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

DE-FE0006821

W. Lynn Watney* and Jason Rush, Joint PIs

Jennifer Raney, Asst. Project Manager

Kansas Geological Survey

University of Kansas *presenter

U.S. Department of Energy
National Energy Technology Laboratory
FY15 Carbon Storage Peer Review
March 2-6, 2015

Presentation Outline

Project Objectives

– Demonstrate state-of-the-art MVA (monitoring, verification, and accounting) tools and techniques

– Integrate MVA data and analysis with reservoir modeling studies to demonstrate and ensure 99% CO_2 storage permanence.

Progress to Date on Key Technical Issues

– Evaluated injectivity and storage

– Characterized caprock and internal baffle

– Optimized MVA design to successfully evaluate -

- CO_2 storage for CO_2-EOR
- Saline aquifer

– Evaluating USDW & Seismicity

Plans for Remaining Technical Issues

Project wrap-up

Project Team

DOE-NETL Contract #FE0006821

KANSAS GEOLOGICAL SURVEY
The University of Kansas

L. Watney (Joint PI), J. Rush (Joint PI), J. Raney (Asst. Project Manager), T. Bidgoli, J. Doveton, E. Holubnyak, M. Fazelalavi, R. Miller, D. Newell, J. Victorine *(static & dynamic modeling, well test analysis, high-resolution seismic, passive seismic, geomechanical analysis, project management)*

Brian Dressel, P.M.

BEREXCO

Dana Wreath, Adam Beren *(field operator and operations, repeat 3D multicomponent seismic)*

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

Tom Daley, Barry Freifeld *(soil gas, CASSM, U-Tube, cross well seismic)*

THE LINDE GROUP Linde

PRAXAIR Making our planet more productive

CO_2 supply

DEPARTMENT OF GEOLOGY KANSAS STATE UNIVERSITY

Saugata Datta *(fluid sampling and USDW monitoring)*

IRIS PASSCAL Instrument Center
Program for Array Seismic Studies of the Continental Lithosphere

15 seismometer array
NSF's- Portable Array Seismic Studies for the Continental Lithophere

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

T. Birdie, Lawrence, KS *(Class VI application, engineering, monitoring synthesis, reporting, closure)*

KU THE UNIVERSITY OF KANSAS Department of Geology

Mike Taylor *(cGPS, InSAR)*, George Tsoflias *(passive and active seismic)*

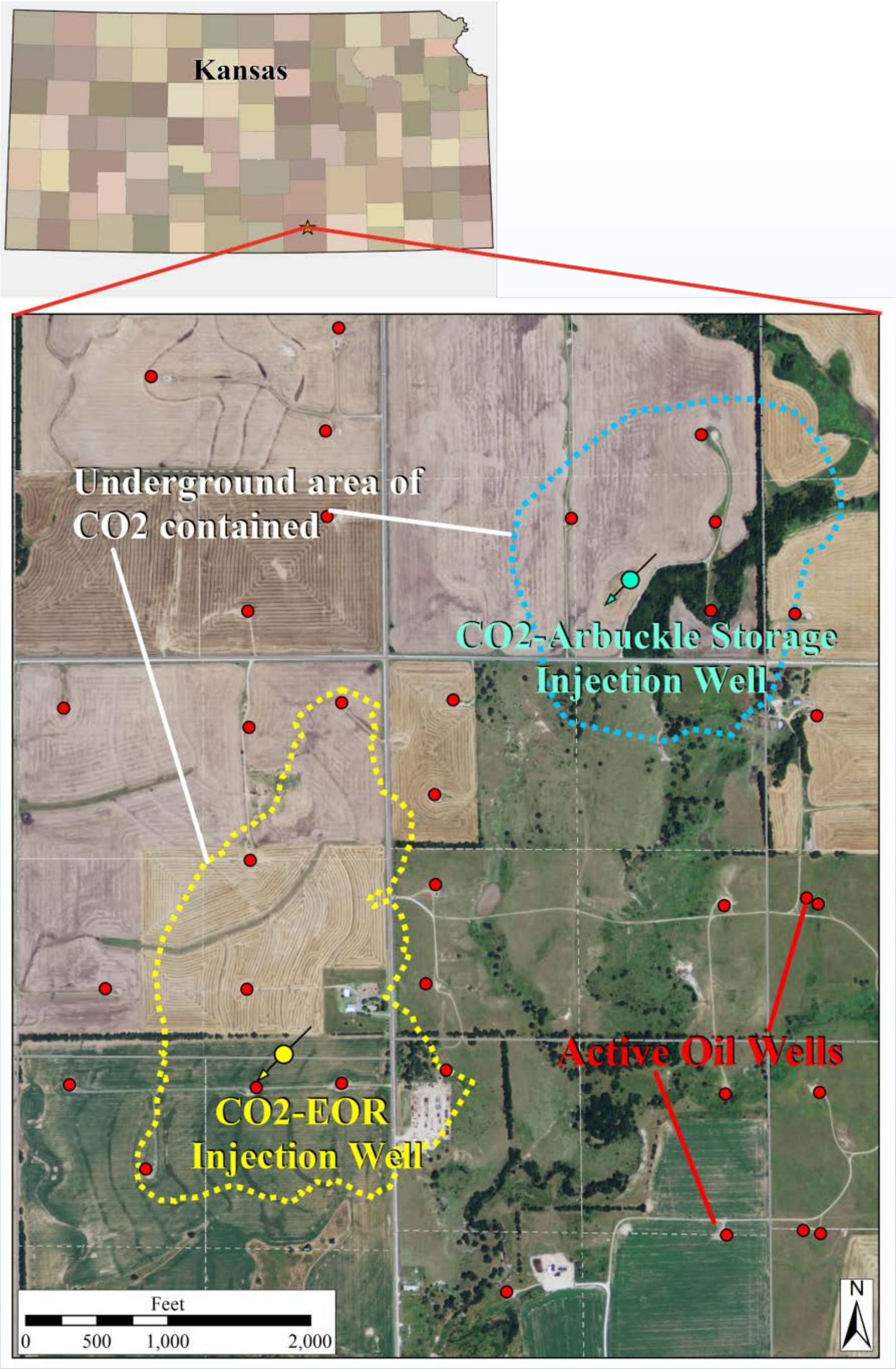
Goals and Objectives

- **Program goals being addressed :**
  - – Demonstrate that 99 percent of injected CO_2 remains in the injection zone
  - – Conduct small field test to support characterization, site operations, monitoring, and closure practices for Class VI geosequestration permit, Region 7 EPA, Kansas City, KS
  - -- Conduct small scale field test to demonstrate geosequestration and improve oil recovery from oil reservoir overlying the saline aquifer test.

- **Project benefits of this small scale field test:**
  - – Advance the science and practice of carbon sequestration in the Midcontinent and carbonate reservoirs & saline aquifers
  - – Evaluate reliable, cost effective MVA tailored to the geologic setting
  - – Optimize methods for remediation and risk management
  - – Technology transfer to local petroleum industry for implementation of CCUS
  - – Enable additional projects and facilitate discussions on regulations and policy

Wellington Field
Sumner County
Kansas

- Site at rural oil field operating since 1929
- 55 current operating wells, 20.7 MM bbls produced, 46k bbls annually
- Effective waterflood, ready for CO_2-EOR
- *Phase I* -- Approximately 26,000 tons to be injected in the Mississippian dolomite reservoir for EOR (2015)
- *Phase II* -- Approximately 26,000 tons to be injected in the Arbuckle dolomite aquifer for CO_2 sequestration (2016)



Progress to Date on Key Technical Issues

Injectivity and storage -- 2 basement tests, 490 m core, extensive log suite, multi-component 3D seismic, multiple well tests

- Flow-unit based injectivity & storage –> *Petrel static model*
- Characterize complex, multi-scale pore system typical of carbonate reservoirs
- Fracture/fault and geomechanical characterization based on core, microimaging and spectral sonic logs, well tests, step-rate test, 3D seismic
- Compositional simulations to maximize CO_2-EOR oil recovery and predict fate of CO_2 in saline injection zone → *CMG dynamic model*

Caprock and internal baffle characterization

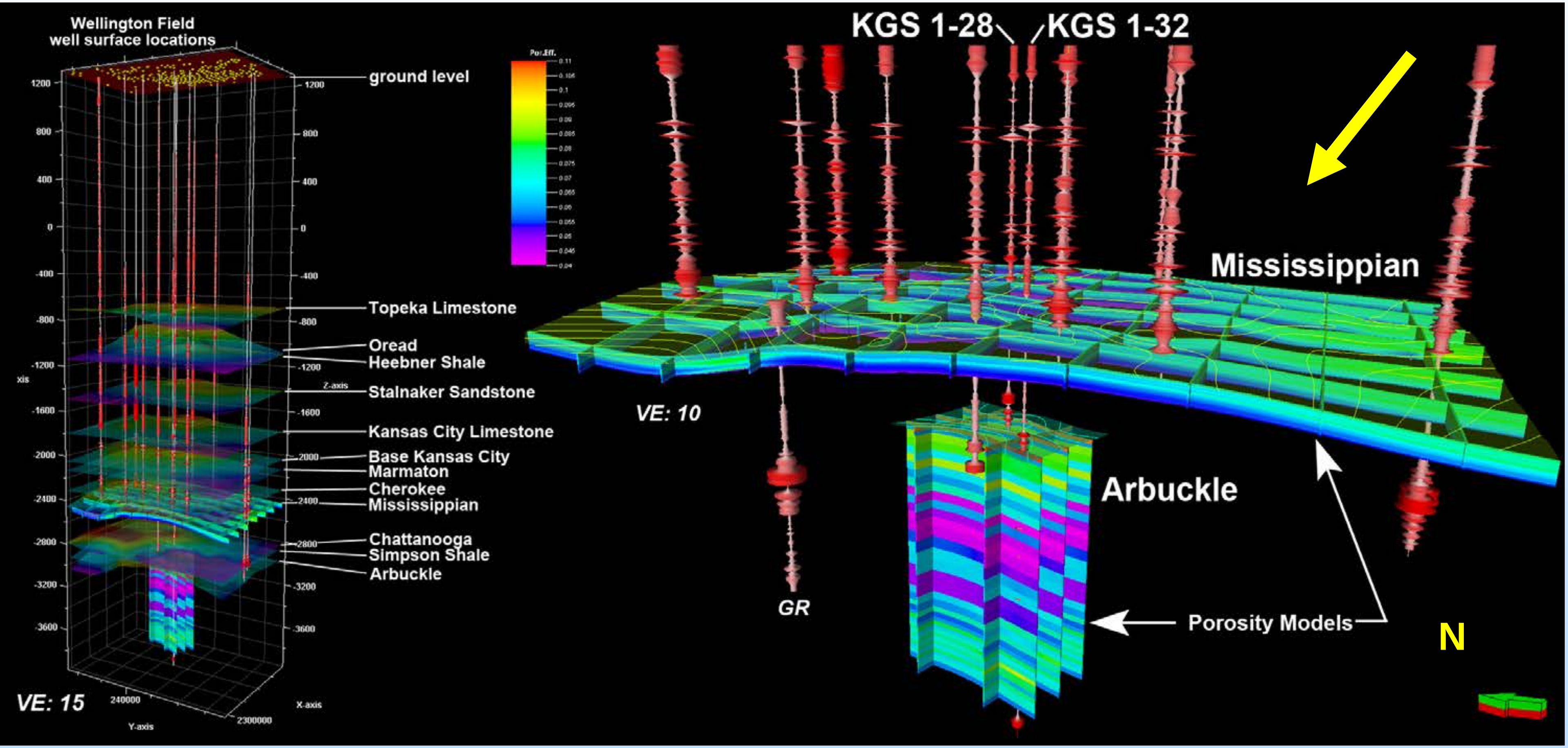
- Multi-faceted characterization using full core, imaging logs, seismic, lab tests
- In situ geochemical studies including reactive transport modeling (S. Carrol, LLNL via separate contract with NETL)

EPA permit review & assessment of water quality of the USDW

- Received only *Request for Additional Information (RAI),* but no *Notice of Deficiency (NOD)* after EPA review of Class VI application
- Drilled three shallow MVA wells to evaluate USDW
- Geochemical analysis and observations indicate non-potable, high TDS brine
- Robust static and dyamic models indicate safe injection levels substantially below regulation thresholds

Wellington Field

Mississippian Oil Reservoir & Arbuckle Saline Aquifer Showing Newly Drilled Wells and Wells with Modern Logs

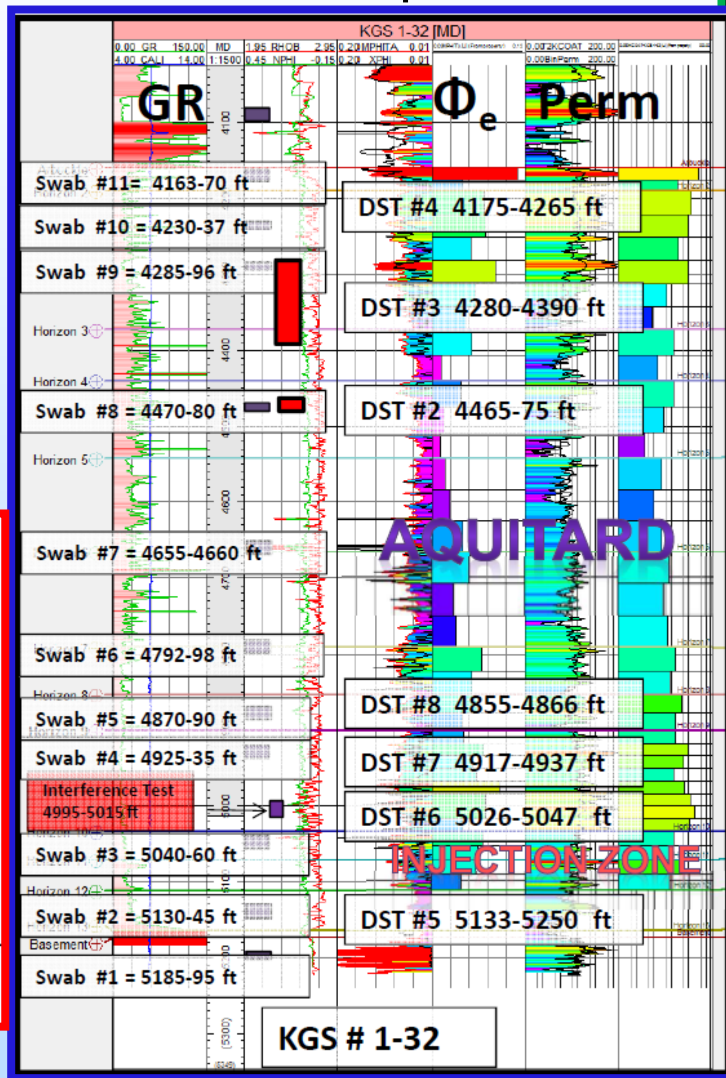


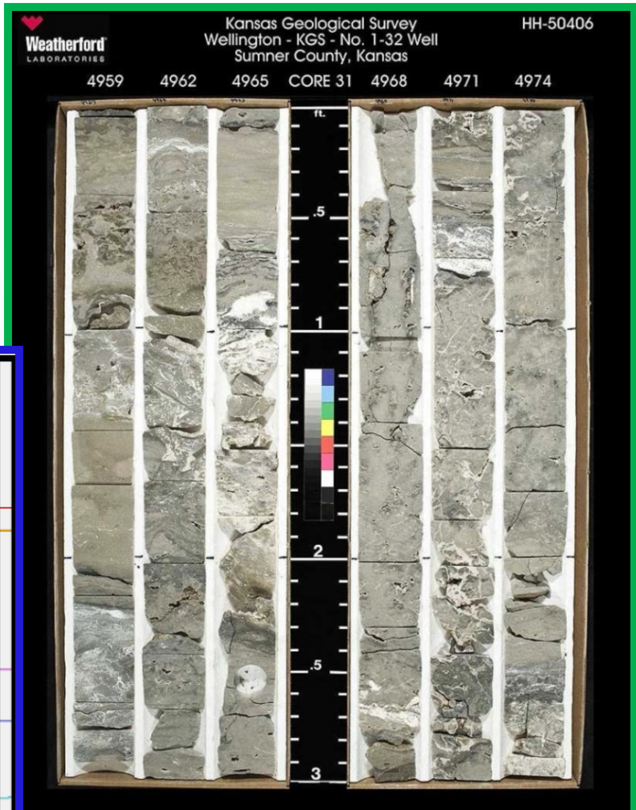
Rush, KGS

Key Technical Issues Resolved

- 2 basement tests
- Multicomponent 3D seismic
- 490 m (1600 ft) core
- Extensive log suite
- Multiple well tests

Arbuckle Saline Aquifer Interval

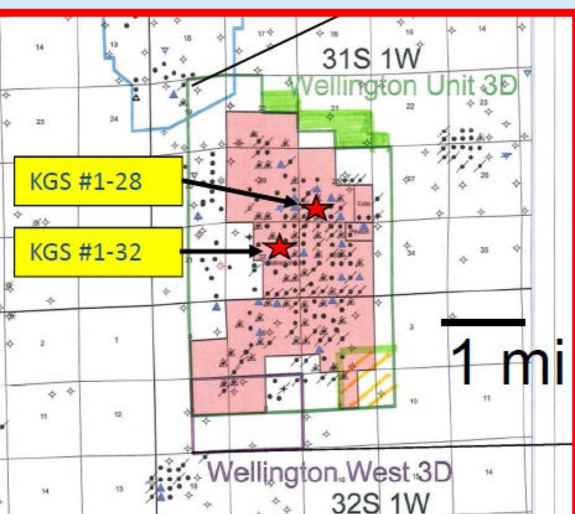




Example of core from CO_2 injection zone in lower Arbuckle

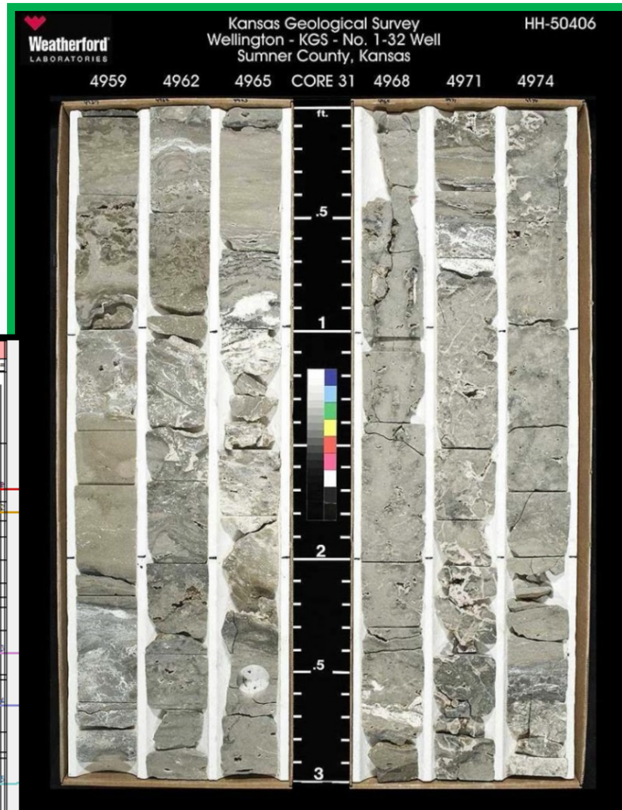
- **11 swabbing intervals and 8 DSTs targeted**
- **Evaluate both tight and high porosity zones throughout the Arbuckle**
- **Three distinct hydrostratigraphic units in the Arbuckle**

