Modeling CO_2 Sequestration in Saline Aquifer and Depleted Oil Reservoir to Evaluate Regional CO_2 Sequestration Potential of Ozark Plateau Aquifer System, South-Central Kansas Project Number (DE-FE0002056)

W. Lynn Watney & Jason Rush (Joint PIs)

Jennifer Raney (Asst. Project Manager)

Kansas Geological Survey

Lawrence, KS 66047

U.S. Department of Energy

National Energy Technology Laboratory

Carbon Storage R&D Project Review Meeting

Developing the Technologies and Infrastructure for CCS

August 12-14, 2014

5:35 Tues

Brighton

Presentation Outline

1. Benefits to the Program
2. Project Overview
3. Technical Status
4. Accomplishments to Date
5. Summary

1. Benefit to the Program

- **Goal–**
  - **Predict geologic CO_2 storage capacity within ±30%**
  - **Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.**
- **Project benefits --**
  - Refine CO_2 storage capacity of the Arbuckle saline aquifer with regional simulation through the use of large-scale simulation (currently 9-75 billion tonnes, 200 yrs. KS emissions)
  - Quantify CO_2 storage at Wellington, Cutter, Pleasant Prairie South, Eubank, and Shuck fields through compositional reservoir simulation addressing storage efficiency and optimized use of CO_2 for EOR
  - Utilize extensive digital (LAS) log database, 3D seismic, gravity-magnetics, and remote sensing to evaluate site suitability, risk, and storage efficiency, regionally, and 10 simulated sites with most favorable conditions for commercial scale (>30 MM tonnes) storage
  - Allow user to query and analyze information via *Interactive Project Mapper, NATCARB, and suite of Java applications*

Project Overview: Goals and Objectives

- **Static and dynamic modeling of the Lower Ordovician Arbuckle Group in 25,000 mi^2 area** *(Predict CO_2 storage within ±30 percent and develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness)*
  - ***Success*** –

  a) Mapped the aquifer's hydrostratigraphic units/flow units and confining strata;

  b) Simulated commercial scale CO_2 injection at 10 sites;

  c) Estimating regional storage capacity through composition simulation using flow units and their key properties (Φ, kv, kh, Pc) using neural net realizations founded on core, test, and petrophysical data from Wellington and Cutter field calibration coreholes.
- **Model CO_2 storage at Wellington & Cutter flds and three additional fields in southwestern Kansas**
  - ***Success*** –

  a) Drilled 3 basement tests, 2@ 5200 ft TD at Wellington Fld & 1@7700 ft (Cutter Fld)

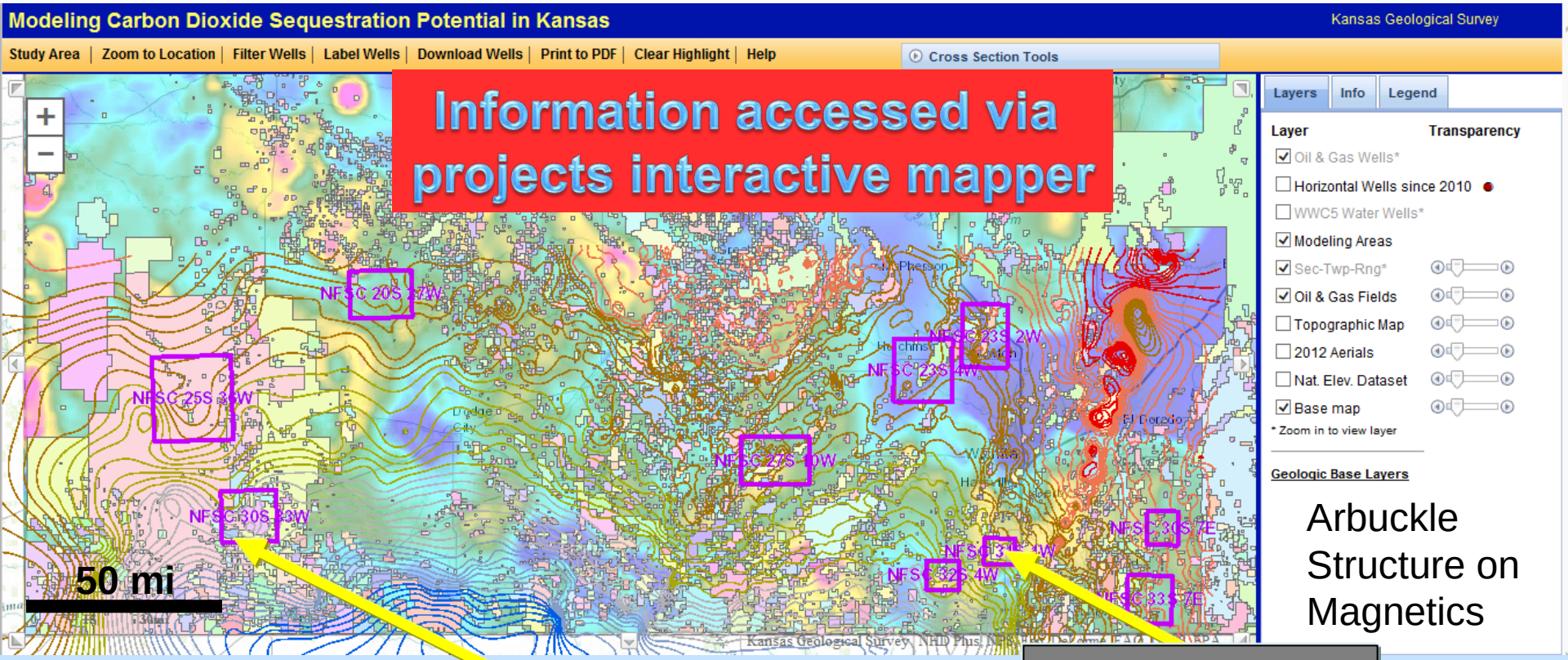
  b) Cored 2552 ft of Arbuckle and caprock in Wellington and Cutter fields

  c) Collected 22 mi^2 of multicomponent 3D seismic

  d) Built static (Petrel) and dynamic models (CMG) with CO_2 storage and EOR outcomes

Static and dynamic modeling of the Lower Ordovician Arbuckle Group in 25,000 mi² area

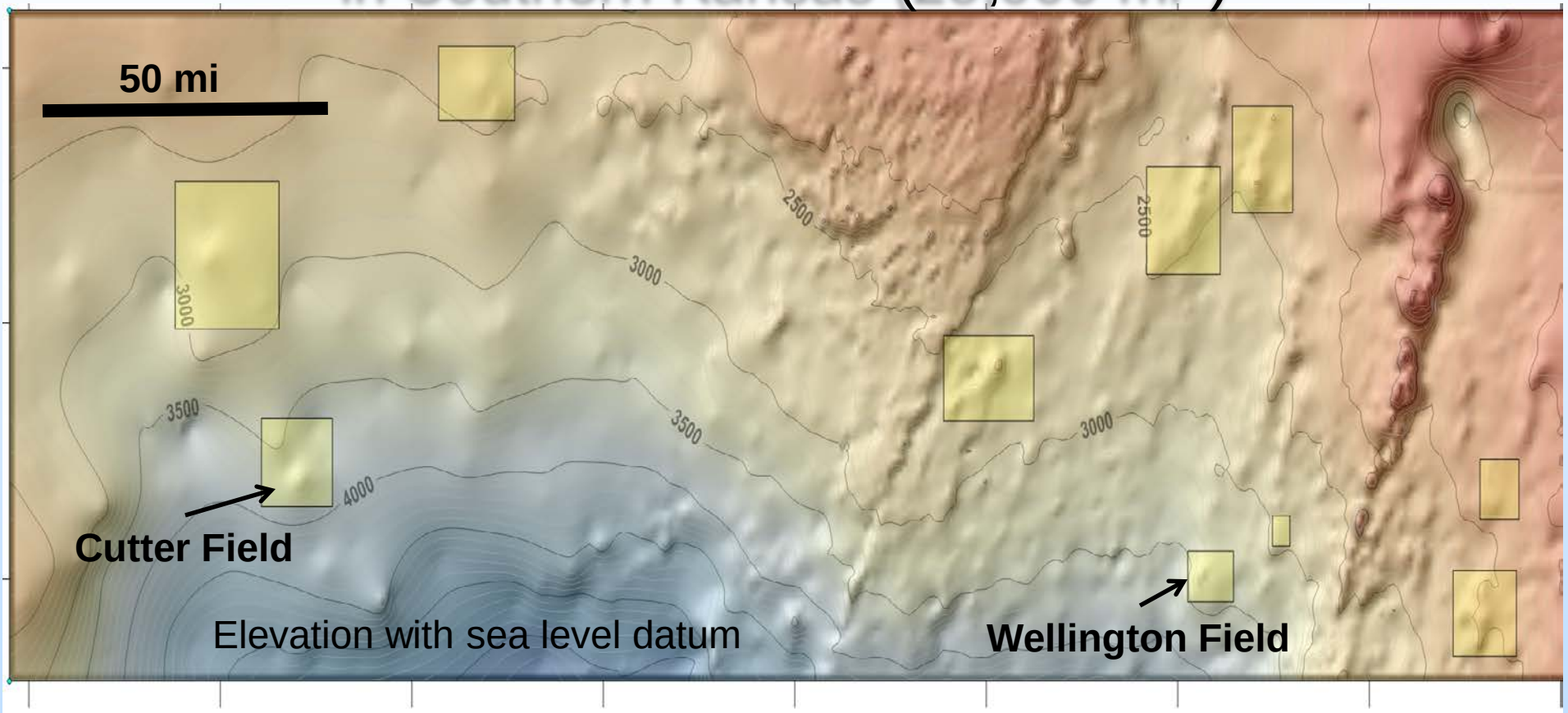
Predict CO_2 storage within ±30 percent



Cutter Field
Stevens Co.

