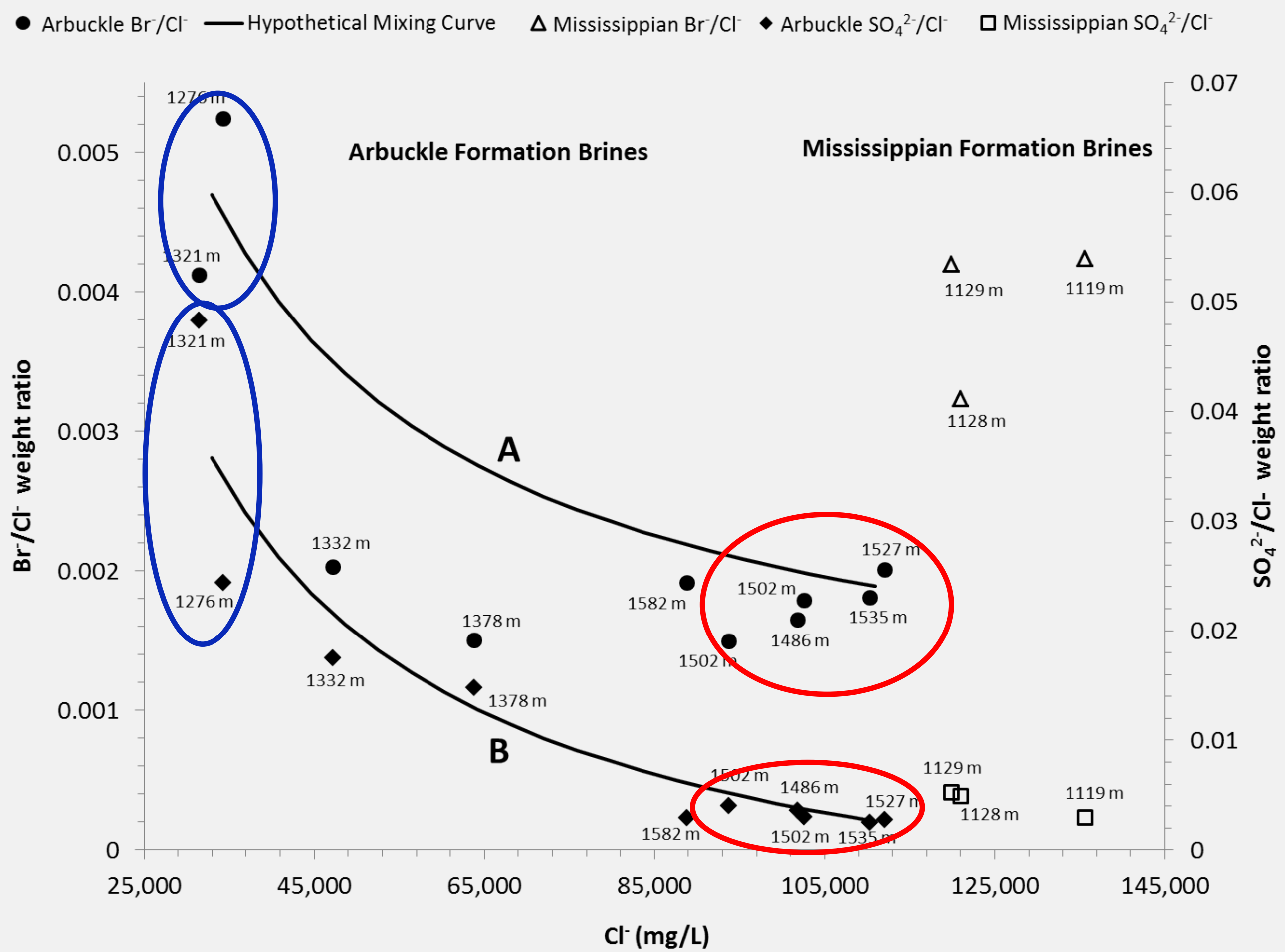


Core fractures



Br^-/Cl^- and SO_4^{2-}/Cl^- Baffles and lack of vertical communication

- Br^- and Cl^- are conservative during water/rock interactions
- Very useful in detecting brine sources and mixing
- Values for brine of Lower Arbuckle vary substantially from Upper Arbuckle
- Lower Arbuckle brines cluster together
- Upper Arbuckle values more spaced out, suggests smaller baffles



