Integrating Modern Suite of Geophysical Logs, Geochemistry, and Seismic Data for Characterizing Deep Aquifers

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Tools, Techniques and Methods
Thursday, May 8, 2014: 1:20 p.m. -1:40

Outline

- Lower Ordovician Arbuckle Group saline aquifer in Kansas for $scCO_2$ storage
- Comprehensive log suites and full diameter core data from two anchoring wells (790 m in length)
- 3-D seismic (~400 km^2) from 5 oil fields; 65 km2 newly aquired multicomponent (*converted shear wave*)
- Arbuckle – Distinct, and at least locally, isolated hyrostratigraphic units
  - defined by petrophysics, geochemistry, and geomicrobiology
- Independent, multi-scale estimates important in defining effective porosity, permeability (kv & kh), and capillary pressure
- Flow Zone Interval (*FZI*), Reservoir Quality Index (*RQI*), and Neural Network used to establish petrophysical correlation to lithofacies and model permeability and capillary pressure for regional storage assessment

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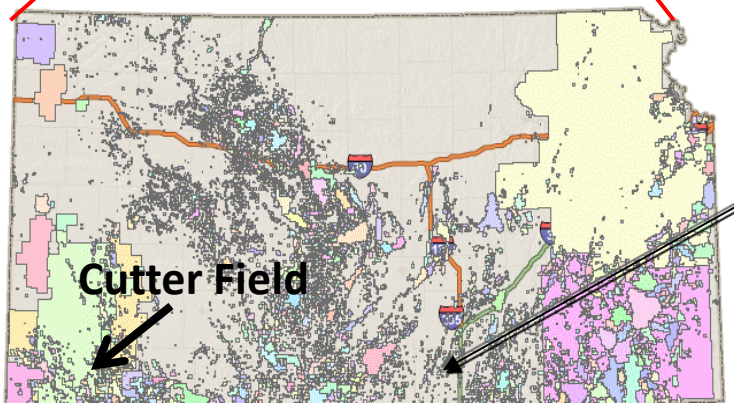
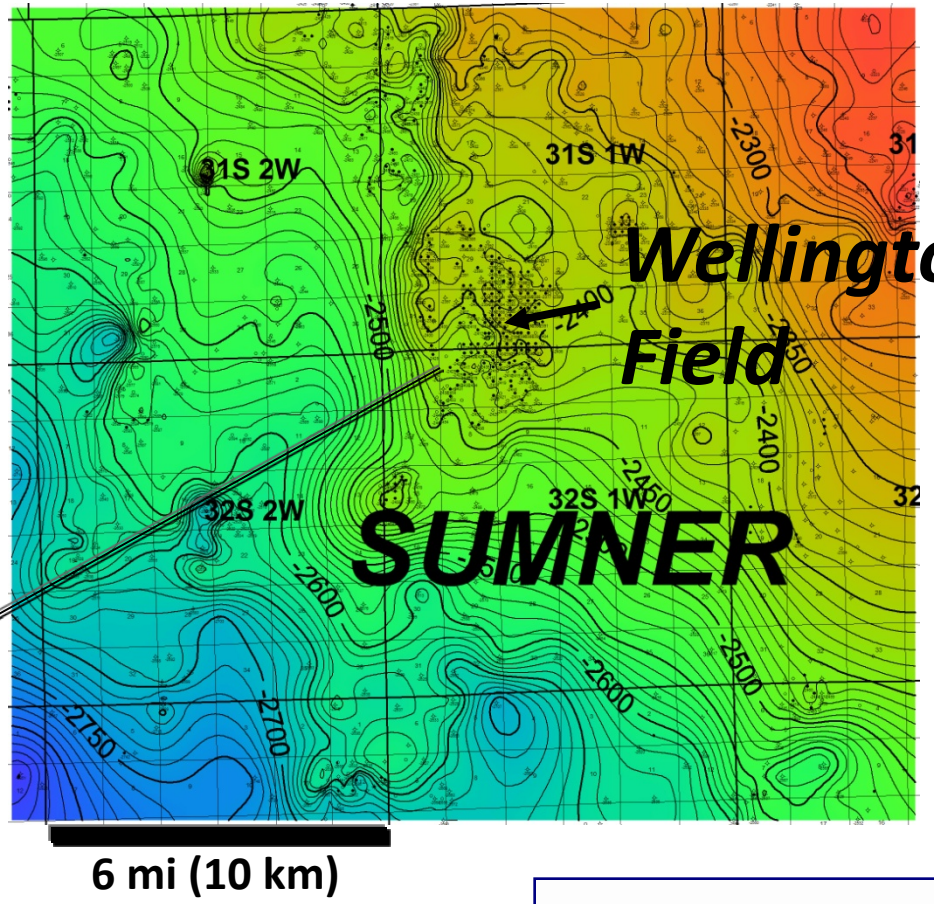
The study is a collaboration, multi-disciplinary effort between the KGS, Geology Departments at Kansas State University and The University of Kansas, BEREXCO, INC., Bittersweet Energy, Inc. Hedke-Saenger Geoscience, Ltd., Improved Hydrocarbon Recovery (IHR), Anadarko, Cimarex, Merit Energy, GloriOil, Dawson-Markwell Exploration, and Noble Energy.

Wellington Field

Site of Proposed Small Scale Field Test



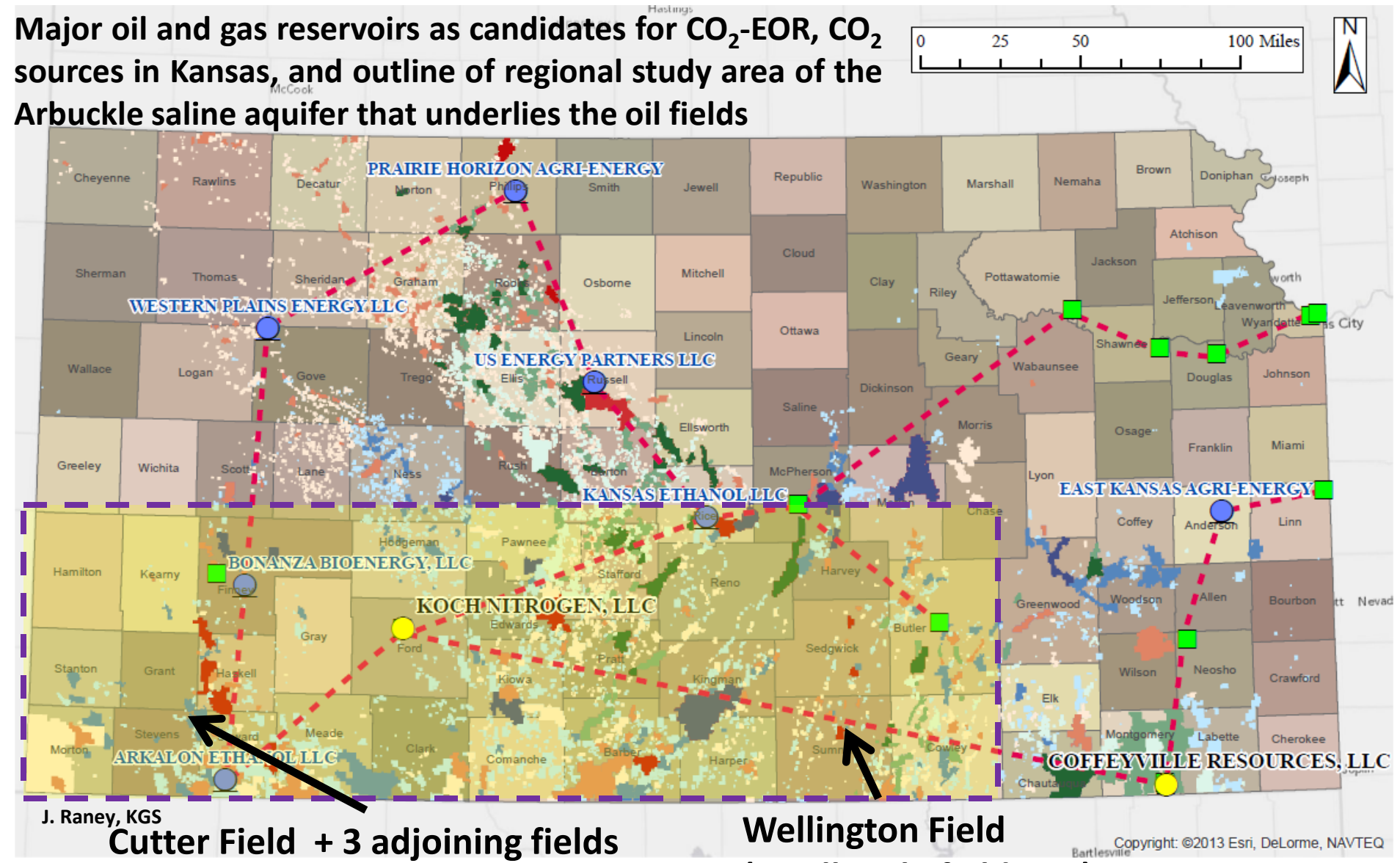
Top Mississippian Structure, 10 ft C.I.



20 MM Barrel Oil Field above Arbuckle Group

KANSAS GEOLOGICAL SURVEY
The University of Kansas

Major oil and gas reservoirs as candidates for CO_2-EOR, CO_2 sources in Kansas, and outline of regional study area of the Arbuckle saline aquifer that underlies the oil fields



J. Raney, KGS

Cutter Field + 3 adjoining fields

Wellington Field (small scale field test)

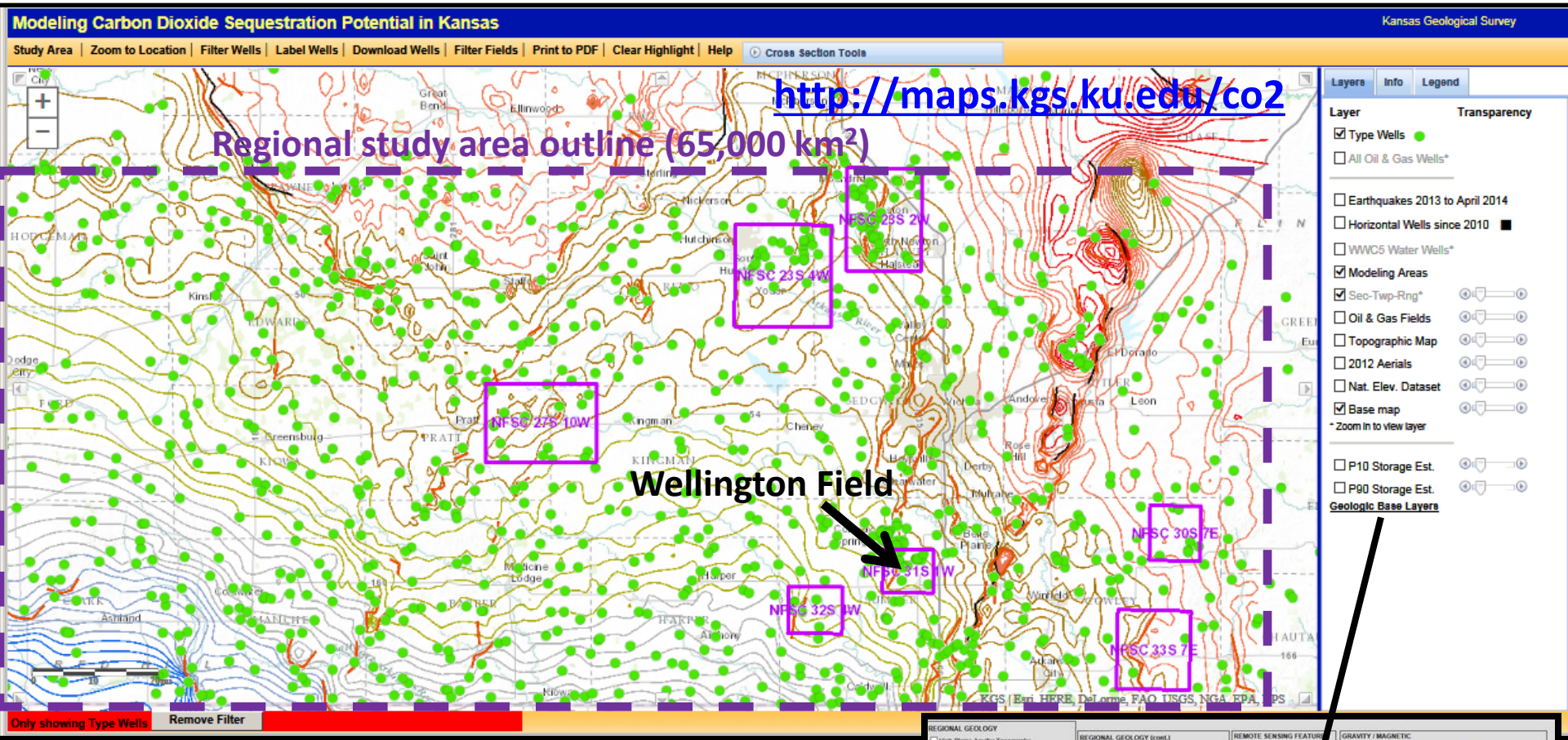
Cummulative Oil Produced (as of 2013)

