CO_2-EOR in the Wellington Field Sumner County South Central Kansas

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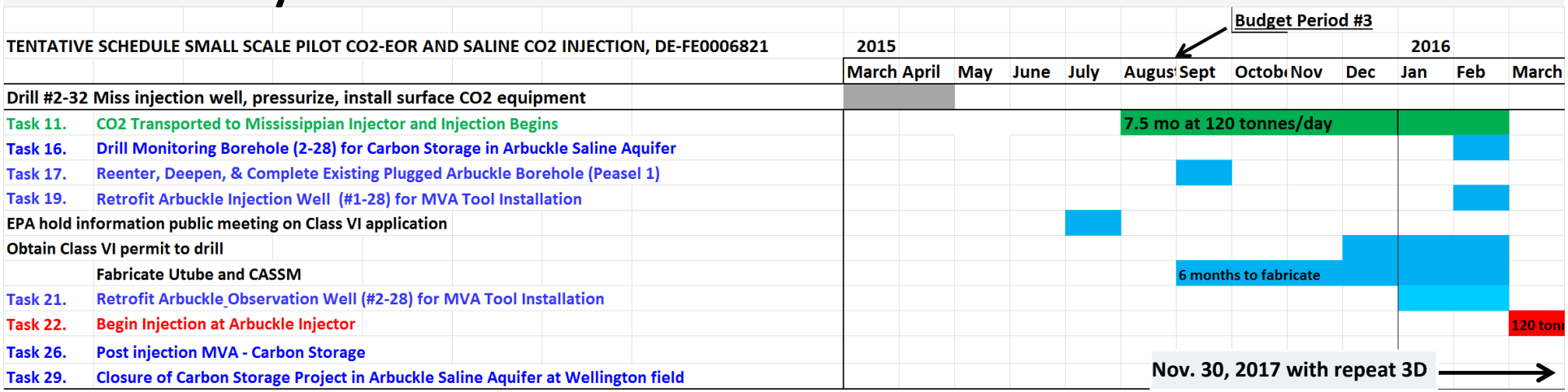
1930 Constant Avenue
The University of Kansas
Lawrence, KS 66047

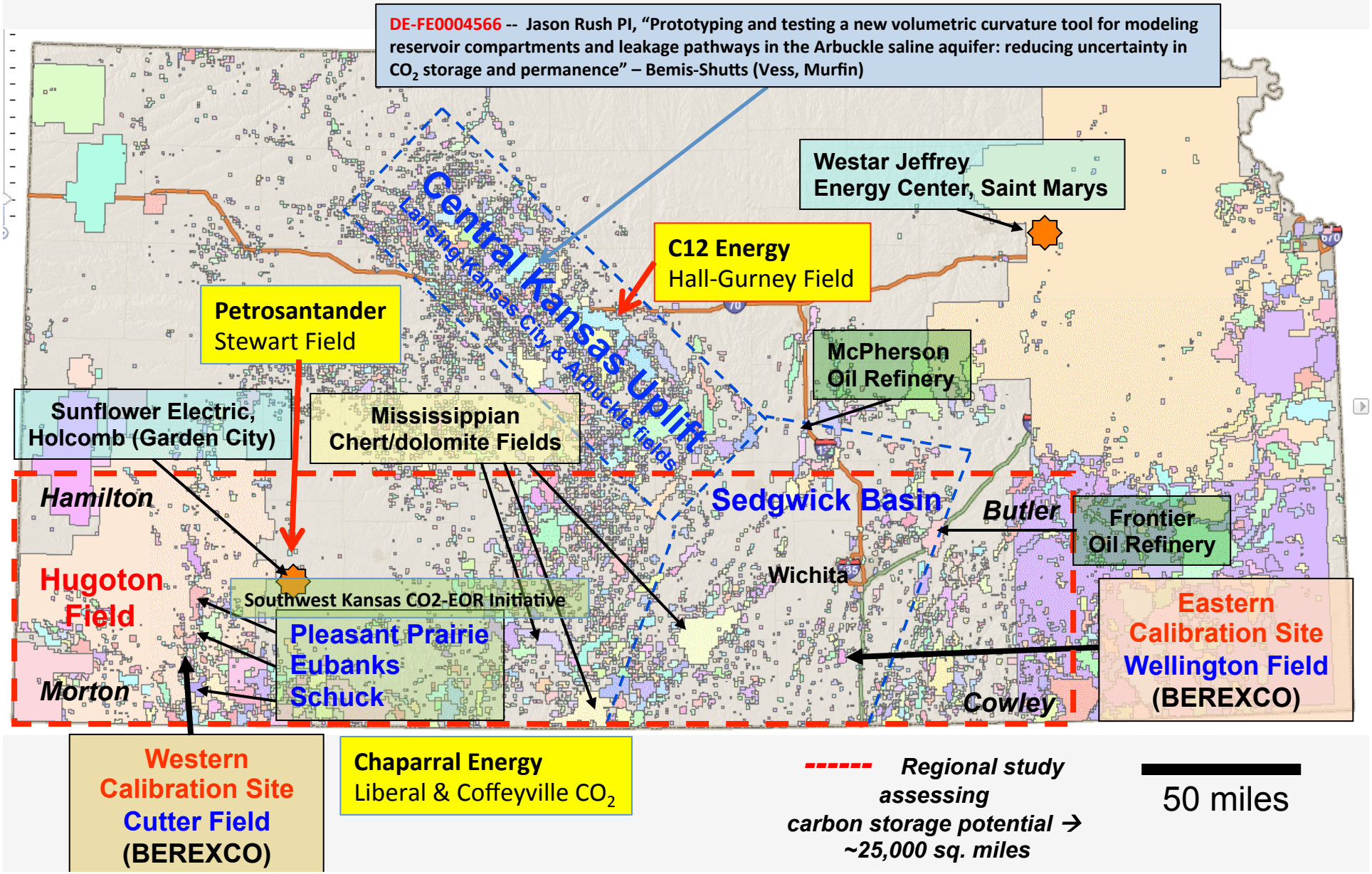
2015 KU TORP
Improved Oil Recovery
Conference
May 4, 2015

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, Steven Co.
  - Wellington Field site characterization, Sumner Co.
- **Pilot CO_2-EOR in summer & fall 2015 in Mississippian dolomite reservoir in Wellington Field, Sumner County, Kansas (DE-FE0006821)**
- **Pilot CO_2 injection in 2016 into Arbuckle at Wellington, pending EPA Class VI permit**
- **Implementing CO2 Utilization and Storage (CCUS) in Kansas**
- **Summary**



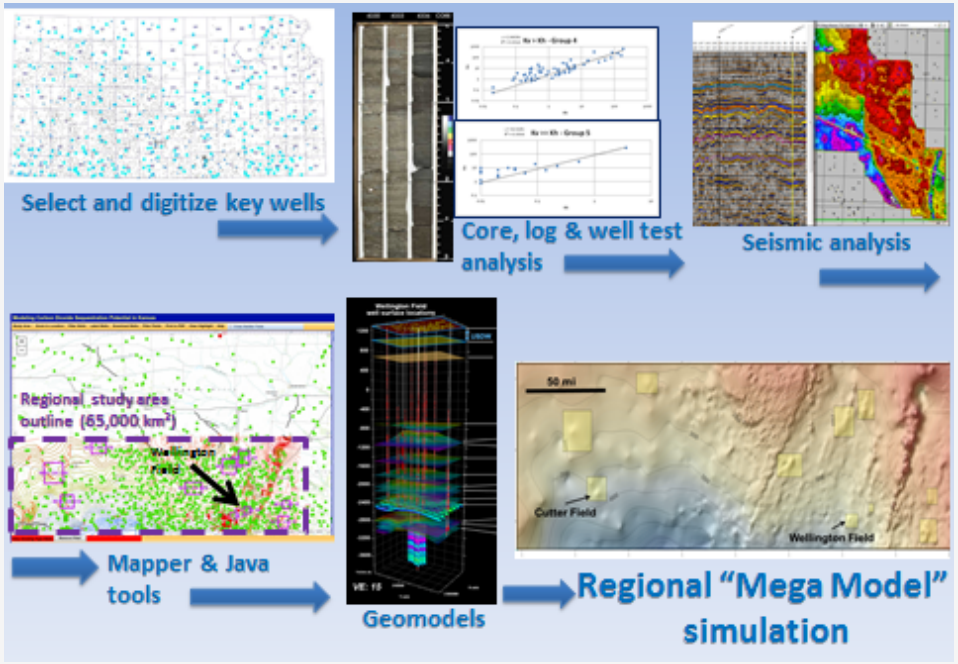
CO_2-EOR field implementation sites and study areas on map of Kansas oil and gas fields



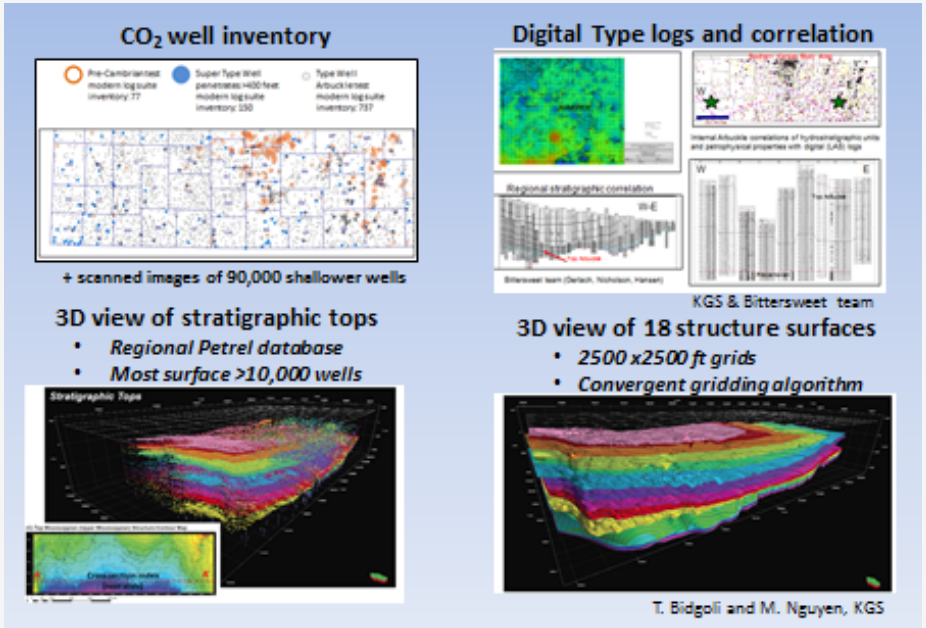
Completed evaluation of CO_2 storage capacity of a 25,000 mi², 33-county area in southern Kansas

- 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 with injectivity)
- 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/

SW Kansas CO_2-EOR Initiative under DE-FE0002056

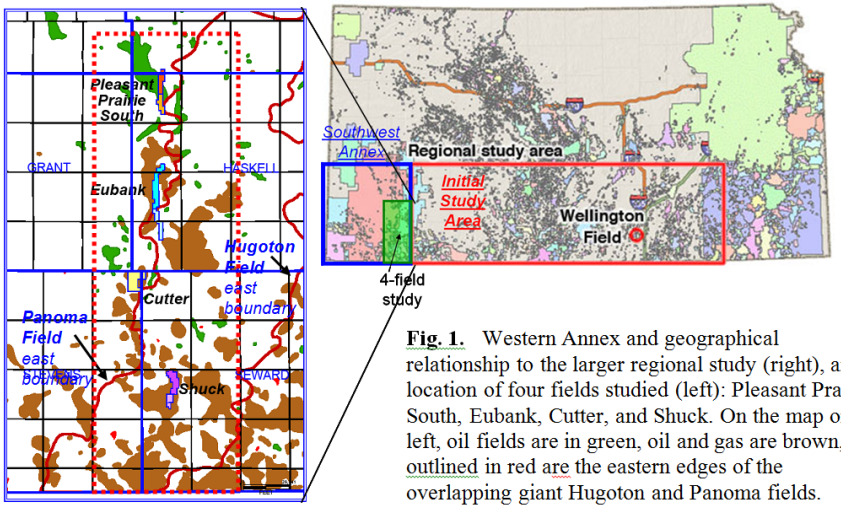


Fig. 1. Western Annex and geographical relationship to the larger regional study (right), and location of four fields studied (left): Pleasant Prairie South, Eubank, Cutter, and Shuck. On the map on the left, oil fields are in green, oil and gas are brown, and outlined in red are the eastern edges of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

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

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

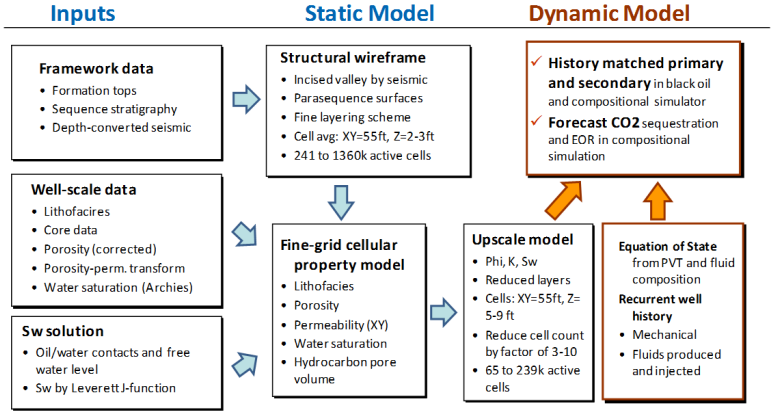


Fig. 3. Simplified workflow for the technical work showing the main inputs and construction of the static model and inputs and simulation in the dynamic model.

