"Update on Induced Seismicity Studies by the Kansas Geological Survey"

December 9, 2015‡

to the Kansas Geological Society

‡revised 1-11-16

Yevhen "Eugene" Holubnyak* and W. Lynn Watney*

(speakers)

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Jennifer (Raney) Hollenbach, K. David Newell

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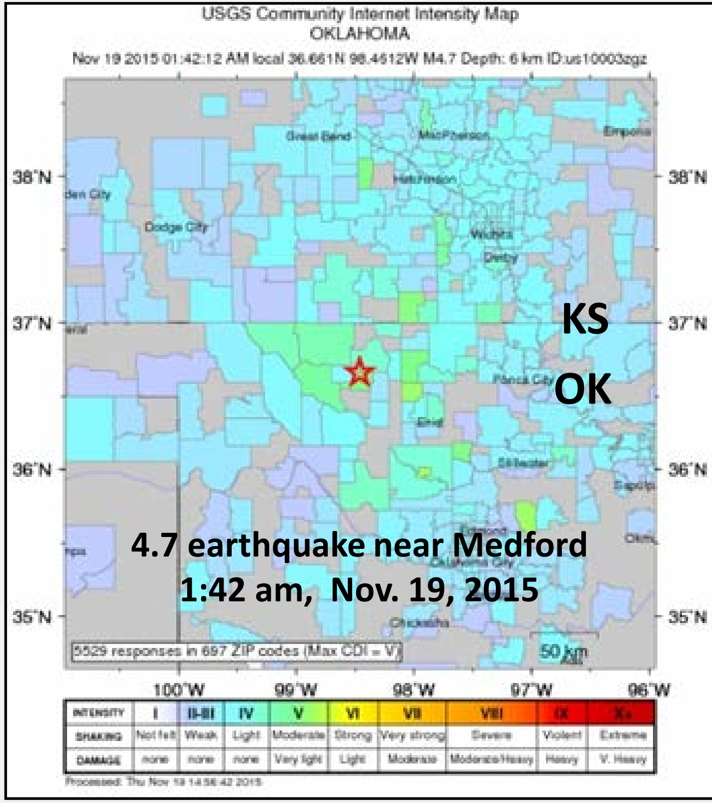
KU KANSAS GEOLOGICAL SURVEY

The University of Kansas

Outline



- **Seismicity**
  - <u>Earthquakes and brine disposal</u>
  - <u>Seismic monitoring</u>

    *R. Miller, S. Petrie (**KGS array**),*

    G. Tsoflias, KU Geology, A. Nolte, Brandon Graham, J. Victorine,

    *J. (Raney) Hollenbach (**Wellington Array**)*

    *J. Rubenstein, P.I., (**USGS temporary array, ismpkansas**)*

  <u>Kansas Induced Seismicity Task Force</u>

    R. Buchanan, Ryan Hoffman, Mike Tate

- **Geoscience characterization and modeling**
  - <u>Mechanics of induced earthquakes</u>

    T. Bidgoli, C. Jackson, D. Schwab, M. Taylor (KU Geology), T. Birdie

  - <u>Basement Geology – Midcontinent Rift System &</u>
  - <u>Mississippian Lime Play &</u> <u>Arbuckle geology</u>

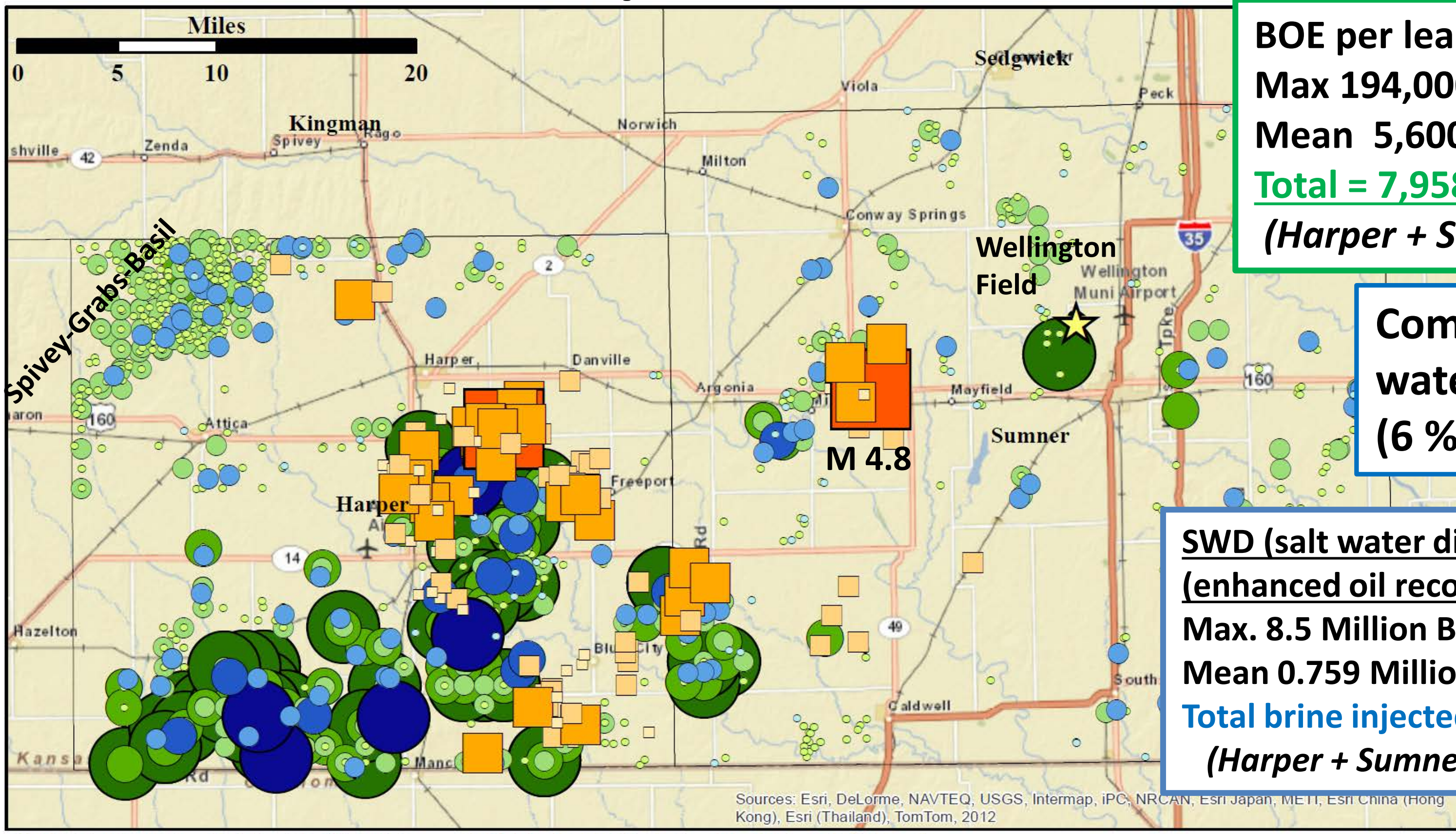
    J. Rush, M. Fazelalavi, J. Doveton, L. Watney

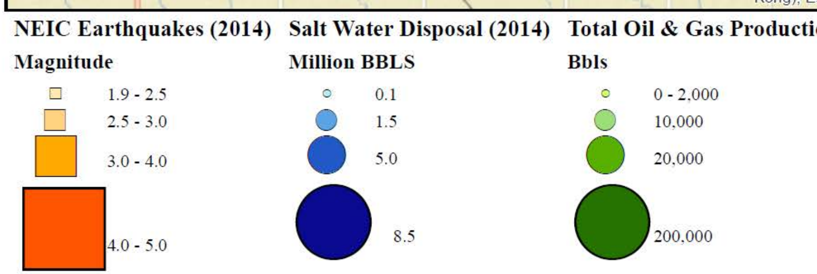
- **Fluid flow simulation in the Arbuckle and basement –** <u>Y. Holubnayak</u> along with

  T. Bidgoli, C. Jackson, M. Fazelalavi, G. Williams, T. Hansen, P. Gerlach, J. Doveton, D. Newell, L. Watney

- **Summary**
- **Ongoing and future studies**

Total salt water injected by well (blue) and BOE (barrels of oil equivalent) by lease (green), and earthquakes (squares), 2014
Harper and Sumner Counties





Wellington CO2 Injection Site

BOE per lease:
Max 194,000 (531 BOE per day)
Mean 5,600 (15 BOE per day)
Total = 7,958,340 BOE
(Harper + Sumner. 2014)

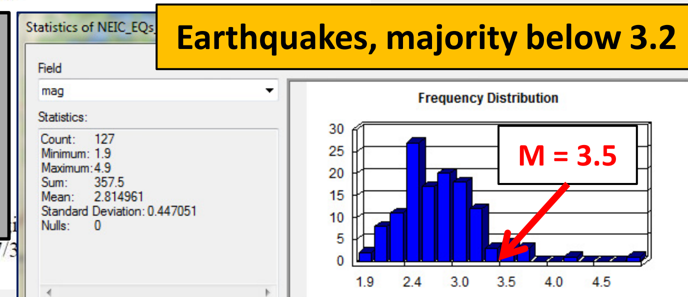
Composite BW (bbls water)/BOE = 16:1
(6 % oil cut)

SWD (salt water disposal) and EOR (enhanced oil recovery) (Class II) per well
Max. 8.5 Million BW (23k BW/day)
Mean 0.759 Million BW
Total brine injected = 128,254,699 bbls
(Harper + Sumner Co., 2014)

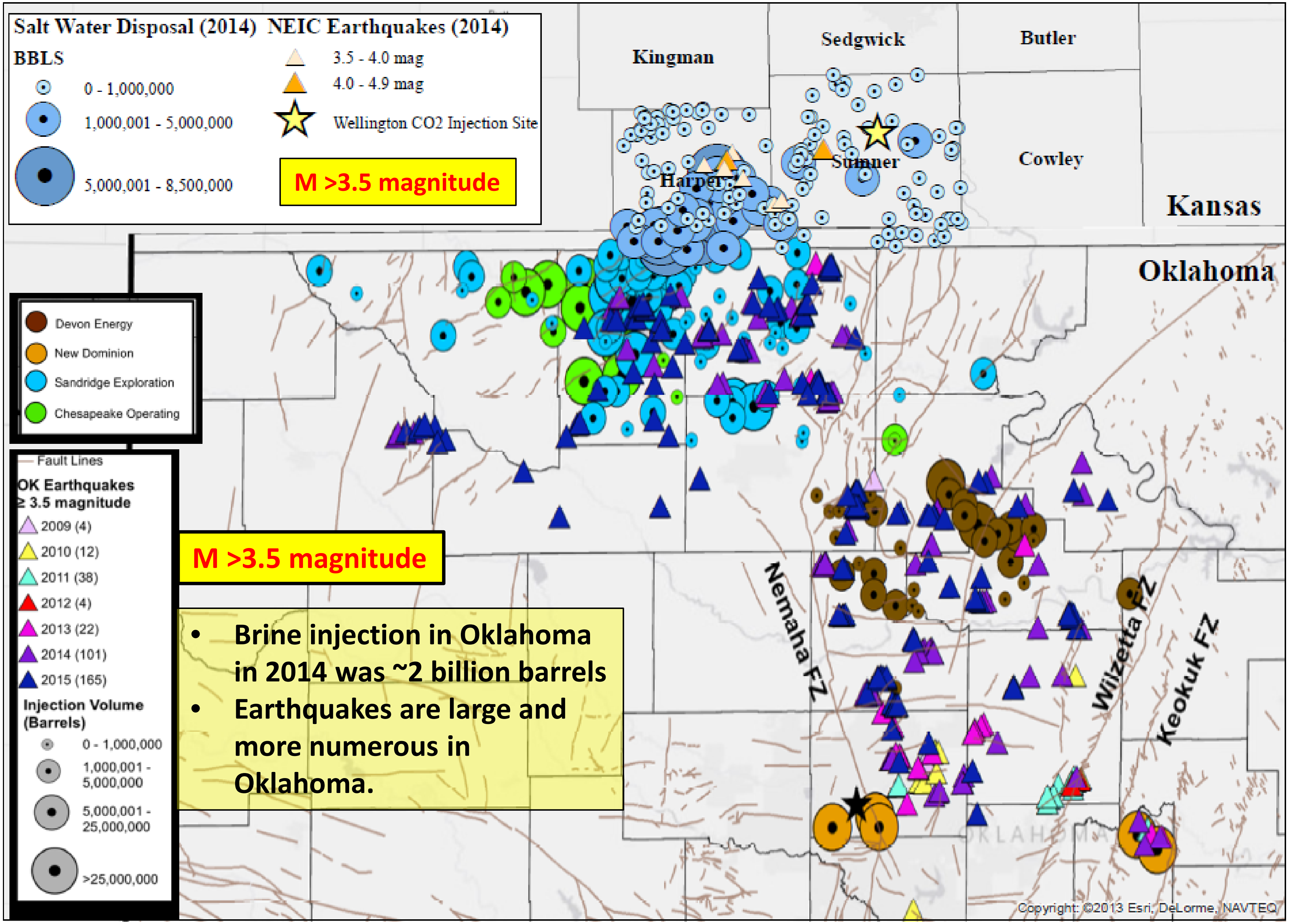
Hollenbach, KGS

Min 1.9
Max 4.9
127 Earthquakes in 2014

Earthquakes, majority below 3.2



Earthquakes and geology in south-central KS and north-central OK



Map printed by J. Hollenbach 12/8/2015

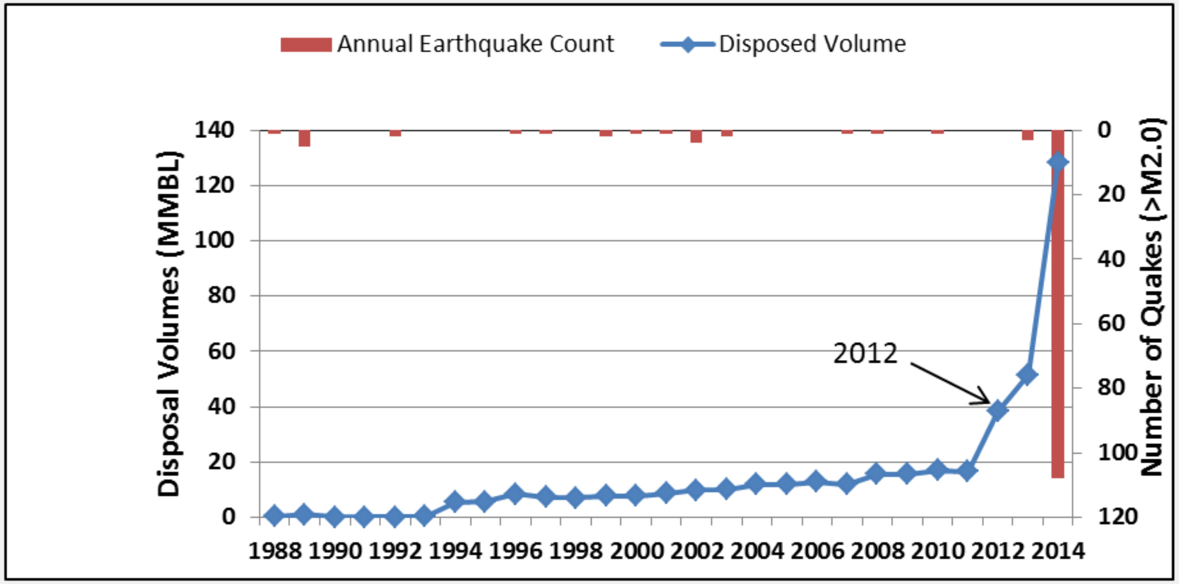
0 25 50 Miles

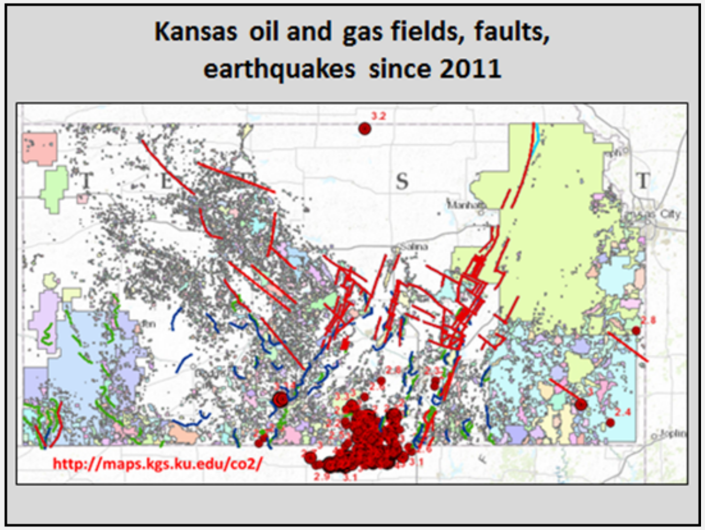
N

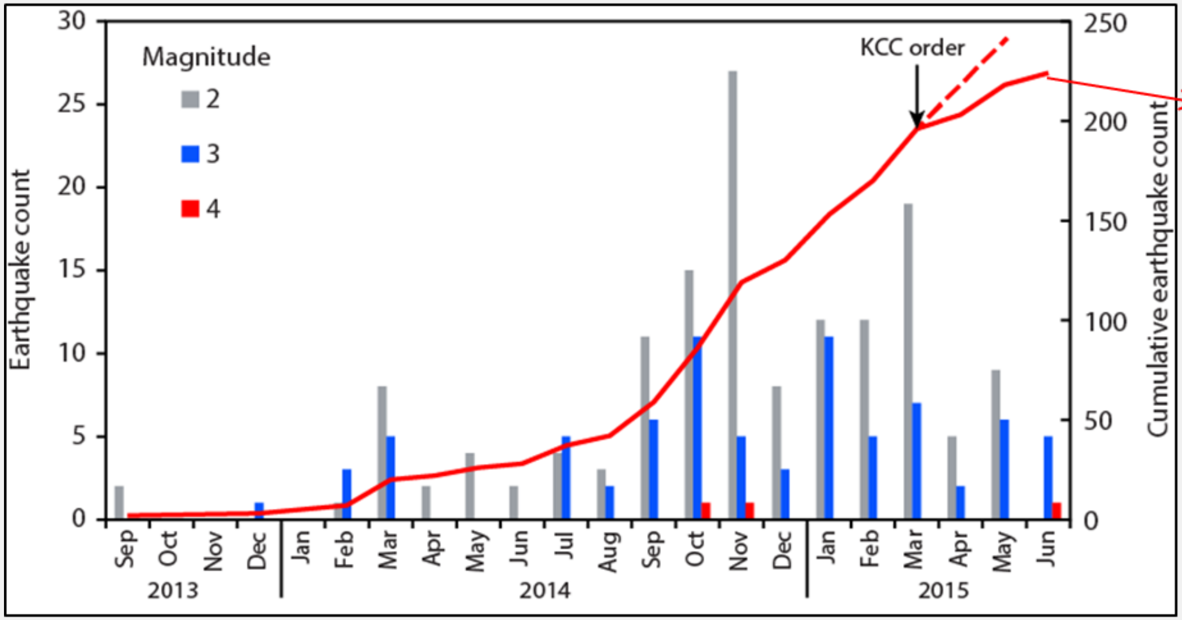
Sources: Kansas Geological Survey, Kansas Corporation Commission, NEIC, USGS, ESRI, Oklahoma Geological Survey, Oklahoma Corporation Commission
Oklahoma map - Public Justice lawsuit on behalf of the Sierra Club dated 10/29/2015

Hollenbach, KGS

Seismic Trends in Southern Kansas







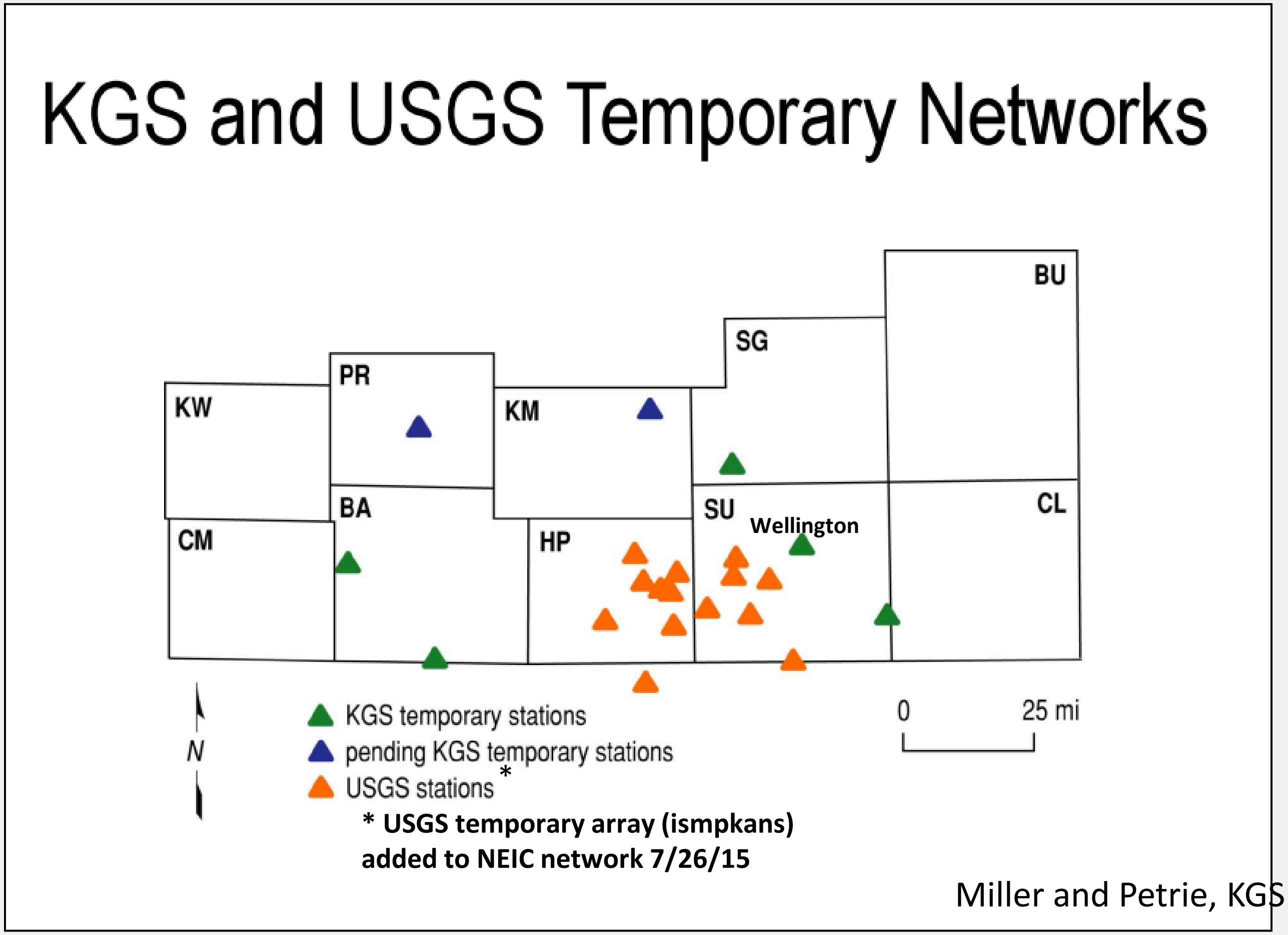
- **Until July 1 – Slight reduction in seismicity following state restrictions in disposal rates and volumes and effects of lower oil prices**

Bidgoli, KGS

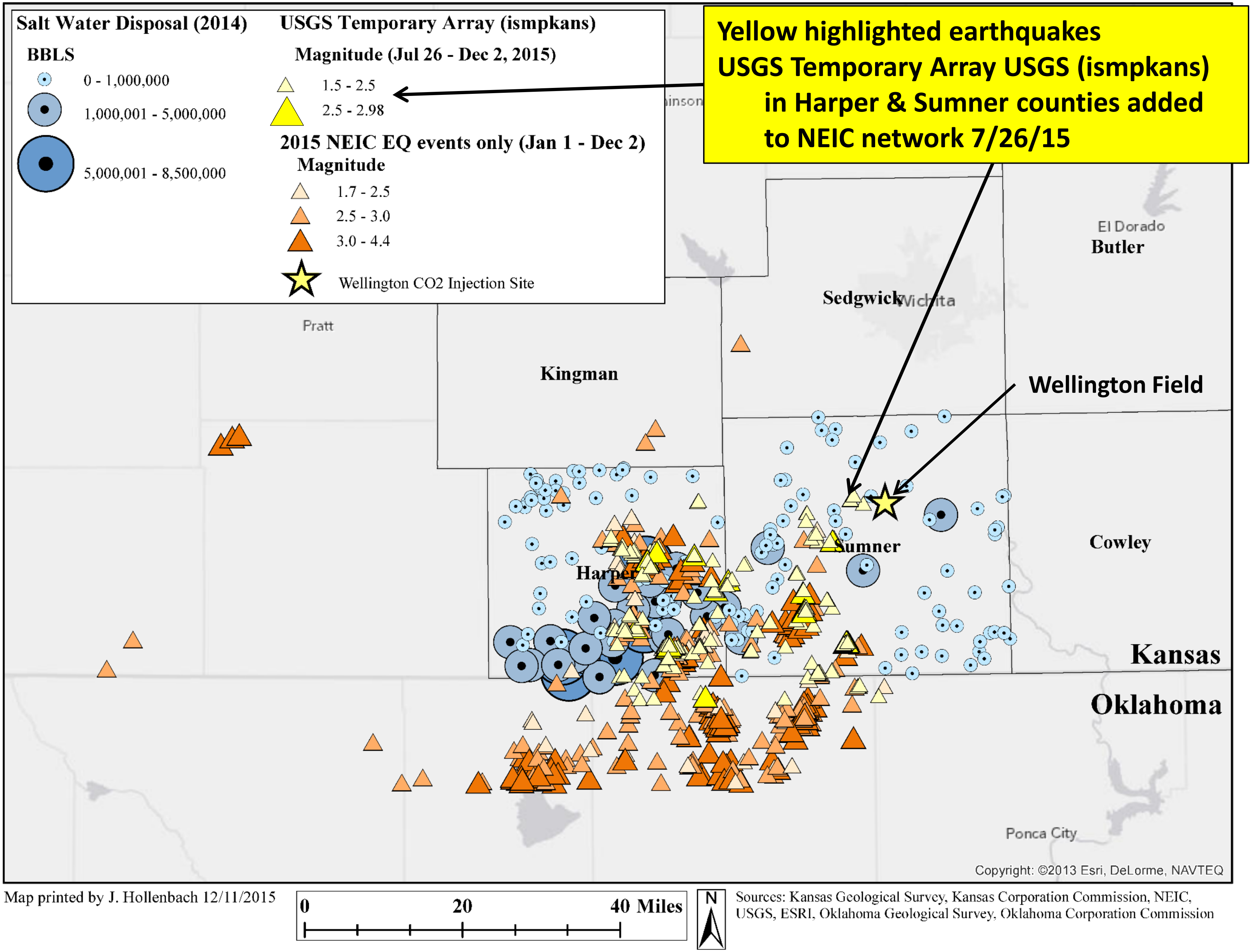
Location of KGS and USGS Temporary Seismometer Arrays

KGS presentation to *House Standing Committee on Energy and Environment*

Rep. Dennis Hedke, Presiding

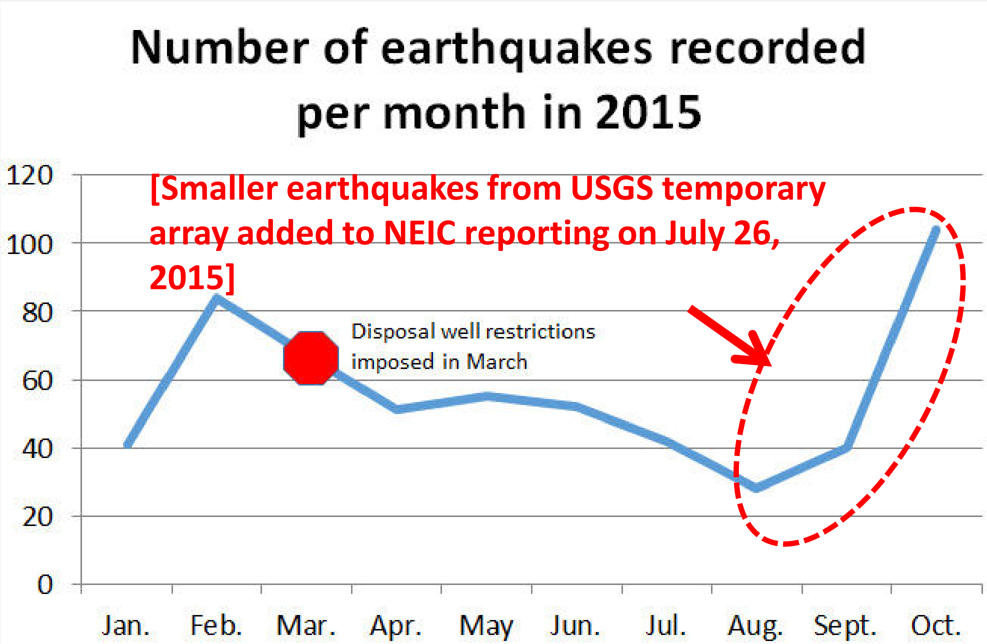


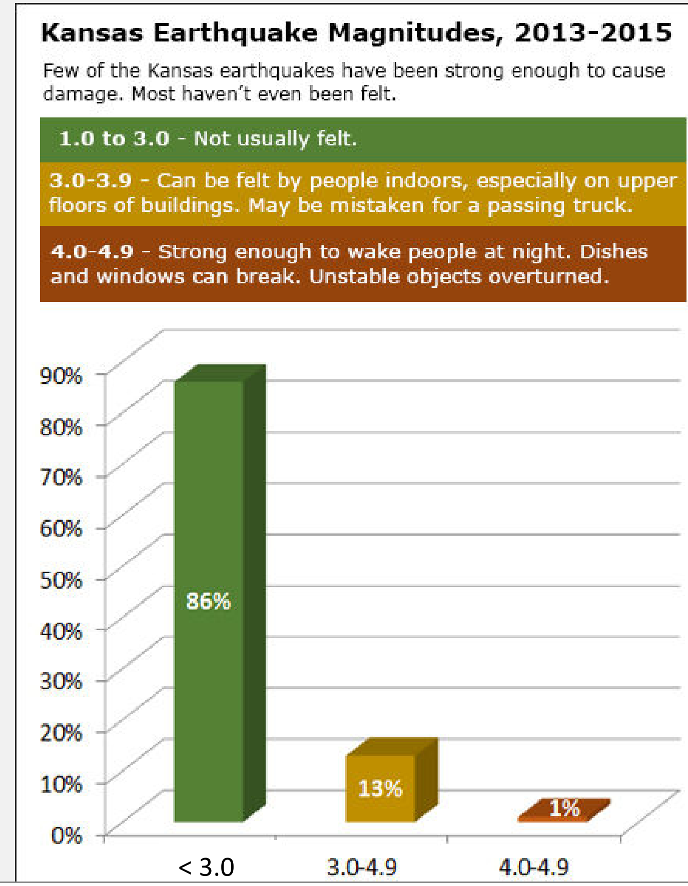
http://www.kgs.ku.edu/PRS/Seismicity/2015/01-26-15_KGS_Seismic_Monitoring.pdf



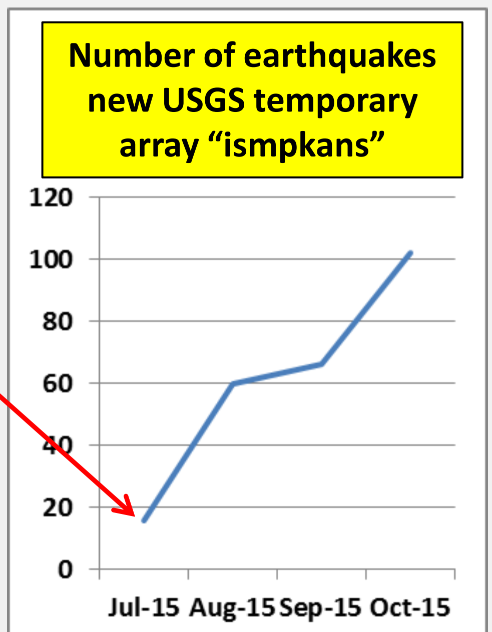
Map printed by J. Hollenbach 12/11/2015

Sources: Kansas Geological Survey, Kansas Corporation Commission, NEIC, USGS, ESRI, Oklahoma Geological Survey, Oklahoma Corporation Commission

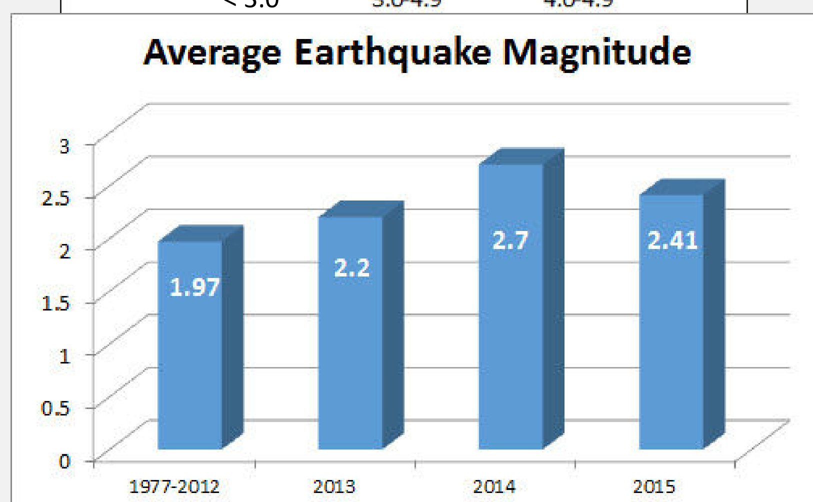




Introduction of USGS ismpkans catalog on July 26, 2015 → inclusion of smaller events



Average magnitude = **2.07**
Minimum magnitude = **1.5**
Maximum mag = **2.98**
Total count from = **304**

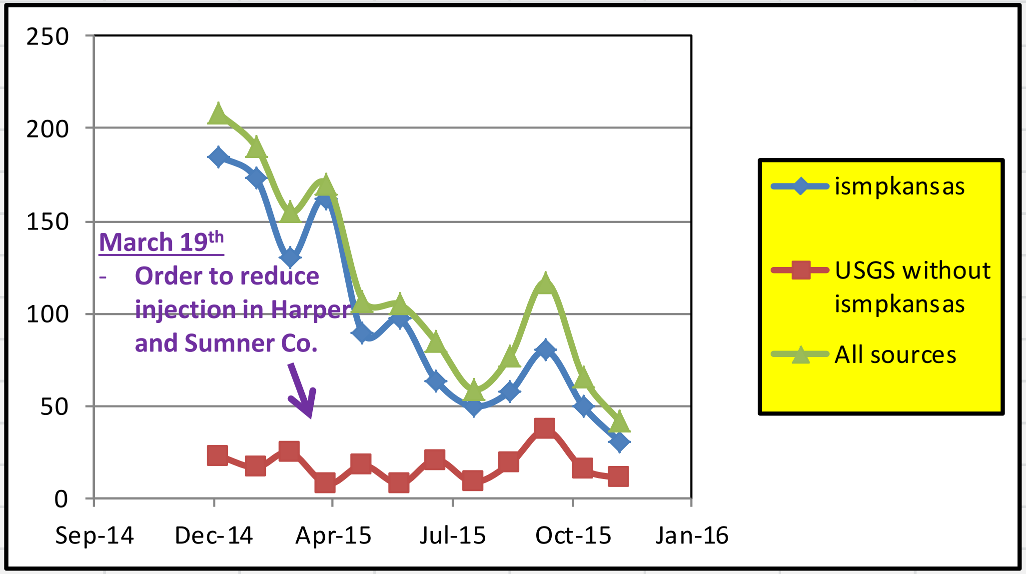


L. Watney, KGS

http://www.**hutchnews.com**/kansas_earthquakes/

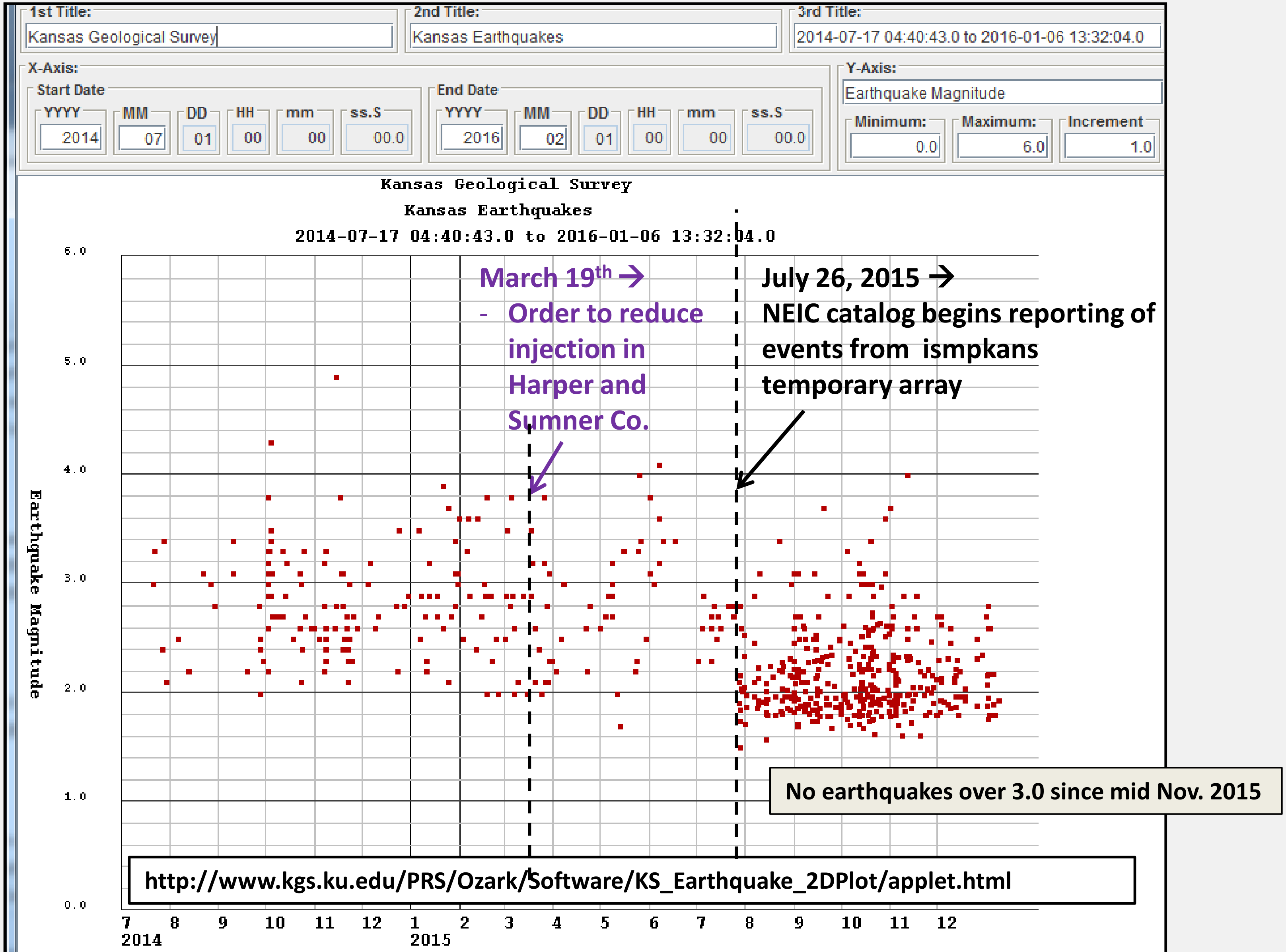
Kansas Earthquakes included on USGS NEIC database January 1, 2015 to Jan. 11, 2016 →decrease in number and intensity

Month	ismpkansas	USGS without ismpkansas	All sources
Jan-15	185	23	208
Feb-15	173	17	190
Mar-15	130	25	155
Apr-15	162	8	170
May-15	89	18	107
Jun-15	97	8	105
Jul-15	64	21	85
Aug-15	50	9	59
Sep-15	58	19	77
Oct-15	80	37	117
Nov-15	50	16	66
Dec-15	31	11	42
Jan-16	5	1	6
total	**816**	**173**	**989**



Kansas earthquakes as reported by NEIC

including first report on July 26, 2015 of new USGS temporary array "ismpkans" in Harper & Sumner counties



Action by KCC on March 19 to reduce disposal volumes in Harper and Sunner counties

Conservation Division
266 N. Main St., Ste. 220
Wichita, KS 67202-1513

Kansas
AD ASTRA PER ASPERA
Corporation Commission

Phone: 316-337-6200
Fax: 316-337-6211
http://kcc.ks.gov/

News Release

For Immediate Release
March 19, 2015

Contact Information
Amy Gilbert, (785) 271-3190

**KCC ISSUES ORDER REDUCING DISPOSAL VOLUMES
IN PORTIONS OF HARPER AND SUMNER COUNTIES**

Wichita, KS – Today, the Kansas Corporation Commission (KCC) issued an Order requiring a reduction in volumes of saltwater injected into the Arbuckle formation in certain areas of Harper and Sumner counties.

