"Arbuckle Fluid Disposal Considerations – Regional and Local Perspectives in the Context of the Mississippian Play in Kansas"

Lynn Watney and Jason Rush
Kansas Geological Survey
and collaborating team

PRODUCTION GEOLOGY
OF THE NORTH MIDCONTINENT
December 4-5, 2012

NETL

TORP

KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

Outline

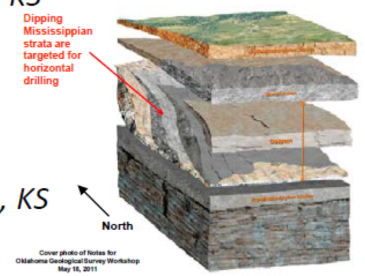
- Overview
- Mississippian Lime Play
  - Drilling activity
  - Stratigraphy, reservoir properties, and implications for water production
- Arbuckle Fluid Disposal
  - UIC Class I and II wells in Kansas
  - Stratigraphy
  - Hydrostratigraphy
  - Petrophysical and geophysical properties
  - Controls on Ø-k – Lithofacies, diagenesis, fracturing
  - Preview western Kansas portion of DOE-CO_2 study

"Mississippian Carbonates in Kansas: Integrating Log, Core & Seismic - An AAPG E-Symposium"

W. Lynn Watney[1], Jason Rush[1], John Doveton[1], Mina Fazelalavi[1], K. David Newell[1], Mike Killion[1], Dennis Hedke[2], Aimee Scheffer[9], Jennifer Roberts[3], David Fowle[3], Dana Wreath[4], Randy Koudele[4], Paul Gerlach[5], Larry Nicholson[6], Tom Hansen[7], John Victorine[1], Georgios Tsoflias[3], Ayrat Sirazhiev[3], Robin Barker[8], Saugata Datta[8] Eugene Holubnyak[1], Marty DuBois[10], John Youle[11], Gene Williams[12], Ray Sorenson[13], Dave Koger[14]

[1]Kansas Geological Survey/The University of Kansas, Lawrence, KS
[2]Hedke-Saenger Geoscience, Ltd., Wichita, KS
[3]Department of Geology, University of Kansas, Lawrence, KS
[4]Berexco, LLC, Wichita, KS
[5]Consultant, Miramar, FL
[6]Consultant, Hanover, KS
[7]Bittersweet Energy, Wichita, KS
[8]Department of Geology, Kansas State University, Wichita, KS
[9]KGS/KU, currently Conoco-Phillips, Houston, TX
[10]IHR, LLC., Lawrence, KS
[11]Sunflower LLC, Longmont, CO
[12]Williams Engineering, Houston, TX
[13]Consultant, Tulsa, OK
[14]Koger Remote Sensing, Ft. Worth, TX

Mississippian Oil Play
Stacked and shingled Mississippian Strata developed along the southern Kansas and northern Oklahoma



Oklahoma Geological Survey Workshop cover, 2012

DOE Contract #FE0002056
and partner cost share

NETL

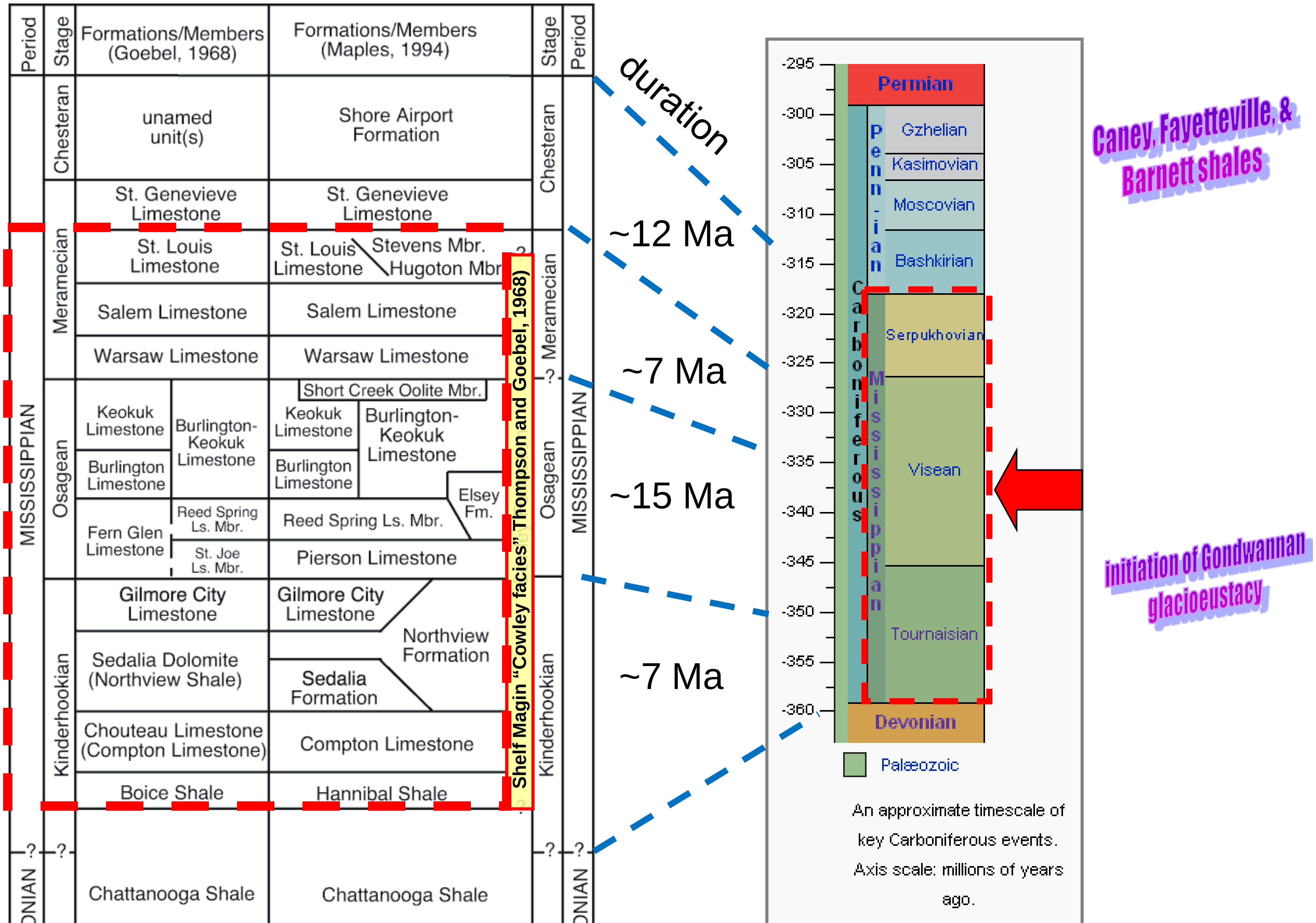
KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

August 2012

http://www.aapg.org/education/online/details.cfm?ID=249

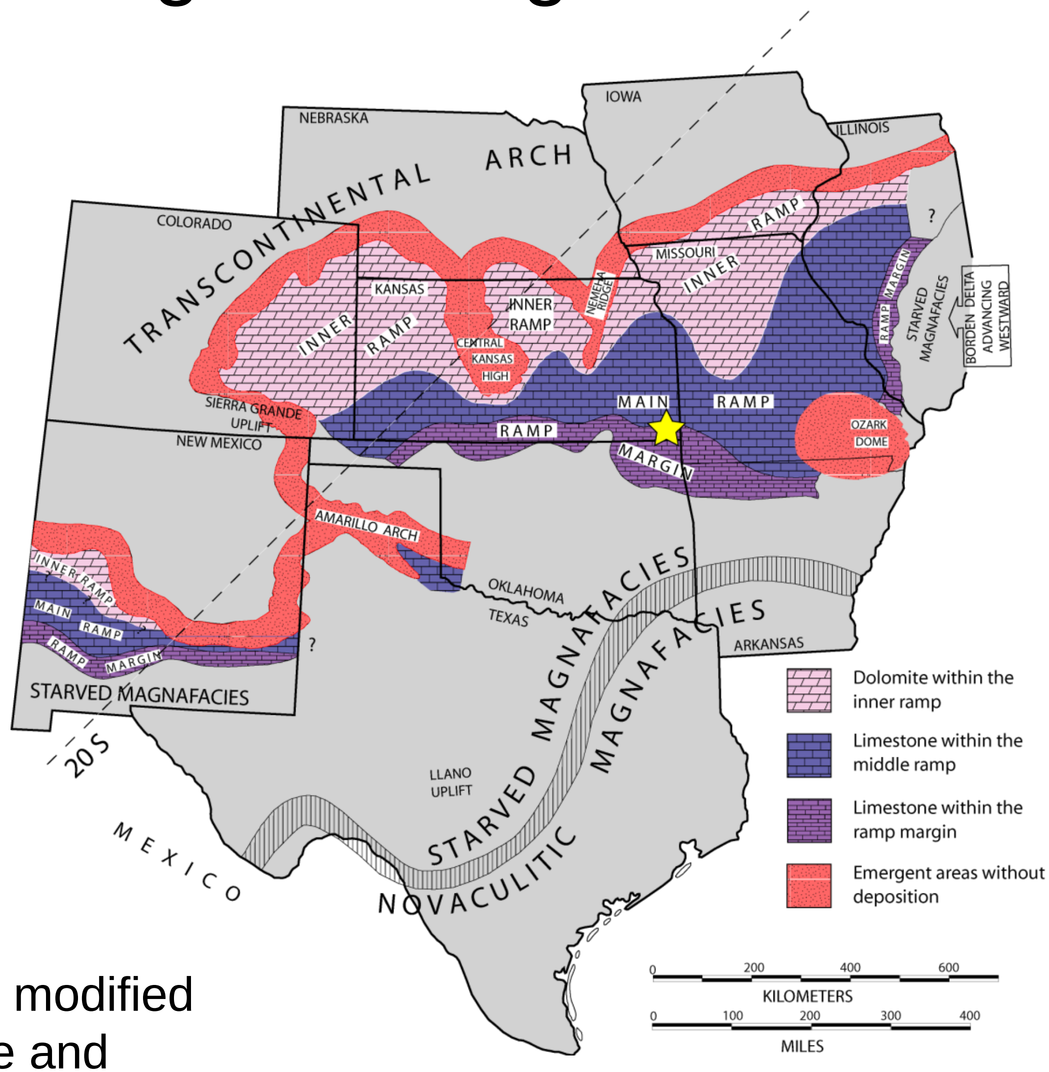
Kansas Mississippian Stratigraphic Column (Maples, 1994)

Lower Carboniferous – Mississippian Subsystem



http://en.wikipedia.org/wiki/Carboniferous

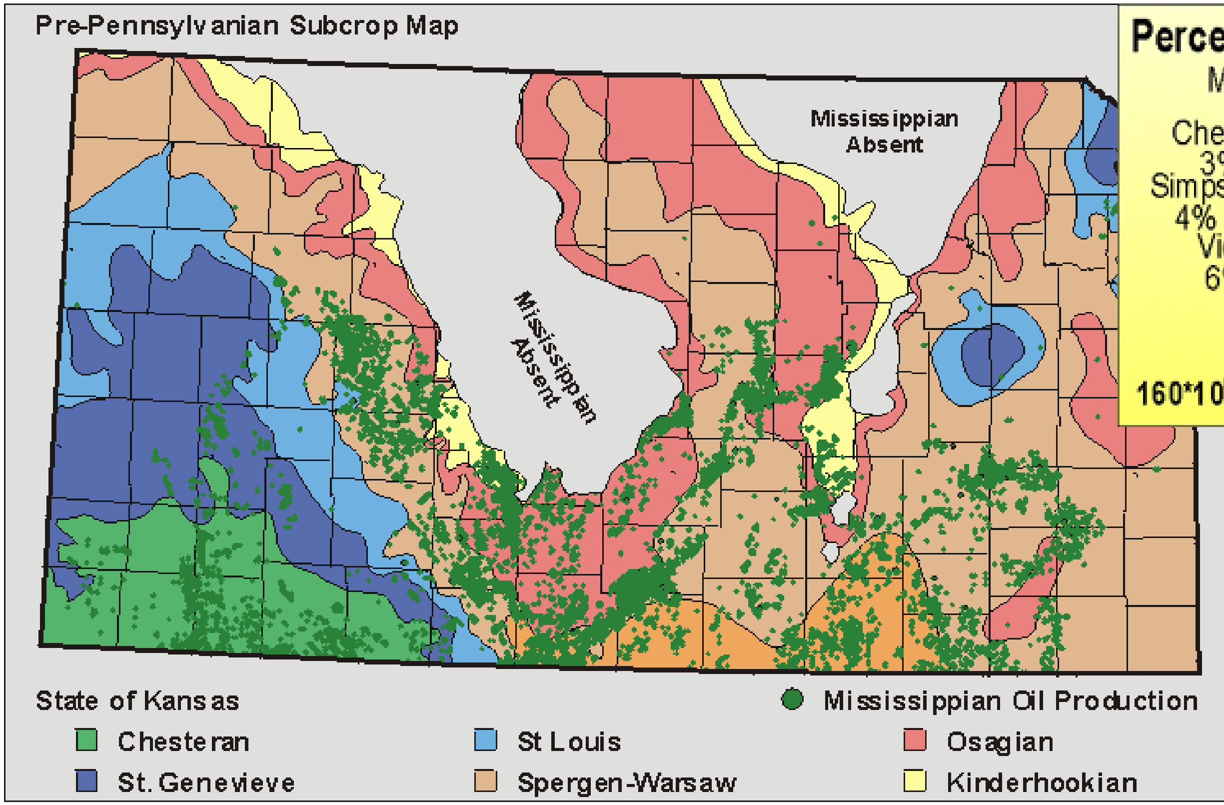
Paleogeographic map during the Osagean-Meramecian

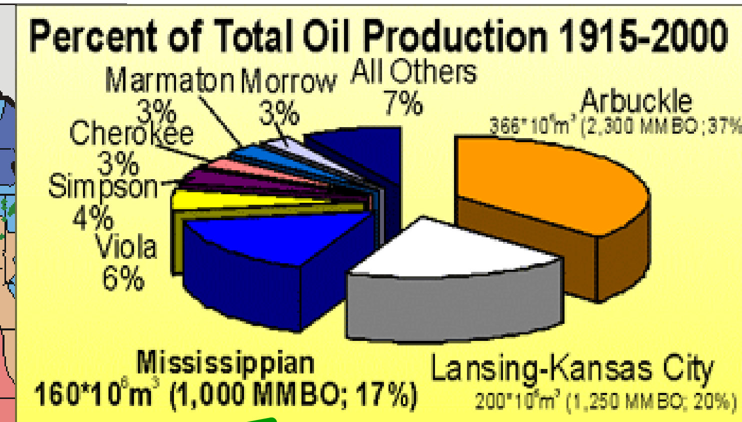


Young (2007) modified from Lane and DeKeyser (1980)

Mississippian Reservoirs

-- Long-term importance to Kansas oil and gas production





Mississippian

- **>1 Billion BO Cumulative**
- **33% of Current Production**

Gerlach, 1998

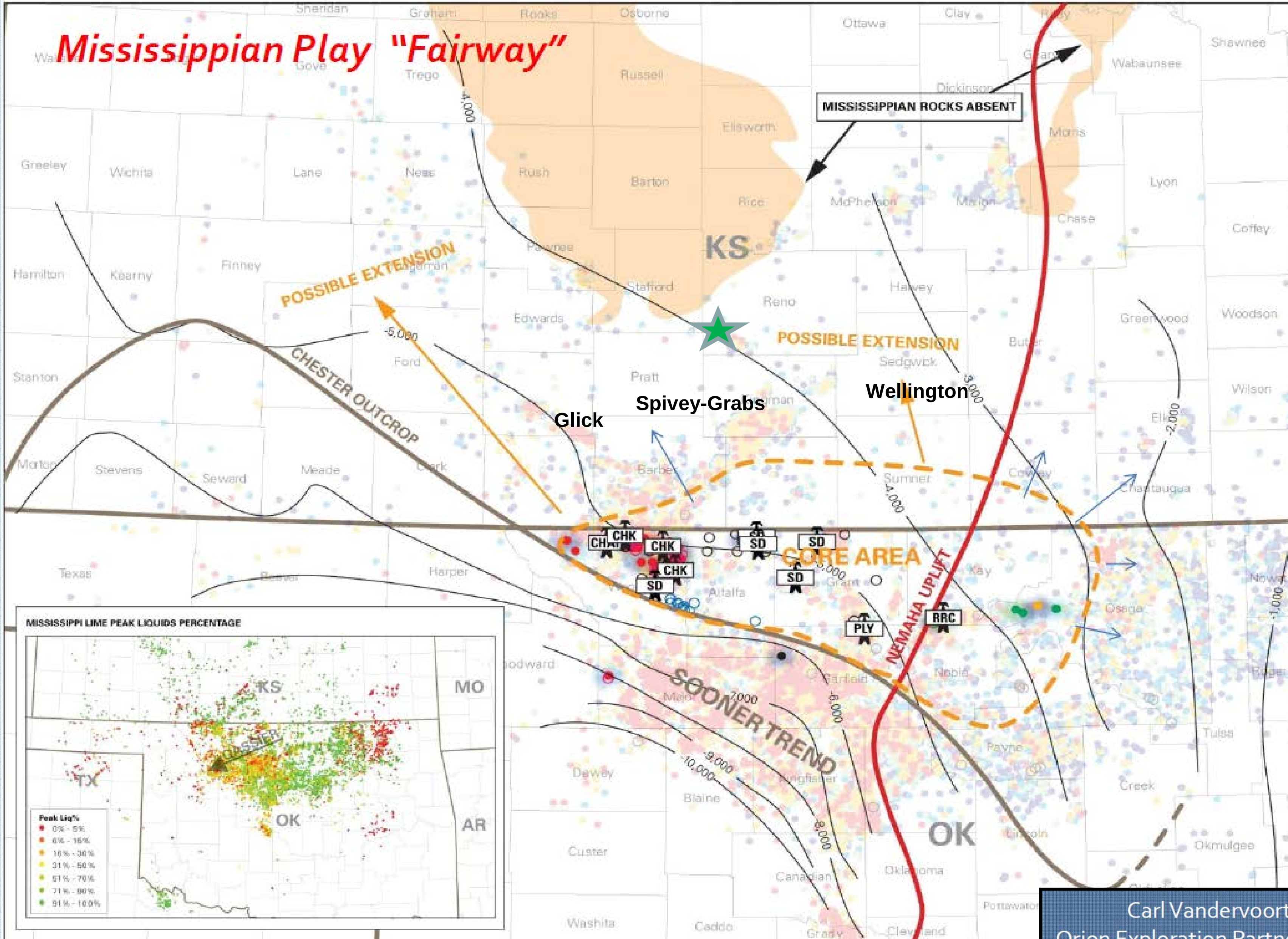
http://www.kgs.ku.edu/DPA/Plays/ProdMaps/miss_sub_oil.html

Pre-Pennsylvanian Subcrop Map of Kansas

Miss Oil Production in Green

Dubois (2003)

Mississippian Play "Fairway"

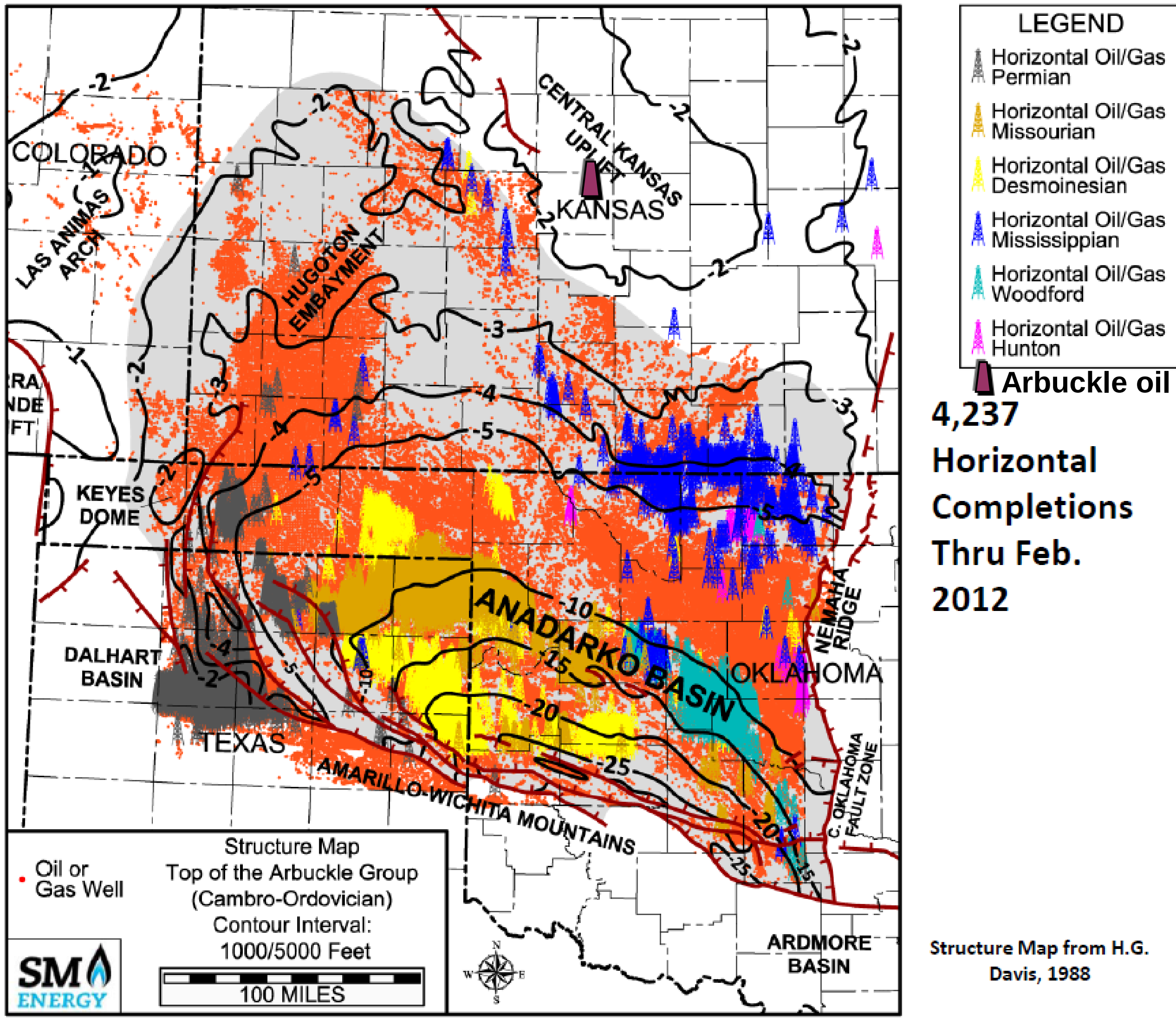


Map Courstey of ITG IR

Carl Vandervoort
Orion Exploration Partners, LLC
Tulsa, OK

August 2, 2011

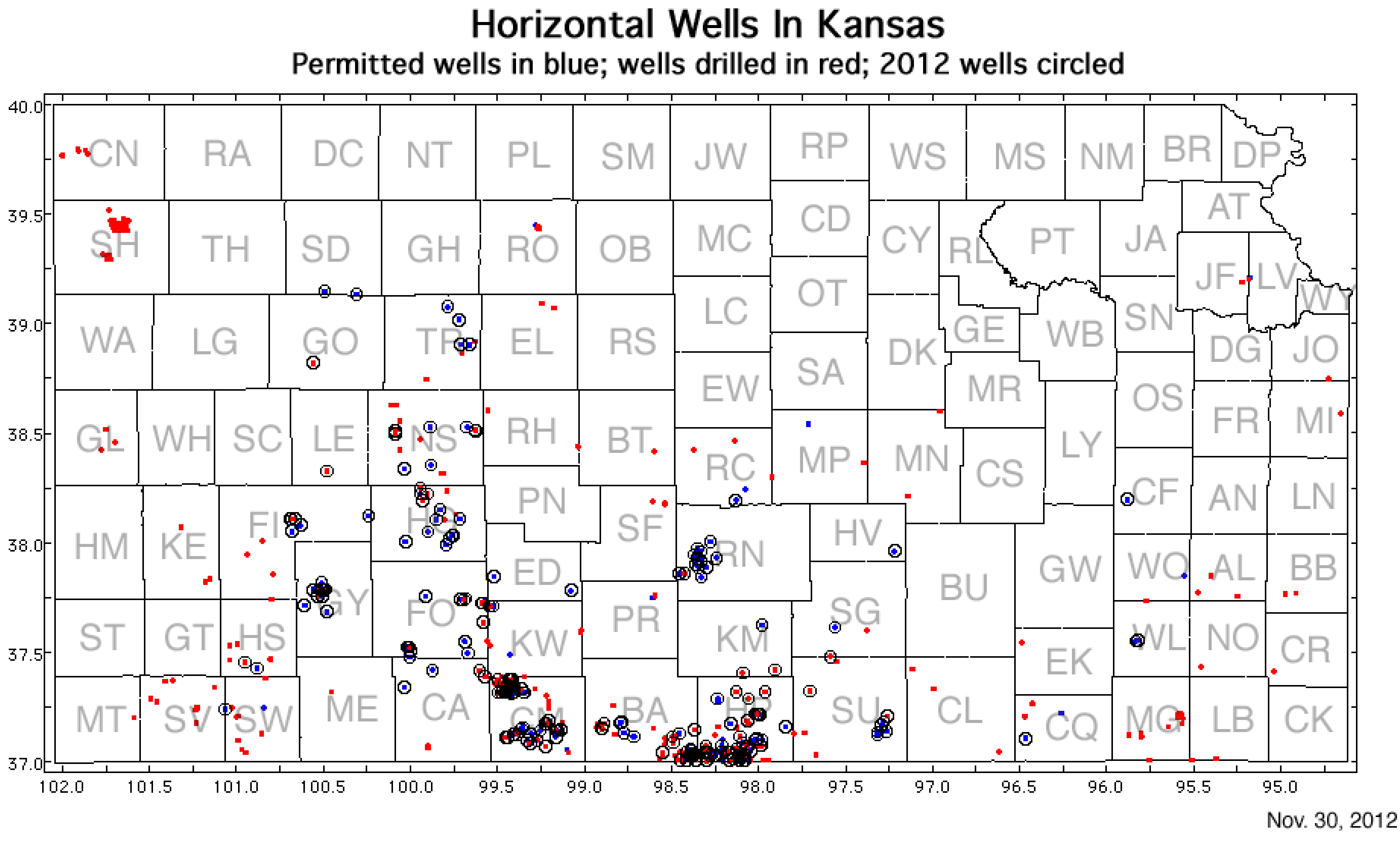
Regional Structural Features-Horizontal Wells



4,237 Horizontal Completions Thru Feb. 2012

Structure Map from H.G. Davis, 1988

John Mitchell,
Senior Geologist
SM Energy Co.
Tulsa, Oklahoma
March 2012
Email: jmitchell@sm-energy.com

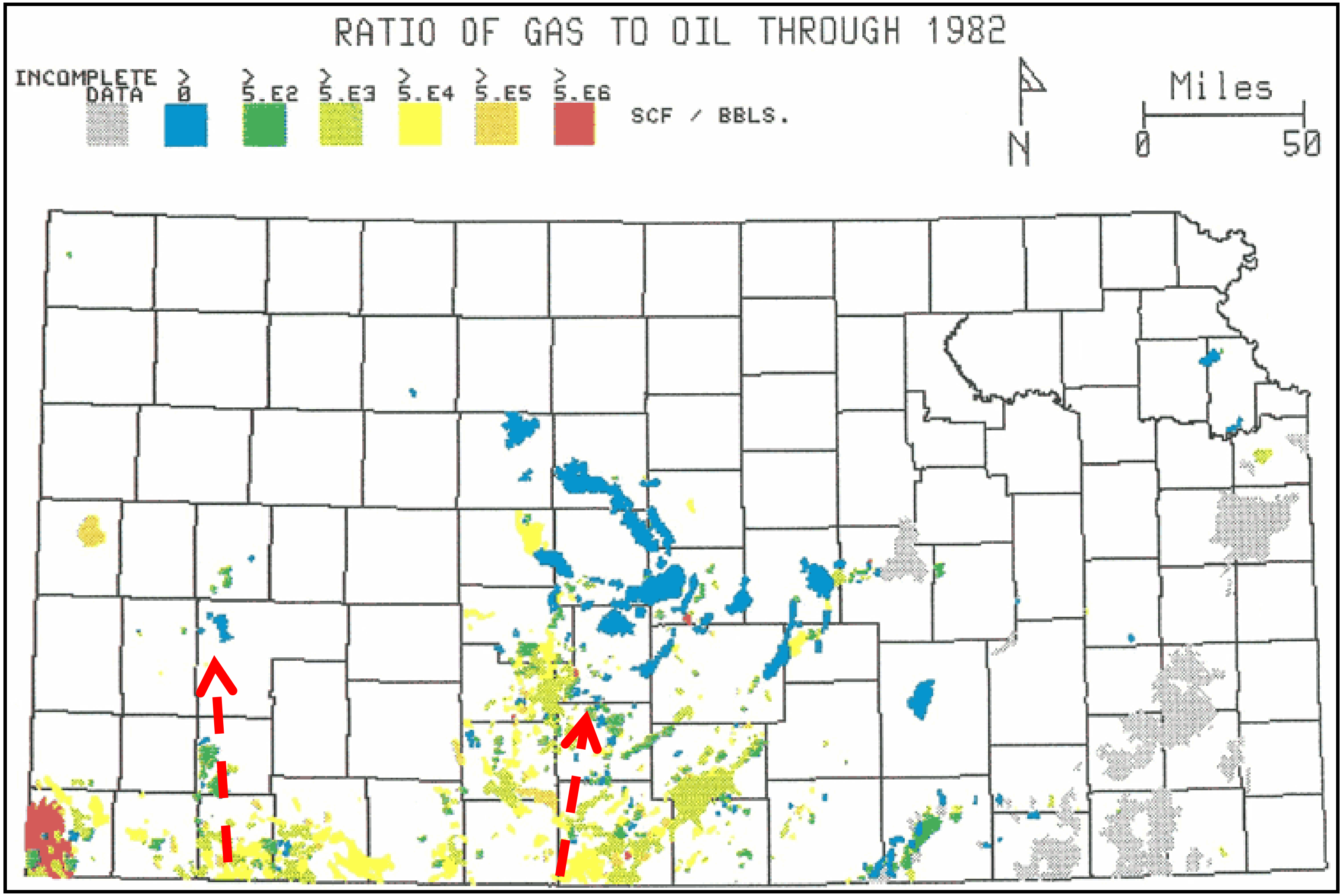


HORIZONTAL WELL DRILLED BY YEAR

2009-6 **2010-**10 **2011-**44 **2012-114**

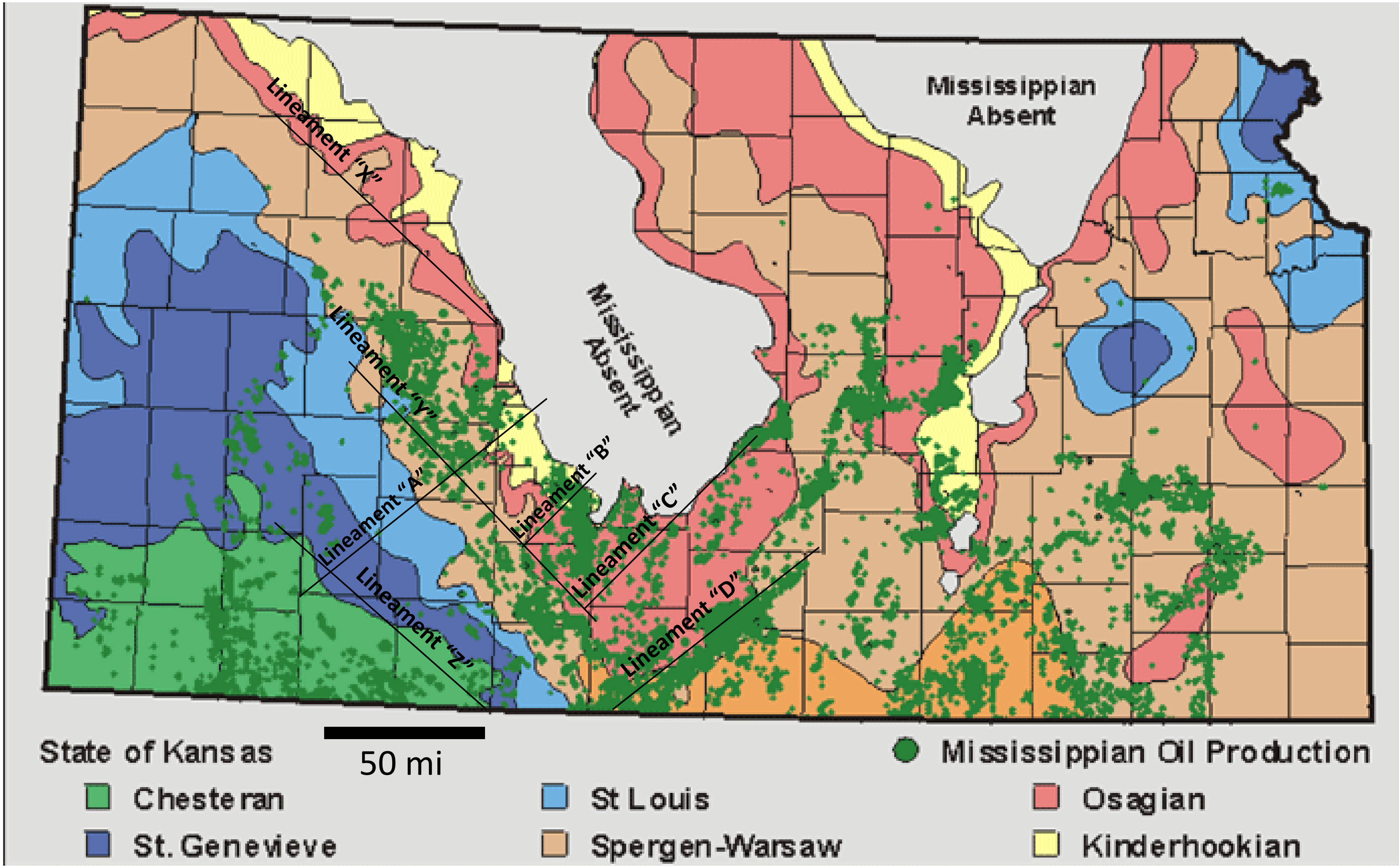
http://www.kgs.ku.edu/PRS/wellStats.html

Higher gas:oil ratio in south-central and southwest Kansas



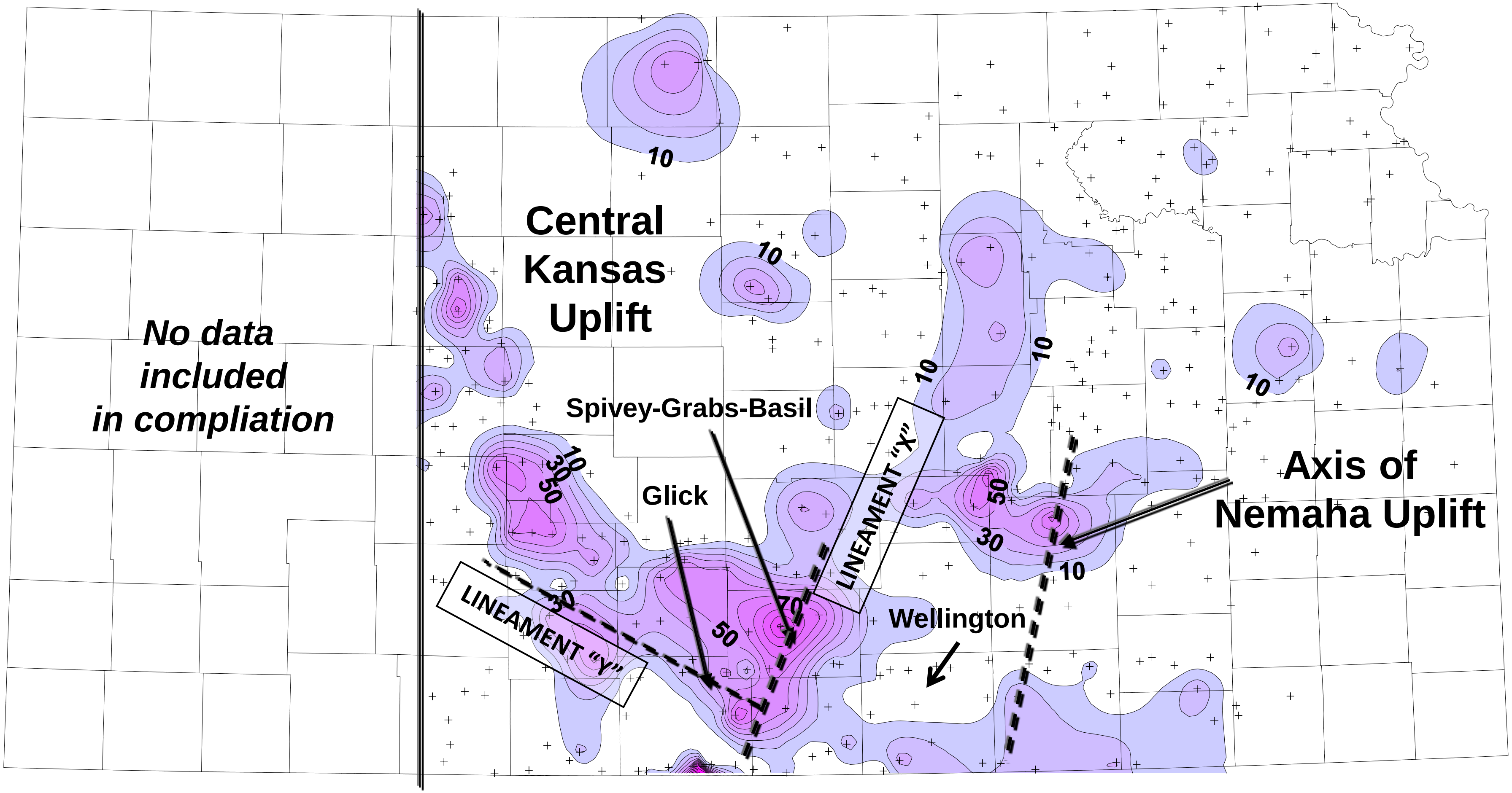
Newell et al (1989)

Mississippian Subcrops, Oil Production, and Pennsylvanian Structural Lineaments



http://www.kgs.ku.edu/DPA/Plays/ProdMaps/miss_sub_oil.html
Gerlach (1998)

Thickness of residual chert & basal Pennsylvanian conglomerate

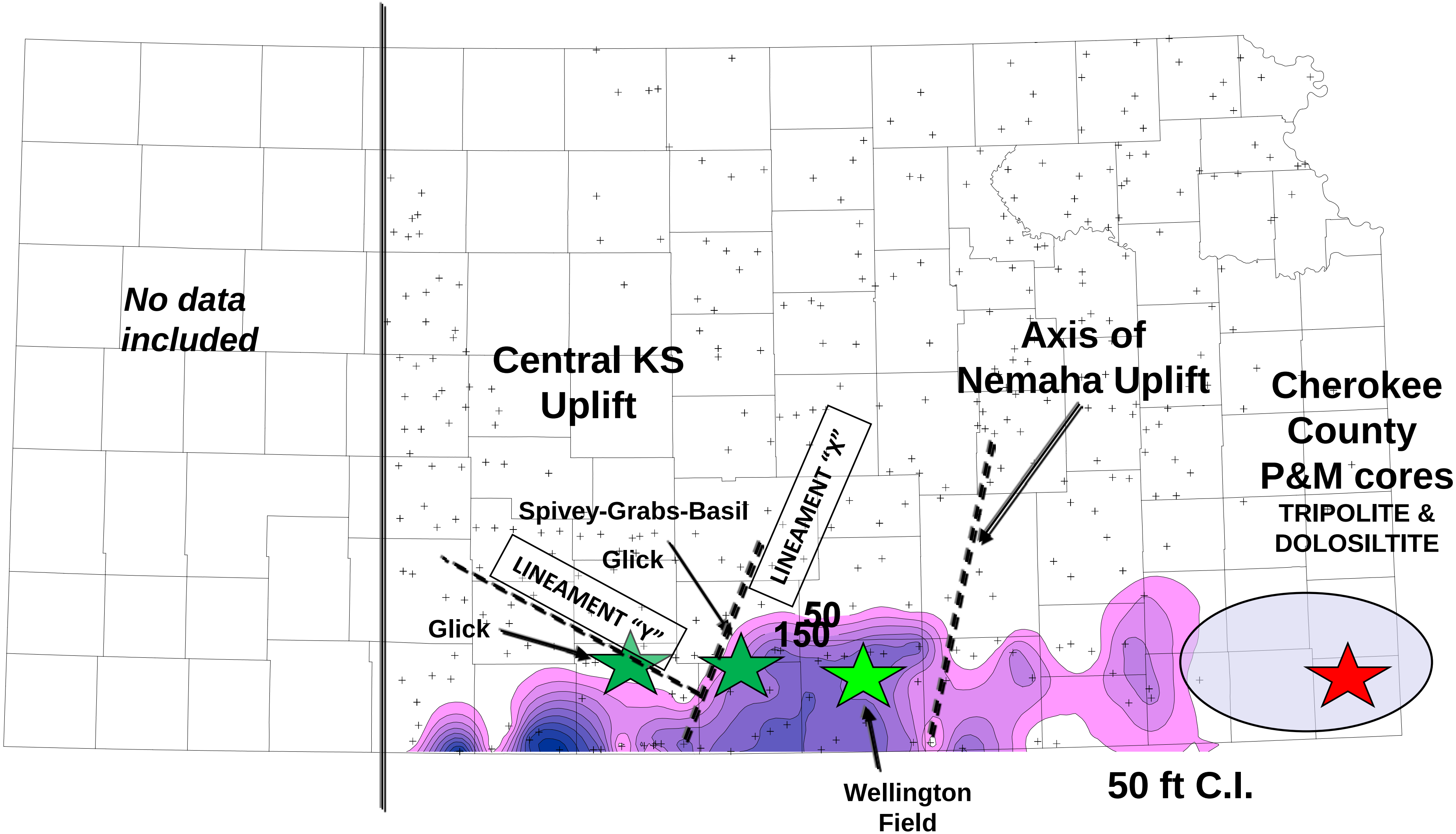


*Residual chert conglomerate – silt & sand matrix with chert at basal Pennsylvanian unconformity, not clean, low resistivity bedded chert

Watney, Guy, and Byrnes (2001)

Thickness of low resistivity* Mississippian strata

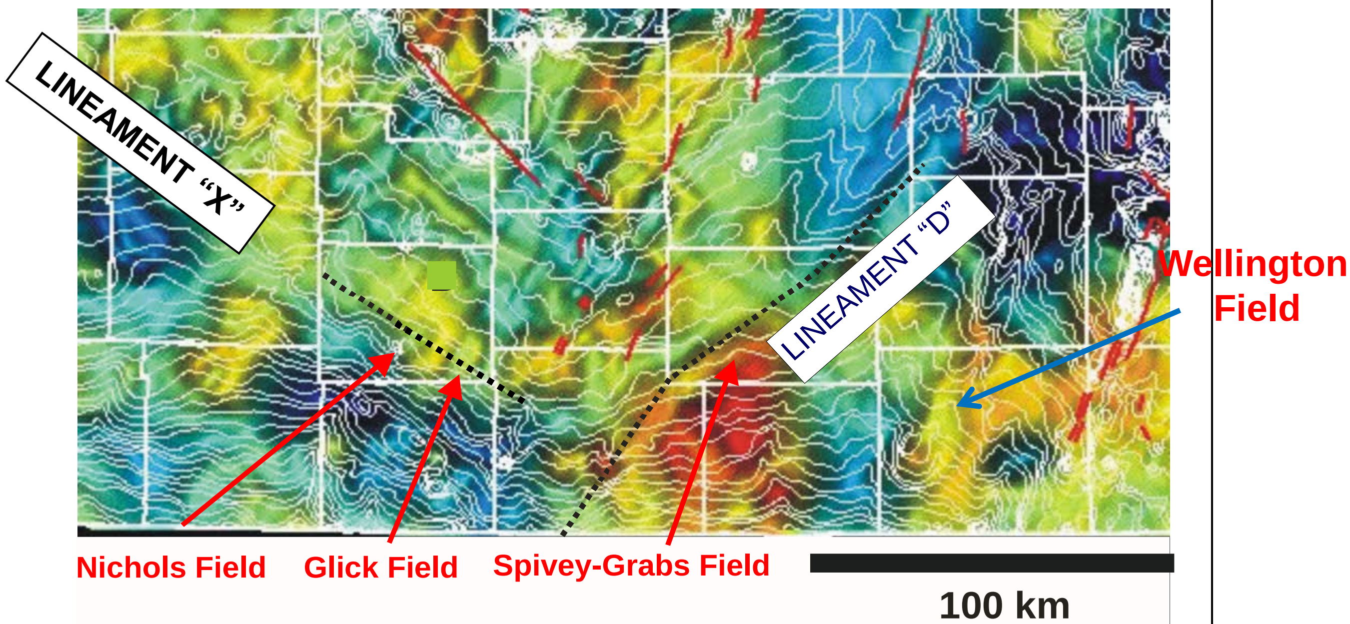
and structural lineaments important in deposition and later uplift



