Evaluating CO2-EOR and CO2 Storage Capacity in Kansas

Lynn Watney and Jason Rush
Kansas Geological Survey
and collaborating team

Kansas Geological Society
March 6, 2012

Outline

1. Overview
2. Regional assessment – CO2 capacity
3. Wellington Field – Mississippian & Arbuckle characterization and modeling
4. *Southwest Kansas CO2 EOR Initiative* – characterization and modeling of four Chester & Morrow fields
5. Small-Scale field test at Wellington
6. Summary

1. Overview

"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 --

John Doveton, Aadish Gupta, Mina Fazelalavi, Evan Franseen, Dana Adkins-Heljeson, Mike Killion, Rick Miller, David Newell, Jennifer Raney, Marios Sophocleous, Debora Stewart, Dan Suchy, John Victorine, Jianghai Xia[1] -

Kansas Geological Survey, Lawrence, KS

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**

Tom Hansen - **Bittersweet Energy, Inc., Wichita, KS**

Larry Nicholson - **Consultant, Hanover, KS**

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 China Geosciences University, Wuhan*

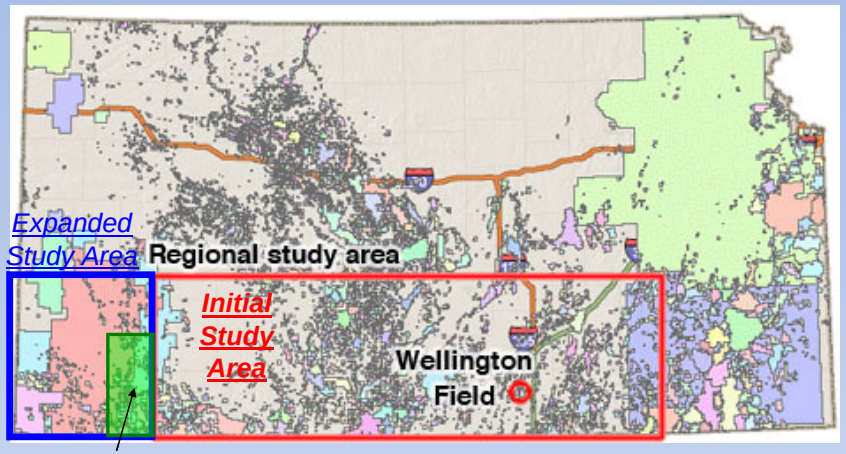
Regional and Wellington Field Studies

DOE Contract #FE0002056

and partner cost share

KANSAS GEOLOGICAL SURVEY
The University of Kansas

Southwest Kansas CO_2 Initiative
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.

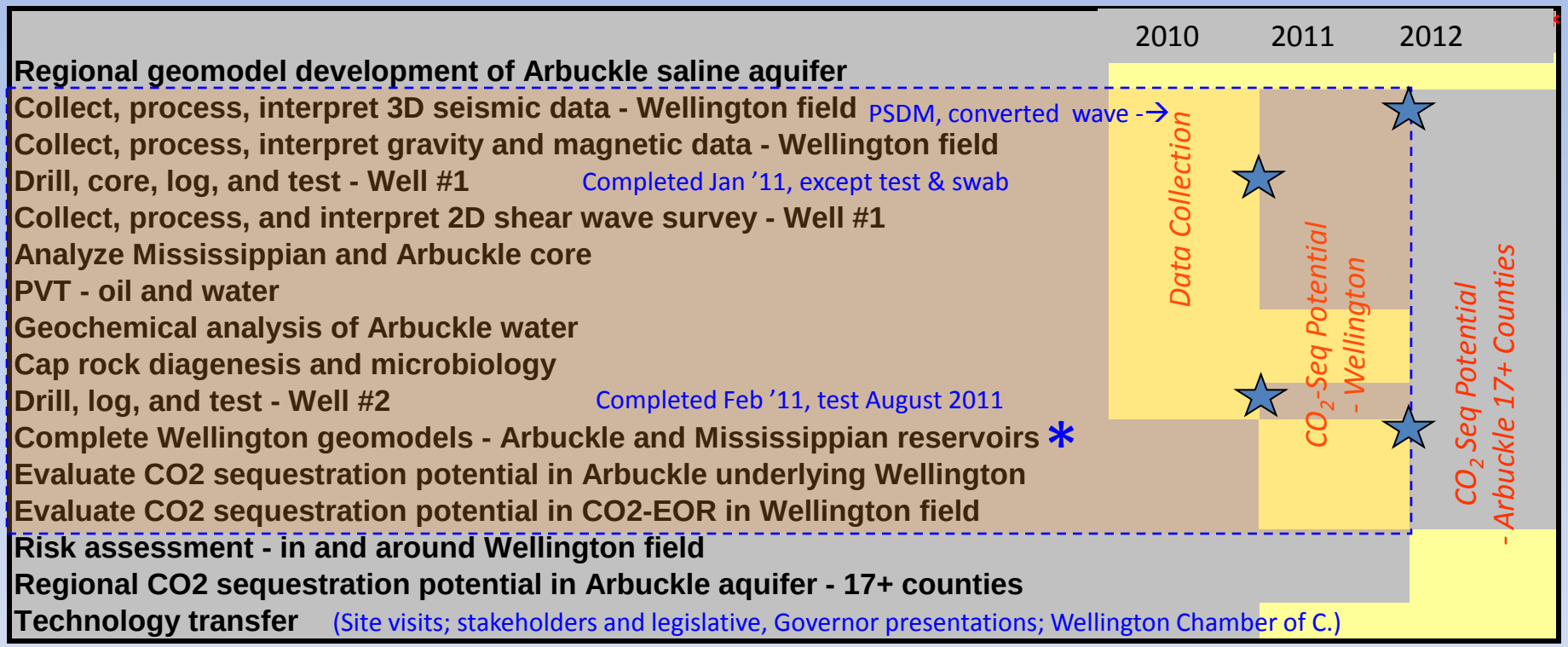
Technical Team:

	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

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

Small Scale Field Test Demonstrating CO_2 sequestration in Arbuckle Saline Aquifer and by CO_2-EOR at Wellington field, Sumner County, Kansas --

W. Lynn Watney and Jason Rush
Kansas Geological Survey
Lawrence, KS 66047
& collaborators and partners

Funding Opportunity Number: DE-FOA-0000441
Contract #FE0006821
Starting date: October 1, 2011
$11,484,499 DOE
$3.236 million cost share

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The University of Kansas

NETL

BEREXCO

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

DEPARTMENT OF GEOLOGY
KANSAS STATE UNIVERSITY

THE UNIVERSITY OF KANSAS
Department of Geology

Sandia Technologies, LLC

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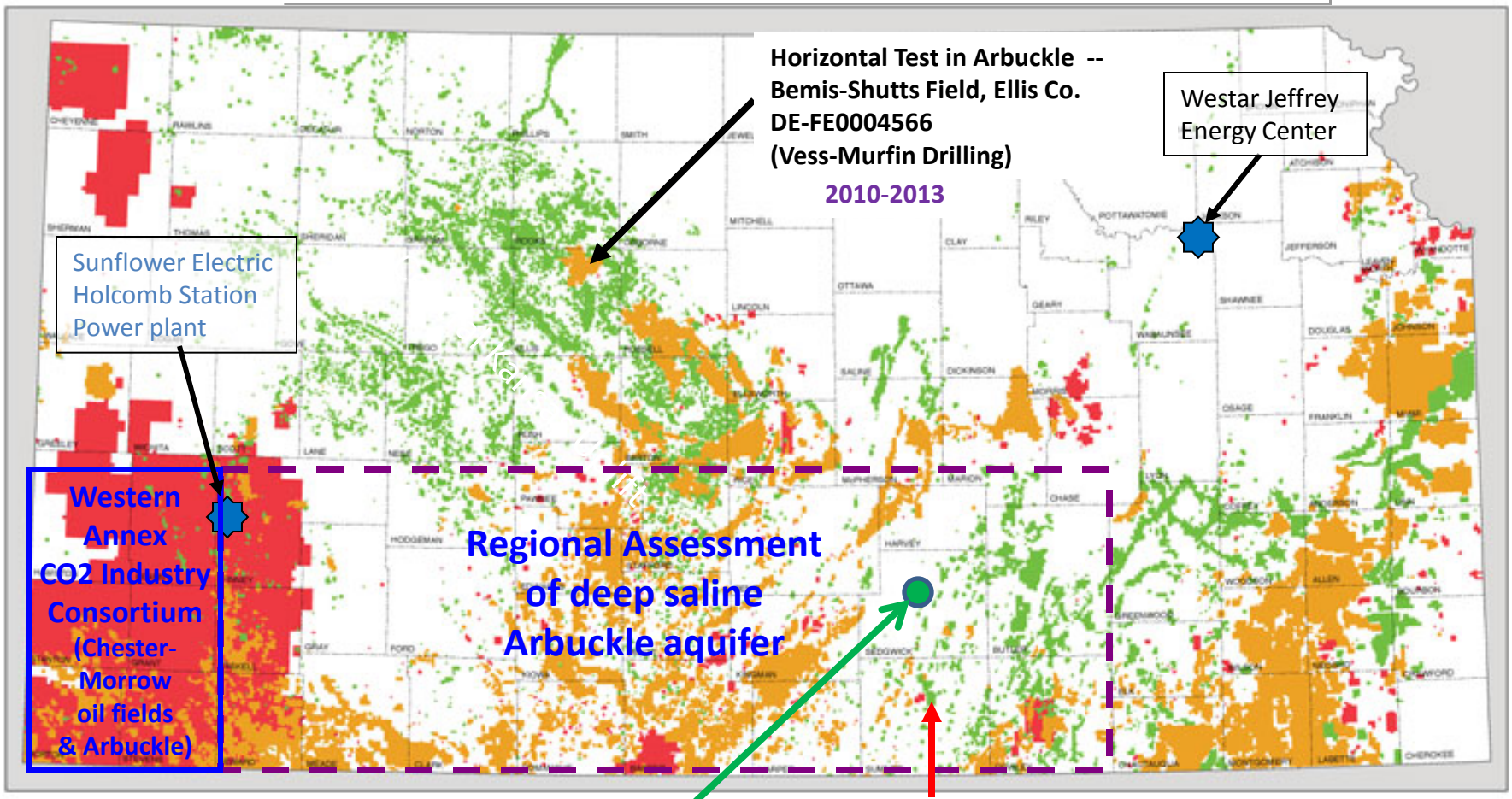
The University of Kansas

Location of DOE-CO_2 Studies



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

Modeling CO_2 Sequestration Potential in Kansas

- **Regional distribution of Arbuckle saline aquifer and caprock**
  - *Caprock continuity and integrity*
  - *Storage*
    - *Continuity of hydrostratigraphic flow units*
    - *Evaluating open or closed hydrologic system*
    - *Capacity via volumetrics and compositional simulation*
- **Structure**
  - *Systematically characterize fractures/faults/flexures*
  - *Map deep-seated structures and assess nature and timing of reactivation*
- **Preliminary simulations of commercial scale CO_2 injection**
  - *Footprint & stratigraphic constraint of commercial scale CO_2 plume in saline aquifer*
  - *-- Improved efficiency and effectiveness of CO_2-EOR in prime candidate oil fields*
- **CO_2-EOR Potential**
  - *Wellington Field, Sumner County Kansas and Chester/Morrow sandstone reservoir (TBN) in SW Kansas*
  - *Multicomponent 3D seismic*
  - *Gravity/magnetics & remote sensing*
  - *3D geocellular geomodels*
  - *Reservoir simulation*

Kansas is part of the Southwest Regional Partnership on Carbon Sequestration (SWP)

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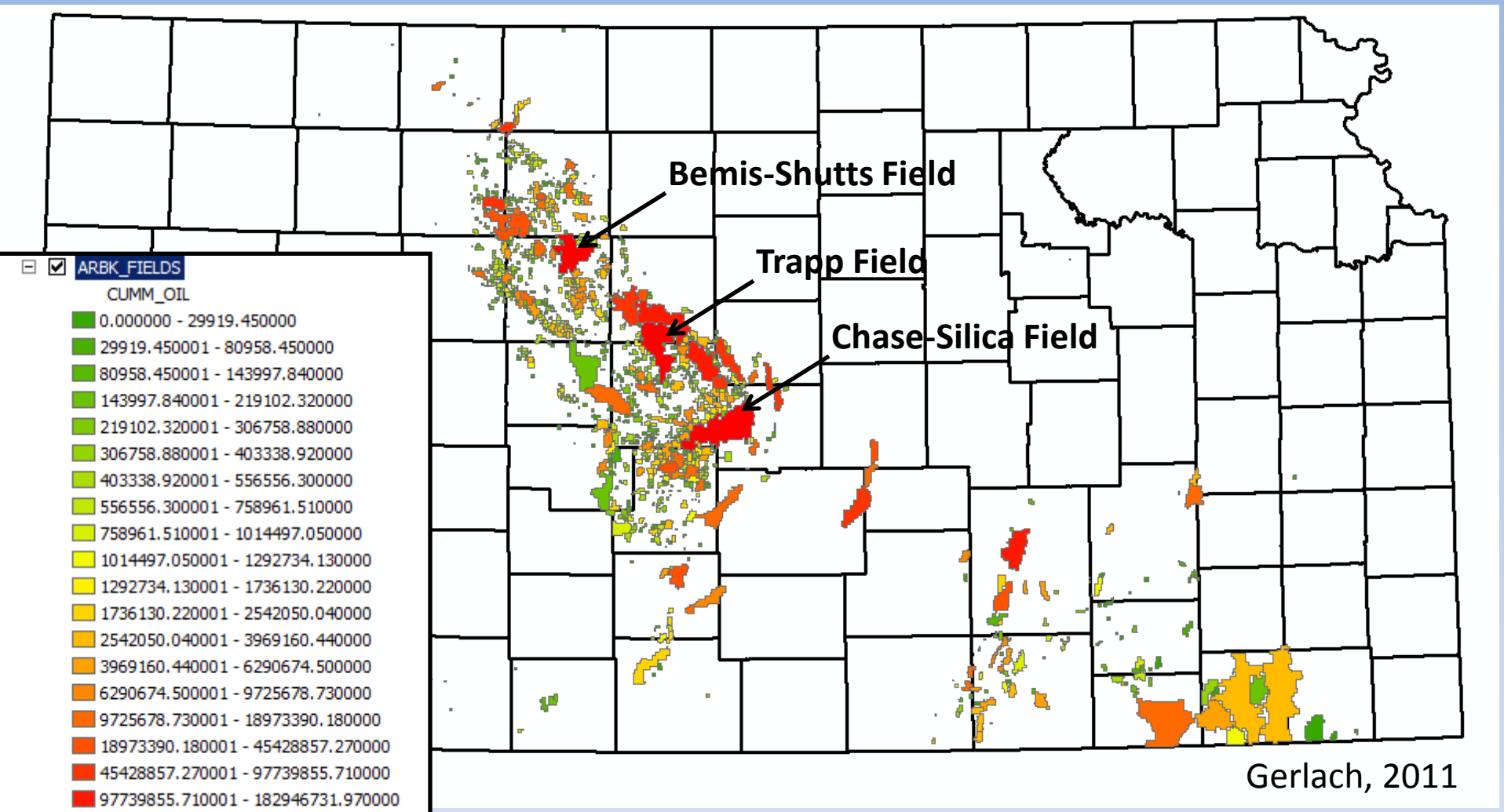
The University of Kansas



CO2-EOR Potential Targets
Cumulative Production
Arbuckle Fields

DOE-FE0002056

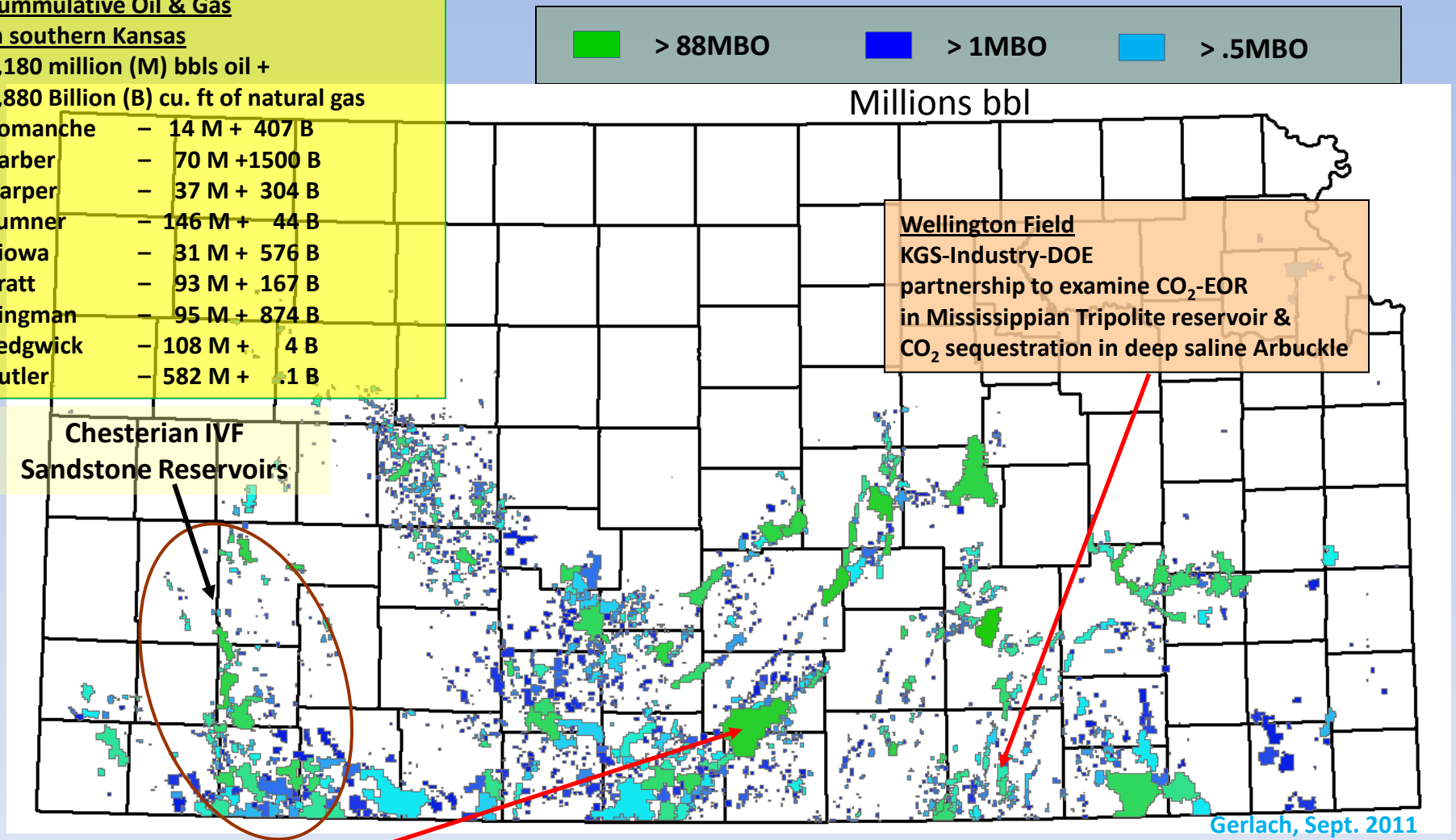
Map of Mississippian Oil and Gas Producing Fields in Kansas

CO2-EOR – 1) Tripolite Chert Reservoir at Wellington Field, Analogous to Mississippian Oil and Gas Fields in Southern Kansas and

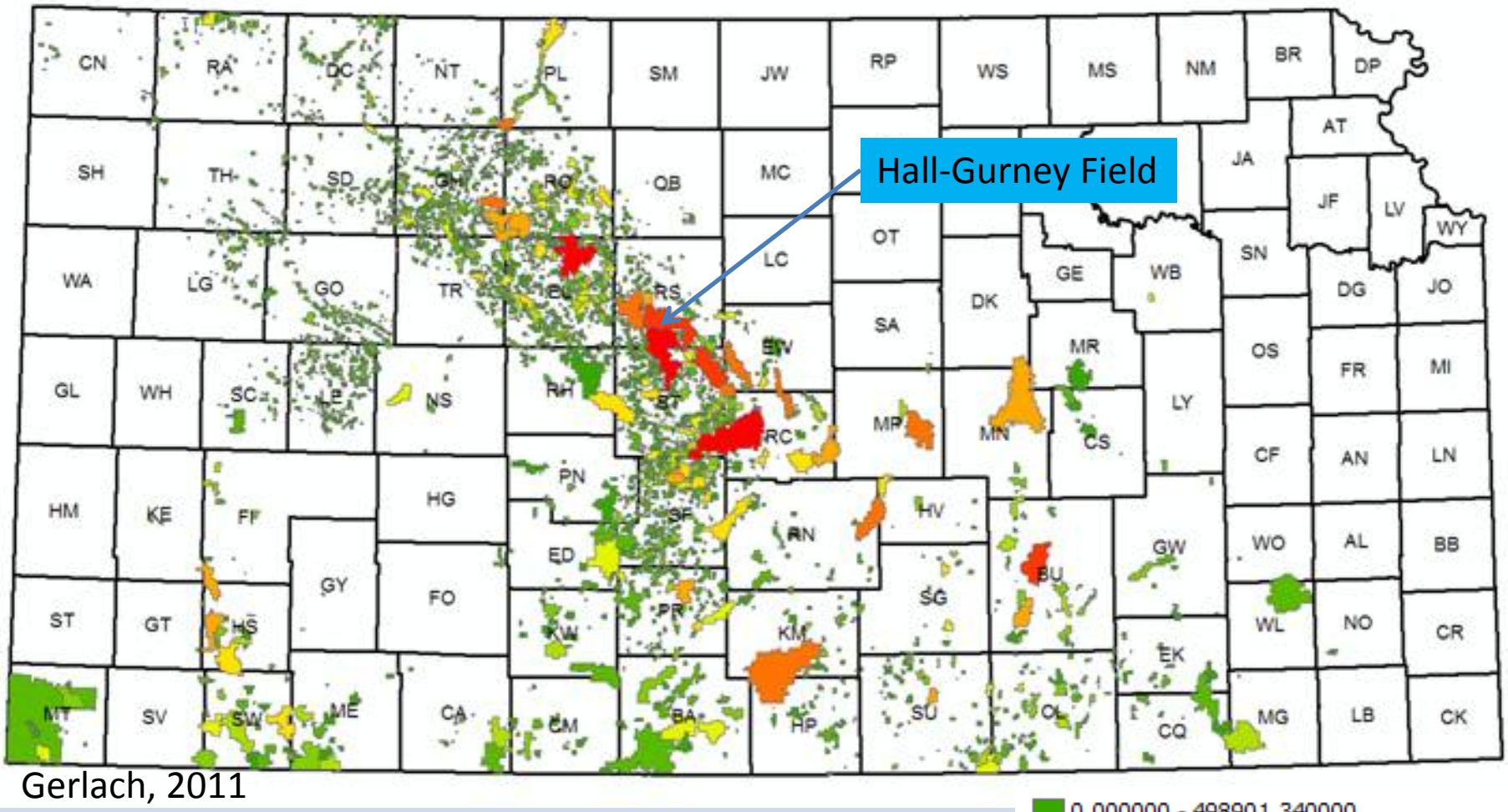
2) Mississippian Chester Sandstone Reservoirs in Western Kansas

Cummulative Oil & Gas in southern Kansas
1,180 million (M) bbls oil +
3,880 Billion (B) cu. ft of natural gas

Comanche	–	14 M + 407 B
Barber	–	70 M +1500 B
Harper	–	37 M + 304 B
Sumner	–	146 M + 44 B
Kiowa	–	31 M + 576 B
Pratt	–	93 M + 167 B
Kingman	–	95 M + 874 B
Sedgwick	–	108 M + 4 B
Butler	–	582 M + .1 B



Spivey-Grabs Basil is the largest Mississippian oil field in Kansas with 69 MM BO & 841 BCFG
Produces from the tripolite and could benefit from horizontal drilling and, in later maturity, by CO_2-EOR



Gerlach, 2011

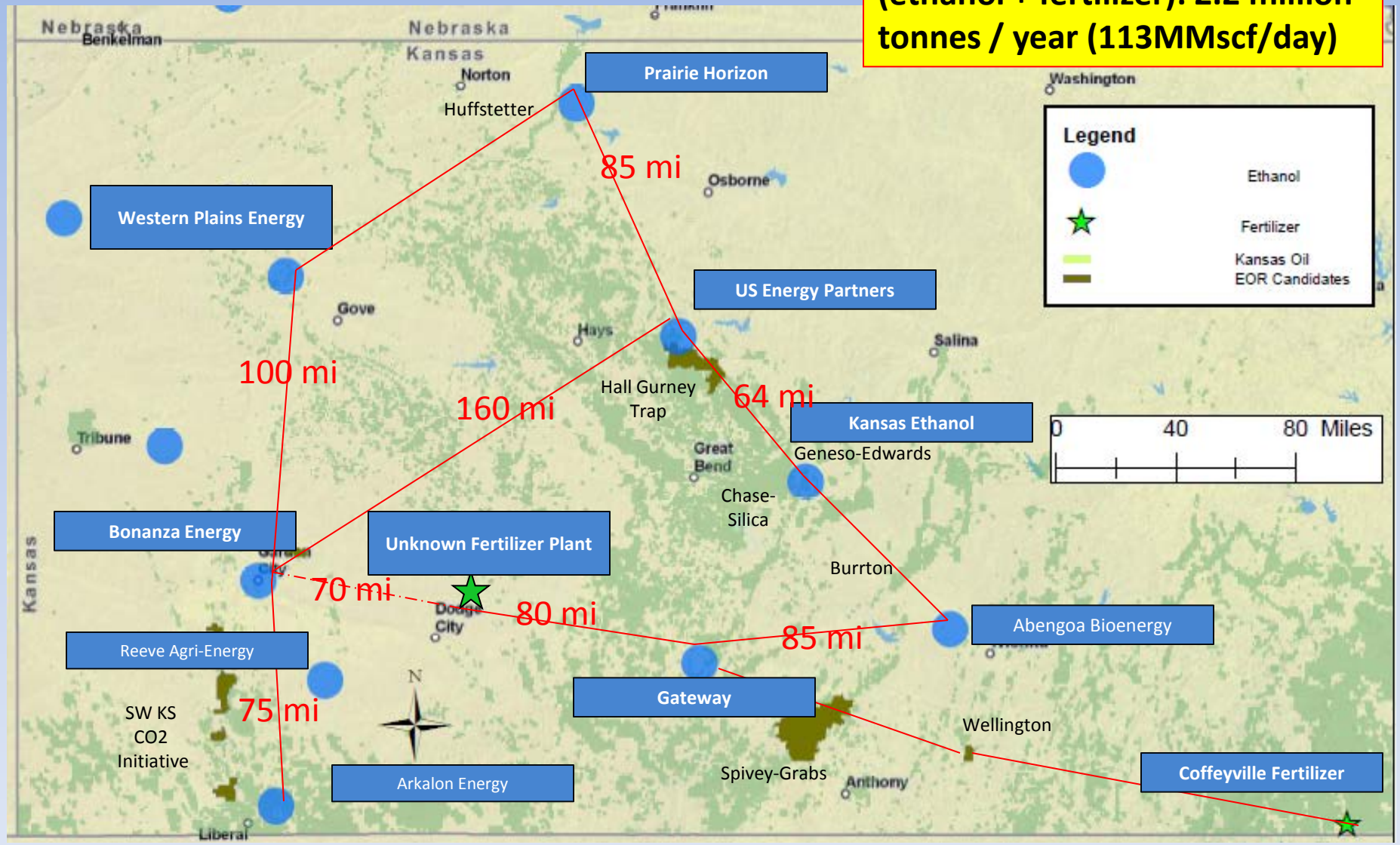
CO2-EOR Potential Targets

Cumulative Oil Production from Upper Pennsylvanian, Lansing and Kansas City Groups

- 0.000000 - 498901.340000
- 498901.340001 - 1660137.170000
- 1660137.170001 - 3647332.050000
- 3647332.050001 - 6541130.210000
- 6541130.210001 - 11501300.930000
- 11501300.930001 - 19760005.100000
- 19760005.100001 - 45428857.270000
- 45428857.270001 - 97739855.710000
- 97739855.710001 - 182946731.970000
- 182946731.970001 - 281461705.740000

Ethanol CO2 pipeline concept – initial step

Total annual CO2 emissions (ethanol + fertilizer): 2.2 million tonnes / year (113MMscf/day)



Collaboration with MGA & Clinton Foundatation

Volume and Area Report -- Initial Estimate of CO_2 Capacity in Deep Saline Arbuckle Group in Southern Kansas (Gerlach et al.)

Report Date: 2/8/2012

Project: KANSAS CO2

Area of Interest: CO2 PROJECT

Layer: ISOPACH ARBK PORO FT (from Grid to Grid)

Total Area: 18,851,937 Acres

Total Volume: 9,997,806,629,348 Barrels

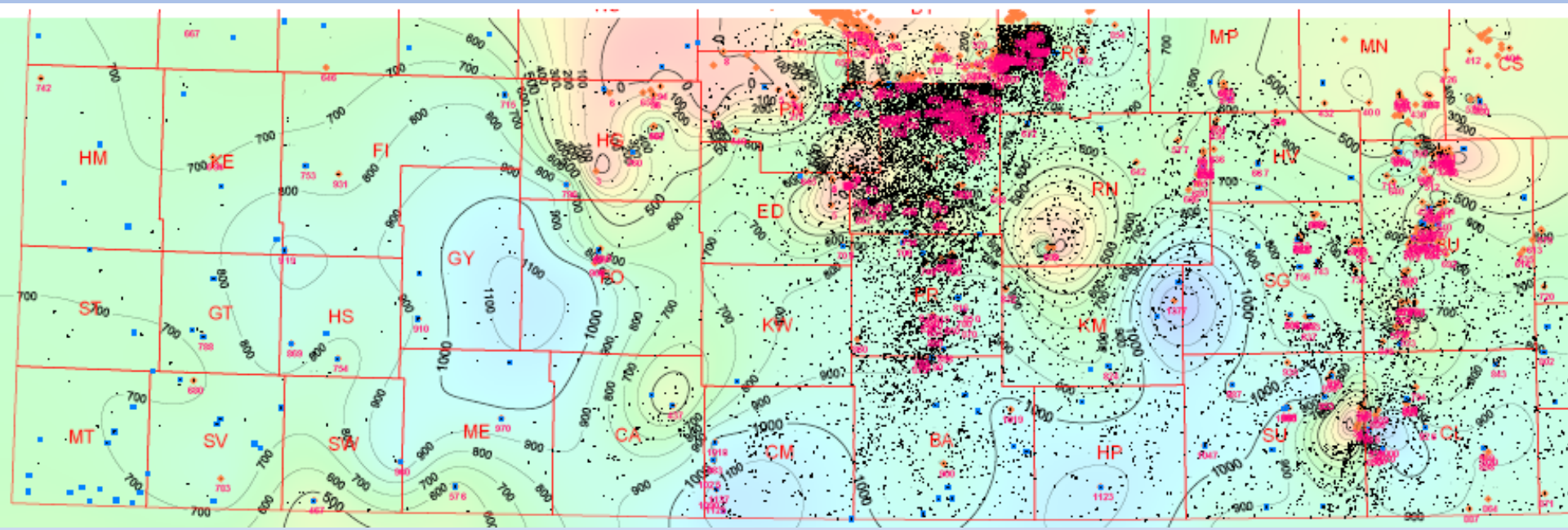
Layer: ISOPACH ARBK PORO FT (contoured from well data)

Total Area: 18,851,937 Acres

Total Volume: 11,206,456,917,400 Barrels

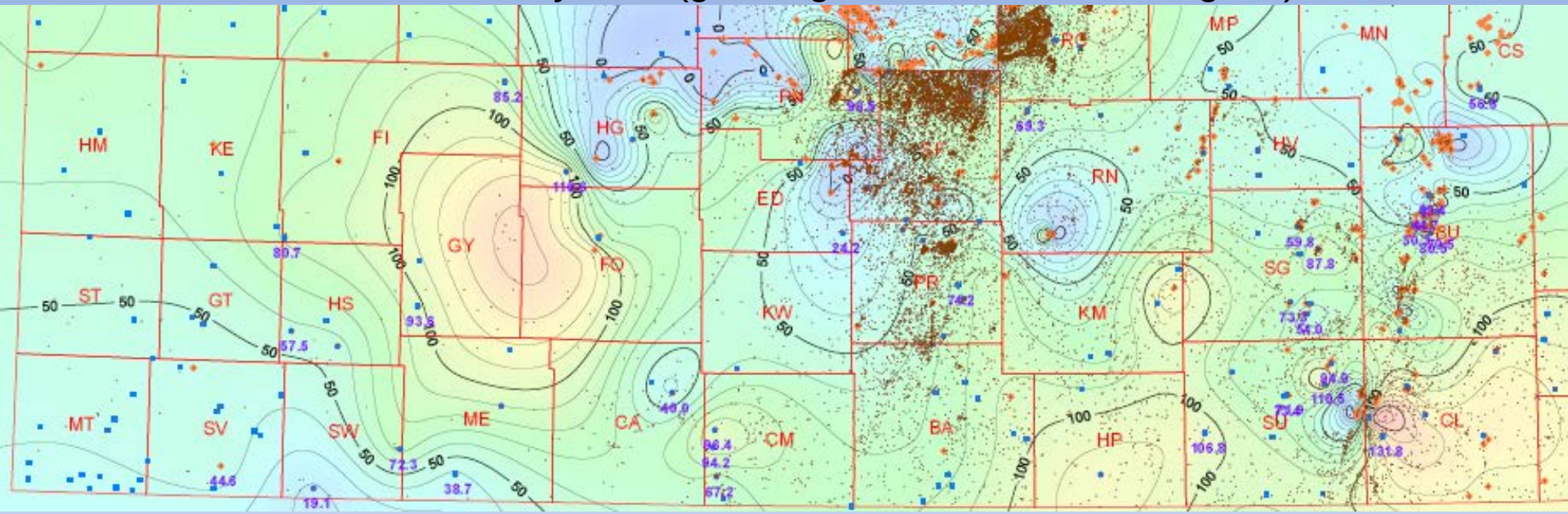
Density Porosity values using matrix 2.83 and Neutron Porosity unchanged. Calculate average porosity and total porosity feet with no minimum Ø cutoffs.