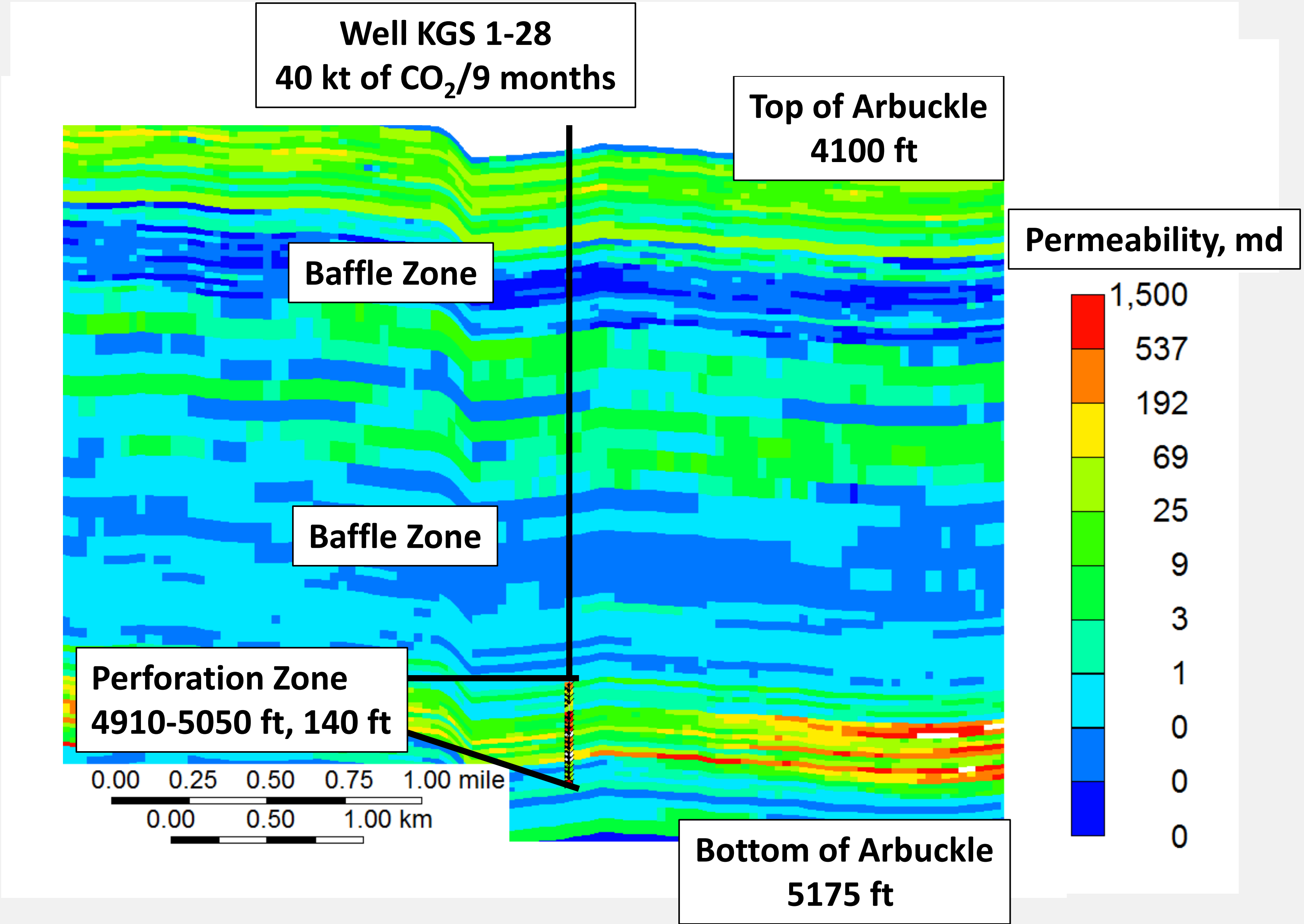
Arbuckle reservoir model considerations

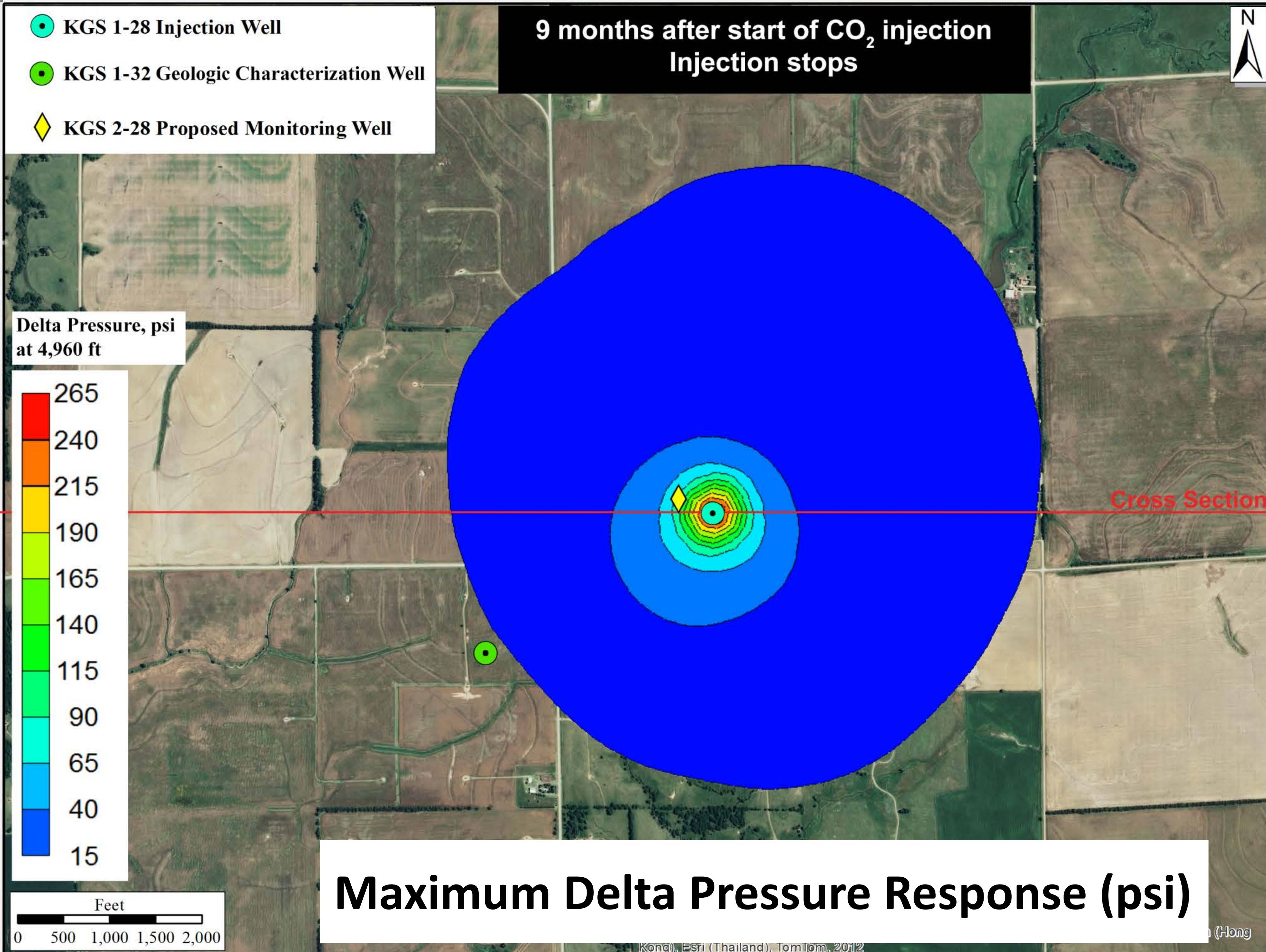
- Highly complex system with many sub-zones and different conditions
- Highly fractured system may require dual porosity/permeability model in future
- Unclear medium zone permeability
- Discrepancies in log, core, and SRT permeability estimations