The Order sets limits for Arbuckle injection wells located within five areas of seismic concern identified by the Kansas Geological Survey (KGS) in Harper and Sumner counties. The KGS determined areas of seismic concern by applying the Kansas Induced Seismicity Task Force's Seismic Action Score (SAS) to the areas' earthquake activity recorded from January 2014 through February 2015. The recorded data is available from the U.S. Geological Survey's National Earthquake Information Center. The SAS used here is part of the Seismic Action Plan developed at the direction of Governor Brownback through the coordinated efforts of the KGS, the KCC, and the Kansas Department of Health and Environment.

The Order requires operators of Arbuckle saltwater disposal wells in these five areas to limit their injection wells to 16,000 barrels of saltwater per day within 10 days of the Order; to 12,000 barrels per day within 55 days; to 8,000 barrels per day within 100 days, for a total reduction of up to 60% on certain injection wells over this timeframe. These operators also will be required to regularly report data showing their compliance with the Order. The KGS will continue to measure the seismic activity in these areas. The Order directs KCC staff to work in conjunction with the KGS to review the data, with recommendation to the Commission for further action, if necessary.

The Order further sets a maximum daily injection permit limit of 25,000 barrels of saltwater on all Arbuckle injection wells in Harper and Sumner counties that are not in these five areas.

There are currently more than 4,300 Arbuckle injection wells statewide and the formation has long been utilized for both production and disposal in different parts of Kansas. The wells impacted by today's action represent only a small fraction of the total active Arbuckle injection wells. Arbuckle injection currently occurs in many areas throughout Kansas without any recorded seismic activity.

A complete copy of the Order can be found by visiting the home page of www.kcc.ks.gov, or also by clicking on Docket Filings, and entering Docket No. 15-CONS-770-CMSC.

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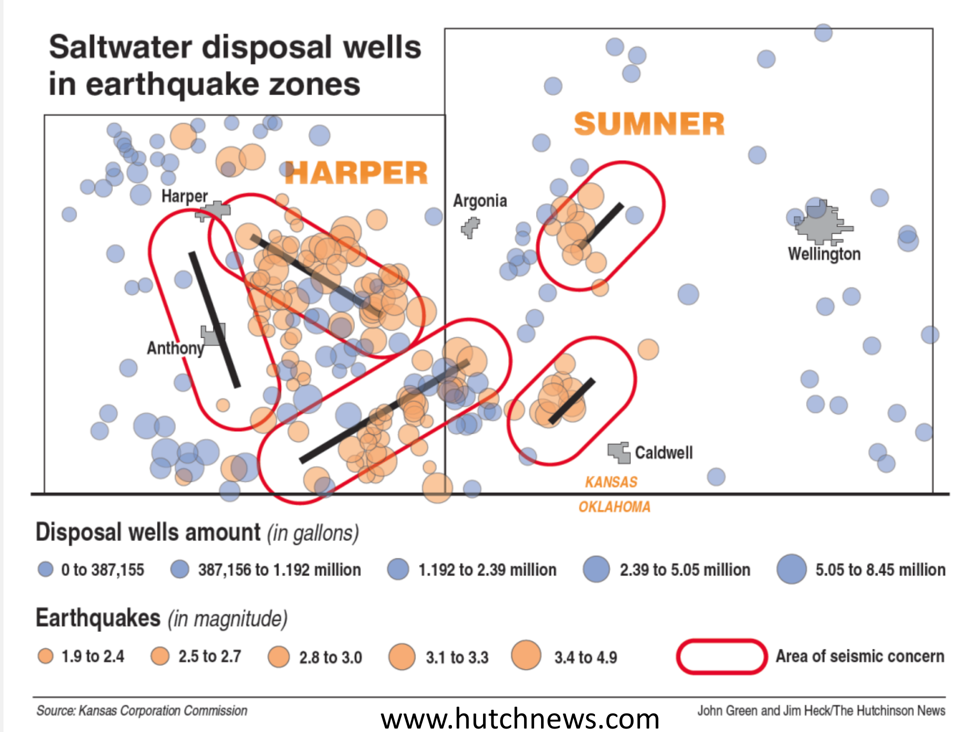
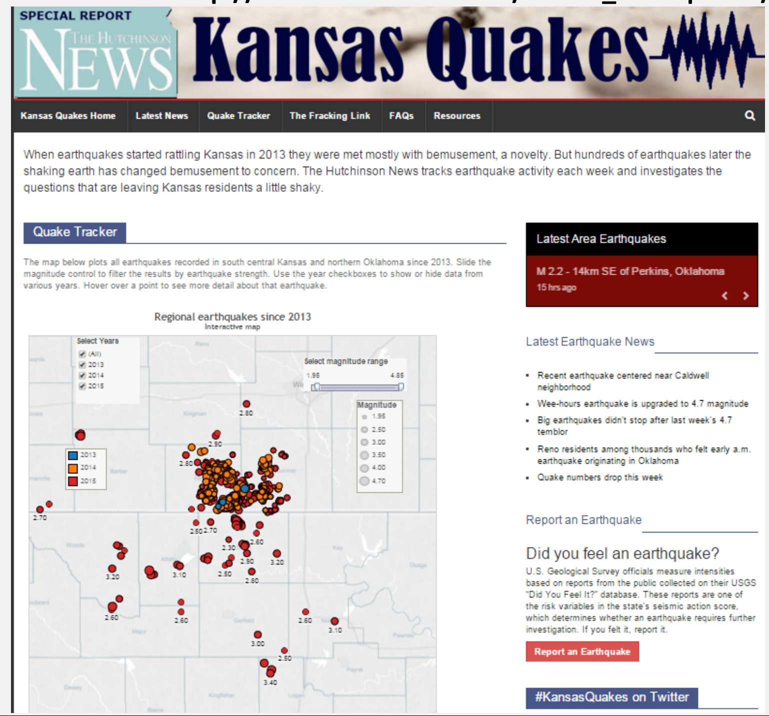
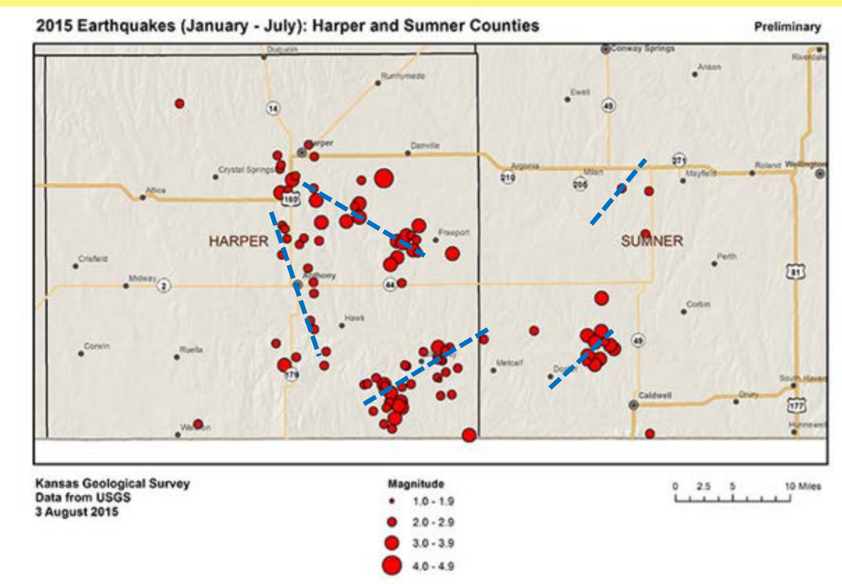


12-9-2015 --- http://www.hutchnews.com/kansas_earthquakes/





Monitoring Earthquakes in Kansas

KGS Publications PIC index http://www.kgs.ku.edu/Publications/PIC/pic36.html

Kansas Geological Survey, Public Information Circular (PIC) 36
A complete version of this PIC is available as a pdf document.

Induced Seismicity: The Potential for Triggered Earthquakes in Kansas

Rex C. Buchanan, K. David Newell, Catherine S. Evans, Richard D. Miller, and Shelby L. Peterie
Kansas Geological Survey
Revised August 2015

Introduction

Earthquake activity in the Earth's crust is known as seismicity. When linked to human activities, it is commonly referred to as "induced seismicity." Industries that have been associated with induced seismicity include oil and gas production, mining, geothermal energy production, construction, underground nuclear testing, and impoundment of large reservoirs (National Research Council, 2012).

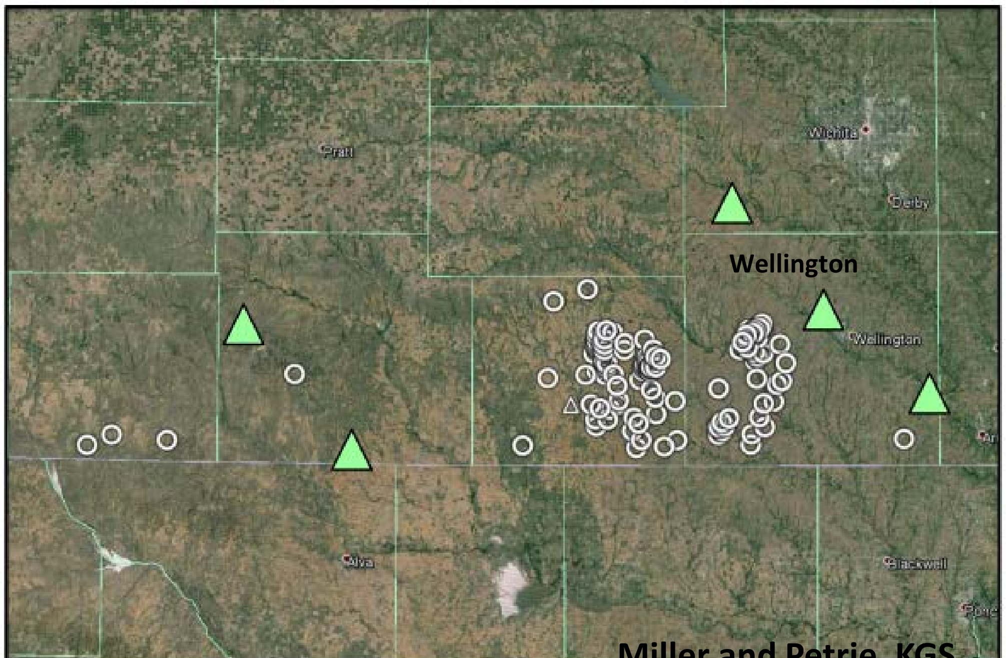
In the early 2000s, concern began to grow over an increase in the number of earthquakes in the vicinity of oil and gas exploration and production operations, particularly in Oklahoma, Arkansas, Ohio, Colorado, and Texas. **Horizontal drilling** in conjunction with **hydraulic fracturing**, popularly called "fracking," has often been singled out for blame in the public discourse. The actual process of hydraulic fracturing, however, has been confirmed as the cause of felt earthquakes only a few times worldwide. More often, detected seismic activity associated with oil and gas operations is thought to be triggered when wastewater is injected into disposal wells. In Kansas, both conventional and hydraulic fracturing processes produce saltwater along with oil and gas. In the disposal process, waste products--including saltwater and recovered hydraulic fracturing fluids--are injected into deep and confined porous rock.

Linking a specific earthquake to a specific human activity, such as wastewater disposal at a single well, is difficult. Complex subsurface geology and limited data about that geology make it hard to pinpoint the cause of many seismic events in the midcontinent. However, an established pattern of increased earthquake activity in an area over time may indicate a correlation between human activity and seismic events.

KGS testimony and presentations, Jan. 26, 2015

House Standing Committee on Energy and Environment

Earthquakes detected using only the KGS Temporary Network

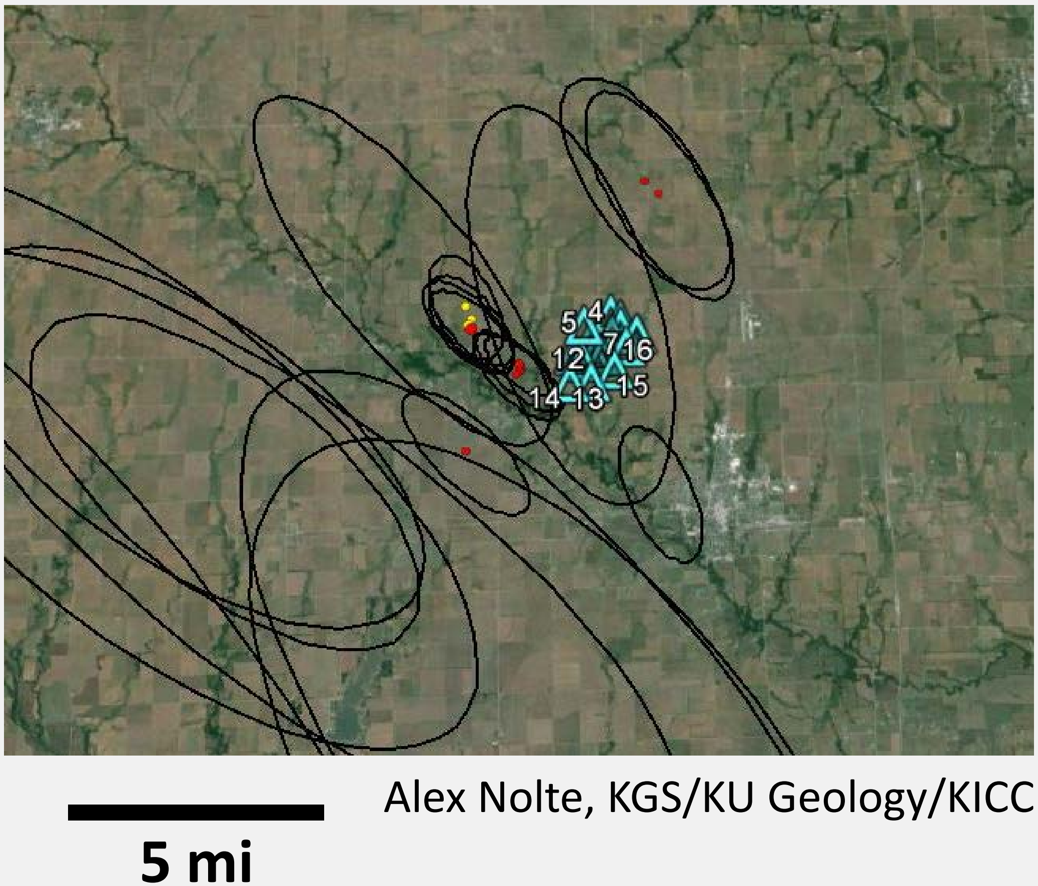


A total of 123 earthquakes (white circles) were detected by the KGS temporary network (green triangles) during the first 16 days of recording.

http://www.kgs.ku.edu/PRS/Seismicity/2015/01-26-15_KGS_Seismic_Monitoring.pdf

Error ellipses of earthquakes recorded near Wellington Field

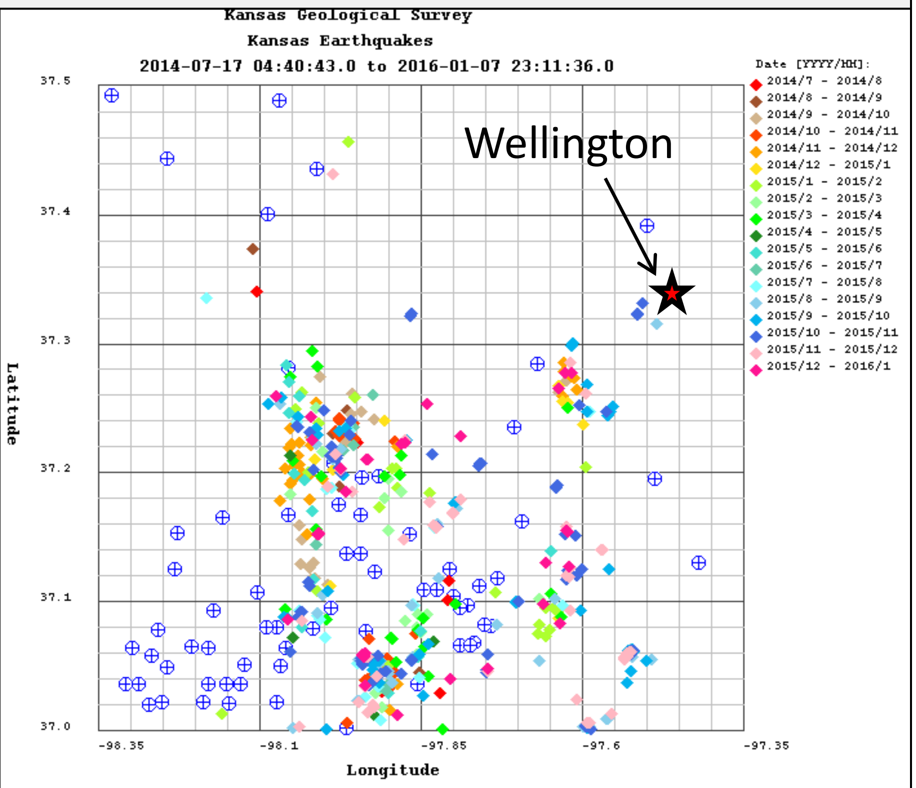
from the ***Wellington IRIS/DOE Seismometer Array***

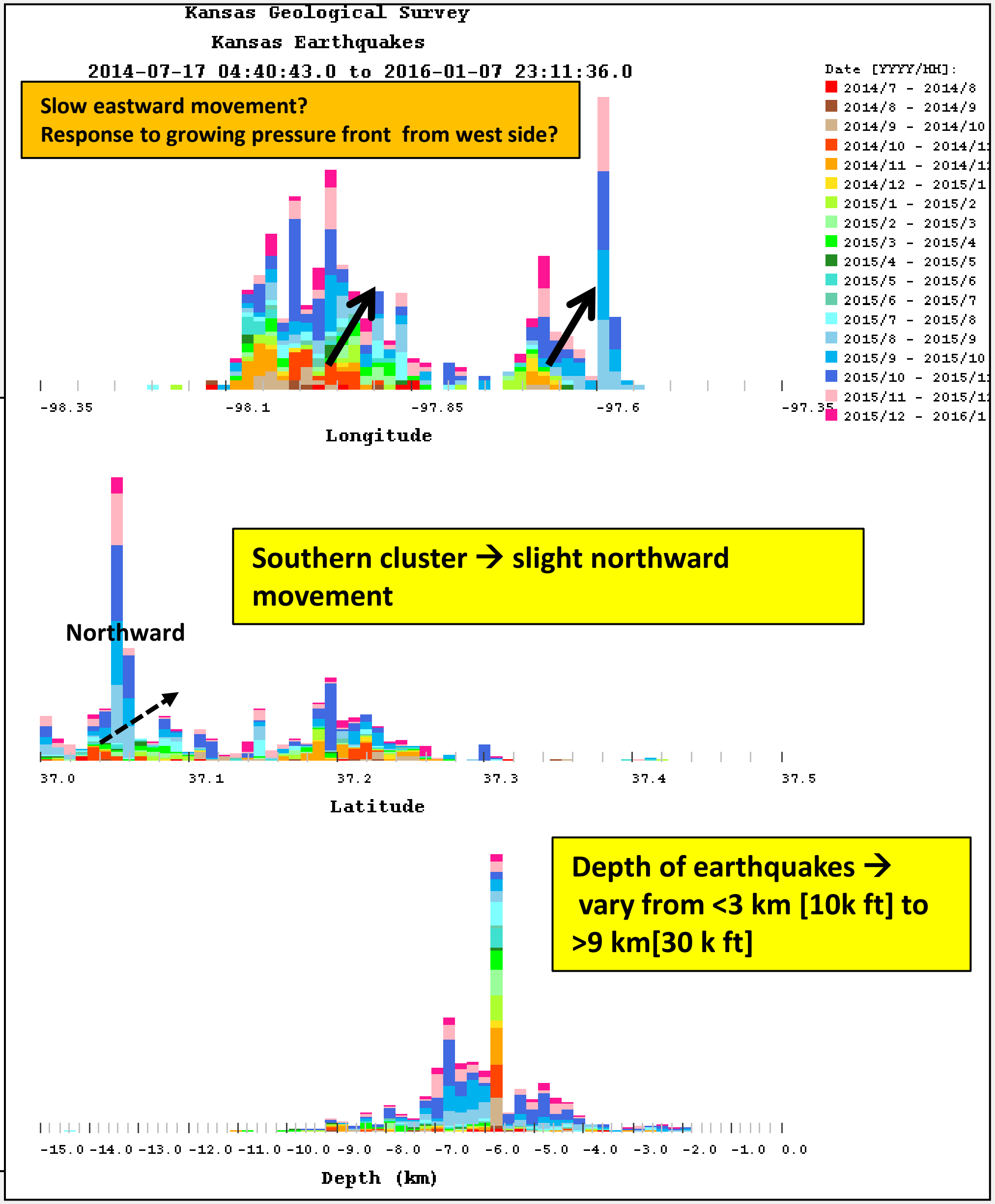


Alex Nolte, KGS/KU Geology/KICC

- Earthquake (red dots) magnitudes detected and with Wellington seismometer array (blue triangles)
- Earthquakes range from magnitudes 0.8 to 1.6
- Earthquakes (yellow dots) from USGS temporary array (ismpkans)
- 2 sigma error shown as elipses with black solid lines indicating 95% confidence level
- Array managed by KGS and KU Geology for DE-FE0006821 (CO_2 injection project)
- Earthquake detection level in field ~0.5 magnitude

Dates vs. location of <u>all</u> earthquakes reported by NEIC including *<u>ismpkans</u>* south-central Kansas 7-17-2014 to 12-7-2015





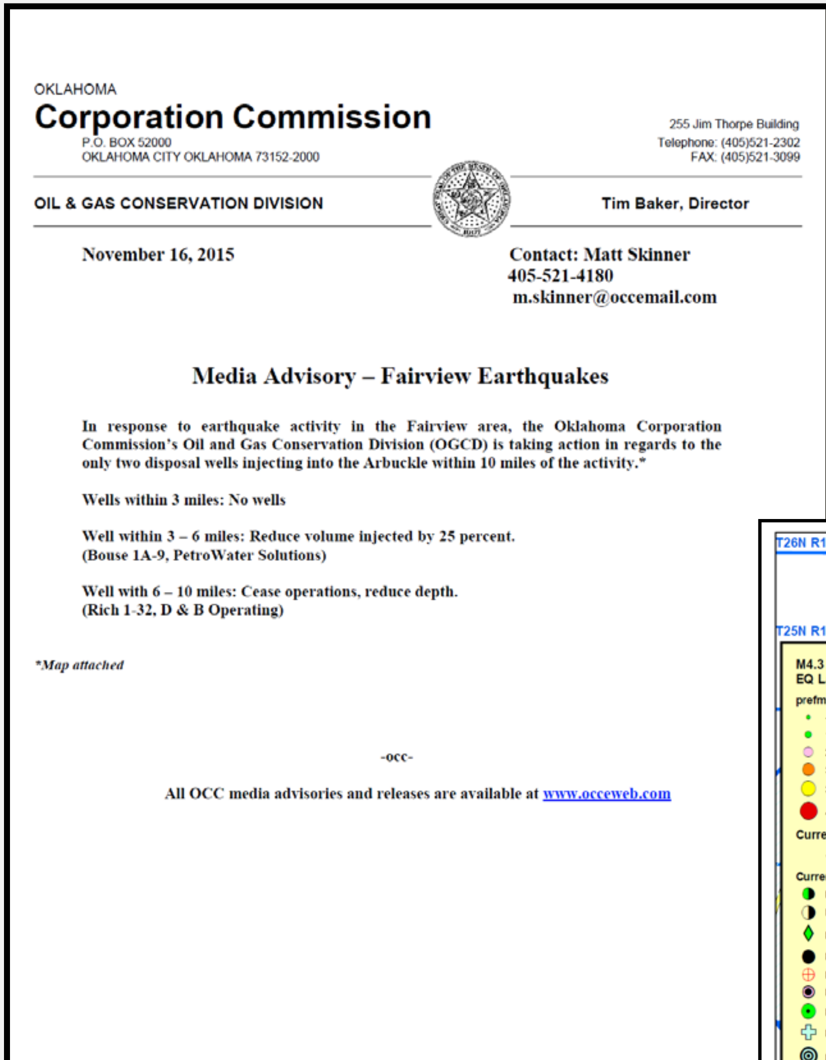
J. Victorine, KGS

http://www.kgs.ku.edu/PRS/Ozark/Software/KS_Earthquake_3DPlot/index.html

Example of action taken to restrict brine injection in Oklahoma, November 16, 2015 after 4.2 event

** Wells within 3-6 miles → reduce volume by 25%*

** Wells 6-10 miles → cease operations, reduce depth*



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255 Jim Thorpe Building
Telephone: (405)521-2302
FAX: (405)521-3099

OIL & GAS CONSERVATION DIVISION **Tim Baker, Director**

November 16, 2015

Contact: Matt Skinner
405-521-4180
m.skinner@occemail.com

Media Advisory – Fairview Earthquakes

In response to earthquake activity in the Fairview area, the Oklahoma Corporation Commission's Oil and Gas Conservation Division (OGCD) is taking action in regards to the only two disposal wells injecting into the Arbuckle within 10 miles of the activity.*

Wells within 3 miles: No wells

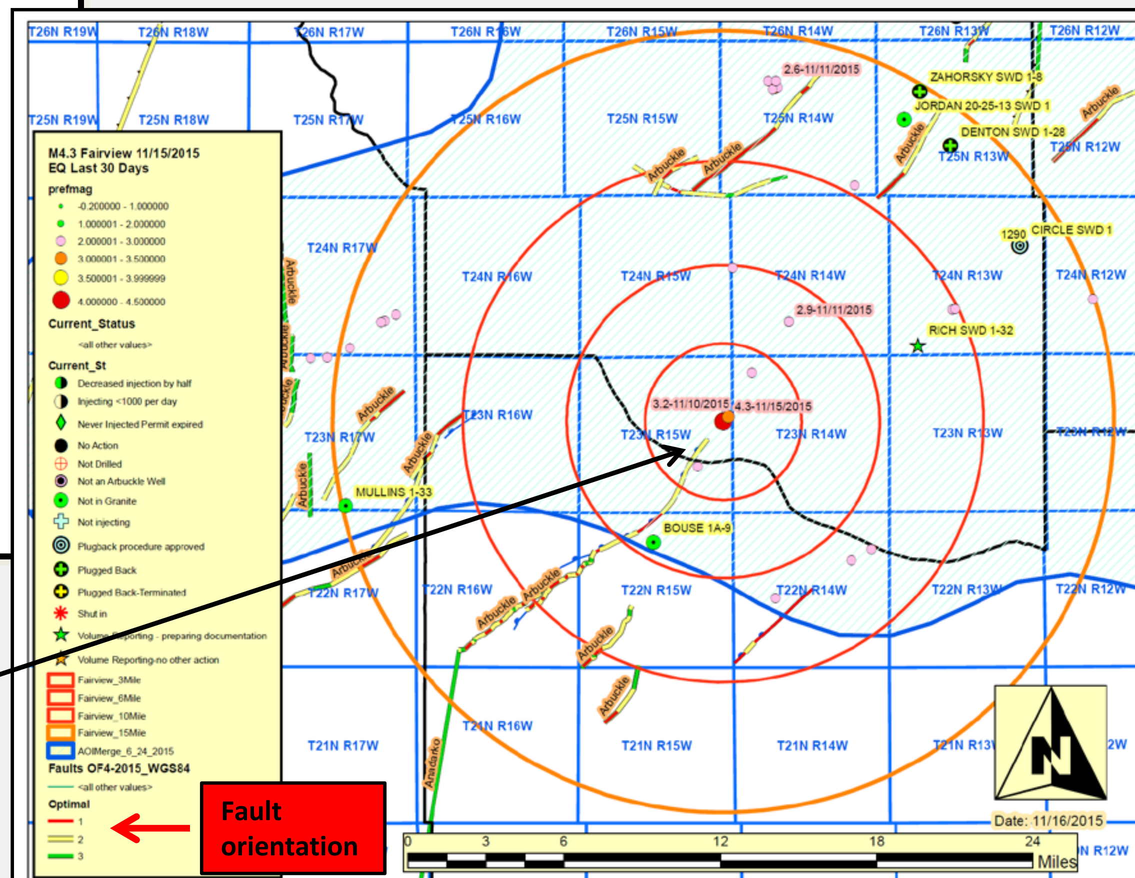
Well within 3 – 6 miles: Reduce volume injected by 25 percent.
(Bouse 1A-9, PetroWater Solutions)

Well with 6 – 10 miles: Cease operations, reduce depth.
(Rich 1-32, D & B Operating)

**Map attached*

-occ-

All OCC media advisories and releases are available at www.occeweb.com



Fault orientation

- **Mapping faults with earthquakes**
- **NE-SW fault trends optimal for movement**

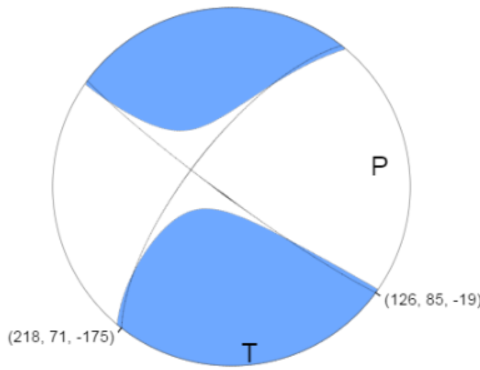
M4.7 - 13km SW of Cherokee, Oklahoma

November 19, 2015

V DYFI?	VI ShakeMap	GREEN PAGER

Focal Mechanisms

Oblique strike slip



Scientific - Moment Tensor

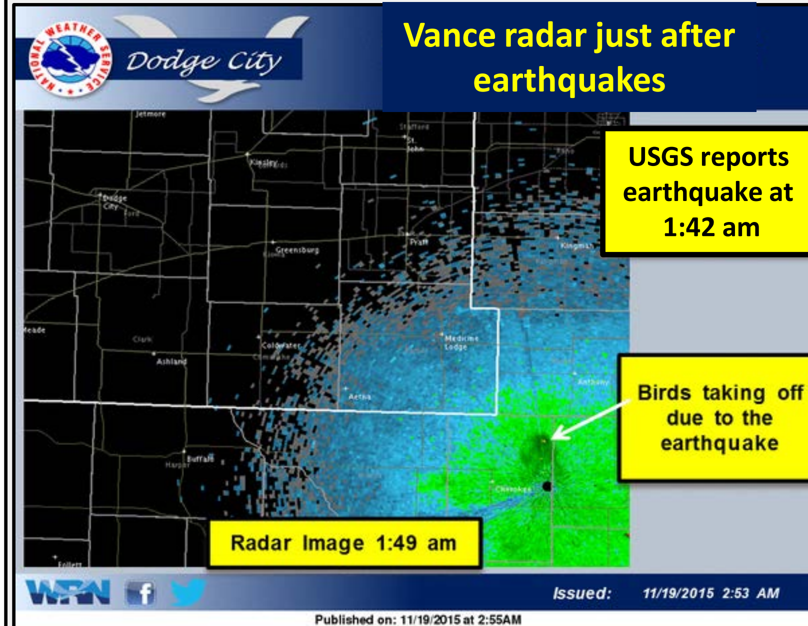
Data Source US[1]

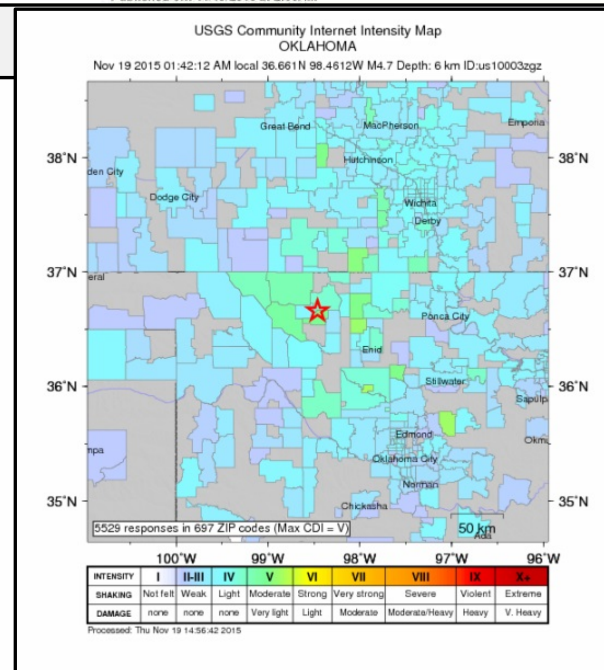
Regional Moment Tensor (Mwr)

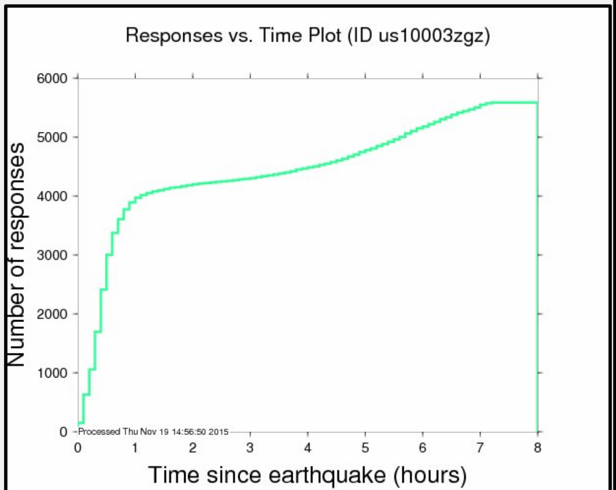
Moment	1.276e+16 N-m
Magnitude	4.67
Depth	10.0 km
Percent DC	79%
Half Duration	-
Catalog	US (us10003zgz)
Data Source	US[1]
Contributor	US[1]

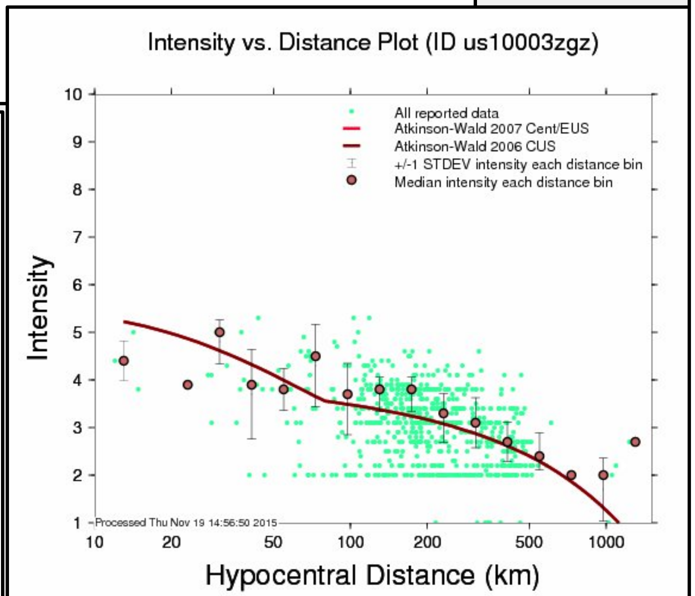
Nodal Planes

Plane	Strike	Dip	Rake
NP1	126°	85°	-19°
NP2	218°	71°	-175°









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OIL & GAS CONSERVATION DIVISION

Tim Baker, Director

November 19, 2015

Contact: Matt Skinner
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m.skinner@occemail.com

Media Advisory – Cherokee-Carmen area Earthquakes

The Oklahoma Corporation Commission's Oil and Gas Conservation Division (OGCD) is implementing a plan in response to today's earthquakes in the Cherokee-Carmen area. The plan calls for changes to oil and gas wastewater disposal wells in the area that dispose into the Arbuckle formation.

The plan calls for 2 disposal wells to stop operations, and for 23 others to reduce disposed volumes. The plan may change based on any new data.

The total net volume reduction is 41 percent.

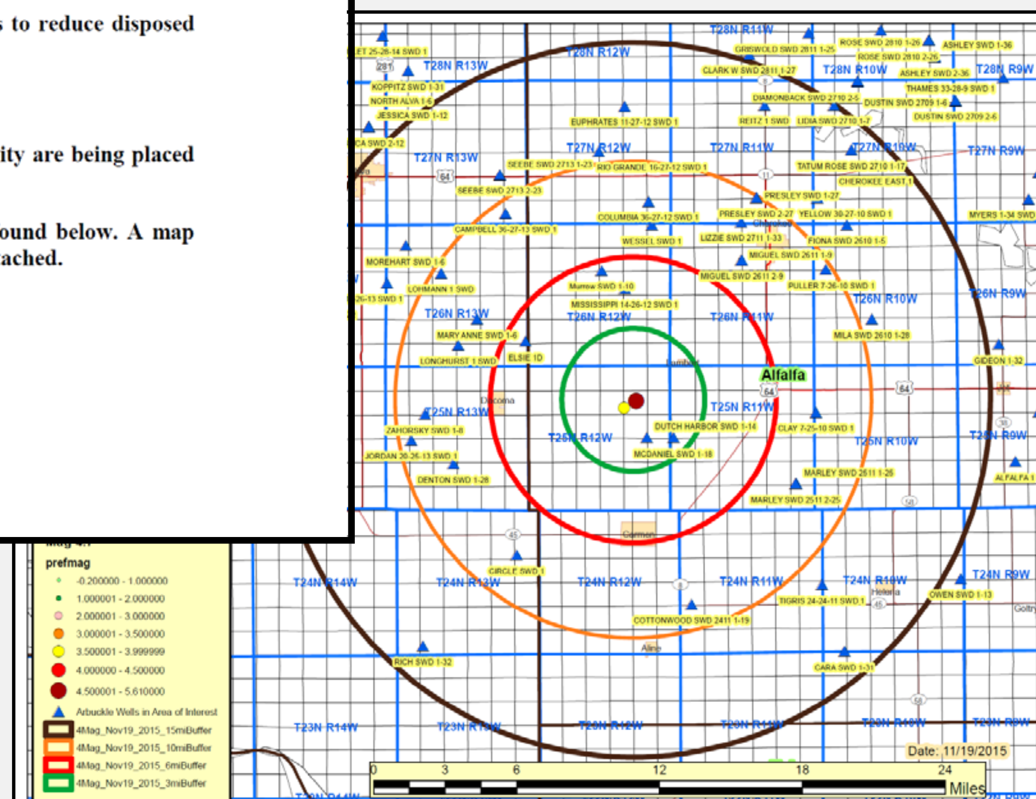
In addition, disposal wells within 10 to 15 miles of the earthquake activity are being placed on notice to prepare for possible changes to their operations.

A full listing of the wells, operators, and action for each well can be found below. A map showing the well locations within the 3-6, 6-10, and 10-15 mile areas is attached.