Wellington Field
Sumner Co.

MegaModel (simulation) and 10 regional sites for commercial-scale simulation CO_2 Storage Capacity of the Arbuckle in Southern Kansas (25,000 mi^2)



- 10 local modeling sites (*yellow boxes*) including Cutter and Wellington fields
- Simulation of entire 25,000 mi^2 based on estimation of rock properties
- ***Predict CO_2 storage within ±30 percent***

MegaModel grid showing local refinement

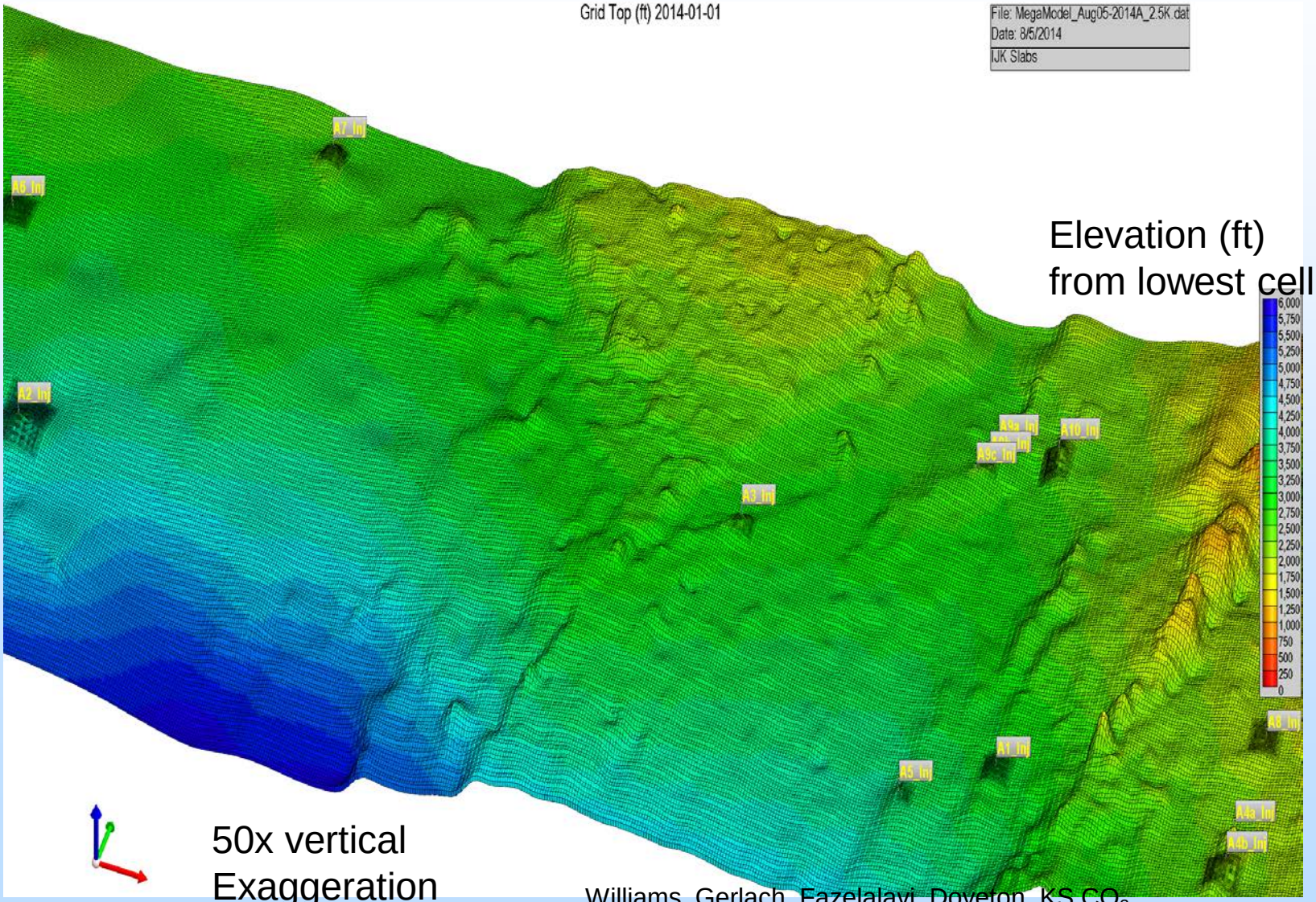
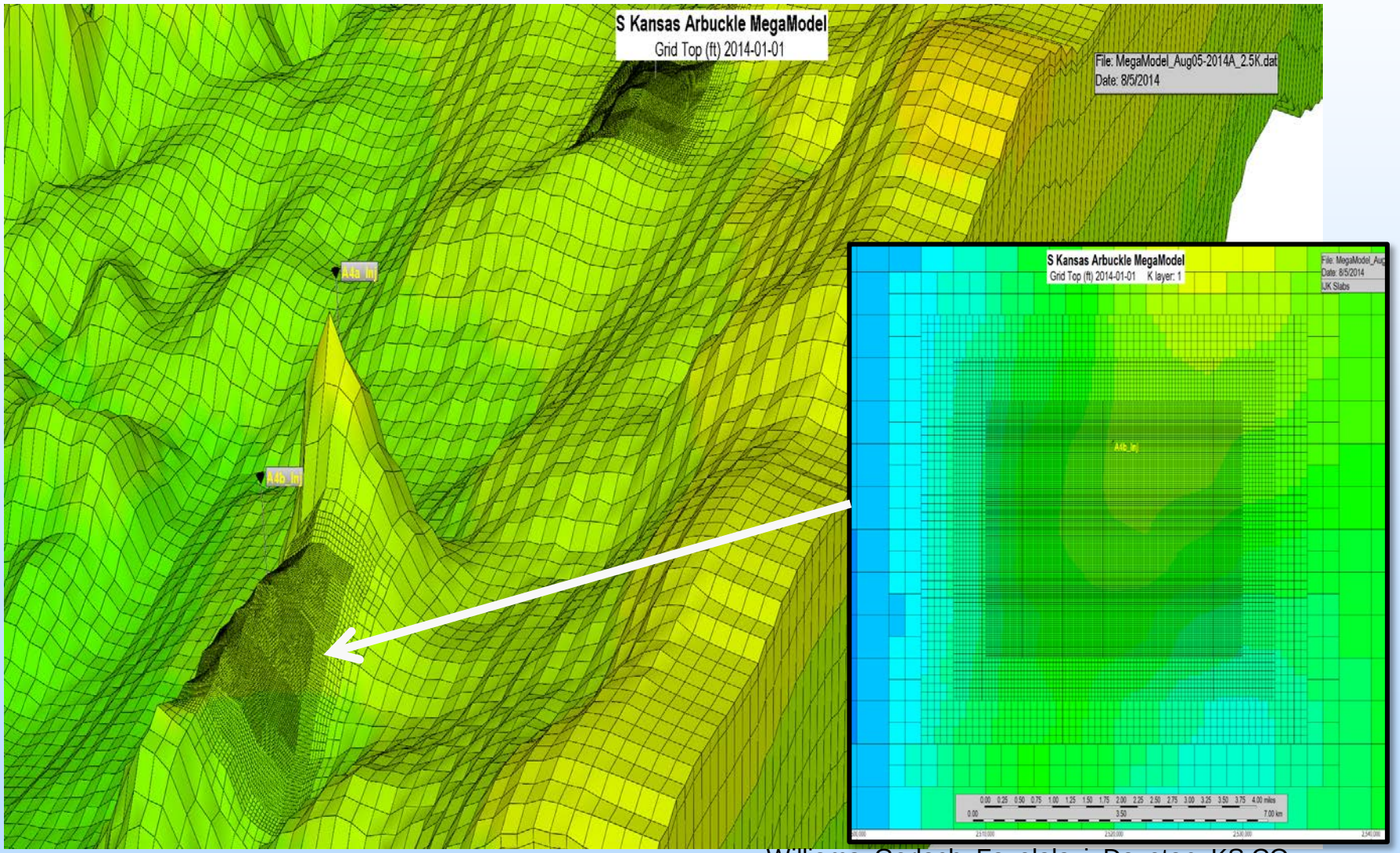
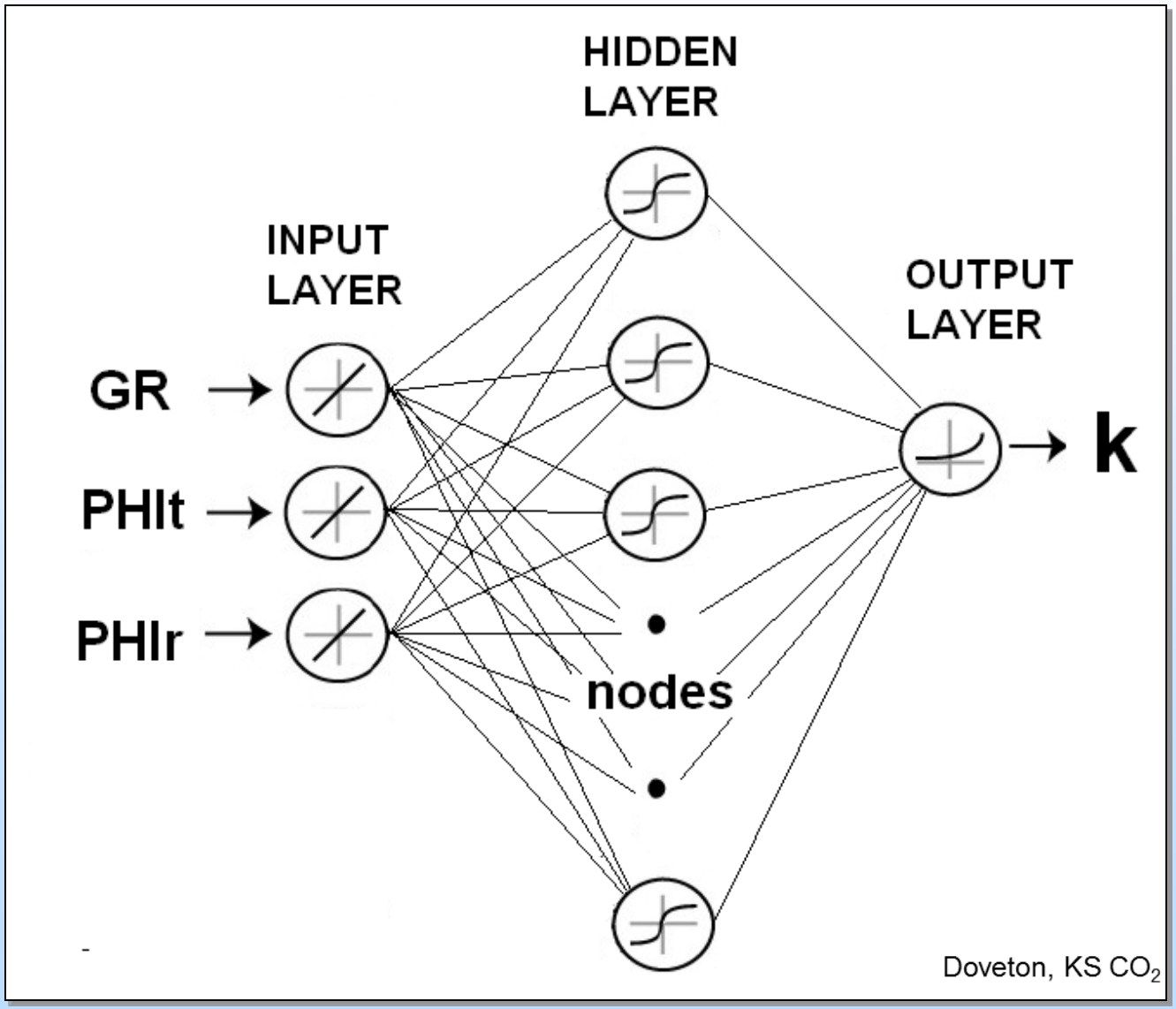


