Geologic Carbon Sequestration Research in Kansas: Subsurface Storage Capacities and Pilot Tests for Safe and Effective Disposal

W. Lynn Watney, Tandis Bidgoli[1]; Tiraz Birdie[2]; John Doveton[1]; Jennifer (Raney) Hollenbach[1]; Yevhen 'Eugene' Holubnyak[1]; Fatemeh "Mina" FazelAlavi[1]; K. David Newell[1]; Jennifer Roberts[3]; Jason Rush[1]; Leigh Stearns[3]; Mike Taylor[3]; George Tsoflias[3]; John Victorine[1]; Dana Wreath[4], et al.

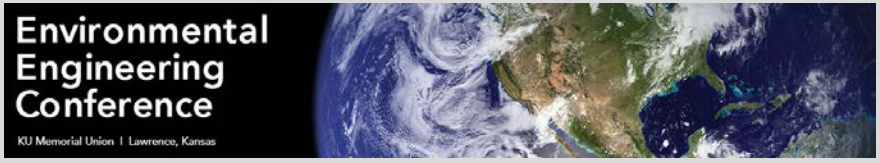
[1]Kansas Geological Survey, University of Kansas, Lawrence, Kan.; [2]Tbirdie Consulting, Lawrence, Kan.; [3]Department of Geology, University of Kansas, Lawrence, Kan.; [4]Berexco, LLC, Wichita, Kan.

KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

KU THE UNIVERSITY OF KANSAS
Department of Geology

DEPARTMENT OF ENERGY
NETL

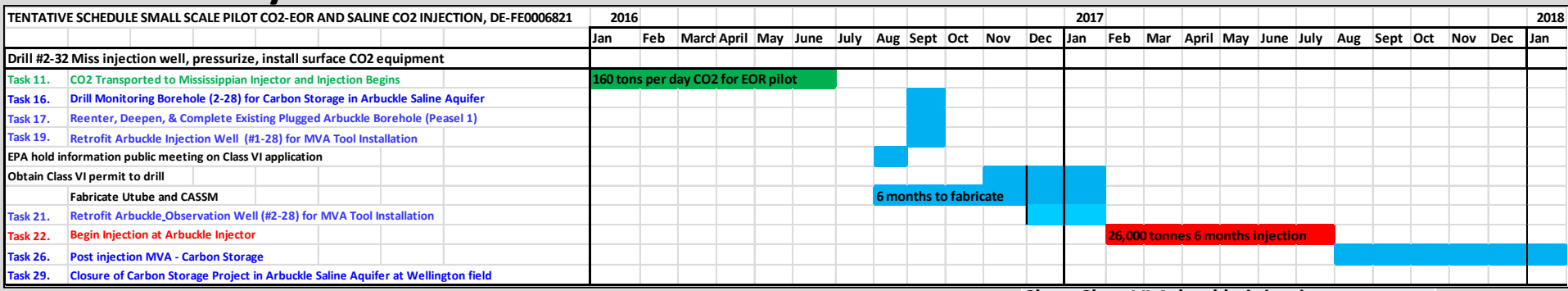
KSCO2



KANSAS

Overview

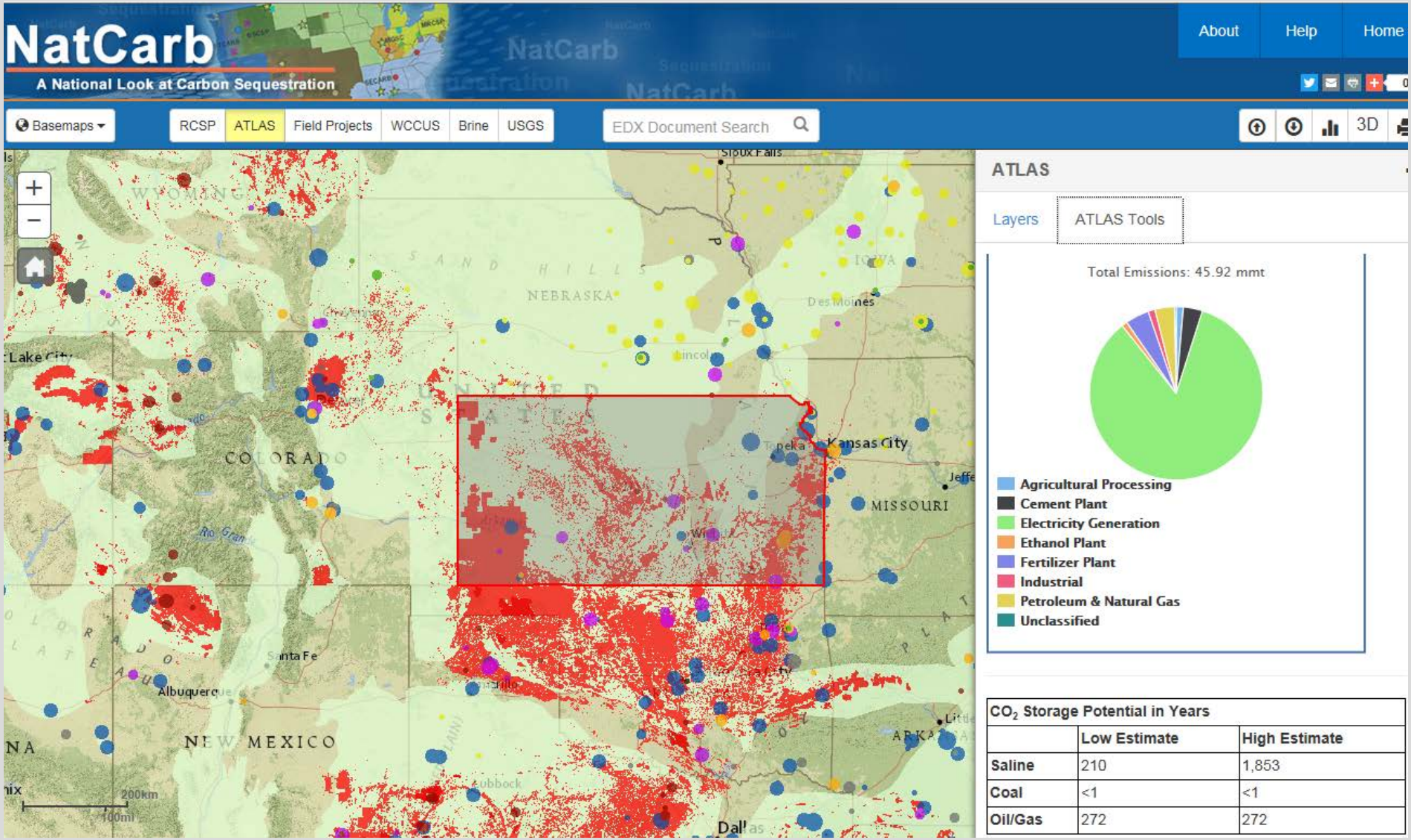
- **Completed evaluation of CO_2 storage and utilization in 25,000 mi^2, 33-county area in southern Kansas, DOE-NETL contract *DE-FE0002056* and partner cost share**
  - Southwest Kansas CO_2-EOR Initiative
  - CO_2 utilization in oil fields and storage in Arbuckle saline aquifer in southern Kansas
  - Cutter Field site characterization, Stevens Co.
  - Wellington Field site characterization, Sumner Co.
- **Pilot CO_2-EOR injection began January 9, 2016 in Mississippian dolomite reservoir in Wellington Field, Sumner County, Kansas (*DE-FE0006821*)**
- **Pilot CO_2 injection into Arbuckle at Wellington, pending EPA Class VI permit**
- **Steps toward implementing CO_2 Utilization and Storage (CCUS) in Kansas**
- **Summary**



Total annual CO_2 emissions in Kansas in 2015
45.92 million tonnes

Potential Saline storage capacity for 210 to 1,853 years of Ks emissions

Oil and gas reservoir storage capacity for 271 years



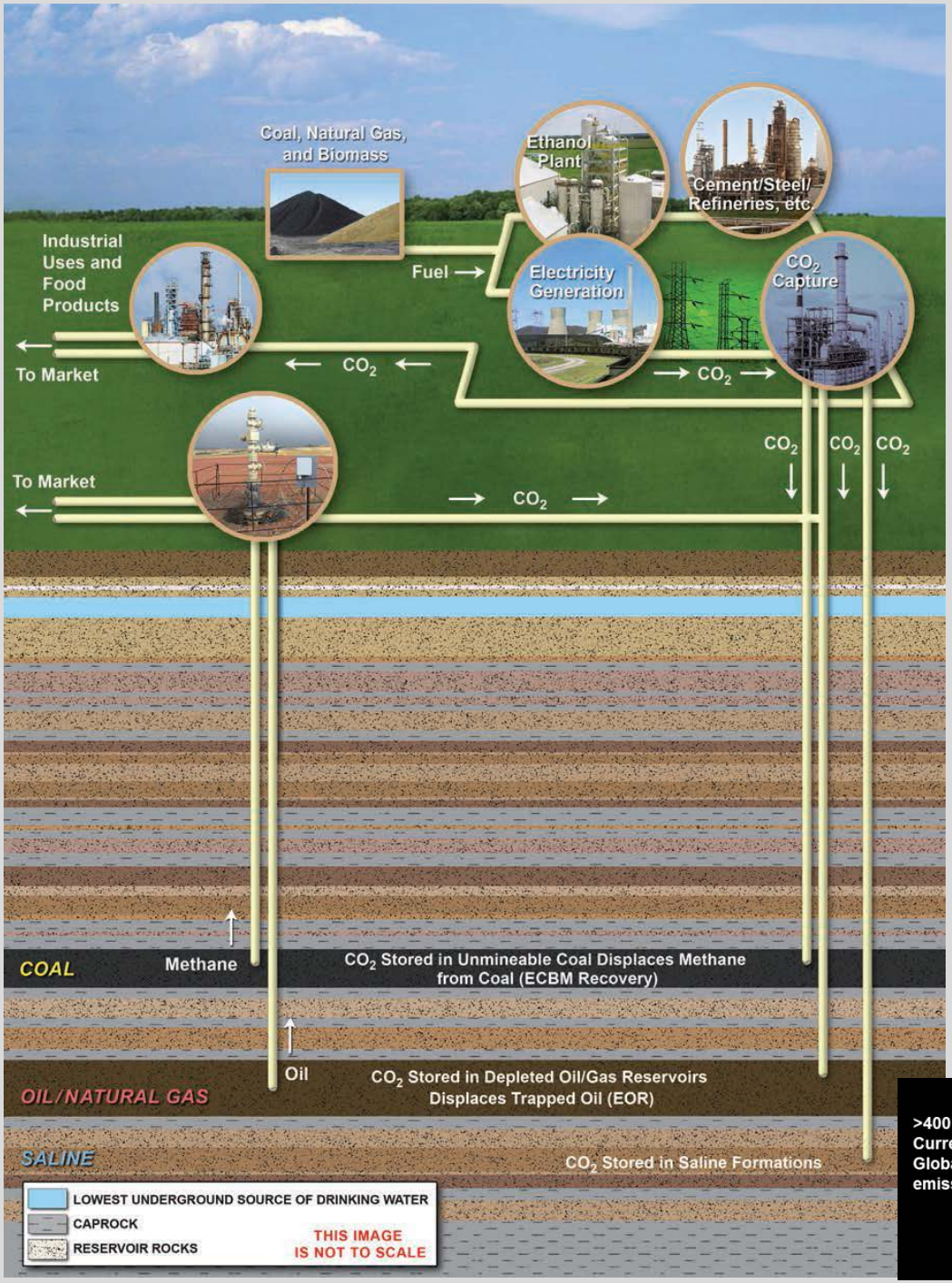
CO_2 Storage Potential in Years		
	Low Estimate	High Estimate
Saline	210	1,853
Coal	<1	<1
Oil/Gas	272	272

Geologic Carbon Utilization & Storage

The 2015 United States Carbon Utilization and Storage Atlas – Fourth Edition (Atlas IV)
DOE-NETL

Global annual CO_2 emissions ≈ 8 * 10^9 tons

Earth Policy Institute



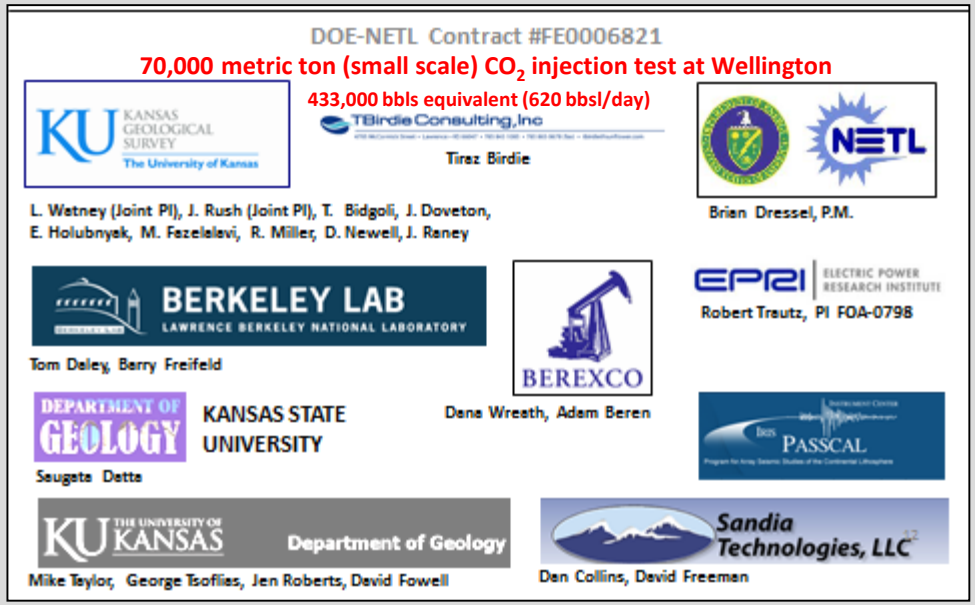
>400 yrs Current Global emissions

Formation Type	10^9 Metric Tons	%
Saline Aquifers	3,297 – 12,618	91.8 – 97.5
Unmineable Coal Seams	157 – 178	4.4 – 1.4
Mature Oil & Gas Reservoirs	138	3.8 – 1.1
Total Capacity	3,592 – 12,934	100.0

CO_2-EOR Technology & Carbon Management Research in Kansas

SW Kansas CO_2-EOR Initiative

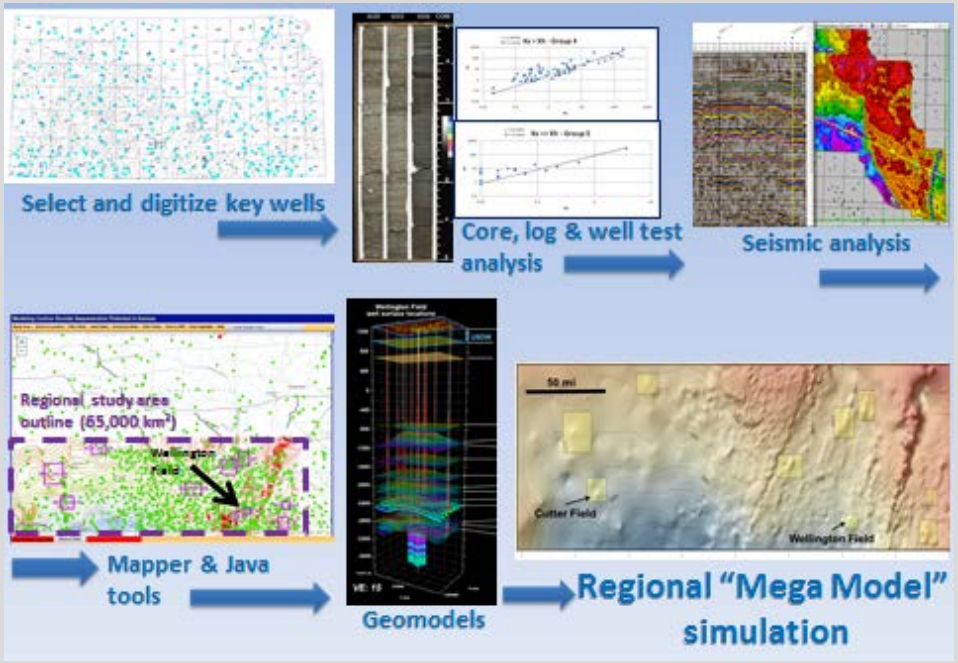
- Utilize oil and gas field Infrastructure
- Utilize comparable approaches to characterization and simulation of oil and reservoirs
- Evaluated 10 sites for commercial scale carbon storage sites in aquifers beneath existing oil fields
- Conduct small scale CO2-EOR injection at Wellington Field, Sumner County Kansas
- KU & partners have performed extensive research on:
  - -monitoring
  - -verification
  - -accounting of the CO_2 over the long term



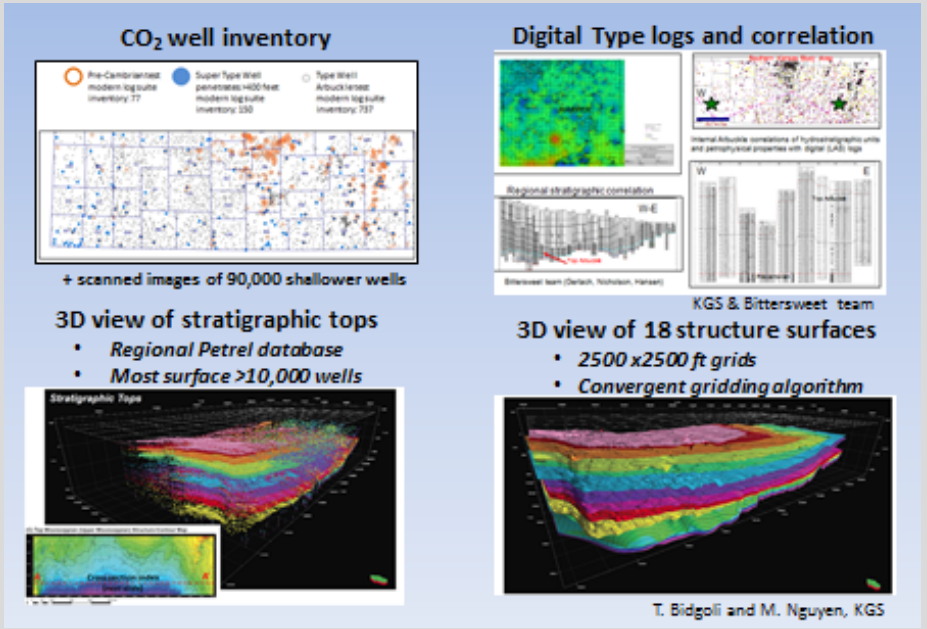
Completed evaluation of CO_2 storage capacity of a 25,000 mi^2, 33-county area in southern Kansas

- Southwest Kansas CO_2-EOR Initiative
- CO_2 utilization in oil fields and storage in Arbuckle saline aquifer in southern Kansas (8-70 billion metric tonnes CO2, P10/P90; volumetrically; 4 billion by simulation based on injectivity and storage)
- Site characterization → Cutter Field site, Steven Co., Wellington Field, Sumner Co.