Example of action taken to restrict brine injection in Oklahoma – **after 4.7 earthquake on Nov. 19**

2 wells stop operations
23 wells reduce disposal volumes

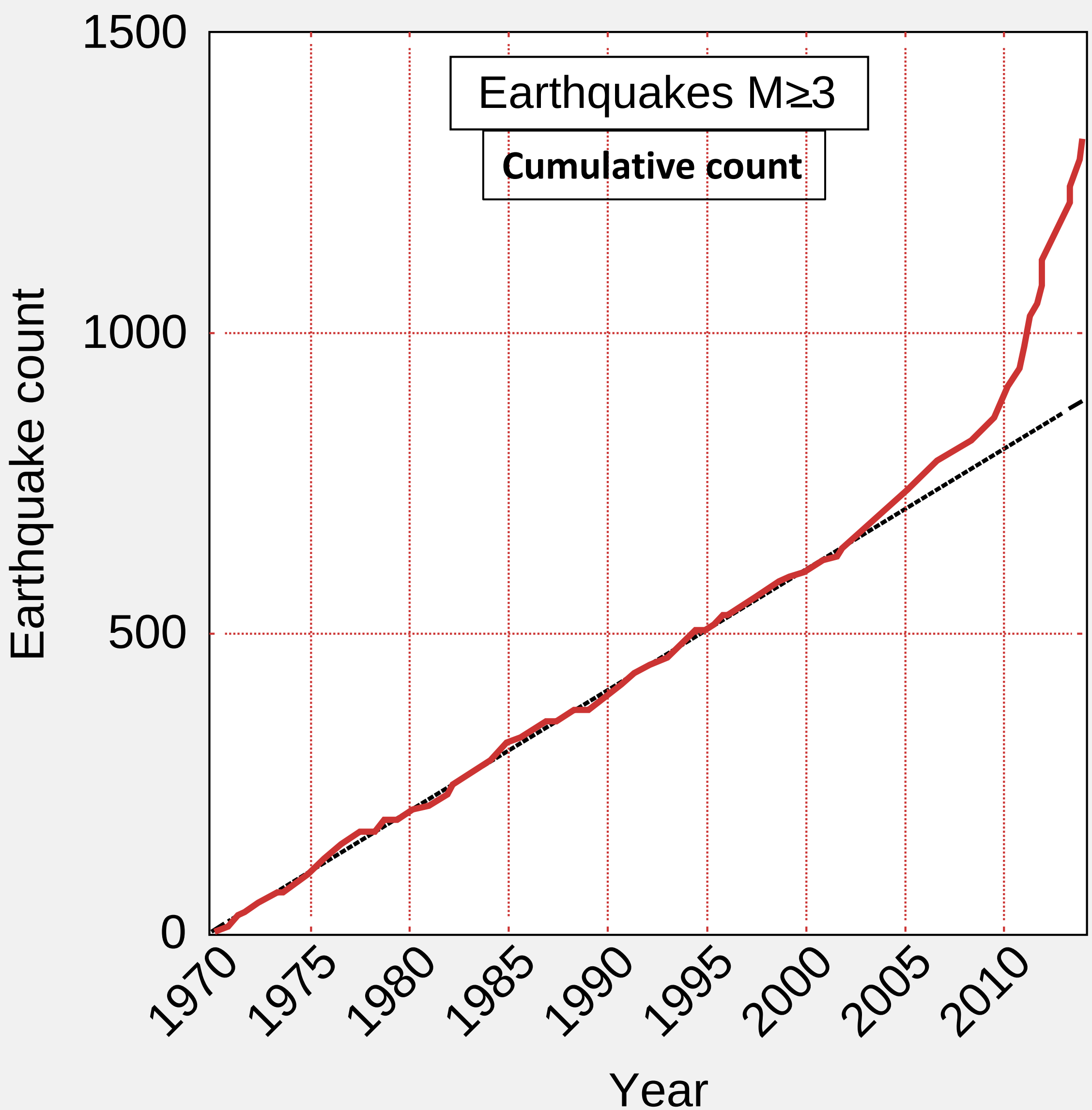
Net reduction of 41%
Wells within 10-15 miles on notice



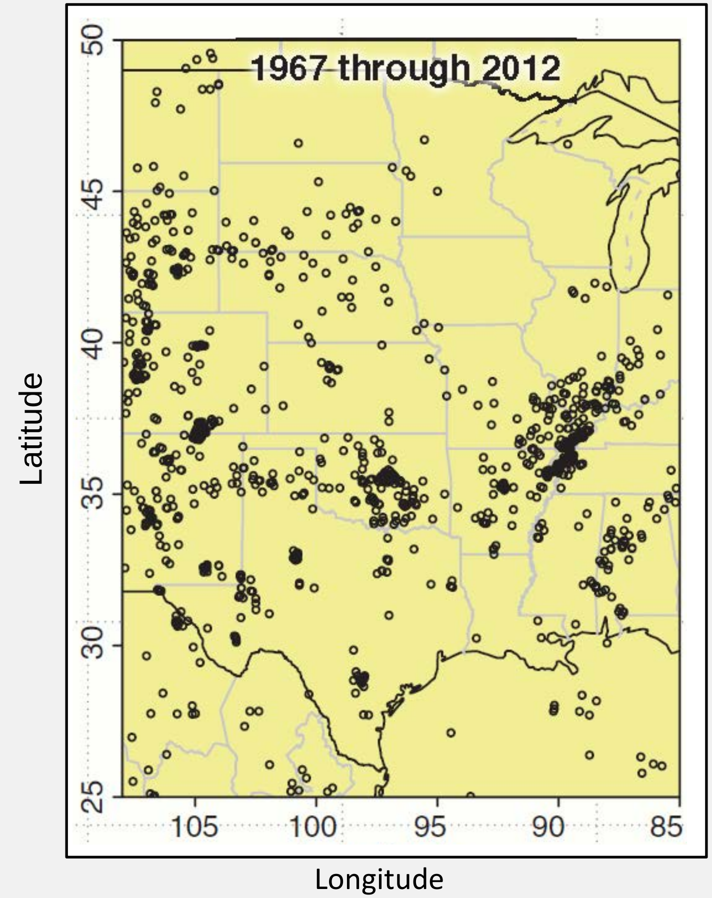
Geoscience characterization and modeling

- Mechanics of induced earthquakes
- Fault characterization and stress field analysis – ancient and modern
- Basement geology – Midcontinent Rift System
- Mississippian Lime Play
- Arbuckle disposal zone

Trends in the central and eastern United States

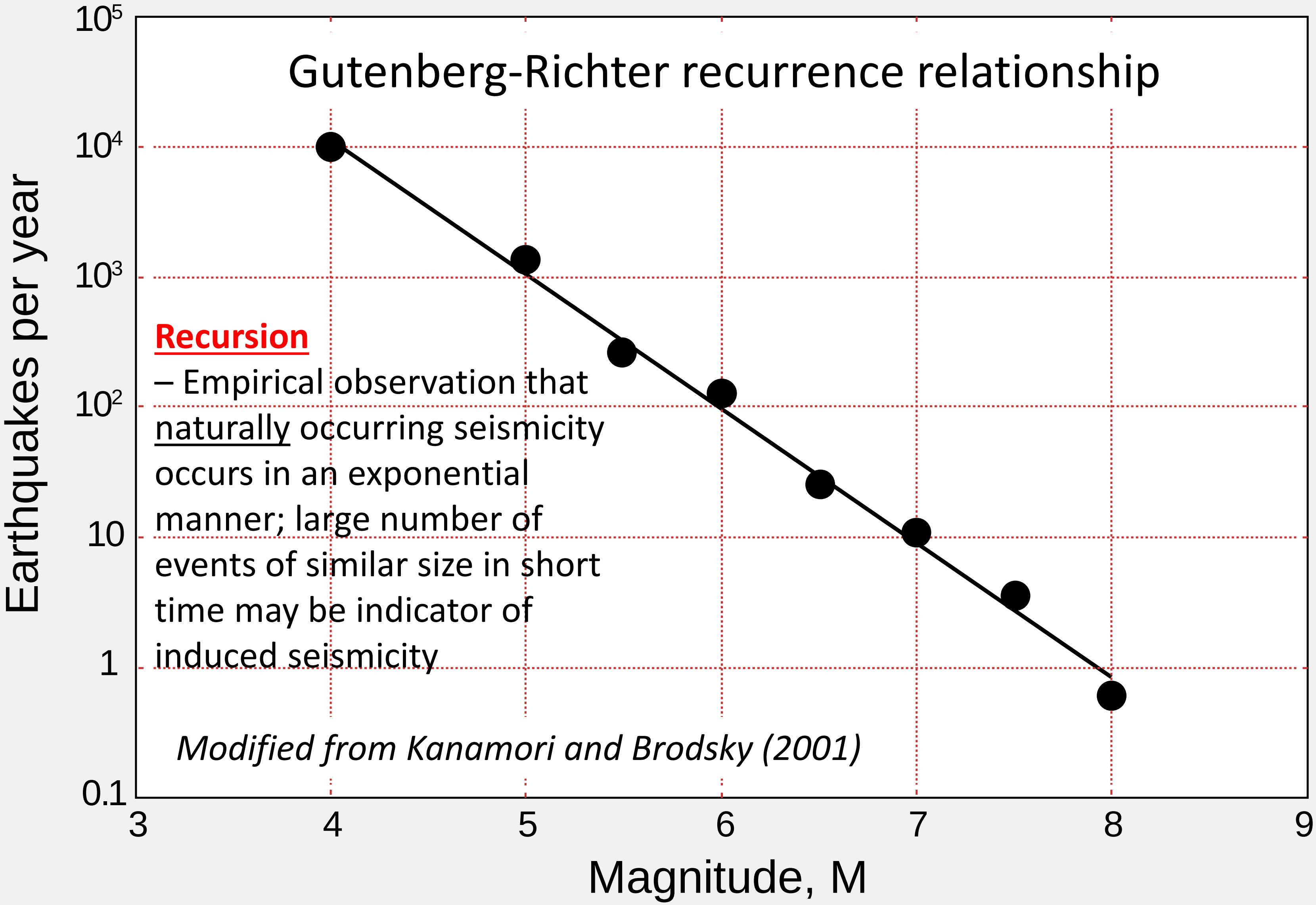


Modified from Ellsworth (2013)



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

Why care about seismicity?



Magnitude vs. size of fault
→Need large fault to create a large earthquake

Bulletin of the Seismological Society of America, Vol. 84, No. 4, pp. 974–1002, August 1994

New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement

by Donald L. Wells and Kevin J. Coppersmith

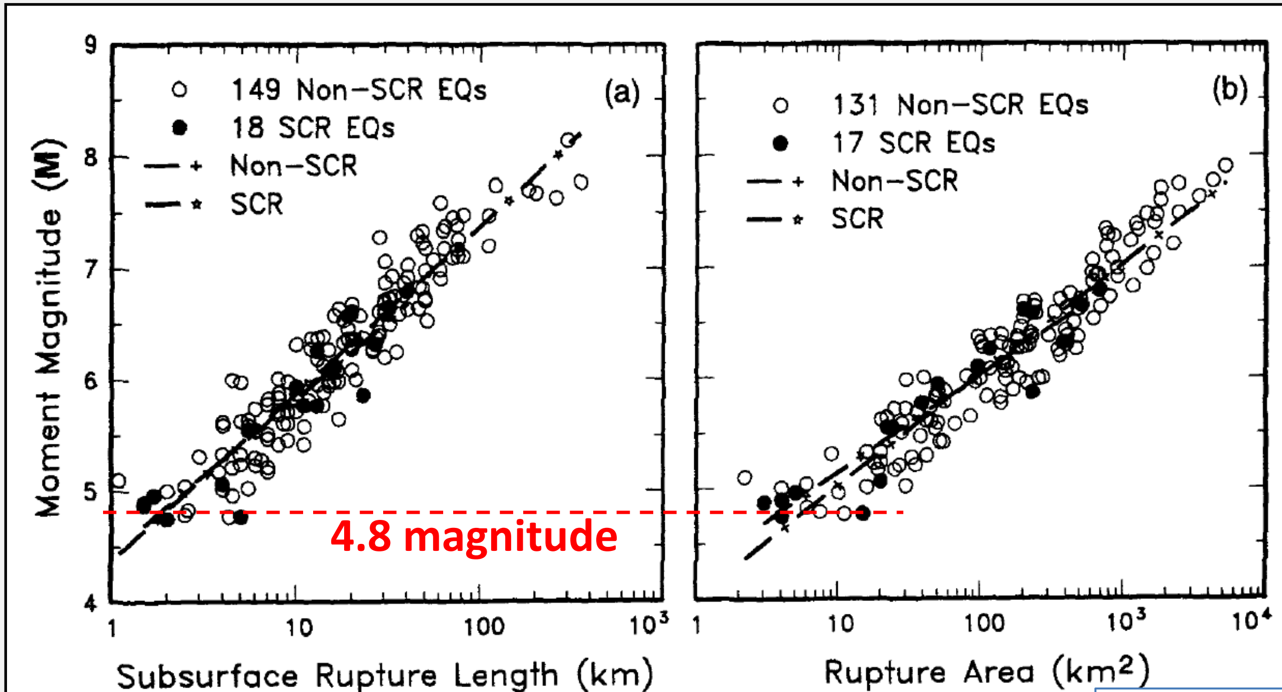


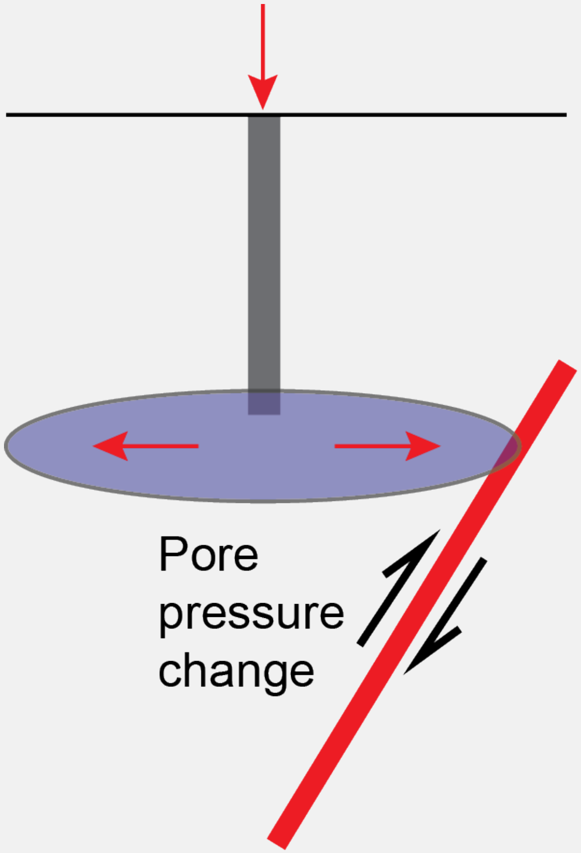
Figure 17. Regression lines for stable continental region (SCR) earthquakes and non-SCR continental earthquakes. (a) Regression of surface rupture length on magnitude (M). (b) Regression of rupture area on magnitude (M).

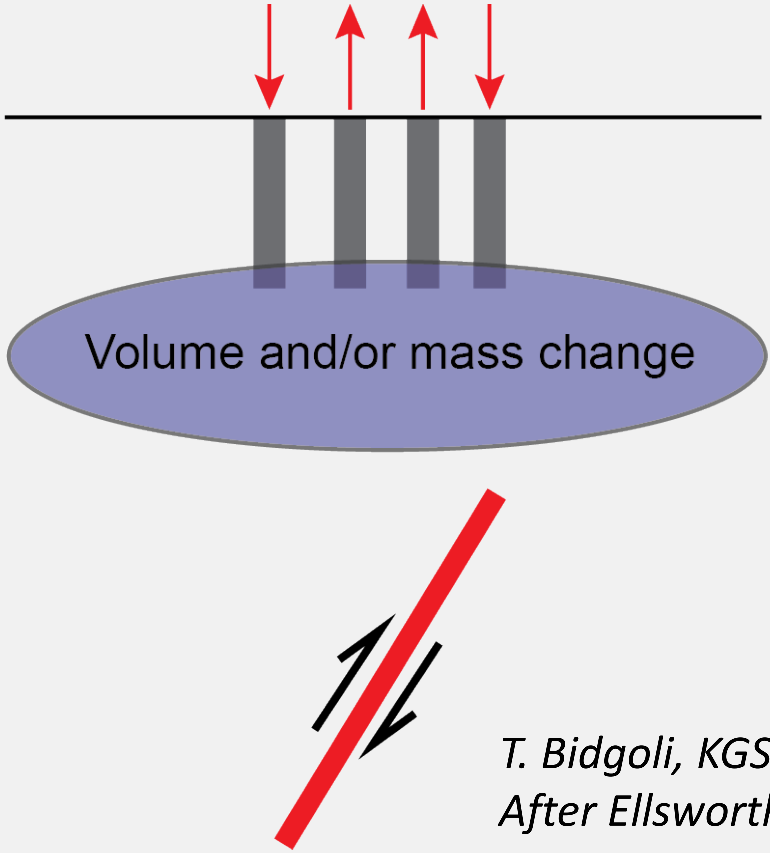
1 km^2 = 0.4 mi^2

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**

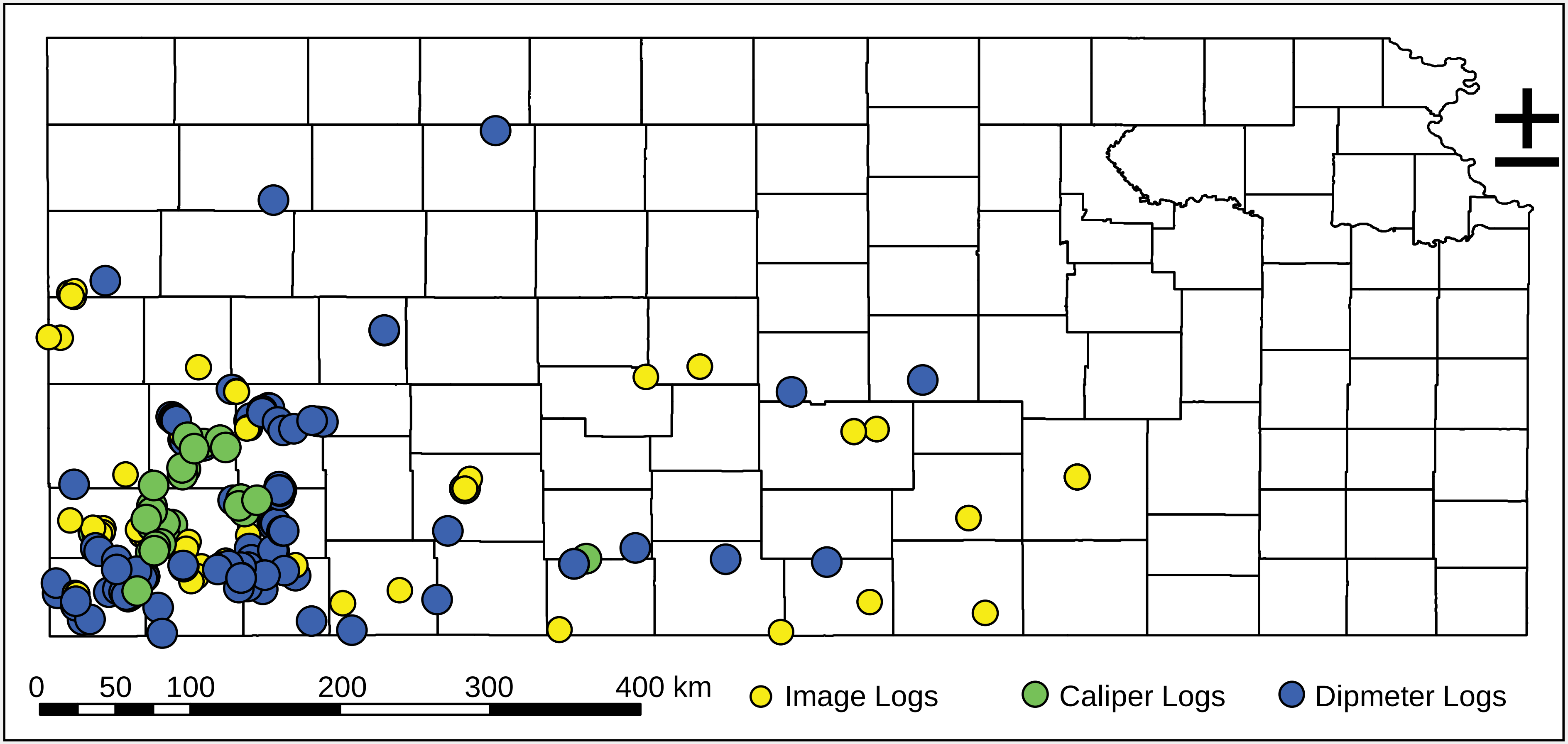




T. Bidgoli, KGS
After Ellsworth, 2013

Stress field analysis: Statewide

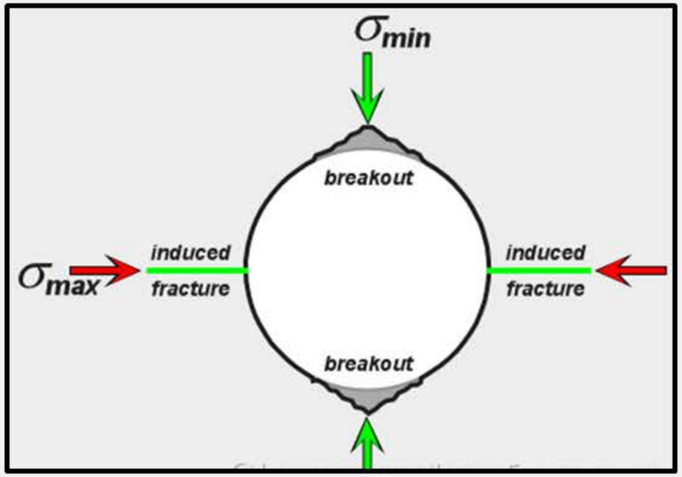
240 well logs with data types suited for stress analysis

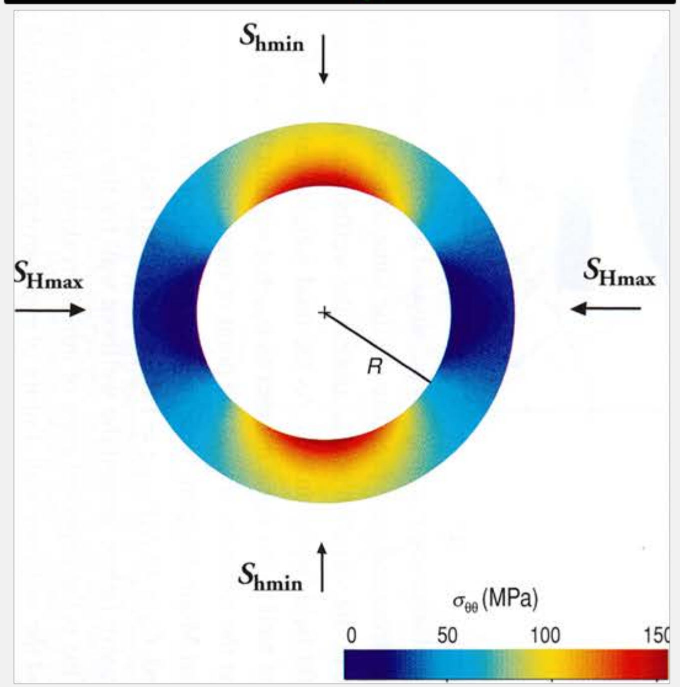


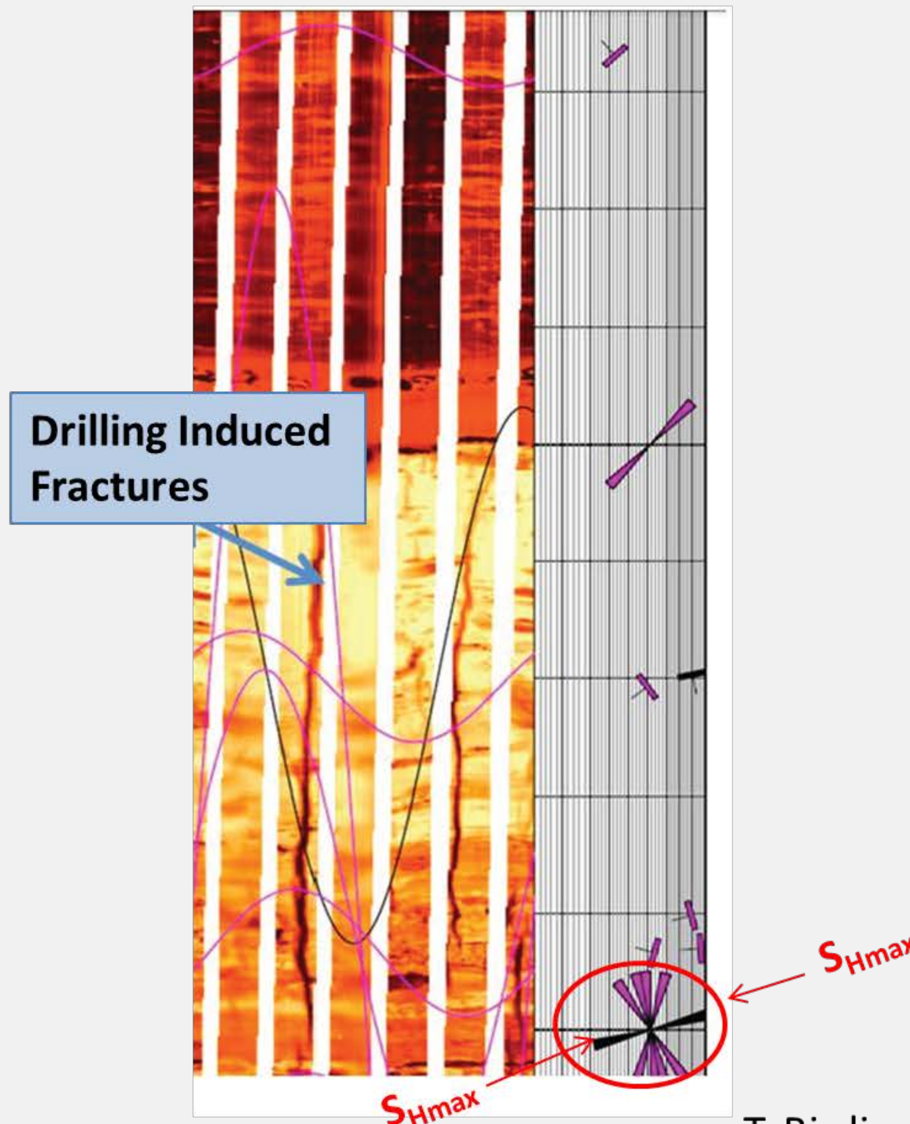
- 109 are scanned
- 131 in paper form

T. Bidgoli, KGS

Drilling Induced Fractures to Estimate Present-Day Principal Stress Directions at Wellington Field



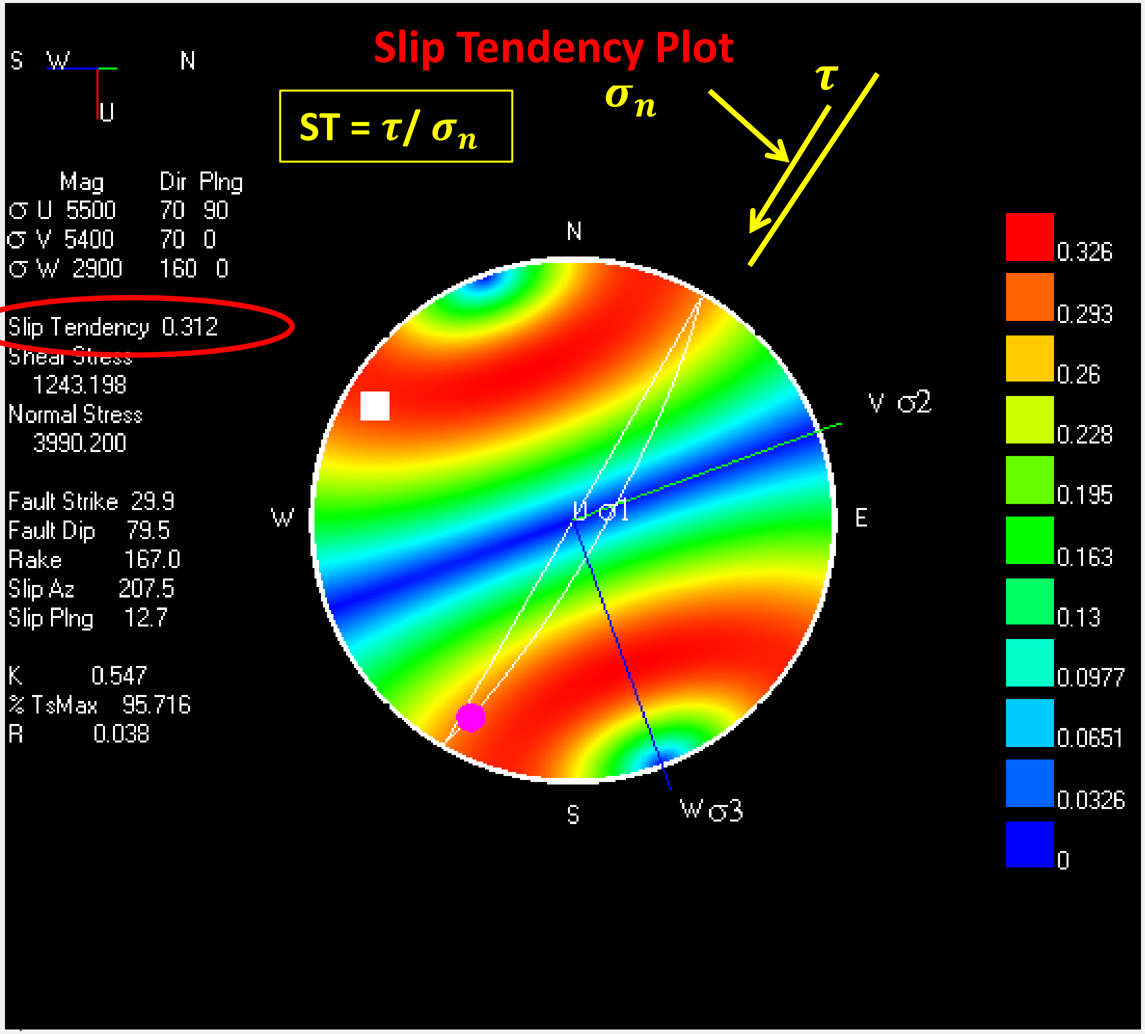




T. Birdie, 2015

3D Stress Analysis Using SWRI 3D Stress Software

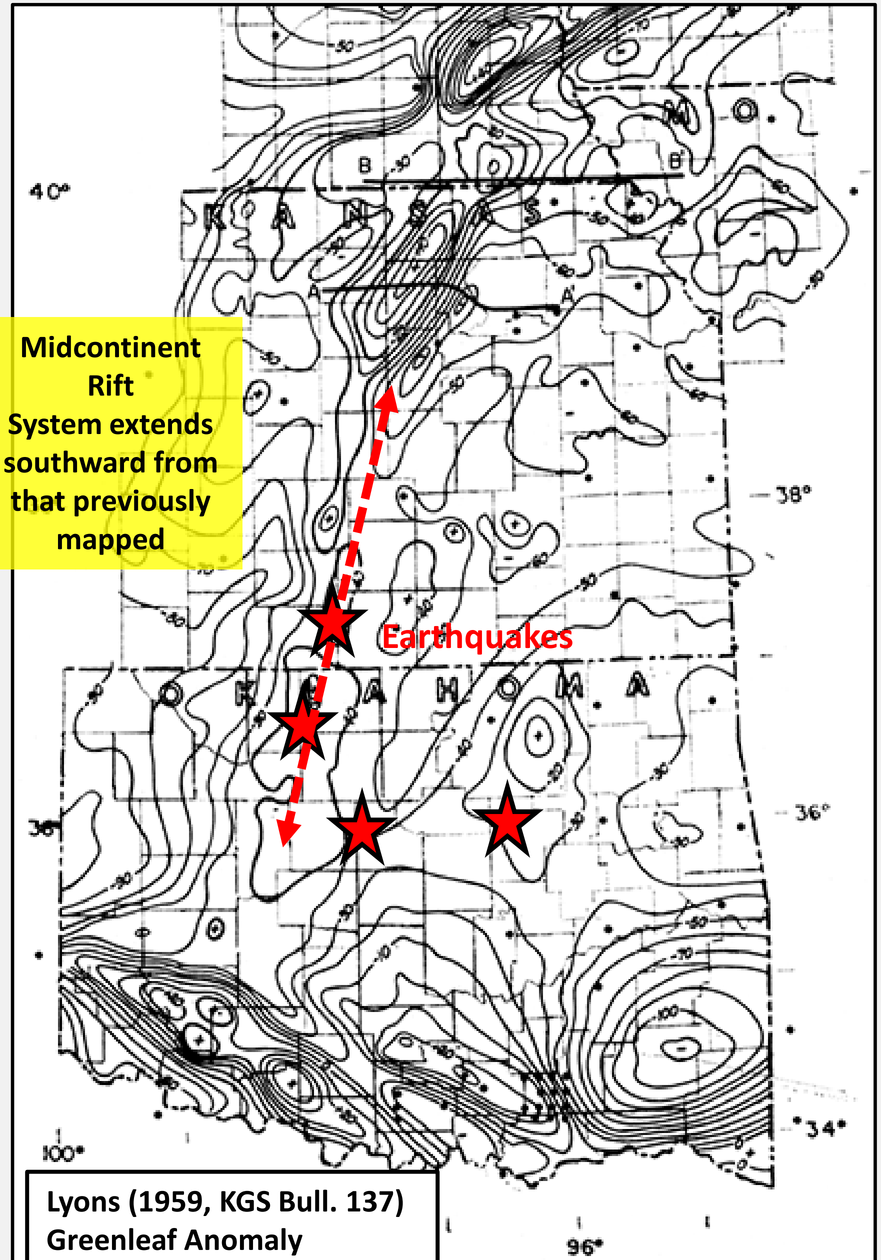
→ Faults oriented NE-SW most succeptible to movement



- **Slip Tendency (ST = Shear Stress/ Normal Stress)** is used to estimate potential for fault slippage
- ST= 0.3 (lower than 0.5 that is typically assumed).
- Conducting sensitivity studies to assess Slip Tendency
- **Stress analyses indicate that critically stressed faults are in the Proterozoic basement and can slip at low pressure**
- **Schwab and Bidgoli (2015) – optimally oriented fault in Arbuckle requires ~300 psi in Wellington Field area to slip**

Adapted from T. Birdie (2015)
EPA Class VI geosequestration permit

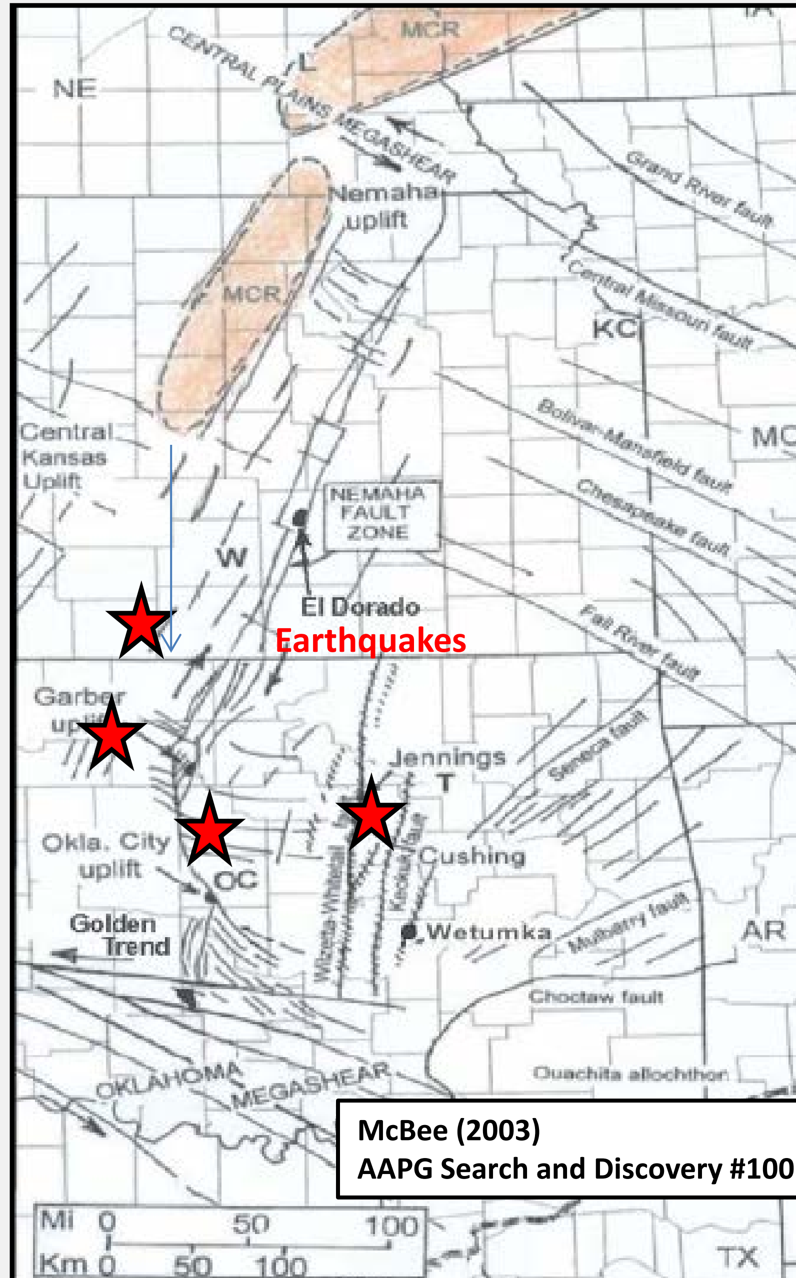
Bouguer Gravity



Midcontinent Rift System extends southward from that previously mapped

Lyons (1959, KGS Bull. 137)
Greenleaf Anomaly

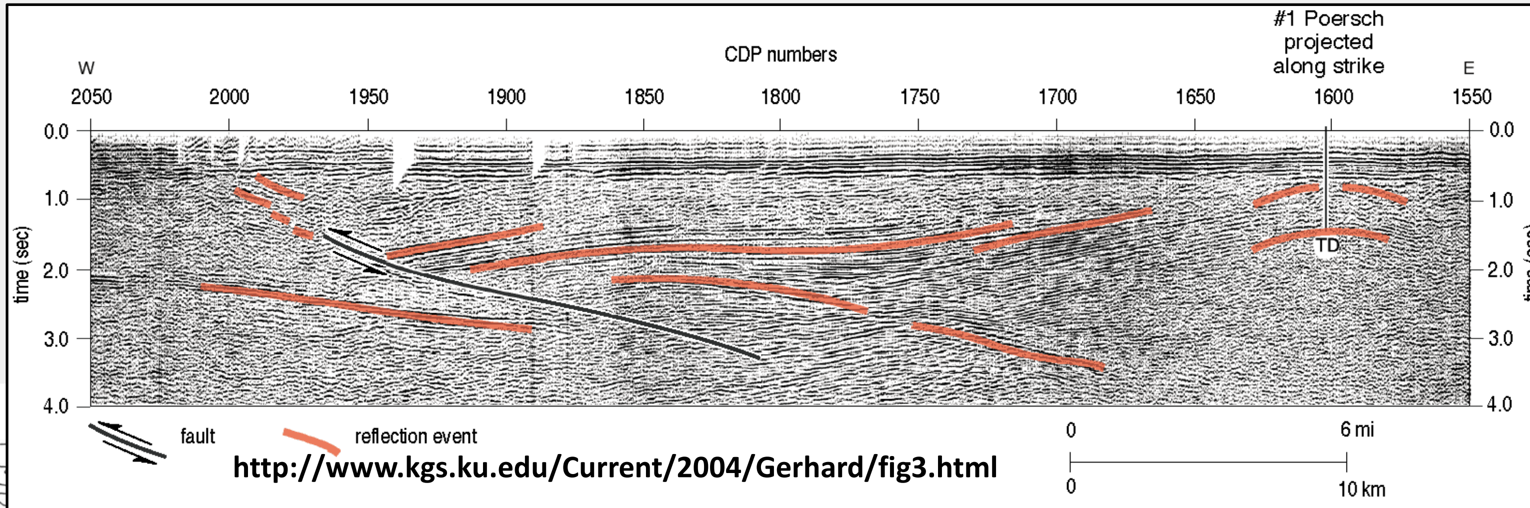
Generalized fault framework



McBee (2003)
AAPG Search and Discovery #10055

Midcontinent Rift System

COCORP seismic interpretation indicates large basement faults (10's of kilometers length) and thick sediment (up to 10 km [*6.2 mi*])