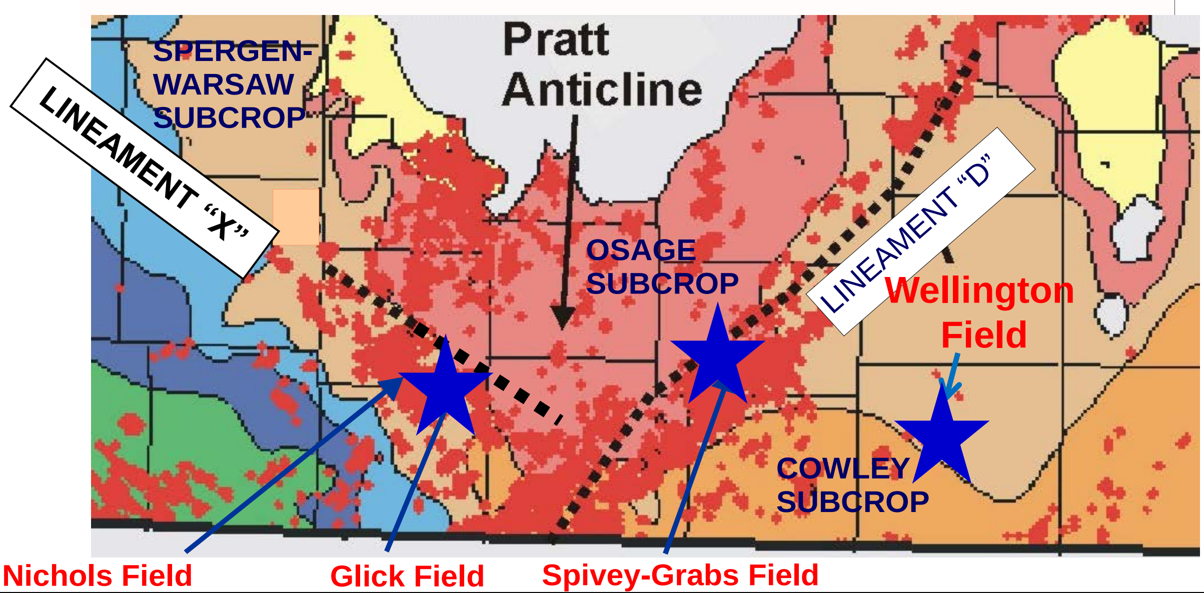
***Low resistivity, <2 ohm-m, equivalent to "in situ" chert "TRIPOLITE"**

Watney, Guy, and Byrnes (2001)

Total Magnetic Field Intensity

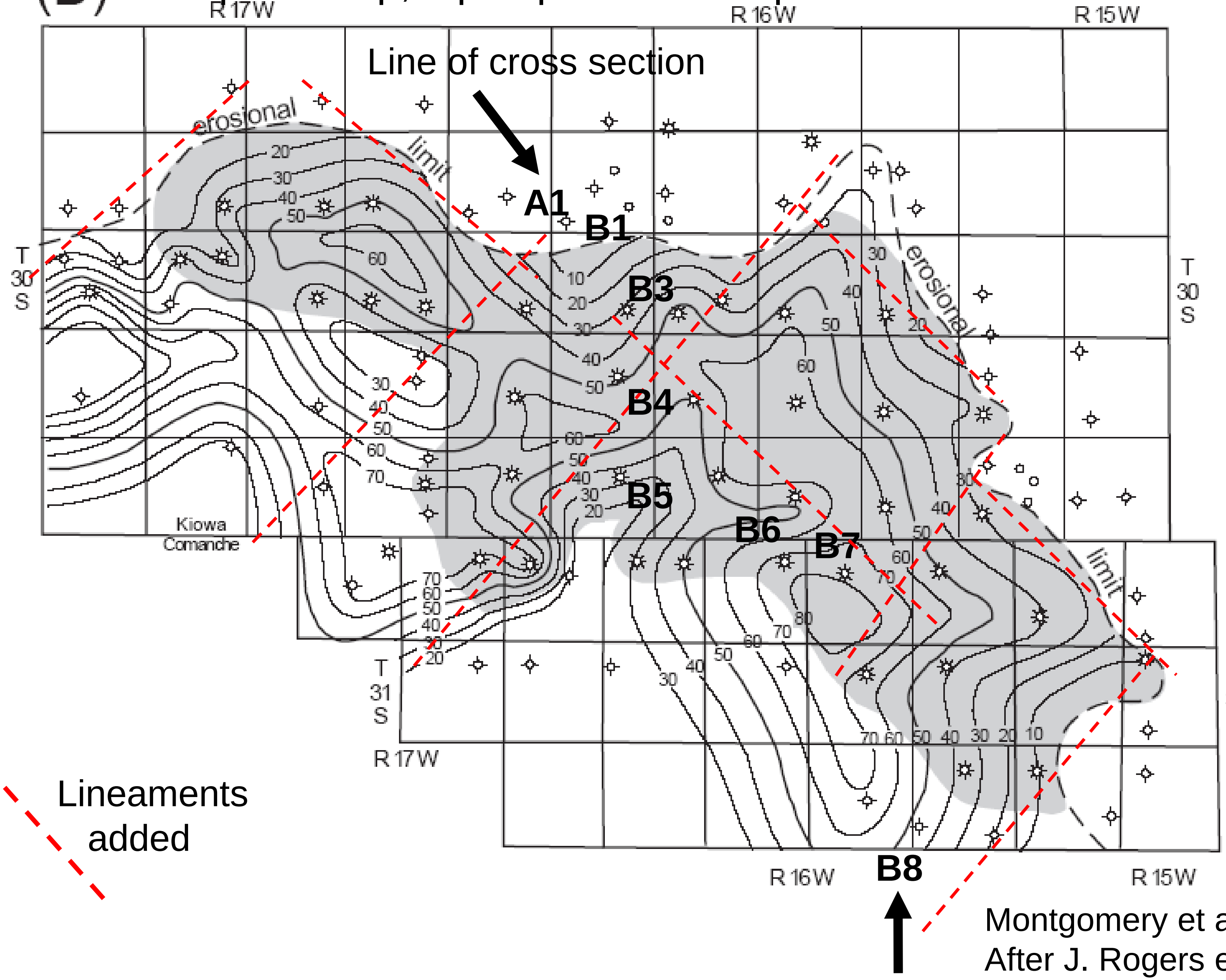


Basal Pennsylvanian Subcrop



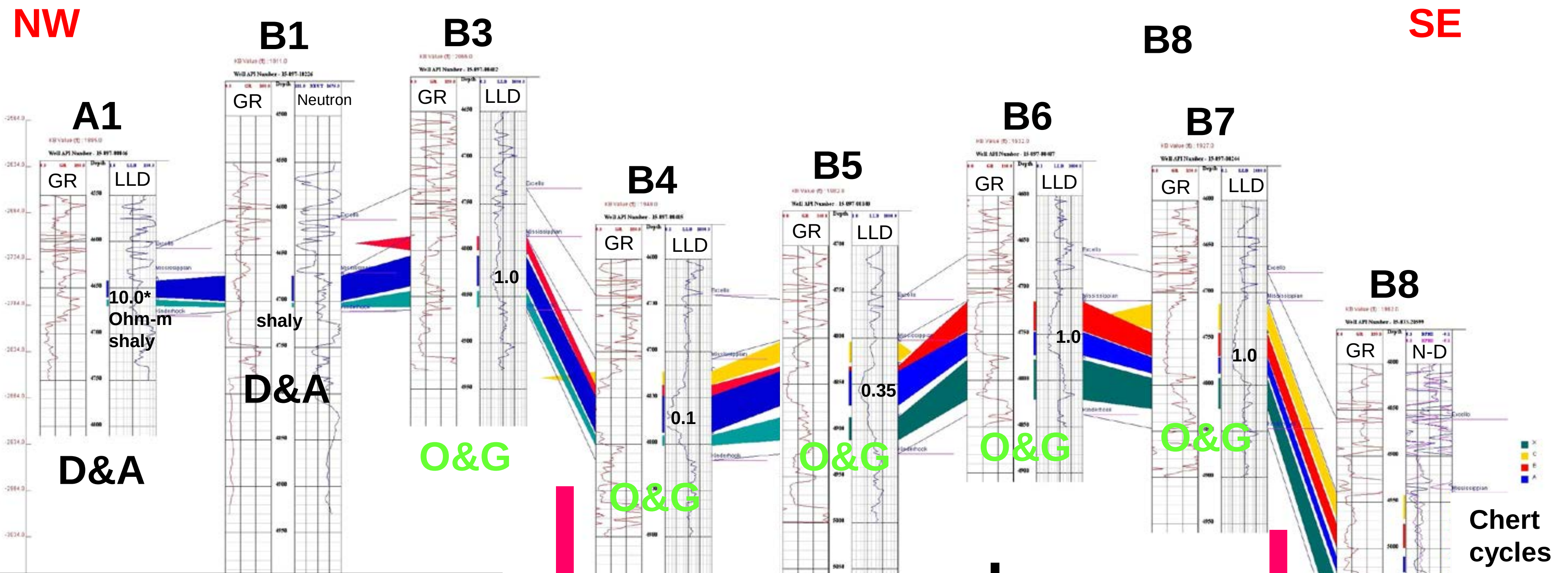
Glick Field

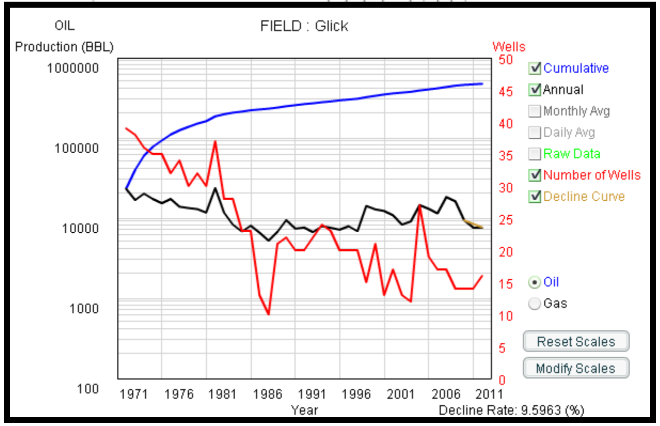
(B) Isopach map, top of productive tripolitic chert reservoir



Montgomery et al. (1998)
After J. Rogers et al. (1995)

Structural cross section through tripolitic, low resistivity chert pay Mississippian reservoir in Glick Field

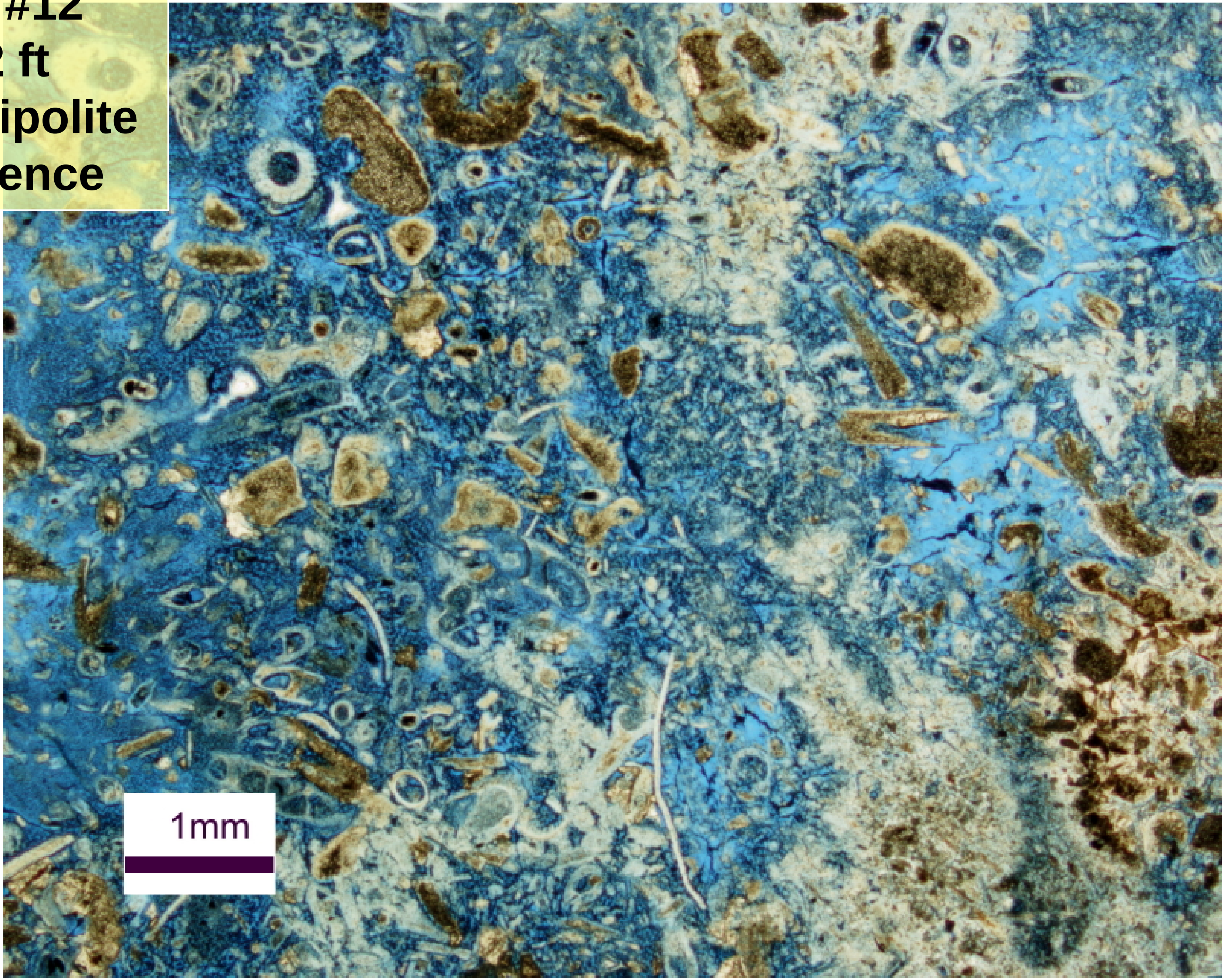




***Annotated with Rt of chert bearing strata at horizon of the pay zone**

No horizontal scale, section length ~9 mi
Equidistant wells

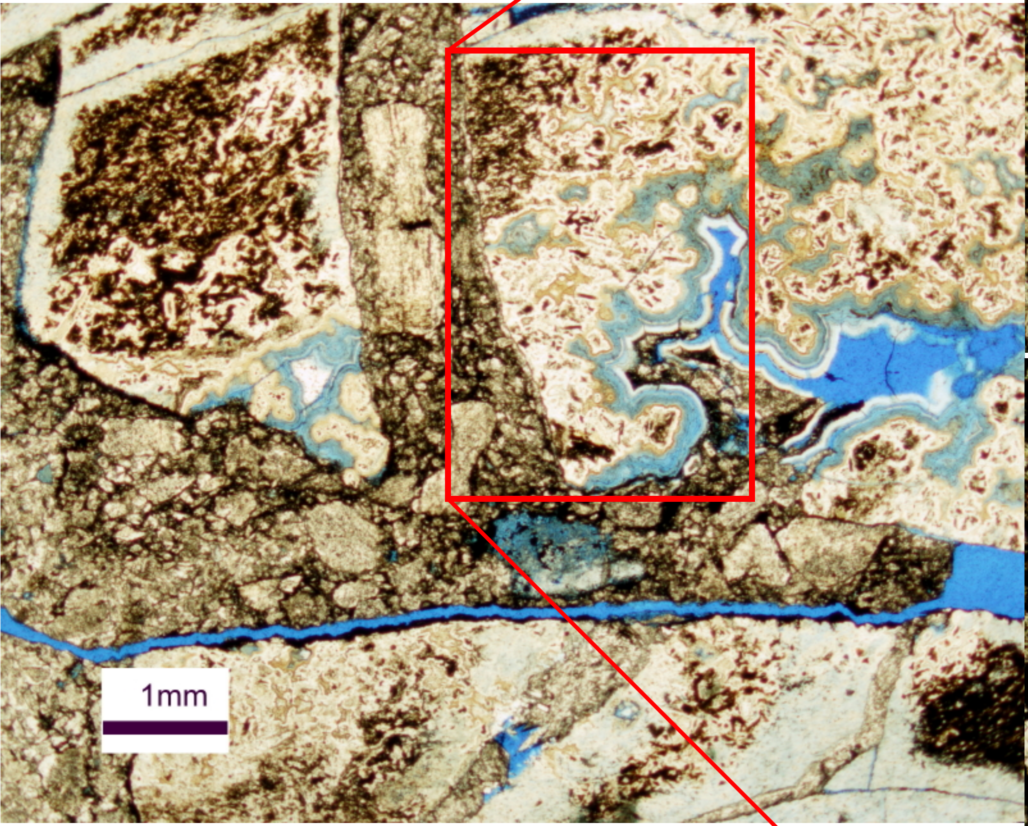
P&M #12
505.2 ft
2nd tripolite sequence

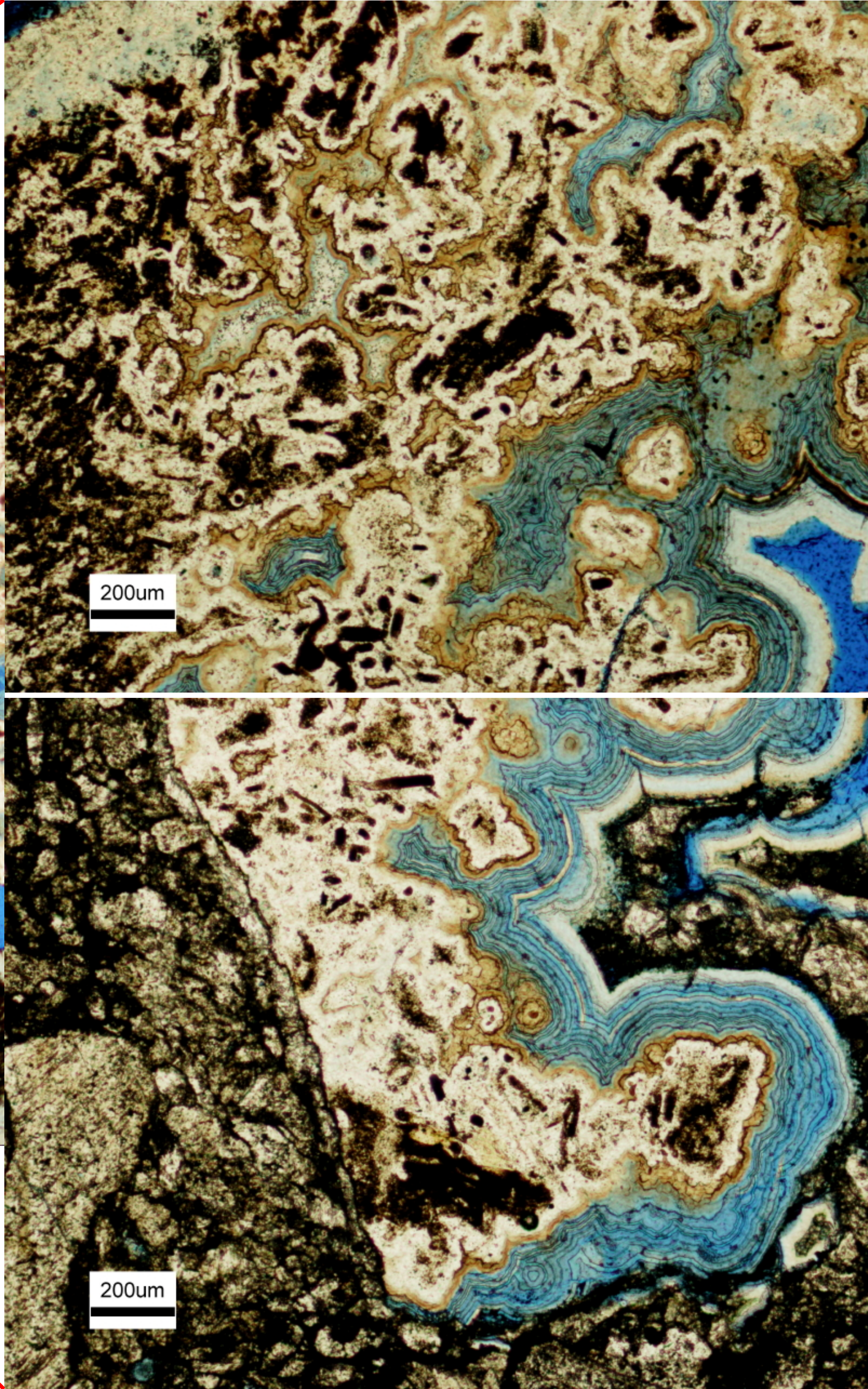


Crinoids, forams, bivalves, brachiopods, monaxon sponge spicules

Brecciated microporous chert with complex textures infilled by crinoidal packstone

(tripolite)

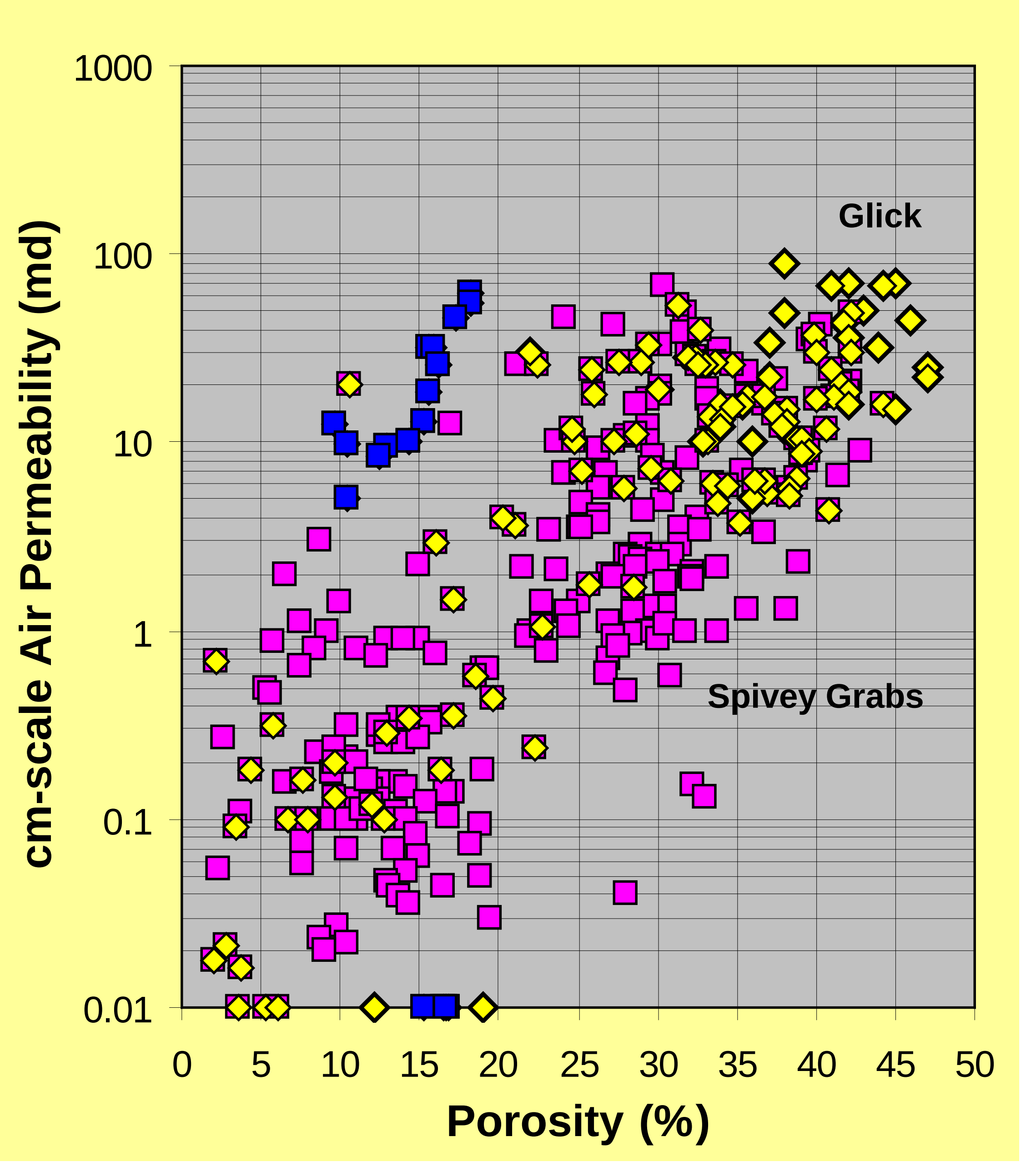




P&M #12
529.4 ft
2nd tripolite sequence

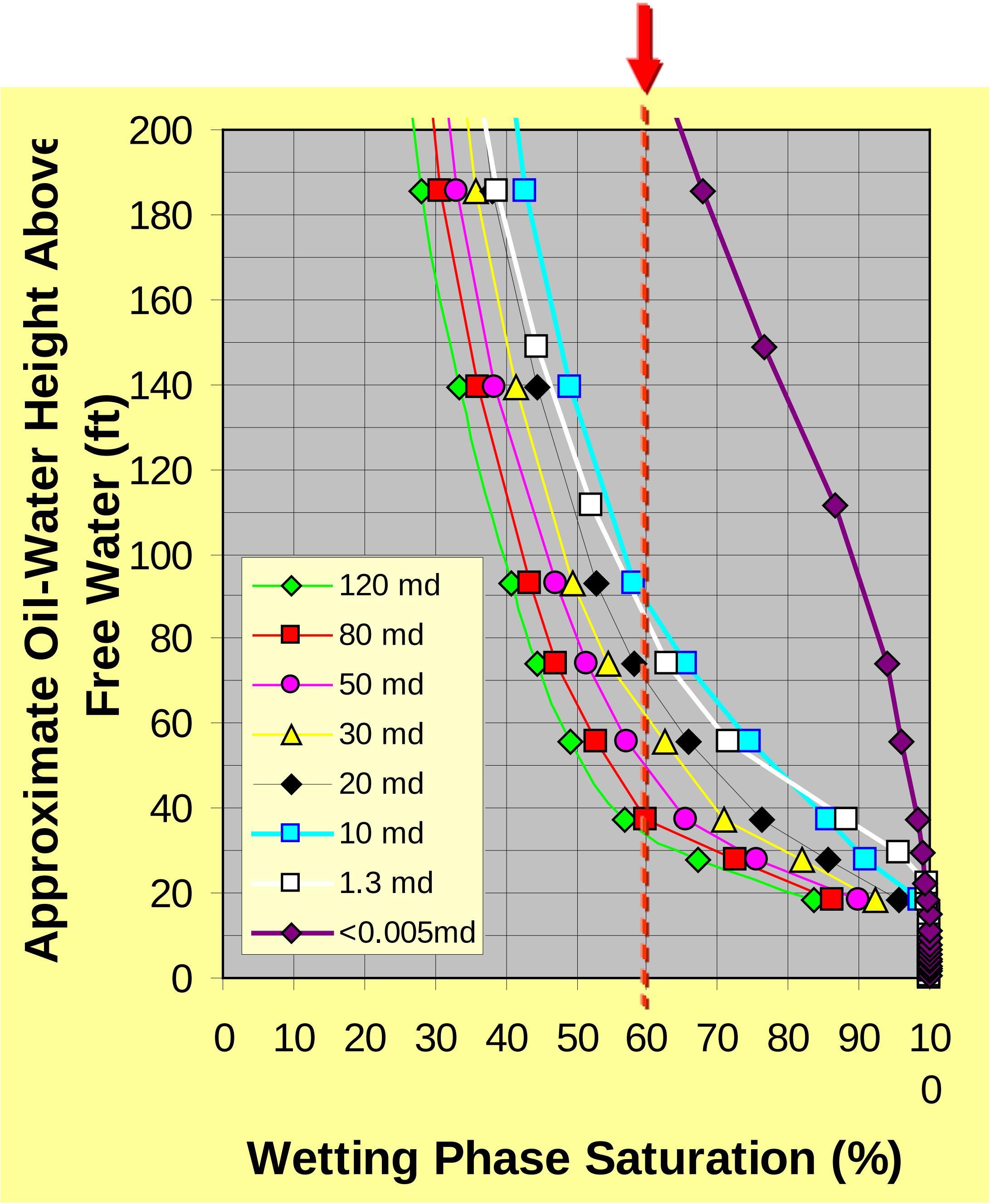
Air permeability versus porosity for normalized whole core and plugs for four chat fields

- **Anson-Bates sucrosic dolomites (blue square) lie off chert trend**



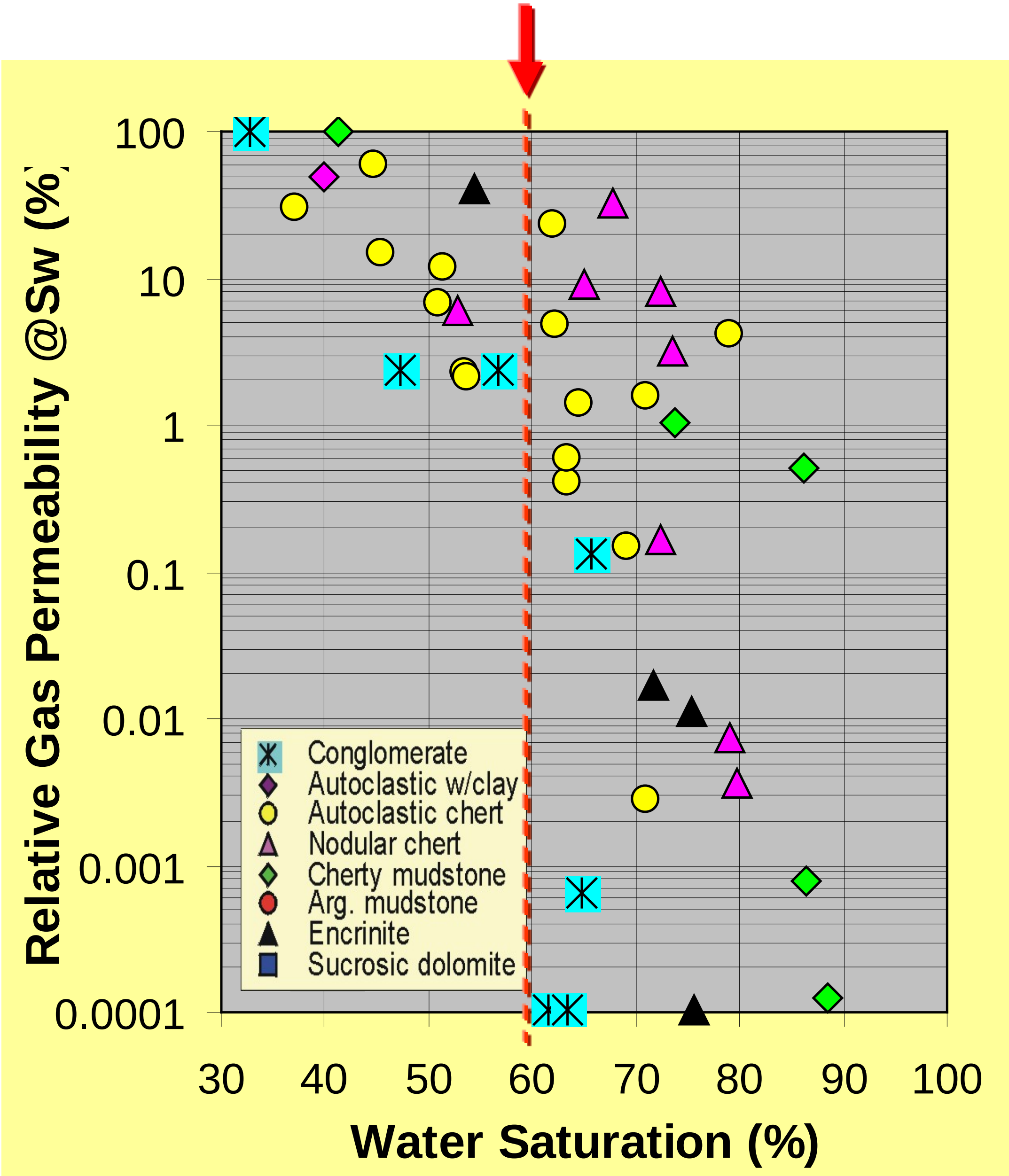
Byrnes in Watney et al. (2001)

Capillary pressure curves – Glick Field



(after Duren , 1960)

- Autoclastic chert facies and clay
- All curves exhibit high irreducible saturations indicative of microporosity and consistent with wireline log measurements of high water saturation
- Purple diamond shows the curve for the green infilling clay



Byrnes in Watney et al. (2001)

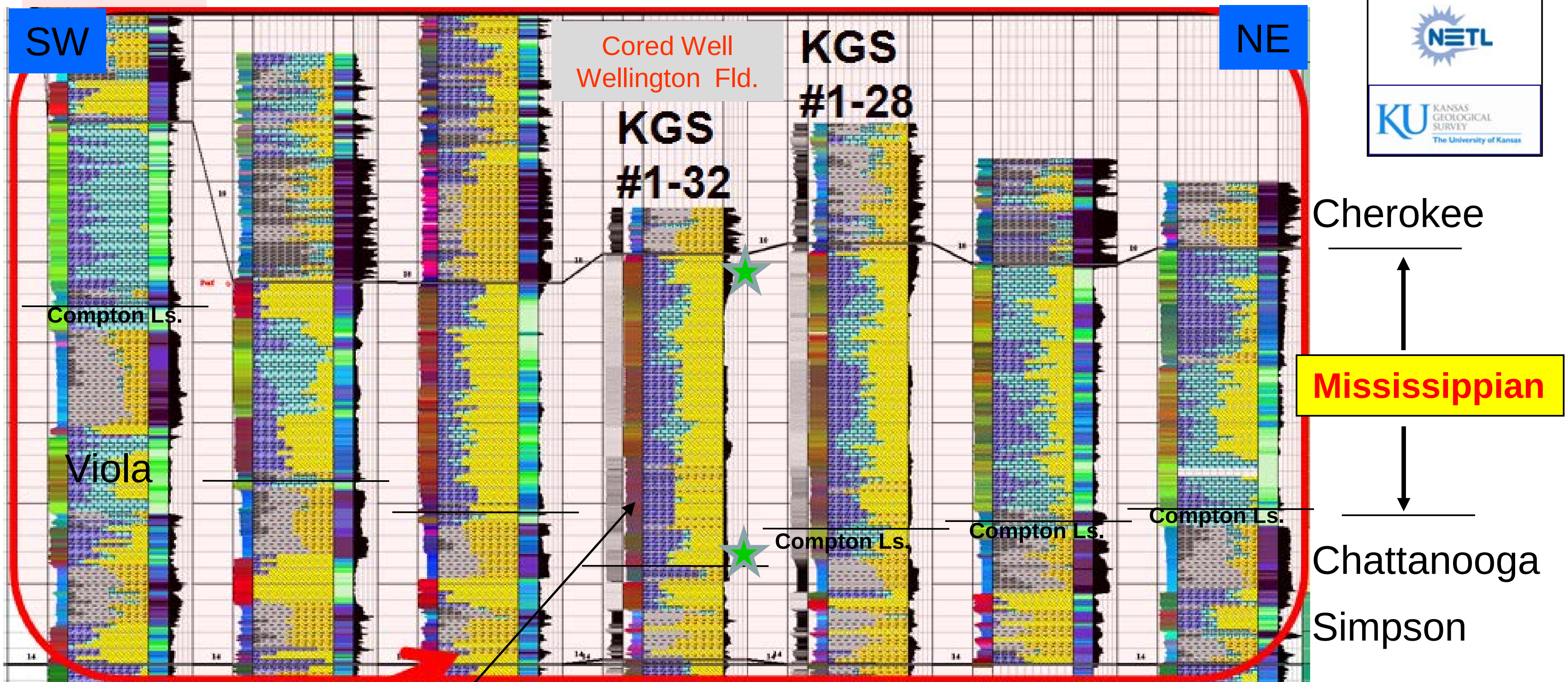
Relative gas permeability versus water saturation

- **Saturations -Pc $_{\text{air-brine}}$ = 33 psia, 55 feet above free water level**
- **<u>Relative permeabilities to gas decrease rapidly at water saturations greater than 60%</u>**
- **Nodular cherts, dolomite mudstones, and bioclastic wackestones exhibit low $k_{rg,Sw}$**

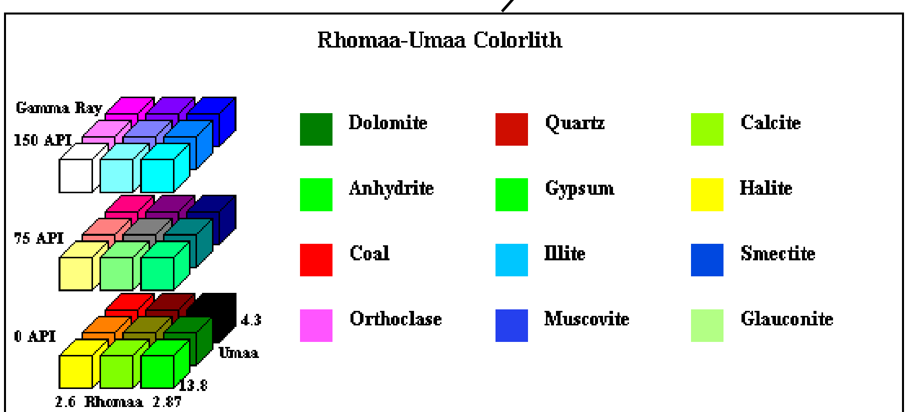
West side
Hartner Field
Barber Co.

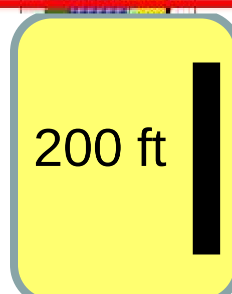
Lithologies Within the Mississippian Oil Play (Chert Embayment, South Central Kansas)

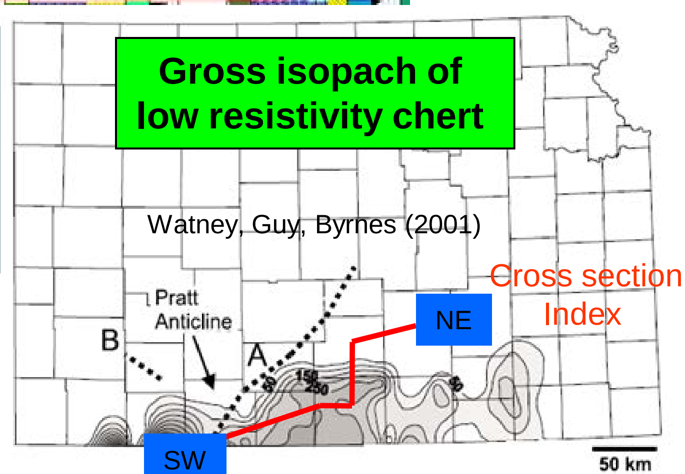
DOE-FE0002056



Datum: Top Arbuckle Group



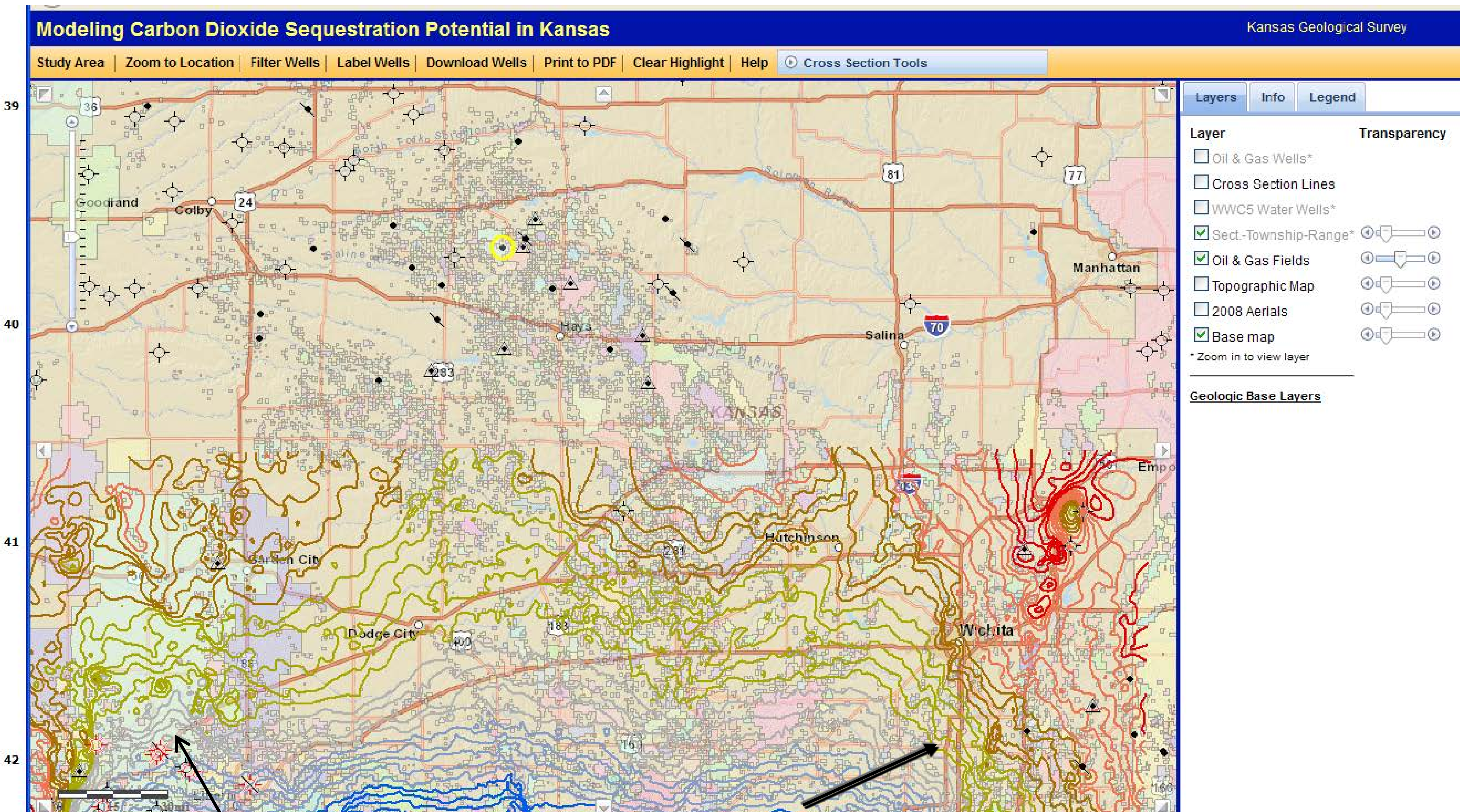




Structure Top Mississippian with oil and gas fields

- interactive map for project area of DOE-CO2 project (DE-FE0002056)

- access to map layers and digital (LAS) logs and viewer



30 mi

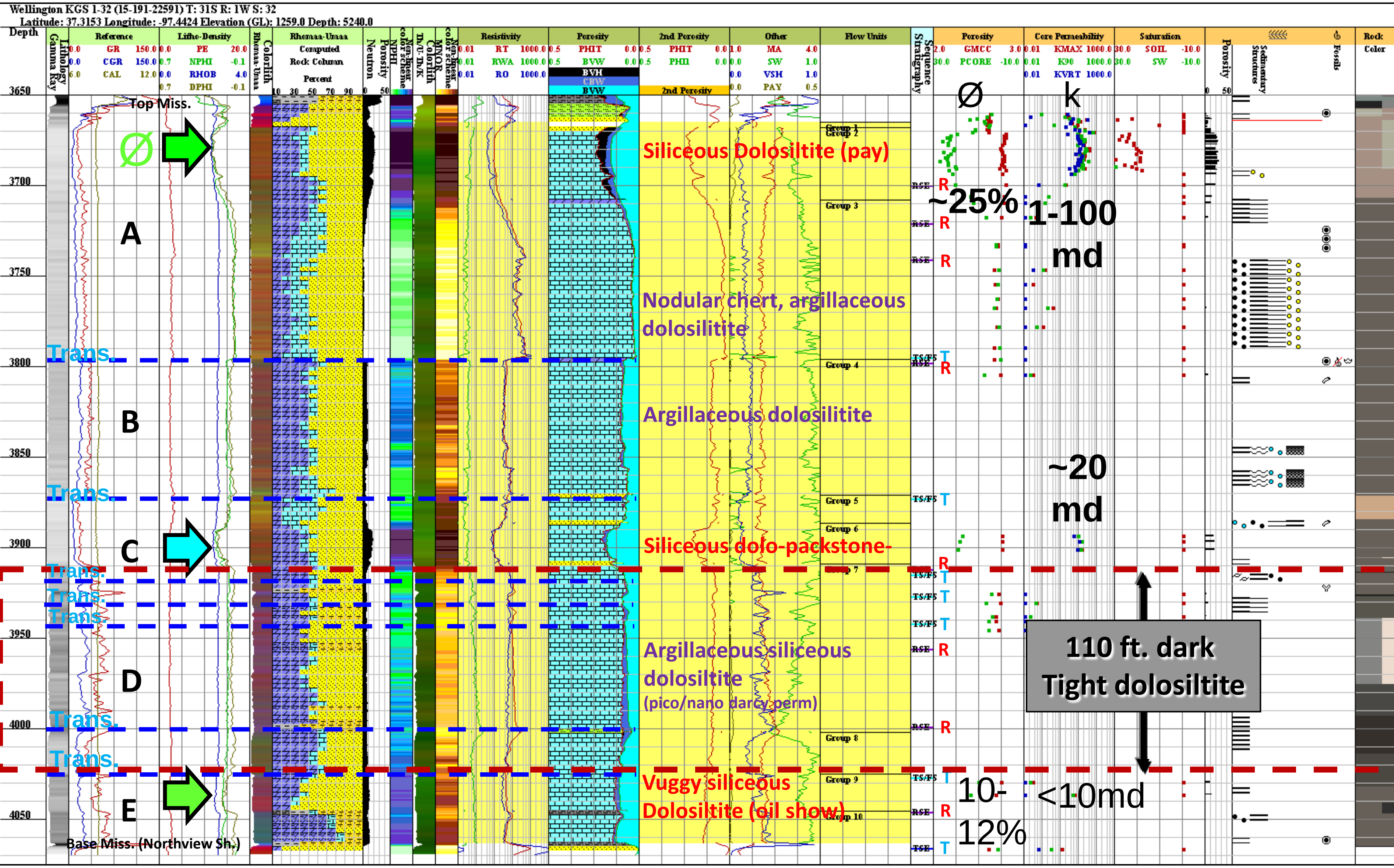
Cutter Field

(**new seismic & well**)