Arbuckle reservoir model assumptions

- Performed with CMG GEM software
- 9 cases with varying porosity and permeability
- Infinite acting Carter-Tracy aquifer with no leakage
- Relative permeability tables from literature sources for carbonates
- Solubility is included in the model
- No mineral reactions were considered

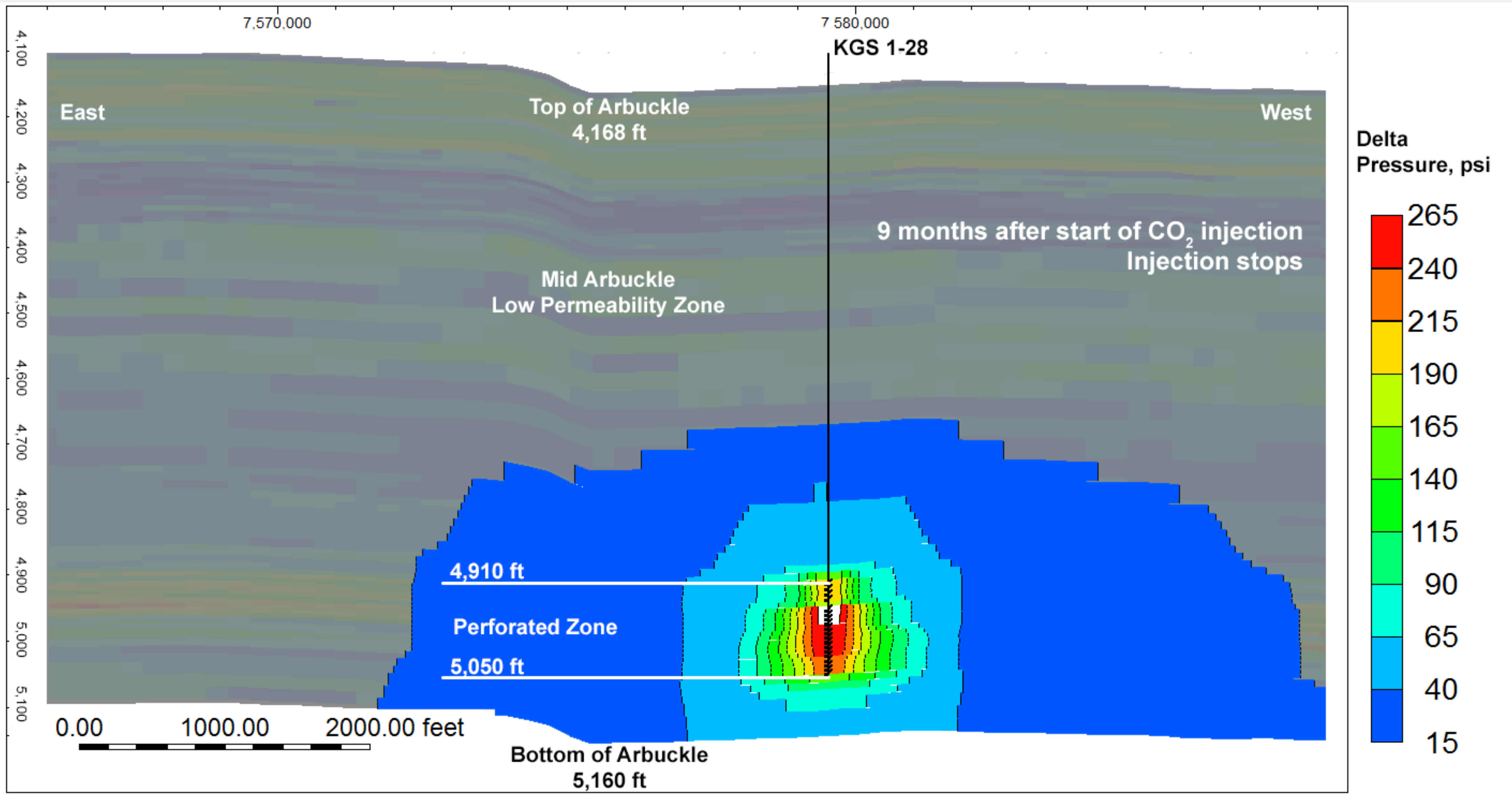
Dynamic simulation model



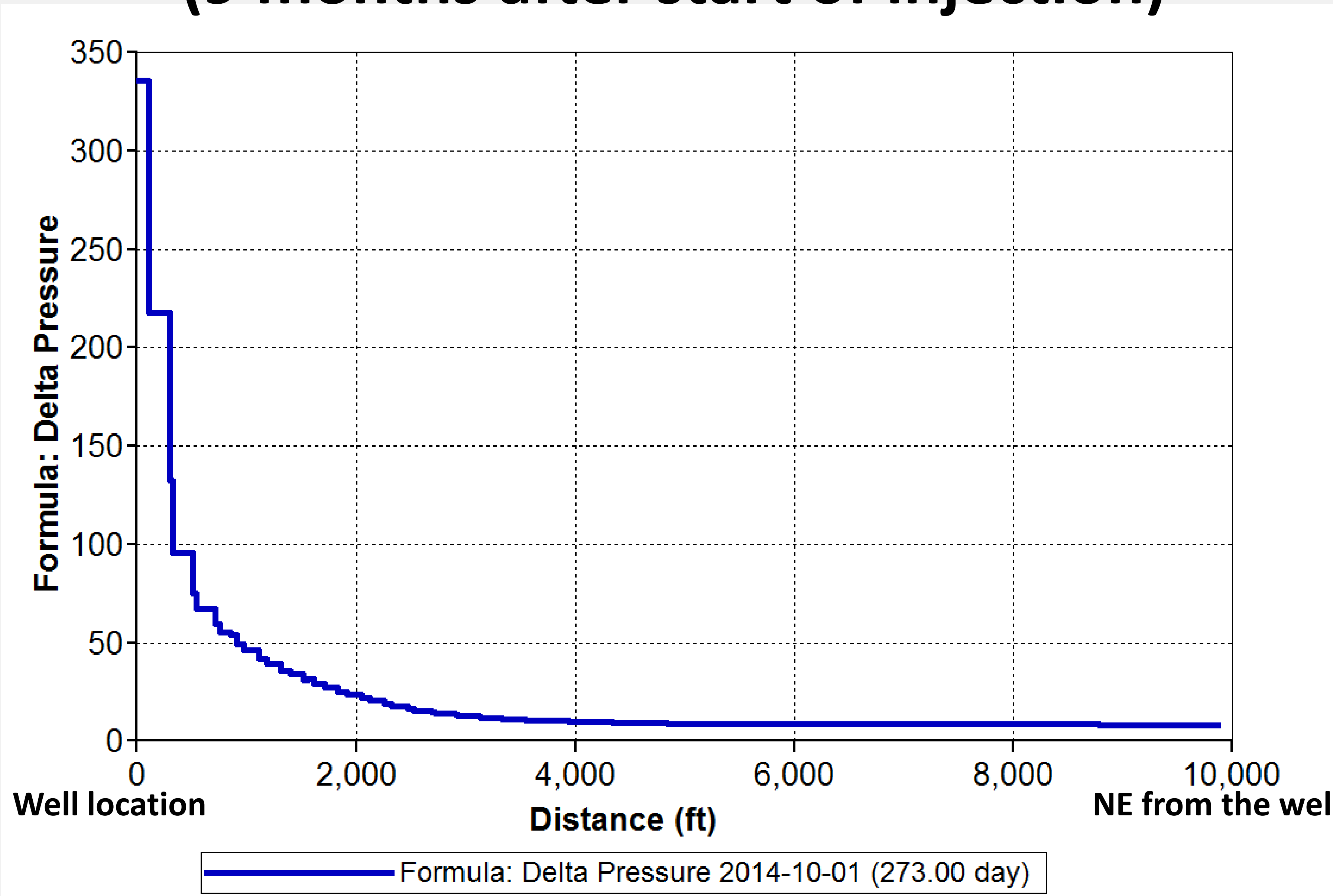


Sources: ESRI, USGS, Kansas Geological Survey

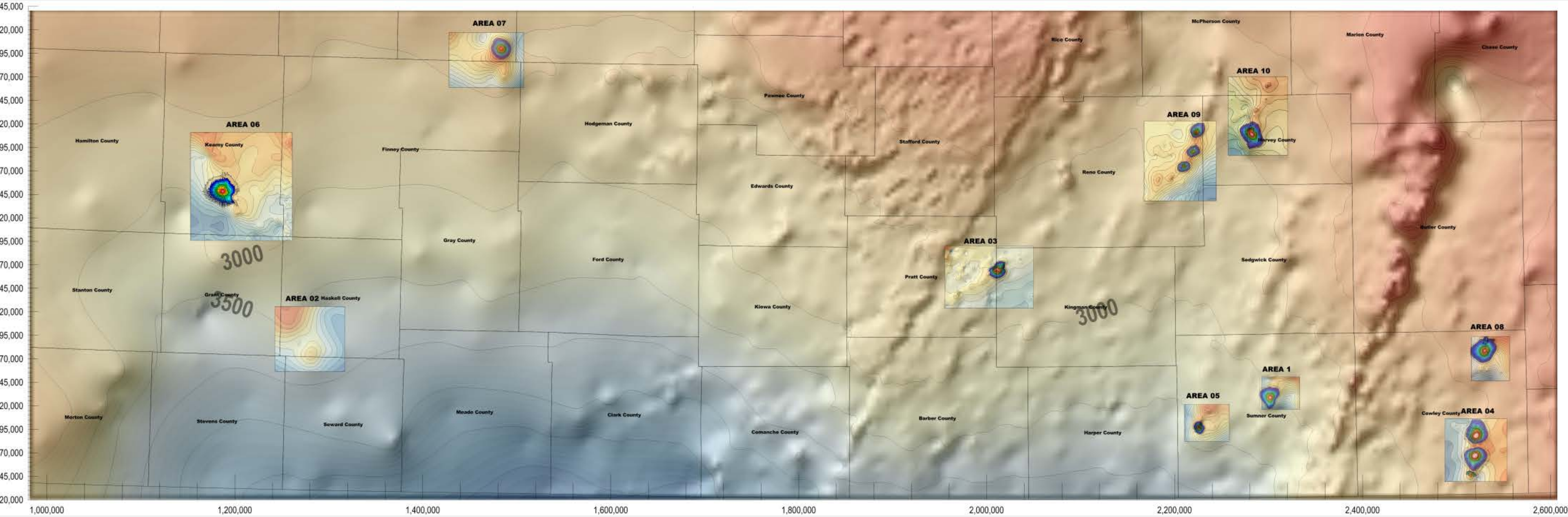
Vertical pressure distribution at max. stress (before the injection stops)