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 in preparation

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. Raney
(static & dynamic modeling, well test analysis, high-resolution seismic, passive seismic, accelerometers, geomechanical analysis, project management)

NETL

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

Saugata Datta *(brine and USDW monitoring)*

Schlumberger

CMG COMPUTER MODELLING GROUP LTD.

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

donate 15 seismometers

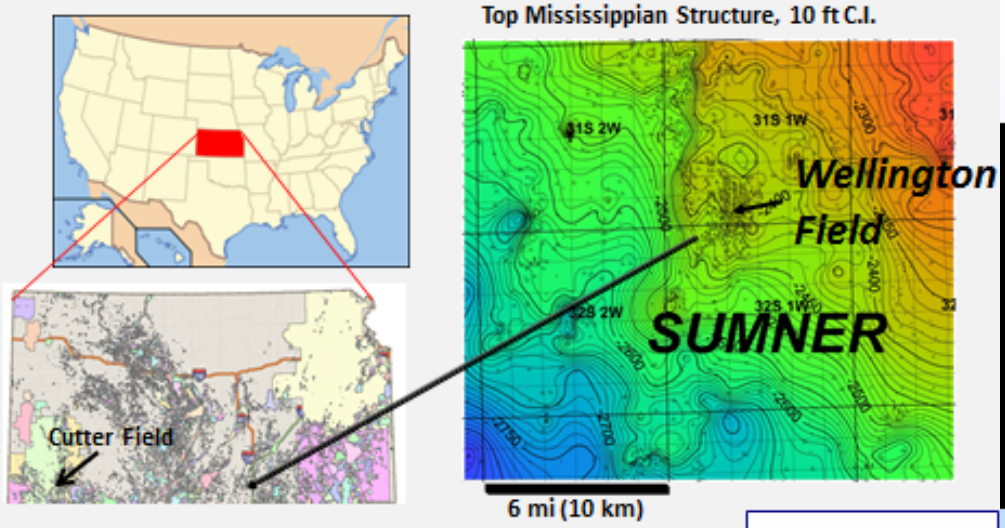
TBirdie Consulting, Inc
4705 McCormick Street • Lawrence • KS 66047 • 785 843 1085 • 785 865 0678 (fax) • tbirdie@sunflower.com

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

KU THE UNIVERSITY OF KANSAS Department of Geology

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

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

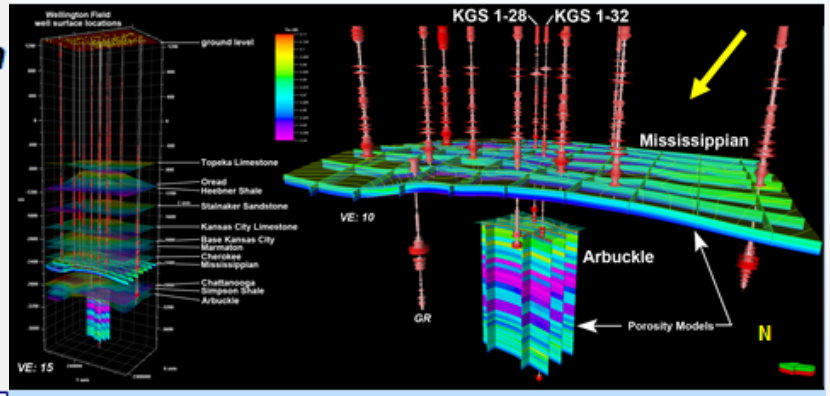


20 MM Barrel Oil Field above Arbuckle Group

KU Kansas Geological Survey, The University of Kansas

Wellington Field

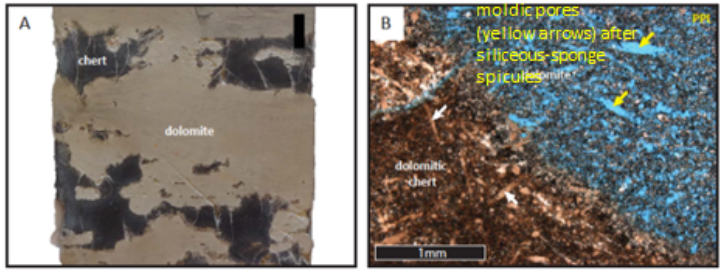
Mississippian Oil Reservoir & Arbuckle Saline Aquifer
Showing Newly Drilled Wells and Wells with Modern Logs



Rush, KGS

Cherty Sucrosic Dolomite

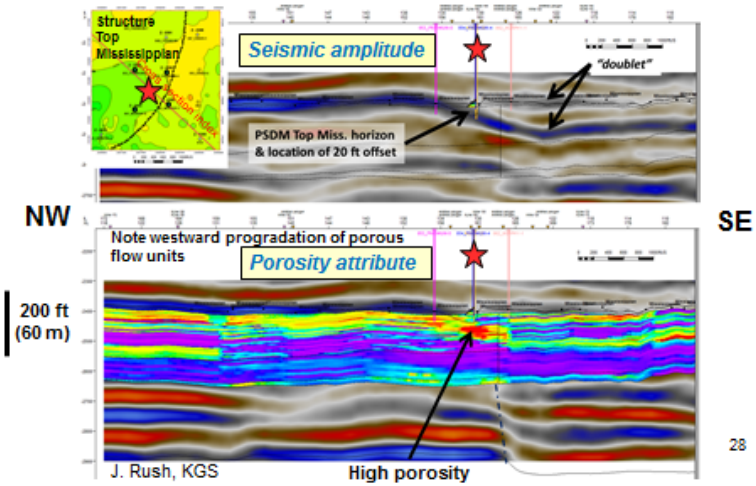
Sedimentary Features Have Been Masked During Dolomitization



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

Montalvo, KU & Barker, KSU

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



Wellington Field has experienced an excellent waterflood

File Product Plot Curves ON/OFF

1st Plot Title: Field Production

2nd Plot Title: Wellington

3rd Plot Title: OIL

X-Axis — Year: Minimum: 1938; Maximum: 2015; Increment: 4

Y-Axis — Production/Cumulative: Minimum: 1.0; Maximum: 1000.0; Cycles: 3

Production Decline Curve Calculator

Decline Curve Analysis Methods: ○ Exponential ◉ Harmonic ○ Hyperbolic

Enter Production Rate for Computations: ○ Daily ○ Monthly ◉ Yearly

Initial (Qi): Rate: 191439; Year: 1974

Final (Qt): Rate: 52784; Year: 1998

Decline Curve Equation: Qt = Qi / (1+Kt); t=time

Constant (K): 0.109459

Exponent (n): 0.0

Cumulative Production:

Production (Actual): 12990396 BBL

Present (Computed): 11731445 BBL

Production at Economic Limit:

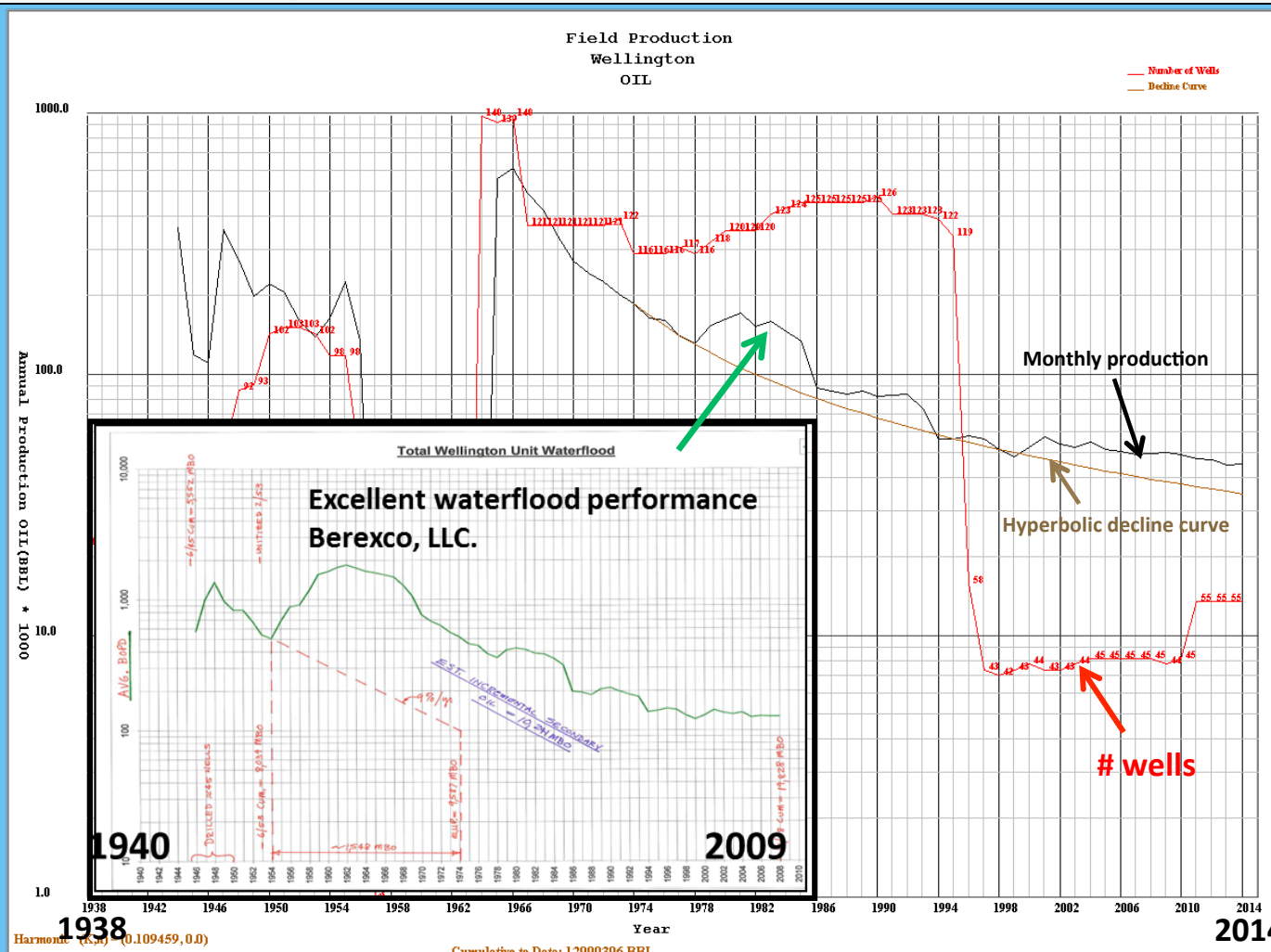
Economic Limit Rate (Qf): Rate: 15 BBL Per ◉ Day ○ Month ○ Year; Date: 2284

Economic Limit (EUR): 15694578 BBL

Reserves (RR): 2704182 BBL

Extend to Limit

Production



Harmonic (Ki,n) = (0.109459, 0.0)

Initial Production Year Rate (Qi): 191439 BBL at 1974

Present Production Year Rate (Qt): 52784 BBL at 1998

Decline Rate (De): 3.018 % Per Year

Economic Limit Year Rate (Qf): 5475.0 BBL at 2284

Cumulative to Data: 12990396 BBL

Computed: 11731445 BBL

Cumulative at Limit: 15694578 BBL

Remaining Reserves: 2704182 BBL

J. Victorine, KGS

Production Plot & Decline Curve Analysis Applet

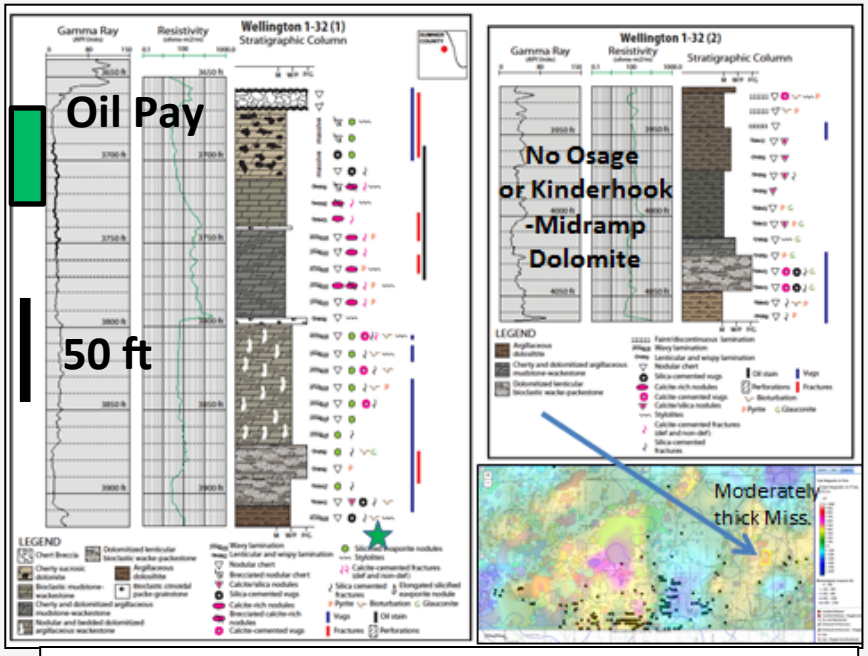
http://www.kgs.ku.edu/software/production/applet.html