Wellington Field

http://maps.kgs.ku.edu/co2/?pass=project

Cored Well, Berexco Wellington KGS #1-32
Top Mississippian to Kinderhook Shale (410 ft)

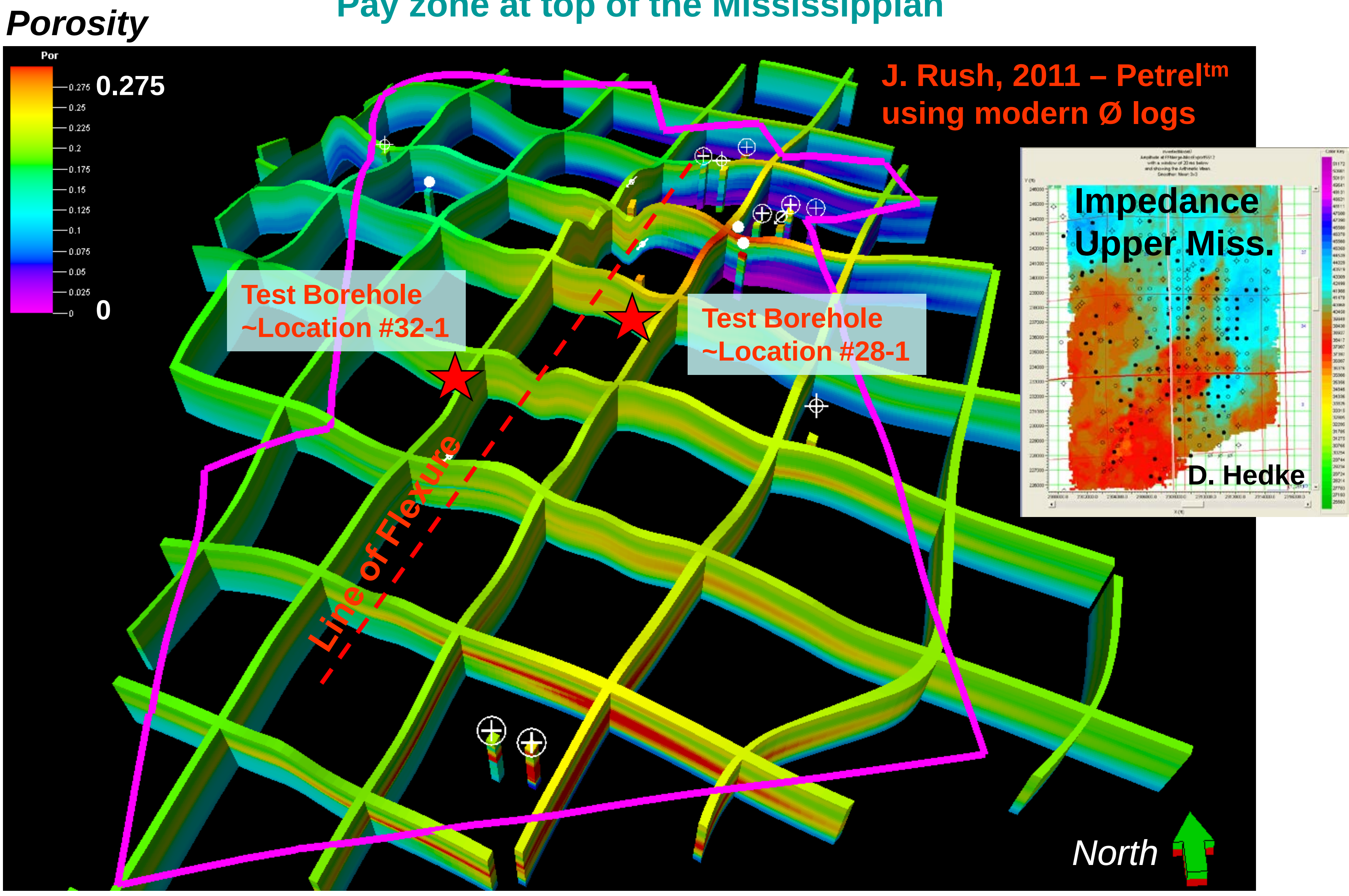


Freeware:http://www.kgs.ku.edu/stratigraphic/PROFILE/

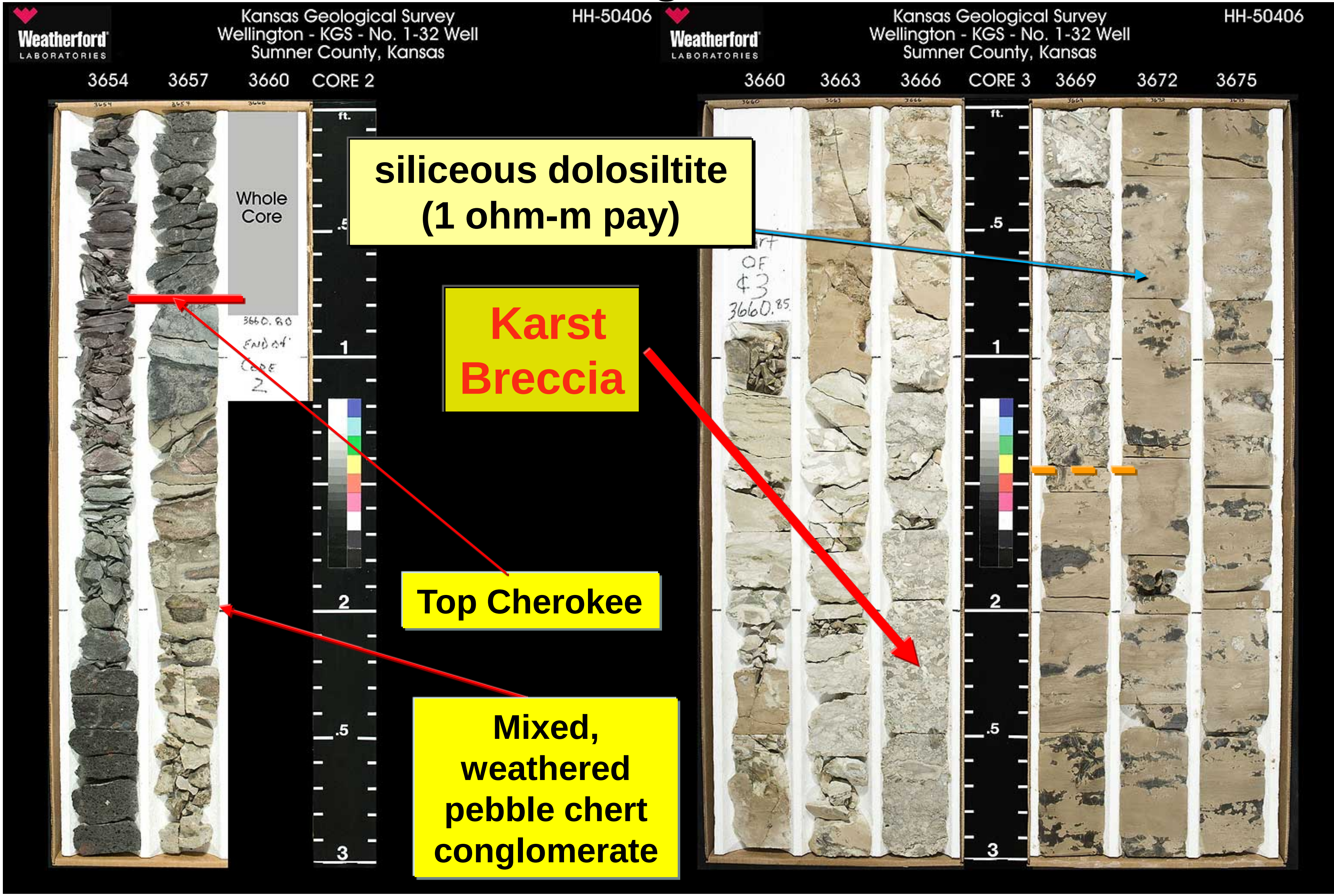
Wellington Field

Porosity Fence Diagram

Pay zone at top of the Mississippian

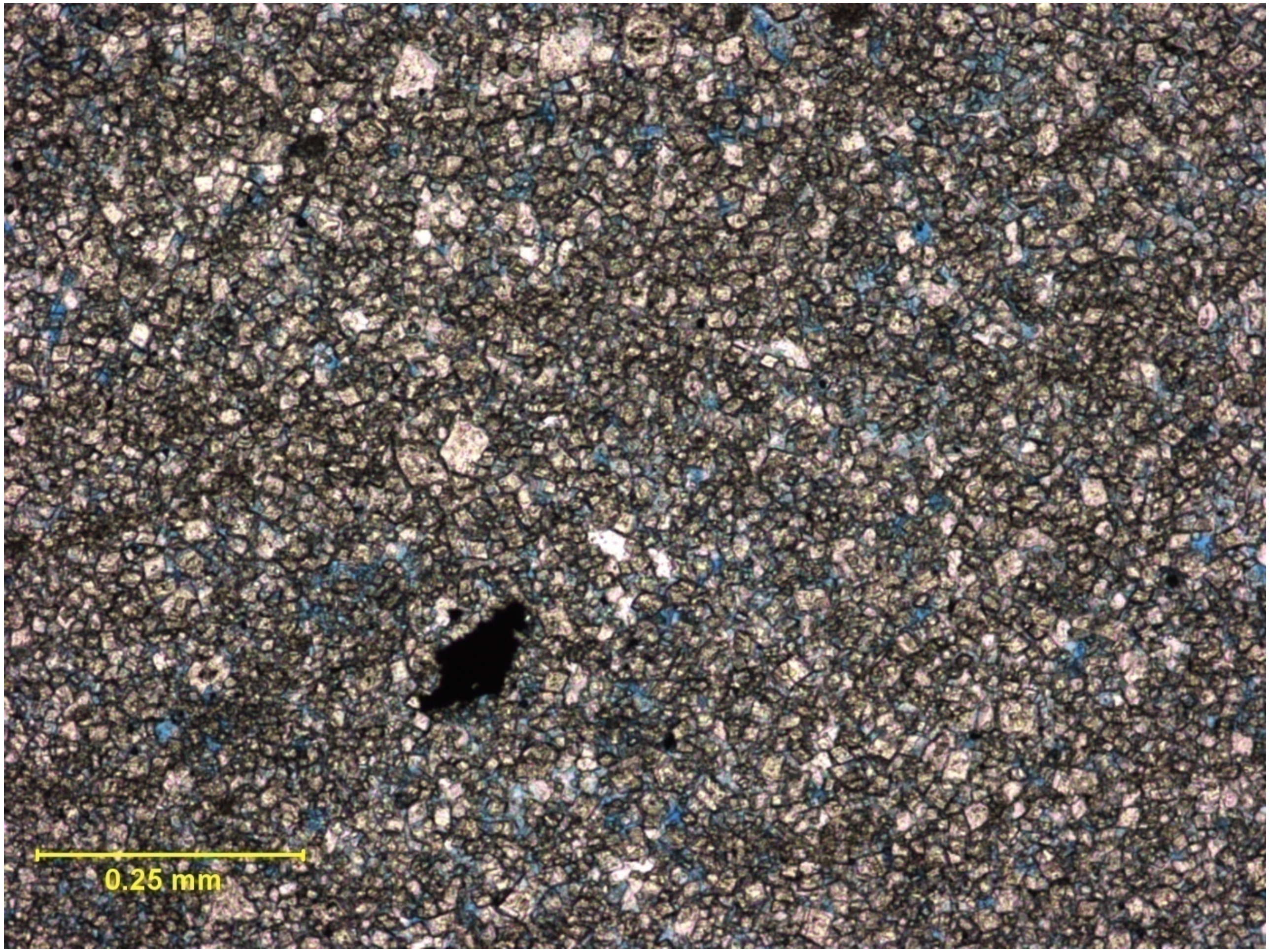


Mississippian pay zone in Berexco Wellington KGS #1-32



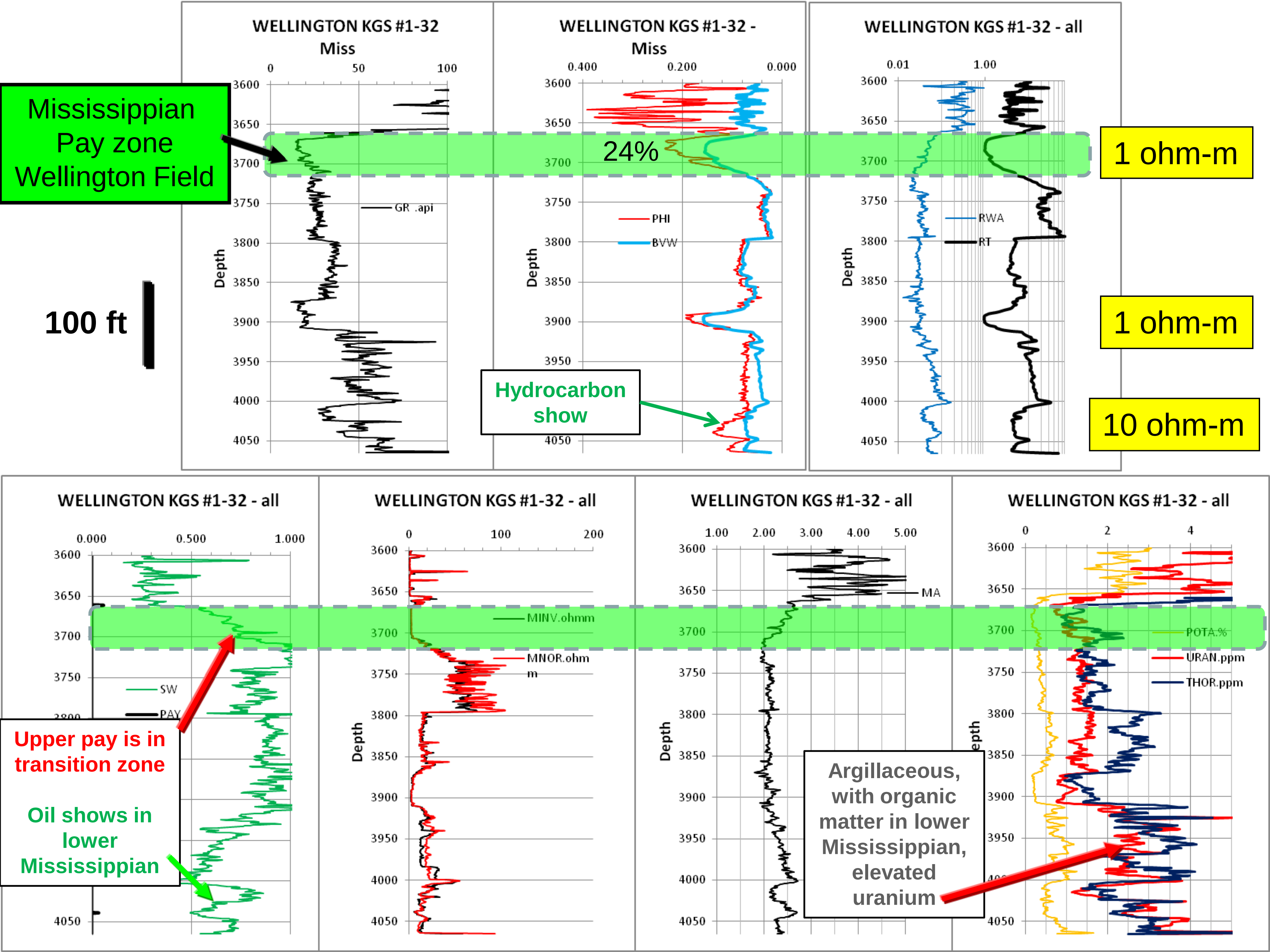
Mississippian Pay Zone Mineralogy

3670.6’



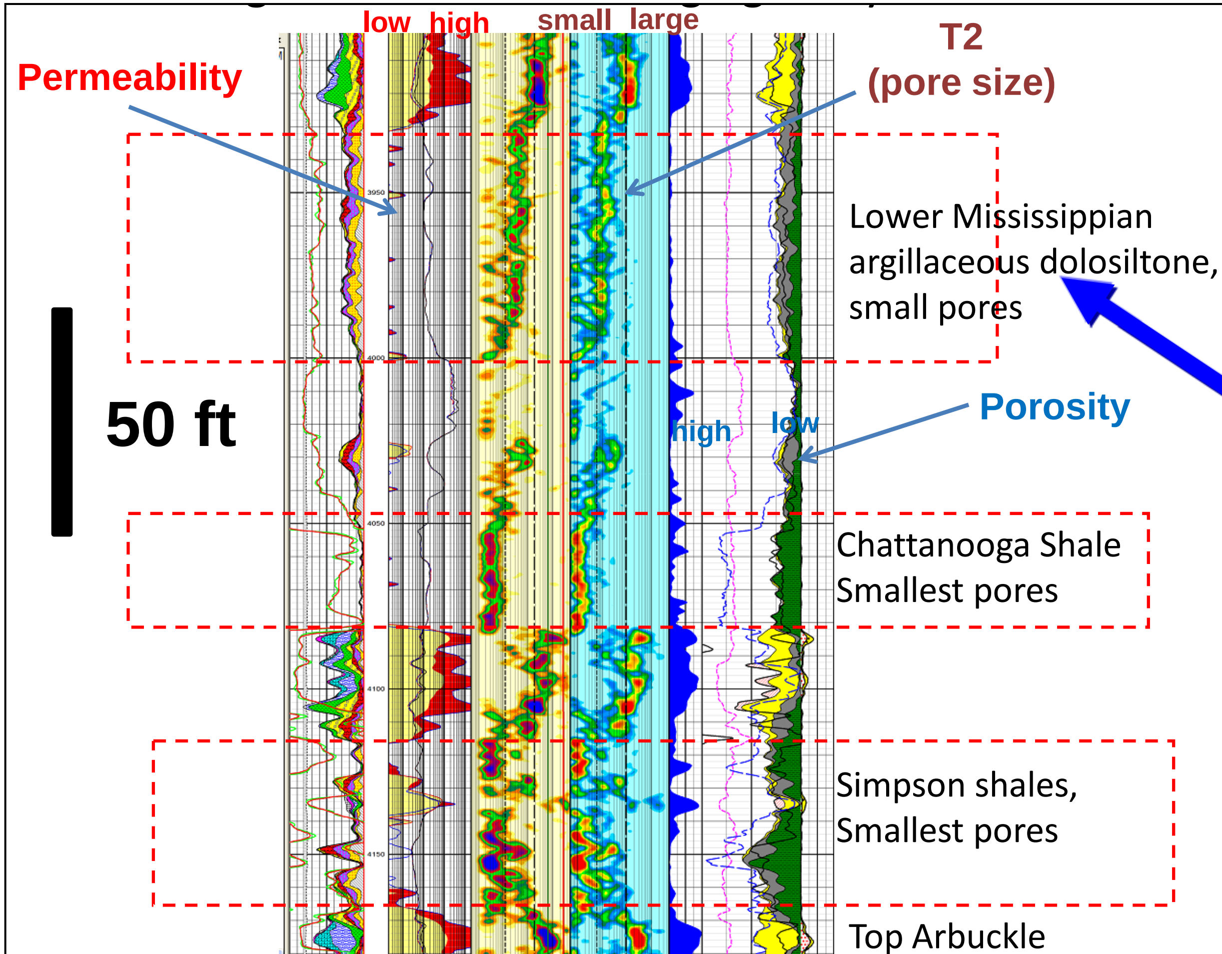
- **Plain Light (10x zoom)**
- **Finely crystalline subhederal dolomite with intercrystalline porosity (micropores)**
- **Opaque oxide/sulfide (?) present and secondary replacive anhydrite present**

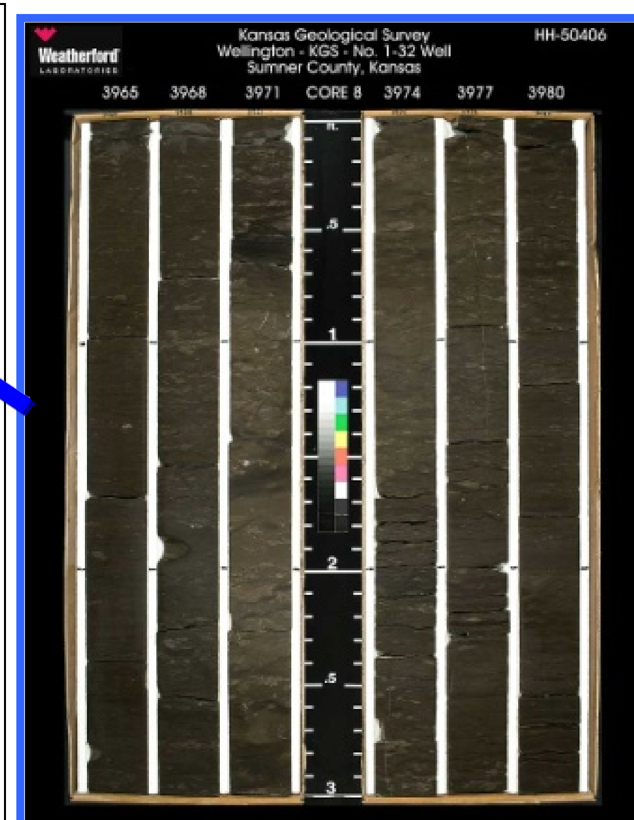
TS provided by Datta & Barker, KSU



WELLINGTON KGS #1-32 Miss
WELLINGTON KGS #1-32 - Miss
WELLINGTON KGS #1-32 - all
Mississippian Pay zone Wellington Field
100 ft
GR .api
PHI
BVW
24%
Hydrocarbon show
RWA
RT
1 ohm-m
1 ohm-m
10 ohm-m
Depth
SW
PAY
MINV.ohmm
MNOR.ohmm
MA
POTA.%
URAN.ppm
THOR.ppm
Upper pay is in transition zone
Oil shows in lower Mississippian
Argillaceous, with organic matter in lower Mississippian, elevated uranium

230 ft gross thickness interval of primary caprock
in KGS #1-28 (injection well)
including lower Mississippian tight dark dolomitic siltstone –
illustrated by nuclear magnetic resonance log





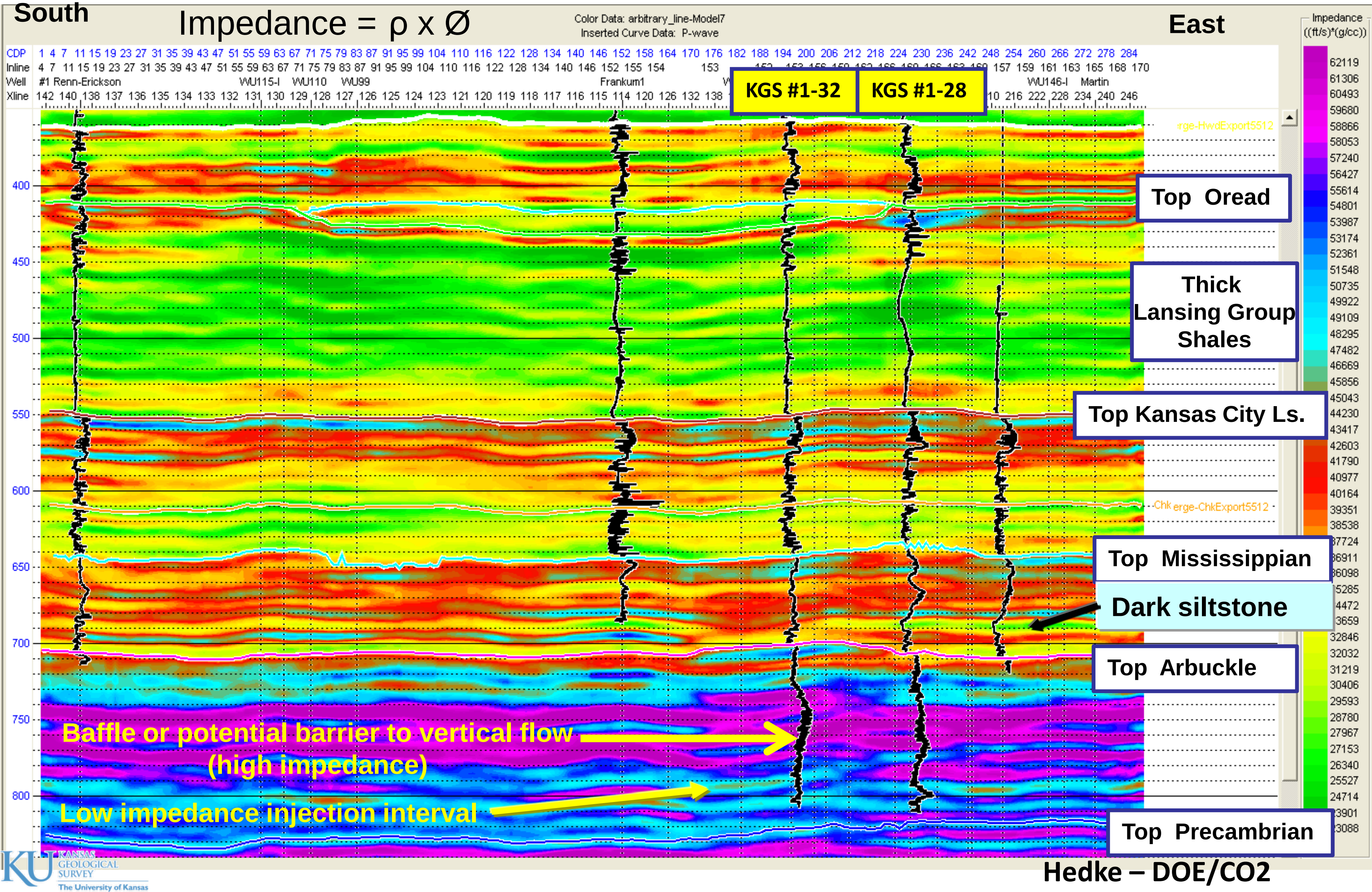
Caprock evidence of lower Miss. :

- Micro-nano darcy perm
- Quiet fracture wise in interval
- Organic matter ~2% TOC

KANSAS GEOLOGICAL SURVEY
The University of Kansas

Arbitrary seismic impedance profile

distinct Mississippian pay and dark argillaceous siltstone facies in "Pierson Fm."
also mid-Arbuckle tight, lower Arbuckle injection zone



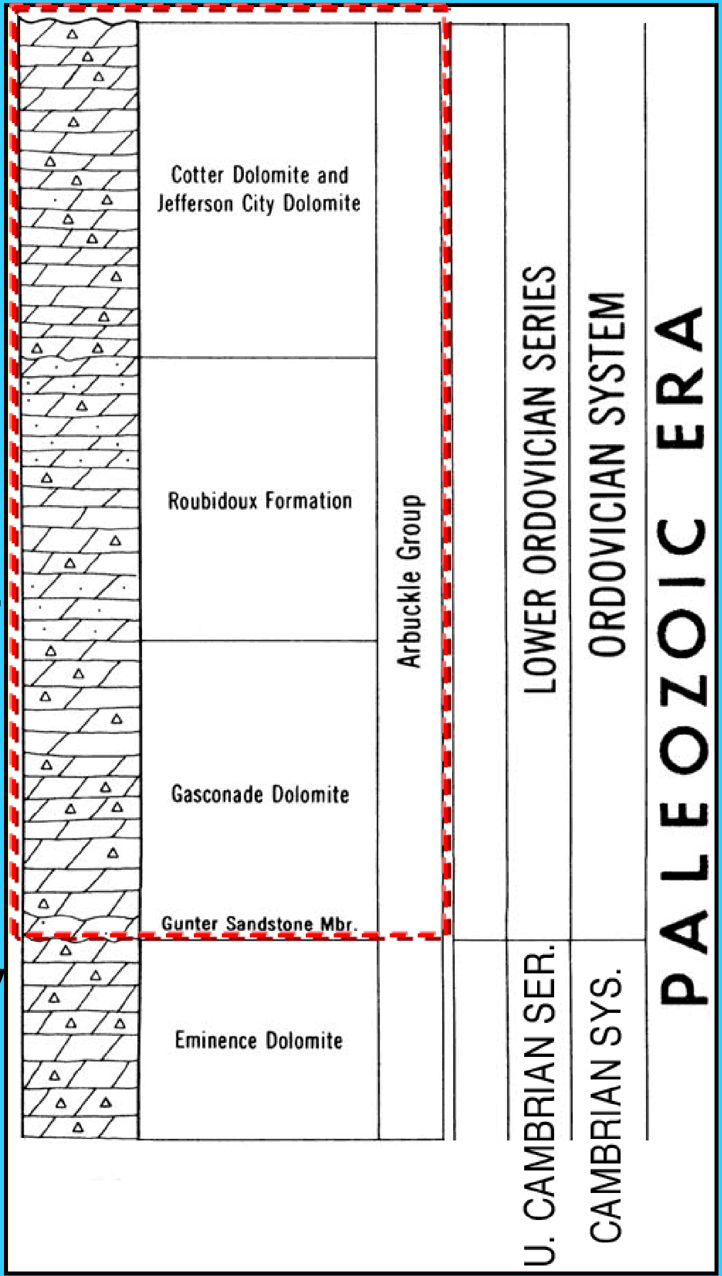
Hedke – DOE/CO2

Summary of Kansas Mississippian Play

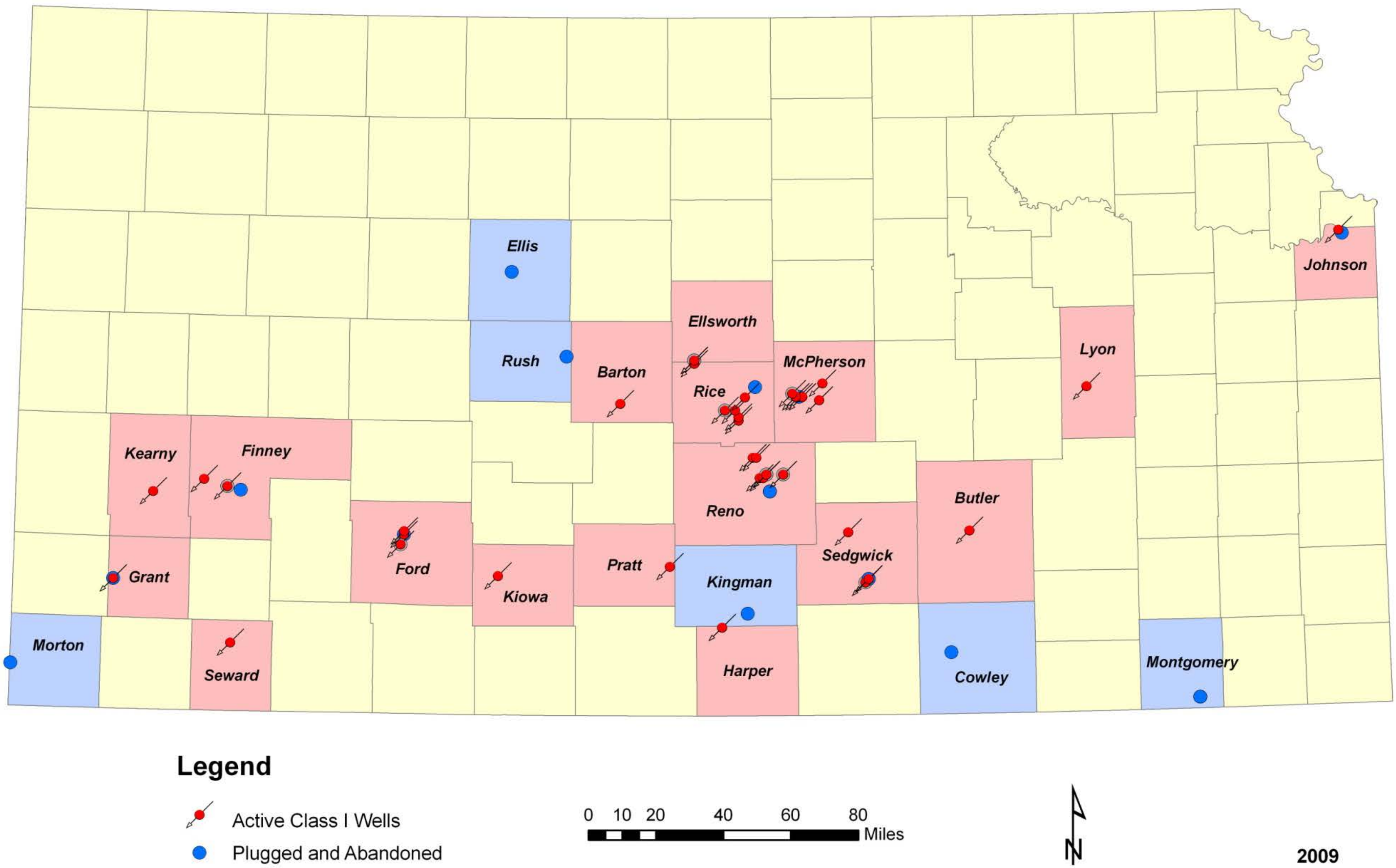
- Stratified reservoir with distinct pay lithofacies with contrasting petrophysical properties that affect ability to produce from them.
  - Dolomitic grainstone-packstones, tripolitic (microporous) chert, & dolosiltite are primary pay lithofacies
  - Tripolites are distinct microporous chert lithofacies capping shallowing upward cycles
  - Capillary pressure measurements indicated long (>40 ft) transition zones that are lithofacies dependent
  - Southern shelf margin distinguished by complex stacking and progradation into developing Arkoma and Anadarko basins
- Significant local and regional structure coupled with changes in sea level affect --
  - Shelf configuration and depositional facies, early & late diagenesis
  - Pay compartmentalization by early and late structural movement

Arbuckle Fluid Disposal

- UIC Class I and II wells
- Stratigraphy
- Hydrostratigraphy
- Petrophysical properties
- Controls on permeability – Lithofacies, diagenesis, fracturing
- Preview western Kansas portion of DOE-CO2 study

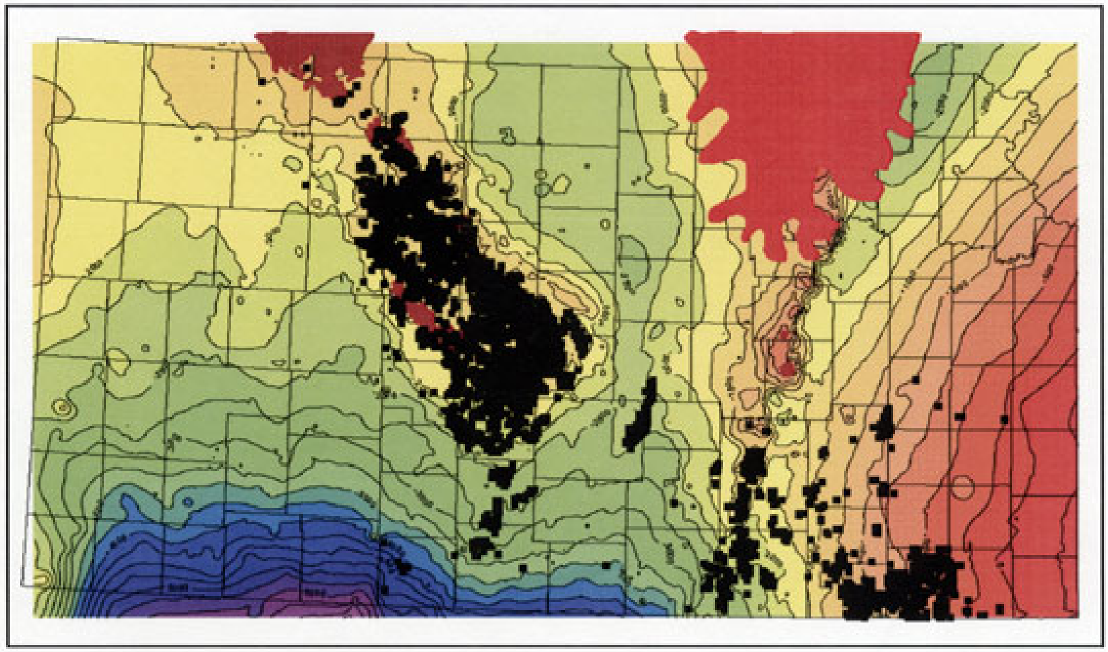


UIC Class I Disposal Wells

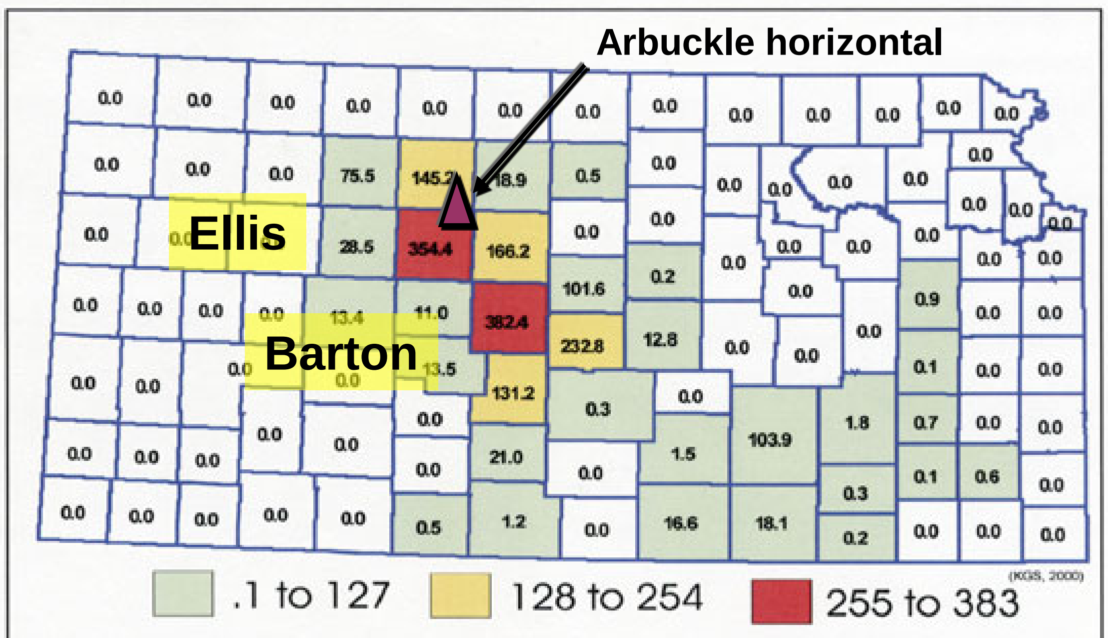


2009

Petrotek



A

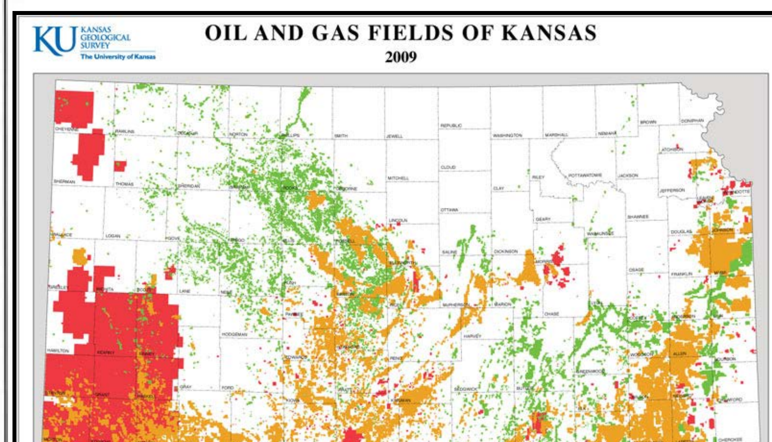


B

A) Structure map (subsea elevation) on Arbuckle

B) Arbuckle cumulative oil production (MMBO) by county

-- Of the 31 counties in which the Arbuckle has been productive, over 70% of the production has come from the 10-county area coinciding with the CKU.



GEOLOGIC CONSIDERATIONS FOR CLASS I DISPOSAL WELLS

Ken Cooper & Tom Hansen

Petrotek Engineering Corp. Bittersweet Energy, Inc.