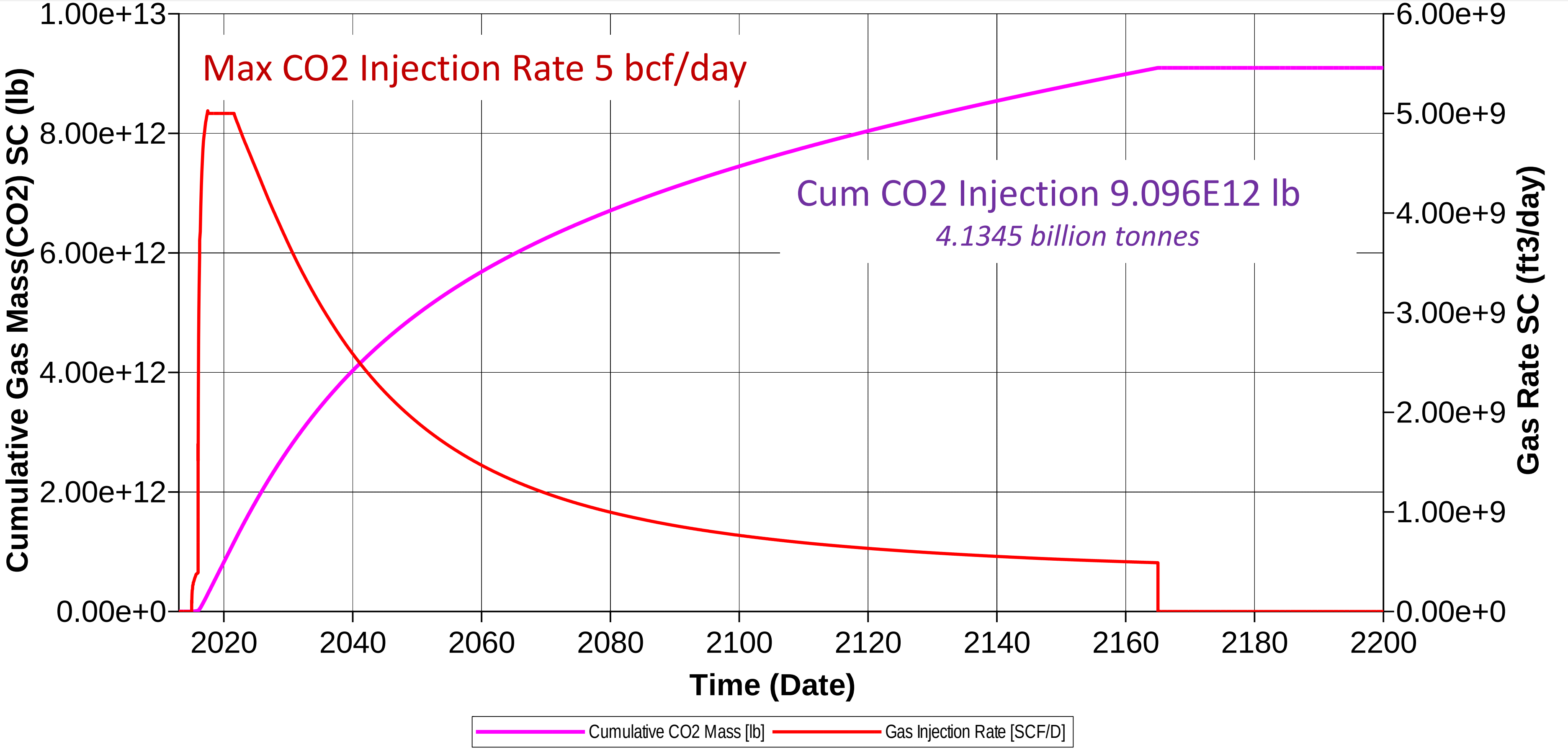
Delta pre pressure profile at max stress (9 months after start of injection)