Main Page | Description | Applet | Help | Copyright & Disclaimer |

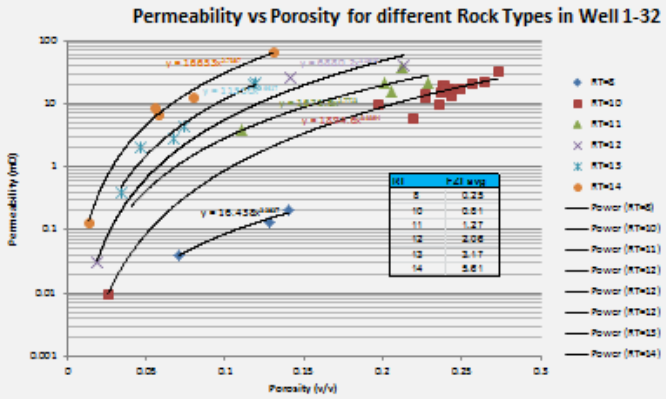
Production

Site characterization of the Mississippian oil reservoir

Wellington Field → 1600 ft core (base Penn to granite), 2 wells, 3D multi-component seismic, 420 whole core analyses, multiple Mississippian and saline Arbuckle tests



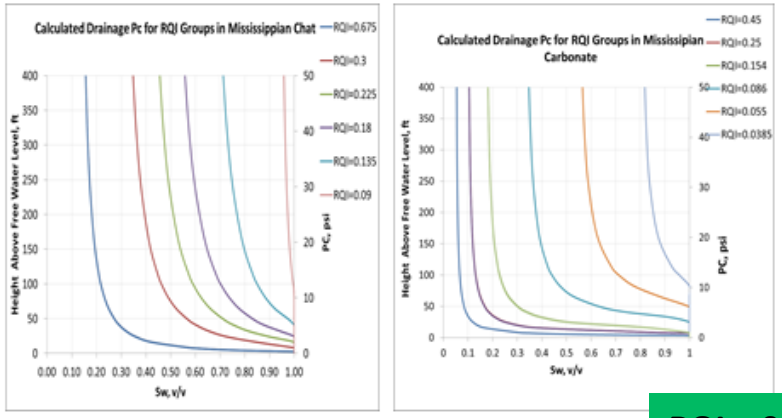
Upper Mississippian Reservoir Quality



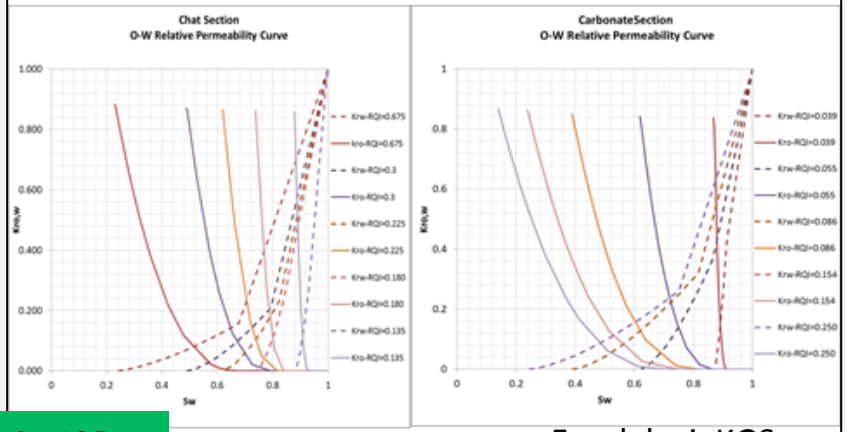
Schlumberger Techlog Wellbore Software Platform

M. Fazelalavi, KGS

Drainage Capillary Pressure Curves for Each RQI Range in the Mississippian



Relative Permeability Curves for Each RQI Range in the Mississippian



Fazelalavi, KGS

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

Pilot CO_2-EOR in summer & fall 2015 in 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.

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

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

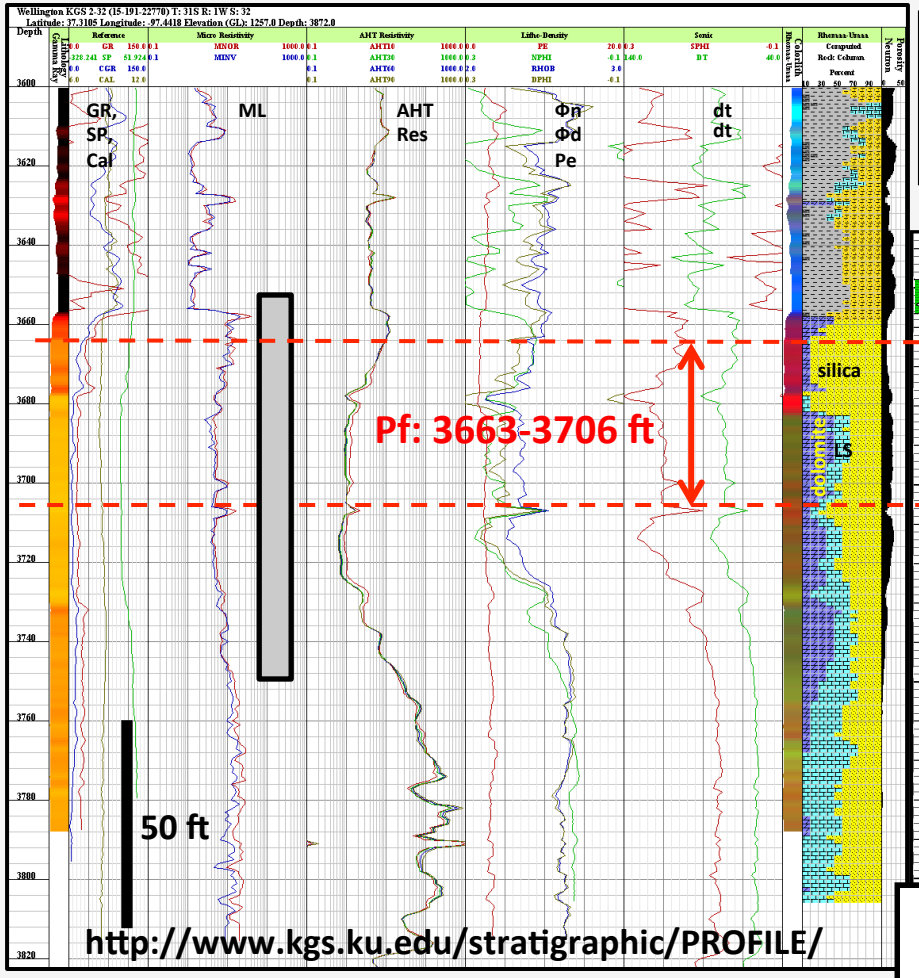
World's first industrial project to deliver CO_2 separated onshore back offshore and injected into a reservoir

- 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

March 2015 -- Drilled, cored, logged, and cased Berexco Wellington KGS #2-32

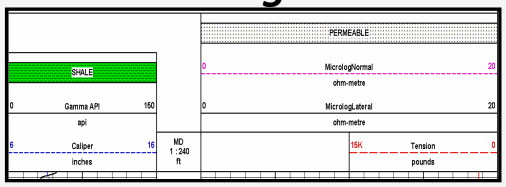
Perforated and acidized, completed April 30th, preparing for 5-well interference test mid May

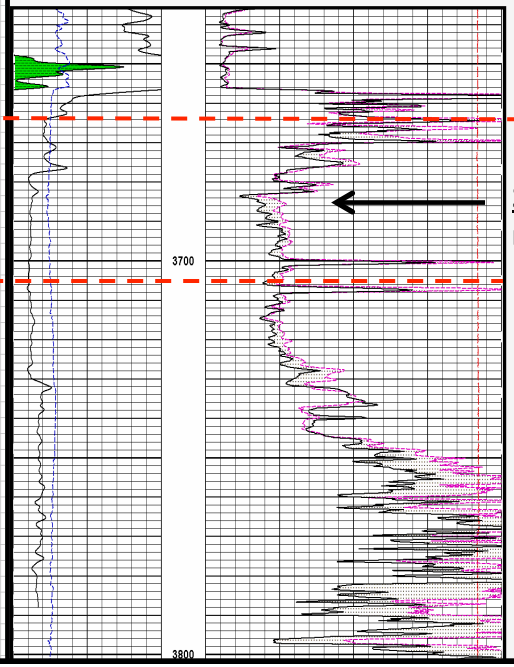
http://www.kgs.ku.edu/stratigraphic/PROFILE/



2 preserved 1 1/2 inch diameter plug samples (for relative permeability)

Microlog





3685 ft, top dolomite reference depth for next slide

Core Lab

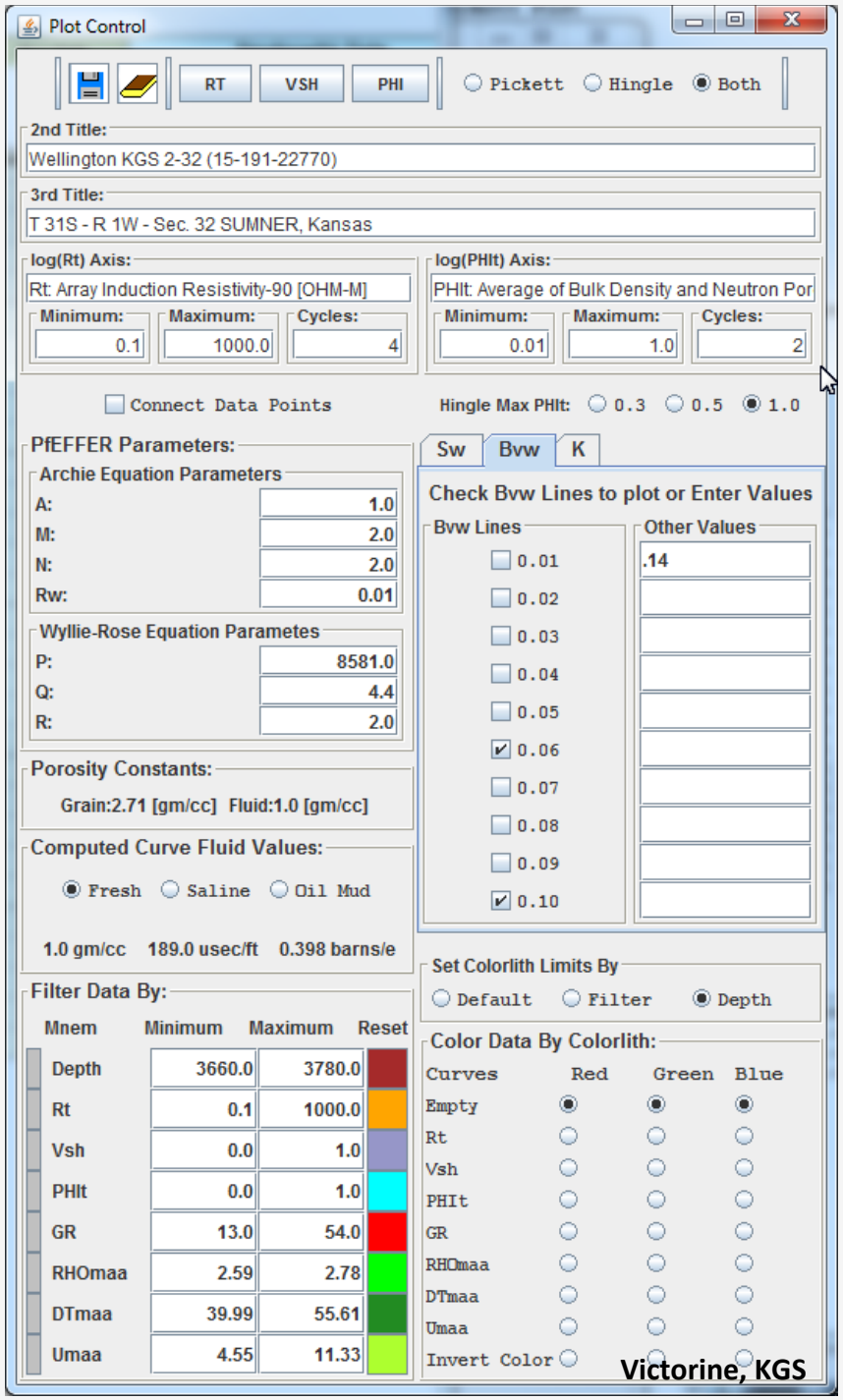
Full Diameter Analysis Dean Stark

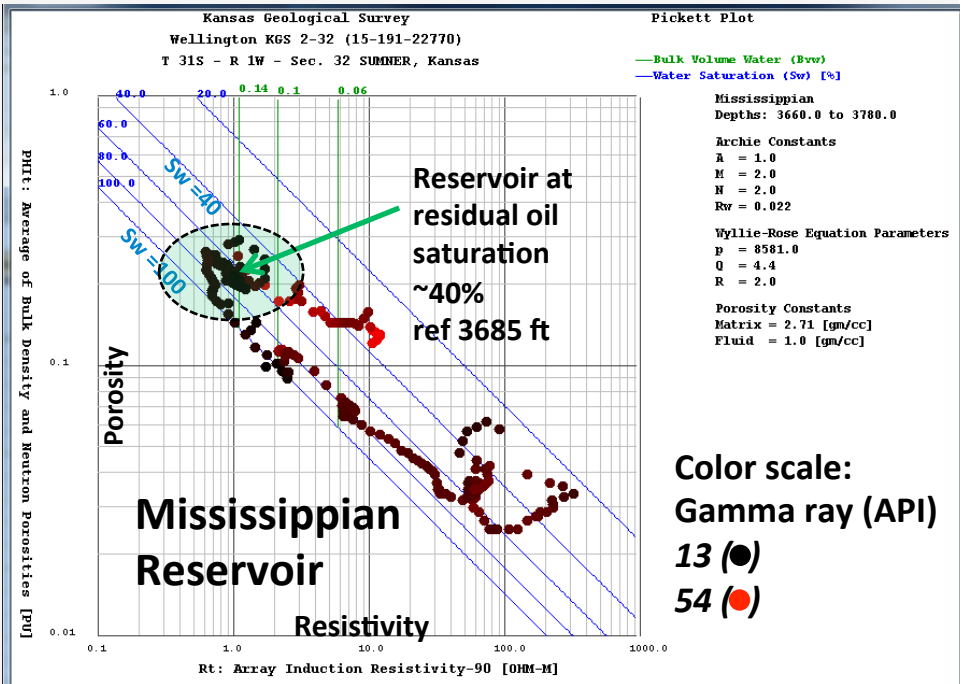
Company: Berexco LLC
Well Name: Wellington KGS #2-32
Location: 2680'FSL & 709'FEL, Sec 32, T 31S, R 1W
Co. & St.: Sumner County, Kansas