Arbuckle Isopach

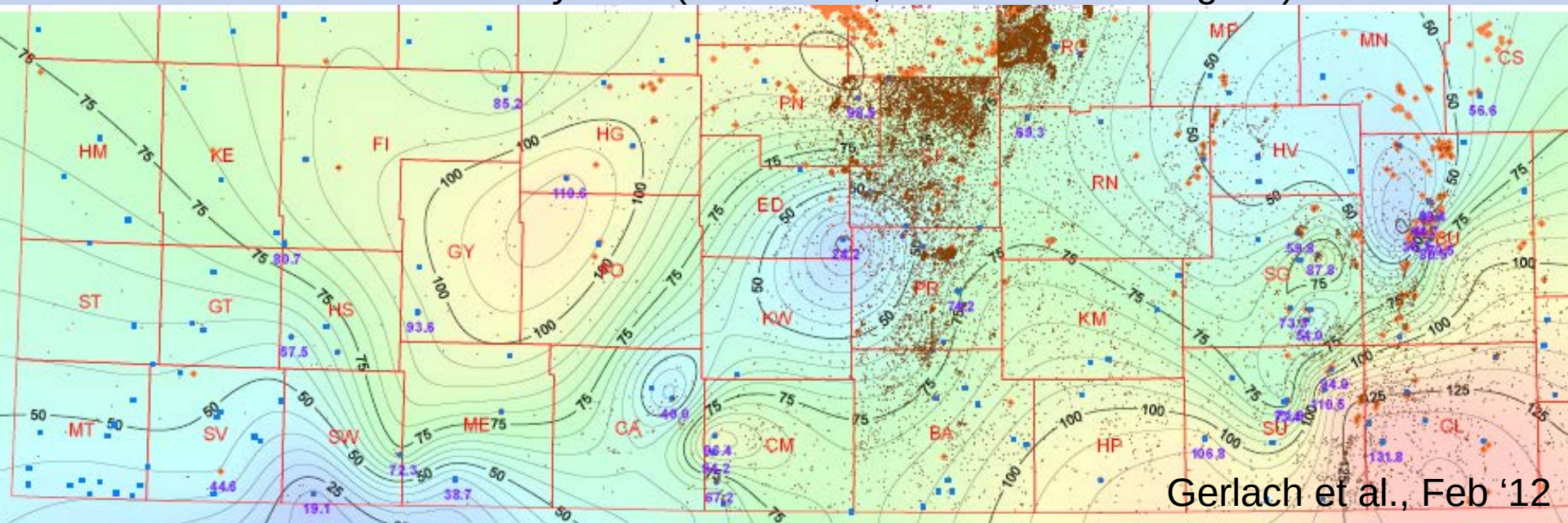


Gerlach et al., Feb ‘12

Arbuckle Porosity-Feet (grid to grid, thickness x average Ø)



Arbuckle Porosity-Feet (well based, thickness x average Ø)

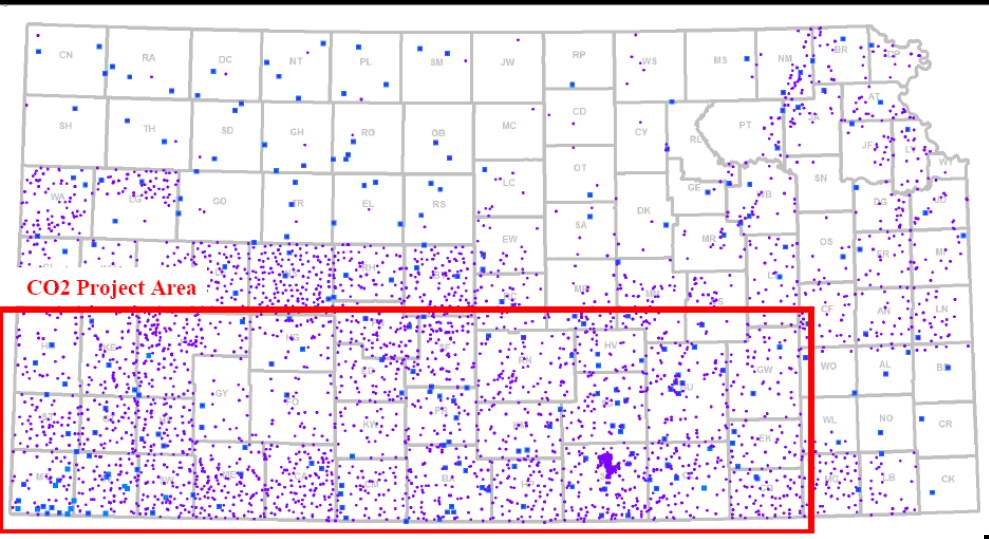


Gerlach et al., Feb ‘12

2. Regional studies

Well Data Inventory

Wells with LAS or Raster = 3792



Regional Team – Tom Hansen, Paul Gerlach, Larry Nicholson, and Anna Smith

- 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

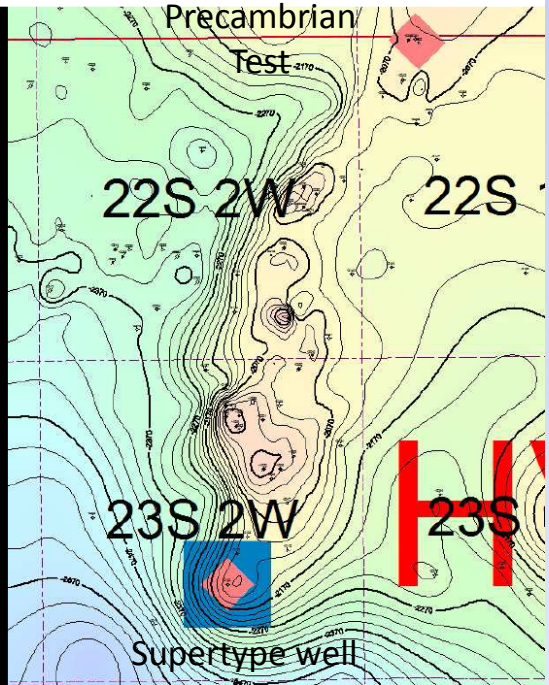
Non-Faulted Structural Closures Candidate:

Township

22S-2W

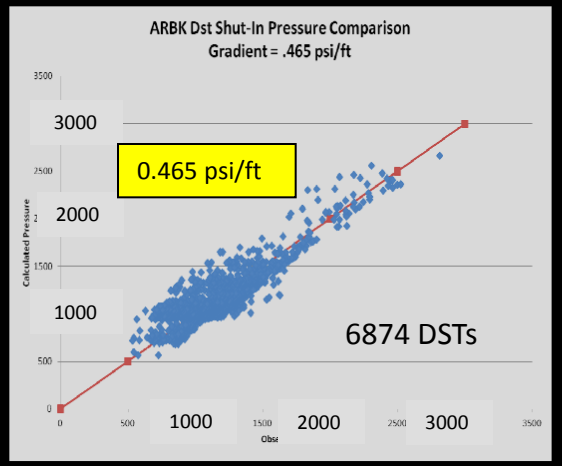
Arbuckle Subsea

C.I. 25 ft



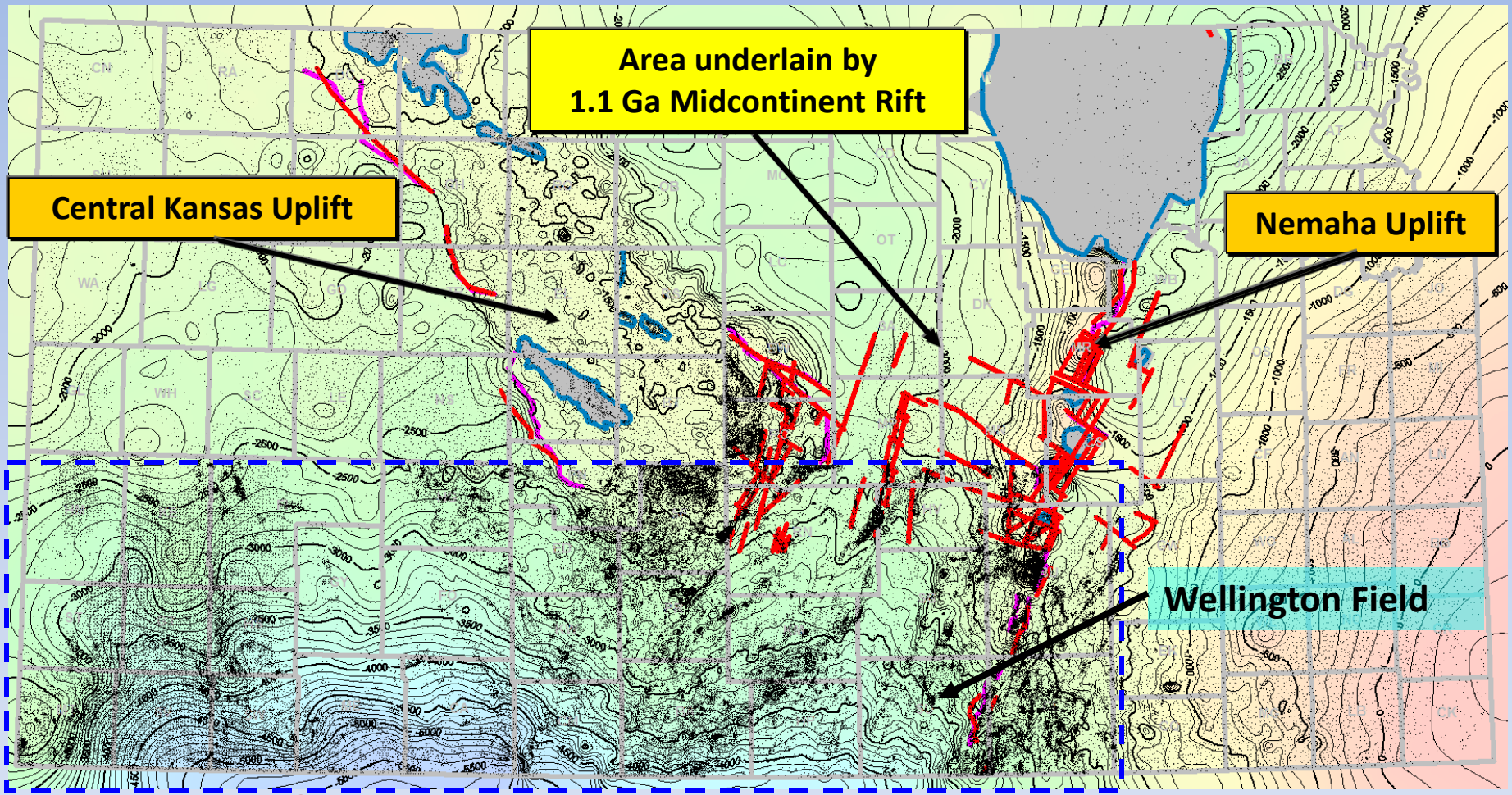
Calculated Pressure vs. Observed Pressure (psi)

6874 ARBK Dst's (observed gradient filtered)



Structural mapping and evaluation of faulting

Top Arbuckle Group

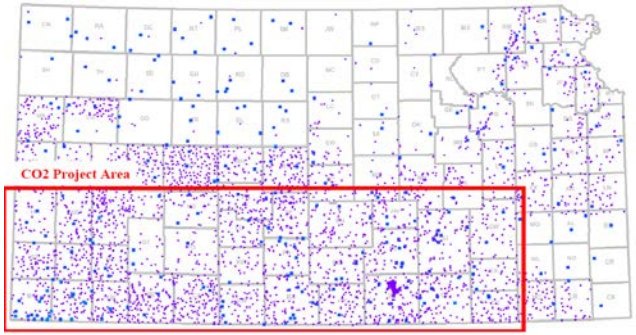


- Published faults are being compiled and new ones are under investigation
- Focus on <u>quantitative</u> assessment of CO_2 storage capacity of Arbuckle saline aquifer is within dashed blue area

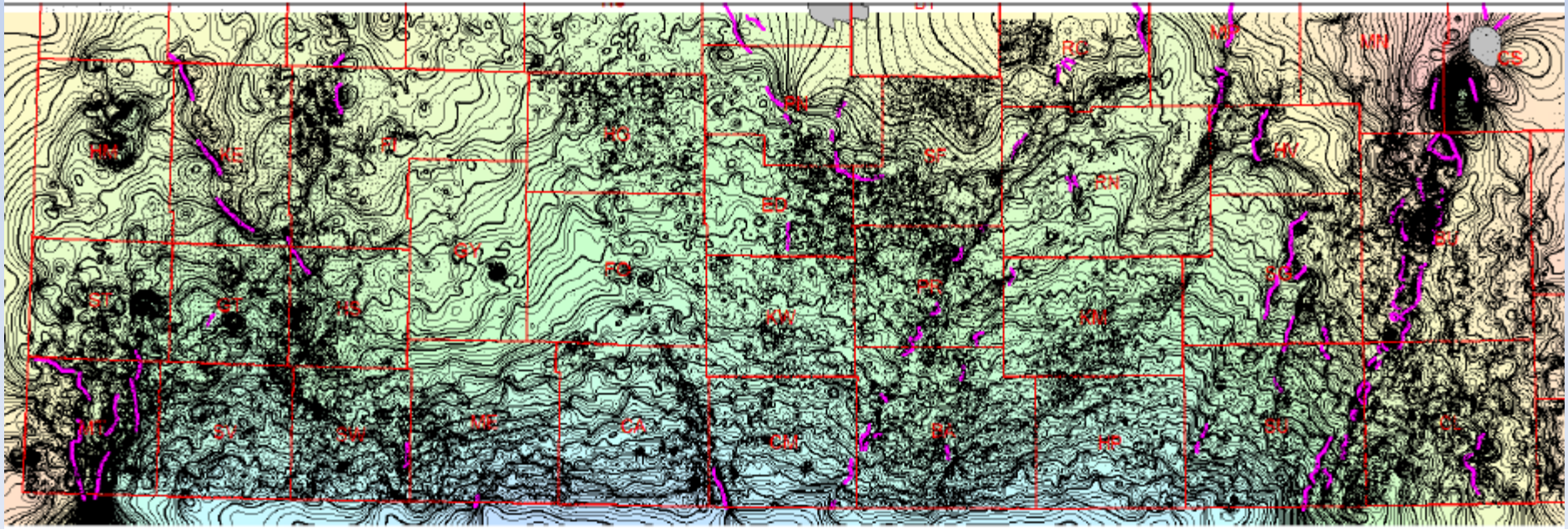
Structure Contour Map -- Top Mississippian

Subcontractor
Bittersweet Energy

Current Status
Of
2) Fault Detection & Verification – Regional & Compartment

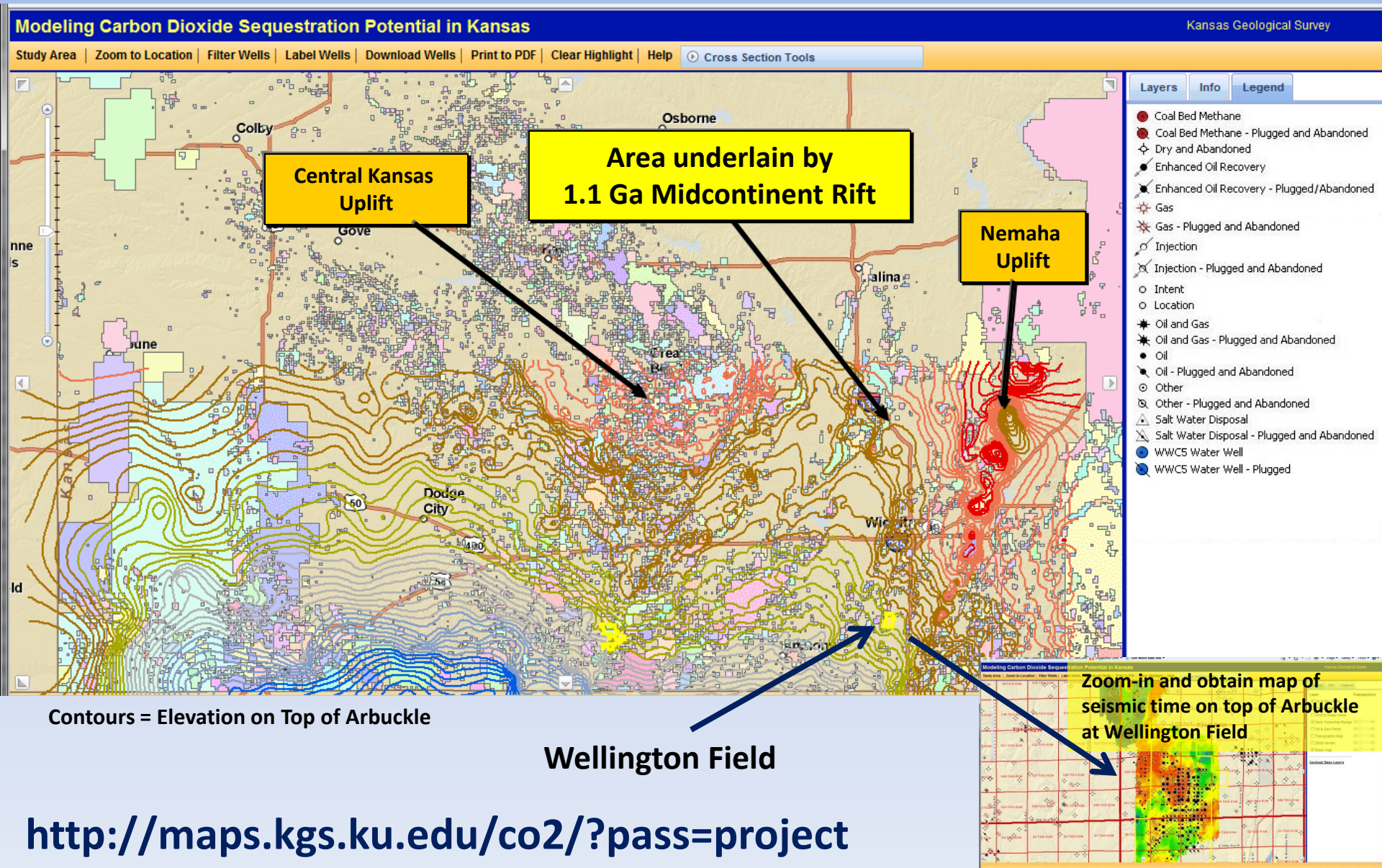


MISS Subsea ci: 25 ft with ARBK Verified Faults



Web-based Interactive Project Mapper

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



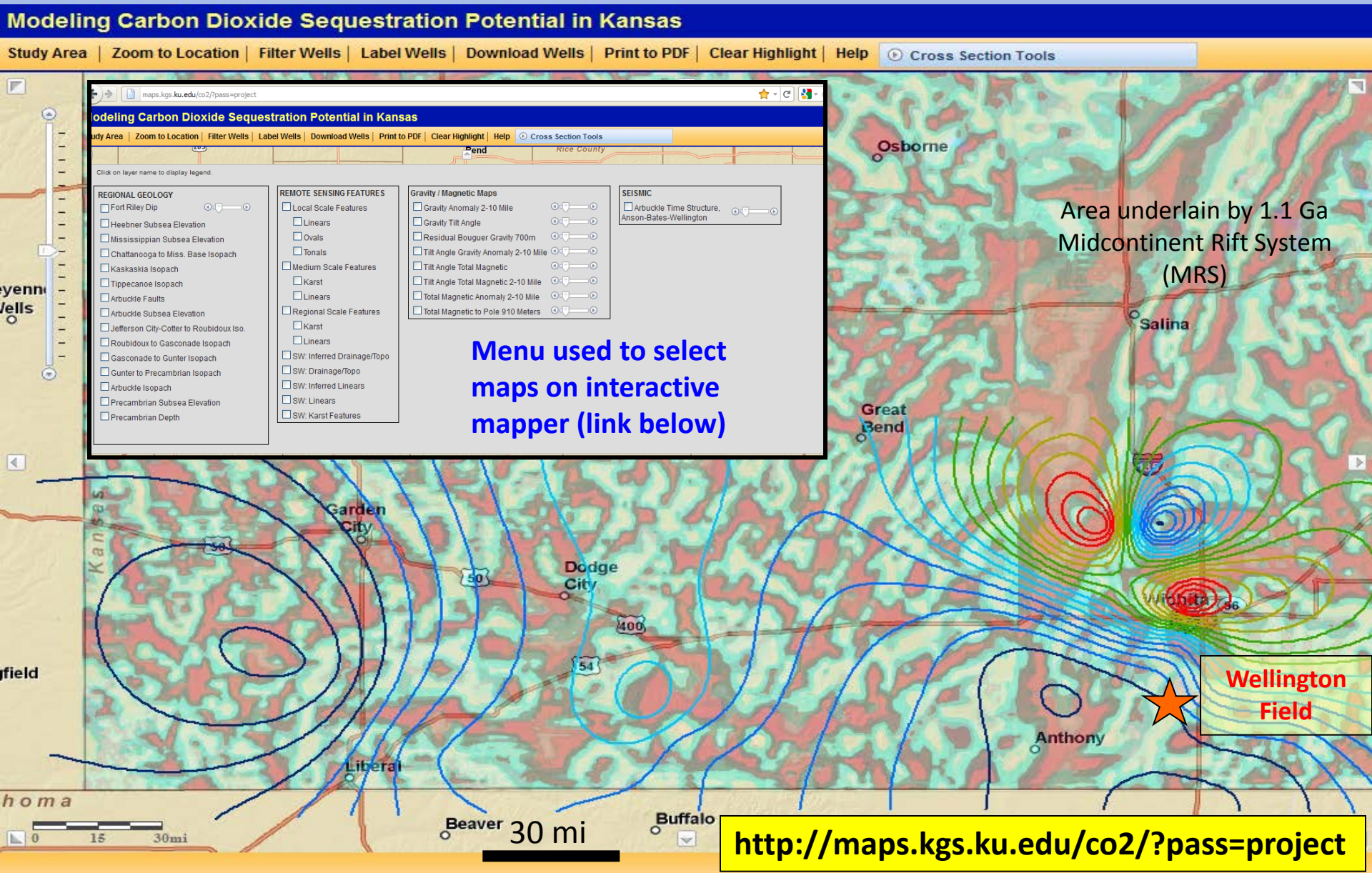
Contours = Elevation on Top of Arbuckle

Wellington Field

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

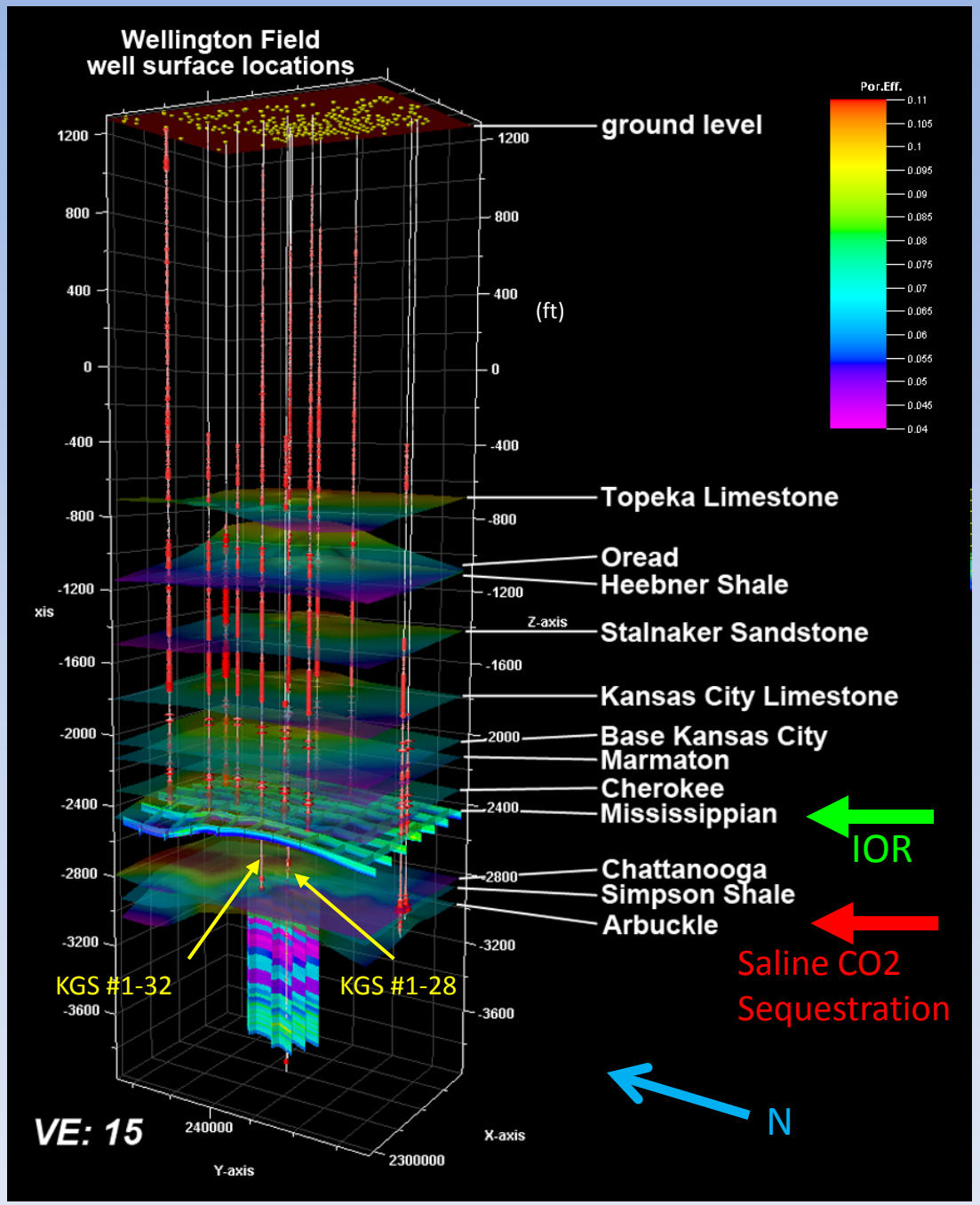
2-10 mile filtered Total Magnetic Field Intensity and Magnetic Tilt Angle overlain by isopach Gasconade to Gunter Sandstone

--> Lower Arbuckle Porosity Zone at Wellington Field



3. Wellington Field

Calibration point for CO2 storage in deep saline Arbuckle Aquifer and CO2-EOR in Mississippian chert/dolomite reservoir



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 70,000 tonnes CO_2 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

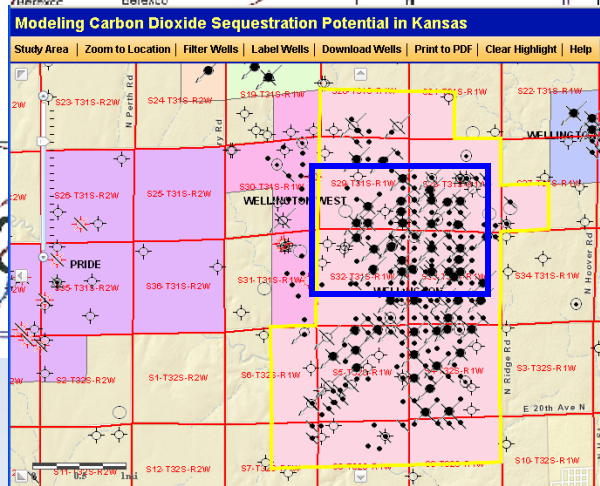
Also, **30,000 tonnes CO_2 into Mississippian reservoir for EOR pilot**

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

KGS
32-1
1600 ft core
Cherokee to basement

KGS
28-1
(CO2 Injection well for Small scale field test)

3000 ft apart

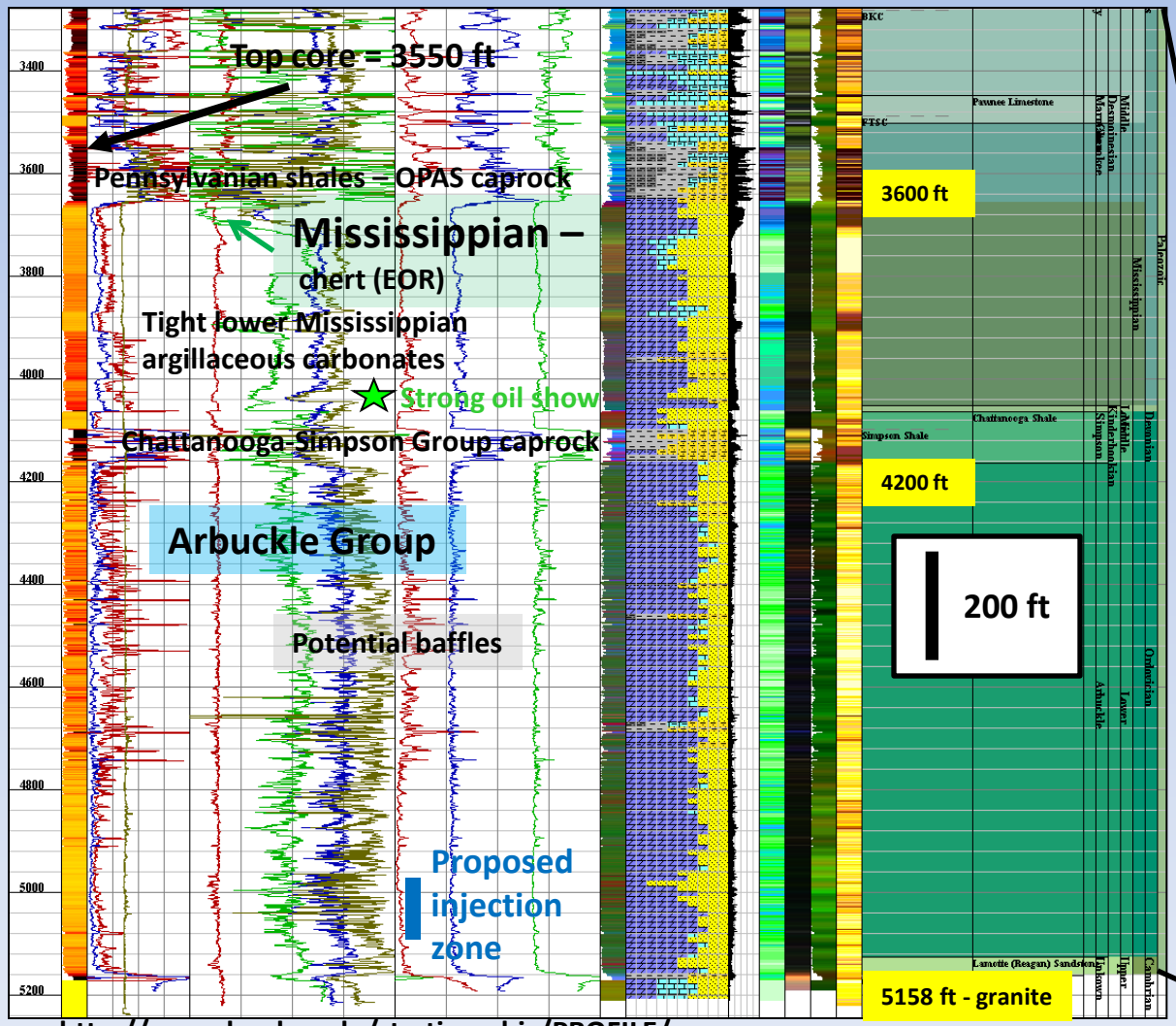


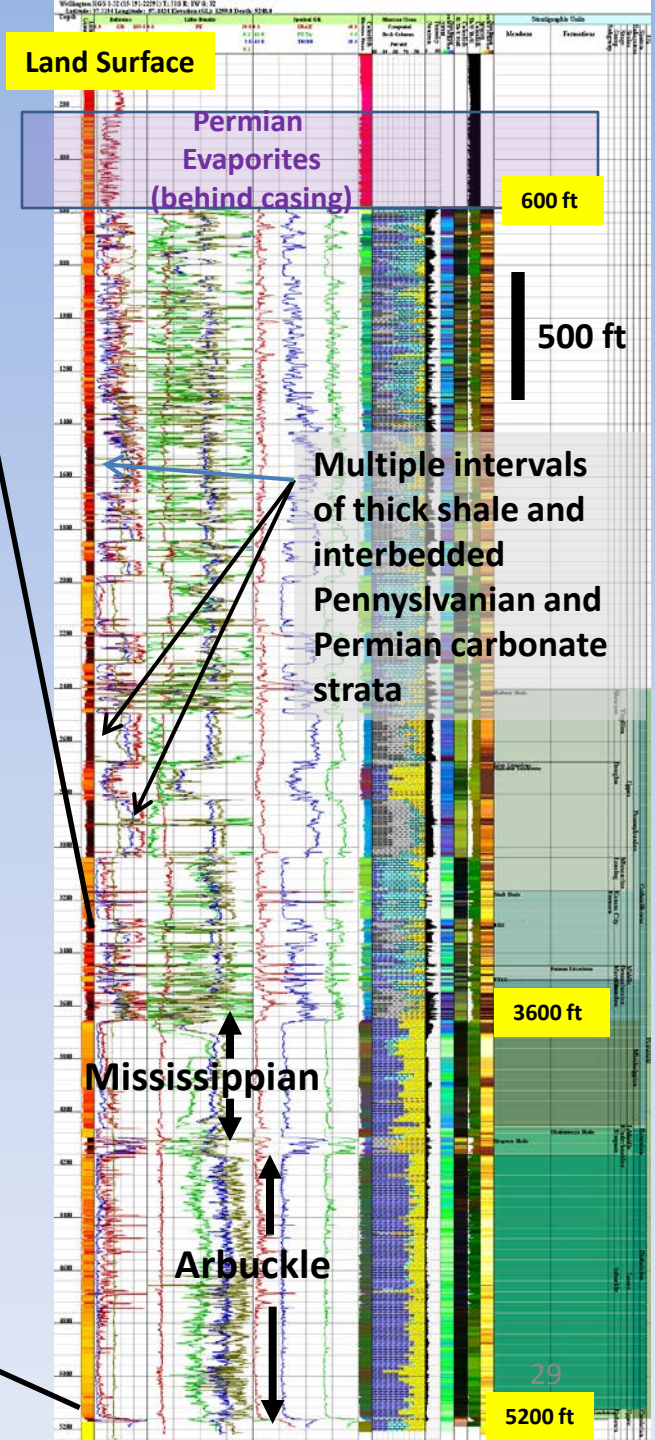
Stratigraphic Column New Basement Test
Berexco Wellington KGS #1-32

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/

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 of multicomponent 3D seismic

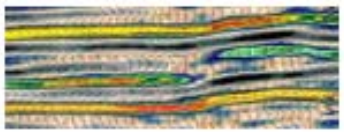
Wellington Field Operator

BEREXCO

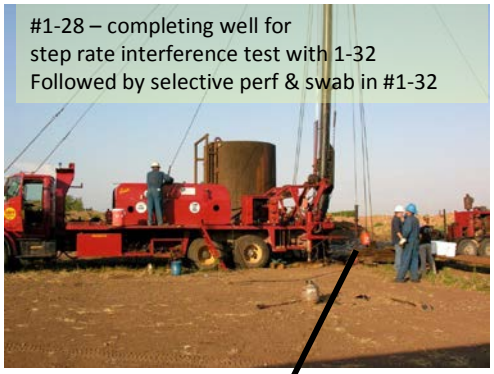
PARAGON GEOPHYSICAL SERVICES, INC

fairfieldnodal

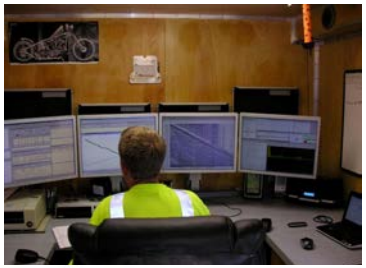
HEDKE-SAENGER GEOSCIENCE, LTD

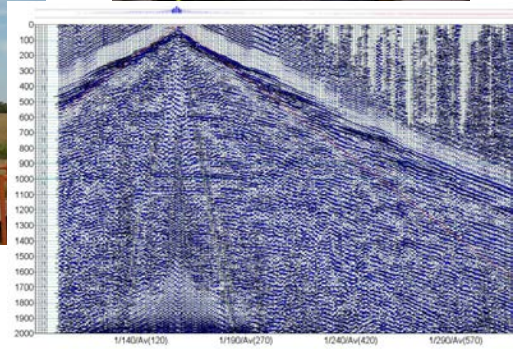


Weekend July 31st @ Wellington



KU THE UNIVERSITY OF KANSAS Department of Geology

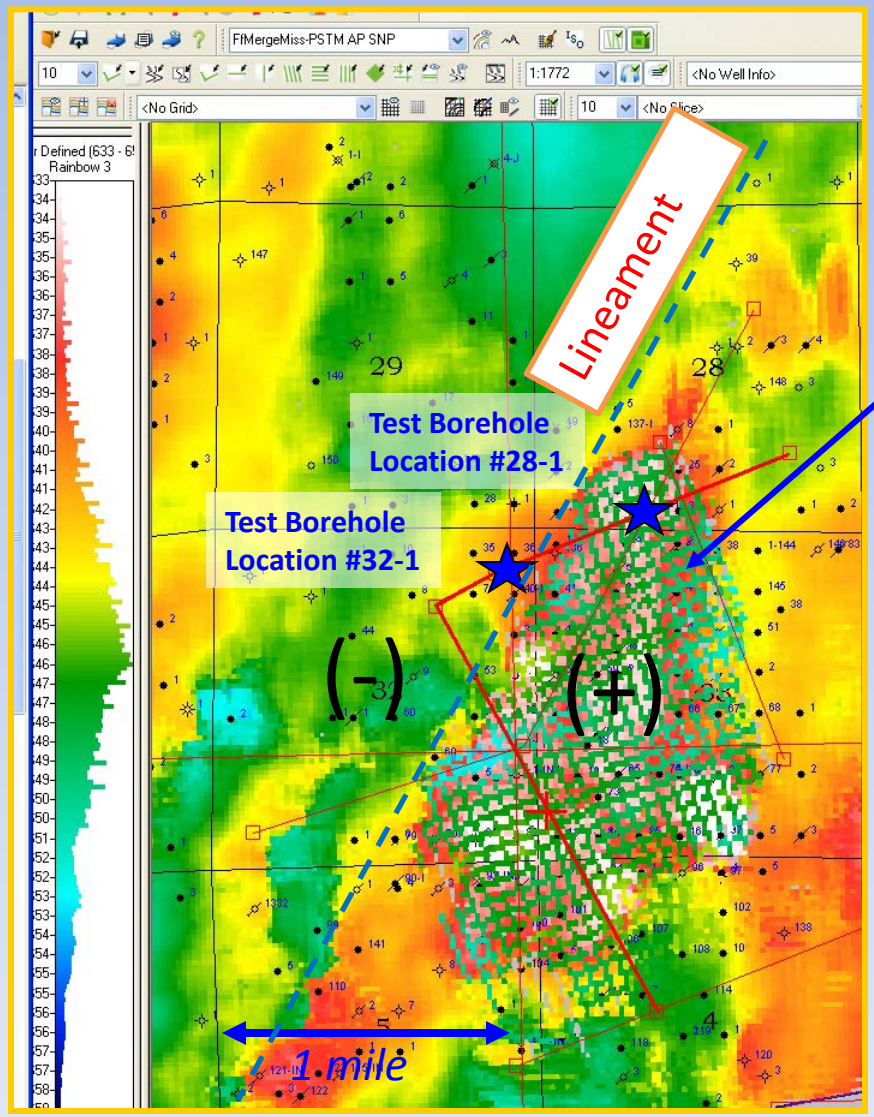




Wellington Field

Initial P-Wave Interpretation of 3D Seismic with Location of Test Boreholes

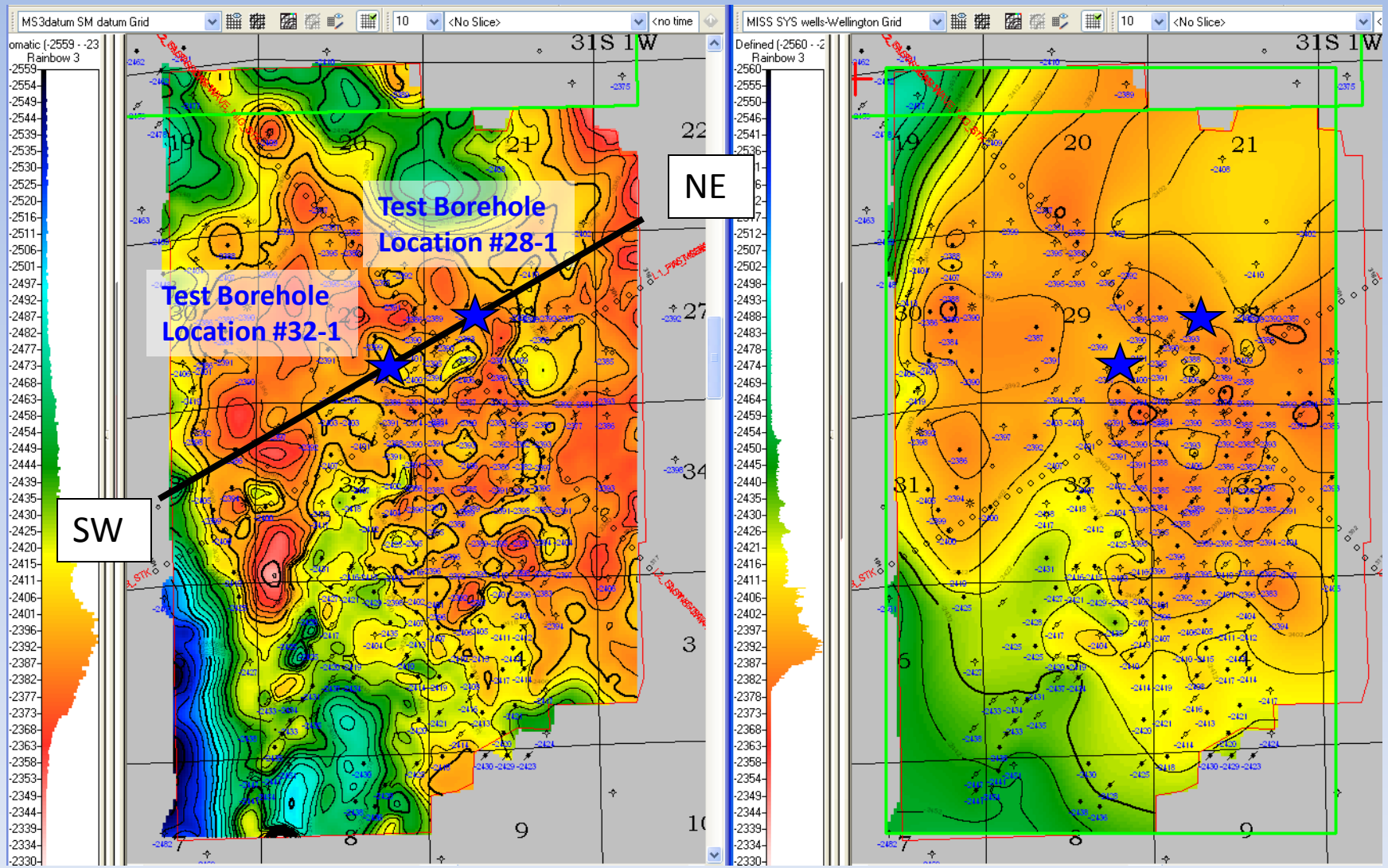
Mississippian time structure



Area of Mississippian dual reflector identifying buildup of uppermost tripolitic chert reservoir (exhumed topography?)