Multicomponent 3D Seismic Survey



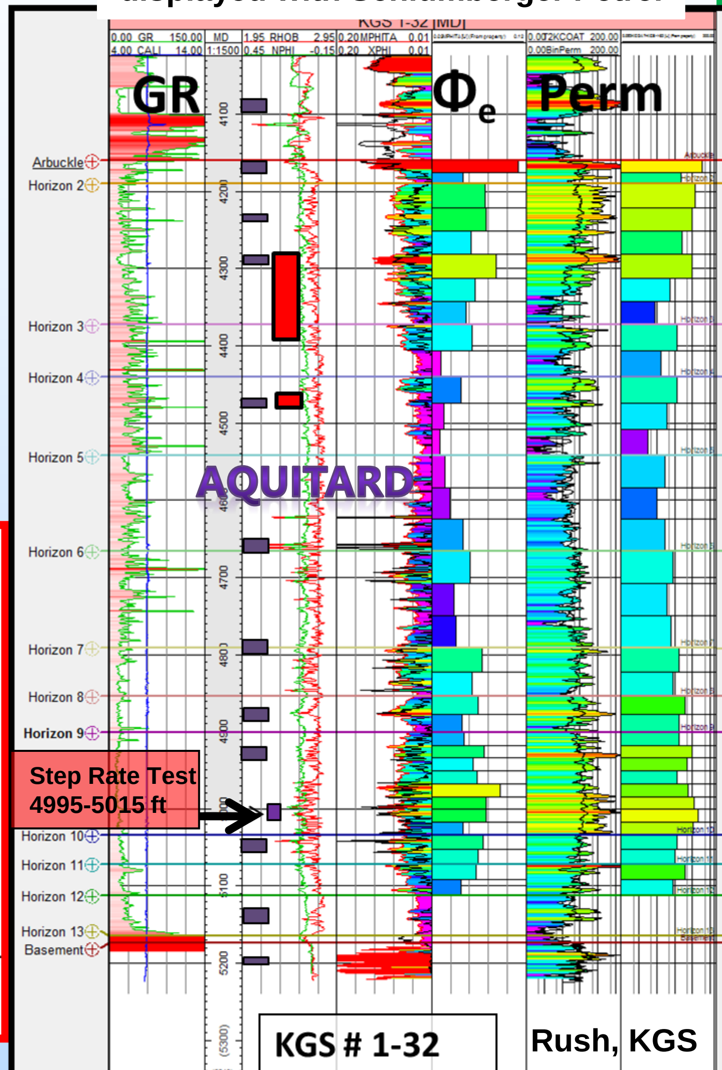
Key Technical Issues Resolved

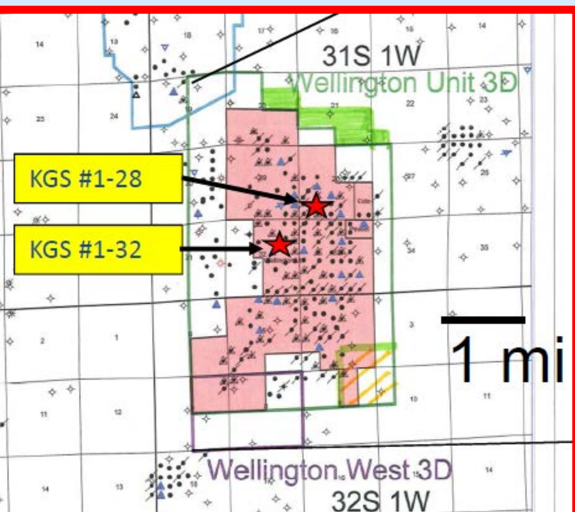
- 2 basement tests
- Multicomponent 3D seismic
- 490 m (1600 ft) core
- Extensive log suite
- Multiple well tests



Example of core from CO_2 injection zone in lower Arbuckle

Halliburton NMR log displayed with Schlumberger Petrel

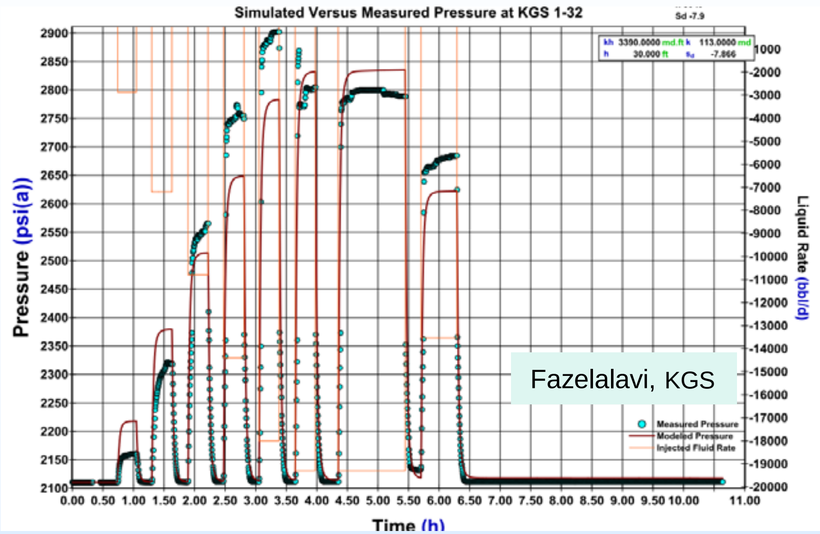




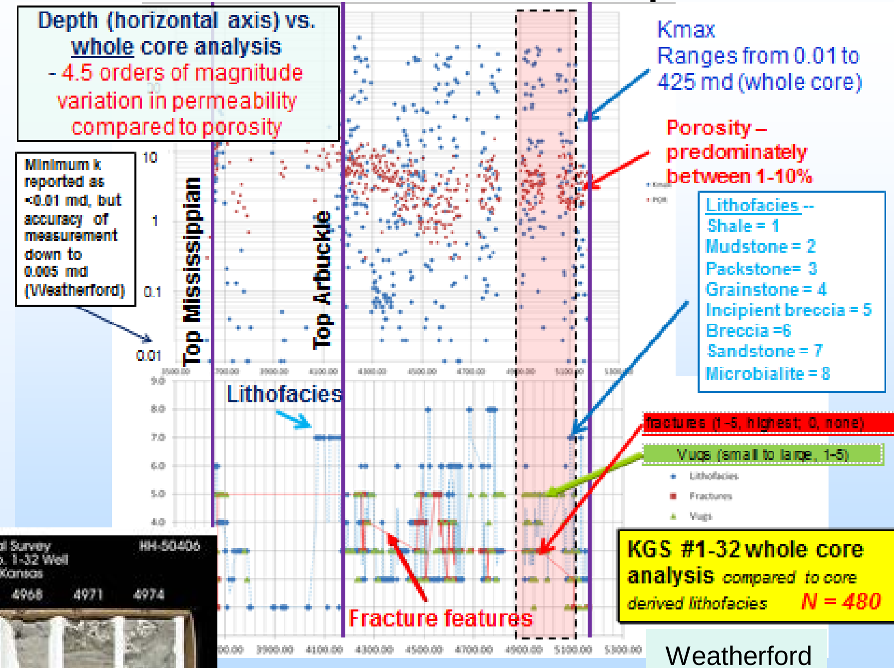
- **11 swabbing intervals and 8 DSTs targeted both tight and high porosity zones in all parts of the Arbuckle**
- **Resolved three distinct and isolated hydrostratigrahic units in the Arbuckle**

Extensive, Integrated Characterization of the Arbuckle Saline Aquifer at Wellington Field

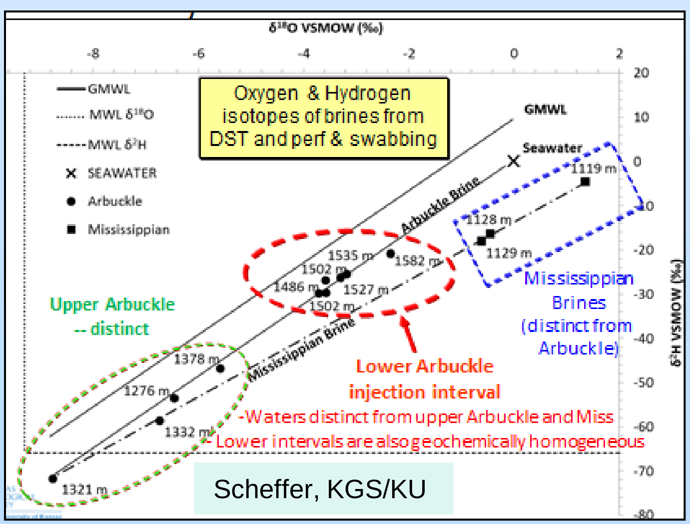
Step-rate test pressure-time plot, #1-32 & #1-28, 1 km apart

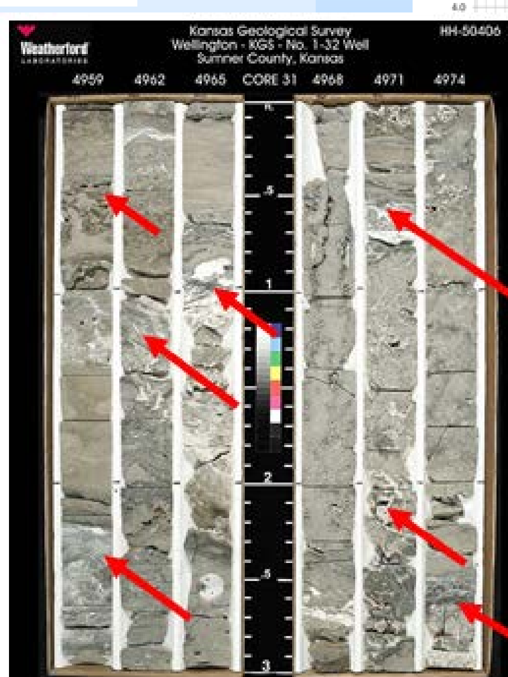


Depth vs. Φ & k, fracture features plot from 480 whole core samples

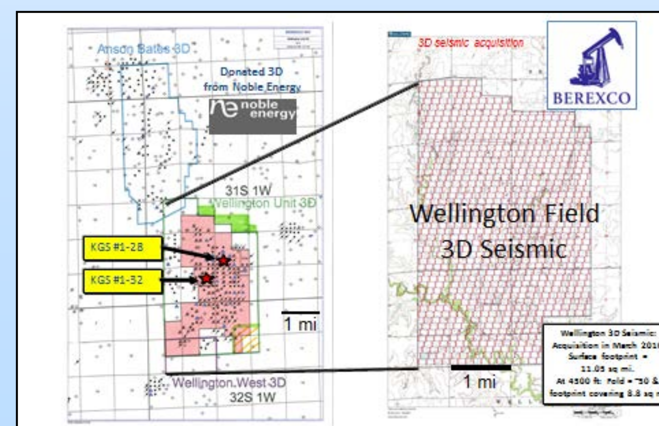


Oxygen and hydrogen isotopes → Lower and Upper Arbuckle at Wellington are not in hydraulic communication



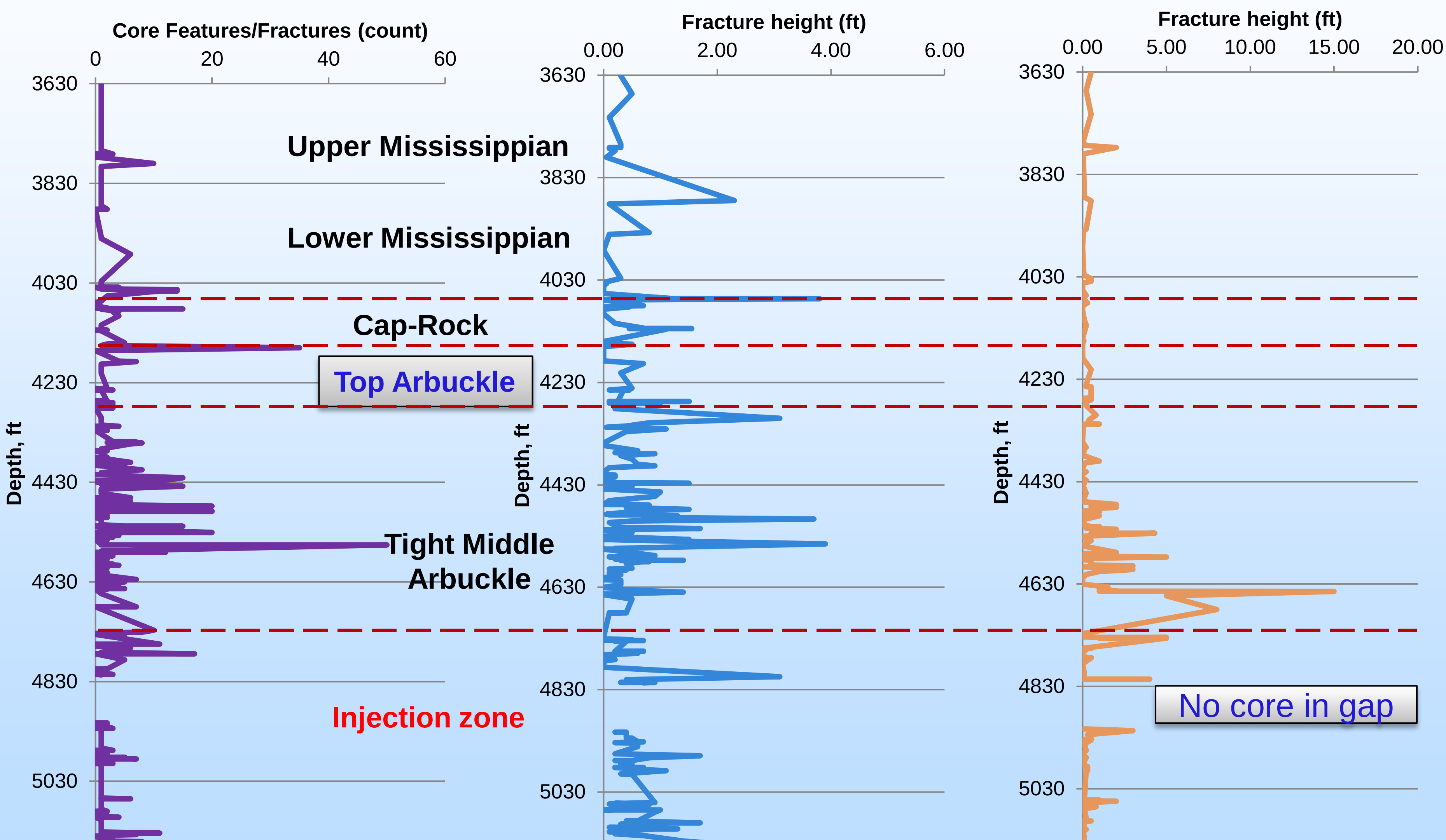


12 mi² Wellington multi-component 3D



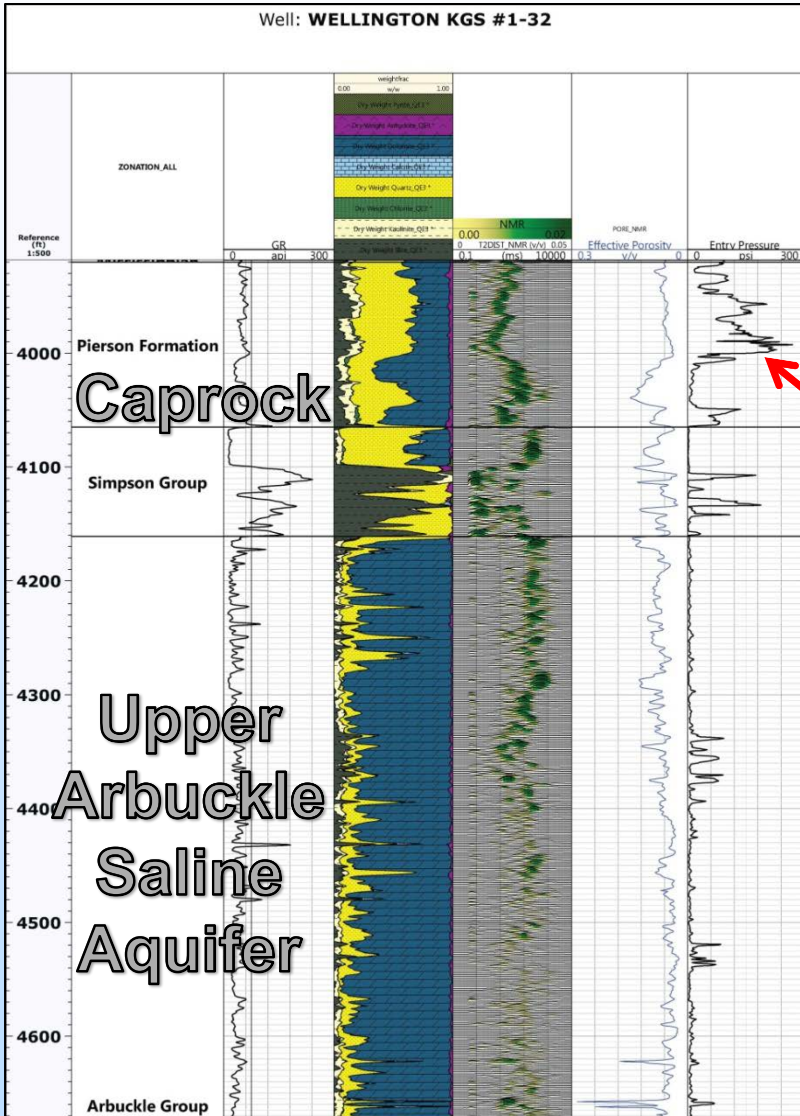
Paragon Geophysical, Wichita

Core Features/Fractures, KGS #1-32 Also Analyzed via Helical CT Scans, Microresistivity Imaging, and Dipole Sonic



Lorenz and Cooper, FractureStudies, Inc.

Confining Zone Characterization
Entry Pressure Analysis

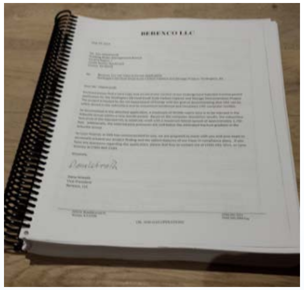


- Entry Pressure methodology applied to estimate sealing integrity of confining zone.
- High Entry Pressure in confining zone suggesting high probability for CO_2 confinement.