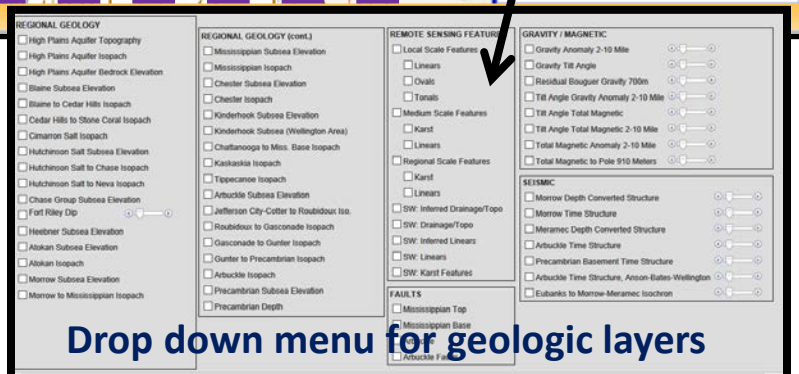
Source: USGS, Kansas Geological Survey, DASC

Arbuckle Fields	Lansing-KC Fields	Mississippian Fields
0 - 1,000,000 bbls	0 - 1,000,000 bbls	0 - 1,000,000 bbls
1,000,000 - 10,000,000	1,000,000 - 10,000,000	1,000,000 - 10,000,000
10,000,000 - 100,000,000	10,000,000 - 100,000,000	10,000,000 - 100,000,000

- Ammonia Plant
- Ethanol Plant
- 500,000+ tonnes CO2 emmitted in 2011
- Potential CO2 Pipeline Network

Digital type wells used to archive well information including stratigraphic correlations, geologic reports



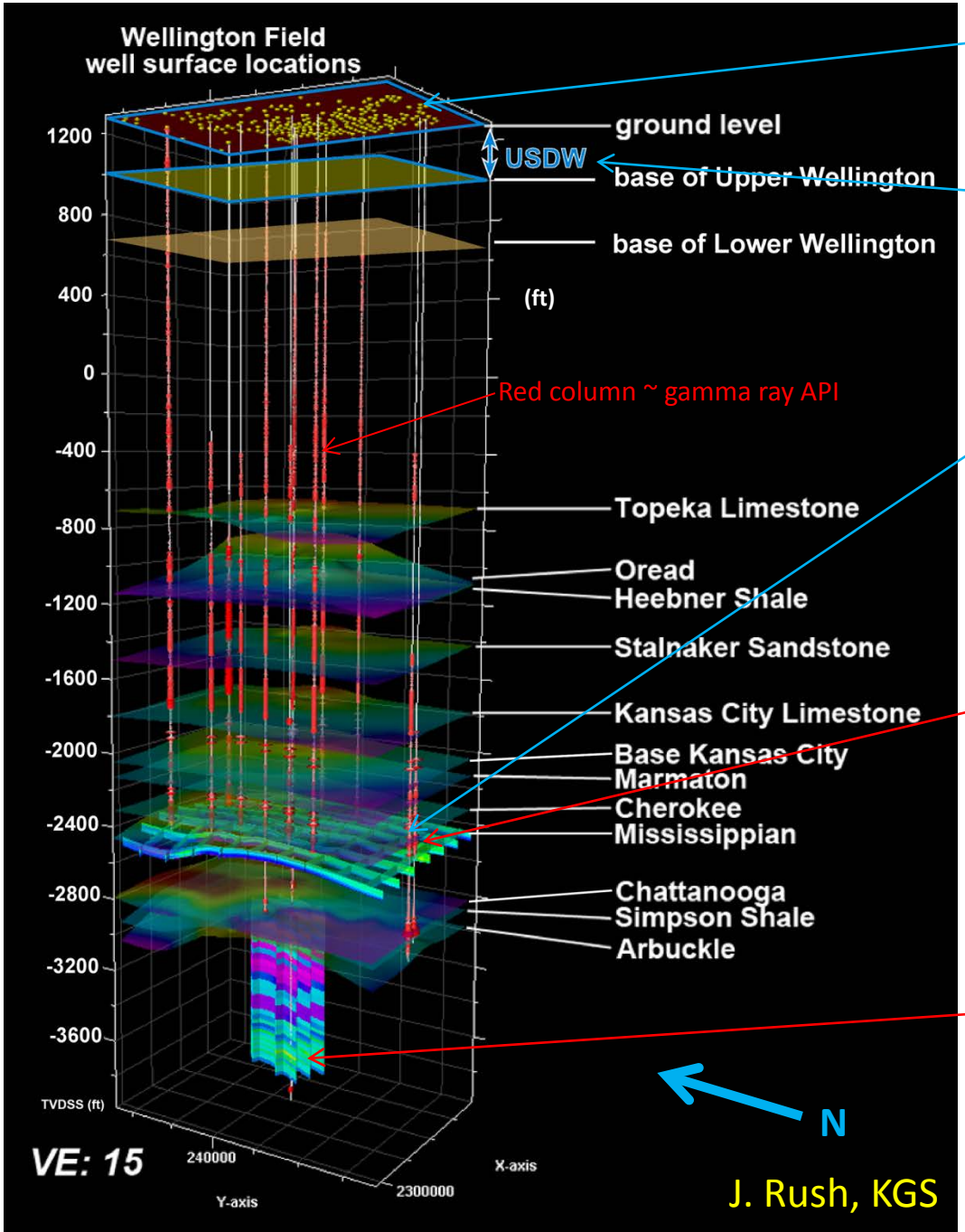


Drop down menu for geologic layers

- Type Wells
- Faults cutting top Arbuckle
- Contours – Top Arbuckle Structure (*100 ft contour interval*)
- Simulation sites for commercial storage eval

30 km

CO2-EOR & Saline Injection, Wellington Field



- InSAR & CGPS
  → surface deformation
- IRIS seismometers & 3C accelerometers

- Tracers to detect injected CO_2
- Monitor ~600 ft deep well below shallow evaporite cap rock

- Test for CO_2 in Mississippian wells
  (*Underpressured oil reservoir should trap any vertically migrating CO_2*)

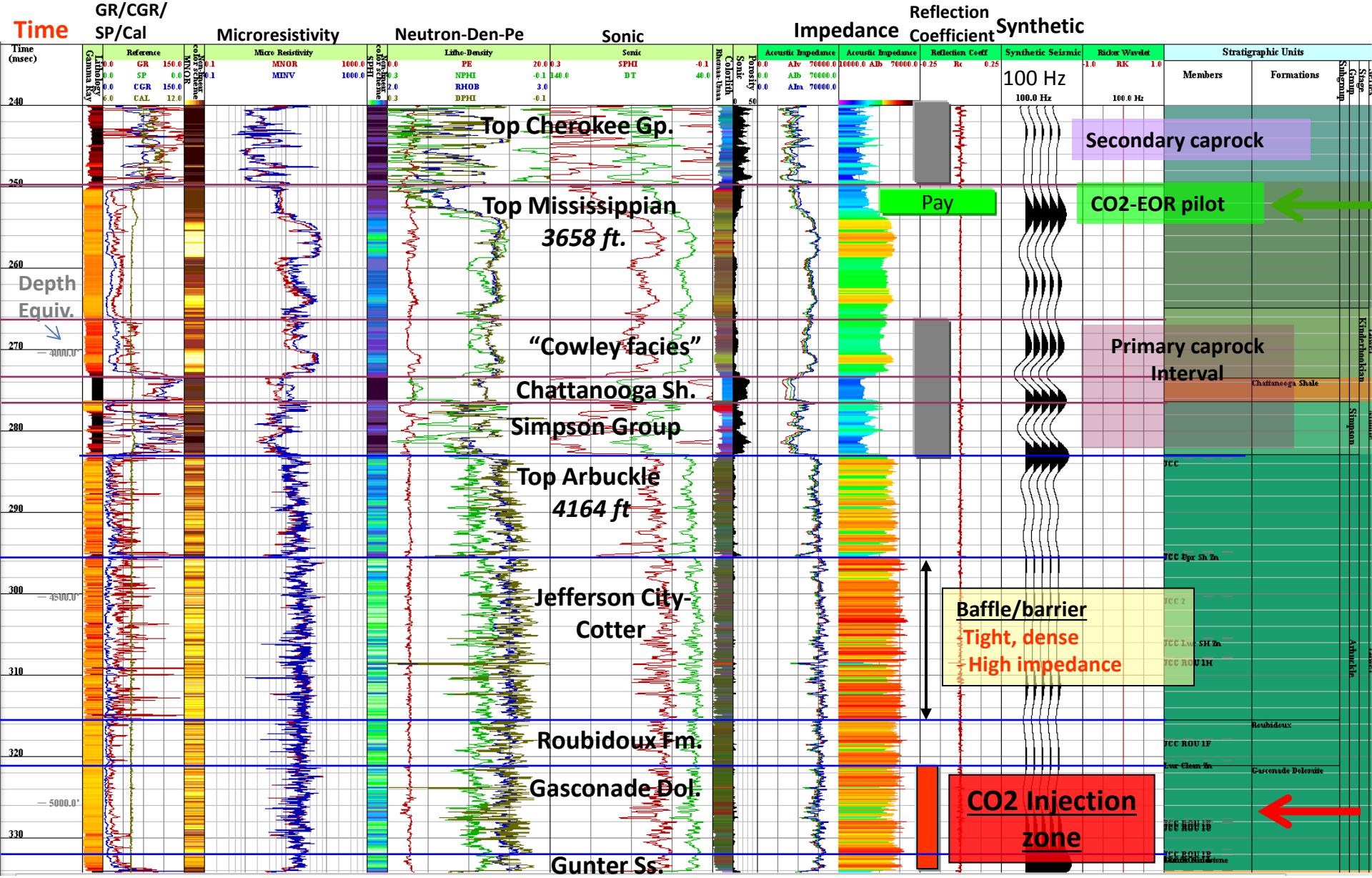
Inject 28,000 tonnes of CO_2 into Mississippian oil reservoir to demonstrate CO_2-EOR and 99% assurance of storage with MVA

Pending Class VI permit and DOE funding -- Inject up to ~40,000 tonnes of CO_2

- U-Tube, CASSM and cross hole seismic
- DTS & acoustic fiber optics (long string fiber pending)

CO_2 Injection Zones in Arbuckle and Mississippian

Wellington Field KGS #1-28 --- Synthetic seismogram and seismic impedance (density x velocity)

