"Modeling CO_2 Sequestration in Saline Aquifer and Depleted Oil Reservoir to Evaluate Regional CO_2 Sequestration Potential of Ozark Plateau Aquifer System, South-Central Kansas"

W. Lynn Watney and Jason Rush, Joint PIs, and team members --

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Dana Wreath, Randy Koudele, Bill Lamb -**BEREXCO LLC, Wichita, KS (Wellington Industry Partner)**

Robert Goldstein, Breanna Huff, Bradley King, Jennifer Roberts, Aimee Scheffer, George Tsoflias, Ayrat Sirazhiev - **Department of Geology, University of Kansas,** Lawrence, KS

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Paul Gerlach - **Charter Consulting, Miramar, FL**

Ken Cooper, **Petrotek Engineering, Littleton, CO**

Anna Smith - **Department of Geology, Wichita State University, Wichita, KS**
Robinson Barker, Saugata Datta, Abdelmoneam Raef - **Department of Geology, Kansas State University, Manhattan, KS**
Dennis Hedke - **Hedke-Saenger Geoscience, Ltd., Wichita, KS**
Susan Nissen - **Geophysical Consultant, McLouth, KS**

David Koger - **Koger Remote Sensing, Ft. Worth, TX**
Ralph Baker - **Geological Consultant, Houston, TX**

John Lorenz & Scott Cooper - **Fracturestudies.com, Edgewood, NM**

Martin Dubois, Ray Sorensen, Ken Stalder, Eugene Williams, John Youle, **Improved Hydrocarbon Recovery Subcontract, Lawrence, KS**

[1]*Currently Chesapeake Energy, Oklahoma City, OK*

[2]*Currently China Geosciences University, Wuhan*

DOE Contract #FE0002056
and partner cost share

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Partners
FE0002056

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

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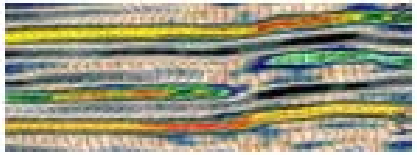

Bittersweet Energy Inc.

Charter Consulting
Integrated Geology & Geophysics

Petrotek

KOGER
REMOTE SENSING

LOGDIGI
A LEADING CONSULTING COMPANY

Industry Partners (Enhancement to FE0002056)

SW Kansas CO_2 Consortium/Western Annex

IHR Improved Hydrocarbon Recovery LLC

HEDKE-SAENGER GEOSCIENCE, LTD

SUNFLOWER ENERGY LLC

+drilling and seismic contractors TBN

CIMAREX

GloriOil

Anadarko Petroleum Corporation

Dawson-Markwell Exploration Co.

BEREXCO

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

Outline

- Background
- Status of Project
- Regional Analysis
- Wellington Activities
  - Drilling, coring, core and log analysis
  - Step rate test between #1-32 and #1-28
  - 3D multicomponent (converted wave) and 2D-9C seismic processing and interpretation → toward refined 3D geomodel and simulation
  - Hydrogeochemistry and Microbial Research
- Southwest Kansas CO_2 Consortium (Chester/Morrow EOR)
- Summary

NETL Program Manager: Brian Dressel

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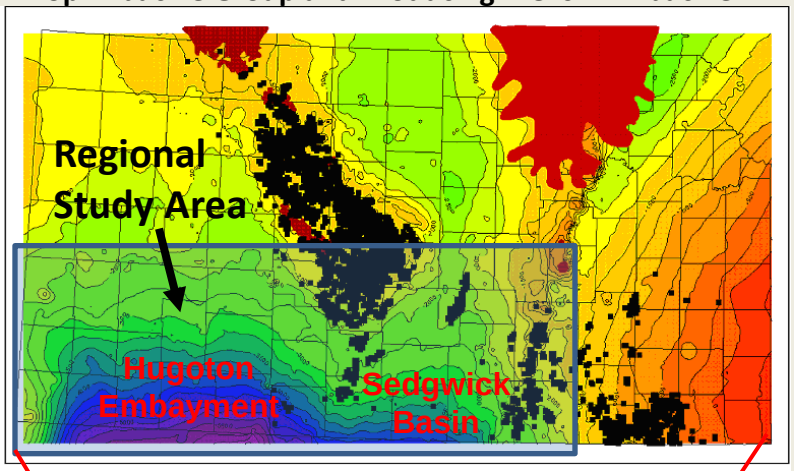
Project Overview

- Start Date - Dec 2009
- Build static geomodels
  - *Wellington field (Sumner County, KS)*
    - *Depleted Mississippian oil field*
    - *Underlying Arbuckle saline aquifer*
  - *Four Chester/Morrow field in SW KS*
  - *Regional Arbuckle saline aquifer*

Ozark Plateau Aquifer System

- Conduct simulation studies to estimate CO_2 storage capacity
- Arbuckle saline aquifer – 23 county area
  - Identify potential ~8 CO_2 storage sites
  - Estimate storage capacity of Arbuckle saline aquifer in southern KS
- Risk analysis related to CO_2 sequestration
  - Caprock integrity
  - Rock heterogeneity including fault mapping
  - Assess abandoned wells
- Technology transfer

Top Arbuckle Group and Producing Wells in Arbuckle



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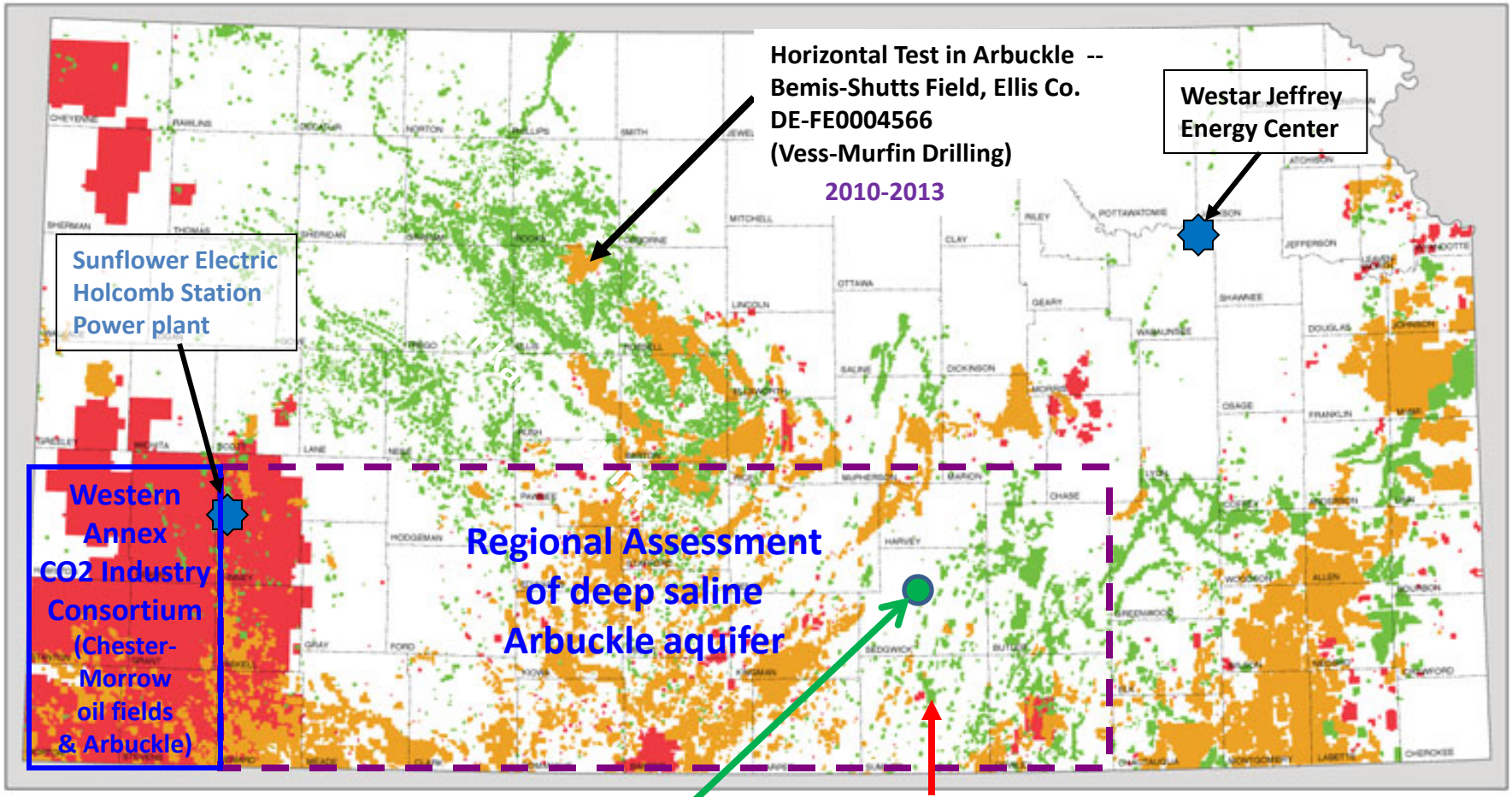
The University of Kansas

OIL AND GAS FIELDS OF KANSAS

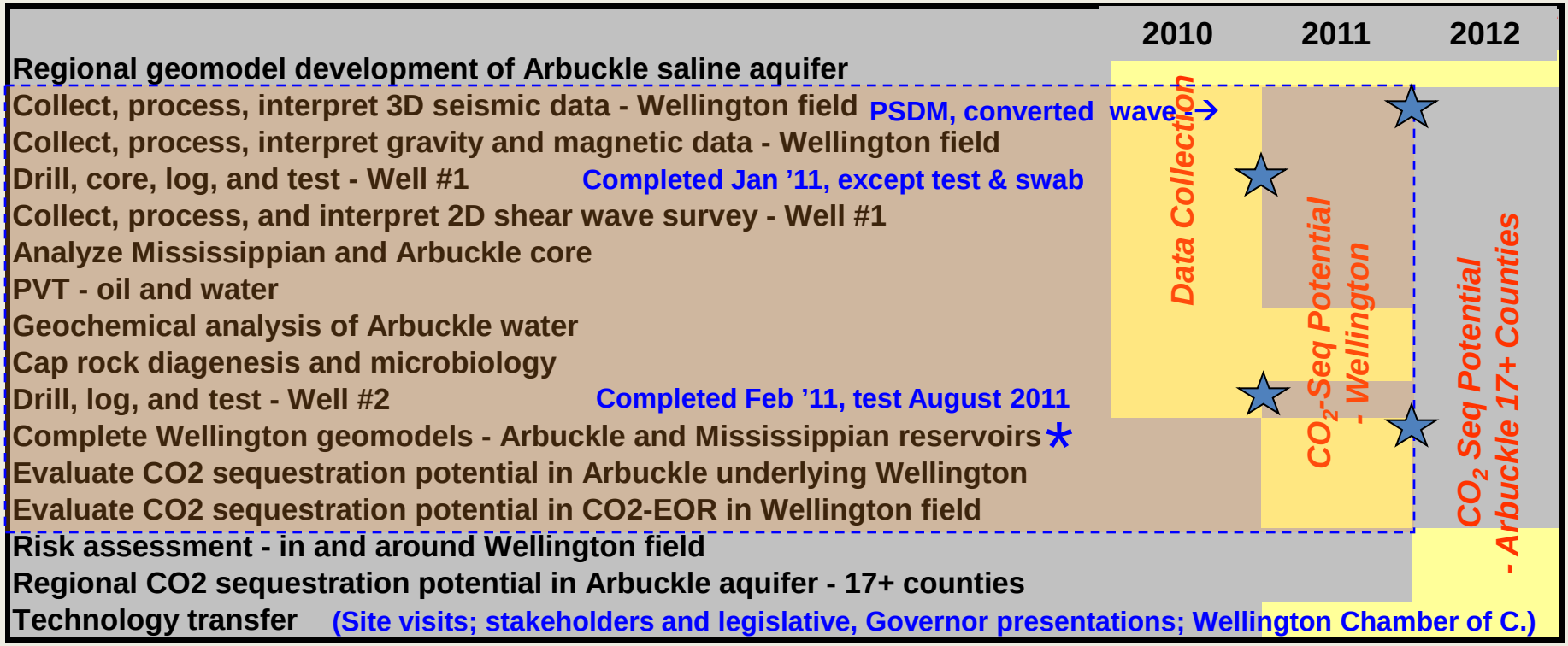


http://www.kgs.ku.edu/PRS/petro/ogSheetMap.html

Gantt Chart Review
FE00002056
2011 (BP2) Tasks - Completed, In Progress

**Start Date Dec. 8, 2009

End date: August 7, 2013

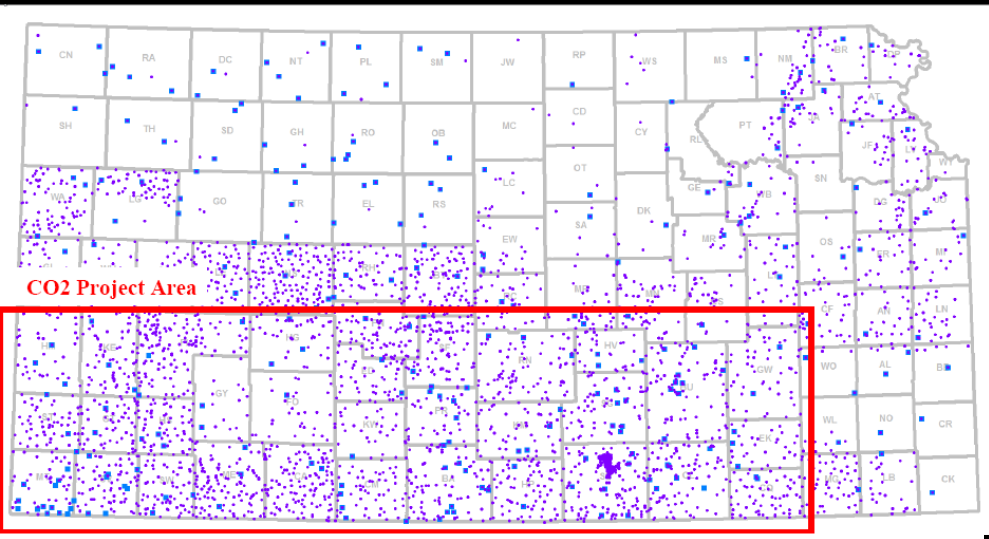


✶ Updated geomodels to be completed in January-March 2012 --

1) Depth migrated, converted shear wave, volumetric curvature, and simultaneous inversion of multicomponent 3D
2) Core analysis from #1-32 to calibrate porosity and permeability estimates from wireline logs (NMR)
3) Petrel geomodel to utilize shear wave anisotropy and fracture analysis, dynamic bulk moduli from seismic calibrated with core measurements and dipole (spectral) sonic, NMR, microresistivity imaging, and density logs