CLASS II DISPOSAL WELLS KANSAS CORPORATION COMMISION

10,331 enhanced oil recovery (EOR)
5,484 salt water disposal wells (SWDW)

76 Formations Used for Injection

CLASS II DISPOSAL WELL TOP 10 FORMATIONS

Arbuckle	1987 SWDW
Cedar Hills	820 SWDW
Lansing-KC	326 SWDW
Mississippian	264 SWDW
Granite Wash	104 SWDW
Glorietta	101 SWDW
Stalnaker	86 SWDW
Douglas	61 SWDW
Topeka	54 SWDW
Hunton	51 SWDW

Cooper/Hansen 2009 KDHE Seminar

K. Cooper and T. Hansen (2009)

Why is Class I injection technology so safe for use in Kansas? (continued)

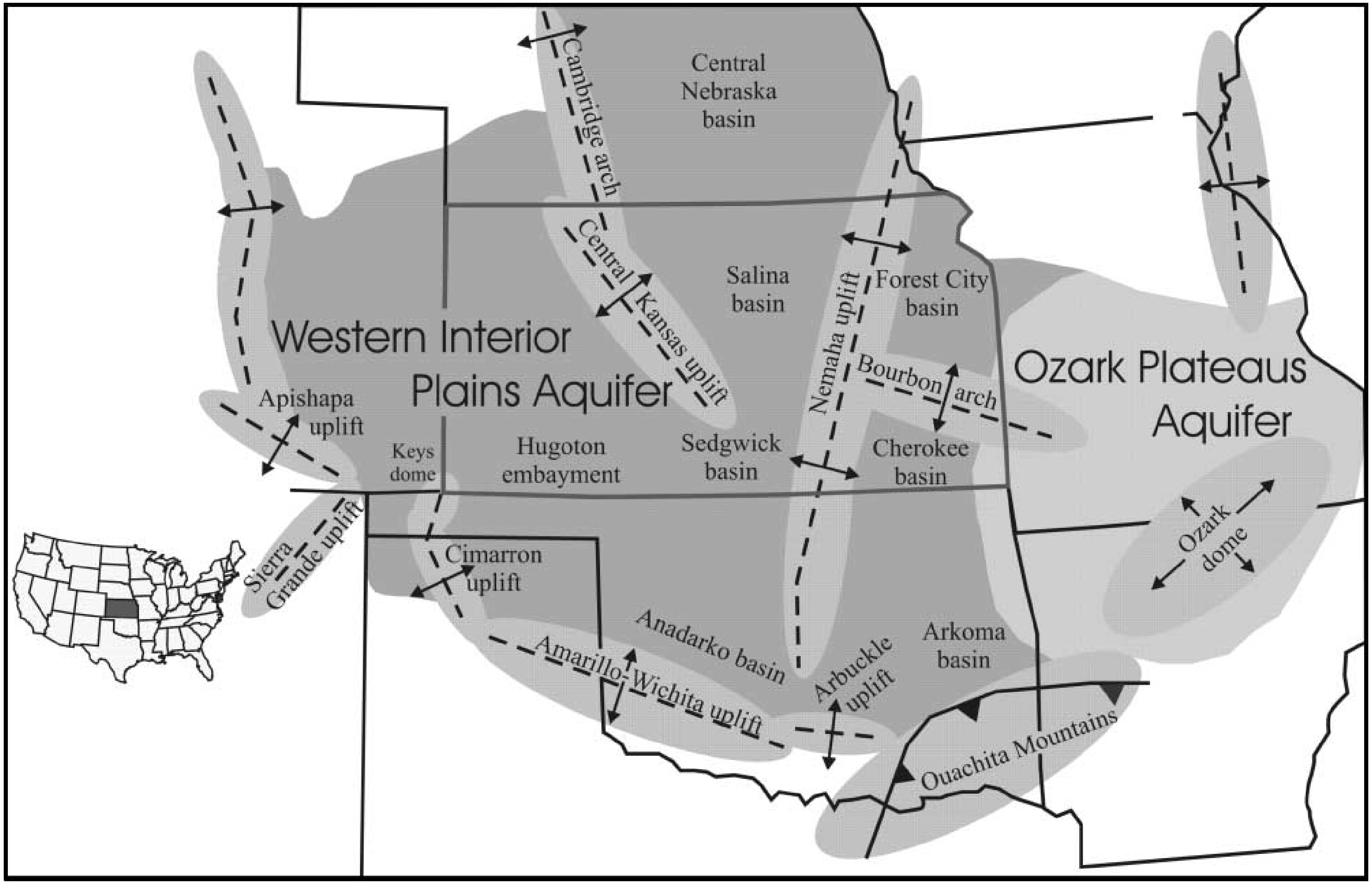
- Well developed UIC programs at both the State and Federal levels (regulation, policy, and procedure)
- Available injection zones with substantial injectivity and other required properties
  - Depth – relatively large separation between USDW and injection
  - Thickness – relatively large, several hundred to 1,000 feet
  - Permeability – relatively high
  - Reservoirs cover large areas
  - Confinement – pervasive, thick, low permeability
  - Injection Pressure – mandated gravity flow
  - Natural Pressure Gradients – fluid stands below ground level
  - Often no cone of influence (fluid can naturally flow downward into injection zones)

Cooper/Hansen 2009 KDHE Seminar 50

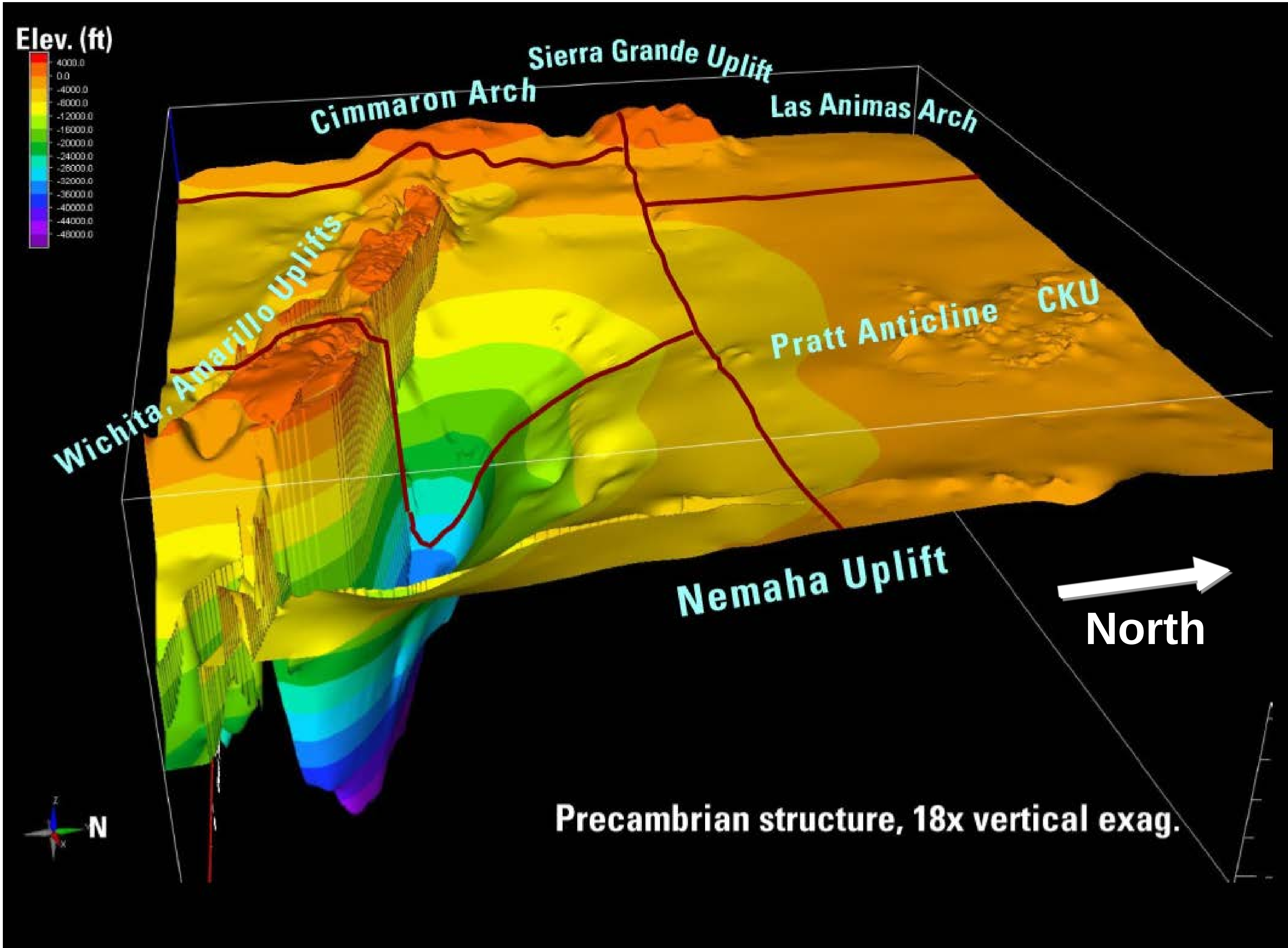
K. Cooper and T. Hansen (2009)

Typical Class I well:
10 to 1000 gpm
(460 to 46,000 bbls/day)

Structural features and aquifer systems of the mid-continent



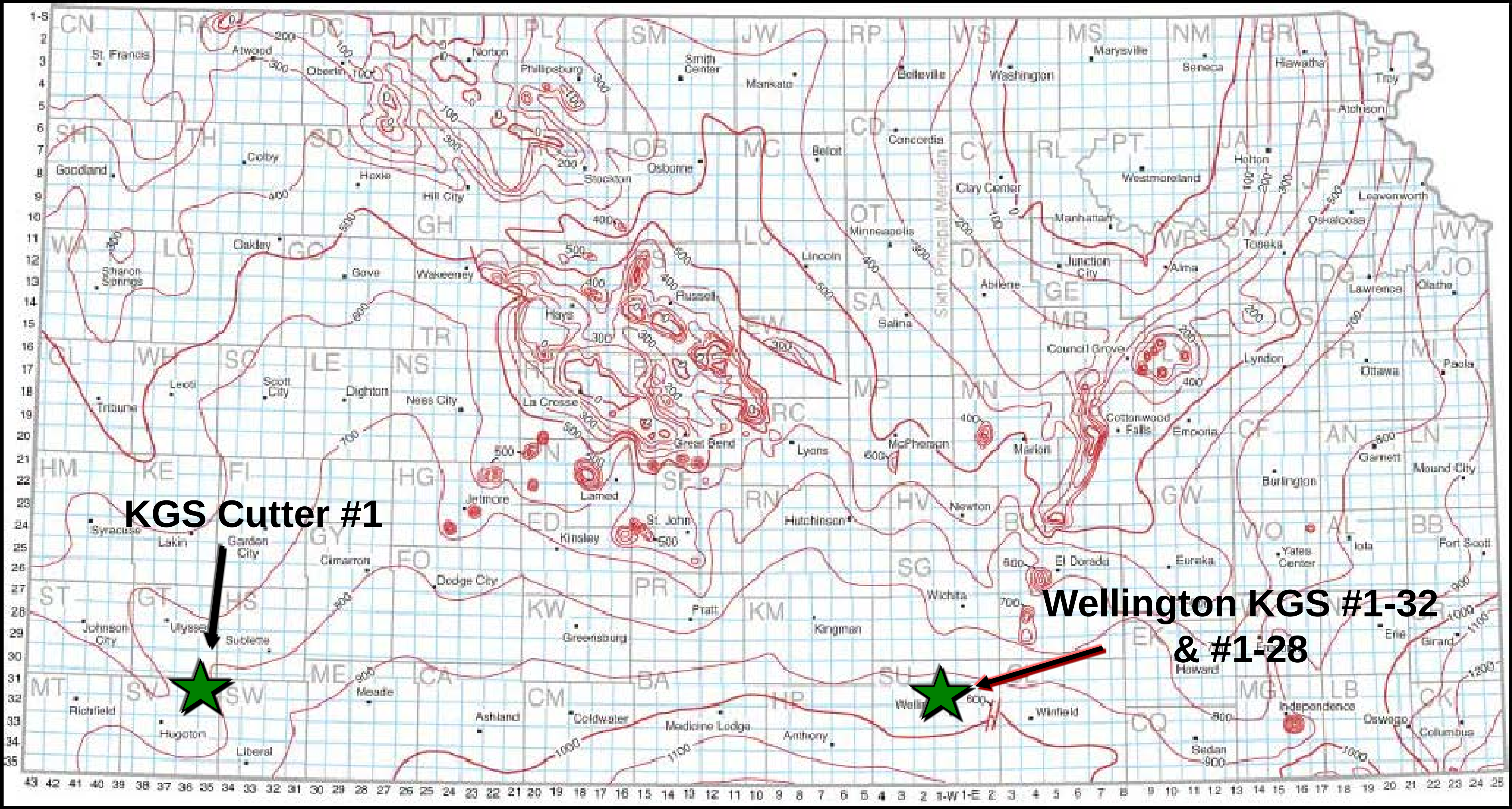
(modified from Merriam, 1963; from Jorgensen et al. (1993).
Carr et al., AAPG Bulletin, v. 89, no. 12 (December 2005), pp. 1607–1627



IHS (2009); KGS data; Adler and others (1971), modified after Bayley and Muehlberger (1968)

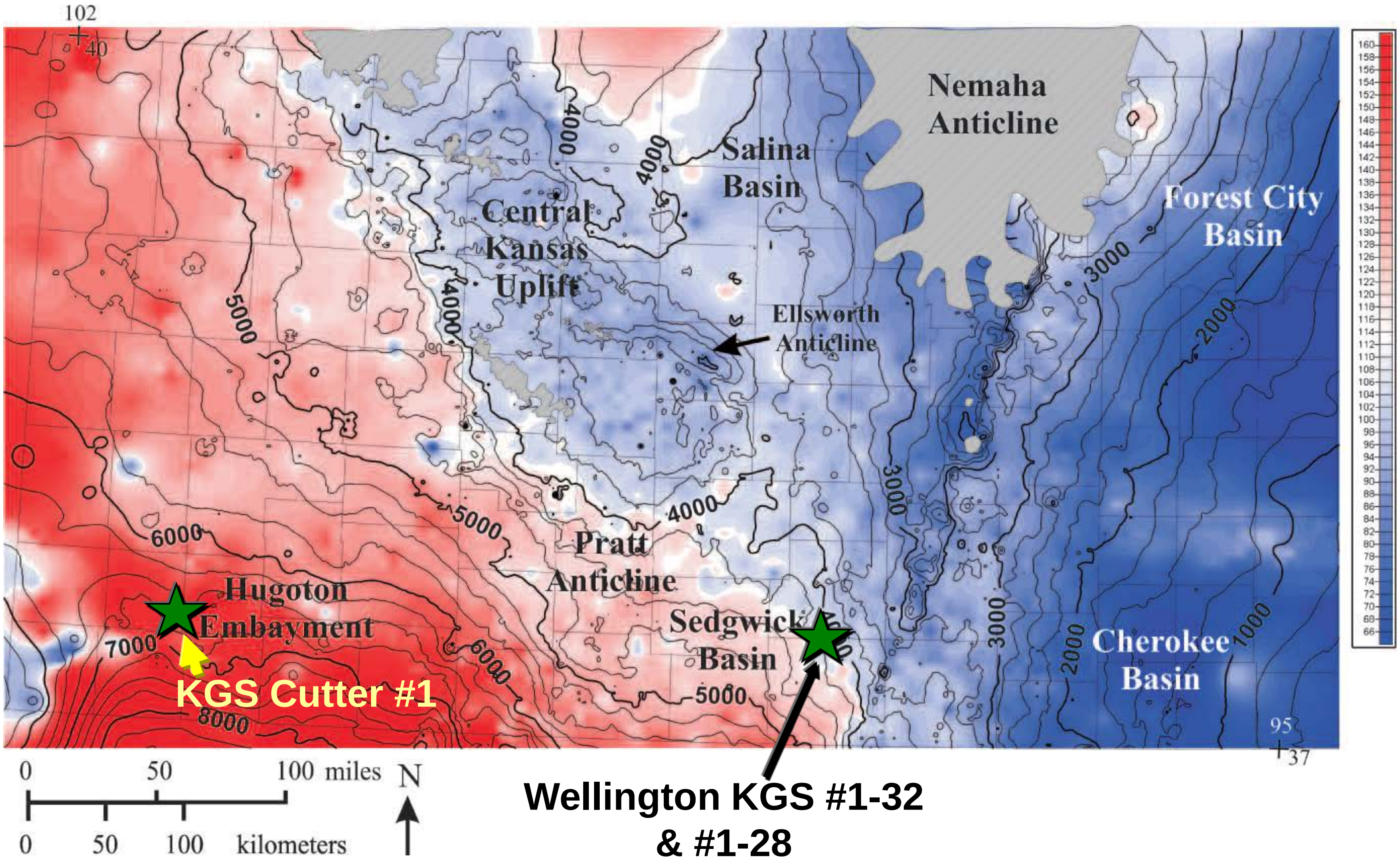
D. Higley, USGS, 2012

Arbuckle Isopach Map



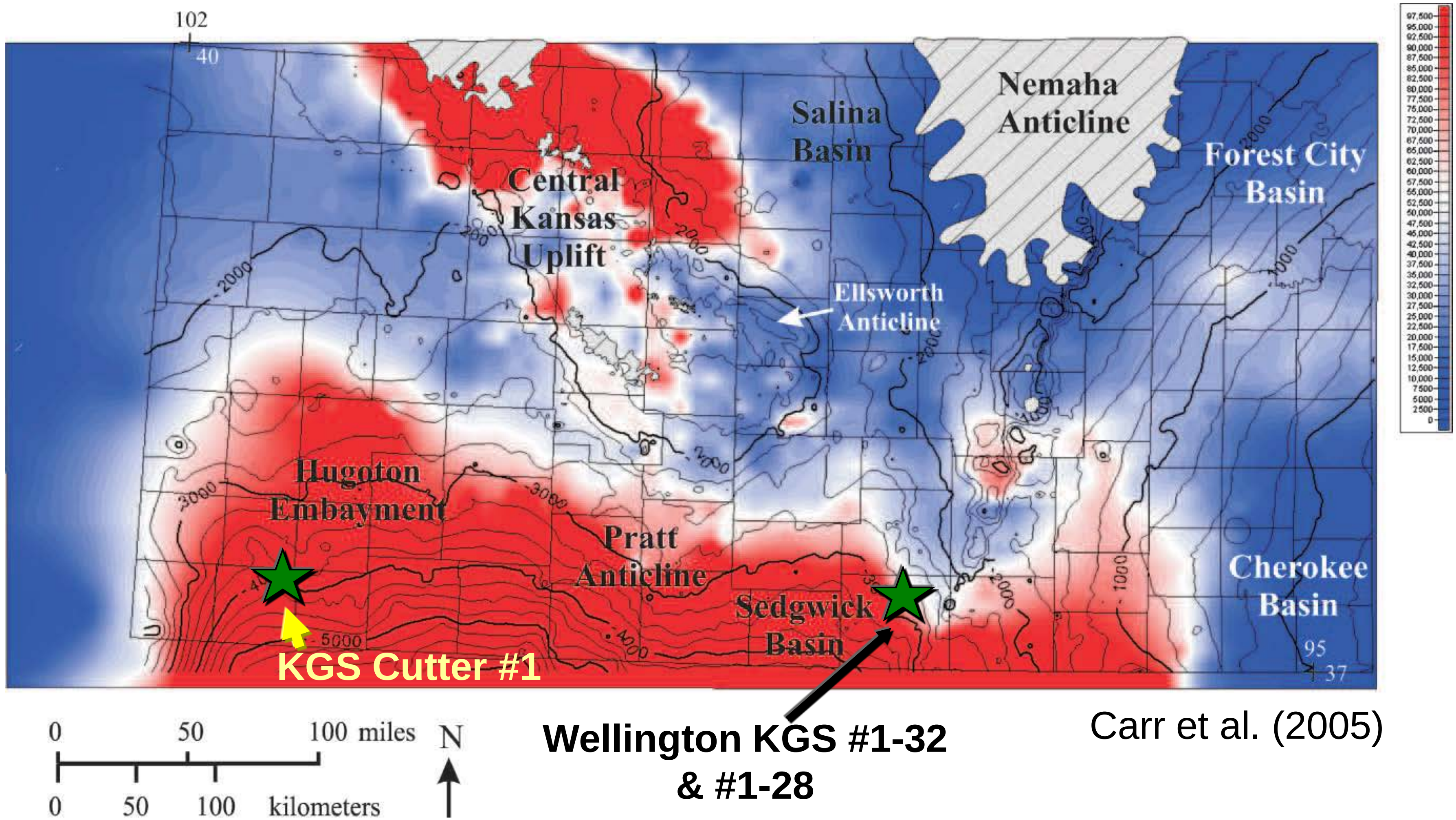
KGS Website

Map of corrected BHT values in Arbuckle for Kansas based on 19,161 points (CI = 2°F) overlain on structure top Arbuckle



Carr et al. (2005)

Total dissolved solids in Arbuckle brines (color C.I. = 2500 ppm TDS)

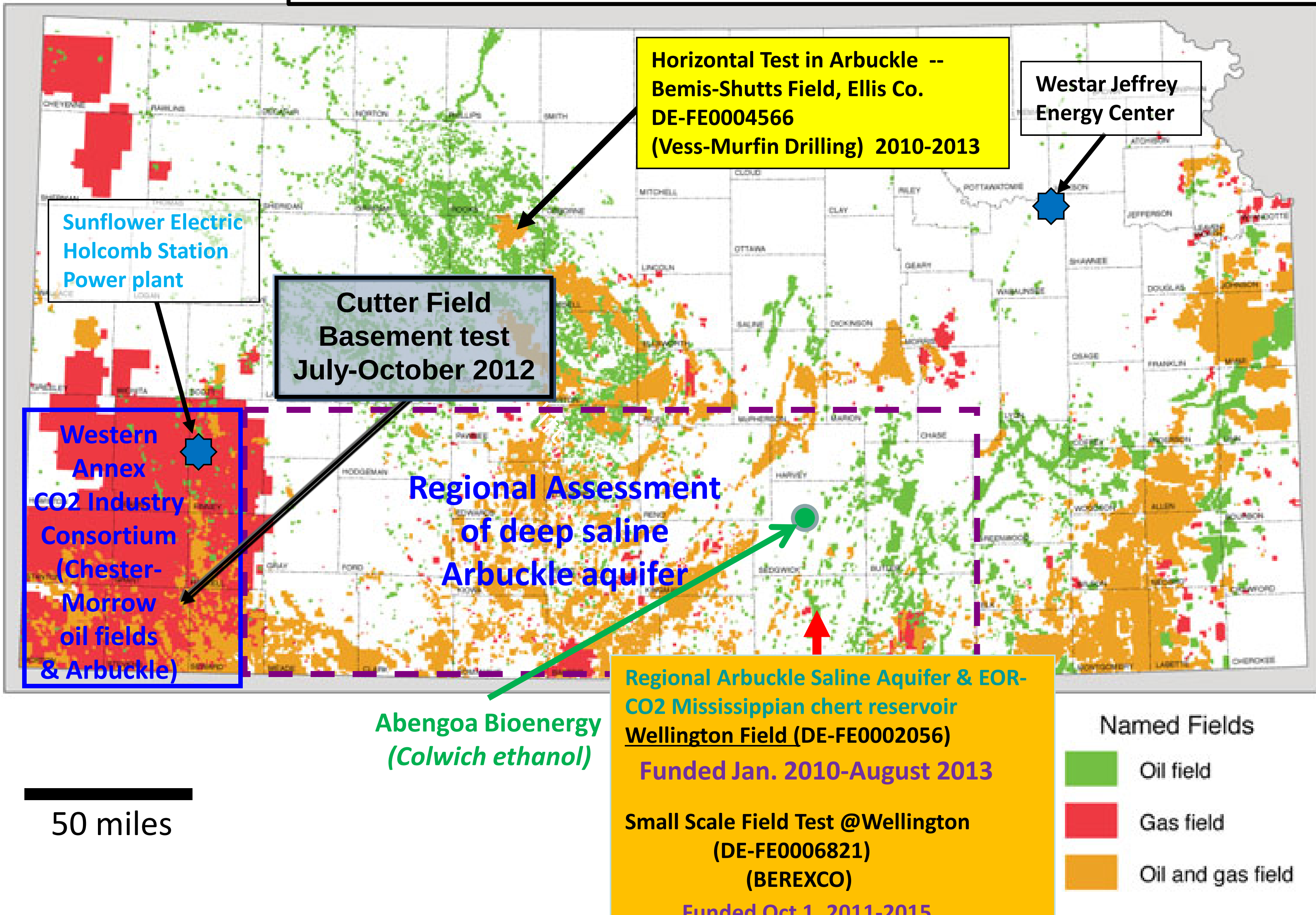


Carr et al. (2005)

All TDS concentrations more than 100,000 ppm are shown in red. Data were derived from Arbuckle water samples from various sources (2929 records).

KANSAS GEOLOGICAL SURVEY
The University of Kansas

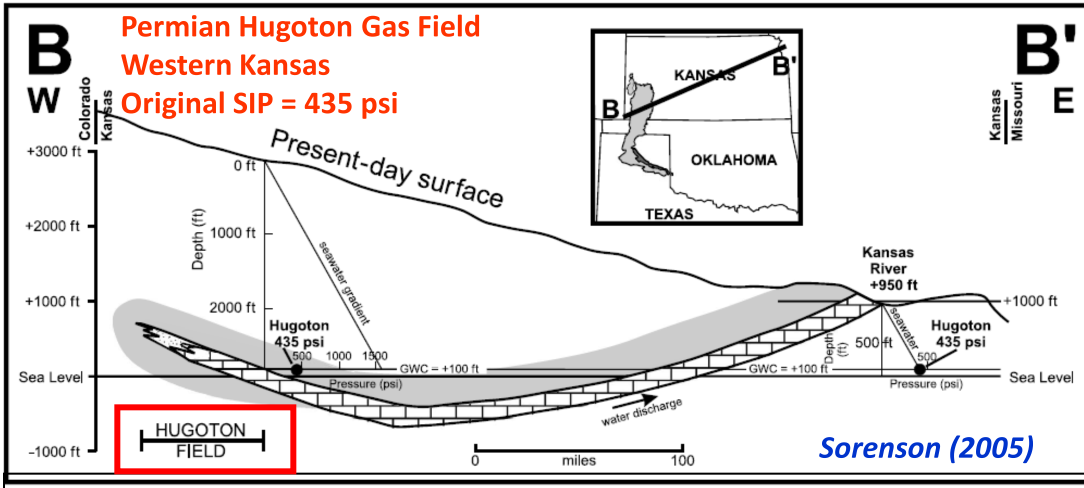
Areas of DOE-Funded CO_2 Investigations by the KGS and Partners



http://www.kgs.ku.edu/PRS/petro/ogSheetMap.html

Arbuckle saline aquifer is an open system

Arbuckle Saline Aquifer Connected to Outcrop

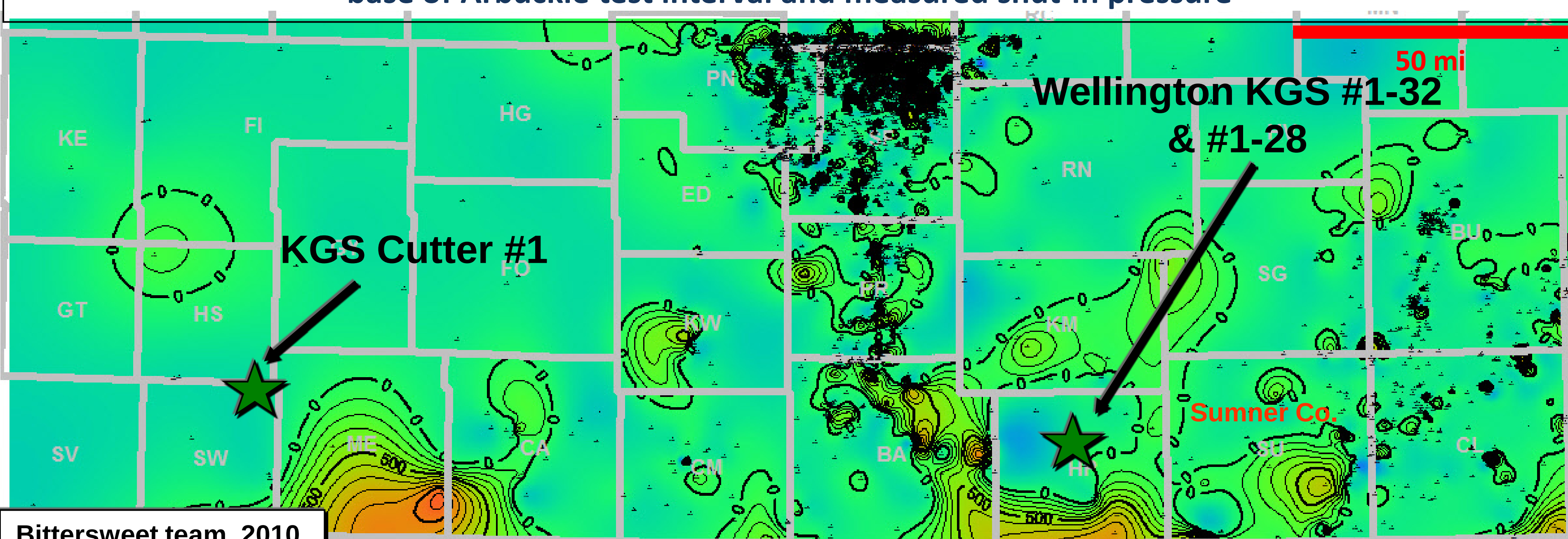


Arbuckle exposure at base of Missouri River, north-central Missouri –

Elevation 450 ft; surface exposures located ~200 mi northeast

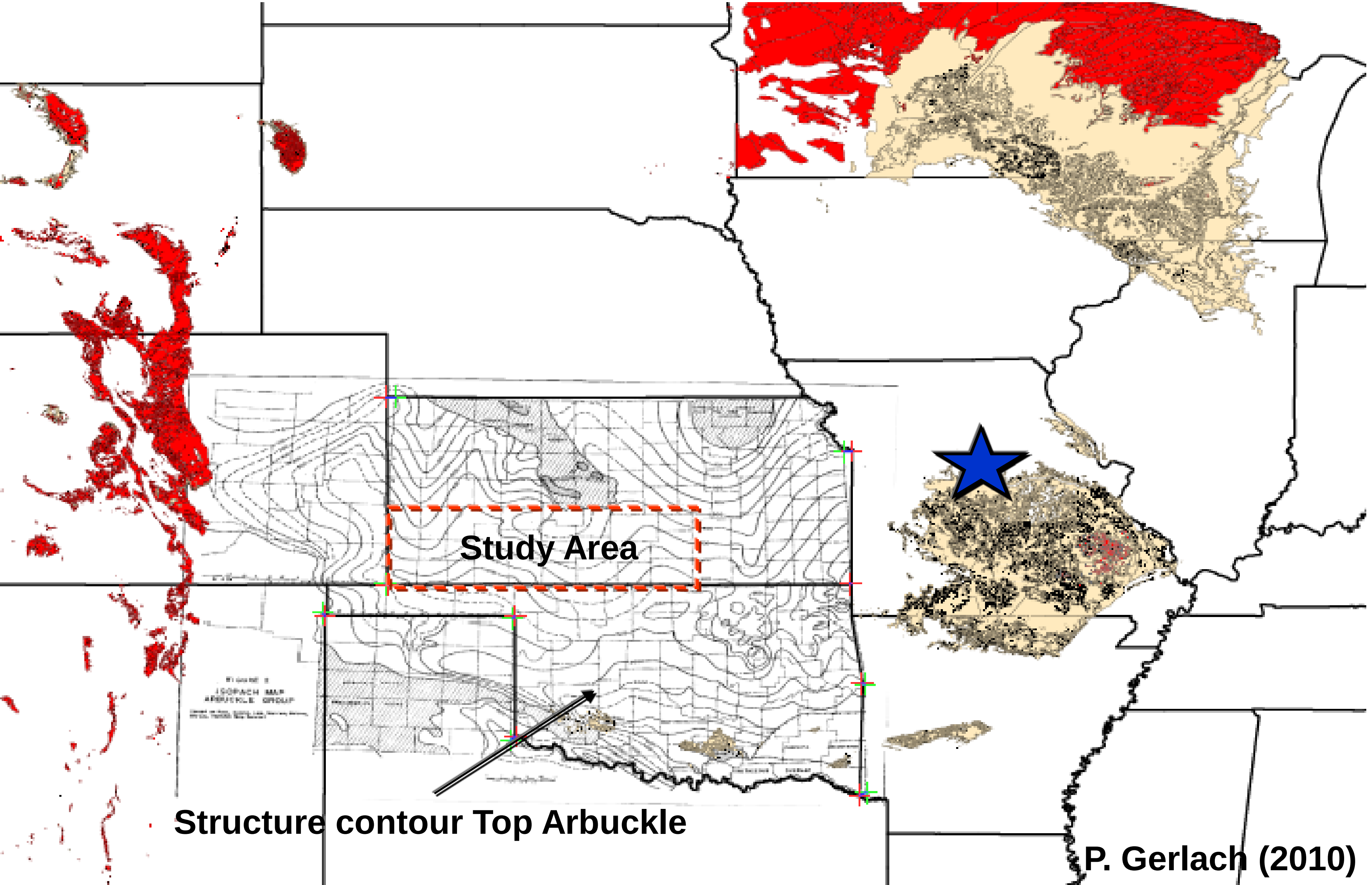
Assume hydrostatic gradient = 0.465 psi/ft

Map of the difference between estimated hydraulic head at base of Arbuckle test interval and measured shut-in pressure



Bittersweet team, 2010

Lowest elevation of exposed Arbuckle strata on west flank of Ozark Uplift is along Missouri River at Jefferson City, MO (450 ft)

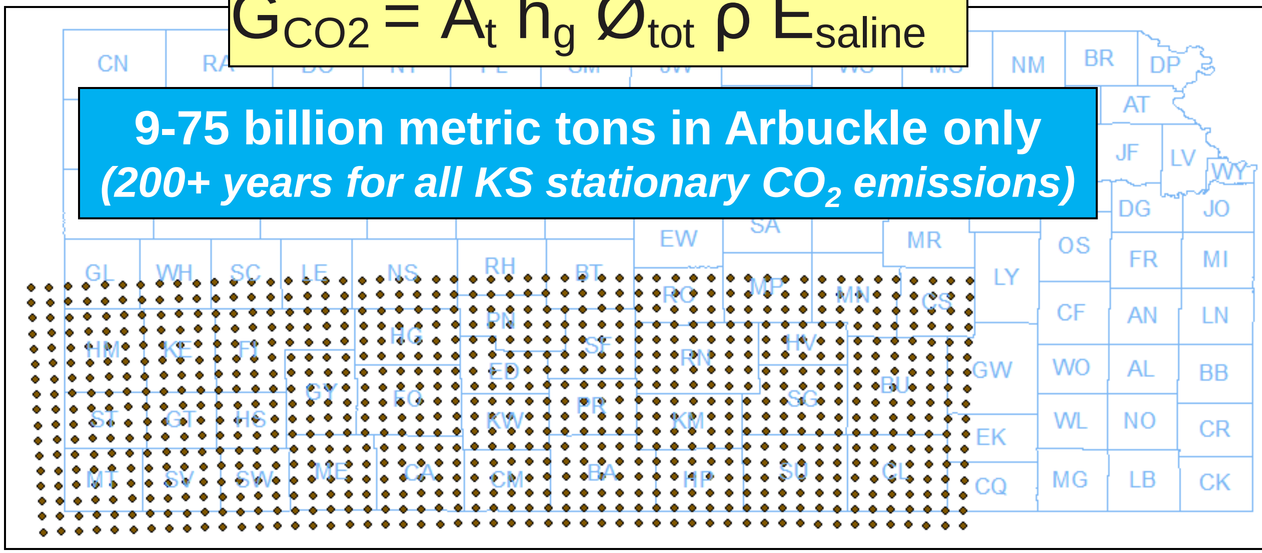


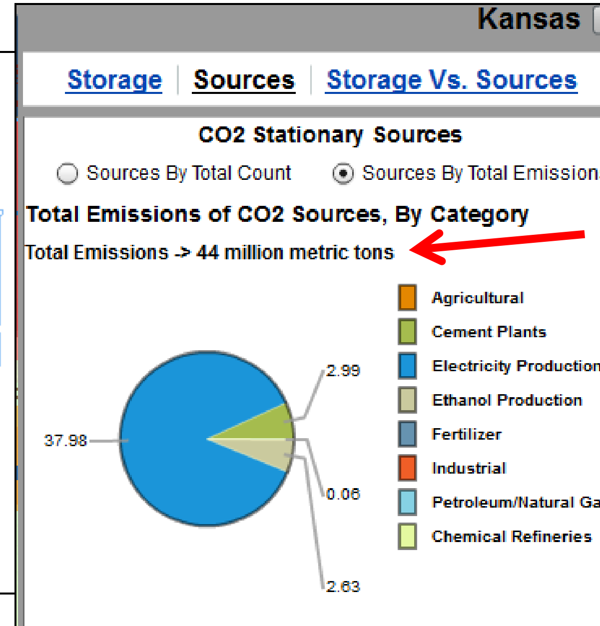
Initial CO_2 Storage Capacity Estimate

(reported April 2011 for NATCARB) Deep Arbuckle Saline Formation

$$G_{CO2} = A_t \, h_g \, Ø_{tot} \, \rho \, E_{saline}$$

9-75 billion metric tons in Arbuckle only
(200+ years for all KS stationary CO_2 emissions)





NATCARB, accessed 8-12

Metric tons CO_2 per Grid Cell
10 km^2
(3.8 mi^2)

0.769 tonne/m3

1 m3 = 6.29 bbls

8.179 bbl/tonne CO2

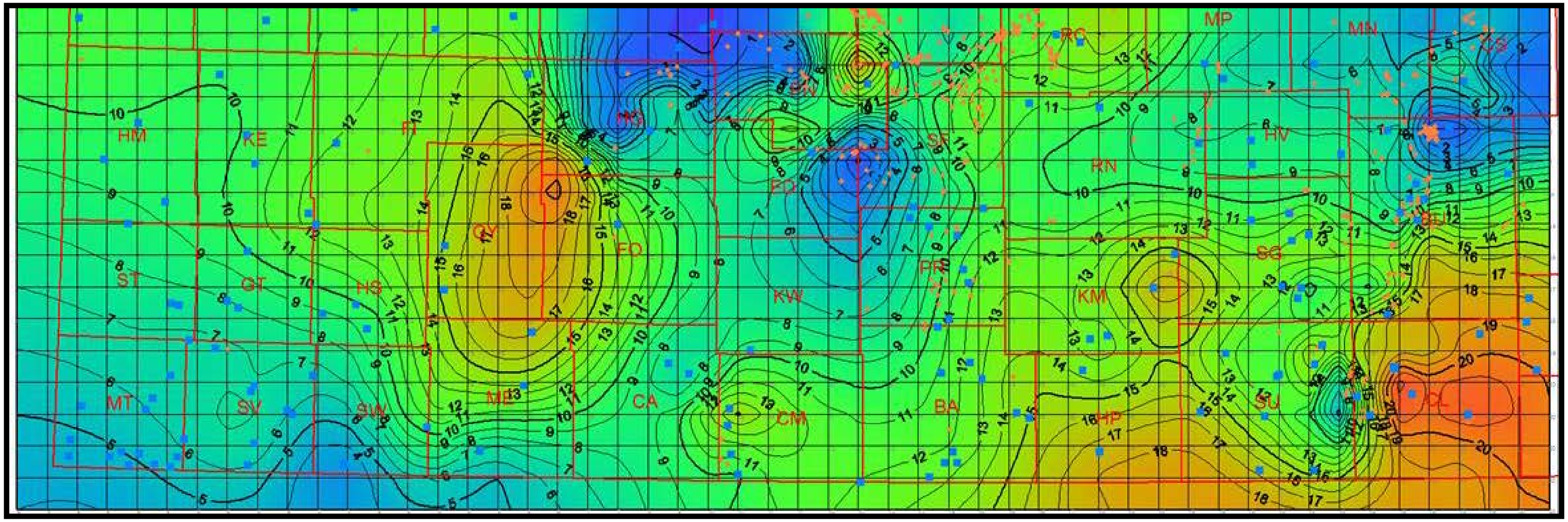
Gerlach and Bittersweet team, 2012

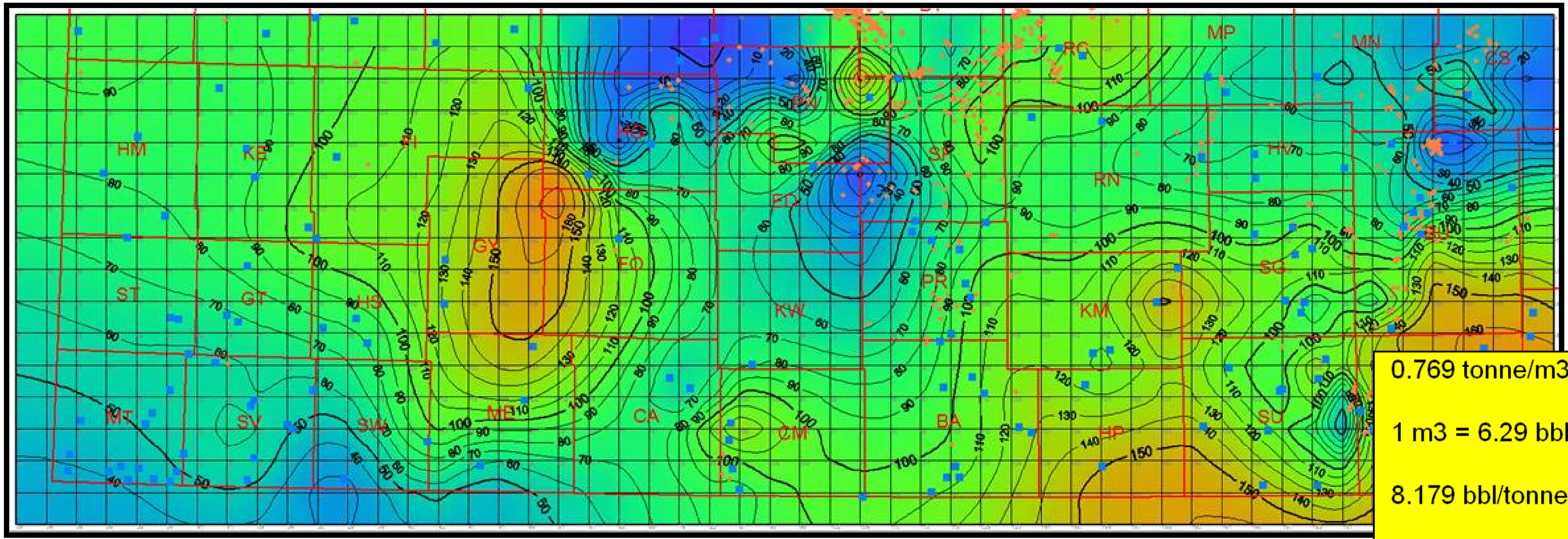
Each grid cell is 10K (+/-)

P10	
8,781,380,535	Total All Cells
22,214,247	High Cell
10,287,863	Median Cell
10,554,544	Mean Cell

P90	
75,464,988,970	Total All Cells
190,903,682	High Cell
88,411,323	Median Cell
90,703,112	Mean Cell

P10 (top) and P90 (bottom) storage volume CO_2 (million tonnes)



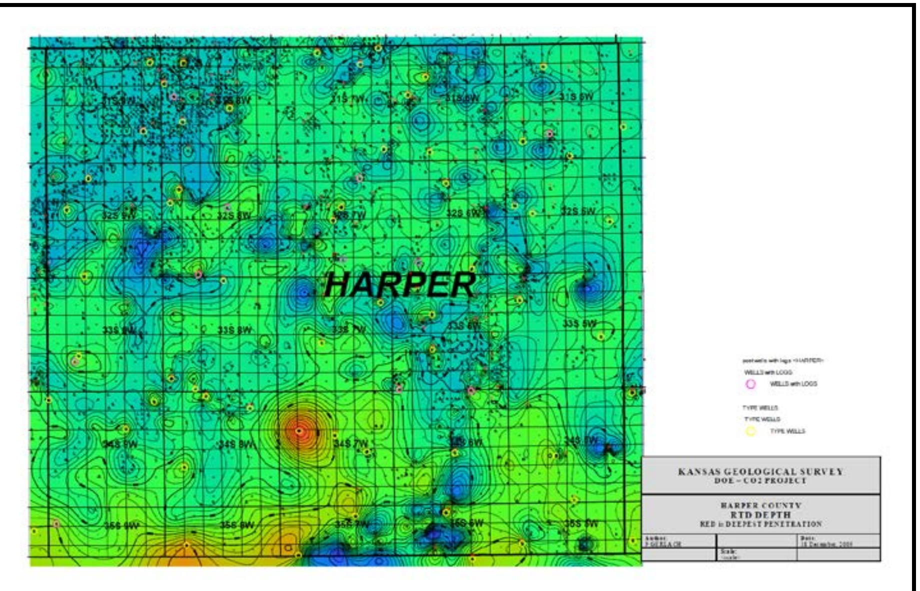


0.769 tonne/m3

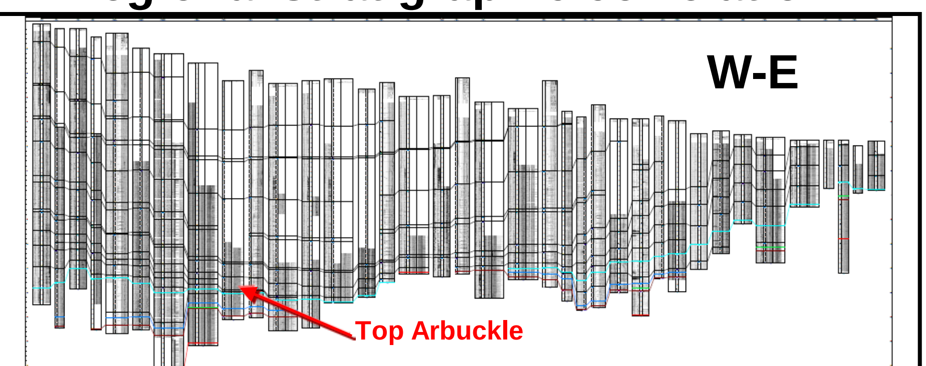
1 m3 = 6.29 bbls

8.179 bbl/tonne CO2

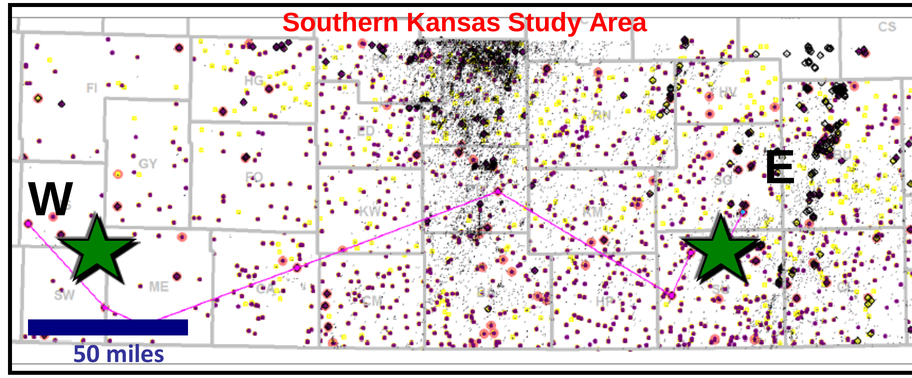
Selection and correlation of Digital Type Wells for DOE-CO2 project



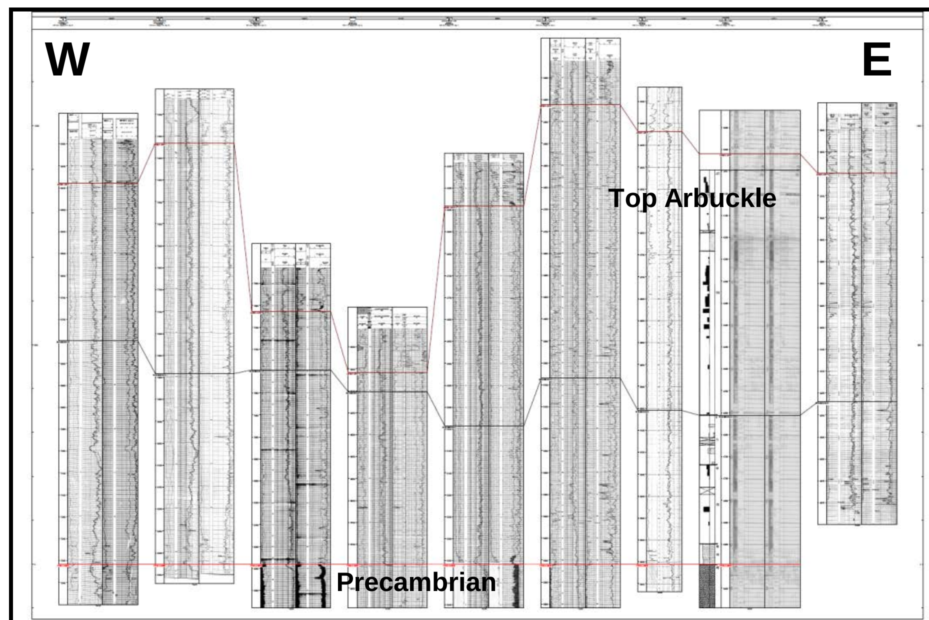
Regional stratigraphic correlation



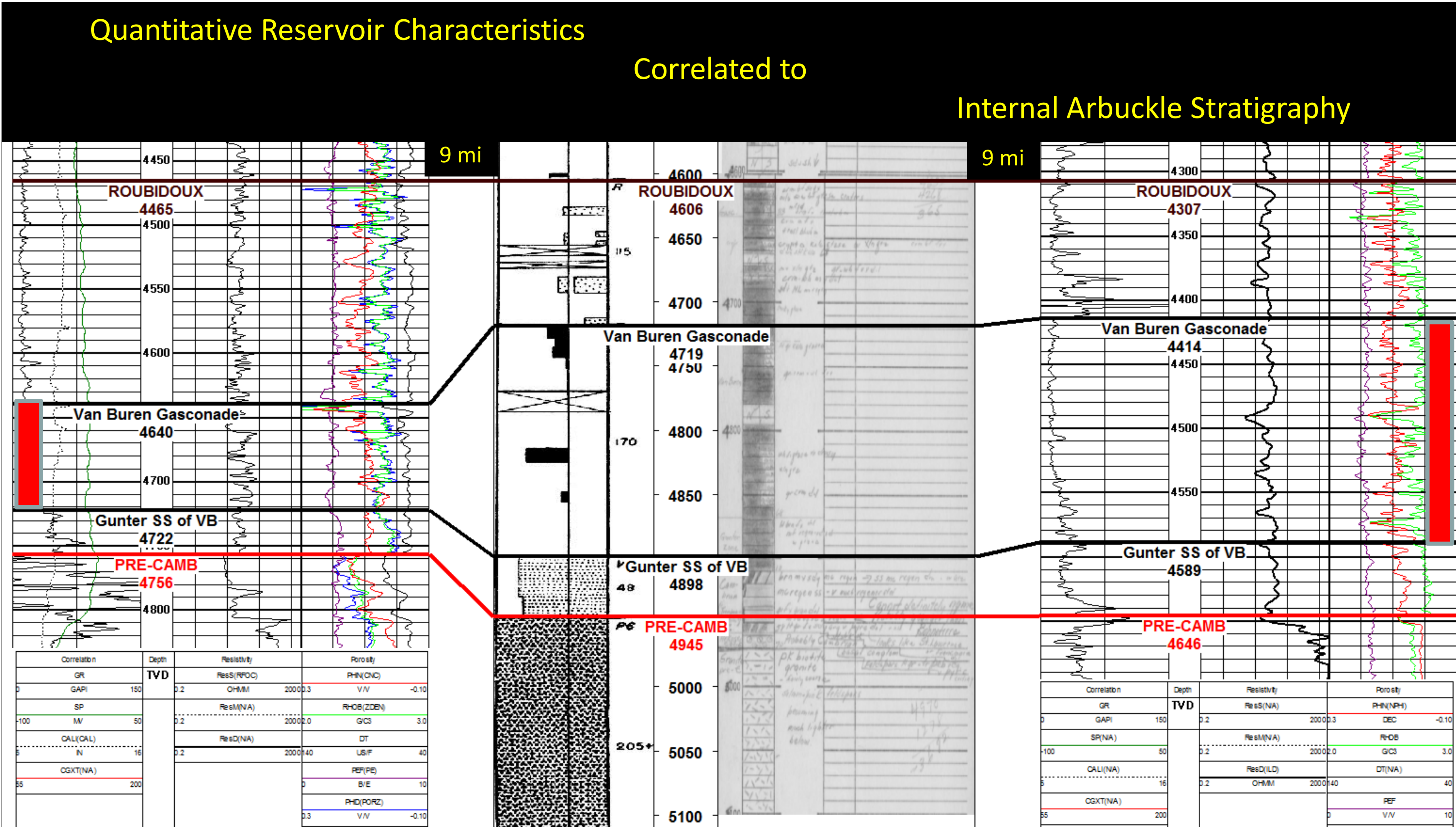
Bittersweet team (Gerlach, Nicholson, Hansen)



Internal Arbuckle correlations and petrophysical properties



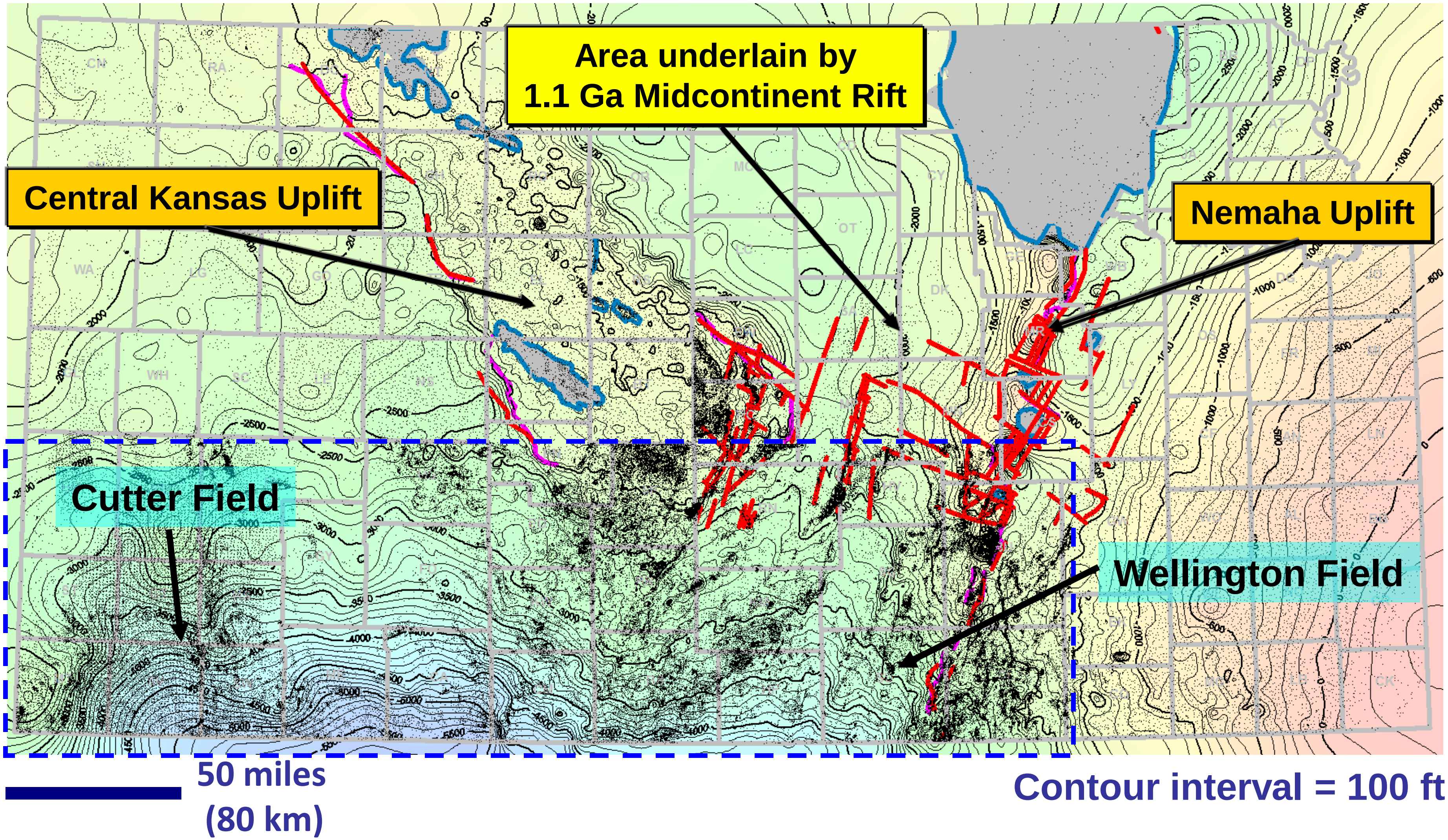
Quantitative Characterization of Arbuckle in southern Kansas



Example cross section of lower Arbuckle from top Roubidoux (datum) to basement including new and old well data (insoluble residue logs, georeports, and modern suite of logs managed as LAS files) – Bittersweet (Gerlach et al.)