Illustration of local grid refinement, site 4b, SE Kansas



Neural network (NN) prediction of Arbuckle permeability from logs



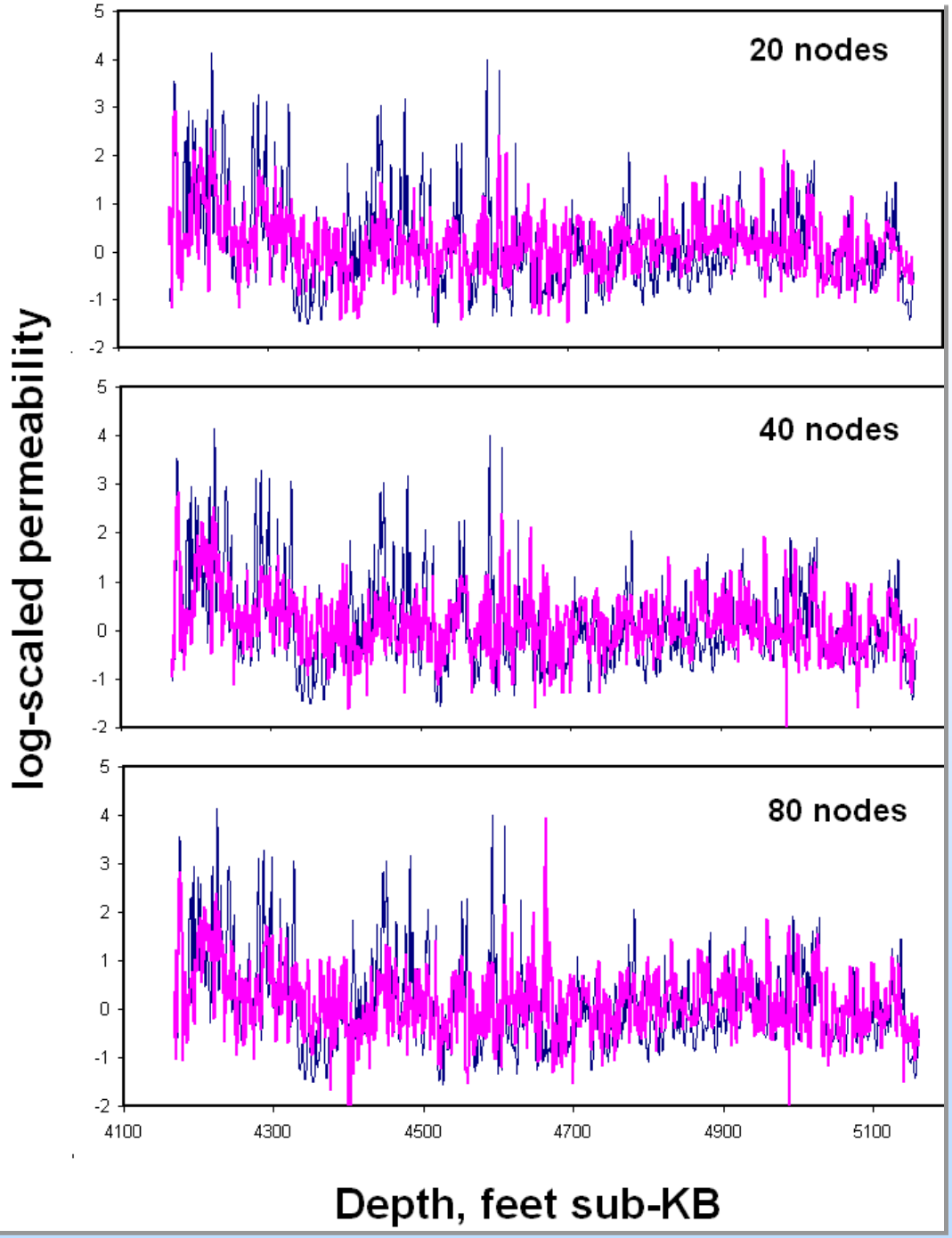
Comparison of permeability predictions in validation well (#1-28) by neural network with different numbers of nodes in the hidden layer

- **core-log calibrated**

$$k = 1014\left[\frac{a}{S_{wir}\phi_e} + b\right]^2 \frac{\phi_e^3}{(1-\phi_e)^2}$$