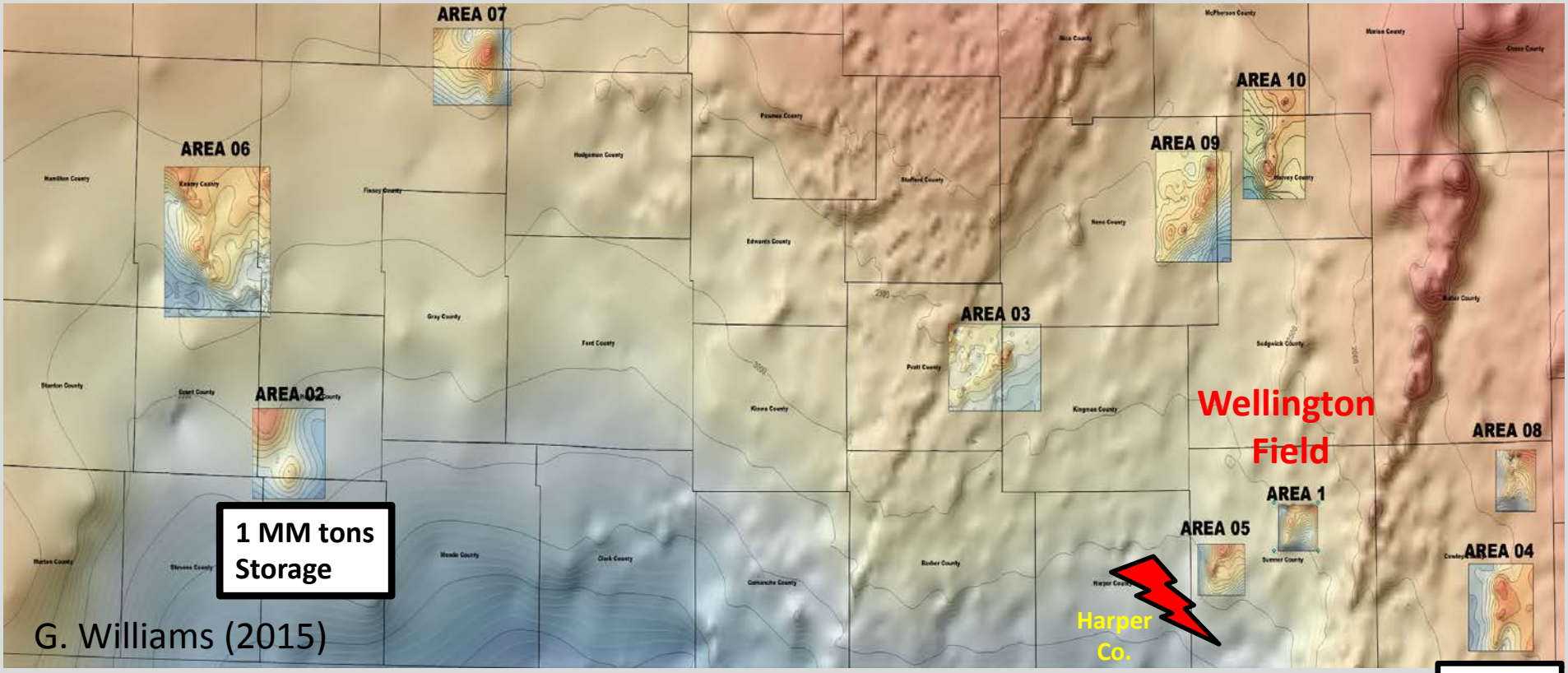
Project workflow



Maximize new information gained to quantify key variables in CO_2 injection and storage in Kansas



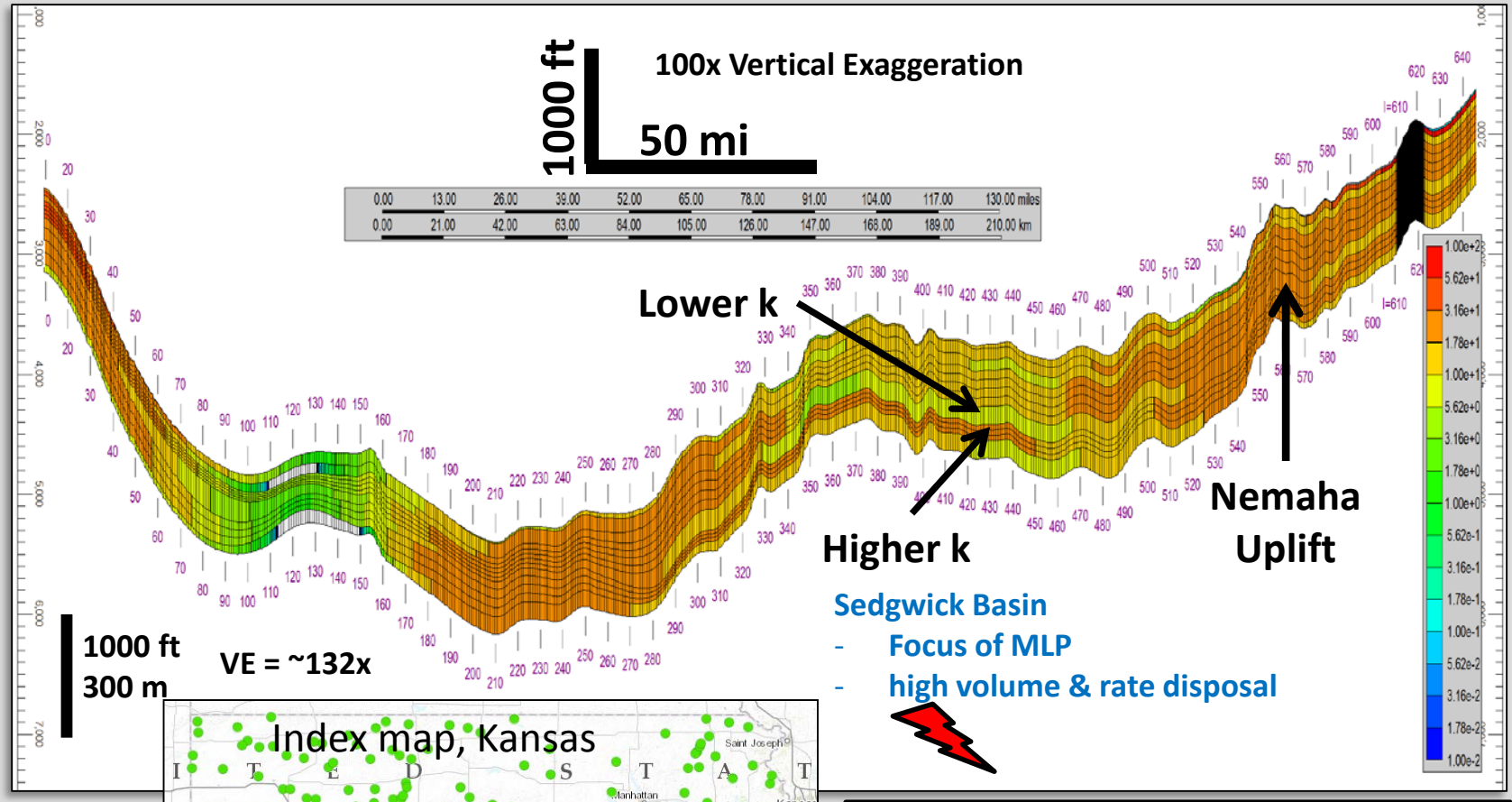
Interactive mapper: http://maps.kgs.ku.edu/co2/



Regional Scale CO_2 Storage Capacity Simulation in the Lower Ordovician Arbuckle Group

- South Western and South Central Kansas
- 10 areas – benchmark sites
- One “mega” model
- Utilized database for simulating large scale brine disposal to understand induced seismicity in south-central Kansas

West-East structural cross section showing permeability distribution in 16 Arbuckle flow units, southern Kansas

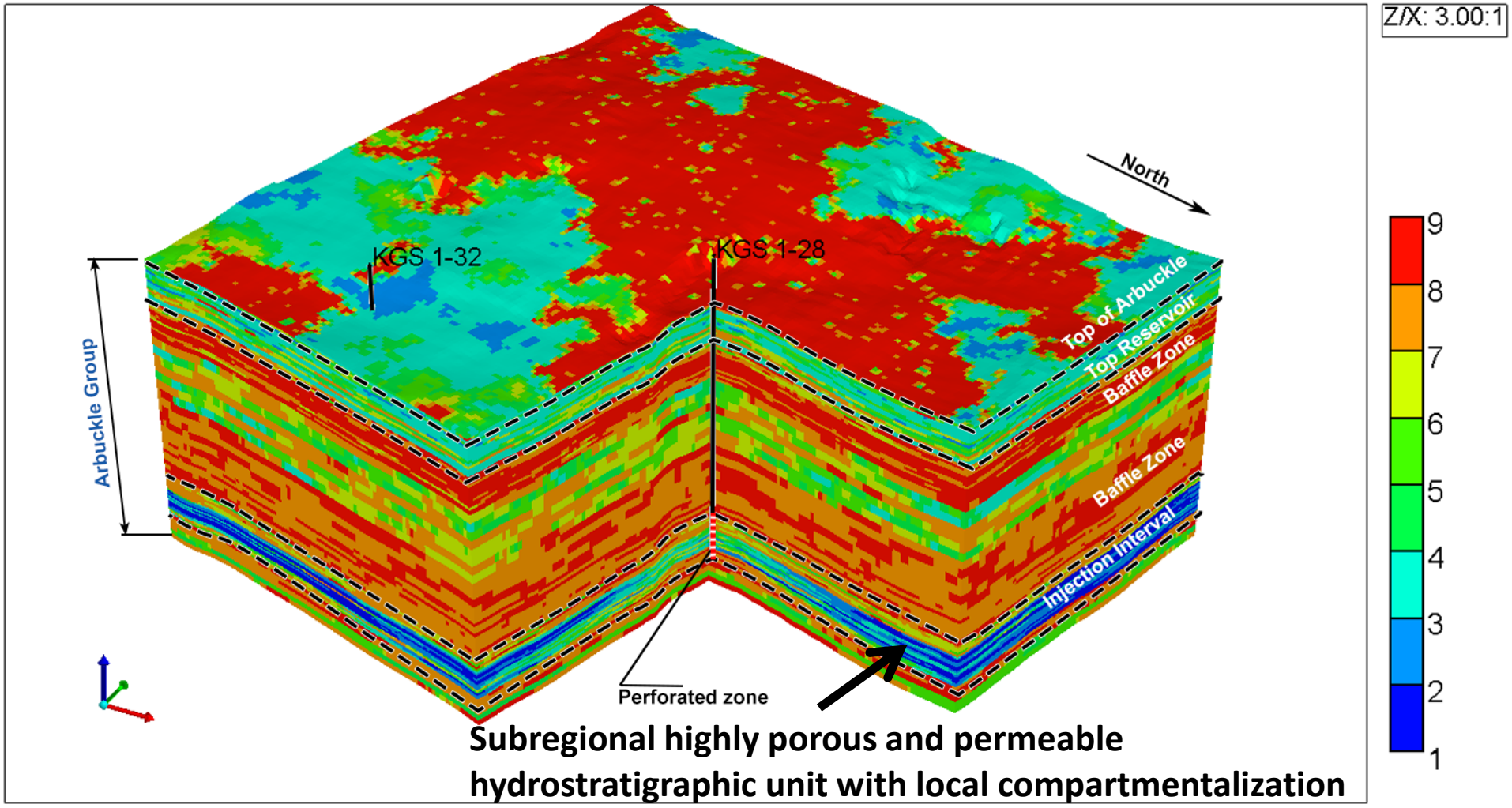


- Based on realizations of horizontal permeability, md
- Calibrated with core, logs, test data at Wellington and Cutter Fields

Williams, Gerlach, Fazelalavi, Doveton, KGS team, KS CO_2

Rock types mapped in Arbuckle at Wellington Field Based on RQI

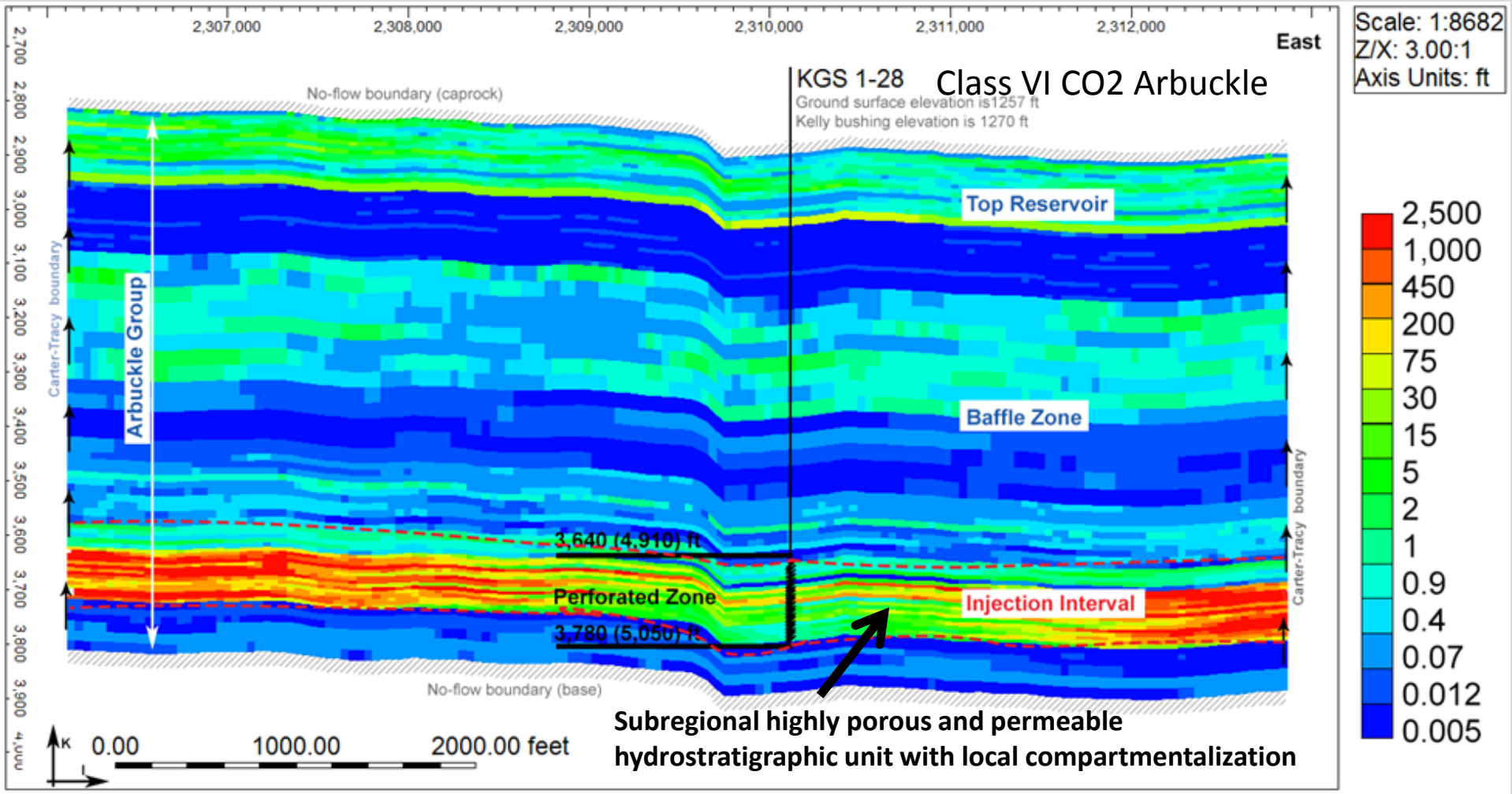
$$RQI(reservoir\ quality\ index) = 0.0314\sqrt{Perm/Porosity}$$



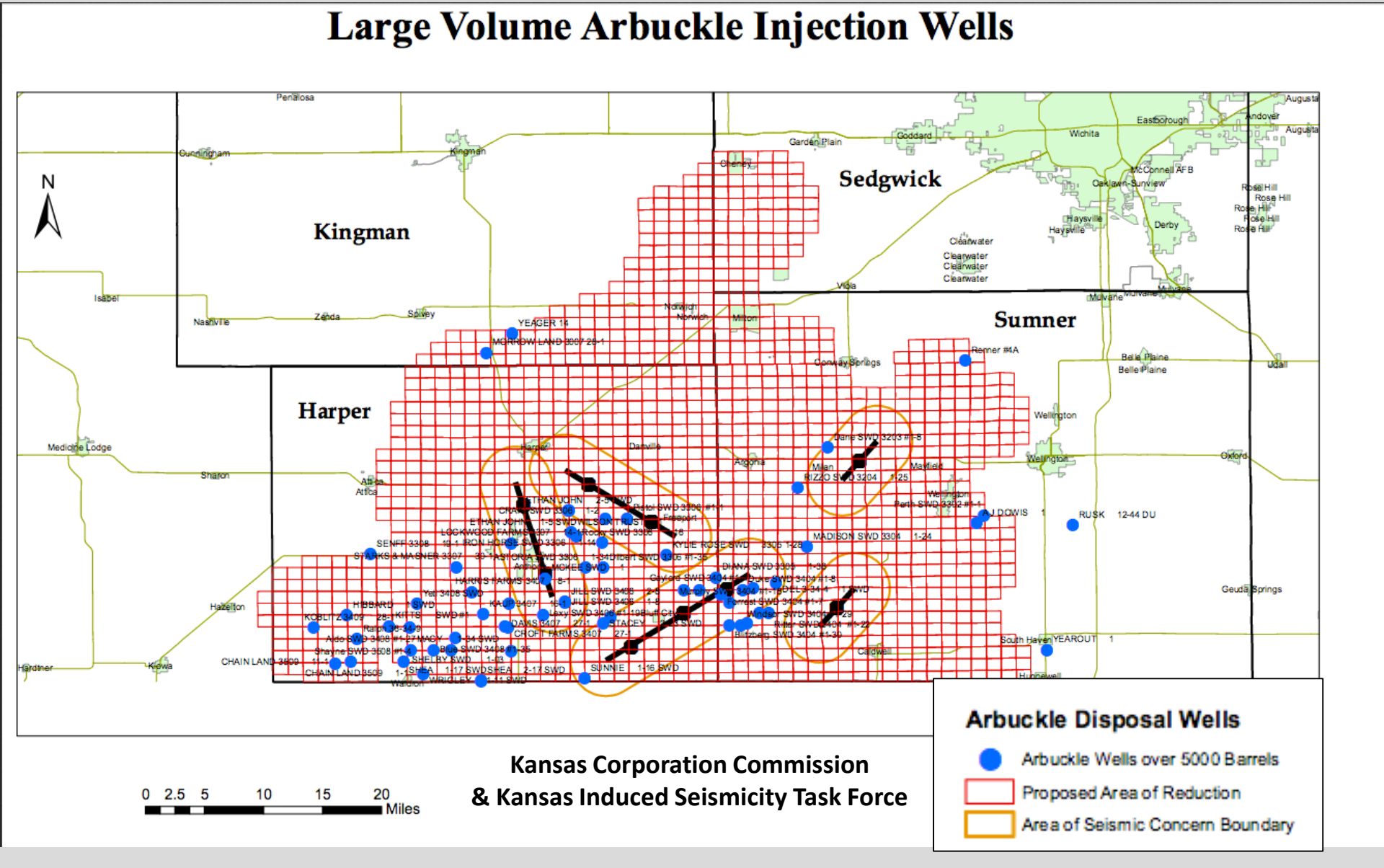
Subregional highly porous and permeable hydrostratigraphic unit with local compartmentalization

Vertical permeability (mD) distribution in the Arbuckle saline aquifer beneath Wellington oil field

-- east-west cross section through the injection well (KGS 1-28)



Proposed area of reduction of disposal for management of induced seismicity



Kansas Corporation Commission
& Kansas Induced Seismicity Task Force

SW Kansas CO_2-EOR Initiative under DE-FE0002056

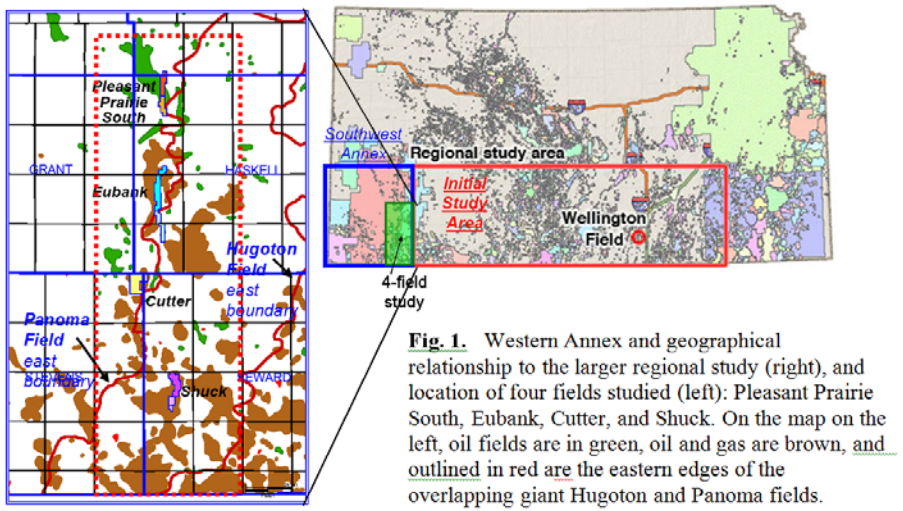


Fig. 1. Western Annex and geographical relationship to the larger regional study (right), and location of four fields studied (left): Pleasant Prairie South, Eubank, Cutter, and Shuck. On the map on the left, oil fields are in green, oil and gas are brown, and outlined in red are the eastern edges of the overlapping giant Hugoton and Panoma fields.

Pleasant Prairie South, Eubank, Cutter, and Shuck fields, southwest Kansas

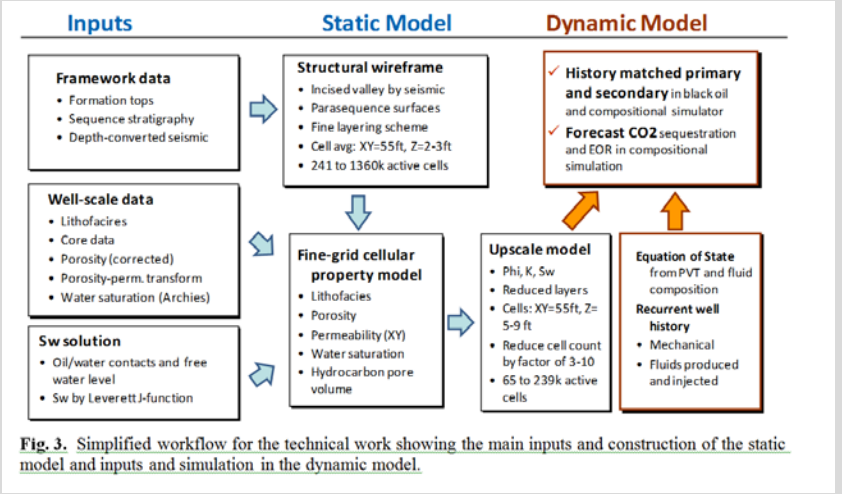


Fig. 3. Simplified workflow for the technical work showing the main inputs and construction of the static model and inputs and simulation in the dynamic model.

Potential for CO_2 Storage and Enhanced Oil Recovery in Four Southwest Kansas Oil Fields - *an extended abstract*

Martin K. Dubois, Eugene T. Williams, John C. Youle, and Dennis E. Hedke

Dynamic simulation suggests that the four small fields could be viable target for CO_2 storage with concurrent EOR. Combined the four fields are projected to be capable of storing 5.41 million tons of CO_2 (93.3 bcf) while producing an additional 13.2 million barrels of oil (18% of original oil in place).

Final Report, DE-FE0002056 October 2015

WELLINGTON FIELD PILOT DEMONSTRATION

DOE-NETL Contract #FE0006821

KANSAS GEOLOGICAL SURVEY
The University of Kansas

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

Brian Dressel, DOE Project Manager

BEREXCO

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

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

Tom Daley, Barry Freifeld *(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

Schlumberger
CMG COMPUTER MODELLING GROUP LTD.