Hedke (2010)

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



Hedke (Feb. 2012)

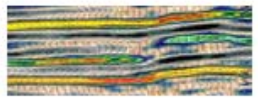
Preview of Converted Wave, Prestack Depth Migrated Multicomponent 3D Seismic Volume in Wellington Field

Coincident w/ Shear Wave Line #1

PARAGON GEOPHYSICAL SERVICES, INC

fairfieldnodal

HEDKE-SAENGER GEOSCIENCE, LTD



Chert/Dolomite Reservoir at Wellington Field is Closely Analogous to Other Mississippian Oil and Gas Fields in Southern Kansas

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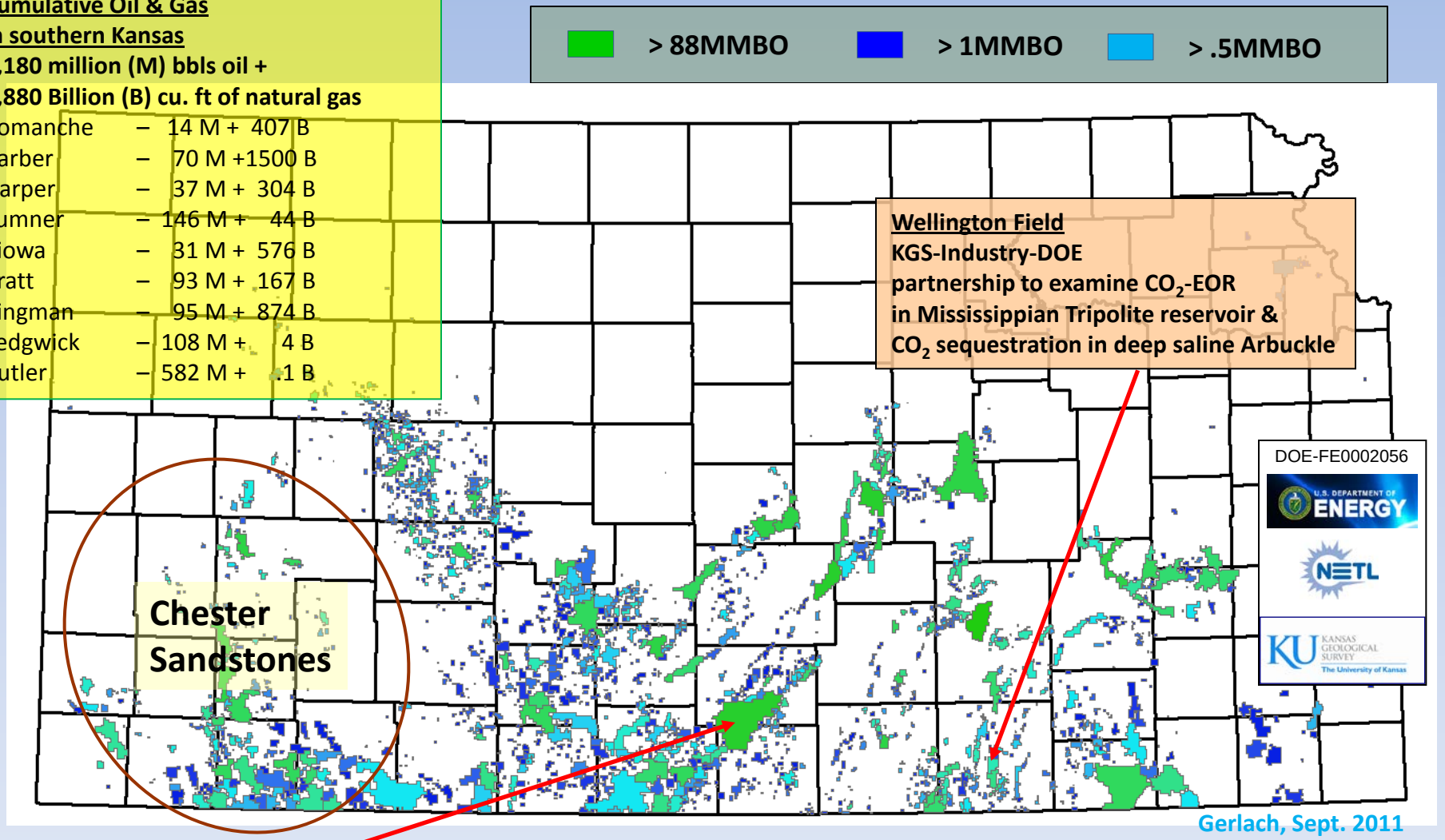

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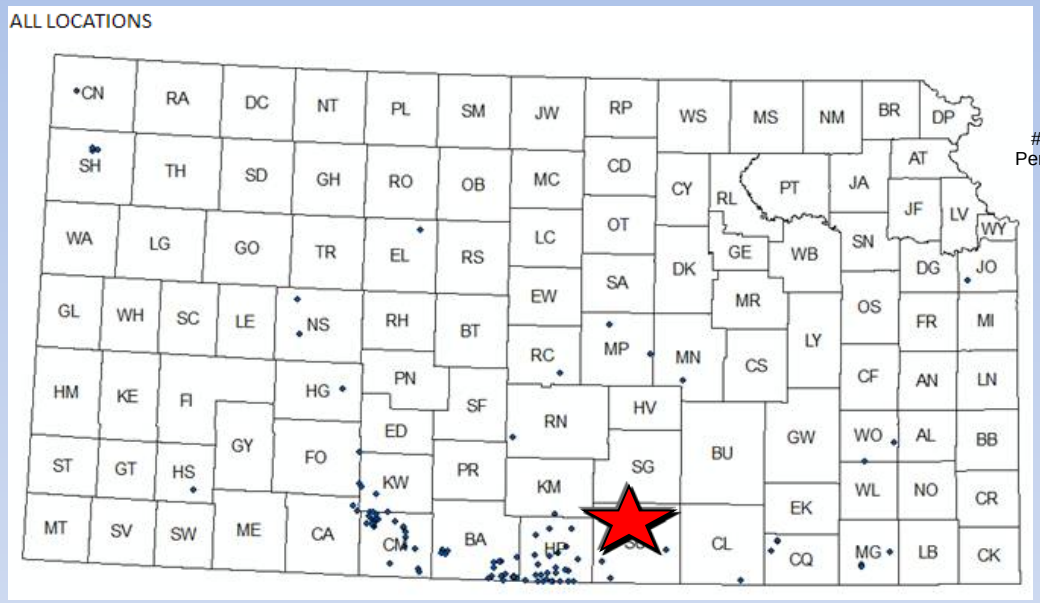
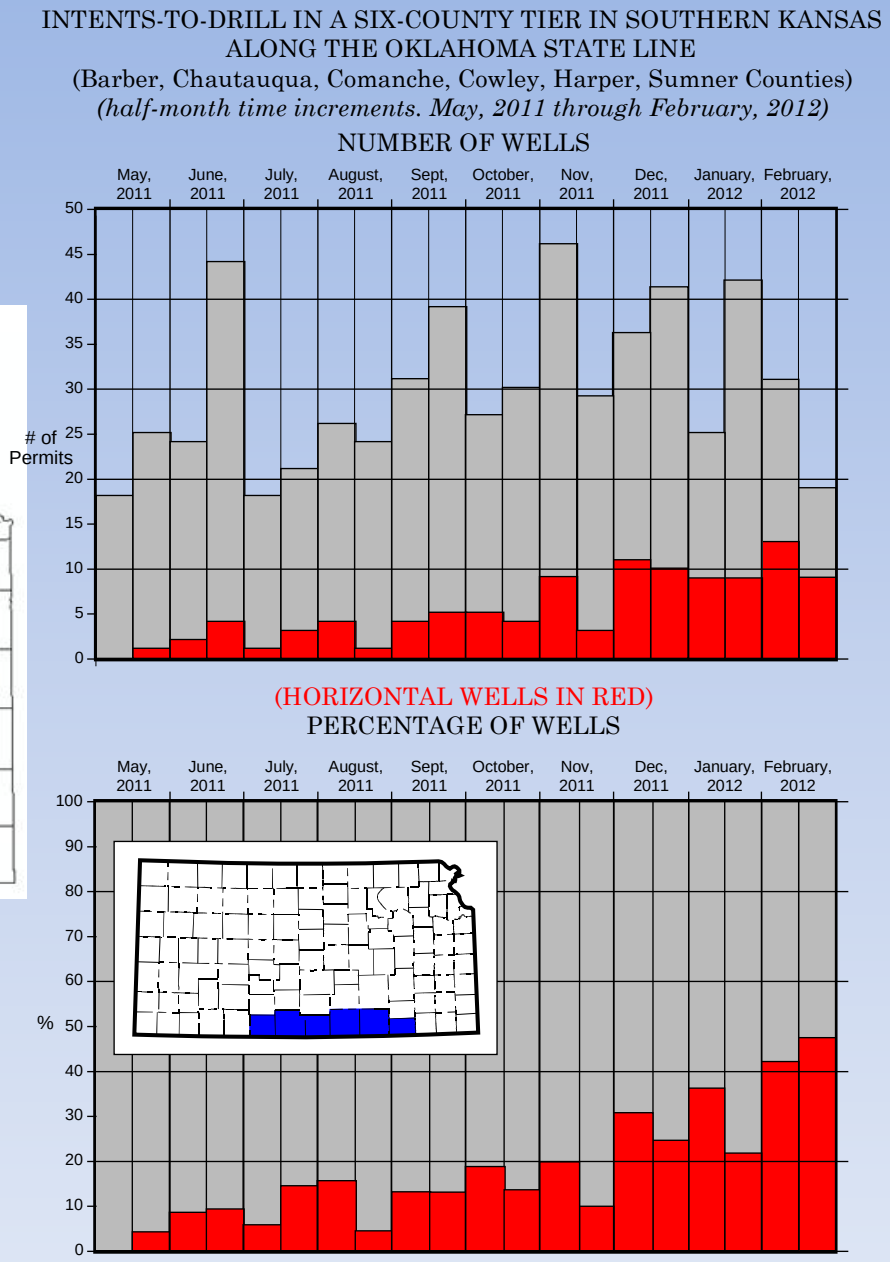
New Horizontal Well Locations





Newell and Gerlach, March 2012

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

West side
Hartner Field
Barber Co.

DOE-FE0002056

SW

NE

Cored Well
Wellington Fld.

KGS
#1-28

KGS
#1-32

Compton Ls.

Viola

Compton Ls.

Compton Ls.

Compton Ls.

Cherokee

Mississippian

Chattanooga

Simpson

Datum: Top Arbuckle Group

Rhomaa-Umaa Colorlith

Gamma Ray
150 API
75 API
0 API
4.3
Umaa
13.8
2.6 Rhomaa 2.87

Dolomite
Quartz
Calcite
Anhydrite
Gypsum
Halite
Coal
Illite
Smectite
Orthoclase
Muscovite
Glauconite

200 ft

Gross isopach of low resistivity chert

Watney, Guy, Byrnes (2001)

Cross section Index

Pratt Anticline

B

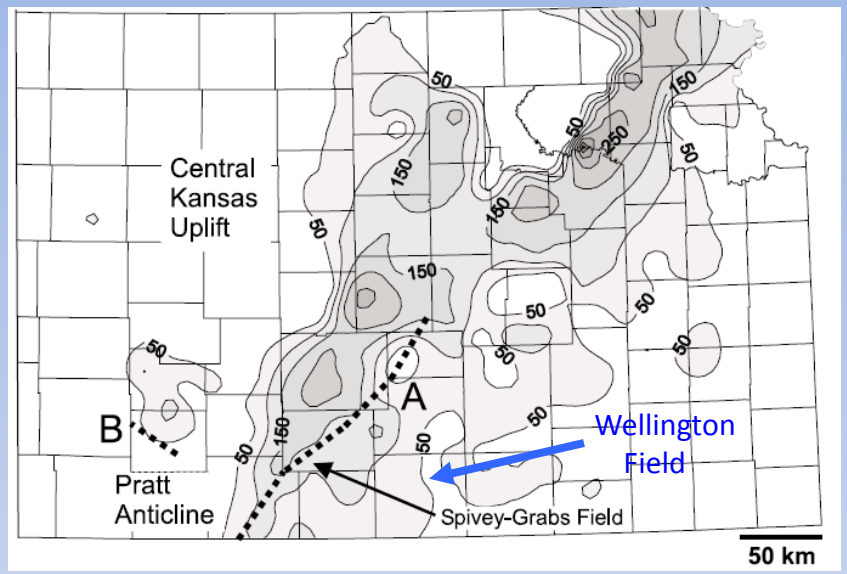
A

NE

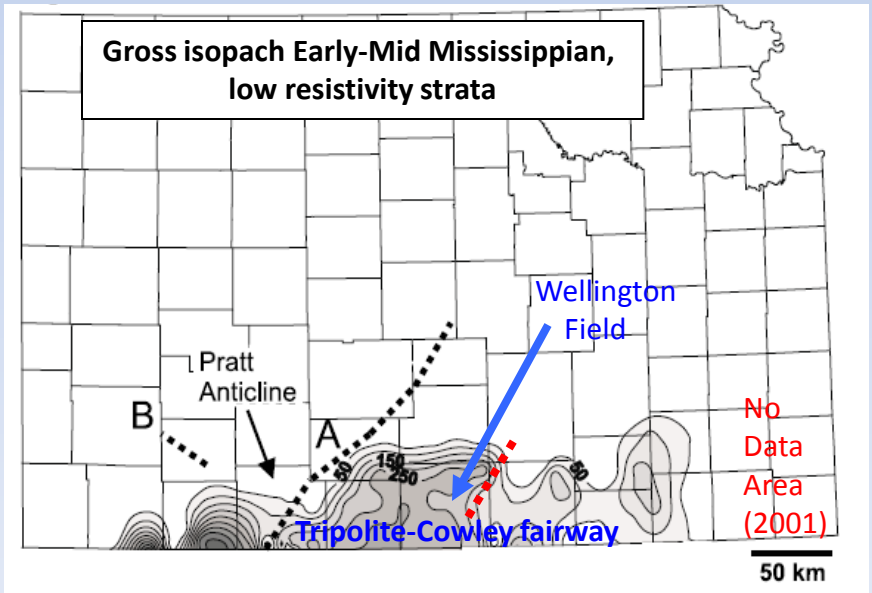
SW

50 km

Gros Isopach Late Devonian- Early Mississippian Chattanooga Shale & Kinderhook Shale

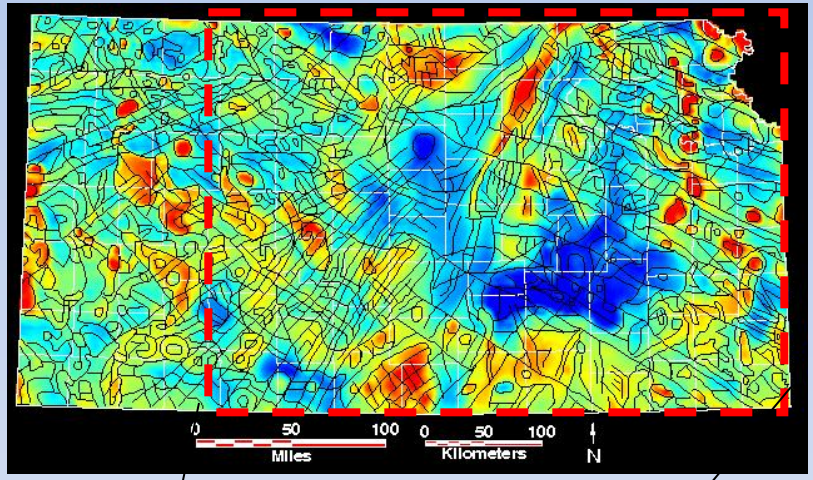


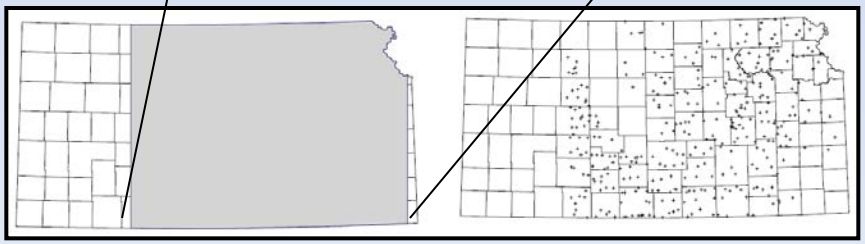
Watney, Guy, Byrnes (2001)



- **Late Devonian to Early Mississippian, NW-trending sag basin overlying Midcontinent Rift System**
- **During late Kinderhookian - abrupt change to shelf margin in southern Kansas, bordering early Anadarko and Arkoma basins**
- **Tripolitic chert and siliceous dolo-pack/grainstone cycles developed along shelf margin**

Magnetics with regional lineaments – Kruger (1997)



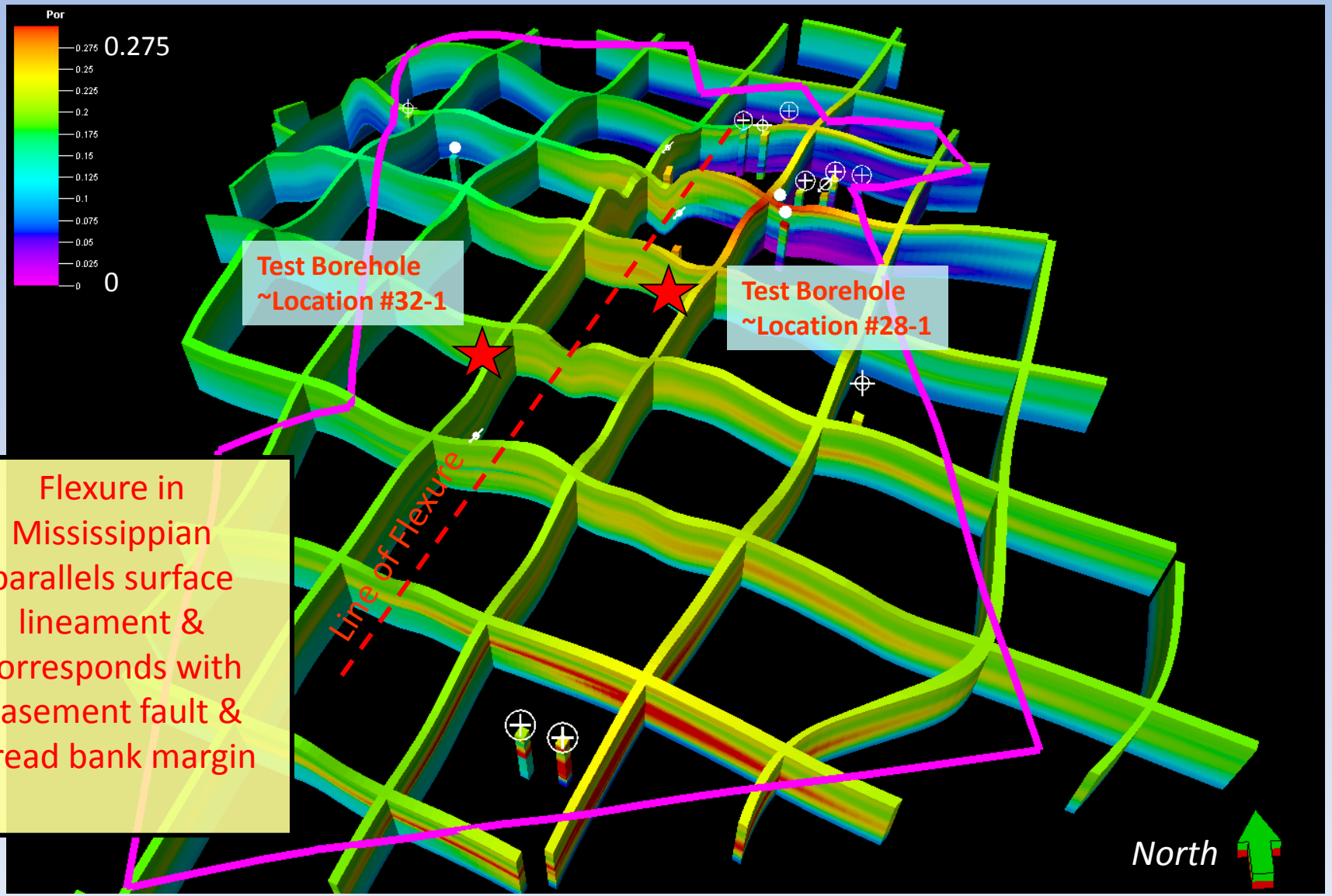


Wellington Field

Porosity Fence Diagram

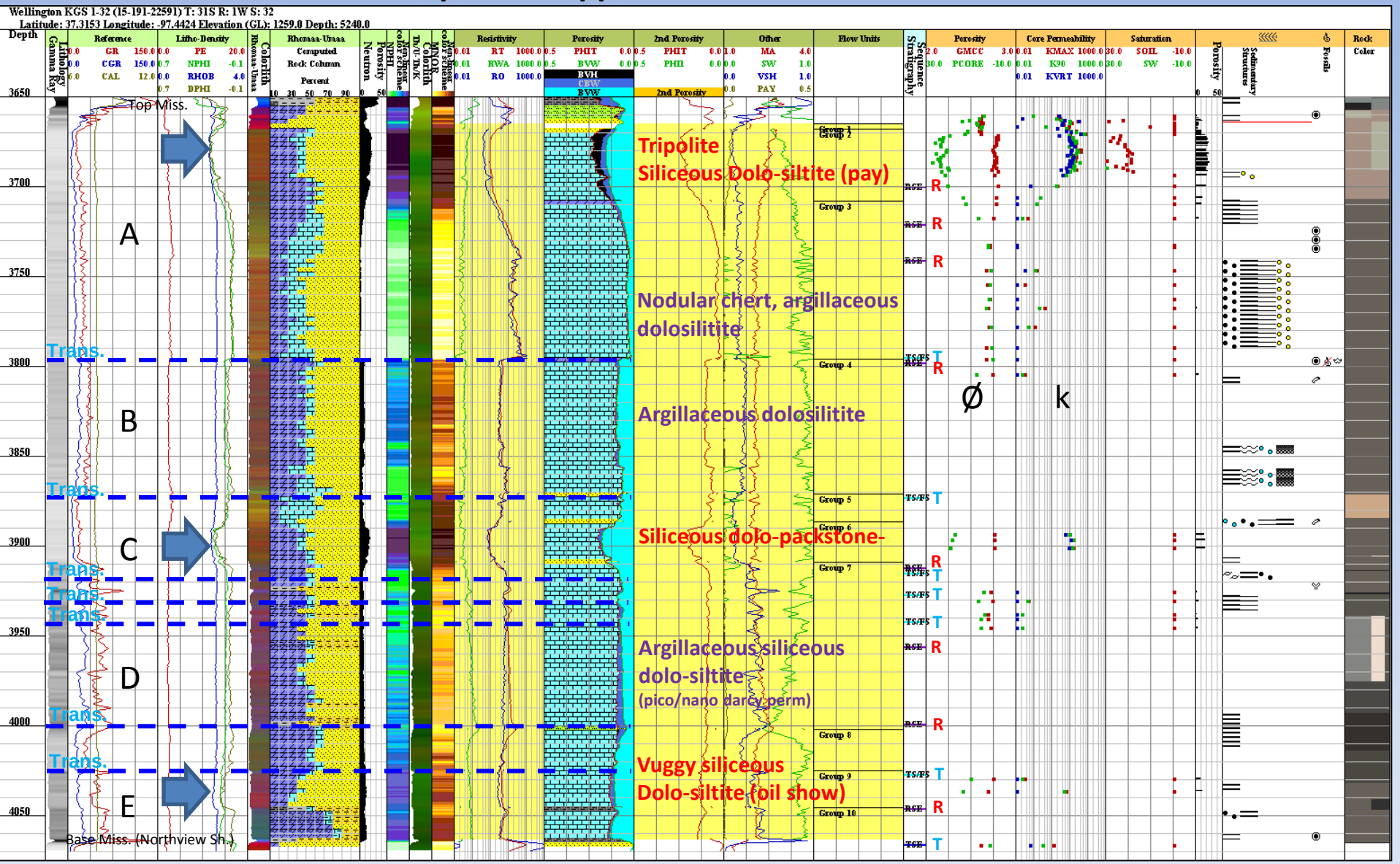
Mississippian Tripolitic Chert Oil Reservoir

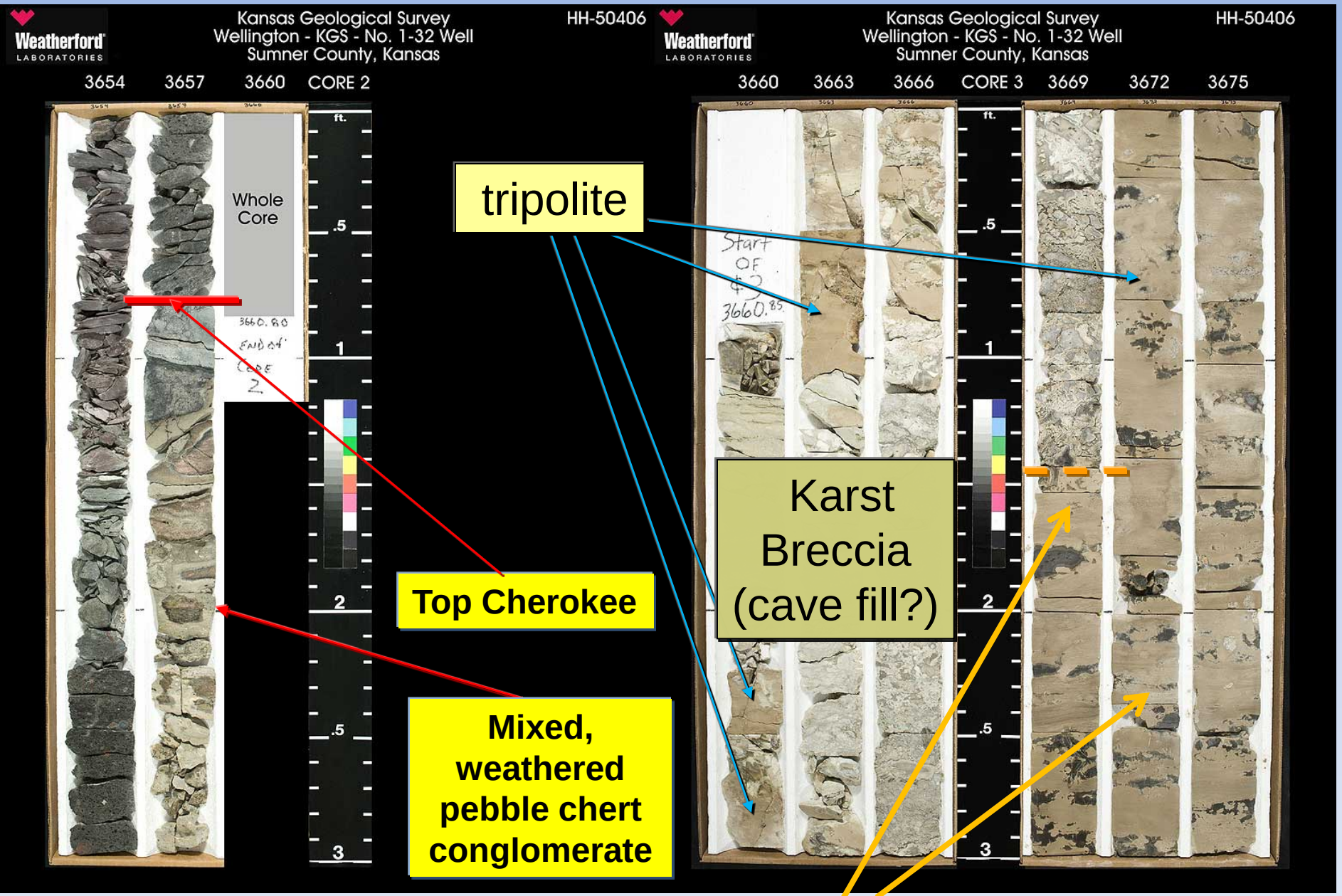
Porosity

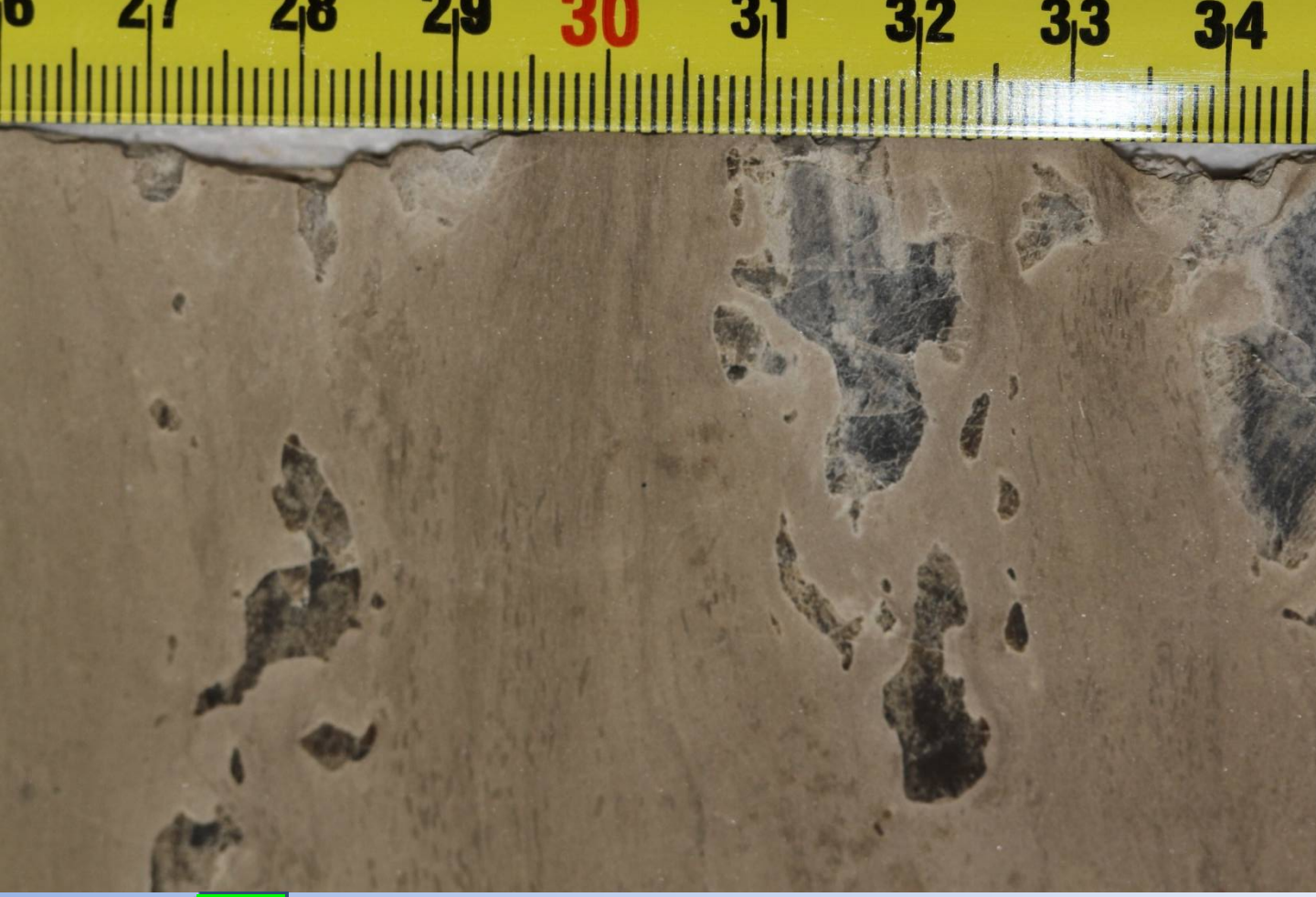


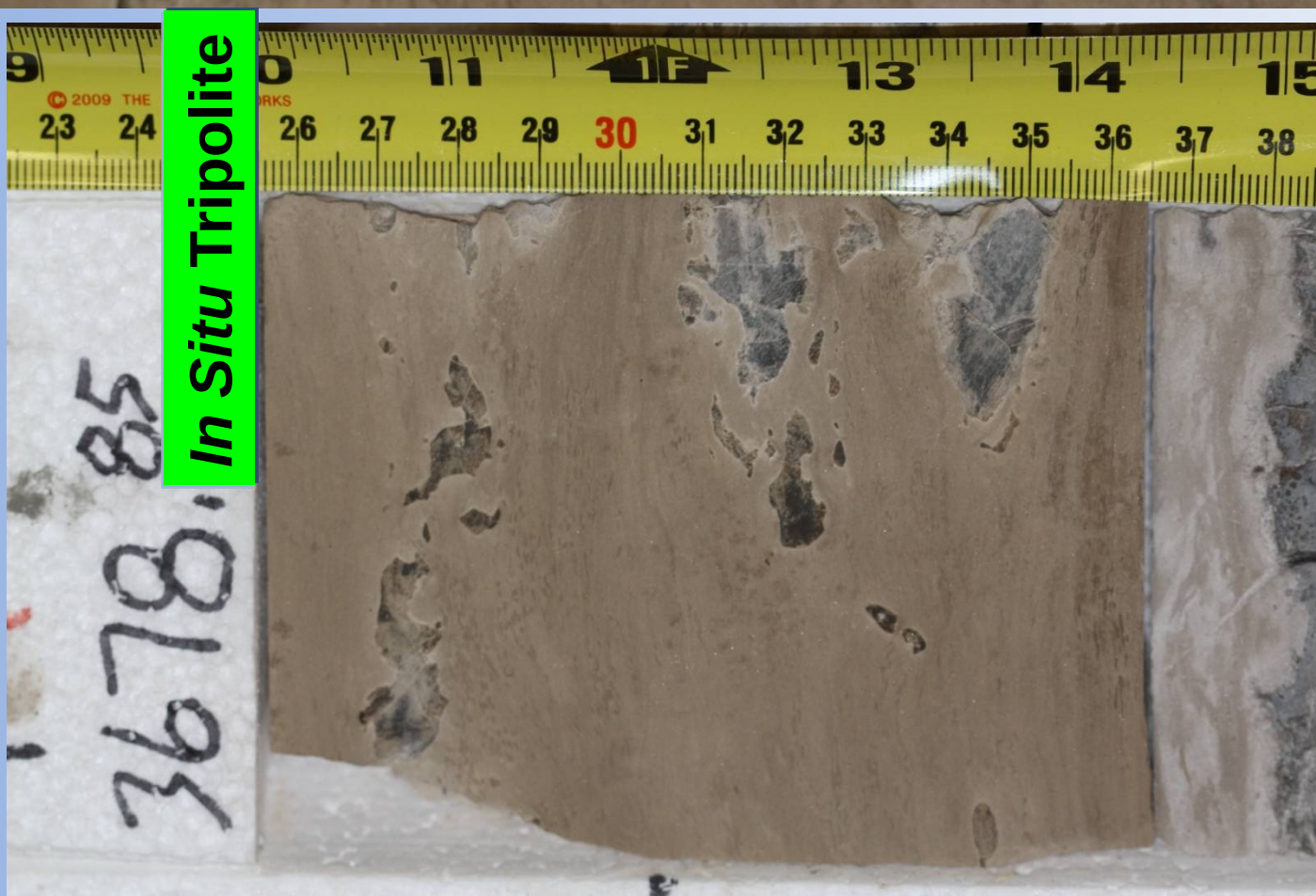
Flexure in Mississippian parallels surface lineament & corresponds with basement fault & Oread bank margin