Using Halliburton NMR Log and Schlumberger Techlog software to display

Fazelalavi, KGS

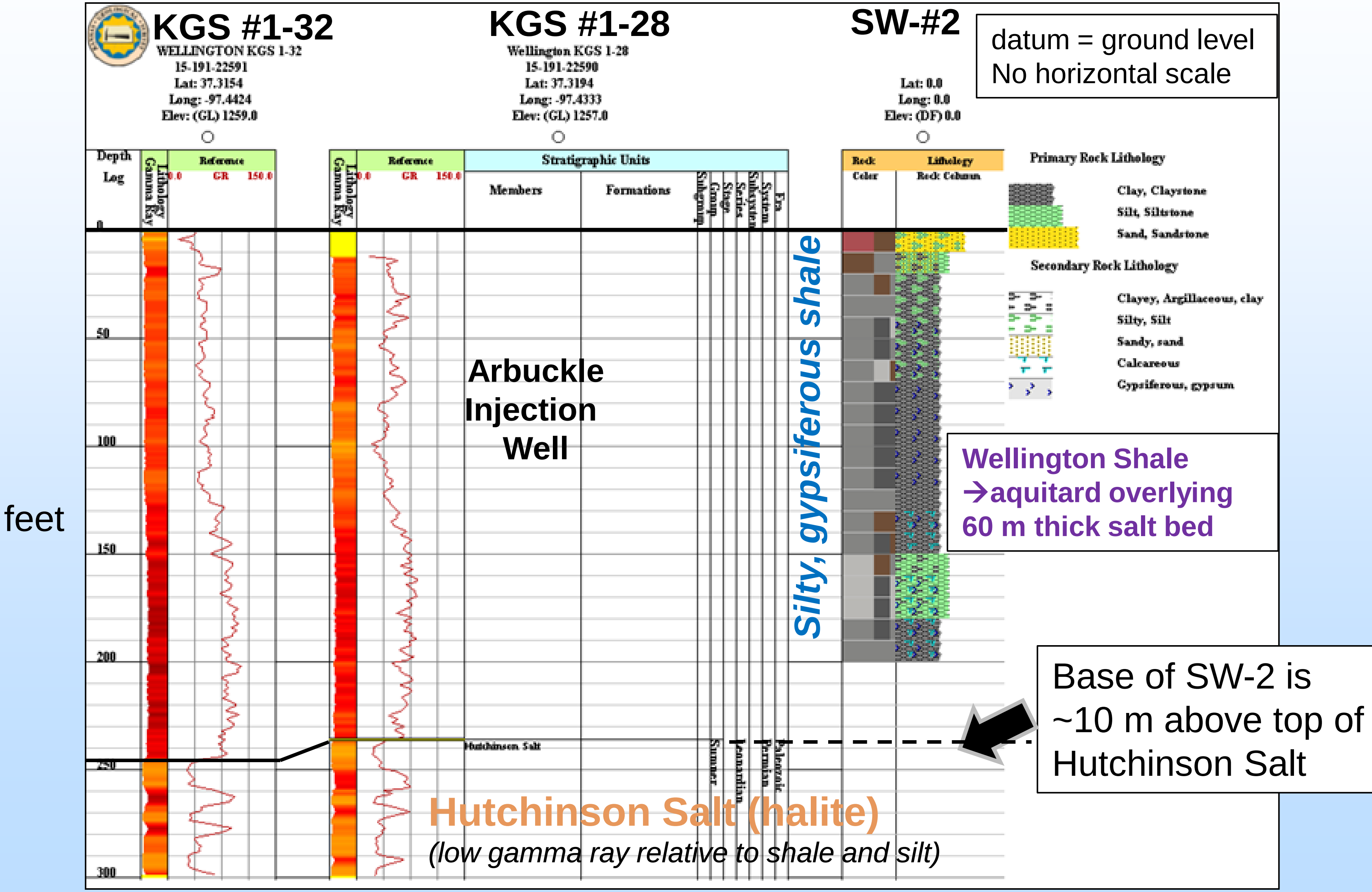
Progress to Date
Key Technical Issues



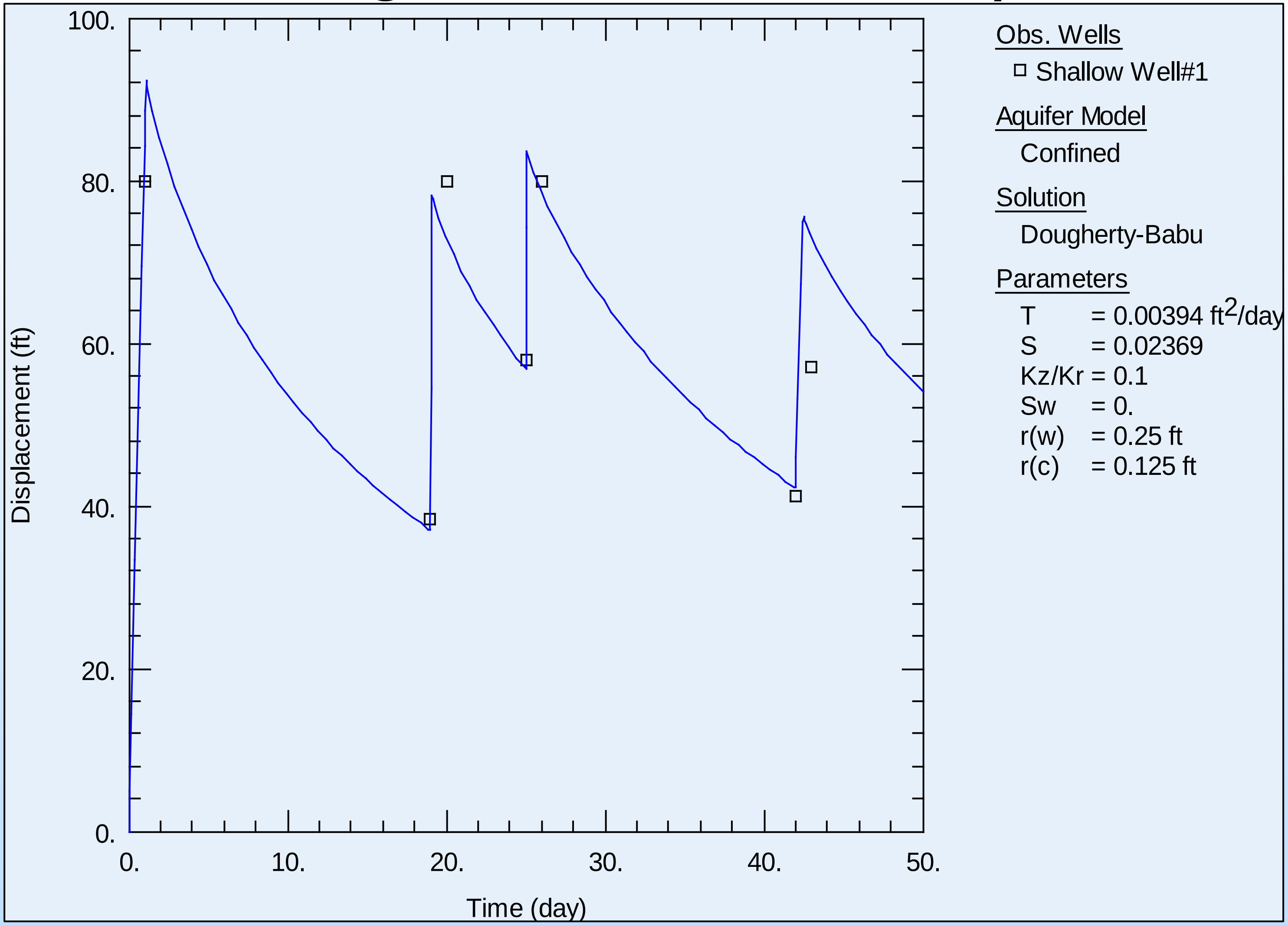
- **Milestone 1. - Submitted Class VI application, June 2014**
  - Vetted application with extensive interval review prior to submission to EPA
  - Response to EPA through 3/1/2015 – addressed questions, no USDW in AOR, final discussions to reduce financial assurance → low pressure and small lateral extent of supercritical CO_2
- *Task 5* -- Secured reliable CO_2 industrial suppliers (Praxair, Linde), July 2014
- **Milestone 2. Refined static and dynamic models of the Mississippian oil reservoir**
  - *Task 3* -- Obtained Class II to inject CO_2 in Mississippian in February 2015
  - Task 9 -- Drill Berexco Wellington KGS #2-32 in late March 2015
  - Task 10 -- Re-pressurize reservoir to prepare for CO2 injection in April-May
- **Milestone 3. Pre-injection MVA baseline recording**
  - Obtaining data from a 15 seismometer array since Fall 2014
  - Collecting data from cGPS and inSAR for processing since August 2014
  - Drilling and sampling of three shallow monitoring wells indicate low yield and high salinity (absence of USDW?)

Gamma Ray and Sample Log Cross Section

-- Evaluating characteristics of Permian Wellington Shale for USDW potential in the AOR



Permeability Estimation in Well SW -1
→ *Wellington Shale is an Aquitard*



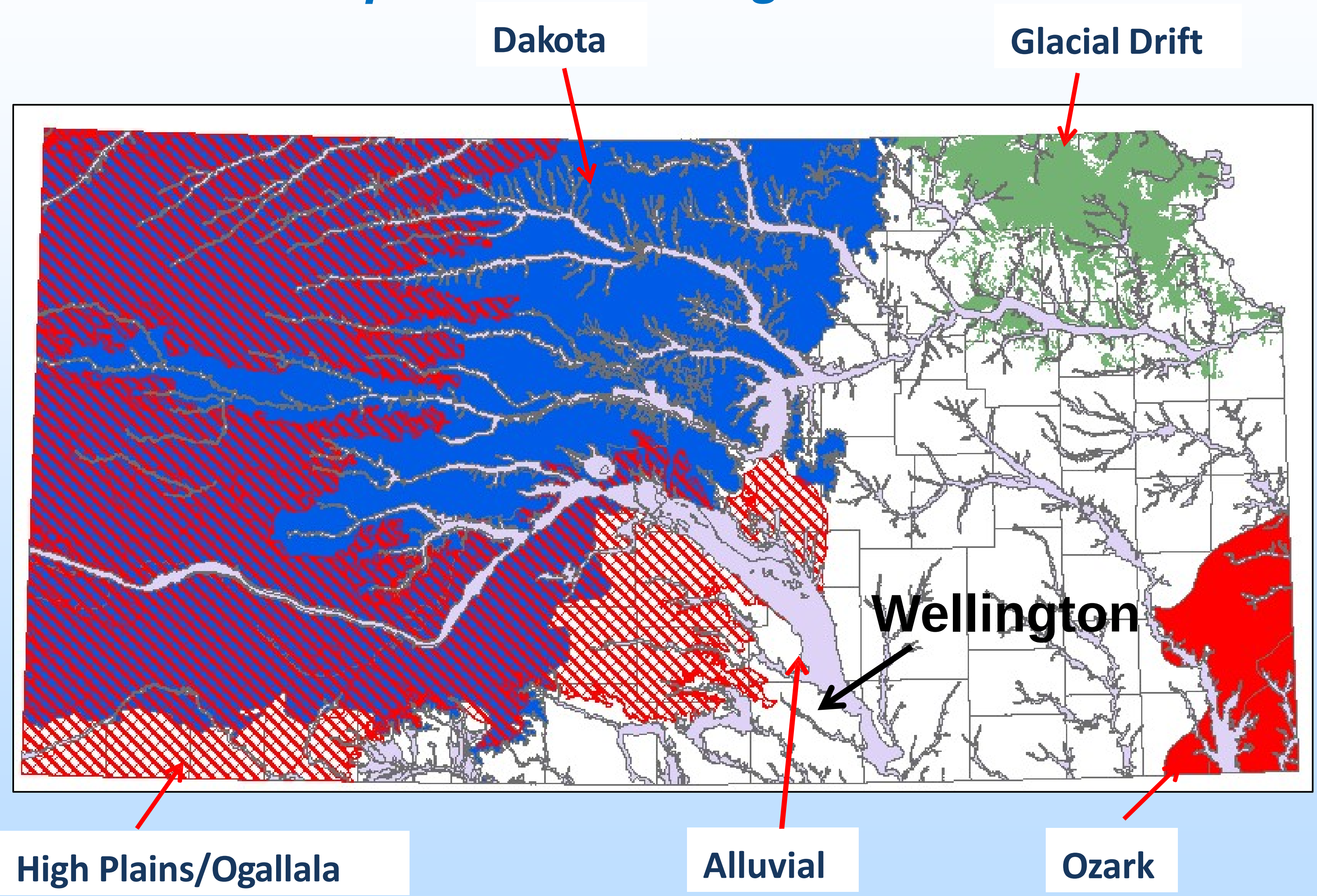
- Low permeability of 0.00005 ft/day ~0.01 md
- An aquitard with properties equivalent to a caprock

T. Birdie

Risk Assessment

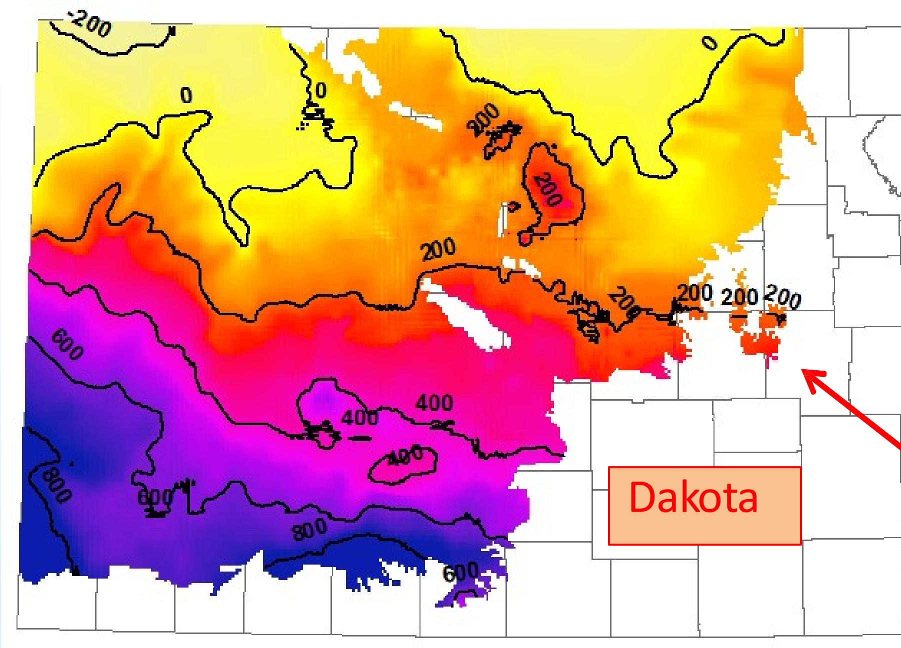
Freshwater aquifers in Kansas

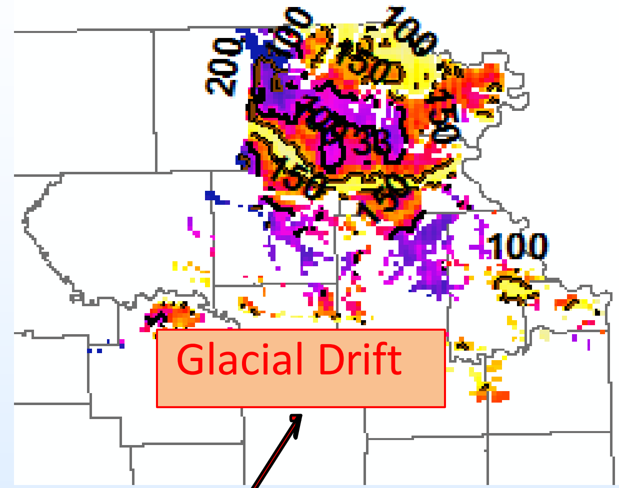
Minor aquifers in Wellington Field area

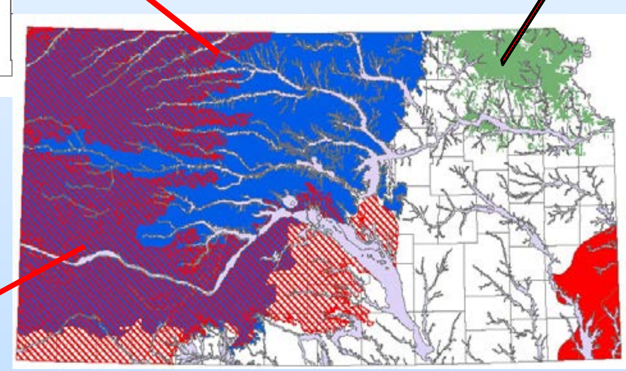


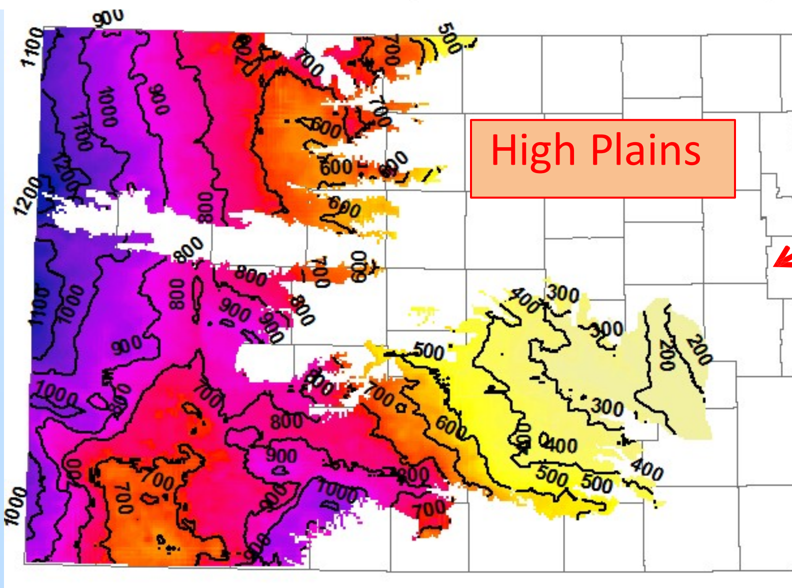
T. Birdie

Required Increase in Pore Pressure (*psi*) in Arbuckle for Migration of Brines from the Arbuckle into Freshwater Aquifers









- **Need to ensure these pressures are not exceeded if improperly abandoned wells or communicative faults are present within zone of influence**

T. Birdie

Milestone 3. Install and Operate Continuous GPS

→ *Stable baseline for InSAR study of ground motion*

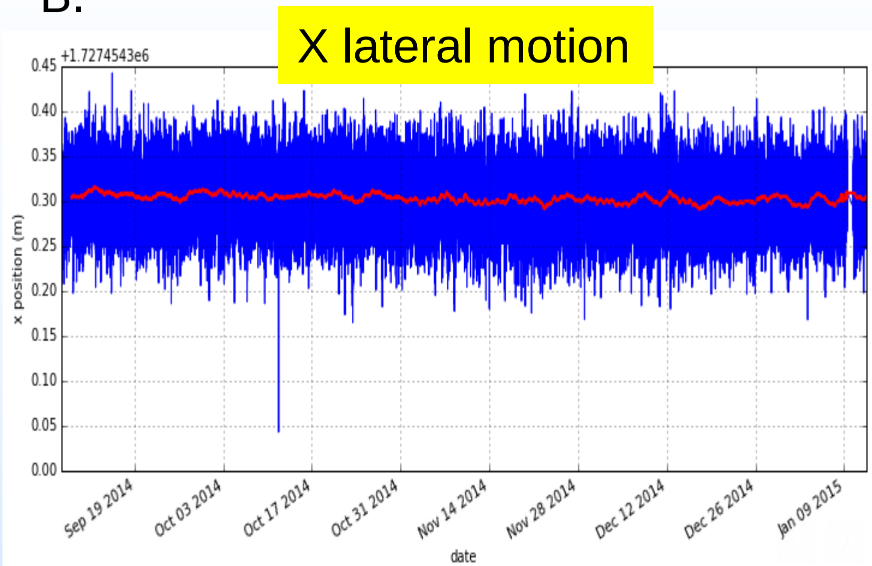
- Trimble NETR9 Receiver
- Zephyr GNSS Geodetic Antenna
- Sampling rate of 15hz
  - Monthly, on-site data collection
  - High resolution ground motion for calibration of SAR images

D. Schwab, M. Taylor, T. Bidgoli (KGS, KU)

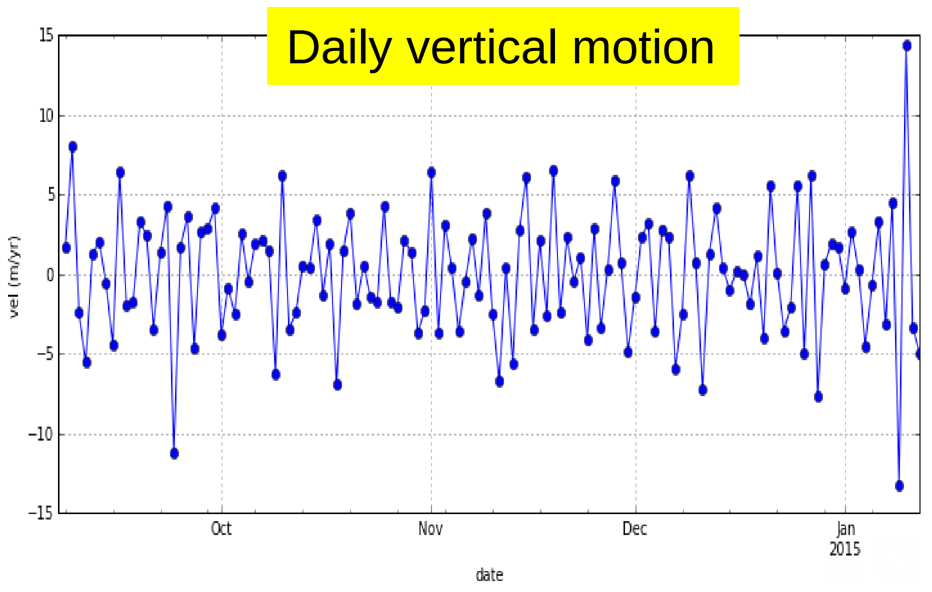
Raw cGPS Data (Recorded 9/14 → 2/15)
→ *a Steady Baseline for Calibration of InSAR*

- Data processed at KU under the direction of Leigh Stearns using GIPSY-OASIS
- Noise is primarily due to tidal effects

B.