Well Data Inventory

Wells with LAS or Raster = 3792

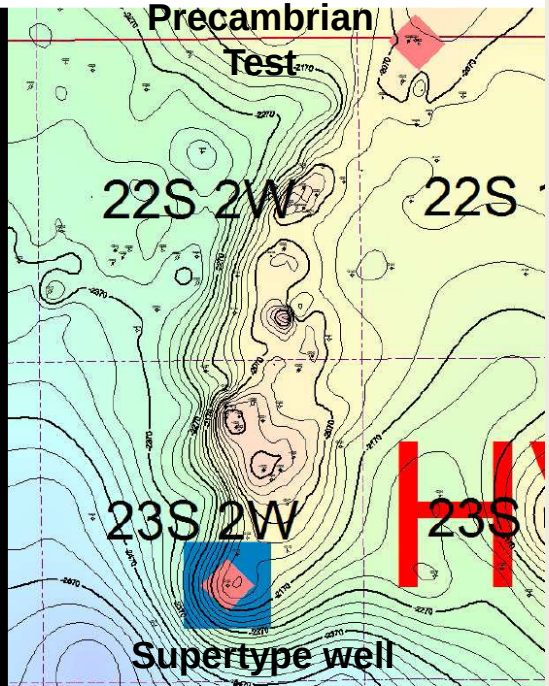


Regional Team

- Developed regional database
- Correlated logs and identified Type Wells for digitizing to LAS files
- Established that Arbuckle is an open aquifer system, hydraulically connected to outcrops in Missouri (~150 miles to east)
- Evaluating faults, fractures, flexures
- Establishing additional 8+ sites in region for additional simulation beyond field studies

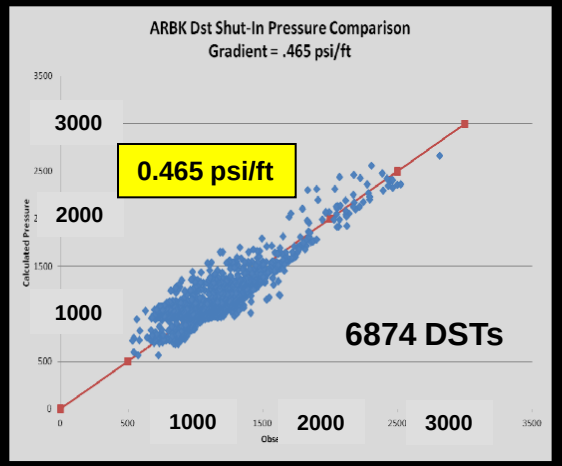
Non-Faulted Structural Closures Candidate:

Township 22S-2W Arbuckle Subsea C.I. 25 ft



Calculated Pressure vs. Observed Pressure (psi)

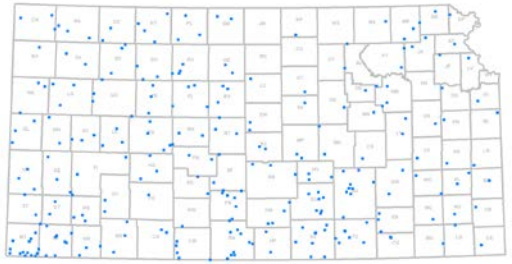
6874 ARBK Dst's (observed gradient filtered)



Structural mapping and recognition of faults

Top Arbuckle Group

Supertype Wells (263):
- **Digitized to LAS**
- **Penetrate at least 2/3rd Arbuckle**
- **Modern log suite**



- **Published faults are being 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**

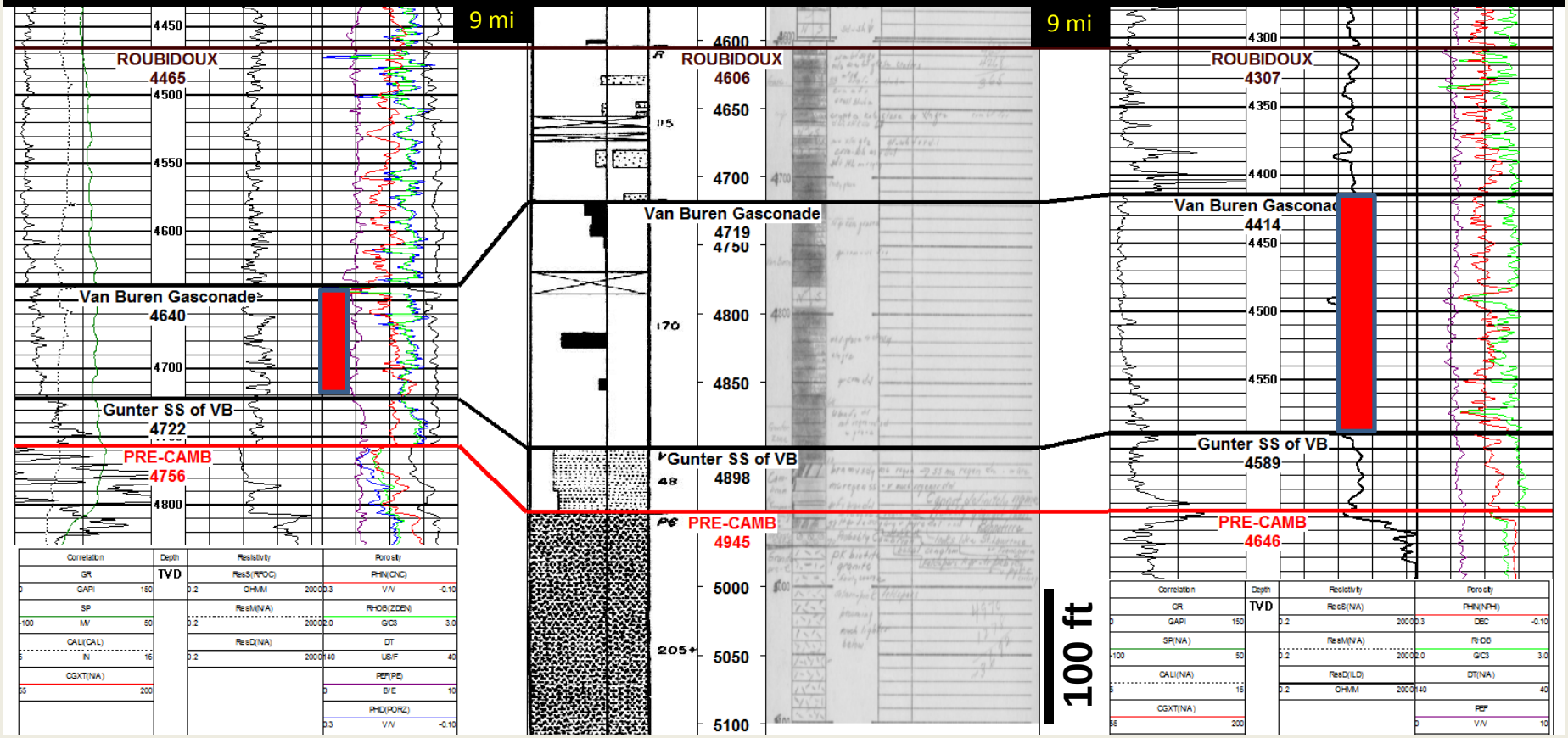
Quantitative characterization of Arbuckle in southern Kansas

Lower Arbuckle Porosity Zone (Gasconade to Gunter Ss.) at Wellington Field

Quantitative Reservoir Characteristics

Correlated to

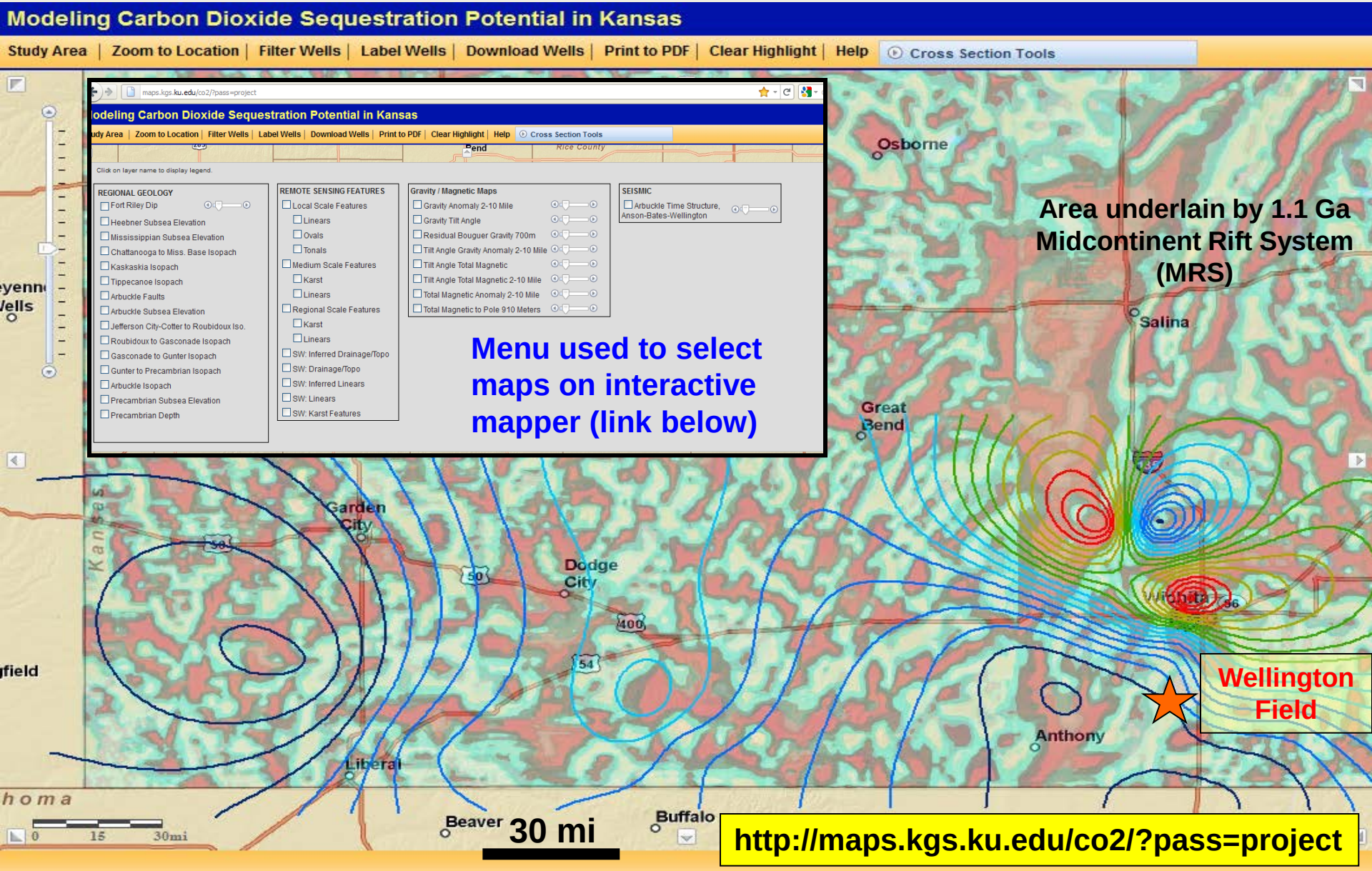
Internal Arbuckle Stratigraphy

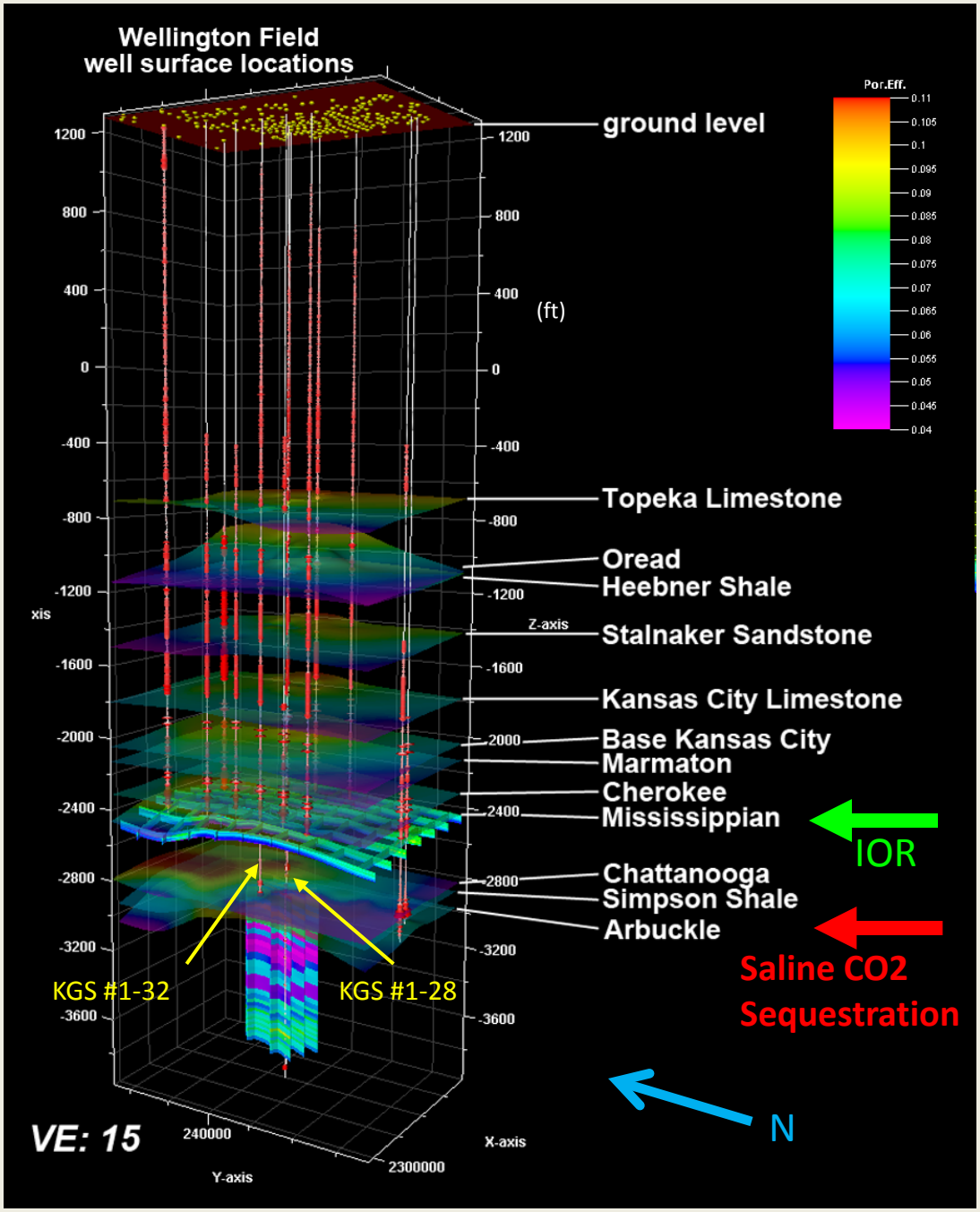


Example stratigraphic cross section of lower Arbuckle from top Rubidoux (datum) to basement including new and old well data (*insoluble residue logs, georeports, and modern suite of logs managed as LAS files*)

2-10 mile filtered Total Magnetic Field Intensity and Magnetic Tilt Angle overlain by isopach Gasconade to Gunter Sandstone