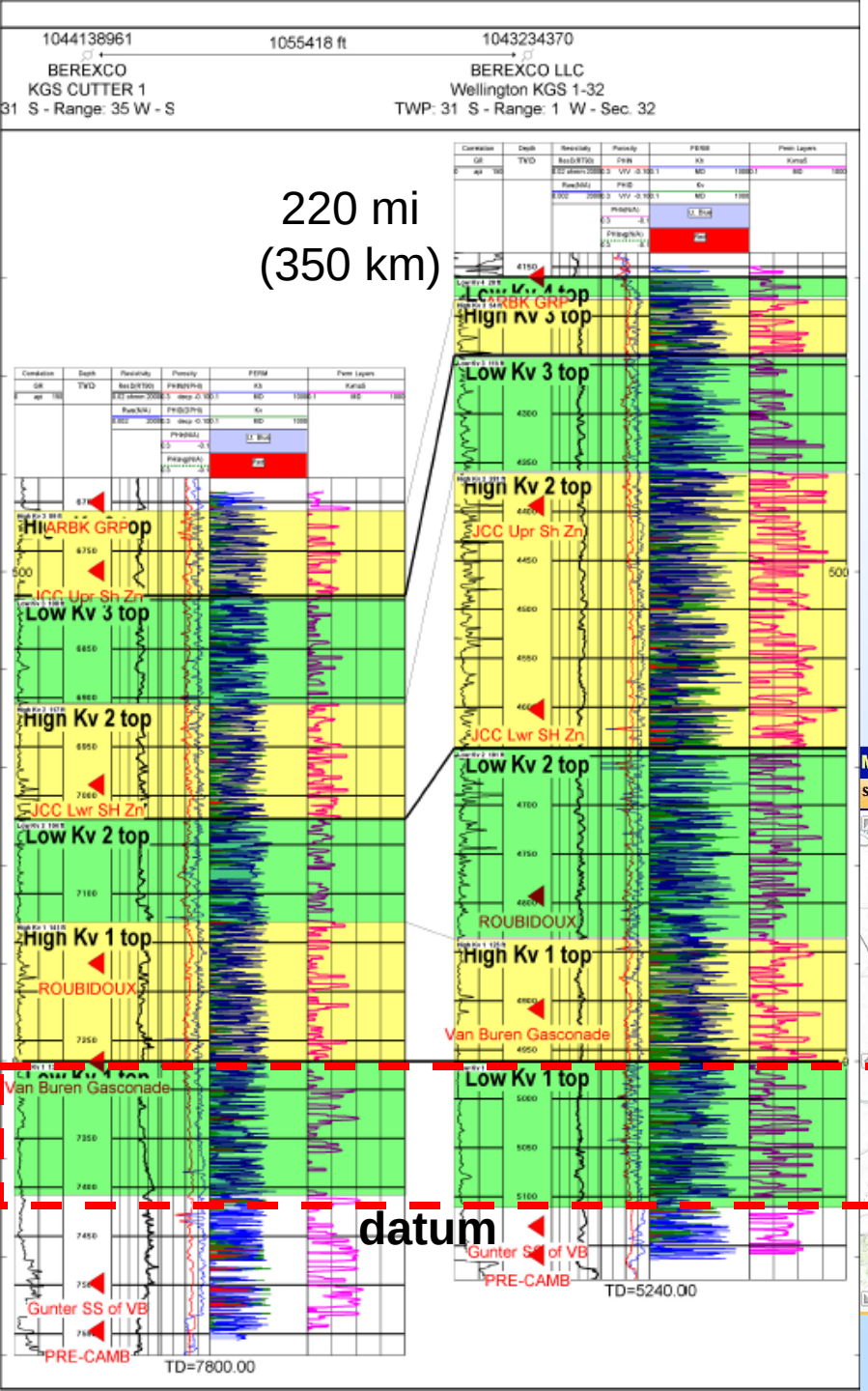
- **predicted**

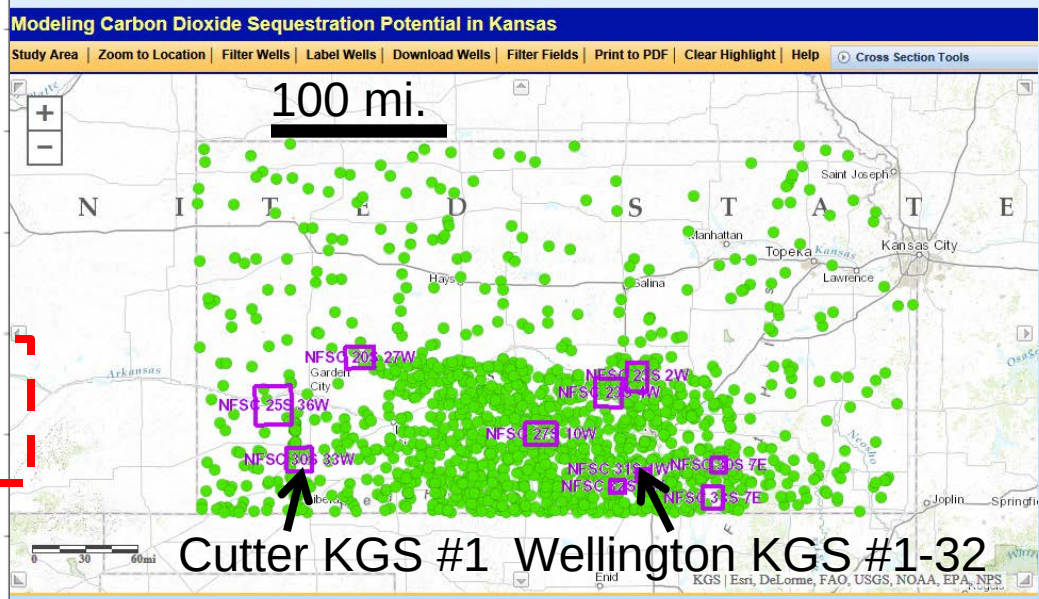
Neural network



Flow units & computed Kh & Kv in Arbuckle Group for Digital Type Wells (●)

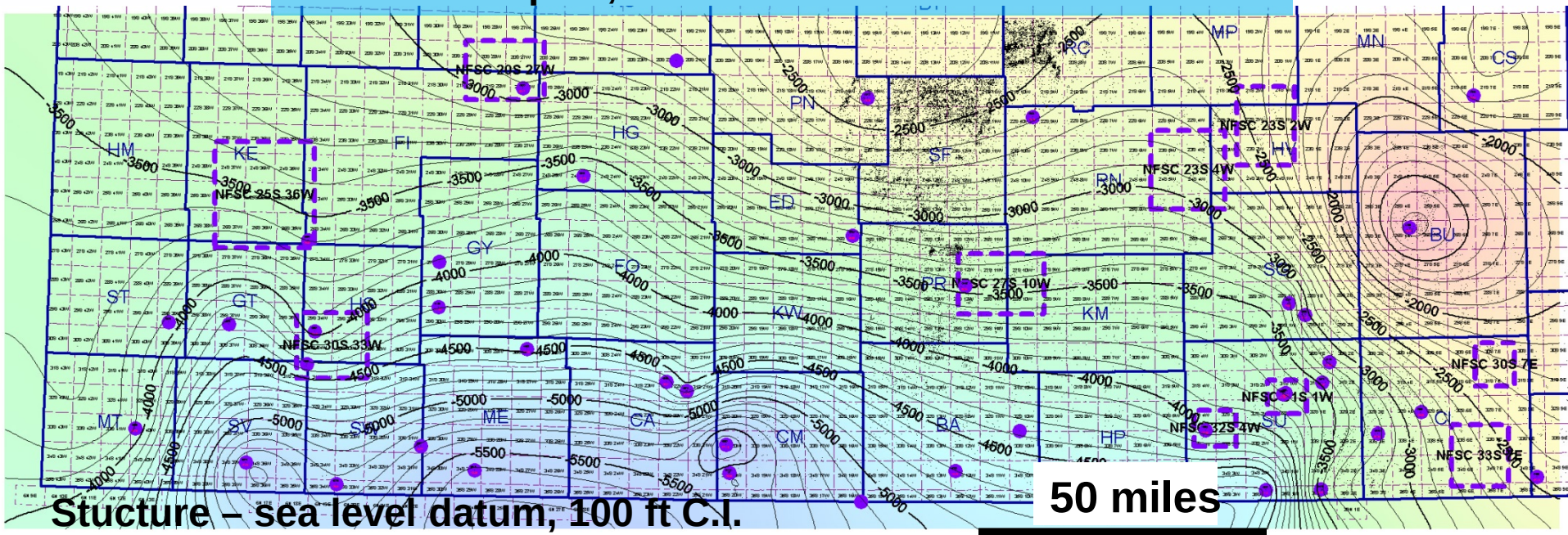
- Correlation of flow units
- Between Cutter and Wellington Fields (350 km)





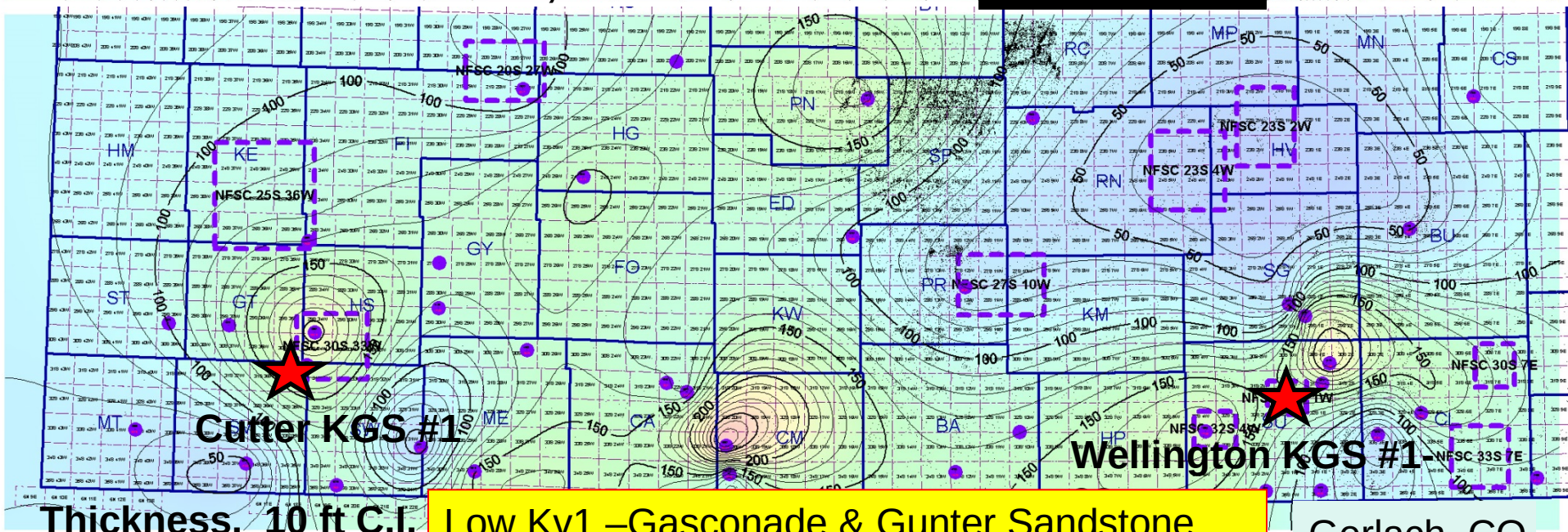
Williams, Gerlach, Fazelalavi, Doveton, KS CO_2