A.



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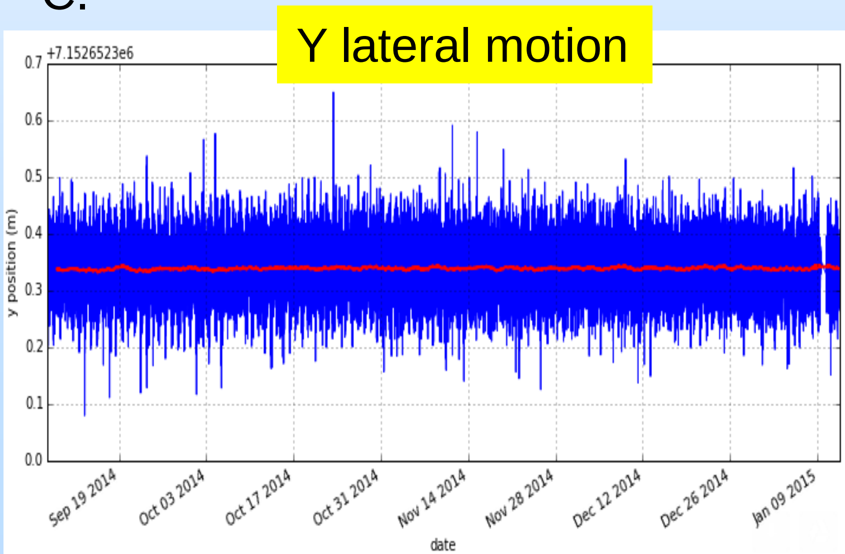


D. Schwab, M. Taylor, T. Bidgoli (KGS, KU)

Progress to Date
Key Technical Issues (Continued)

– **Seismicity**

- Expanded and refined seismometer array augmented by KGS investment to r*ecord field operational seismic events down to -0.5 M*
  - *1+M events sufficient to observe barriers or conduits of flow,*
  - *fracture orientation,*
  - *understand earthquake focal mechanisms and stress regime,*
  - *improve geomechanical model*

– **Factors impacting CO_2 storage**

- Capillary entrapment – defined using reservoir quality index
- CO_2 miscibility
- Fracture and parting pressure
- Permeability – kv & kh, relative permeability
- Geochemical reactions – employ reactive transport models

IRIS Seismometer Installation

Housing setup for Sercel (Mark Products) L-22D-3D sensors, ~5 ft below surface to minimize surface noise; installed below frost line in bedrock

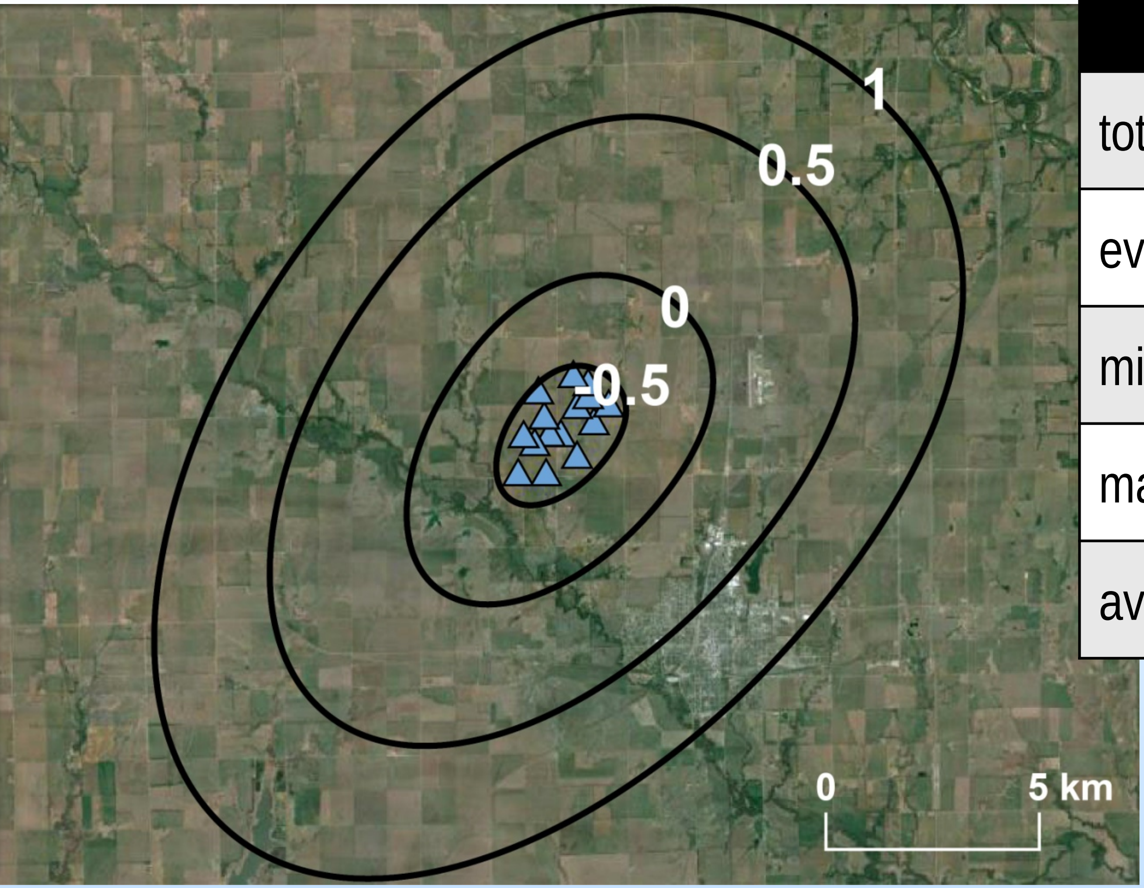
Shelby Peterie, KGS Exploration Services, checking installation in July 2014

INSTRUMENT CENTER
IRIS PASSCAL
Program for Array Seismic Studies of the Continental Lithosphere

R. Miller and S. Peterie, KGS

Local Activity

Network Sensitivity



Events detected at ≥ 7 stations†	
total events	53
events/day	4
minimum magnitude	-0.3
maximum magnitude	1.4
average magnitude	0.6

- Minimum magnitude versus distance from the network
- Operational seismicity from active waterflood being recorded in Wellington Field
- Research underway to improve location of hypocenters of events

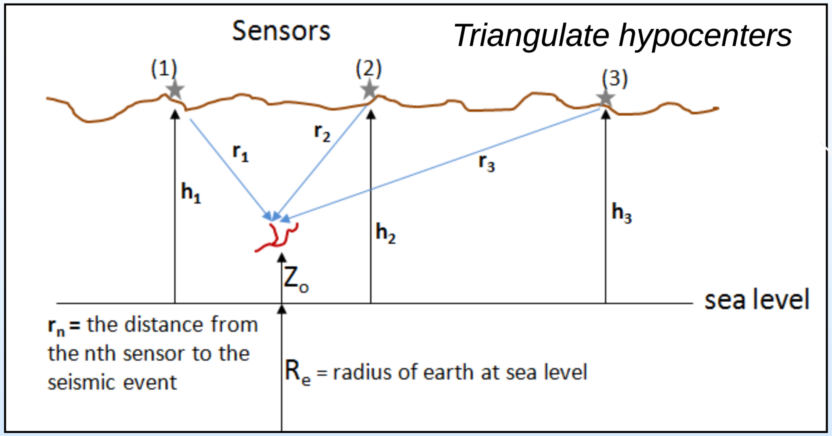
- Earthworm software for automated detection of earthquakes.
- Reporting 2.5+ magnitude per USGS convention.

†initial recording over one weeks time

R. Miller and S. Peterie, KGS

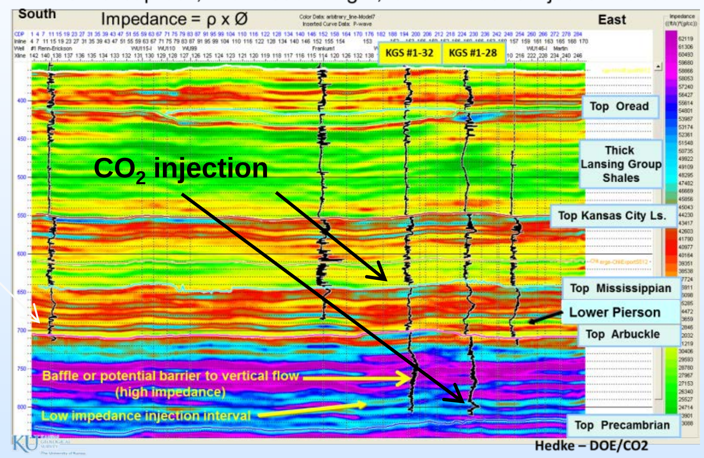
Resolution of Hypocenters from IRIS Seismometer Array at Wellington

Refining location of operational seismicity -- Initially for the CO2-EOR injection to evaluate feasibility of methodology



Mississippian and Arbuckle injection zones have good impedance

Arbitrary seismic impedance profile
distinct caprock, mid-Arbuckle tight, lower Arbuckle injection zone



Adapting Java toolset to manage, interpret, and display solutions on project maps (Victorine, KGS)

→ *Time, location (x,y,z) of event from seismometers*

Enter Seismic Information

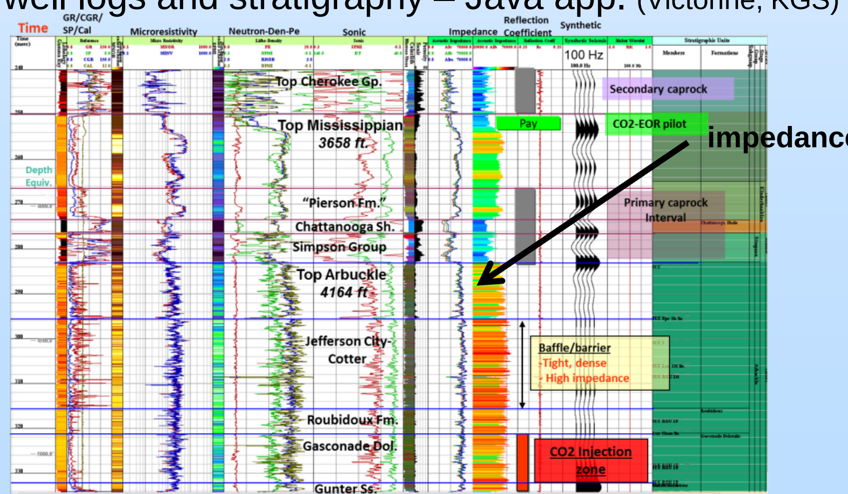
Enter up to 3 Sensor Number from 1 to 15

#	Latitude	Longitude	Elev.(ft)	UTMx	UTMy	Elev.(m)	Distance
13	37.303385	-97.44998	1239.0	637372.67	4129451.03	377.6472	1411.3
15	37.307223	-97.43417	1242.0	638766.89	4129899.94	378.5616	510
6	37.318033	-97.425951	1282.0	639475.34	4131111.39	390.7536	1395.2
=	37.3095	-97.46327	-0.015			-0.00466	
E	37.309547	-97.4367	0.0	638538.39	4130154.07	0.0	

Seismic Event: Latitude (ϕ_q) = 37.309547°, Longitude (λ_q) = -97.4367°, Depth (z_o) = 0.0 [m]

n	latitude (ϕ_n)	longitude (λ_n)	Elevation (h_n) [km]	Distance (r_n) [m]
13	37.303385	-97.449980	0.3776472	1411.3
15	37.307223	-97.434170	0.3785616	510.0
6	37.318033	-97.425951	0.3907536	1395.2

KGS #1-32 --Synthetic seismogram integrated with well logs and stratigraphy – Java app. (Victorine, KGS)



Future Plans and Expectations

- Arbuckle model framework requested and shared with EPA
- Geochemical analyses from USDW well and soil gas lysimeters for baseline & risk mitigation
- Pending supplemental funding from KU for KU Geology & KGS
  - Install several downhole geophones in two T/A wells
  - Install three new 3-component broadband seismometers purchased by KGS
- Spud Mississippian injection well, Berexco Wellington KGS #2-32
  - March (23-27) with Class II permit
- Repressurize and inject CO_2 into Mississippian
  - April/May 2015
  - 120 metric tons per day, up to 26,000 metric tons, ~ 7.5 months maximum
- Drill, complete, and start injection in #2-28 Arbuckle monitoring well
  - 6 mo. fabrication lead time CASSM, U-Tube, and Fiber Optic Array (pending decision); 2 months equip, test, and prepare #1-28 for injection
  - Anticipate public comment period for Class VI permit in May-July, receive permit in August-September
  - Inject ~April 2016 and finish by September 30, 2016 followed by 1 yr. PISC

Future Plans and Expectations (Continued)

- Complete installation and evaluate baseline monitoring data from Wellington Field
- Precise measurements of field response during injection with MVA technology
  - Sampling and analyzing produced fluids during Mississippian injection
  - Actively monitor/process seismometer array data to track events
  - InSAR-cGPS ground motion
- Validation of models and predictions
- Meeting with public in Wellington town hall meeting following commencement of Mississippian injection.

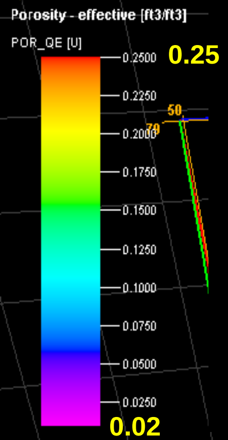
Milestone 3. Site Characterization of the Mississippian Reservoir for CO_2-EOR

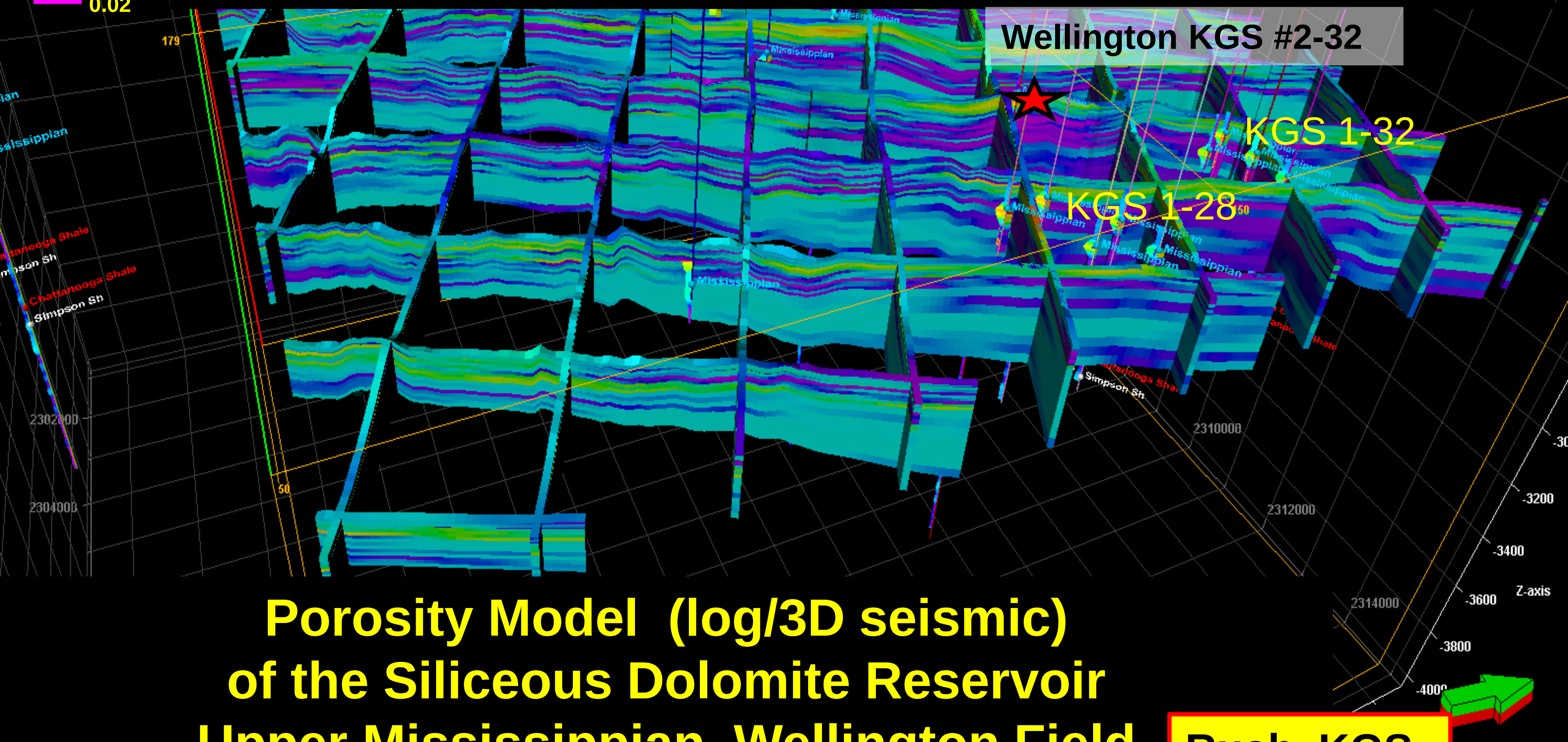
Porosity Inversion of the 3D Seismic Wellington Field

Total Miss thickness ~400 ft including caprock

Pay <50 ft at top (warmer colors)

Complex westward offlapping geometries of porous lithofacies -- Looking SW

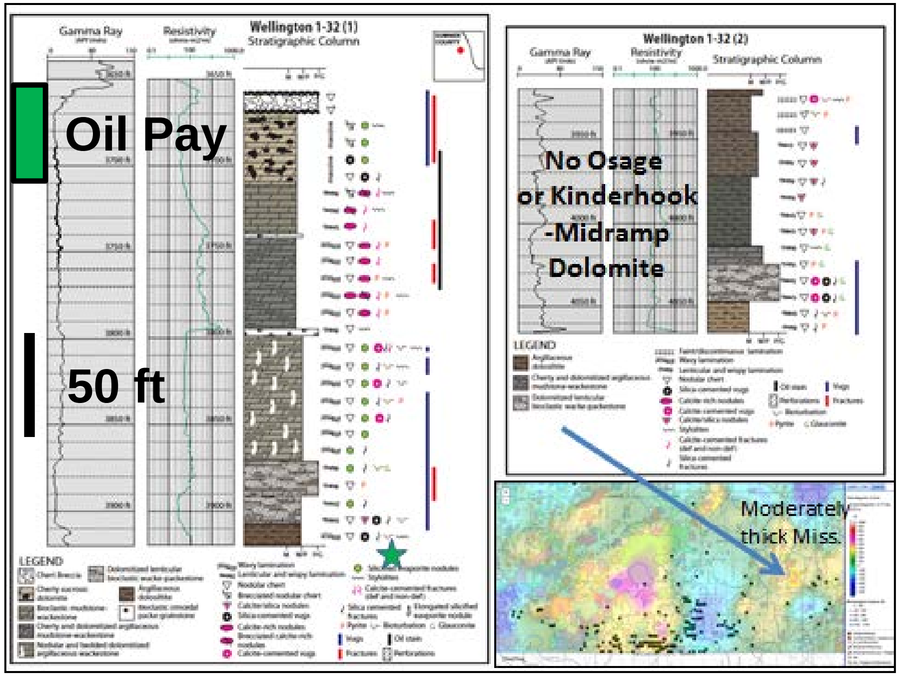




Porosity Model (log/3D seismic) of the Siliceous Dolomite Reservoir Upper Mississippian, Wellington Field