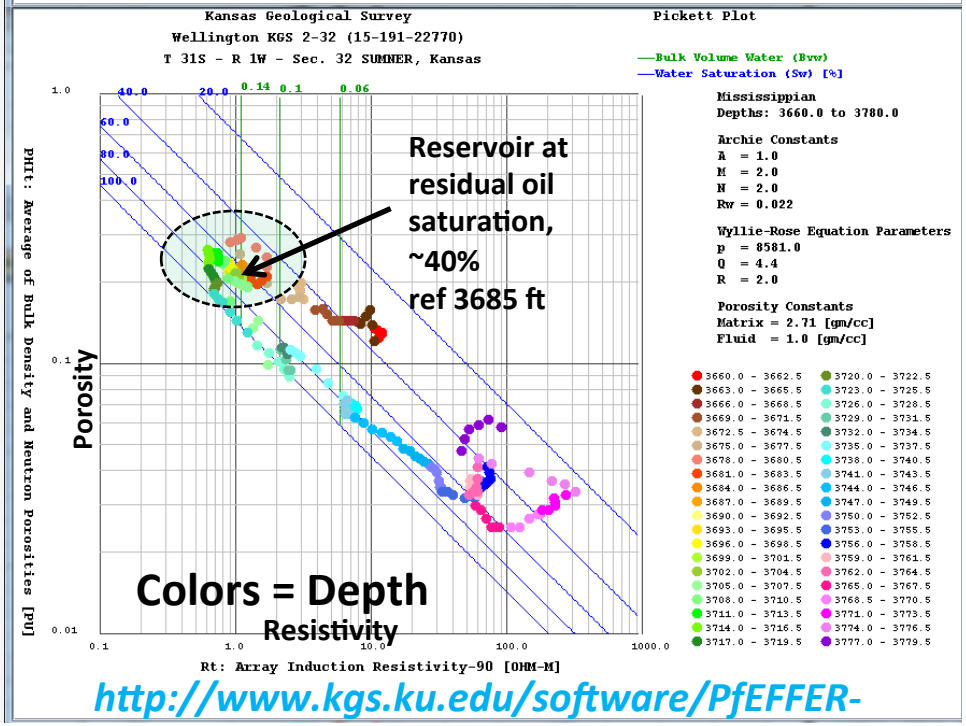
Field: Wellington
Formation: Mississippian
Coring Fluid: Fresh Wtr Mud
Elevation: 1269' KB

File Number: 57181-20573
Date: 04/16/2015
API Number: 15-191-22770
Full Diameter Sample List

Sample Number	Top Depth feet	Bottom Depth feet	K(max) ss, air 400 conf press md	K(90) ss, air 400 conf press md	K(vert) ss, air 400 conf press md	POR Ie, Ambient Ieas Grn Vol % of BV	GD gm/cc	So Core % of PV	Sw % of PV



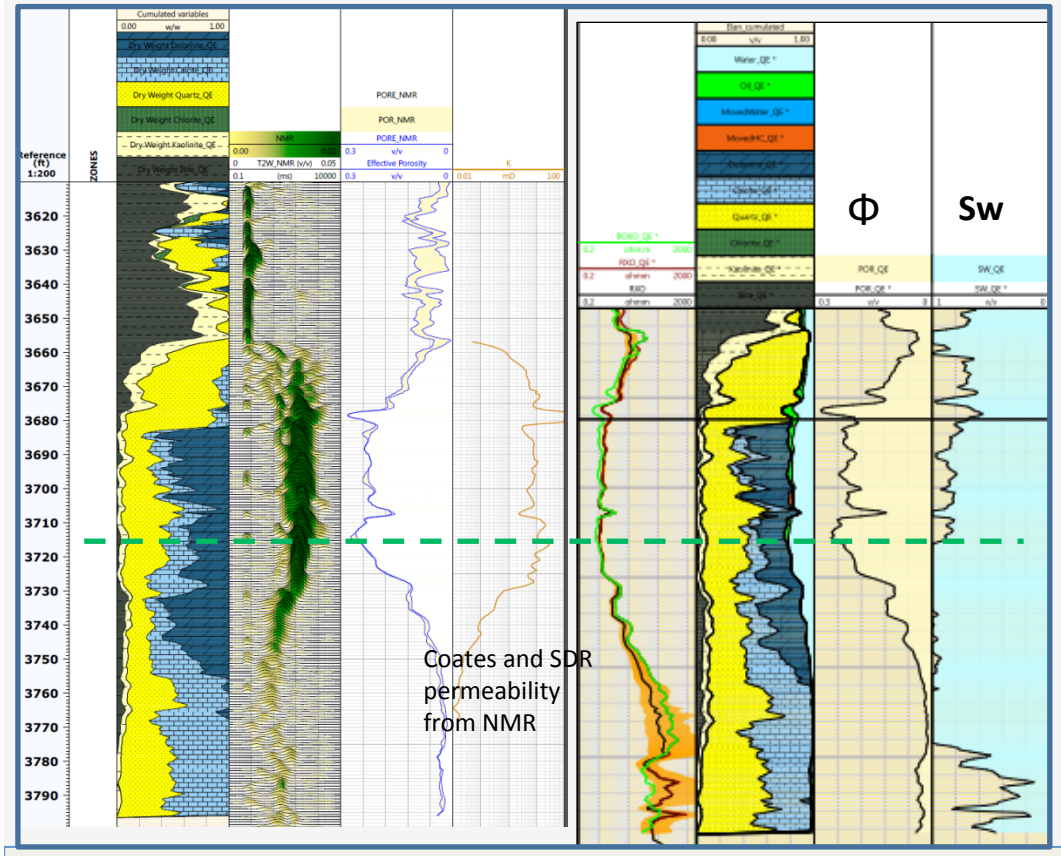




http://www.kgs.ku.edu/software/PfEFFER-

Well logs, DST, and acidizing results used to characterize perforation interval and design interference test

Halliburton MRIL Log **Schlumberger Techlog™ Analysis**



Log interpretation of Berexco Wellington KGS #2-32
Waterflooding has been effective in well with only residual oil is left.
Residual oil is in green color, about 23%- 30%.

-- M. Fazelalavi, KGS

Acidizing results 4/27/15

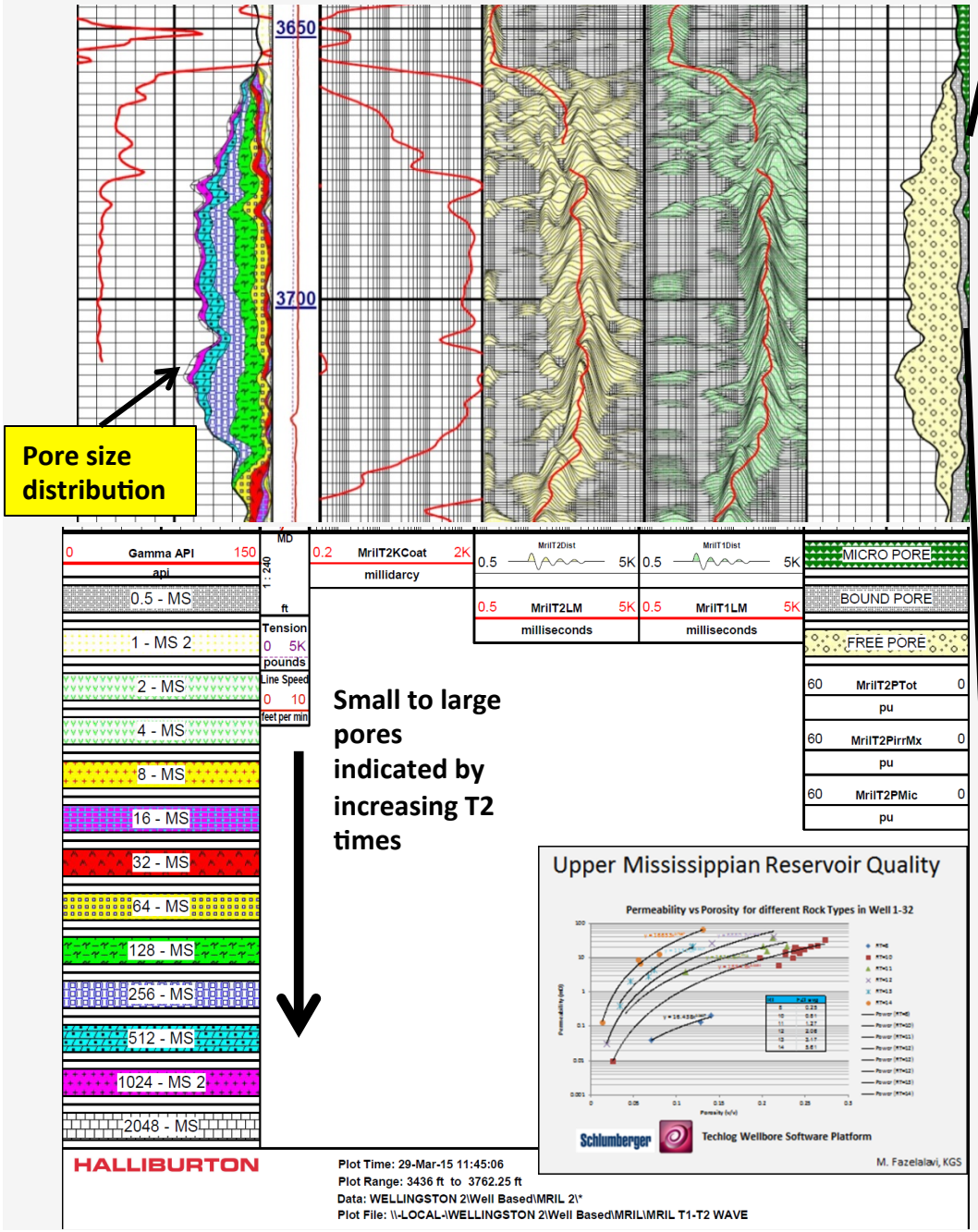
Berexco workover report
Wellington KGS 2-32:

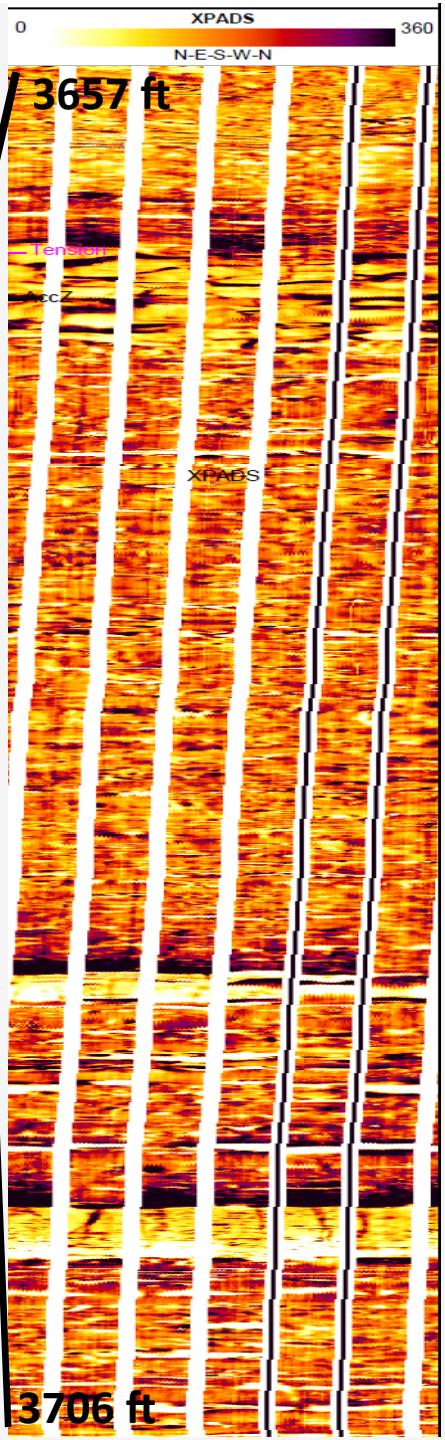
Acidized with **2500 gallons of 10% nefe**, 250 balls. Started treating at 3 BPM 1300#, finished treating at 5.7 bpm, 700#, ISIP 50#, went on a vacuum in 30 seconds. Waited 1 hour then began swabbing.
TIH with swab, hit fluid @ 1100'fs. Swab down 44.66 br(2hrs) swabbed 1hr and recovered 20.82br. Total 65.48br. Show of oil and all acid was spent. Shut down.