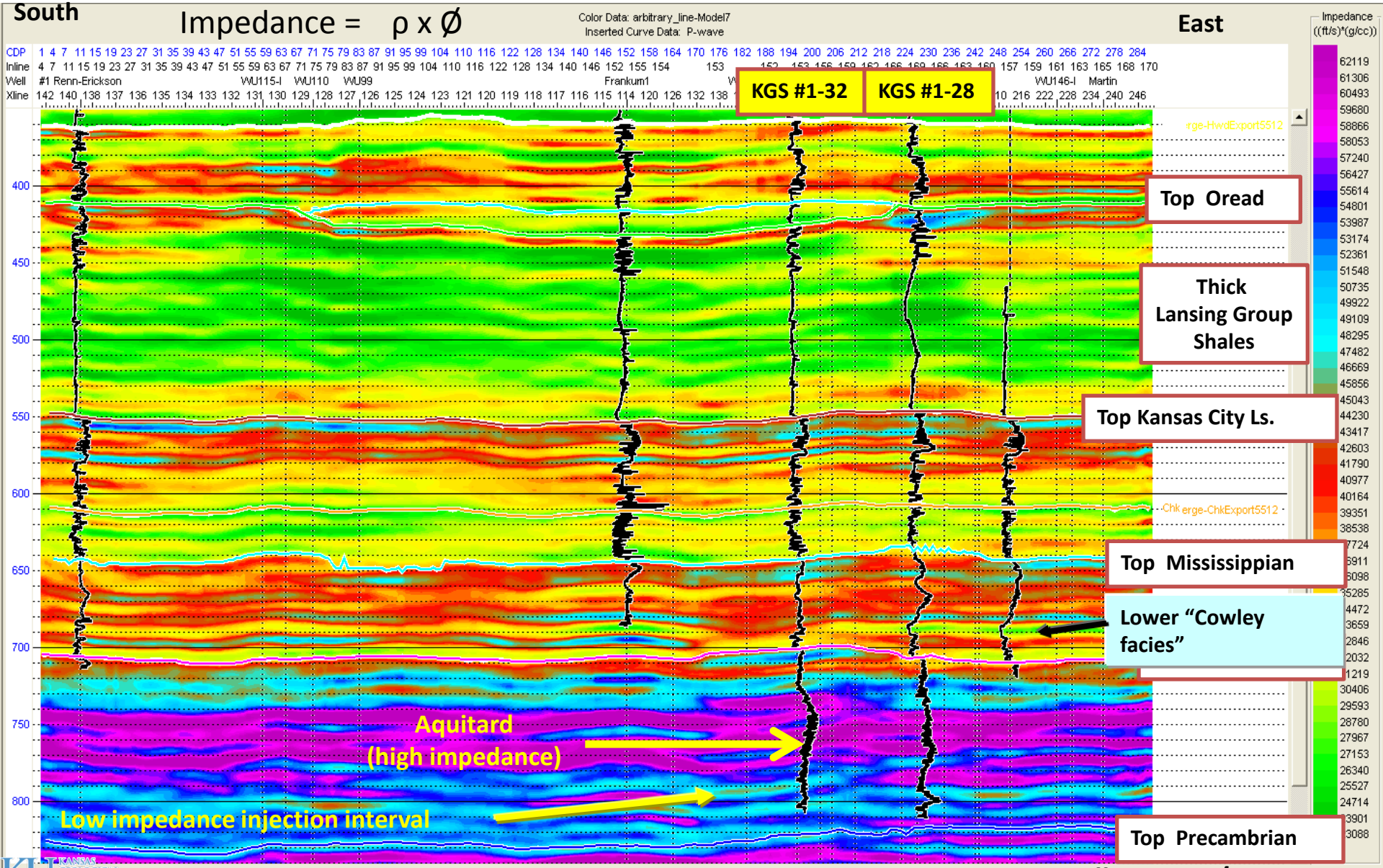


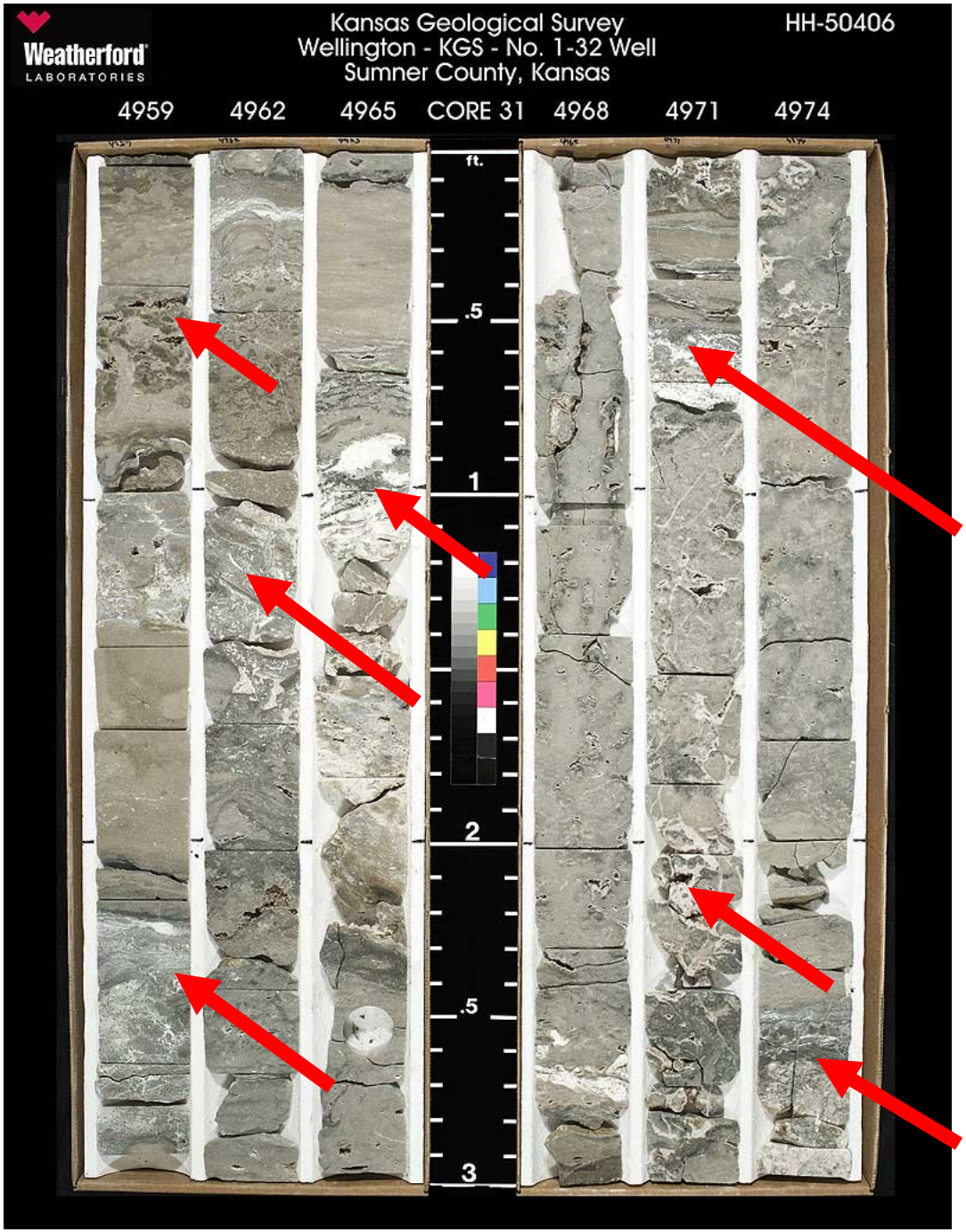
Proterozoic granite – bottom of core = *5174 ft (1600 m)*

Java App: http://www.kgs.ku.edu/software/SS/

Arbitrary seismic impedance profile

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



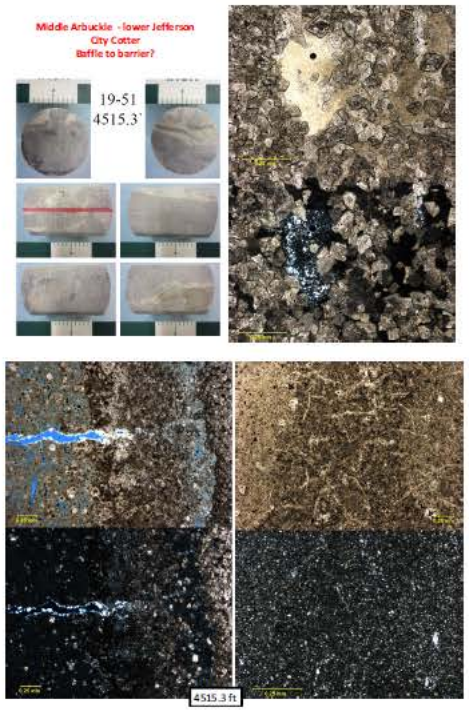


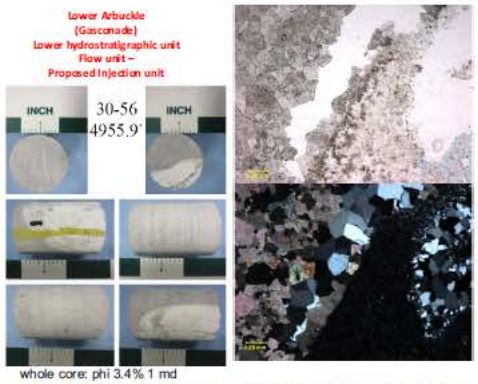
CO_2 injection zone in lower Arbuckle

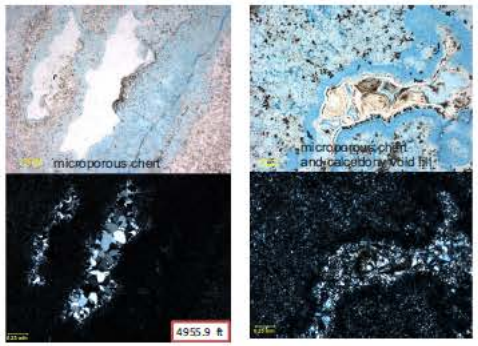
Thin, shallowing-upward peritidal cycles, topped with autoclastic/crackle breccias, silicified in places

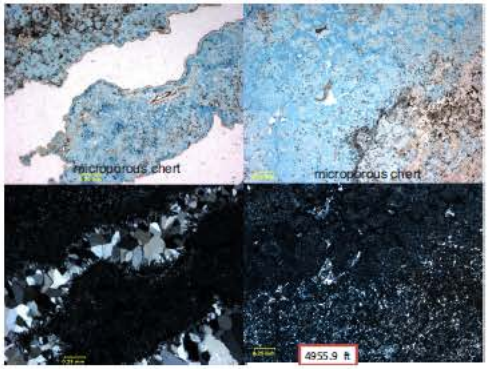
The sealing strata (aquitard/baffle) in the middle of the Arbuckle

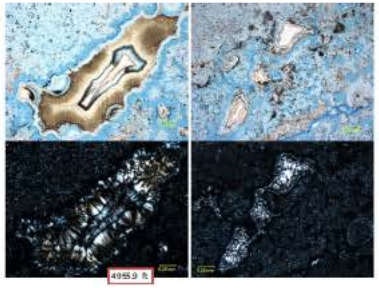
Thin Sections – Baffle Zone (Mid Arb.)