Lower Flow Unit For Regional Modeling in Arbuckle Group 25,000 mi² in southern Kansas



Stucture – sea level datum, 100 ft C.I.

50 miles



Cutter KGS #1

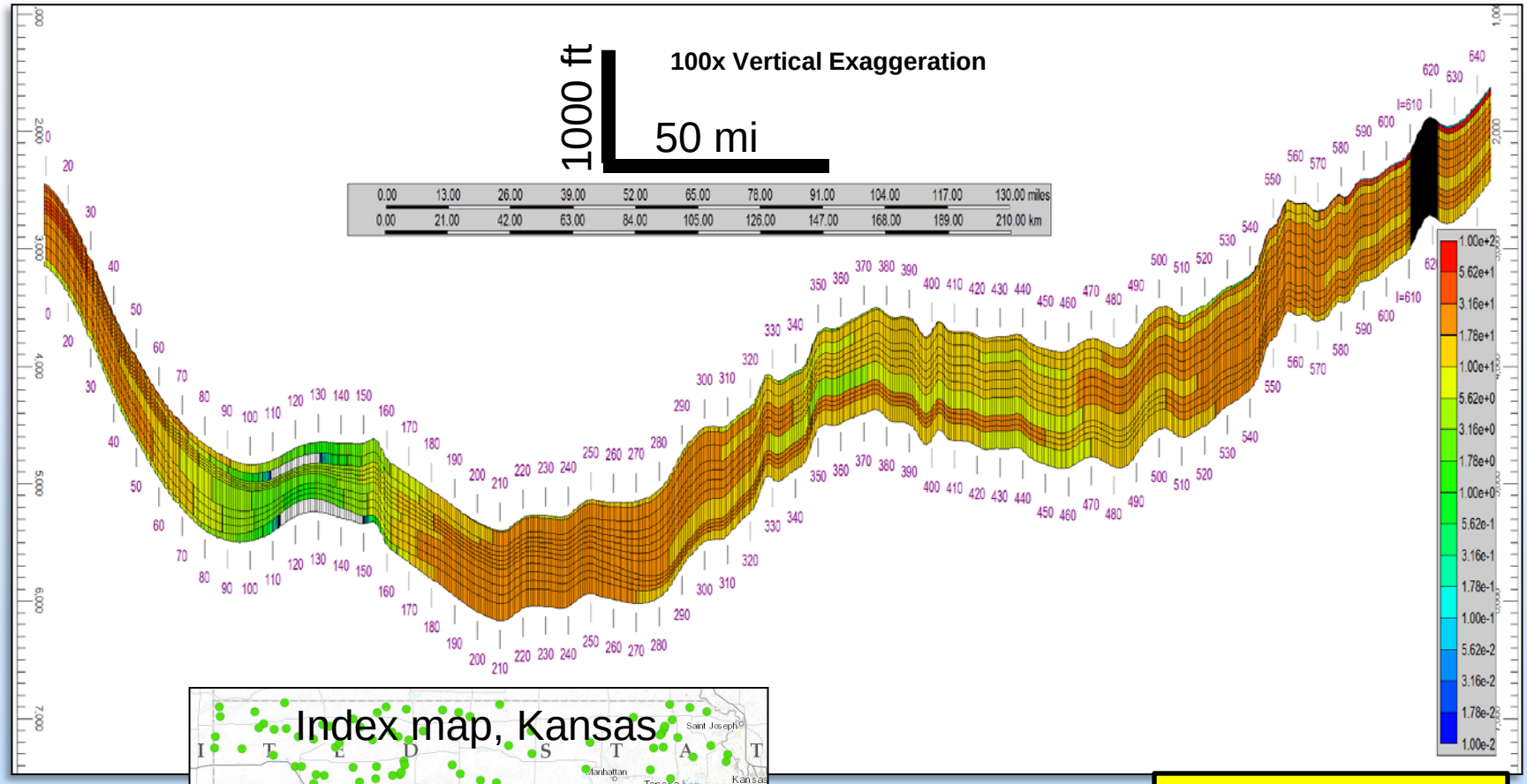
Wellington KGS #1

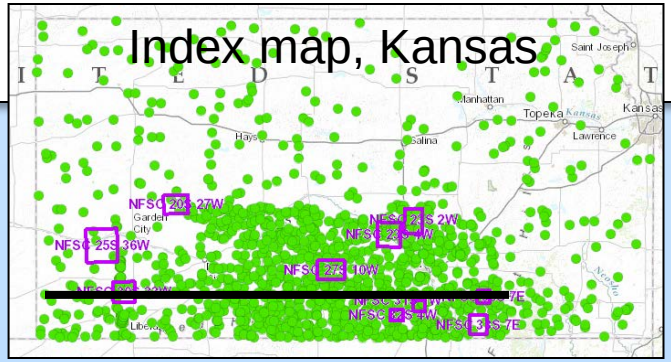
Thickness, 10 ft C.I.

Low Kv1 –Gasconade & Gunter Sandstone

Gerlach, CO_2

Structural cross section showing regional Arbuckle flow units, southern Kansas



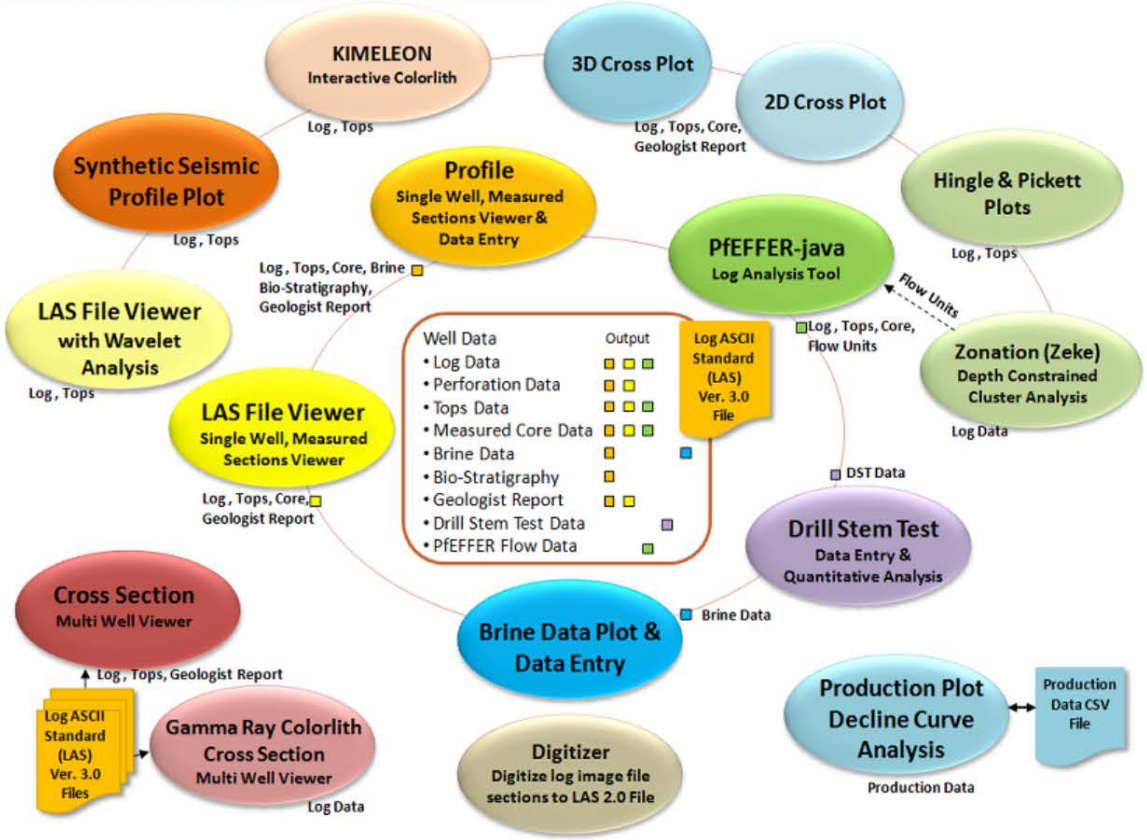


Permeability, md

Java Applets (freeware)
-- assist in geoengineering analysis of reservoirs
Predict geologic CO_2 storage capacity within ±30%