IRIS INSTRUMENT CENTER
PASSCAL
Program for Array Seismic Studies of the Continental Lithosphere
donated 15 seismometers

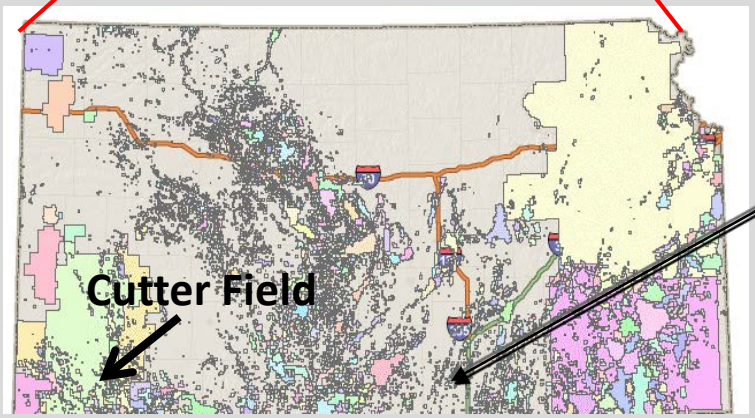
TBirdie Consulting, Inc
4705 McCormick Street • Lawrence • KS 66047 • 785 843 1085 • 785 865 0678 (fax) • tbirdie@sunflower.com

T. Birdie *(Class VI permitting, monitoring, synthesis, reporting, closure)*

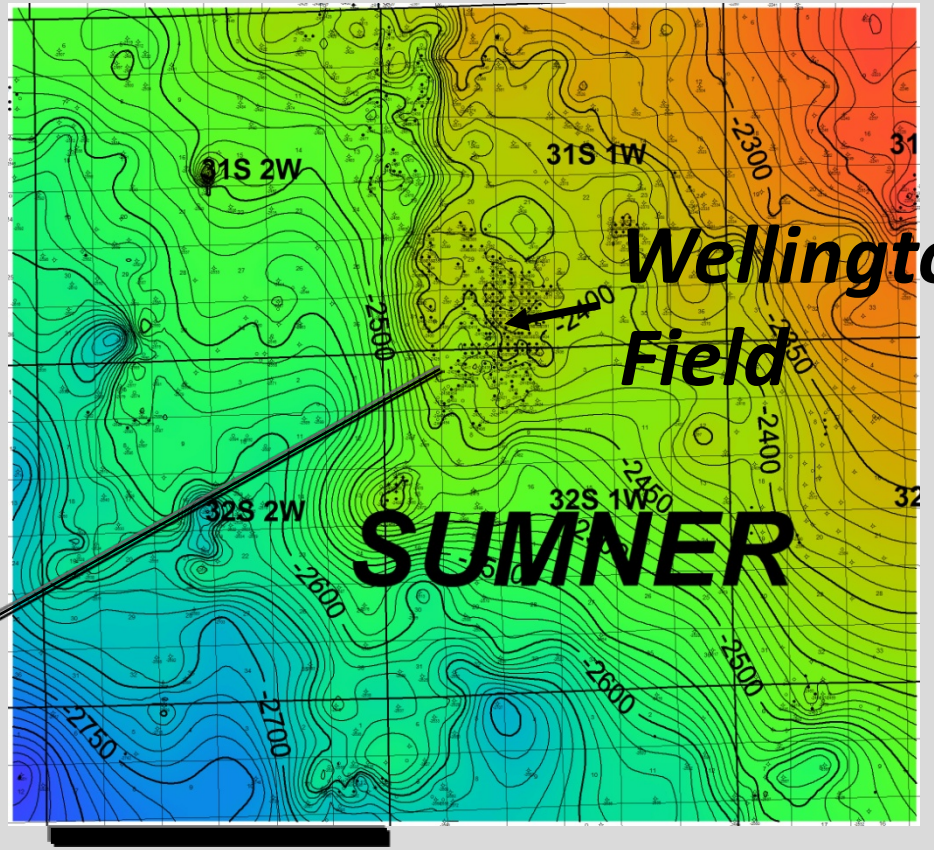
KU THE UNIVERSITY OF KANSAS Department of Geology

Jennifer Roberts, Leigh Stearns (cGPS), Mike Taylor *(InSAR)*, George Tsoflias *(passive and active seismic)*

Wellington Field
Site of Small Scale Field Test



Top Mississippian Structure, 10 ft C.I.



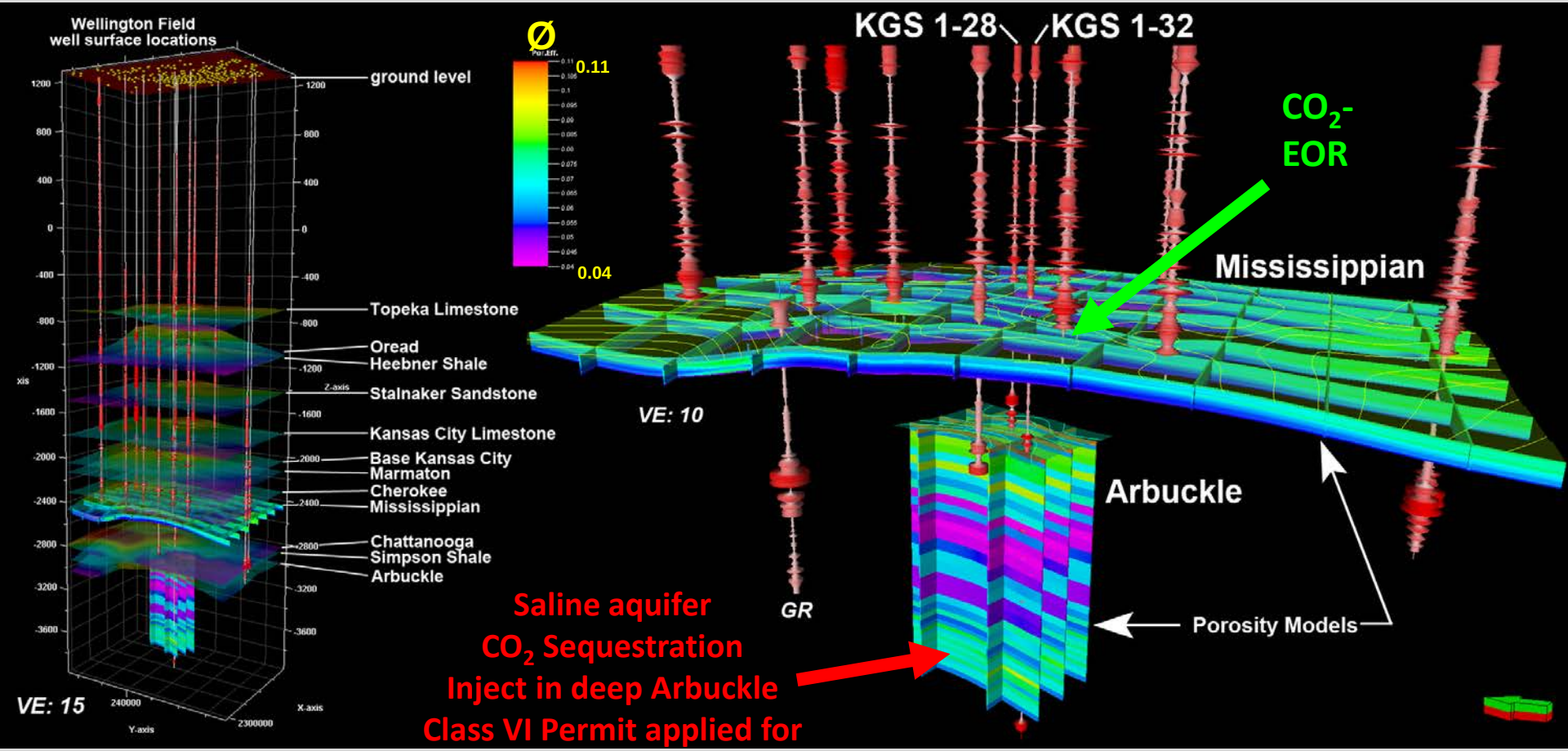
10 km

20 Million Barrel Oil Field above Arbuckle Group

KANSAS GEOLOGICAL SURVEY
The University of Kansas

Wellington Field – eastern calibration site

Mississippian siliceous dolomite reservoir & Arbuckle aquifer saline aquifer



KANSAS GEOLOGICAL SURVEY
The University of Kansas

J. Rush (KGS)

Pilot CO_2-EOR well drilled in 2015 and injection began in January 2016

Mississippian dolomite reservoir in Wellington Field
Sumner County, Kansas

Berexco LLC
Wellington KGS #2-32
2680'FSL & 709'FEL, Sec 32, T 31S, R 1W
Sumner County, Kansas

Drilled in March 2015

BEREXCO

Fossil Drilling

MUDCO

DEVILBISS CORING SERVICE, INC.
"QUALITY SERVICE SINCE 1992"

HALLIBURTON

Core Lab
RESERVOIR OPTIMIZATION

TRILOBITE TESTING, INC.

Linde Group –CO_2 supplier for the Wellington Field pilot CO_2 injection

Hammerfest LNG Project Norway – CO_2-Reinjection

I am taking the lead.

THE LINDE GROUP

World's first industrial project to deliver CO_2 separated onshore back offshore and injected into a reservoir

- Europe`s first export facility for liquified natural gas (LNG)
- Terminal and process plant on Melkøya island outside Hammerfest in northern Norway
- Annual LNG export: 5.67 billion sm^3
- CO_2 - Content: 5.0% to 8.0 %
- CO_2 captured in onshore plant
- Conveyed back with subsea pipeline
- Storage underground
- Emission reduction of more than 50 %
- Norwegian CO_2-Tax: 50 Euro/ton

Praxair -- CO_2 supplier for Wellington Pilot

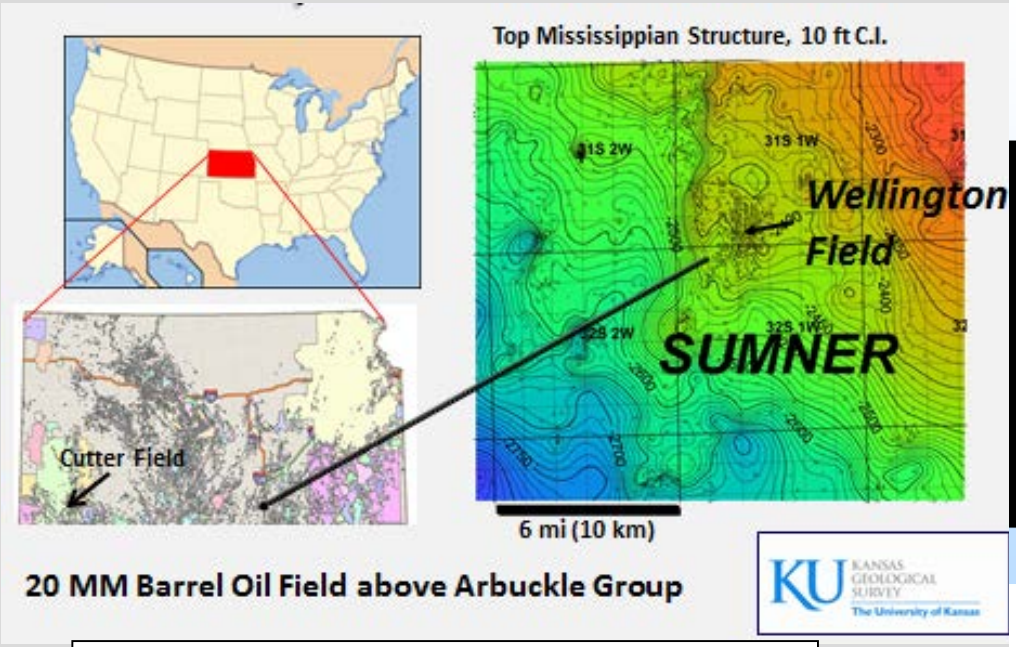
PRAXAIR

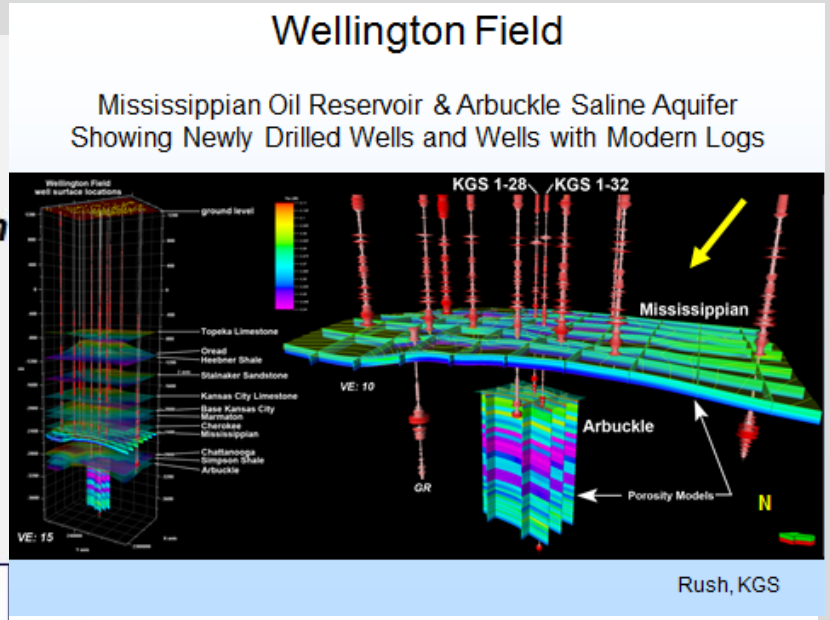
Upstream Oil and Gas

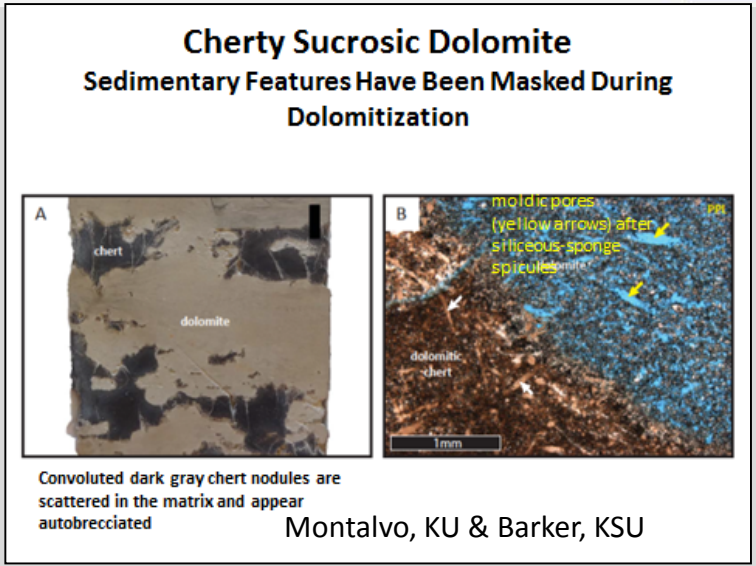
- **Enhanced Oil Recovery**
  - Over 30 years experience with Gas Displacement Recovery (GDR)
    - Nitrogen
    - Carbon Dioxide
  - More than 25 projects
- **Well Stimulation Services**
  - **Fracing**
  - **Wellbore damage cleanup**
- **CO_2/N_2 EOR Services**
  - Pilots
  - Injection test and huff-n-puffs
- **CO_2 Capture & Purification**

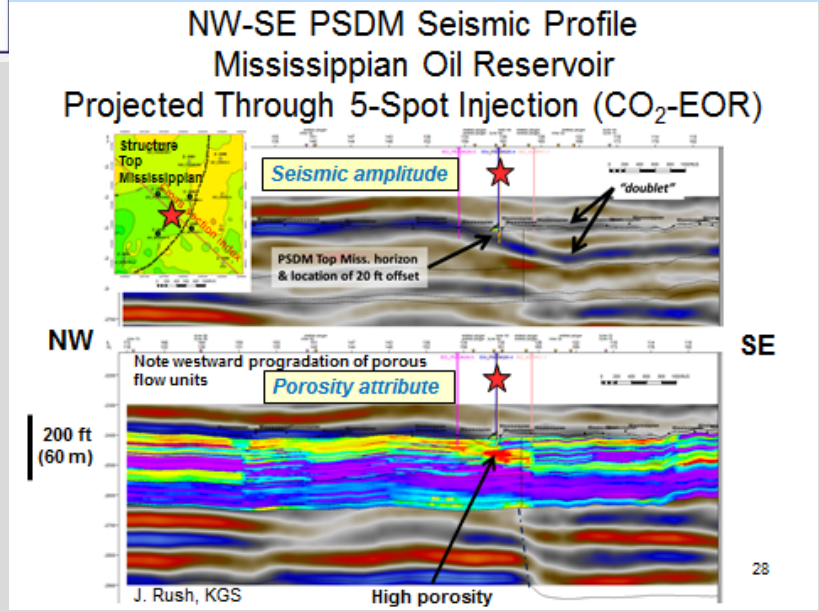
Exxon Hawkins Field,
85 MMscf/d 2,000 psi