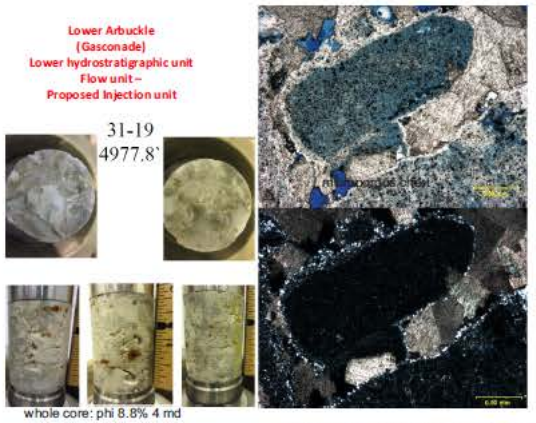


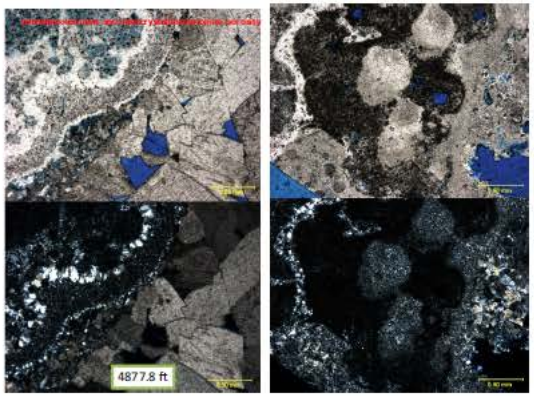


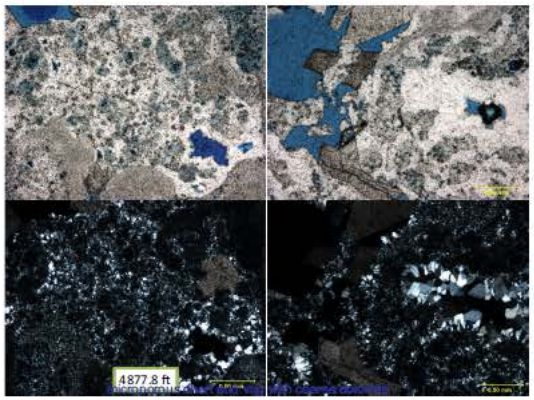




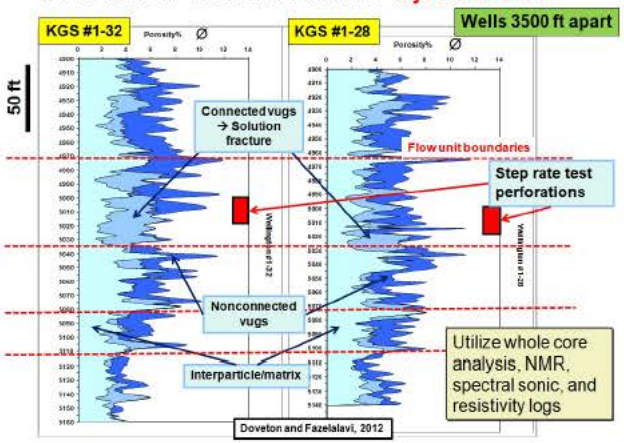
Lower Arbuckle Injection Zone





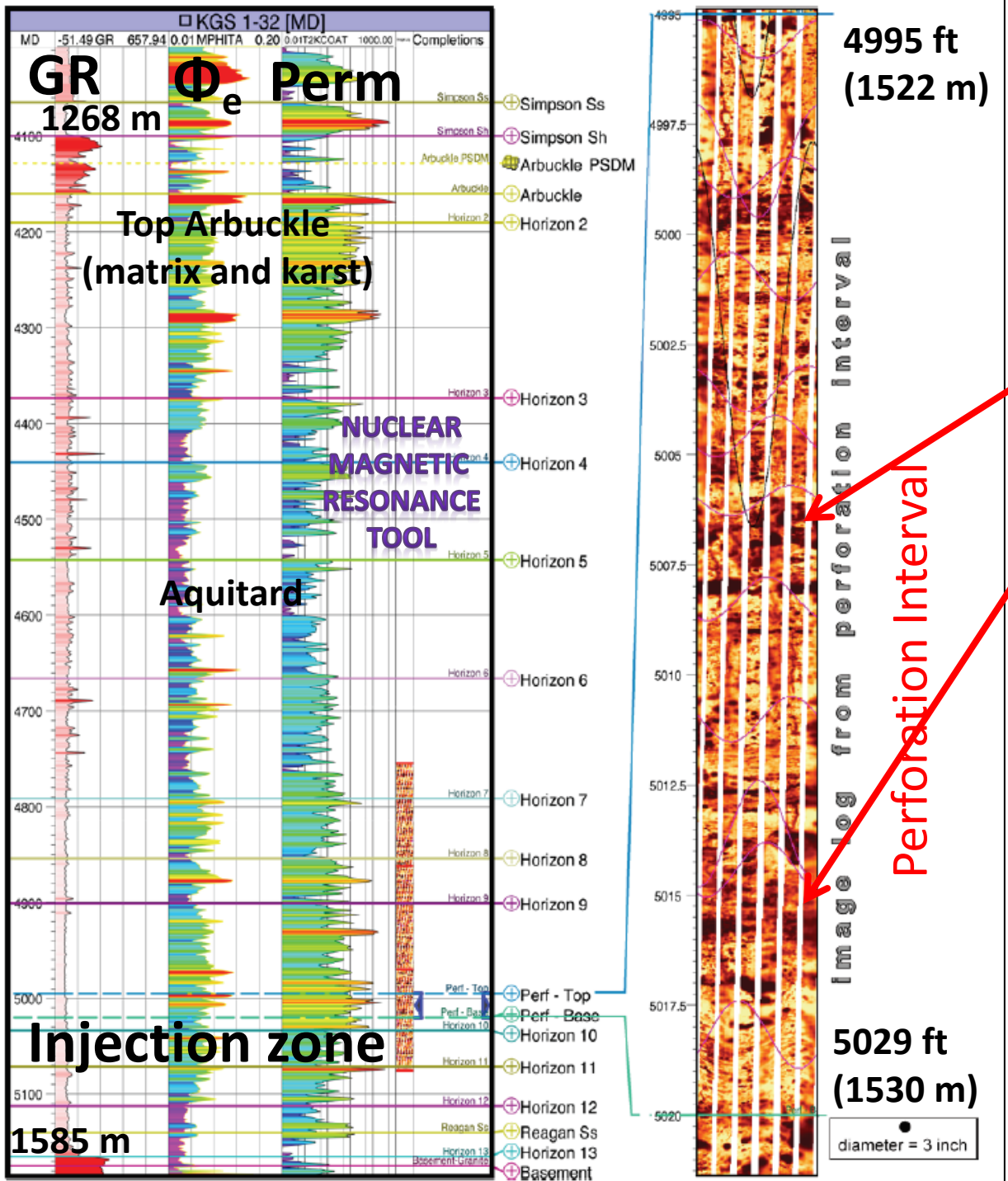


Flow units in the lower Arbuckle **injection zone**



Pairs of photomicrographs
Plane light and crossed nichols

R. Barker, S. Datta, KSU



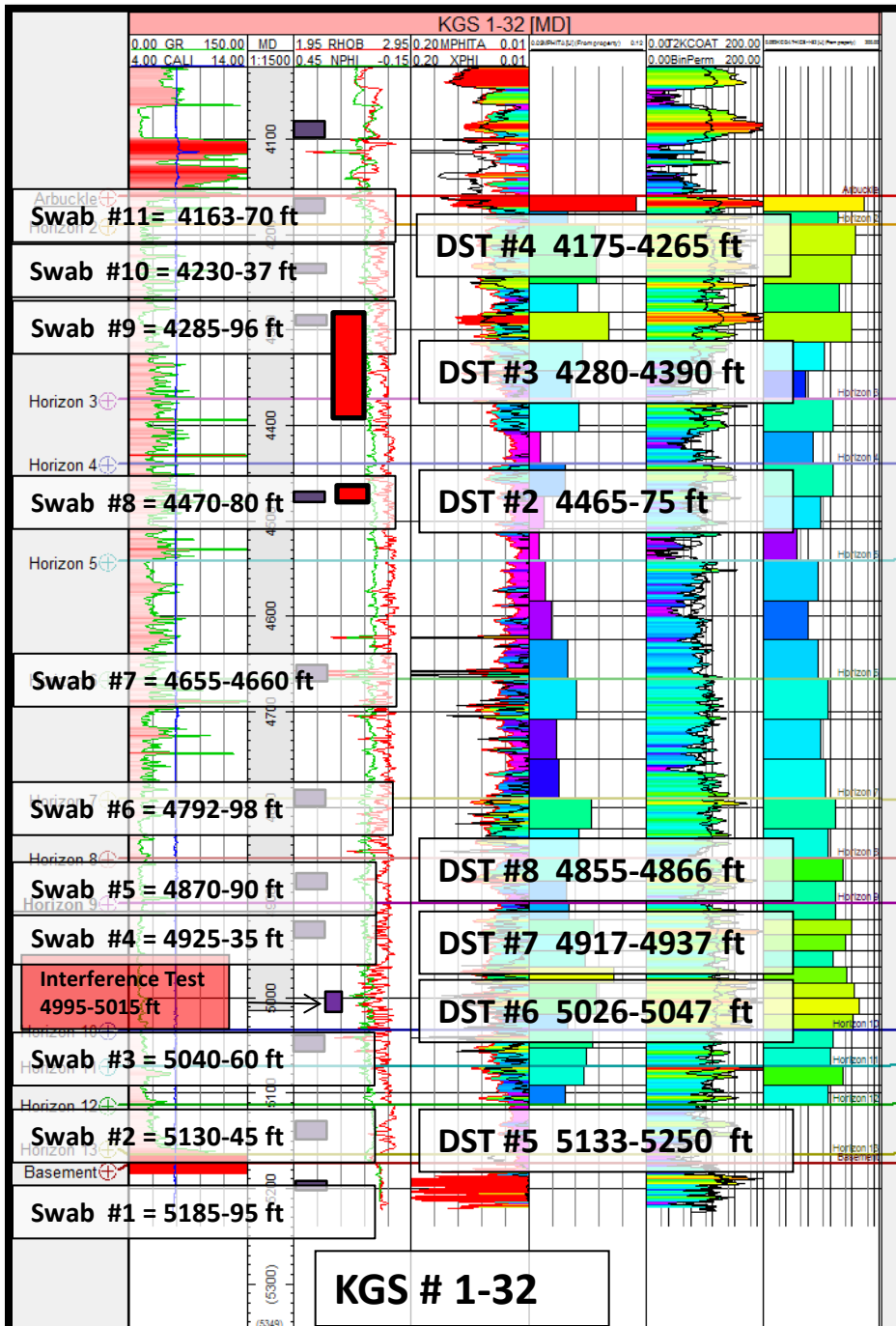
Crackle Breccia Common in Injection Zone (*dissolved evaporites*)

- **Gamma ray**
- **Halliburton derived effective porosity**
- **Coates Permeability from NMR**
- **Microresistivity imaging log (MRIL)**