Final treatment at 5.7 bpm *(~8200 BPD*), 700#, ISIP 50#, went on a vacuum in 30 seconds

Equivalent barrels of CO_2 to inject ~500 BPD

Halliburton Nuclear Magnetic Resonance (MRIL) Log of Mississippian reservoir at Wellington KGS #2-32

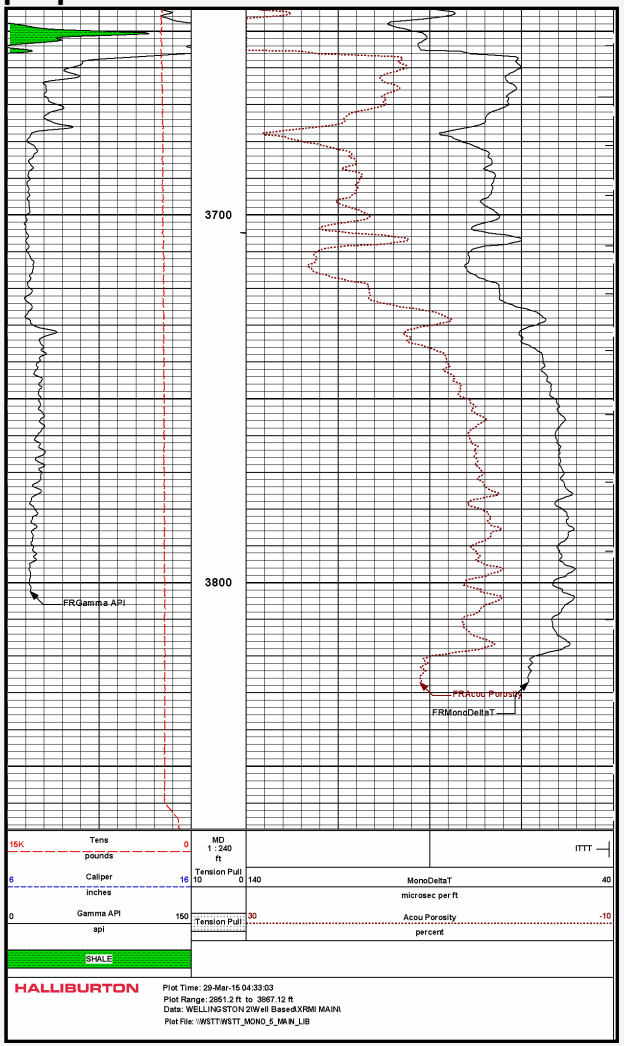




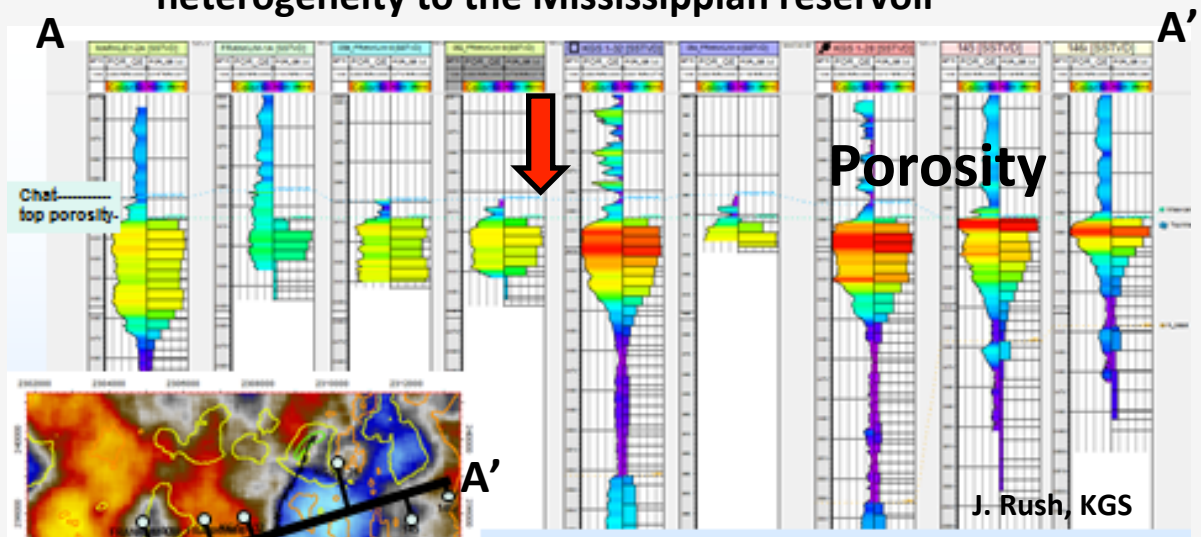
Formation microresistivity imaging log depicting pores in the the Wellington Mississippian reservoir

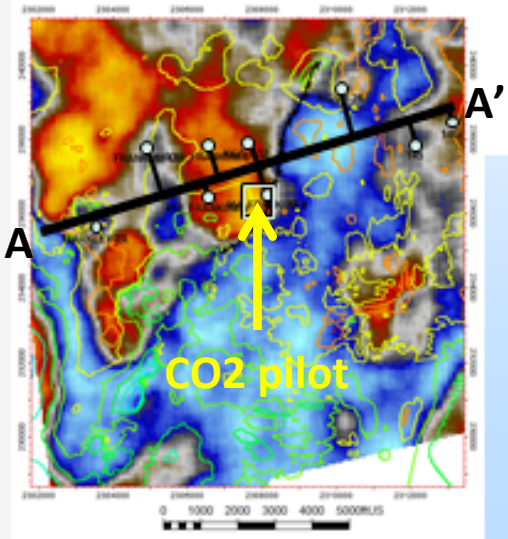
Dipole Sonic log used in fracture and geomechanical analysis

Conventional sonic log presentation from Halliburton's Wave Sonic log
P- and shear wave → geomechanical properties of reservoir



Utilize logs, core, seismic, and well tests to characterize fracture systems that impart additional heterogeneity to the Mississippian reservoir





- Seismic amplitude slice through Mississippian reservoir showing discontinuity immediately east of the CO_2 pilot site
- Black line – line of section for well log based porosity cross section showing lateral variability in the Mississippian dolomite

Interference test to be conducted help verify simulation model before reservoir is repressurized and CO_2 is injected

Wellington KGS 2-32 Pump Test Procedure

-> Set April 30th
5 wells including #2-32

A) Pump at 2 bpm for 20 minutes, then shut down for 20 minutes.

B) Pump at 4 bpm for 20 minutes, then shut down for 20 minutes.

C) Pump at 6 bpm for 20 minutes, then shut down for 20 minutes.

D) Pump at 7 bpm for 20 minutes, then shut down for 20 minutes.

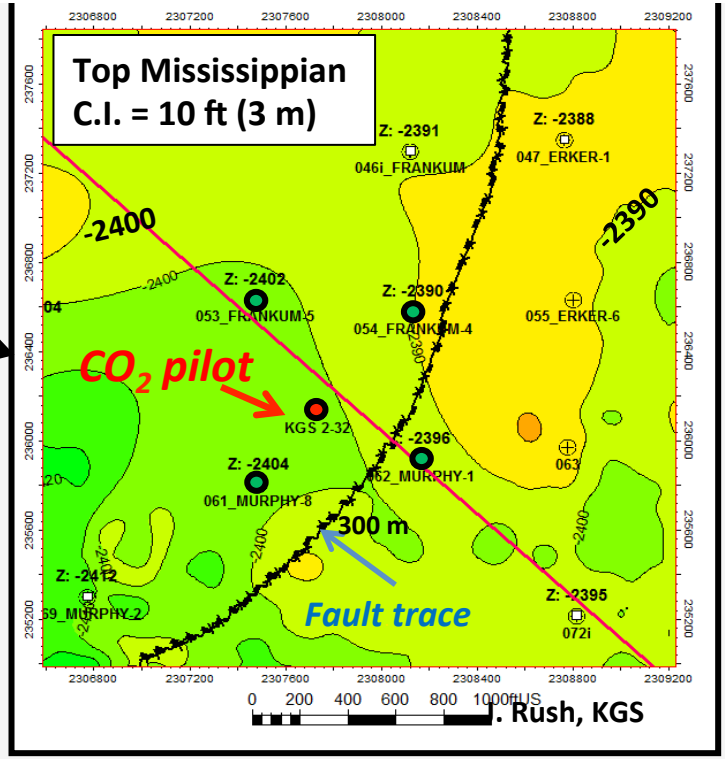
E) Pump at 6 bpm for 20 minutes, then shut down for 20 minutes.

F) Pump at 4 bpm for 20 minutes, then shut down for 20 minutes.

G) Pump at 2 bpm for 20 minutes, or until out of water, then shut down.

TRILOBITE TESTING, INC.

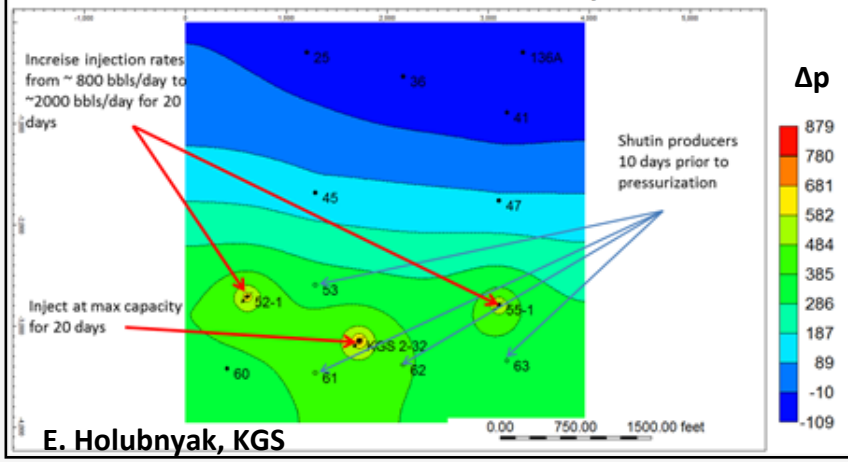
M. Fazelalavi & D. Wreath



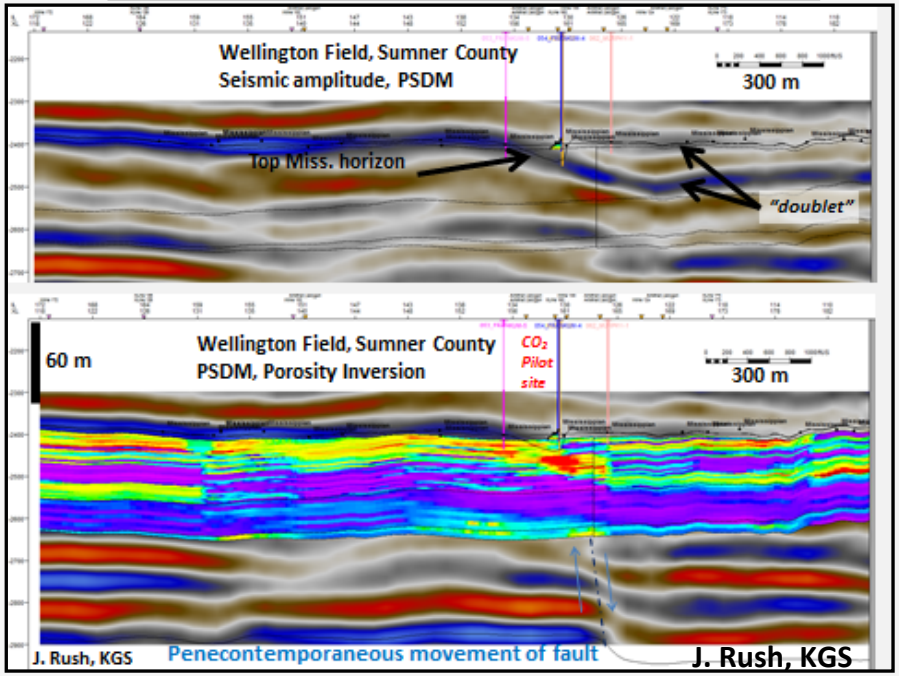
Initial pressurization model for Wellington Field prior to CO_2 injection to achieve miscibility