Wellington Field site characterization
Sumner County, Kansas under DE-FE0002056

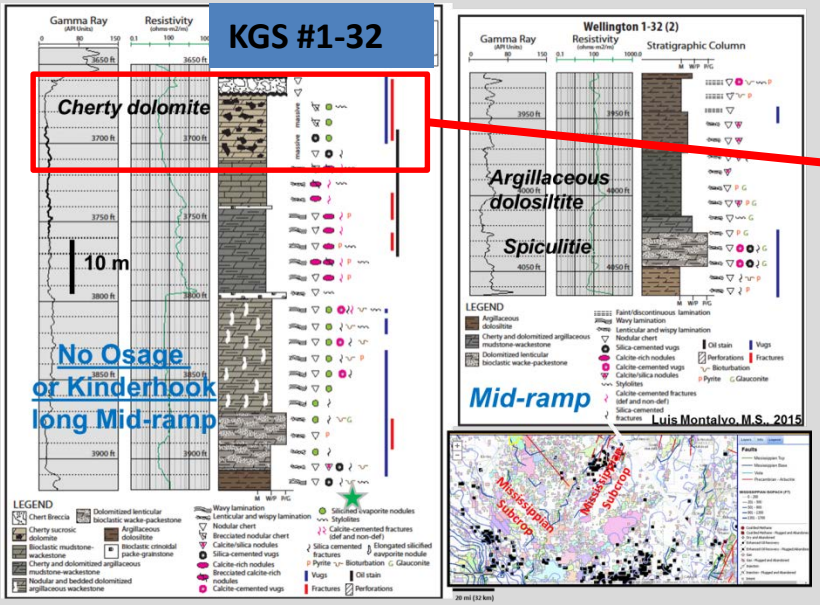




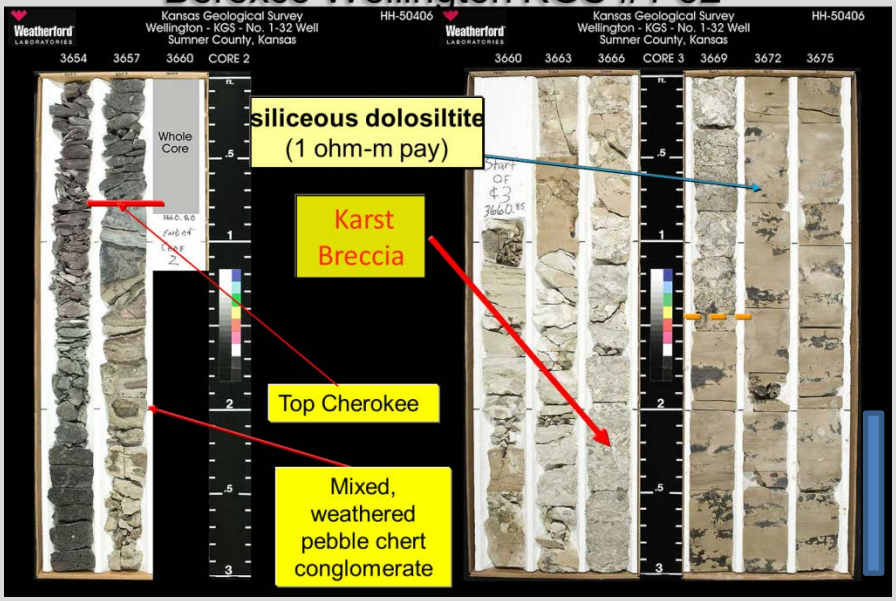




No Osage or Kinderhook Mississippian → mid ramp

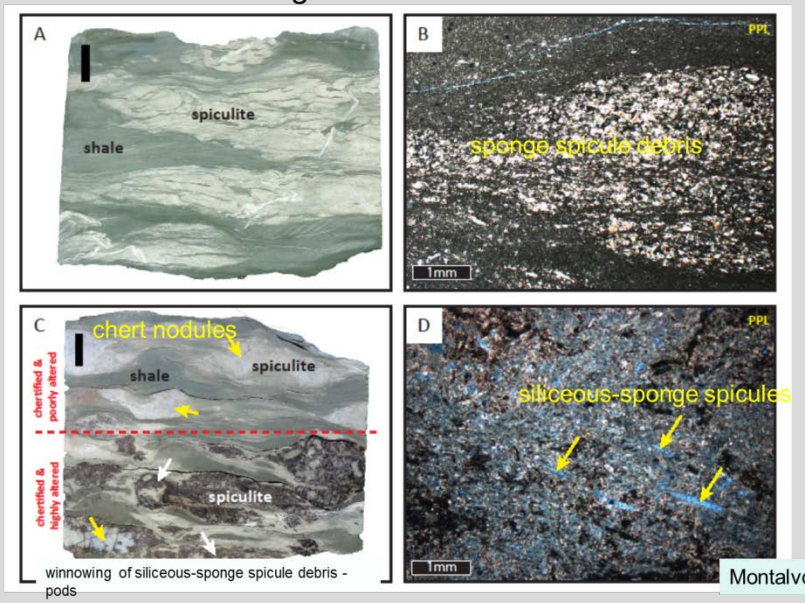


Mississippian pay zone in Berexco Wellington KGS #1-32

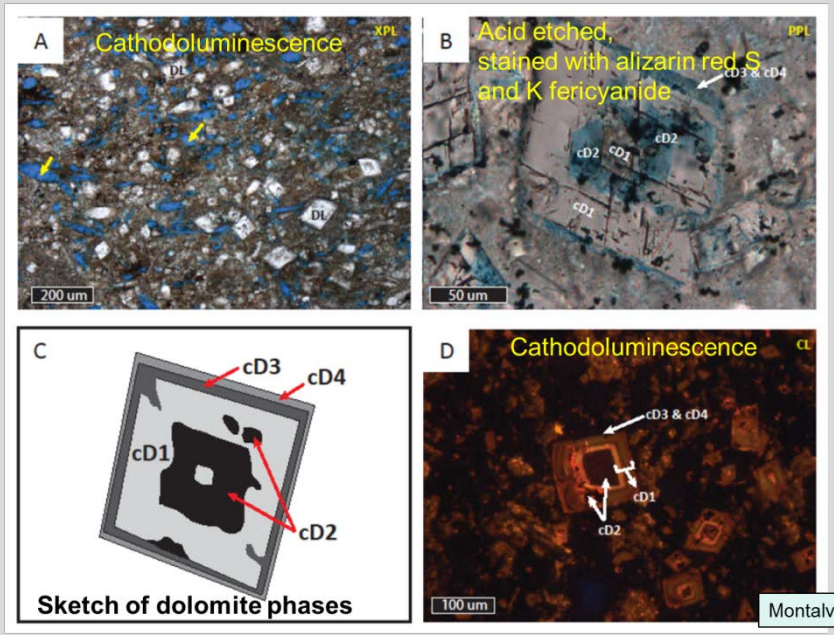


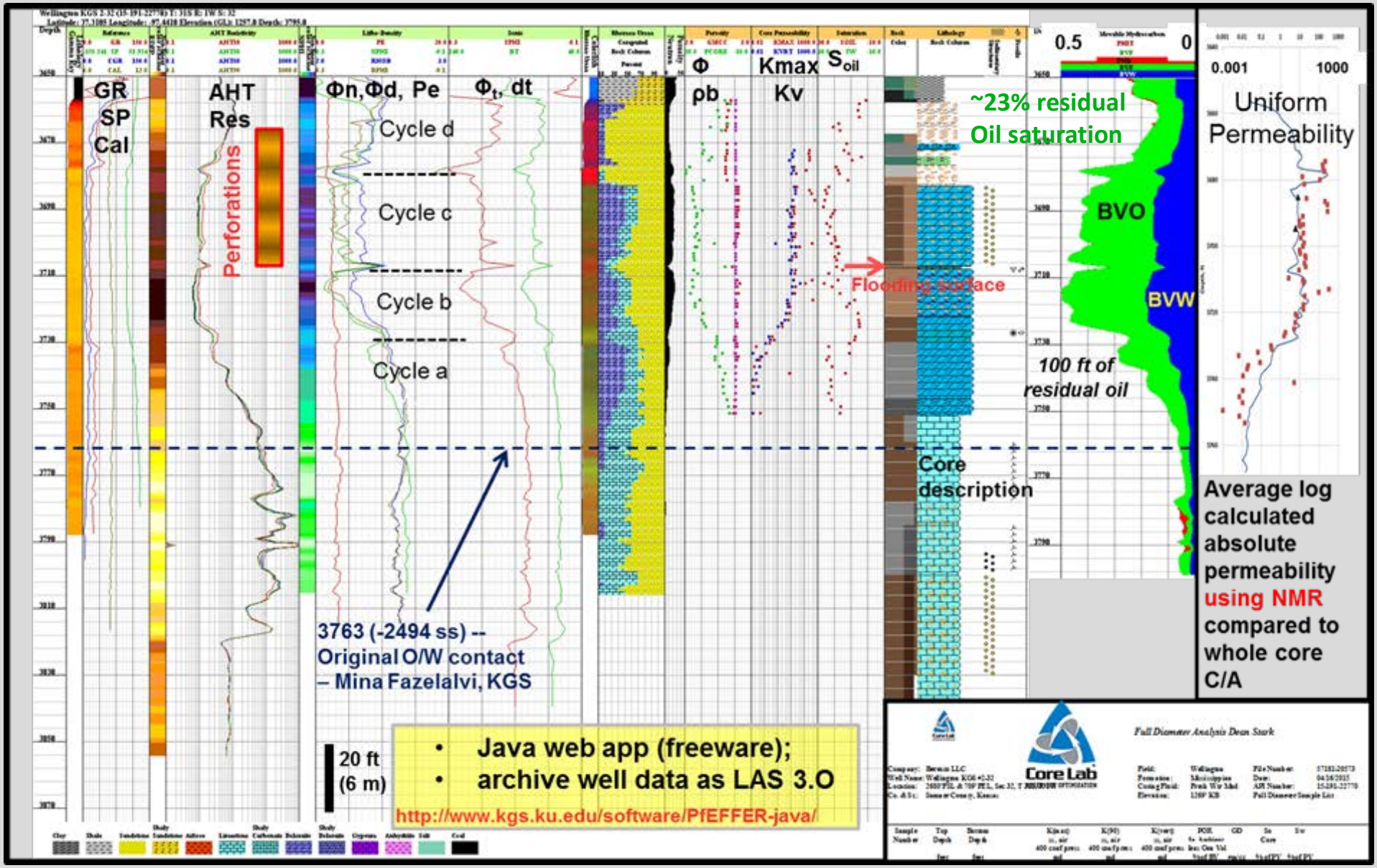
Lenticular Spiculite Wacke/Packestone

Extensive Micro-Porosity Through Dissolution and Etching of the Silica Matrix



Rhombic Dolomite Euheral (idiotopic) Different Phases, Feroan and Non-Feroan

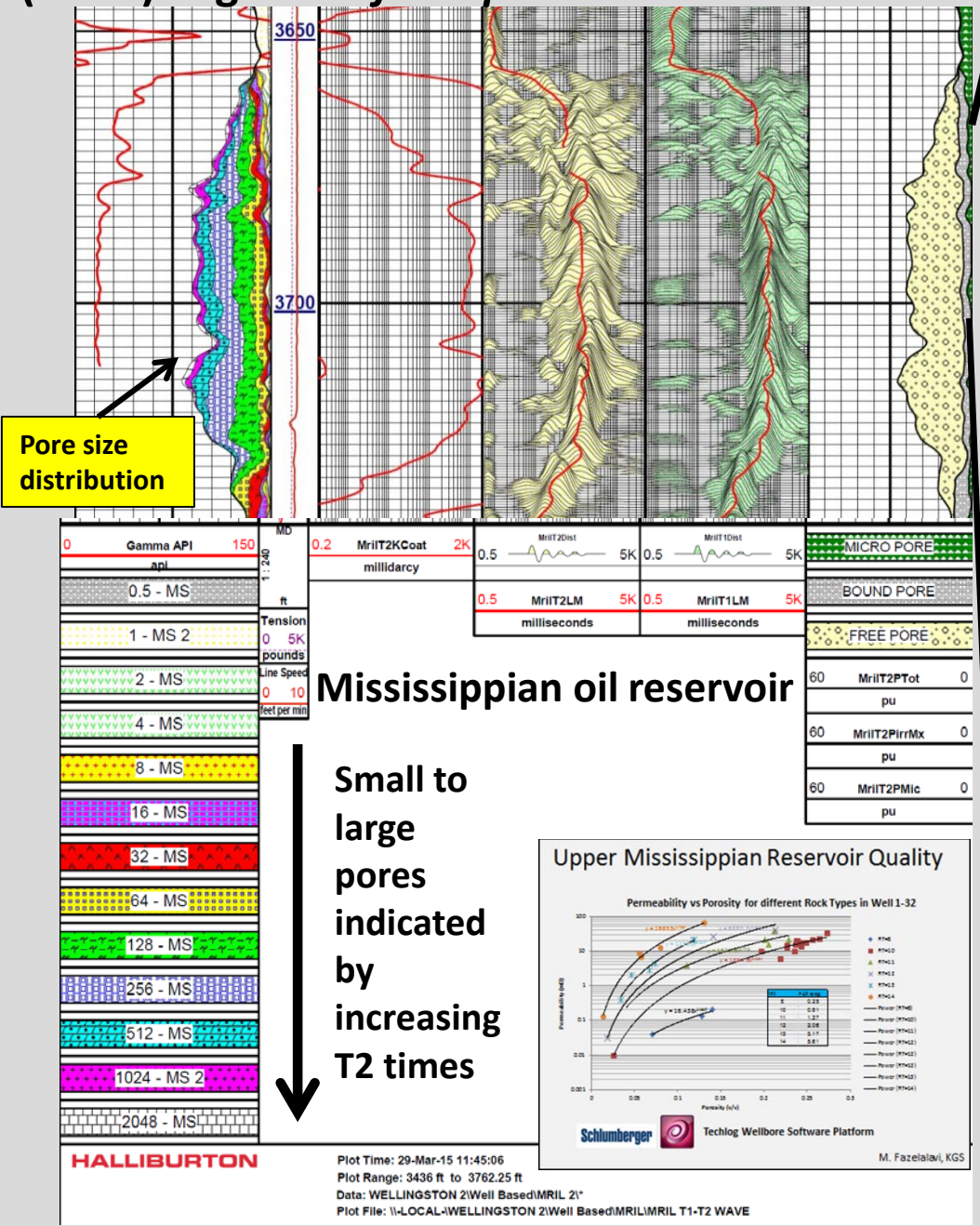


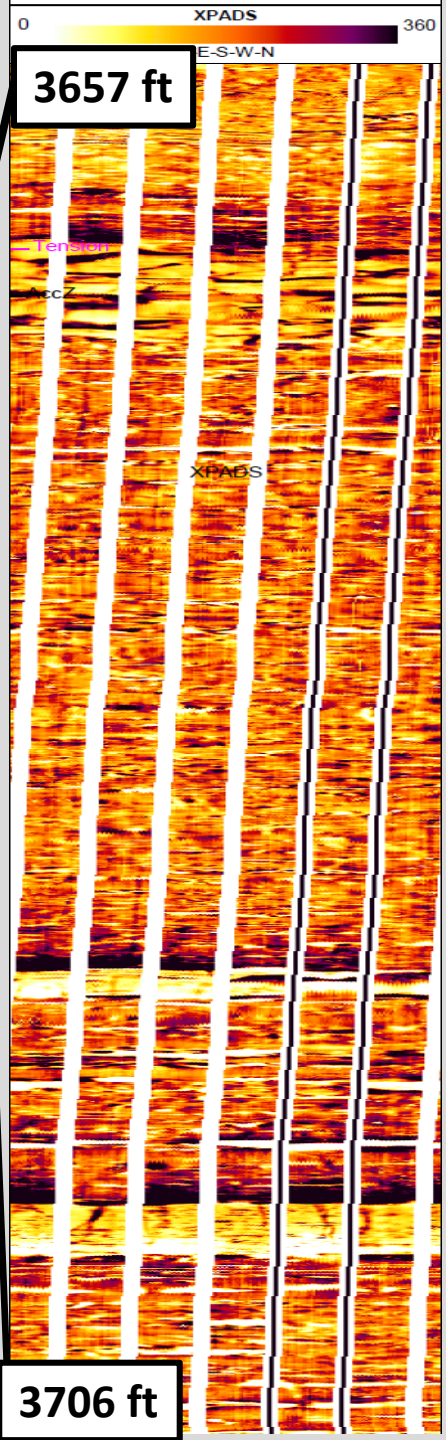


Berexco Wellington KGS #2-32 showing well logs, lithologic interpretation from logs, core analysis, lithology from core description, and moveable oil (green, residual oil saturation).

J. Victorine (KGS)

Halliburton Nuclear Magnetic Resonance (MRIL) Log → *uniform pore distribution*





Formation microresistivity imaging log

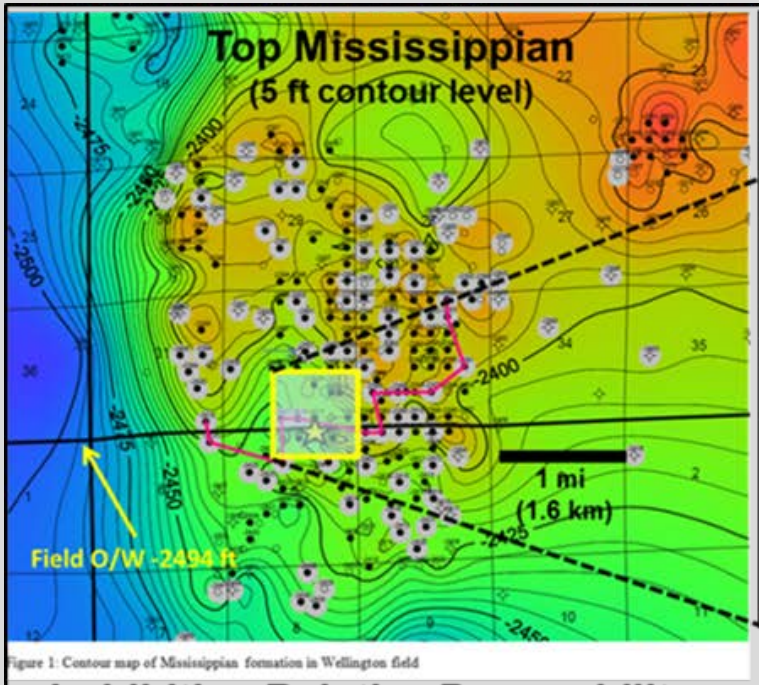
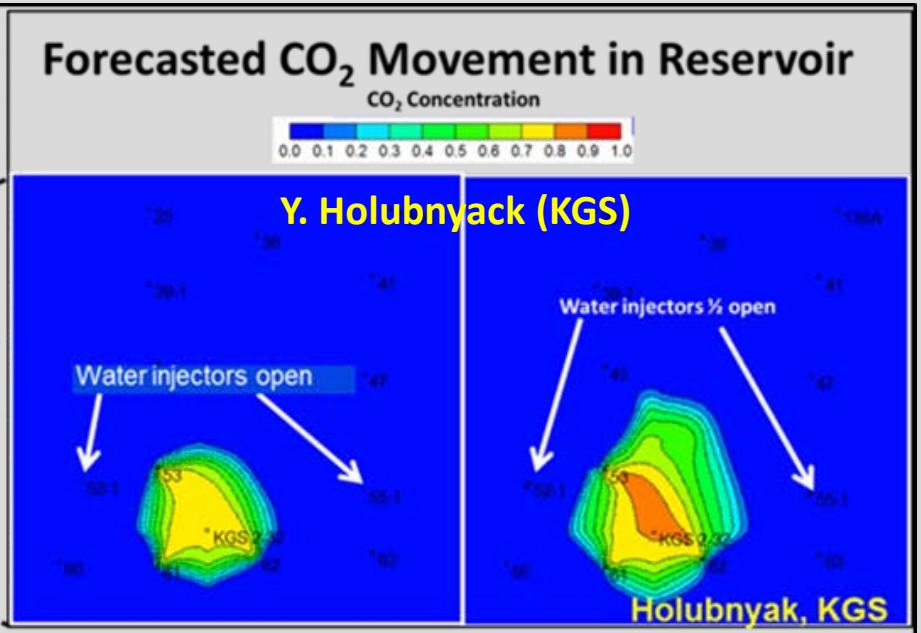
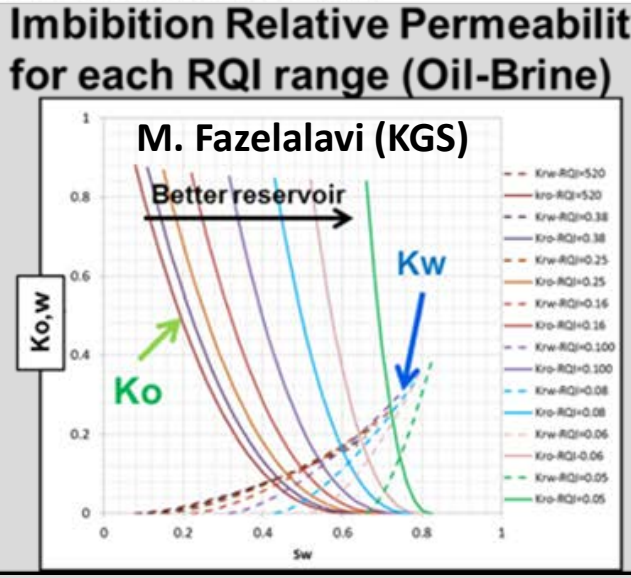
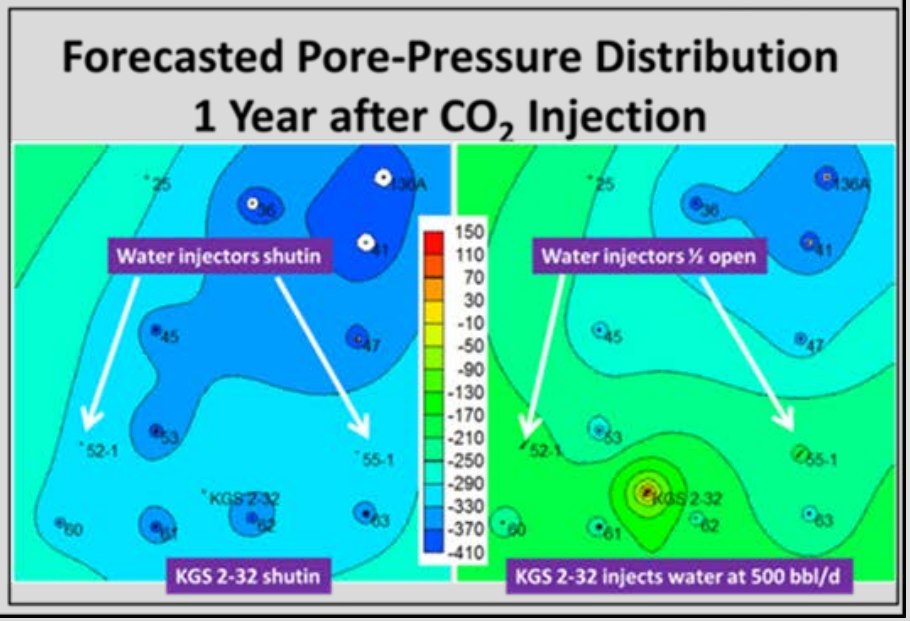


Figure 1: Contour map of Mississippian formation in Wellington field



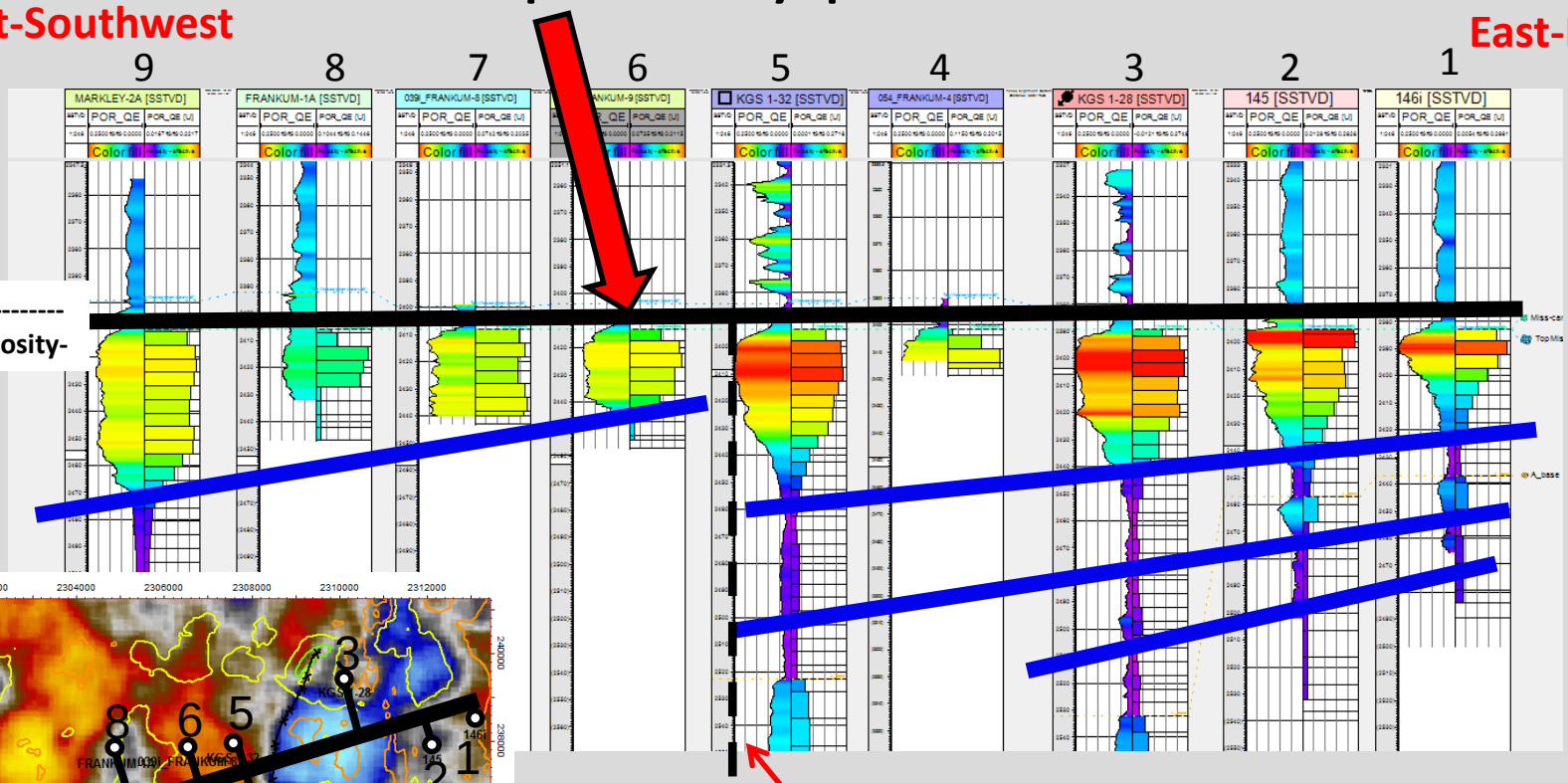


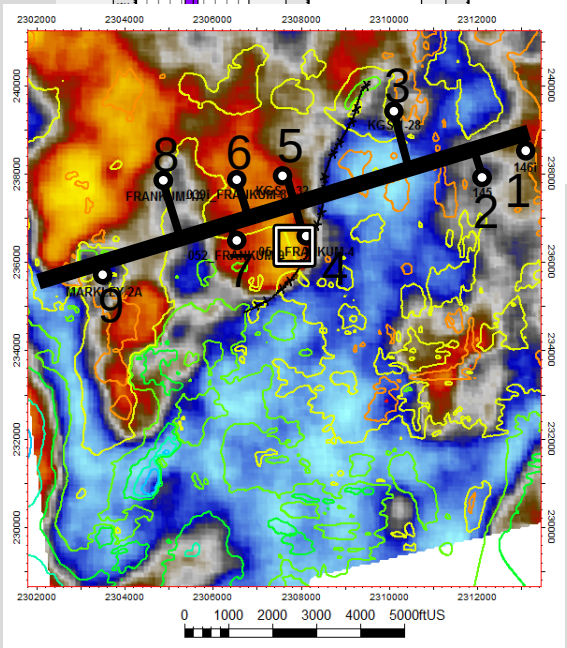


Top Mississippian structural elevation (25 ft contour interval), (upper right) forecasted CO2 movement after 26,000 tonnes, (lower right) pore pressure distribution used to control the sweep of the CO2, and (lower left) relative permeability curves determined for each reservoir rock type (reservoir quality index).