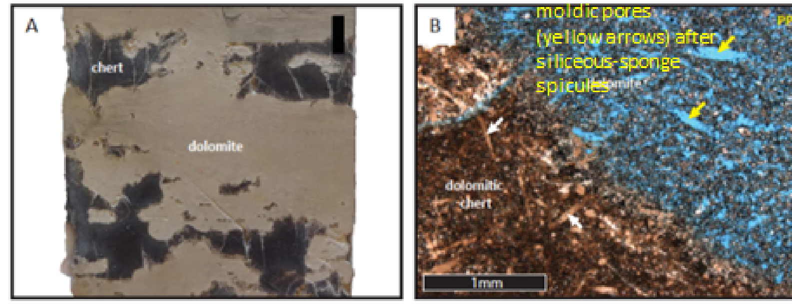
Rush, KGS

Milestone 3. Site Characterization of the Mississippian



Cherty Sucrosic Dolomite

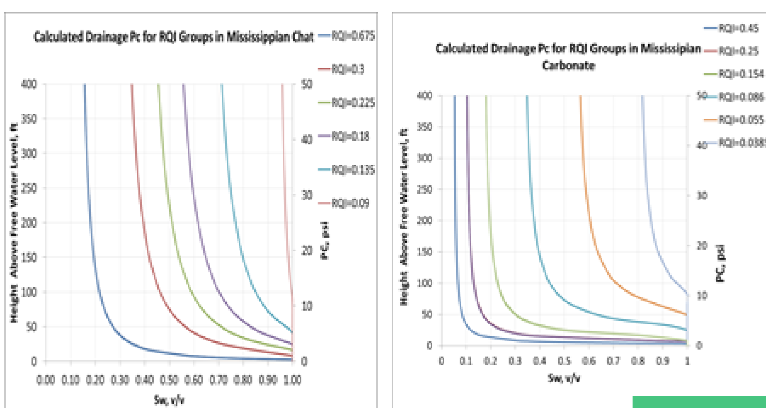
Sedimentary Features Have Been Masked During Dolomitization



Convoluted dark gray chert nodules are scattered in the matrix and appear autobrecciated

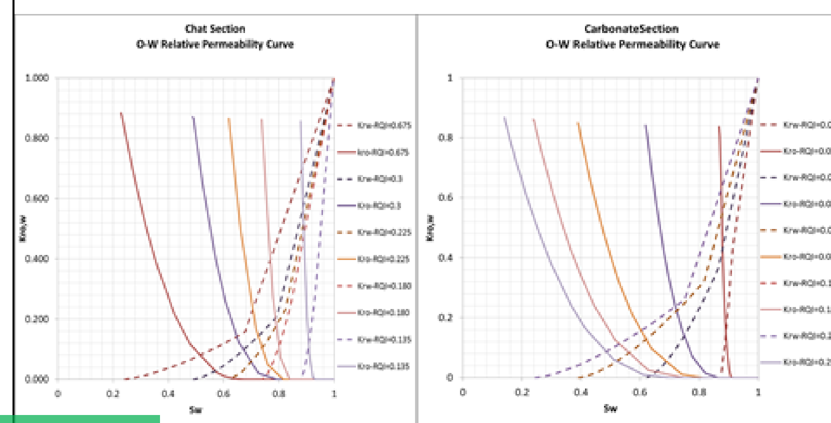
Montalvo, KU & Barker, KSU

Drainage Capillary Pressure Curves for Each RQI Range in the Mississippian



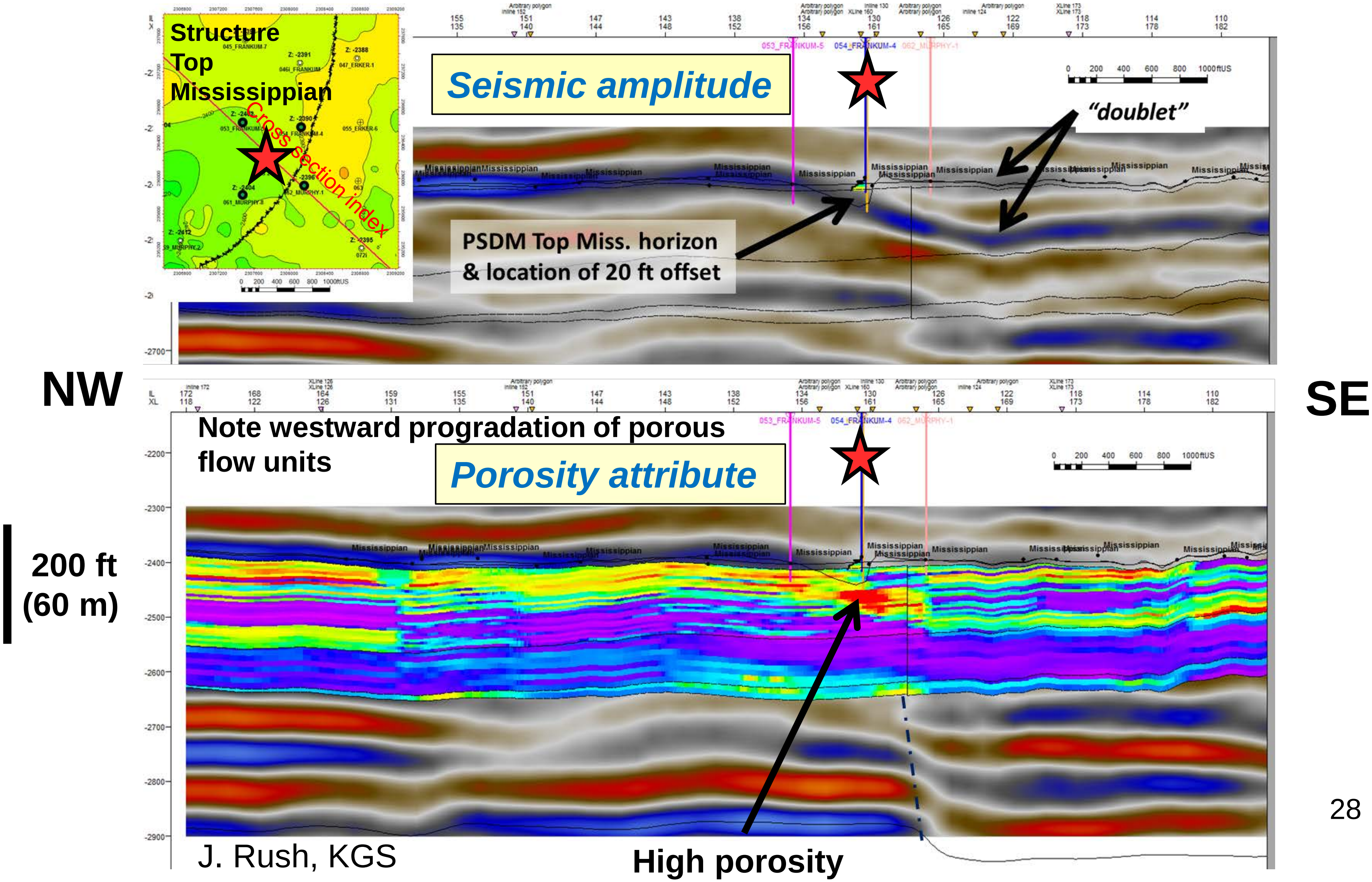
$$RQI = 0.0314\,(K/\Phi_e)^{0.5}$$

Relative Permeability Curves for Each RQI Range in the Mississippian

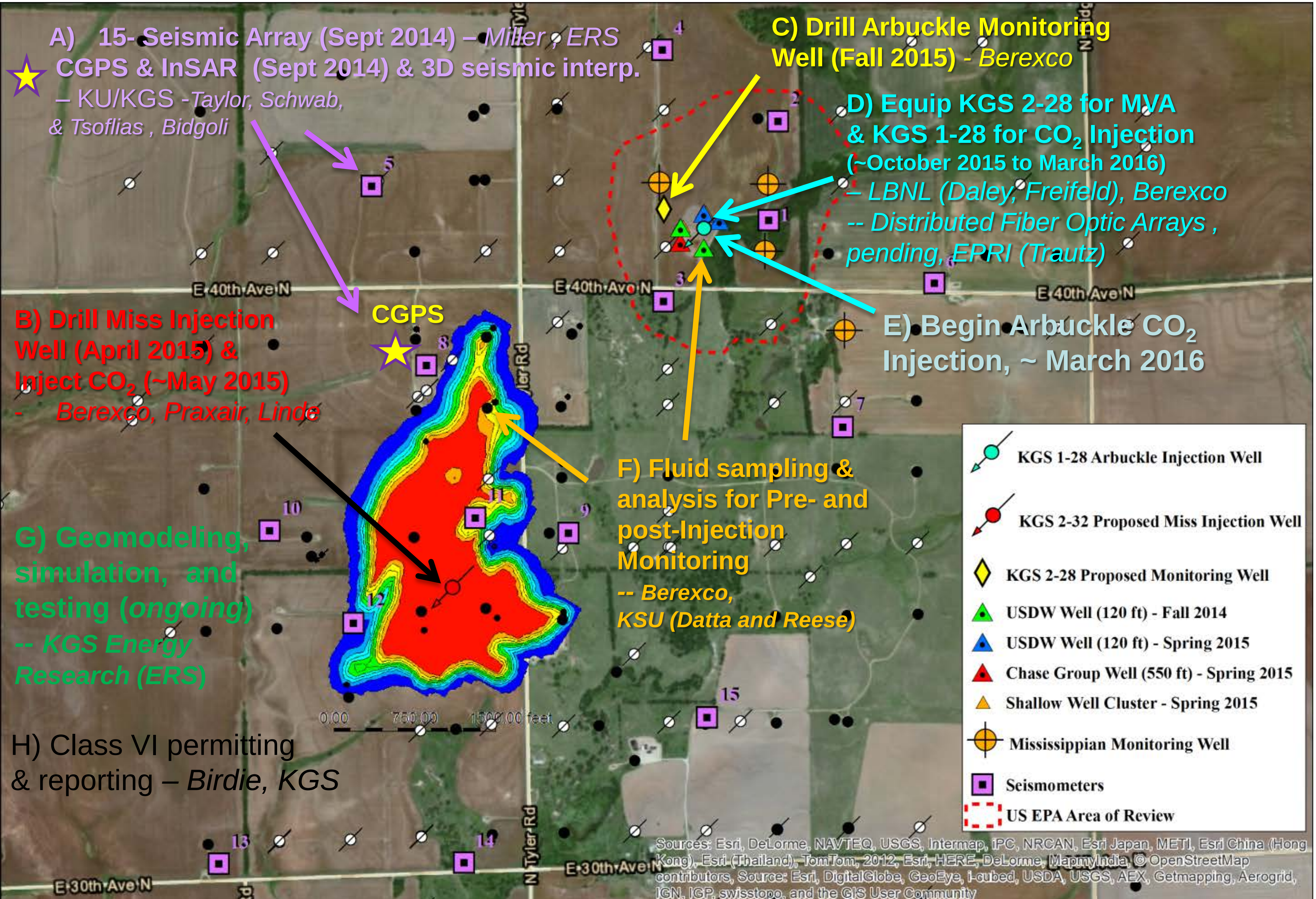


Fazelalavi, KGS

NW-SE PSDM Seismic Profile Mississippian Oil Reservoir Projected Through 5-Spot Injection (CO_2-EOR)



J. Rush, KGS



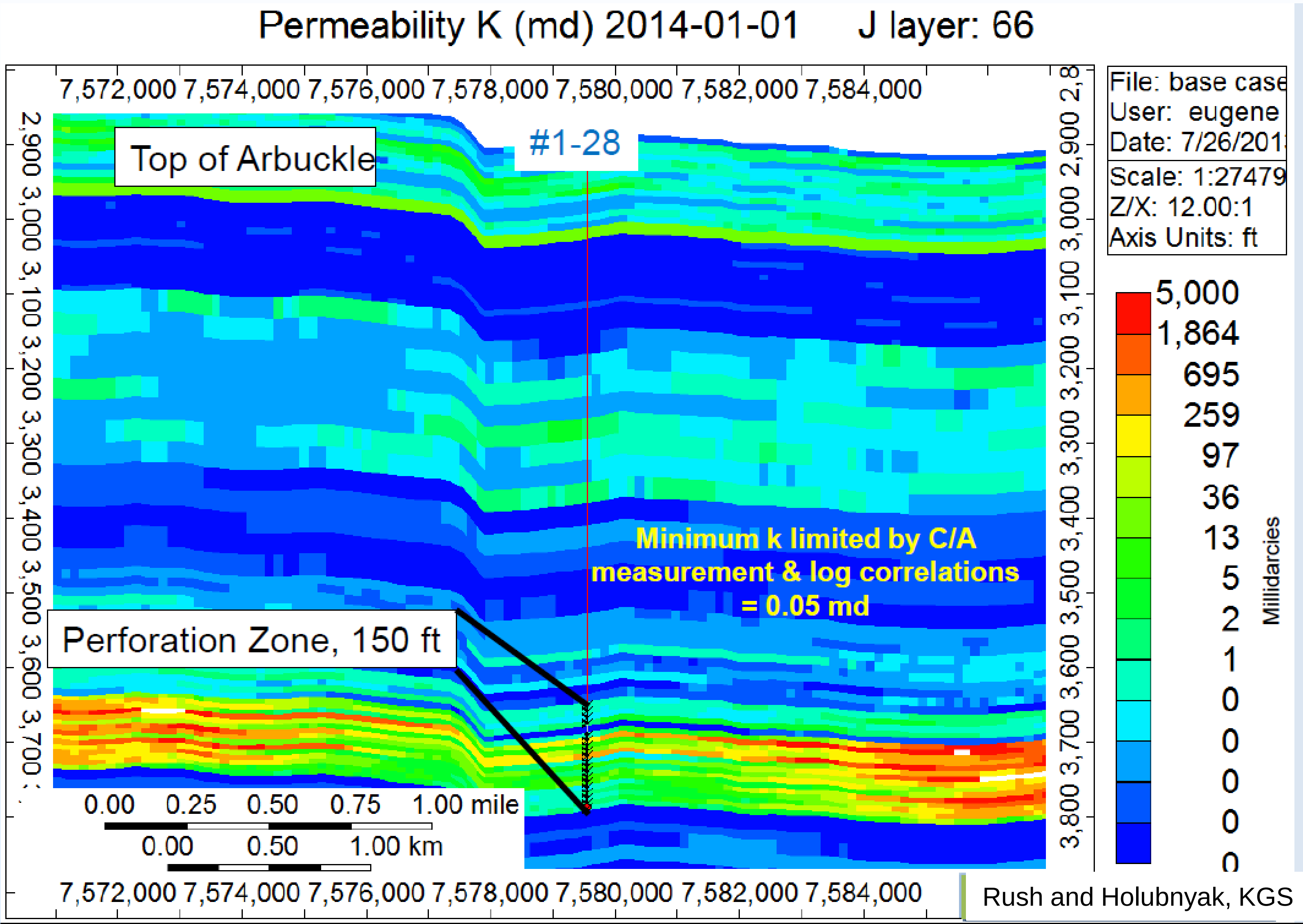
MVA Activity at Wellington CO2 injection site
Sumner County, Kansas
Twn 31S - R 1W

N

Feet
0 750 1500 3000

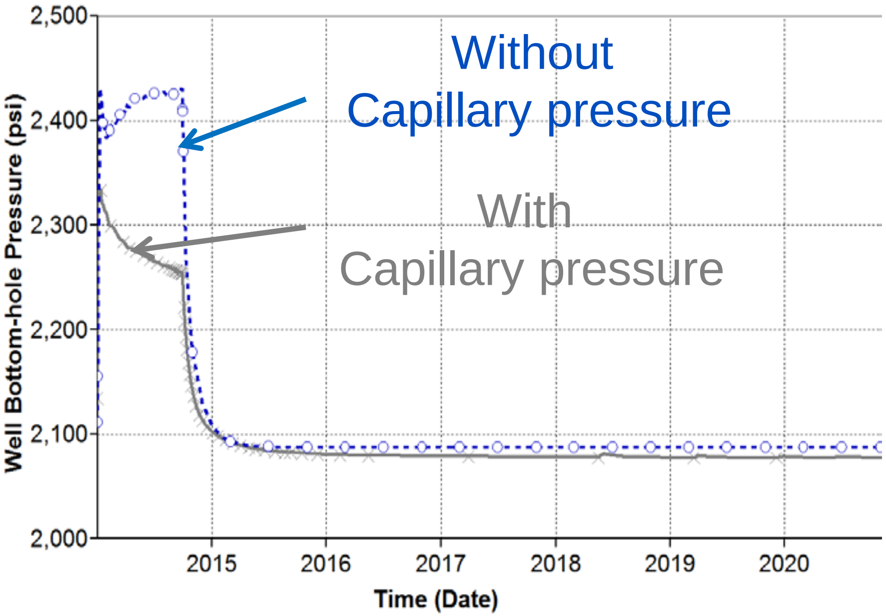
Sources: USGS, Kansas Geological Survey, Kansas Corporation Commission, DASC.
Map Created October 14, 2014

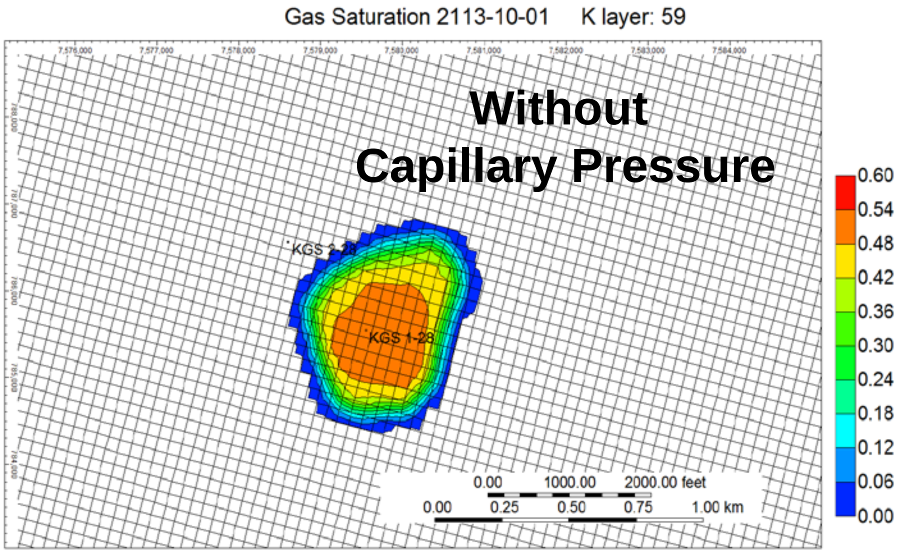
Arbuckle Geocellular Permeability Model

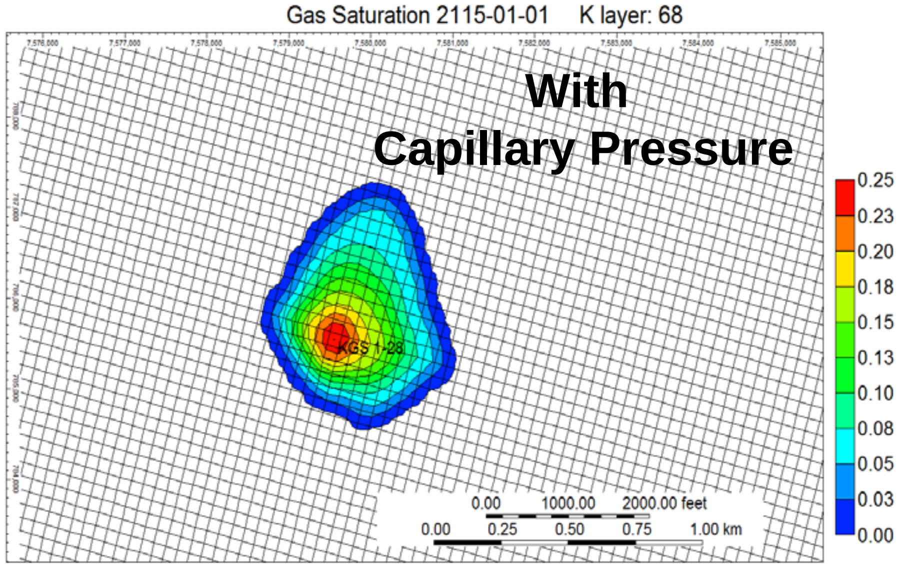


Rush and Holubnyak, KGS

Simulation of Arbuckle CO_2 Injection Bottom Hole Pressure and Free-Phase CO_2 Maximum Plume