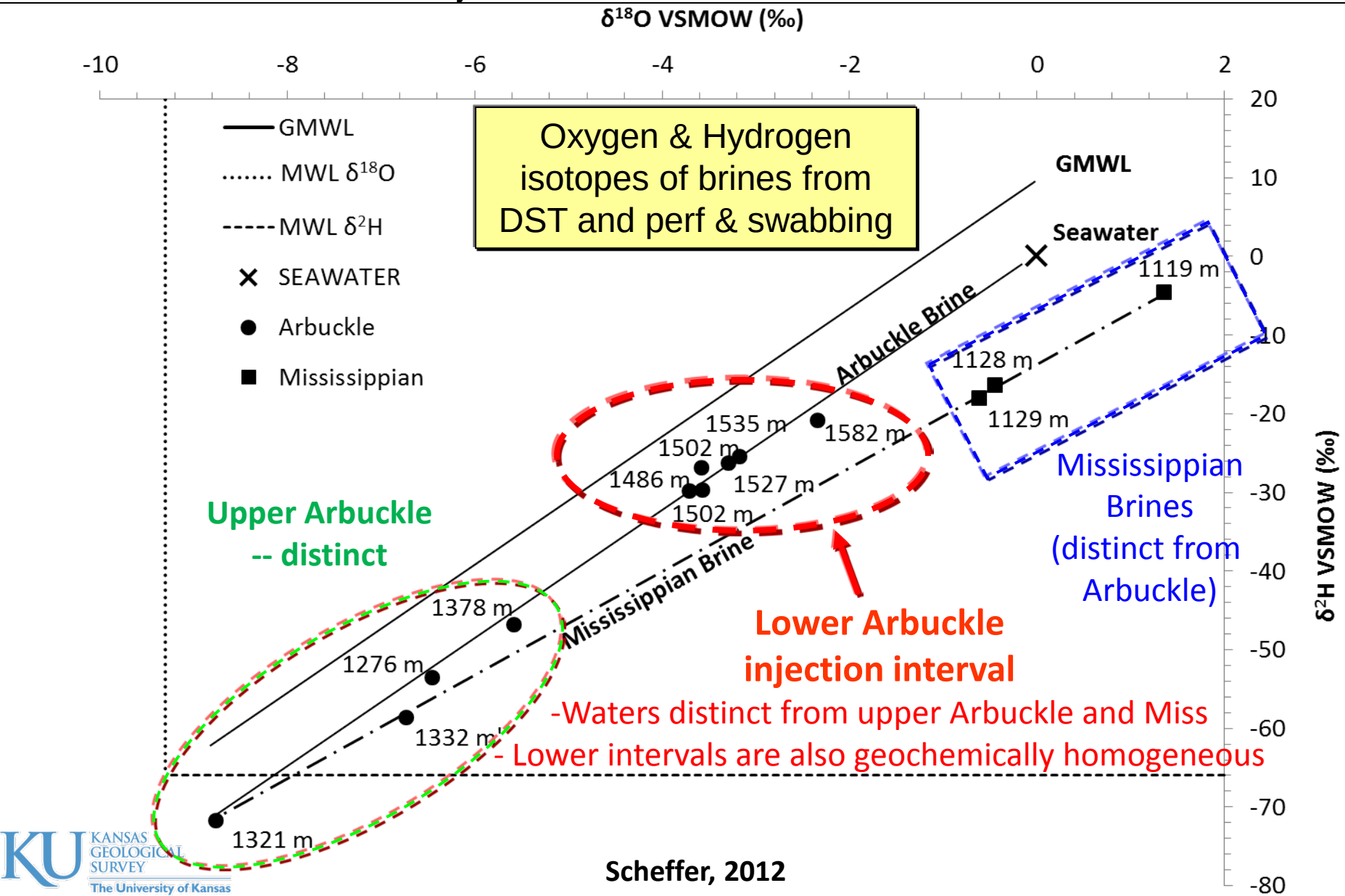
HALLIBURTON Schlumberger

Brine Samples – Wellington KGS 1-32 Perforation and Swabbing

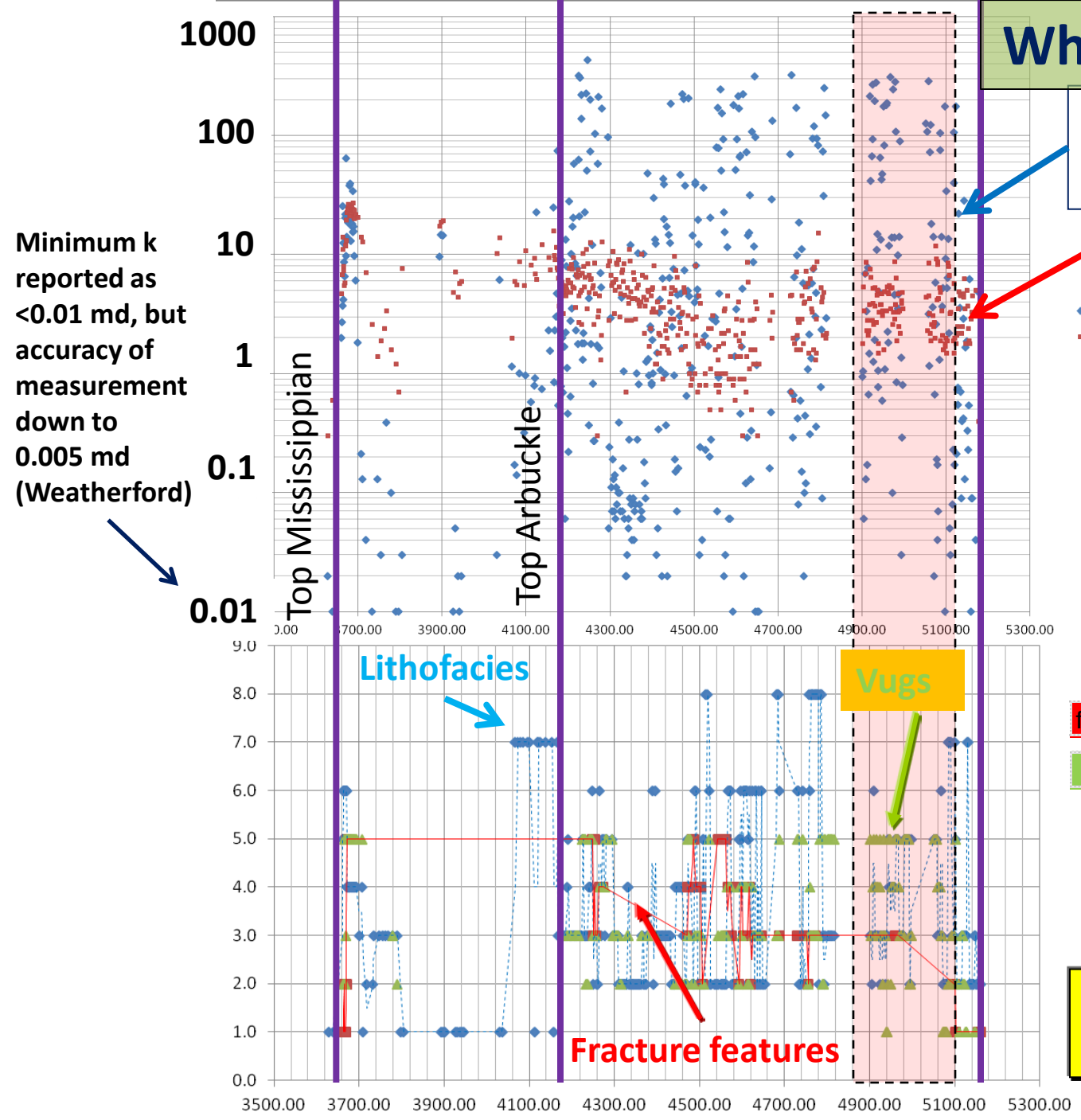
- 11 swabbing interval target specific tight and high porosity zones in Arbuckle
- Overlap of DSTs and swabbing for comparison
- Fluids collected, preserved and analyzed for:
  - Geochemistry
  - Microbiology
- Compared results between the two sampling events



Lower and Upper Arbuckle Are Not in Hydraulic Communication



Whole Core Analysis



Minimum k reported as <0.01 md, but accuracy of measurement down to 0.005 md (Weatherford)

Kmax
Ranges from 0.01 to 425 md (whole core)

Porosity –
predominately between 1-10%

◆ Kmax
■ POR

Shale = 1
Mudstone = 2
Packstone= 3
Grainstone = 4
Incipient breccia = 5
Breccia =6
Sandstone = 7
Microbialite = 8

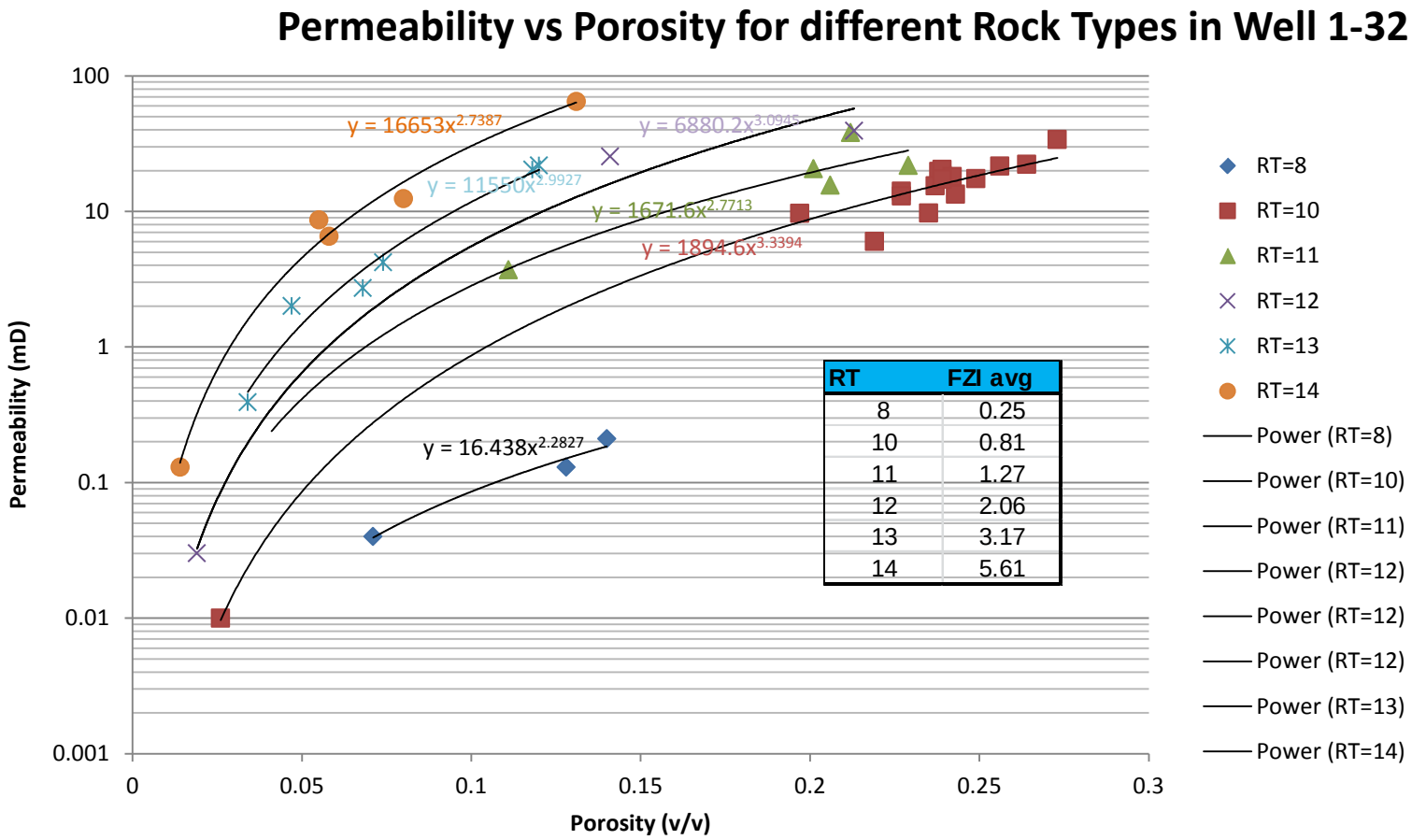
fractures (1-5, highest; 0, none)

Vugs (small to large, 1-5)

◆ Lithofacies
■ Fractures
▲ Vugs
2 per. Mov. Avg. (Lithofacies)
2 per. Mov. Avg. (Fractures)