CO_2-EOR injection in area of reservoir with uniform porosity profile of reservoir

West-Southwest **East-Northeast**

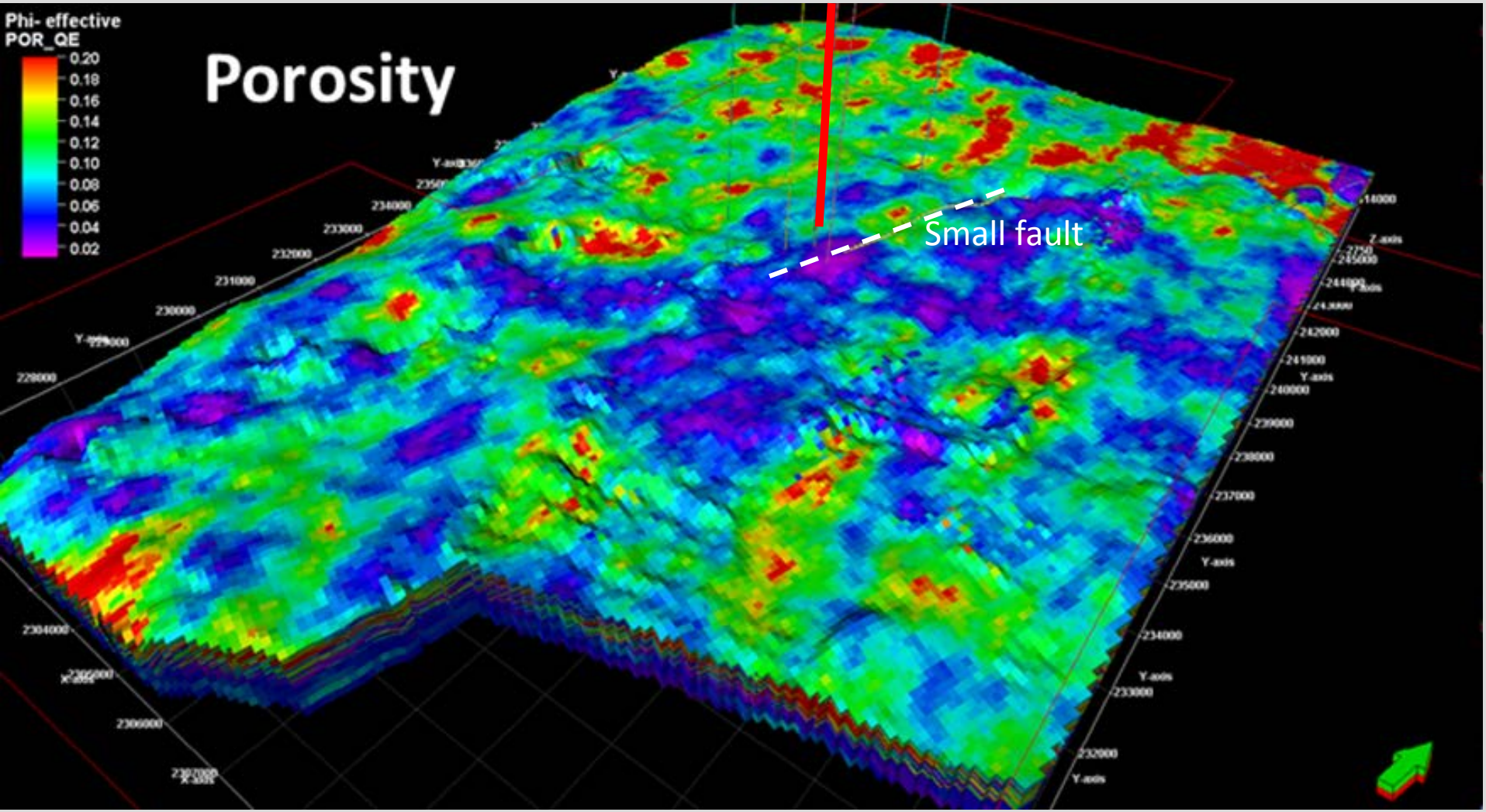




Small fault acting as barrier to flow on east side of pilot site (250 ft from the fault)

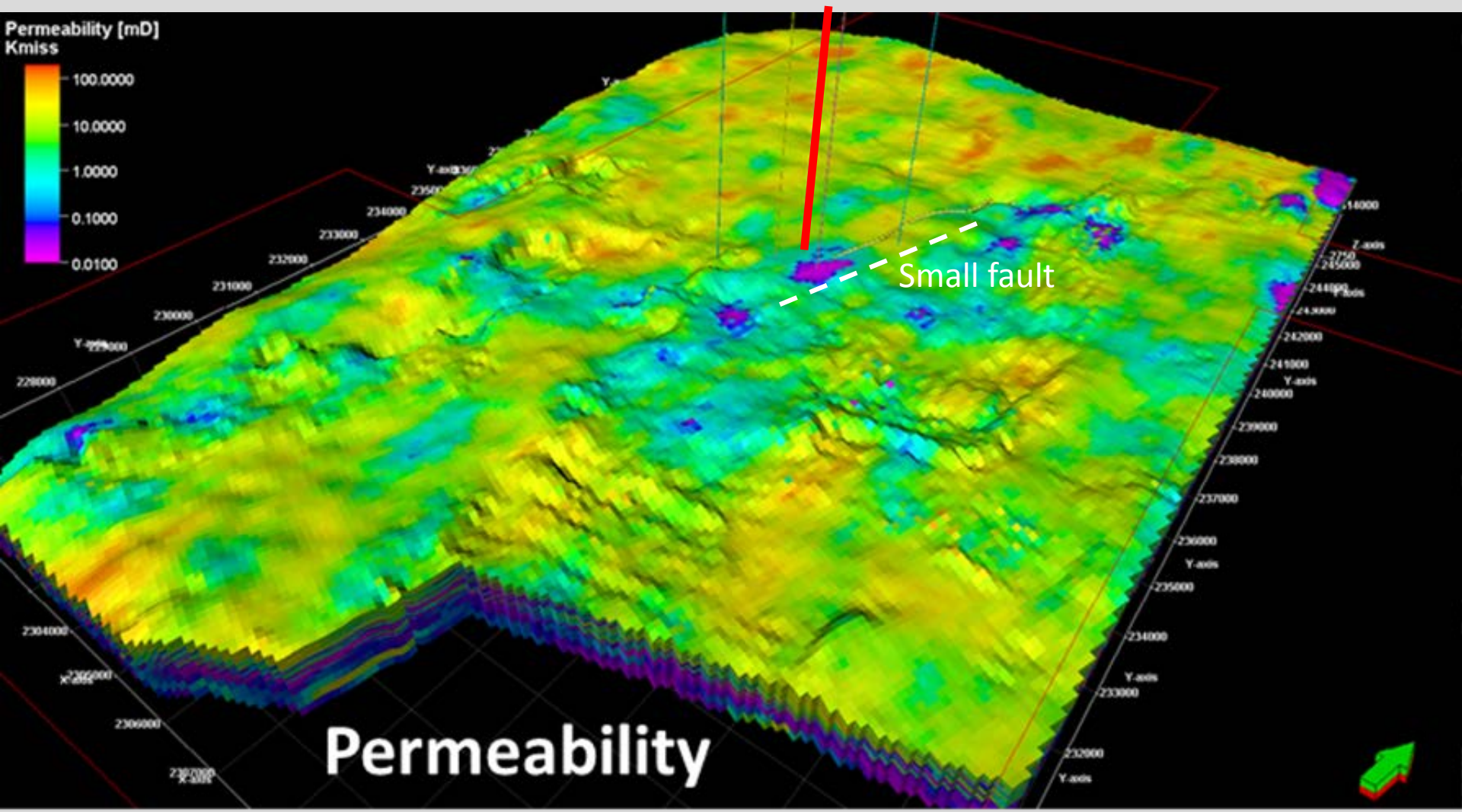
- **Porosity thickening indicative of low-angle, westward progradational wedges**
- **Confirmed by 3D seismic**

J. Rush (KGS)



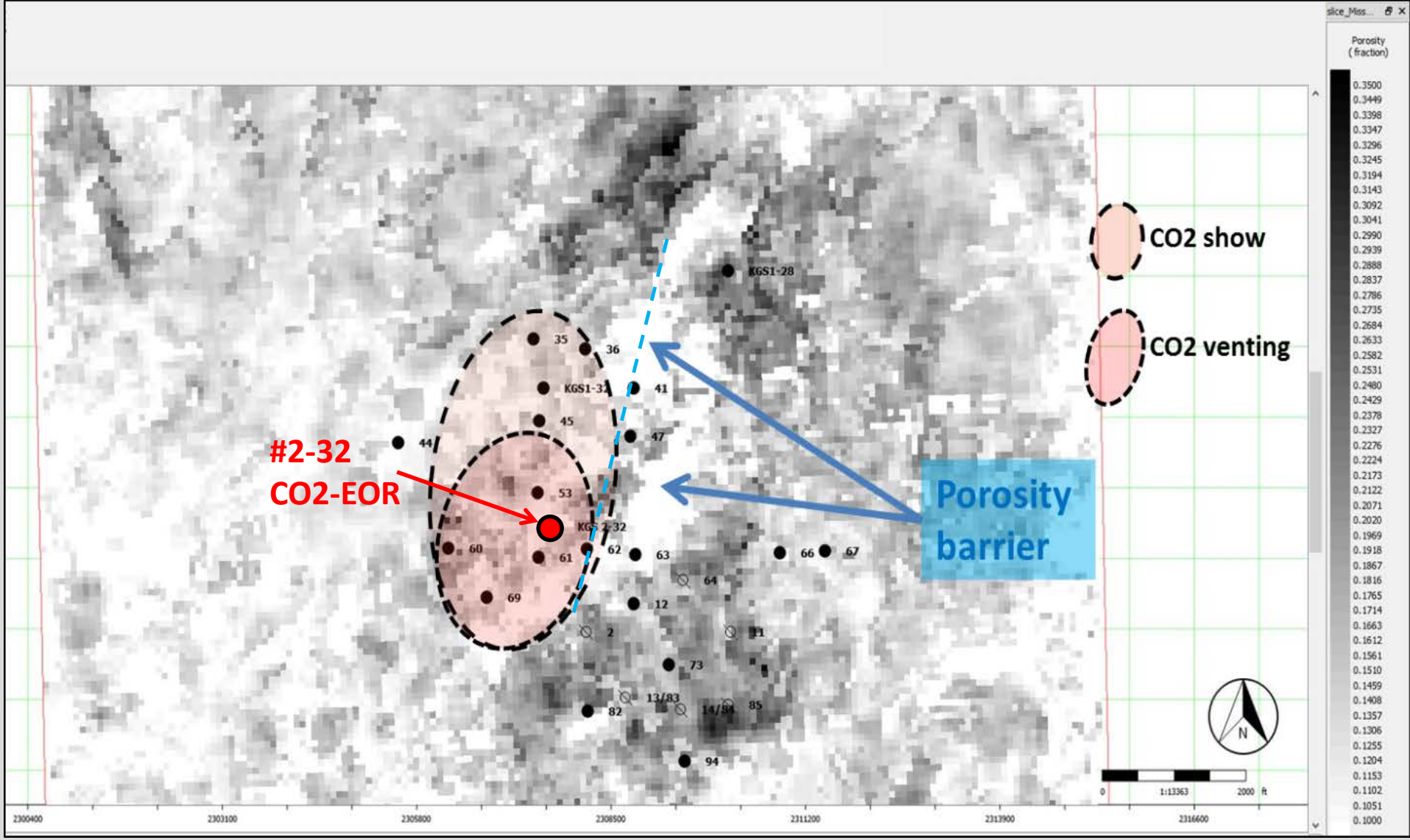
- Petrel-based porosity map of the Mississippian reservoir
- CO2 injection well is red colored vertical line
- Low porosity noted east and south of the injection well, KGS #2-32.
- Thin north-northwest trending yellow line is the trace of the medial fault.

J. Rush (KGS)



- Petrel-based map of permeability for the Mississippian oil reservoir.
- CO2 injection well is red colored vertical line.
- Lower permeability noted east and south of the injection well, KGS #2-32.
- Thin north-northwest trending yellow line is the trace of the medial fault.

J. Rush (KGS)



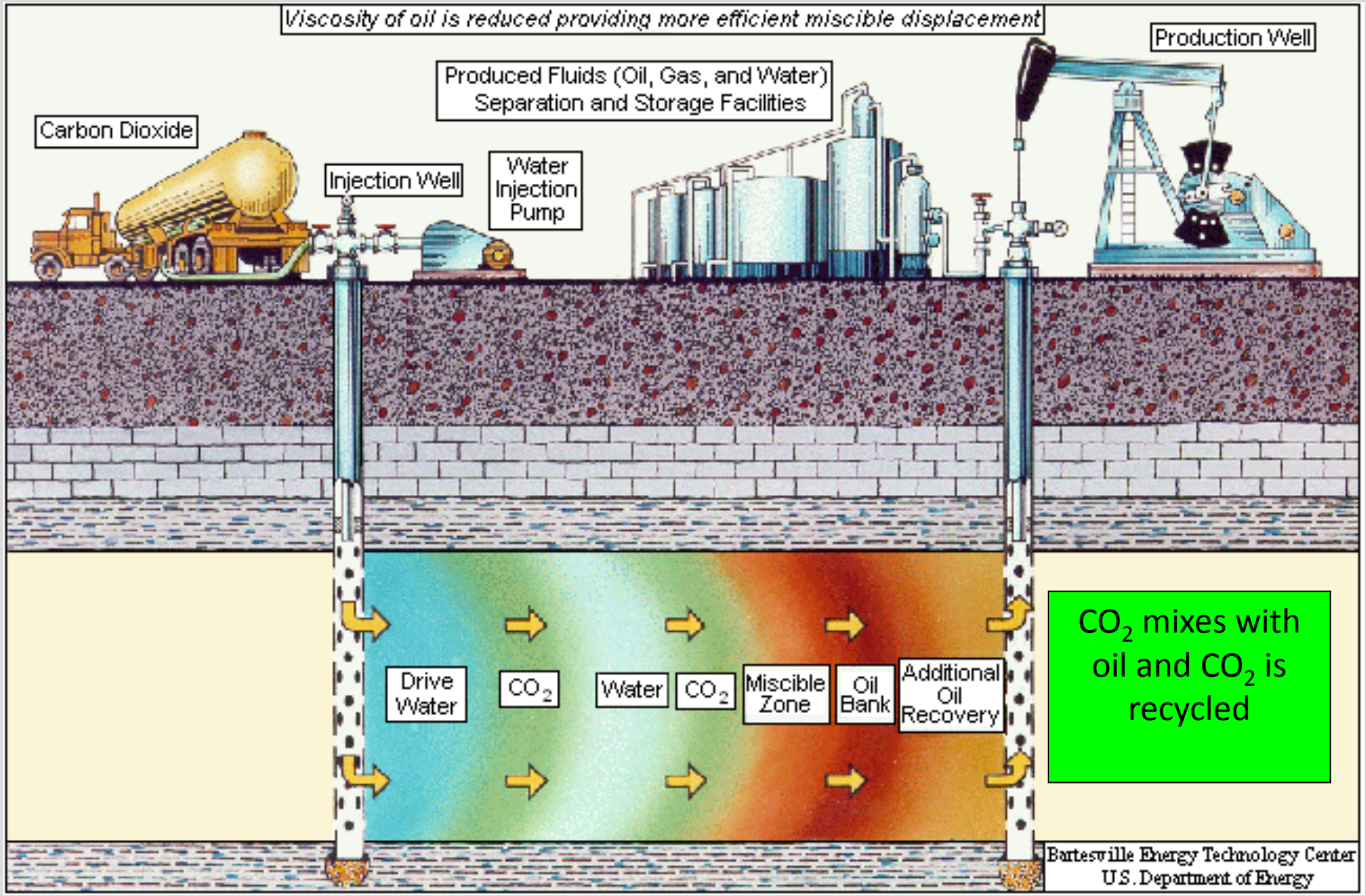
- AVO (amplitude vs. offset) derived porosity along zone of maximum porosity in upper Mississippian oil reservoir.
- White area to east and south of the CO2 injection well corresponds with lower porosity.

B. Graham and G. Tsofilas (KU)

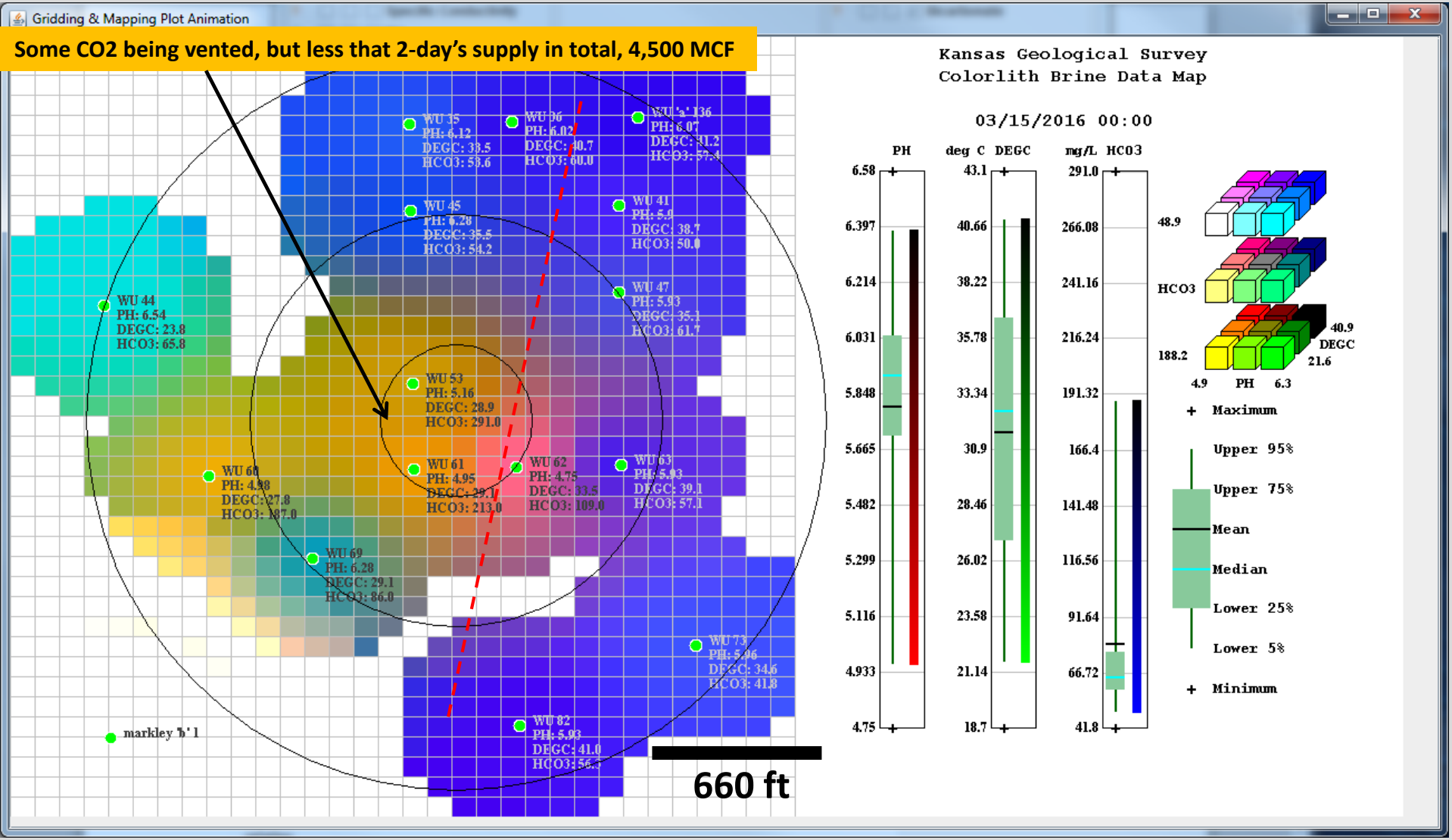
Wellington Mississippian CO2-EOR Small Scale Injection began January 9, 2016 → operated by Berexco, LLC

Wellington Field small scale CO2-EOR
Jason Bruns (Canon Well Services) and Dana Wreath (VP Berexco, LLC) with KGS staff

CO_2 Utilization in Enhanced Oil Recovery (EOR)