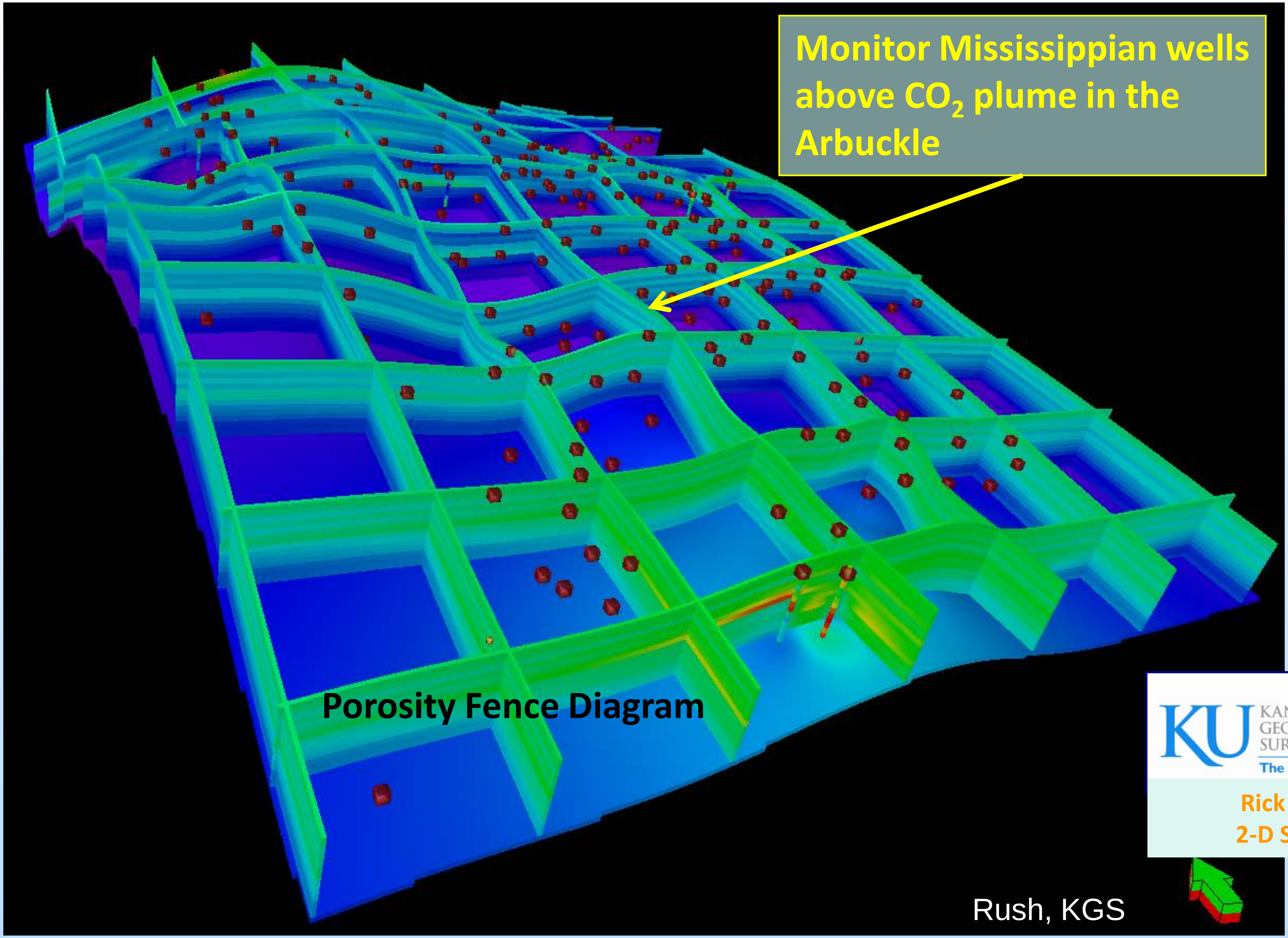




Holubnyak, KGS

Mississippian Reservoir Will Serve as Ideal Trap for Leaking

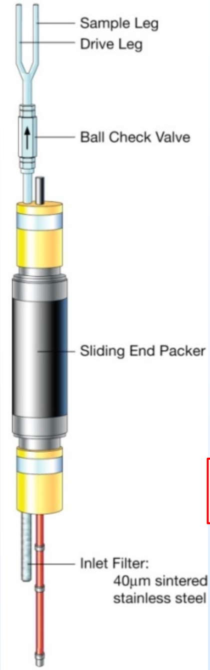
-- is under-pressured and blanket-like in distribution
-- will act as to capture leaking CO_2 if escape from the Arbuckle test
-- if detect CO_2, run high resolution 2D seismic to characterize leakage



KANSAS GEOLOGICAL SURVEY
The University of Kansas

Rick Miller
2-D Seismic

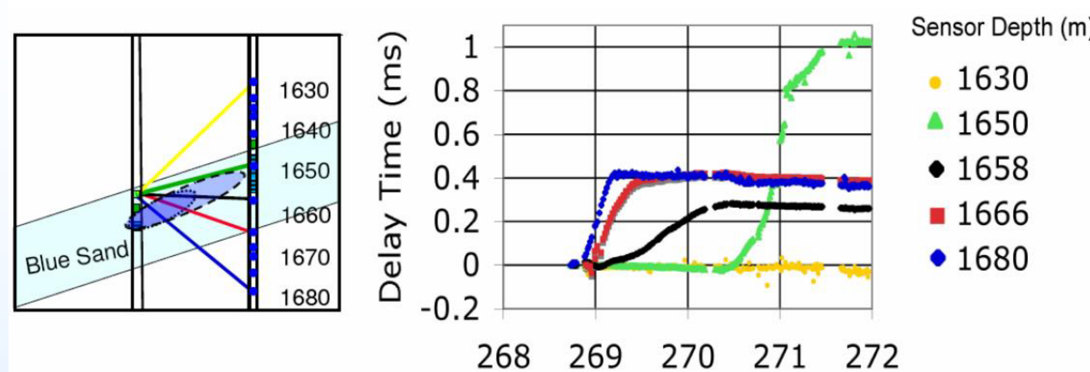
Monitoring, Verification, and Accounting



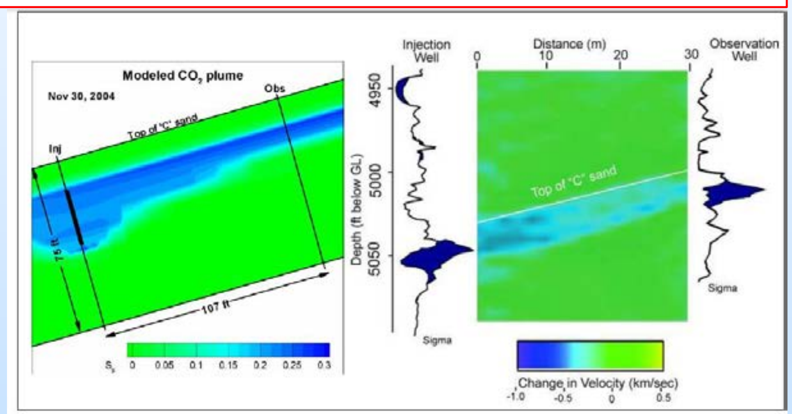
U-Tube

B. Freifeld, LBNL

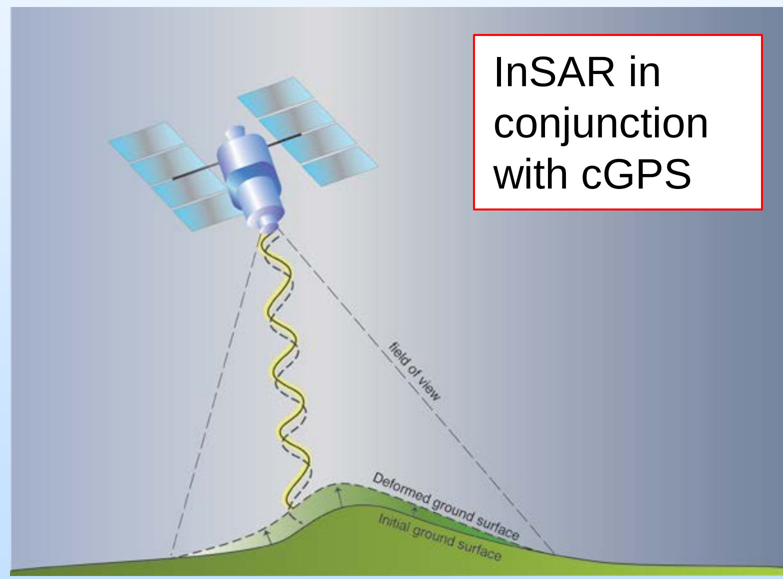
Real time detection using continuous source cross-well seismic



CASSM & Croswell Seismic Tomography



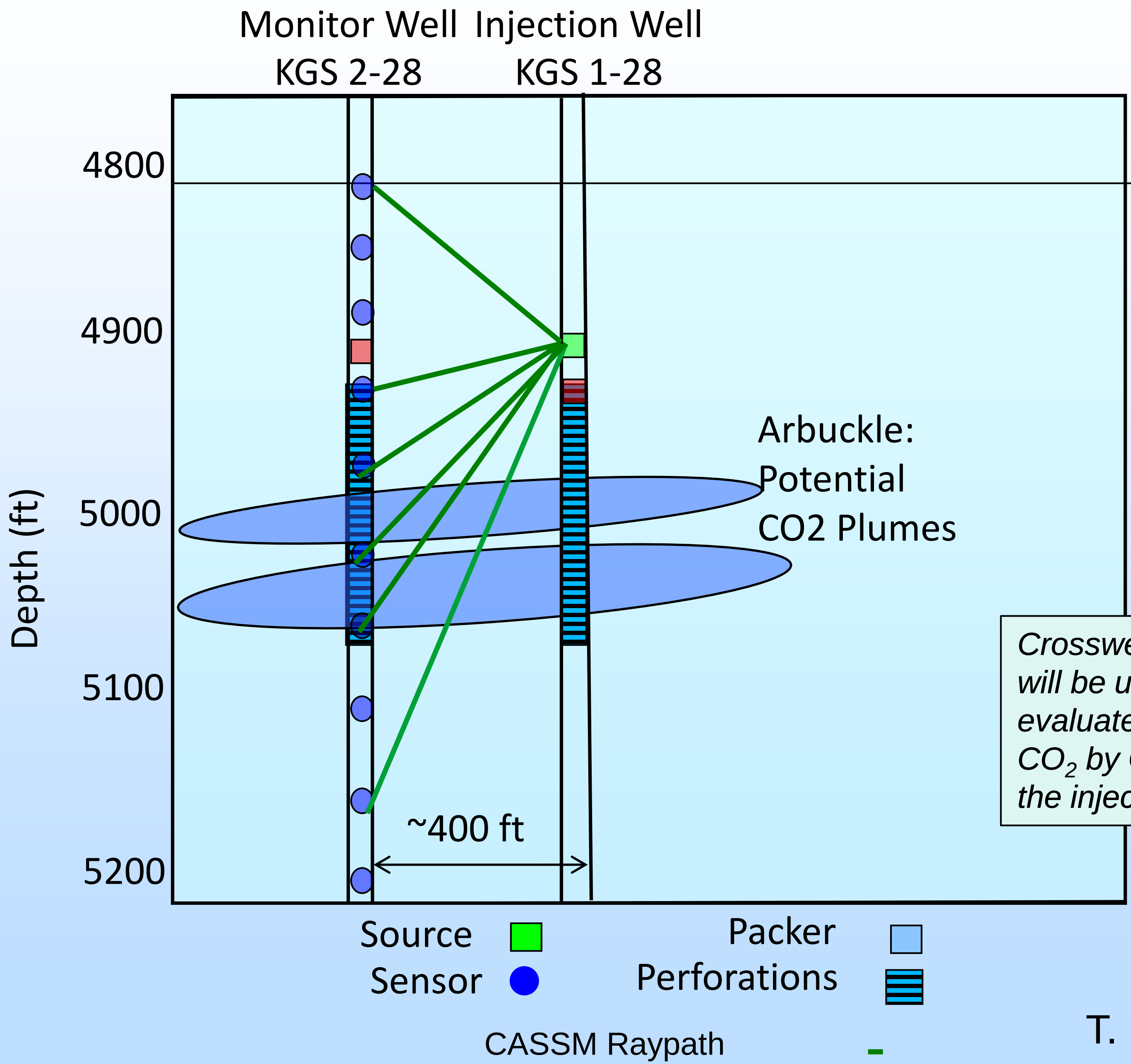
T. Daley, LBNL



M. Taylor, KU

- Innovative monitoring technologies:
  - cGPS recording since August 2014
  - SAR data being collected ~20 day intervals
  - Observe small (-0.5 to 1 M) operational (waterflood) seismicity since Sept. 2014
  - Prospect remains to secure Disttributed Fiber Optic Arrays with VSP for Arbuckle monitoring

CASSM Design for Arbuckle Monitoring



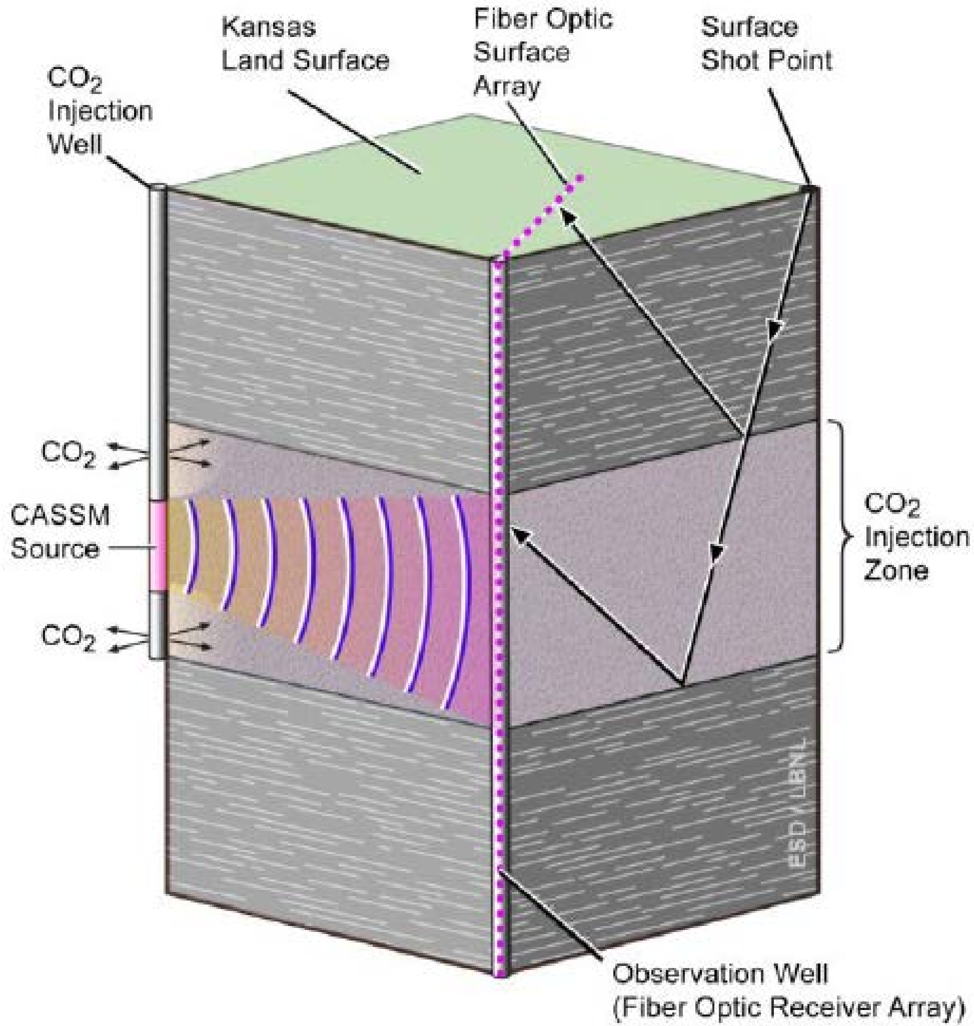
Crosswell Tomography will be used to evaluate imaging of CO_2 by CASSM during the injection

T. Daley, LBNL

DE-FE-OO12700 -- *Integrated Temperature and Seismic Sensing for Detection of CO_2 Flow, Leakage and Subsurface Distribution - Rob Trautz, EPRI, PI*

- Multiple seismic shots currently budgeted to create a pseudo-3D volume to image the CO_2 plume

High Resolution Vibroseis source for VSP, R. Miller, KGS

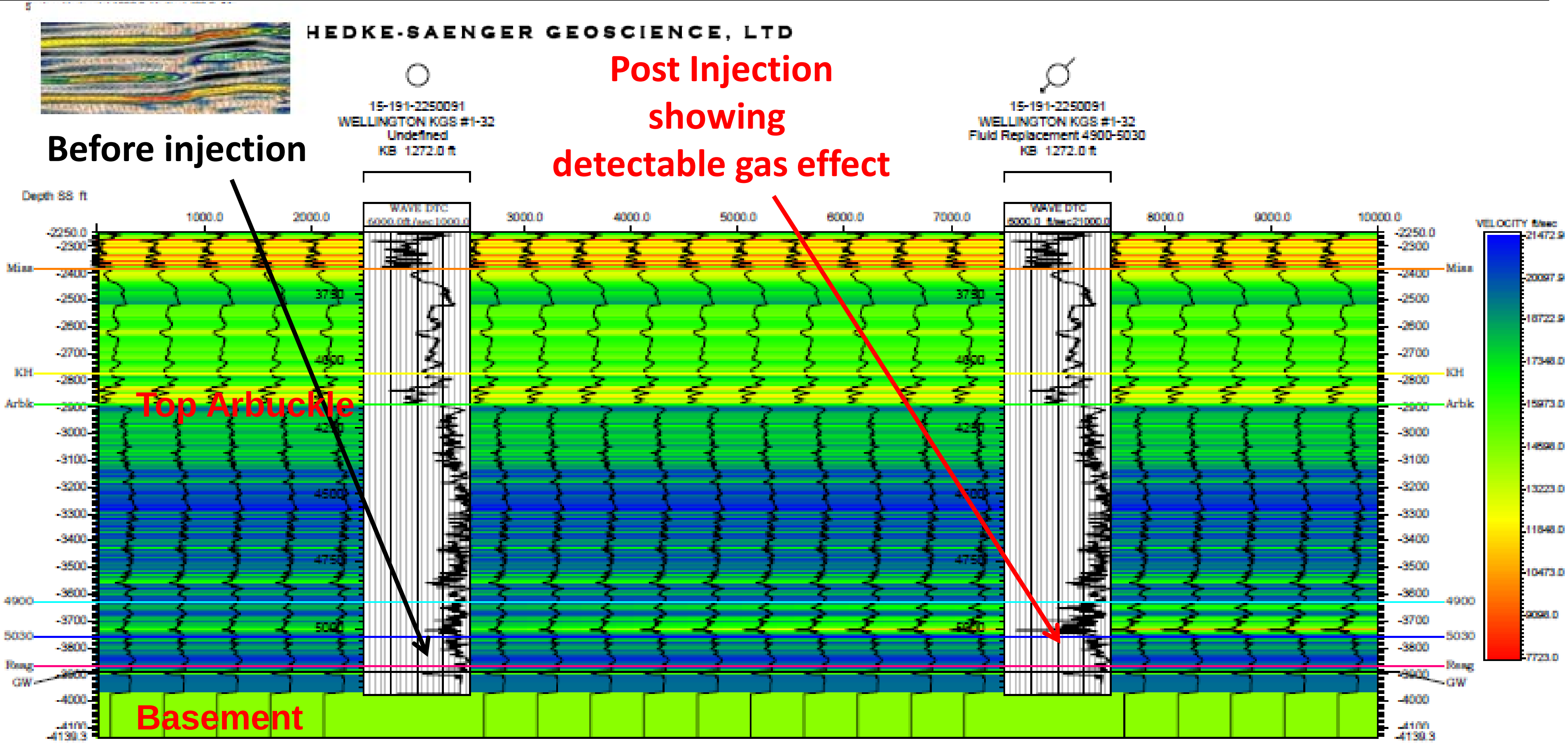


DE-FE-OO12700
R. Trautz, EPRI, P.I.