--> Lower Arbuckle Porosity Zone at Wellington Field





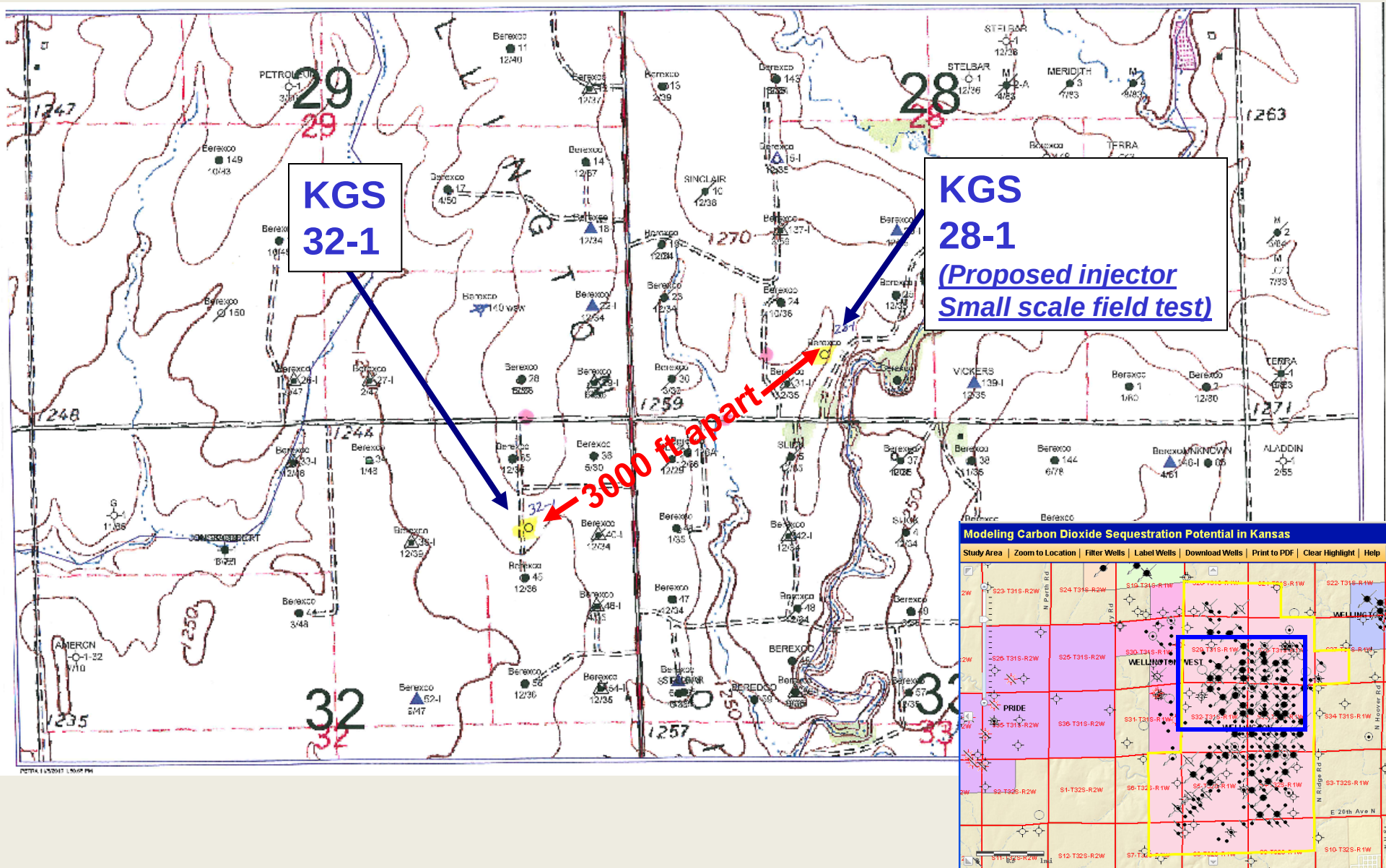
Wellington Field

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

- New 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

(Start Oct. 1, 2011) Small scale field test with 70k tonnes CO2 into Arbuckle – MVA deployment and testing – LiDAR/InSAR, shallow groundwater monitoring, microseismic monitoring
Mississippian reservoir – underpressured, well sampling, 2D high resolution seismic
Arbuckle - in situ cross hole tomography, U-tube plume sampling, CASM (continuous seismic imaging), repeat 3D
Also, 30 Tonnes CO2) into Mississippian reservoir

Surface location of stratigraphic tests drilled in Wellington Field during Jan-Feb 2011



Drill, Core, Log, Test Berexco Wellington #1-32

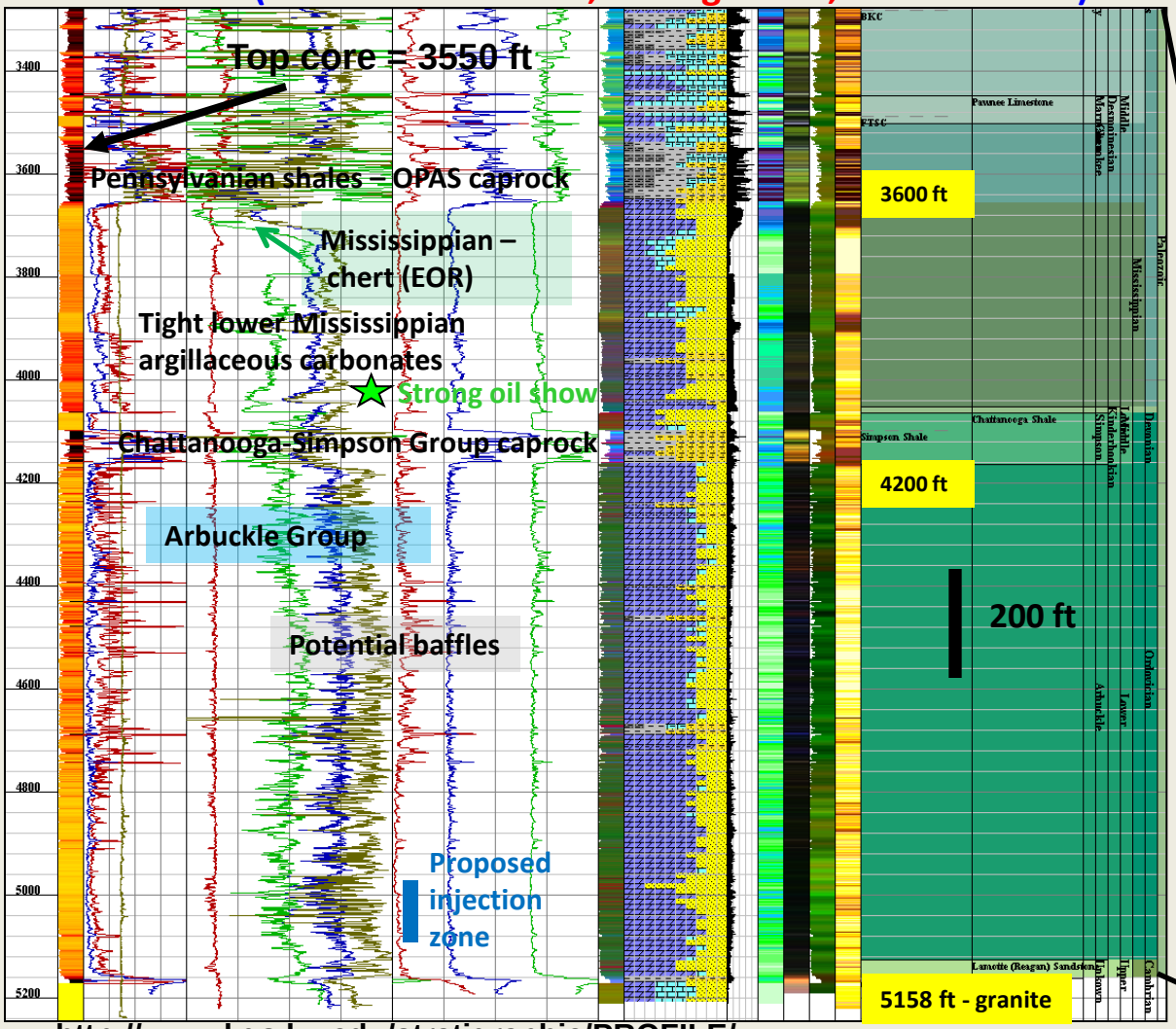
Spudded 12/30/10

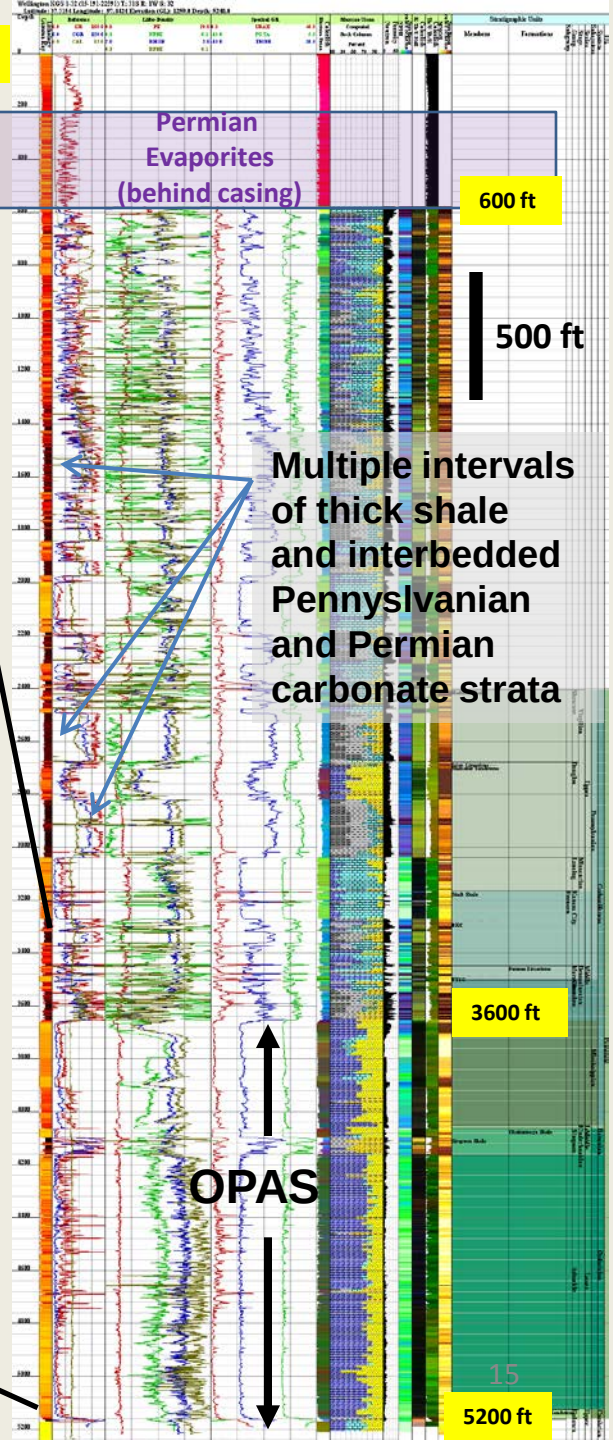
Reached TD 2/9/11

Ran new, API 5½", 15.5# casing. Set @5238'. **Cemented from 5238' to surface in three stages.** Ran casing to TD. Tagged bottom & pulled up 2'. DV's @3938' and 2460'. Baskets @4860', 4480', 3980', 3510', 2500', and 980'. Centralizers every 3rd collar from TD to 3100'. Centralizer above and below each basket and above and below each DV. Had good circulation. Cemented bottom stage w/200 sacks AA2 @15 ppg w/10% salt, 6# Gilsonite, and **C-44 Gas Blok CO2 resistant additive**. Had good circulation during job.

Stratigraphic Column
Berexco Wellington KGS #1-32

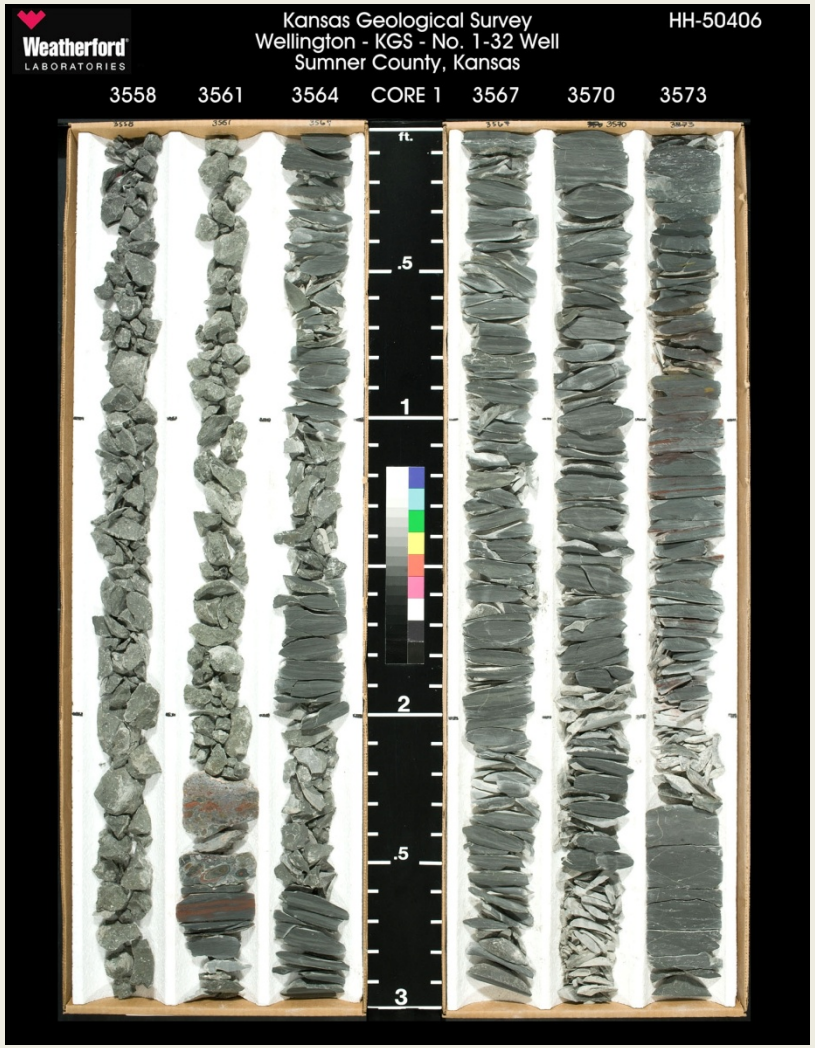
Completed at Wellington Field
February 2011
Conventional 4.5 inch core from base Pennsylvanian shales to basement (3550-5178 interval, 1628 gross ft, 1528 net feet)