http://www.kgs.ku.edu/Current/2004/Gerhard/fig3.html

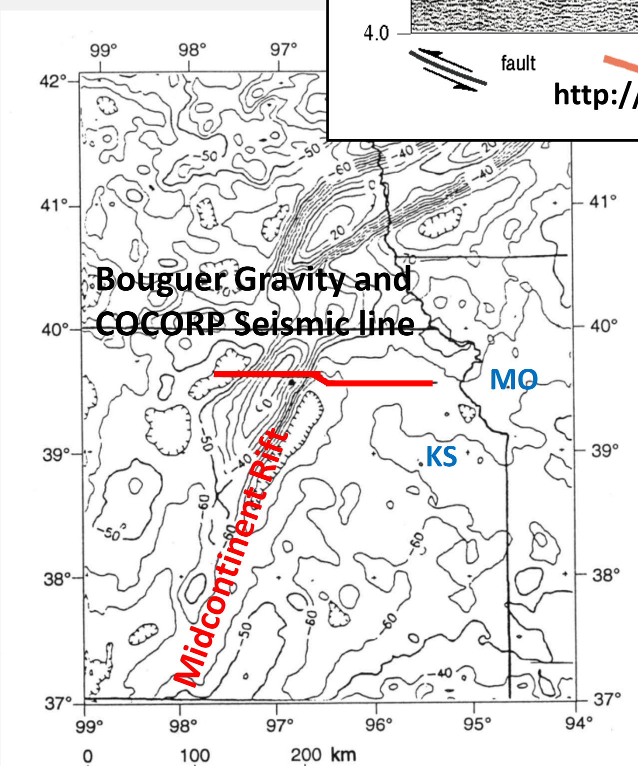
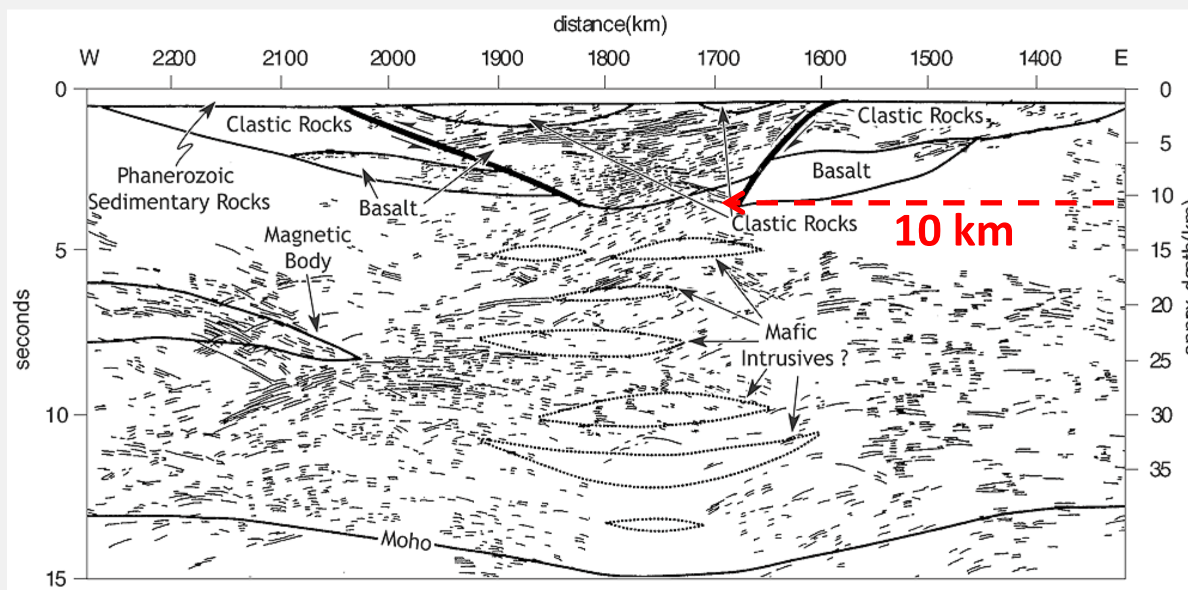
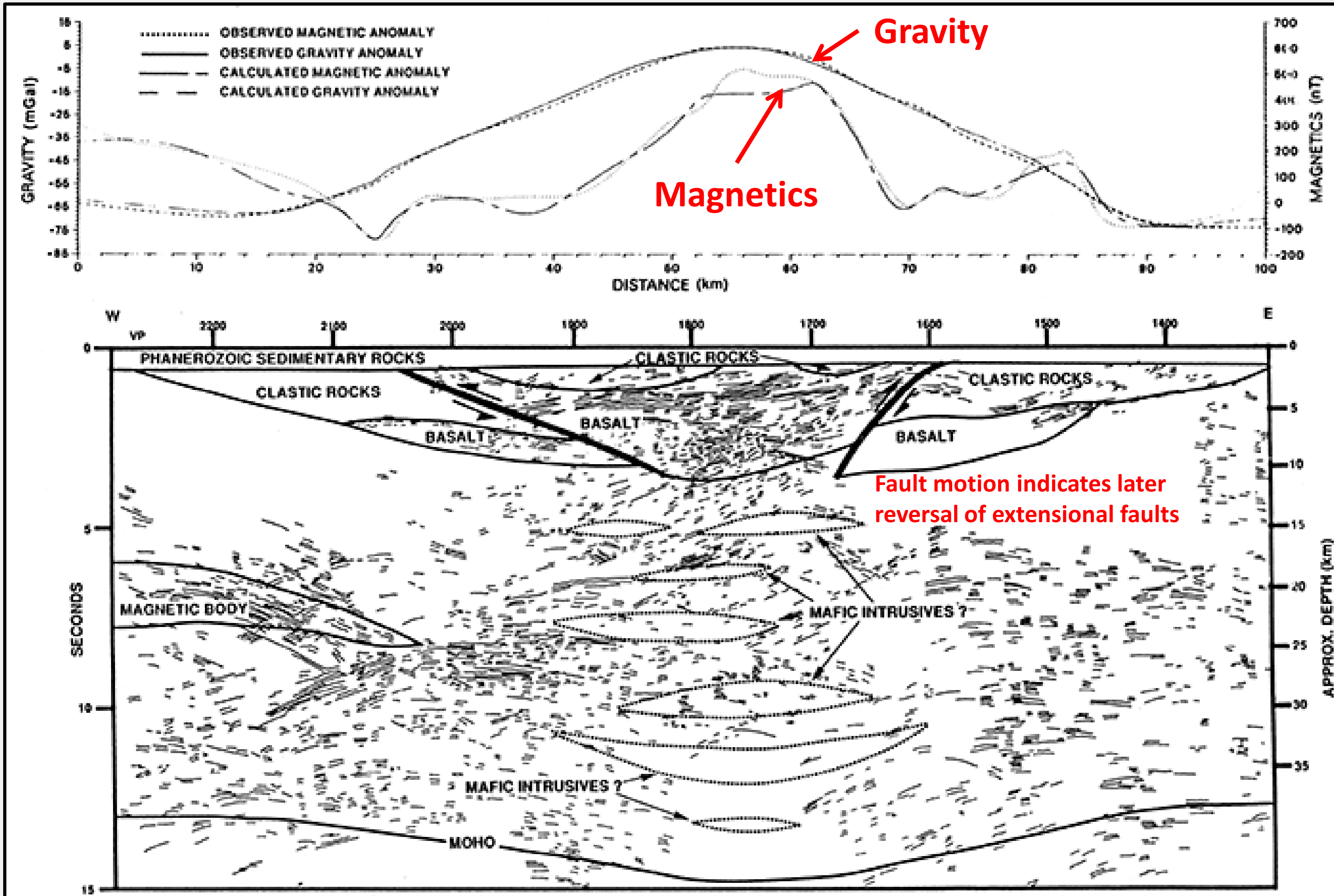


FIGURE 2—Kansas Line 1 and Texaco Poersch #1 borehole (dot).



From Woelk and Hinze (1995, KSG Bulletin 237)

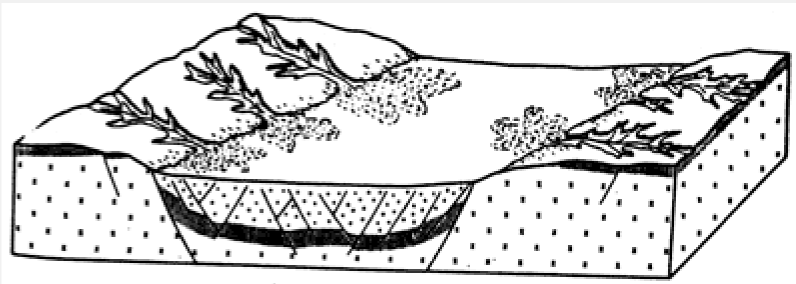
Close match between measured and modeled gravity and magnetics along COCORP seismic line



http://www.kgs.ku.edu/Current/2004/Gerhard/fig3.html

from Woelk and Hinze (1995, KSG Bulletin 237)

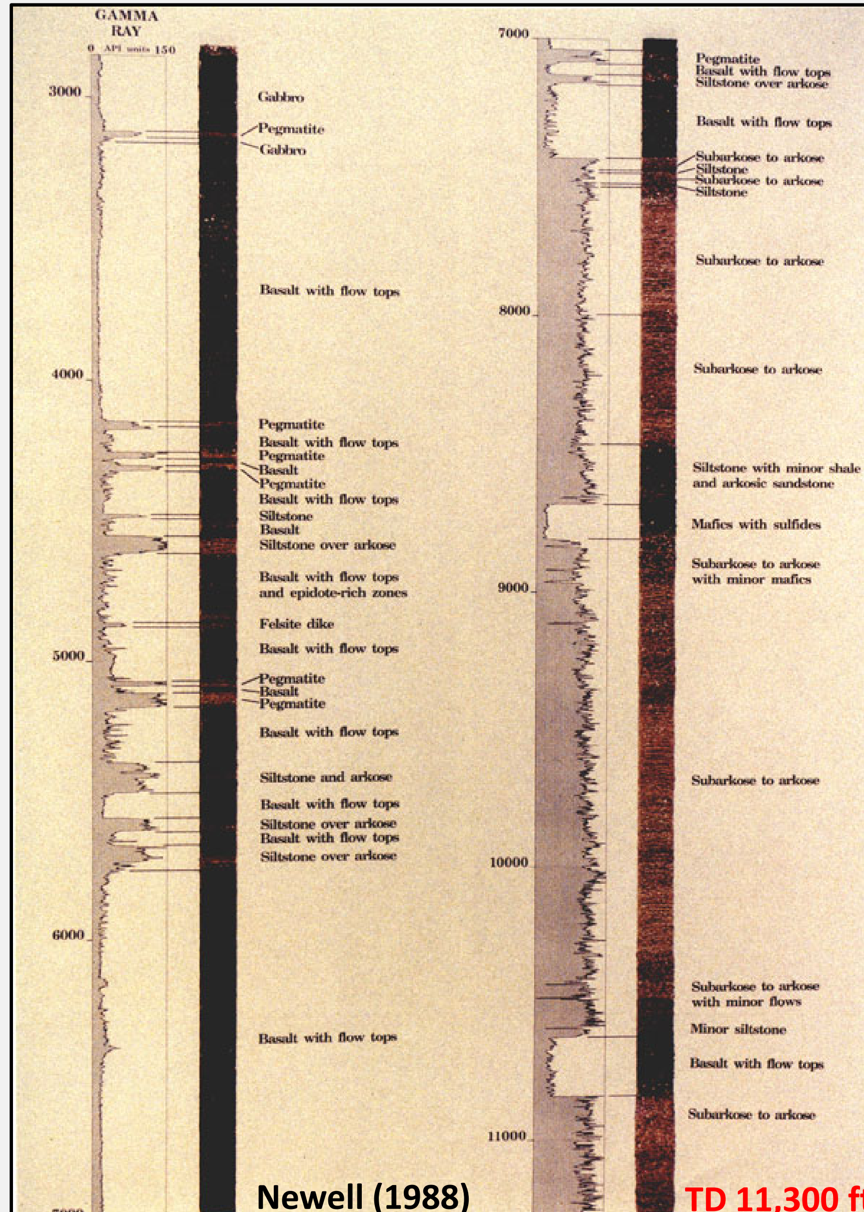
East African Rift is a Modern analog to the Midcontinent Rift System
→ Both large graben systems



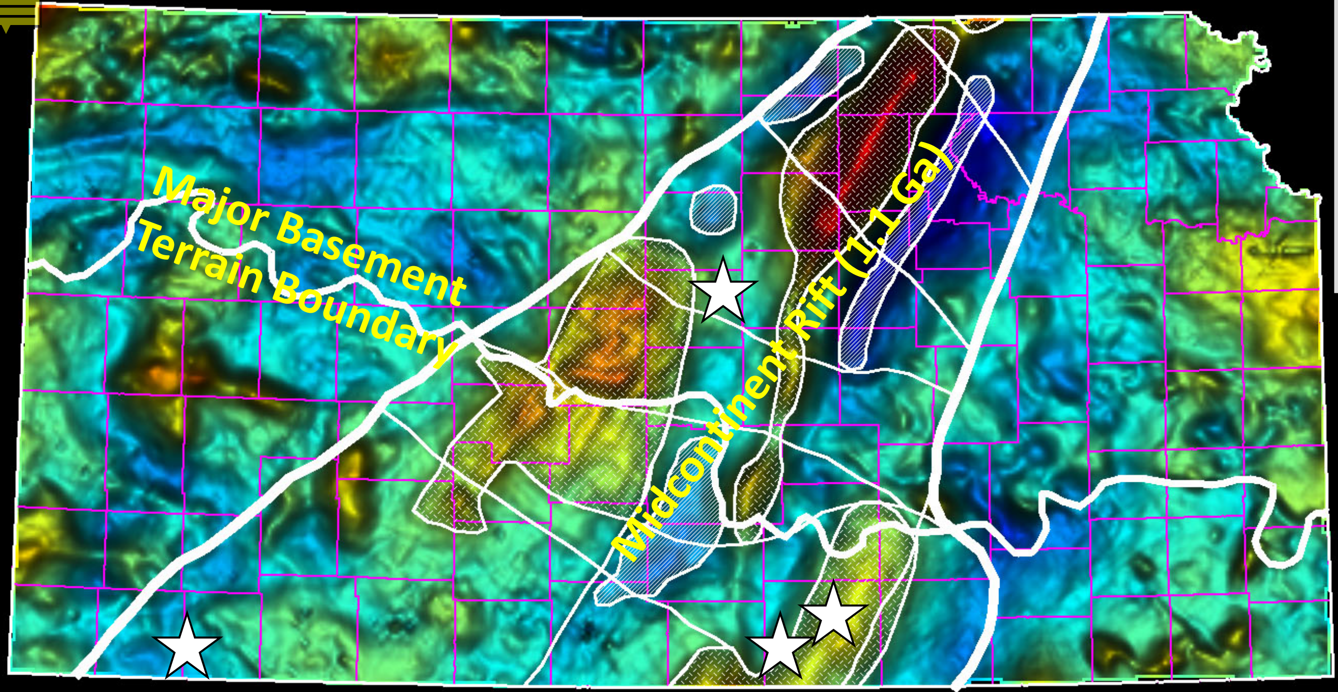
Illies, 1981

"Albertine Rift, East African Rift (artificial rendering)" by Christoph Hormann - http://earth.imagico.de/view.php?site=rift2a

Texaco Poersch #1, Washington County, Kansas
Deep well penetrating a portion of the Midcontinent Rift System consisting of arkose, gabbro, and basalt

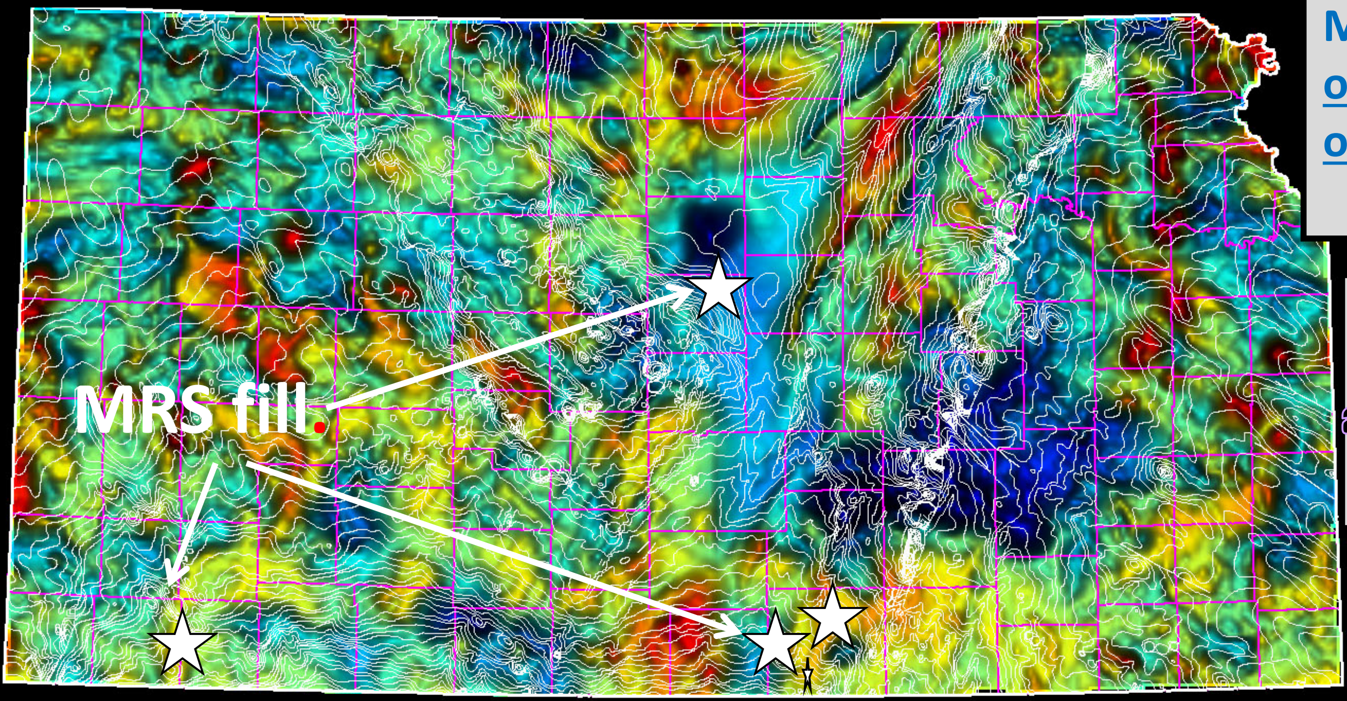


http://www.kgs.ku.edu/Publications/OFR/1988/OFR88_22/06_summ.html



Bouguer Gravity --
with rift and sub-elements, terrain boundary extending through Kansas (Kruger, 1999)

MRS arkosic and greywacke sediments



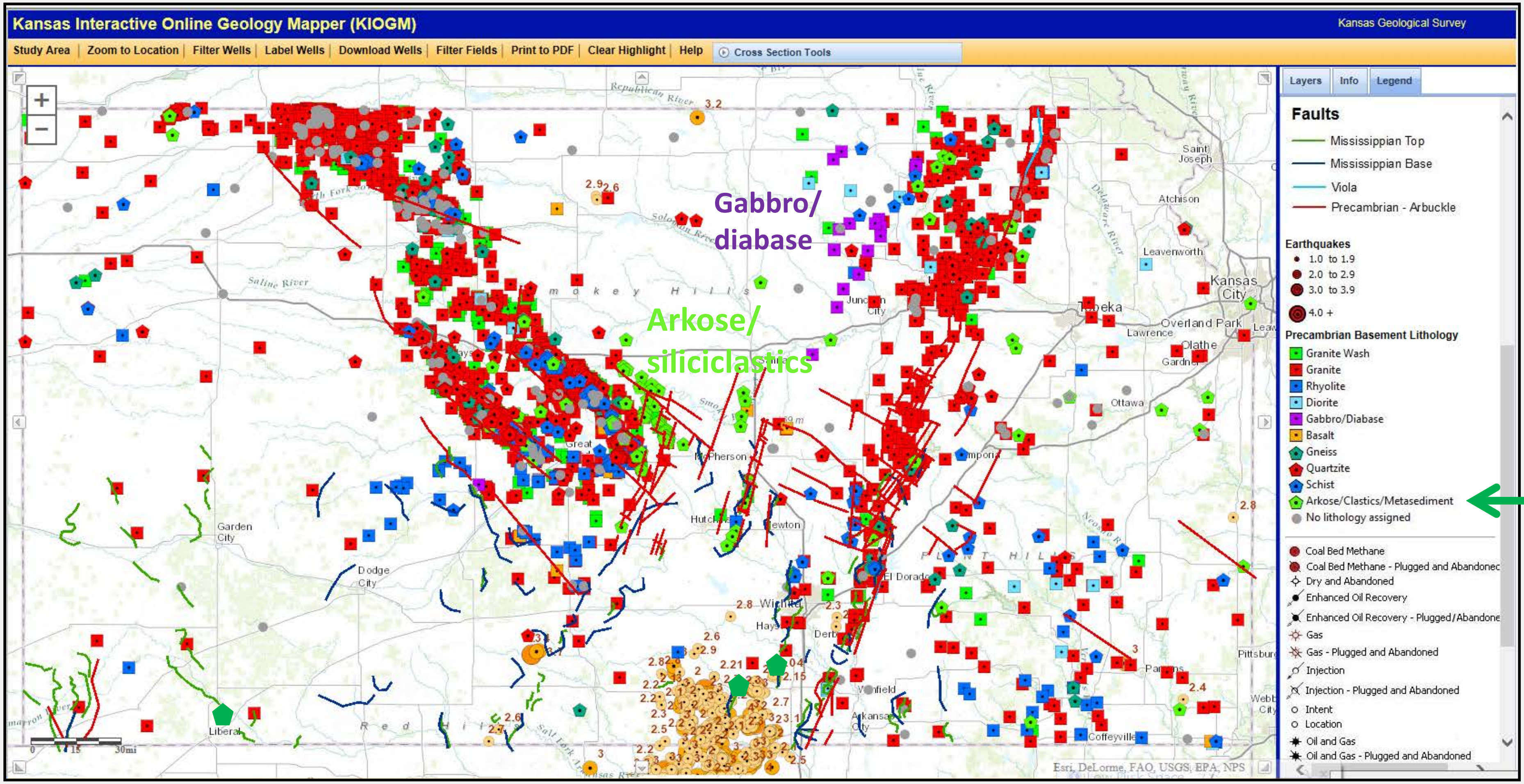
Magnetic – reduced to pole, **overlain with configuration of Precambrian surface** (Kruger, 1999)

Far reaching basement faults associated with the Midcontinent Rift serving as template for Phanerozoic structural reactivation

- 1 x 4 mi. grid
- high values = warmer colors

Basement geology from sample rock types in the area of the induced seismicity

→ thick arkosic sediment fill indicative of the Midcontinent Rift System (MRS)

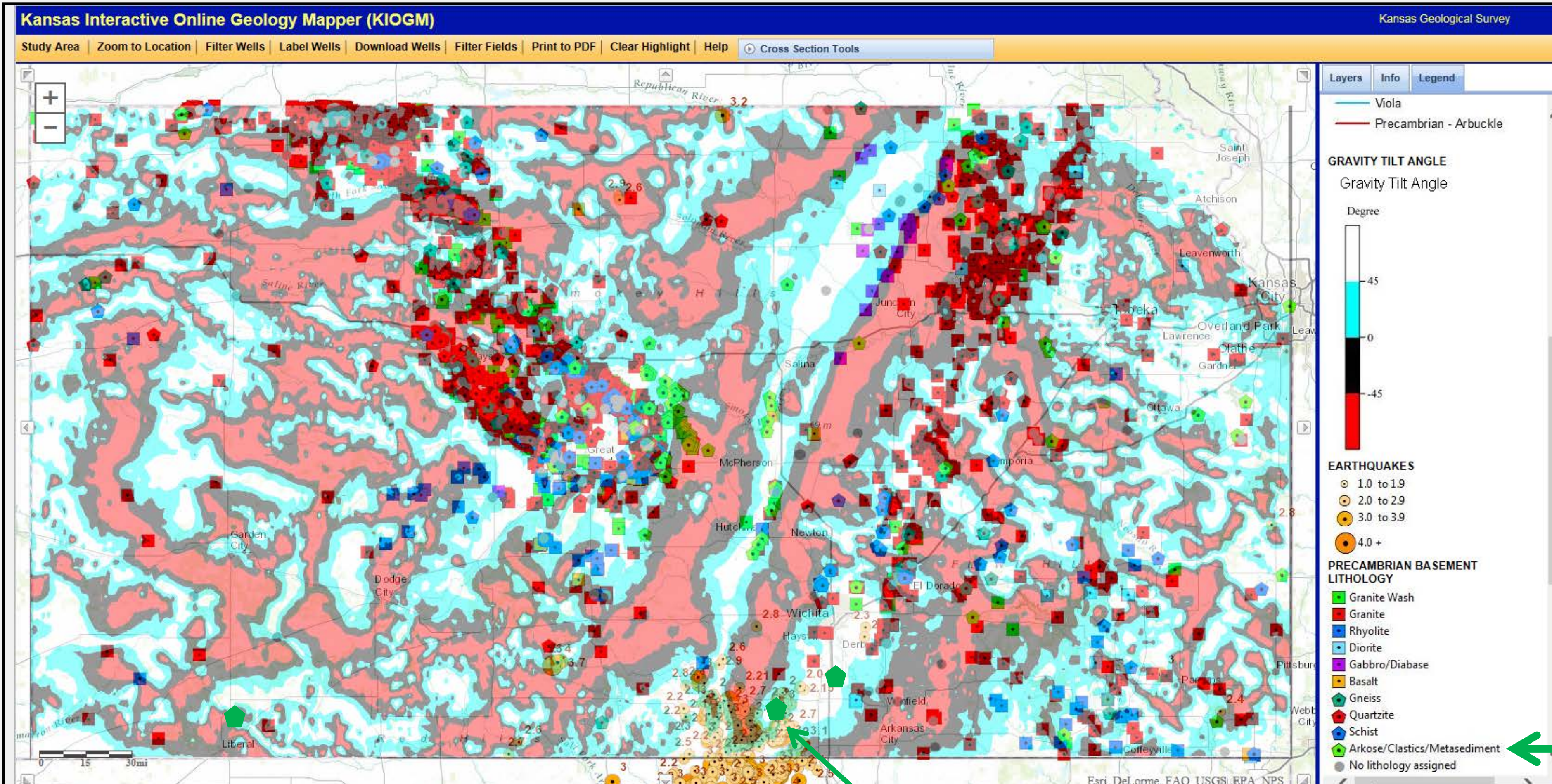


Interactive map
Proterozoic lithology (n=~3800 wells), faults, earthquakes

M. Killian, KGS
http://maps.kgs.ku.edu/co2/

Basement geology overlain on gravity tilt angle

→ distinct gravity anomaly and presence of sediment fill in the Proterozoic Midcontinent Rift System in the area of the induced seismicity in south-central Kansas

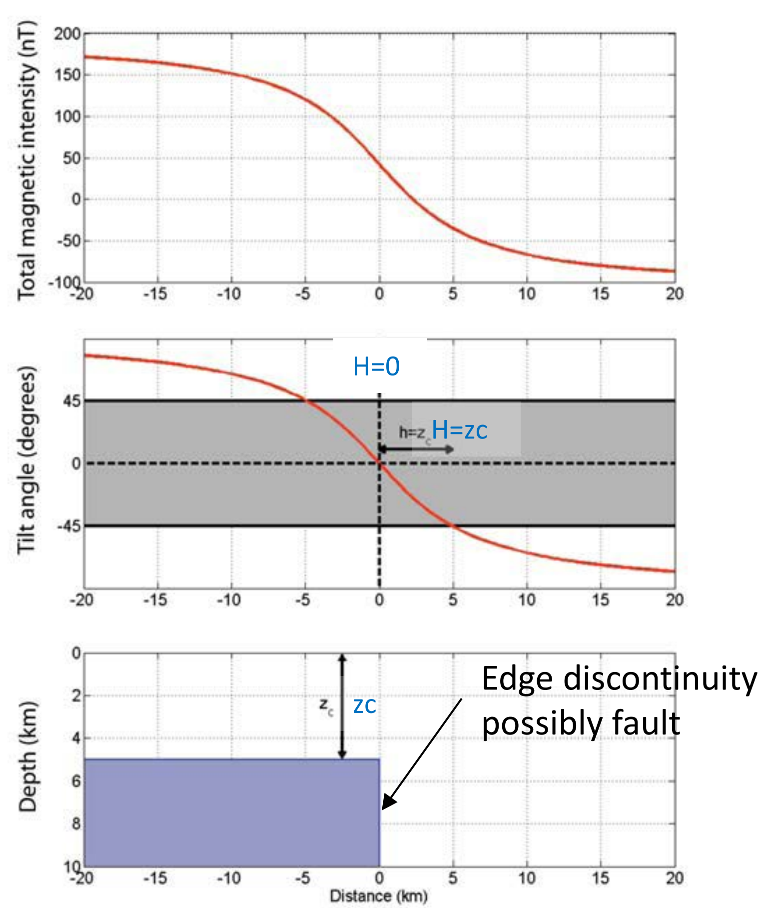


Thick Arkosic sediment basement samples inferred as Midcontinent Rift fill

Illustration of tilt angle computation to locate discontinuities in mapped data

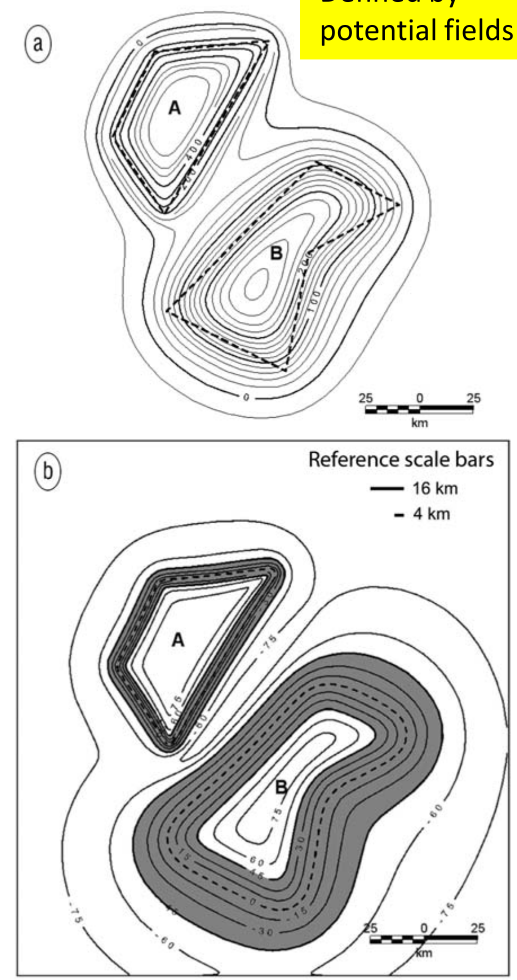
$$\theta = \tan^{-1}\left[\frac{\partial M}{\partial z} \Big/ \frac{\partial M}{\partial h}\right]$$

arctangent of the ratio of the 1st-order vertical derivative by the 1st-order horizontal derivative



Salem et al., 2007

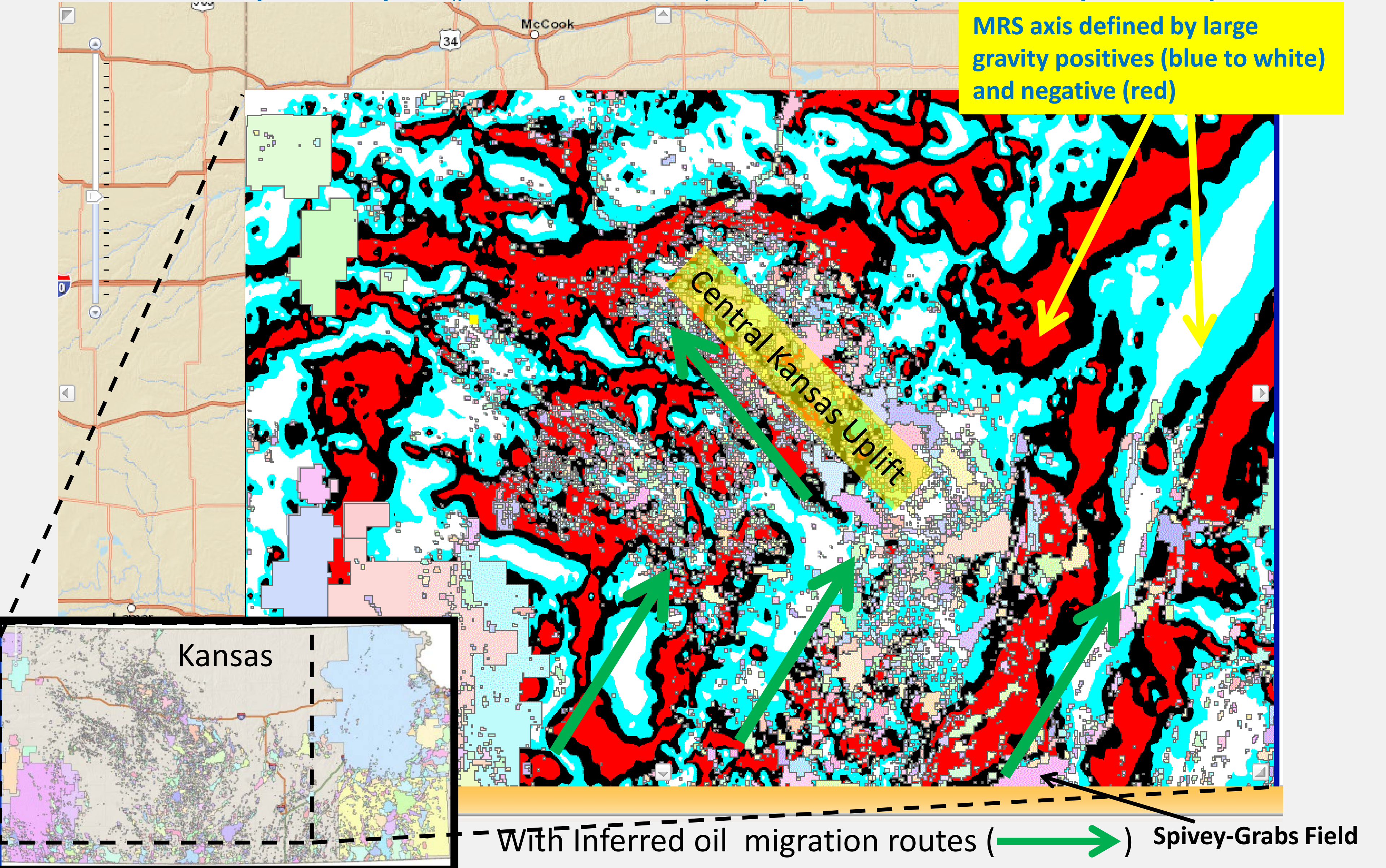
Delimiting the Geobody as Defined by potential fields



Tilt Angle of Bouguer gravity with 2-5 mile filter overlain with outlines of oil fields in western two-thirds of Kansas

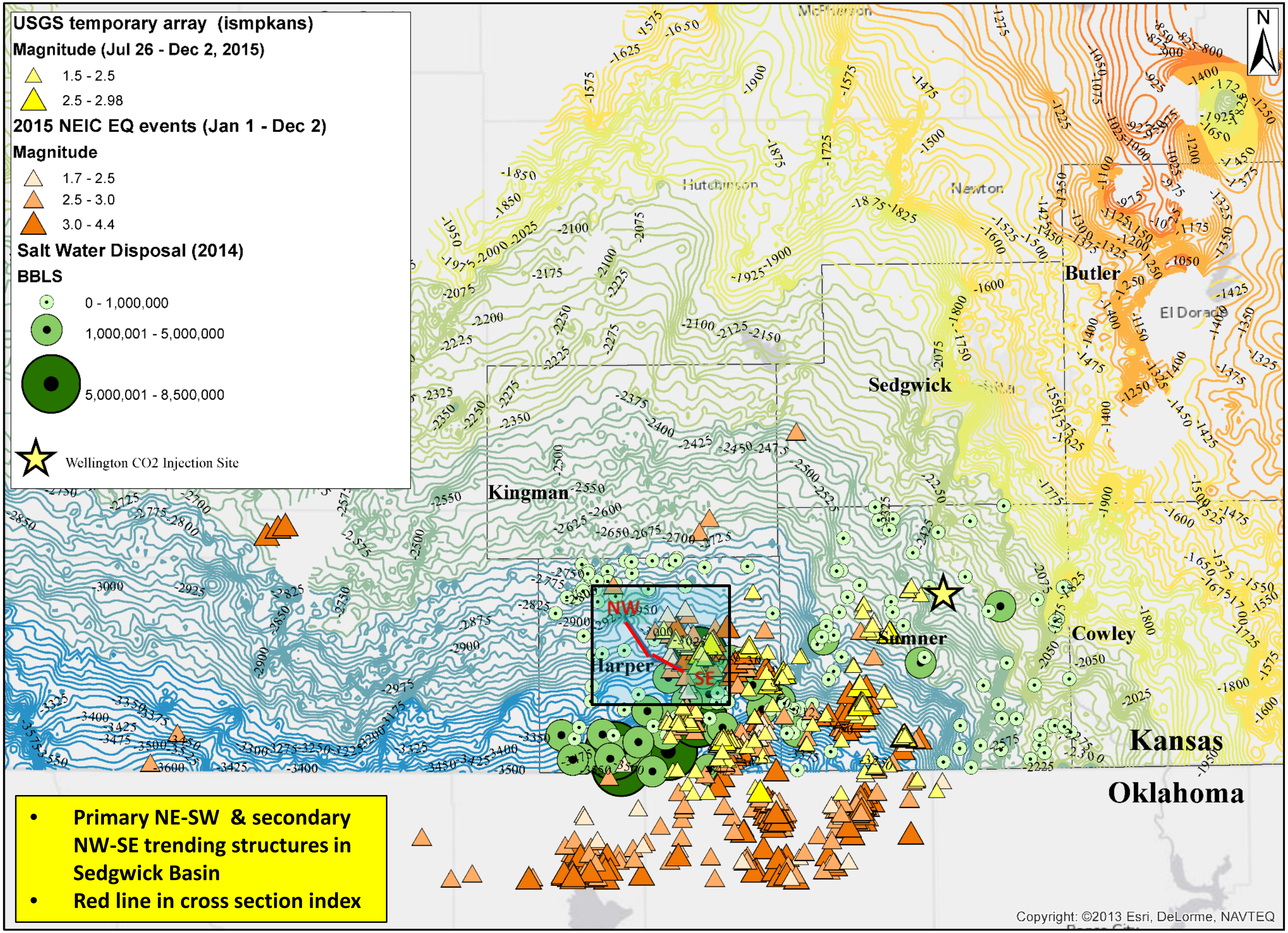
Strong delineation of inferred basement structures expressed by gravity lineaments

Distribution of oil and oil fields (pastel-colored outlines) likely influenced by reactivation of basement faults



Mississippian Lime Play and Arbuckle Disposal in southern Kansas and northern Oklahoma