Cored Well, KGS #1-32
Top Mississippian to Kinderhook Shale



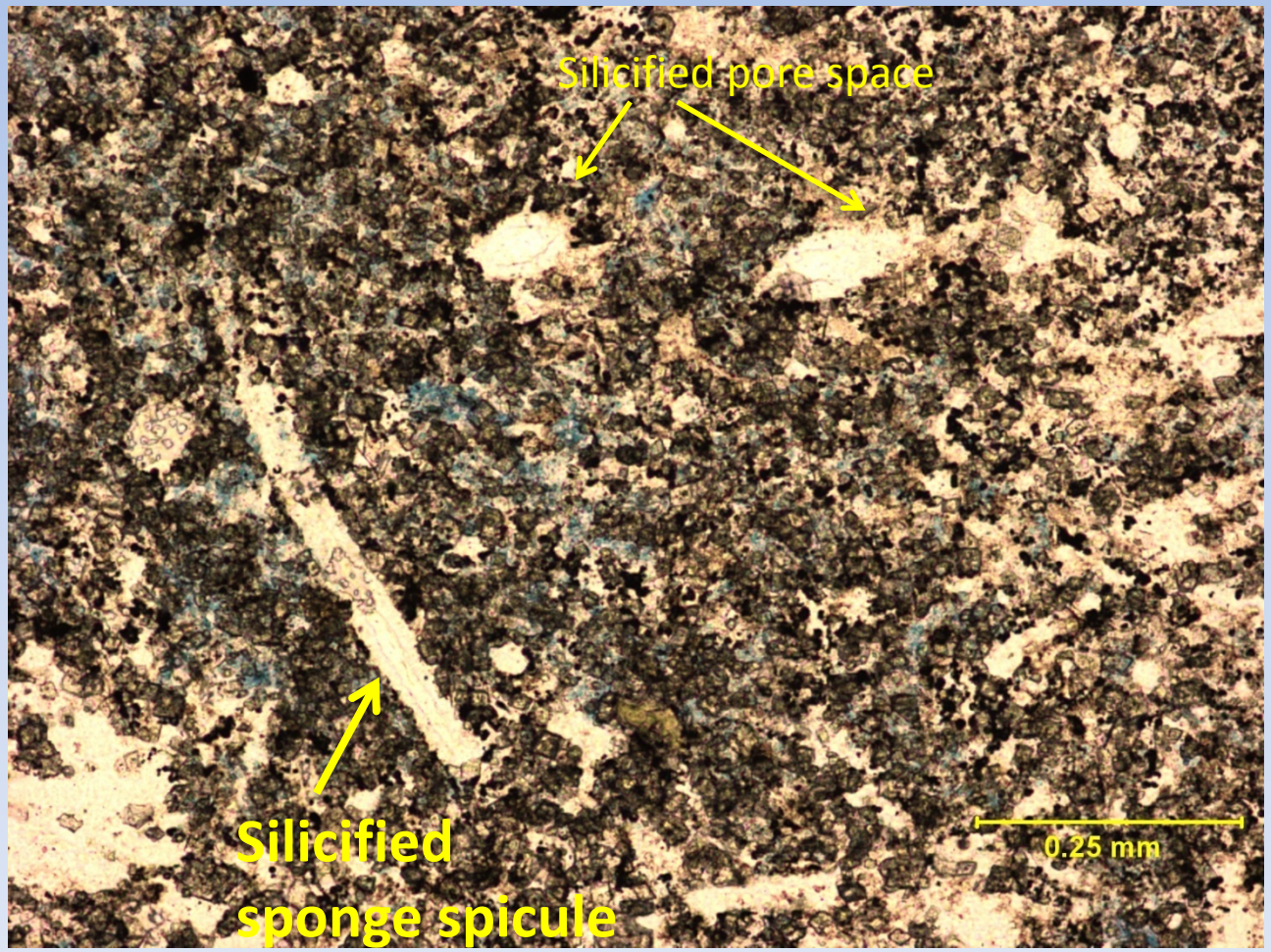

Weatherford LABORATORIES
Kansas Geological Survey
Wellington - KGS - No. 1-32 Well
Sumner County, Kansas
HH-50406
3654
3657
3660
CORE 2
Whole Core
ft.
Weatherford LABORATORIES
Kansas Geological Survey
Wellington - KGS - No. 1-32 Well
Sumner County, Kansas
HH-50406
3660
3663
3666
CORE 3
3669
3672
3675
ft.
tripolite
Karst Breccia (cave fill?)
Top Cherokee
Mixed, weathered pebble chert conglomerate
In Situ Tripolite




In Situ Tripolite
3678.85

Mississippian Topmost Pay Zone Mineralogy
Berexco Wellington KGS #1-32

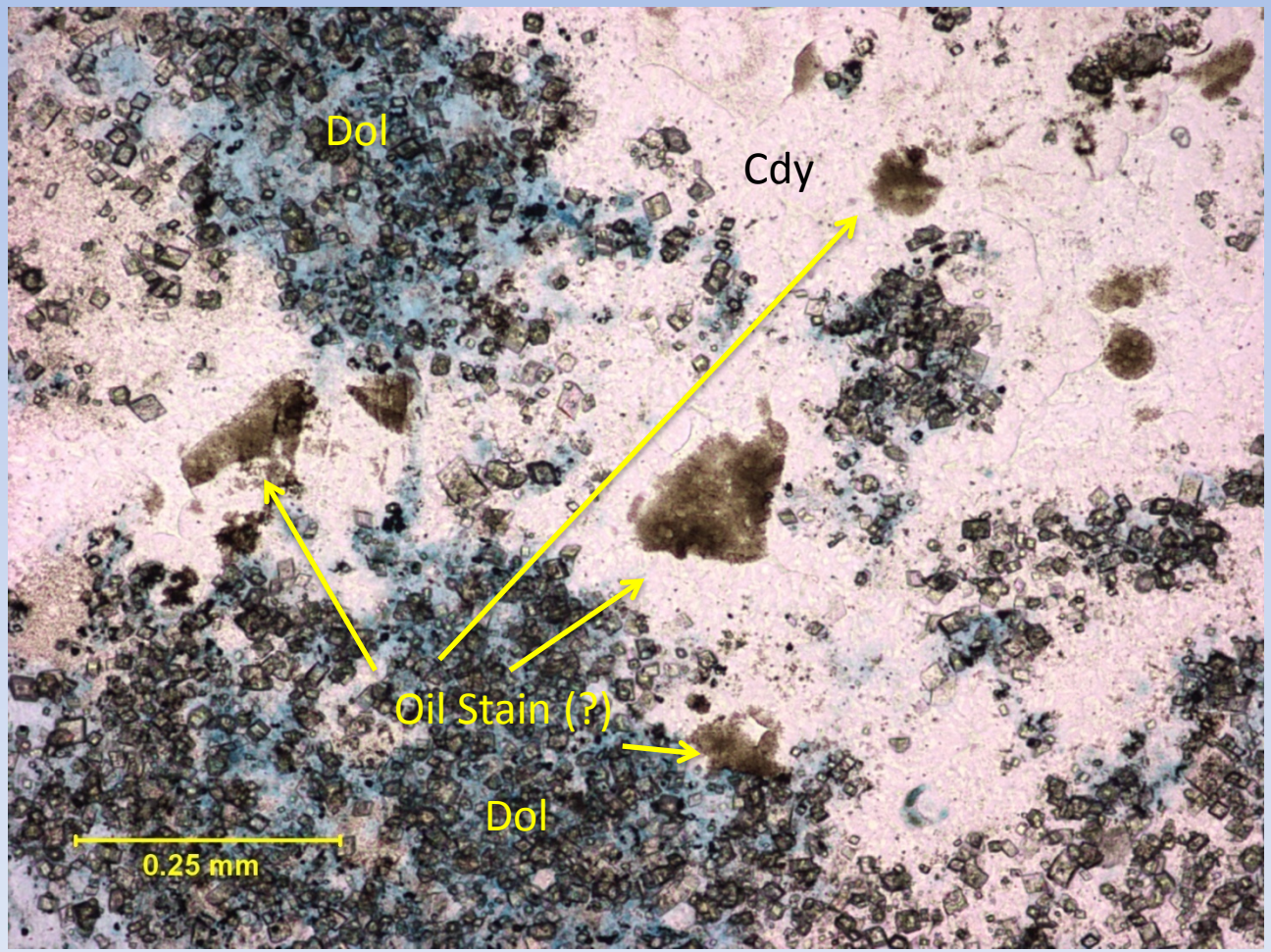
3670.6’



- Plain light (10x zoom)
- Fine grained dolomite with silica cement
- Silicified sponge spicule (?)
- Pore spaces filled with precipitated silica (chert)

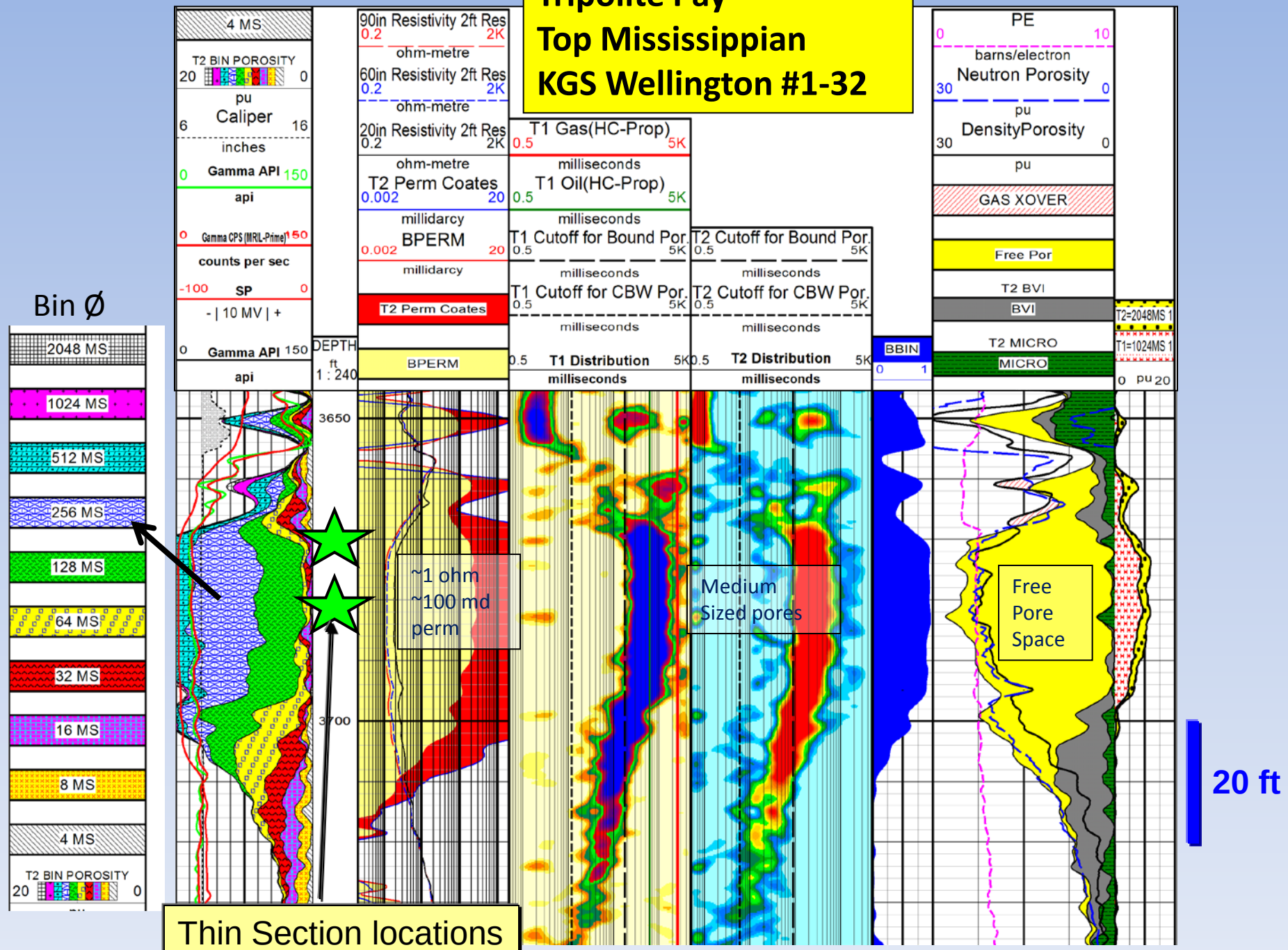
Mississippian Topmost Pay Zone Mineralogy

3681.95’

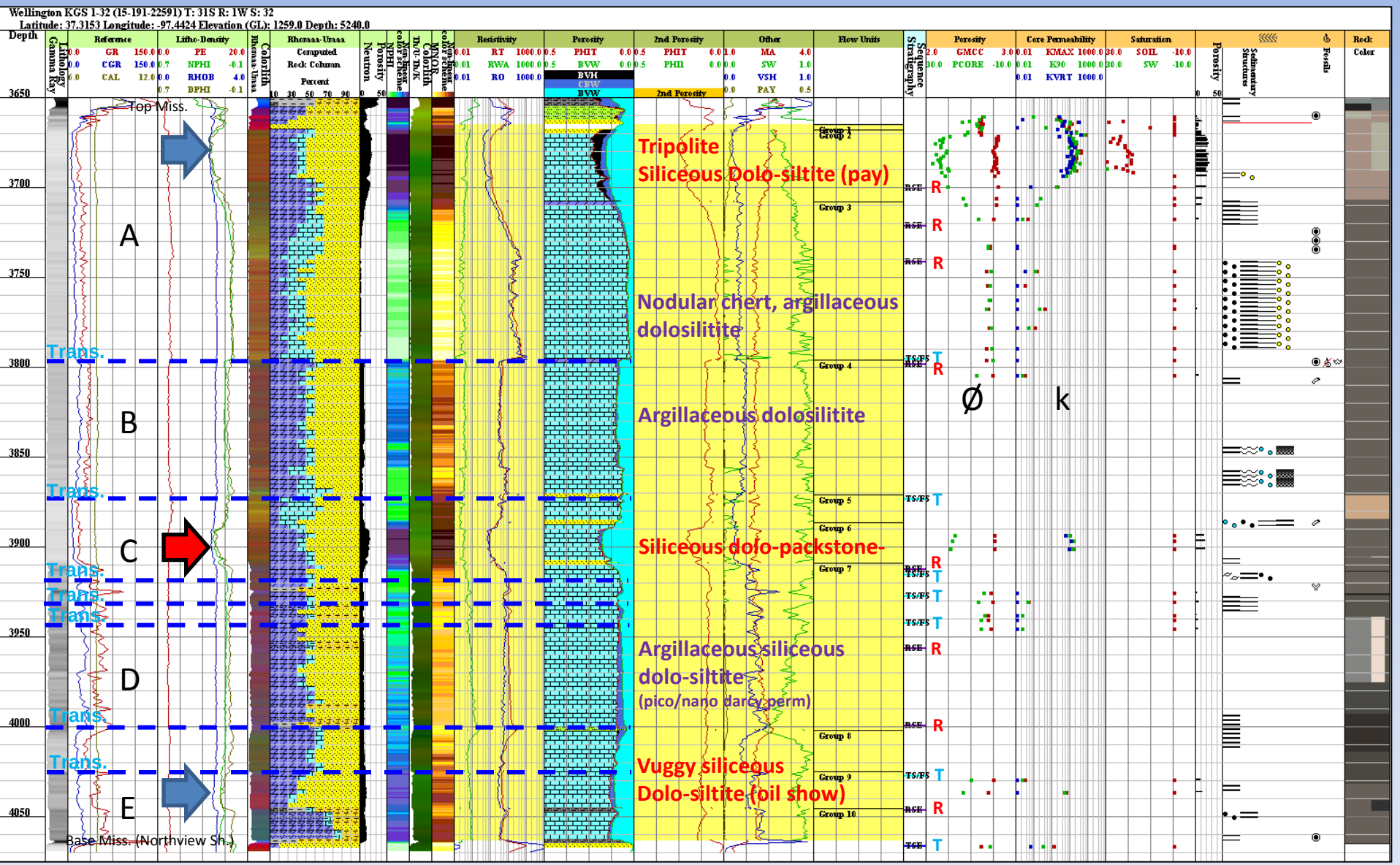


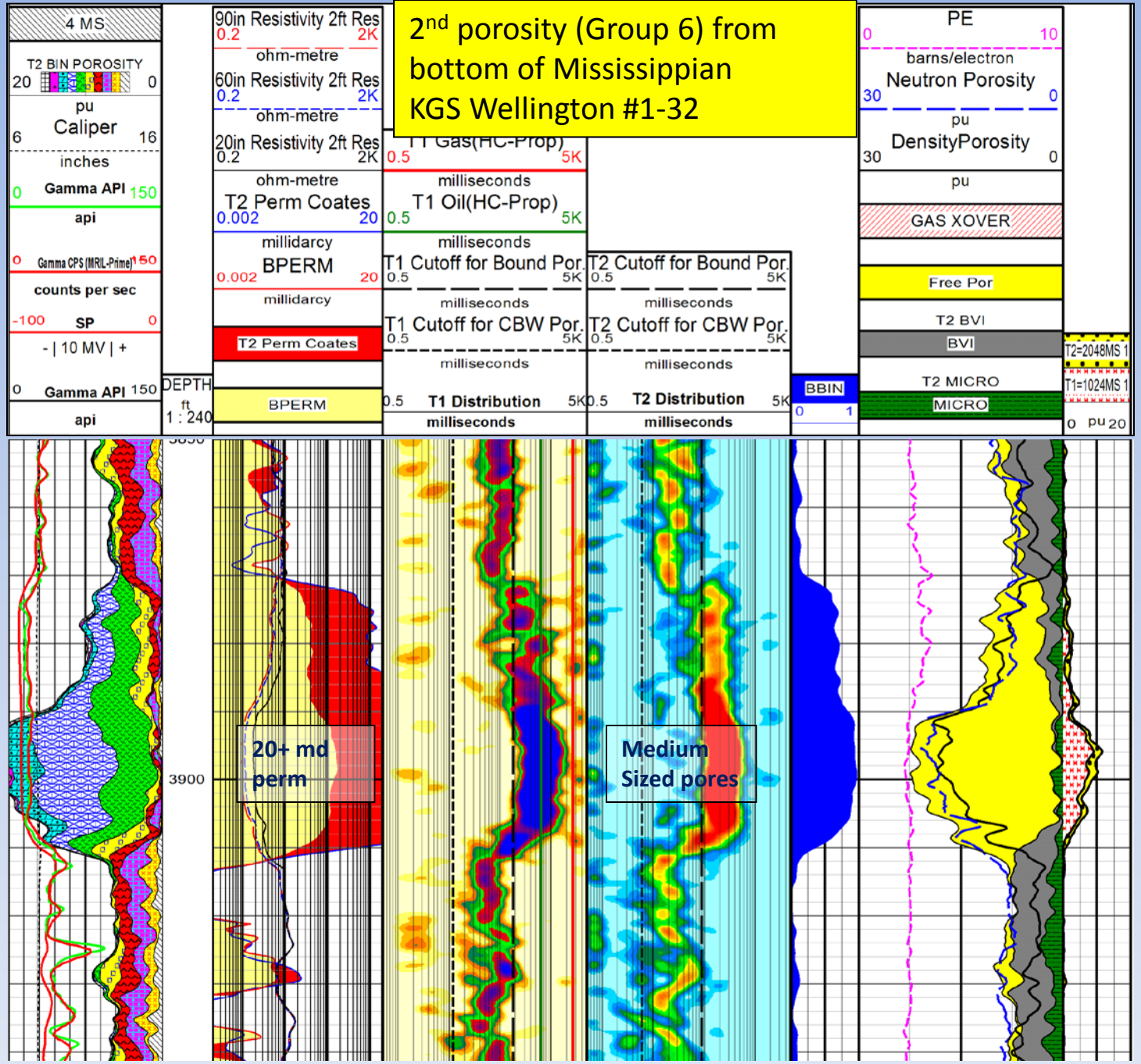
- Plain light (10x zoom)
- Close up of possible oil stain on chert
- Fine grained dolomite in porous zone

Cdy = Chalcedony;
Dol = Dolomite

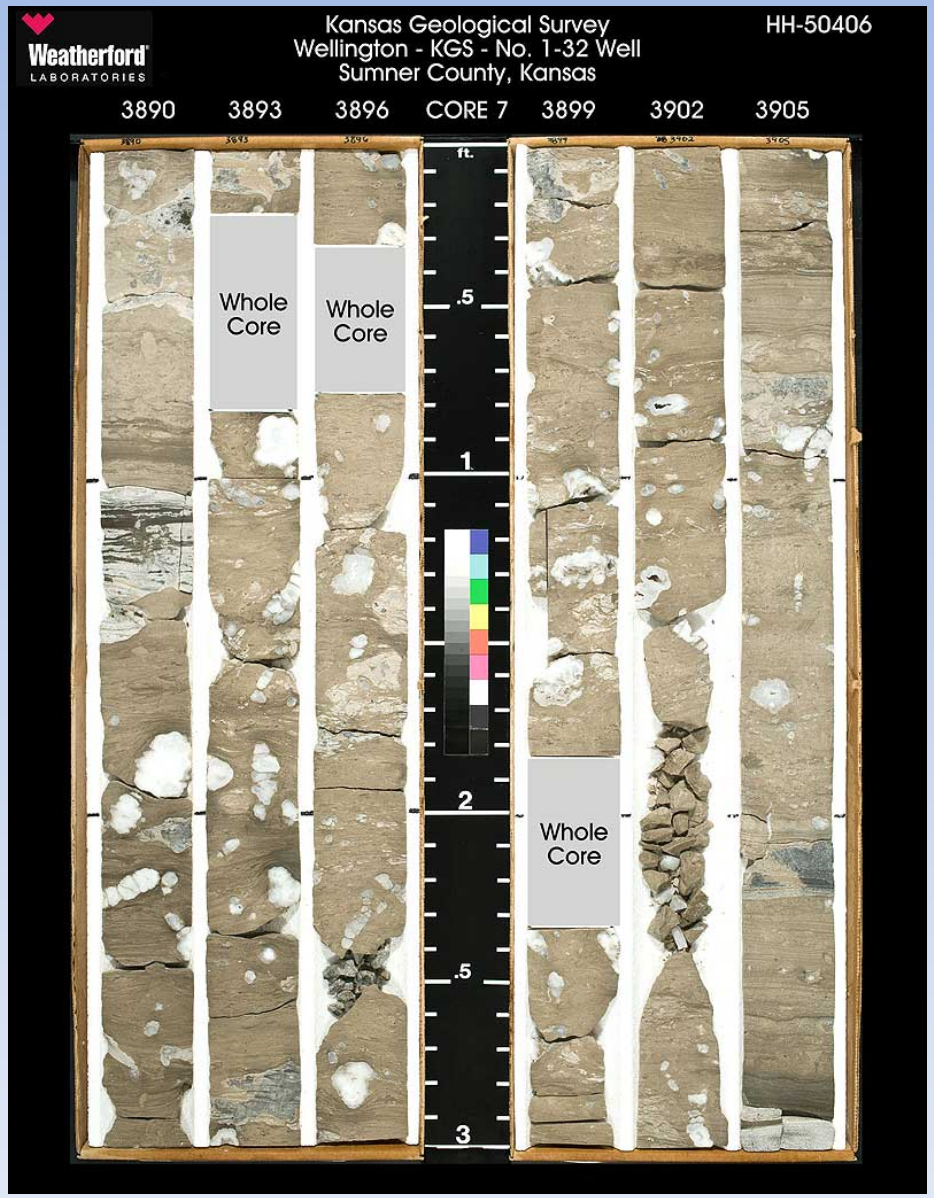

Tripolite Pay
Top Mississippian
KGS Wellington #1-32
4 MS
T2 BIN POROSITY
20 0
pu
Caliper
6 16
inches
0 Gamma API 150
api
0 Gamma CPS (MRIL-Prime) 150
counts per sec
-100 SP 0
- | 10 MV | +
0 Gamma API 150
api
90in Resistivity 2ft Res
0.2 2K
ohm-metre
60in Resistivity 2ft Res
0.2 2K
ohm-metre
20in Resistivity 2ft Res
0.2 2K
ohm-metre
T2 Perm Coates
0.002 20
millidarcy
BPERM
0.002 20
millidarcy
T2 Perm Coates
BPERM
T1 Gas(HC-Prop)
0.5 5K
milliseconds
T1 Oil(HC-Prop)
0.5 5K
milliseconds
T1 Cutoff for Bound Por.
0.5 5K
milliseconds
T1 Cutoff for CBW Por.
0.5 5K
milliseconds
T1 Distribution
0.5 5K
milliseconds
T2 Cutoff for Bound Por.
0.5 5K
milliseconds
T2 Cutoff for CBW Por.
0.5 5K
milliseconds
T2 Distribution
0.5 5K
milliseconds
PE
0 10
barns/electron
Neutron Porosity
30 0
pu
DensityPorosity
30 0
pu
GAS XOVER
Free Por
T2 BVI
BVI
T2 MICRO
MICRO
T2=2048MS 1
T1=1024MS 1
0 pu 20
DEPTH
ft
1 : 240
3650
3700
BBIN
0 1
Bin Ø
2048 MS
1024 MS
512 MS
256 MS
128 MS
64 MS
32 MS
16 MS
8 MS
4 MS
T2 BIN POROSITY
20 0
~1 ohm
~100 md
perm
Medium
Sized pores
Free
Pore
Space
20 ft
Thin Section locations

Cored Well, KGS #1-32
Top Mississippian to Kinderhook Shale

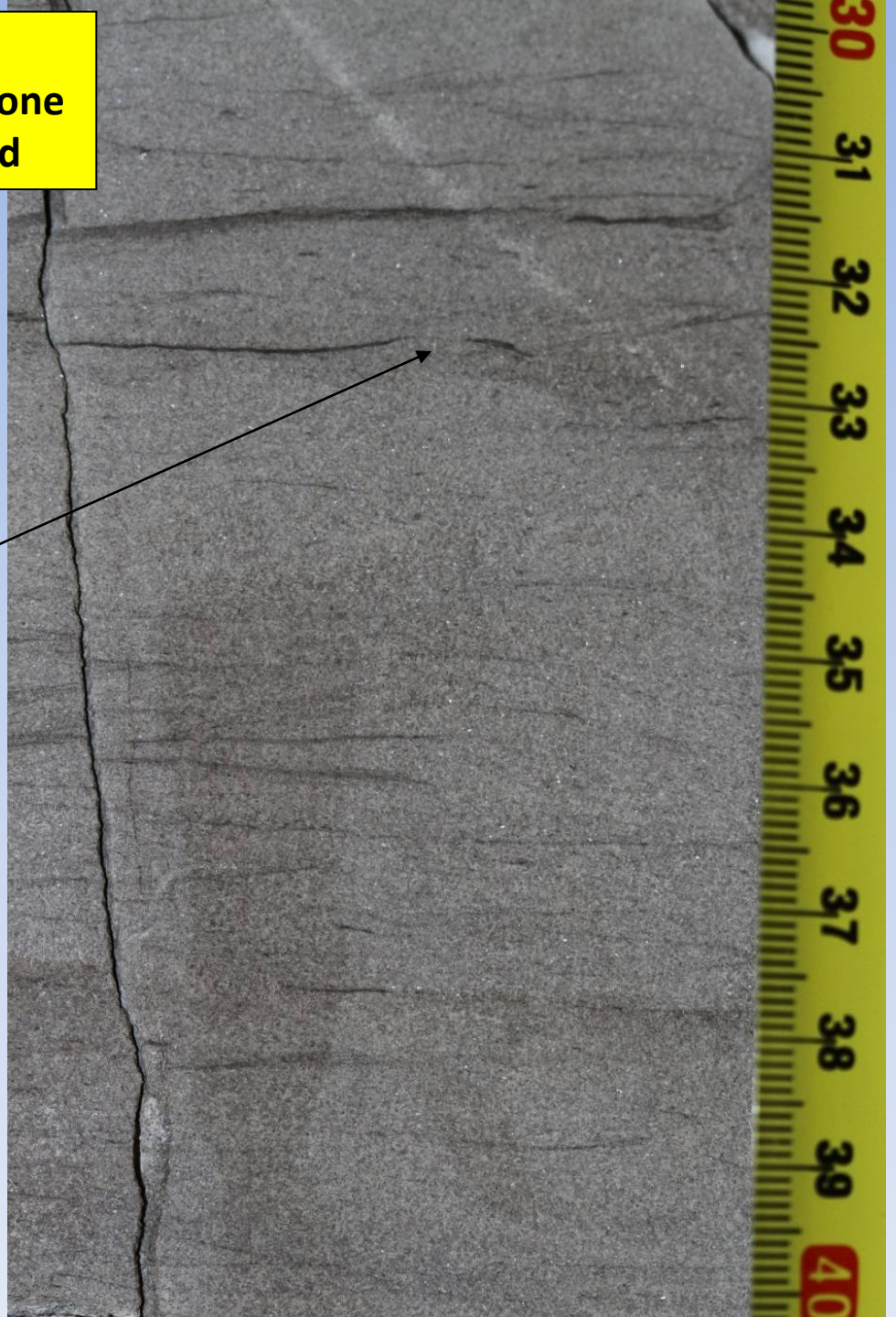



2nd porosity (Group 6) from bottom of Mississippian
KGS Wellington #1-32
4 MS
T2 BIN POROSITY
20
0
pu
Caliper
6
16
inches
0
Gamma API
150
api
0
Gamma CPS (MRIL-Prime)
150
counts per sec
-100
SP
0
- | 10 MV | +
0
Gamma API
150
api
DEPTH
ft
1 : 240
90in Resistivity 2ft Res
0.2
2K
ohm-metre
60in Resistivity 2ft Res
0.2
2K
ohm-metre
20in Resistivity 2ft Res
0.2
2K
ohm-metre
T2 Perm Coates
0.002
20
millidarcy
BPERM
0.002
20
millidarcy
T2 Perm Coates
BPERM
T1 Gas(HC-Prop)
0.5
5K
milliseconds
T1 Oil(HC-Prop)
0.5
5K
milliseconds
T1 Cutoff for Bound Por.
0.5
5K
milliseconds
T1 Cutoff for CBW Por.
0.5
5K
milliseconds
T1 Distribution
0.5
5K
milliseconds
T2 Cutoff for Bound Por.
0.5
5K
milliseconds
T2 Cutoff for CBW Por.
0.5
5K
milliseconds
T2 Distribution
0.5
5K
milliseconds
BBIN
0
1
PE
0
10
barns/electron
Neutron Porosity
30
0
pu
DensityPorosity
30
0
pu
GAS XOVER
Free Por
T2 BVI
BVI
T2 MICRO
MICRO
T2=2048MS 1
T1=1024MS 1
0
pu
20
3900
20+ md perm
Medium Sized pores
20 ft

Middle calc- & dolo-siltite and dolo-packstone

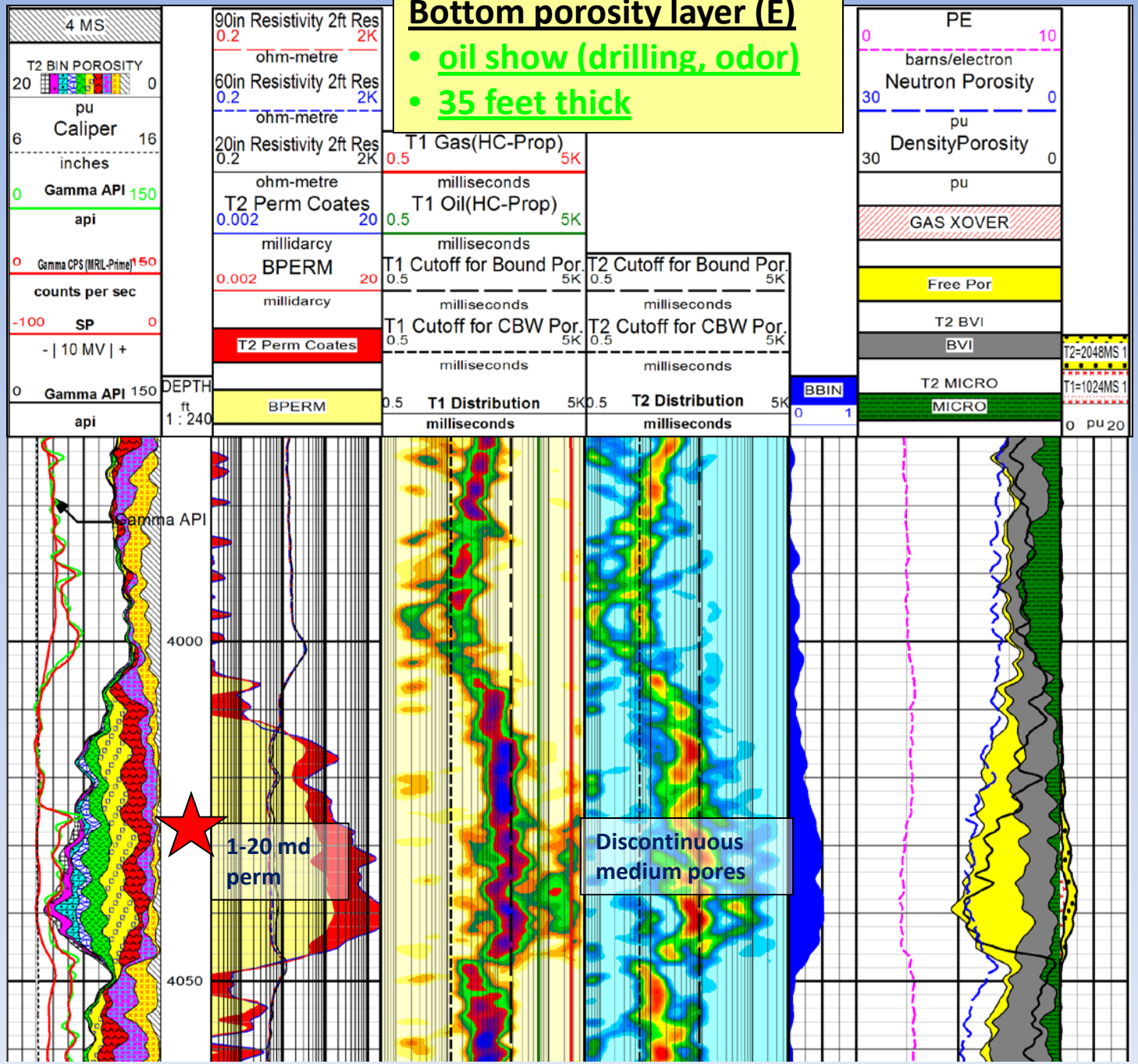


3877 ft
Fine to medium grained siliceous calc-packstone with elongate siliceous pelloids, wavy bedded