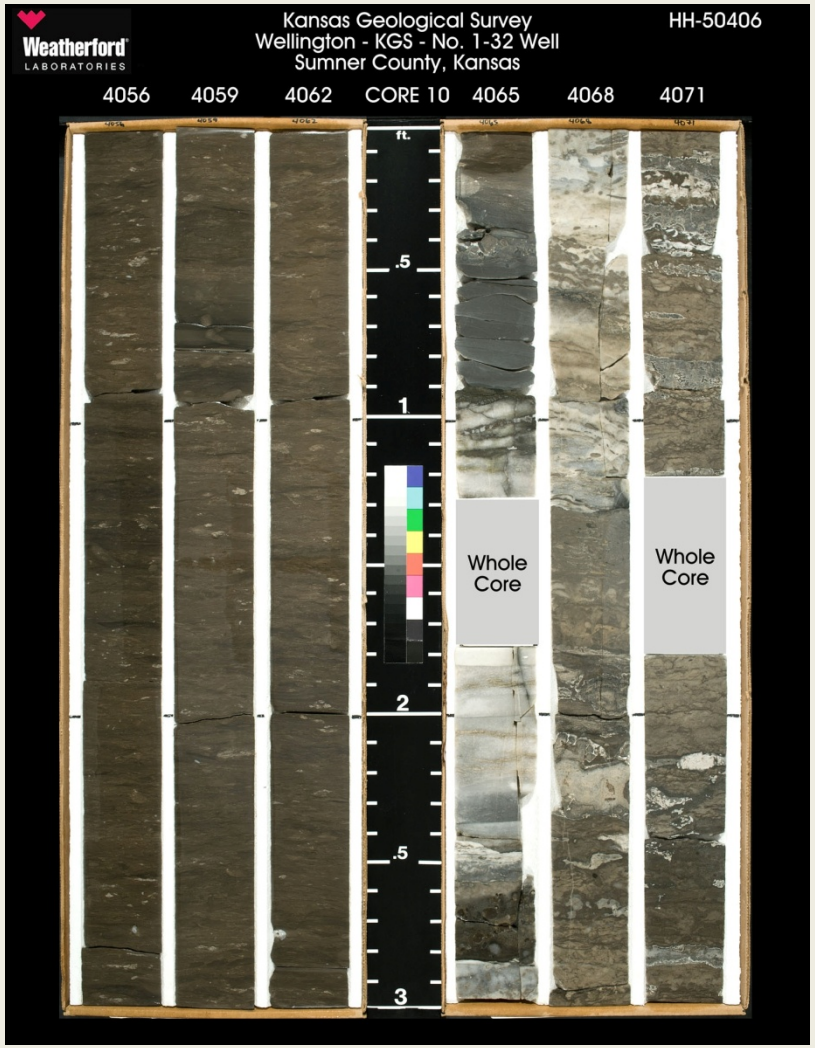


http://www.kgs.ku.edu/stratigraphic/PROFILE/

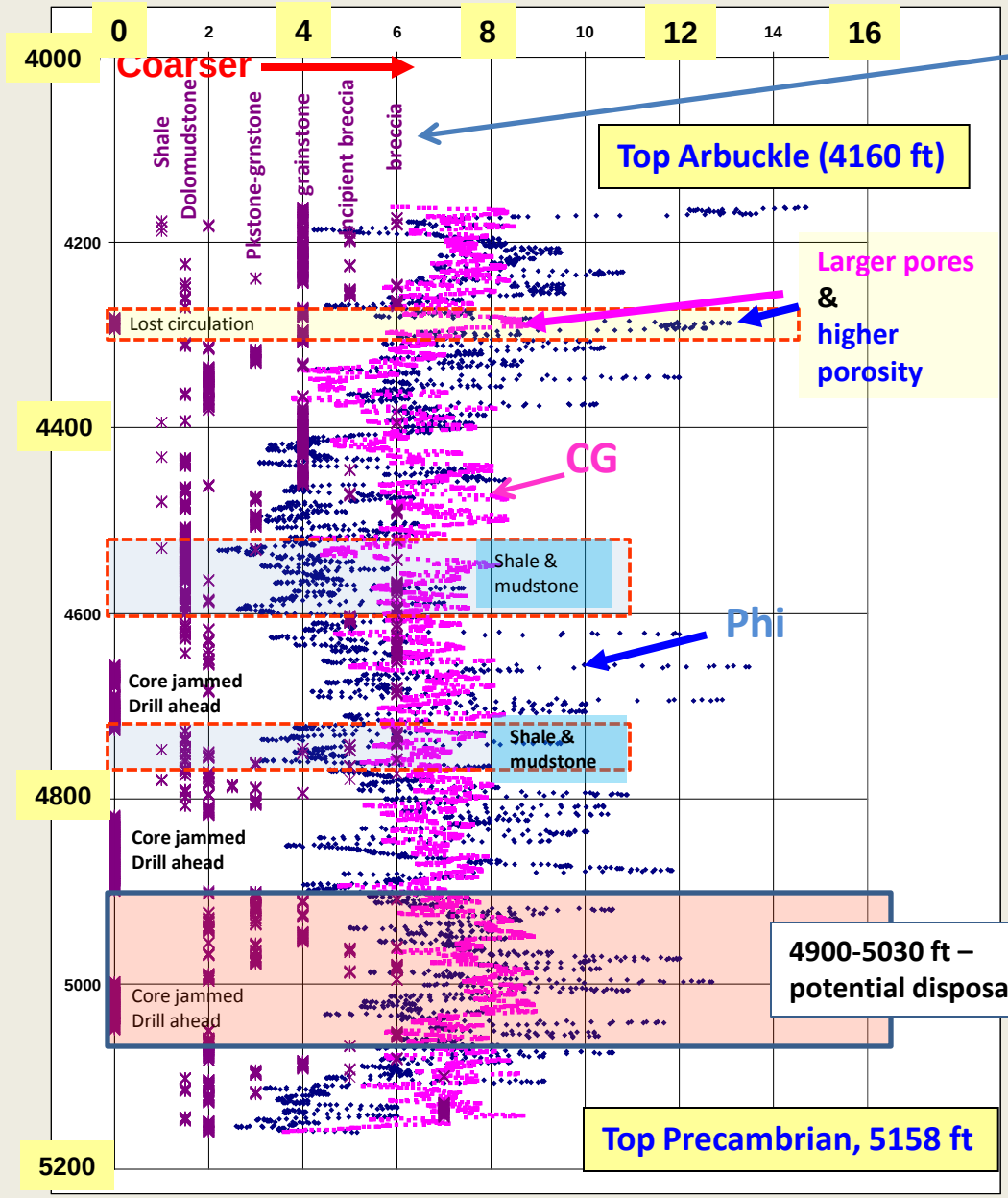
Pennsylvanian Cherokee Shale (primary caprock on top of OPAS /Mississippian)



Lower Mississippian-Devonian shale& argillaceous carbonate on shale and sandstone of Upper Ordovician Simpson Group (caprock on top of Arbuckle)



Preliminary analysis of nuclear magnetic resonance (Halliburton's MRIL) log in Arbuckle Group compared with core in Wellington #1-32



Lithofacies from core (vertical columns) (x)

0 = no core recovered
1 = shale
1.5 = argillaceous dolomudstone
2 = mudstone-wackestone
3 = packstone-grainstone
4 = grainstone
5 = incipient autoclastic breccia
6 = autoclastic breccia
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
- Karst overprinting
- Lithofacies control porosity & permeability in persistent stratal packages

ZONAL FRACTURES AND AUTOCLASTIC BRECCIAS IN THE POROUS INTERVALS OF THE ARBUCKLE

4593 ft

4556.2 ft

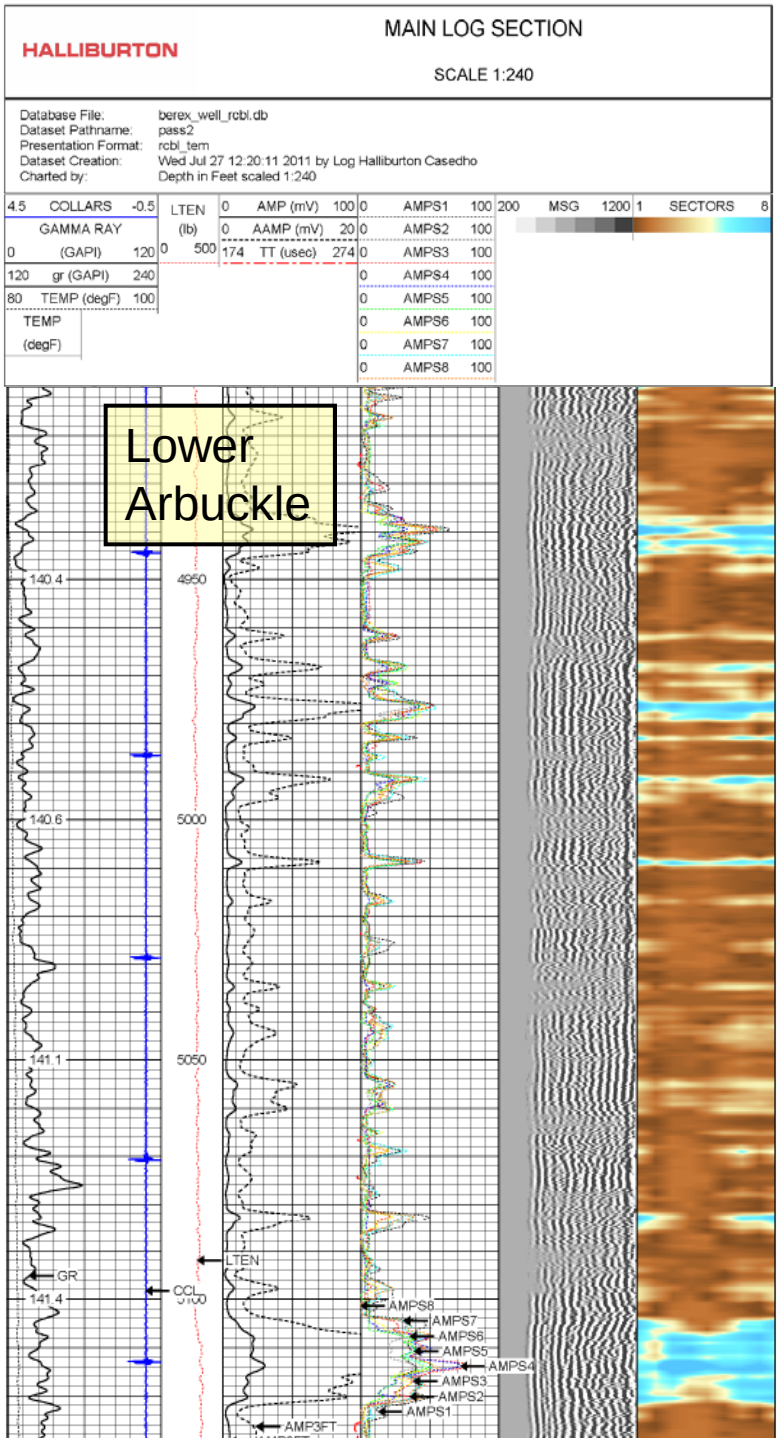
4609 ft

Proposed Arbuckle CO_2 Injection Well At Wellington Field

Berexco Wellington KGS #1-28

Spud: 1-19-11, TD: 3/3/2011, 5250'

Cement Integrity



1. CO2 resistant cement
2. 3-stage centralizers
3. Ran Halliburton's Radial Cement Bond Log to evaluate cementing of casing string
4. Eight sectors concentric cement map (image)

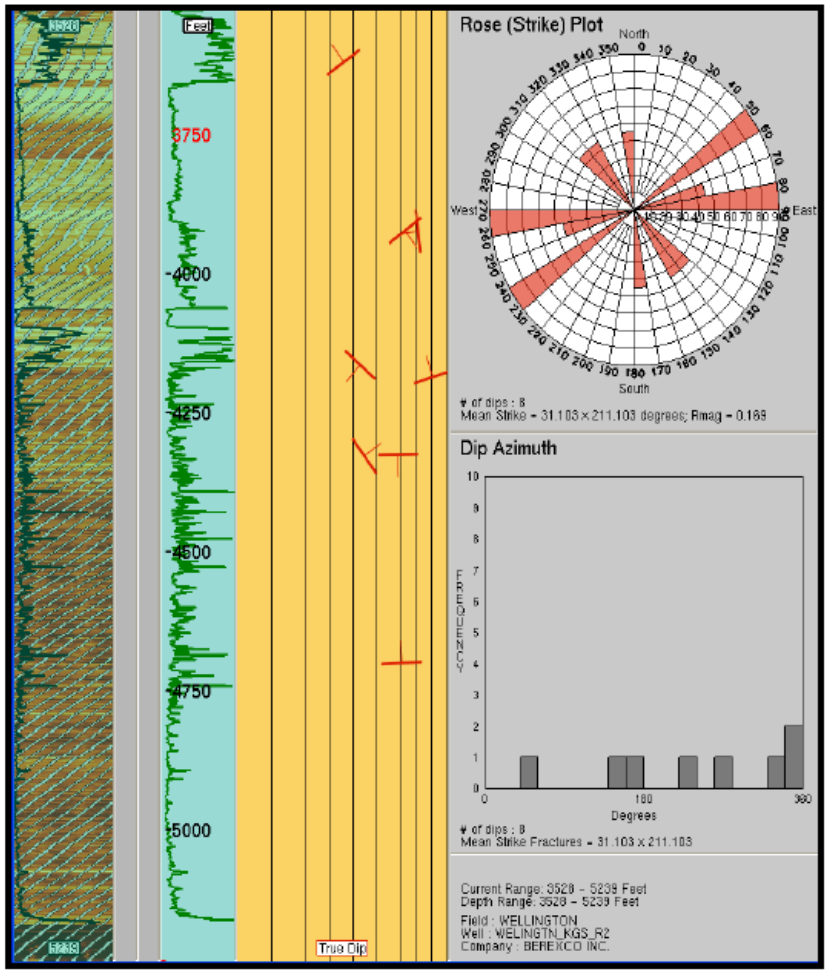
- Cement map showing good bonding (brown) and no channeling
- Less well cemented, horizontally oriented zones (white and blue)

MAXIMUM HORIZONTAL COMPRESSIVE STRESS

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

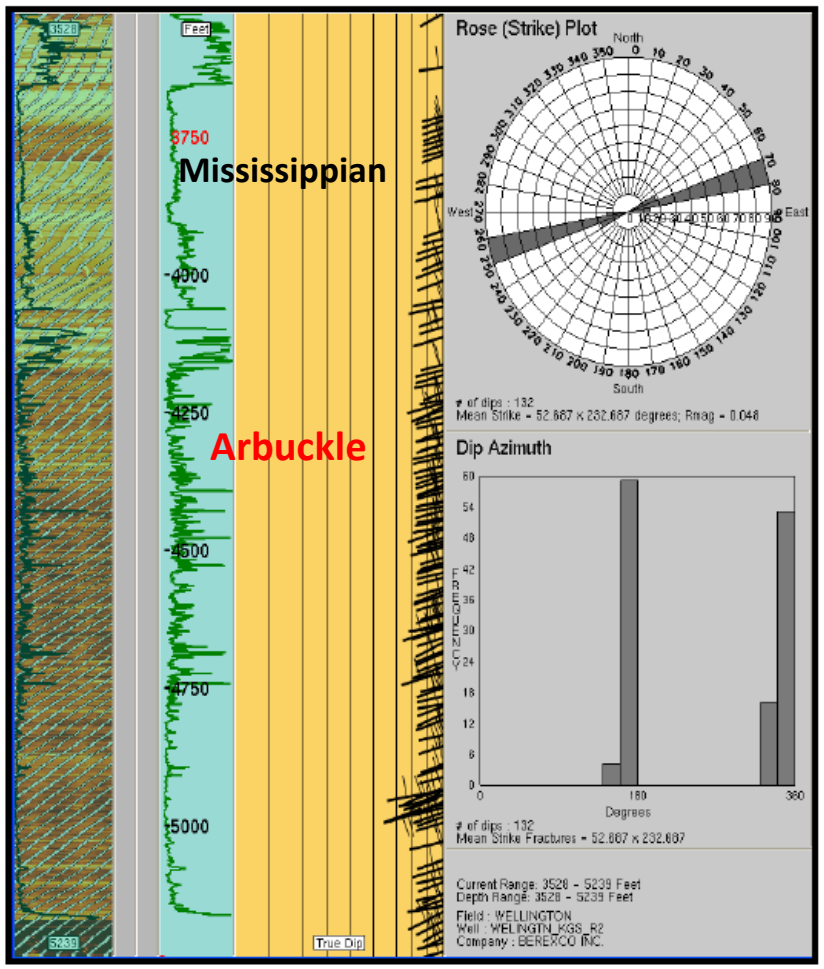
Fracture Statistics: 5239'-3528'