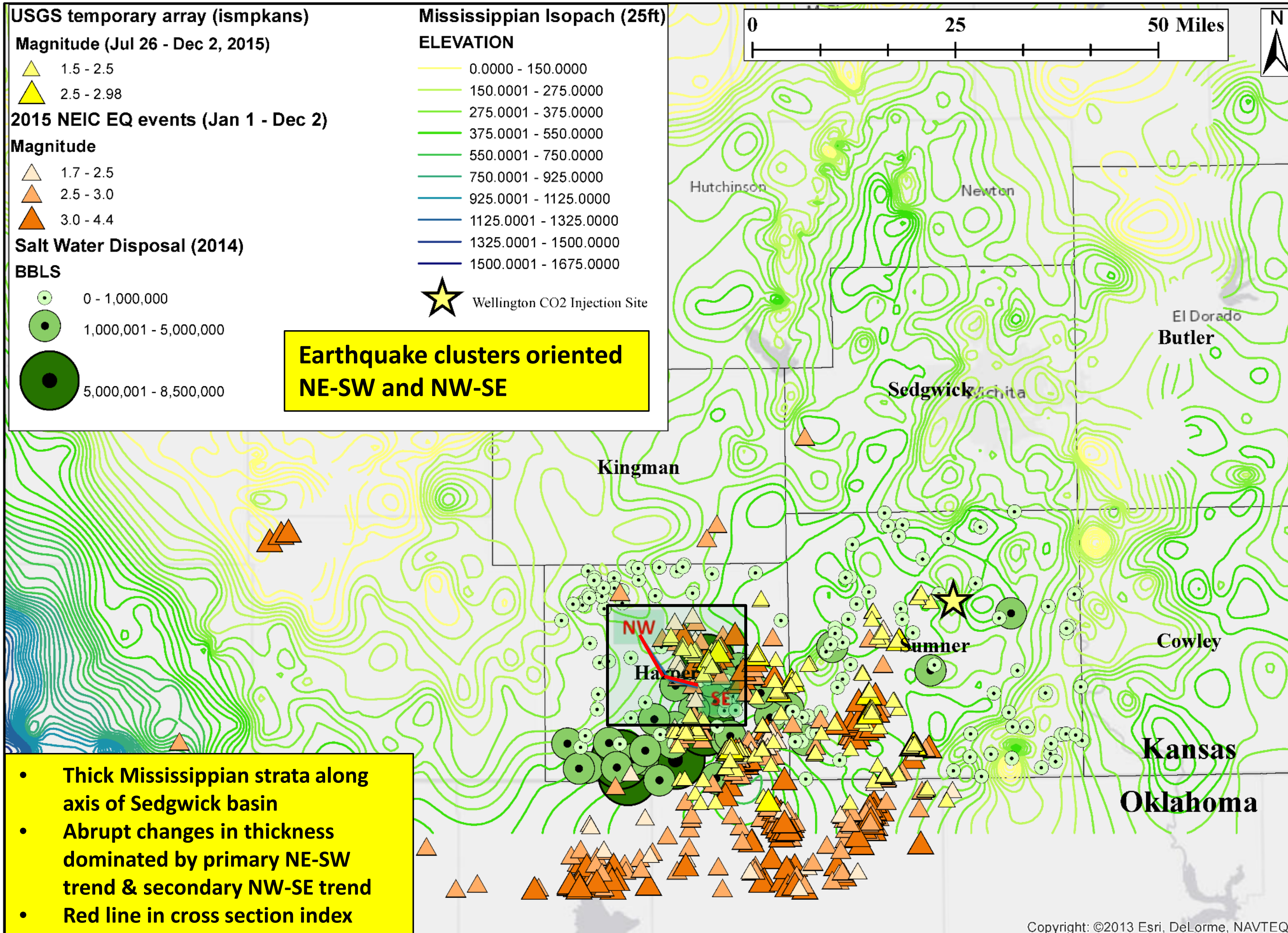
- **Mississippian geology** - depositional ramp, underpressuring, reservoir compartments, fractures and faults, high water cuts and the corollary, minimizing produced water with selective completions
- **Arbuckle geology** - spatial changes in hydrostratigraphic units and their hydraulic (phi-k) properties, regional simulation to understand limits of storage and injectivity, connectivity with basement lack of bottom seal, fluid exchange via faults and within Proterozoic sediment of Midcontinent Rift System



Top Mississippian

0 10 20 Miles

Kansas Geological Survey, Kansas Corporation Commission, NEIC, USGS, ESRI, Oklahoma Geological Survey, Oklahoma Corporation Commission
Map printed 12/7/2015

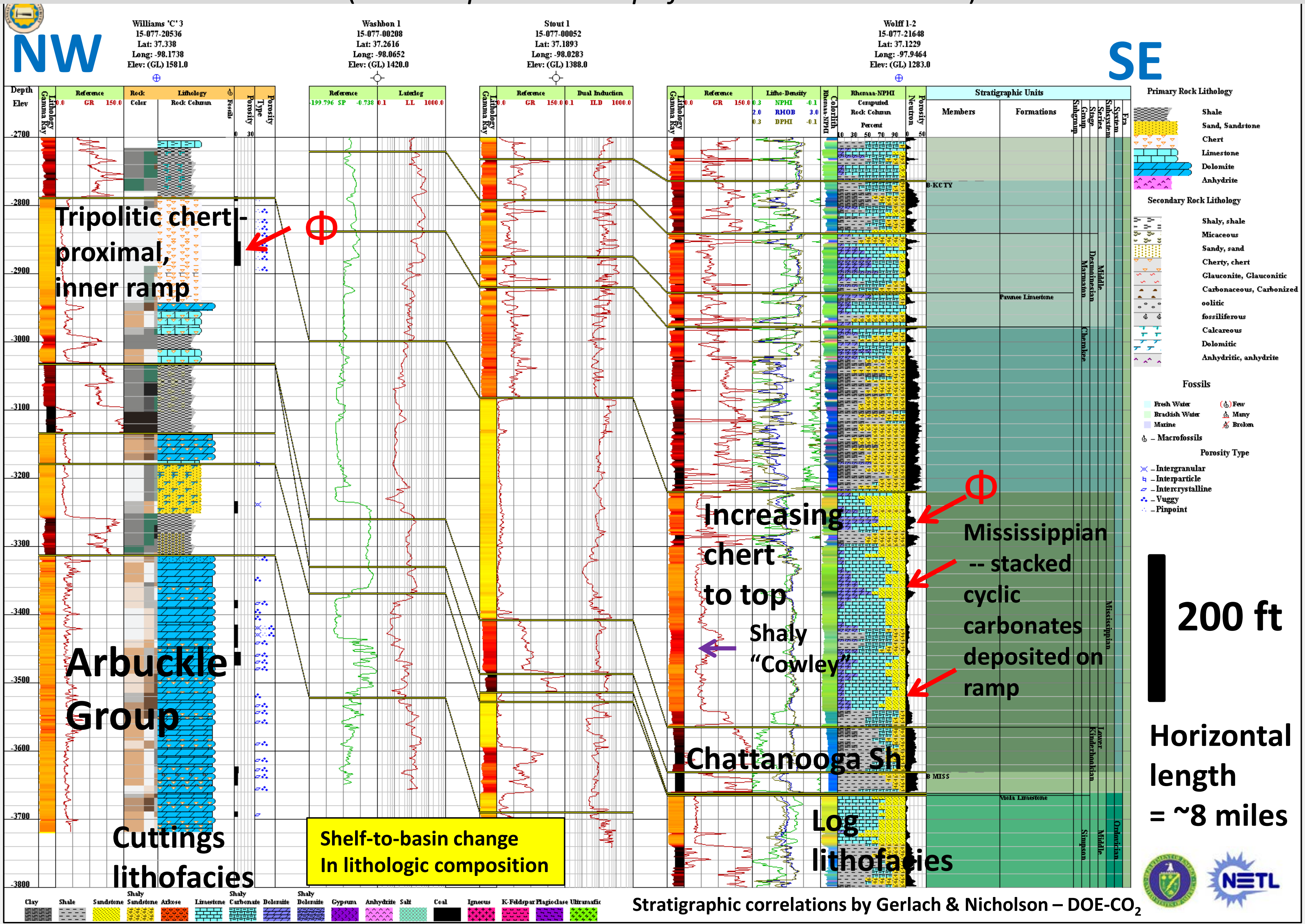


Mississippian Isopach

Kansas Geological Survey, Kansas Corporation Commission, NEIC, USGS, ESRI, Oklahoma Geological Survey, Oklahoma Corporation Commission

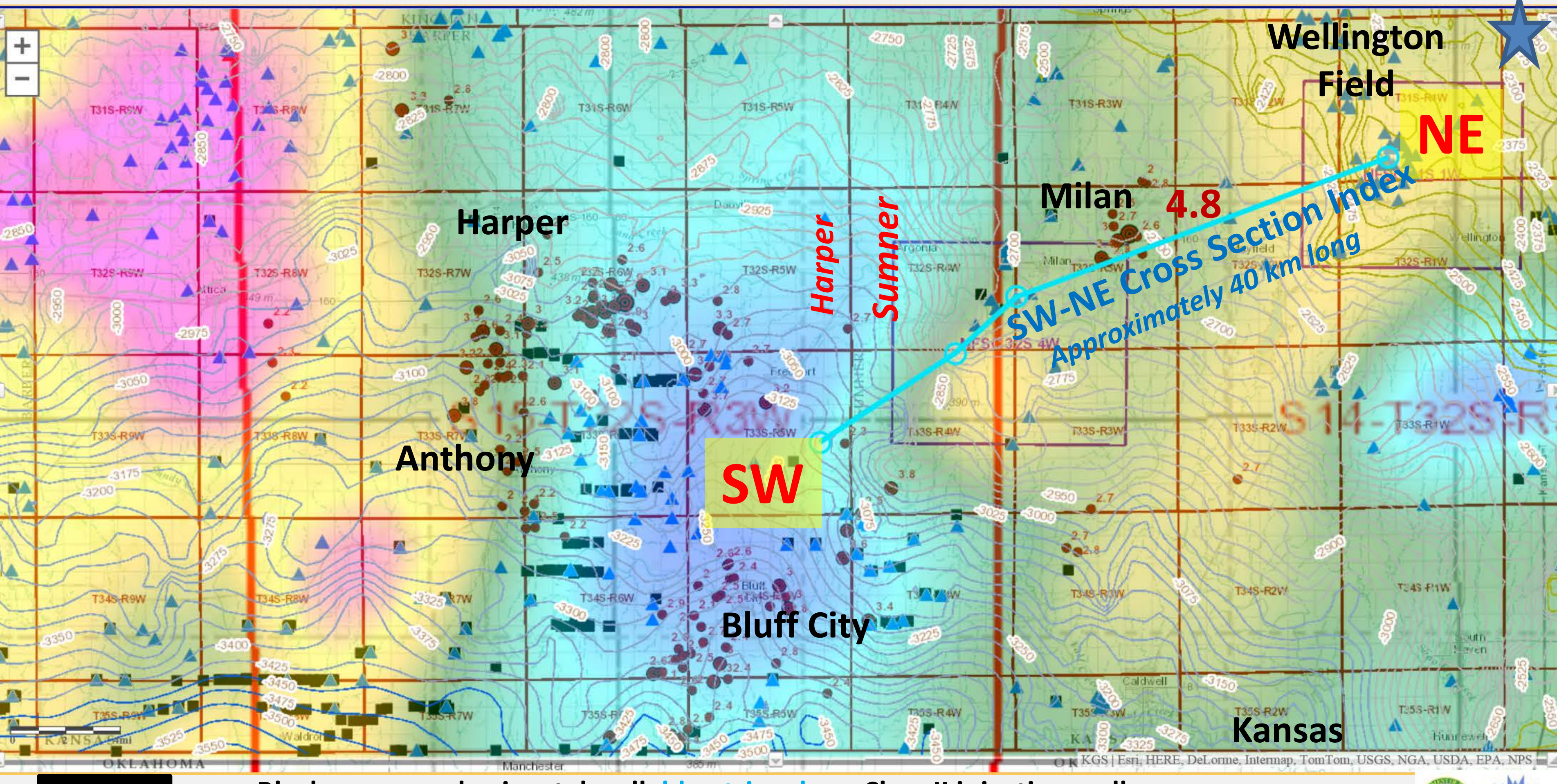
Map printed 12/7/2015

NW-SE structural cross section across Mississippian structural ramp
(*see two previous maps for cross section index*)



Mississippian structure map (25 ft contours) & colored map of total magnetic field intensity

-- main axis of N-NE trending Proterozoic Midcontinent Rift follows the large magnetic low (blue color) that also closely corresponds to a structural low in the late Paleozoic Sedgwick Basin

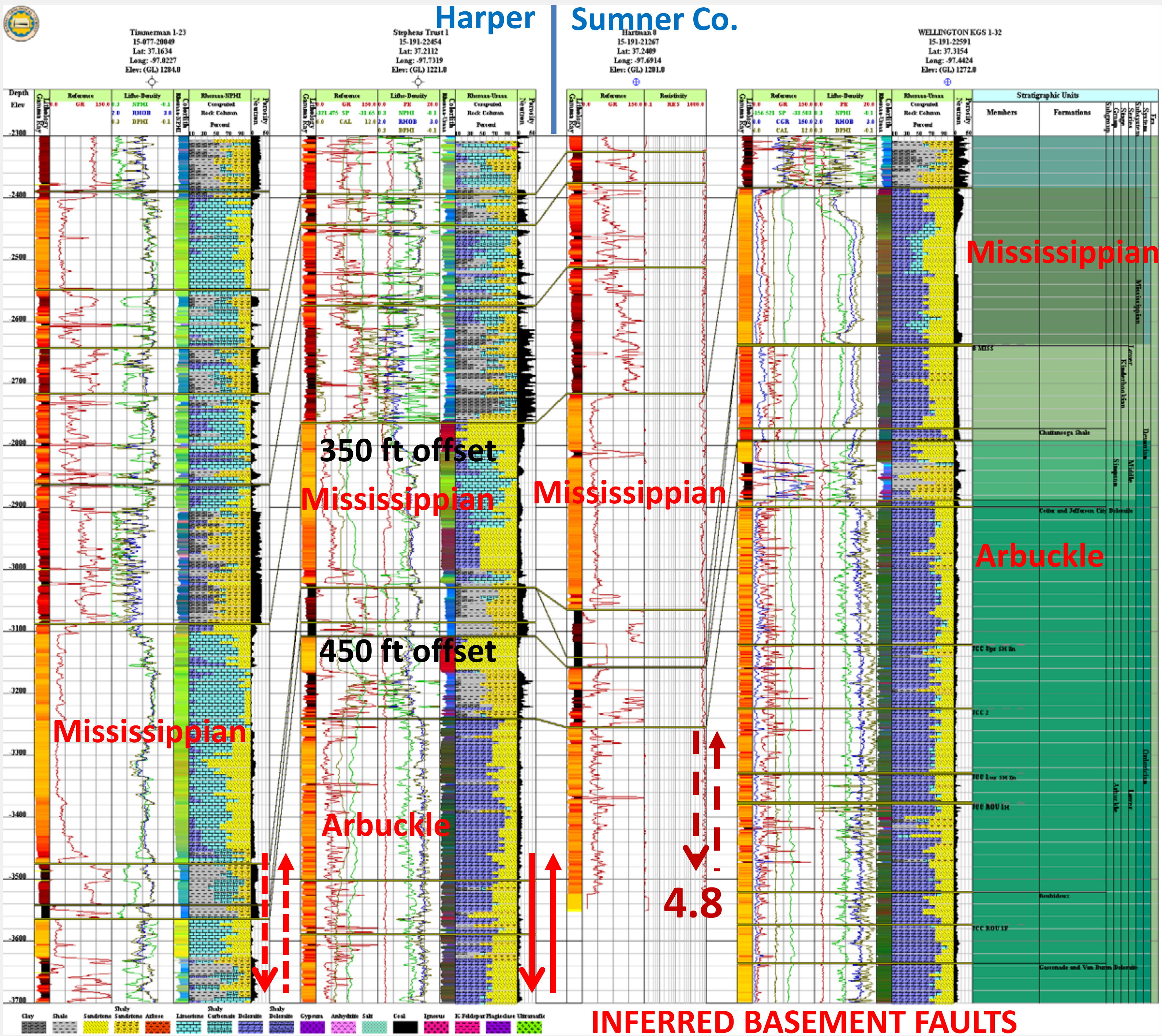


Black squares – horizontal well; blue triangles – Class II injection wells

Red dots - earthquakes

maps.kgs.ku.edu/co2

Oklahoma

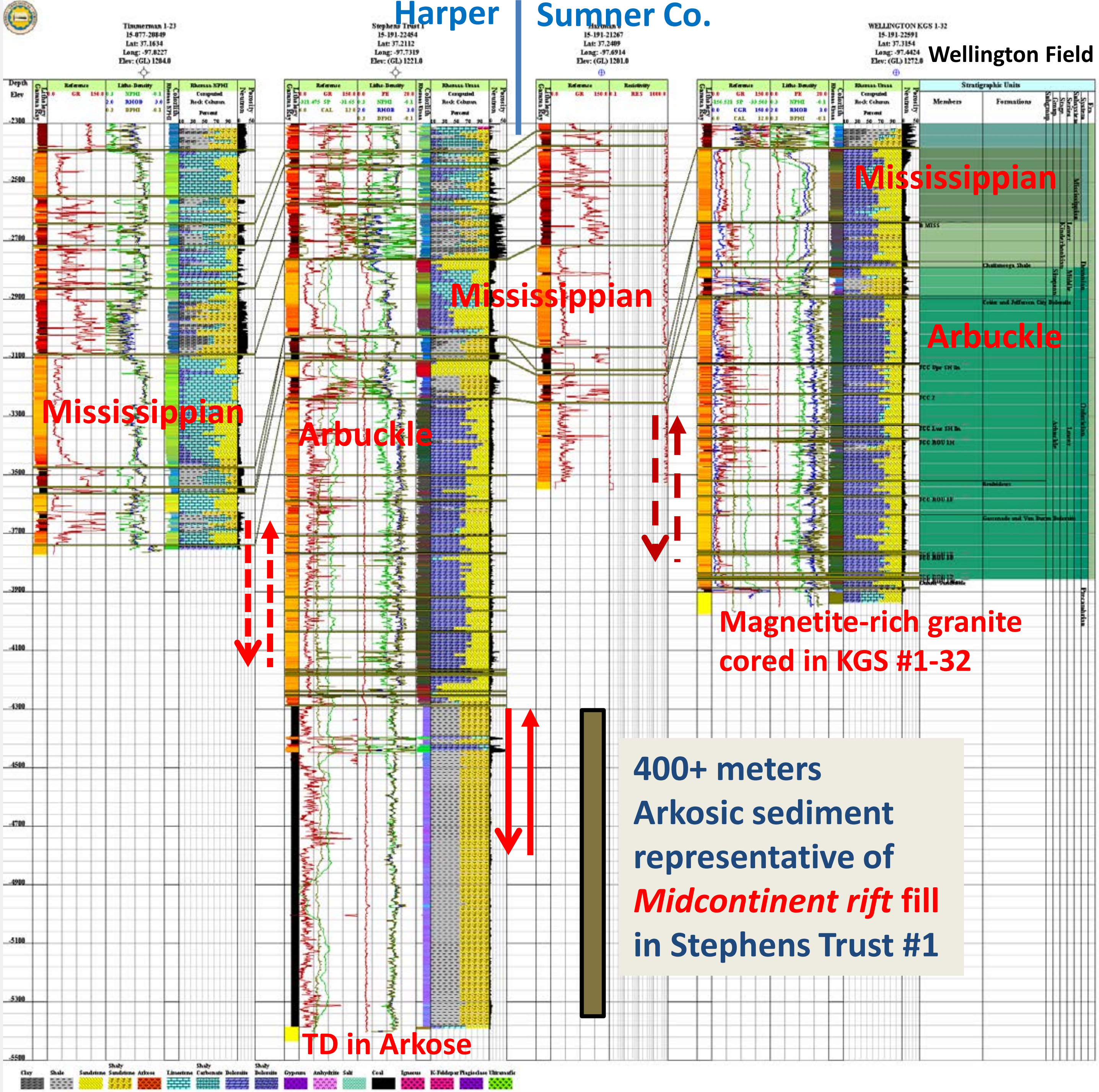


SW-NE Structural Cross Section (upper section)

- *Notable offset at Miss*
- *Increasing with depth*

~40 km long

60 m



SW-NE Structural Cross Section (lower section)

Large basement faults inferred within Proterozoic-age Midcontinent rift basin

~64 km long

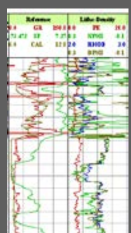
120 m

Workflow for reservoir simulation and geomechanical analysis

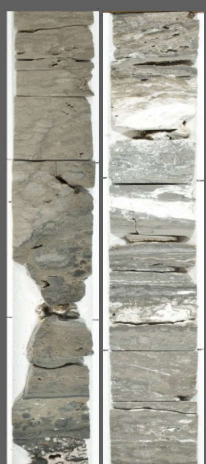
Data

Well logs

Tops



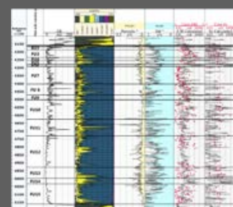
Core data



Dynamic data

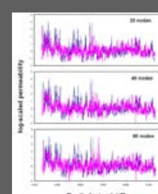
Reservoir Characterization

Multi-mineral FE

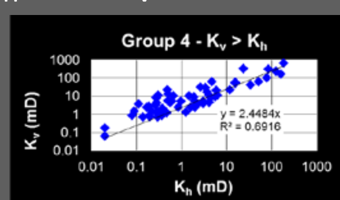


FZI-SWPHI

K prediction via ANN



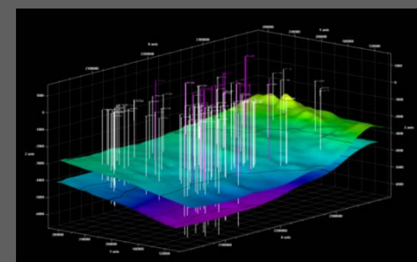
K_h and K_v relations



Flow units

Static model

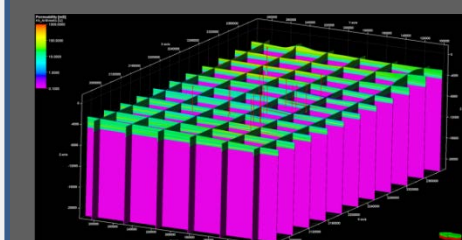
Structural model



Upscale logs

Statistical analysis

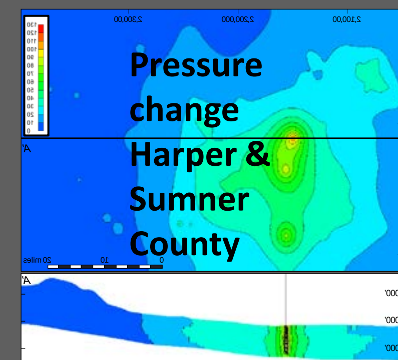
Property models



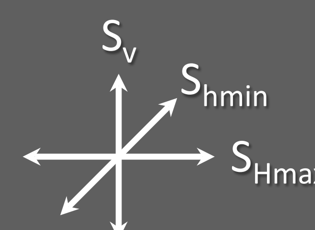
Geomechanical model

Dynamic model

Reservoir simulations



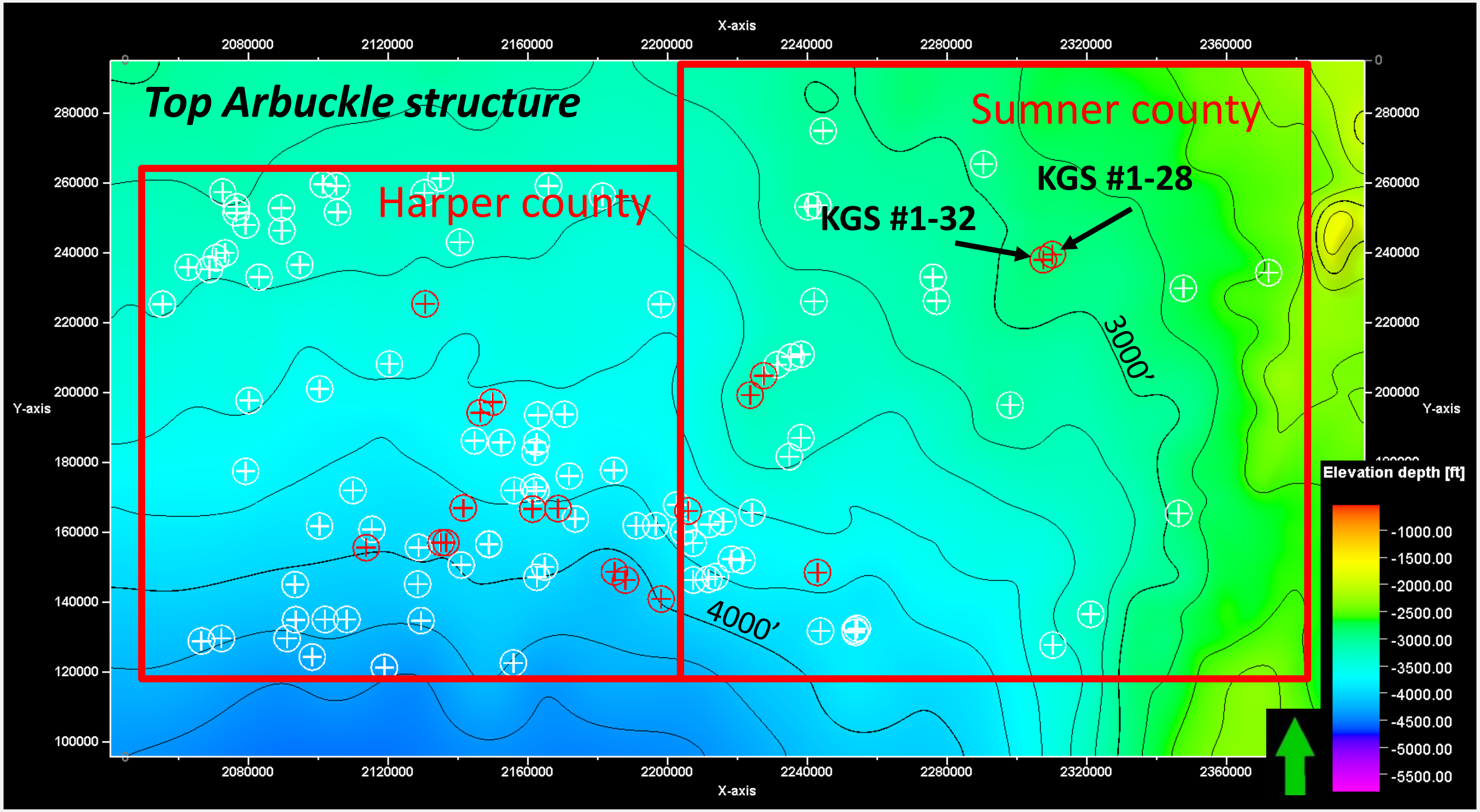
Geomechanical simulations



"Evaluating Potential for Induced Seismicity Through Reservoir-Geomechanical Analysis of Fluid Injection in the Arbuckle Saline Aquifer, South Central Kansas" Annual Meeting AAPG 2015, Denver ---T. S. Bidgoli, Y. Holubnyak, M. FazelAlavi

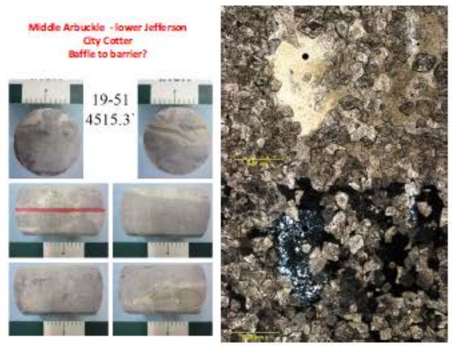
Model Area – Preliminary Simulation

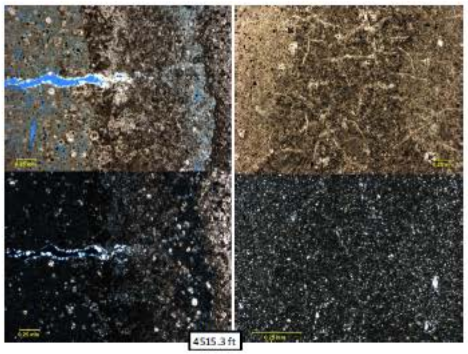
- 18 wells for property analysis
- 4 complete penetrations with log data
- 103 SWD wells with yearly injection data



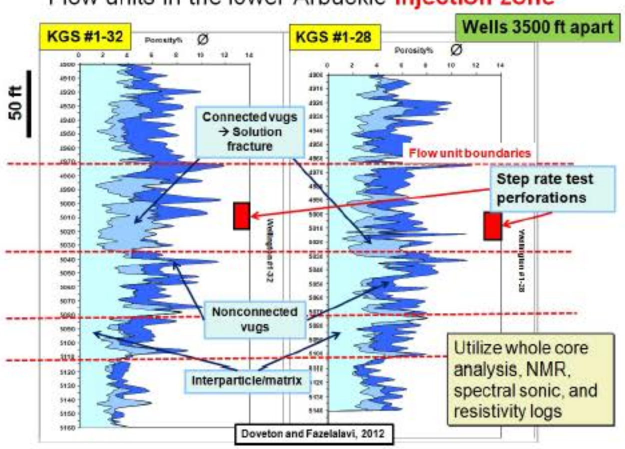
"Evaluating Potential for Induced Seismicity Through Reservoir-Geomechanical Analysis of Fluid Injection in the Arbuckle Saline Aquifer, South Central Kansas" Annual Meeting AAPG 2015, Denver ---T. S. Bidgoli, Y. Holubnyak, M. FazelAlavi

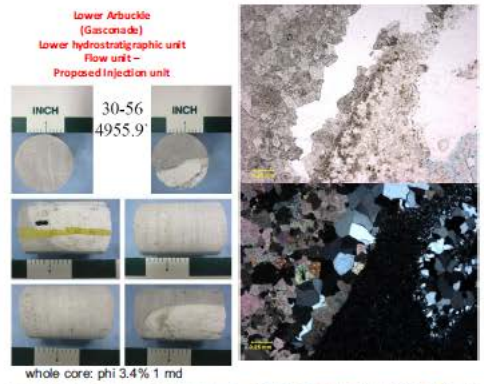
Thin Sections – Baffle Zone (Mid Arb.)

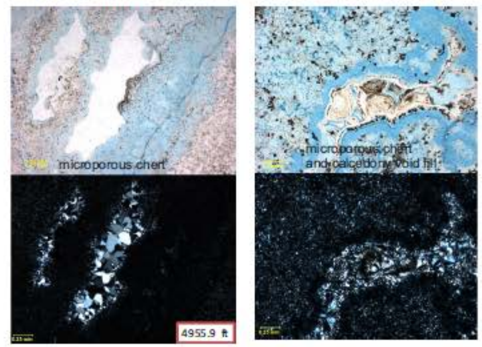


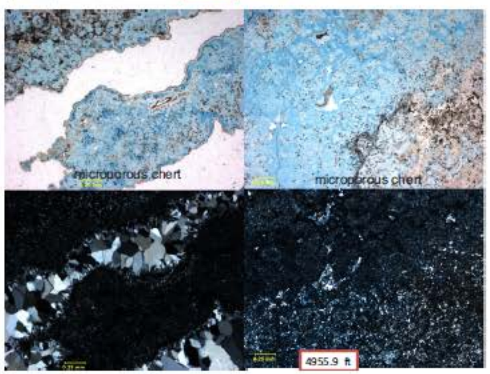


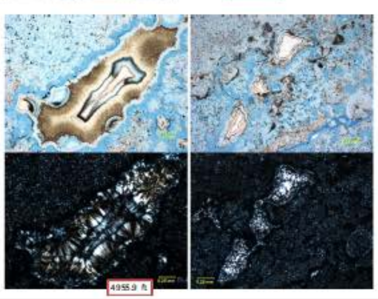
Flow units in the lower Arbuckle **injection zone**



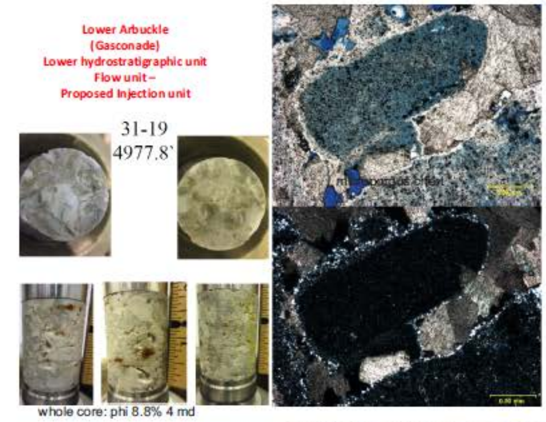


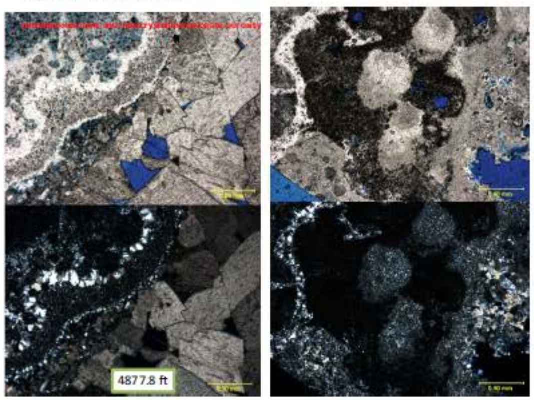


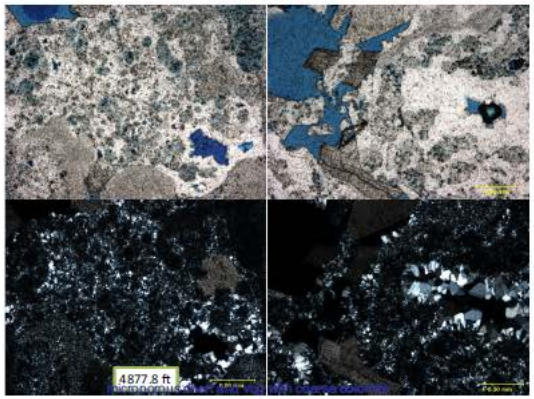




Lower Arbuckle Injection Zone





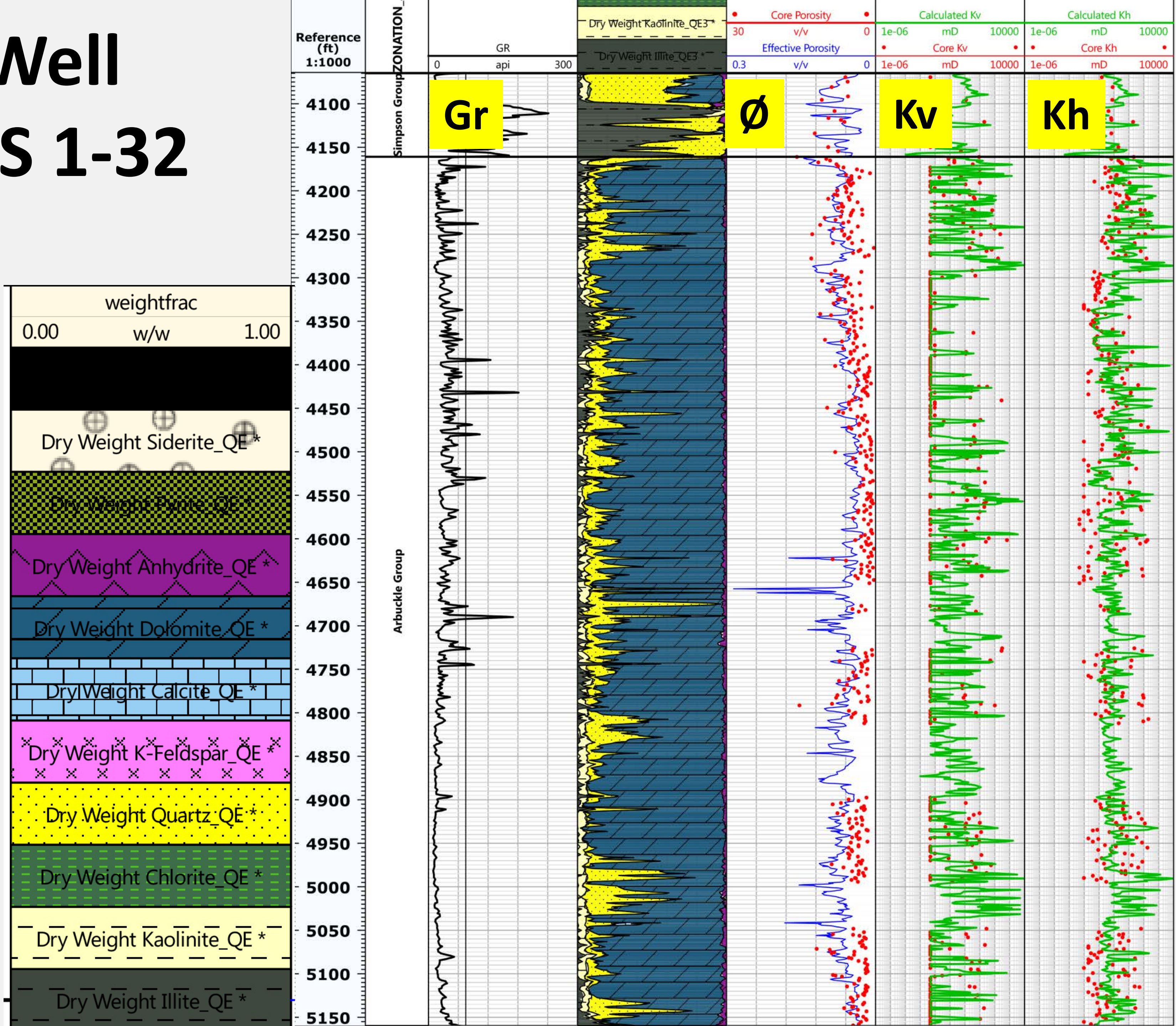


Pore types are complex in the Arbuckle

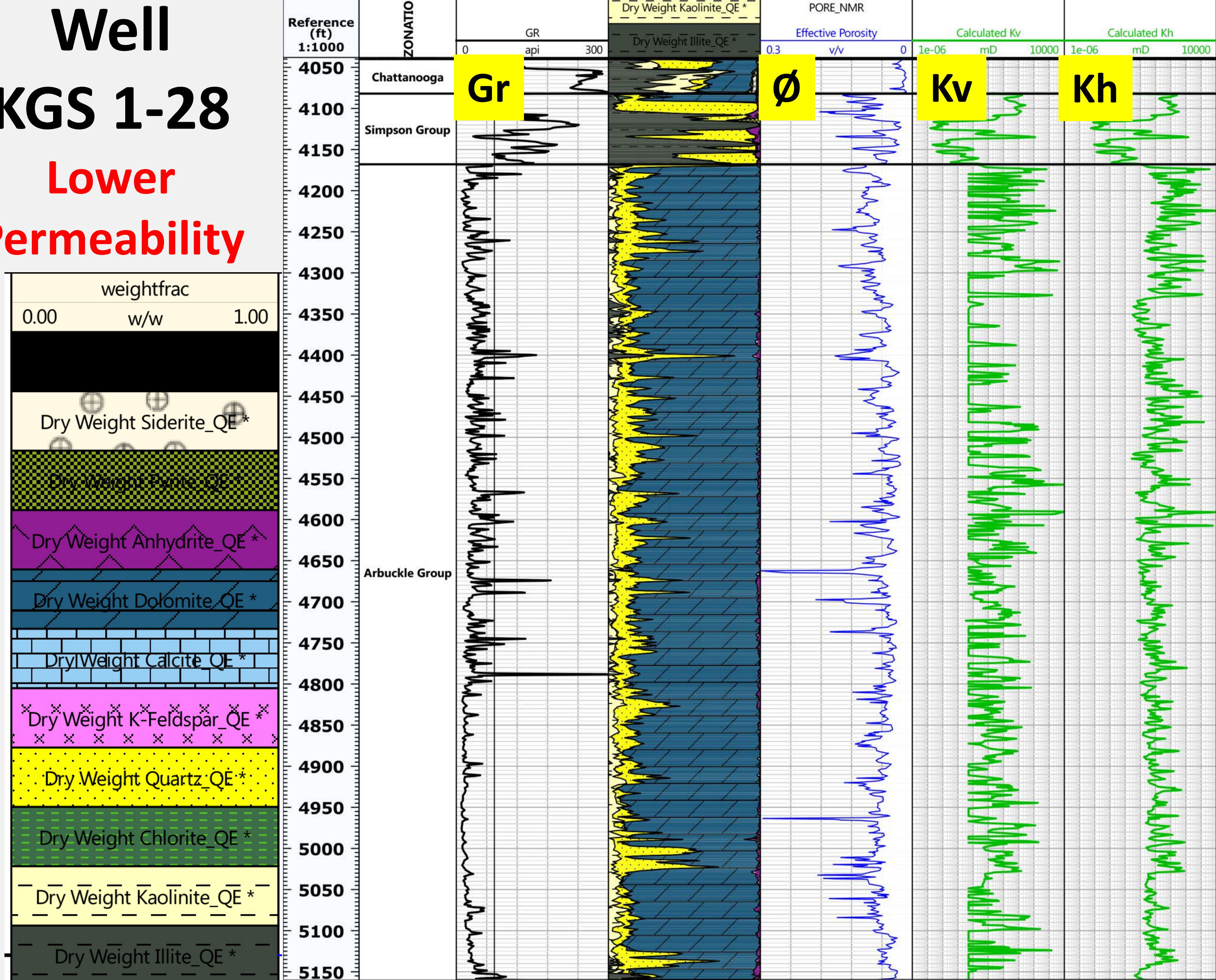
Pairs of photomicrographs
Plane light and crossed nichols

R. Barker, S. Datta, KSU

Well KGS 1-32


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 *
Reference (ft) 1:1000
ZONATION_
Simpson Group
Arbuckle Group
GR
0 api 300
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
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