Structural mapping and evaluation of faulting

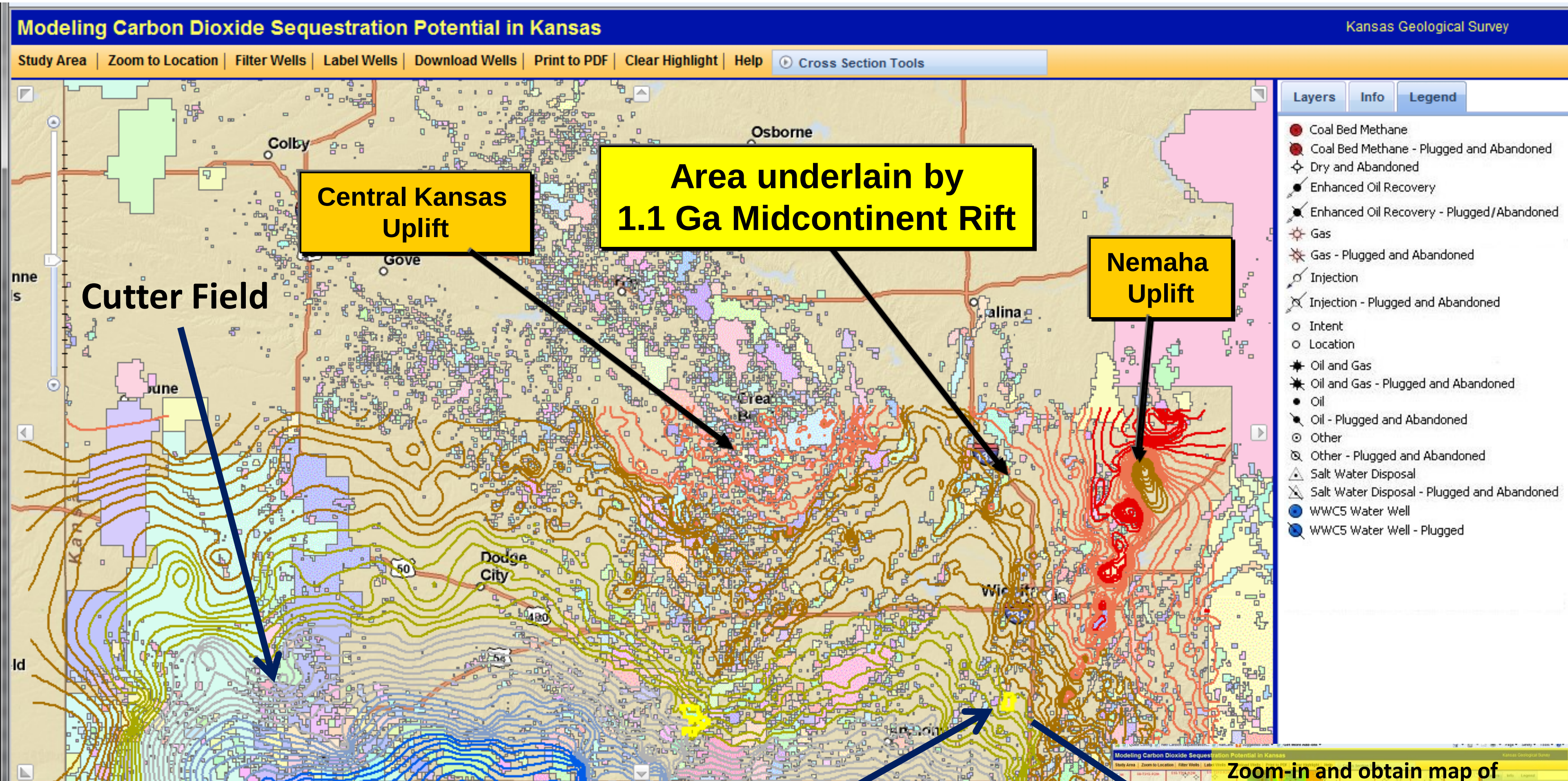
Top Arbuckle Group



- Published faults have been compiled and new ones are under investigation
- Focus on <u>quantitative</u> assessment of CO_2 storage capacity of Arbuckle saline aquifer is within dashed blue area

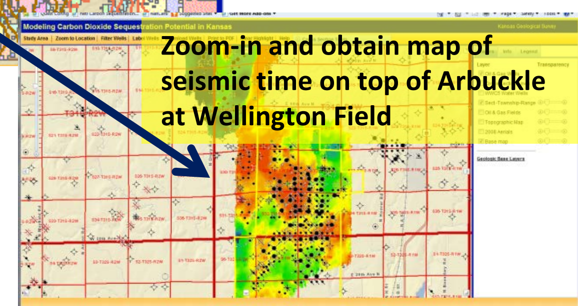
Web-based Interactive DOE-CO2 Project Mapper

Overlay of Oil and gas field outlines and Top Arbuckle Group in study area of southern Kansas



Contours = Elevation on Top of Arbuckle

Wellington Field

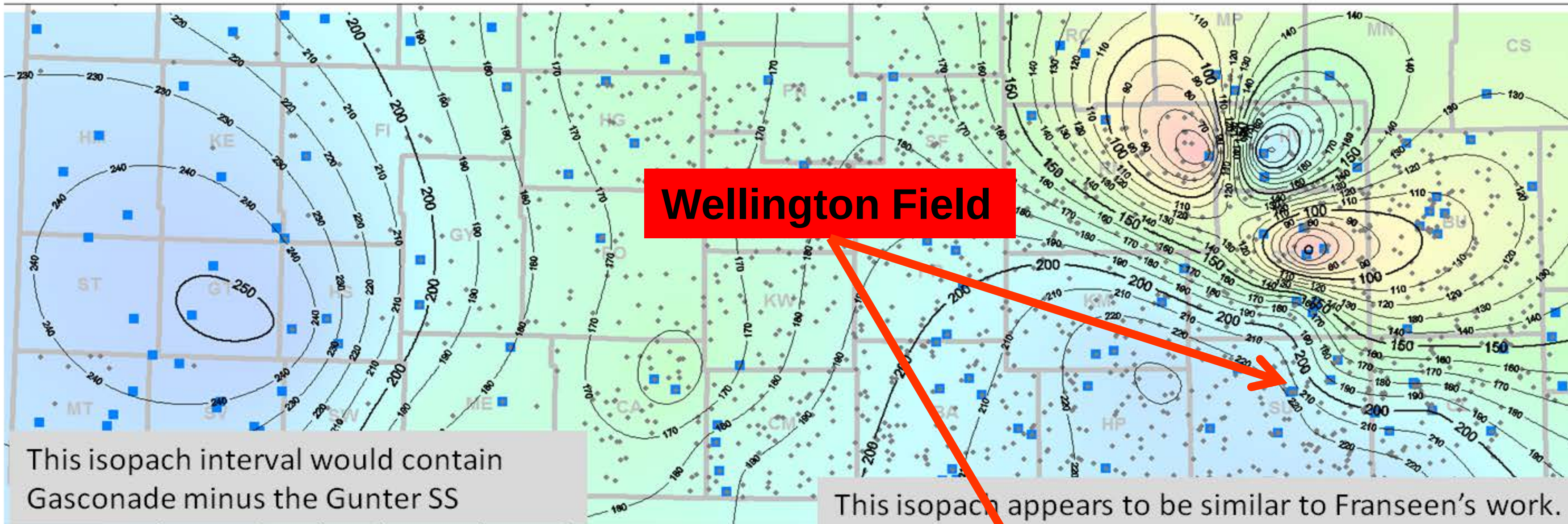


http://maps.kgs.ku.edu/co2/?pass=project

Lower porous zone in Arbuckle

Gerlach et al.

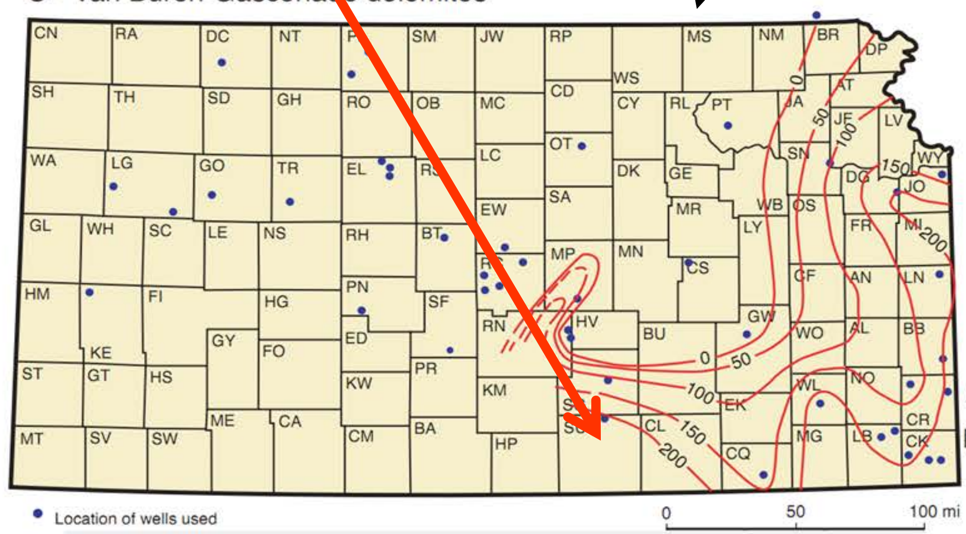
ISOPACH GASCONADE to GUNTER SS



This isopach interval would contain Gasconade minus the Gunter SS

This isopach appears to be similar to Franseen's work.

Early Ordovician (approx Gasconade time) Paleogeography, Chenoweth, 68

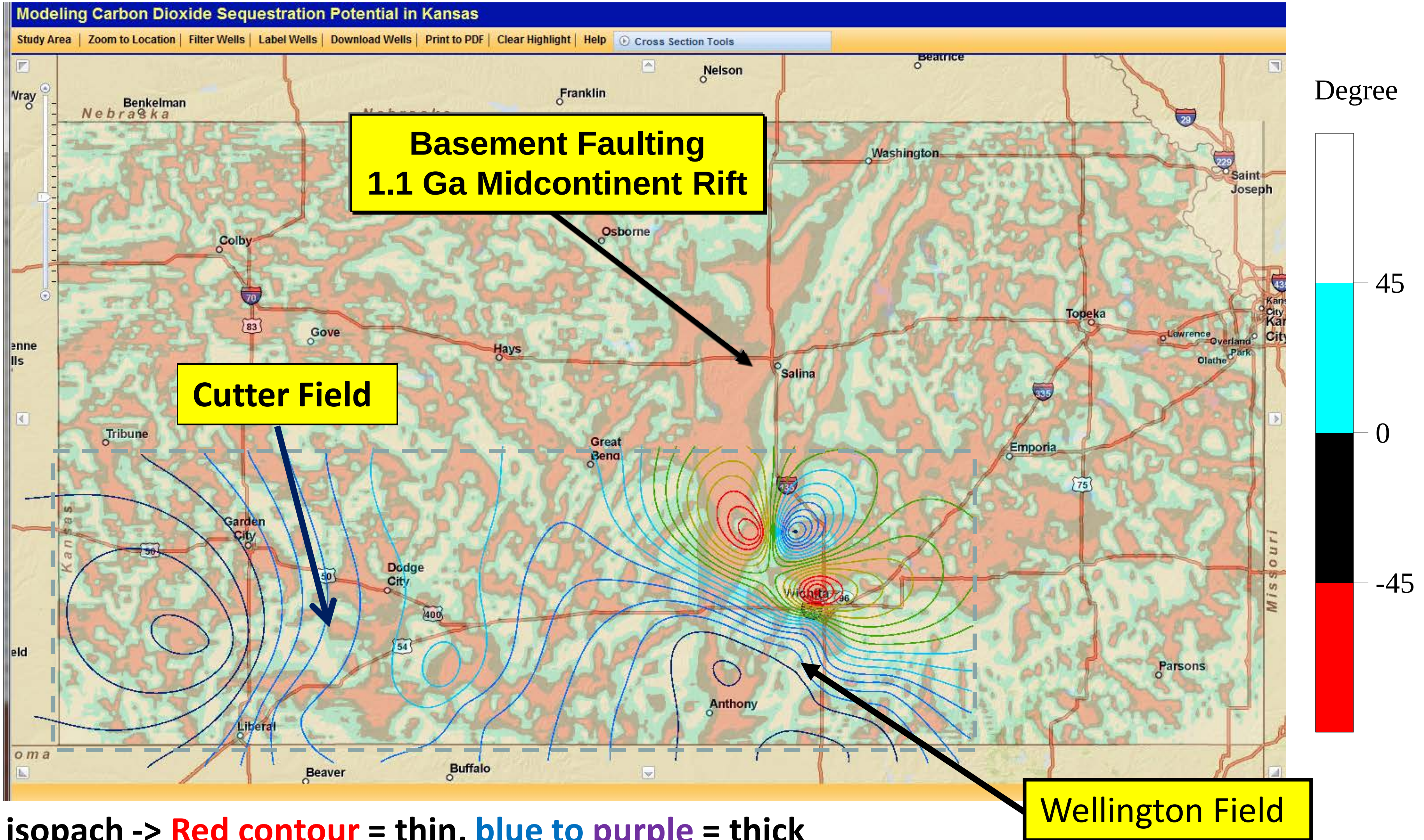


Van Buren Gasconade Isopach, Franseen et al., 2004

Tilt angle map of the total magnetic field intensity in Kansas

overlain with isopachous contours of Arbuckle Group's

Gasconade to Gunter Sandstone interval



isopach -> Red contour = thin, blue to purple = thick

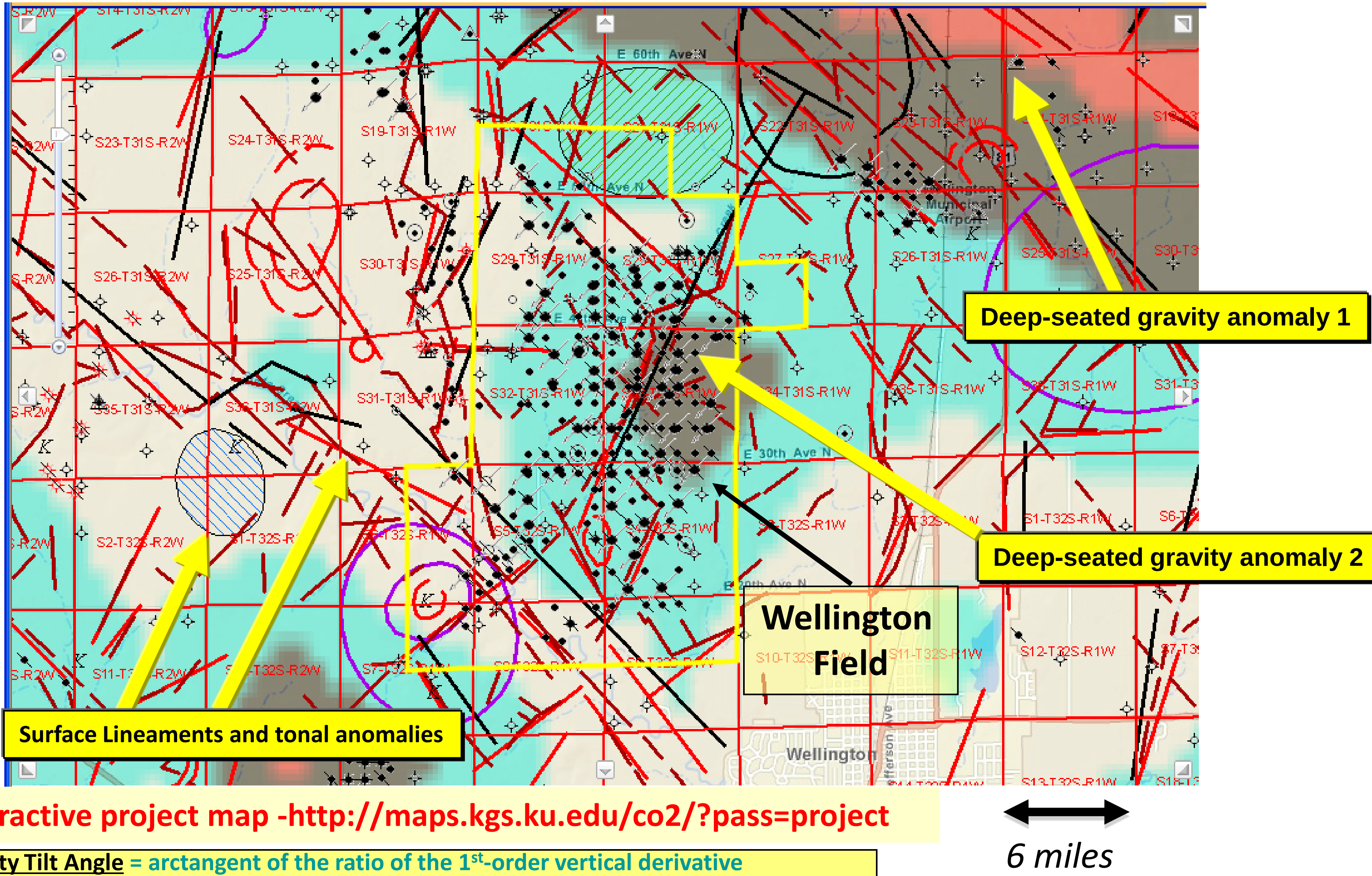
Snapshot from project's interactive mapper -- http://maps.kgs.ku.edu/co2/?pass=project

Wellington Field Area

Landsat lineaments and gravity tilt angle map

Northeast trending surface lineament bisecting Wellington Field

as viewed on interactive mapper

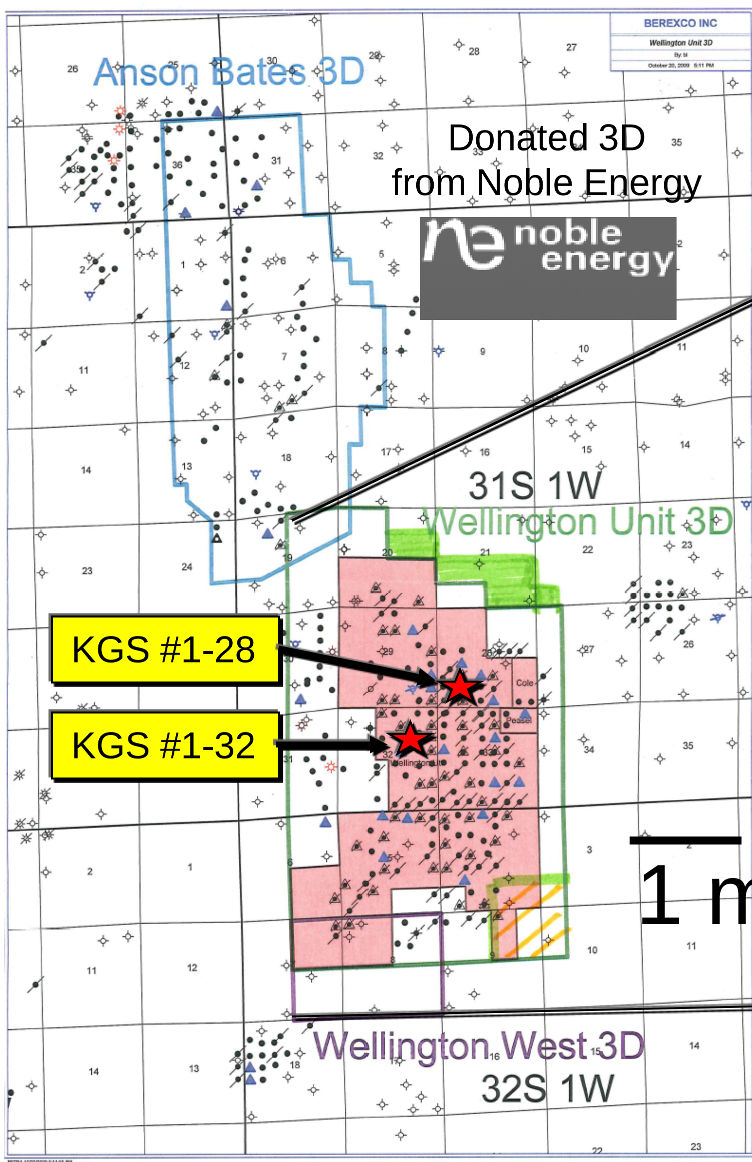


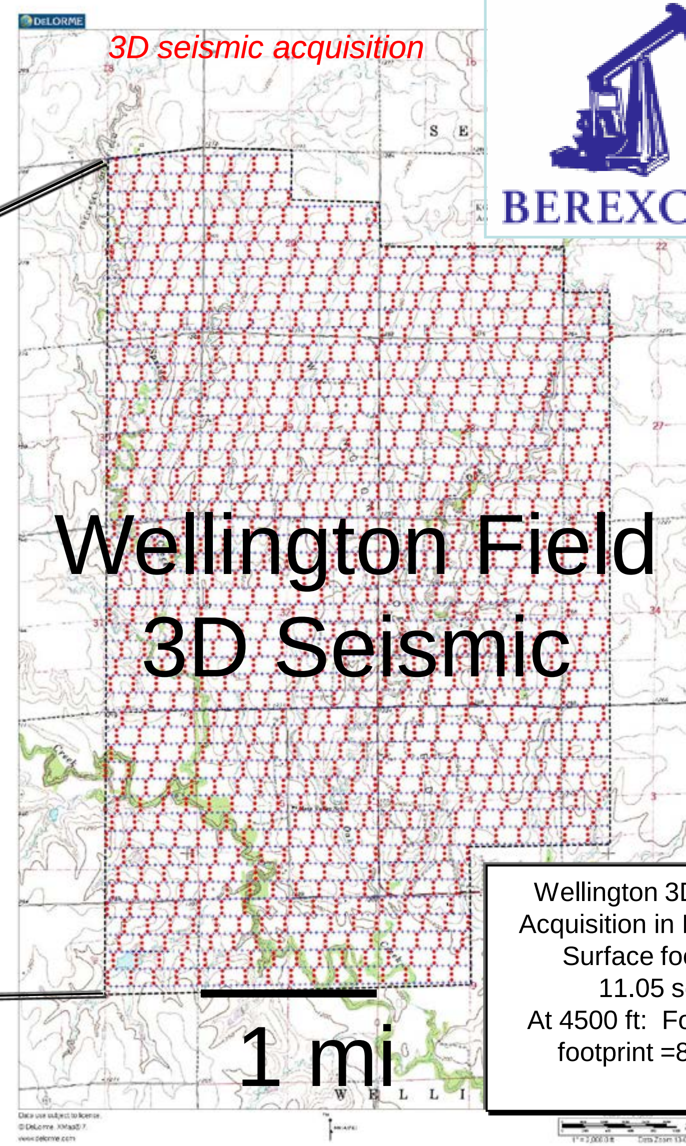
Interactive project map -http://maps.kgs.ku.edu/co2/?pass=project

<u>Gravity Tilt Angle</u> = arctangent of the ratio of the 1st-order vertical derivative by the 1st-order horizontal derivative of the Bouguer anomaly.

Wellington Field

3D Multicomponent 3D Seismic Survey & 2 Basement Tests



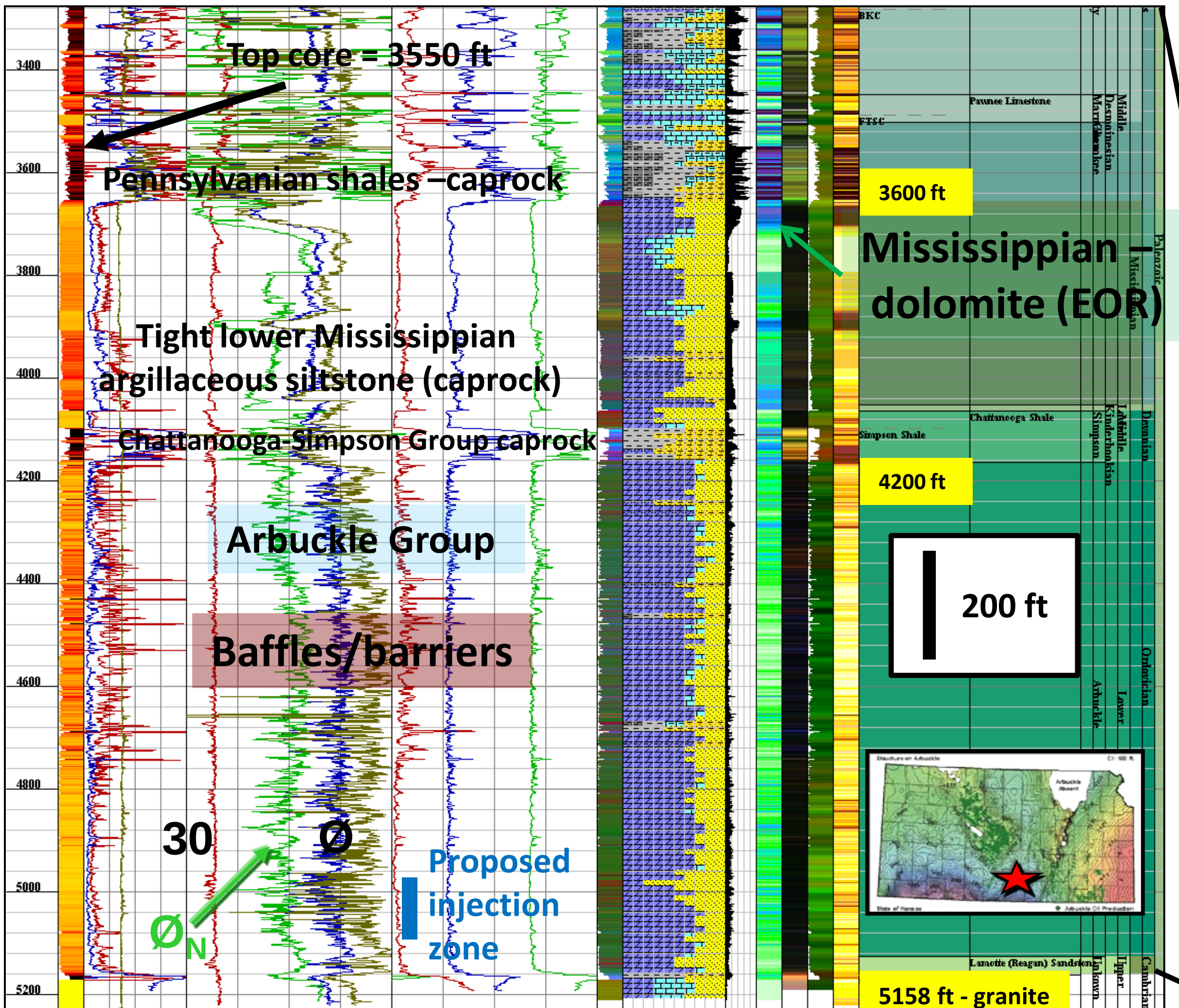


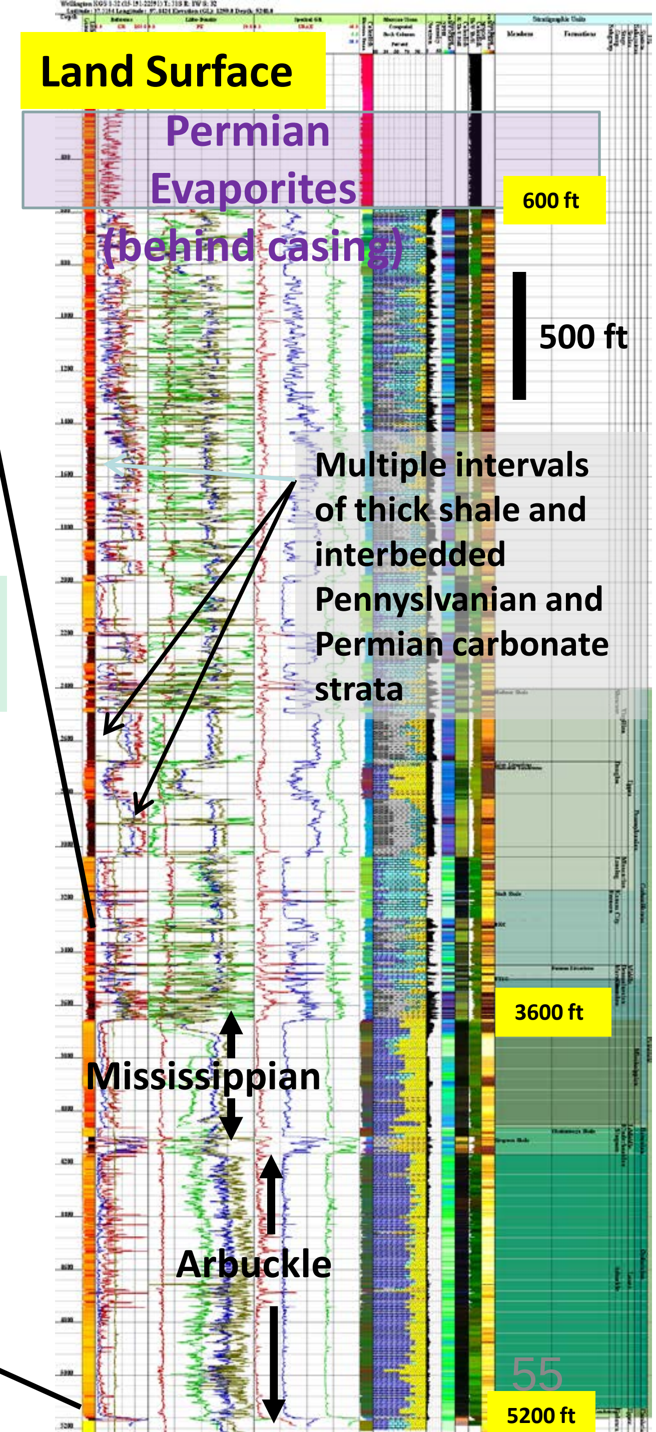
BEREXCO

Wellington 3D Seismic:
Acquisition in March 2010
Surface footprint =
11.05 sq mi.
At 4500 ft: Fold = ~50 &
footprint =8.8 sq mi

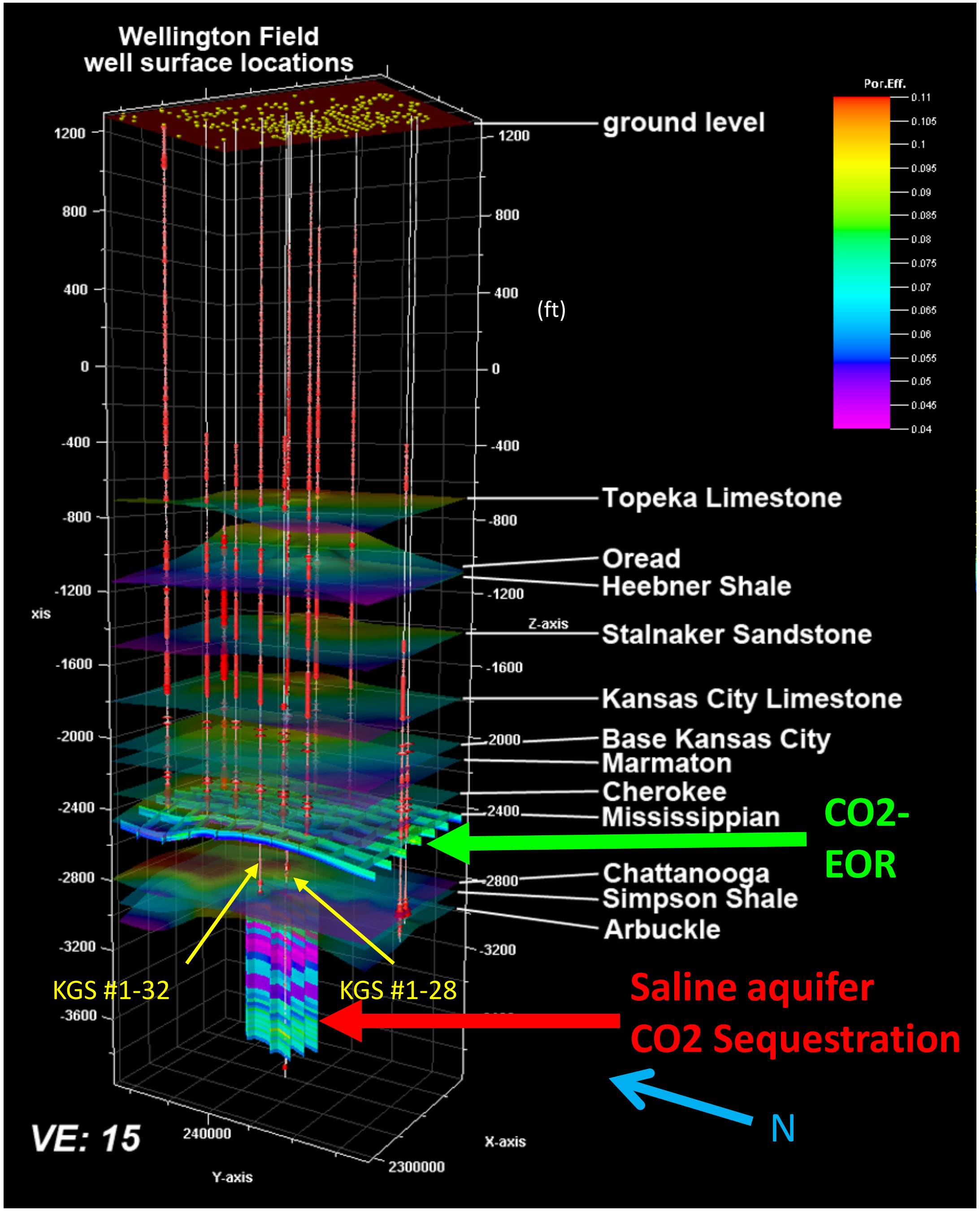
Stratigraphic Column New Basement Test
Berexco Wellington KGS #1-32

Completed at Wellington Field
February 2011
Conventional 4.5 inch core from base Pennsylvanian shales to basement
(3550-5178 interval, 1628 gross ft, 1528 net feet)





http://www.kgs.ku.edu/stratigraphic/PROFILE/



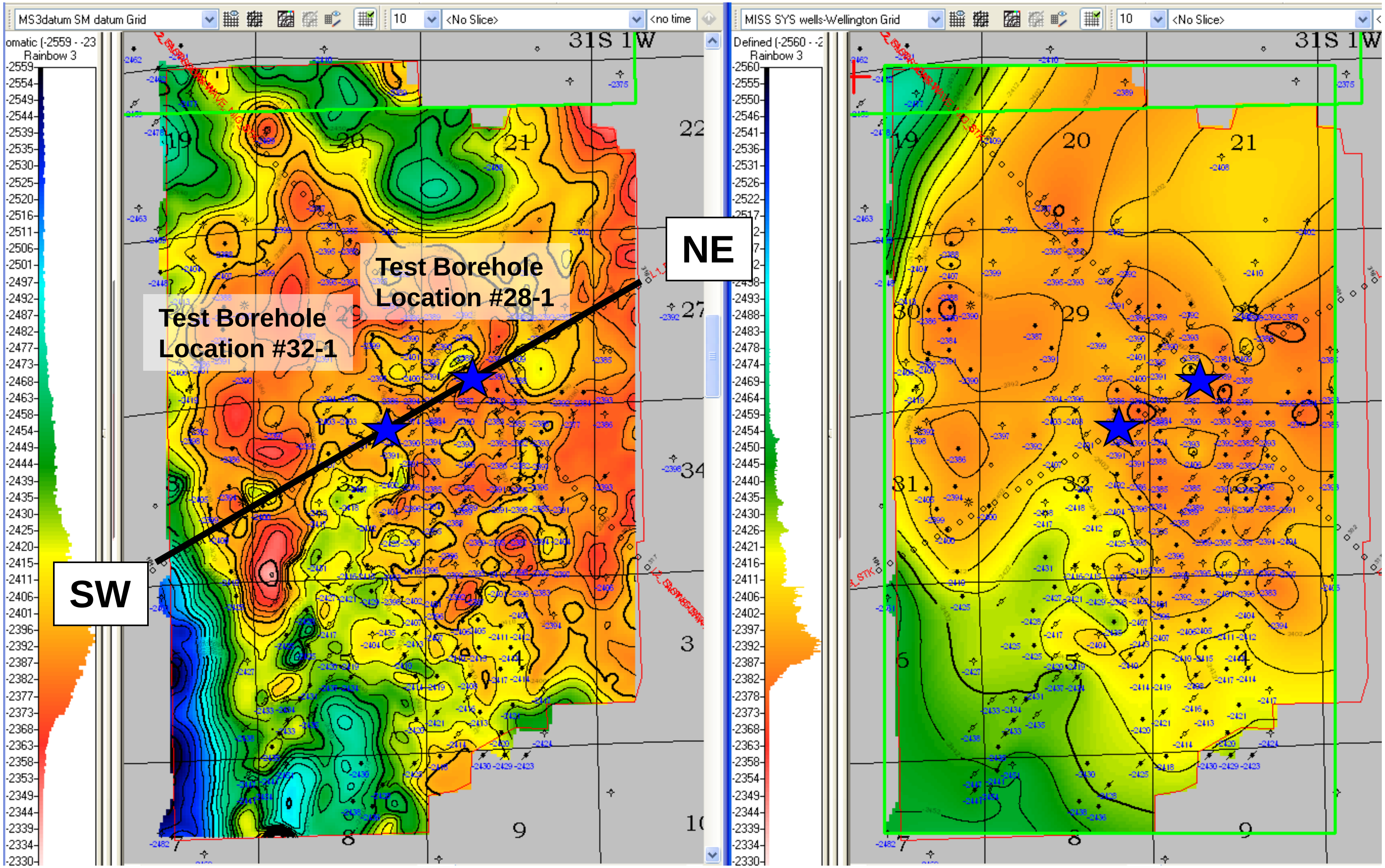
Wellington Field

1) *Mississippian tripolitic chert/dolomite reservoir (20+ million barrels produced)*
1) *Arbuckle saline aquifer*
2) *Intervening caprocks*

- Core and logs from KGS #1-32 and logs from #1-28 obtained in Jan-Feb. 2011
- Using to assess --
  - Integrity of caprocks
  - Porosity types, injectivity, and storage
  - Model potential for C02-EOR in Mississippian saline aquifer
  - Sequestration in Arbuckle

Prestack Depth Migration (PSDM) 3D Seismic Wellington Field

Mississippian Depth Migration (left) vs Mississippian Well Control (right)