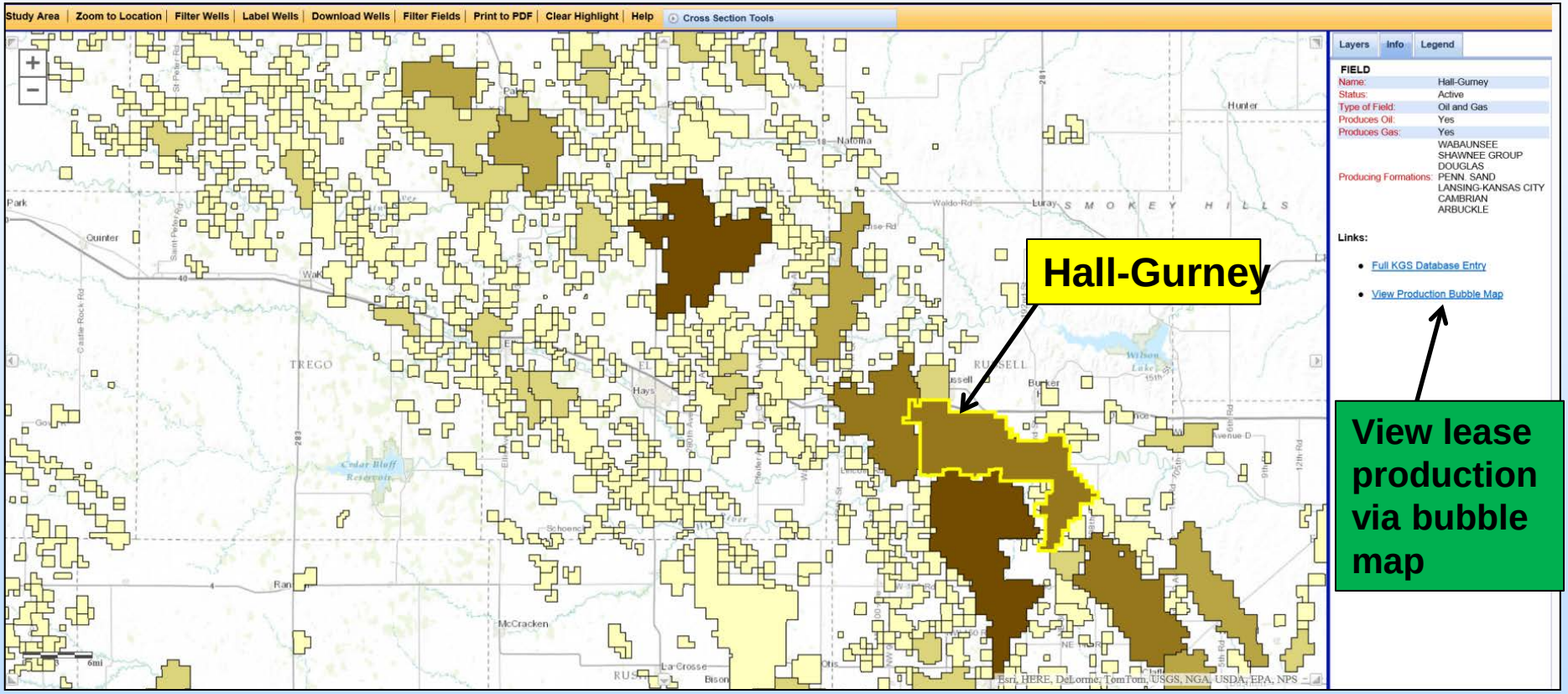
Standalone Applets

Select the bubble button below to display respective module.



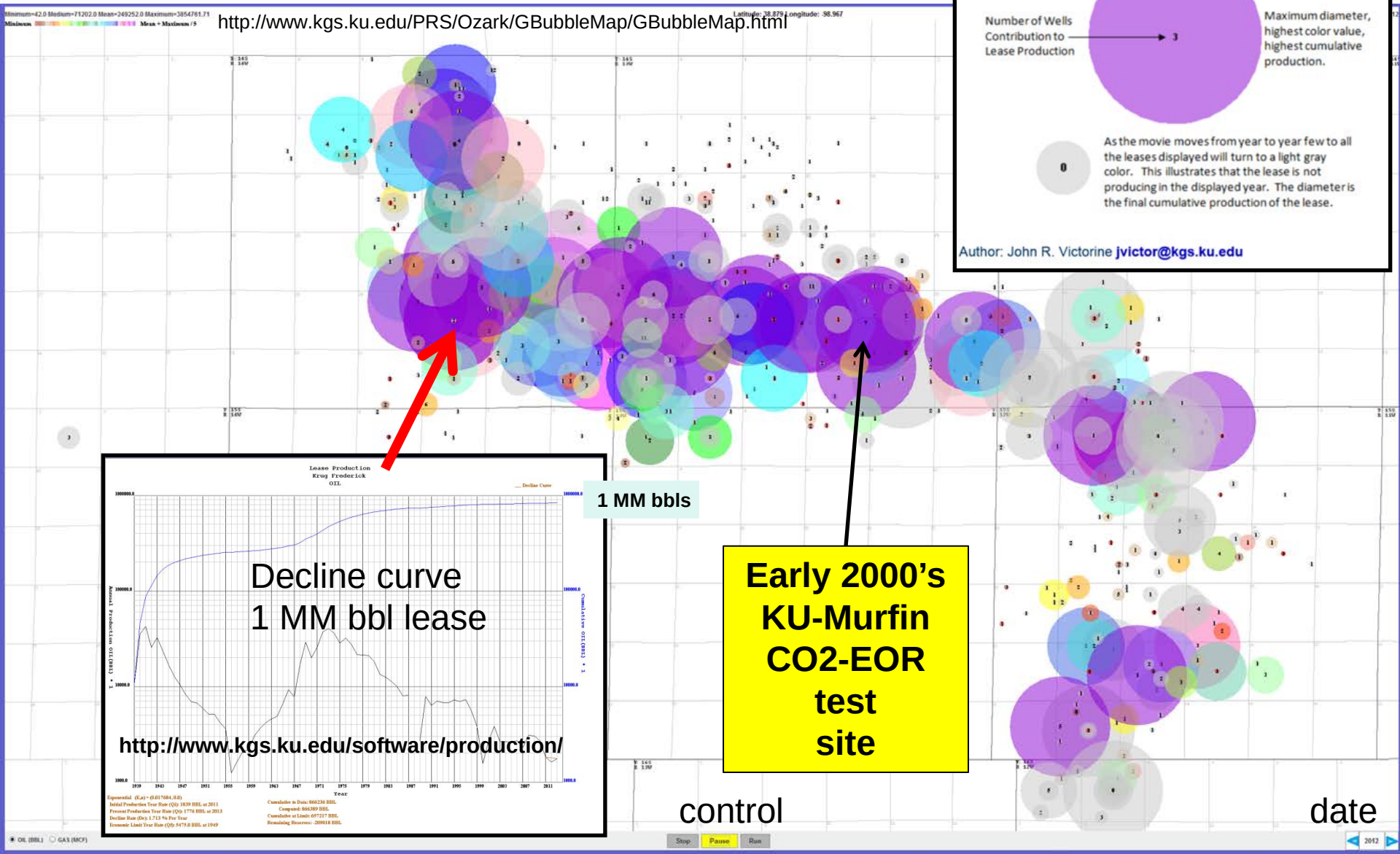
http://www.kgs.ku.edu/Gemini/Tools/Tools.html

CO_2 and oil & gas mapper cumulative oil fields with Upper Pennsylvanian oil production