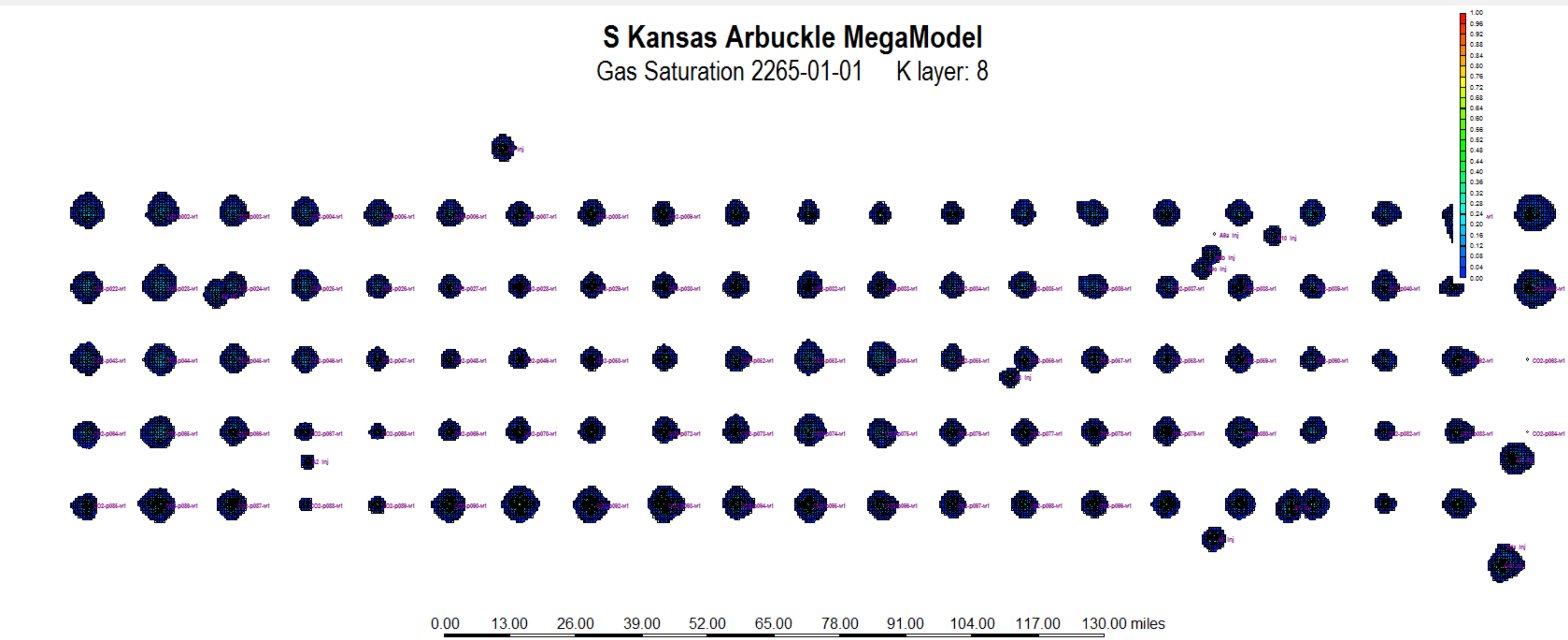
Southern Kansas CO_2 storage model 10 sites