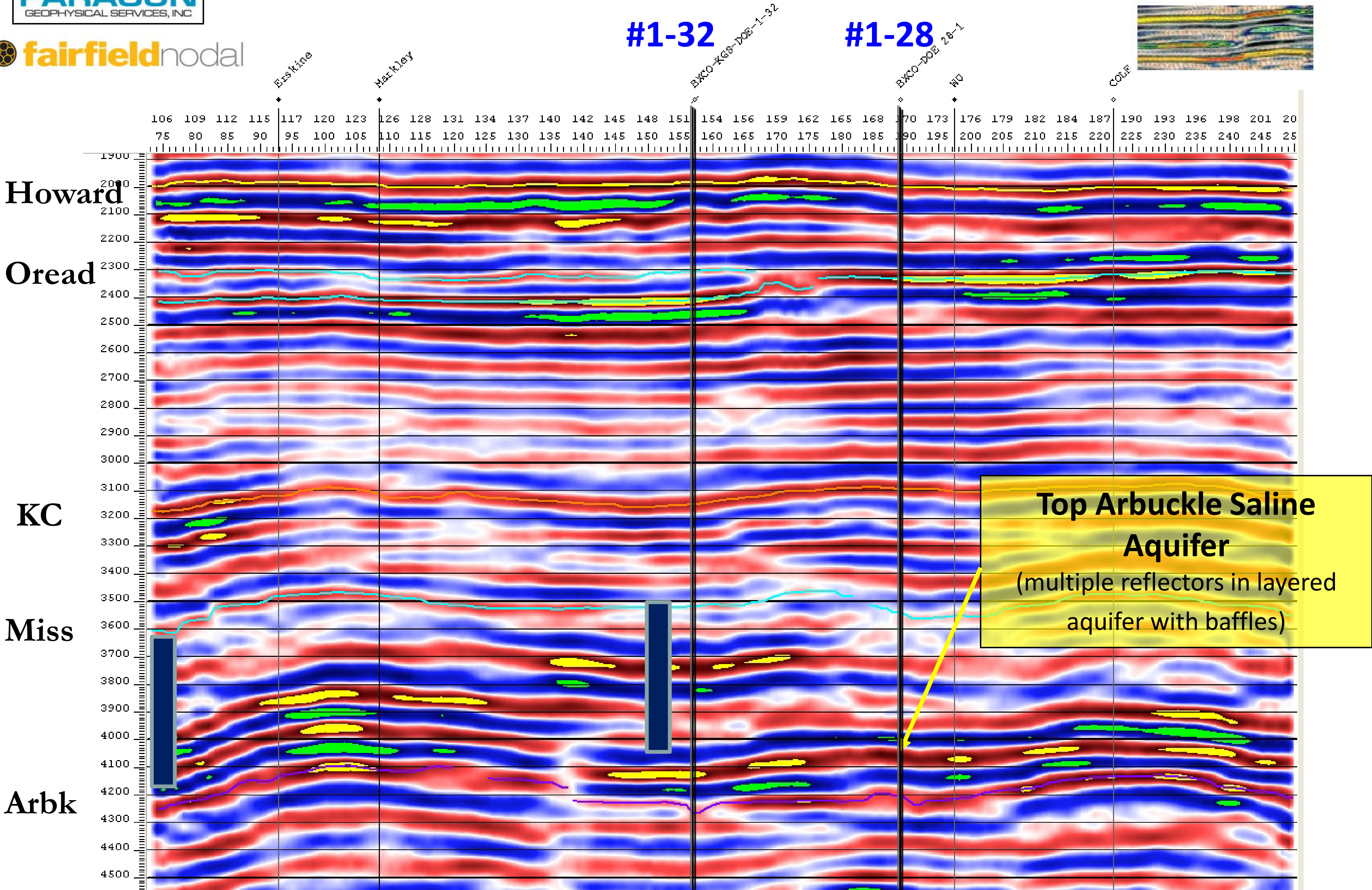


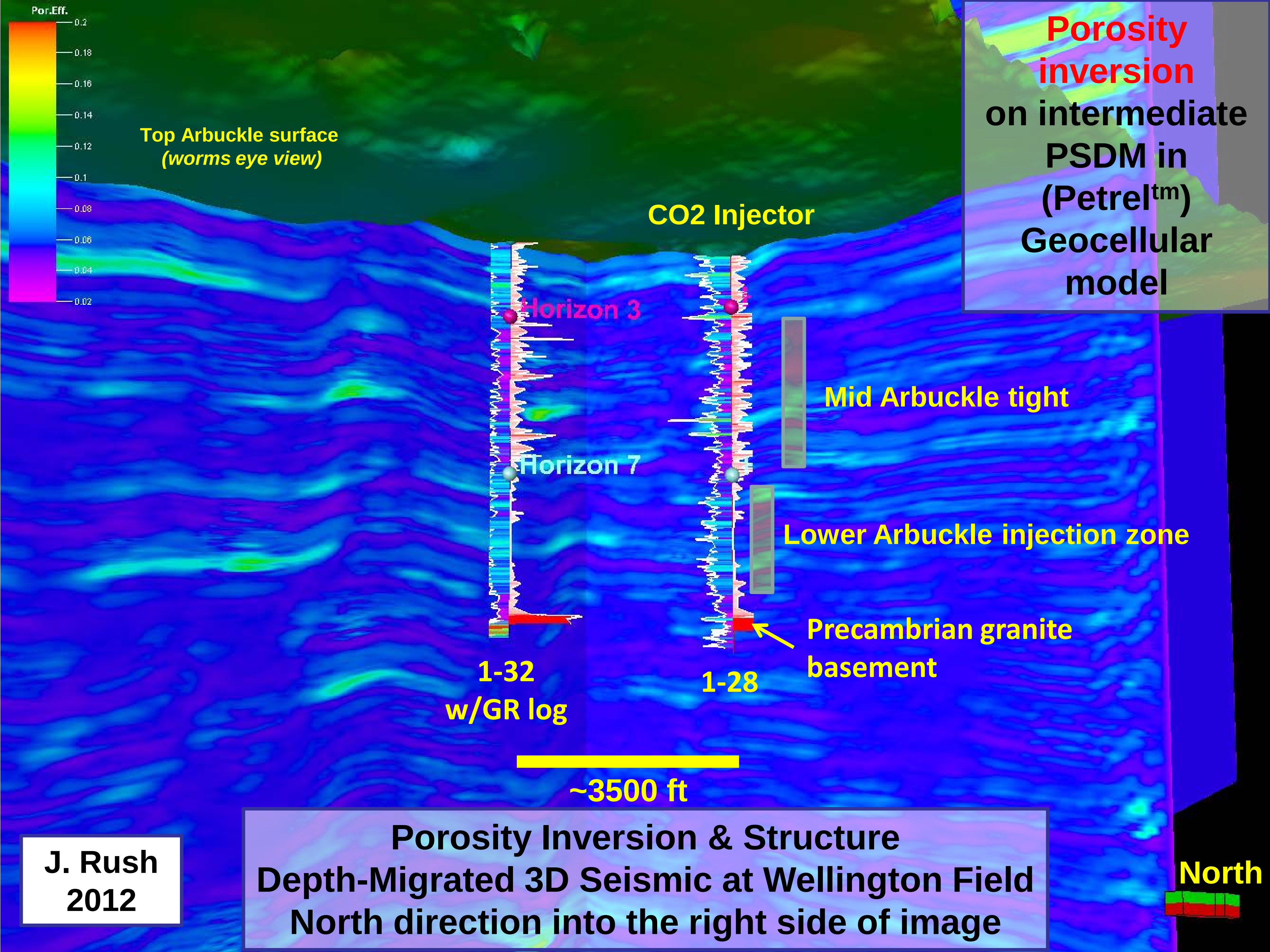
Prestack Depth Migrated
Multicomponent 3D Seismic Volume in Wellington Field
Coincident w/ Shear Wave Line #1

PARAGON GEOPHYSICAL SERVICES, INC

fairfieldnodal

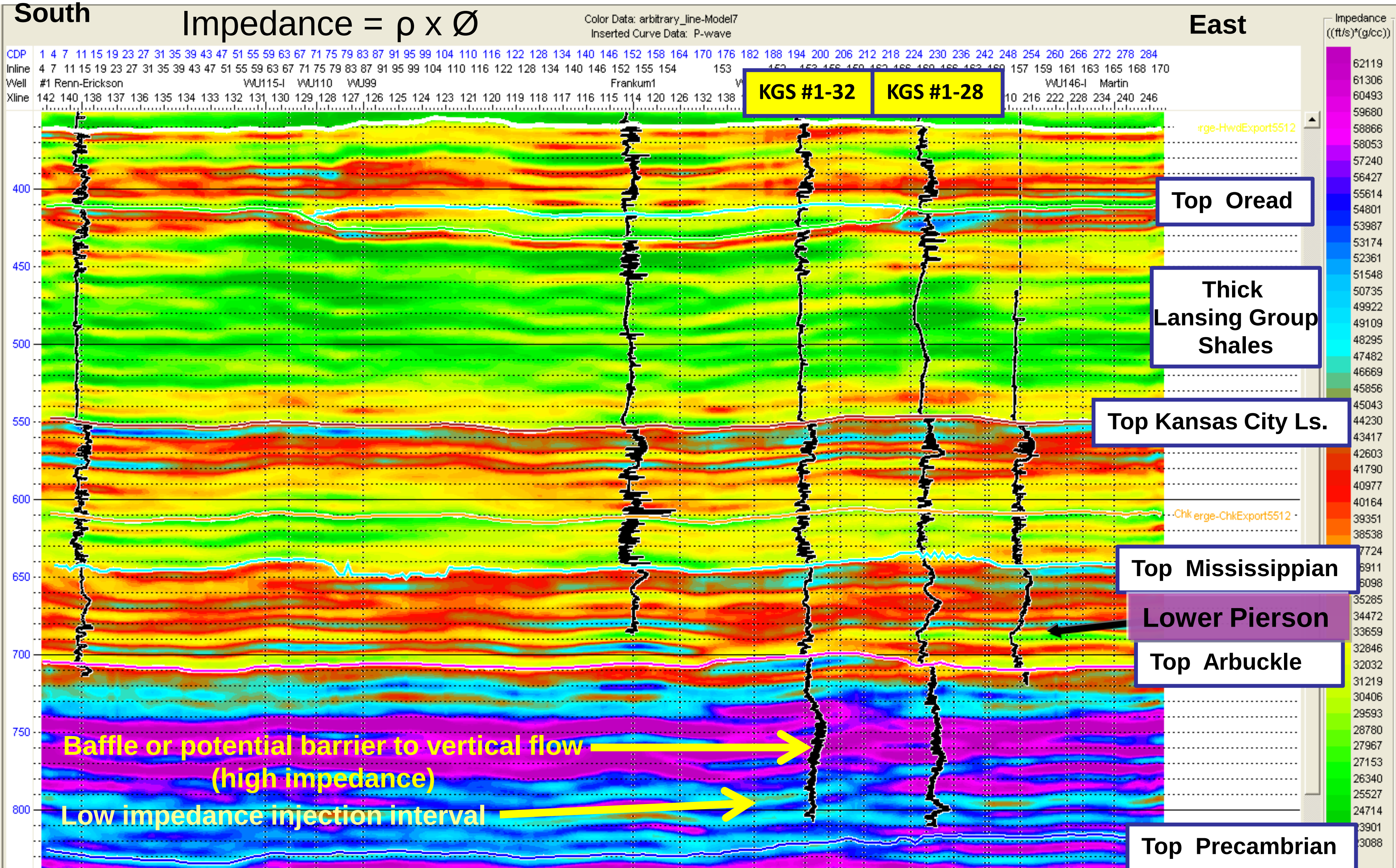
HEDKE-SAENGER GEOSCIENCE, LTD




Por.Eff.
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
Top Arbuckle surface
(worms eye view)
CO2 Injector
Porosity inversion on intermediate PSDM in (Petrel tm) Geocellular model
Horizon 3
Horizon 7
Mid Arbuckle tight
Lower Arbuckle injection zone
Precambrian granite basement
1-32 w/GR log
1-28
~3500 ft
J. Rush 2012
Porosity Inversion & Structure
Depth-Migrated 3D Seismic at Wellington Field
North direction into the right side of image
North

Arbitrary seismic impedance profile

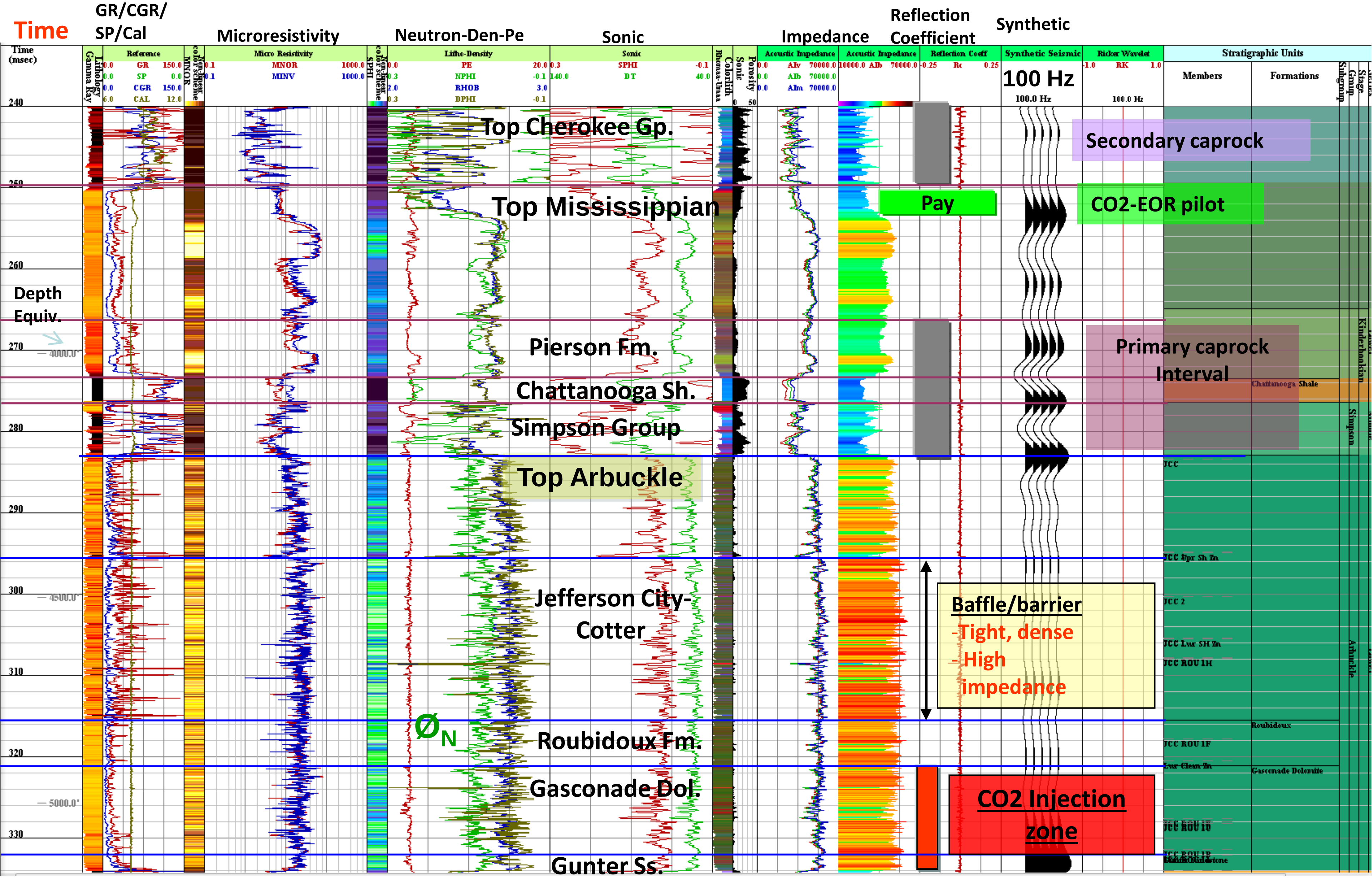
distinct caprock, mid-Arbuckle tight, lower Arbuckle injection zone



Hedke, 2012

CO_2 injection zones in Arbuckle saline formation and Mississippian oil reservoir, and associated caprocks

-- Well profile in 2-way travel time of KGS #1-28 illustrating synthetic seismogram and seismic impedance (velocity x density) and well log suite used to derive these seismic properties

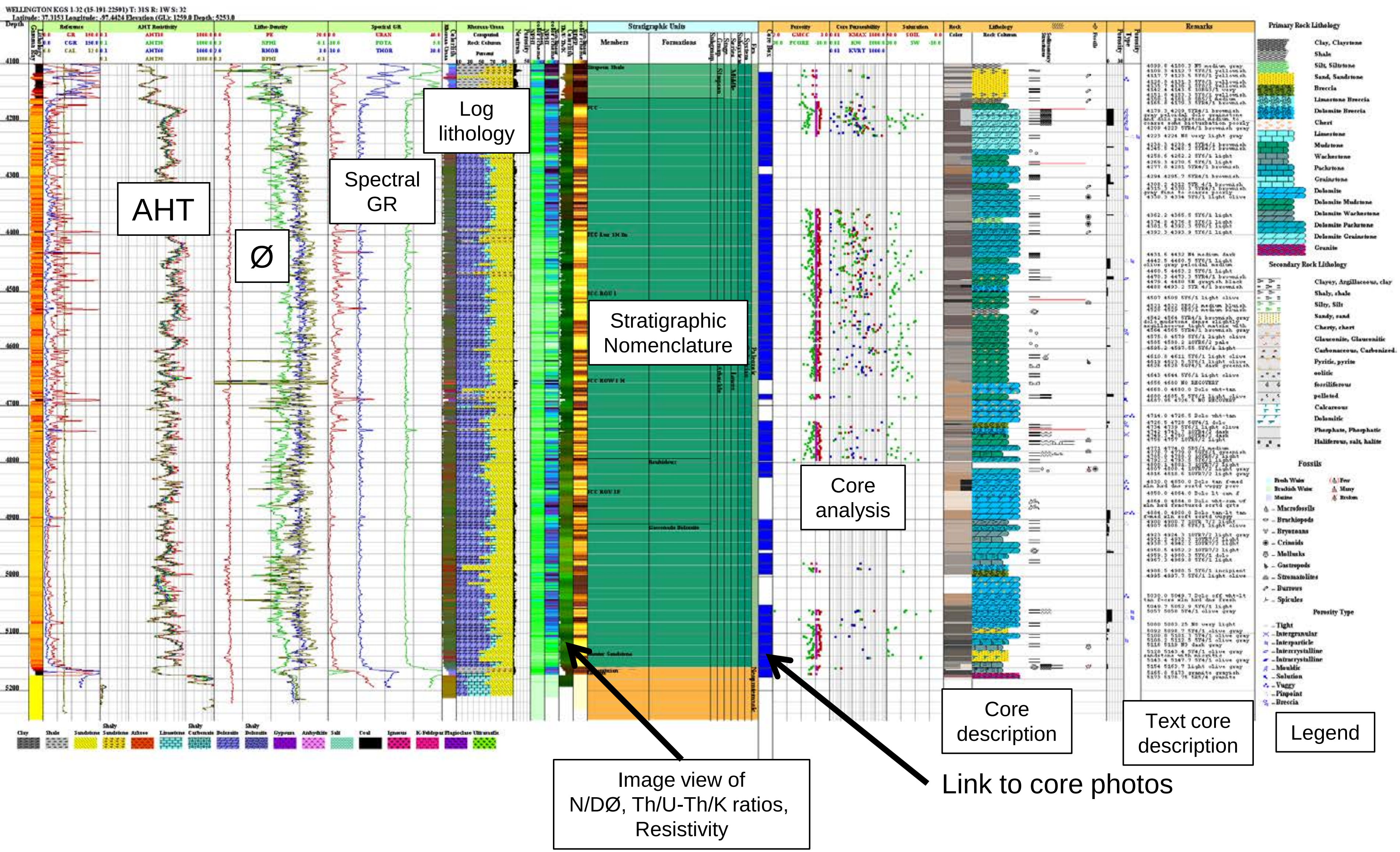


Precambrian granite – bottom of core

Freeware: http://www.kgs.ku.edu/software/SS/

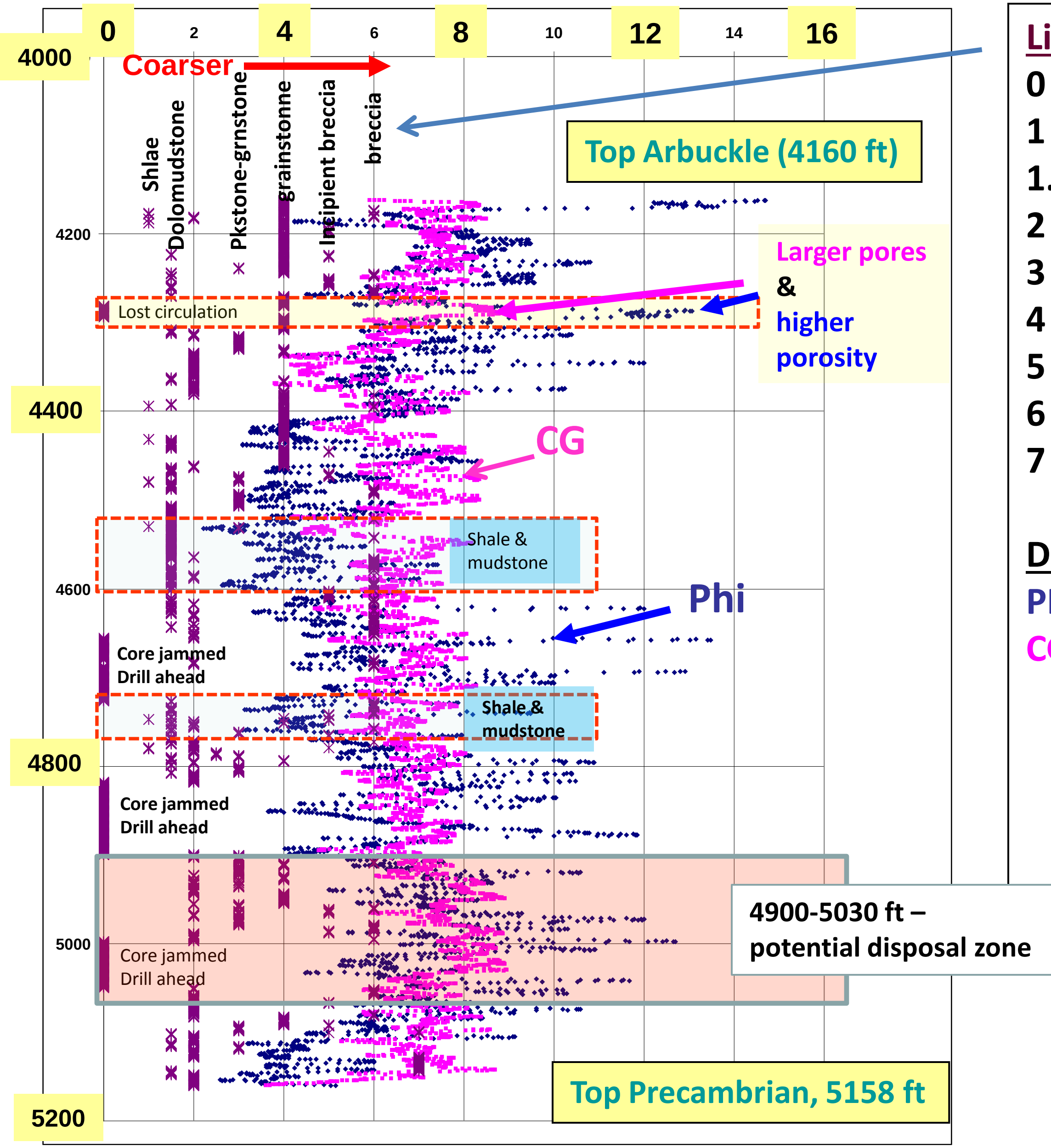
Arbuckle Group

Integration of logs, core, water, and DST analysis, core description, links to core images via an LAS 3.0 file



http://www.kgs.ku.edu/stratigraphic/PROFILE/applet.html

Nuclear magnetic resonance (Halliburton's MRIL) log in Arbuckle Group compared with core lithofacies, Arbuckle in Berexco Wellington KGS #1-32



Lithofacies from core (vertical colums) (x)

0 = no core recovered
1 = shale
1.5 = argillaceous dolomudstone
2 = mudstone-wackestone
3 = packstone-grainstone
4 = grainstone
5 = incipient autoclastic brecca
6 = autoclastic brecca
7 = quartz sandstone

Coarser toward bottom)

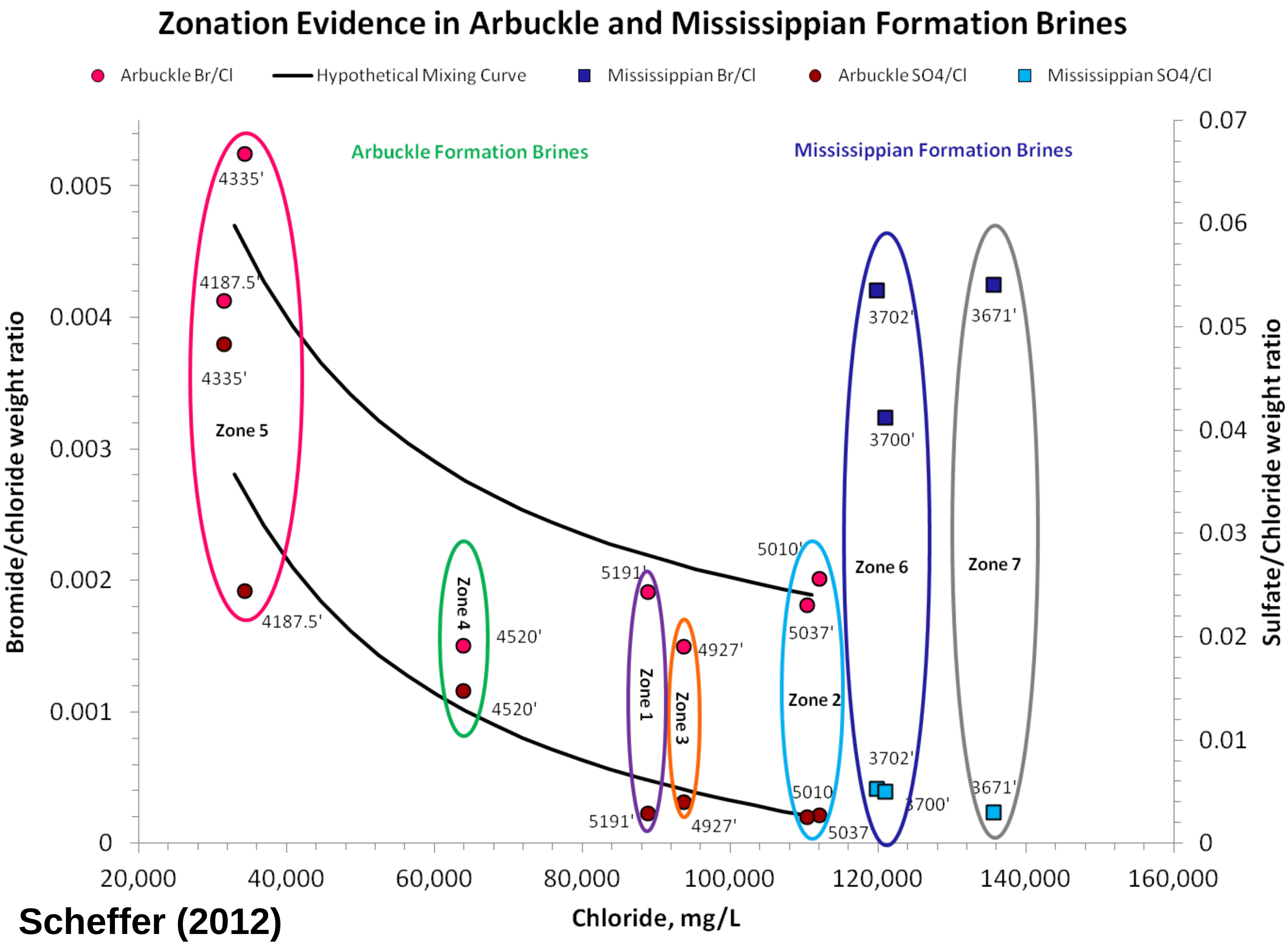
Derived from relaxation time of NMR log:

PHI (+) = sum of porosity in T2 channels
CG (Δ) = center of gravity of T2 spectrum
units are powered relaxation times
e.g. $T2 = CG^2$
=>larger number, larger the size of pores

- **Discontinuous fracturing**
- **Autoclastic breccia (dissolved evaporites)**
- **Lithofacies control porosity & permeability in persistent stratal packages**

Arbuckle Hydrostratigraphy at Wellington Field

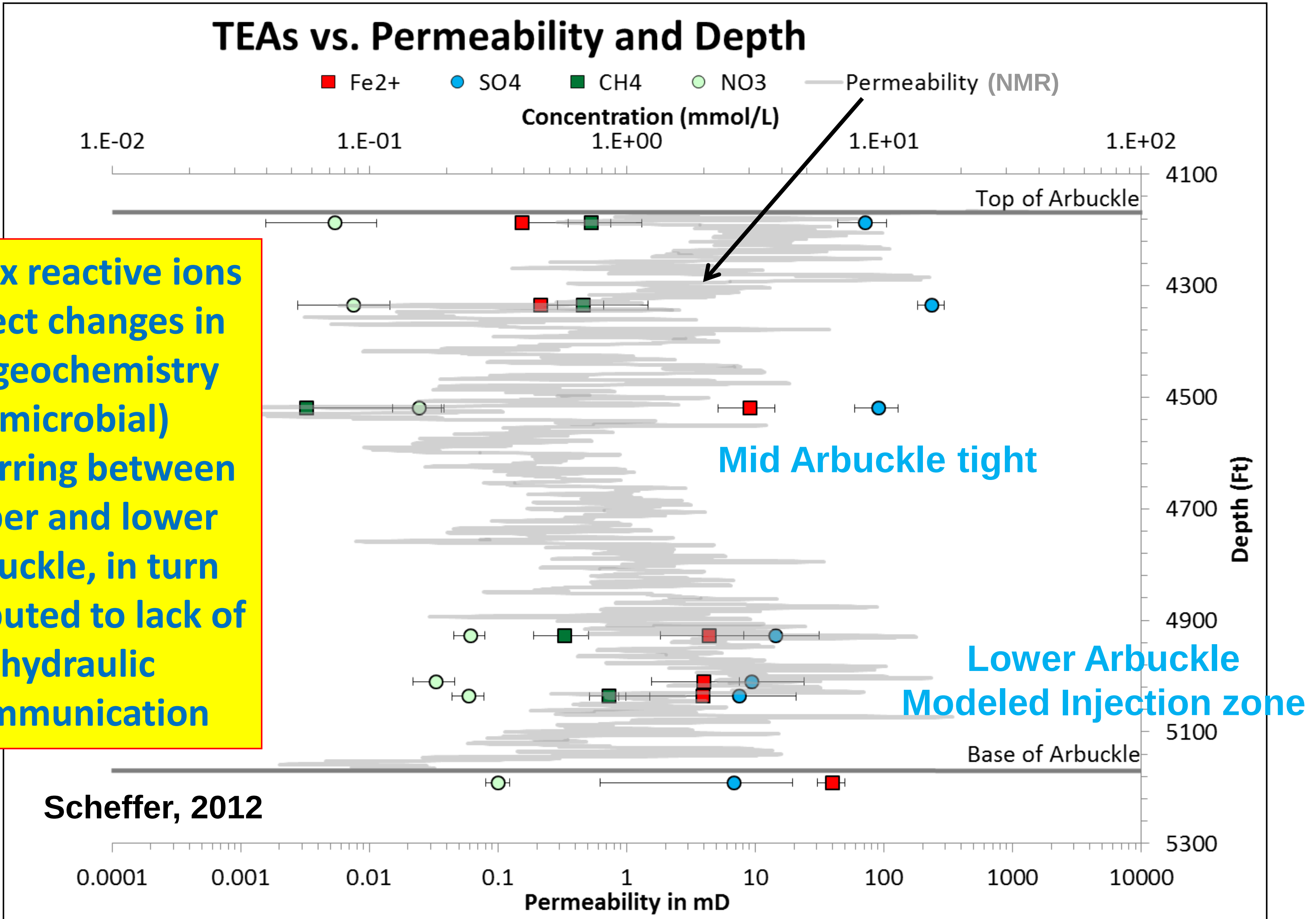
obtained from DST and perf & swab test



Scheffer (2012)

Permeability profile of Arbuckle in cored well - #1-32

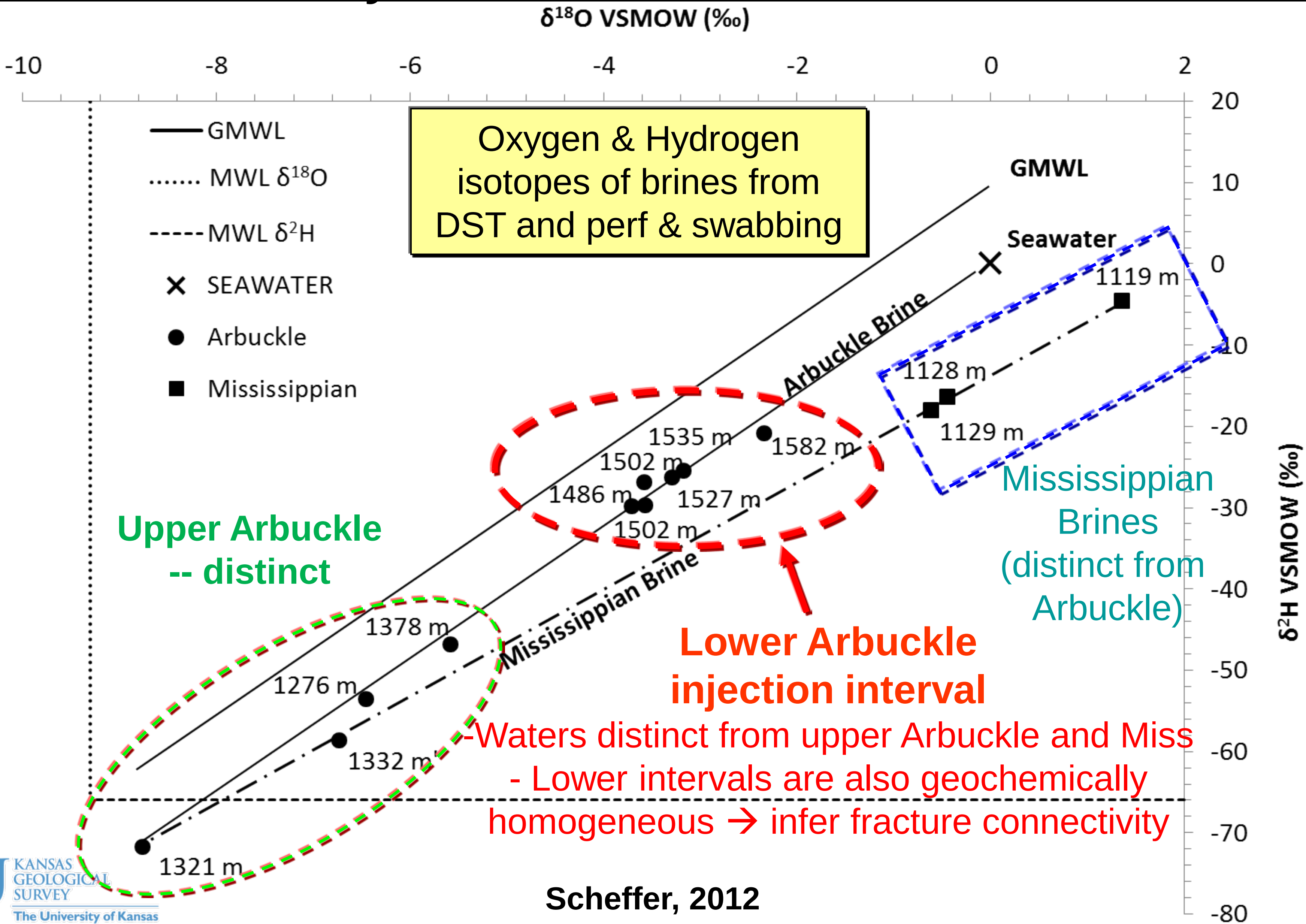
with concentrations of redox reactive ions (Fe^{2+}, SO_4^{2-}, CH_4, NO_3^-) from KGS #1-32 & #1-28



Redox reactive ions reflect changes in biogeochemistry (microbial) occurring between upper and lower Arbuckle, in turn attributed to lack of hydraulic communication

Scheffer, 2012

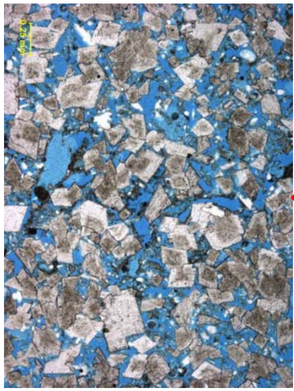
Lower and upper Arbuckle are not in hydraulic communication

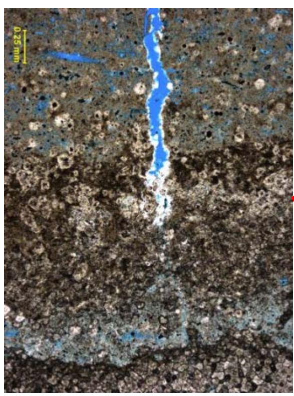


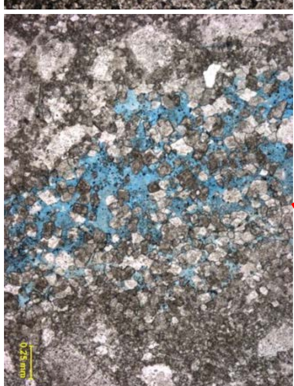
KANSAS GEOLOGICAL SURVEY The University of Kansas

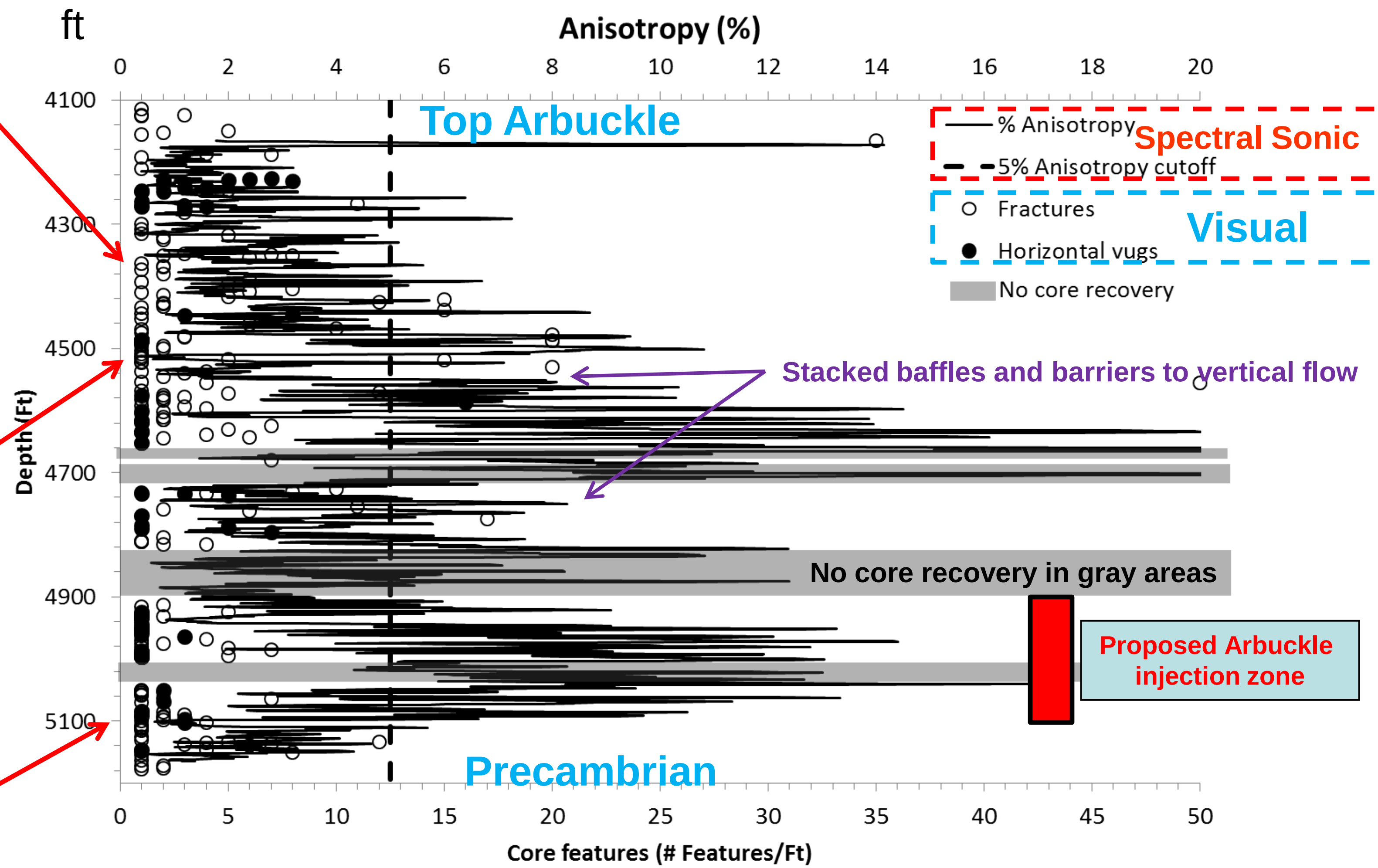
Zonal fracturing in entire Arbuckle

Spectral (dipole) acoustic log and visual core description



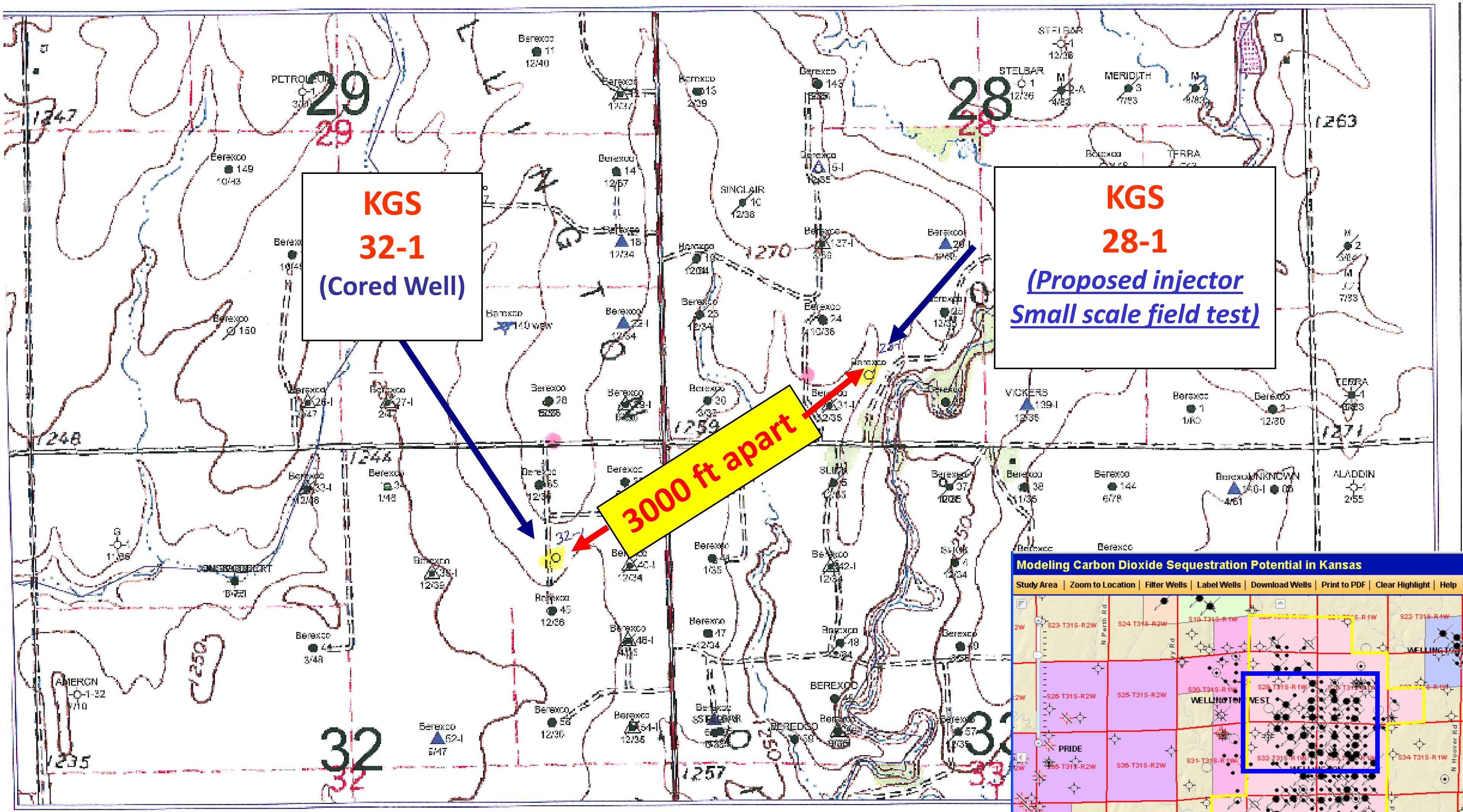






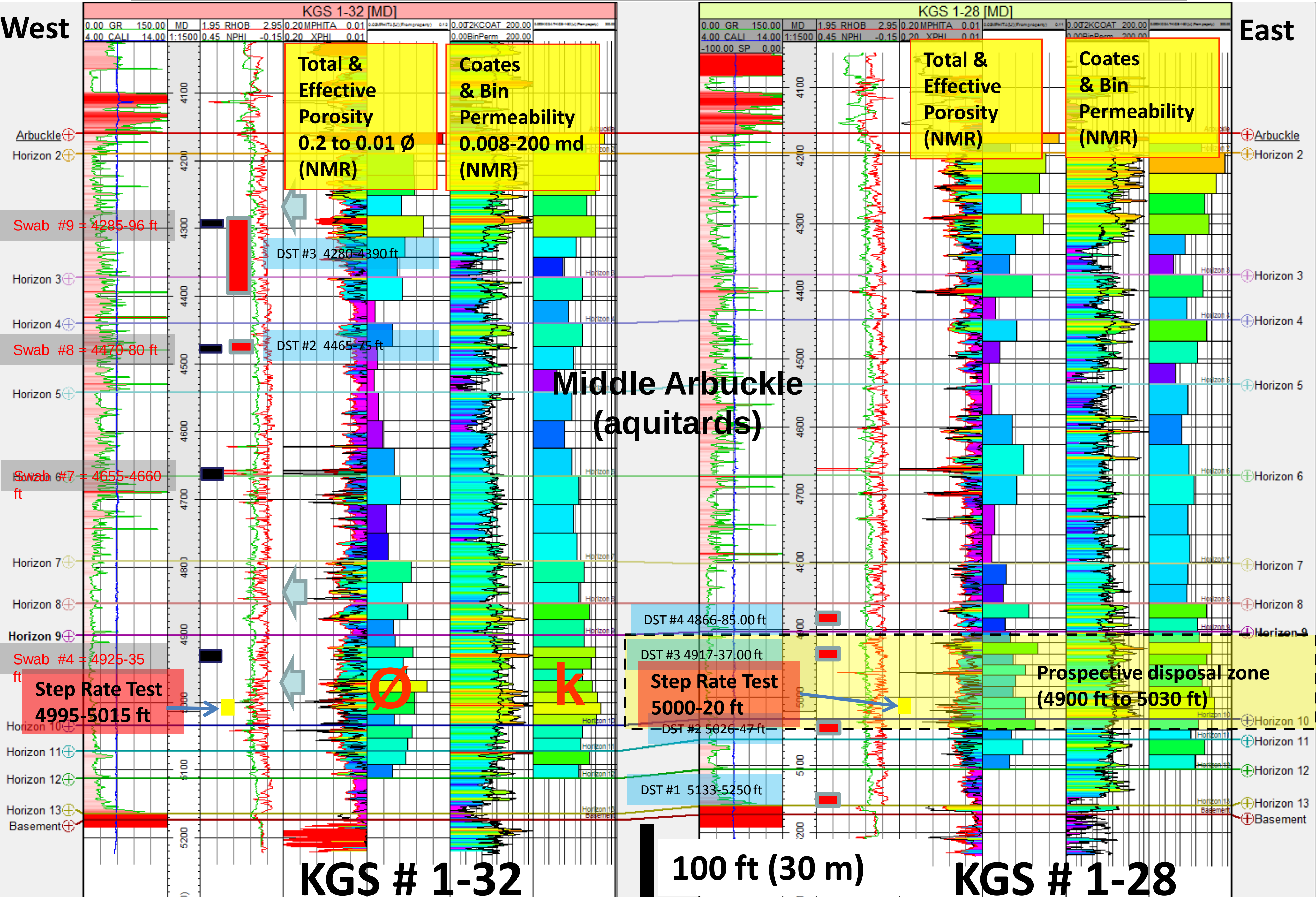
Scheffer, 2012; Lorenz and Cooper, 2011

Surface location of basement test (#1-32 & 31-28) drilled in Wellington Field during Jan-Feb 2011