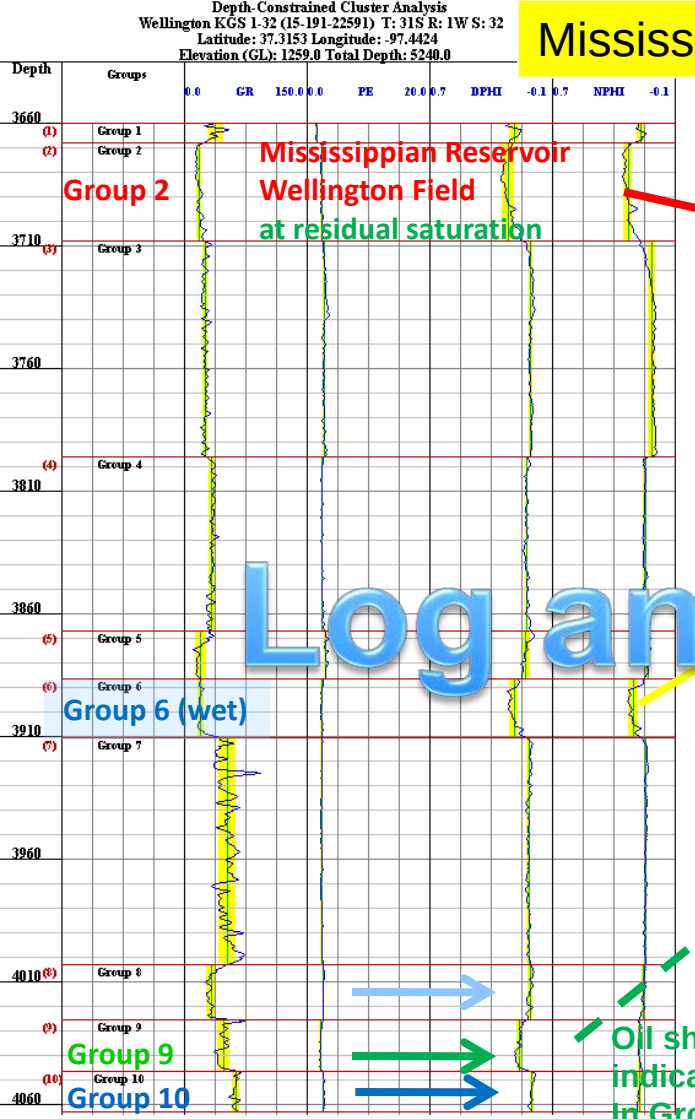


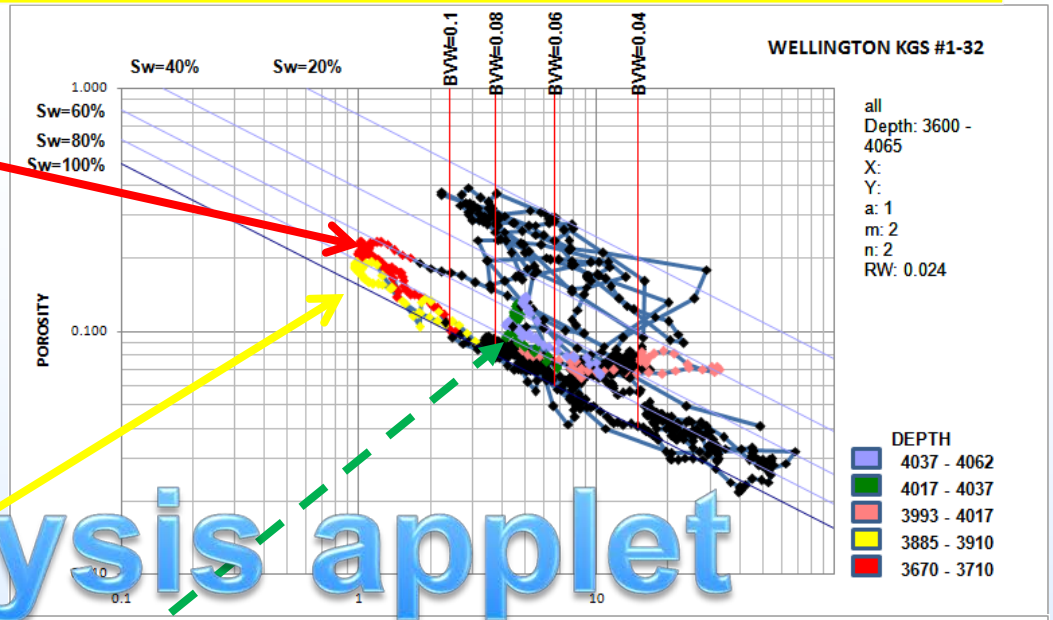
Northwest Kansas

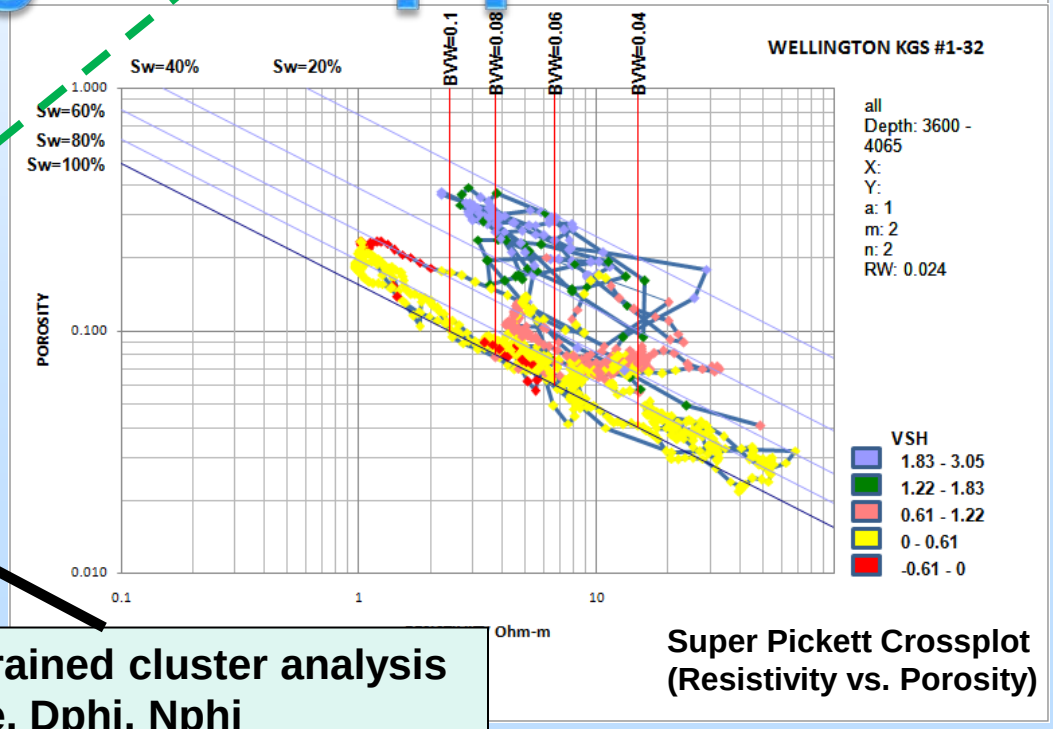
Cumulative Oil Lease Production Hall-Gurney Field, 2012



Mississippian Reservoir and Caprock in Wellington #1-32







Super Pickett Crossplot
(Resistivity vs. Porosity)

Log analysis applet

Cluster Analysis - Group Means
Number of Clusters = 10 R-squared = 17.12 %

Start	End	Group (edit)	GR	PE	DPHI	NPHI
3660.0	3667.5	Group 1	38.402	1.636	0.144	0.12
3668.0	3707.5	Group 2	18.669	2.449	0.182	0.201
3708.0	3795.5	Group 3	25.932	2.916	0.037	0.045
3796.0	3866.5	Group 4	34.478	2.543	0.063	0.091
3867.0	3886.0	Group 5	20.515	3.164	0.068	0.074
3886.5	3910.0	Group 6	20.78	2.474	0.147	0.165
3910.5	4002.5	Group 7	52.983	2.455	0.051	0.088
4003.0	4025.0	Group 8	33.827	2.744	0.041	0.102
4025.5	4046.0	Group 9	48.495	2.316	0.112	0.129
4046.5	4063.0	Group 10	63.334	2.786	0.03	0.126

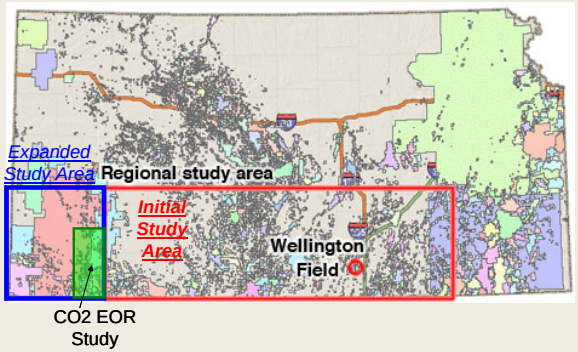
GR Gamma Ray
PE Photoelectric factor
DPHI Density porosity
NPHI Neutron porosity

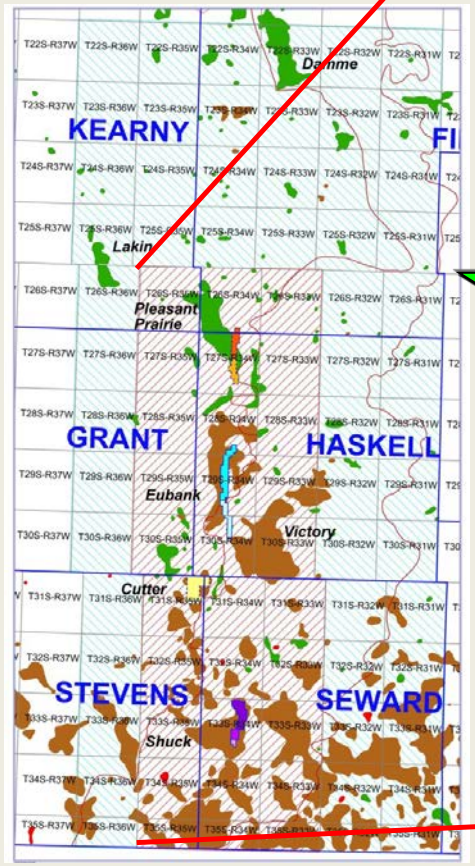
Depth-constrained cluster analysis using GR, Pe, Dphi, Nphi