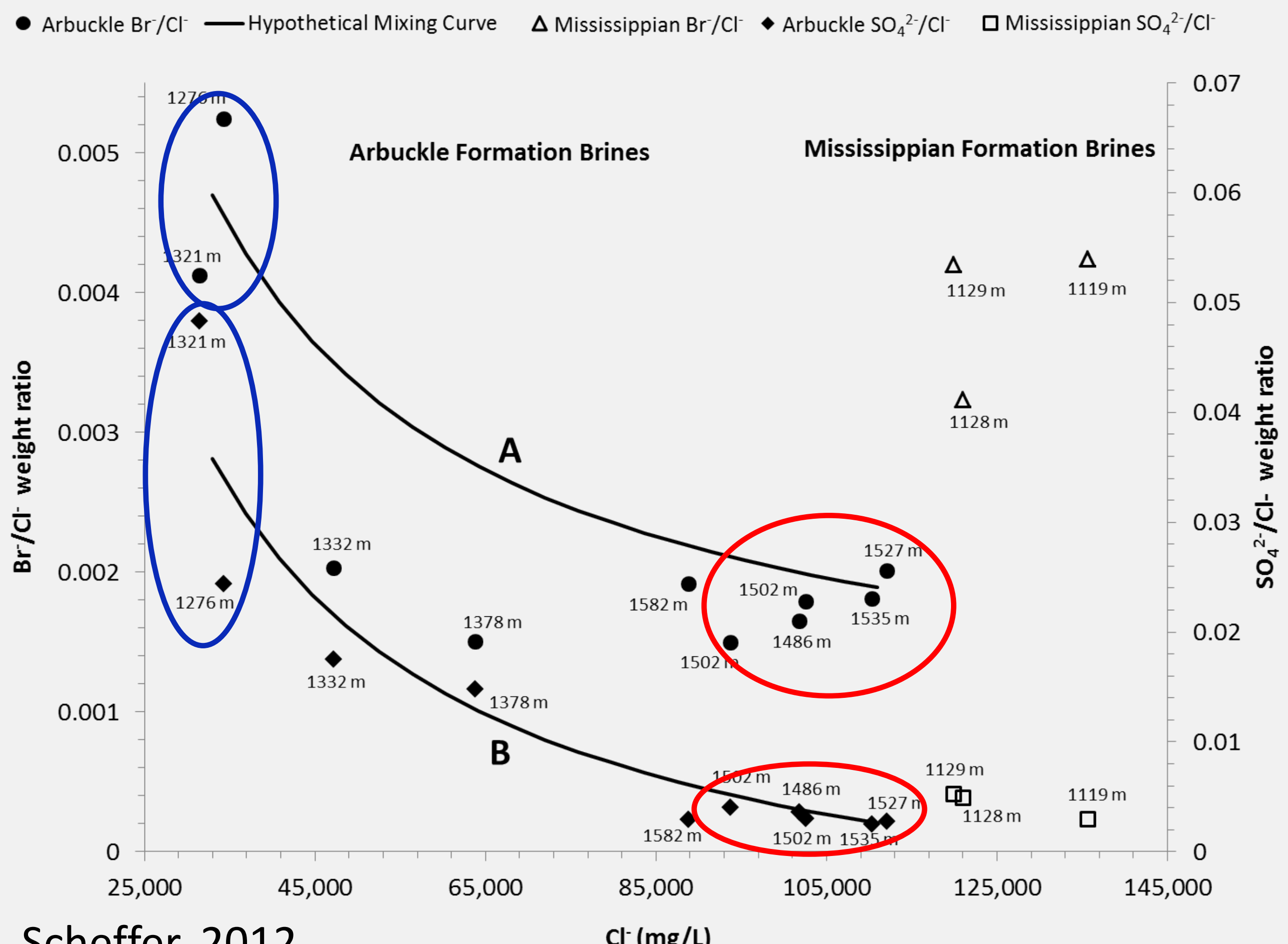
Well
KGS 1-28
Lower Permeability



Bromine/chlorine (Br^-/Cl^-) and sulfate/cloride (SO_4^{2-}/Cl^-) ratios

Used to Confirm of Baffles and Lack of Vertical Communication

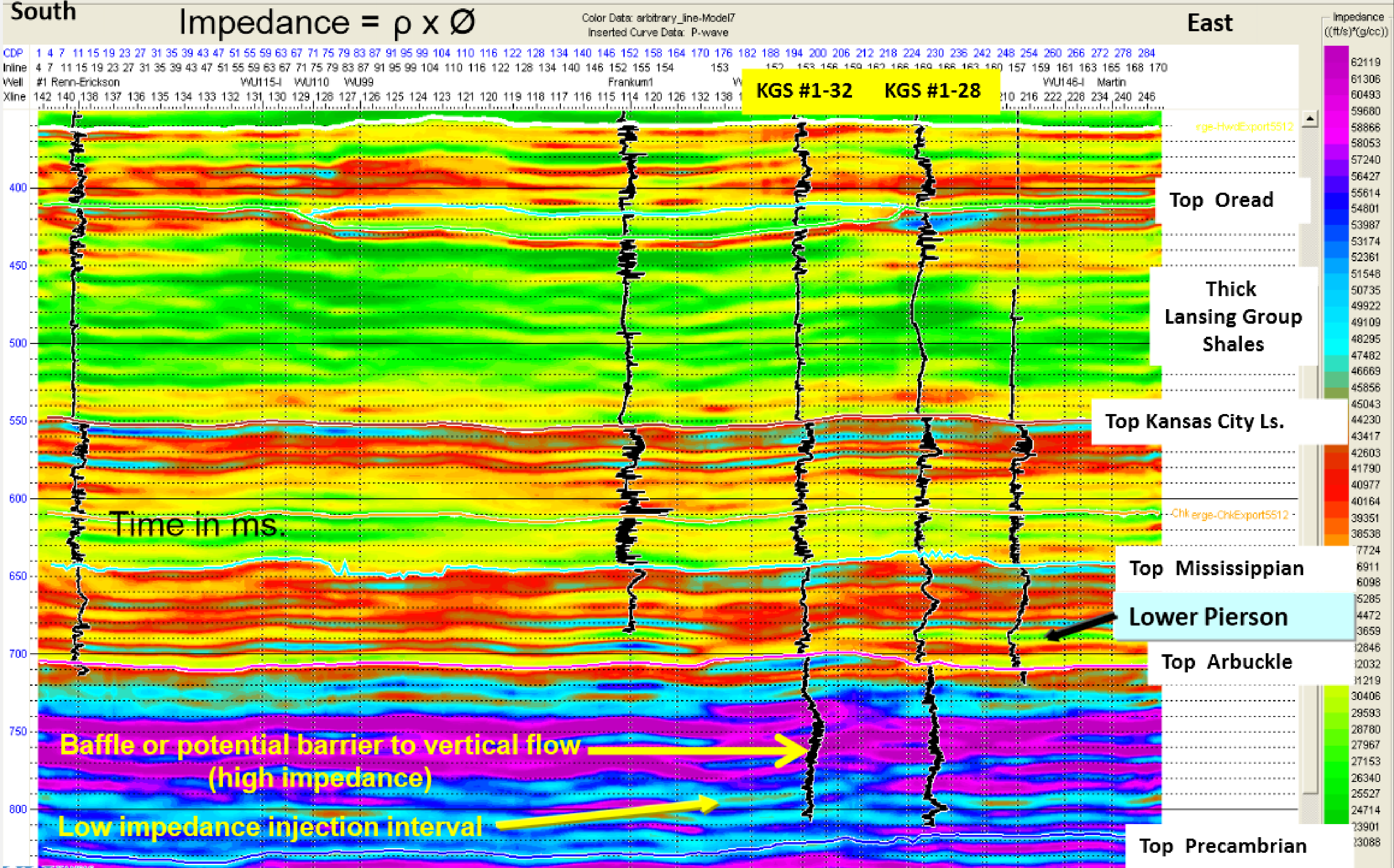
- Br^- and Cl^- are conservative during water/rock interactions
- Very useful in detecting brine sources and mixing
- Values for brine of Lower Arbuckle vary substantially from Upper Arbuckle
- Lower Arbuckle brines cluster together
- Upper Arbuckle values more spaced out, suggests smaller baffles



Scheffer, 2012

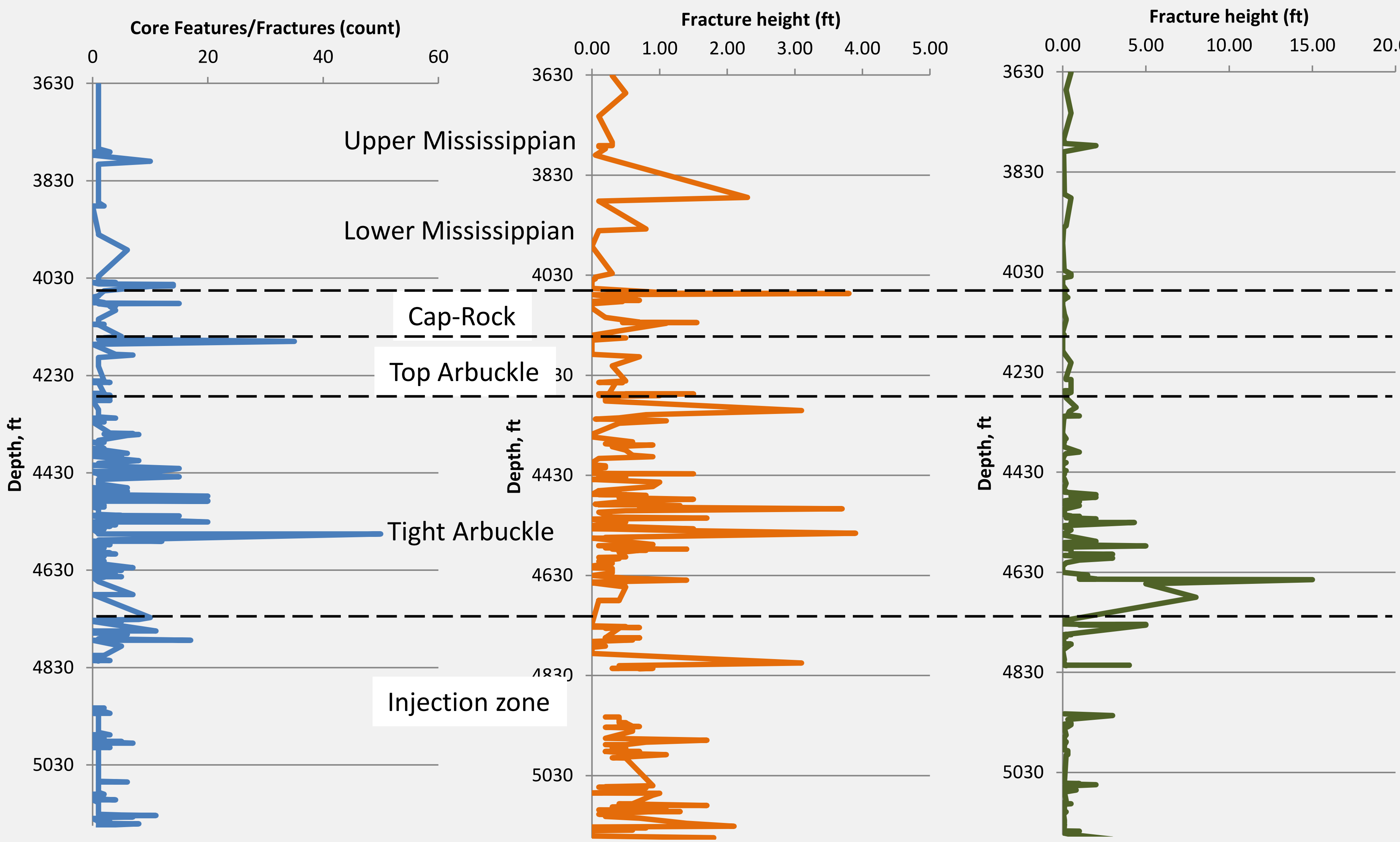
Arbitrary seismic impedance profile – Wellington Field

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

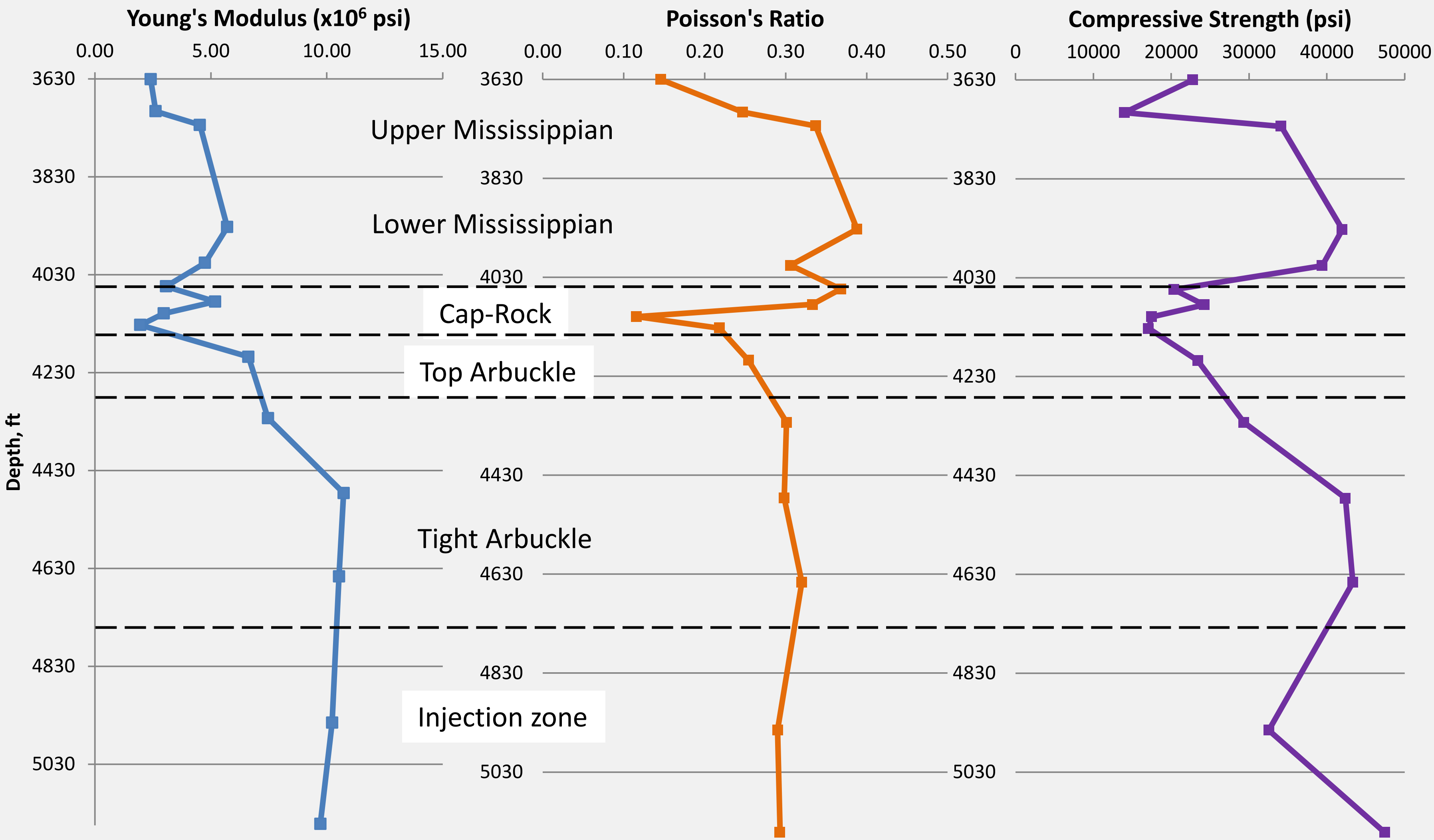


Hedke – DOE/CO2

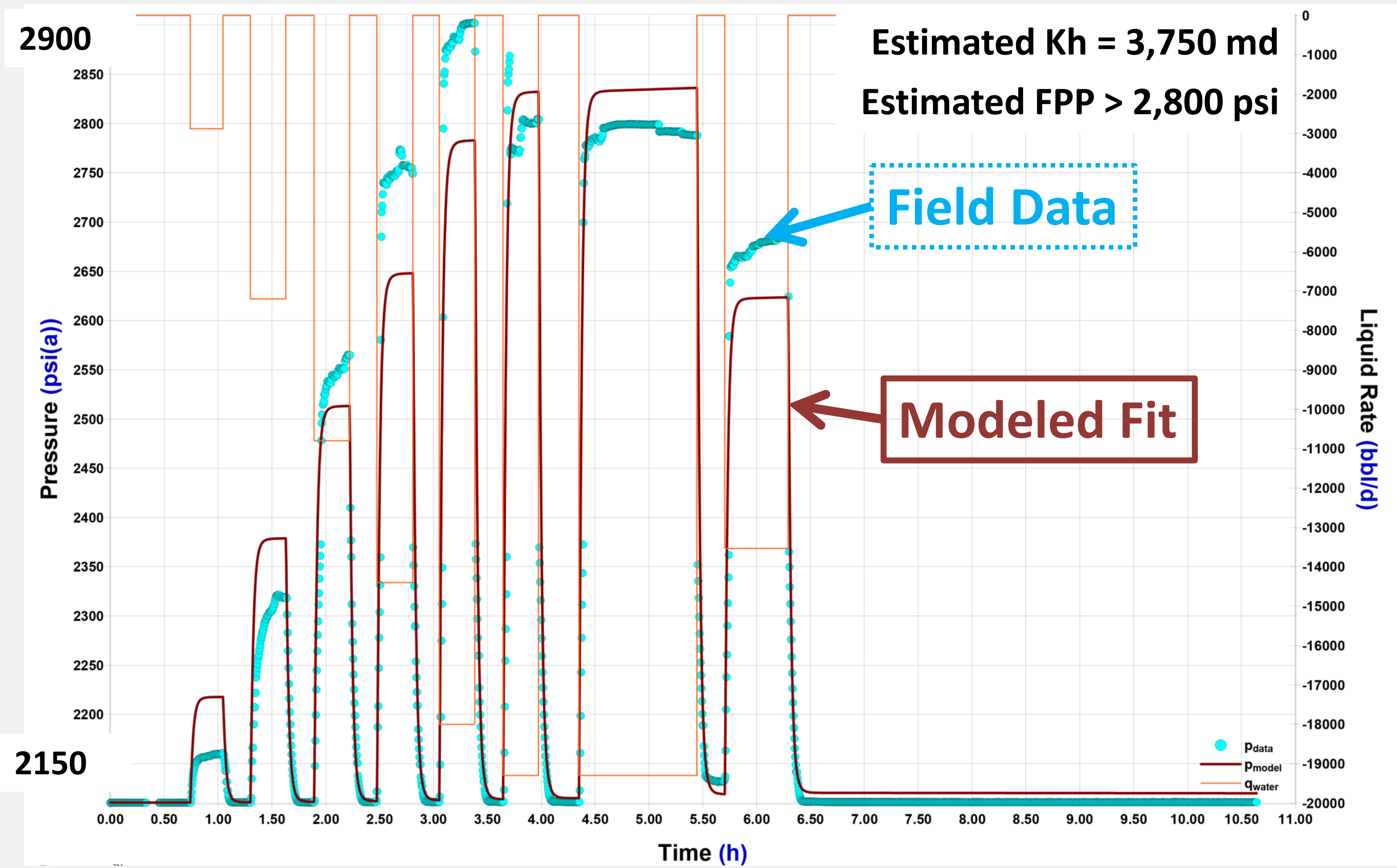
Core Features/Fractures



Rock Mechanical Properties vs. Depth

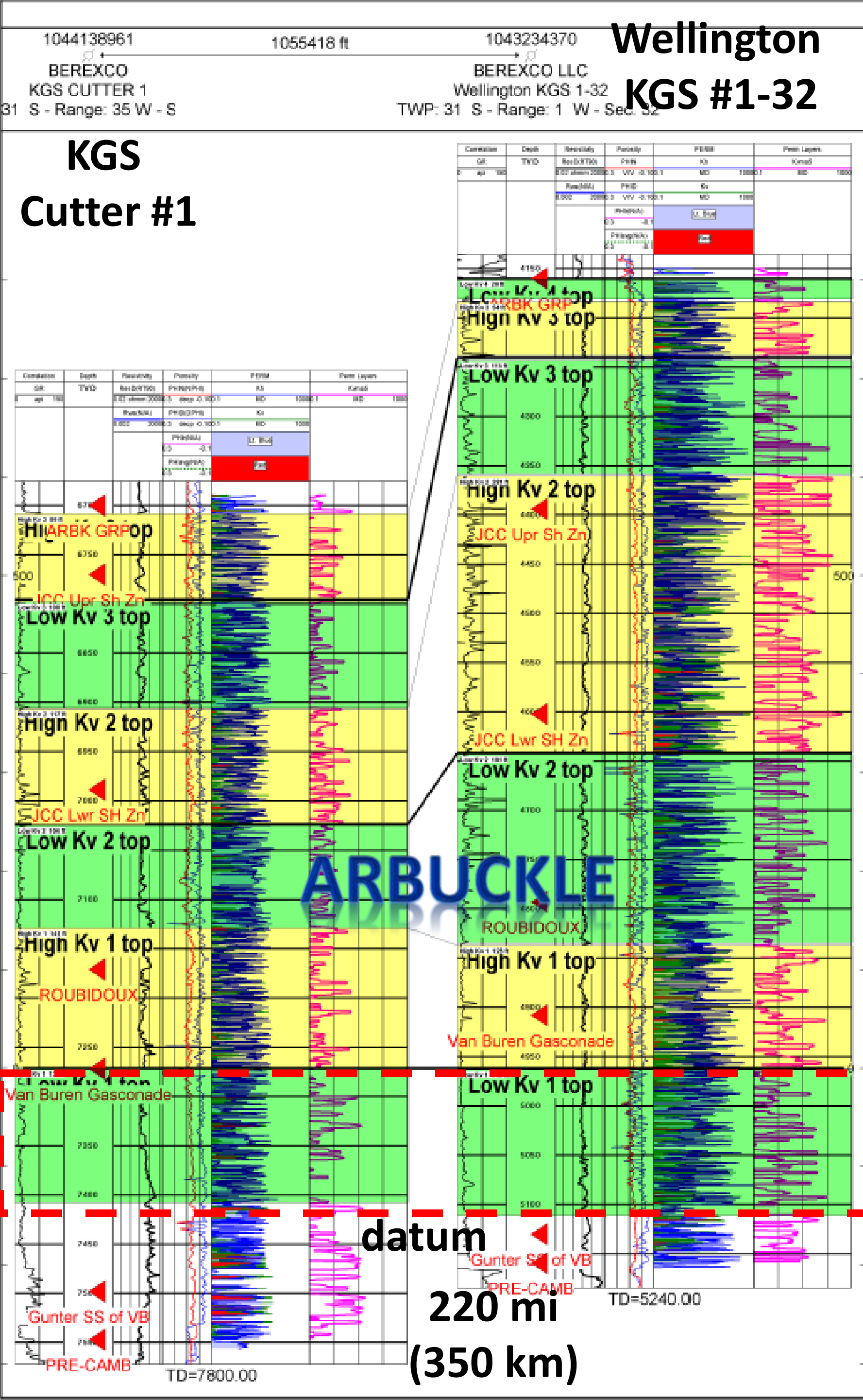


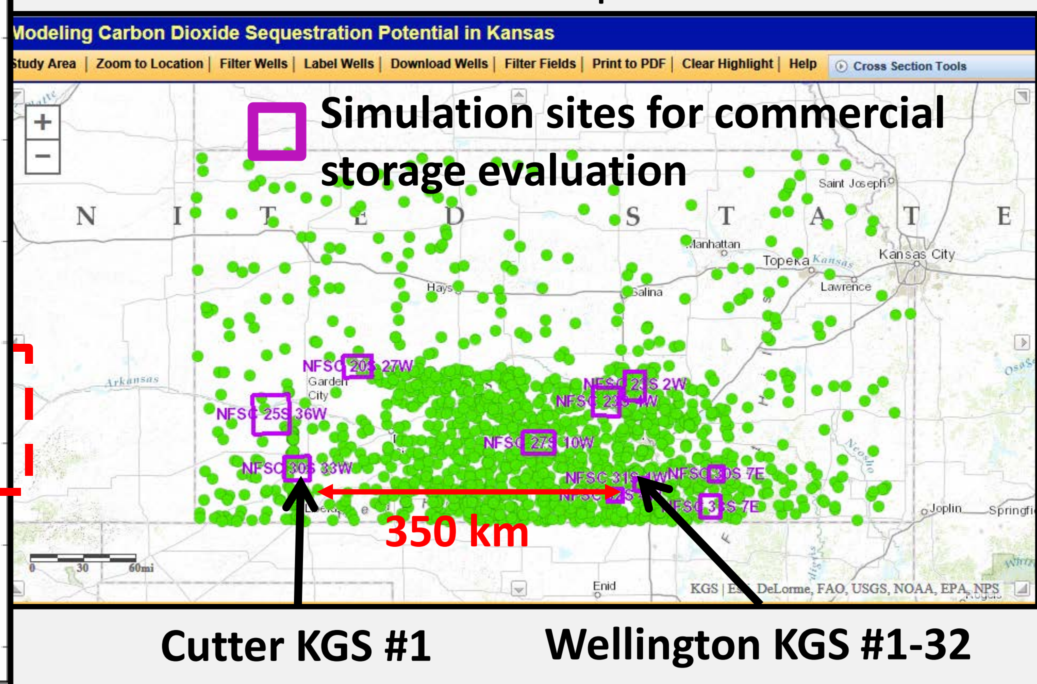
Step Rate Test Analysis Pressure-Time Plot



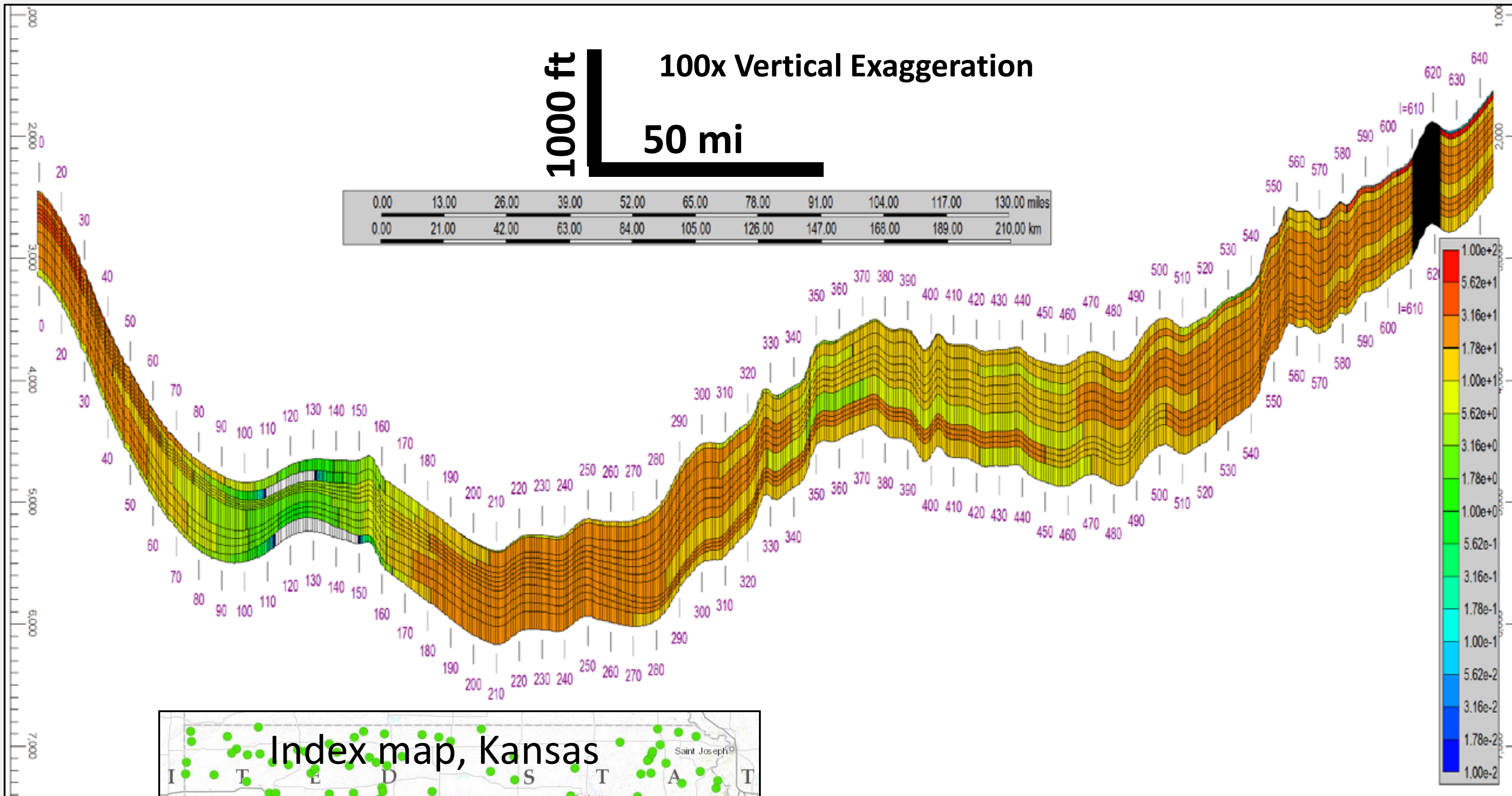
Computed K_h & K_v in Arbuckle Group for Digital Type Wells (●)

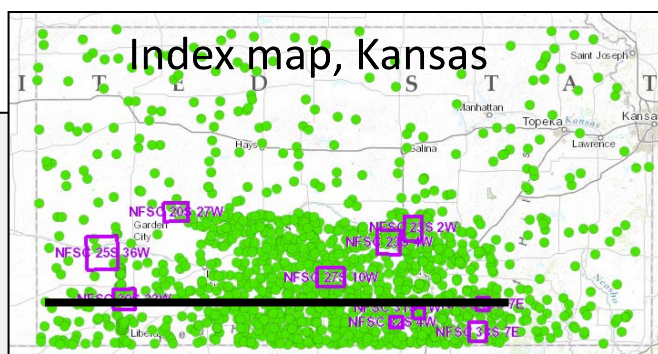
- Correlation of flow units based on K_h & k_v (vertical and horizontal permeability)
- Between Cutter and Wellington Fields (350 km apart)
- Testing log-derived permeability with Class I buildup test data





Structural cross section showing regional Arbuckle flow units, southern Kansas





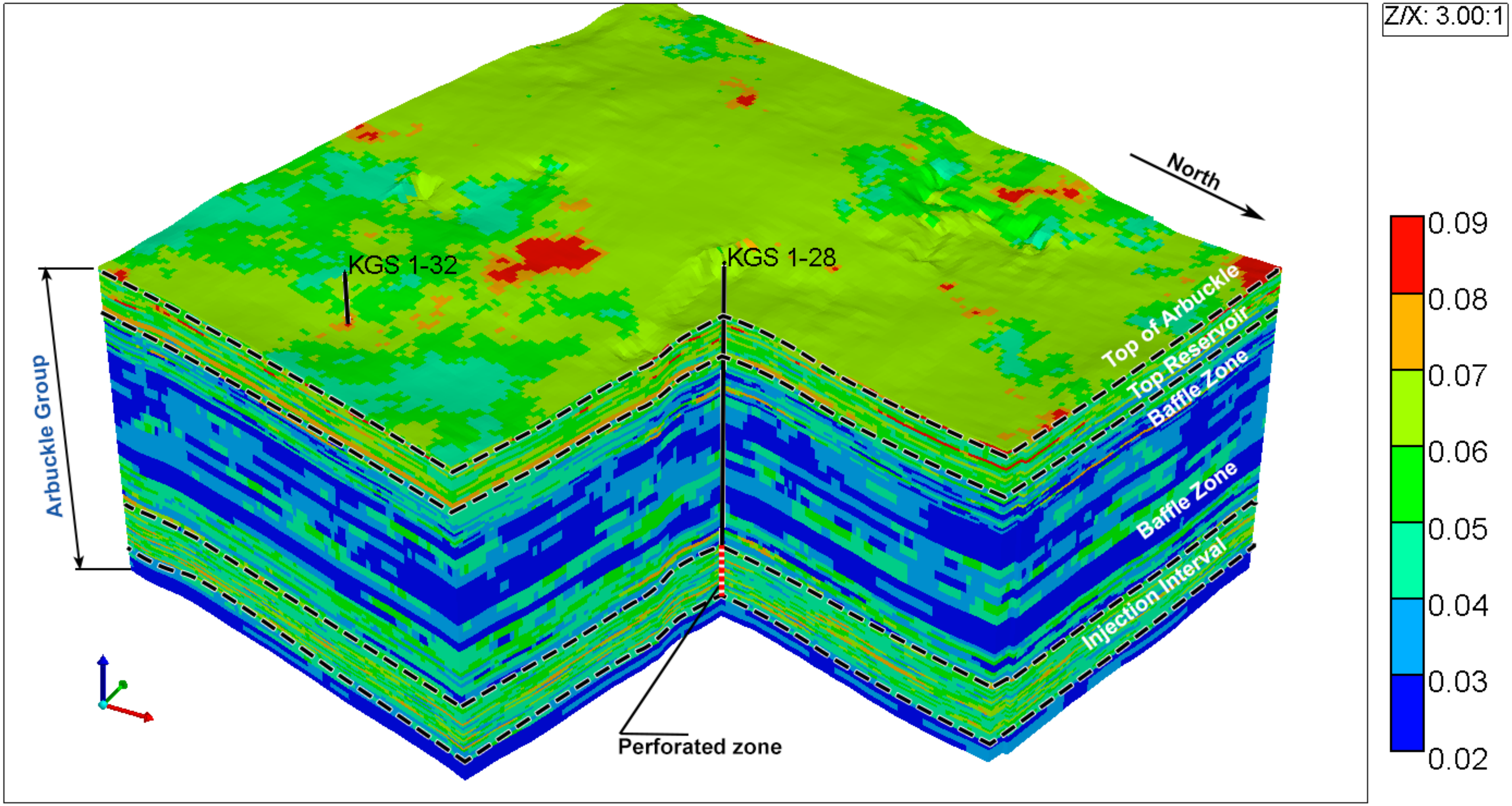
Horizontal Permeability, md

Williams, Gerlach, Fazelalavi, Doveton, KS CO_2

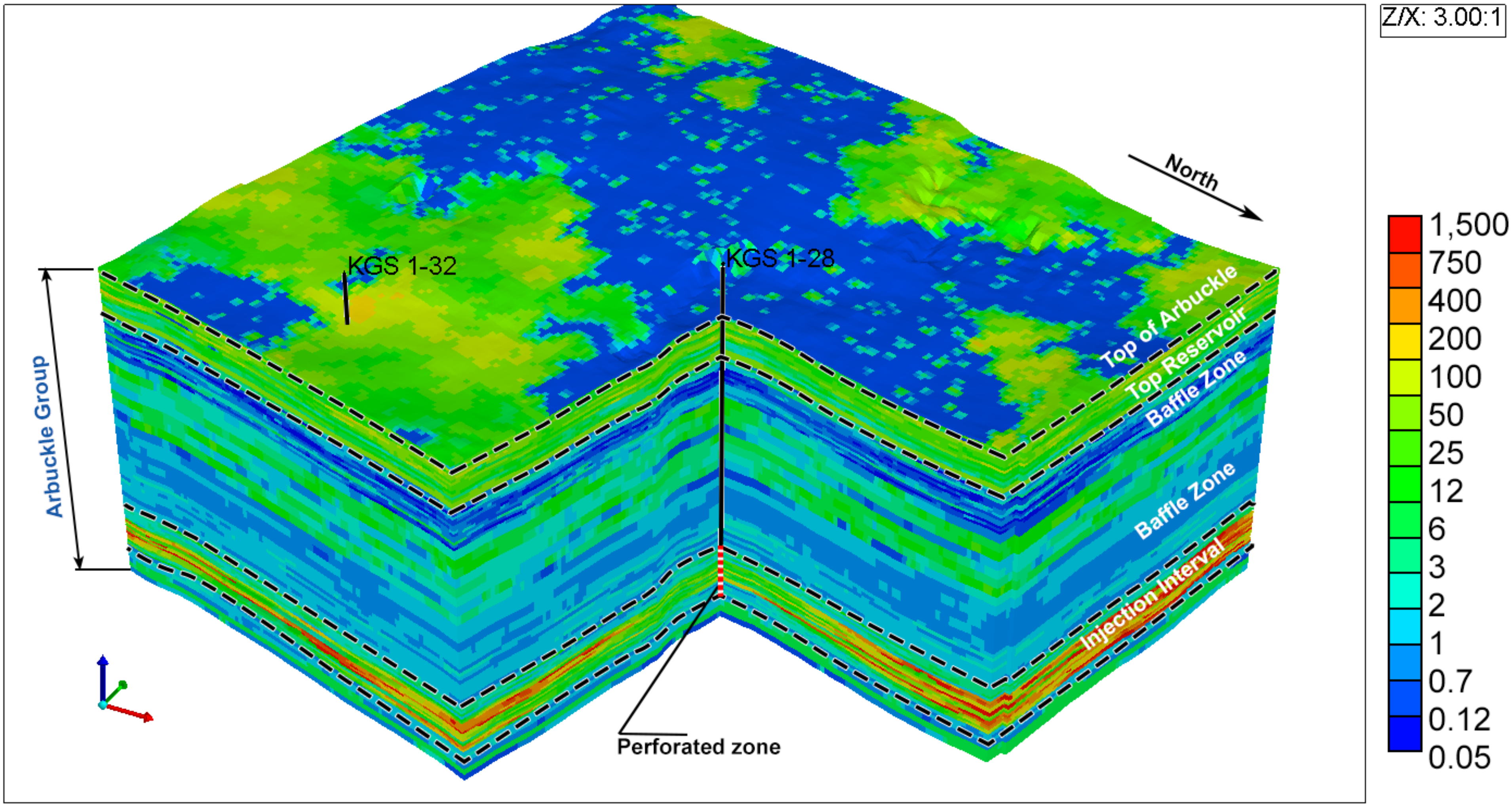
Arbuckle Reservoir Model Summary

- Highly complex system with many sub-zones and different reservoir properties
- Highly fractured system may require dual porosity/permeability model in future
- Faulted system
- High vertical reservoir variability
  - Low permeability – Mid. Arbuckle baffle zone could be a vertical fluid flow barrier
  - High permeability in Upper and Lower Arbuckle
- Horizontal variability

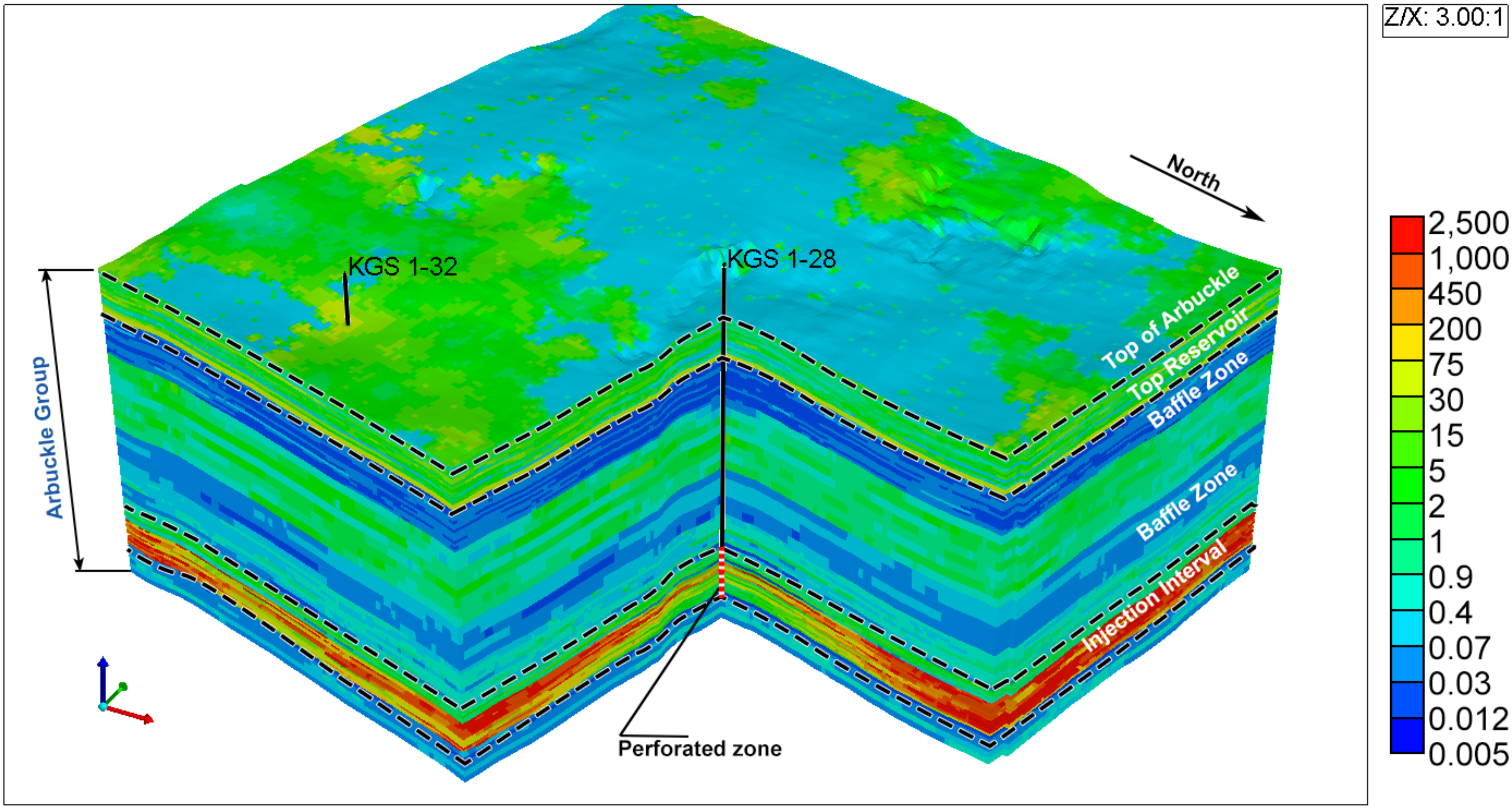
Porosity Model



Permeability Model (K90)