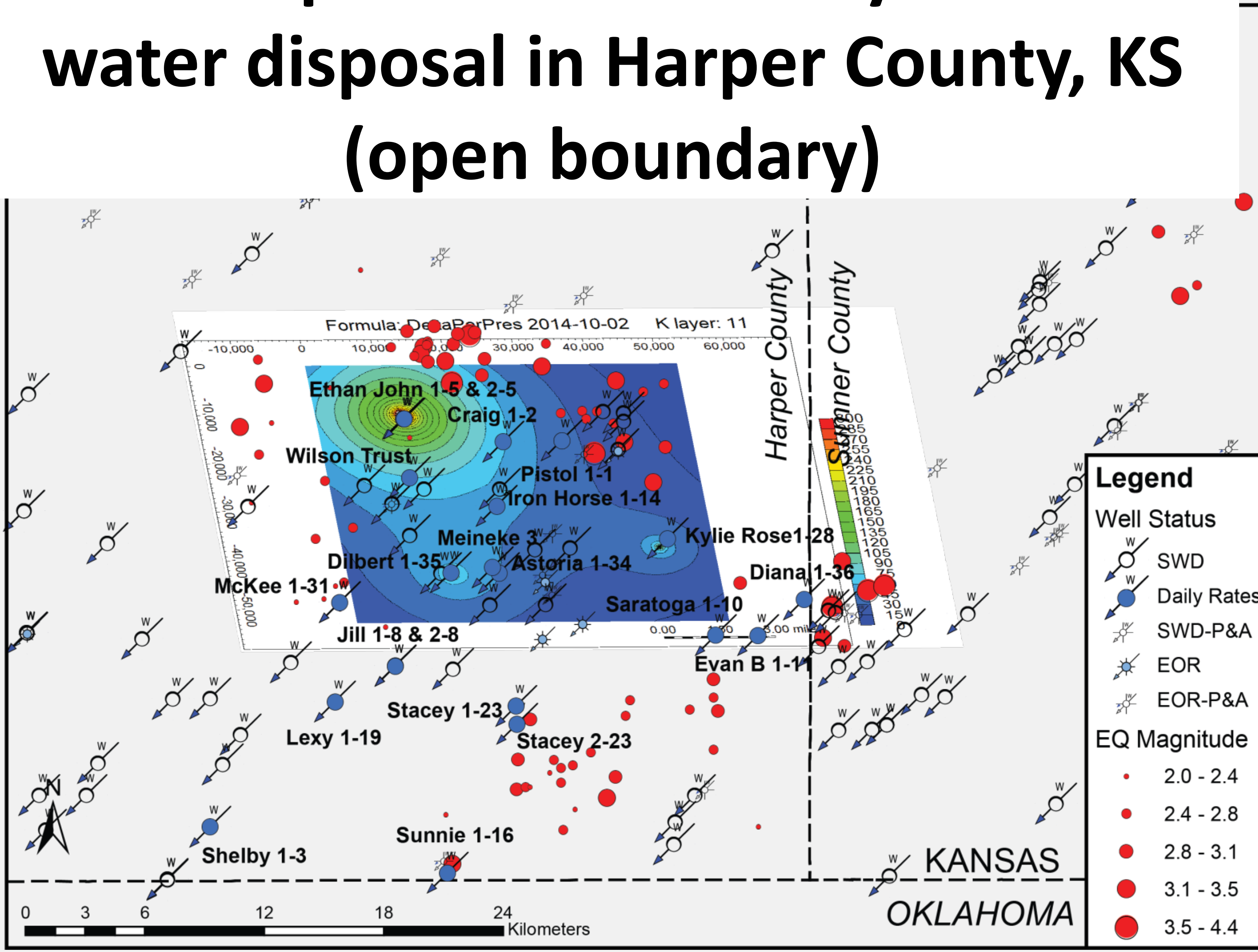
Total area gas injection



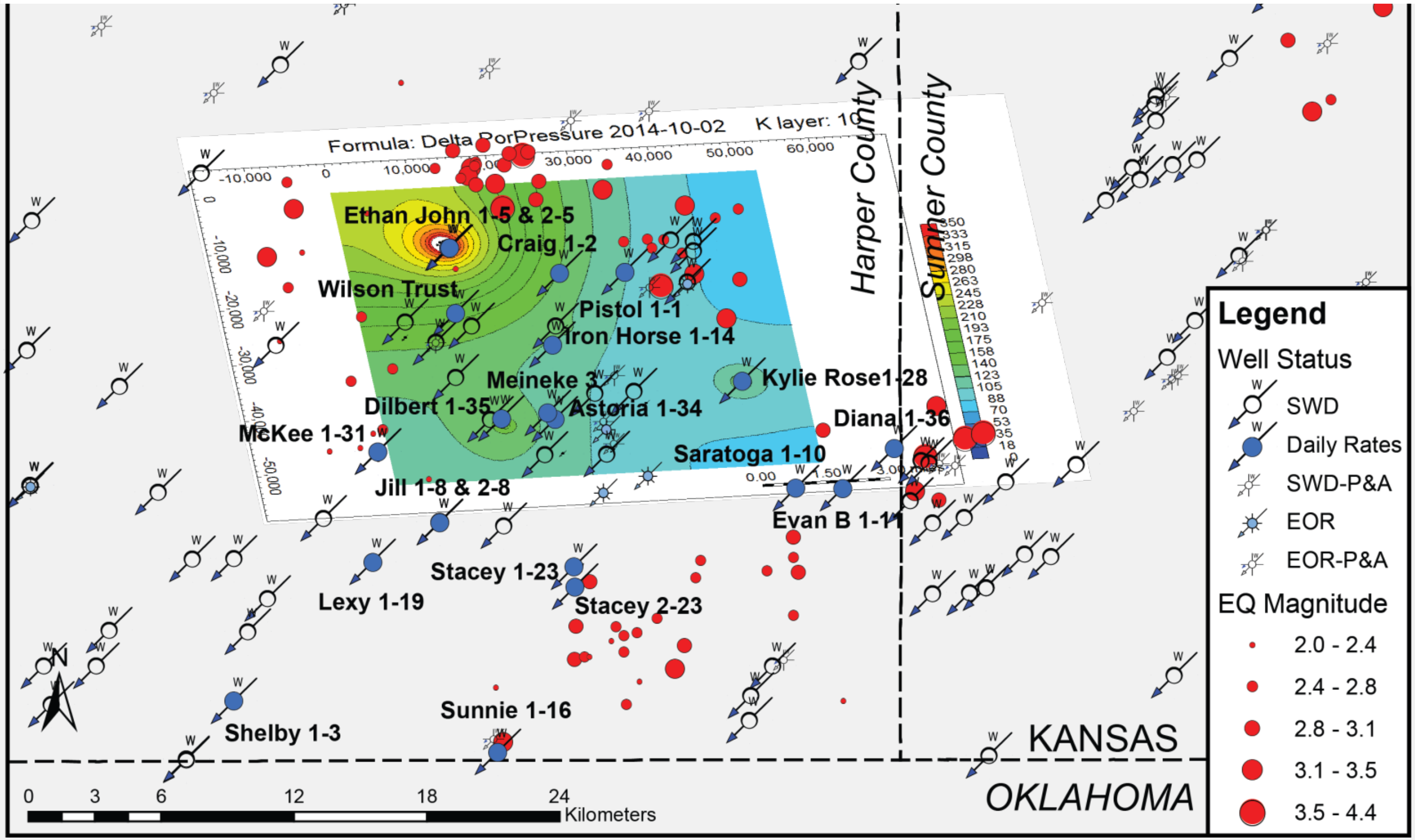
Southern kansas CO_2 injection model gas saturation 100 years after injection stops



Delta pressure after 20 years of water disposal in Harper County, KS (open boundary)



Delta pressure after 20 years of water disposal in Harper County, KS (closed boundary)



Summary

1. **The systematic characterization of the structural framework is needed to ascertain stress-strain history.**
2. **Based on current seismicity, faults appear to be reactivated by large volume brine injection. Elements being investigated --**
   a) size and orientation of faults,
   b) basement heterogeneity (size and length of features),
   c) maximum and minimum stress direction and magnitudes,
   d) critical stress and orientation of larger faults,
   e) time series changes in fluid levels and pore pressure,
   f) refined reservoir-type model for disposal zone (Φ, kv, kh, flow unit definition and correlation).
3. **High angle reverse faults common in Kansas**
   a) many faults are also likely related to regional transpression/strike-slip movement (late Mississippian and early Pennsylvanian) with diagnostic fault geometries,
   b) faults and associated structures act to conduits for fluid migration and trapping of oil and gas in this region and therefore important to understand.