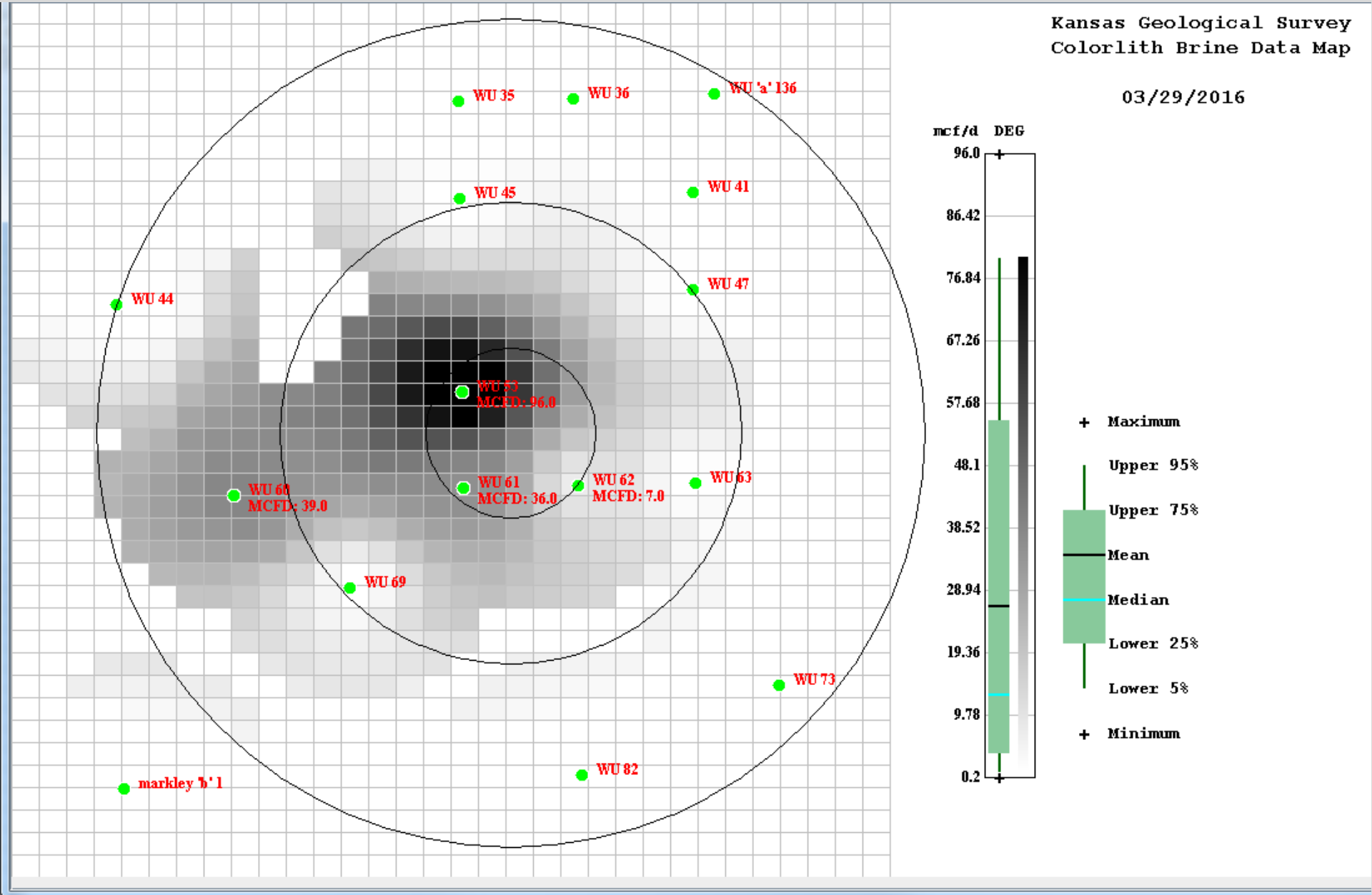


Combined pH, Temp brine, and alkalinity

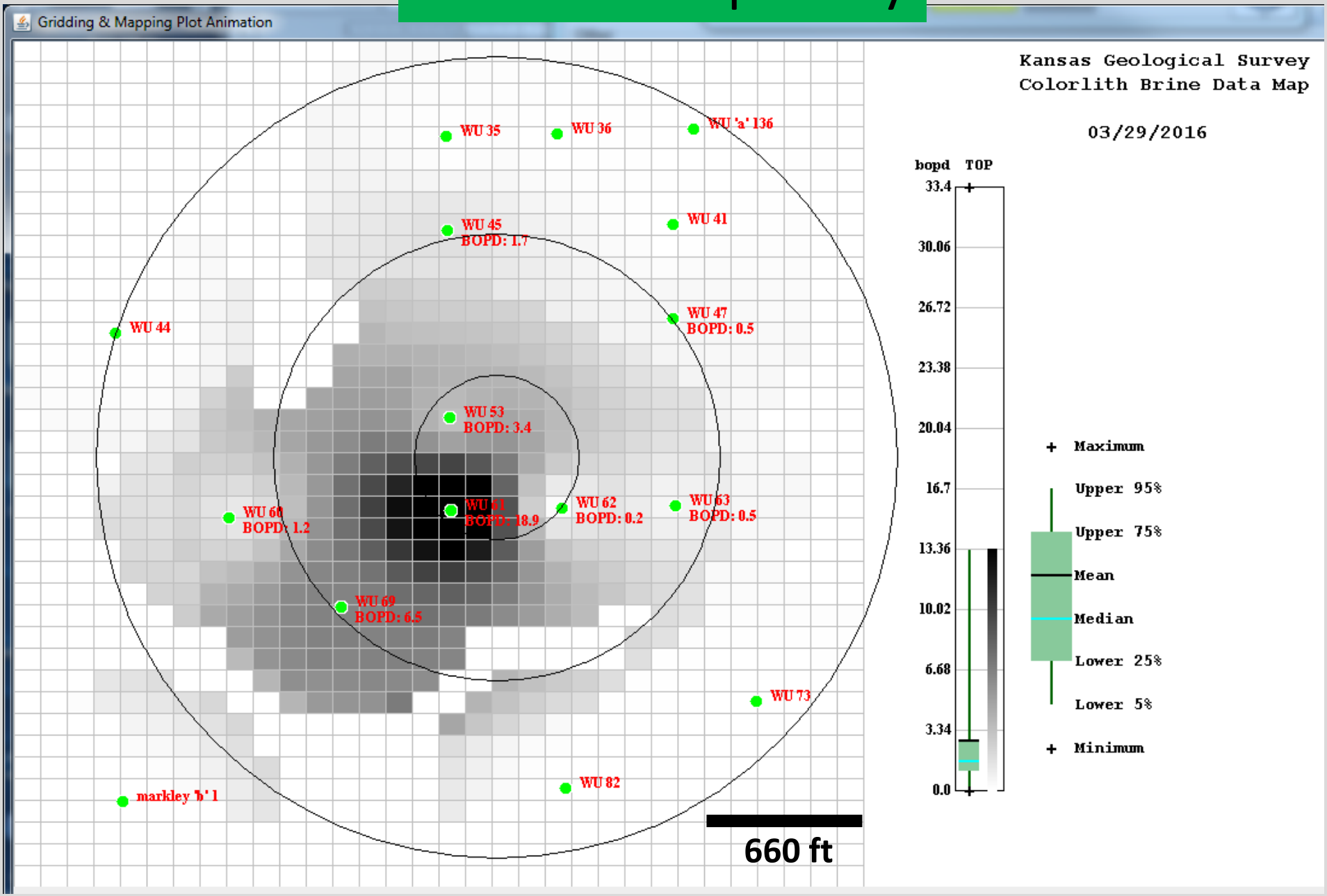


B. Campbell (Berexco), C. Jackson, J. Victorine (KGS)

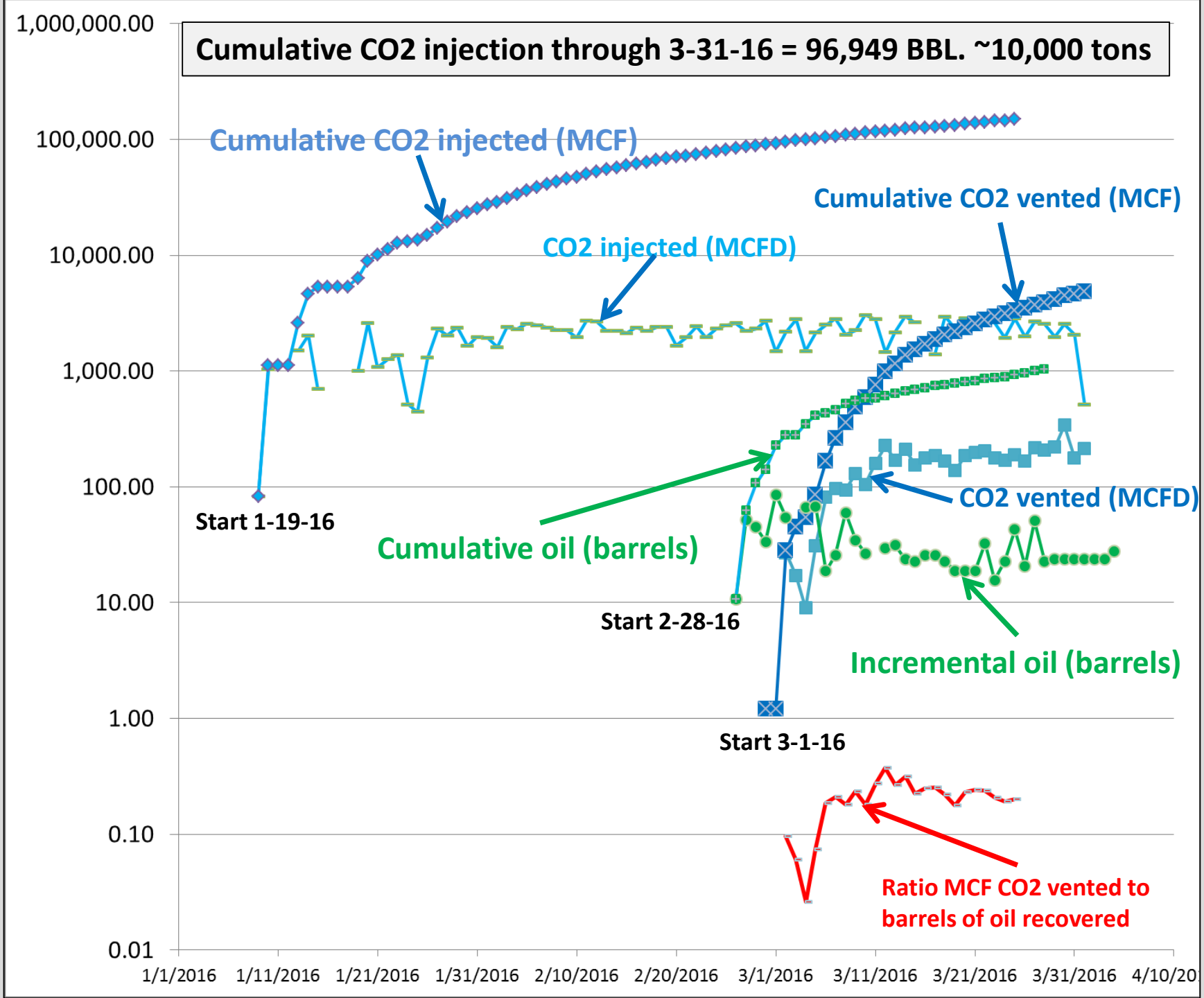
CO2 vented at well



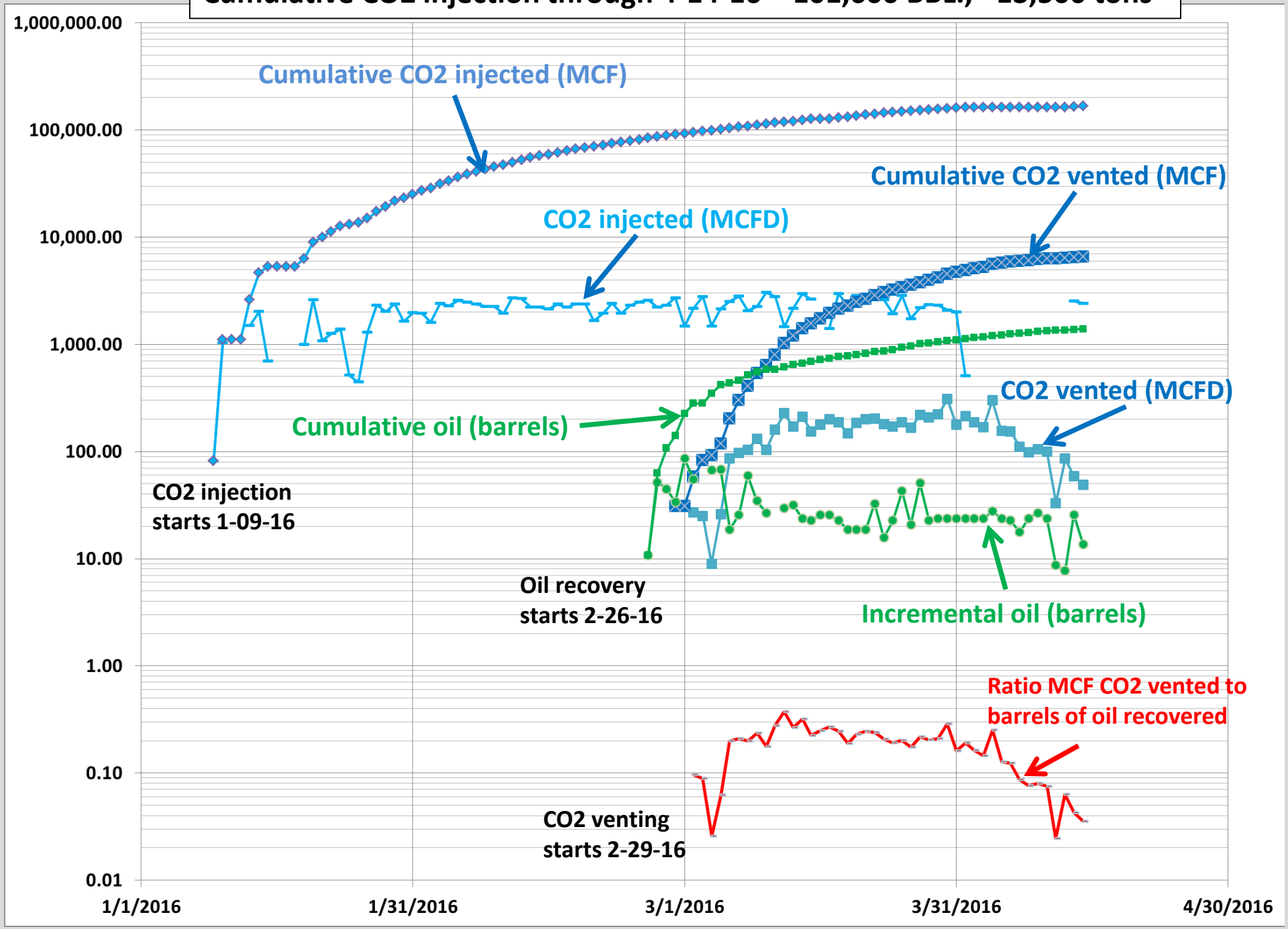
Barrels of oil per day



B. Blazer (Berexco), J. Victorine (KGS)

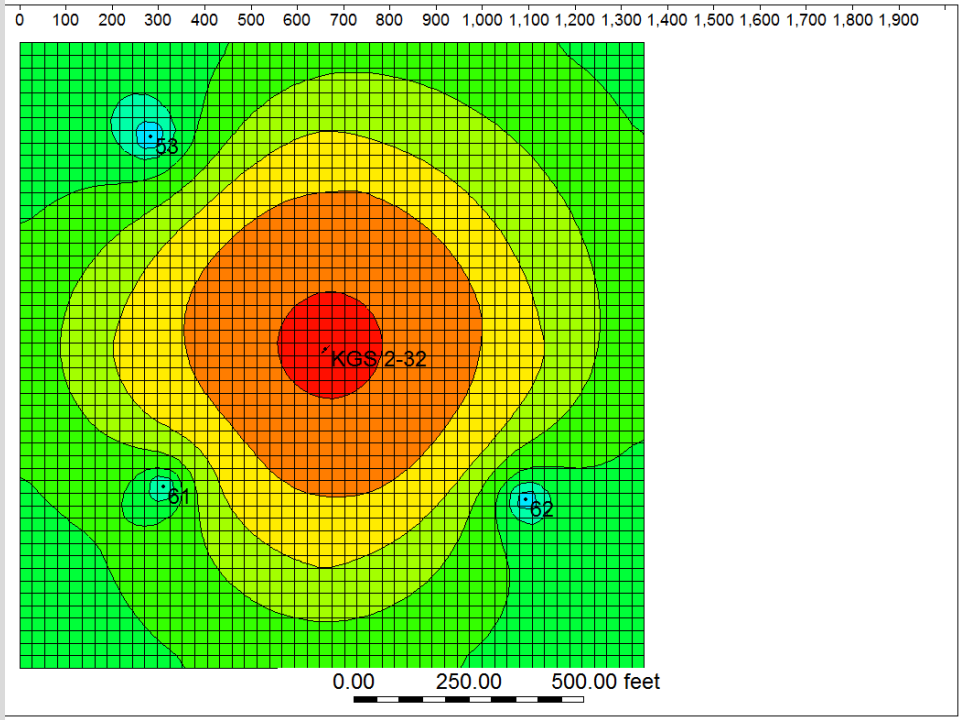

Cumulative CO2 injection through 3-31-16 = 96,949 BBL. ~10,000 tons
1,000,000.00
100,000.00
10,000.00
1,000.00
100.00
10.00
1.00
0.10
0.01
Cumulative CO2 injected (MCF)
Cumulative CO2 vented (MCF)
CO2 injected (MCFD)
CO2 vented (MCFD)
Start 1-19-16
Cumulative oil (barrels)
Start 2-28-16
Incremental oil (barrels)
Start 3-1-16
Ratio MCF CO2 vented to barrels of oil recovered
1/1/2016
1/11/2016
1/21/2016
1/31/2016
2/10/2016
2/20/2016
3/1/2016
3/11/2016
3/21/2016
3/31/2016
4/10/20

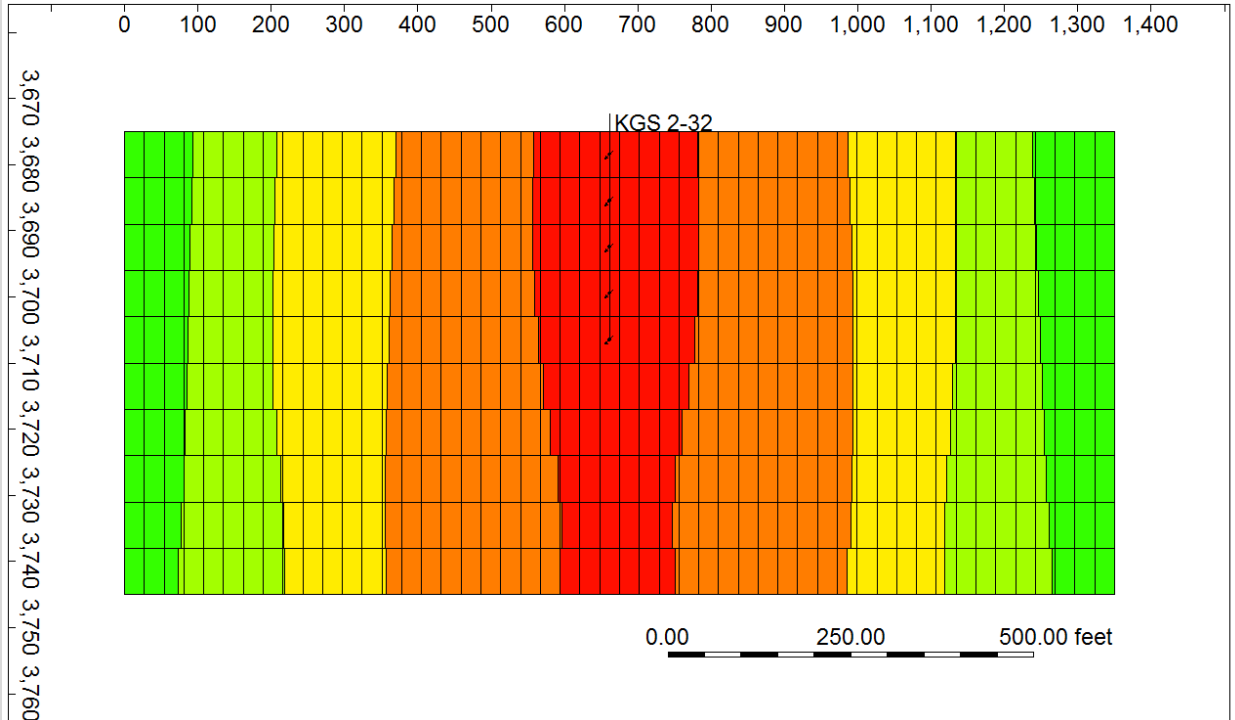
Cumulative CO2 injection through 4-14-16 = 101,600 BBL., ~13,500 tons