Step-rate (pulse test) between wells conducted August 2011

Cross section showing 20 ft interval of step rate test in lower Arbuckle injection zone



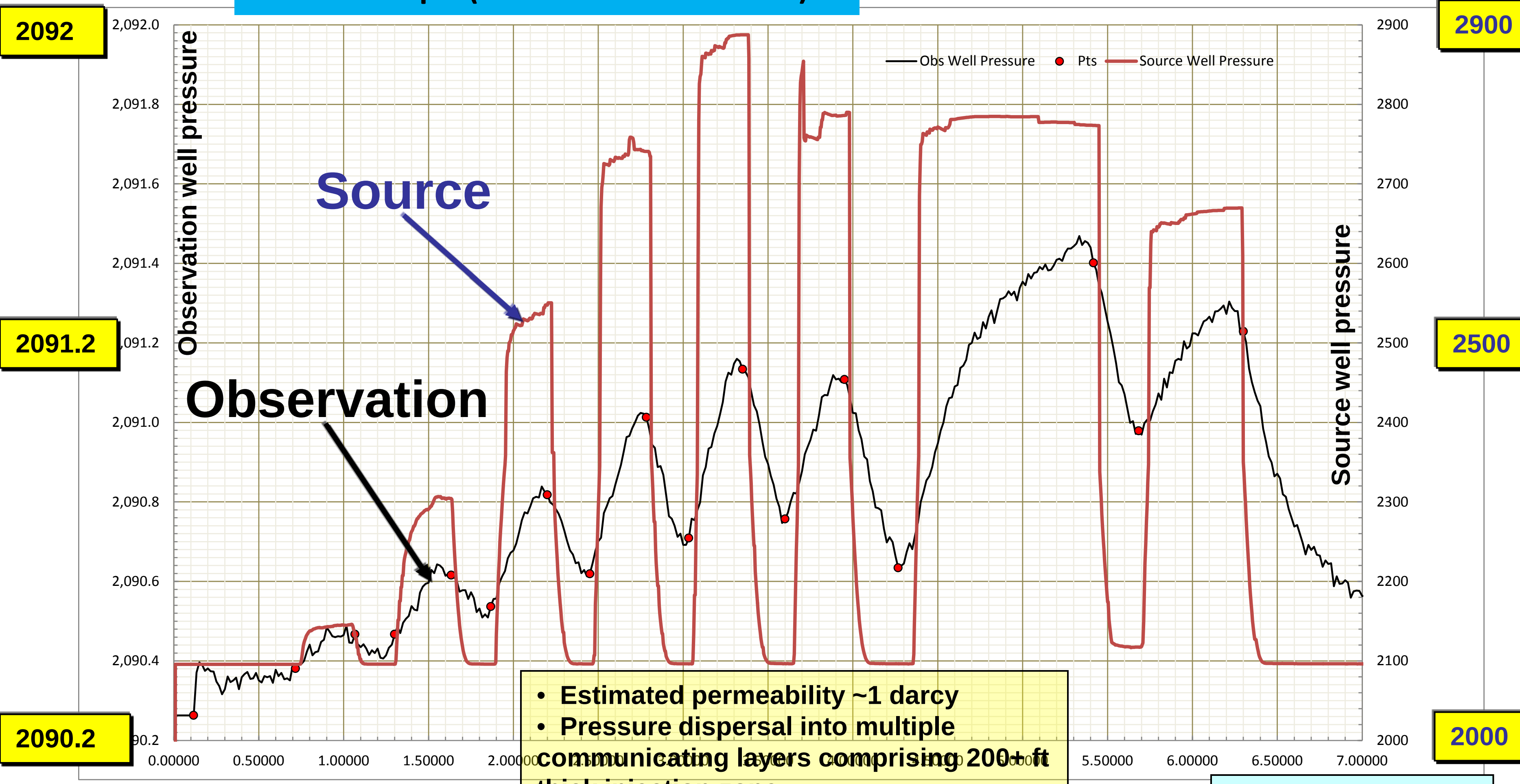
Preliminary upscaled hydrostratigraphic units in Arbuckle Group

HALLIBURTON

Step-Rate Test Pressure-Time Plot

Source Well (#1-32) and Observation Well (#1-28) Pressures in 20 ft Perforated Zone in Lower Arbuckle Injection Interval

Est. fracture pressure = 0.7 psi/ft x 5000 ft = 3500 psi (to create new fracture)

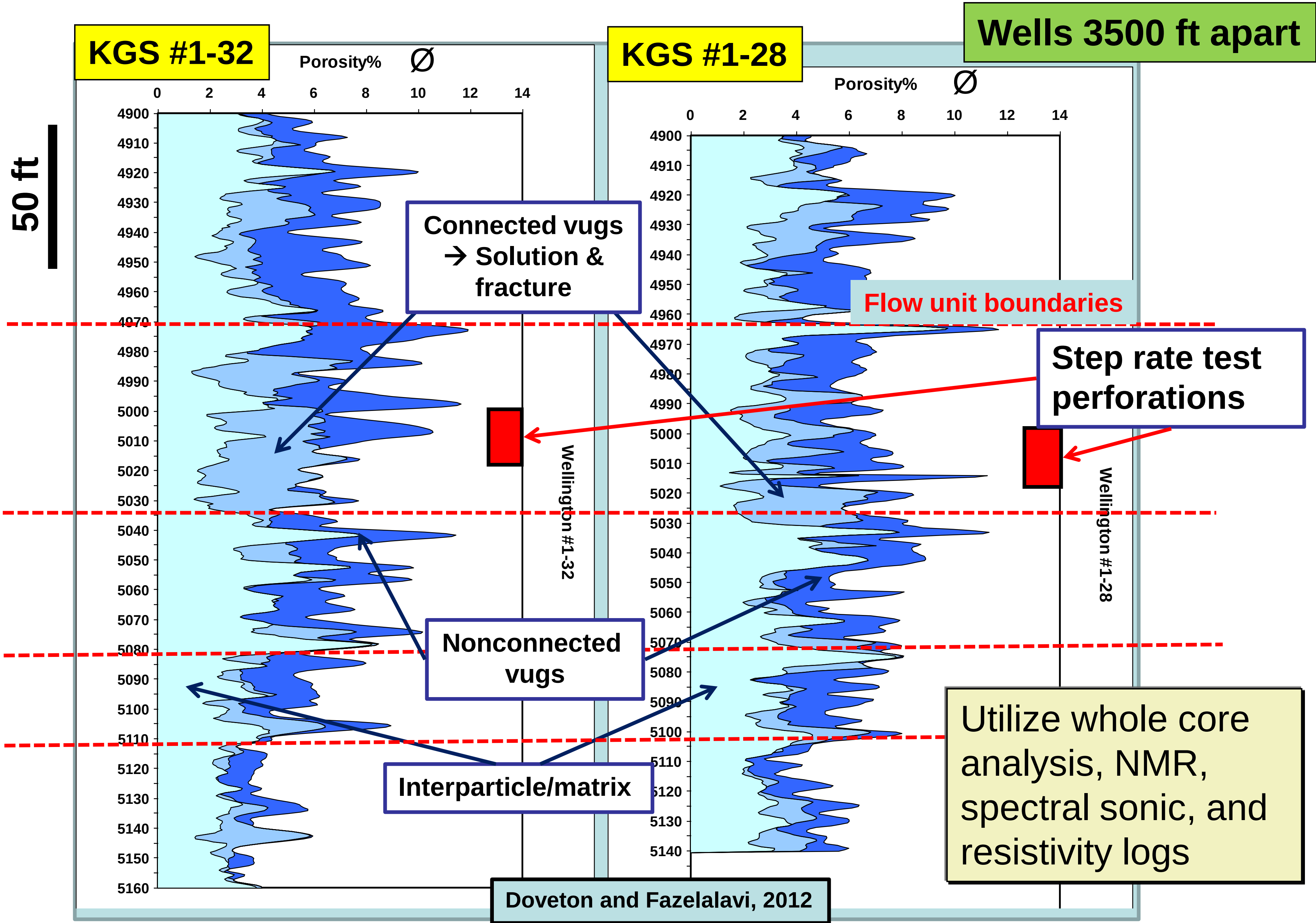


- **Estimated permeability ~1 darcy**
- **Pressure dispersal into multiple communicating layers comprising 200+ ft thick injection zone**

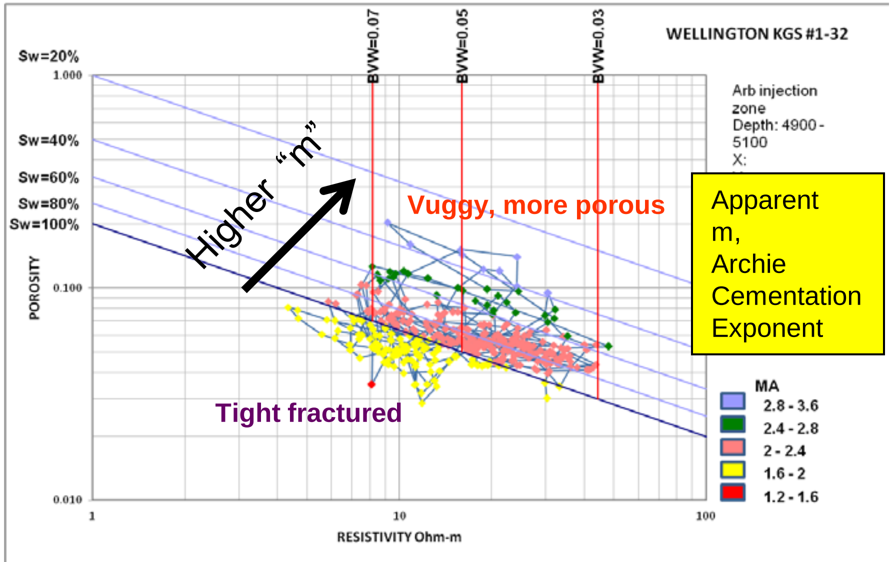
Birdie, June 2012

Time for observation well (#1-28) based on clock and start time for source well (#1-32)

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



Possible use of apparent "m", cementation exponent to indicate greater abundance of fractures (m <2) and vugs (m>2), injection zone



$$S_w = \sqrt[n]{\frac{a}{\phi^m}\,\frac{R_w}{R_t}}$$

S_w = Archie's water saturation

R_w = resistivity of formation water

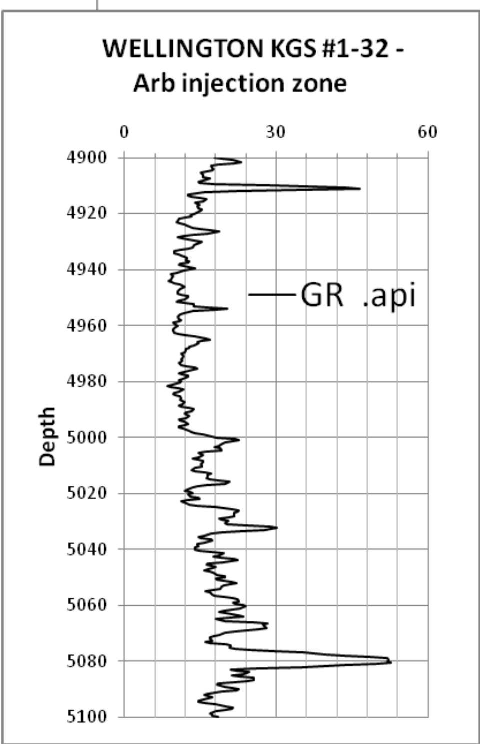
R_t = true formation resistivity

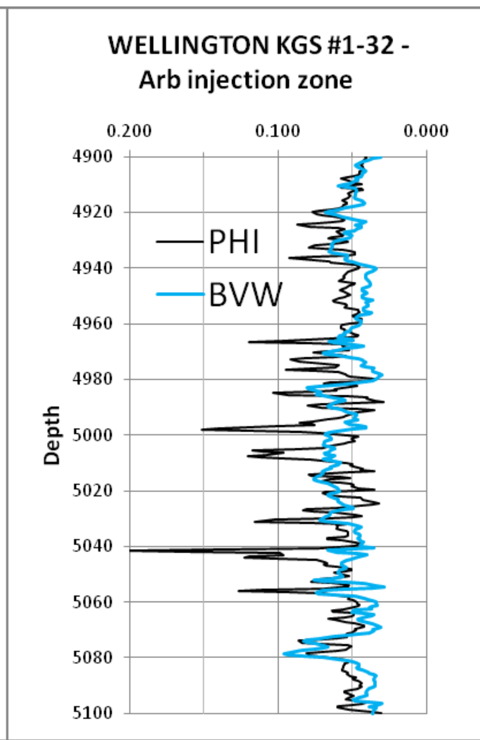
ϕ = porosity

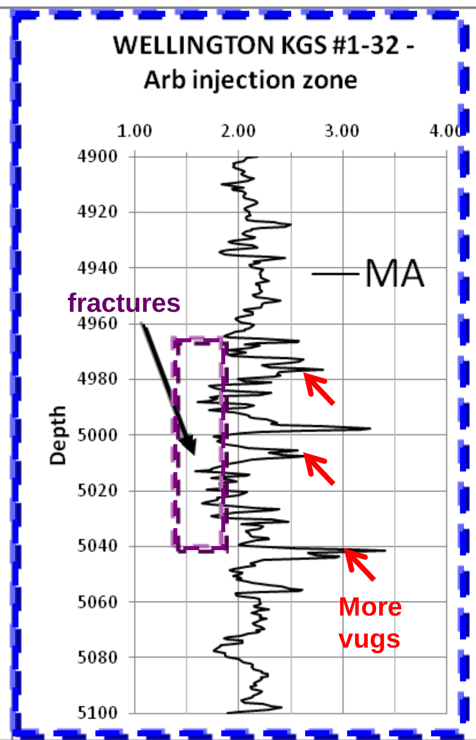
a = formation-factor multiplier

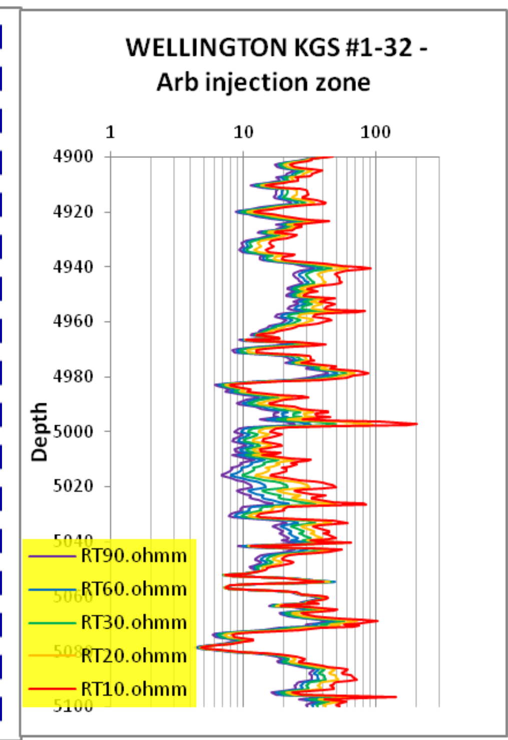
m = cementation exponent

n = saturation exponent

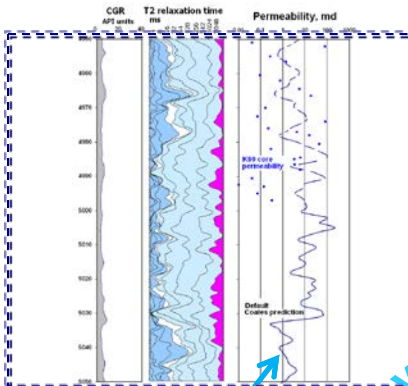


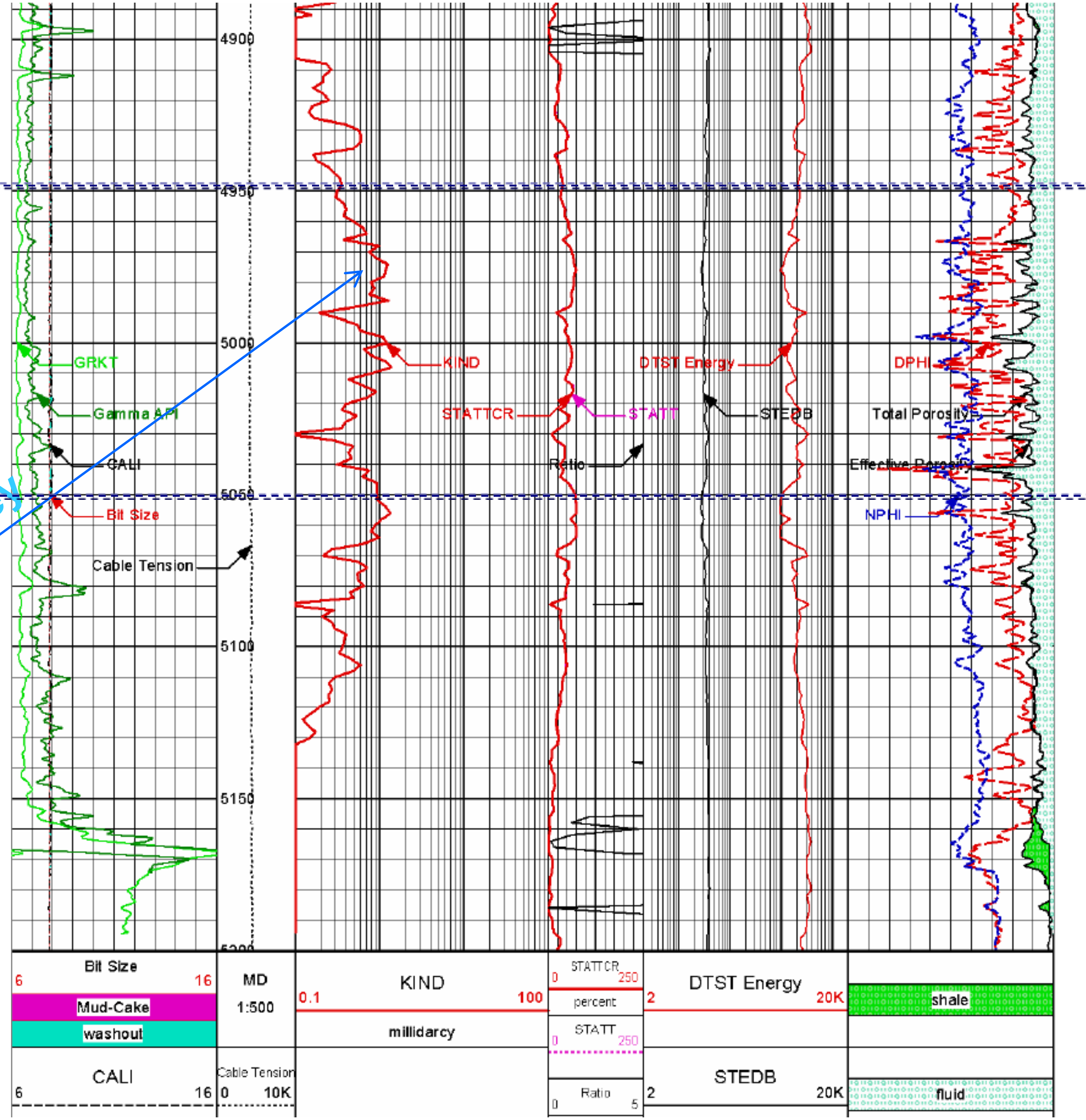




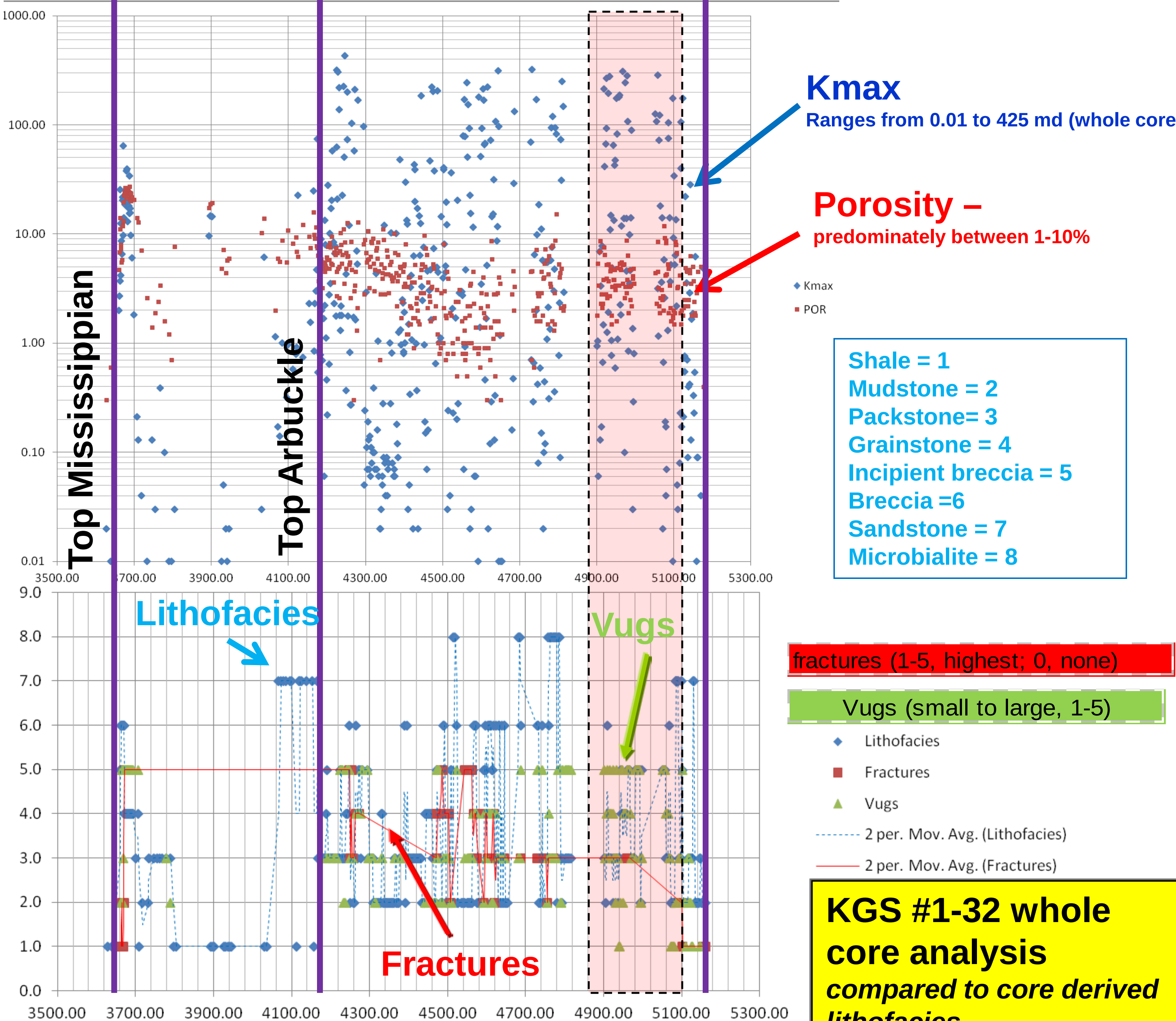


Dipole (Spectral™) sonic log interpretation at lower Arbuckle injection zone 4900 to 5150 ft





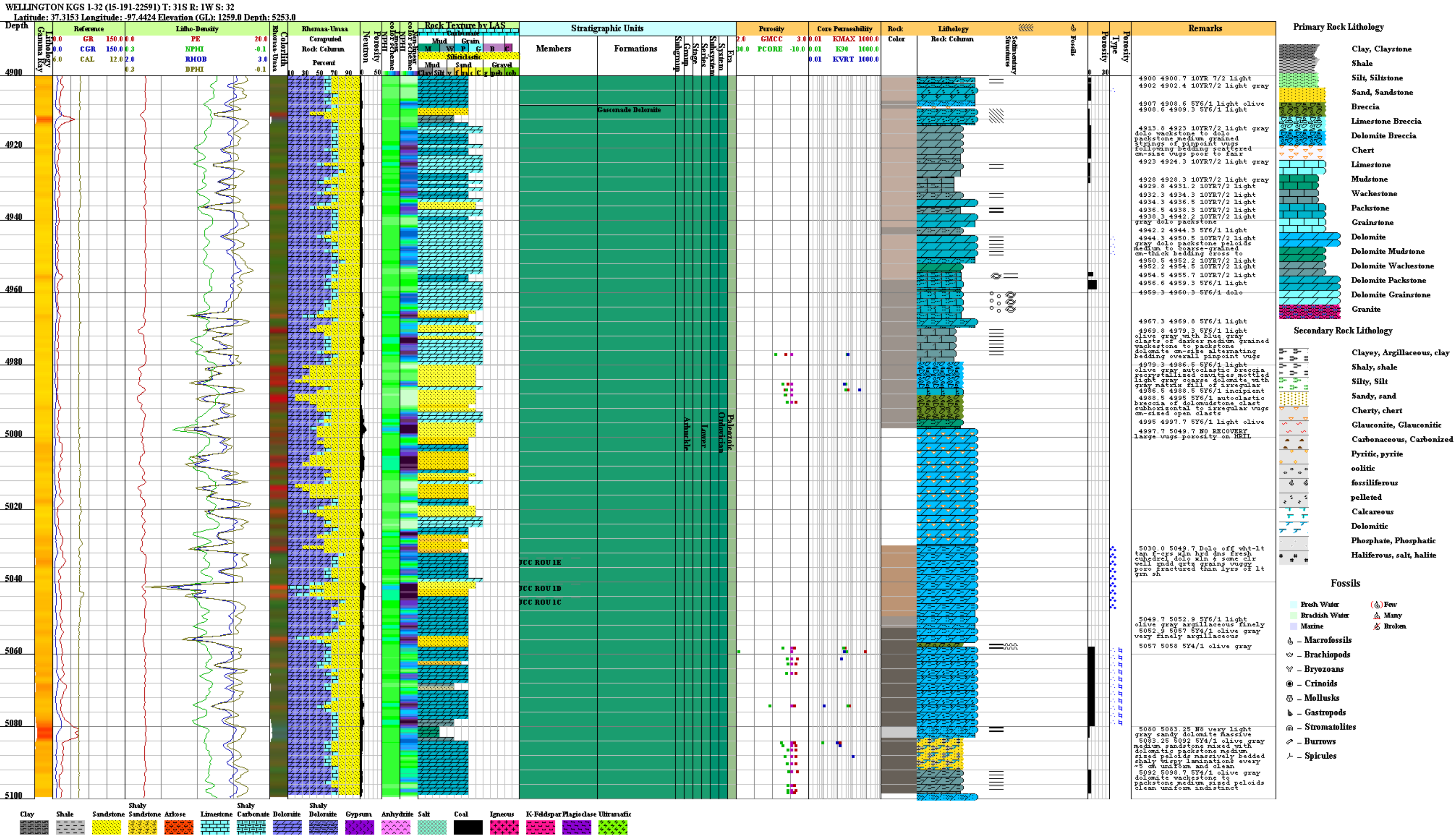
Stoneley wave used to estimate permeability, k compared to Coates k derived from MRIL



KGS #1-32 whole core analysis

compared to core derived lithofacies

Core-Log integration of Wellington KGS #1-32 using well profile tool – INJECTION INTERVAL (4900-5200 ft)



http://www.kgs.ku.edu/stratigraphic/PROFILE/applet.html

Core from Lower Arbuckle Injection Interval

5089-92 ft

5080-83

5053-56

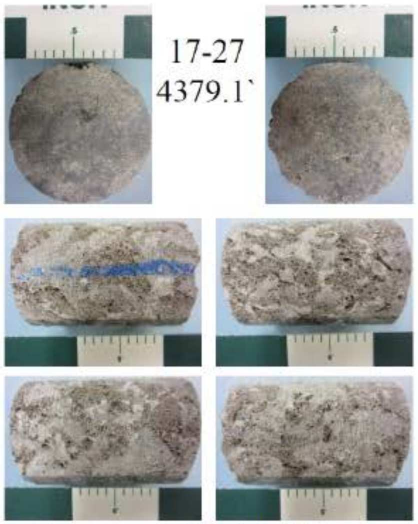
2.3%, 108 md

4995-97.7 ft

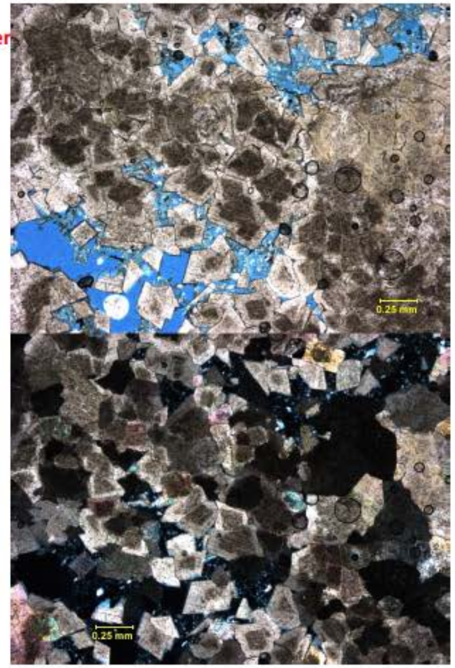
4.8%, 0.29 md

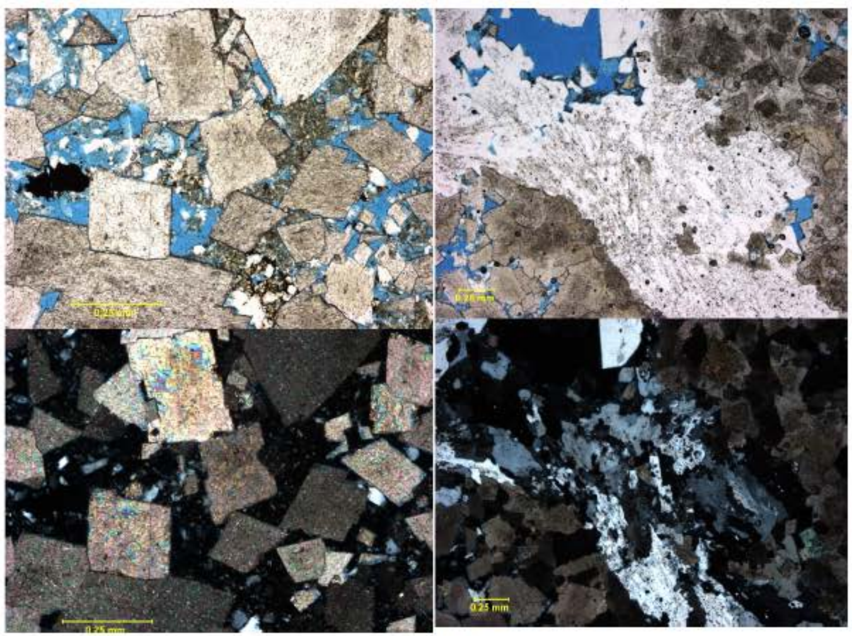
Middle Arbuckle - lower Jefferson City Cotter
Baffle to barrier?

17-27
4379.1`



whole core: phi 4.4%, 10 md

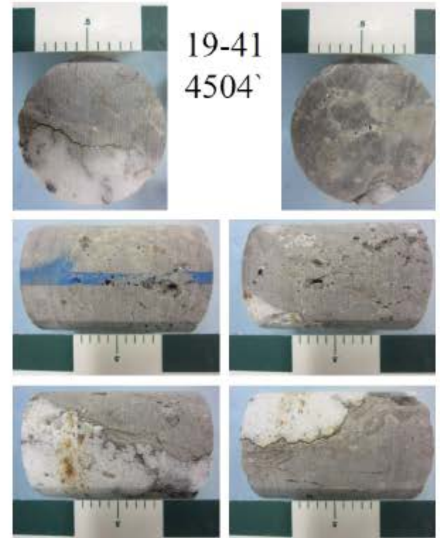




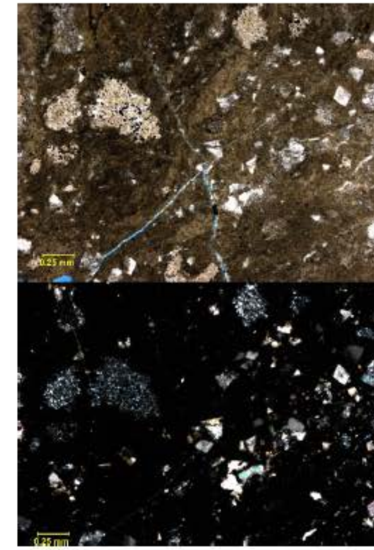
4379.1 ft

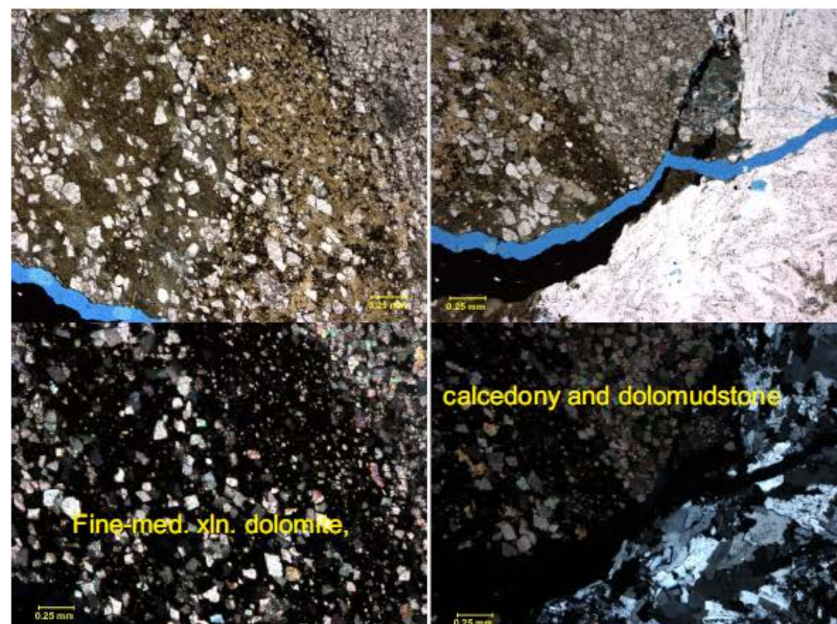
Middle Arbuckle - lower Jefferson
City Cotter
Baffle to barrier?

19-41
4504`



whole core: phi 3%, 8.1 md

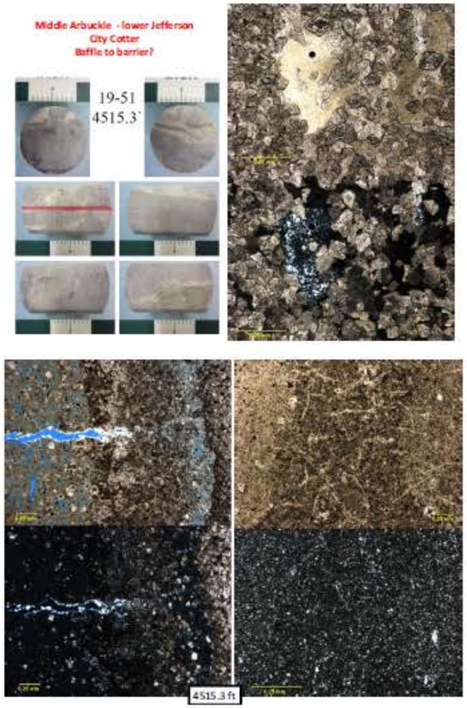




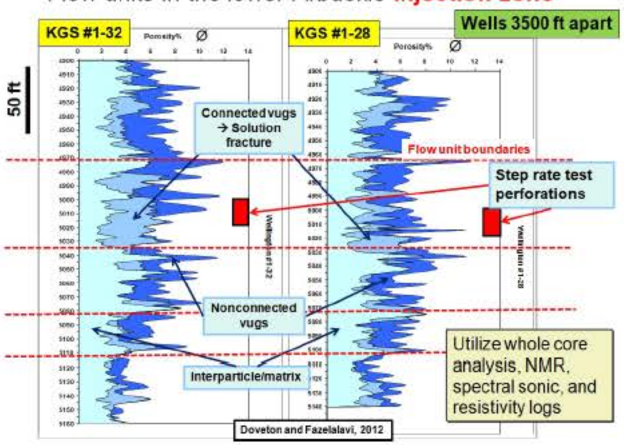
4505 ft

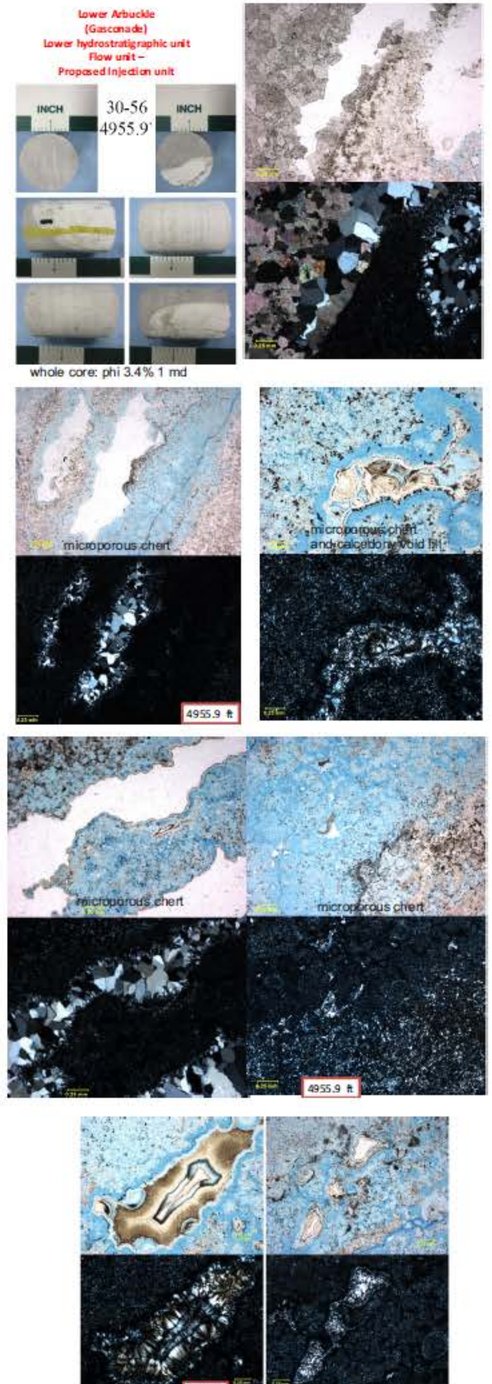
Thin sections and photomicrographs by Robin Barker, KSU, 10-25-12

Thin Sections – Baffle Zone (Mid Arb.)

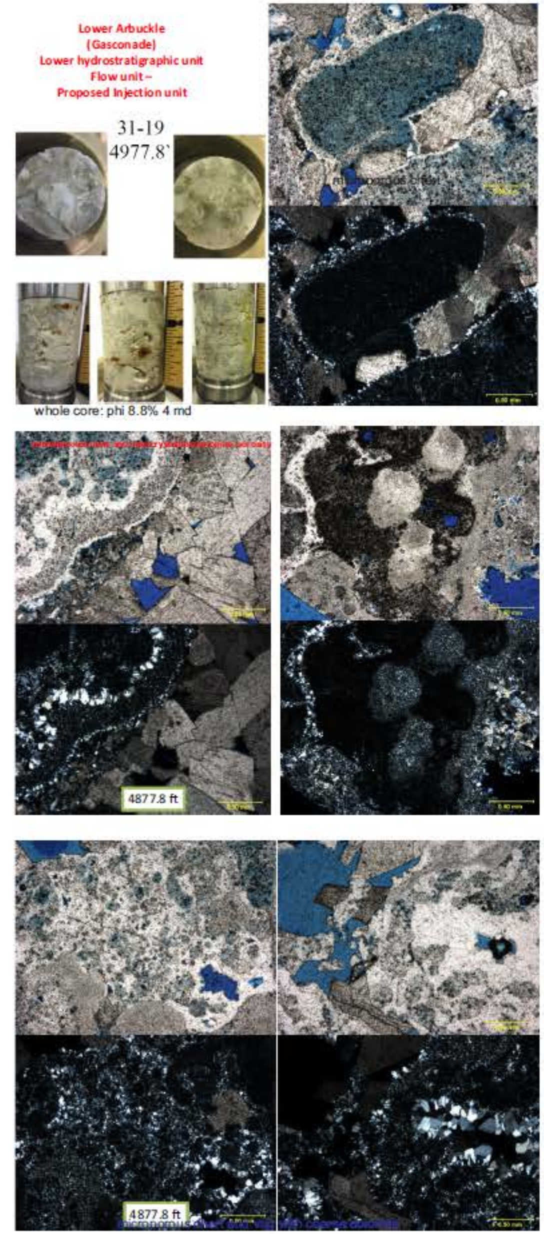


Flow units in the lower Arbuckle **injection zone**





Lower Arbuckle Injection Zone



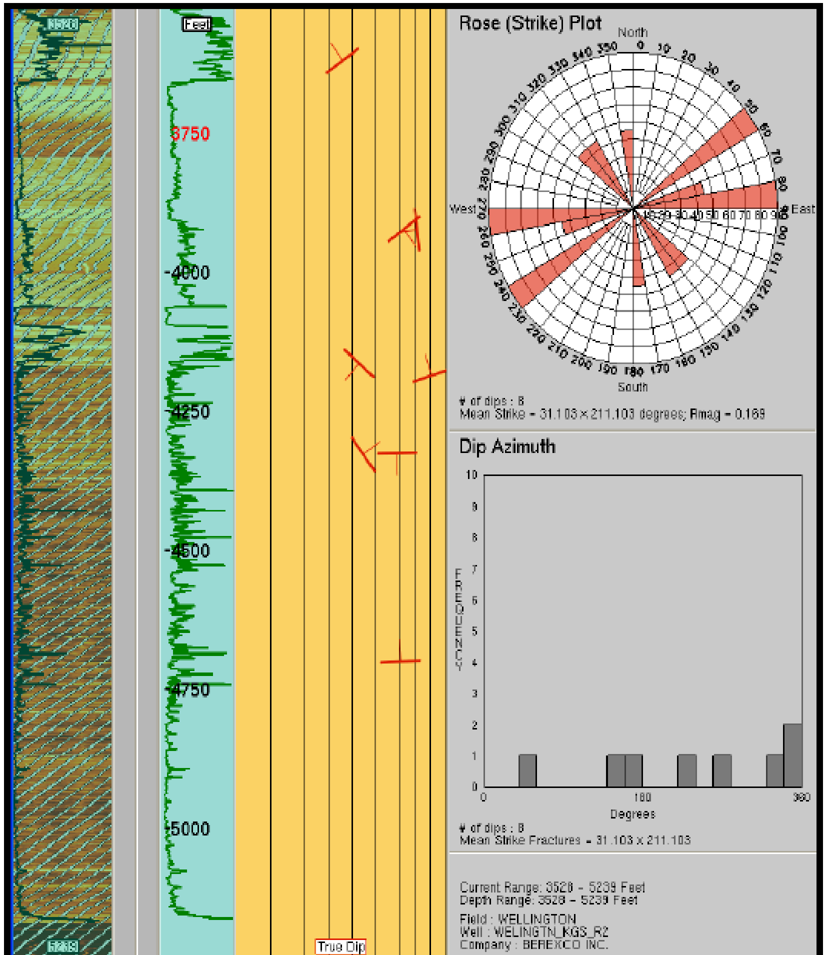
Pairs of photomicrographs
Plane light and crossed nichols

MAXIMUM HORIZONTAL COMPRESSIVE STRESS (East-Northeast)

from microresistivity imaging and dipole sonic logs (KGS #1-32)

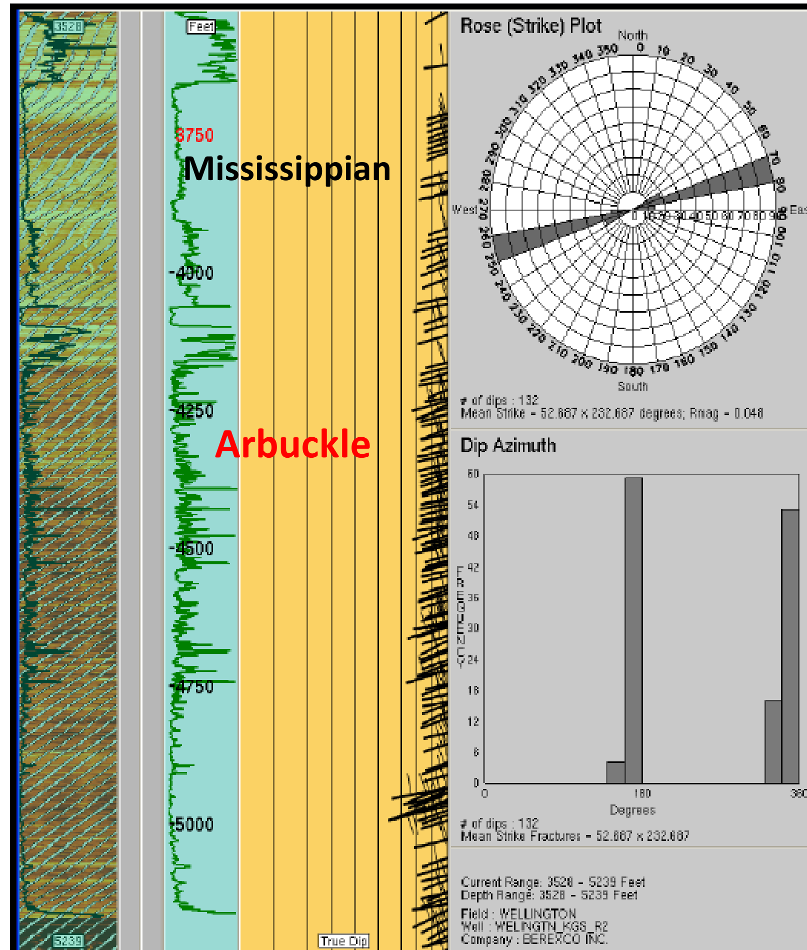
Fracture Statistics: 5239'-3528'

Natural mineralized "closed" fractures



There are natural mineralized "closed" fractures with two orientations, one E x W and the other NE x SW.