Natural mineralized "closed" fractures



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

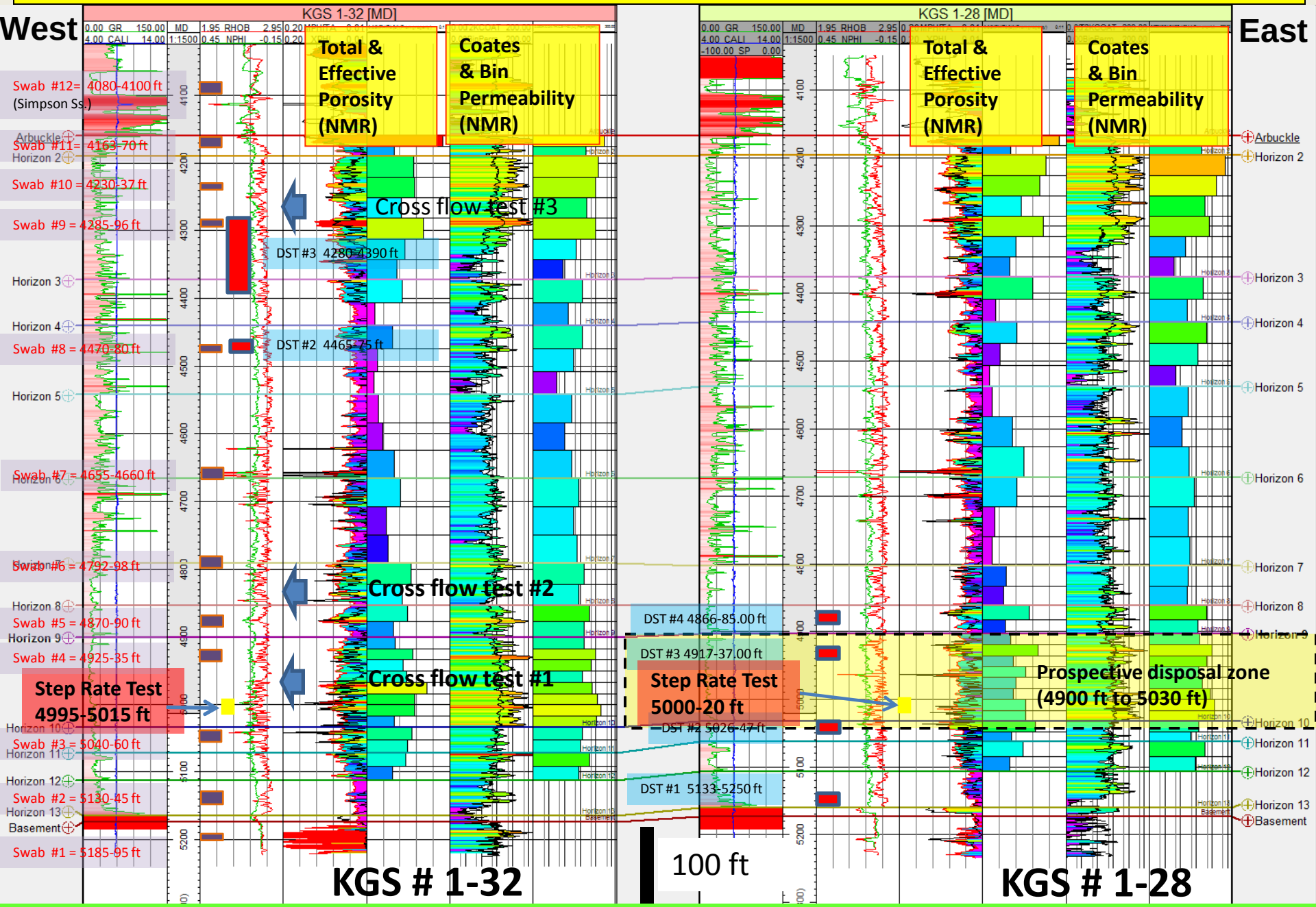
Induced fractures



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

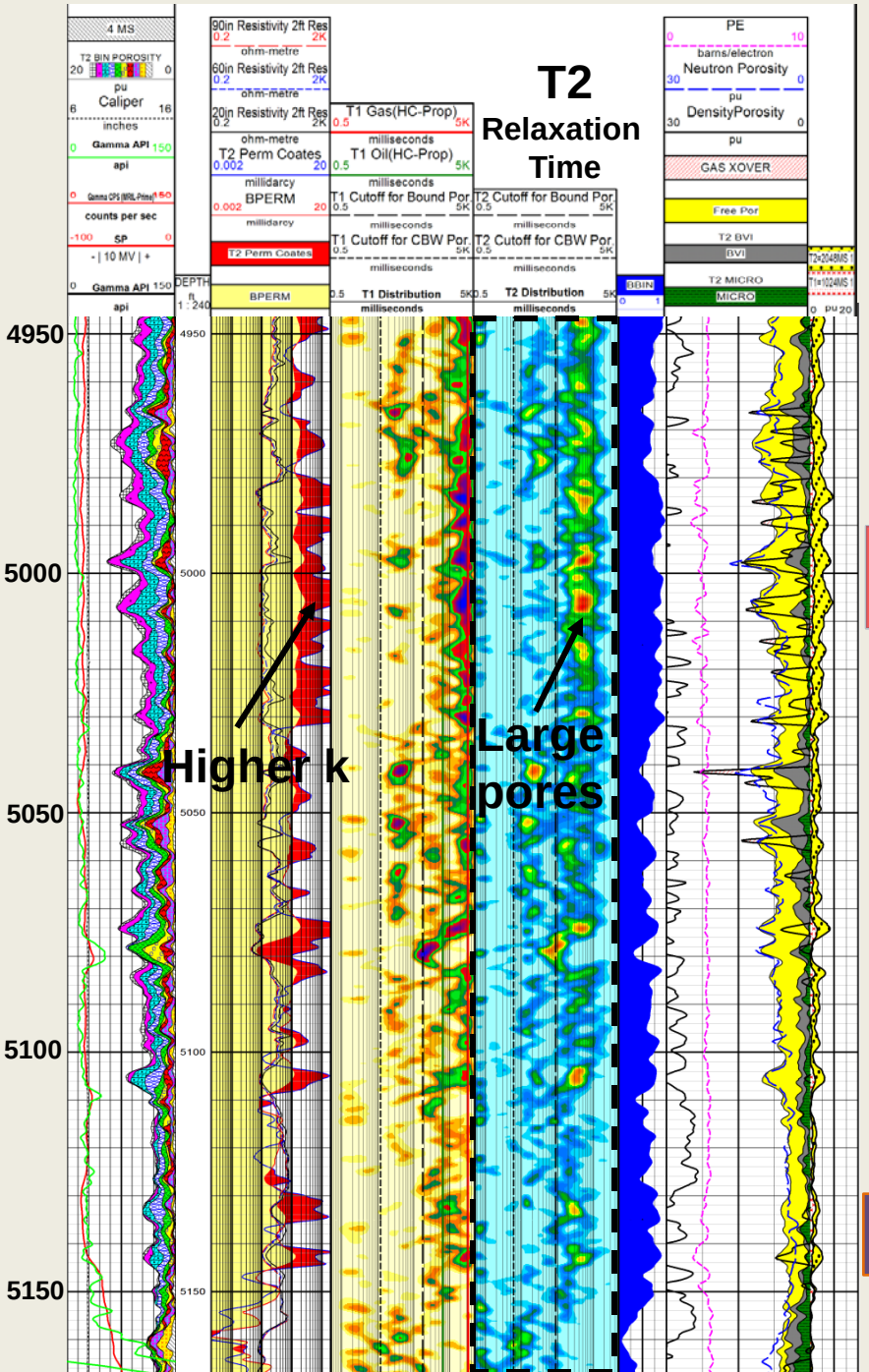
HALLIBURTON

Cross section showing location of step rate test and proposed swab intervals in the Arbuckle



Preliminary upscaled hydrostratigraphic units in Arbuckle Group

NMR composite log showing locations of test & swabbing intervals in lowermost Arbuckle of well #1-32



Pulse Test 4995-15 ft

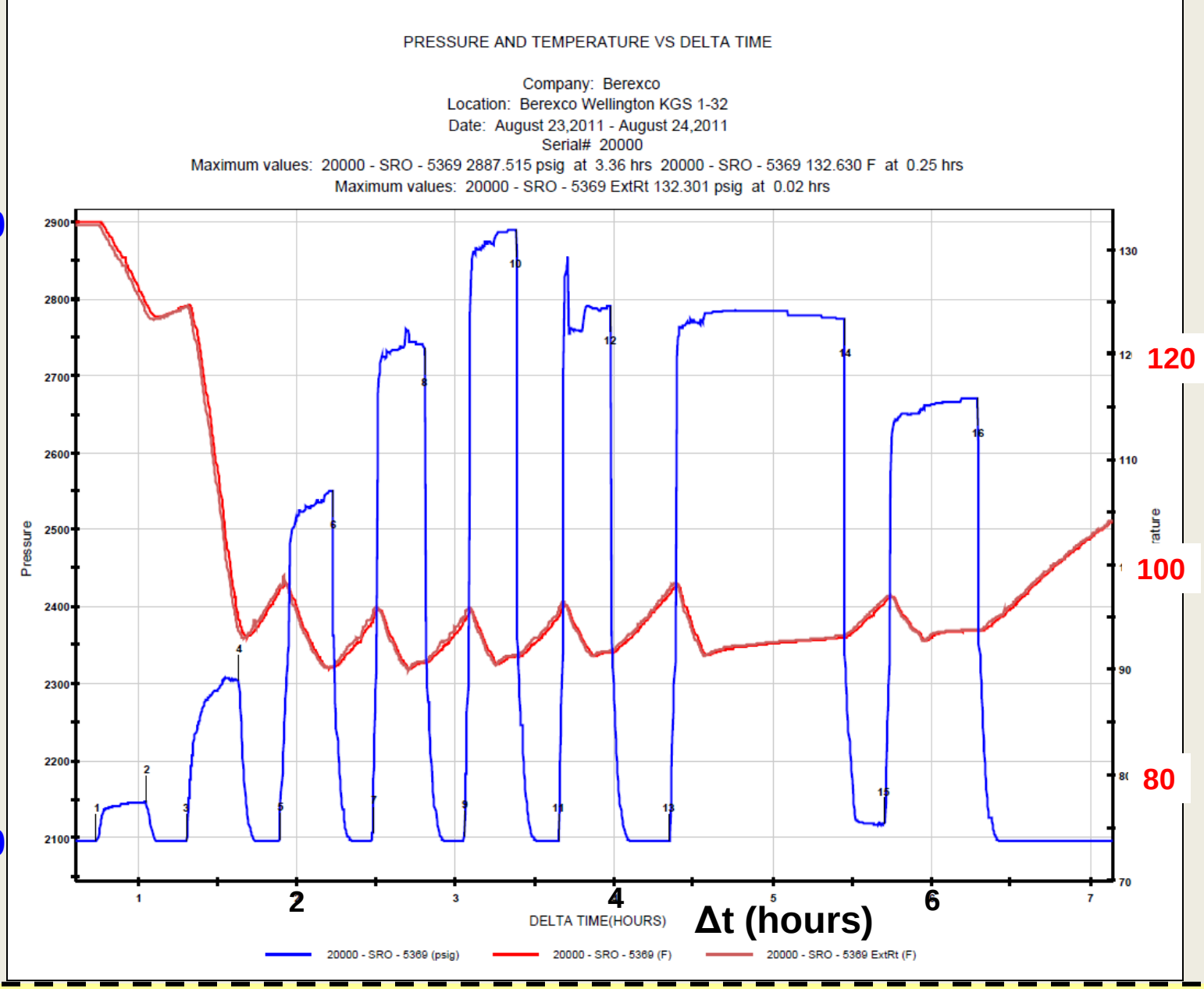
4997.5 to 5049.7; No Core Recovery

Swab #3 = 5040-45 ft

Corresponding to DST #2 in #1-28

Swab #2 = 5130-45 ft

Corresponding to DST #1 in #1-28



2900

2100

Pressure (psi)

120

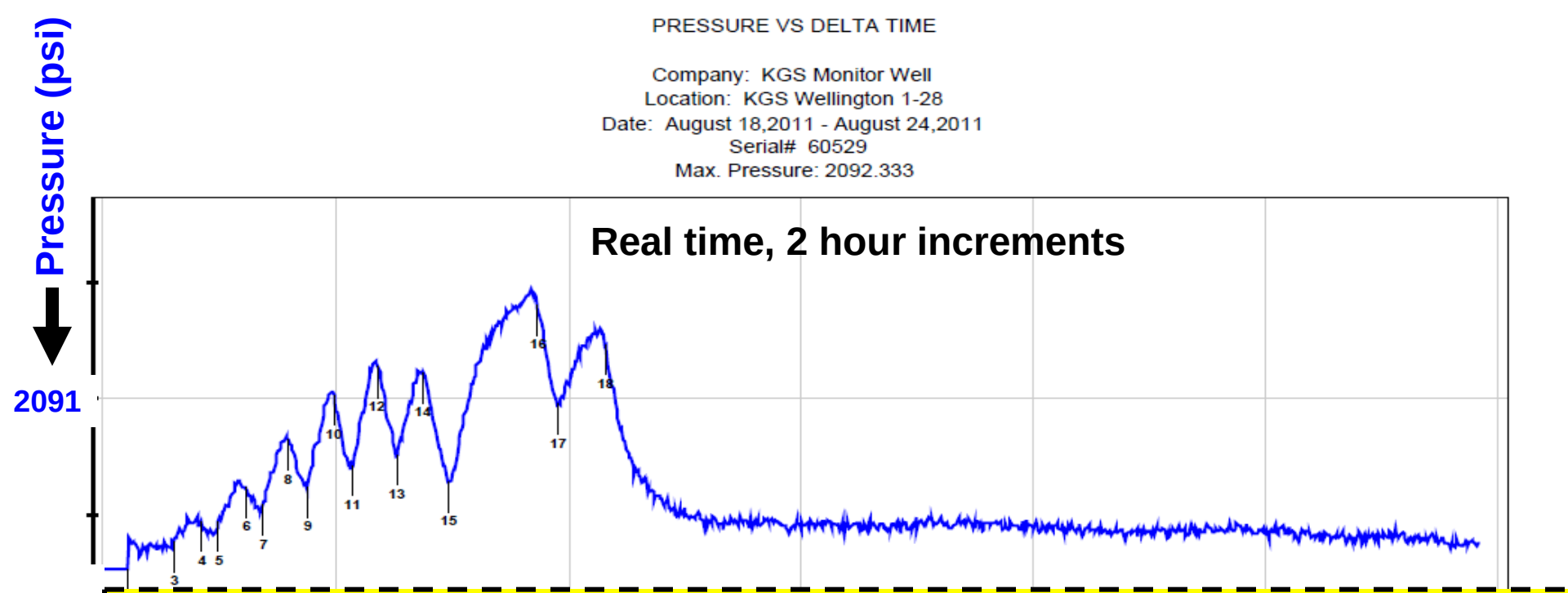
100

80

Temperature (degrees F)

Δt (hours)