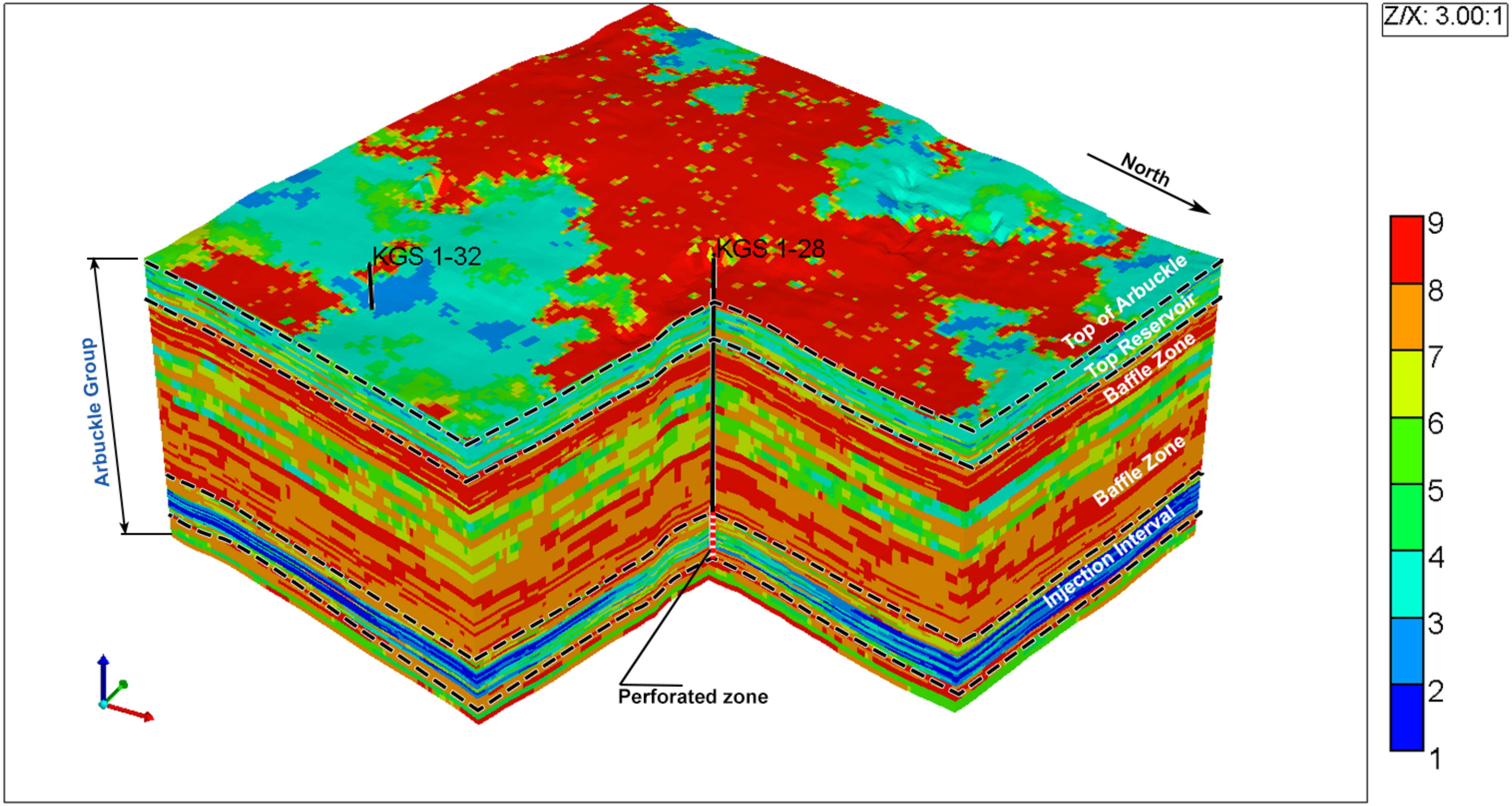


Permeability Model (Vertical)

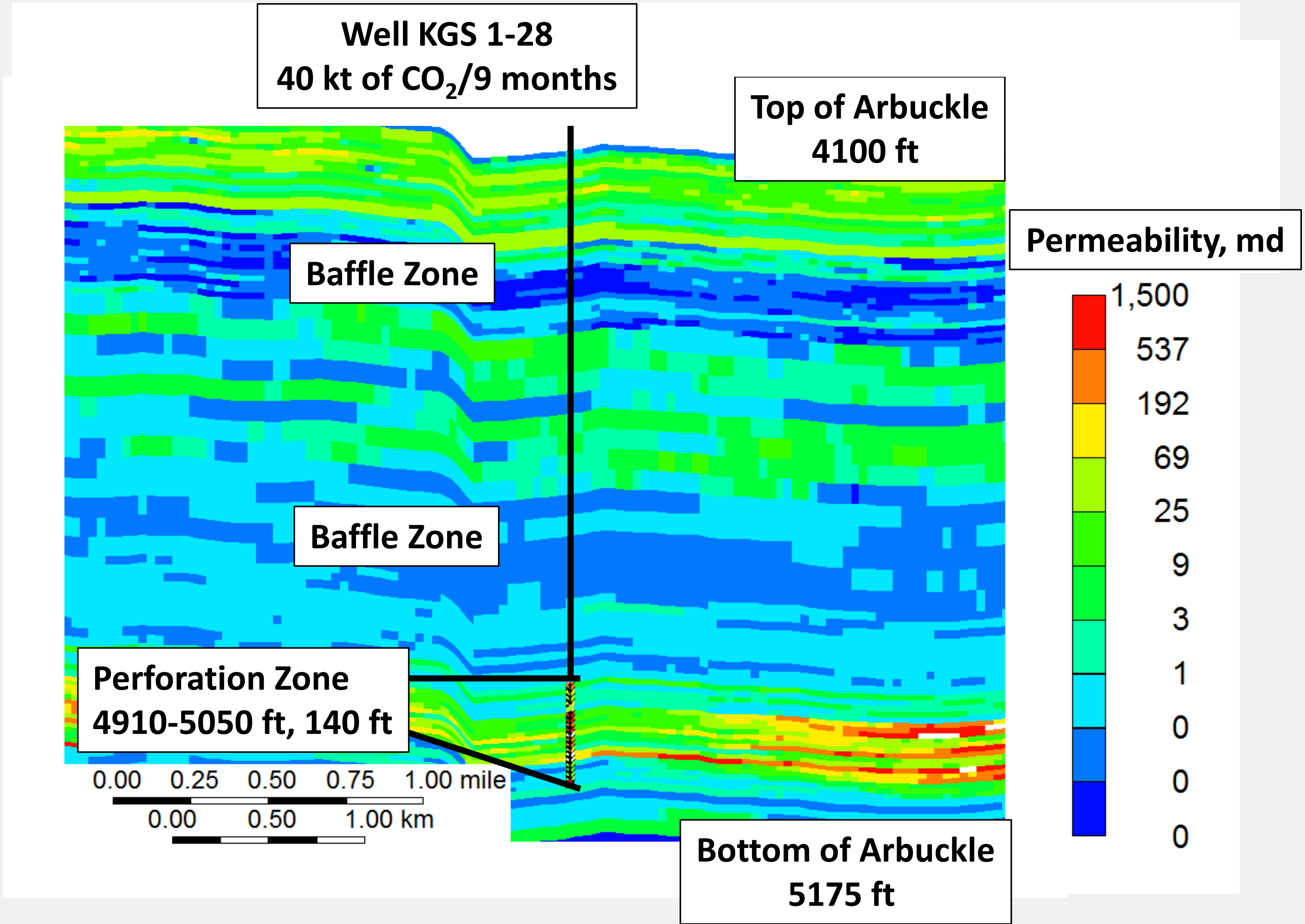


Rock Type Based on RQI

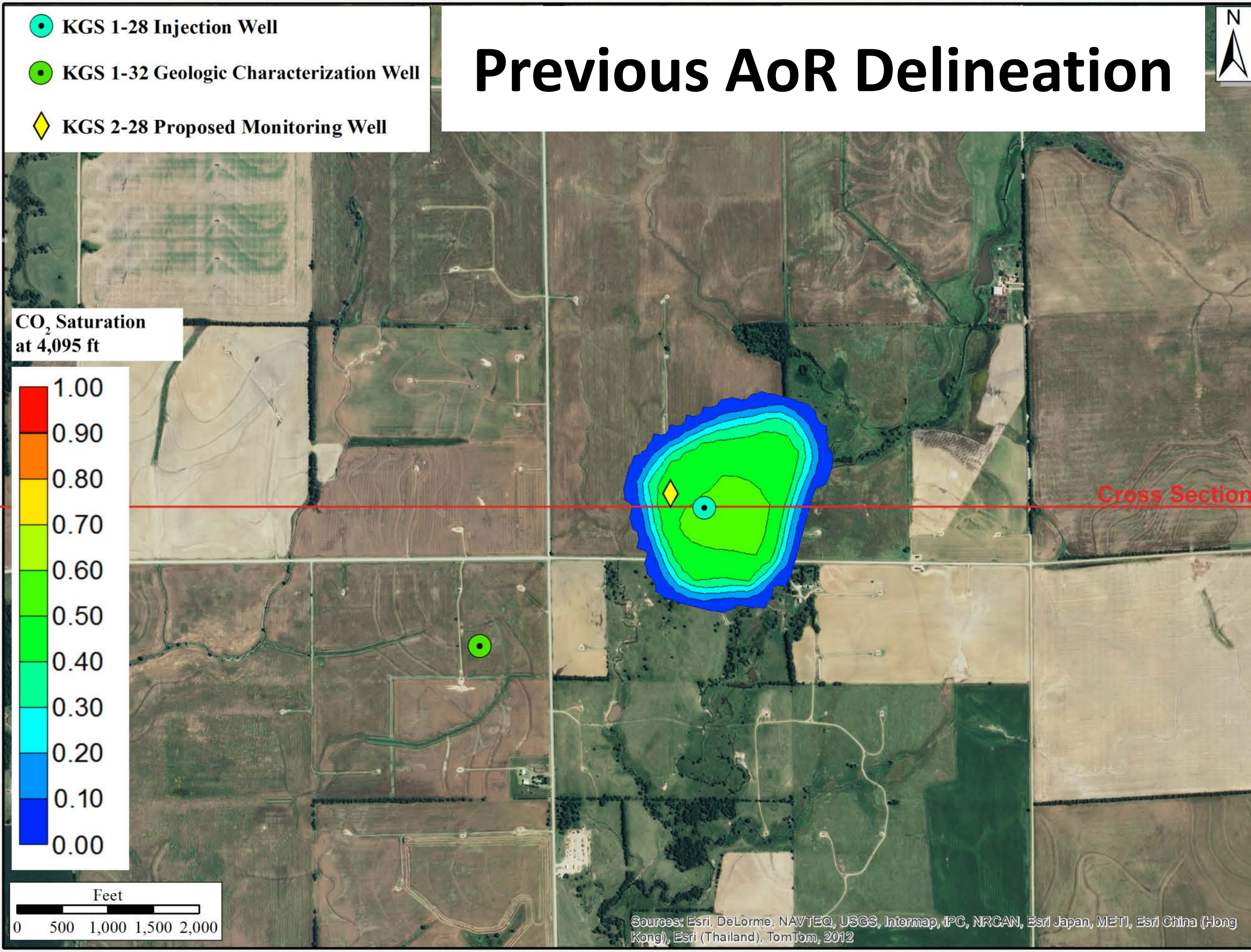
$$RQI = 0.0314\sqrt{{}^{Perm}/_{Porosity}}$$



Dynamic Simulation Model

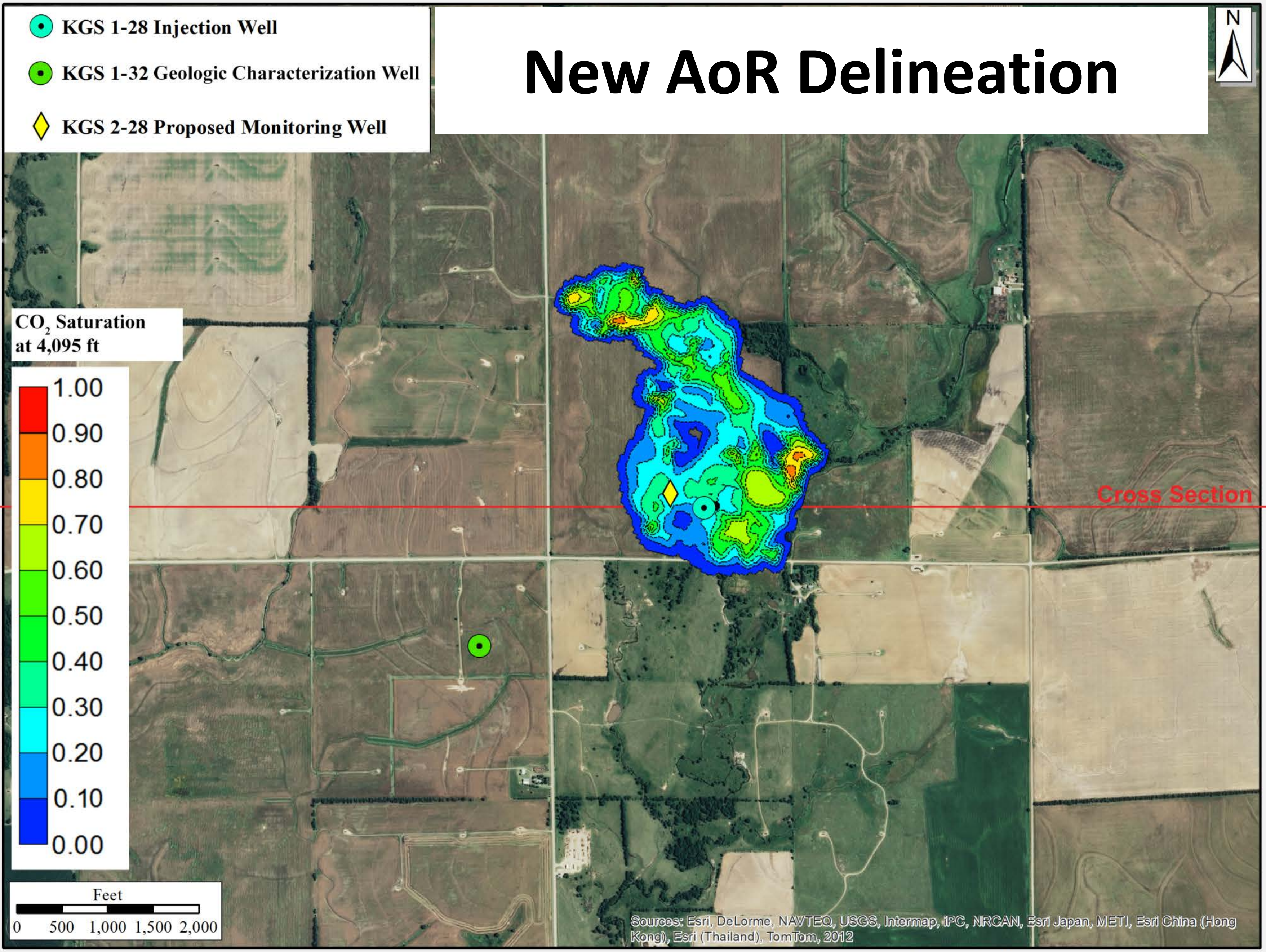


Previous AoR Delineation

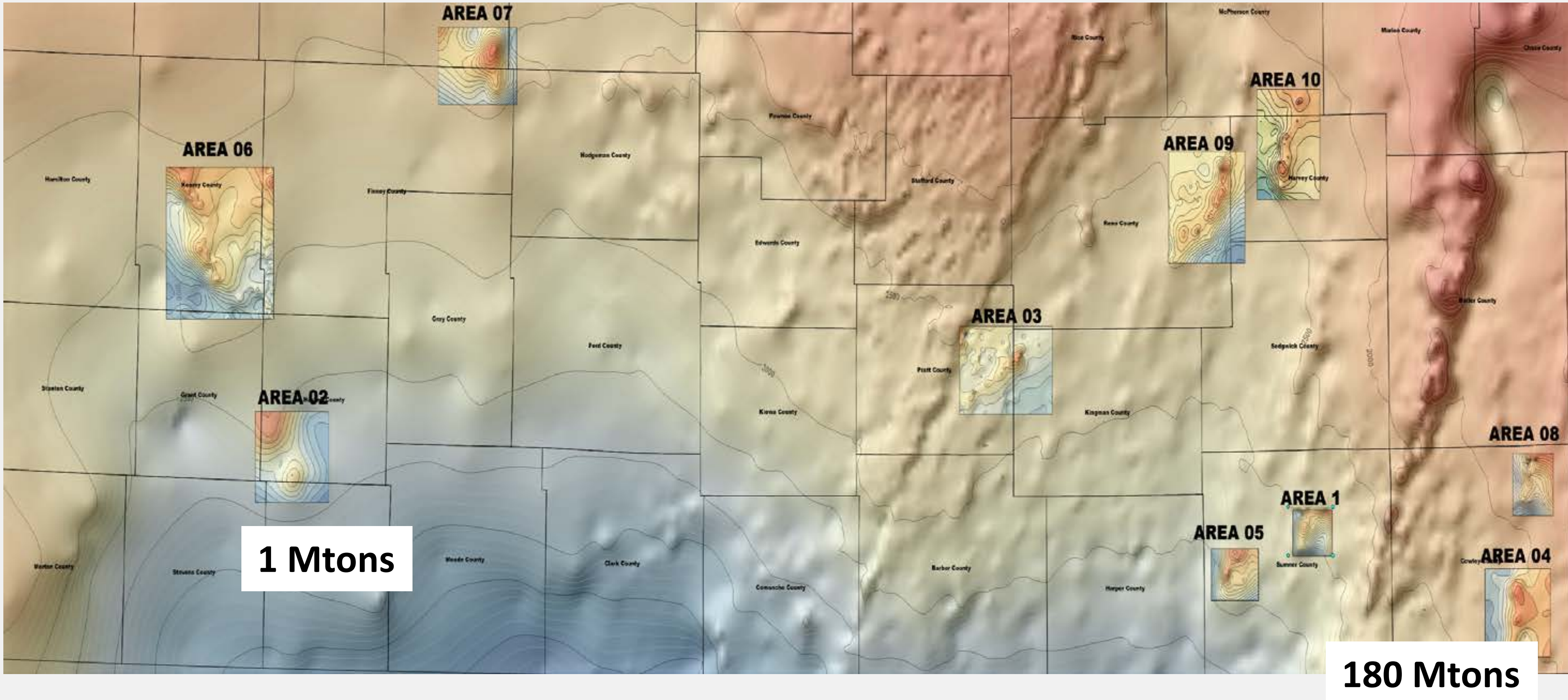


Sources: ESRI, USGS, Kansas Geological Survey

New AoR Delineation



Sources: ESRI, USGS, Kansas Geological Survey



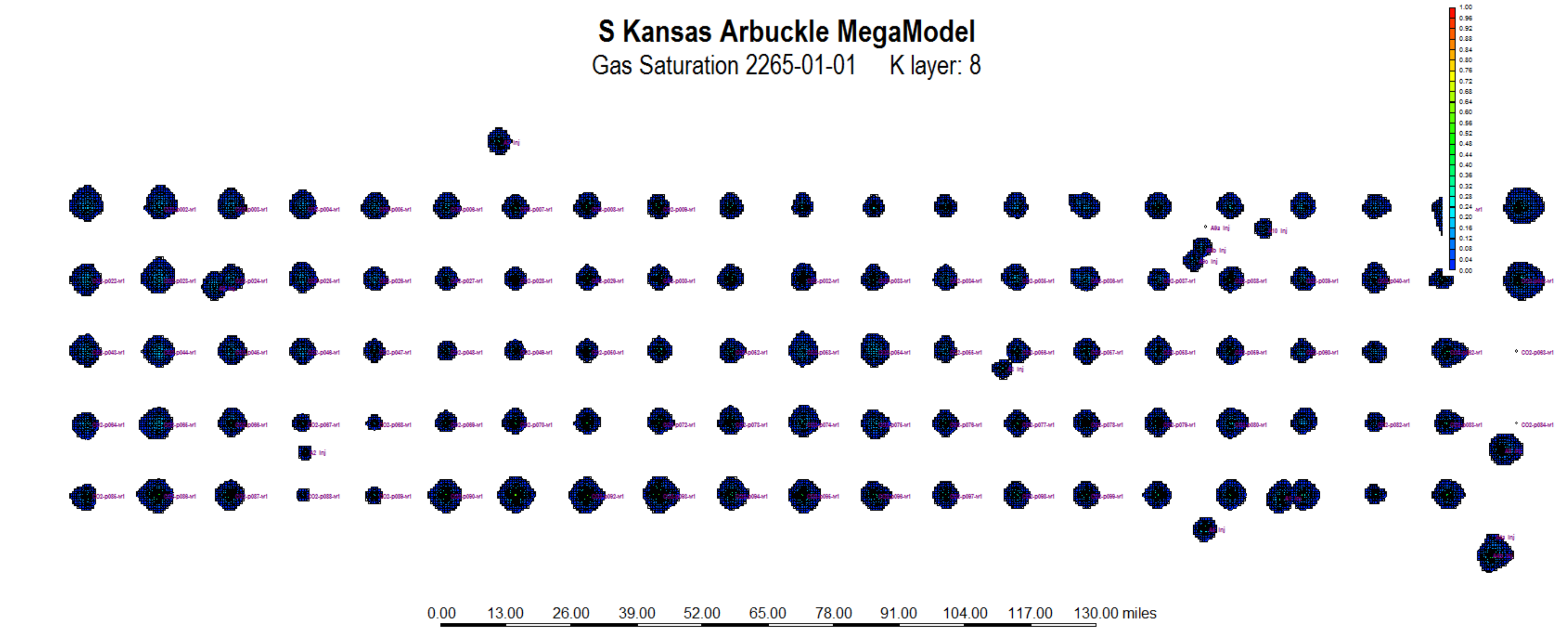
Regional Scale CO_2 Storage Capacity Simulation

- South Western and South Central Kansas
- 10 areas – benchmark sites
- One “mega” model

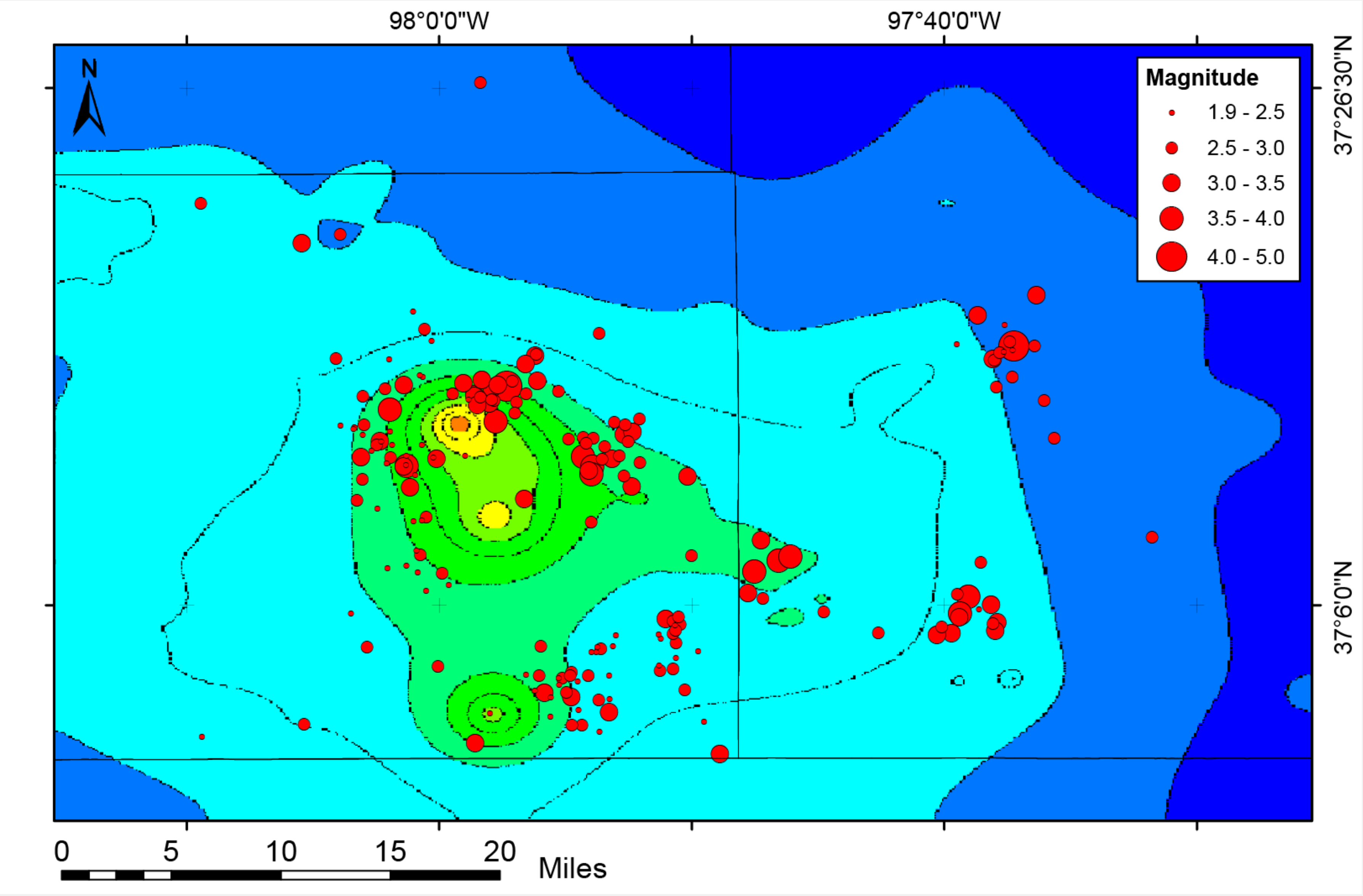
Southern Kansas CO_2 injection model
Gas saturation - 100 years after injection stops

~ 4 Billion tonnes injected

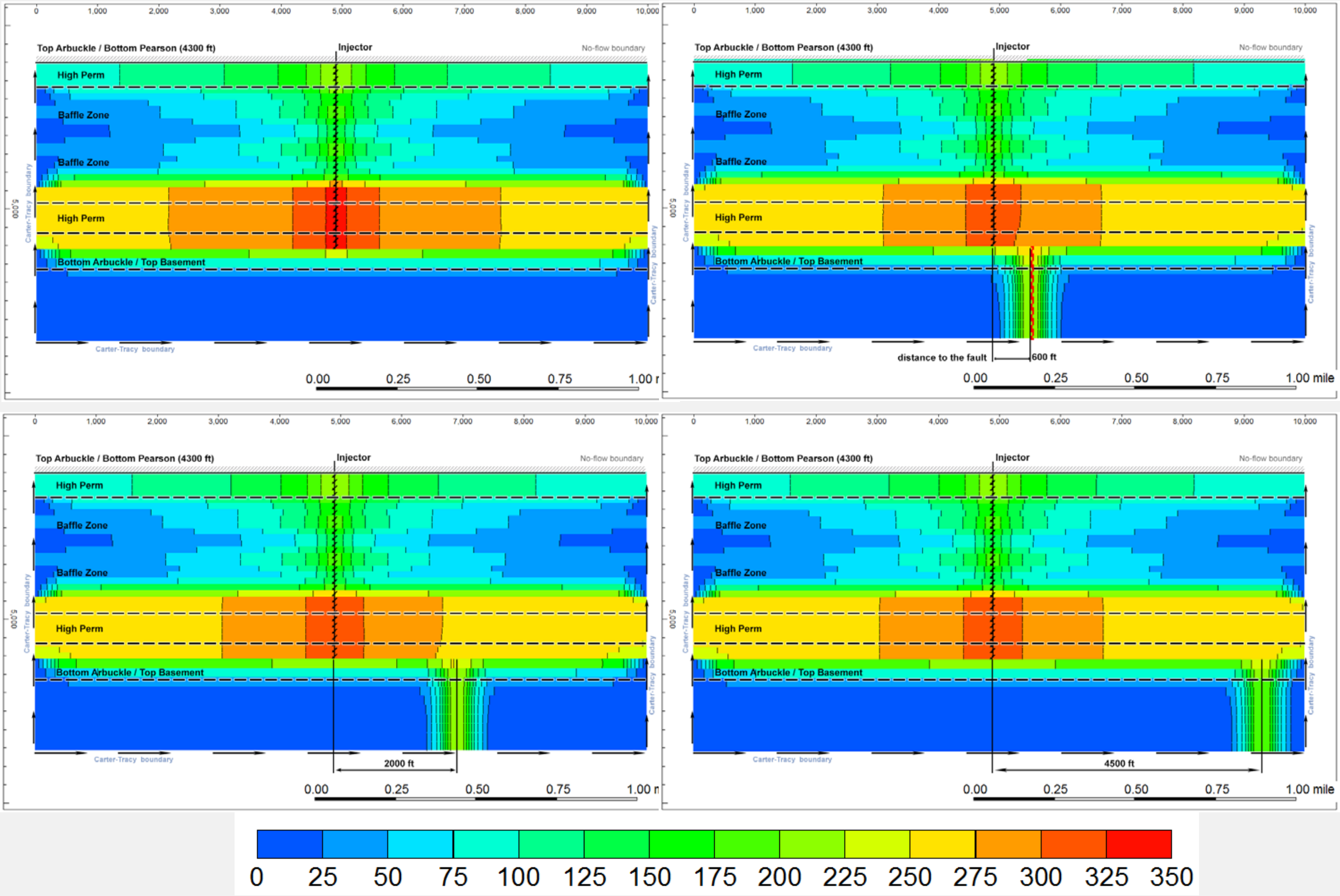
~ 300 psi average pore pressure increase



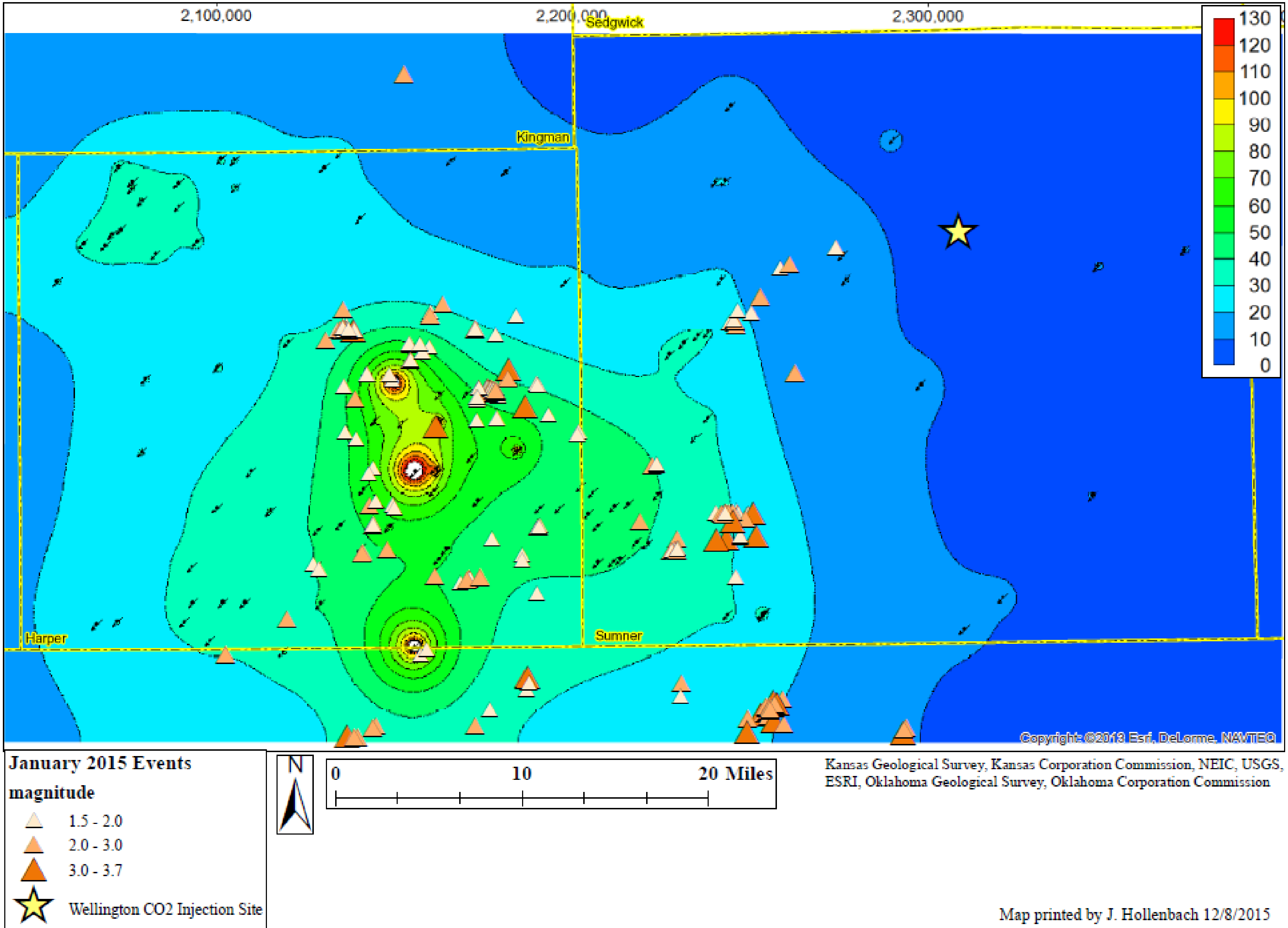
Modeled Delta Pressure for Harper and Sumner Counties in South Kansas



Delta Pressure at a Basement Fault



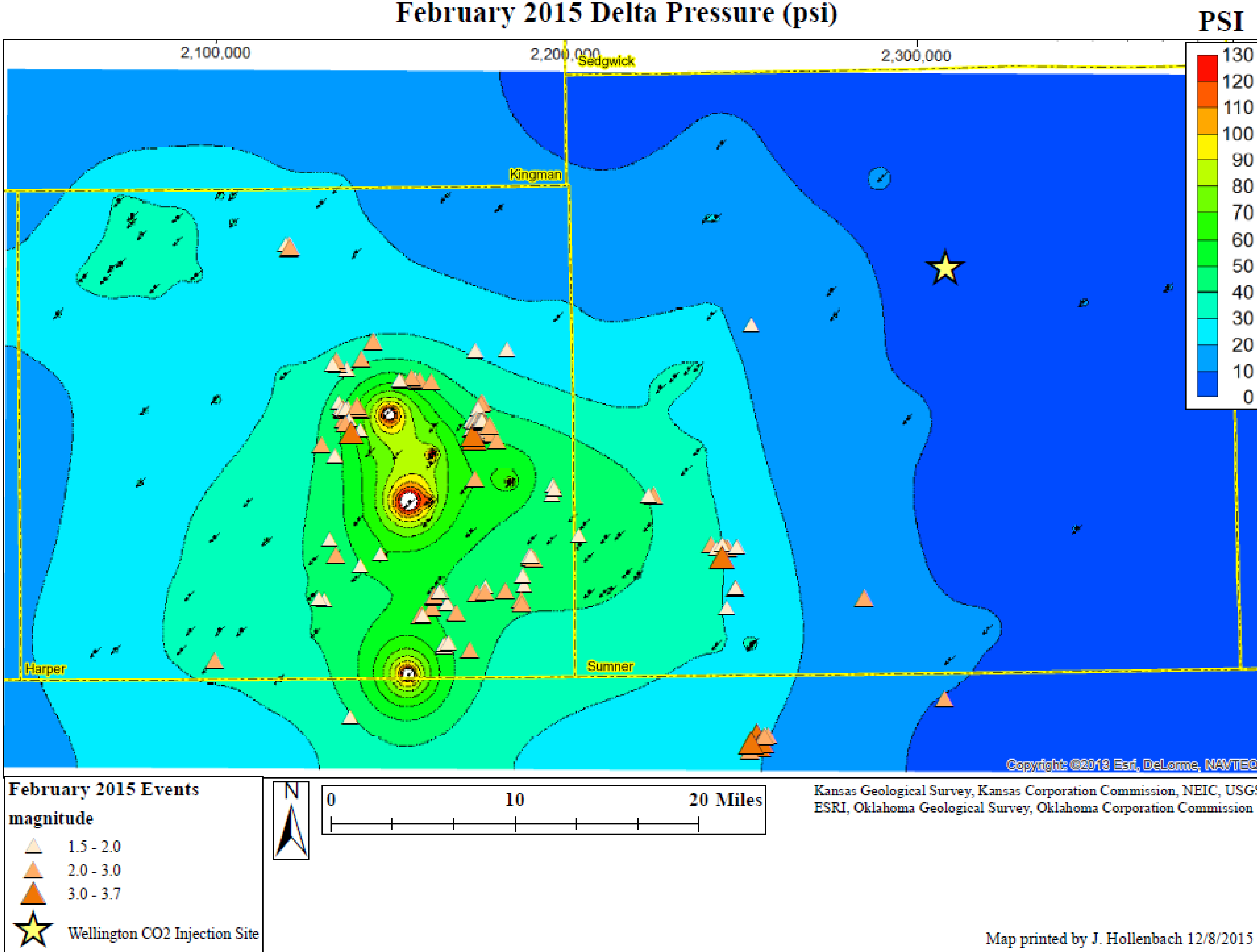
January 2015 Delta Pressure (psi)



Kansas Geological Survey, Kansas Corporation Commission, NEIC, USGS, ESRI, Oklahoma Geological Survey, Oklahoma Corporation Commission