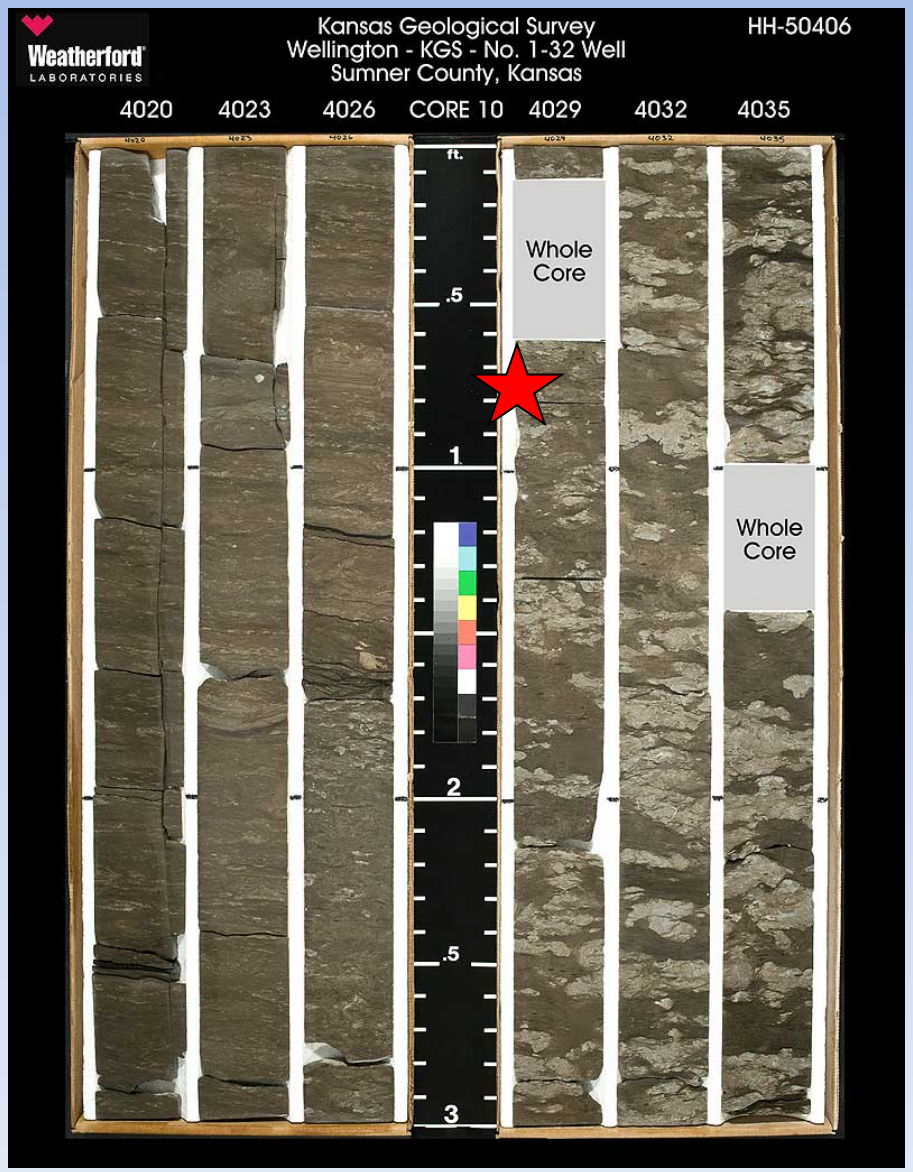


Bottom porosity layer (E)

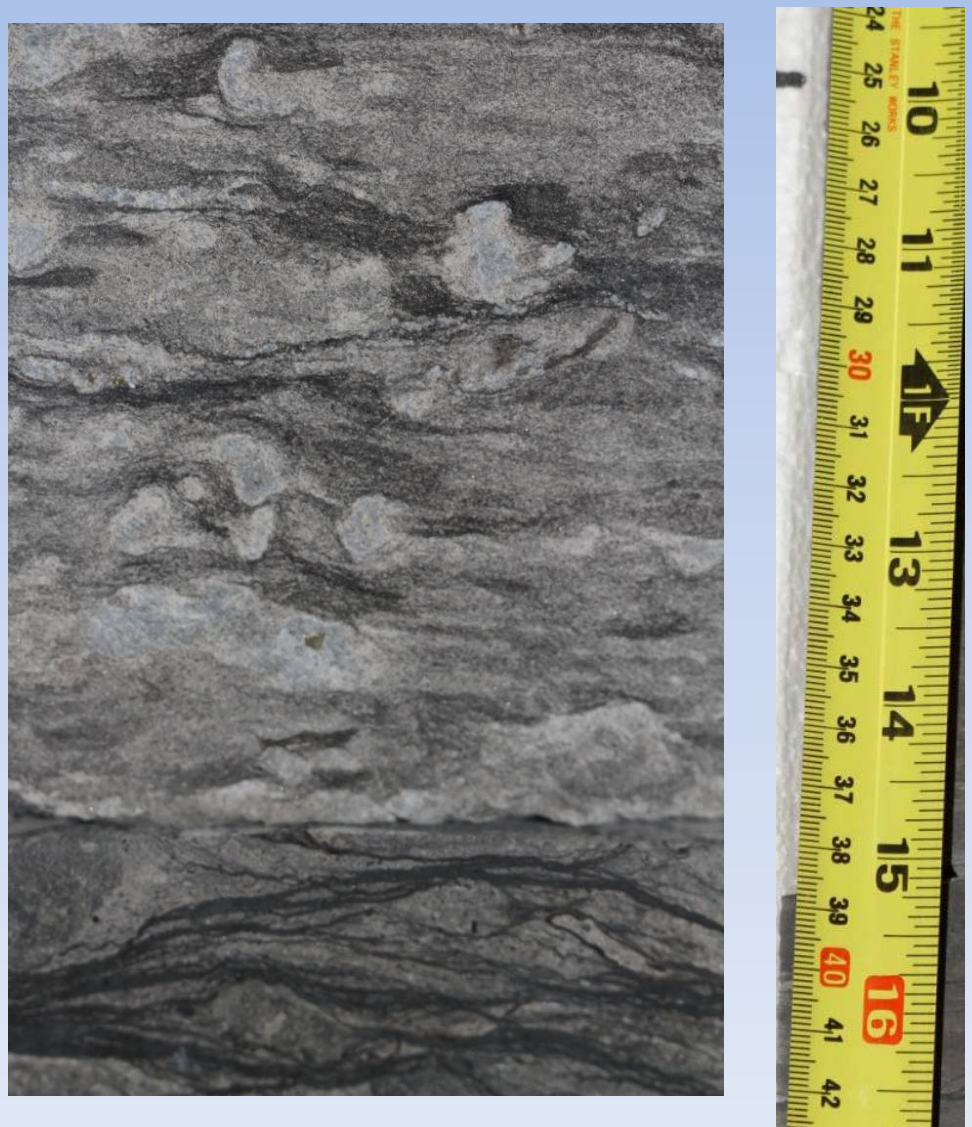
- oil show (drilling, odor)
- 35 feet thick



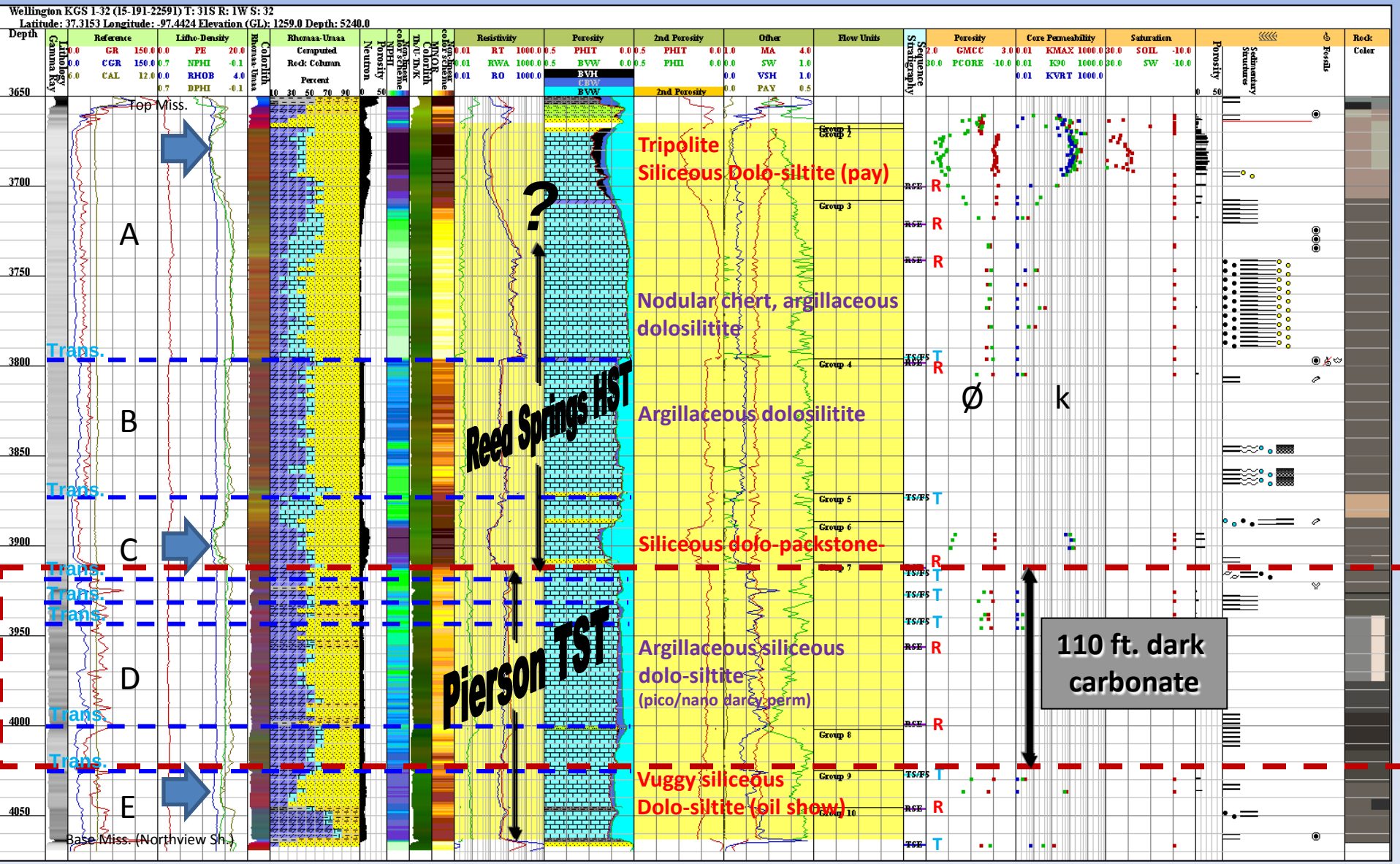
Bottom porosity with oil show near base of Mississippian KGS Wellington #1-32

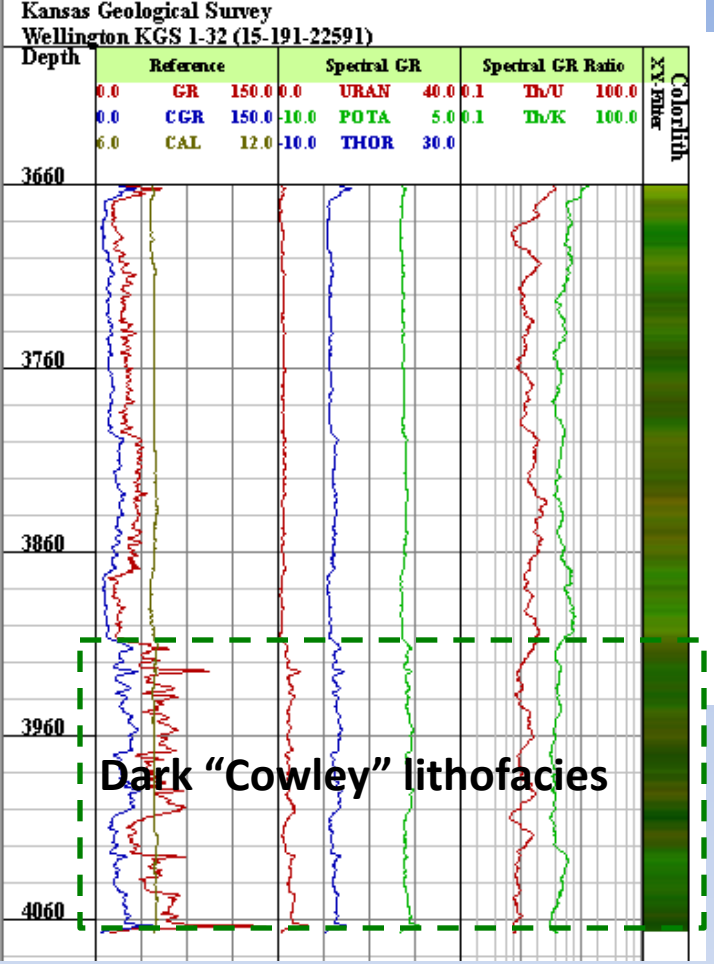


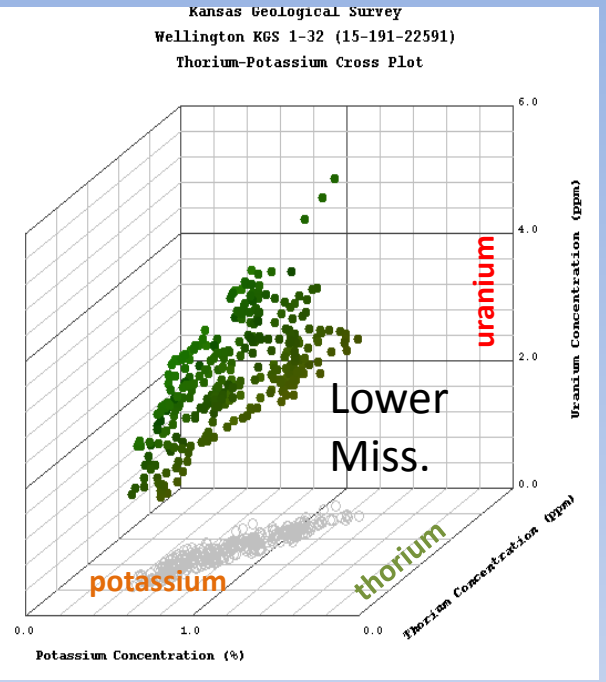
4029 ft – Lowest porosity with oil show --increased bioturbation, cm-sized subhorizontal borrows; siliceous dolo-siltite

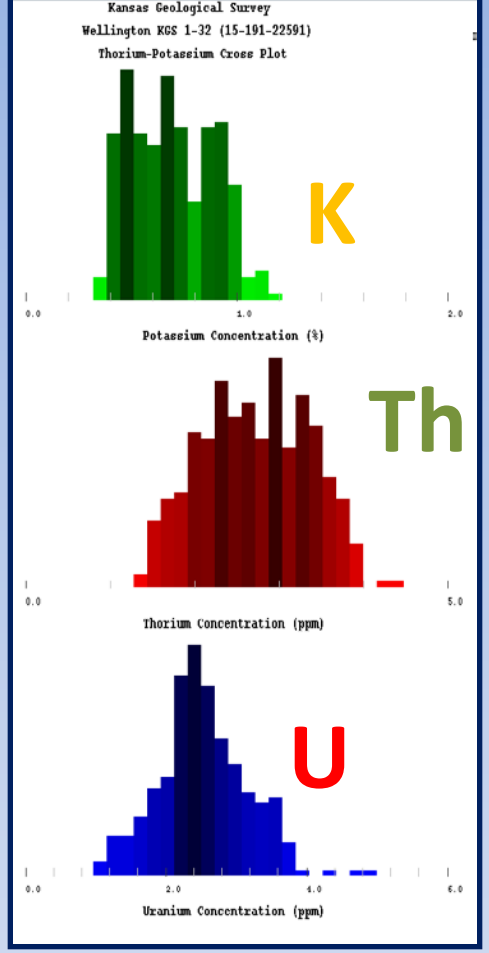


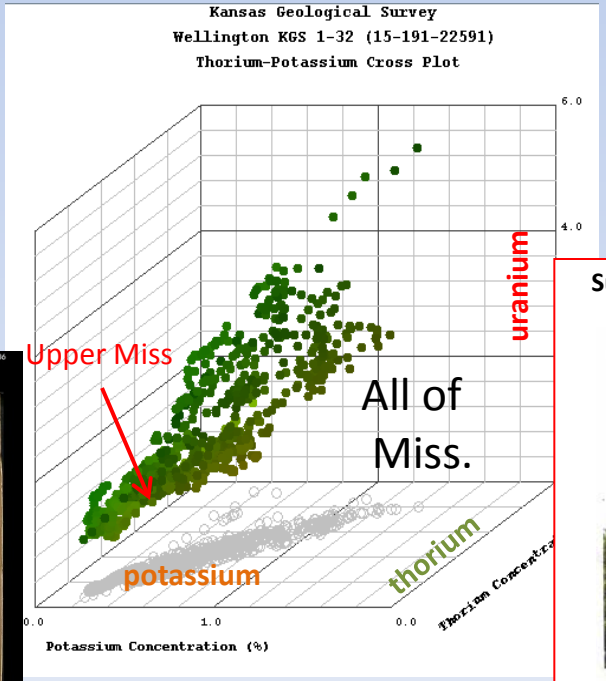
Cored Well, KGS #1-32
Top Mississippian to Kinderhook Shale



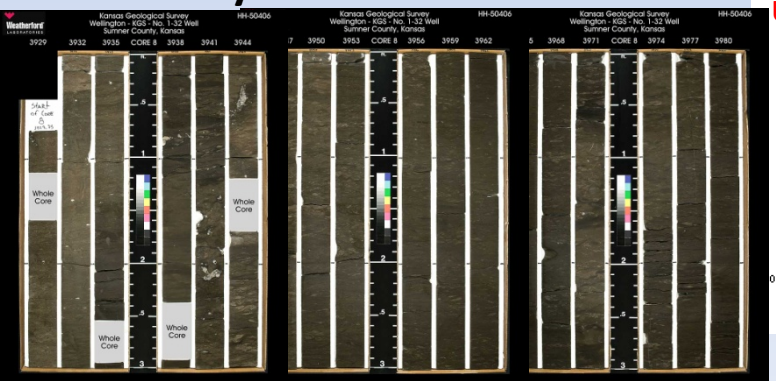








Lower Mississippian
"Cowley" elevated uranium



Surface Stratigraphy and Sequence Stratigraphy
Upper Kinderhook to Middle Osage

Handford and Manger (1993)

Surface Stratigraphy and Sequence Stratigraphy Upper Kinderhook to Middle Osage

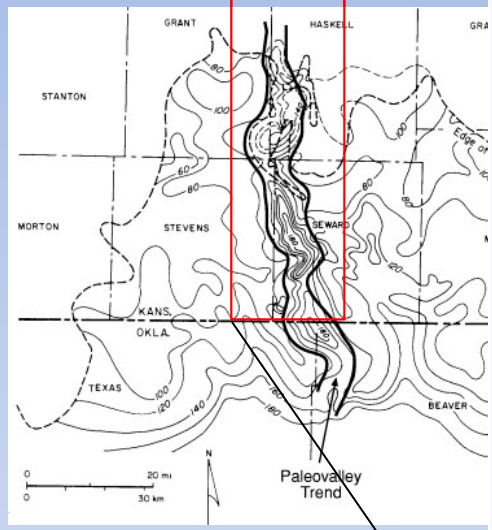
Handford and Manger (1993)

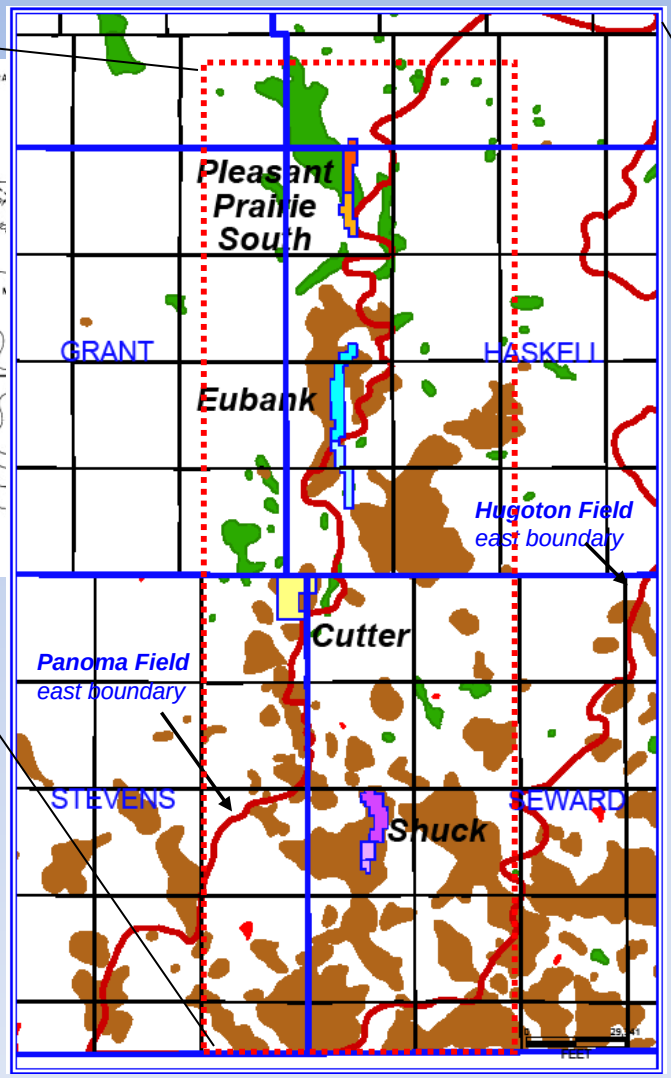
4. Southwest Kansas CO2 EOR Initiative

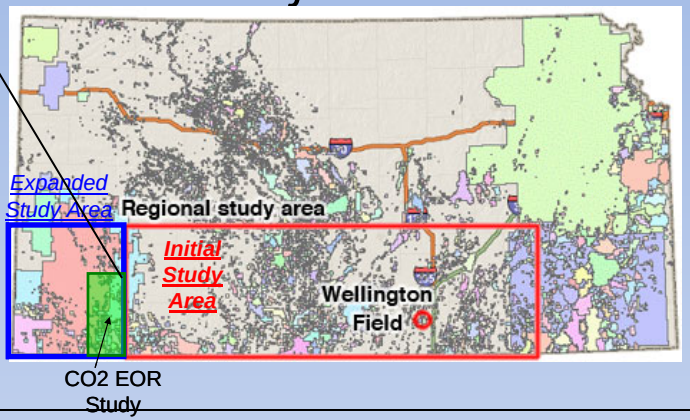
Chester and Morrow Reservoirs

Southwest Kansas CO2 EOR Initiative
Chester and Morrow Reservoirs

Western Annex to Regional CO2 Sequestration Project







Four field studies:

- Detailed reservoir characterization
- 3D cellular geomodel
- History-matched reservoir simulation
- CO2 EOR forecasts

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

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

	Oil production (mmbo)		
	Cumulative	Pre-injection	Post-injection
Pleasant Prairie So.	4.5	2.1	2.4
No. Eubanks	4	2.1	1.9
Shuck	7.8	3.5	4.3
Cutter (est.)	4	2	2
	20.3	**9.7**	**10.6**

Who and Why?

Collaboration between the Kansas Geological Survey and six industry partners:

- Anadarko Petroleum
- Berexco. LLC
- Cimarex Energy Company
- Glori Energy, Inc.
- Elm III, LLC
- Merit Energy Company

Technical team:

- Lynn Watney and Jason Rush, KGS, PIs
- **Martin Dubois, IHR, LLC – project manager and modeling**
- John Youle, consultant, sedimentology
- Gene Williams, consultant, reservoir engineering
- Ray Sorenson, consultant, geologist
- Dennis Hedke, Hedke-Sanger, geophysics

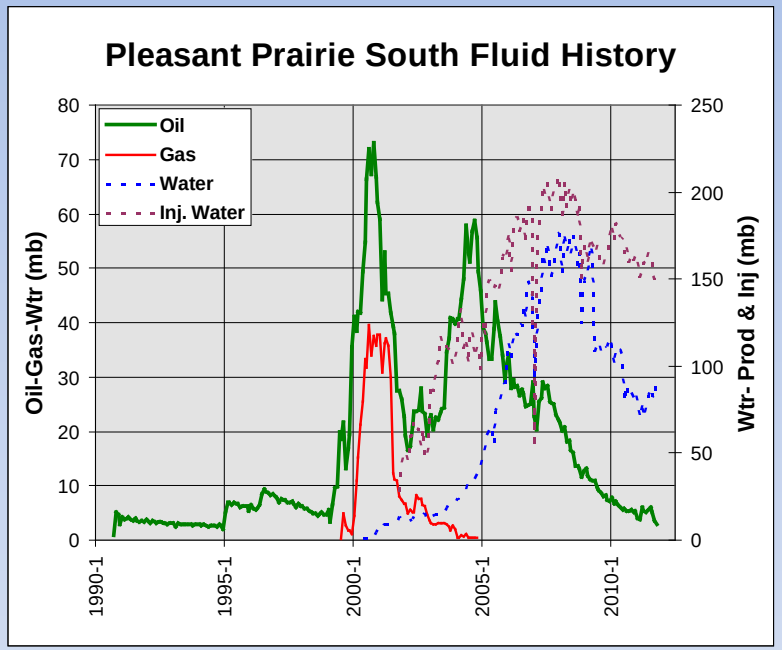
Circumstances make sense for consortium-based study

- Chester and Morrow reservoirs are **good waterfloods**, and likely to be **good CO2 EOR candidates**
- **No single field** is large enough to justify the capital required for CO2 infrastructure alone
- **No single operator** has oil resource base to justify capital costs
- **$5M DOE** opportunity for CO2 EOR and sequestration studies
- CO2 EOR could happen with Cooperation and/or Aggregation
- Primary Goal: **Get fields "CO2 Ready"**

AND…..a comprehensive system-scale study of the Chester IVF reservoir system made possible by the pooling of large data sets

- ✓ Data assembly
- ✓ Detailed geology
- ✓ 3D seismic interp.
- ✓ 3D cellular model
- ➢ Hist-match simulation
- ❑ CO2 EOR simulation

Pleasant Prairie South History



1990 first well completed in Chester sand - Kearny County Feedlot 1

1996 second well completed in Chester sand

1999-2001 rapid development of entire field

2001 waterflood initiated (one operator unitized, the second did not)

Well Count:

19 oil wells 6 later converted to injectors)

Waterflood

10 injectors

13 producers (2 of which are not “plumbed into flood”)

Fluid statistics

Cum. oil: 4.5 mmbo

Cum. Gas: 0.75 BCF

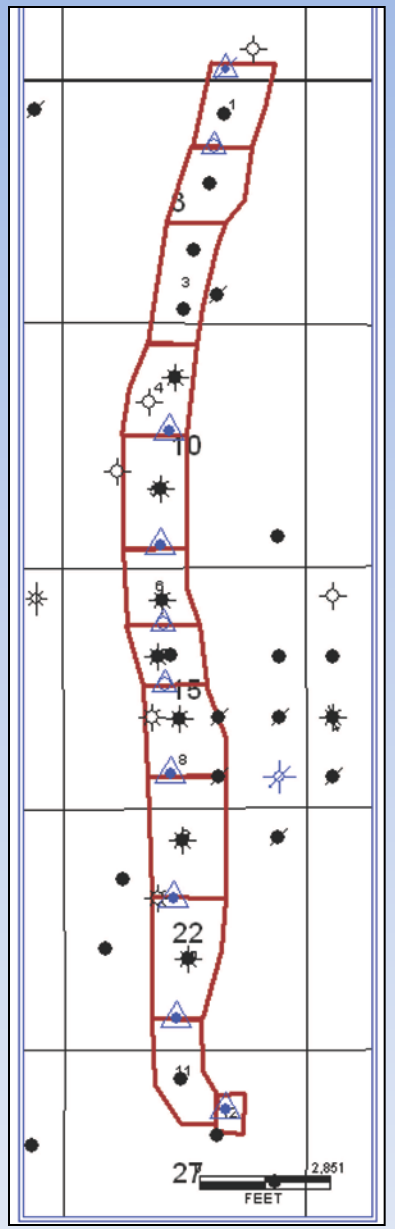
Primary/Second.~ 1/1

RF ~ 30-35% of OOIP

Map of all deep wells

Chester IVF wells inside pattern polygons

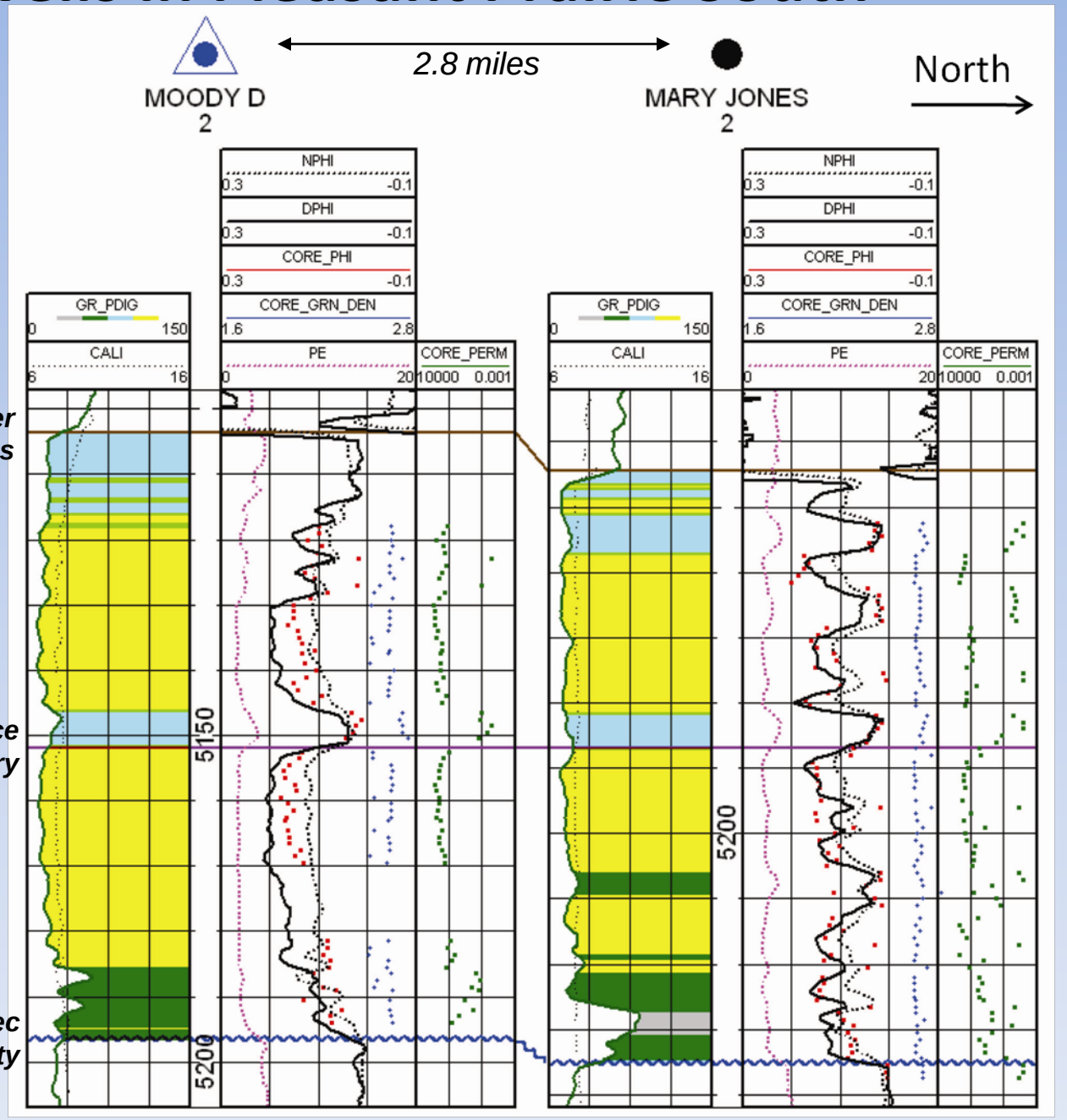
Other wells are outside the narrow valley



Key cored wells in Pleasant Prairie South

Chester IVF

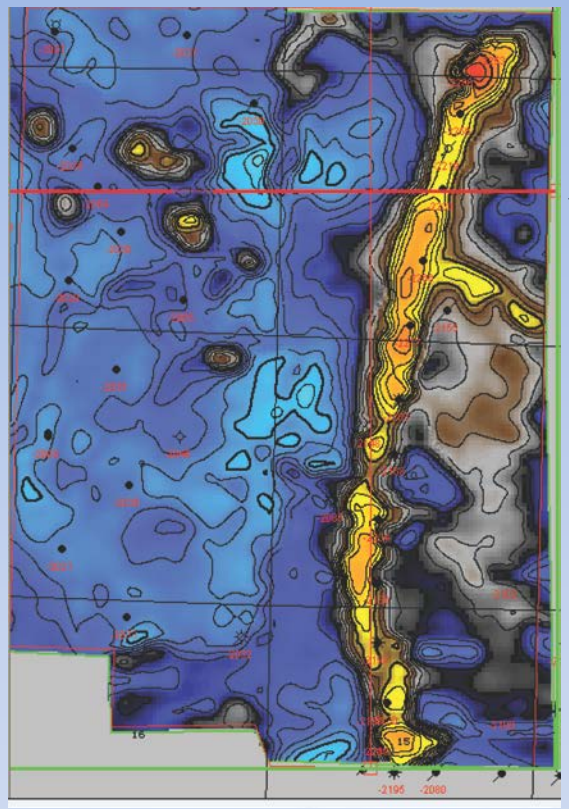
- Two stacked parasequences (Ps)
- Primarily fine-grained, well sorted sand deposited in tidally-influenced estuarine
- Some evidence for fluvial depositional environment
- Ps boundary is placed at base of limestone pebble-sandstone conglomerate traceable through the field
- Less porous non-reservoir sandstone is cemented with calcite and often with limestone pebbles.