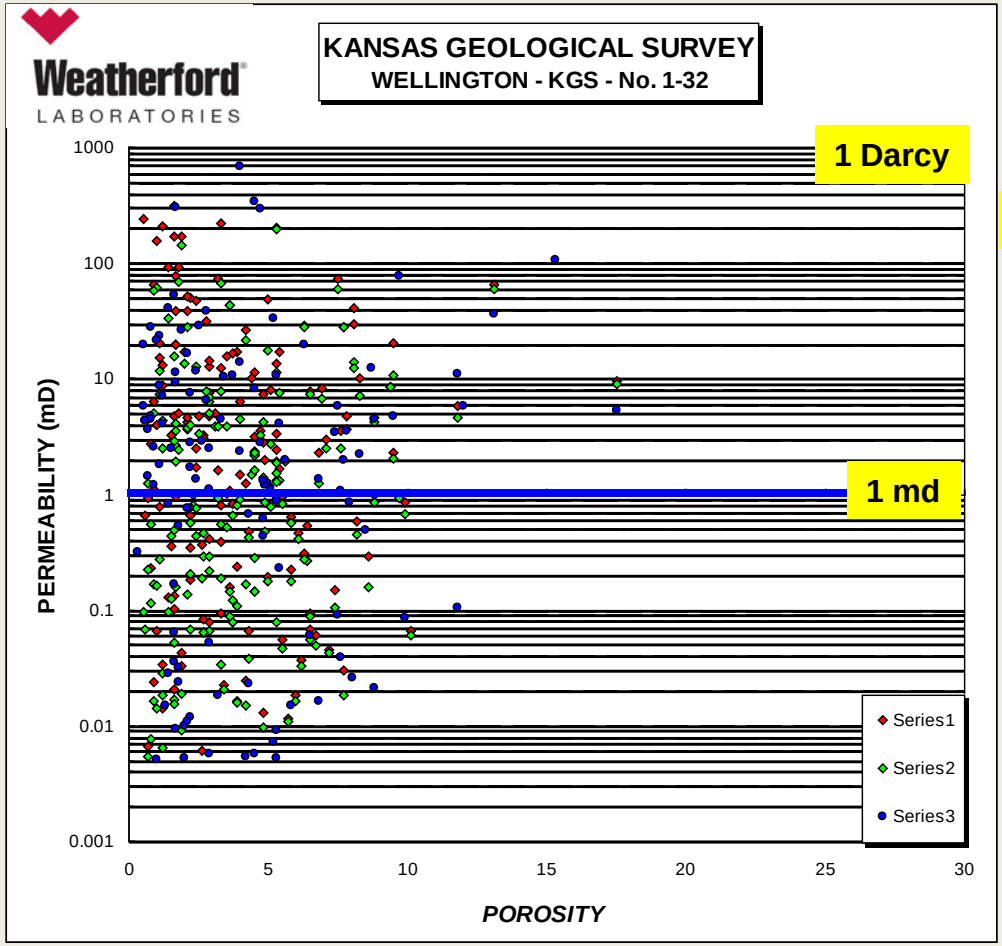
STEP-RATE TEST RESULTS: Pressure and temperature vs. delta T in the test injection well, Berexco Wellington KGS #1-32. Note eight separate periods of injection (blue) that are labeled consecutively as at beginning and end of each period. Temperature in red.

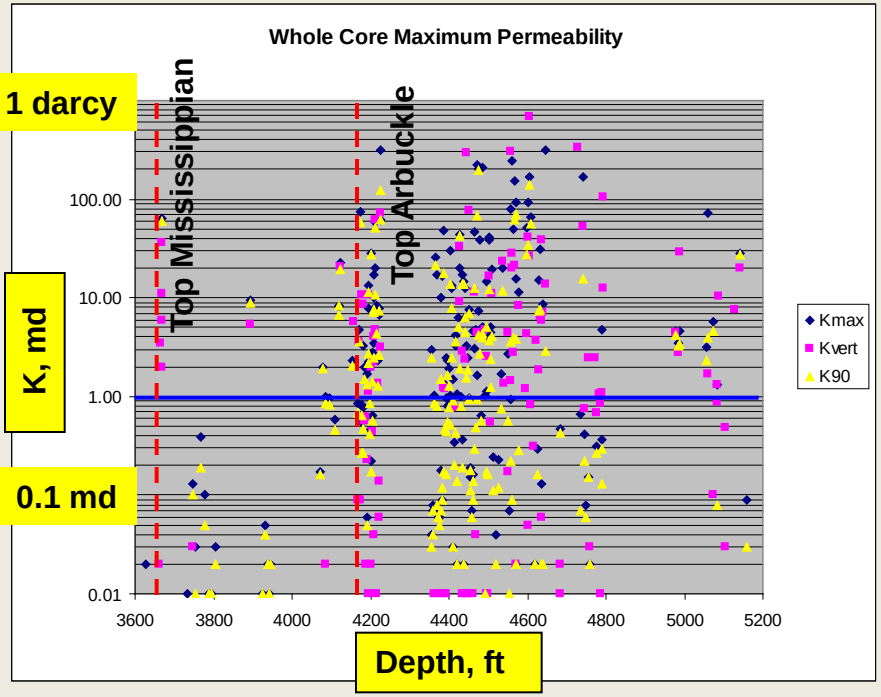


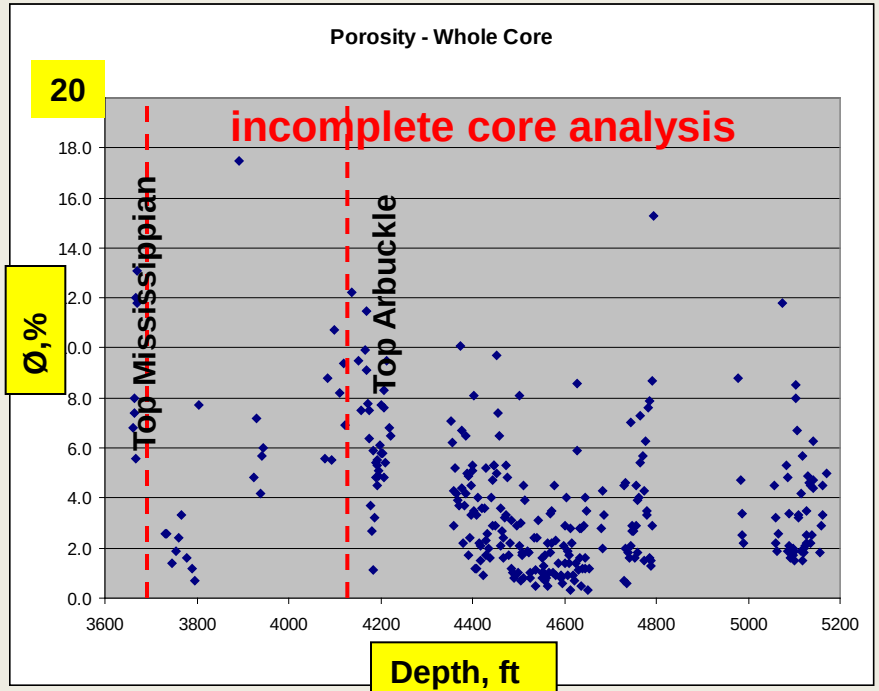
STEP-RATE TEST RESULTS: Pressure response in Berexco Wellington KGS #1-28 matches pressure pulses introduced into #1-32

- **Tested interval has the best wireline log properties of the Arbuckle and test-based permeability is high, perhaps multiple darcies.**
- **Pulse test was designed for limited layer and results appear to confirm this.**
- **Barrier does not limit flow between #1-32 and #1-28 boreholes as suggested by continuity of 3D seismic reflectors.**
- **20 ft thick zone may not be optimal for injection since it could act as a "thief zone."**
- **Other flow units in the 120 ft thick lower porous Arbuckle (*Gasconade to Gunter Sandstone*) appear to be better suited for CO2 injection pending final calibration of logs with core analyses and simulation.**

Incomplete Set of Whole Core Analyses for Berexco Wellington KGS #1-32







- 475 whole core analyses to be done
- Other intervals → Helical CT Scans

Current Studies in Hydrogeochemistry

Dr. Saugata Datta and Robin Barker, Kansas State U.

- Using collected water (8 DSTs and 1 swab test thus far) and 2-inch core plugs from #1-32 and #1-28 to characterize the hydrogeochemistry and mineralogy of the Arbuckle formation
- Water chemistry defined by ICP-OES and IC from 8 DSTs and one swab test (so far)
- Mineralogy data from thin section, XRD, SEM and CT-scan
- Supercritical flow experiment conducted at the National Energy Technology Lab in Pittsburgh, PA
- Provide kinetics for key reactions of CO_2 with actual rock and brine obtained from Kansas Arbuckle

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Hydrogeochemistry

Datta and Barker, KSU

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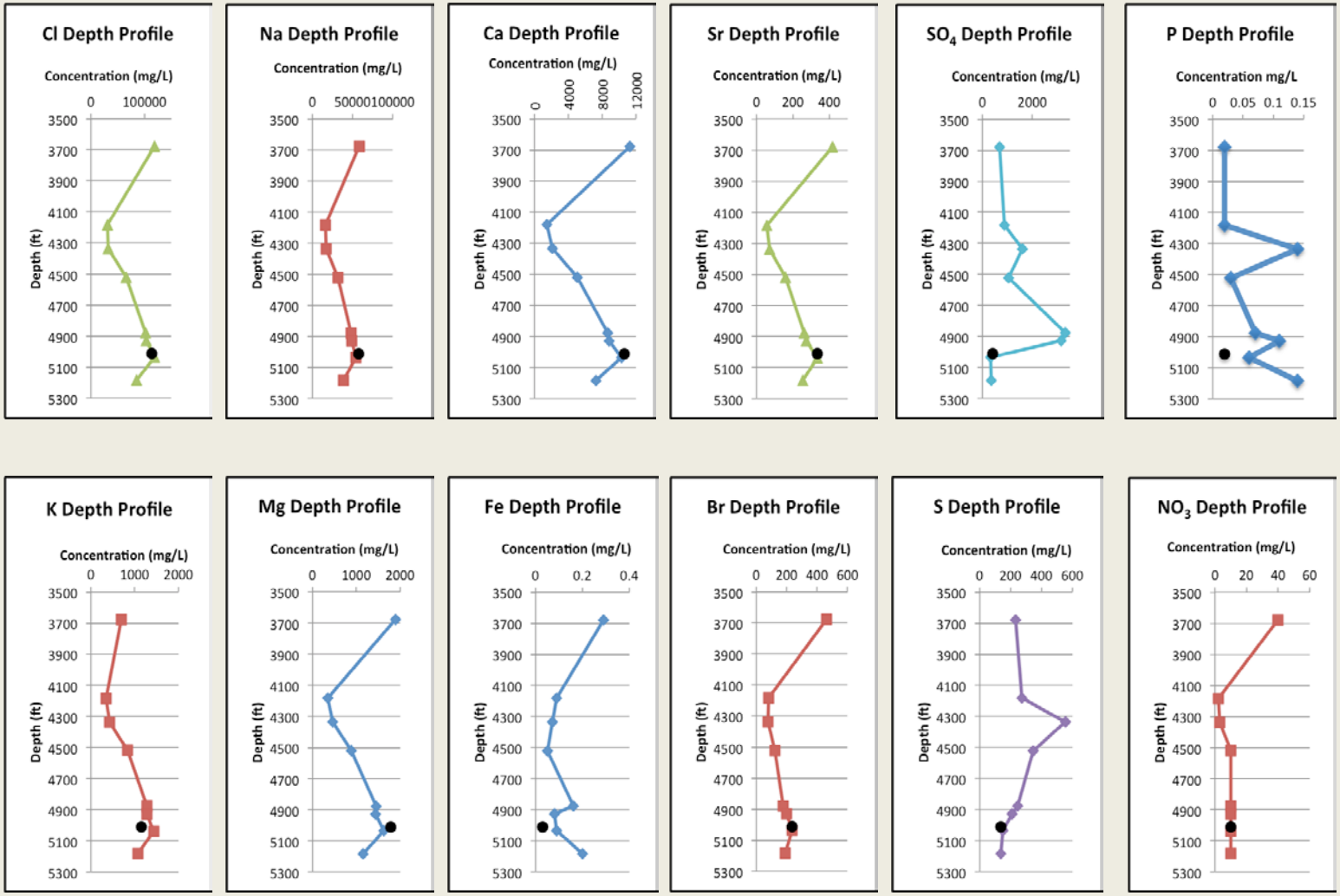
Depth profiles of DST (connected line) and first swab test (black dot)

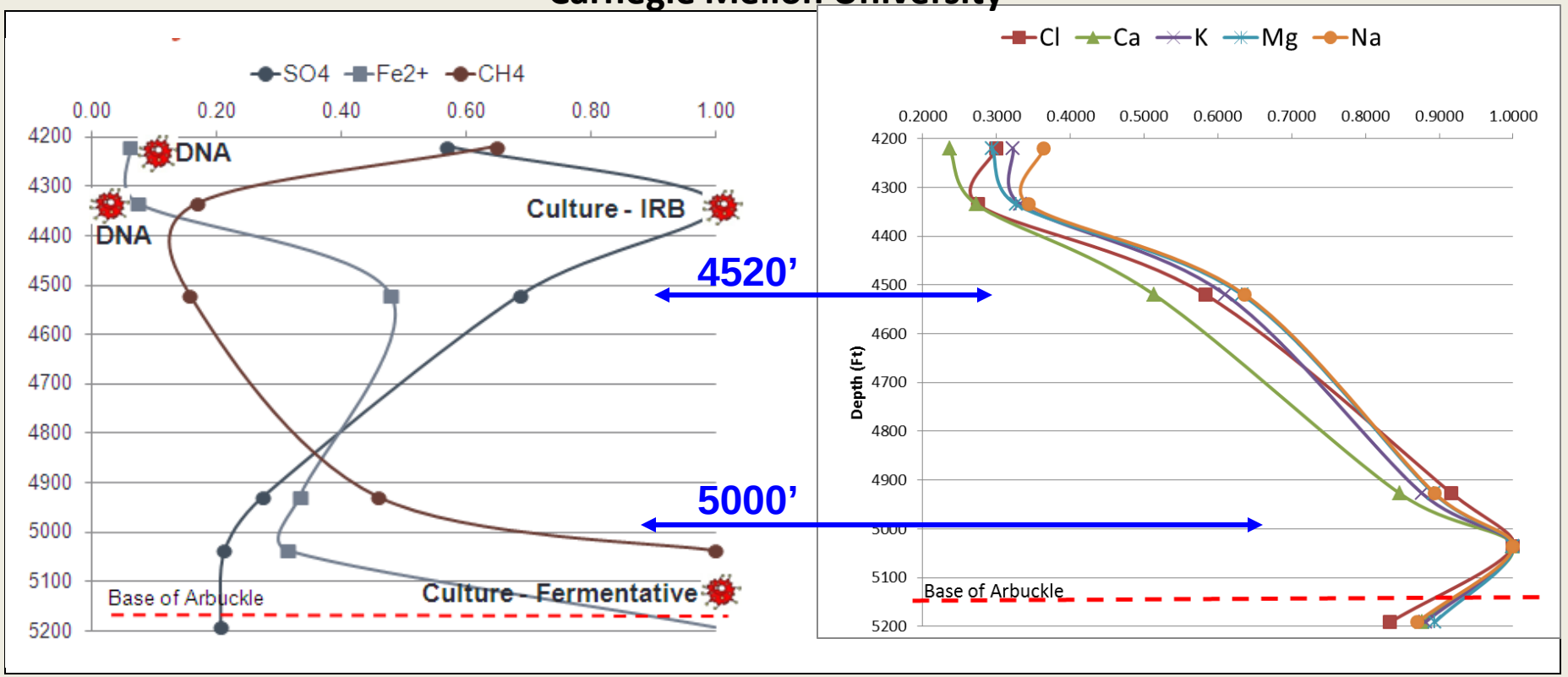
Top Arbuckle @ 4160 feet



Hydrogeochemistry and Microbes from DST and Swab Test in #1-32 and #1-28

Aimee Scheffer, Jennifer Roberts, David Fowle, and Breanna Huff
University of Kansas
Djuna Gulliver, Kelvin Gregory, Greg Lowry
Carnegie Mellon University