Induced fractures

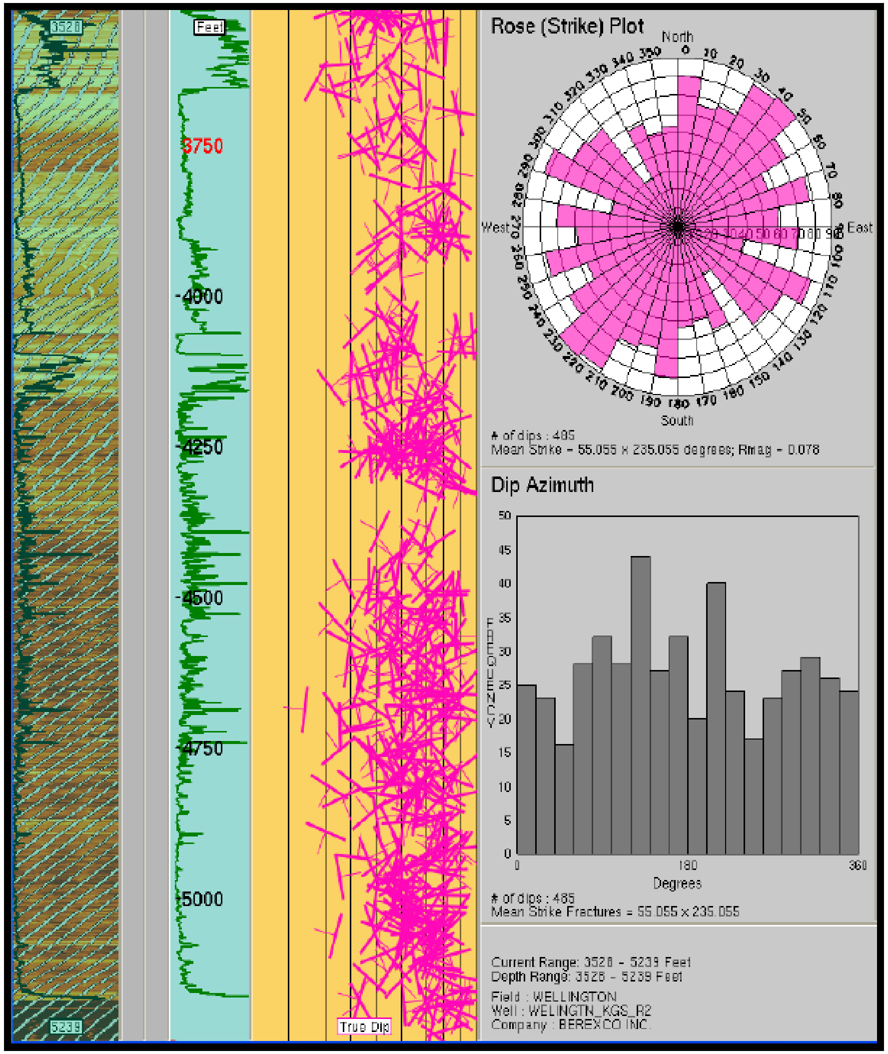


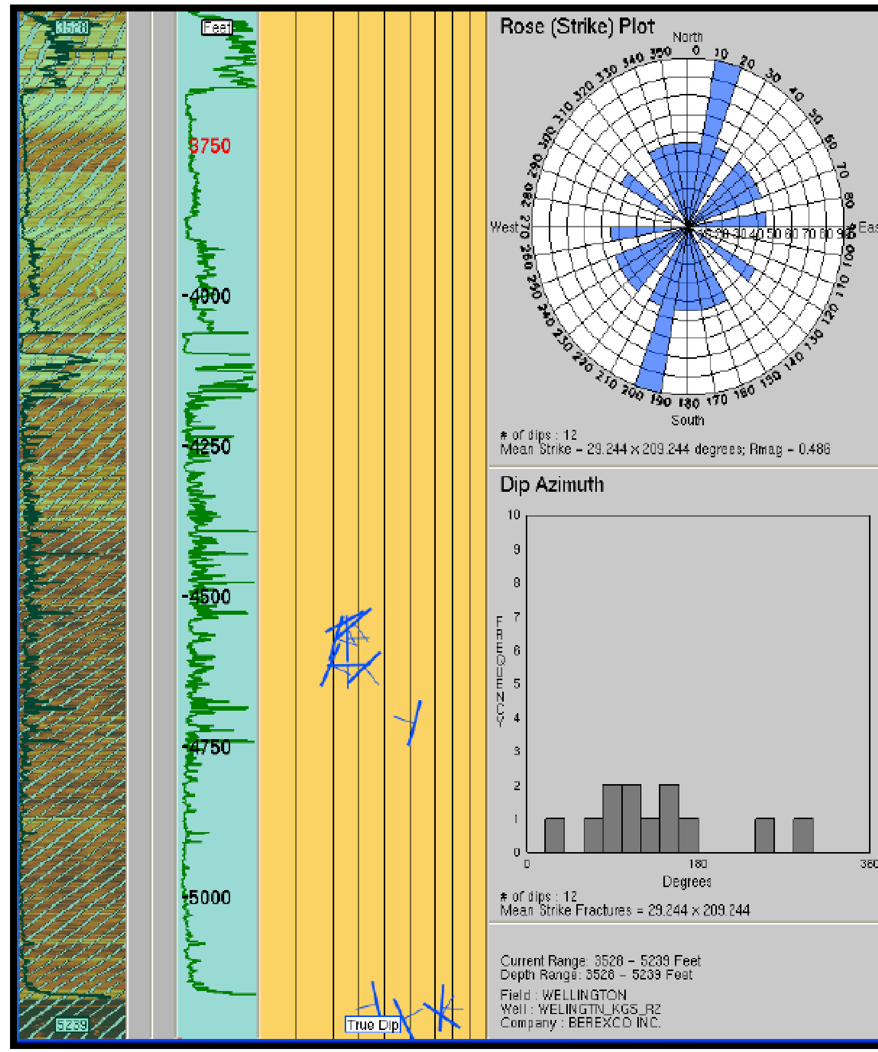
There are 132 drilling induced fractures in this pass, oriented 75°/255°, indicating the maximum stress direction.

HALLIBURTON

Fracture Statistics: 5239'-3528'

Wellington KGS #1-32





There are 485 partial fractures in this pass with random orientation.

There are 12 natural open fractures (360° conductive fractures) with an overall NNE x SSW orientation.

Microresistivity imaging log and spectral sonic

HALLIBURTON

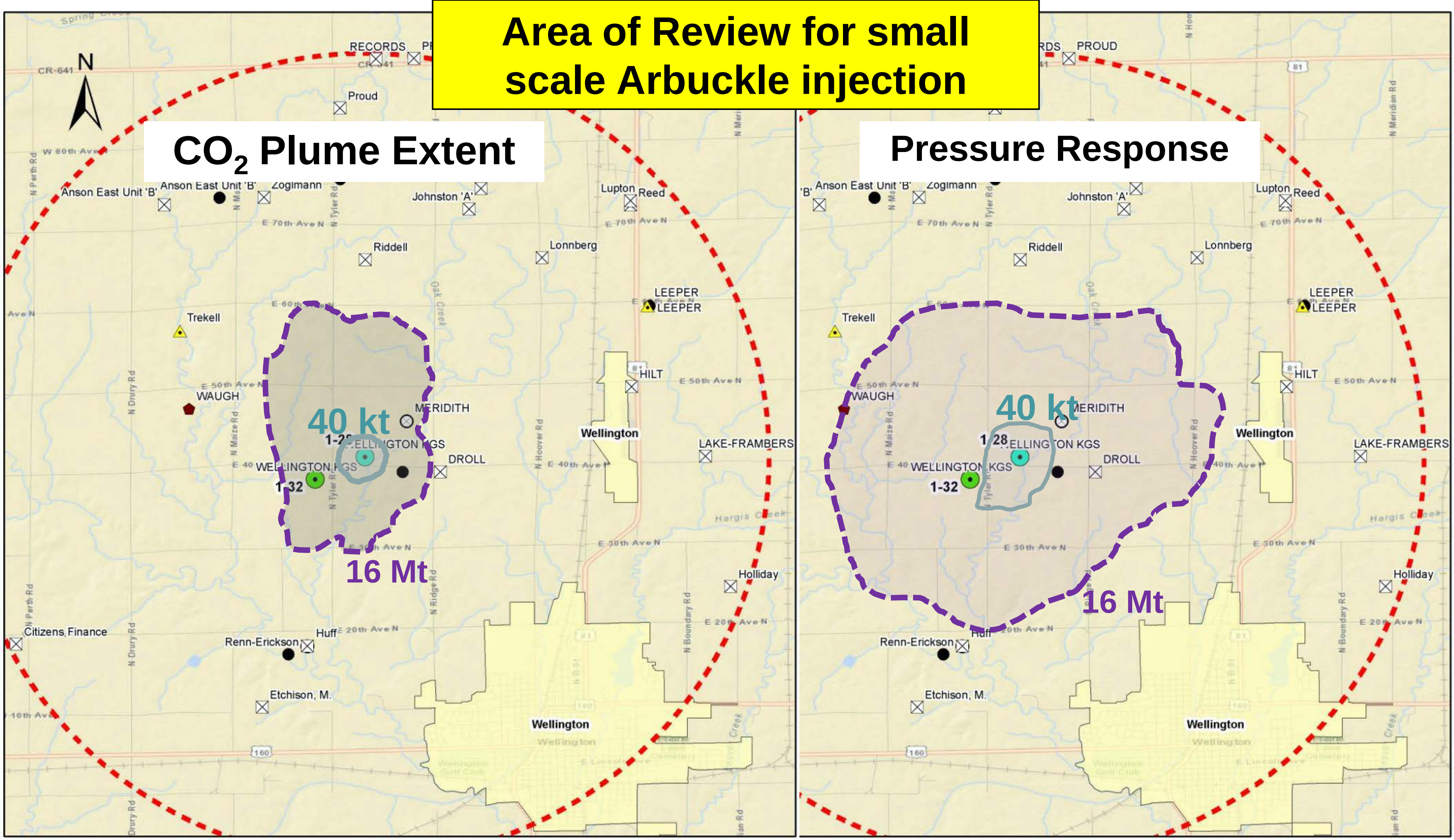
Dynamic Simulation of CO_2 Injection in Saline Aquifer, Arbuckle Fm. in Wellington Field

Yevhen Holubnyak

GeoFest 2012
Lawrence, KS

October 26, 2012

Area of Review for small scale Arbuckle injection



Legend

Arbuckle Wells

- <all other values>
- KGS 1-32
- KGS 1-28
- 5 Mile Radius

STATUS

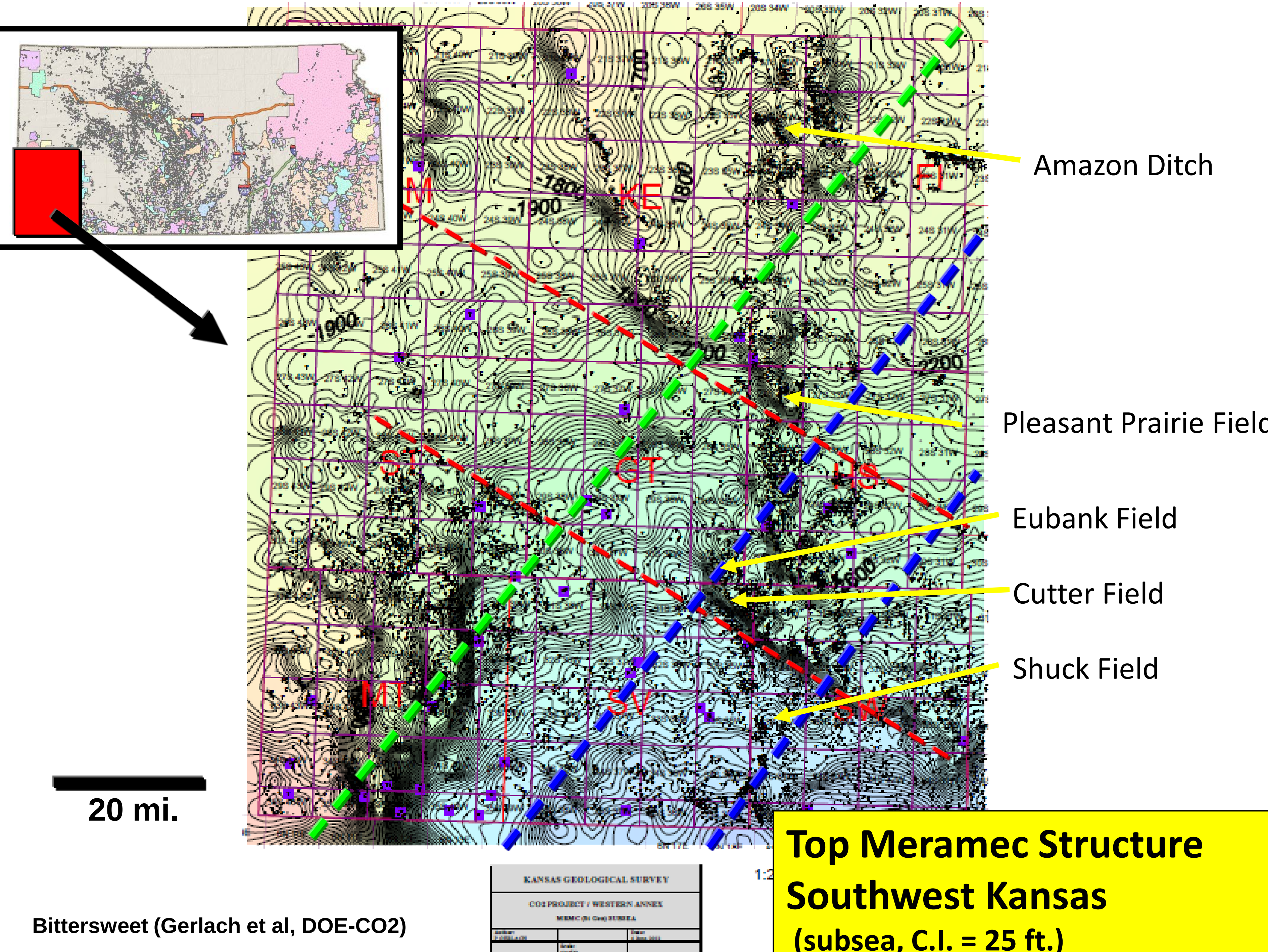
- D&A
- OIL
- OIL-P&A
- OTHER
- SWD

Miles

0 0.4 0.8 1.6 2.4

Dynamic Simulation of CO_2 Injection in Saline Aquifer, Arbuckle Fm. in Wellington Field

Yevhen Holubnyak, KGS

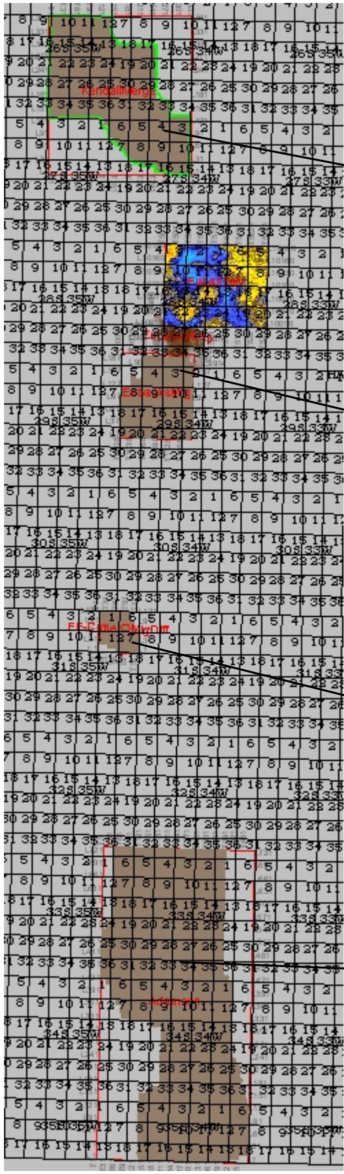


Top Meramec Structure Southwest Kansas

(subsea, C.I. = 25 ft.)

Bittersweet (Gerlach et al, DOE-CO2)

3D Volume Footprints for DOE-CO2 study



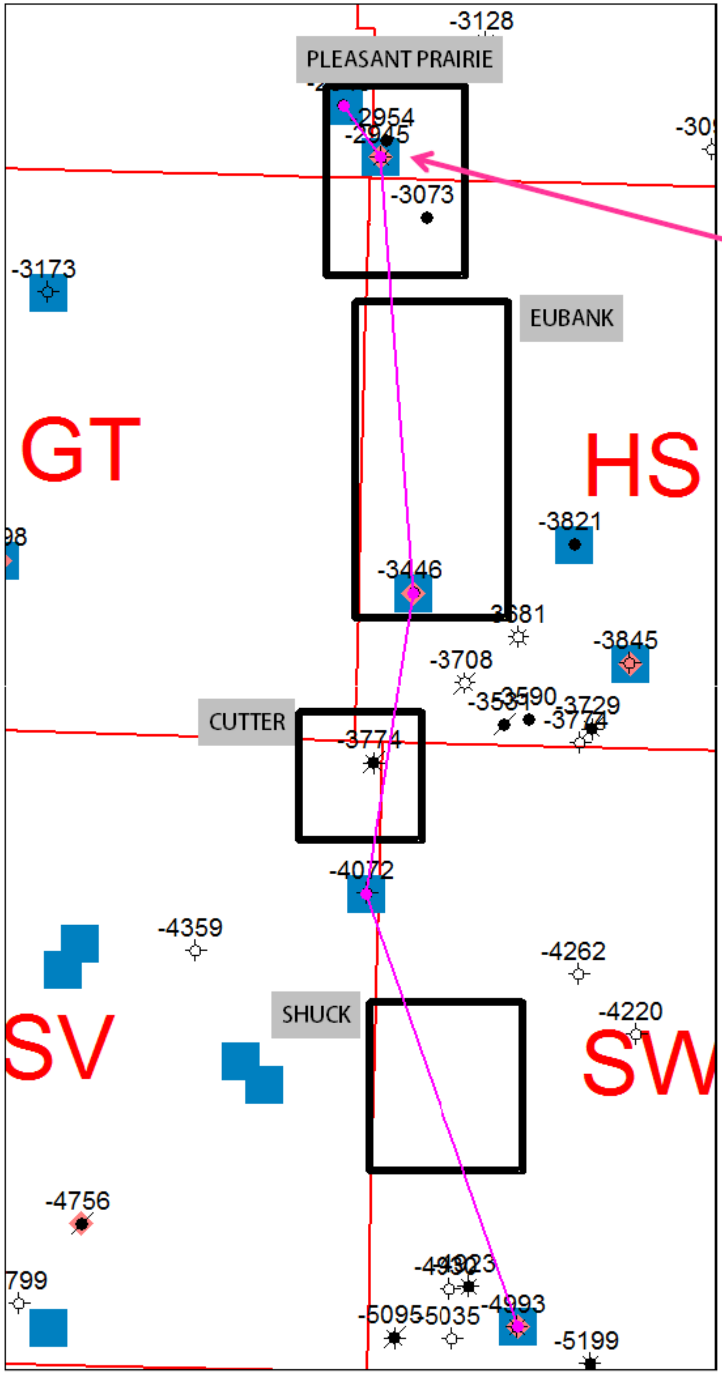
Gross Extent of Seismic coverage verify structure and use in Chester/Morrow EOR Study

= 112 mi N-S, 11 mi E-W

- Pleasant Prairie Merge ~ 32.5 sq mi, processed 1999, can be interpreted as is, bin size 110’ x 110’
- Eubanks Merge ~ 37.5 sq mi; 3 surveys acquired 1996 – 2001, bin size 110’ x 110’, reprocessing underway
- Cutter ~ 3.4 sq mi, acquired 2009, bin size 82.5 x 82.5, can be interpreted as is
- Adamson-Wide Awake (Shuck) ~ 81.5 sq mi, acquisition /processing date unknown, bin size 82.5’ x 110’, can be interpreted as is

Donated to DOE-CO2 project by industry members of Southwest Kansas CO2-EOR Initiative
Managed by M. Dubois
Seismic data management and interpretation by D. Hedke

Western Annex
ARBK Penetrations

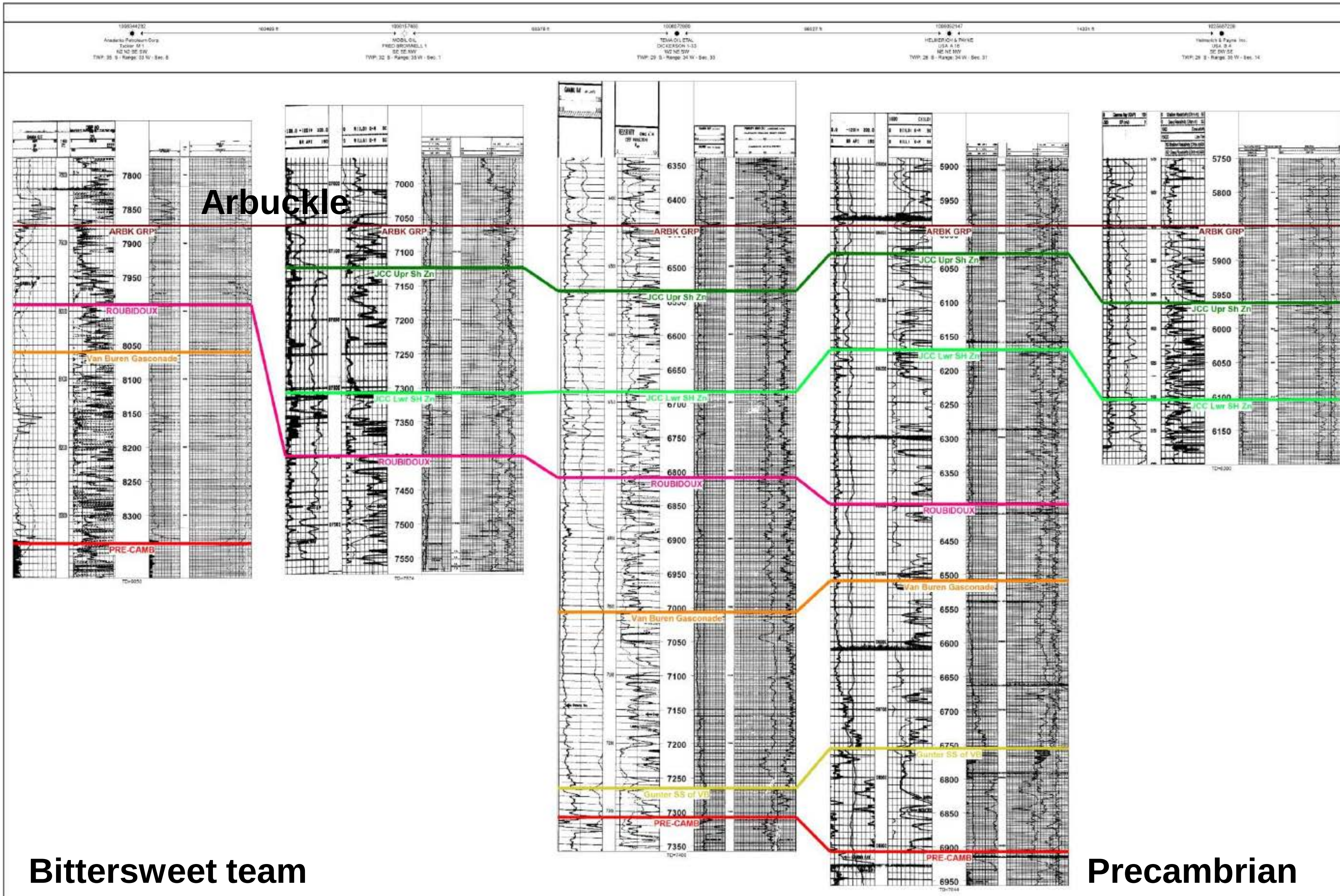


N-S Cross Section
3 Intervals
ARBK to Pre-Camb
MRMC to ARBK
MRRW to MRMC

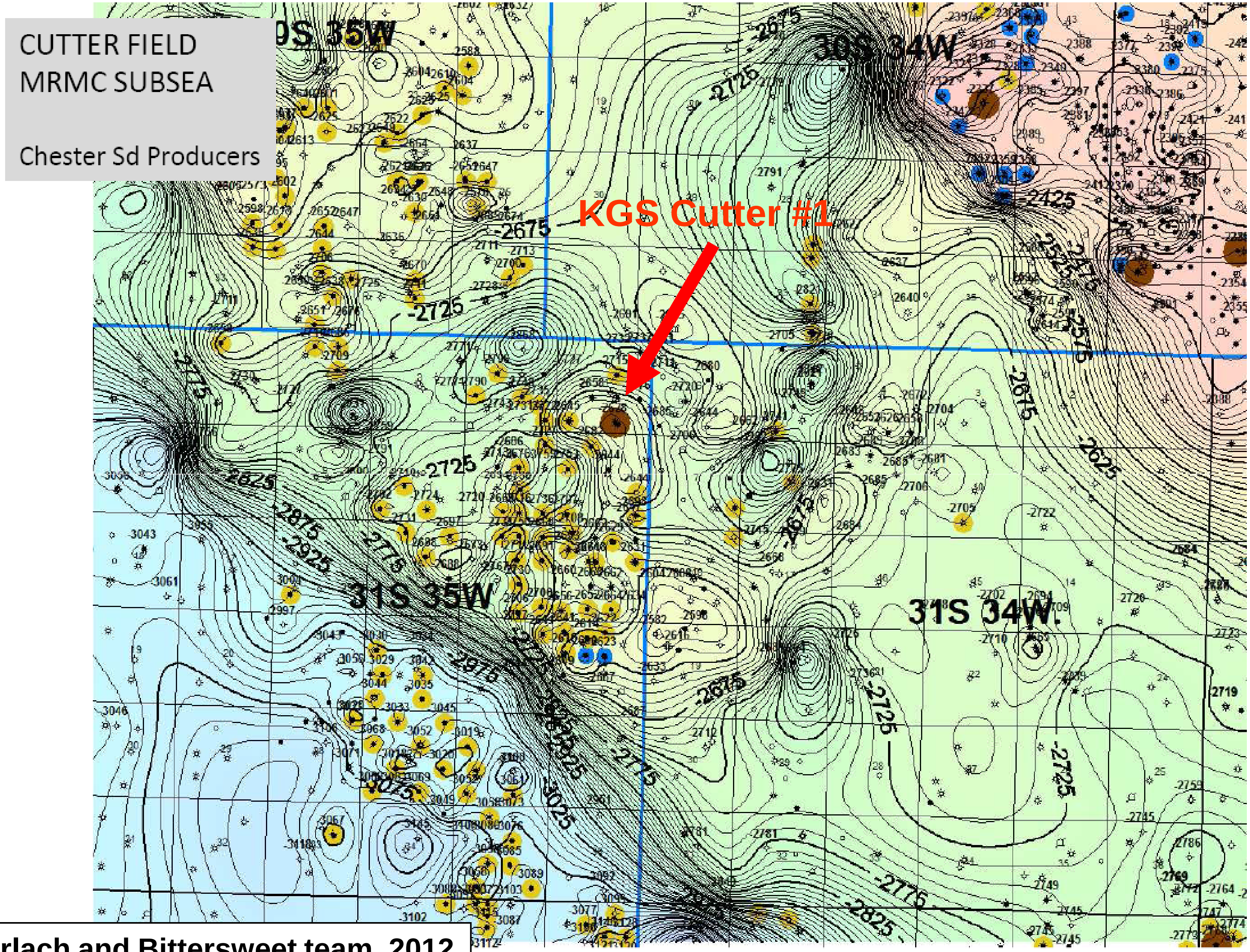
Pre-Camb Penetrations

Bittersweet Team

N-S X-Section
ARBK to Pre Camb Interval



KGS Cutter #1 well on Mississippian structural plateau on local structural high

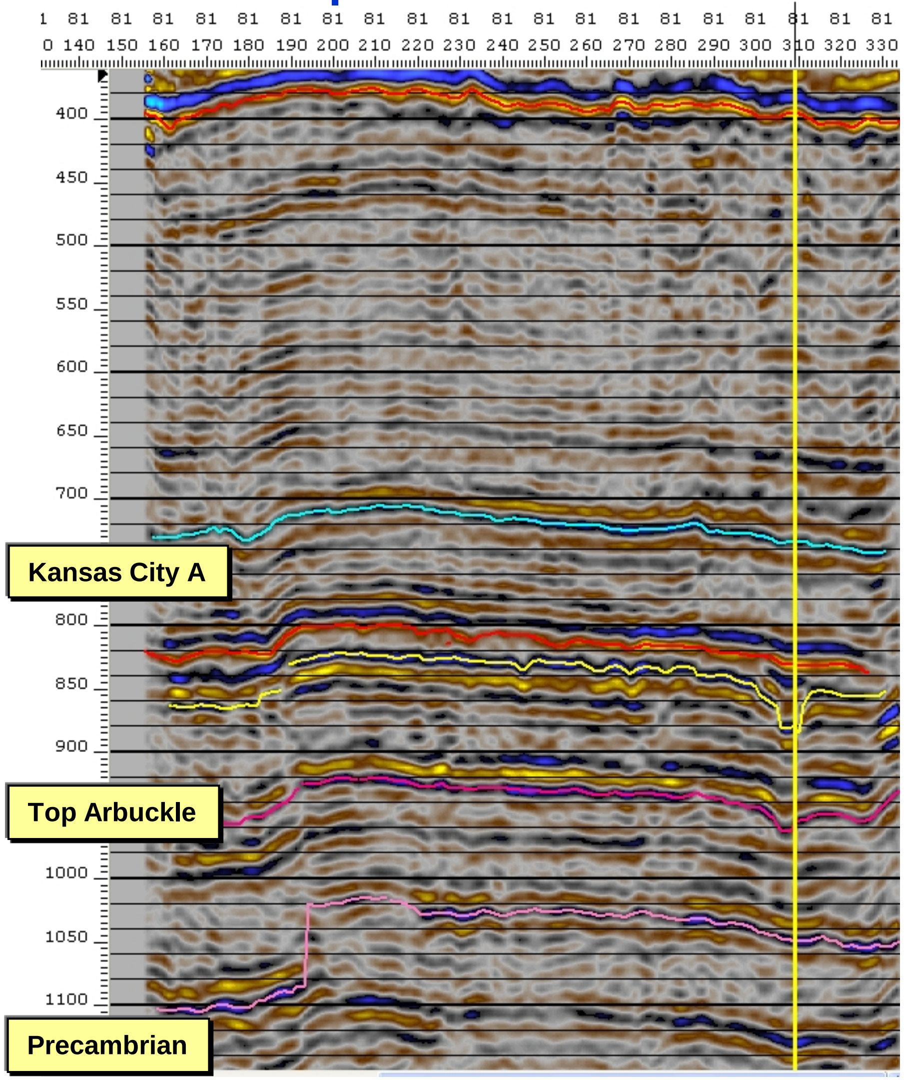


Gerlach and Bittersweet team, 2012

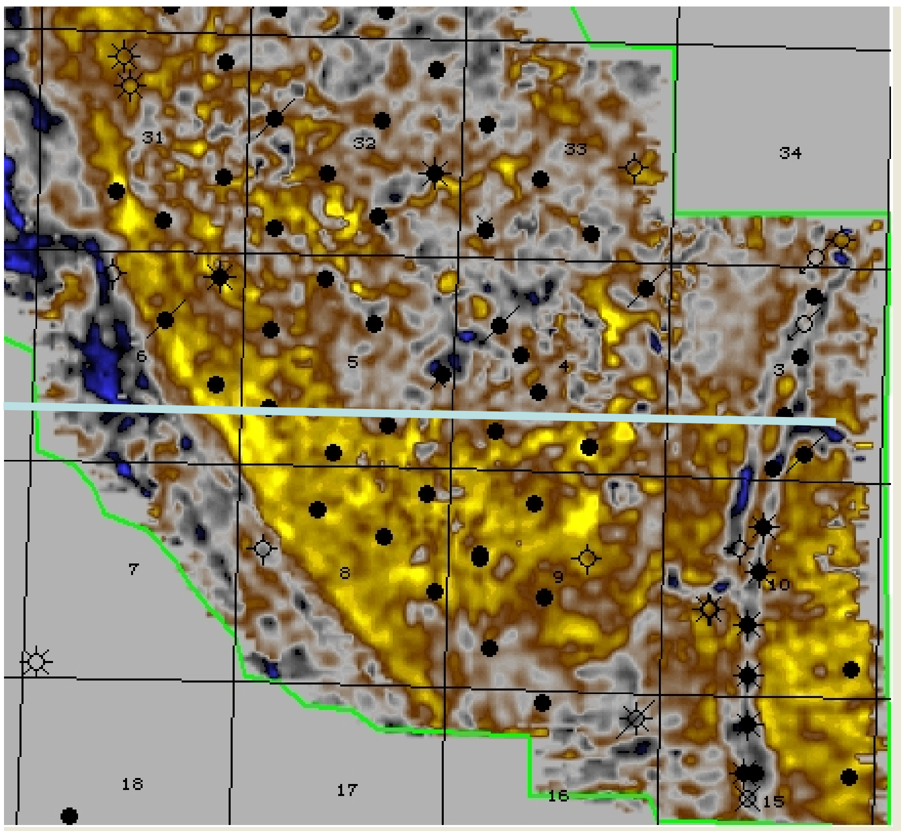
Pleasant Prairie Time Slice –

Chester Incised Valley System, Faults

West side of field --
~800 ft reverse fault
at top of basement

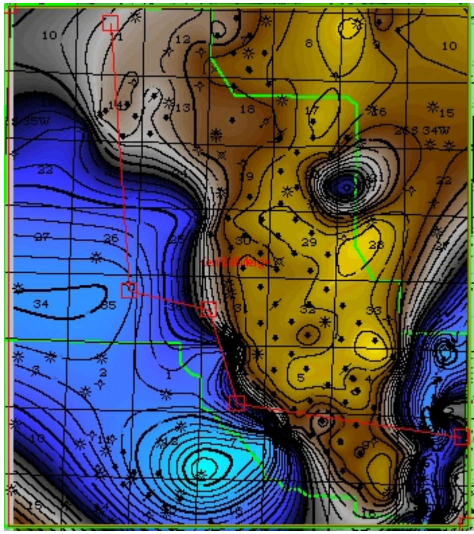


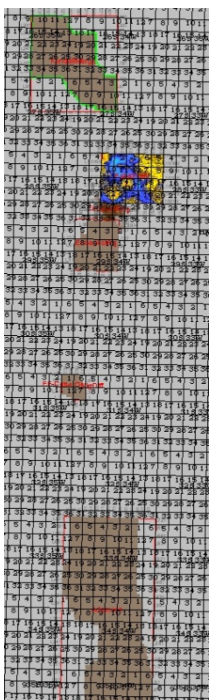
W-E Time Section
Time Slice at top of Meramec

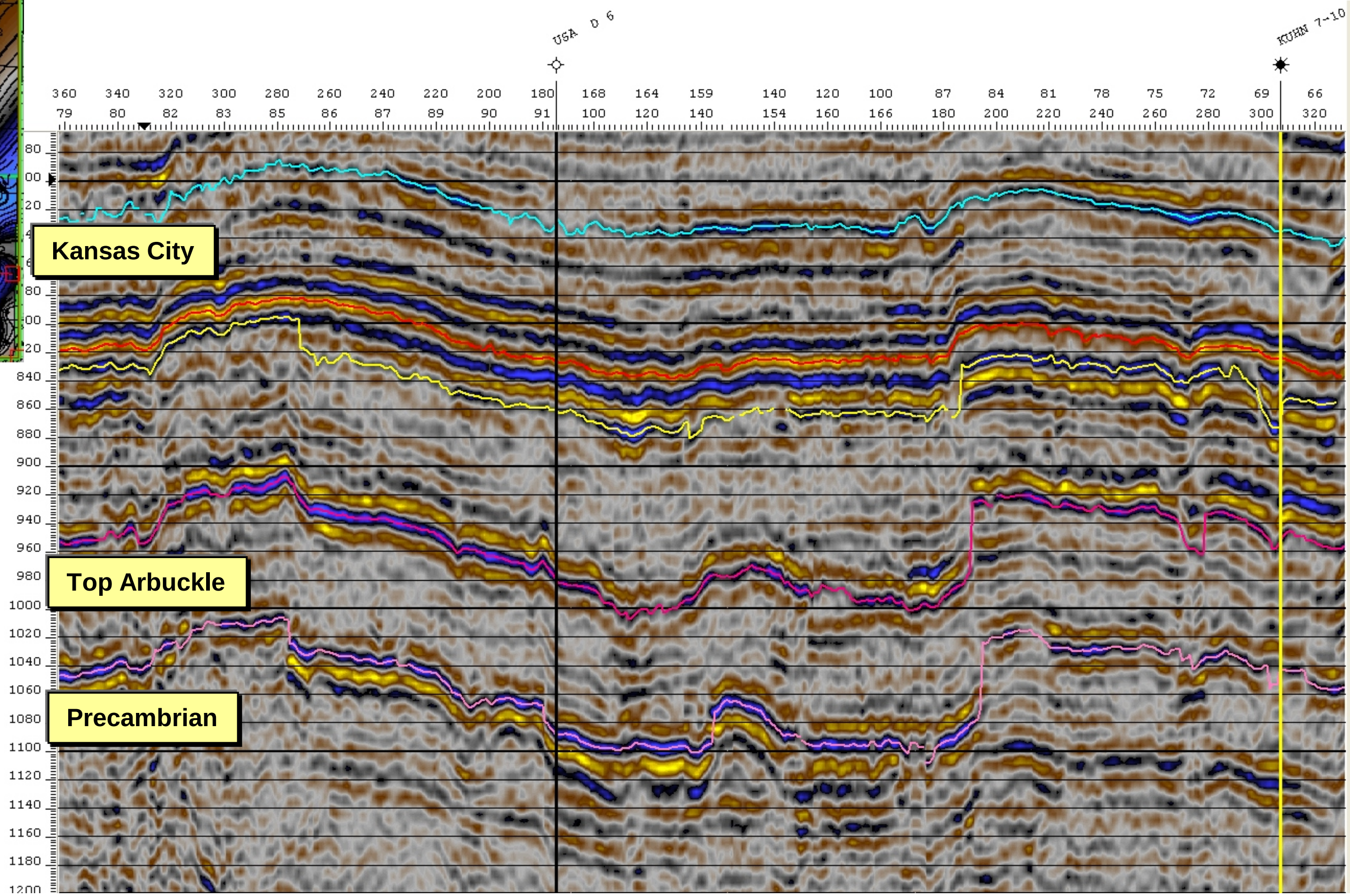


Interpretation by D. Hedke, 2012
DOE-CO2 project

Pleasant Prairie Arbitrary Profile NW - SE







NW-SE Time Section

Interpretation by D. Hedke, 2012
DOE-CO2 project

Summary of Arbuckle Section of Presentation

- Many UIC Class I and II wells successfully operating in the Arbuckle in Kansas
- Complex cyclical internal stratigraphic units important to distribution of petrophysical properties
- Hydrostratigraphy of Arbuckle includes flow (high injectivity), baffle (low injectivity), and vertical barriers to flow
- Petrophysical properties of deep, thick, saline Arbuckle aquifer are similar to shallower oil reservoirs characterized by a layered pore *network dependent on depositional texture modified by karst, brecciation, and fracturing*
- Well logs, seismic, well tests, and core provide means to distinguish and quantify fractures, connected and unconnected vugs, and interparticle pores to define permeable intervals and aid in selection of injection intervals.

Characterization Project Partners FE0002056

KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

NETL

U.S. DEPARTMENT OF ENERGY

DEPARTMENT OF GEOLOGY
KANSAS STATE UNIVERSITY

KU THE UNIVERSITY OF KANSAS Department of Geology

Wellington Field Operator
BEREXCO

fairfieldnodal

PARAGON
GEOPHYSICAL SERVICES, INC

ECHO GEOPHYSICAL CORPORATION
INTEGRITY-STABILITY-INNOVATION

Devilbiss Coring Service

Basic Energy Services

noble energy

LOCKHART GEOPHYSICAL

MUDCO

Weatherford LABORATORIES

TRILOBITE TESTING, INC.

HALLIBURTON

HEDKE-SAENGER GEOSCIENCE, LTD

Bittersweet Energy Inc.

Charter Consulting
Integrated Geology & Geophysics

Petrotek

KOGER REMOTE SENSING

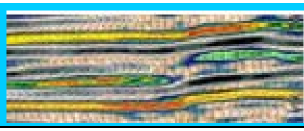
LOGDIGI
A LEADING CONSULTING COMPANY

Southwest Kansas CO_2-EOR Initiative

Industry Partners (modeling 4 Chester/Morrowan oil fields to make CO2 ready)

IHR
Improved Hydrocarbon Recovery LLC

HEDKE-SAENGER GEOSCIENCE, LTD



SUNFLOWER ENERGY LLC

+drilling and seismic contractors TBN

CIMAREX

GloriOil

BEREXCO

Anadarko Petroleum Corporation

Dawson-Markwell Exploration Co.

CELEBRATING 20 YEARS
MERIT ENERGY COMPANY

Industrial and Electrical Power Sources of CO_2

Conestoga Energy Partners, LLC
fueling the new frontier

SUNFLOWER ELECTRIC POWER CORPORATION
A Touchstone Energy Cooperative
. . . energy done right

Abengoa Bioenergy : The Global Ethanol Company

Project Team – Small Scale CO2 Injection Project at Wellington

DOE-NETL Contract #FE0006821

KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

L. Watney (Joint PI), J. Rush (Joint PI), J. Doveton, E. Holubnyak, M. Fazelalavi, R. Miller, D. Newell

TBirdie Consulting, Inc
4705 McCormick Street • Lawrence • KS 66047 • 785 843 1085 • 785 865 0678 (fax) • tbirdie@sunflower.com

T. Birdie

NETL

Brian Dressel, P.M.

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

Tom Daley, Barry Freifeld

BEREXCO

Dana Wreath, Adam Beren

DEPARTMENT OF GEOLOGY

KANSAS STATE UNIVERSITY

Saugata Datta

Abengoa Bioenergy : The Global Ethanol Company

Chris Standlee, Danny Allison, Tim Frazer

KU THE UNIVERSITY OF KANSAS Department of Geology

Mike Taylor, Ross Black, George Tsoflias

Sandia Technologies, LLC

Dan Collins, David Freeman

Acknowledgements & Disclaimer

Acknowledgements

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

Disclaimer