KGS #1-32 whole core analysis ***N = 480***

Upper Mississippian Reservoir Porosity vs. Permeability Resolved by pore type



RT	FZI avg
8	0.25
10	0.81
11	1.27
12	2.06
13	3.17
14	5.61

Schlumberger

Techlog Wellbore Software Platform

M. Fazelalavi, KGS

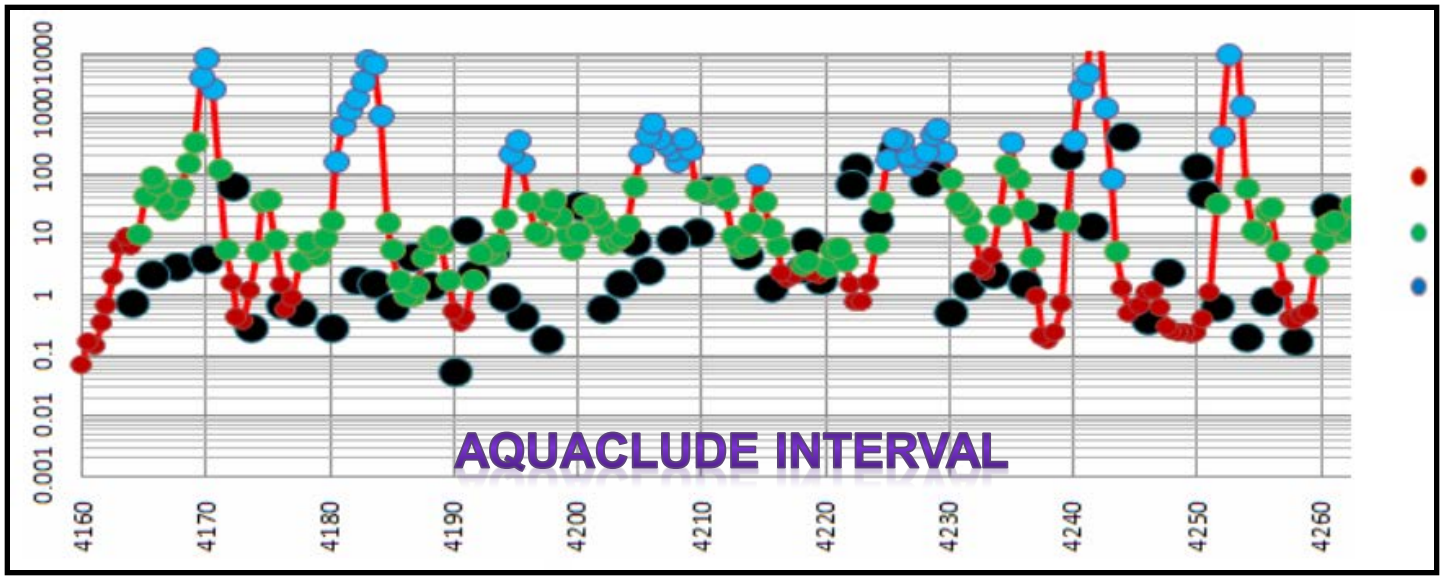
Improved permeability realization in the Arbuckle in Wellington anchor wells

- micro, meso, and mega groups defined in the Arbuckle
- based on core FZI & irreducible water saturation (from MRI)
- permeability computed from FZI value (Fazelalavi method)
  - FZI inversely proportional to surface area per grain volume (Sgv):
  - FZI should be inversely proportional to Swir and Φ_e

$$FZI = \sqrt{\frac{1}{F_s \tau^2 S_{gv}^2}}$$

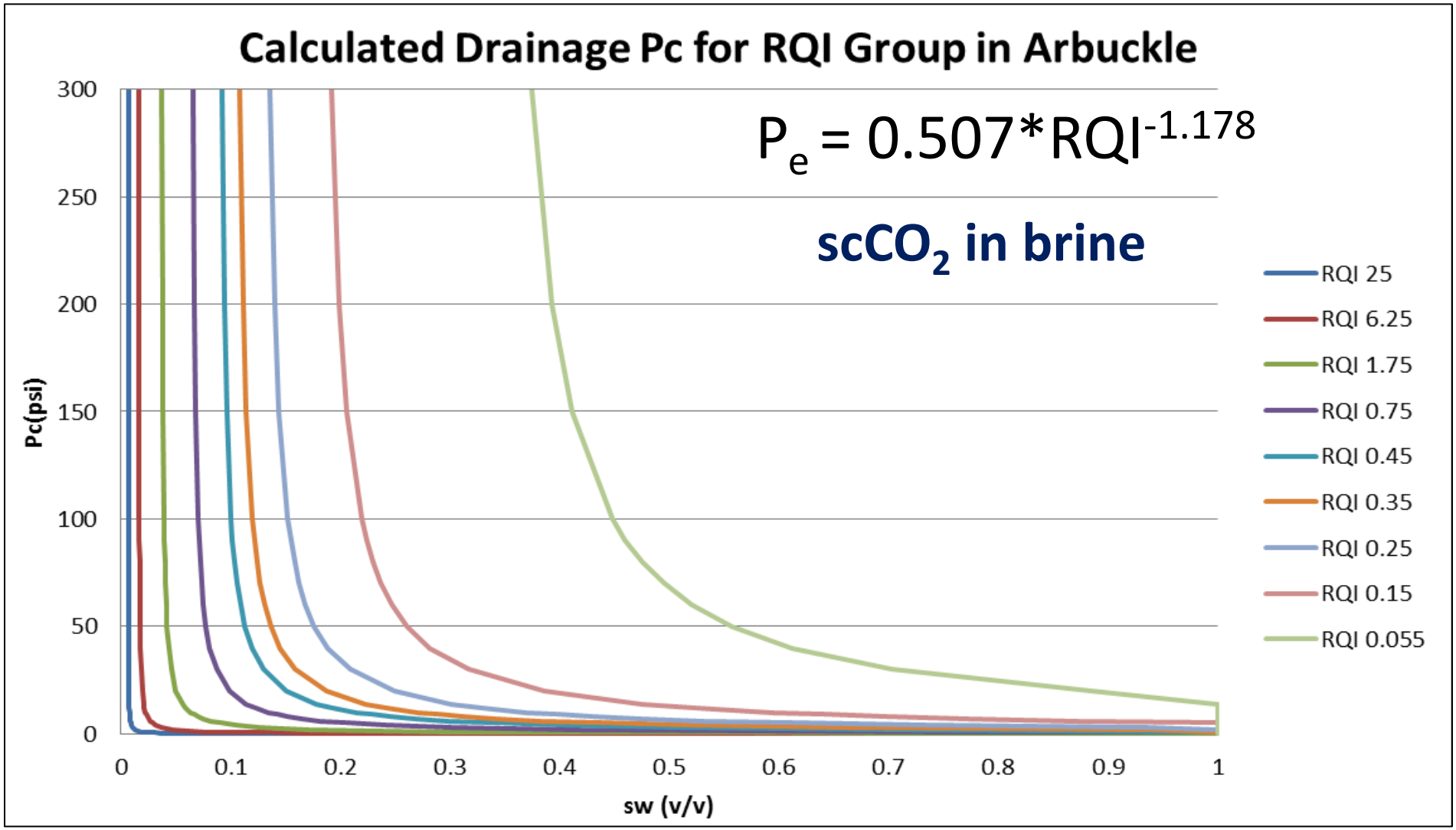
$$FZI = \frac{a}{S_{wir}\phi_e} + b$$

Fazelalavi et al. (2014)



Black points = core measured permeability

Range of Pore Types in Arbuckle Group Quantified by Reservoir Quality Index (RQI)



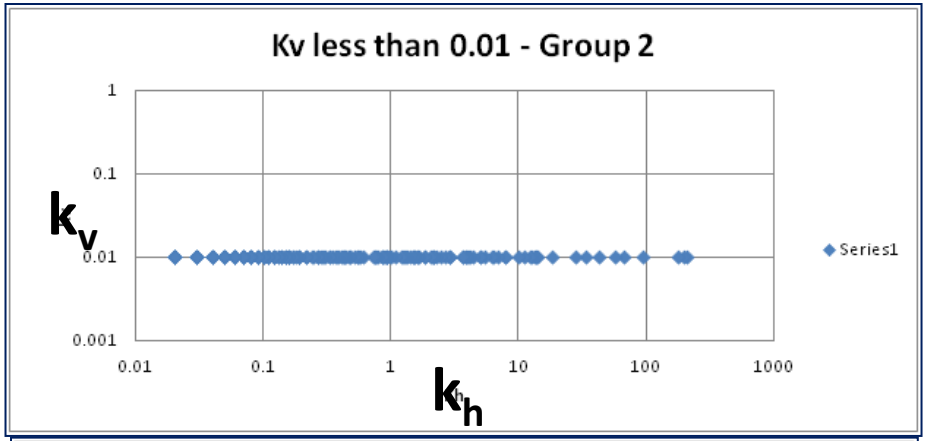
Fazelalavi, KGS

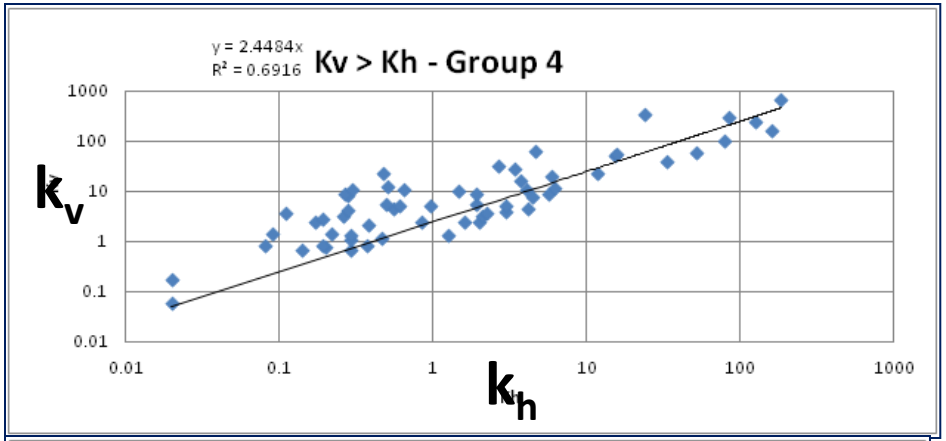
Correlations Between K_v and K_h From Whole Core Analysis & Five *Petrofacies* Groups

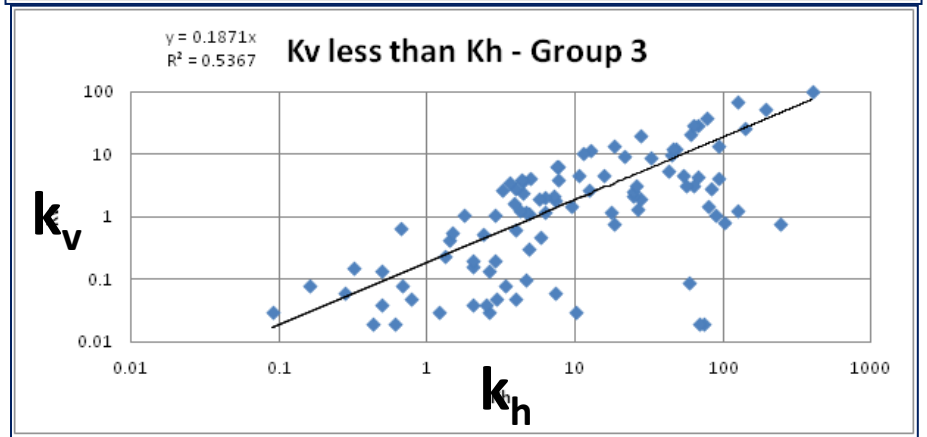
(K_v necessary to model interaction between high flow intervals)

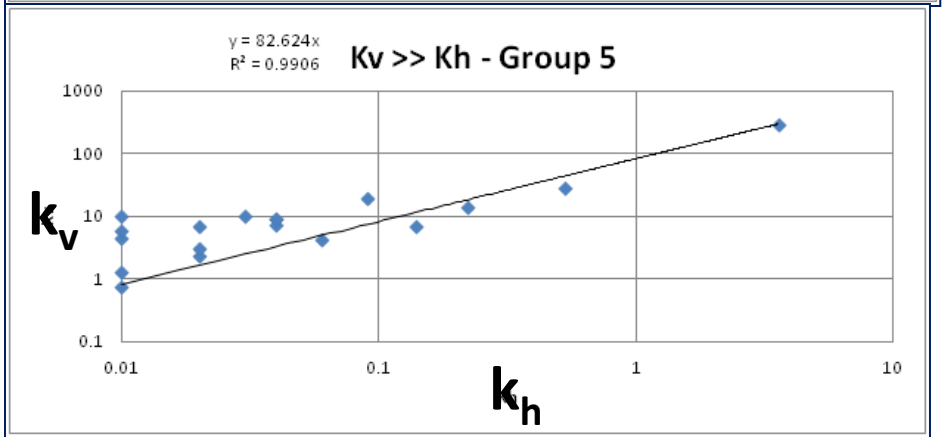
Group 1
There are 15 whole core samples in this group; both vertical and horizontal permeability are less 0.01 mD.