KU THE UNIVERSITY OF KANSAS Department of Geology

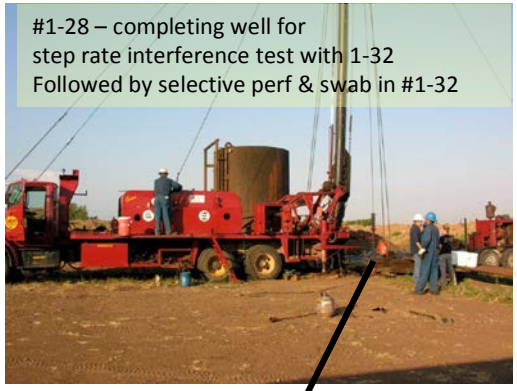


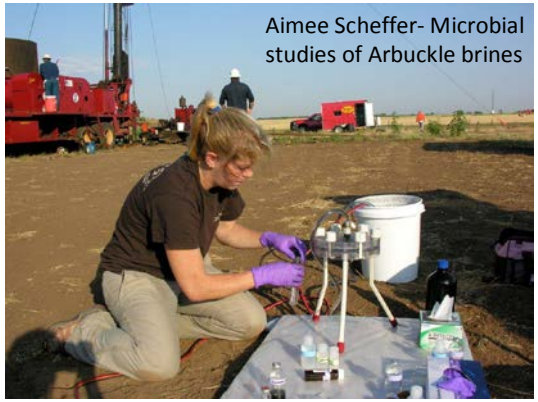
- **@ 4520 ft -- Changes in brine composition and microbes at (also low DOC & PO4) indicate low microbiological activity, corresponding with low Ø & k**
- **@ 5000 ft – microbial anomaly suggesting availability of nutrients corresponding with high Ø & k (in interval with step rate test)**

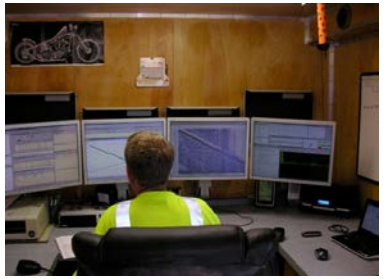
Completing Converted (Shear) Wave Processing and Depth Migration of 3D Seismic

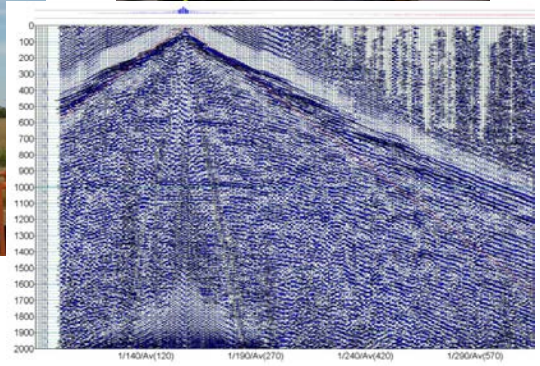
6.5 miles 2D-9C Seismic Survey obtained in July-August 2011 for calibration

Weekend July 31st @ Wellington



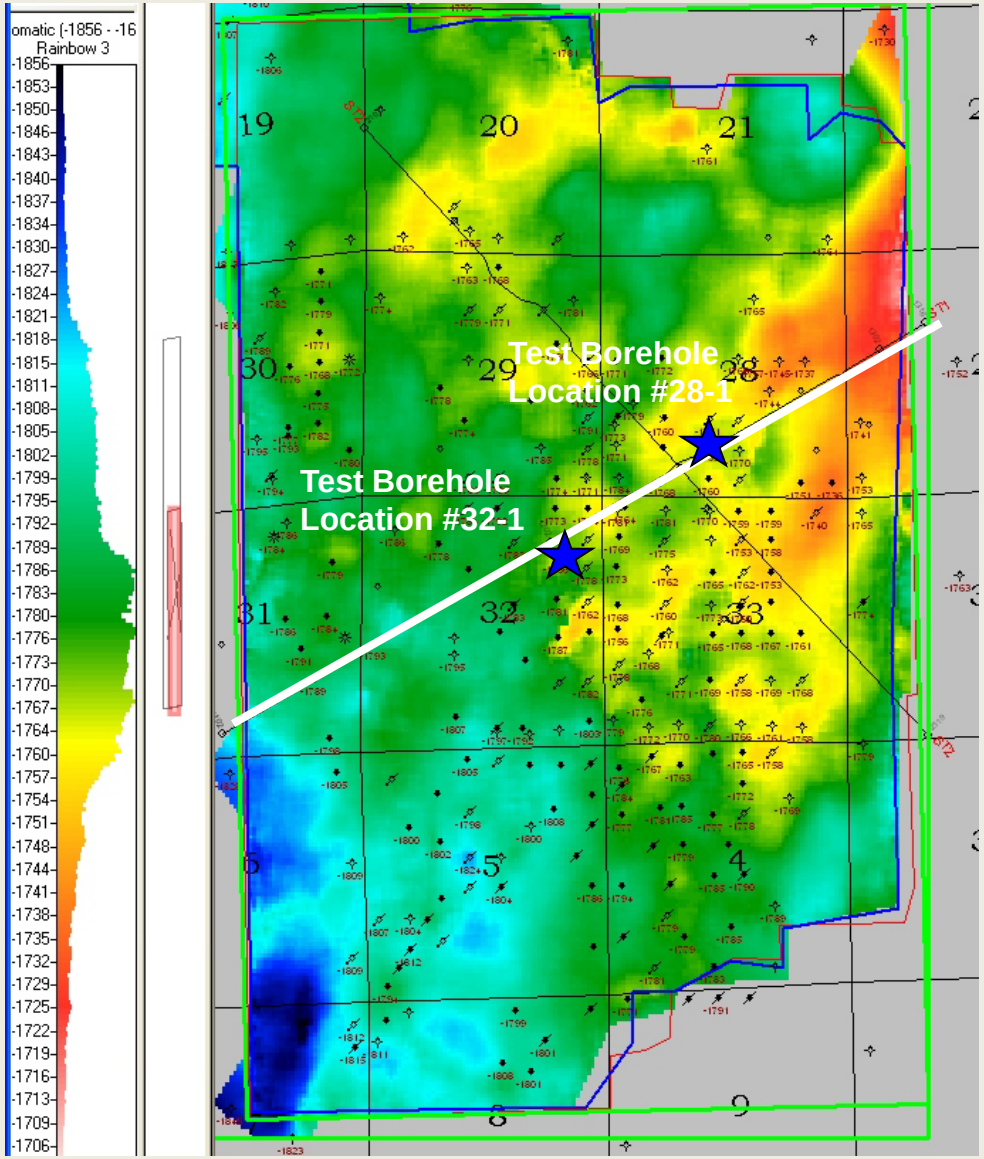




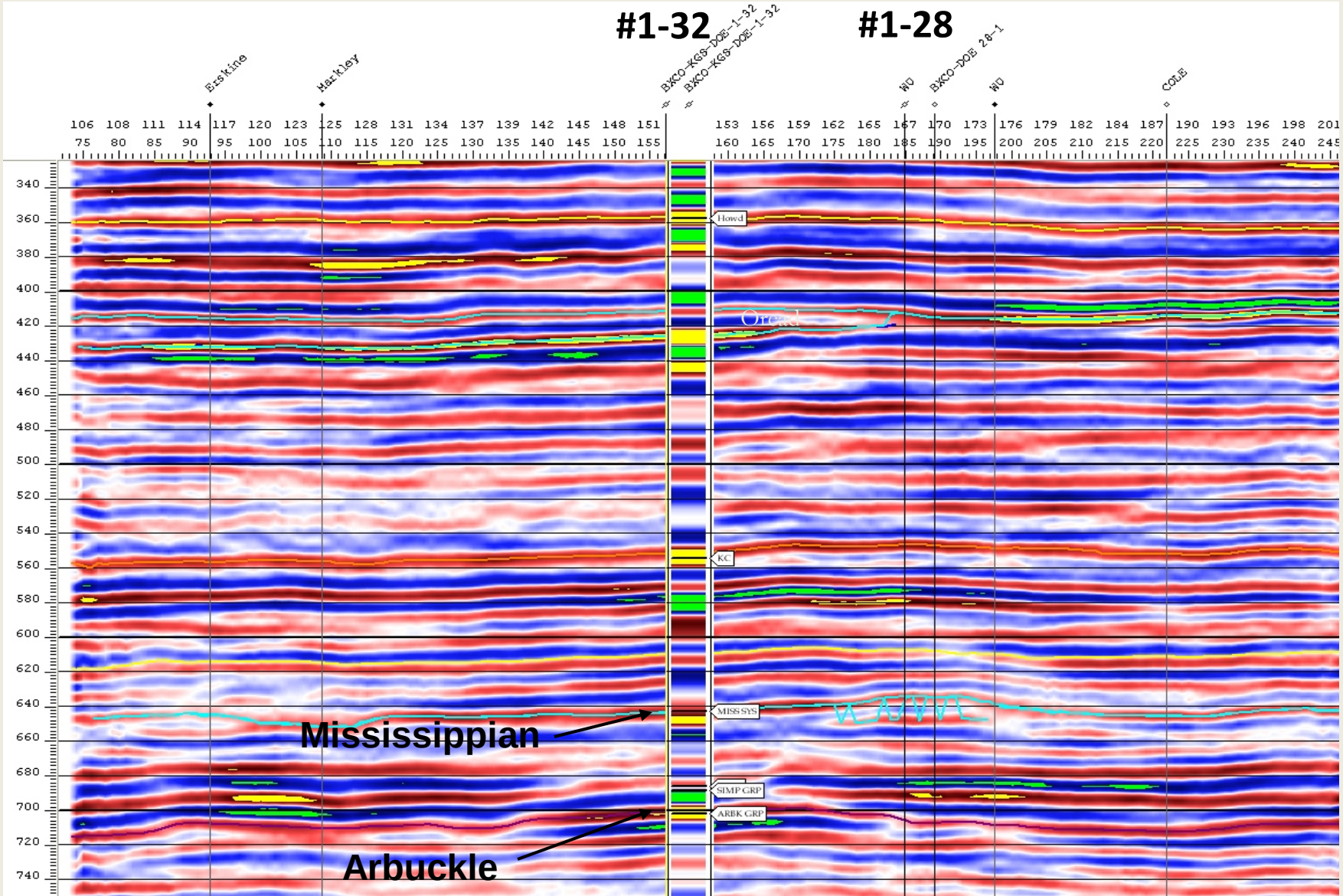


2D Shear Wave Line #1 Index Map

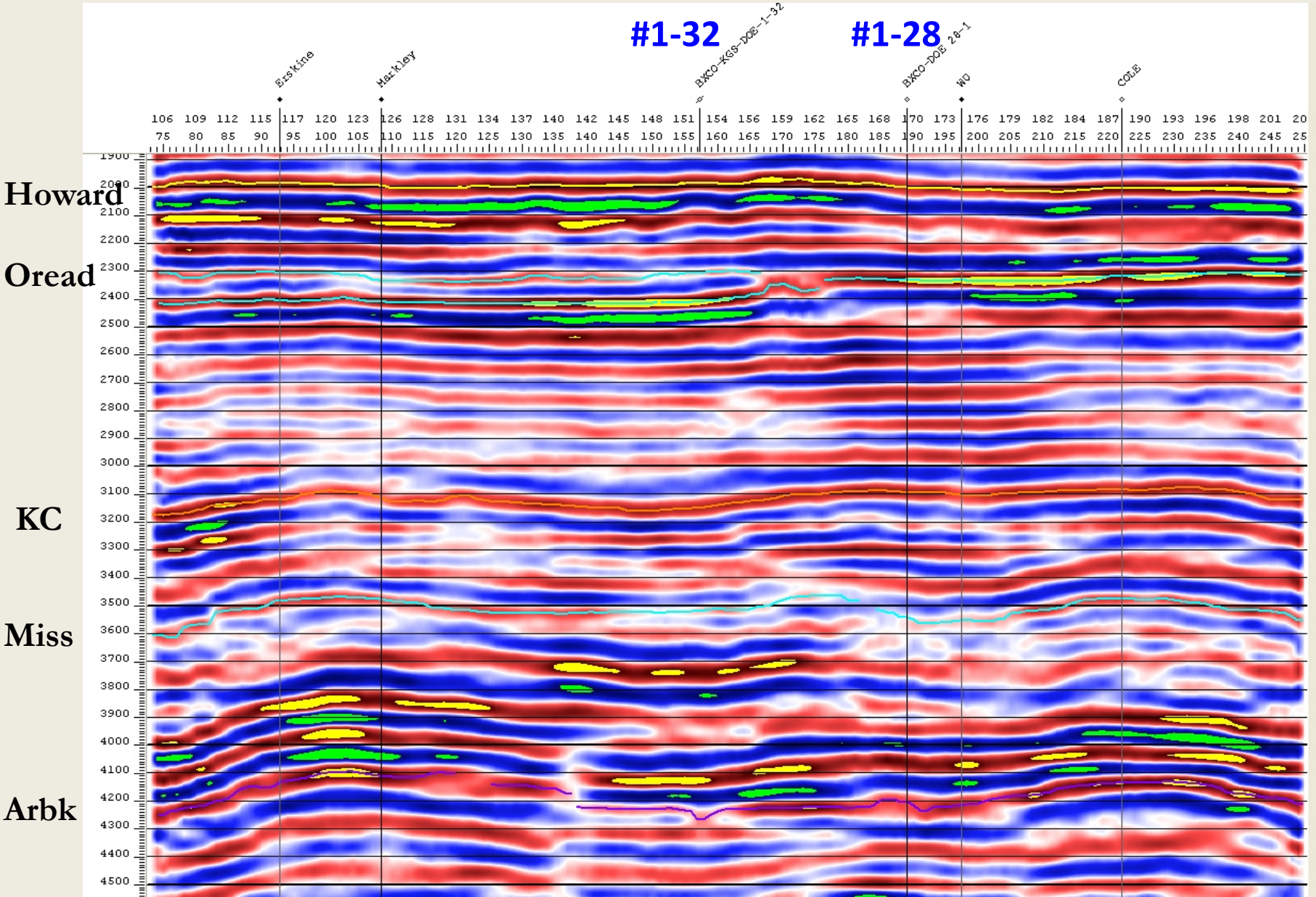
Prestack Time Migrated (PSTM) –
Top Pennsylvanian Kansas City Group



Prestack Time Migration
Coincident w/ Shear Wave Line #1 (3 mi)



Prestack Depth Migration
Coincident w/ Shear Wave Line #1
(preview of converted wave, depth migrated 3D seismic)