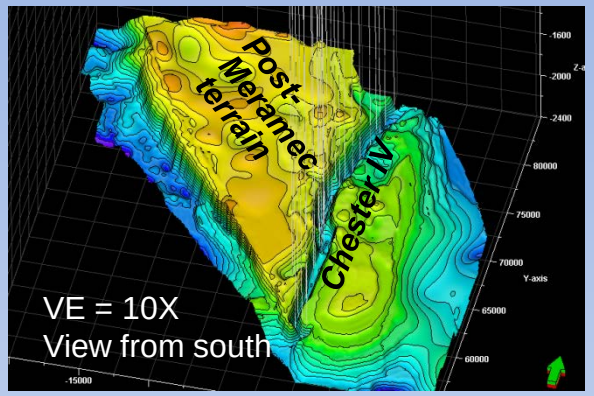
"Lumped" Lithofacies

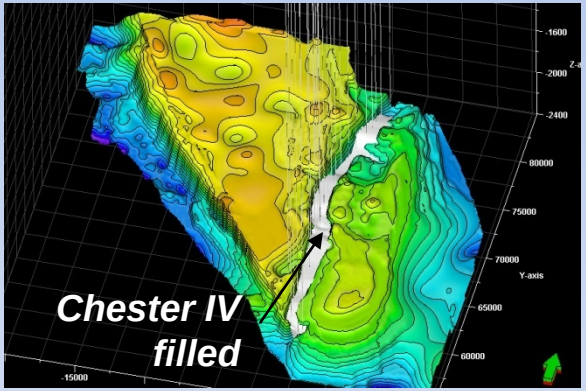
- "Reservoir" sandstone
- Limey congl. ss
- Shaly sandstone
- Shale

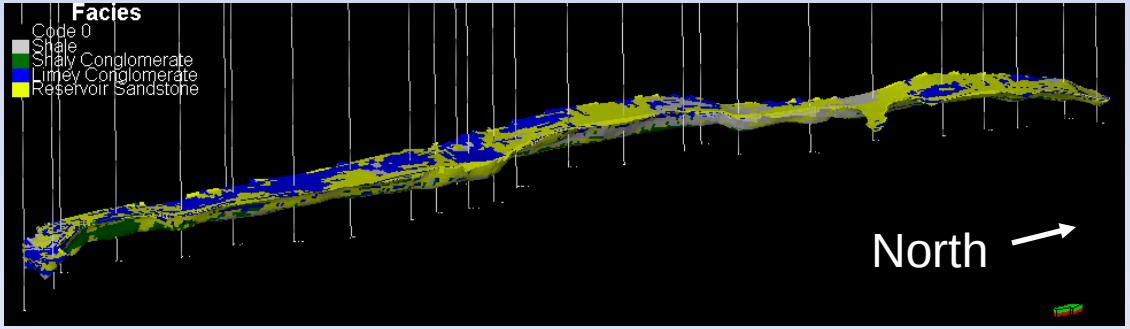
Pleasant Prairie South Modeling



1. Build Meramec surface with 3D seismic tied to wells
2. "Fill" IV with reservoir facies
3. 25 wells along IV with facies
4. Model lithofacies between wells using SIS in Petrel

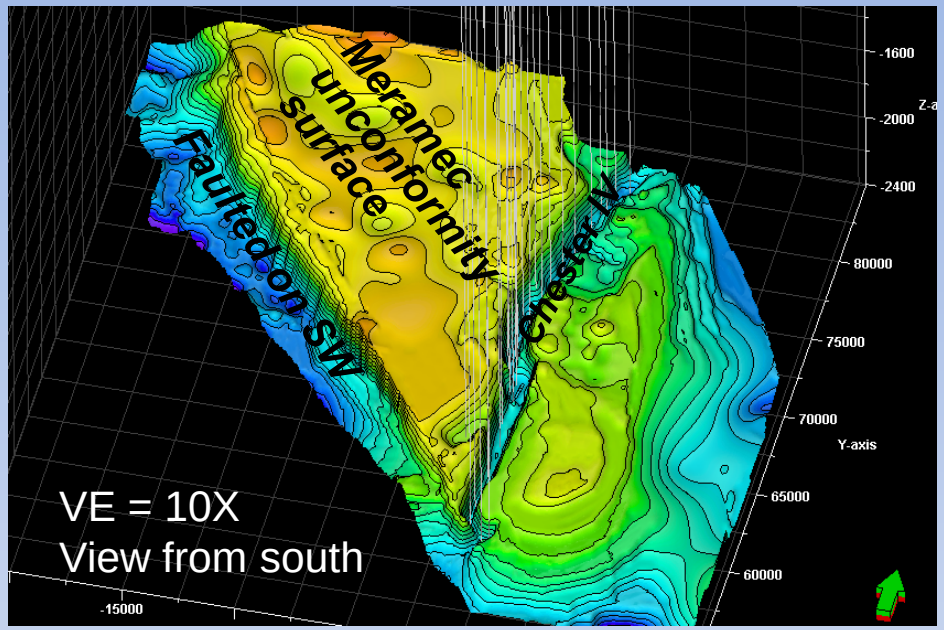


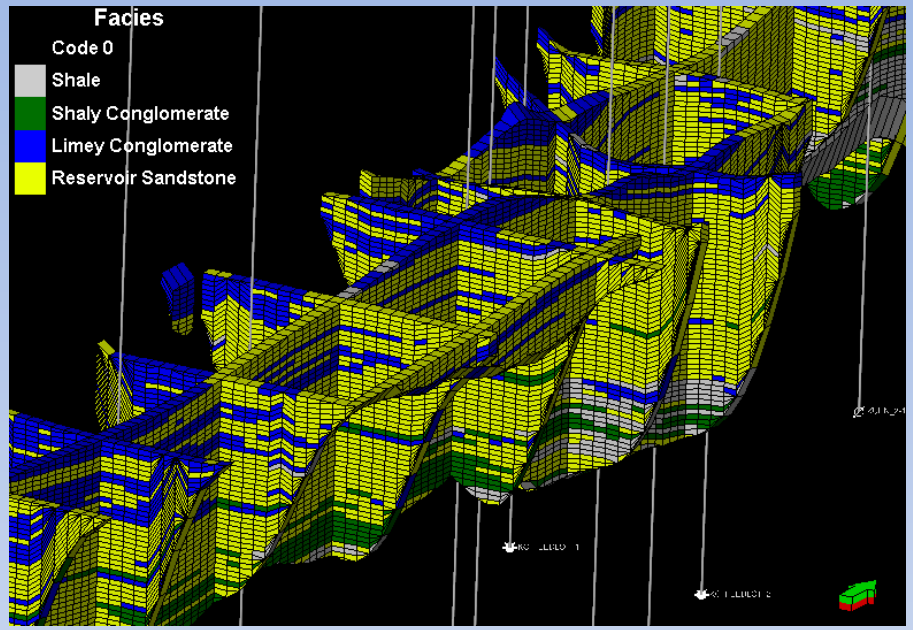


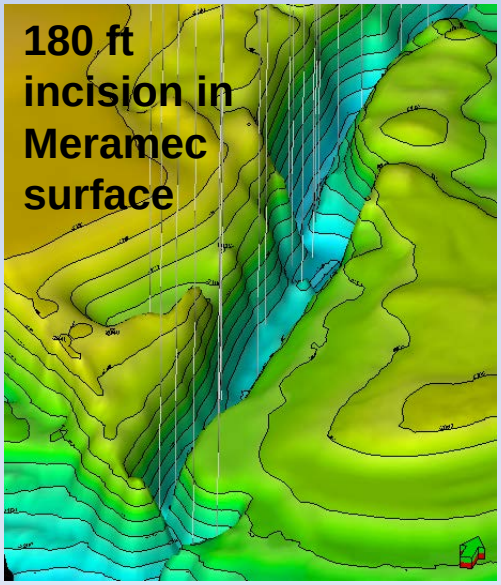


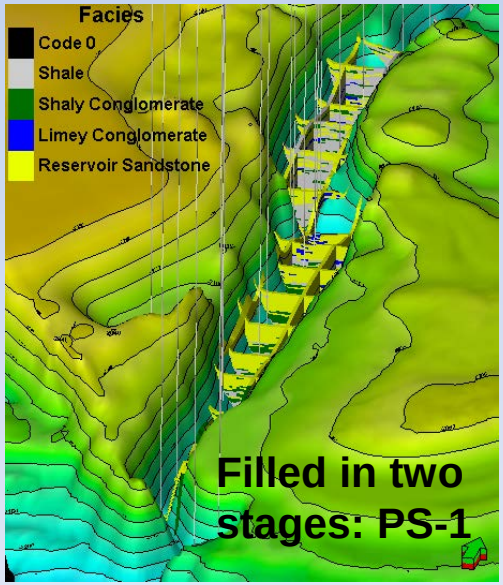
Initial geomodel by Peter Senior (KU MS student). Revisions shown here by Dubois.

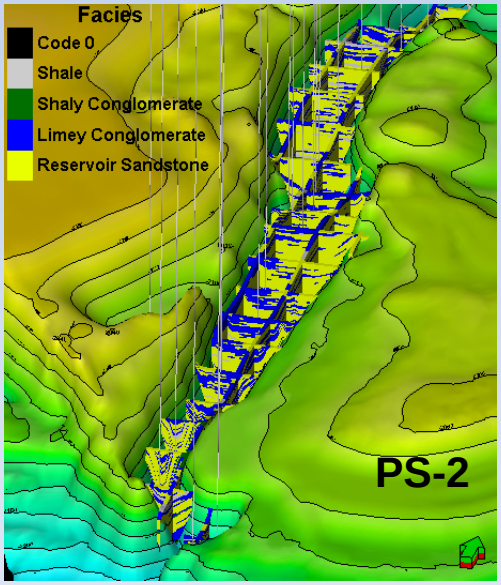
Pleasant Prairie South Modeling







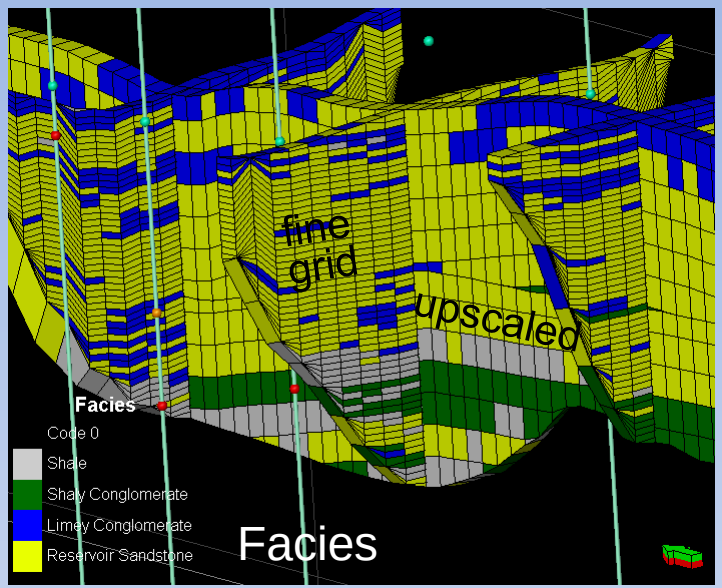


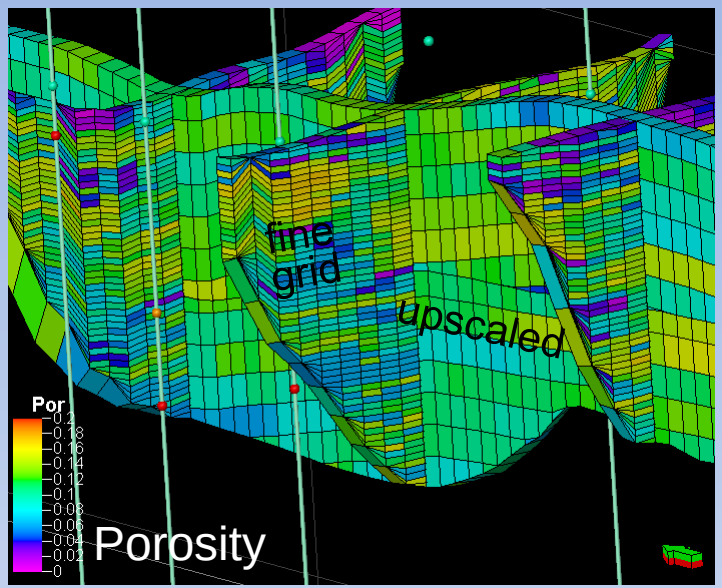


Fence diagram of facies in IVF. Cells are 55x55x2 ft

Upscale for simulation model

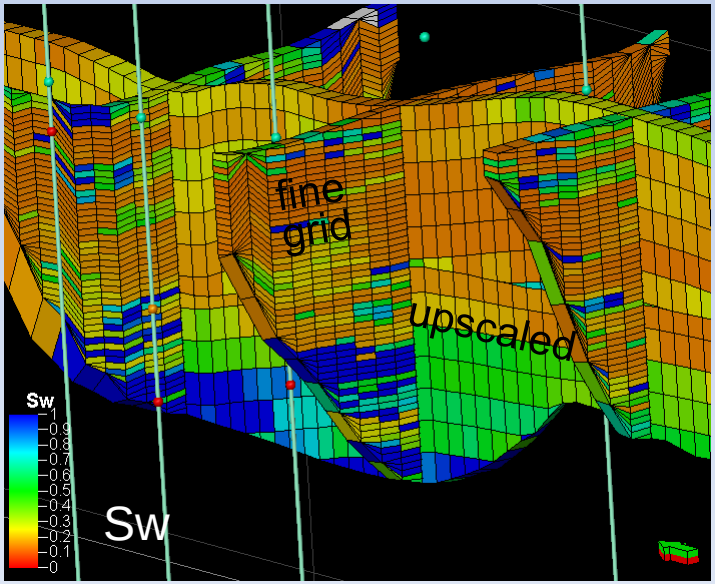
Illustration of key properties in the Pleasant Prairie model in fine and coarse grids (upscaled)

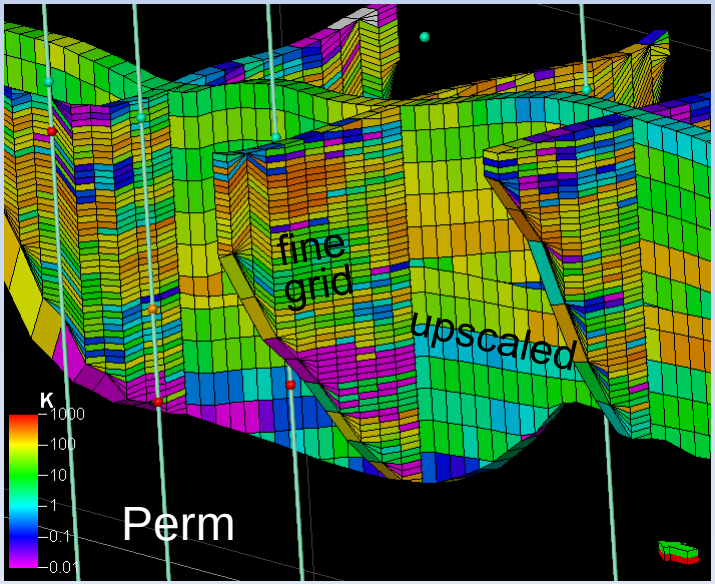




General workflow:

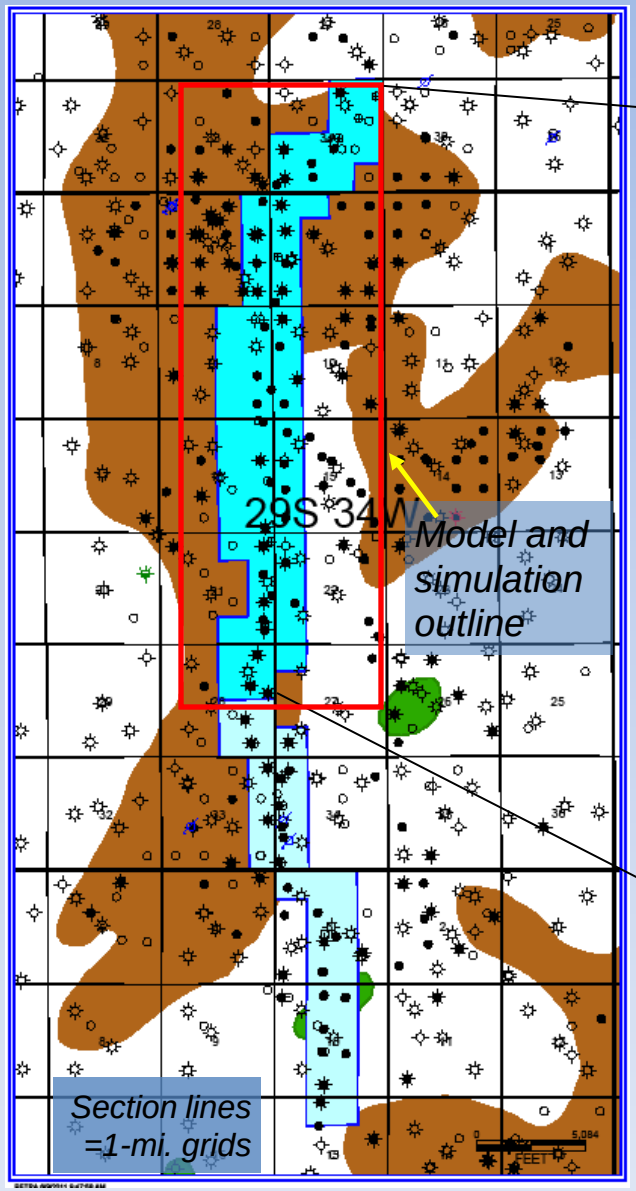
- Facies model
- Facies-constrained porosity model
- K from Phi-K relationships by facies from core
- Sw by J-function constrained by phi, k, and log Sw with estimated FWL =-2245 (O/W contact ~-2235)
- Evaluate volumetircs
- Upscale from fine grid to coarse grid (2 foot to 8 foot)
- Export for simulation

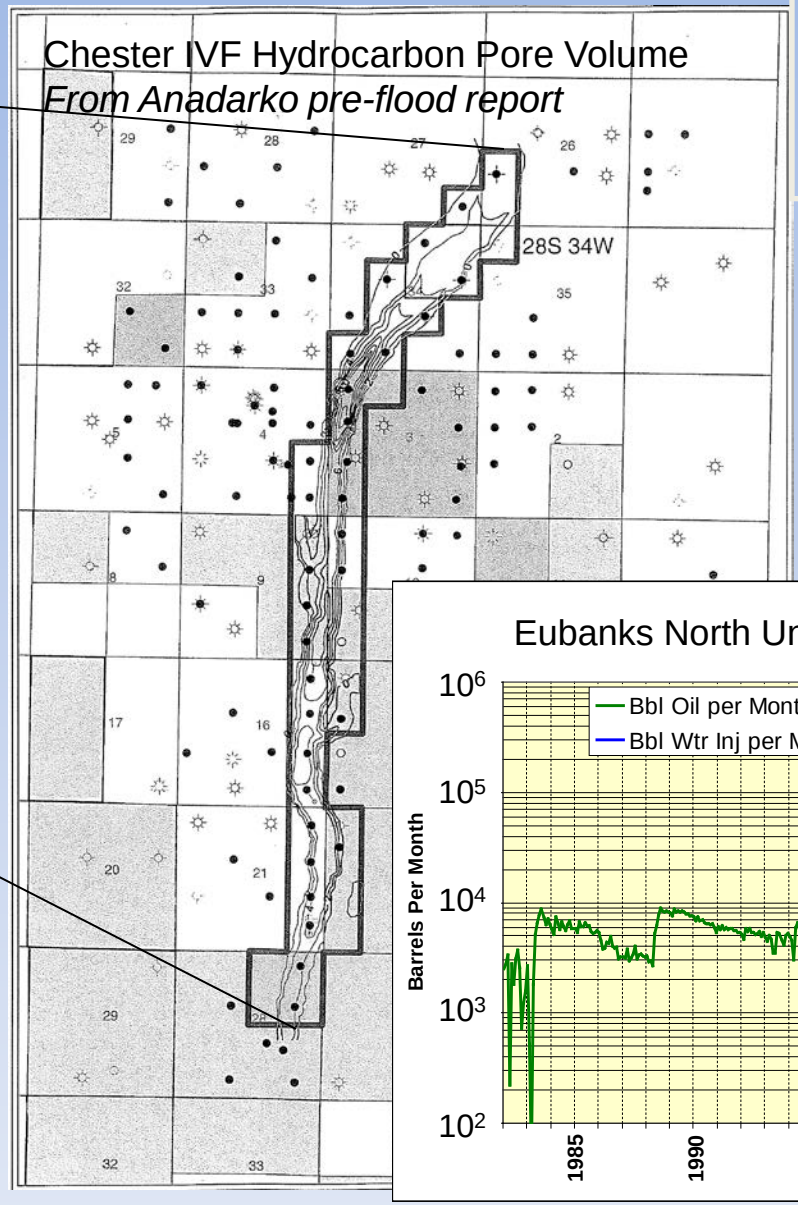




Eubanks North Unit

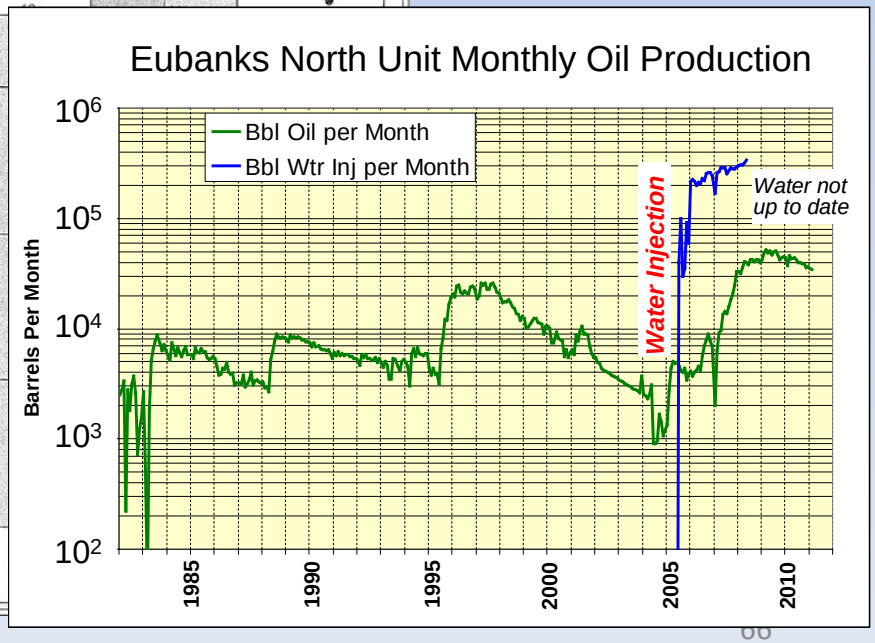
- ✓ Data assembly
- ✓ Detailed geology
- ➢ 3D seismic interp.
- ❑ 3D cellular model
- ❑ Hist-match simulation
- ❑ CO2 EOR simulation





Eubanks North Unit

Discovered: 1982
Waterflood: 2005
Pre-WF: 2.09 mmbo
Since WF: 1.89 mmbo
Cumulative: 3.97 mmbo

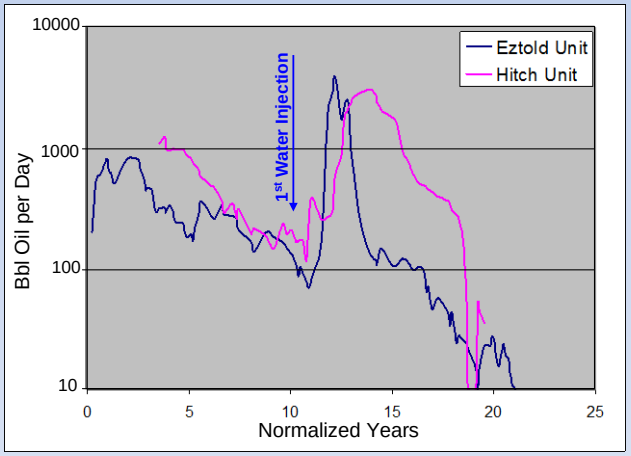


- ➢ Data assembly
- ➢ Detailed geology
- ✓ 3D seismic interp.
- ❑ 3D cellular model
- ❑ Hist-match simulation
- ❑ CO2 EOR simulation

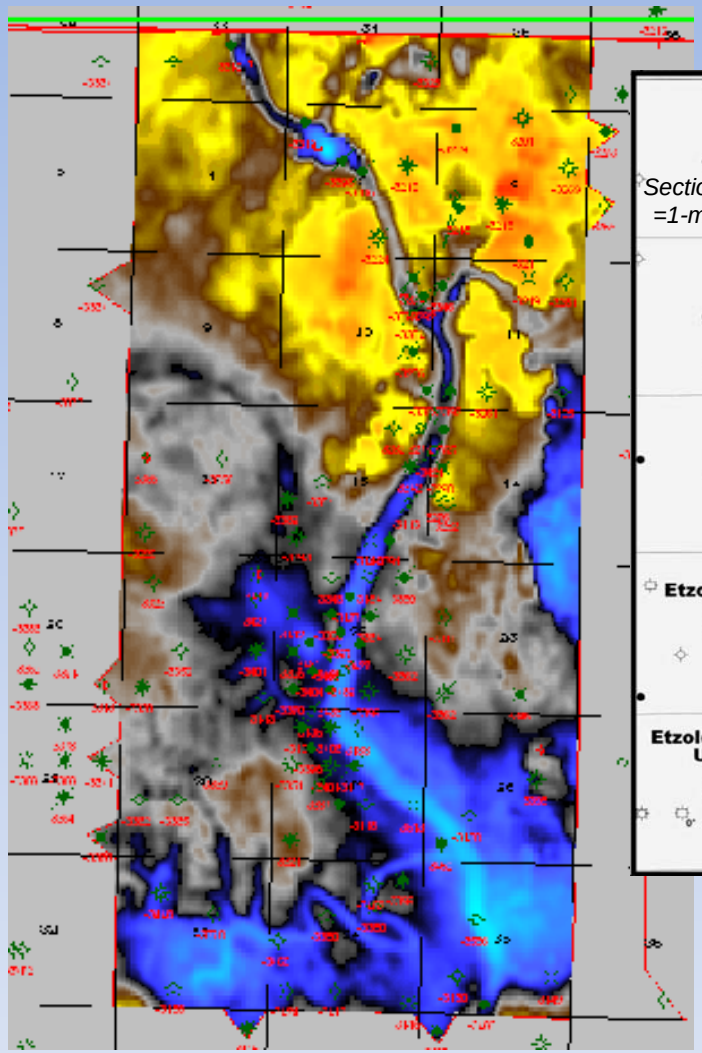
Shuck Field (Hitch and Etzold Units)

Shuck Waterflood Units Unit

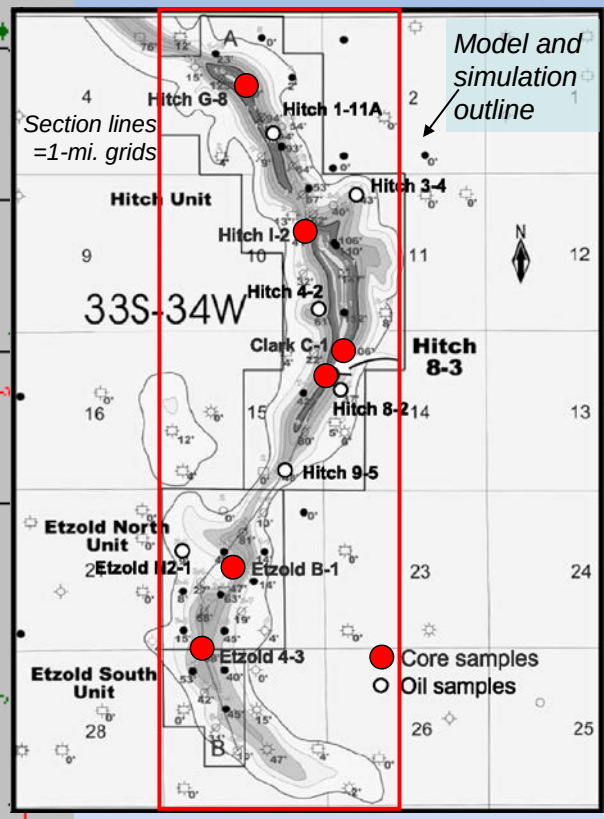
Discovered:	1978
Waterflood:	1989
Pre-WF:	3.53 mmbo
Since WF:	4.28 mmbo
Cumulative:	7.81 mmbo



Production plots for Hitch and Etzold waterflood units in Shuck Field, normalized to waterflood initiation.



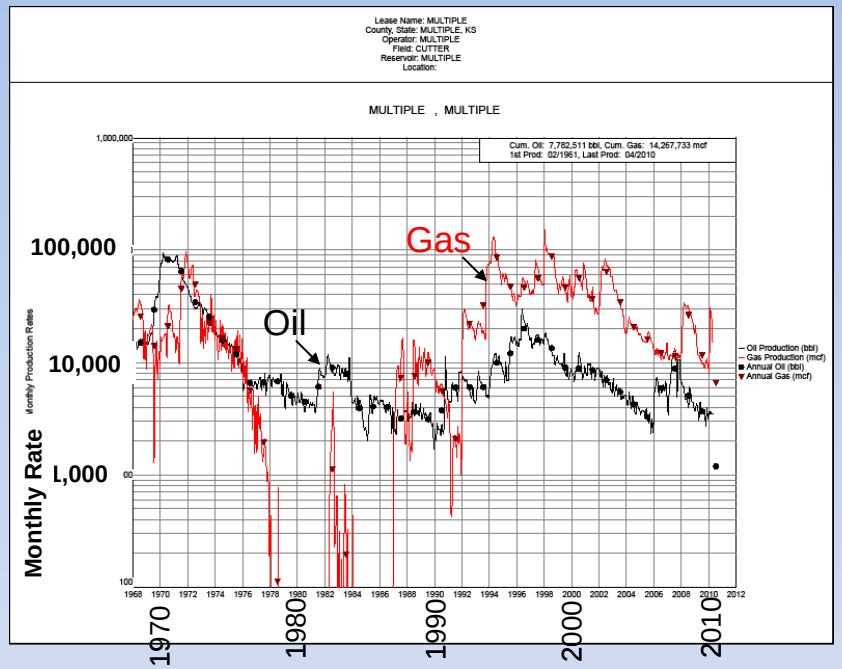
Meramec 3D seismic depth structure tied to well data. (Hedke interpretation)

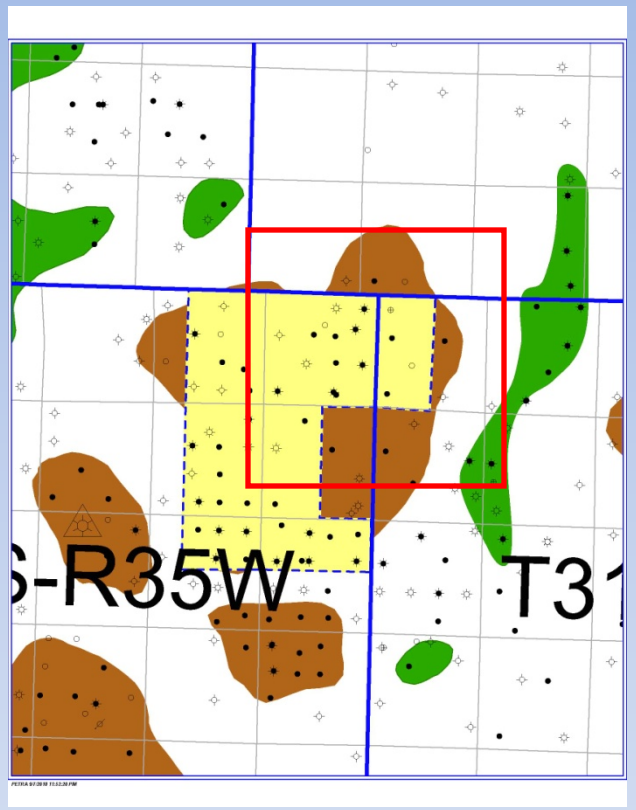


Isopach map of the net basal Chester ss, >8% porosity, CI: 20 ft. *Kim, Philip, and Sorenson, 2010*

- ➢ Data assembly
- ❑ Detailed geology
- ❑ 3D seismic interp.
- ❑ 3D cellular model
- ❑ Hist-match simulation
- ❑ CO2 EOR simulation

Cutter waterfloods (Morrow)





- Cutter field produces primarily from Morrow but also from Chester (not IVF)
- Much of the Morrow has been waterflooded in an older Mobil waterflood.
- Production allocation in later years is yet to be updated. Mobil records indicated that the Morrow waterflood unit cumulative was 3.2 mmbo in 1982.
- Cumulative for the field in 2011 is 6.46 mmbo.