Post-injection Repeat 3-D Seismic

Can Surface Seismic Methods Detect the CO_2 Plume in the Lower Arbuckle?

- **Modeled CO_2 Plume using Gassman Fluid Substitution equation**
- **Assume 50% Water Saturation Post Injection**



[AVO analysis](#) conducted to date suggest certain offset range (source-receiver distance) could detect the fluid changes and therefore help the acquisition design. In general, we expect far offsets (>30 deg) to contain more information about pore fluids than near offsets, but far offset reflections from deep targets are more noisy so subtle changes are difficult to detect with confidence.
– G. Tsoflias, personnel com.
Related references on CO2 detection: http://library.seg.org/toc/leedff/29/2

GeoSyn 2D 02:31 PM Sun Mar 27, 2011

Initial CO_2 Fluid Substitution Modeling with AVO

(ideal case)

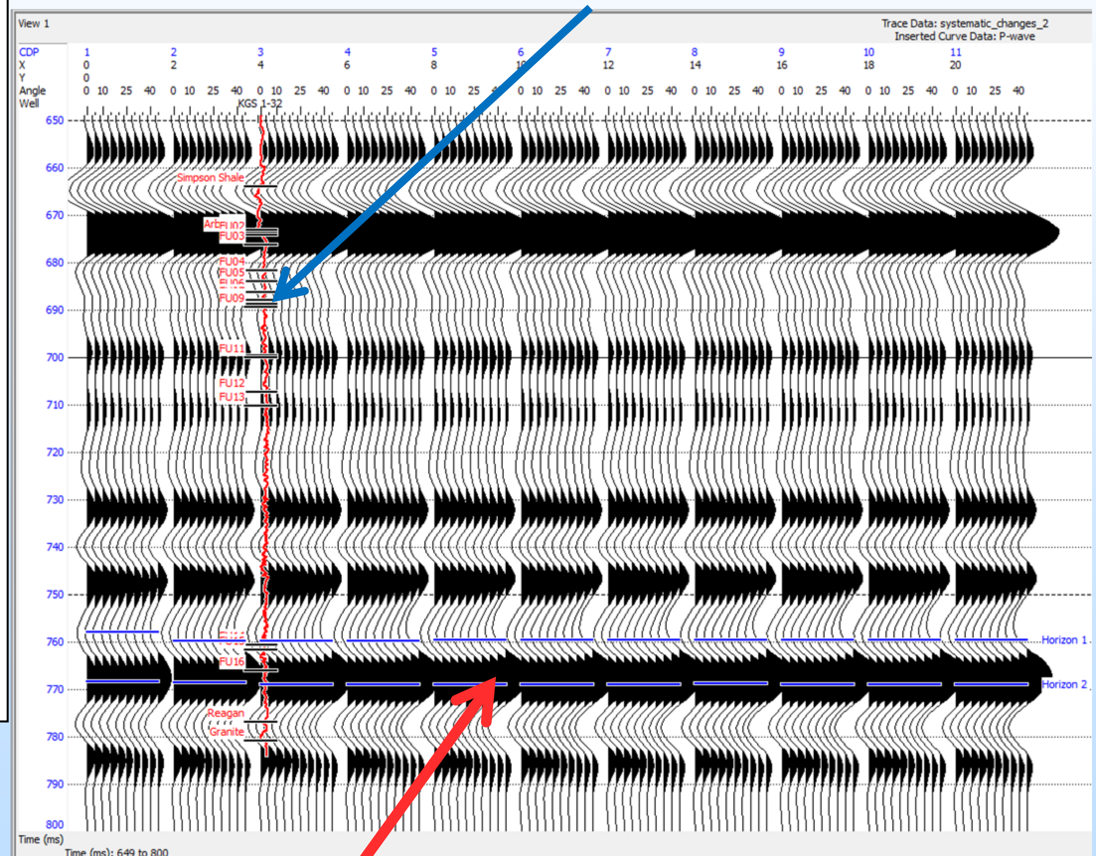
Fluid Substitution Modeling in Hampson-Russell KGS 1-32

Parameters

- Zone: 4910 – 5050 ft
- Fluids: Brine and CO2
  - Brine Density: 1.09 g/cc
  - Brine Modulus: 2.38 GPa
  - CO2 Density: 0.575 g/cc (Temp = 60°C; Pressure = 2093 PSI)
  - CO2 Modulus: 0.05 GPa (Temp = 60°C; Pressure = 2093 PSI)
- Matrix: 100% Dolomite (Density = 2.87 g/cc;
- Bulk Modulus = 94.9 GPa; Shear Modulus = 45 GPa)
- Matrix parameters are calculated with Hashin-Shtrikman average
- Reuss average used for fluid modulus
- Logs: DTC, Fastshear, RHOB, NPHI

Prestack Model

KGS $1-32 with Arbuckle flow units from RQI

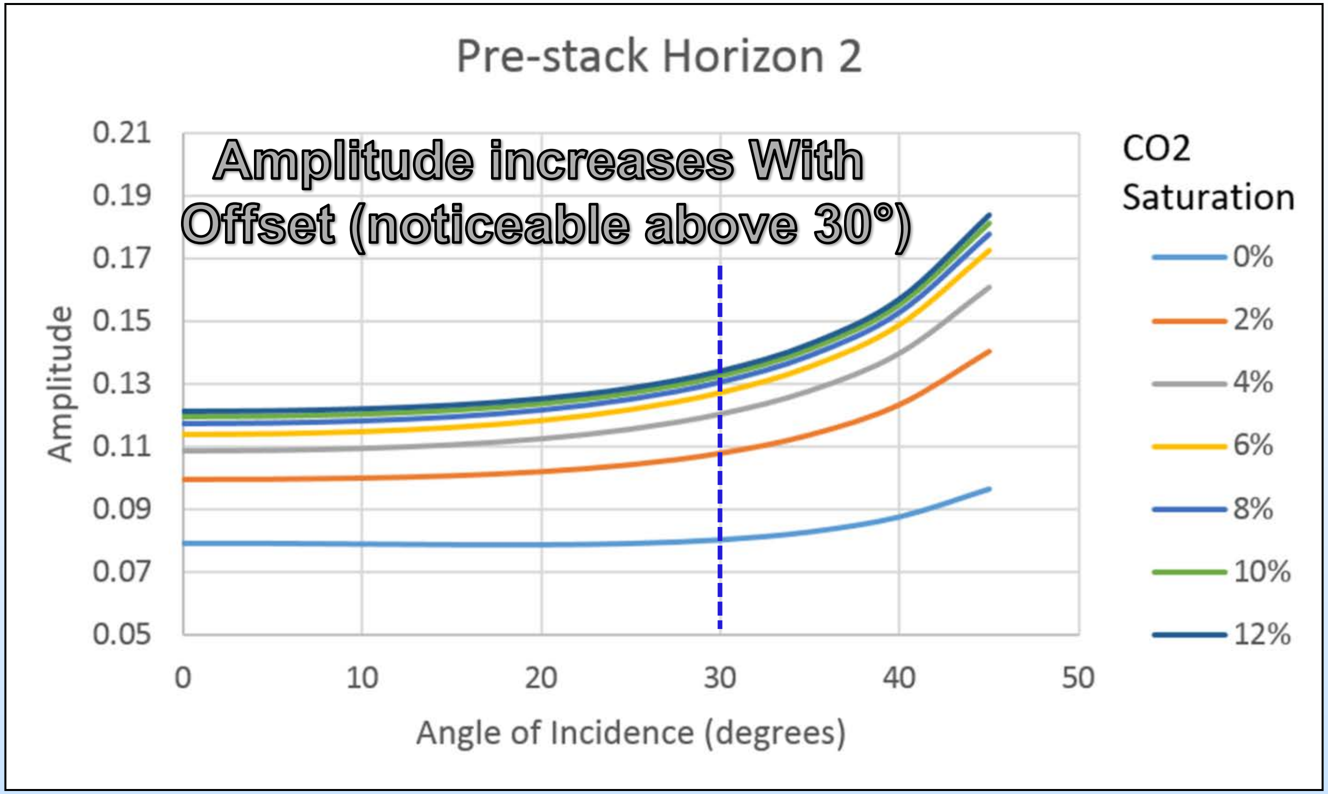


CO_2 saturation increases from 0 to 100% from left to right with amplitude increase in Arbuckle injection zone

C. Redger & G. Tsoflias, KU Geology

CO_2 Fluid Substitution Modeling with AVO

Initial Findings Under Ideal Conditions



a) Normal incidence (0 deg) reflectivity increase of 50% for CO_2 saturation increase from 0% to 12%

b) Oblique incidence (AVO) with significant changes at greater than 35 degree offset. CO_2 saturation increases the AVO effect. The large offsets could be obtained in the VSP data.

C. Redger & G. Tsoflias, KU

Project Wrap-Up

Key Findings to Date

- o Increased relevancy of this project to the DOE portfolio.
  - Potential to improve monitoring of CO_2 plume using passive seismic
  - Refined static and dynamic models → calibration for commercial carbon storage in the Midcontinent
  - Spectrum of seismic methods, core analyses, and petrophysics improving geomechanical models
- o Drilling, coring, logging, testing Mississippian injection well (March 23-27) with Class II permit in hand

Lessons Learned

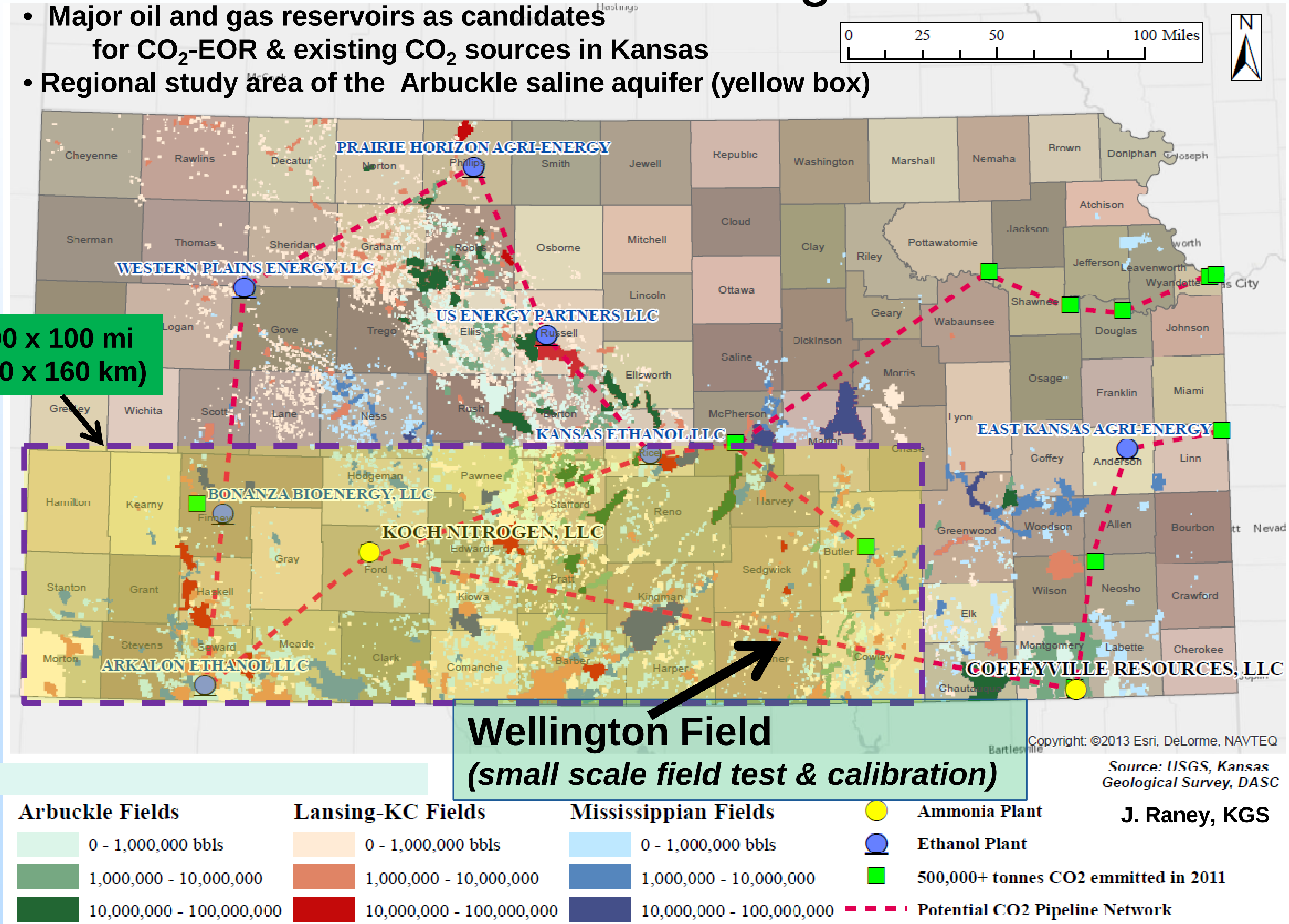
- o Improved methods and outcomes expected from test anticipated using recent efforts to refine Petrel-CMG models

Outstanding Project Issues

- o Obtain Class VI in a timely manner

Kansas Concept of Large-Scale Commercial Carbon Storage Via CCUS

- Major oil and gas reservoirs as candidates for CO_2-EOR & existing CO_2 sources in Kansas
- Regional study area of the Arbuckle saline aquifer (yellow box)



J. Raney, KGS

Wellington Will Continue to Serve as a Calibration Site

Regional CO2 Storage Estimates in Southern Kansas Using Numerical Models from DE-FE-0002056

- **Max injection rate per well** = 5,900 tonnes/day
- **Limiting Injection Pressure** = 150 % of ambient pressure at site
- **CO_2 Trapping Processes Simulated**:
  Structural, Hydrodynamic, Solubility, Residual, Mineral
- **Conservative initial model as a closed system**

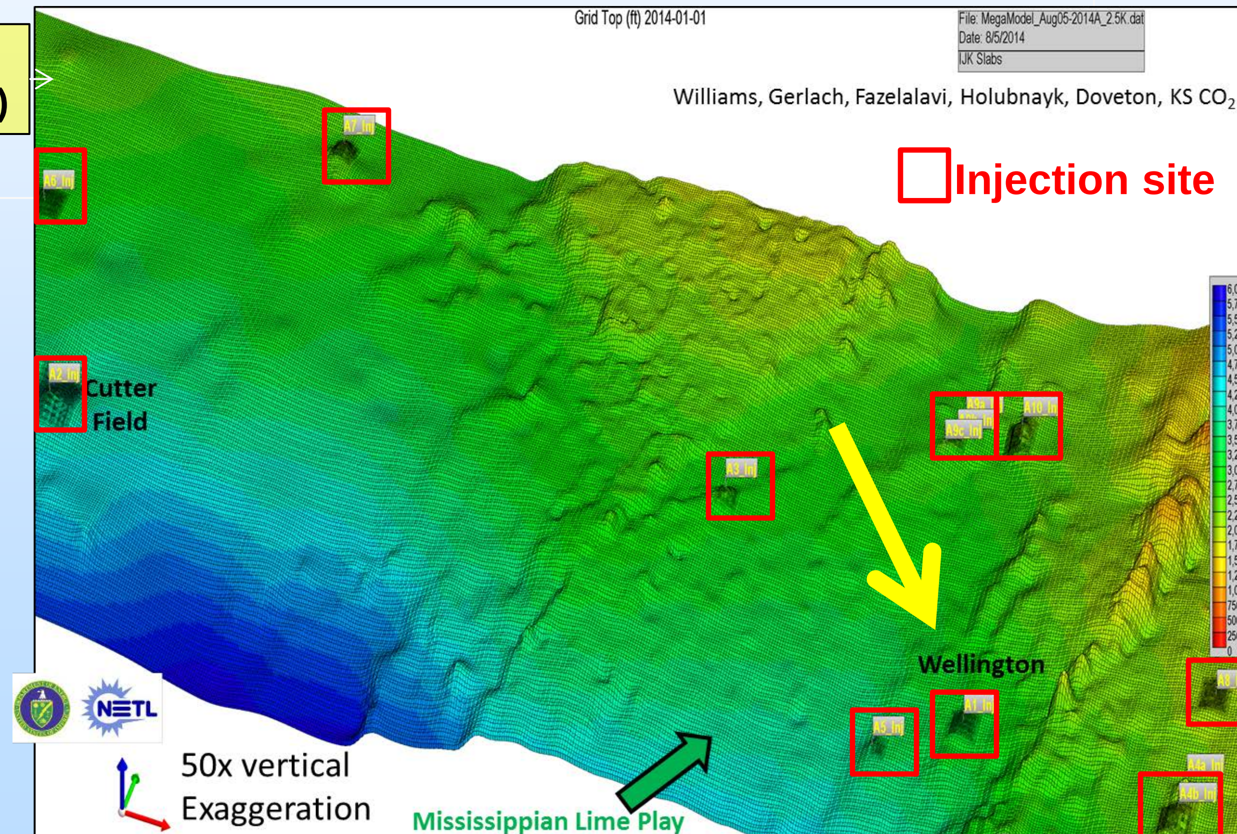
300 x 100 mi (480 x 160 km)