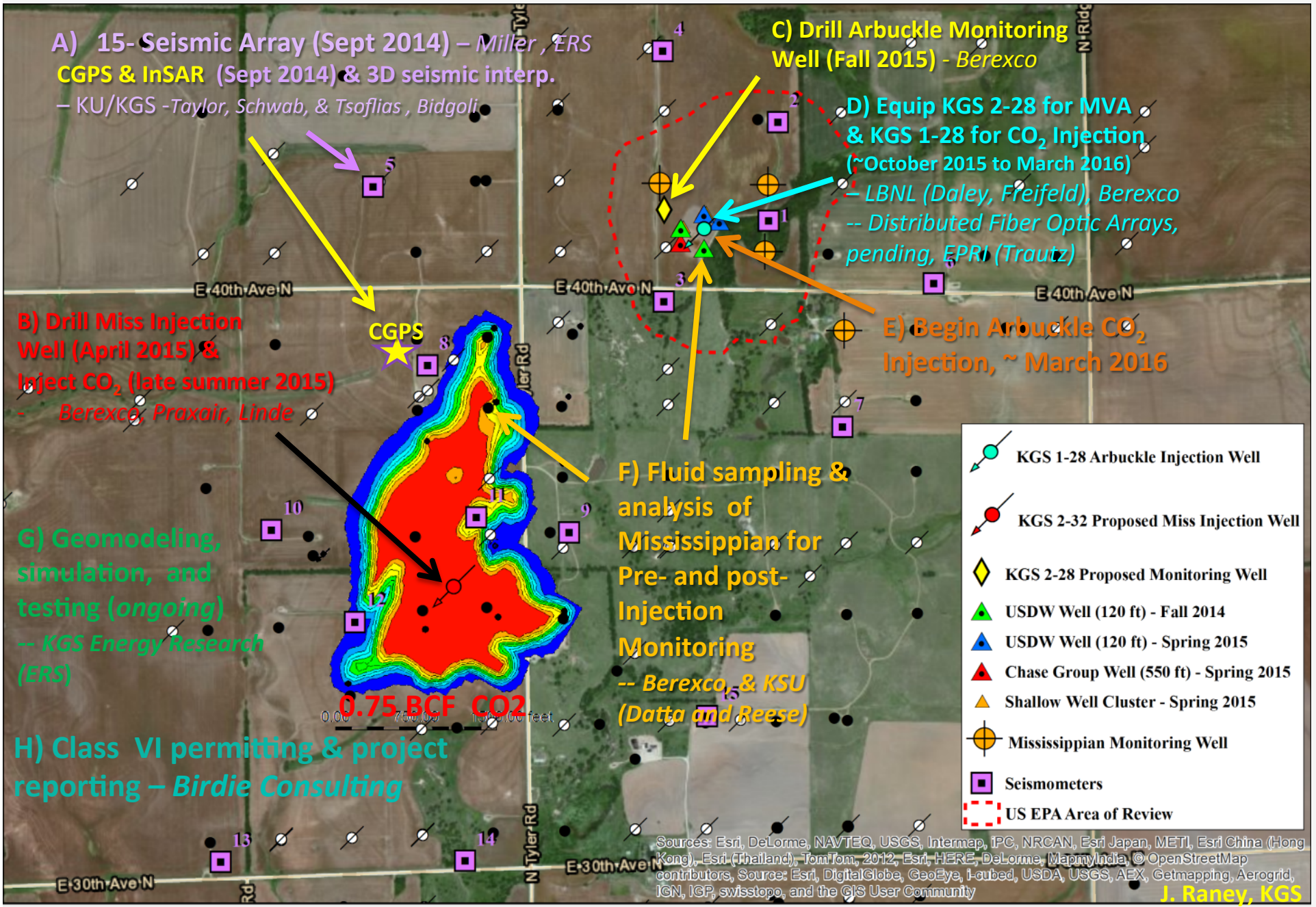
According to this model at least 20 days are required to increase pore pressure from ~ 1000 psi to ~ 1500 psi near proposed KGS 2-32 well
Model assumes homogeneous reservoir with open boundary conditions, k = 70, phi = 0.25, thickness = 60 feet, rel. perm. and cap. press. calculated by Mina FazelAlavi

Formula: Delta P 2015-04-20 K layer: 3



E. Holubnyak, KGS





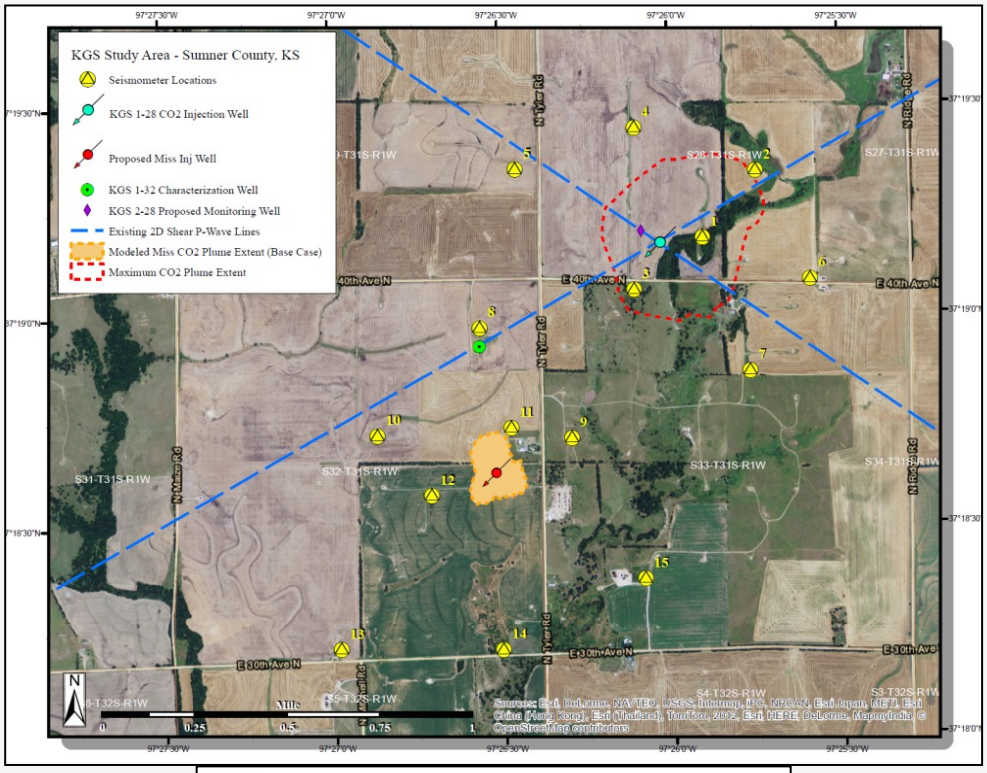
MVA Activity at Wellington CO2 injection site
Sumner County, Kansas
Twn 31S - R 1W

N

Feet
0 750 1500 3000

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

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



R. Miller and S. Peterie, 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

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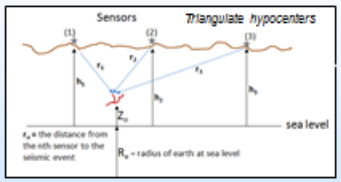
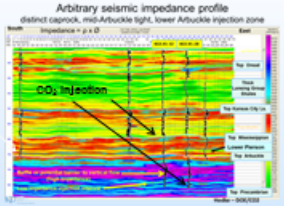
R. Miller and S. Peterie, KGS

Resolution of Hypocenters from IRIS Seismometer Array at Wellington

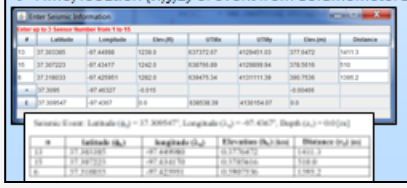
Refining location of operational seismicity -- Initially for the CO2-EOR injection to evaluate feasibility of methodology



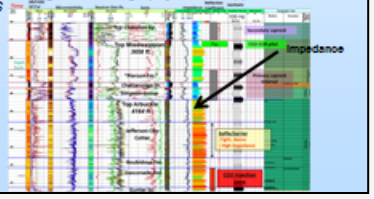
Mississippian and Arbuckle injection zones have good impedance



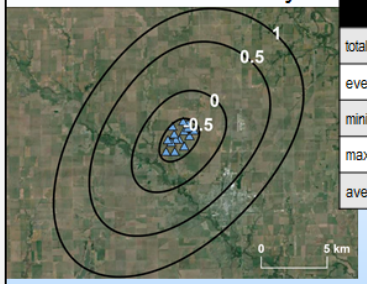
Adapting Java toolset to manage, interpret, and display solutions on project maps (Victorine, KGS)
→ *Time, location (x,y,z) of event from seismometers*