5. Small Scale Field Test

Demonstrating CO_2 sequestration in Arbuckle Saline Aquifer and by CO_2-EOR at Wellington field, Sumner County, Kansas --

Small Scale Field Test Demonstrating CO_2 sequestration in Arbuckle Saline Aquifer and by CO_2-EOR at Wellington field, Sumner County, Kansas --

W. Lynn Watney and Jason Rush
Kansas Geological Survey
Lawrence, KS 66047

Regional Carbon Sequestration Partnerships
Annual Review Meeting
October 15-17, 2011
Pittsburgh, PA

Funding Opportunity Number: DE-FOA-0000441
Contract #FE0006821
$11,484,499 DOE
$3.236 million cost share

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

BEREXCO

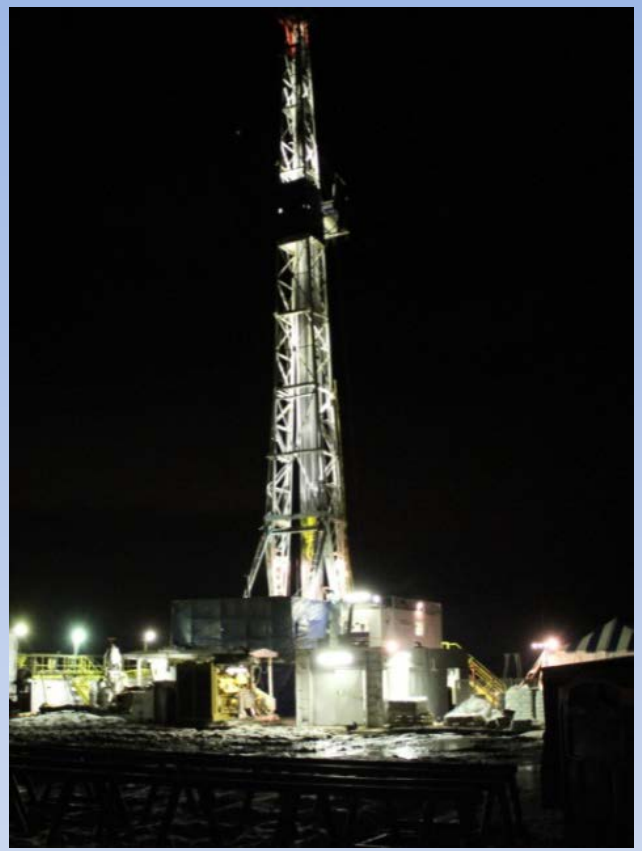
DEPARTMENT OF GEOLOGY
KANSAS STATE UNIVERSITY

THE UNIVERSITY OF KANSAS
Department of Geology

Sandia Technologies, LLC

Outline

- Background
- The Participants
- The Plan
- Leveraging Current Research at Wellington Field
- Inject, Monitor, Verification, and Accounting of CO_2

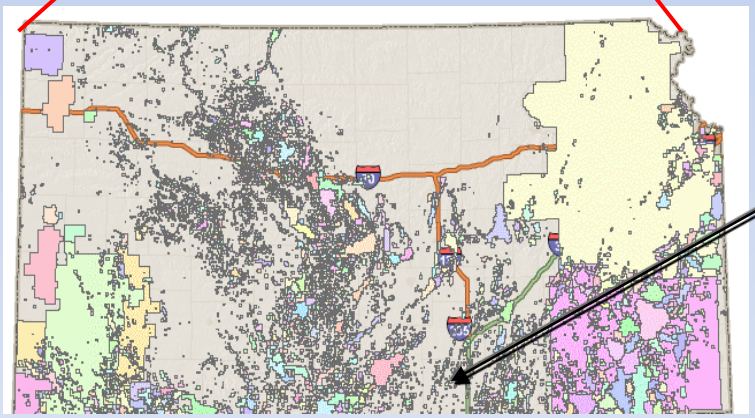


Project Team
Small Scale Field Test – Wellington Field (FE0006821)

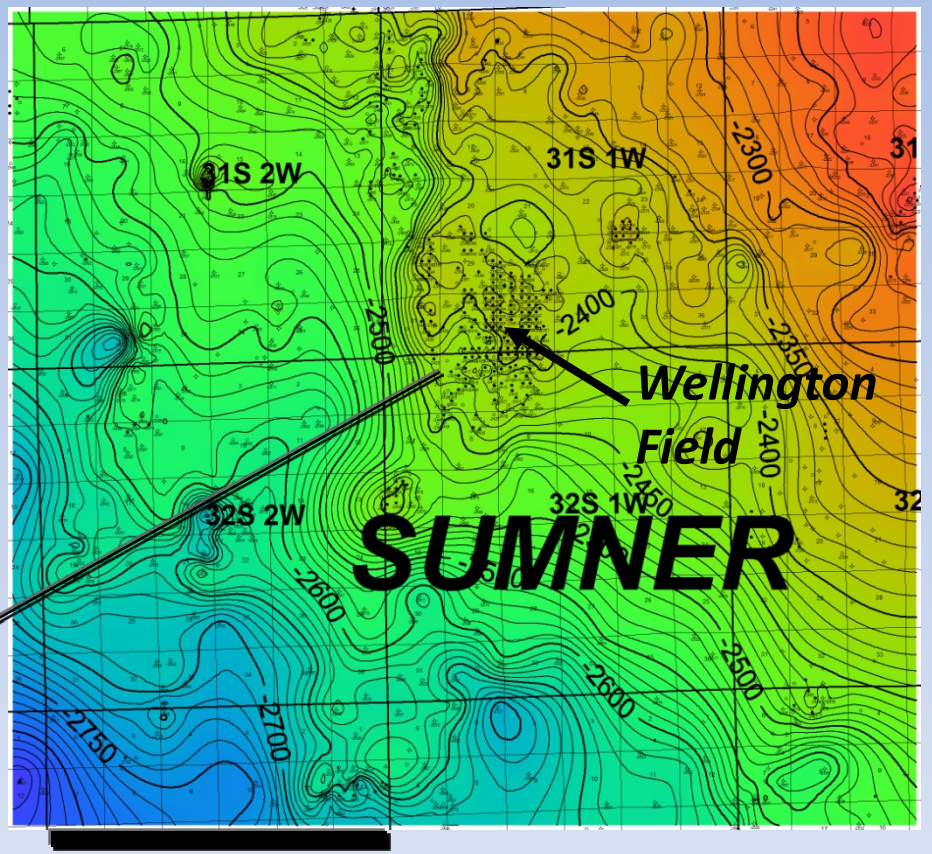
Name	Project Job Title	Primary Responsibility
Lynn Watney	Project Leader, Joint Principal Investigator	Geology, information synthesis, point of contact
Tiraz Birdie	Consulting Engineer	Reservoir engineer, dynamic modeling, synthesis
Jason Rush	Joint Principal Investigator	Geology, static modeling, data integration, synthesis
John Doveton	Co-Principal Investigator	Log petrophysics, geostatistics
Dave Newell	Co-Principal Investigator	Fluid geochemistry
Rick Miller	Geophysicist	2D seismic aquire & interpretation
		LiDAR support, water well drilling/completion
TBN	Geology Technician	Assemble and analyze data, report writing
TBN	Engineering Technician	Assemble and analyze data, report writing
	KU Department of Geology	
Michael Taylor	Co-Principal Investigator	Structural Geology, analysis of InSAR and LiDAR
TBN	Graduate Research Assistant	Structural Geology, analysis of InSAR and LiDAR
	Kansas State Unversity	
Saugata Datta	Principal Investigator	Aqueous geochemistry
TBN	Graduate Research Assistant	
TBN	3- Undergraduate Research Assistants	
	Lawrence Berkeley National Laboratory	
Tom Daley	Co-Principal Investigator	Geophysicist, analysis of crosshole and CASSM data
Jennifer Lewicki	Co-Principal Investigator	Hydrogeology, analysis of soil gas measuremnts
Barry Freifeld	Co-Principal Investigator	Mechanical Engineer, analysis of U-Tube sampler
	Sandia Technologies, Houston	
Dan Collins	Geologist	Manage CASSM and U-Tube operation
David Freeman	Field Engineer	Manage field install of CASSM and U-Tube
	Berexco, LLC	
Dana Wreath	VP Berexco	Engineering, Manager of Wellington Field
Randy Kouedele	Reservoir engineer	Enginering
Staff of Wellington Field		field operations
Beredco Drilling team		Mississippian and Arbuckle drilling operations
	Abengoa Bioenergy Corp. - Colwich, KS	
Christopher Standlee, Danny Alllison		CO2 supply – Colwich Ethanol Facility

Wellington Field

Site of proposed Small Scale Field Test



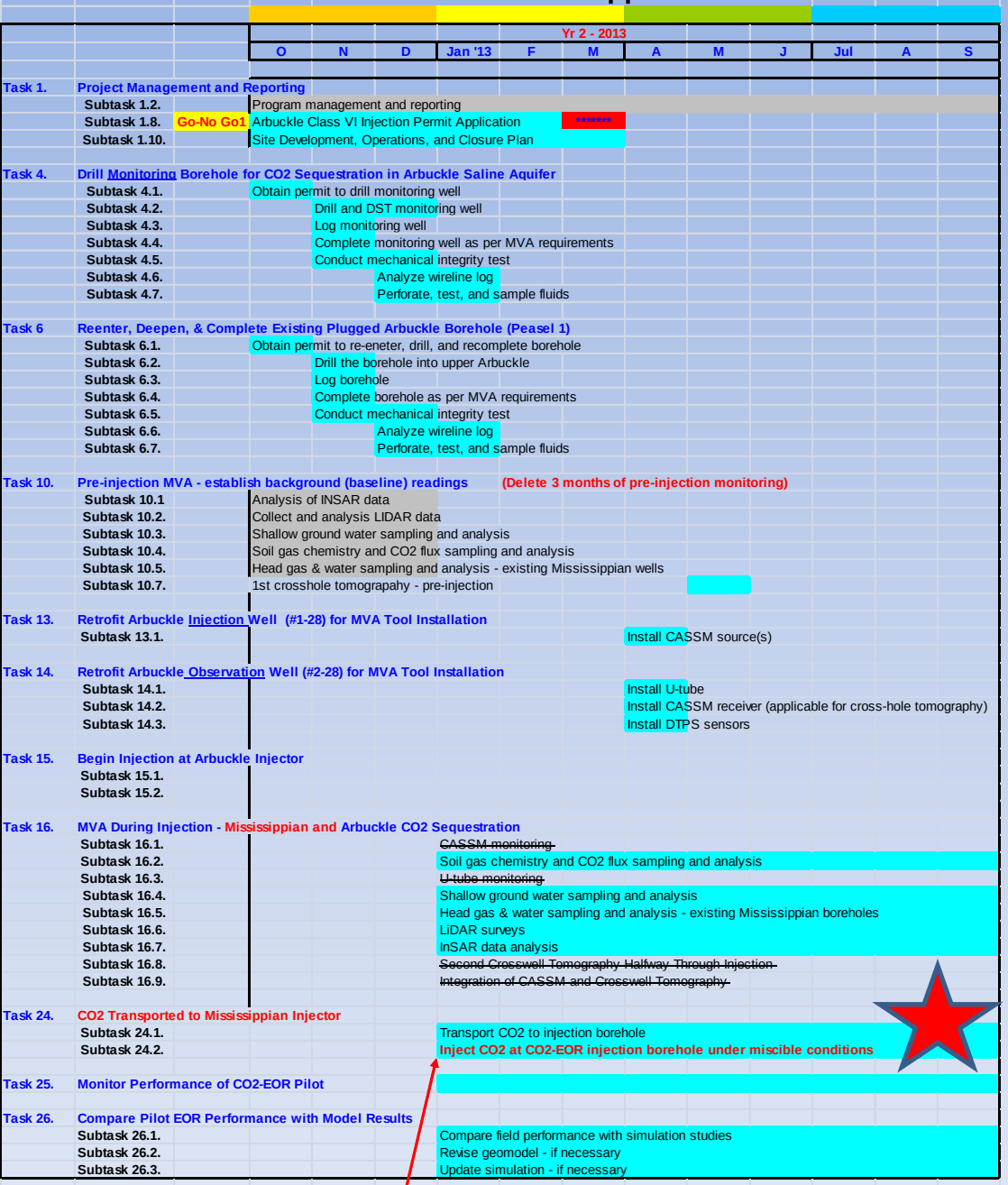
Top Mississippian Structure, 10 ft C.I.



6 miles

KANSAS GEOLOGICAL SURVEY
The University of Kansas

BP2 - Class II Mississippian first

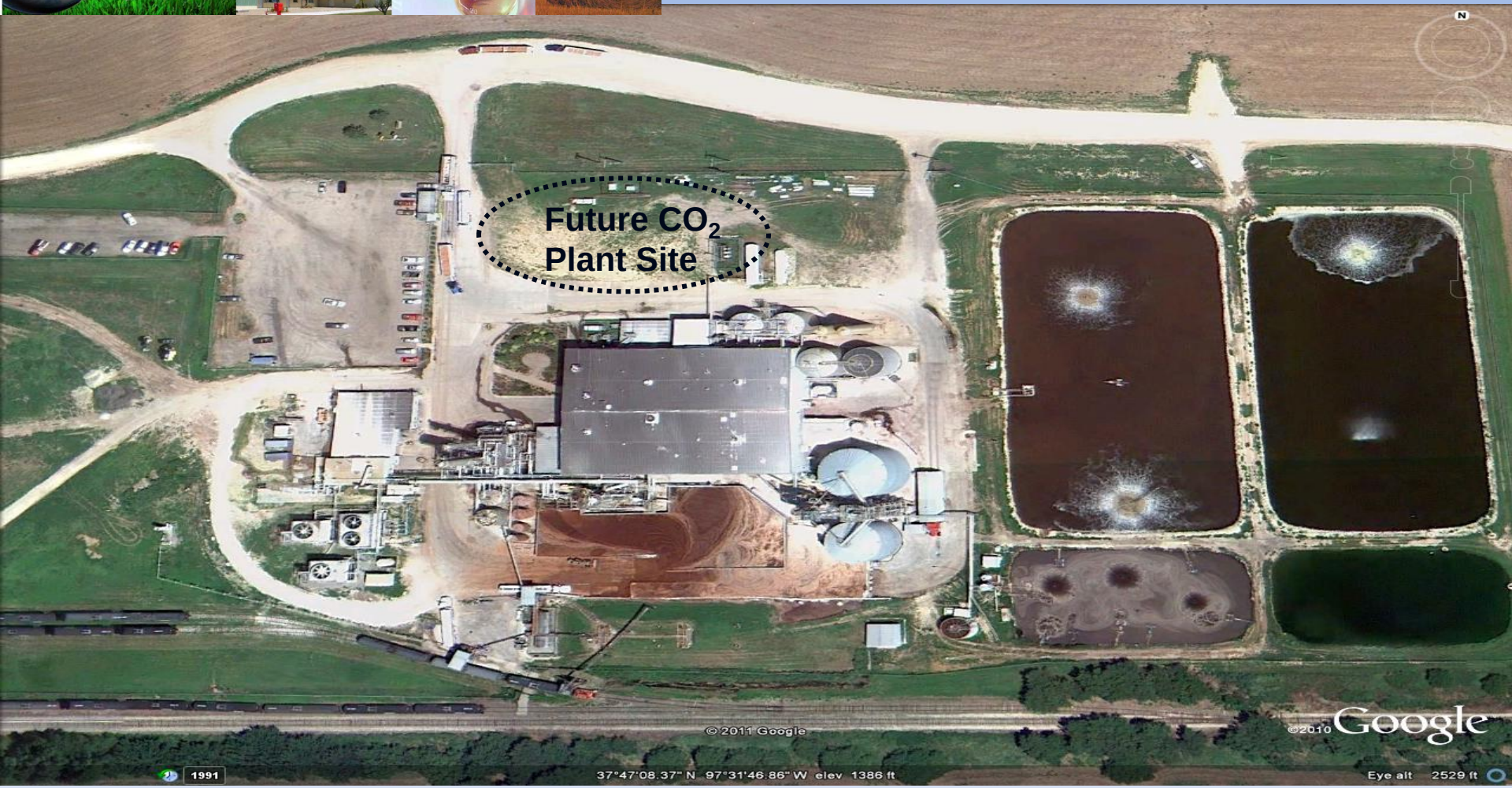


Project Gantt Chart
Budget Period 2
October 2012 - September 2013

Inject CO2 in Mississippian ~January 2013

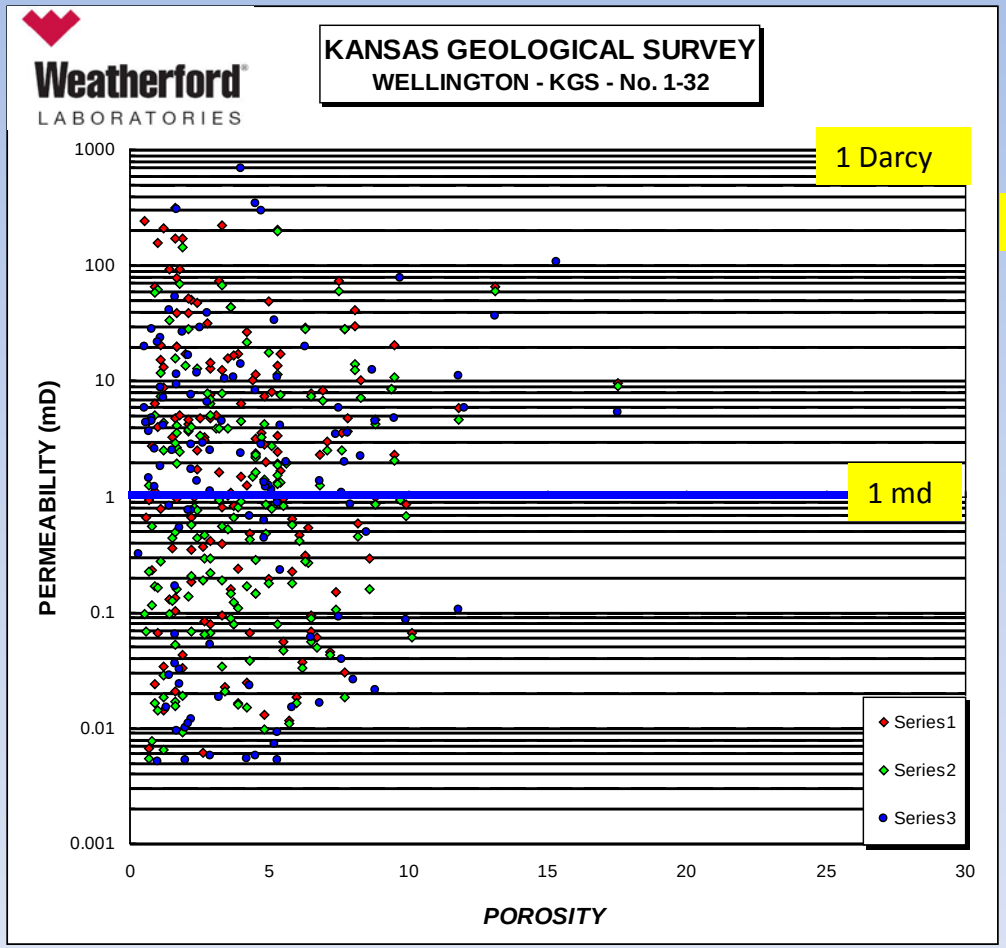
Source of CO2

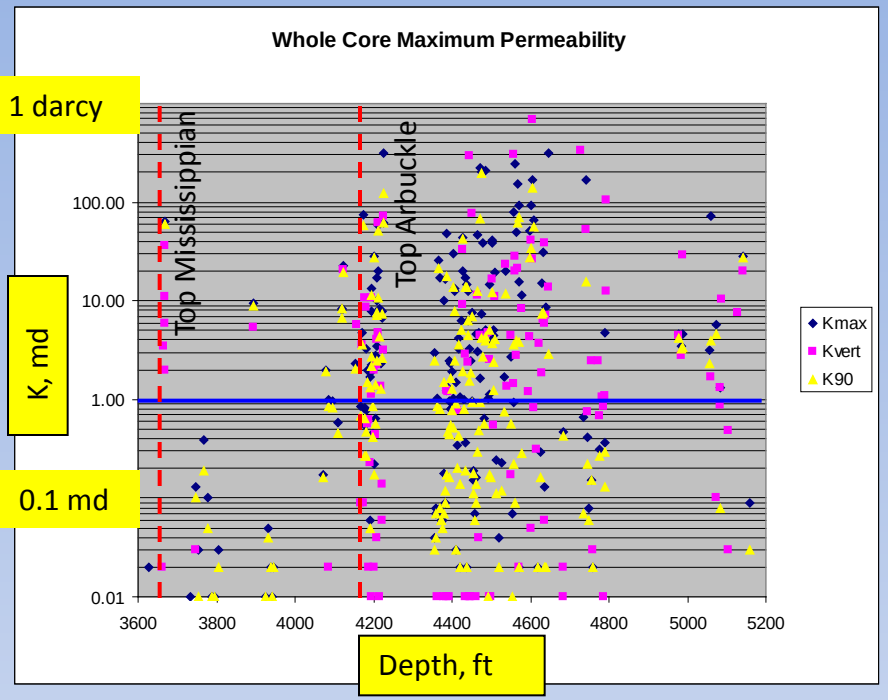
Abengoa Colwich plant and CO_2 site

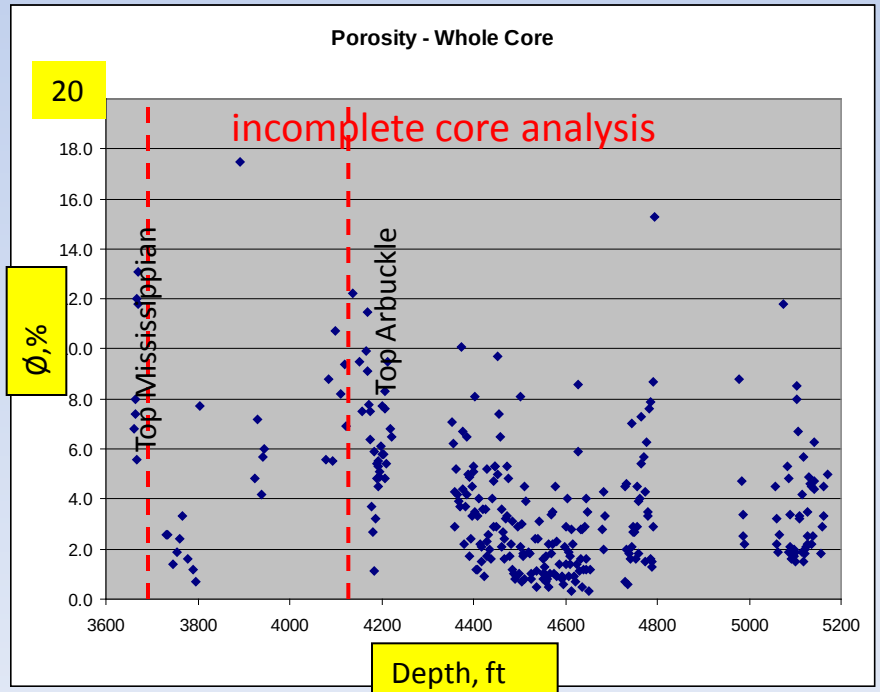


- Constructed in 1982, has been upgraded and expanded many times over the years, and is a modern well equipped plant.
- Production capacity of approximately 25 M gallons of ethanol per year and produces over **200 tons per day of raw CO_2**.
- CO_2 was captured, processed and sold for approximately 10 years from this facility.

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

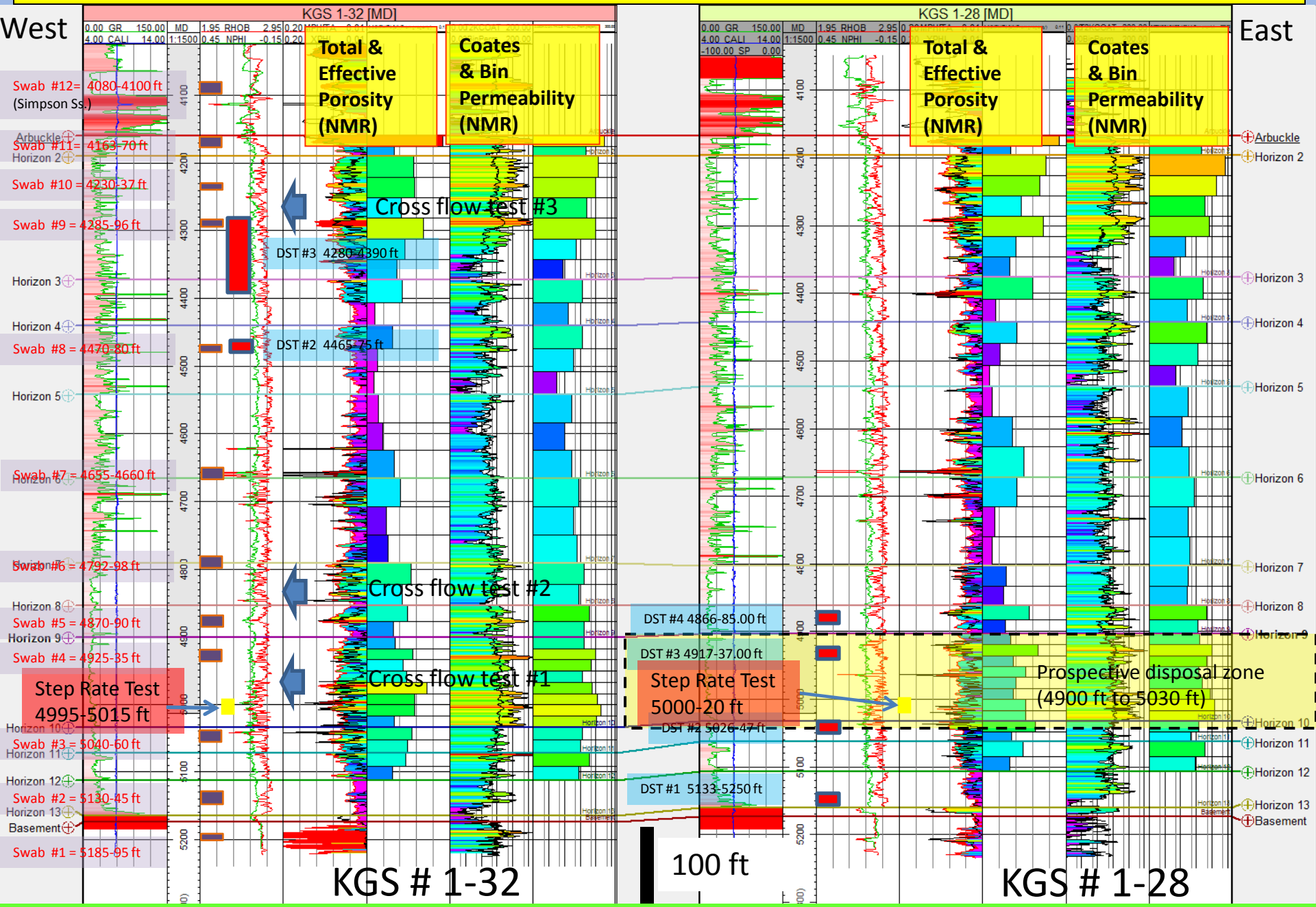




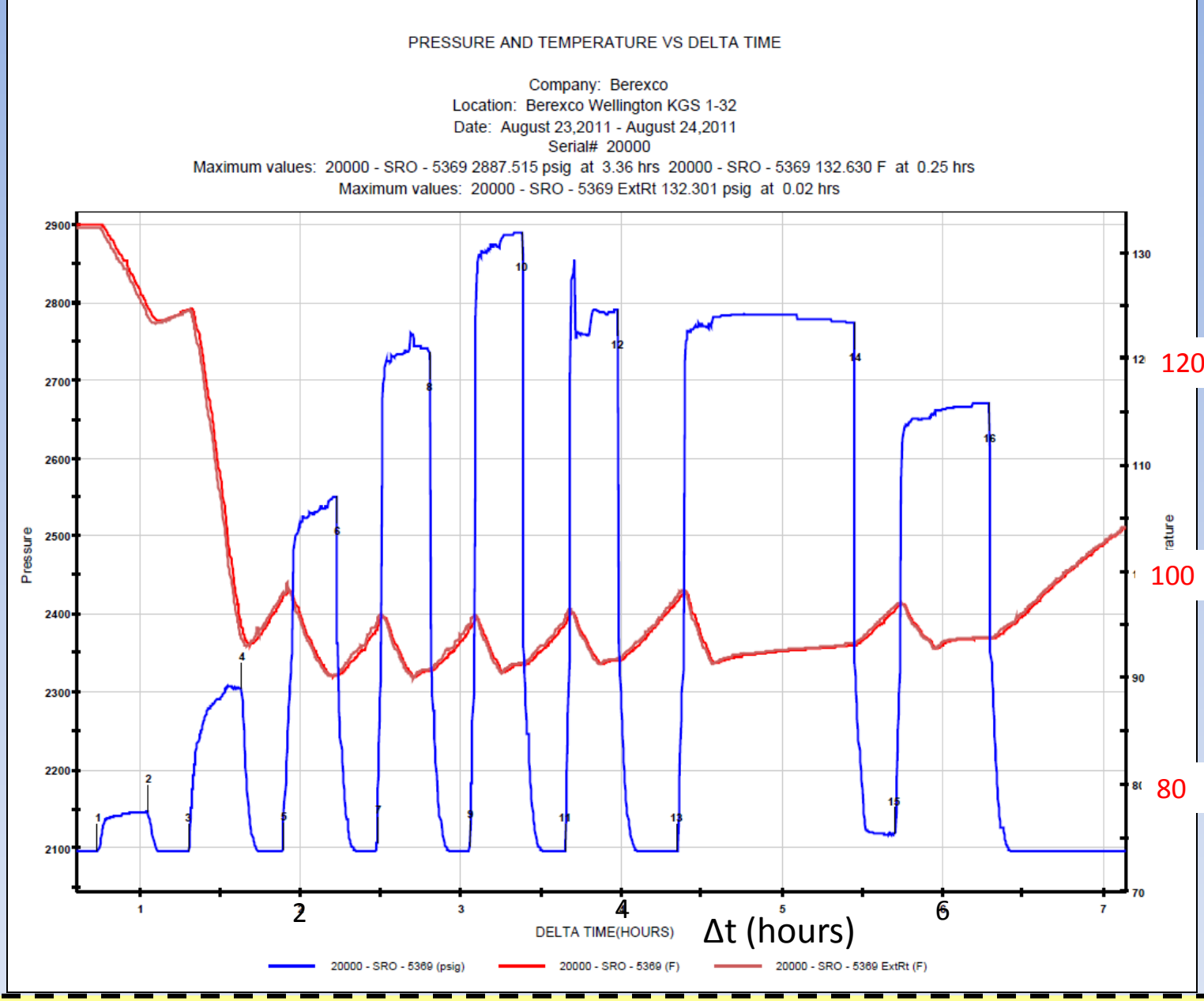


- 475 whole core analyses to be done
- Other intervals → Helical CT Scans

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



Preliminary upscaled hydrostratigraphic units in Arbuckle Group



2900

2100

Pressure (psi)

120

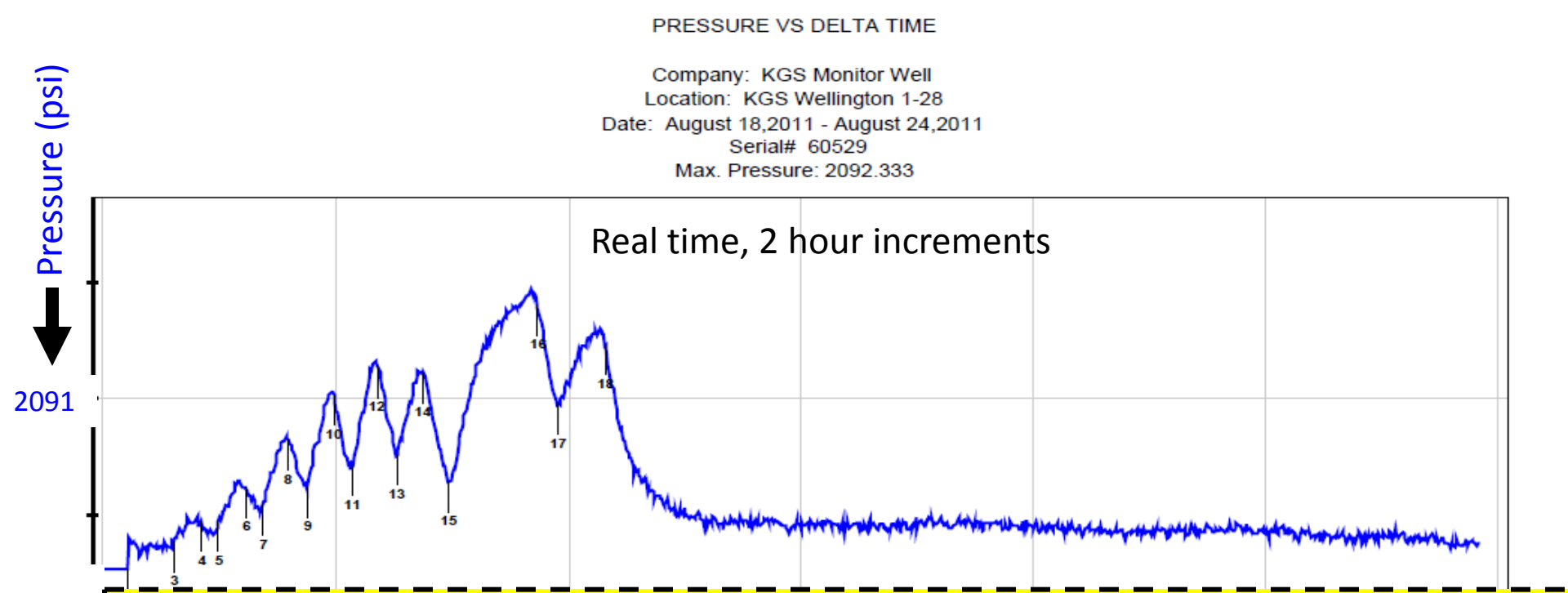
100

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.



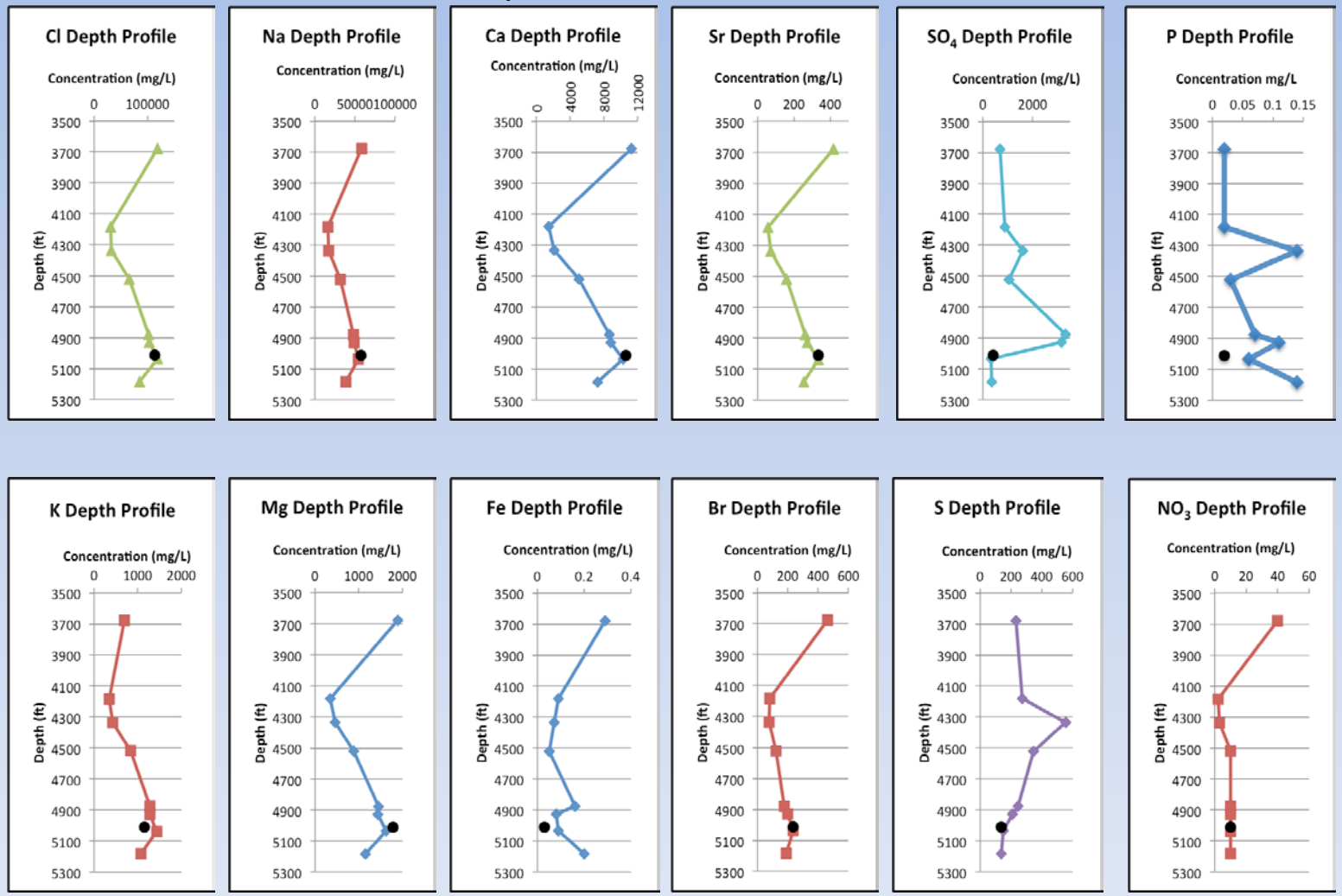
STEP-RATE TEST RESULTS: Pressure response in Berexco Wellington KGS #1-28 matches pressure pulses introduced into #1-32

- 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.