Mega Model 1

- 10 injection sites including Wellington Field (Site #1)
- 50 years to 2065

Mega Model 2

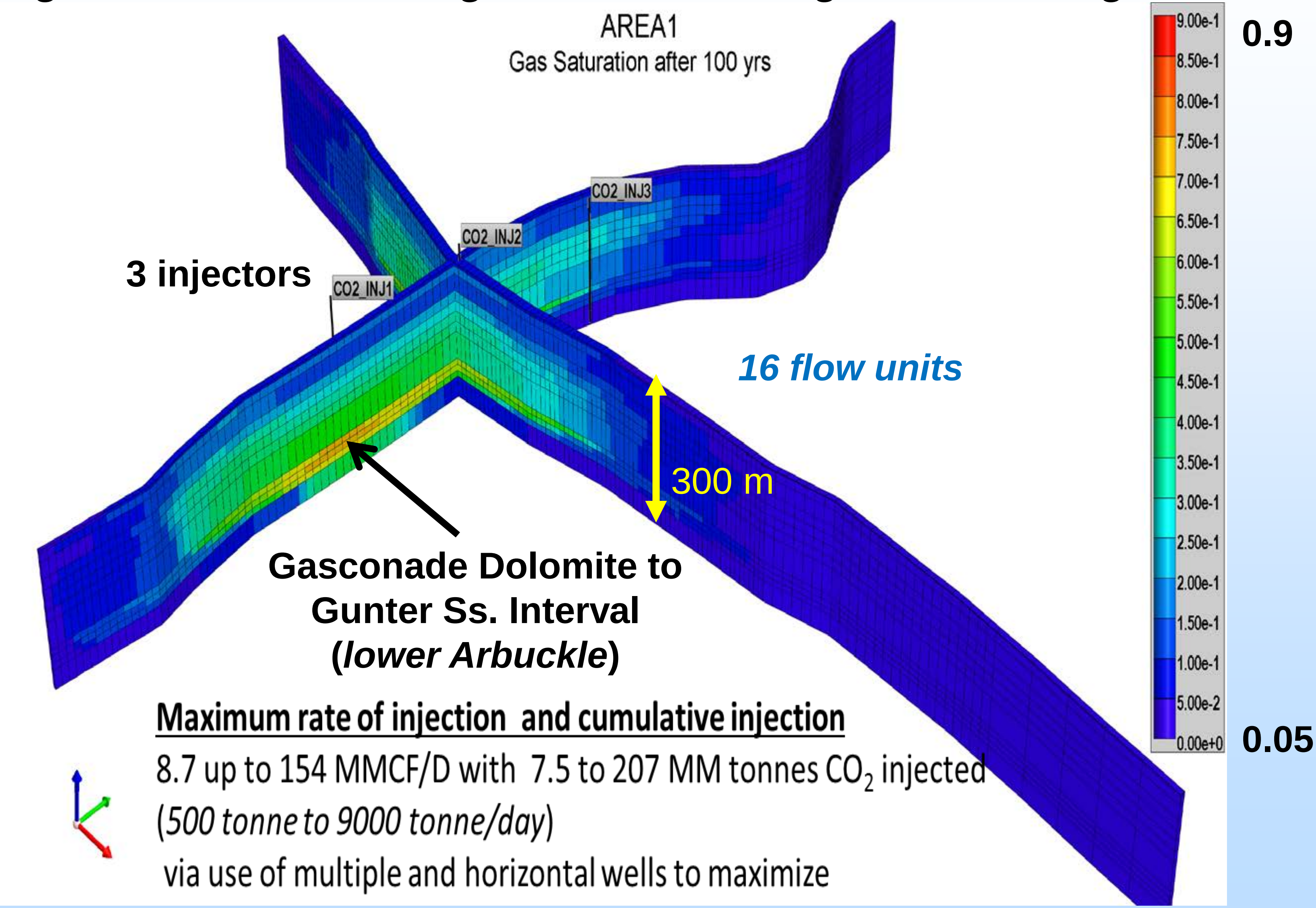
- 10 injection sites of Mega Model 1 plus 103 uniformly distributed wells
- 150 years to 2165



Initial Commercial scale CO_2 Injection Model

DE-FE-0002056

→ *Significant CO2 storage can be managed at Wellington Field*



Maximum rate of injection and cumulative injection

8.7 up to 154 MMCF/D with 7.5 to 207 MM tonnes CO_2 injected

(*500 tonne to 9000 tonne/day*)

via use of multiple and horizontal wells to maximize

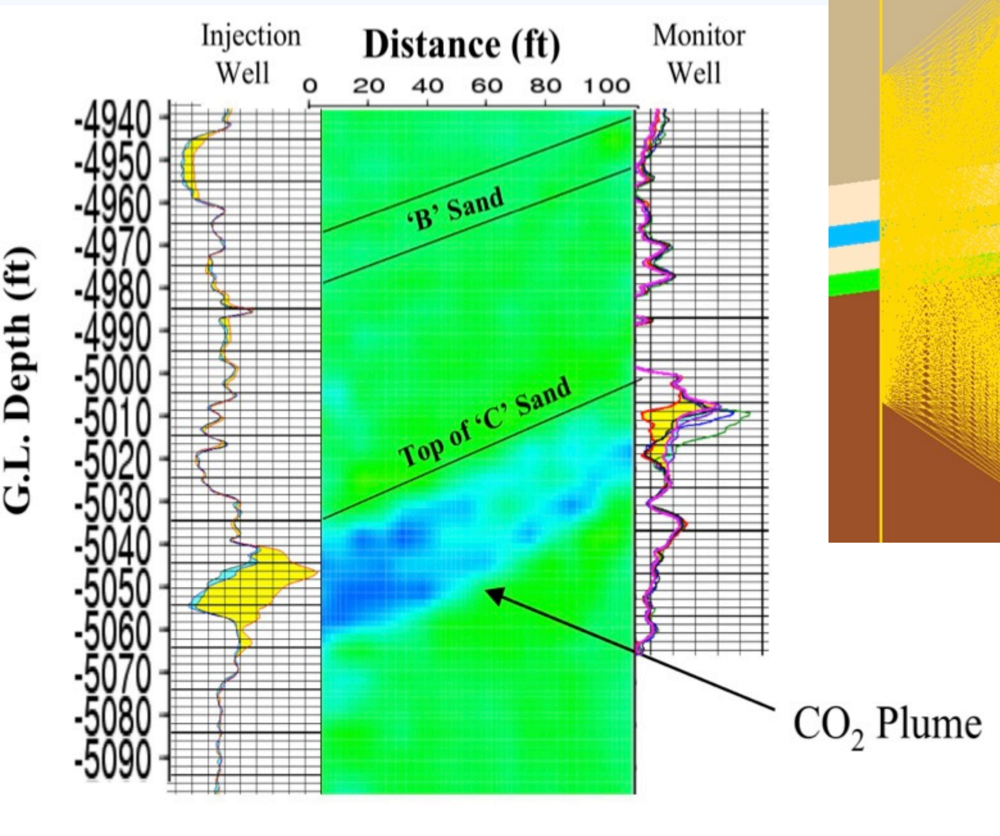
G. Williams, Gerlach, Fazelalavi, Doveton, Holubnayak

Conclusion

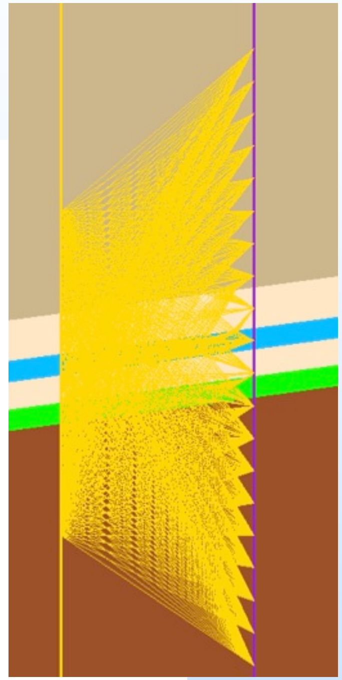
- Unique integration of Wellington Field with the *Kansas CO_2 Initiative* engaging the entire community – petroleum industry, CO_2 suppliers, lawmakers, and regulators
  - Use of Wellington Field as the focal point for discussion
  - Use of Wellington Field as a calibration site and field demonstration to engage petroleum industry on merits of CO_2-EOR
  - Convey requirements for using and storing anthropogenic sources of CO_2
  - Test best practices
    - cost-effective characterization, modeling, and monitoring to aid in applying next-generation CO_2-EOR methods
  - Refine model realizations to optimize for commercial scaleCO_2 sequestration
    - Managing operation, reduce economic and environmental risks, compliance with regulations
  - Couple the oil field and the underlying saline aquifer to increase the CO_2 sequestration capacity

Example Time Lapse Crosswell Imaging of CO2 Plumes

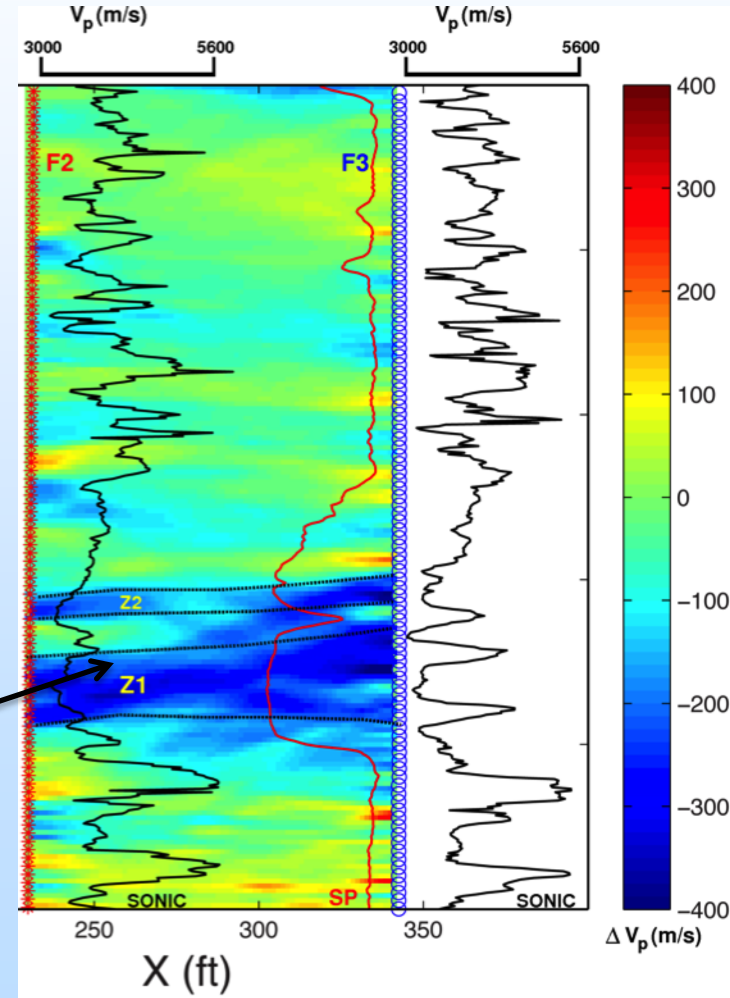
Frio-I 2004



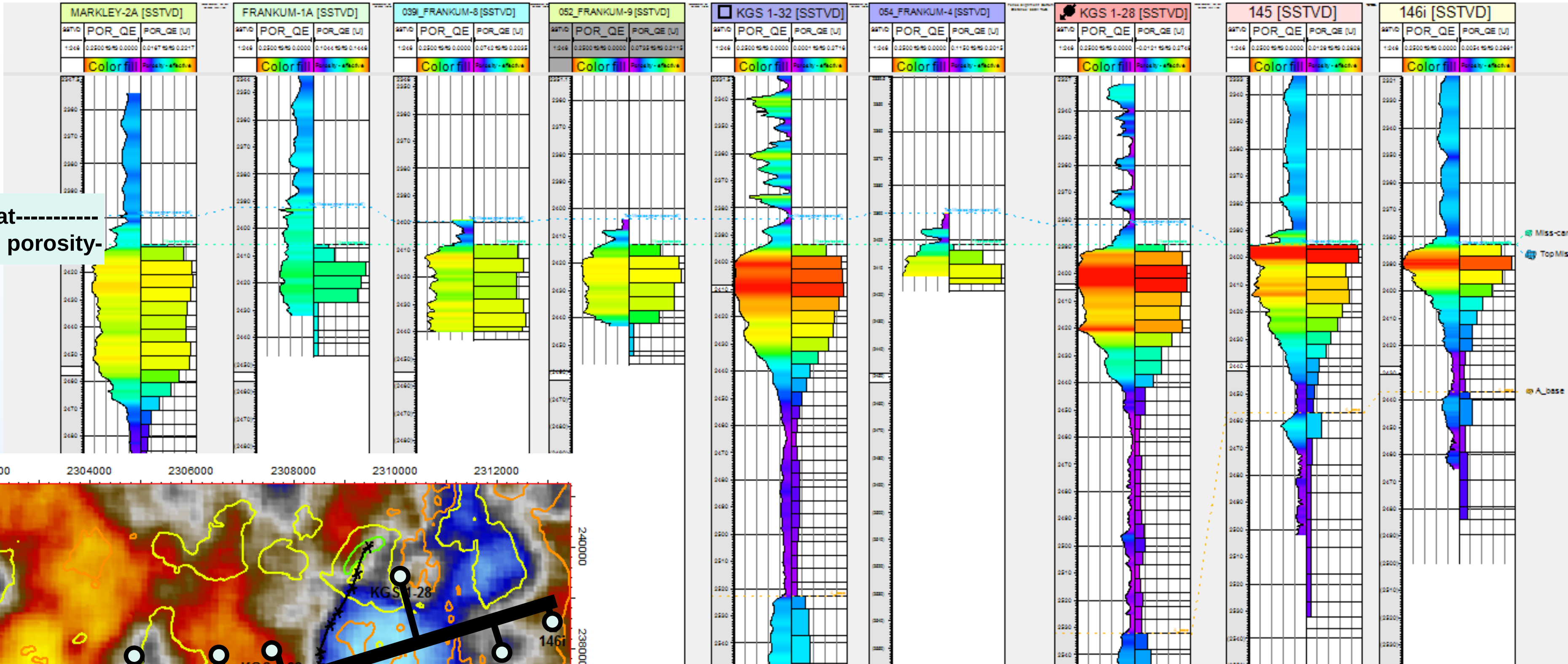
Schematic Crosswell

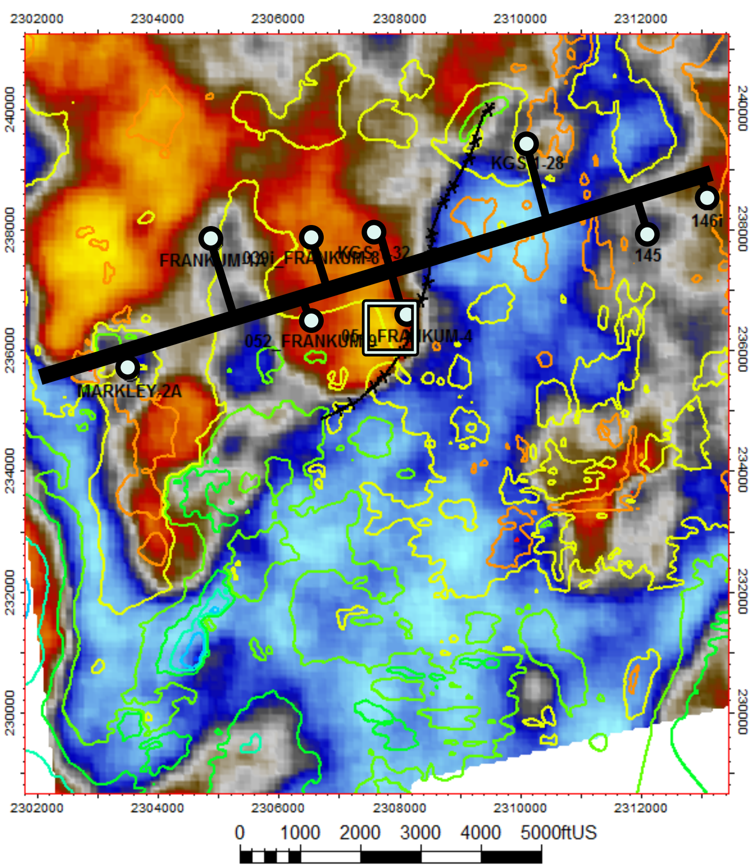


Cranfield 2010

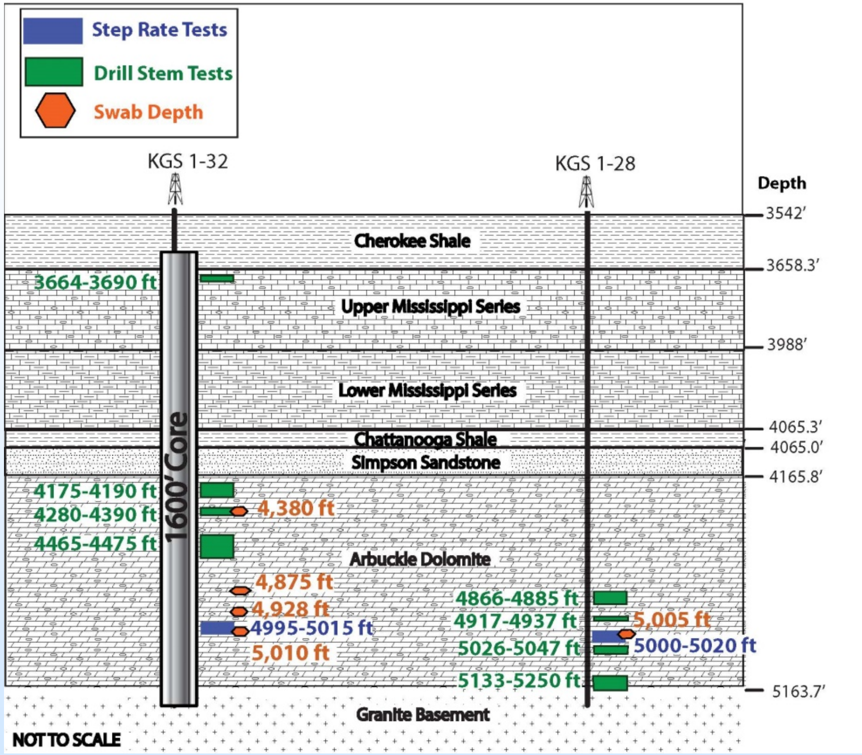


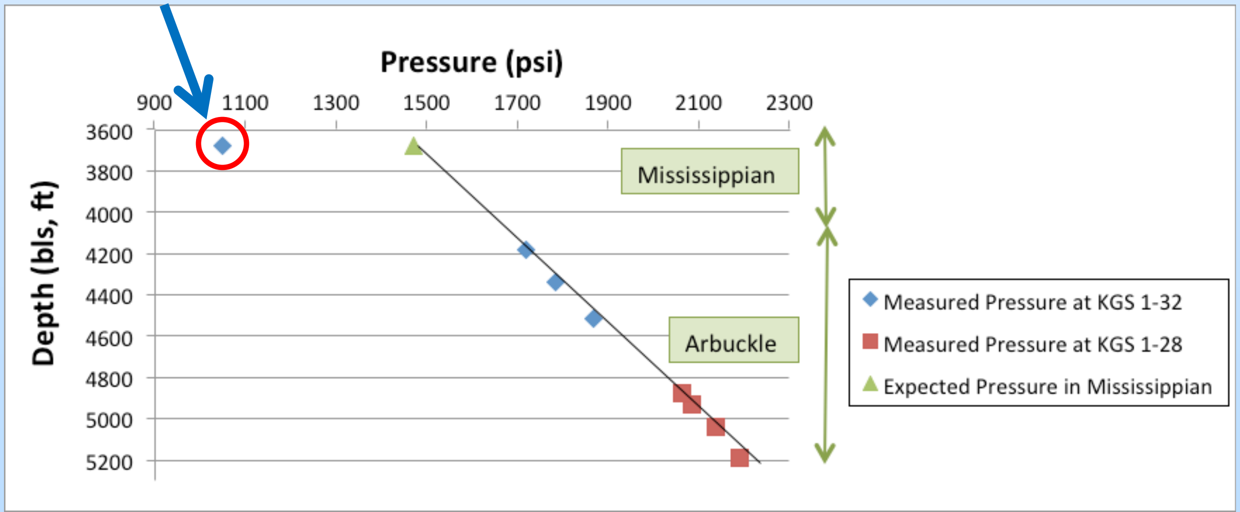
Chat-----------
top porosity-





Drill Stem Test Confirms Underpressured Mississippian





- Multiple DST's conducted to characterize formations