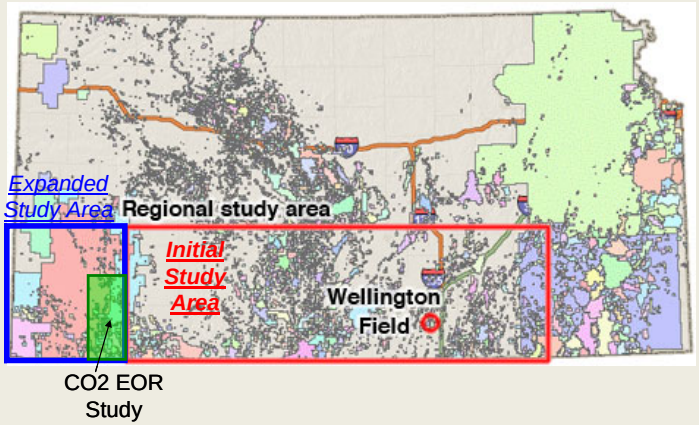


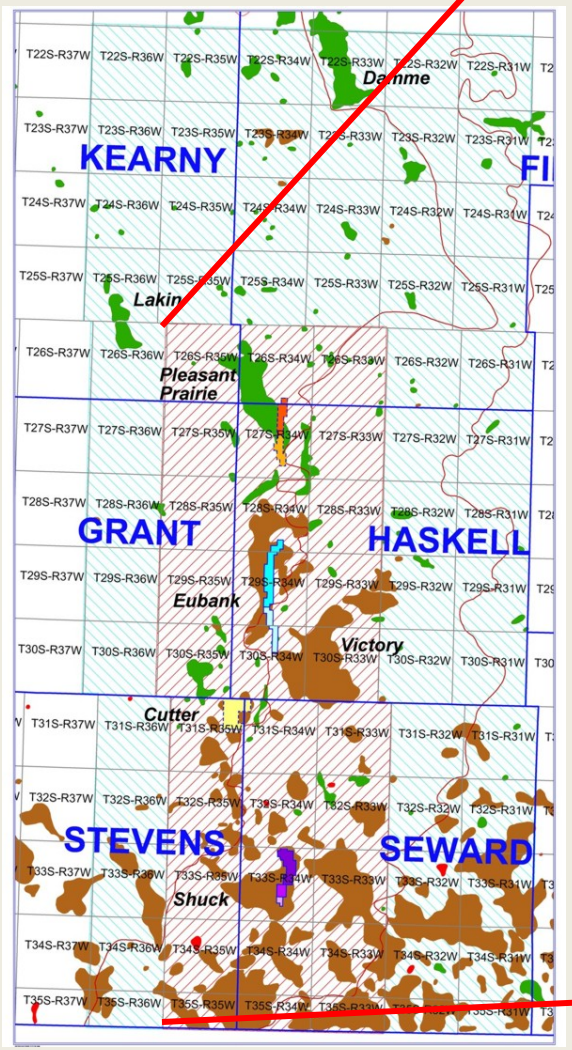
Remaining Seismic Work at Wellington Field

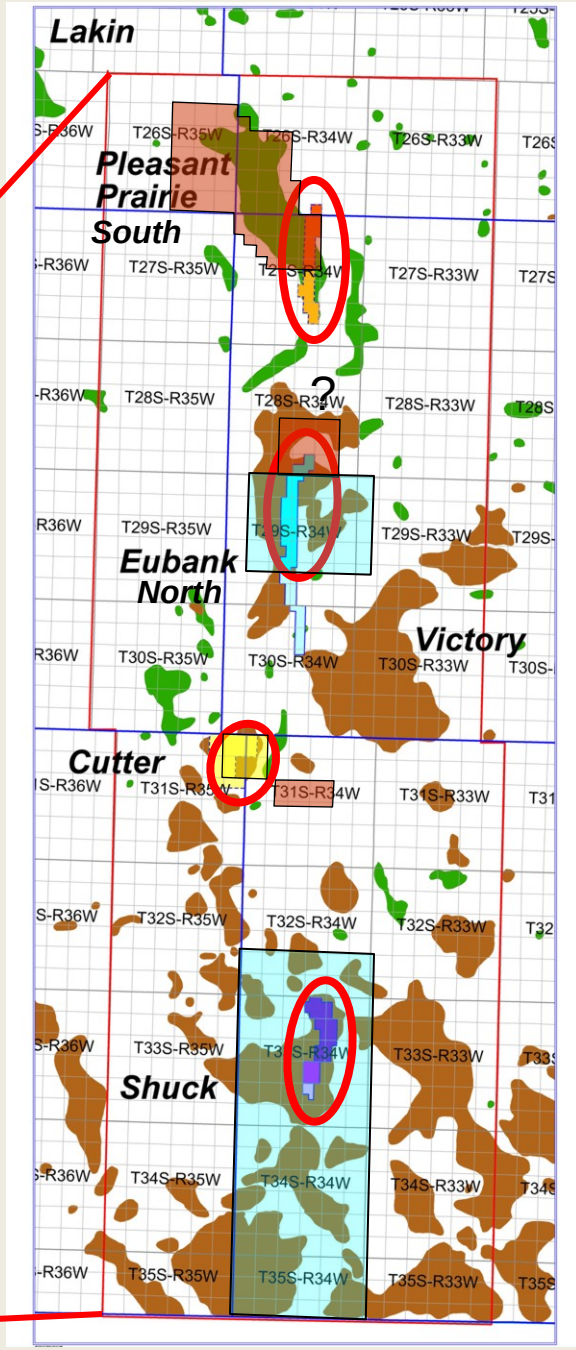
Activity-Entity / Timeline	Nov-11	Dec-11	Jan-12
Wellington Area			
PreStack Depth Migration (PSDM) -FarifieldNodal	X		
PSDM Volumetric Curvature Processing - Geo-Texture			
PSDM Volumetric Curvature Interpretation - Nissen			
PSDM Interpretation -HS Geo		X	
Impedance Inversion - PSDM input-HS Geo		X	
Elastic Inversion - Pre-stack Time Migration (PSTM) Input-HS Geo		X	
Spectral Decomposition (Frequency Domain Processing)-HS Geo			X
2D Shear Wave Processing-FairfieldNodal	X		
2D Shear Wave Interpretation-HS Geo		X	
Converted Wave Processing-FairfieldNodal	X	X	
Converted Wave Interpretation- HS Geo		X	

Southwest Kansas CO2 Consortium (*Western Annex*)

Seismic blocks are color coded by operator (~120 mi^2 of 3D seismic)



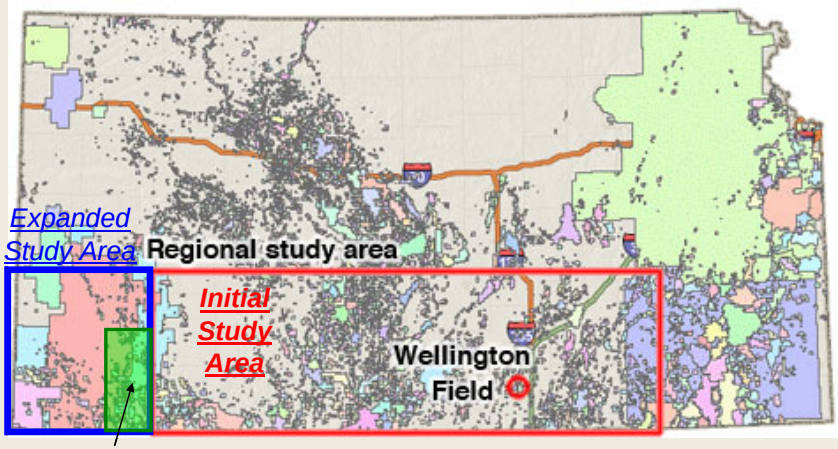




Chester/Morrow Sandstone (IVF) &

Deep saline Arbuckle aquifer

Southwest Kansas CO_2 Consortium – Technical Team



Six Industry partners:

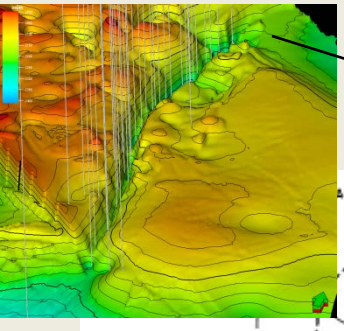
- **Anadarko Petroleum Corp.**
- **Berexco LLC**
- **Cimarex Energy Company**
- **Glori Oil Limited**
- **Elm III, LLC**
- **Merit Energy Company**

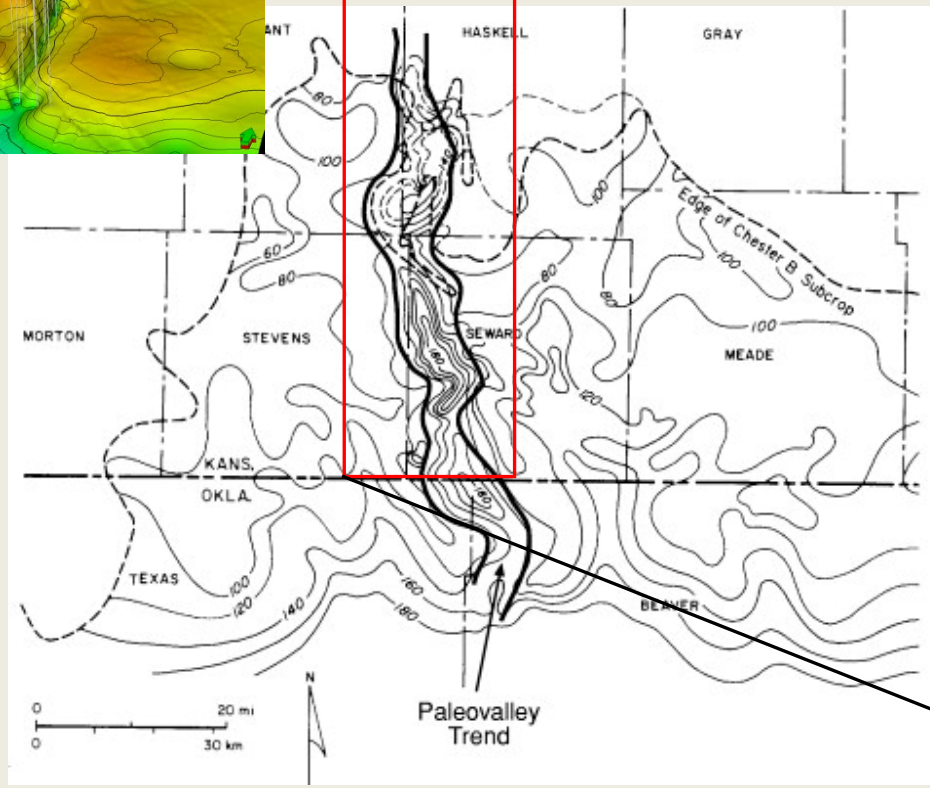
Support by:
Sunflower Electric Power Corp.

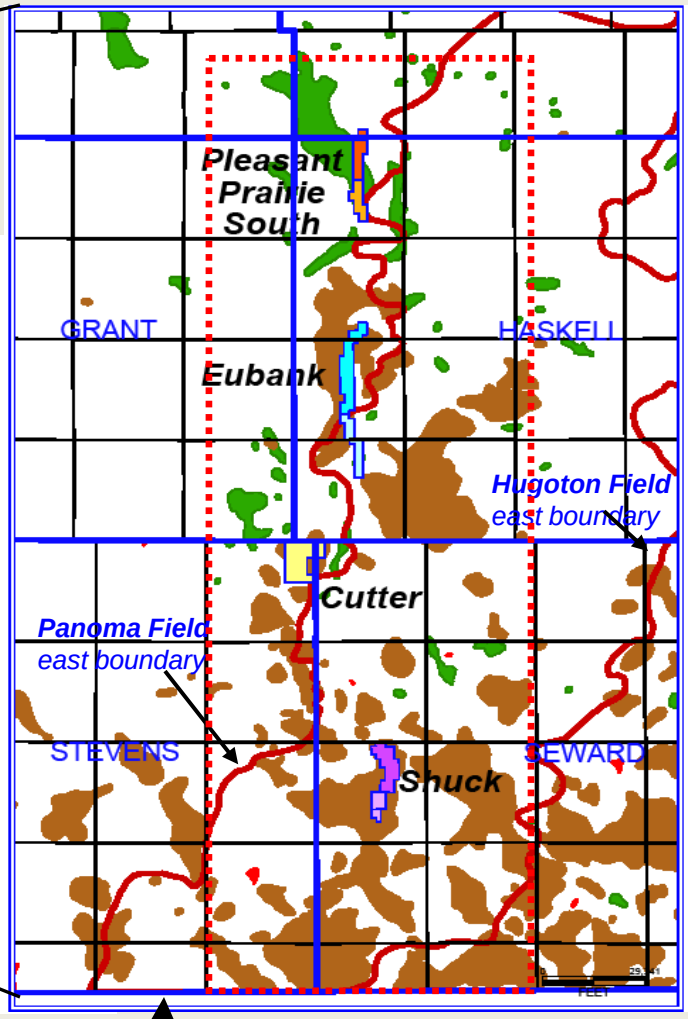
Technical Team:

	Project Role	Company
Martin Dubois	Team Lead, geo-model	Consultant - IHR LLC
John Youle	Core & depo-models	Consultant - Sunflower Energy
Ray Sorenson	Data sleuth & advisor	Consultant
Eugene Williams	Reservoir engineering	Williams Petrol. Consultants
Dennis Hedke	3D Seismic	Consultant - Hedke & Sanger
Peter Senior	Reservoir modeling	MS student
Ken Stalder	Geotech	IHR, LLC
Susan Nissen	3D Seismic	Consultant
Lynn Watney	Project PI	KGS
Jason Rush	Project PI	KGS
John Doveton	Log Petrophysics	KGS
Paul Gerlach	Data support	Consultant - Charter

Fields in study in relation to Chester IVF

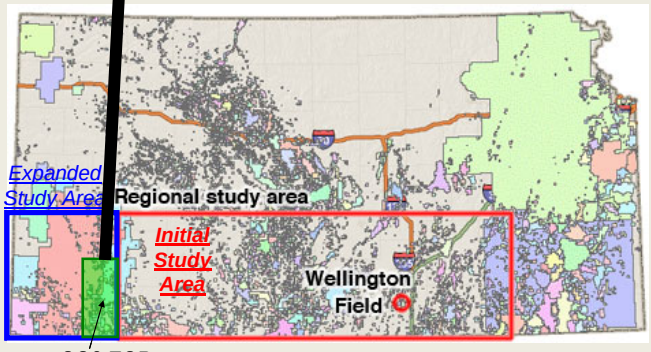






(Above) Regional isopach of lowermost Chesterian incised valley fill (*Montgomery & Morrison, 2008)*

(Upper Right) Four fields in study. Green – Oil; Brown – Oil and Gas. Grid is Township-scale (6 mi.).



Summary

- Project Start Date Dec. 8, 2009; End date: August 7, 2013
- Delayed start of BP2 until test bore holes #1 & #2 drilled and revised schedule
- Key personnel changes with joint PI Saibal Bhattacharya replaced by Jason Rush and simulation engineering by Eugene Williams
- $5 million budget enhancement used to fund Southwest Kansas CO_2 Sequestration Consortium to anchor western side of regional study area --
  - Led by additional science team with five industry partners
  - 120+ mi^2 3D seismic donation
  - Reprocess portion of and interpret donated 3D seismic
  - Field data on four major Chester/Morrow sandstone oil fields
  - Simulate reservoirs to maximize CO_2 storage
  - Select field for 10 mi^2 multicomponent 3D seismic and basement test with ~2200 ft core
- 2D shear wave survey acquired in Wellington Field in August
  - Use to refine processing and interpretation of existing 12 mi^2 multi-component 3D seismic survey
- Core Analysis – delivery end November 2011
- Geochemistry & Geobiology – ongoing into 2012
- Revise Geomodel & Simulation – early 2012

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Acknowledgements & Disclaimer

Acknowledgements

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