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

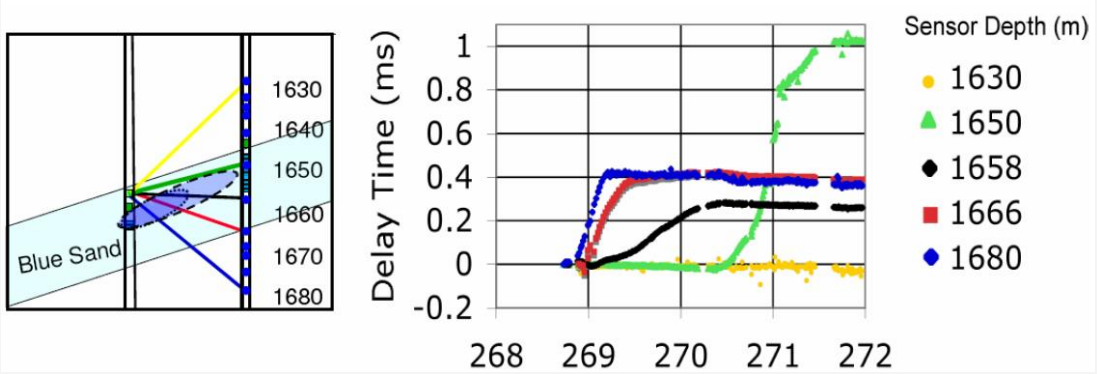
R. Miller and S. Peterie, KGS

Monitoring, Verification, and Accounting in the Arbuckle pilot injection

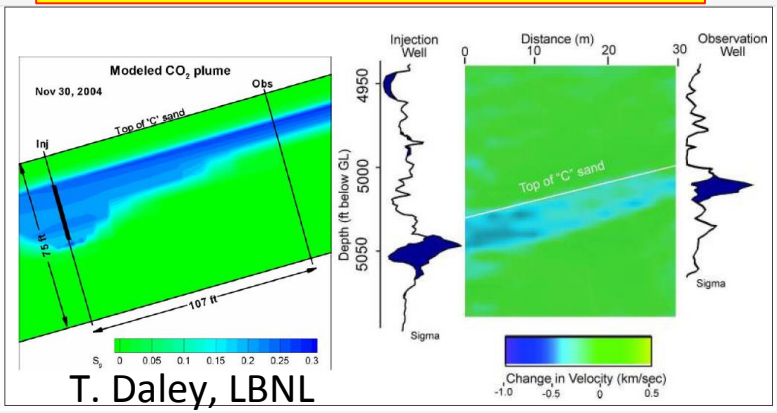
U-Tube

B. Freifeld, LBNL

Real time detection using continuous source cross-well seismic

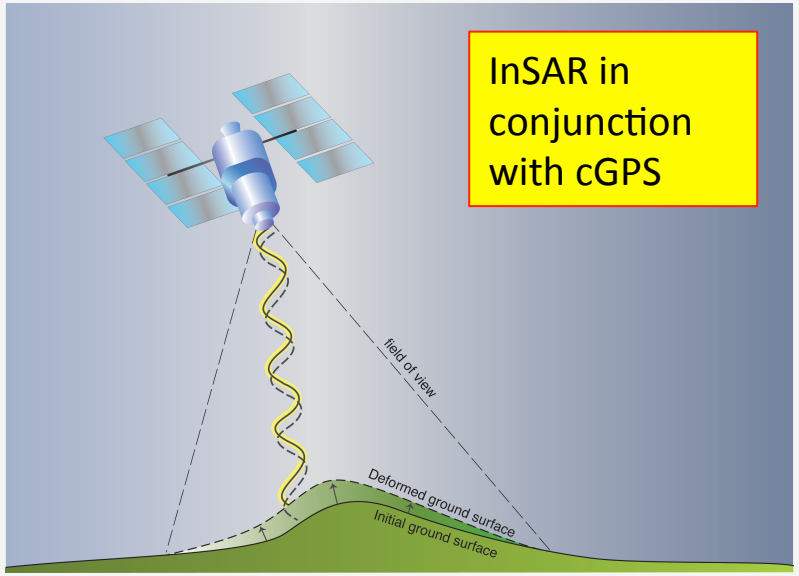


CASSM & Croswell Seismic Tomography



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**

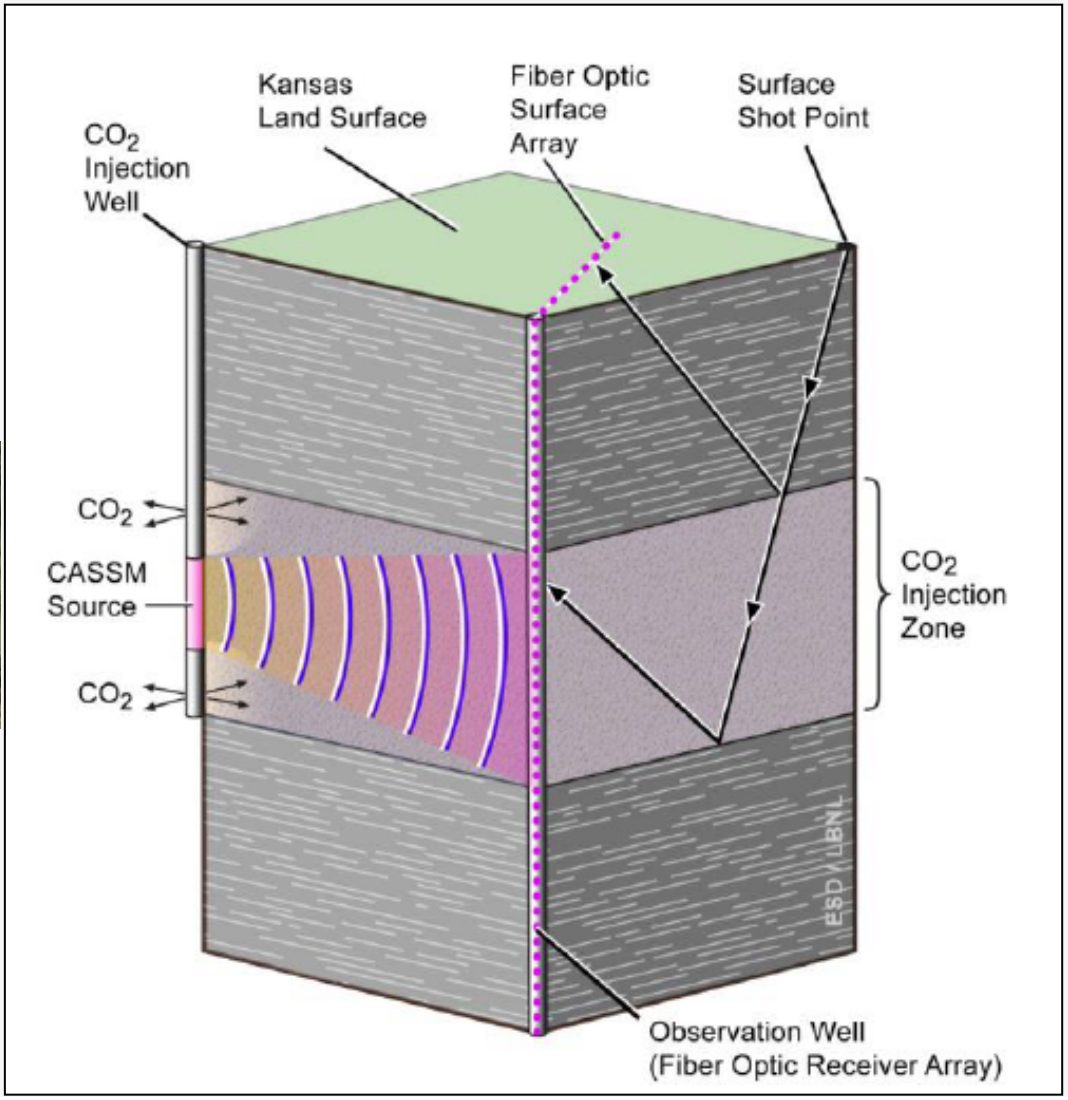
DE-FE-OO12700 -- Integrated Temperature and Seismic Sensing for Detection of CO_2 Flow, Leakage and Subsurface Distribution - Rob Trautz, EPRI, PI

→ *Pending contract to apply acoustic fiber optic cable monitoring technology to the Arbuckle Pilot*

- **Multiple seismic shots currently budgeted to create a pseudo-3D volume to image the CO_2 plume → low cost alternative to repeat 3D**

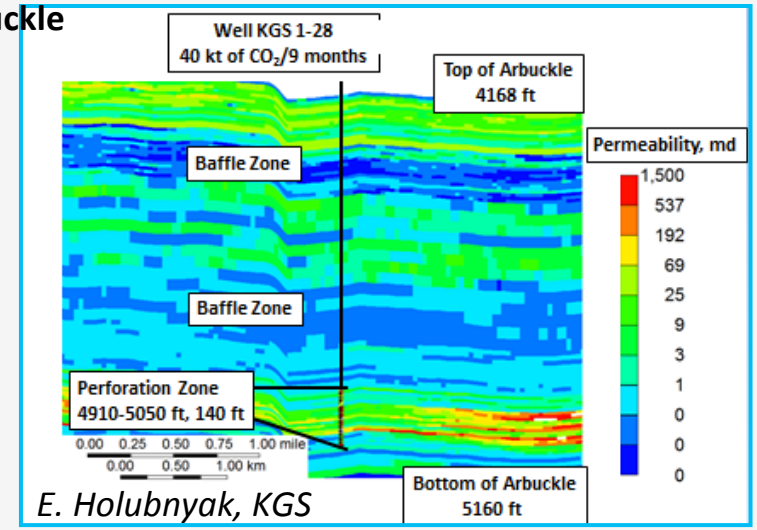
High Resolution Vibroseis source for VSP, R. Miller, KGS

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



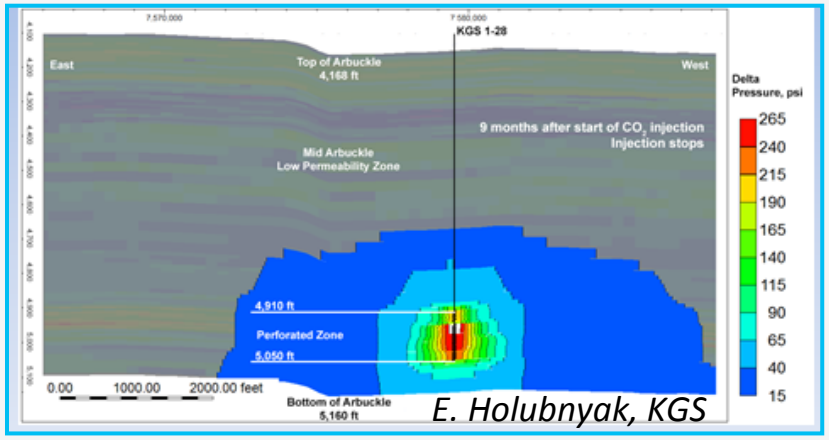
Pilot CO_2 injection in 2016 into Arbuckle at Wellington, pending EPA Class VI permit

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



E. Holubnyak, KGS

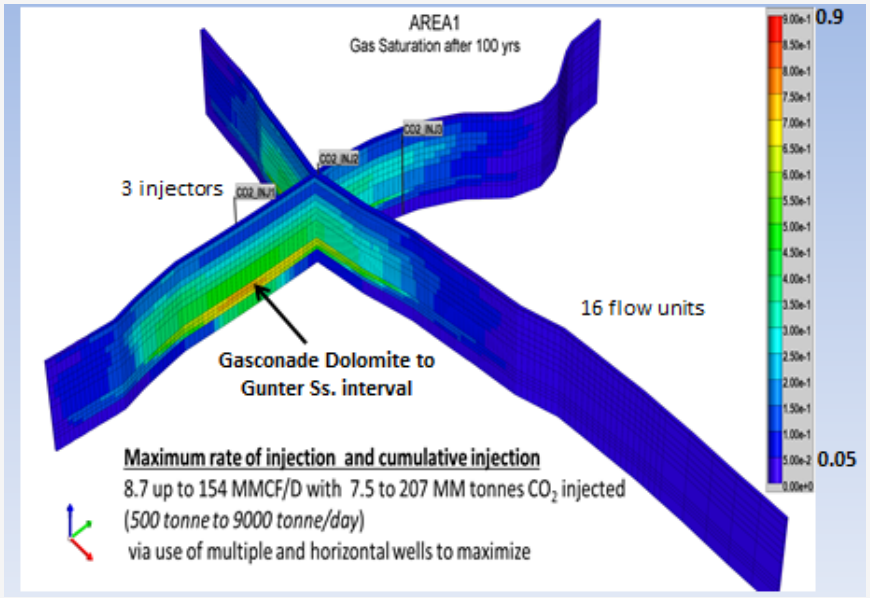
Vertical pressure distribution at maximum stress just before small scale pilot injection (40 k tonnes) stops



E. Holubnyak, KGS

COMPUTER MODELLING GROUP LTD.

CMG Simulation →Commercial scale injection model Area 1 (Wellington Field) – CO_2 gas saturation In the Arbuckle → Up to 207 MM tonnes at Wellington Field



E. Williams Consulting

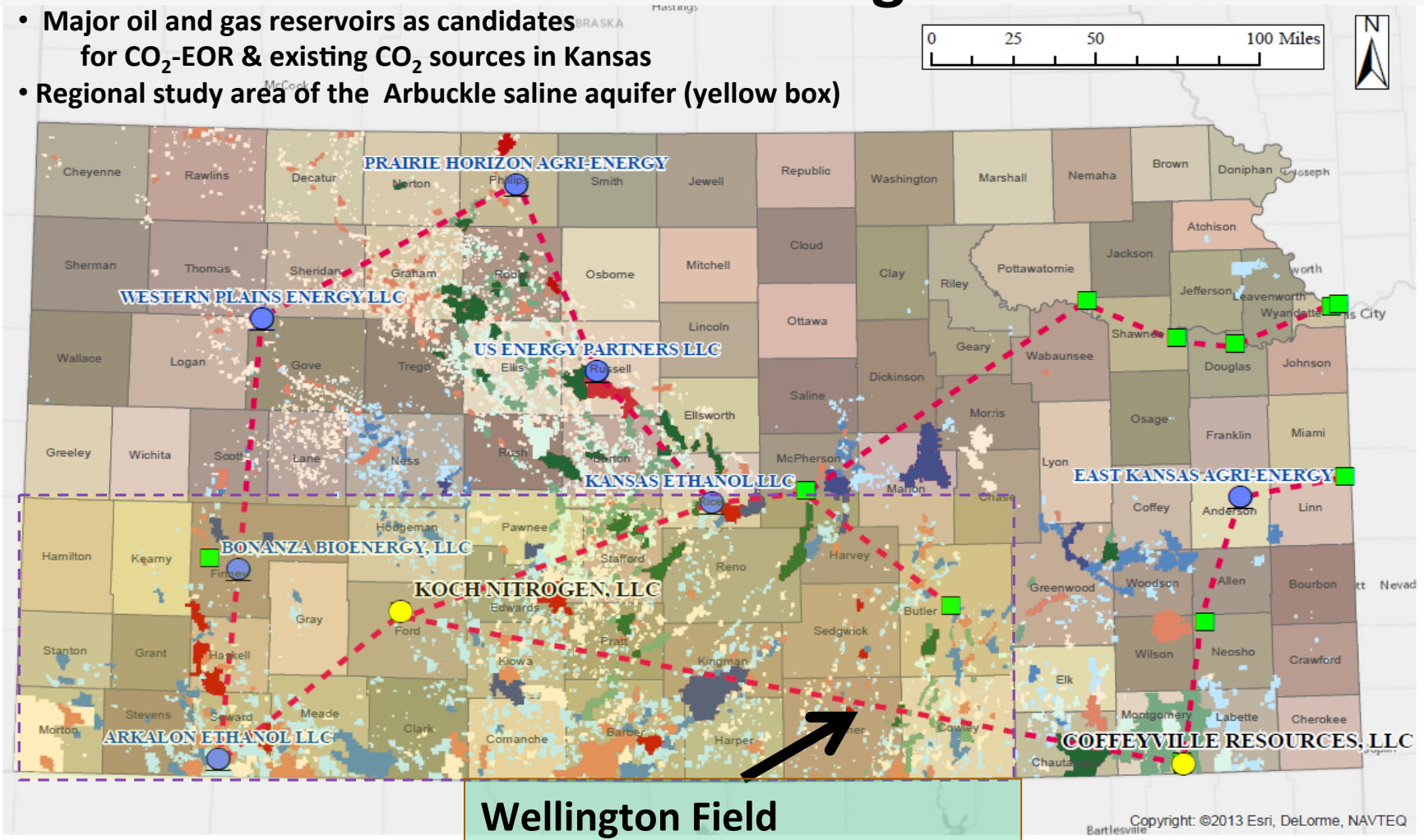
Implementing CO_2 utilization and storage (CCUS) in Kansas

- **Carbon storage and utilization offers significant potential to revitalize Kansas' oil fields.**
  - A 2010 report for the Midwest Governor's Association with input from TORP 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 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?