Fazelalavi, KGS









“TRIPLE COMBO” PERMEABILITY PREDICTION FROM LOGS Using Neural Network

RHOmaa and Umaa were not found to contribute significantly to permeability prediction, although they suggest that chertier dolomites tend to be more permeable than dolomites. However, gamma-ray, porosity, resistivity were useful as predictors, and so the model input requirements are from a basic triple combo well log suite common in Type Well Database:

1. **GR (Gamma-ray, API units)**
2. **PHIt (volumetric porosity%)**
3. **PHIr (connected porosity estimated from resistivity log %)**

PHIDensity[] = (2.71 - RHOB[]) / (2.71 - 1)

Rwa[] = (((PHID[]+PHIN[])/2)^2)*(ResDeep[]/1)

PHIr[] = (Rwa[]/ResDeep[])^.5

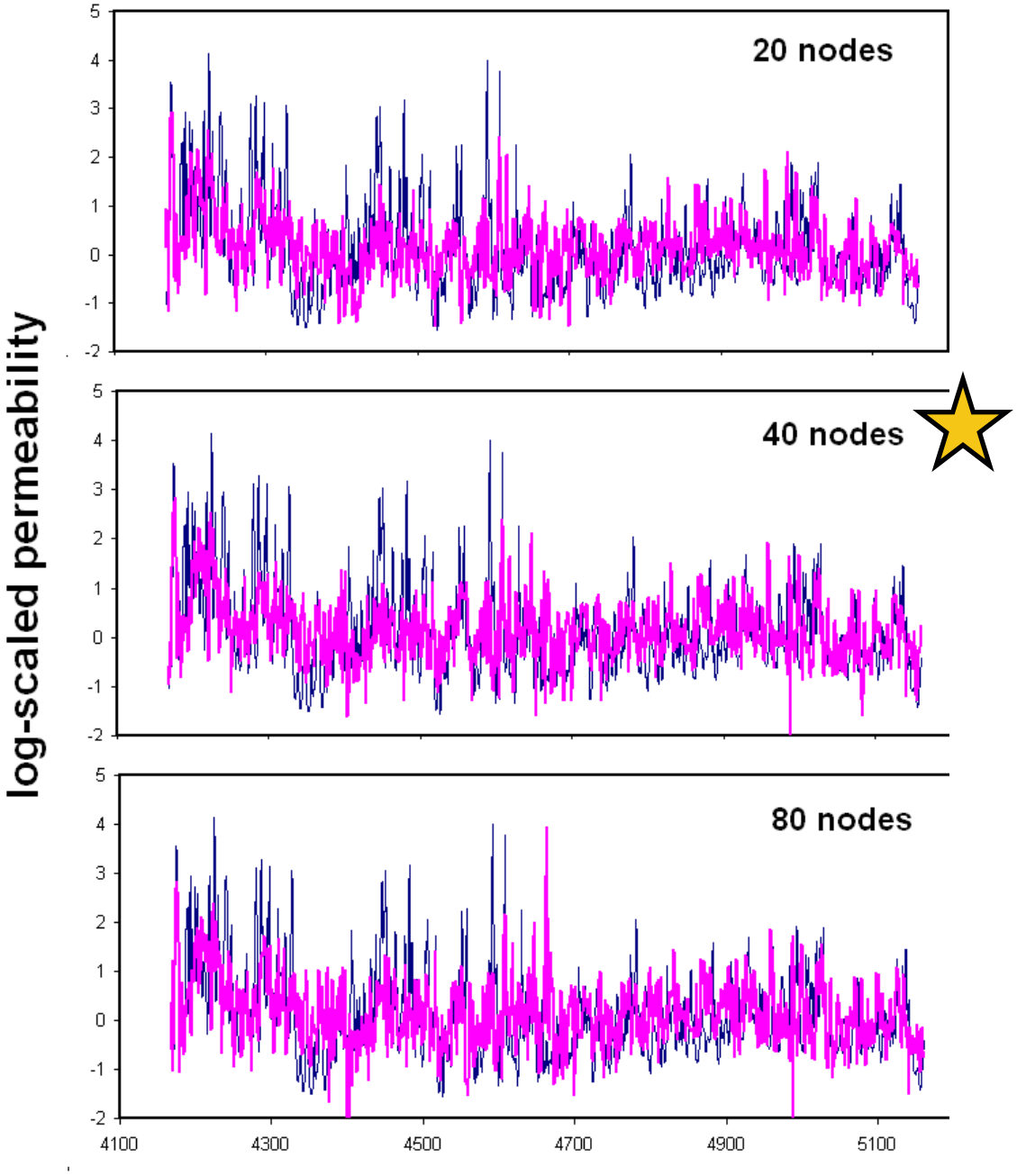
Comparison of k_h permeability in validation well by neural network with different numbers of nodes in the hidden layer

core-log calibrated

(with Swir & Φ_e from NMR)

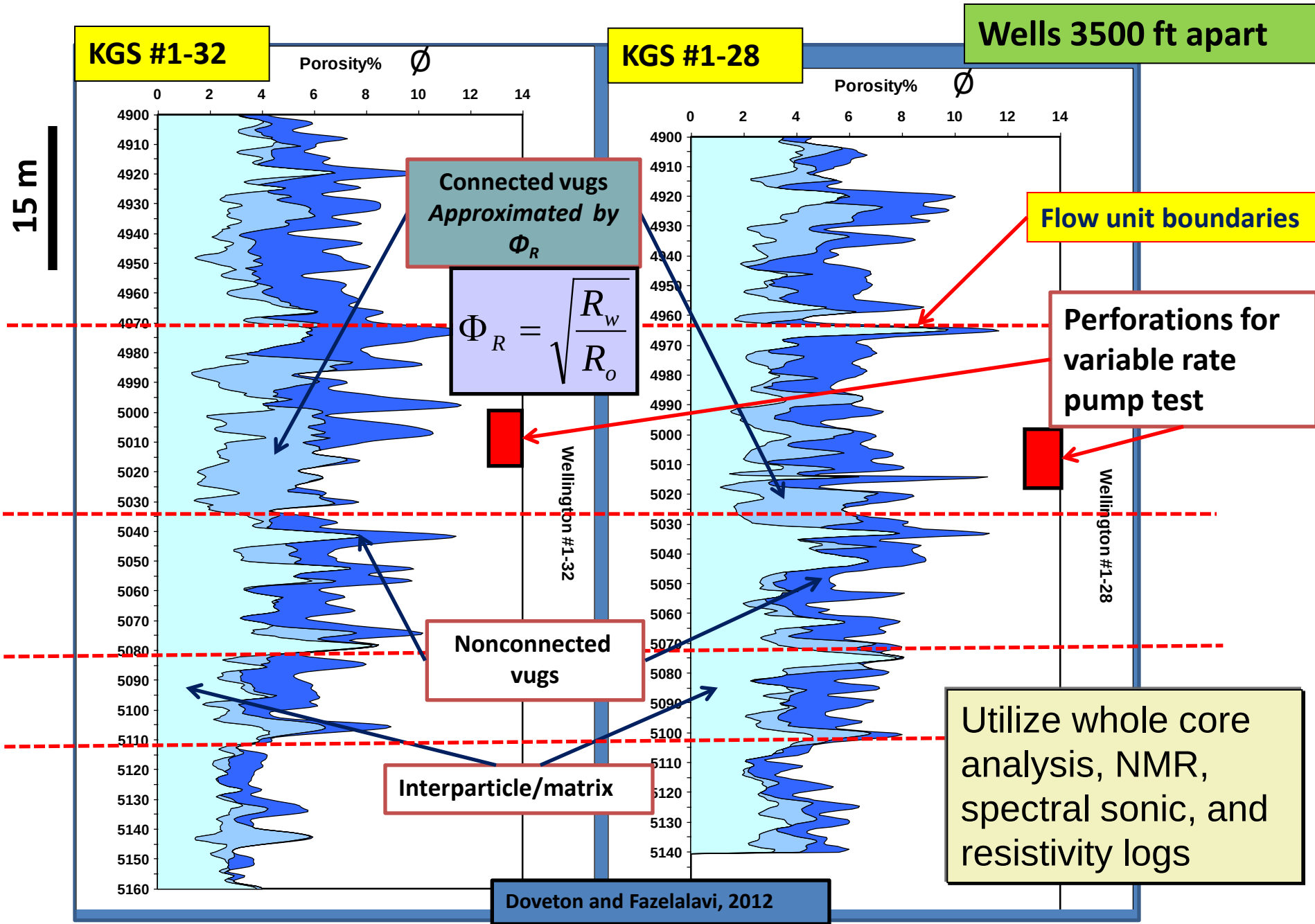
$$k = 1014\left[\frac{a}{S_{wir}\phi_e} + b\right]^2 \frac{\phi_e^3}{(1-\phi_e)^2}$$