Future research collaboration with industry

1. Map faults and refine flow-unit reservoir model of the Arbuckle using seismic and well logs.
2. Evaluate earthquake source and mechanisms, refine fault locations.
3. Analyze well tests including daily and cumulative volume, rates, pressures, and compare with ambient pre-2011 fluid levels/pressures in the Arbuckle.
4. Evaluate stress potentially induced by withdrawal of fluid and pressure decline in Mississippian reservoirs near brine disposal.
5. Refine dynamic models of brine disposal in the Arbuckle saline aquifer in areas affected by increased seismicity.
6. Continue to explore means to reduce amounts of produced water in the MLP and develop best practices for brine disposal.

Acknowledgements

- Bittersweet Energy – Tom Hansen with Paul Gerlach and Larry Nicholson; Dennis Hedke, Martin Dubois and SW Kansas CO2-EOR industry consortium, John Youle, George Tsoflias and students at KU, Gene Williams, and KGS staff supporting the acquisition of data, stratigraphic correlation, regional mapping, and interpretations for the DOE-CO2 project
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- Justin Rubinstein, USGS
- Induced Seismicity Task Force -- Rex Buchanan, Chair

KU The University of Kansas — Department of Geology

KSCO2

KU Kansas Geological Survey — The University of Kansas

Wellington Field Operator — BEREXCO

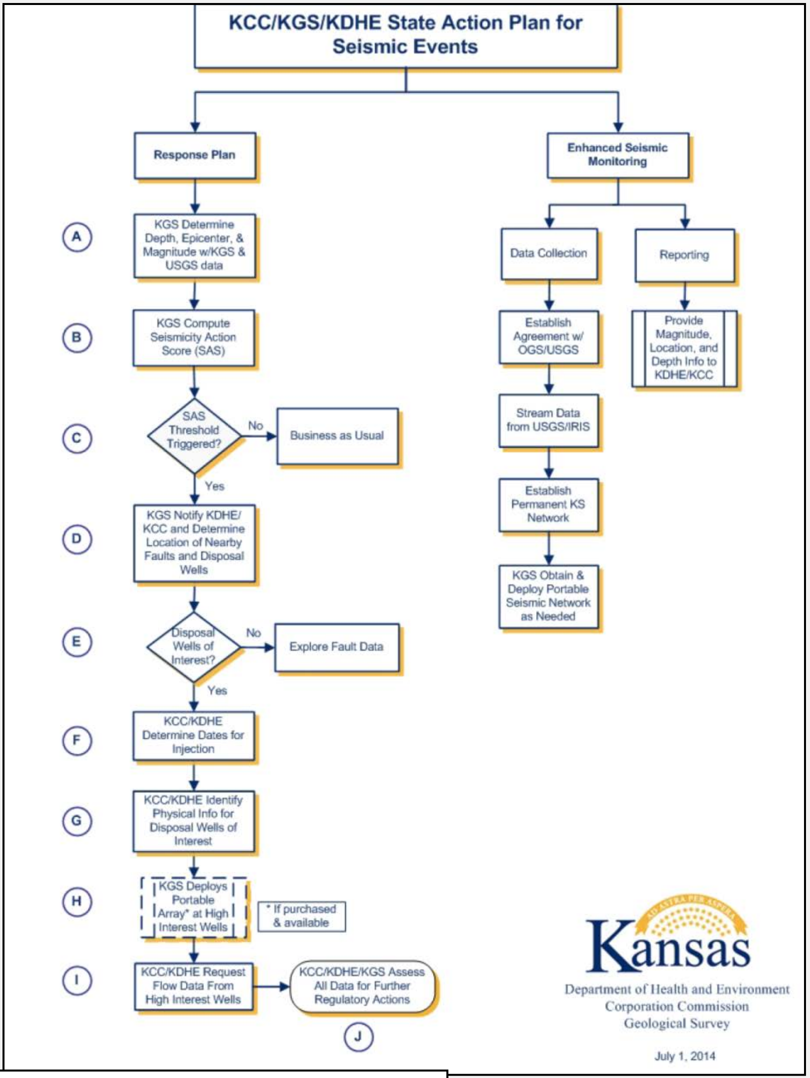
NETL

Kansas Seismic Action Plan

September 26, 2014

Prepared by

Kansas
Department of Health and Environment
Corporation Commission
Geological Survey



Response Plan

A. The occurrence of a recorded seismic event will trigger the Response Plan. KGS will determine the magnitude, location, and depth of the event.

B. KGS will determine the seismic action score (SAS) for the event by adding the numeric value of the magnitude of an earthquake to the sum of the individual weighted scores for each of the variables listed in Table 1.

$$\mathbf{SAS = Magnitude + Score_{felt} + Score_{structure} + (2 \times Score_{number}{}^{3}) + Score_{local\ recursion}{}^{3} + Score_{recursion\ regional} + Score_{recursion\ time}}$$