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)



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 new wells, multicomponent 3D seismic)
    - Cutter Field, Stevens County (1 new 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 and Monitoring, Verification, and Technology
  - 70,000 metric tons CO_2 from Praxair and Linde
- 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

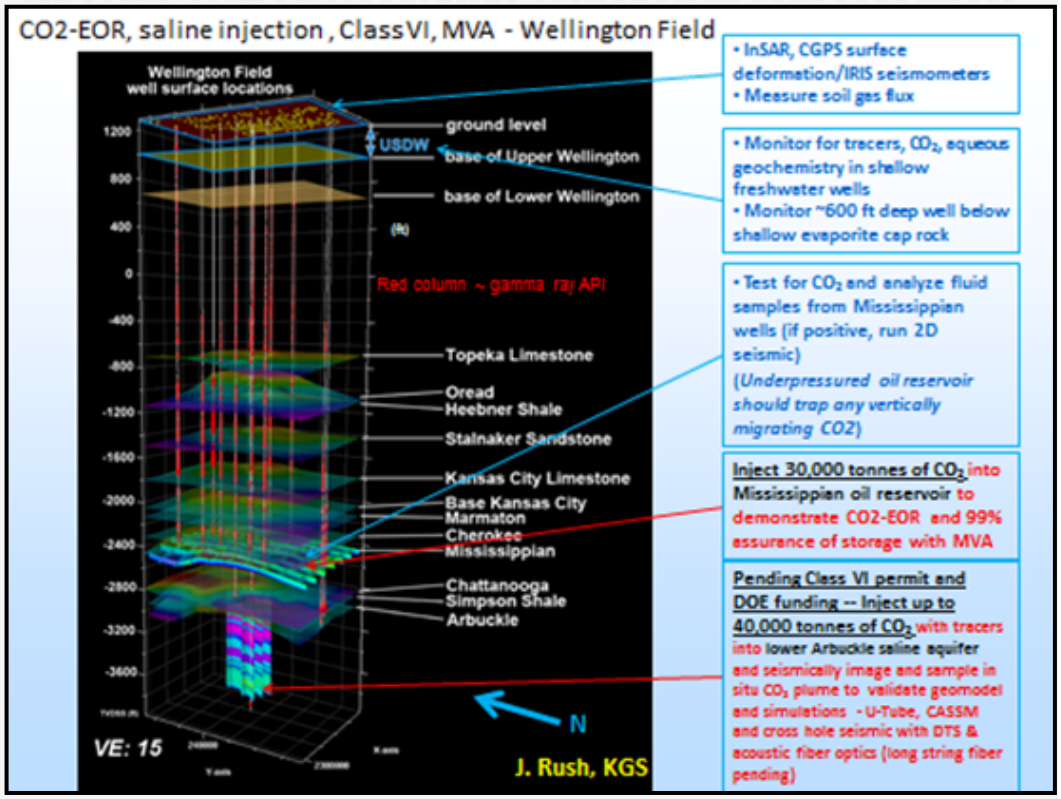
- *The work supported by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) under Grant DE-FE0002056 and DE-FE0006821, W.L. Watney and Jason Rush, Joint PIs. Project is managed and administered by the Kansas Geological Survey/KUCR at the University of Kansas and funded by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

Interdisciplinary Collaboration
CO_2-EOR Technology & Carbon Management Research
Under DOE-DE-FE0006821 & DE-FE0002056

SW Kansas CO_2-EOR Initiative

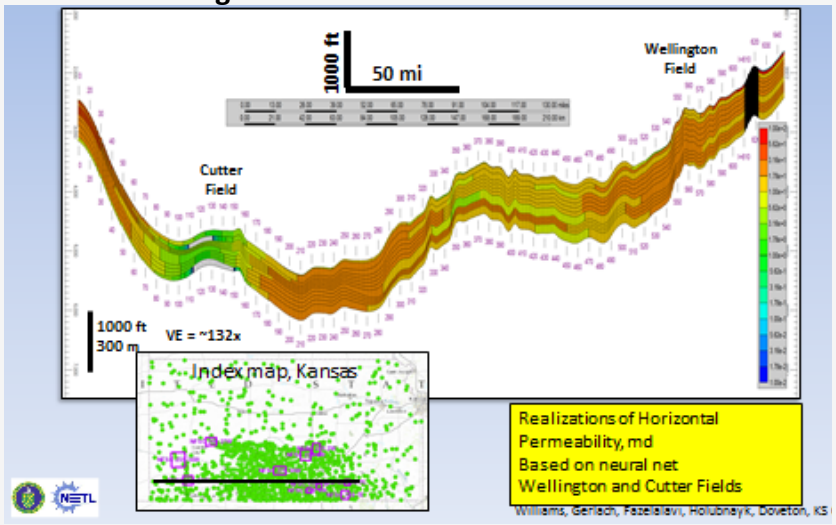
REGIONAL CHARACTERIZATION

WELLINGTON FIELD CHARACTERIZATION FOR CO2 PILOT

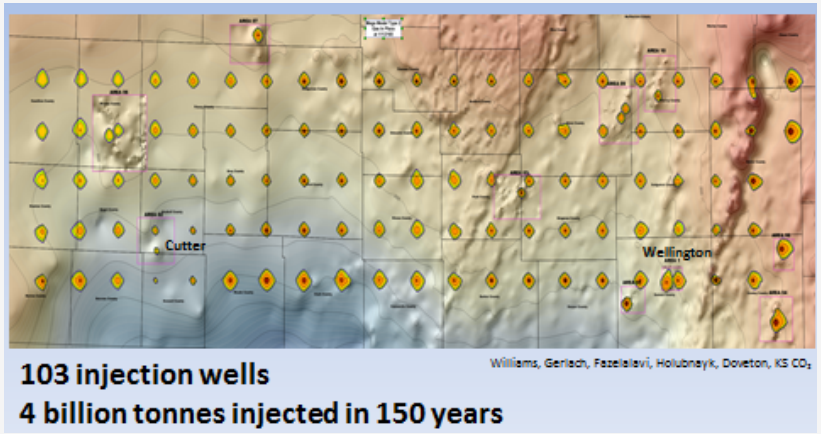


Utilization of Arbuckle beneath oil fields to optimally and safely manage CO_2 obtained from anthropogenic source

West-east structural cross section showing permeability distribution in 16 Arbuckle flow units, southern Kansas, 2500 x 2500 grid

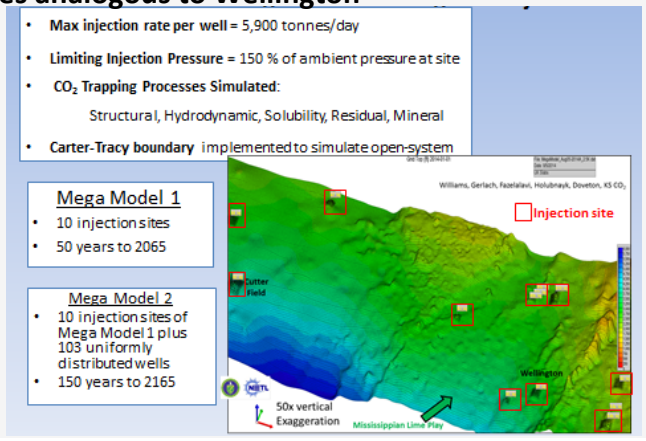


Model 2 – Gridded injection sites for CO2 expressed as supercritical gas in place after 150 yrs injection

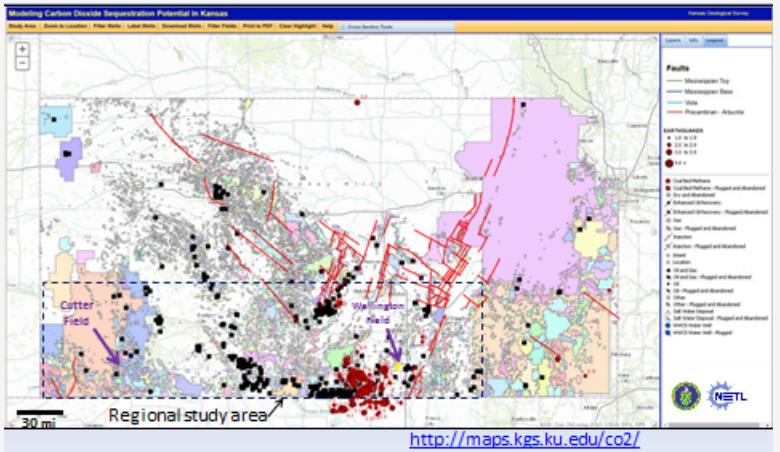


103 injection wells
4 billion tonnes injected in 150 years

Regional CO2 sequestration – numerical models at 9 sites analogous to Wellington



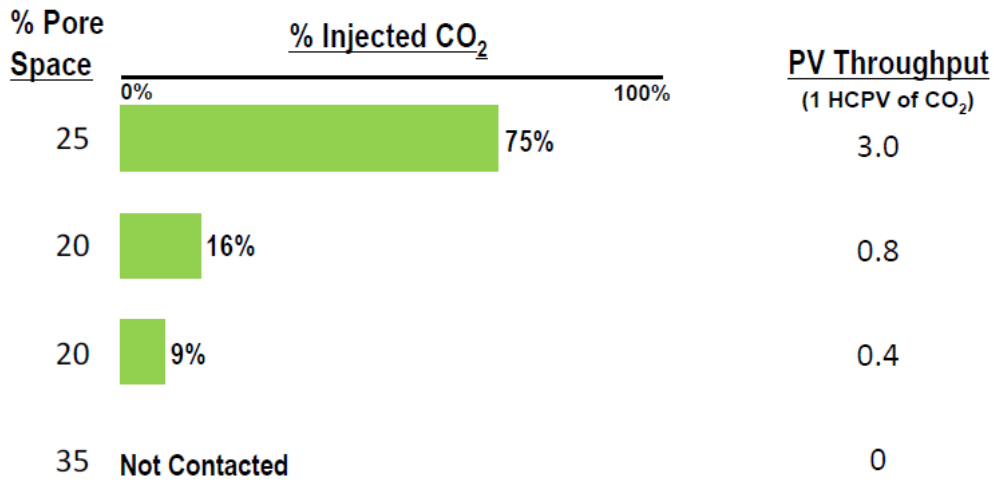
Continuing analysis of safe injection and disposal in a complex Midcontinent structural setting
→ Use of DOE-CO2 interactive mapper



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

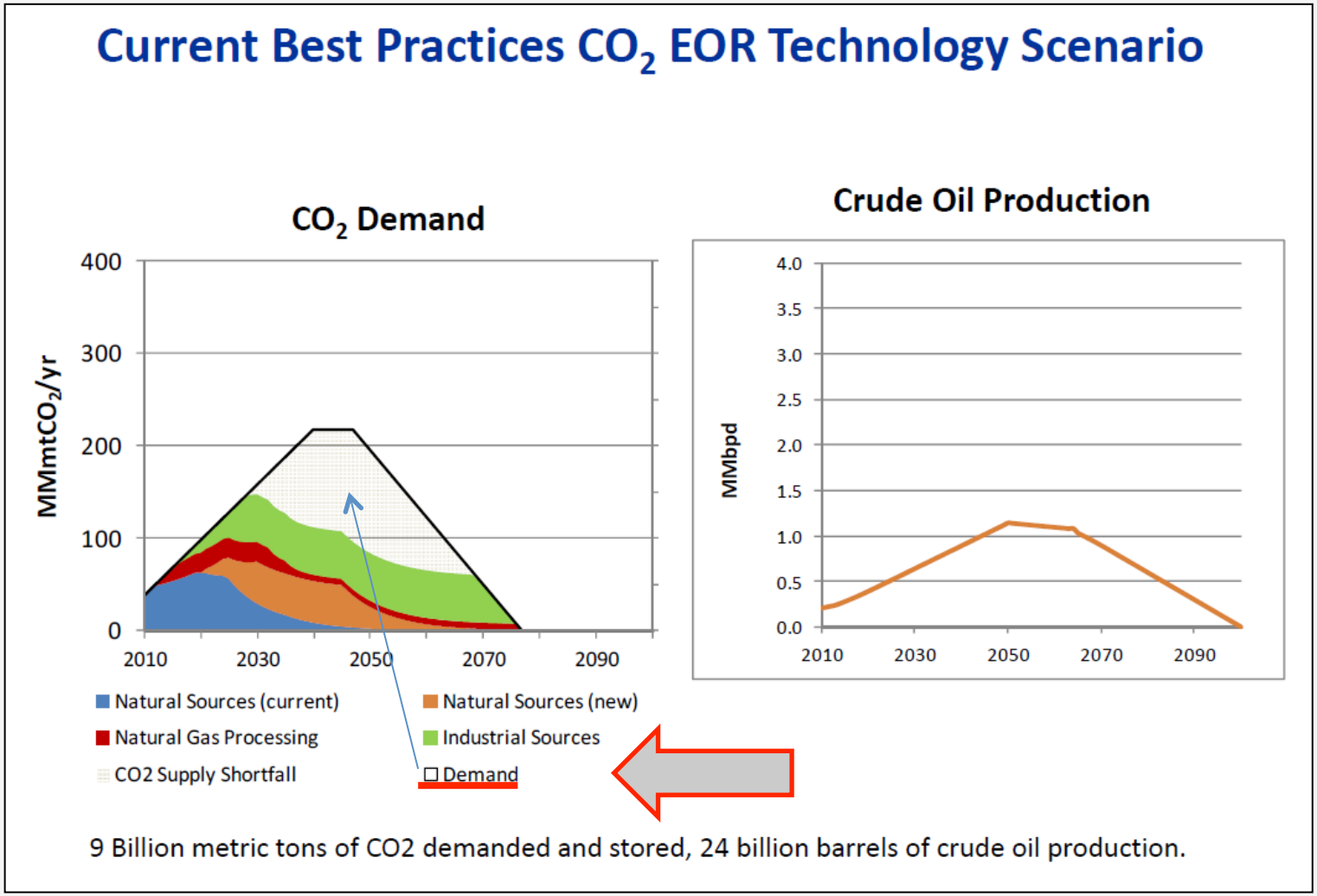
Next Generation CO_2-EOR is needed to *improve efficiencies of oil recovery and CO_2 storage*

Example of Channeling of CO2 in an Oil-Bearing Formation



Source: Modified by Advanced Resources, based on data from Wasson Denver Unit CO2 flood observation pilot (Goodyear and Jensen, 2011).

Next generation CO_2-EOR methods and anthropogenic CO_2 are essential to sustain this type of oil recovery in U.S. beyond 2030



Phil DiPietro, 2013, Carbon Dioxide Enhanced Oil Recovery in the United States, DOE-NETL

CO_2 EOR & Geologic Storage