predicted



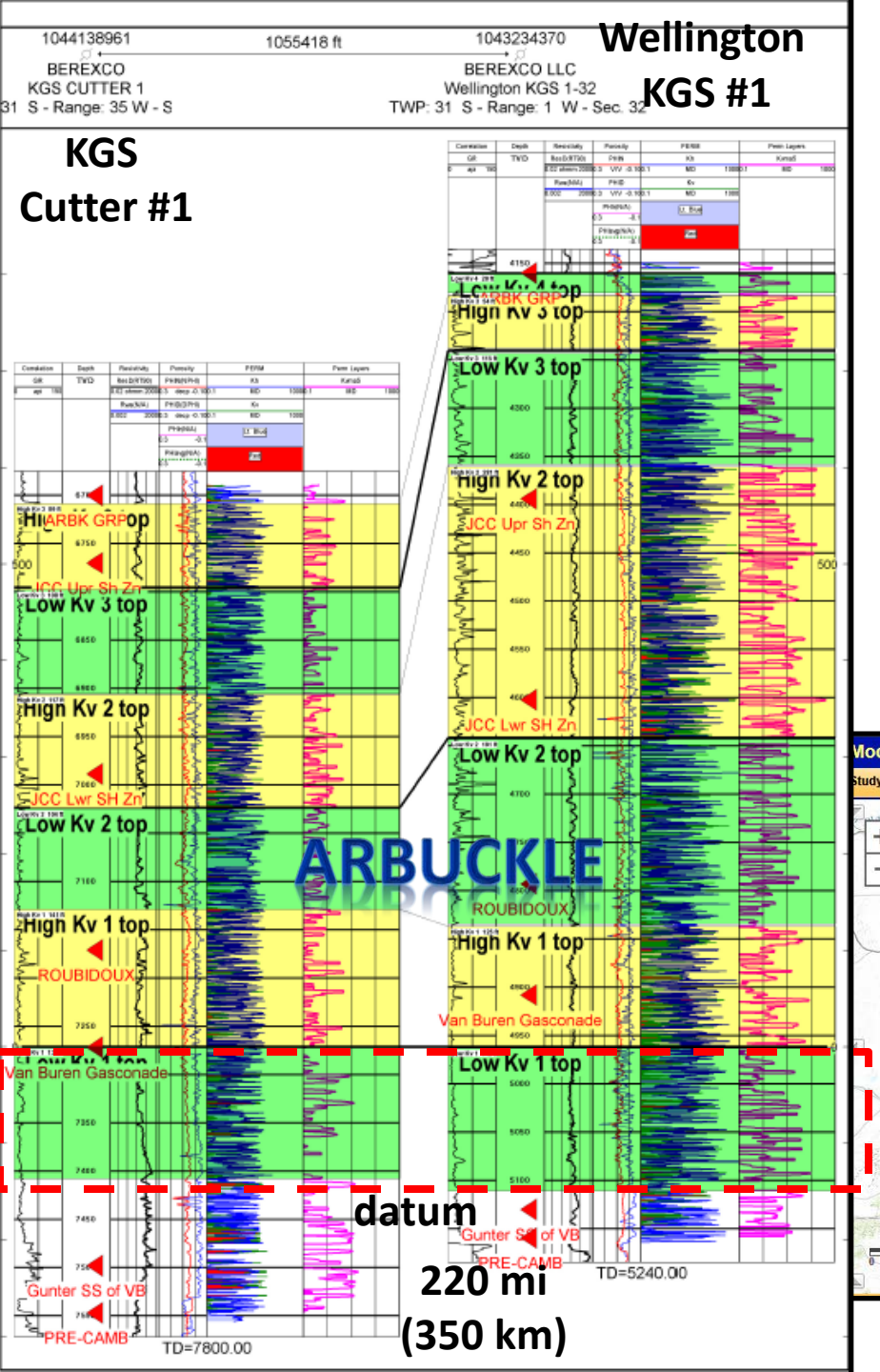
Doveton, KGS

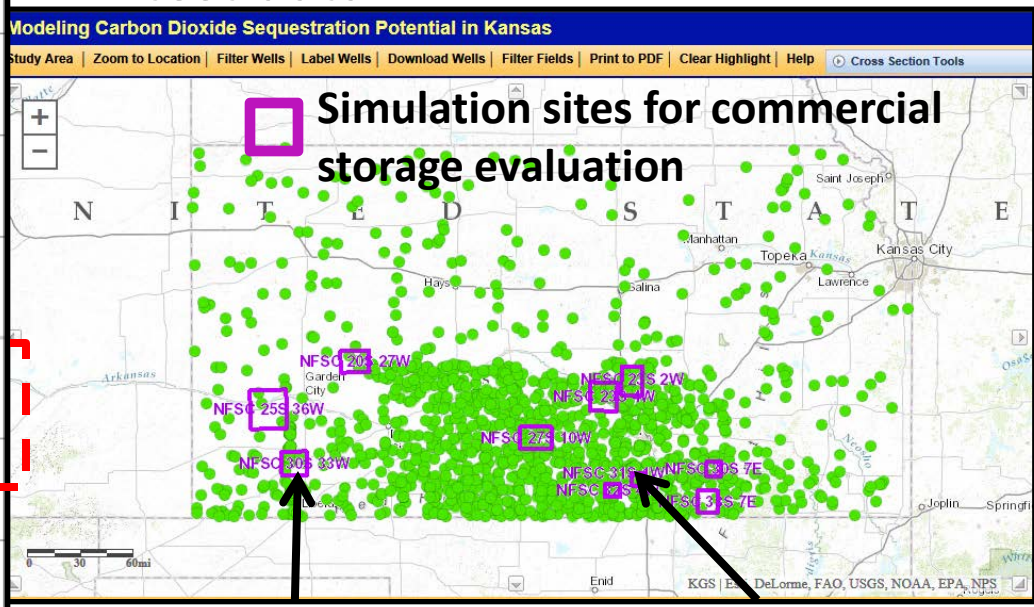
Flow units in the lower Arbuckle injection zone



Computed Kh & Kv in Arbuckle Group for Digital Type Wells ( )

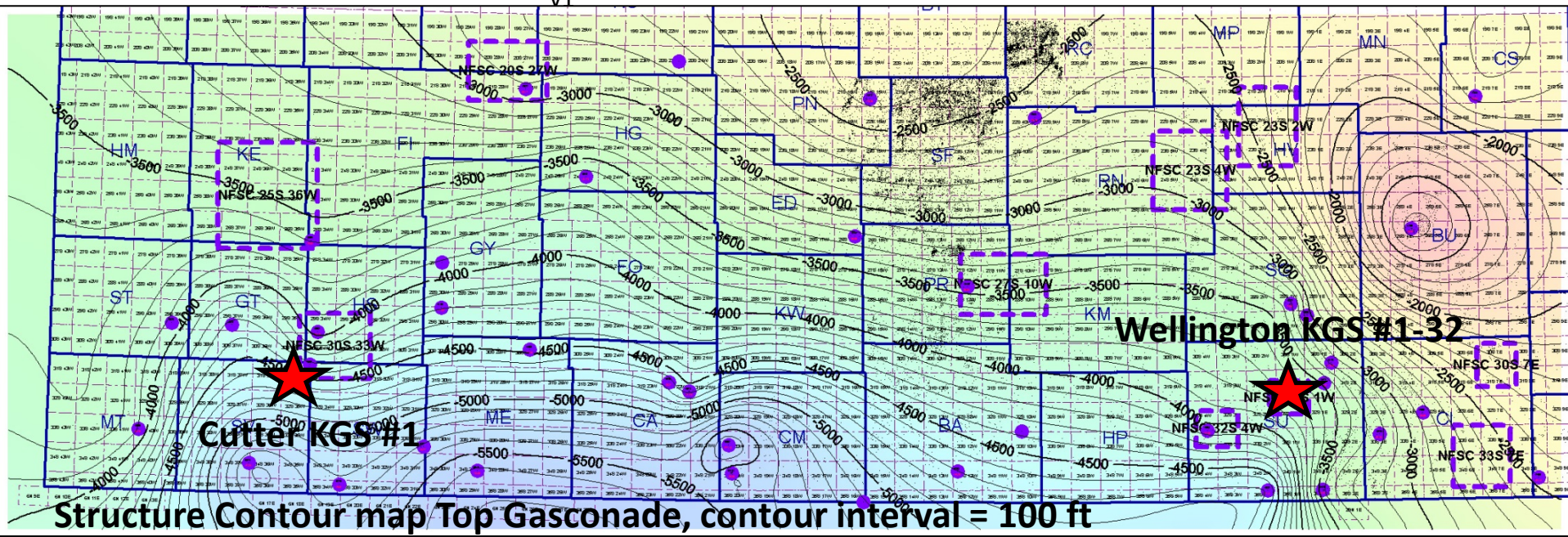
- Correlation of flow units based on K_h & k_v
- Between Cutter and Wellington Fields (350 km apart)
- Testing K with Class I buildup test data



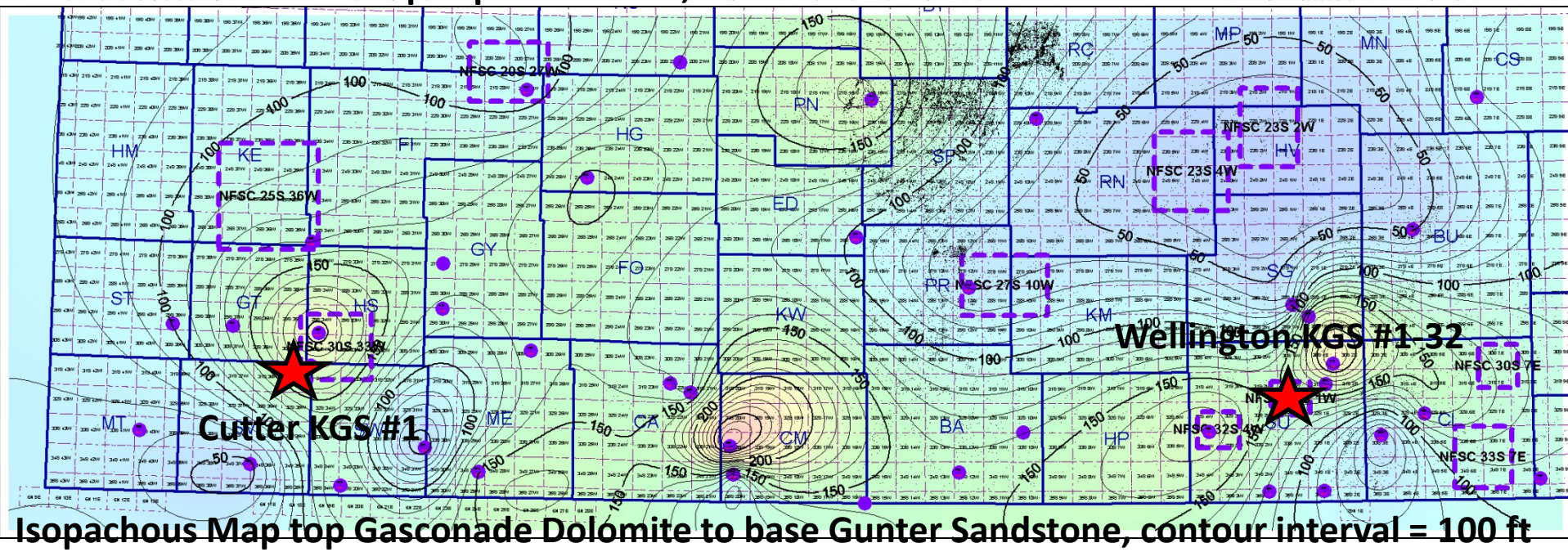


Lower Flow Unit For Regional Modeling in Arbuckle Group

Low K_{v1} –Gasconade & Gunter Sandstone



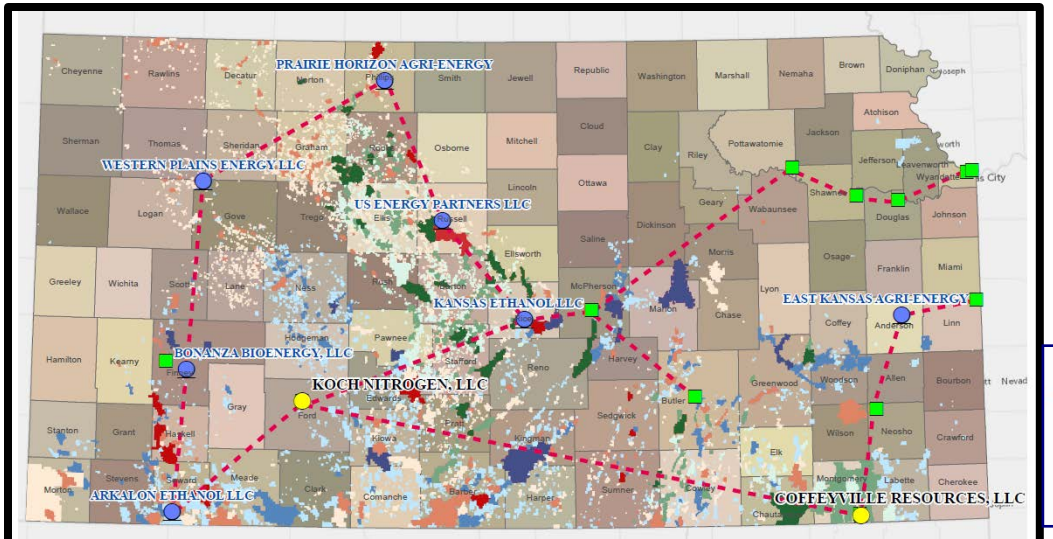
Structure Contour map Top Gasconade, contour interval = 100 ft



Isopachous Map top Gasconade Dolomite to base Gunter Sandstone, contour interval = 100 ft

Summary

- Arbuckle Group saline aquifer is stratigraphically and petrophysically heterogeneneous
- Sufficient subsurface information available to adequately characterize the key petrophysical properties to estimate storage and injectivity
- Characterization and modeling accomplished by extensive collaboration
- Believe that the CO_2 plume can be cost effectively and safely managed beneath existing oil fields



KSCO2

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The University of Kansas