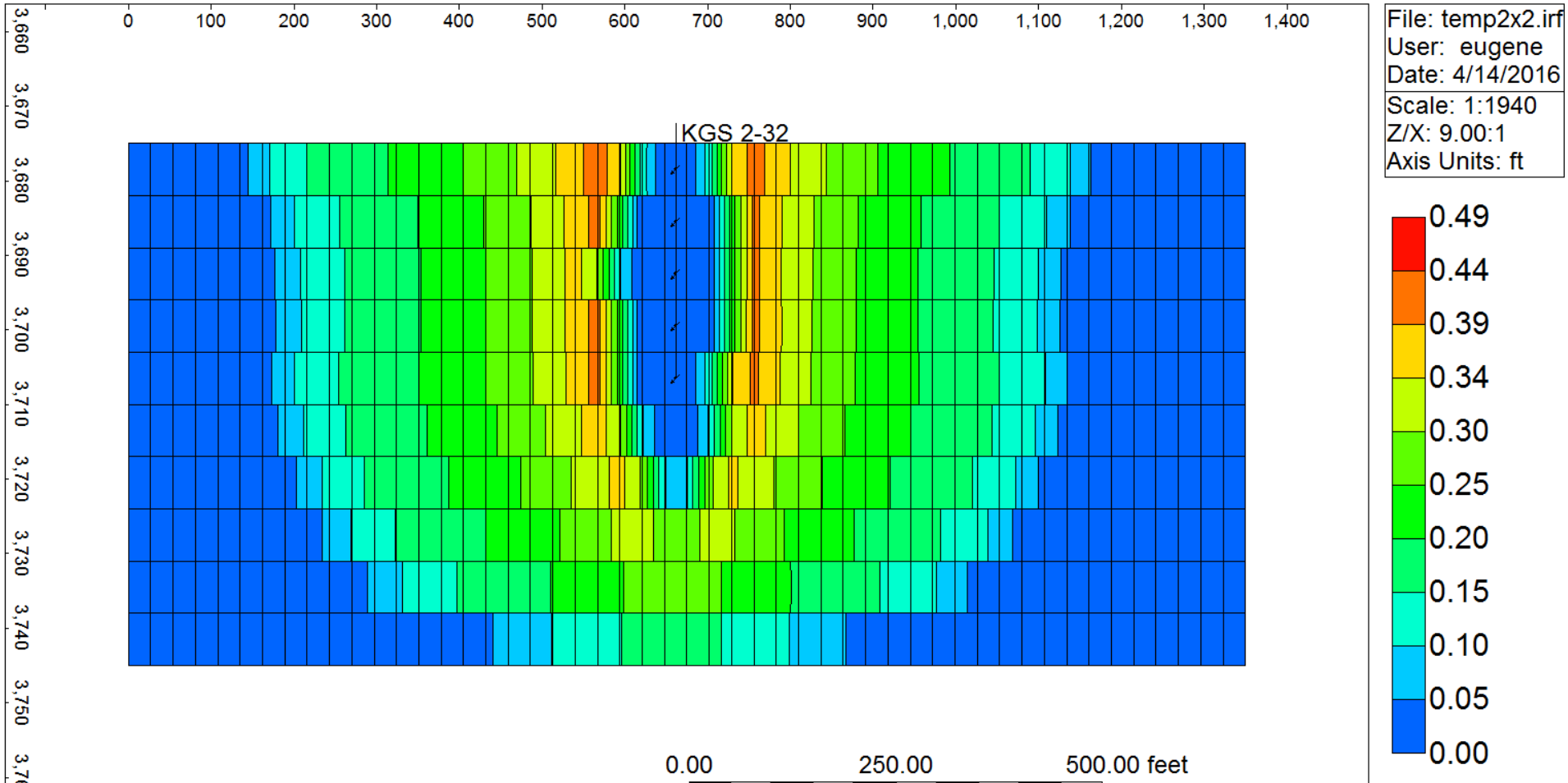
Modeled pressure (psi) map and profile

CO_2 injection at KGS 2-32, vertical cross-section view

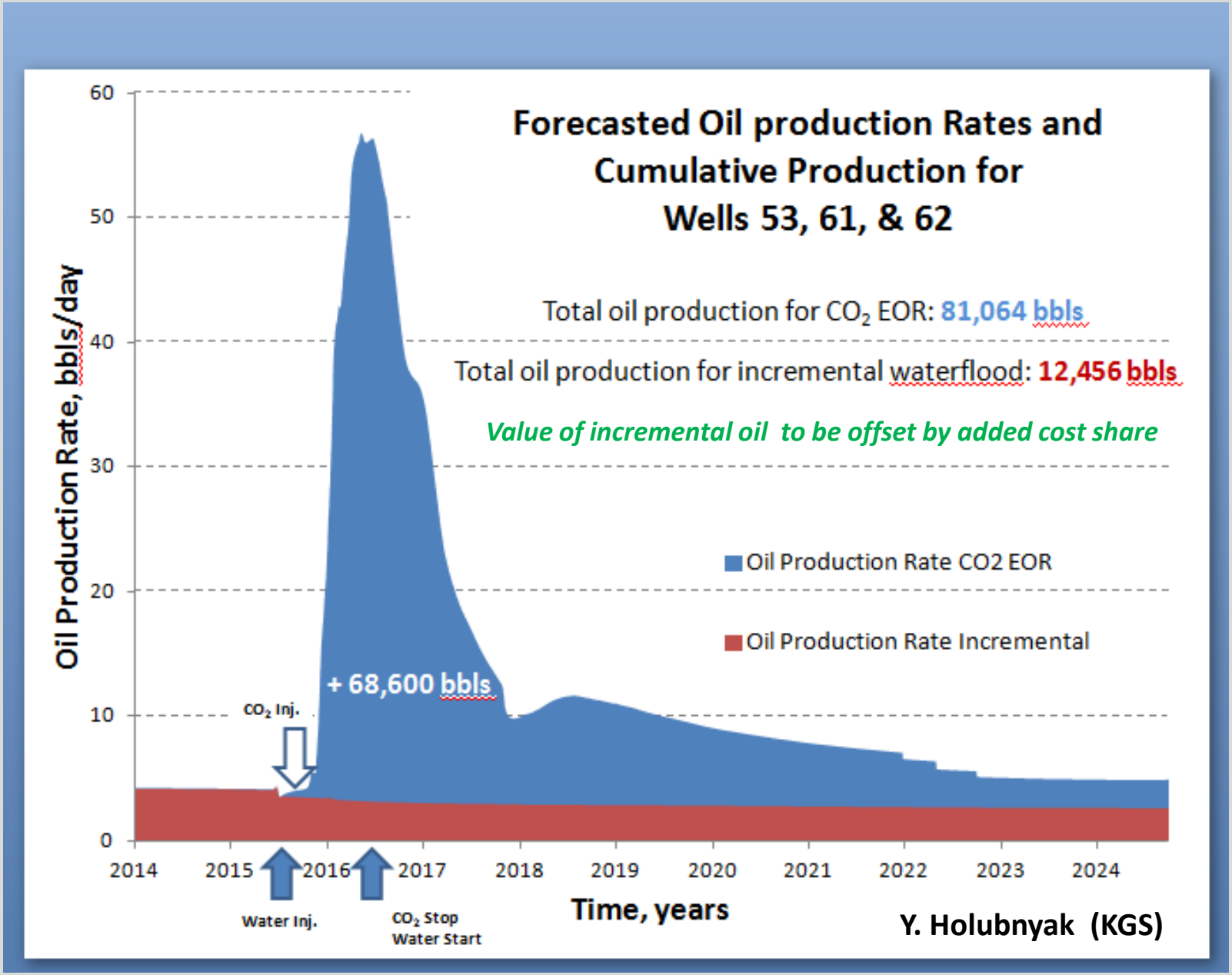




Modeled supercritical CO_2 at KGS 2-32 vertical cross-section

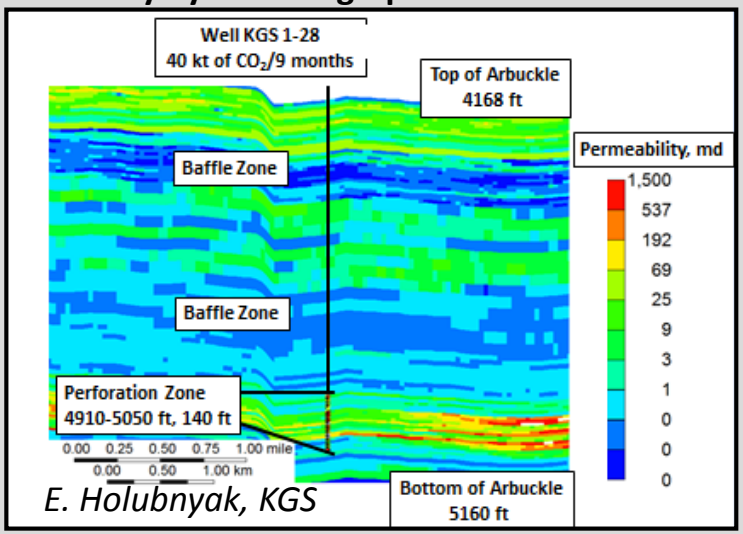


Ideal oil recovery with 26,000 tonnes of CO_2 injected



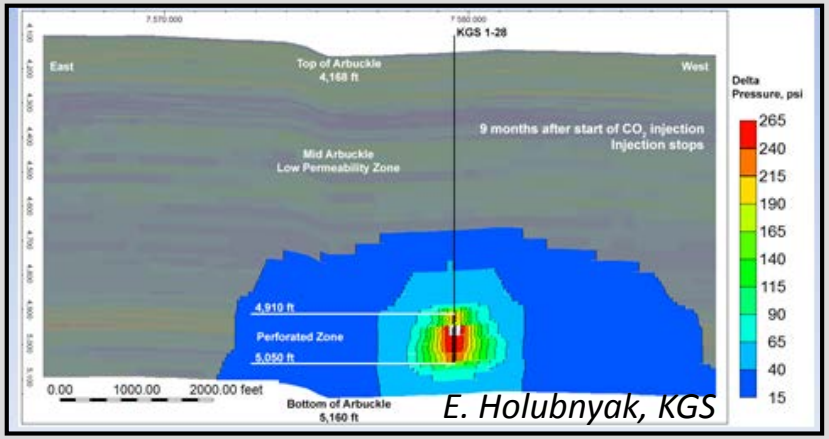
Pilot CO_2 injection anticipated for Arbuckle at Wellington, pending EPA Class VI permit

Simulation of CO2 injection at Wellington into high permeability hydrostratigraphic unit in lower Arbuckle



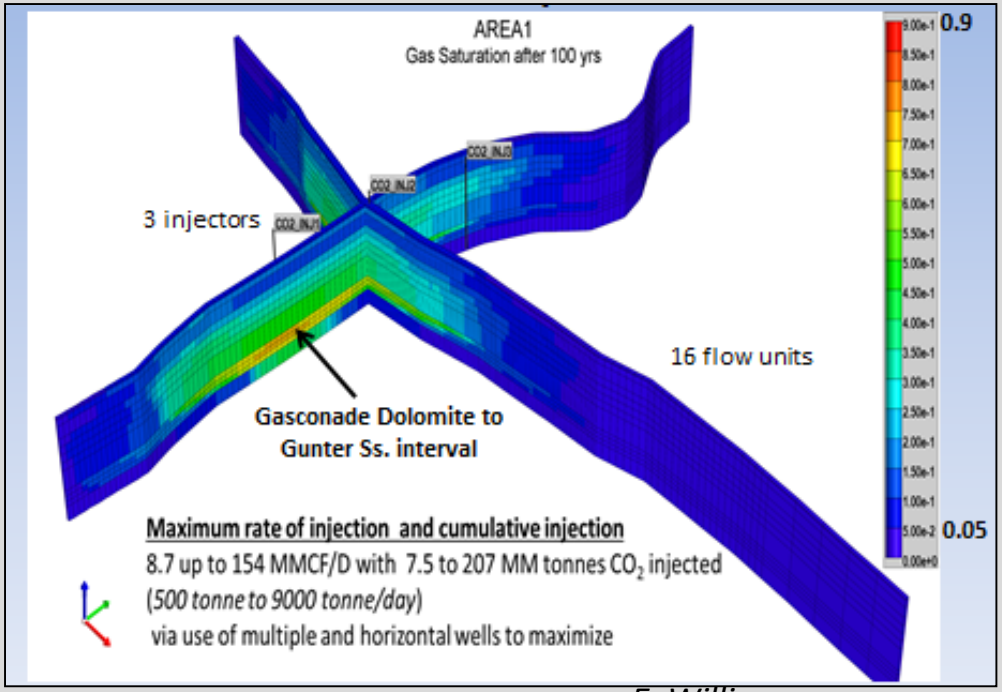
E. Holubnyak, KGS

Vertical pressure distribution at maximum stress just before small scale pilot injection (40 k tonnes) stops

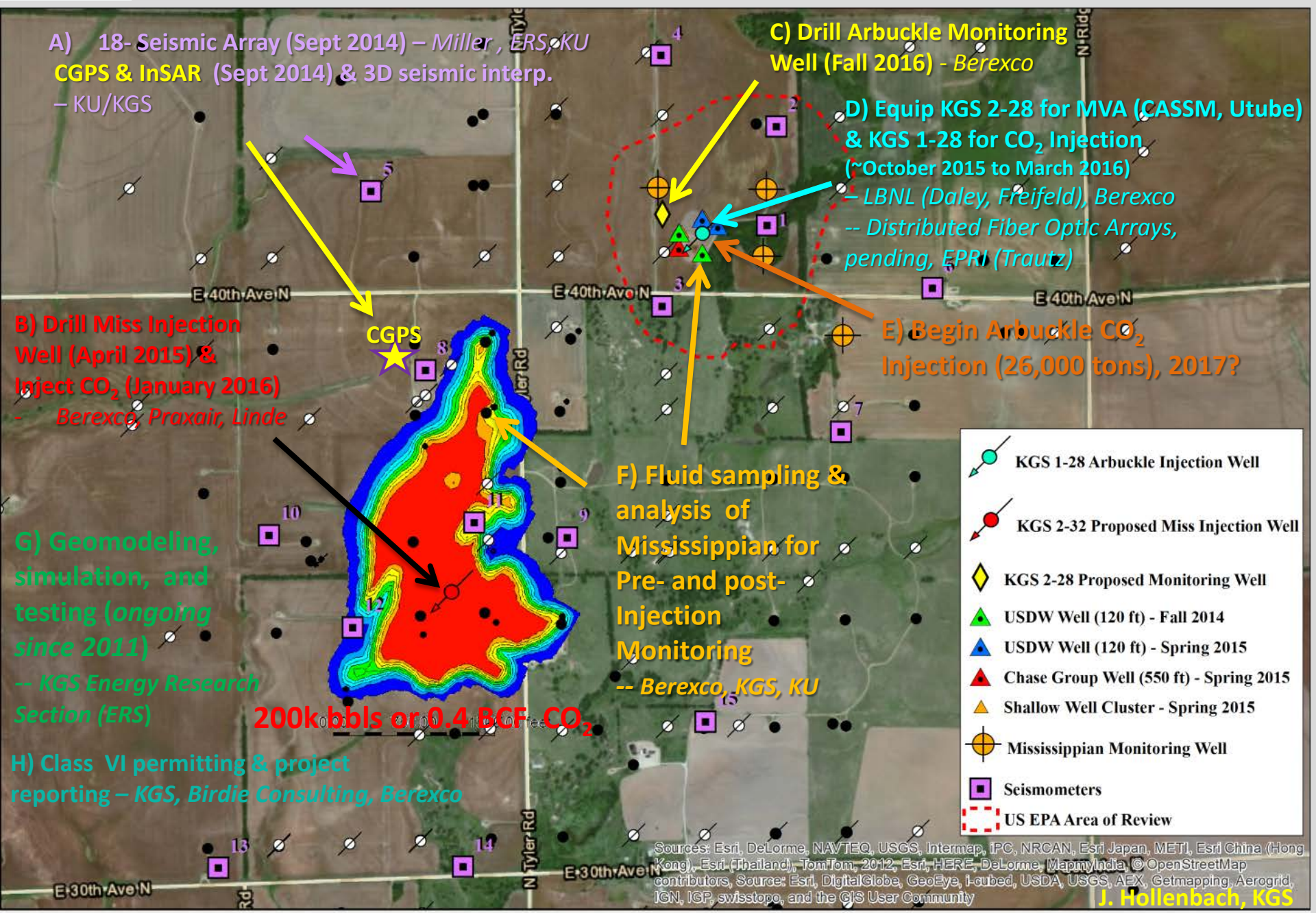


E. Holubnyak, KGS

Comparison to CMG Simulation for <u>Commercial-scale</u> injection -- Area 1 (Wellington Field) – CO_2 gas saturation In the Arbuckle → Up to 207 MM tonnes at Wellington Field



E. Williams



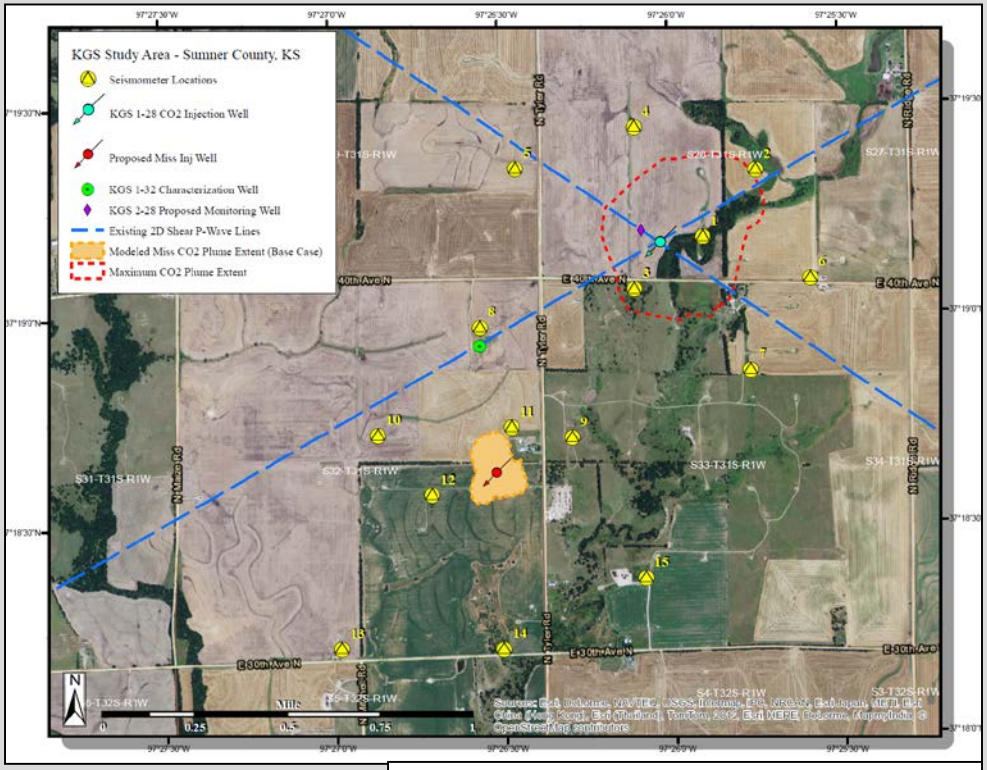
MVA Activity at Wellington CO2 injection site
Sumner County, Kansas
Twn 31S - R 1W

N

Feet
0 750 1500 3000

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

18 seismic seismometer array operating at Wellington Field to monitor CO_2 pilot tests



G. Tsoflias
Alex Nolte
KU Geology
J. Hollenbach &
J. Victorine, KGS

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

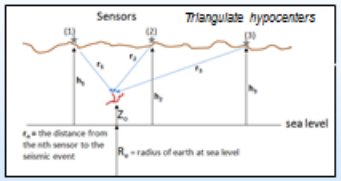
PASSCAL

21

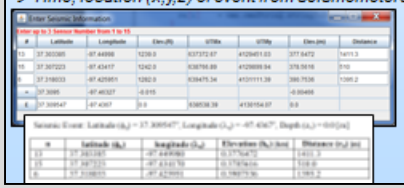
R. Miller and S. Peterie, KGS

Resolution of Hypocenters from IRIS Seismometer Array at Wellington

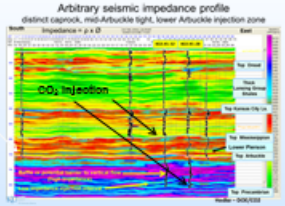
Refining location of operational seismicity -- Initially for the CO2-EOR injection to evaluate feasibility of methodology



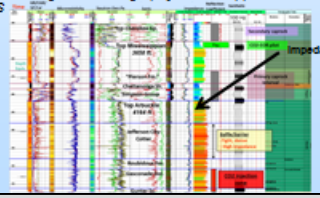
Adapting Java toolset to manage, interpret, and display solutions on project maps (Victorine, KGS)
→ *Time, location (x,y,z) of event from seismometers*



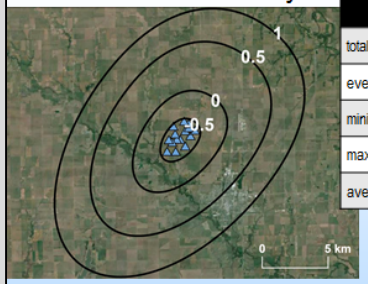
Mississippian and Arbuckle injection zones have good impedance



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



Network Sensitivity



- 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

Local Activity

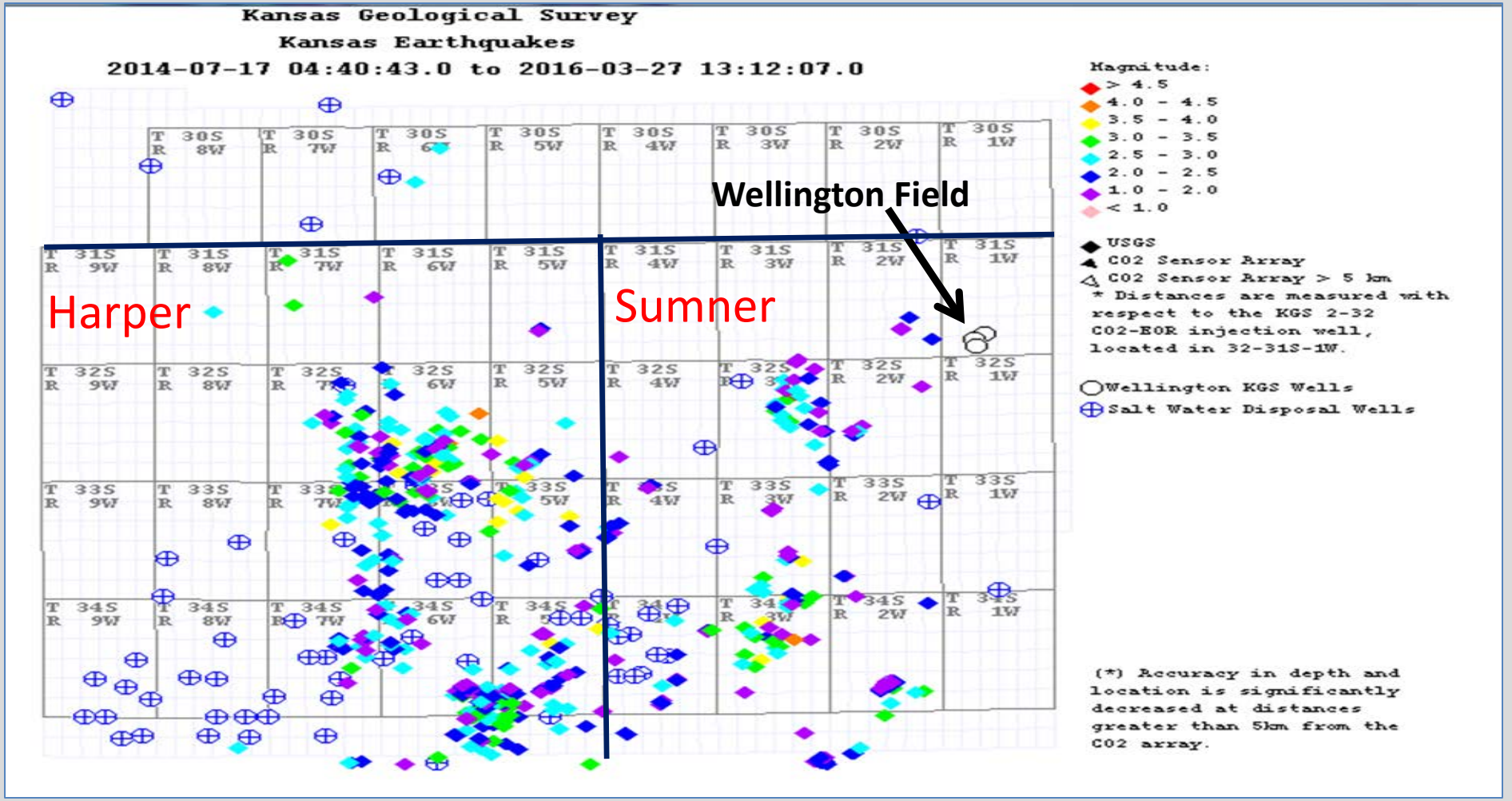
Events detected at ≥7 stations†	
total events	53
events/day	4
minimum magnitude	-0.3
maximum magnitude	1.4
average magnitude	0.6

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

†Initial recording over one weeks time

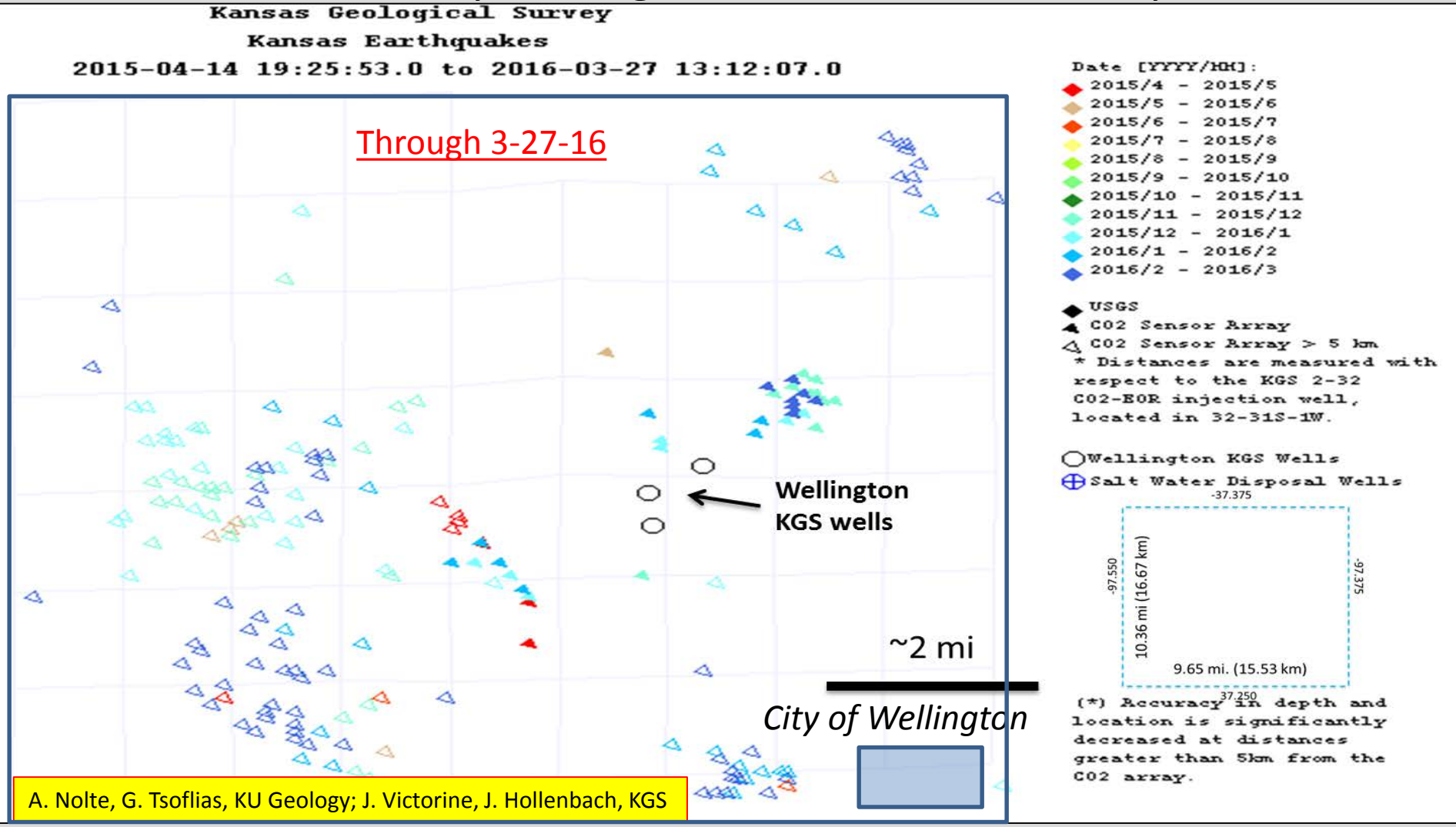
R. Miller and S. Peterie, KGS

Map showing magnitudes of earthquakes recorded by USGS in NEIC catalog during the period 7-17-15 and 3-27-16 in Harper and western Sumner Co.