Map printed by J. Hollenbach 12/8/2015

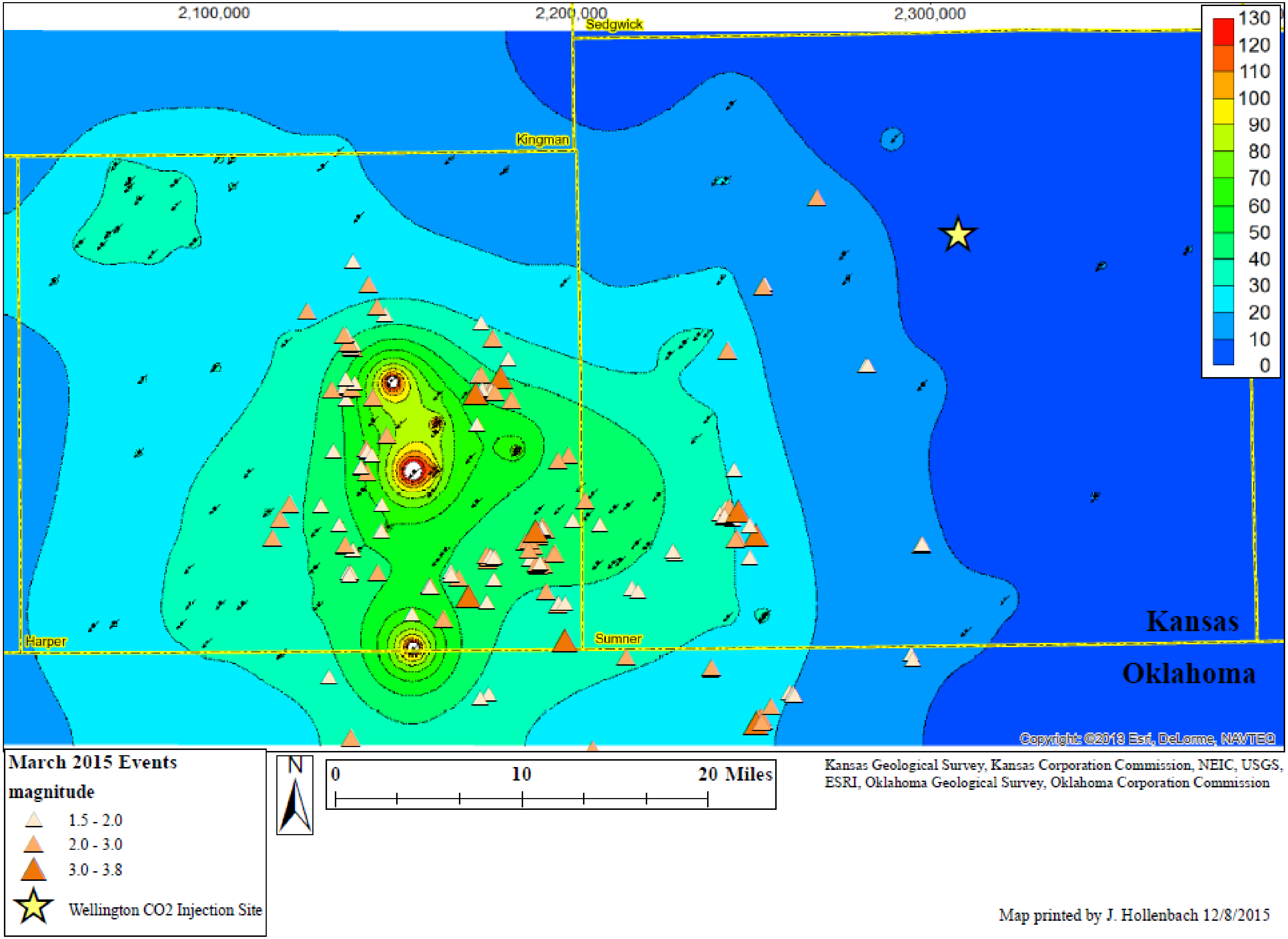
February 2015 Delta Pressure (psi)



Kansas Geological Survey, Kansas Corporation Commission, NEIC, USGS, ESRI, Oklahoma Geological Survey, Oklahoma Corporation Commission

Map printed by J. Hollenbach 12/8/2015

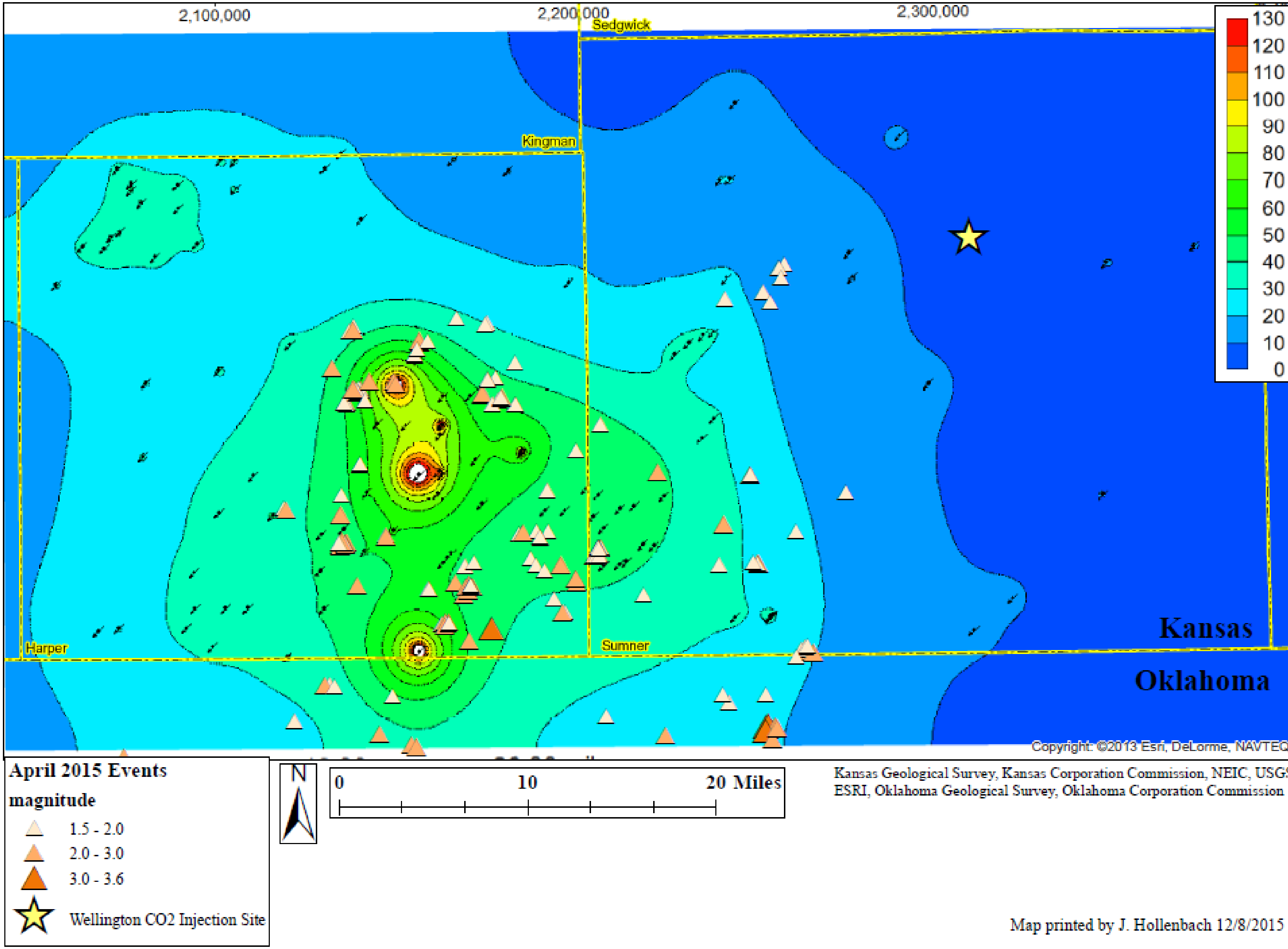
March 2015 Delta Pressure (psi)



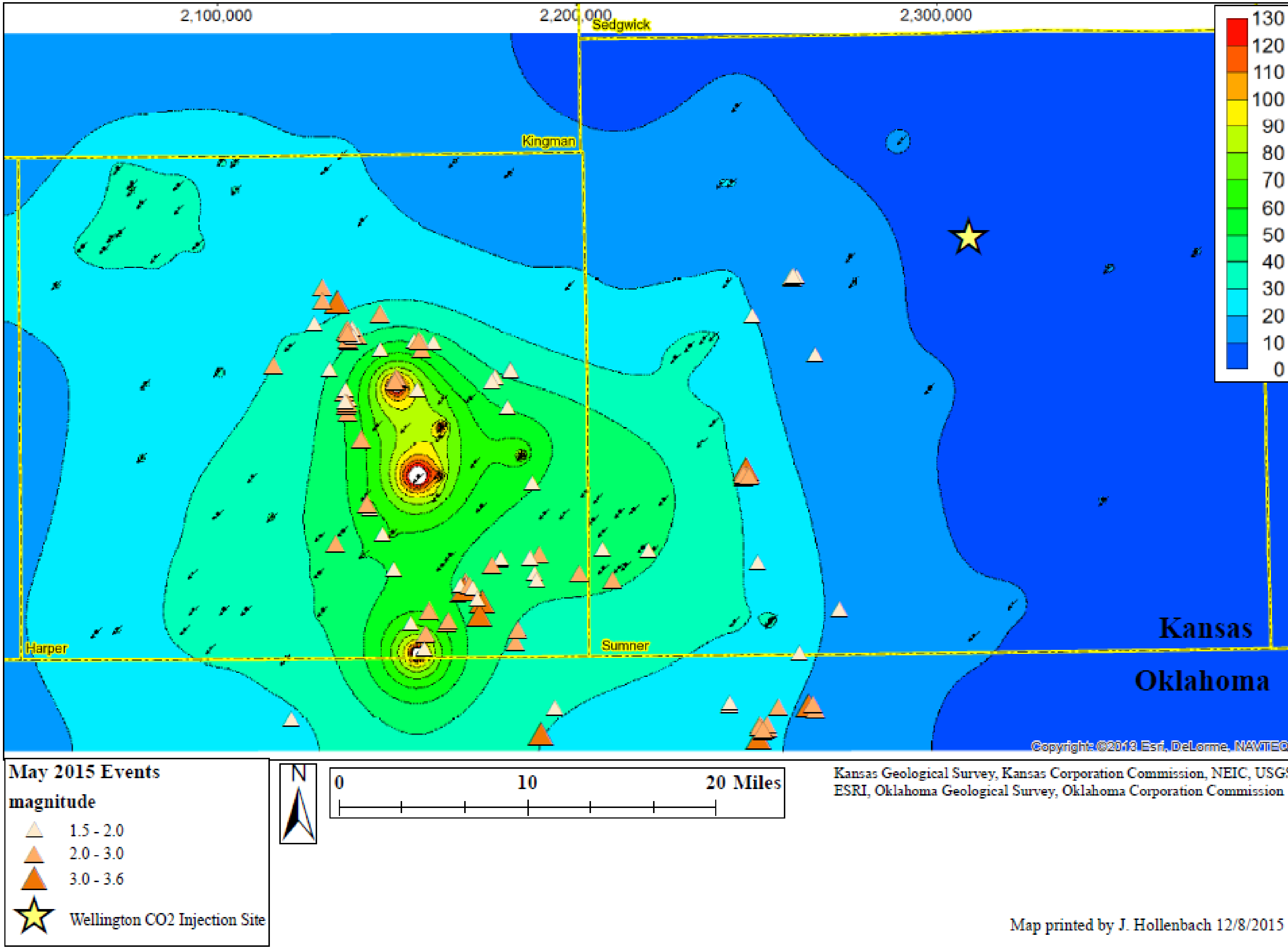
Kansas Geological Survey, Kansas Corporation Commission, NEIC, USGS, ESRI, Oklahoma Geological Survey, Oklahoma Corporation Commission

Map printed by J. Hollenbach 12/8/2015

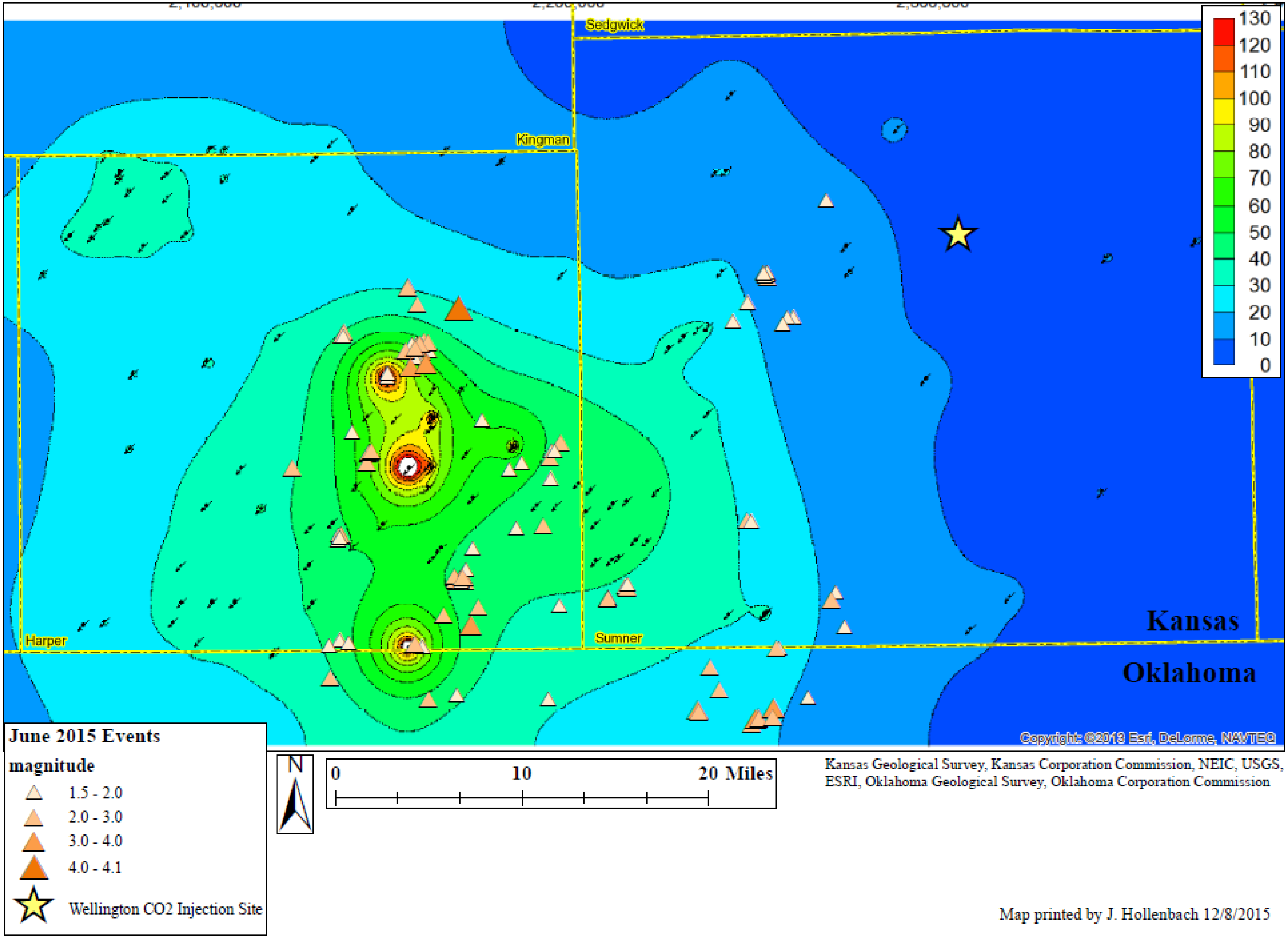
April 2015 Delta Pressure (psi)

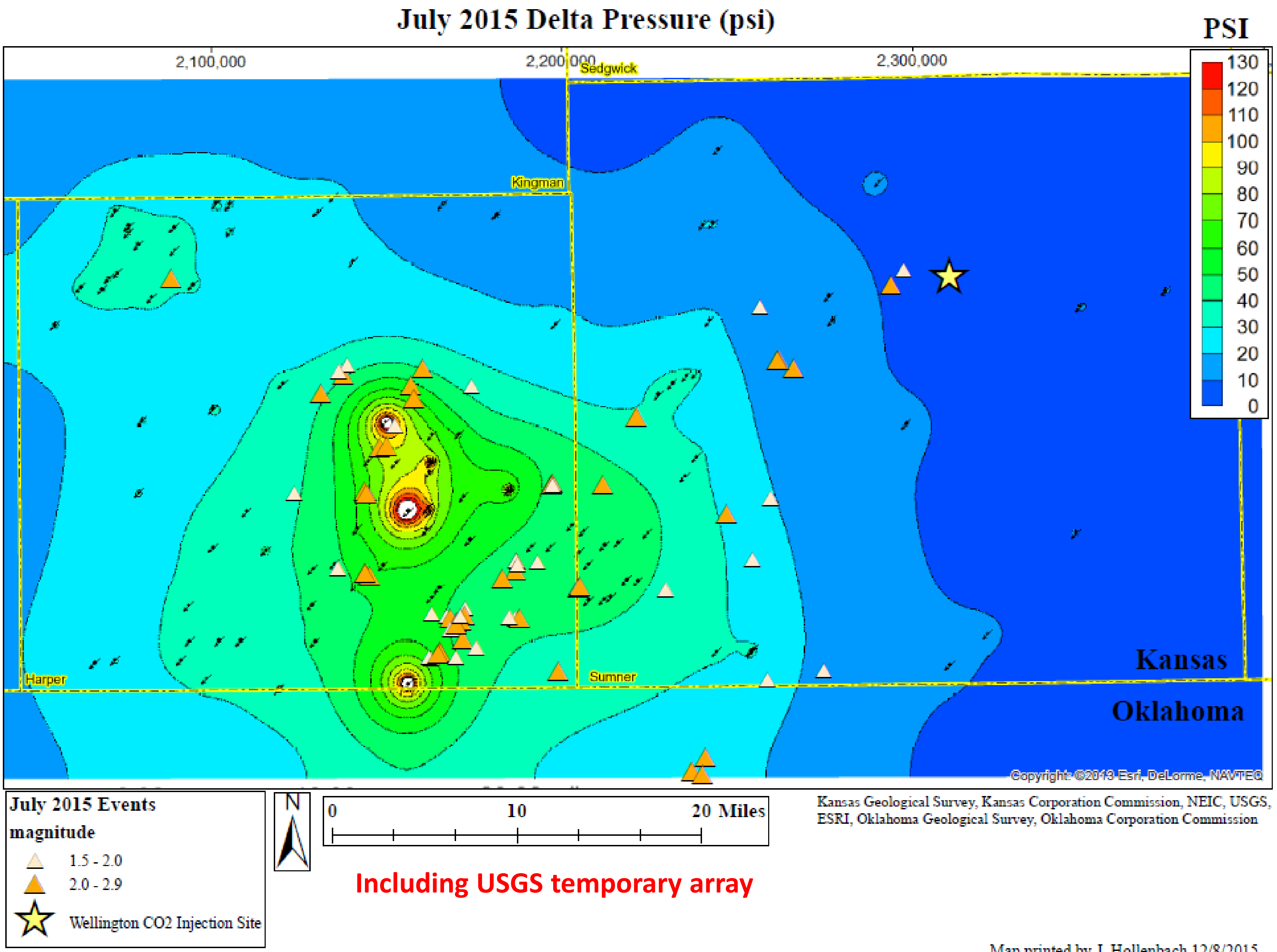


May 2015 Delta Pressure (psi)



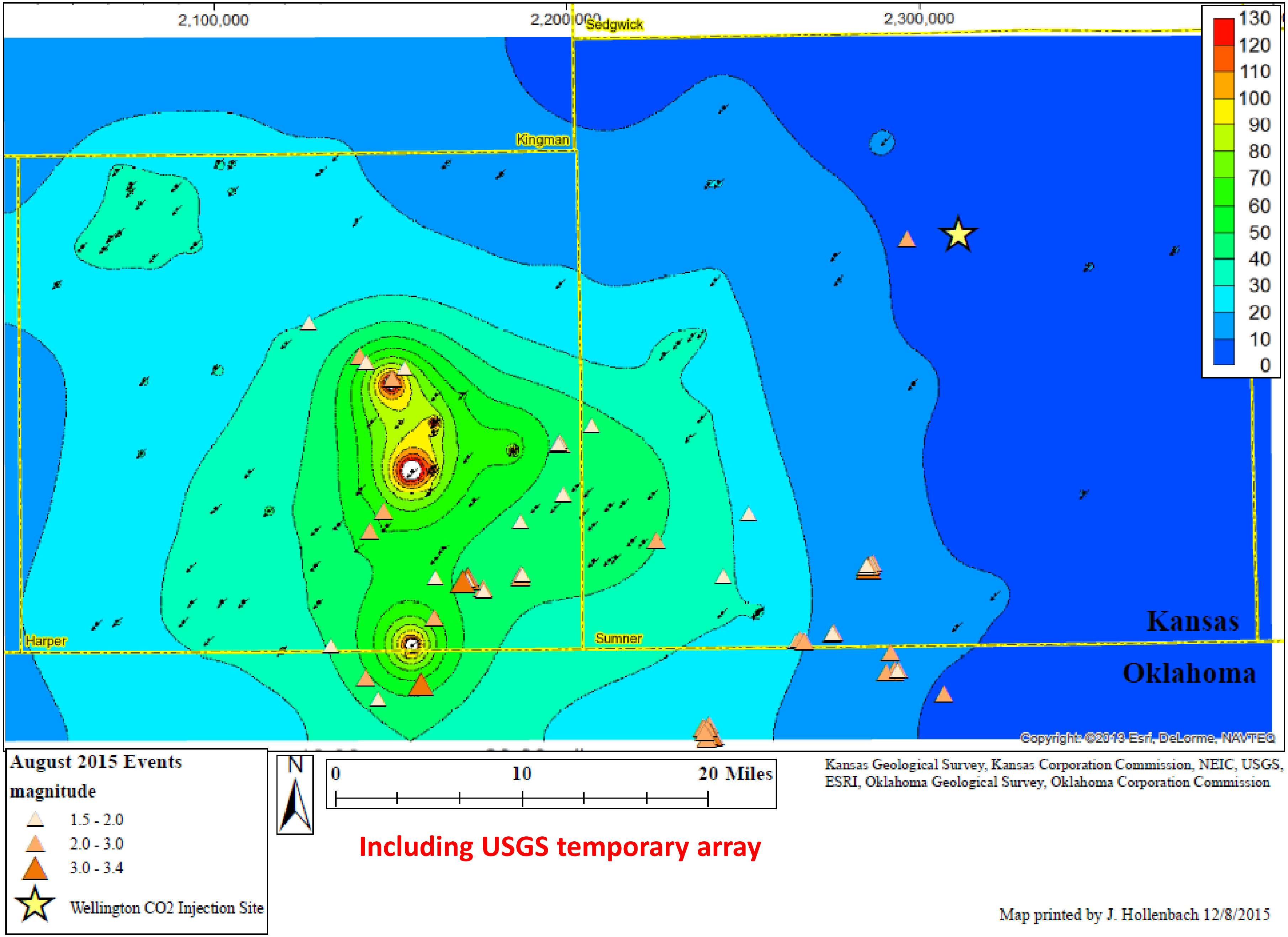
June 2015 Delta Pressure (psi)





Including USGS temporary array

August 2015 Delta Pressure (psi)

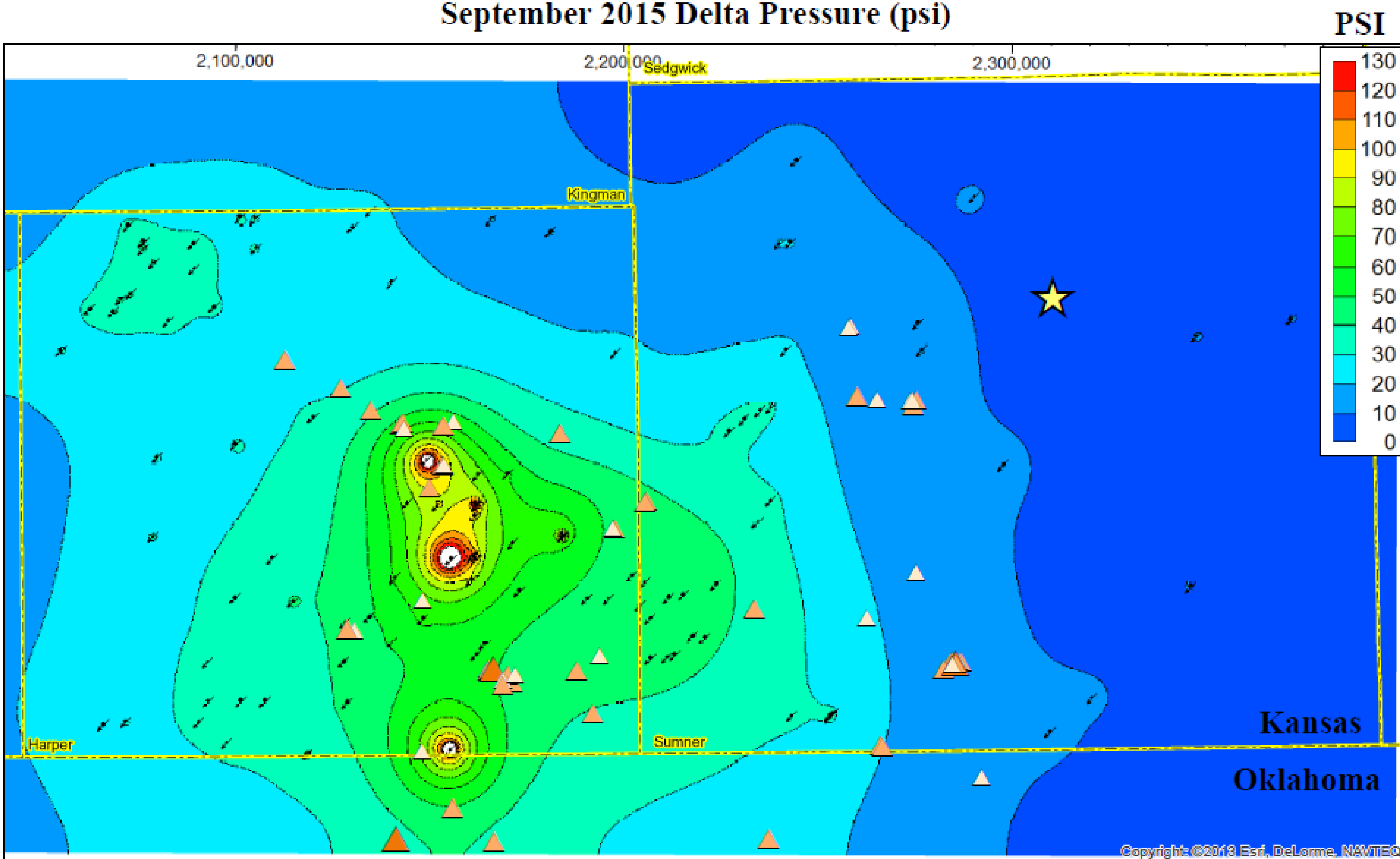


Kansas Geological Survey, Kansas Corporation Commission, NEIC, USGS, ESRI, Oklahoma Geological Survey, Oklahoma Corporation Commission

Including USGS temporary array

Map printed by J. Hollenbach 12/8/2015

September 2015 Delta Pressure (psi)



September 2015 Events magnitude

- 1.6 - 2.0
- 2.0 - 3.0
- 3.0 - 3.4
- Wellington CO2 Injection Site

N

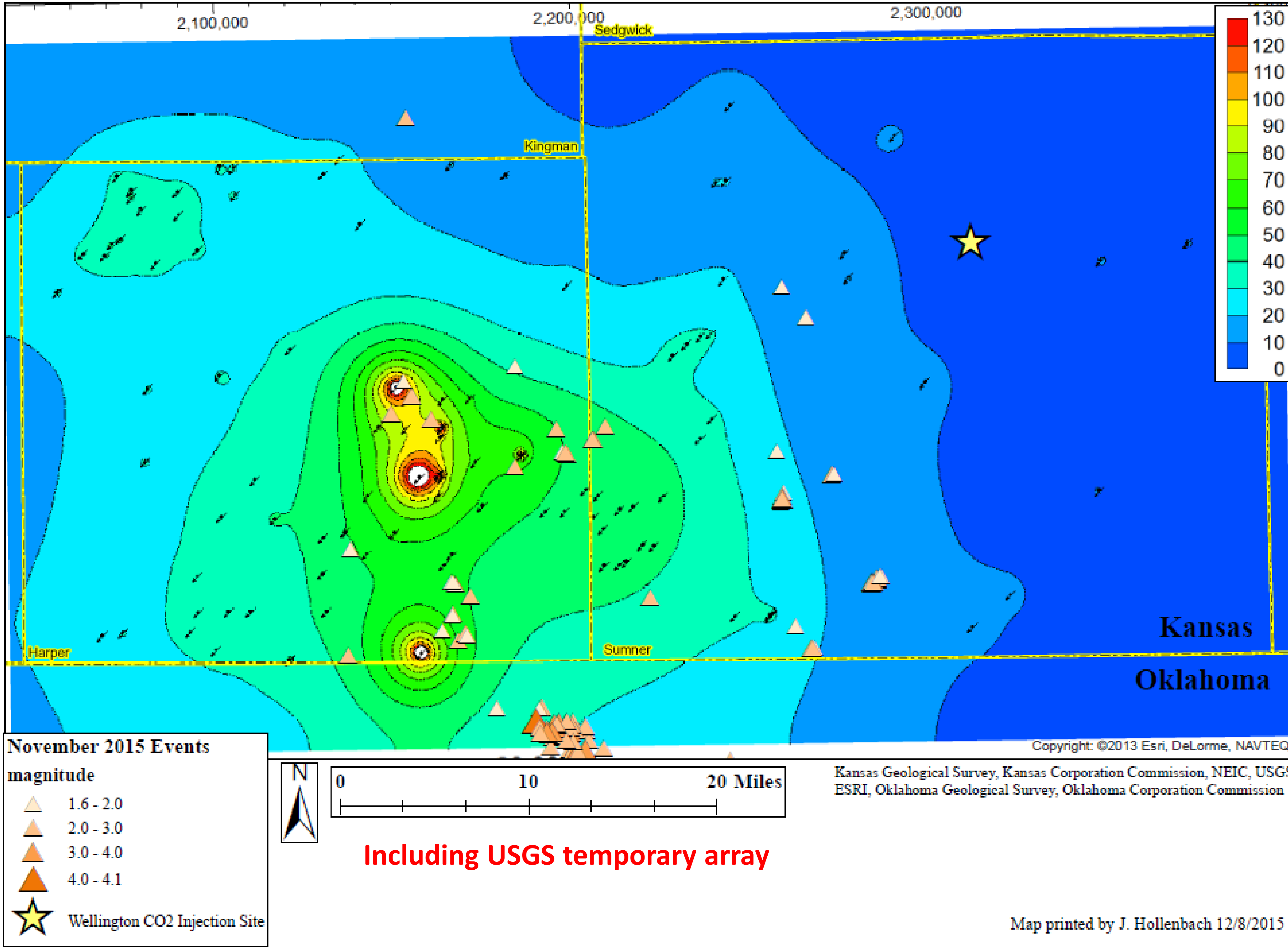
0 10 20 Miles

Kansas Geological Survey, Kansas Corporation Commission, NEIC, USGS, ESRI, Oklahoma Geological Survey, Oklahoma Corporation Commission

Including USGS temporary array

Map printed by J. Hollenbach 12/8/2015

November 2015 Delta Pressure (psi)

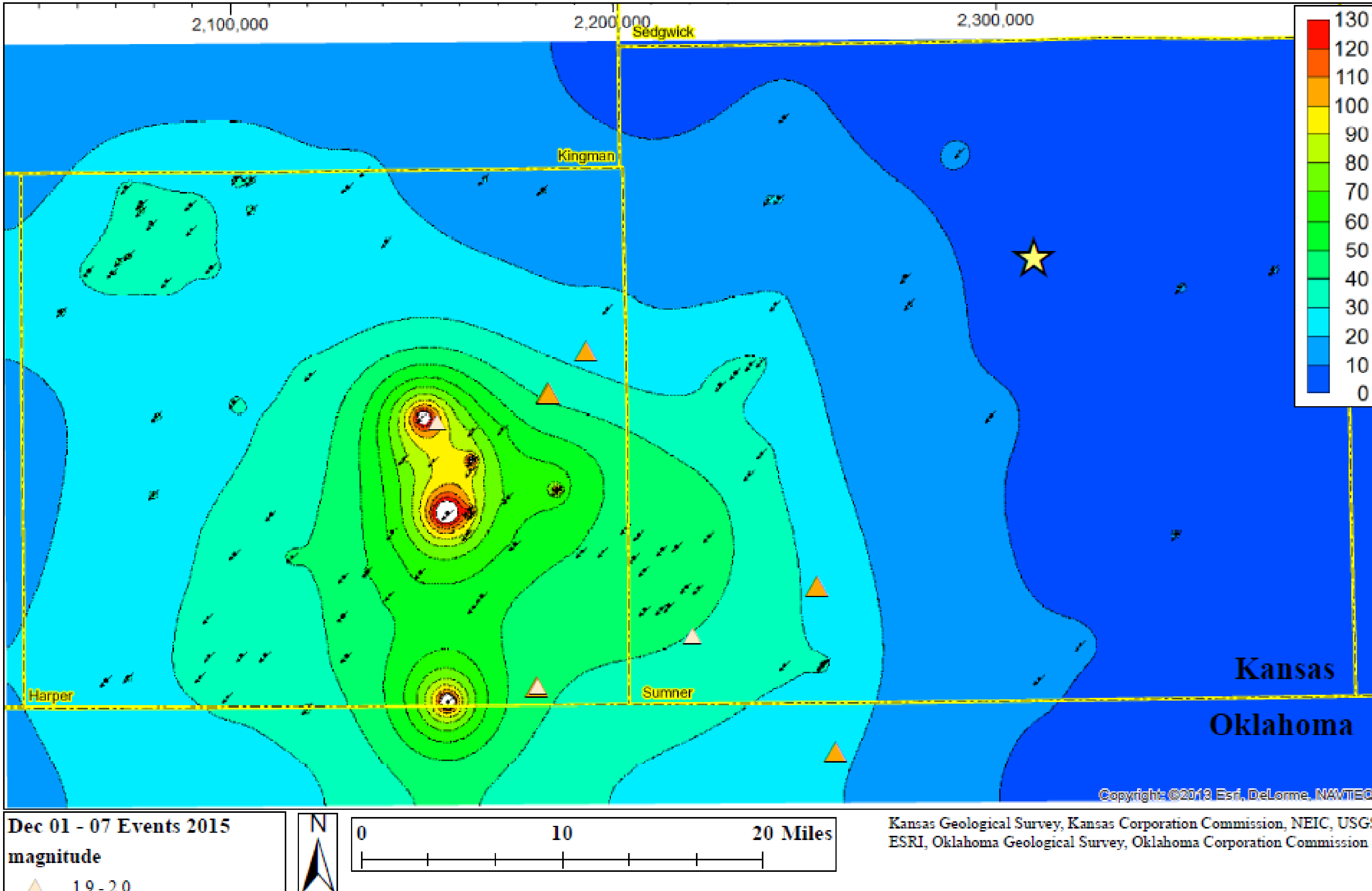


Kansas Geological Survey, Kansas Corporation Commission, NEIC, USGS, ESRI, Oklahoma Geological Survey, Oklahoma Corporation Commission

Including USGS temporary array

Map printed by J. Hollenbach 12/8/2015

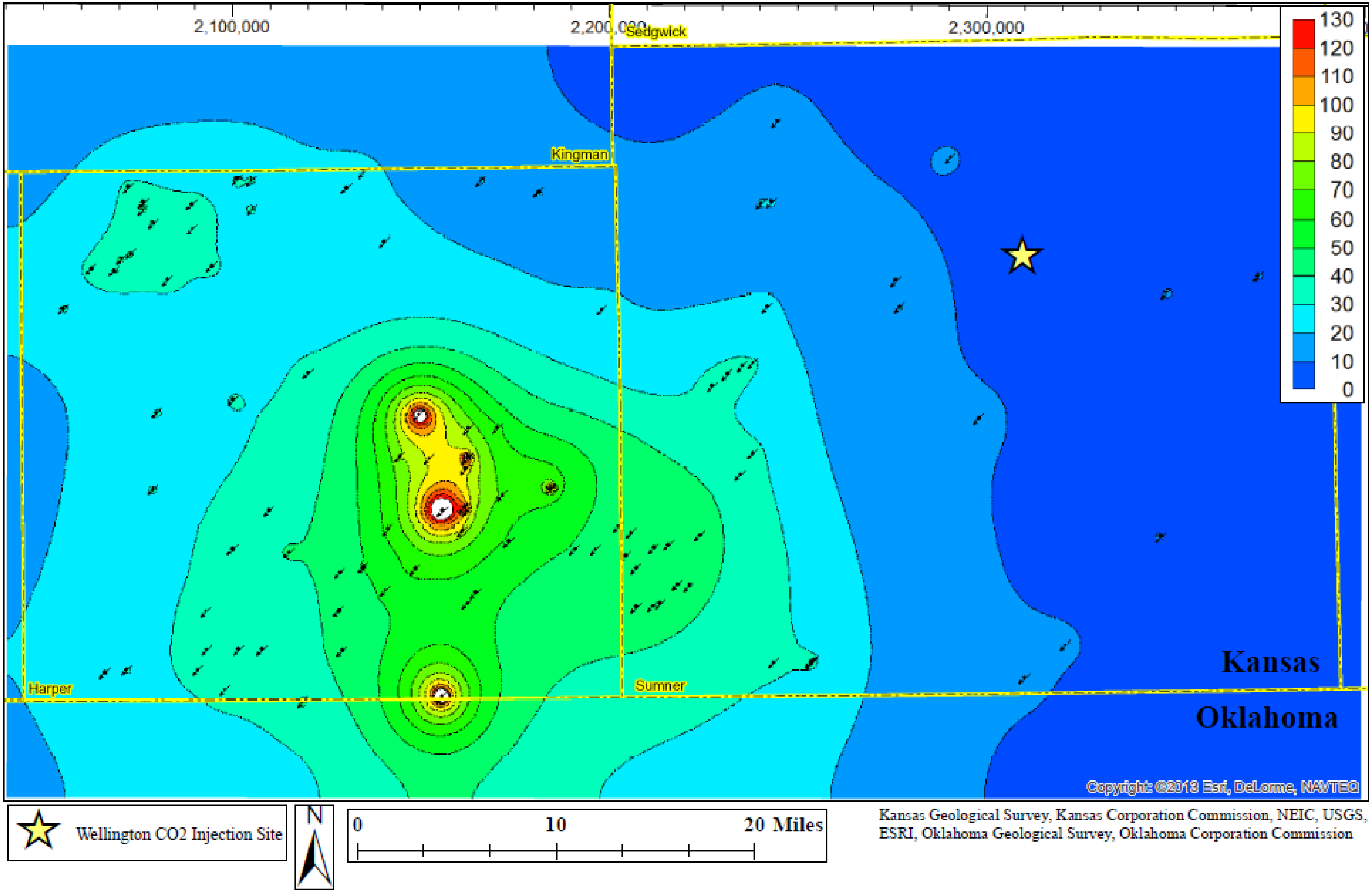
December 2015 Delta Pressure (psi)



Including USGS temporary array

Map printed by J. Hollenbach 12/8/2015

January 2016 - Projected Delta Pressure (psi)



Kansas Geological Survey, Kansas Corporation Commission, NEIC, USGS, ESRI, Oklahoma Geological Survey, Oklahoma Corporation Commission

Map printed by J. Hollenbach 12/8/2015

Summary of Arbuckle characterization and simulation

- Arbuckle is not created equal everywhere and should not be treated this way
- Fluid movement is constrained primarily by permeability (including fractures and faults) and, therefore, vague assumptions are not good enough
  - Compare analog of Empire State Building, 1250 ft tall similar to thickness of the Arbuckle
  - Actual volume in the Arbuckle that has injectable pore space is not 100% of the interval, rather ~30% due to stratabound fractures and matrix permeability
- Geomechanics is a next step

Summary of earthquake monitoring, fault modeling, and basement characterization

1. **Basement faults that are likely critically stressed are current targets of interest** →orientation of faults (NE-SW) are conductive to be activated at relatively low pressures.
2. **Northward migration of earthquakes in south-central Kansas and north-central Oklahoma** → indications of regional fluid or pressure movement along basement faults.
3. **Localized earthquake clustering and aftershocks** → identifying fault zones to be further refined by integration of seismology, geophysics, and geology.
4. **Latest large-scale movement along faults ended in Late Paleozoic followed by smaller, episodic movement** →leading to proportionally small offset and also draping at shallower depths above tips of fault.
5. **Working hypothesis for induced seismicity** → Limited storage and transmissivity in Arbuckle saline aquifer that can be exceeded leading to 1) far-field pressurization and 2) leakage into the basement where faults can be critically stressed.

Continuing and future research

1. Evaluate earthquake source and mechanisms, spatial and temporal patterns, and use to refine locations and properties of active faults.
2. Refine static and dynamic models of the Arbuckle in areas affected by increased seismicity.
3. Update maps of Precambrian basement terrain and validate lineaments and inferred faults.
4. Continue to explore means to reduce amounts of produced water in the MLP and develop best practices for brine disposal and improve well performance.
5. Utilize extensive operational plan with ongoing testing and monitoring to insure safe CO_2 injection at Wellington field and provide lessons learned for stakeholders.

Acknowledgements & Disclaimer

Acknowledgements

- *The work partially supported by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) under Grant DE-FE0002056 and DE-FE0006821, managed and administered by the Kansas Geological Survey/KUCR at the University of Kansas and funded by DOE/NETL and cost-sharing partners*