Hydrogeochemistry
Datta and Barker, KSU

DEPARTMENT OF GEOLOGY
KANSAS STATE UNIVERSITY

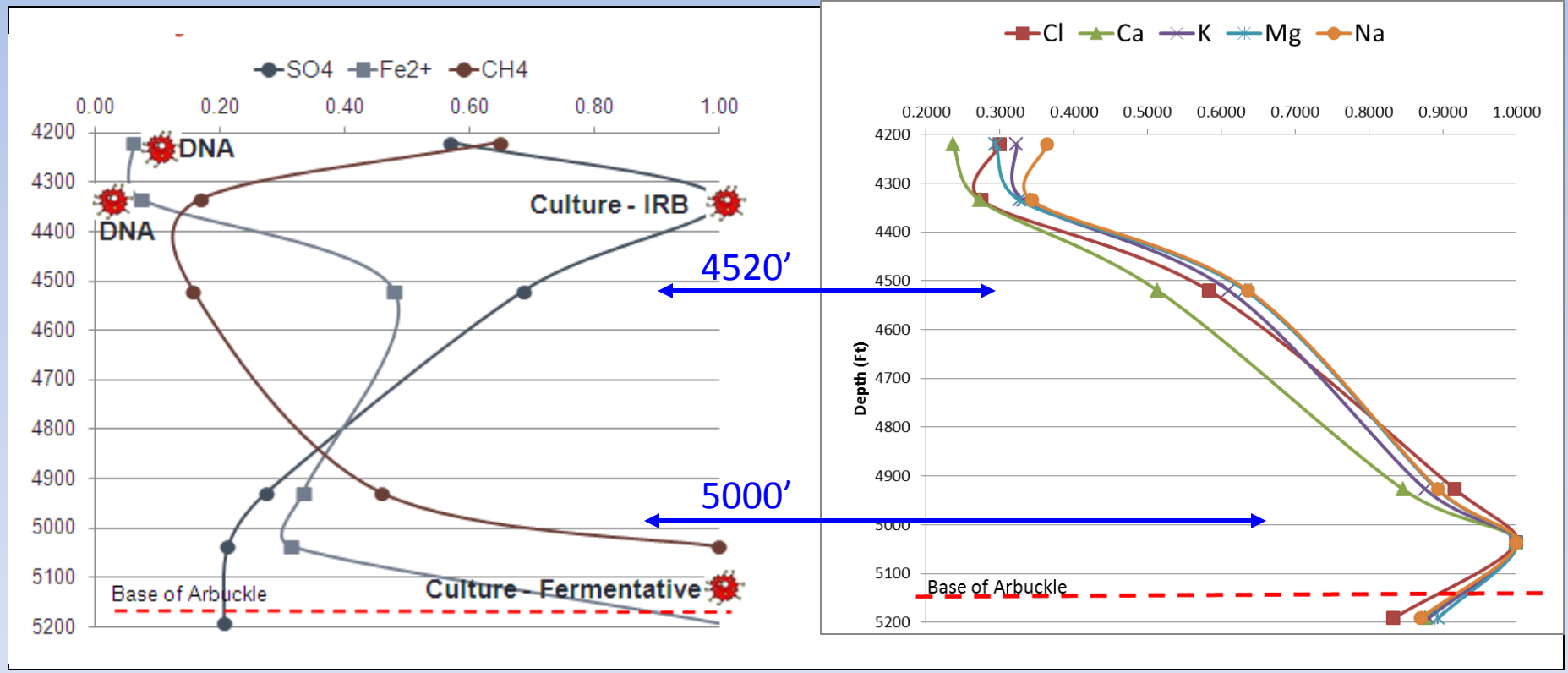
Depth profiles of DST (connected line) and first swab test (black dot)
Top Arbuckle @ 4160 feet



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



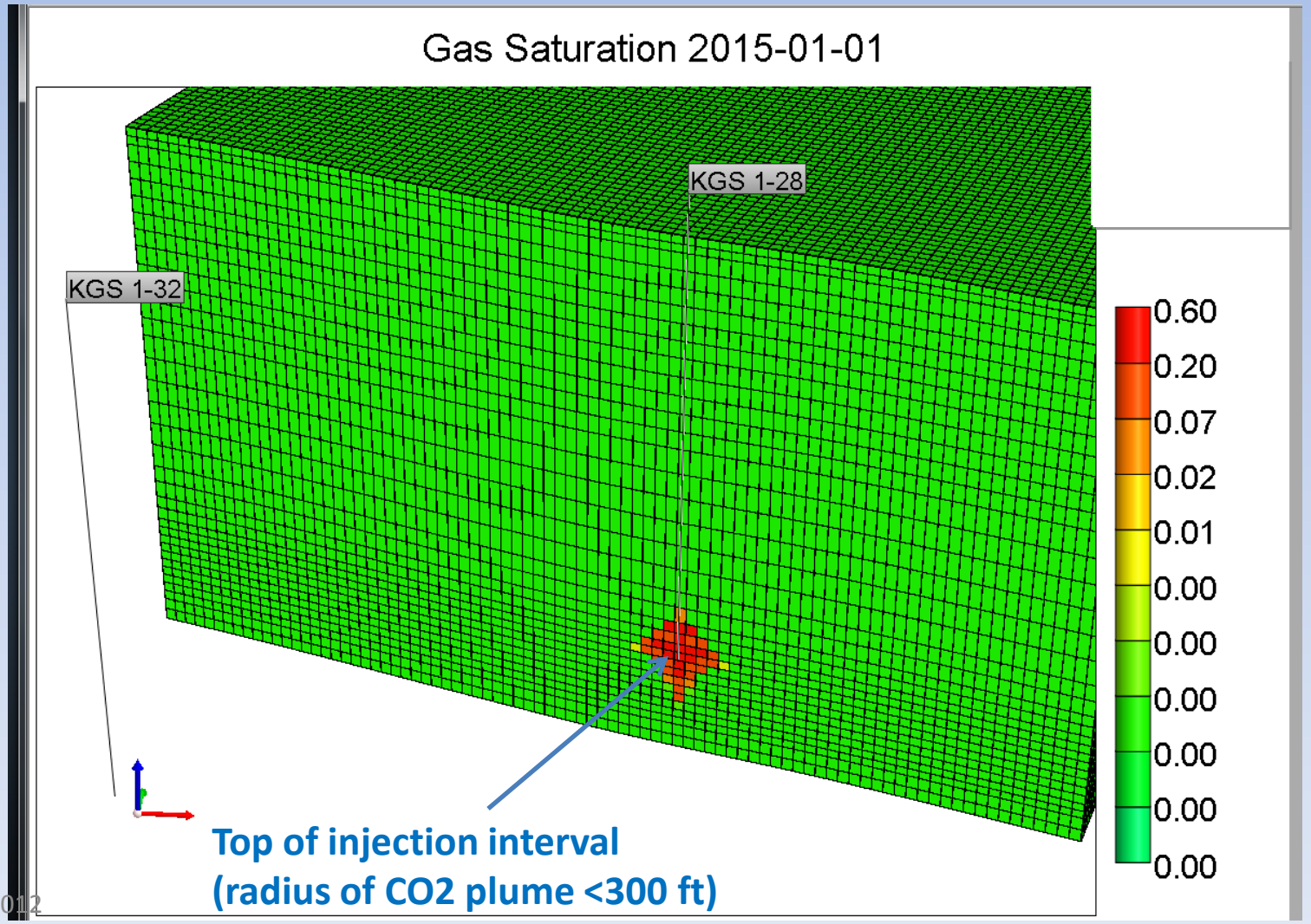
- @ 4520 ft -- Changes in brine composition and microbes at (also low DOC & PO4) indicate low microbiological activity, corresponding with low Ø & k
- @ 5000 ft – microbial anomaly suggesting availability of nutrients corresponding with high Ø & k (in interval with step rate test)

Injection Scenario – Start on Jan 1, 2011 (for 9 months)

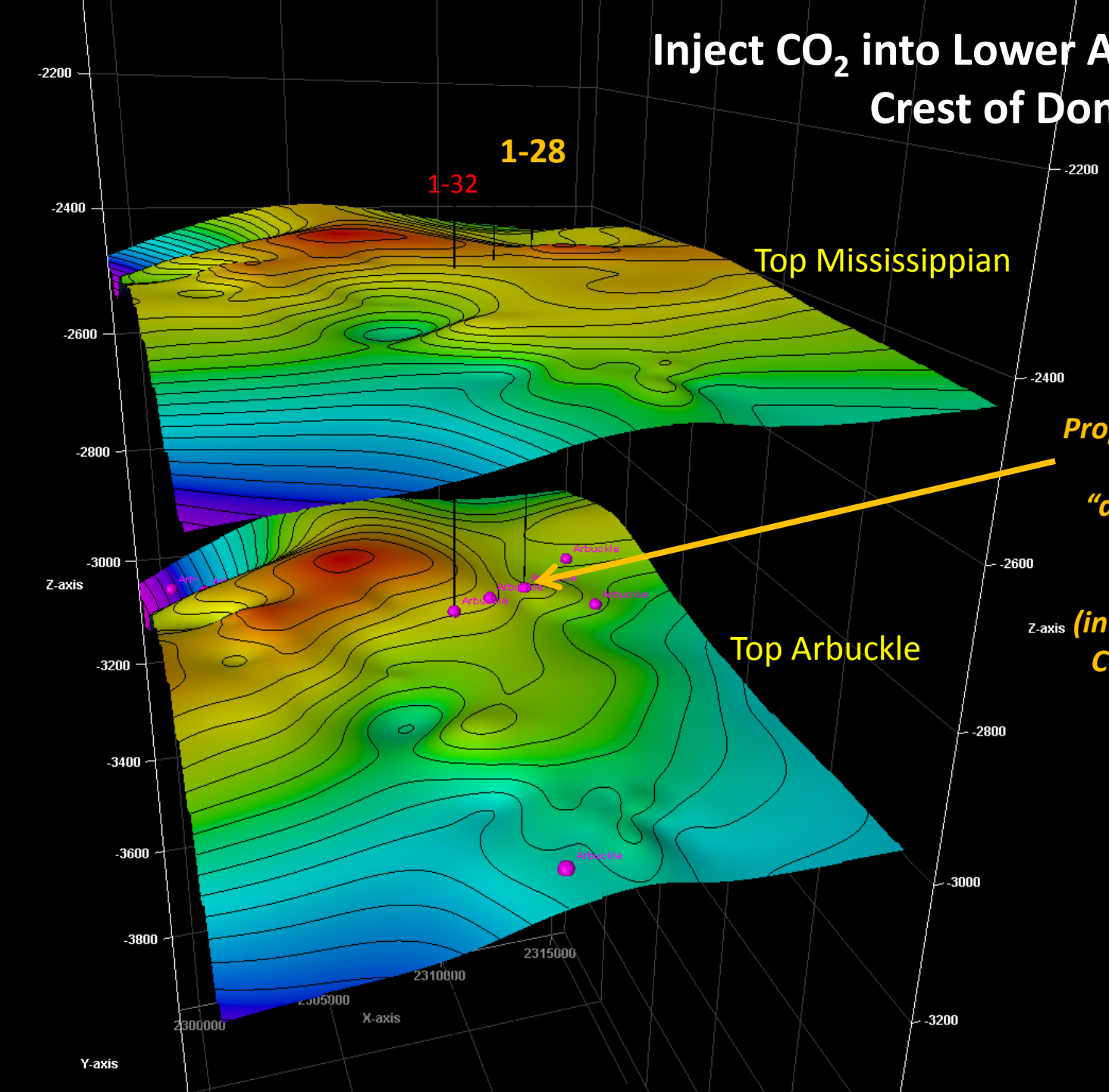
Grid cells 60’ by 60’

Total CO_2 injected ~ 40,000 tons

Injection layers – L25 to L30, each ~20 ft thick, 120 ft total



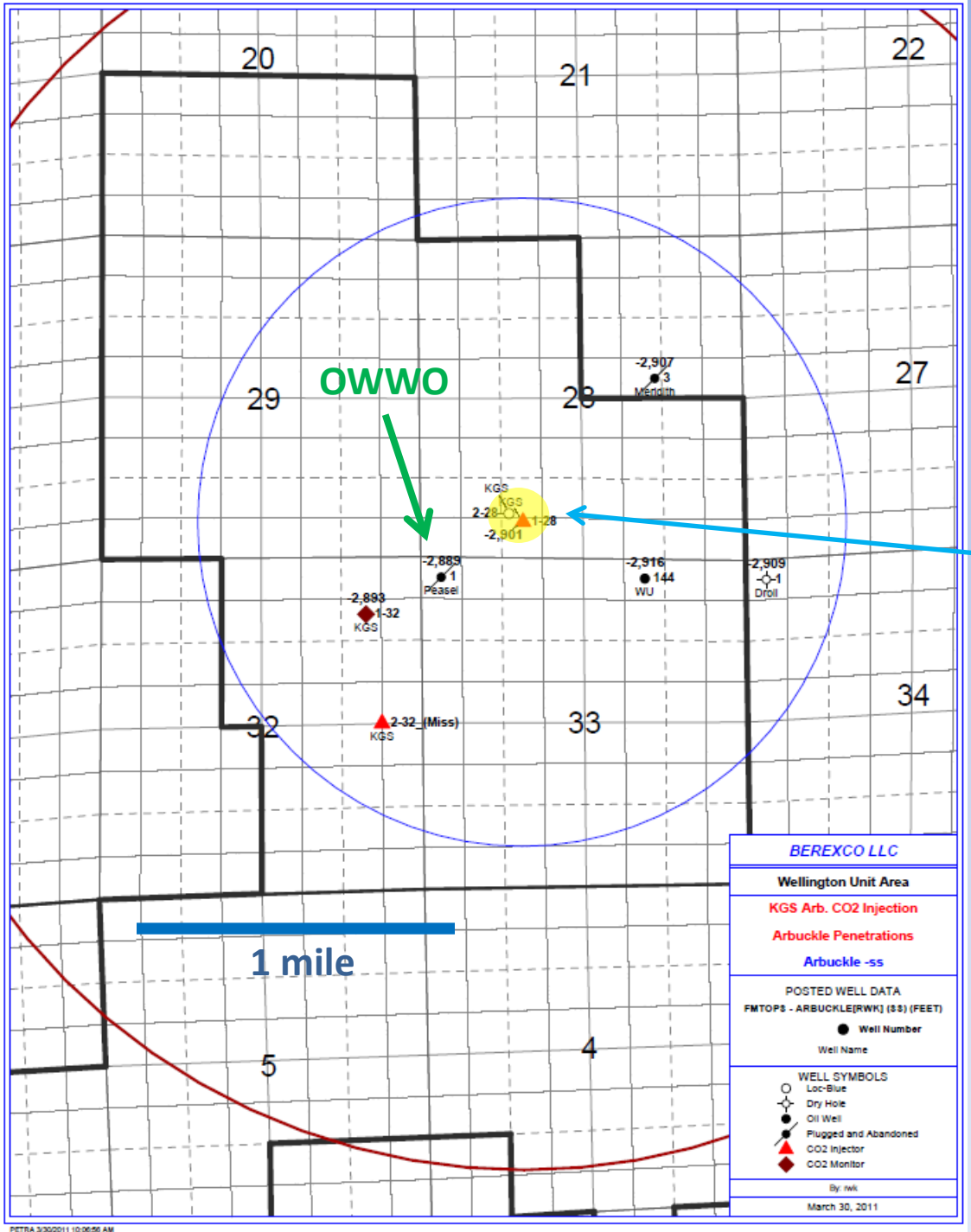
Inject CO_2 into Lower Arbuckle Near Crest of Dome



Proposed – convert new well, #1-28 to CO_2 "disposal" well in the lower Arbuckle

Z-axis ***(in location offset from CO2-EOR pilot in the Mississippian)***

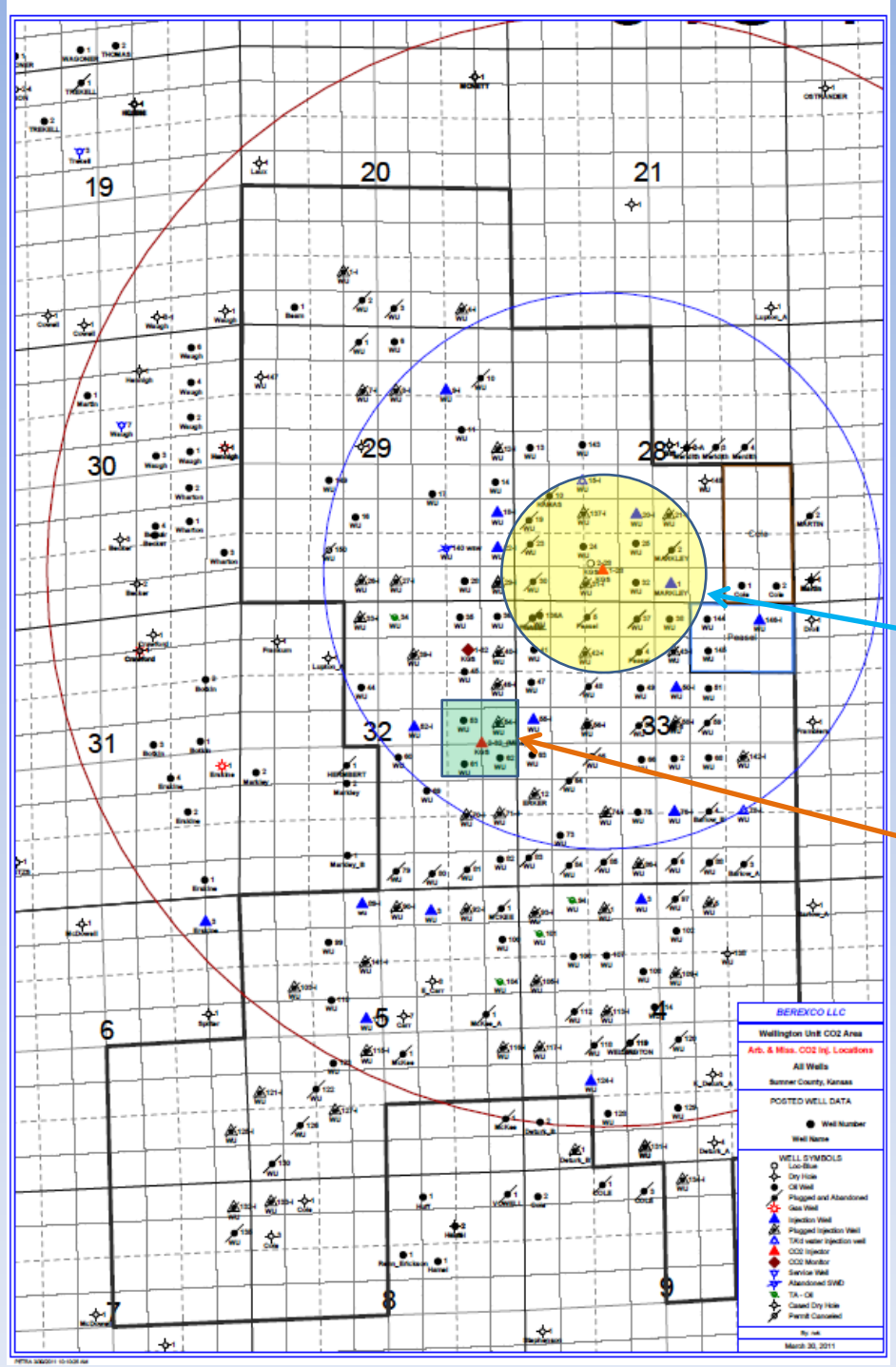
North



Map showing boreholes that penetrate the Arbuckle saline aquifer in Wellington Field

- Proposed monitoring borehole (#2-28) within 300 ft of the existing #1-28 borehole to be converted into CO_2 injector for small scale field test

- Yellow dot shows estimated size of CO_2 plume after injection of 40,000 tonnes in 120 ft interval of lower Arbuckle based on preliminary simulation results



Map showing boreholes that penetrate into the Mississippian oil reservoir in Wellington Field

- Location of Mississippian boreholes to be monitored during and after CO_2 injection into the Arbuckle

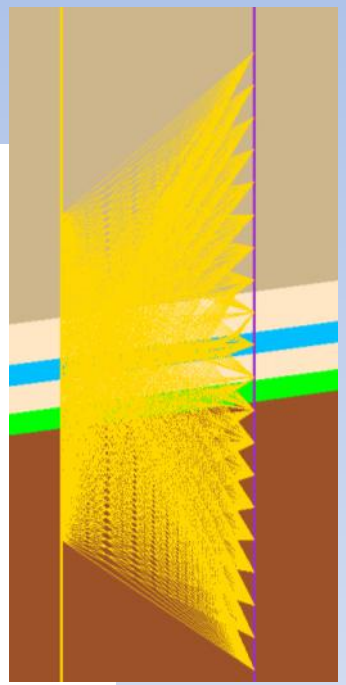
- Location of Mississippian injection borehole and 5-spot pattern of producing boreholes

1 mile

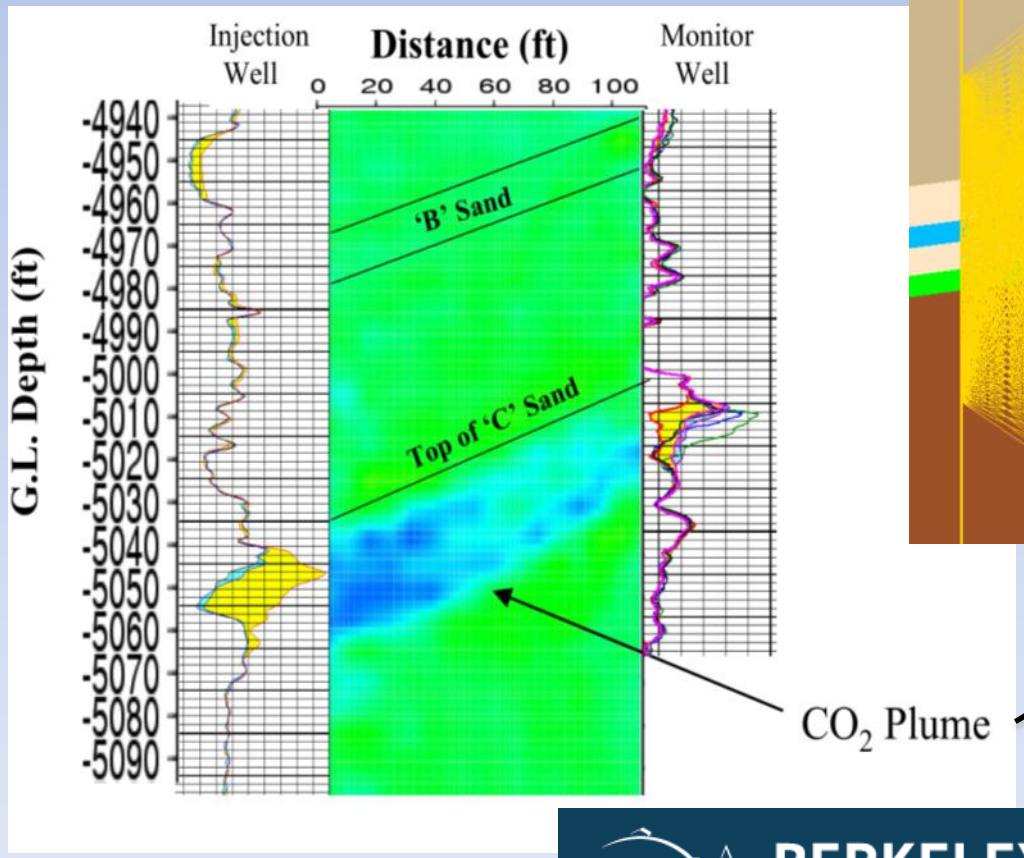
In Situ Monitoring of CO_2 Plume

Example Time Lapse Crosswell Imaging of CO2 Plumes

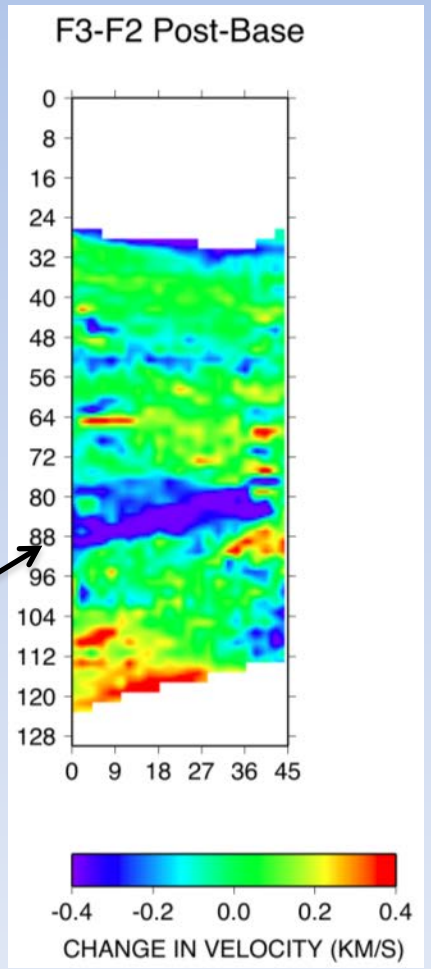
Schematic Crosswell



Frio-I 2004

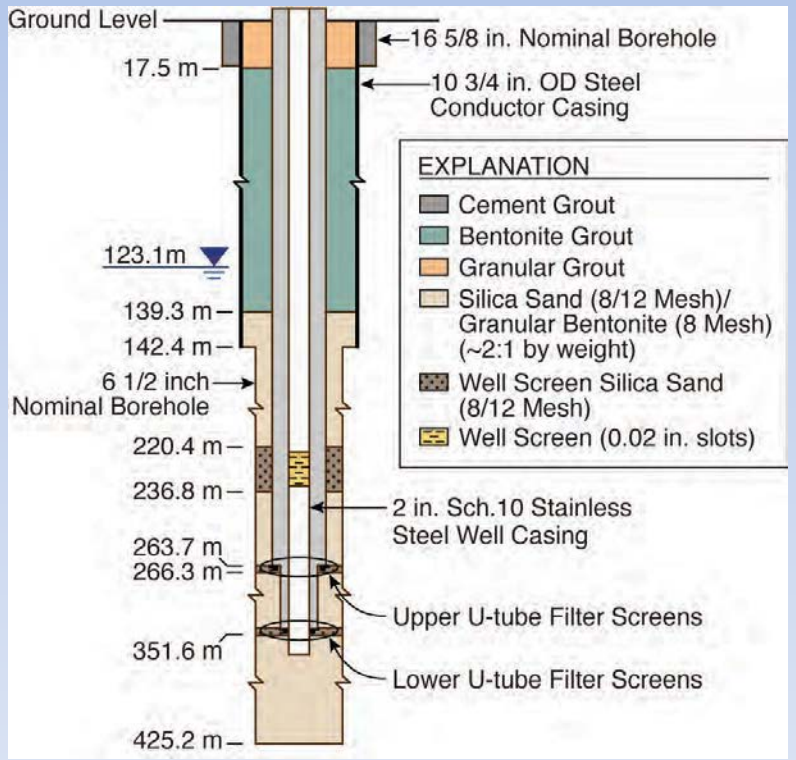


Cranfield 2010



U-Tube In Situ Sampling of CO_2 Plume

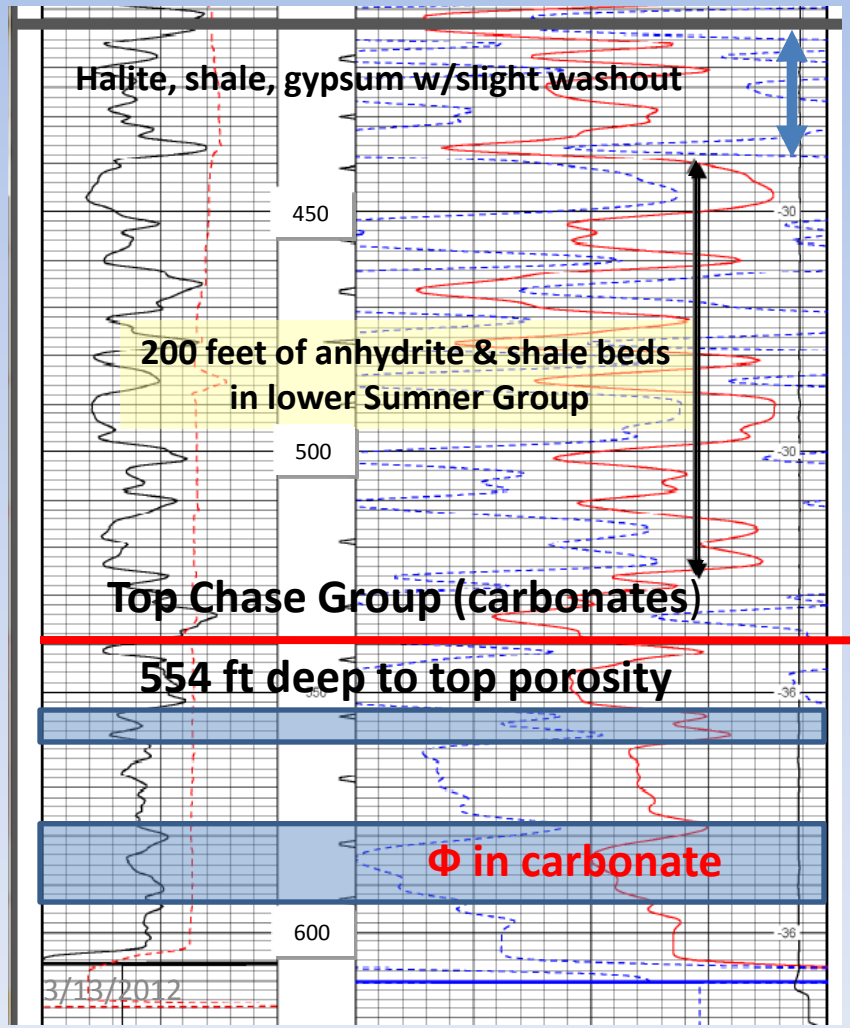
- Handling of multiphase fluid collected at high frequency



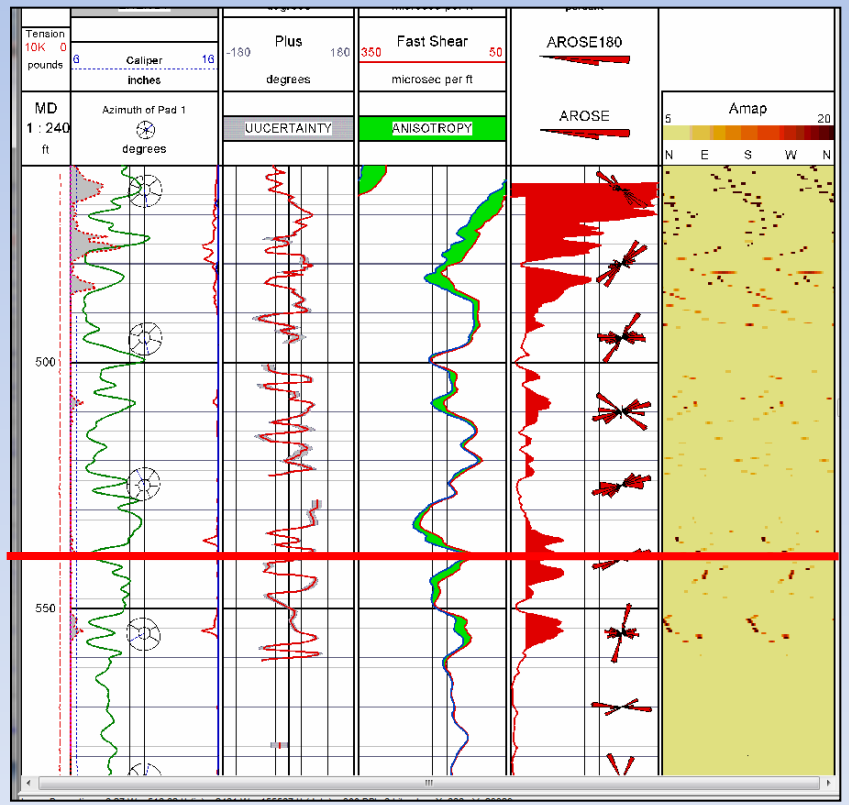
Shallow Evaporite Beds as Logged in KGS #1-32

→ Effectively isolates shallow freshwater aquifers from more deeply buried brine aquifer system

GR (black, solid) and caliper (dashed red)
sonic Δt (red solid), phi (blue dashed)



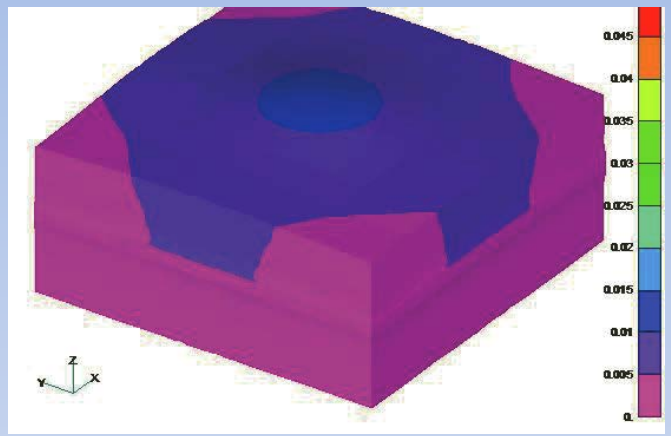
Full-waveform sonic



LiDAR and InSAR to Detect Any Surface Deformation Associated with CO_2 injection

Mike Taylor, University of Kansas

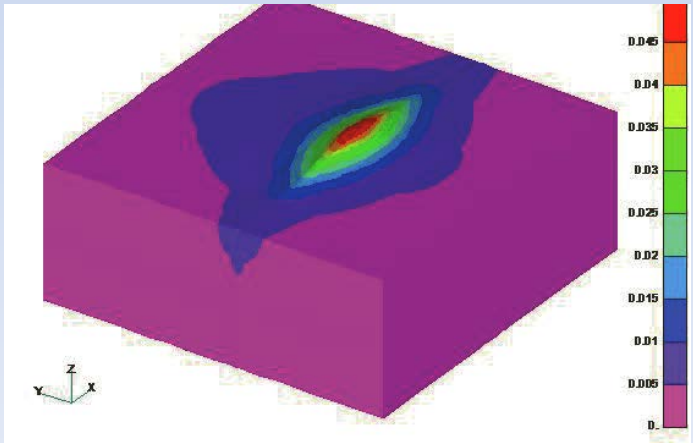
- C-GPS
- IRIS seismometer
- Terra sar x (radar data)
- LiDAR



Simulated vertical displacement (in meter) after 3 years of CO2 injection (top) without and (below) with a permeable fault intersecting the caprock.

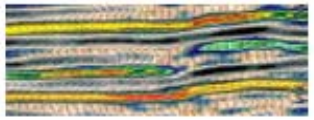
- Injection depth =6000 ft
- Injection interval = 60 ft thick
- Max pressure ~10 Pa above ambient
- Injection rate = 1 MM tons per year
- Observed surface displacement = 10 mm

Modeling Ground Deformation at In Salah

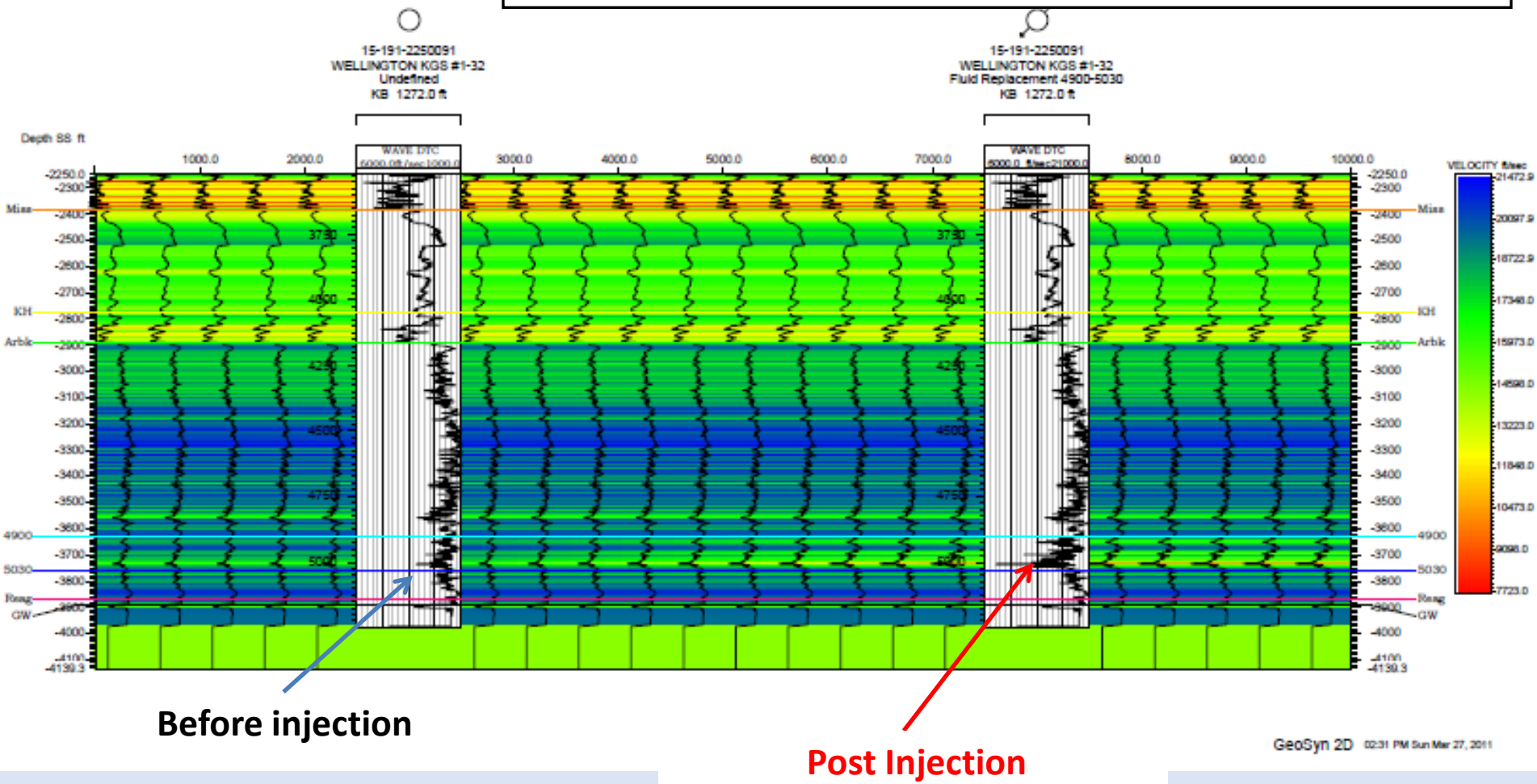


Coupled reservoir-geomechanical analysis of CO2 injection at In Salah, Algeria (CO_2 sequestration Project)
Rutqvista, Vascoa, Myera (2009)

HEDKE-SAENGER GEOSCIENCE, LTD



- **Can seismic methods detect the CO2 plume in injection zone in the lower Arbuckle?**
  - **Modeled CO2 plume using Gassmann fluid substitution**
  - **Assume 50% water saturation post injection**
  - **Answer is <u>YES</u> prior to having inversion modeling done**



Before injection

Post Injection showing detectable gas effect

Summary

- Original Project Start Date Dec. 8, 2009; End date: August 7, 2013
- $10 million project including $5 million budget enhancement 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 February 2012
- Geochemistry & Geobiology – ongoing into 2012
- Revise Geomodel & Simulation – early 2012

NETL

KSCO2

KU KANSAS GEOLOGICAL SURVEY The University of Kansas

Summary

- Start Date: October 1, 2011
- Inject Arbuckle: April, 2013
- Inject Mississippian oil reservoir: June, 2014
- End Date: September, 2015
- The Participants: KU/KGS, KSU, LBNL, Sandia Technology, Berexco, LLC, Abengoa Bioenergy, Tiraz Birdie – Consultant, Lawrence, KS
- Mississippian reservoir underpressured, blanket-like, 0.25 psi/ft (900 psi), located above Arbuckle injection to trap leaked CO_2
- Possible use operation of Mississippian field for post-project monitoring (offered by Berexco who operates unitized field)
- Separate, offset pilot CO2 for EOR evaluation in Mississippian reservoir
- Leveraging current research at Wellington Field, site of extensive aquifer, caprock, and oil reservoir characterization that began December 2009.
- Injection & Monitoring, Verification, and Accounting of CO_2 will be evaluated as appropriateness and cost-effectiveness for MVA in Kansas with potential to be utilized by local petroleum industry.

Acknowledgements & Disclaimer

Acknowledgements

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