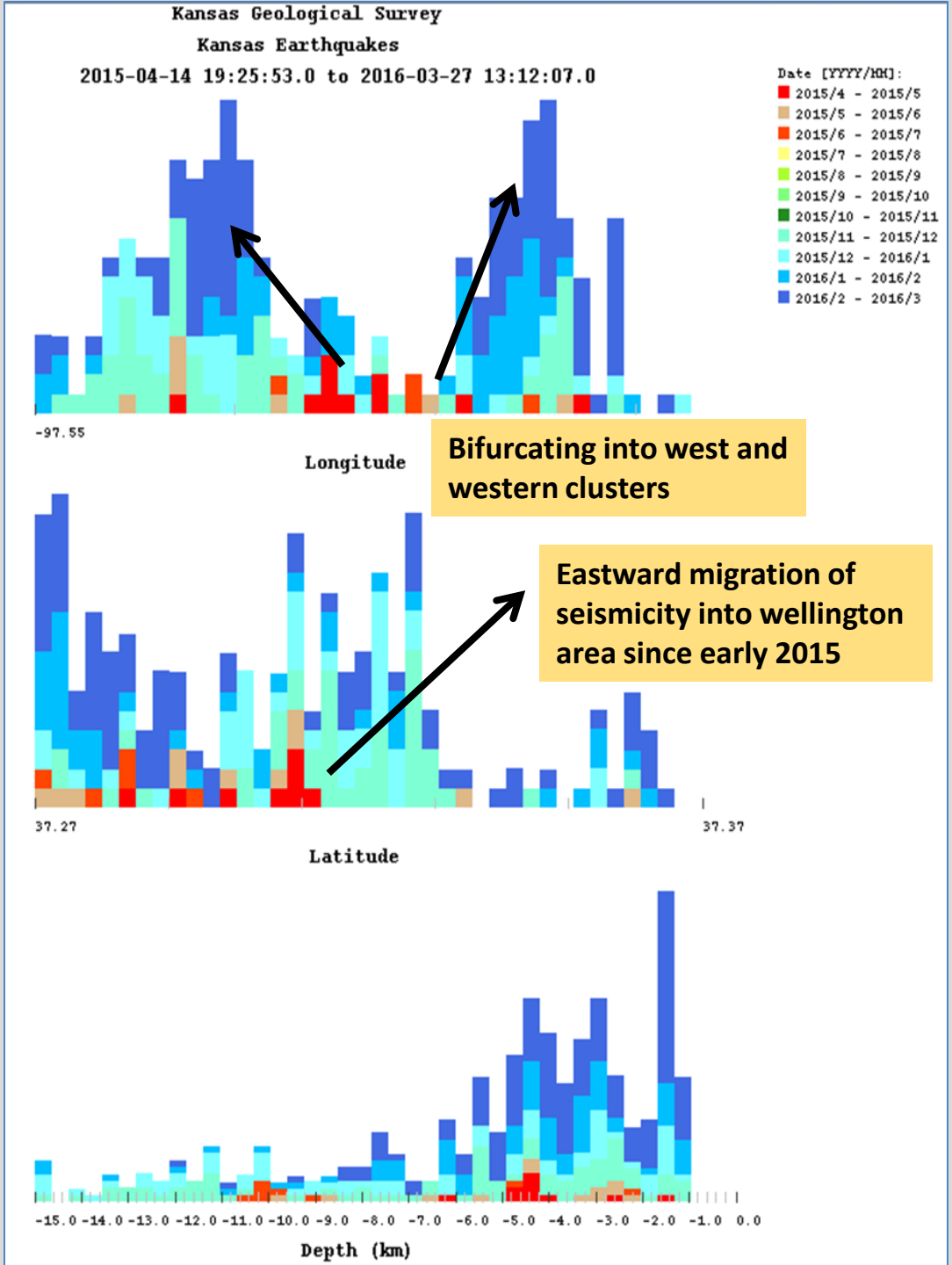


J. Victorine (KGS)

Preliminary map of dates of earthquakes
in ~10 x 10 mile area around Wellington Field
recorded by Wellington 18-seismometer array

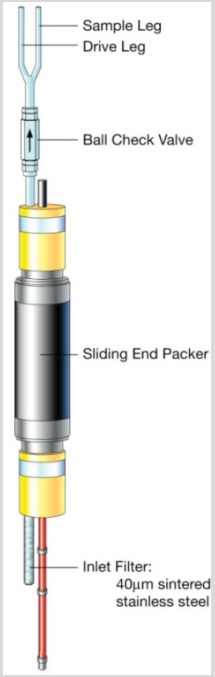


Earthquakes recorded within 5 km of the array are highlighted as a solid triangle. The events within 5 km are more reliable due to proximity to the array.



- Histogram of earthquake dates compared to longitude, latitude, and depth for earthquakes recorded from Wellington seismometer array
- 10 x 10 mi area surrounding Wellington Field
- April 2015 through the end of March 2016

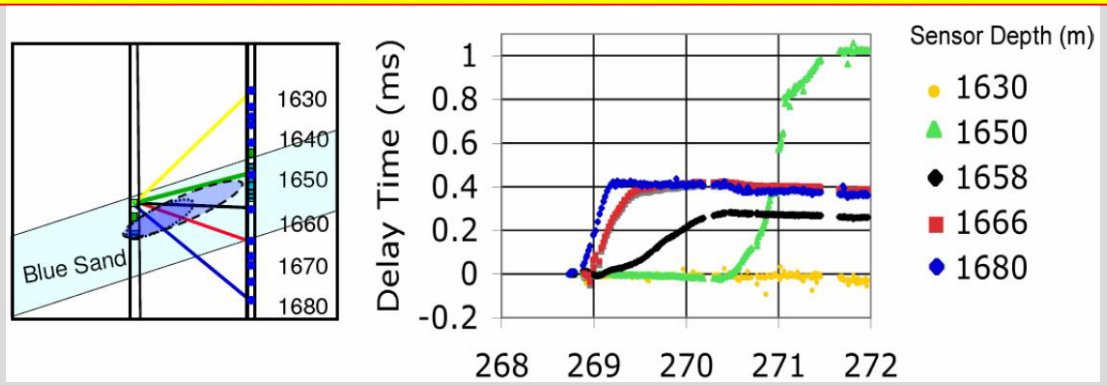
Monitoring, Verification, and Accounting in the Arbuckle pilot injection



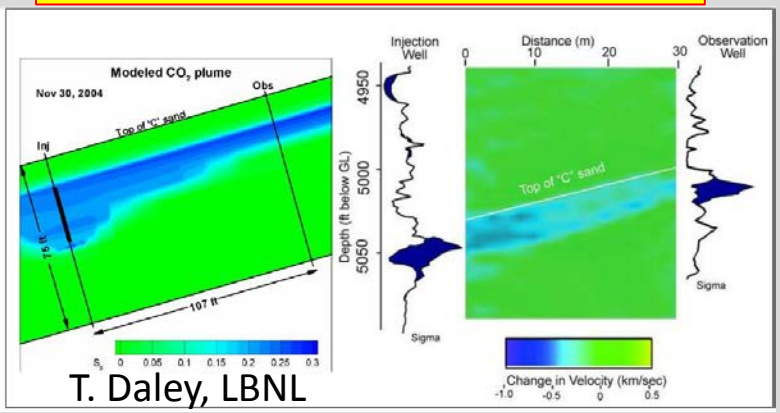
U-Tube

B. Freifeld, LBNL

Real time detection using continuous source cross-well seismic

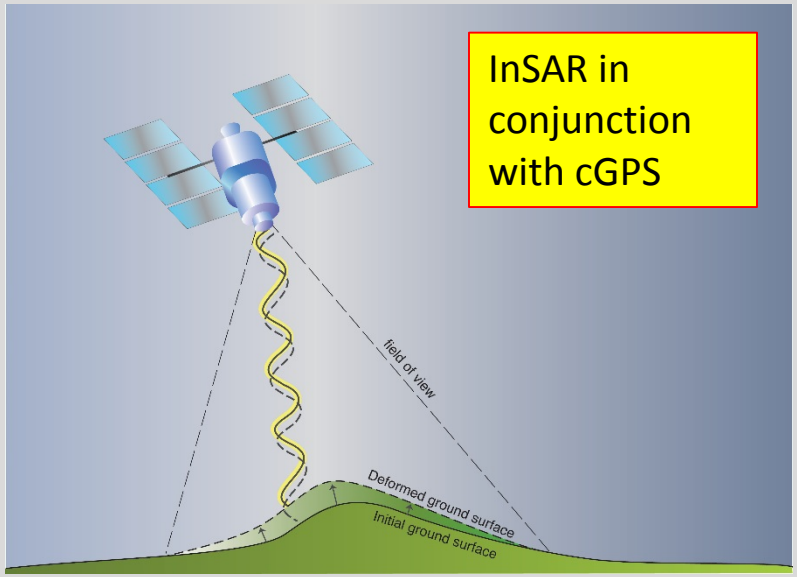


CASSM & Croswell Seismic Tomography



T. Daley, LBNL

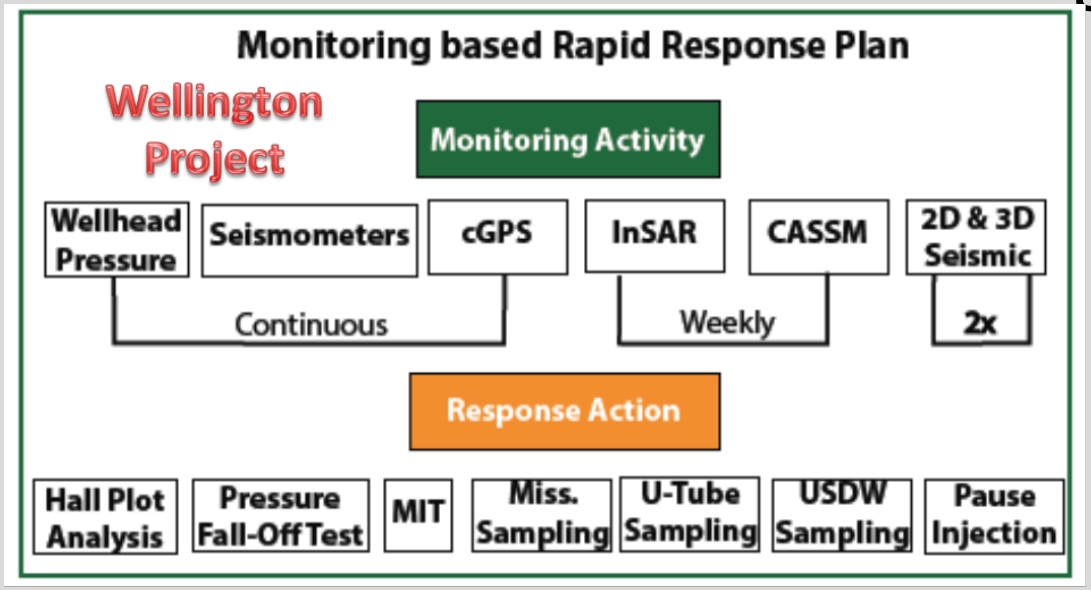
T. Daley, LBNL



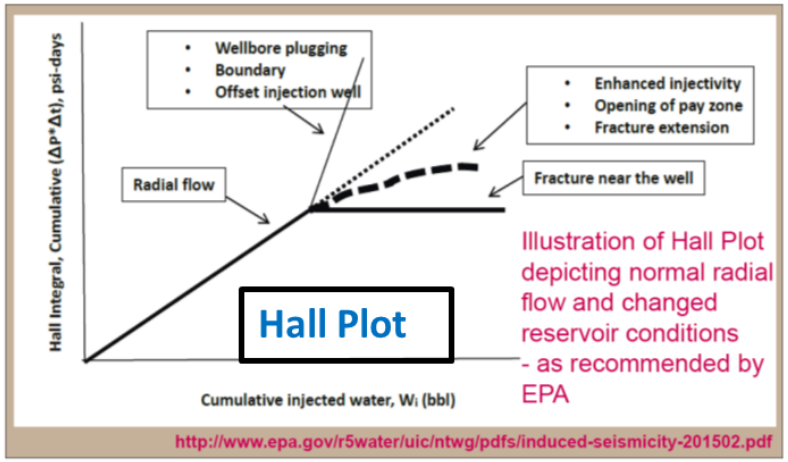
M. Taylor, KU

- **Innovative monitoring technologies:**
  - **cGPS recording since August 2014**
  - **Satellite based radar data being collected to monitor ground motion at mm-scale**
  - **Observe small (-0.5 to 1 M) operational (Mississippian waterflood) seismicity since Sept. 2014**
  - **Prospect remains to secure *Distributed Fiber Optic Arrays* with VSP for Arbuckle monitoring**

Operational plan for safe and effective injection in the Arbuckle at Wellington Field



- Injection Control Plan
- Wellington Seismic Action Plan
- Monitoring-based Rapid Response Plan
- Emergency Remedial Response Plan



Under review by EPA

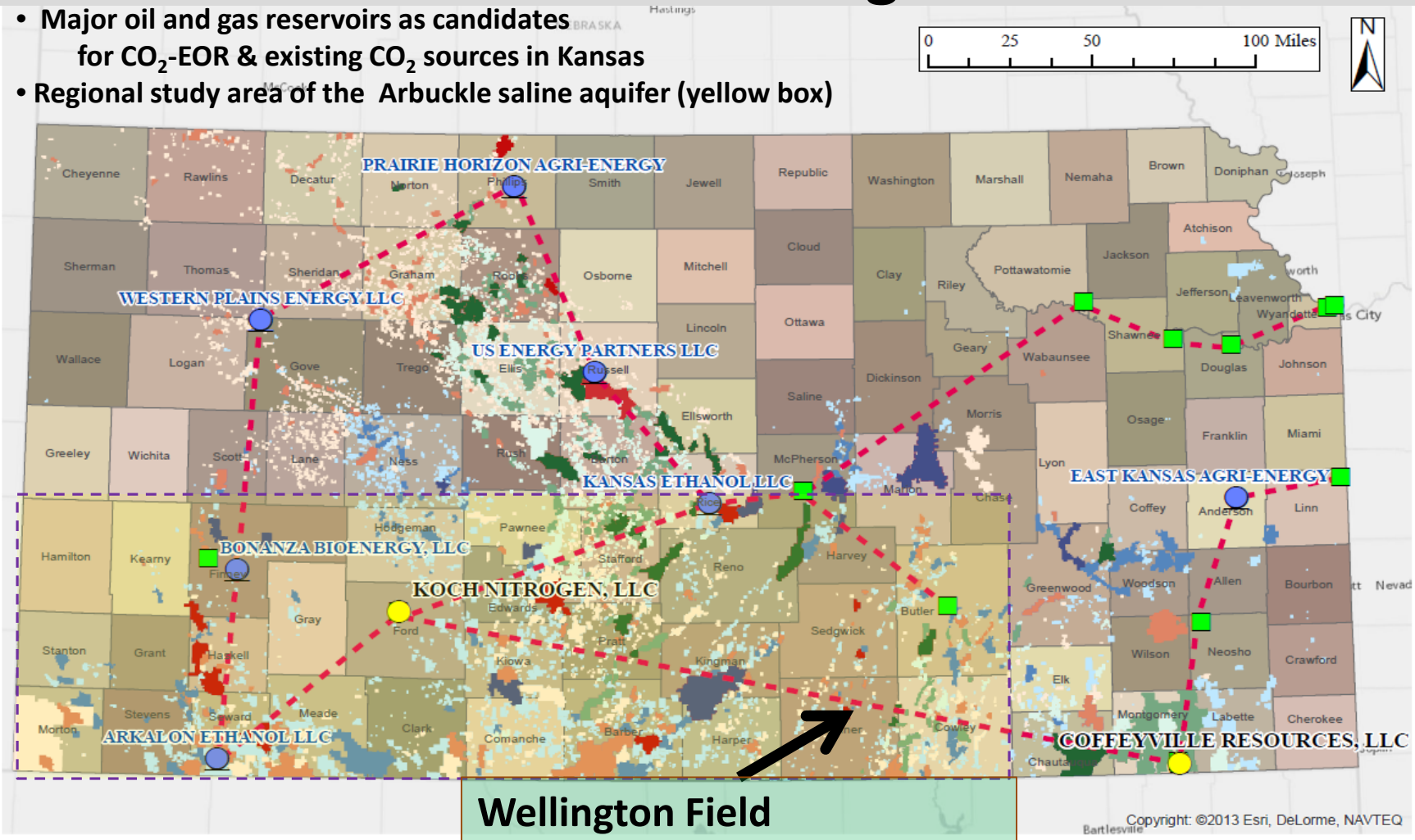
Operational plan for safe and efficient CO2 injection as part of Draft emergency and remedial response plan for Class VI permit

The success of the Monitoring and Rapid Response Plan developed for the Wellington Project is based on prioritizing the monitoring technologies:

1) Reliability of the data and approaches used to analyze the data,
2) Frequency that the data is acquired during injection
3) Sensitivity and precision of the monitoring method and its ability to detect small changes in CO_2 plume behavior;
4) Location and therefore resolution from which the data is collected,
5) Spatial resolution and coverage of the CO_2 plume; and
6) Ability to detect movement out of the injection zone both above and below the injection zone.

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)



Source: USGS, Kansas Geological Survey, DASC

J. Hollenback, KGS

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

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

Implementing CO_2 utilization and storage (CCUS) in Kansas

- **Carbon storage and utilization offers significant potential to revitalize Kansas' oil fields.**
  - A 2010 report for the Midwest Governor's Association with input from Tertiary Oil Recovery Program and KGS indicated more than 750 million barrels of oil are potentially recoverable in Kansas with enhanced recovery methods using carbon dioxide
  - Over 50 million metric tons of geologic sourced CO_2 are injected annually into oil reservoirs in the US, mainly in West Texas, with roughly 400,000 bbls of incremental oil recovered per day using the available supplies of naturally occurring CO_2.
- **Why now?**
  - Improved reservoir characterization with the widespread use and availability of cost-effective 3D seismic
  - Improved geoengineering models and monitoring technologies
  - All combined will likely overcome the decades of inertia that have faced the implementation of CO_2-EOR in Kansas

Are you ready?

Summary

- **Accomplishments**
  - Regional geology & estimate of CO_2 storage capacity in the Arbuckle saline formation in southern Kansas
  - Source-sink network for CO_2 utilization and storage
  - Calibration sites for CO_2-EOR and Arbuckle saline formation
    - Wellington Field, Sumner County (3 wells, multicomponent 3D seismic)
    - Cutter Field, Stevens County (1 well, multicomponent 3D seismic)
    - Pleasant Prairie South, Eubank North, and Shuck fields (120 mi^2 of donated seismic data and
- **Small scale field test at Wellington Field**
  - Assessment of CO_2 injection zone, caprocks, and isolation from USDW
  - CO_2 plume management through simulation, monitoring, verification, and accounting
  - 52,000 metric tons CO_2 pilot injections from Praxair and Linde sources
- Spin-off research on the Mississippian Lime Play, lower Paleozoic hydrocarbon system, induced seismicity
- **Are you ready for CCUS in Kansas?**

KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

NETL

BEREXCO

KSCO2

Acknowledgements & Disclaimer

Acknowledgements

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