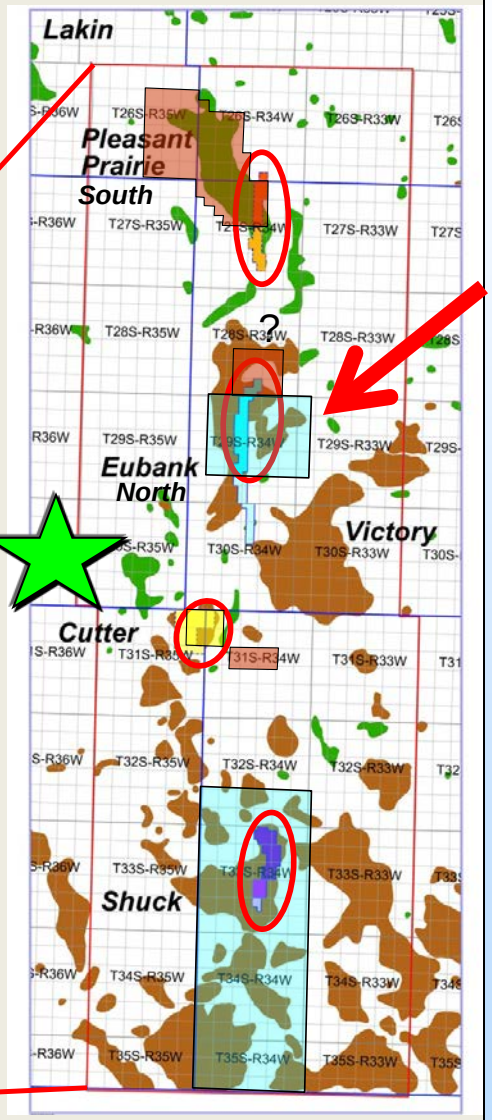
Southwest Kansas CO_2-EOR Initiative

Evaluate CO_2 sequestration potential in Arbuckle Group saline aquifer and CO_2-EOR in four fields in southwestern Kansas – Anadarko, Berexco, Cimarex, Glori, Elm III, Merit

Southwest Kansas CO2 Consortium (*Western Annex*)



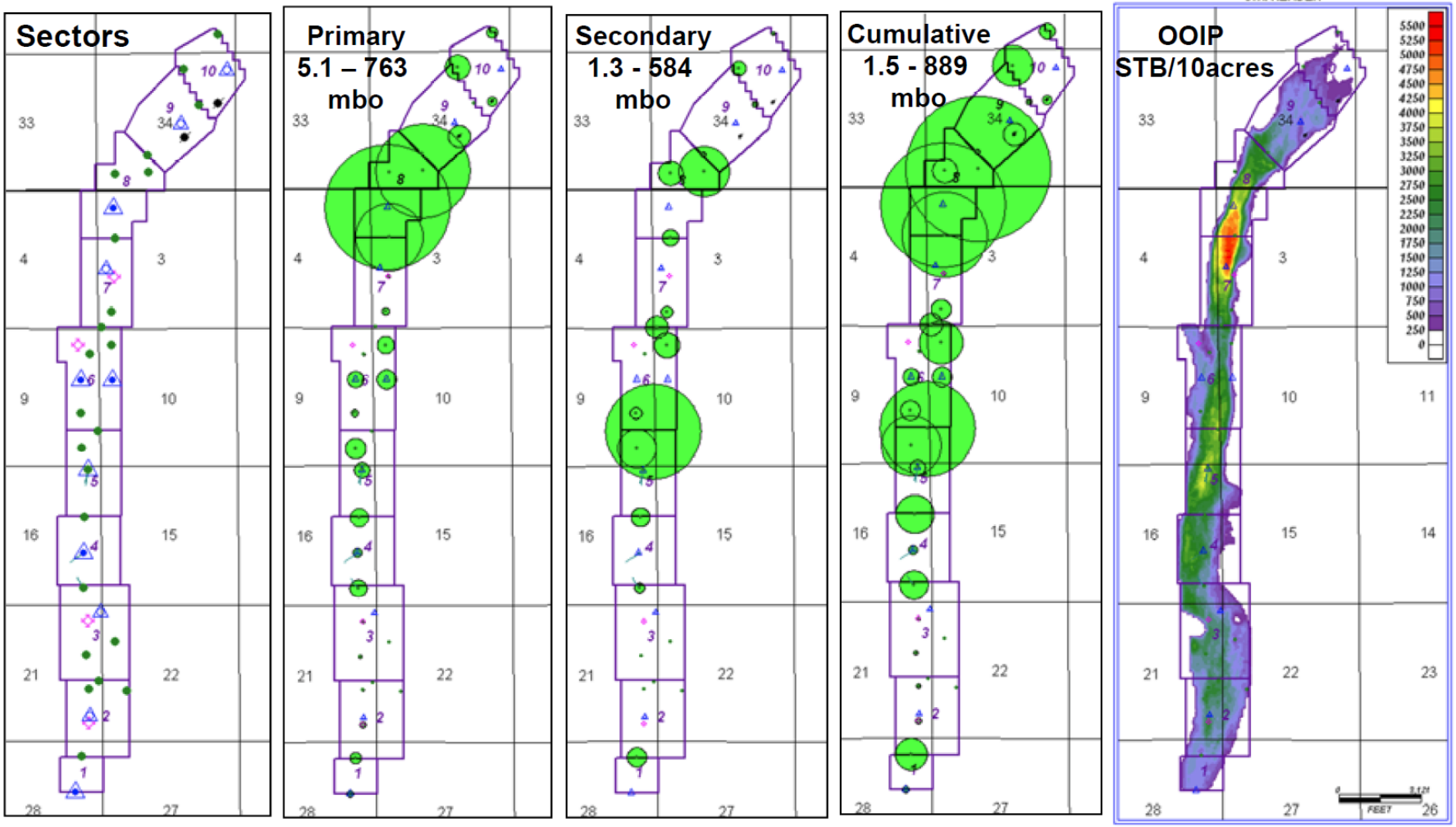




KANSAS GEOLOGICAL SURVEY
The University of Kansas

Oil production unevenly distributed in valleys

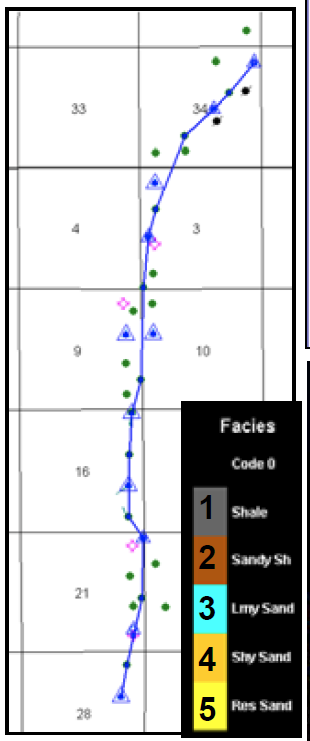
shown by well and OOIP in North Eubank unit

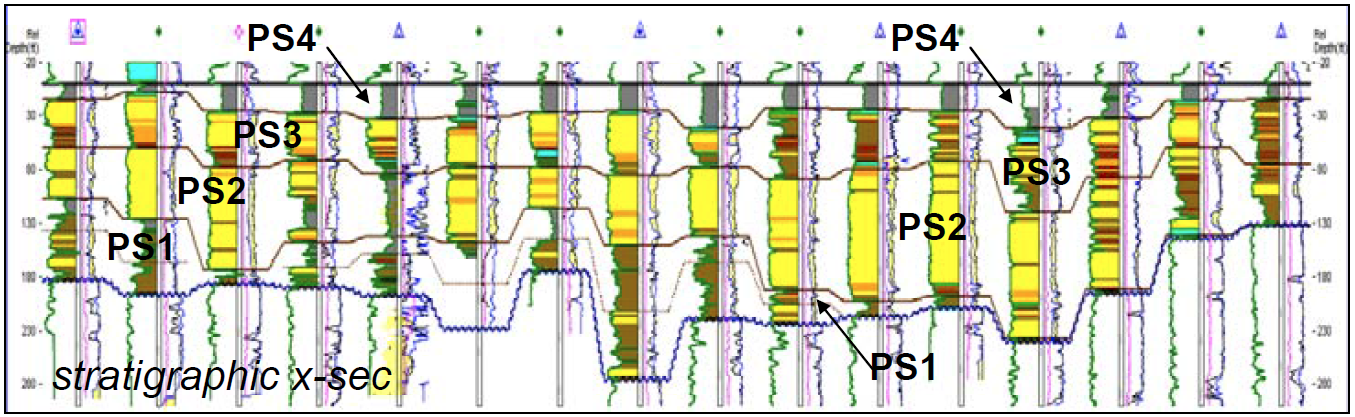


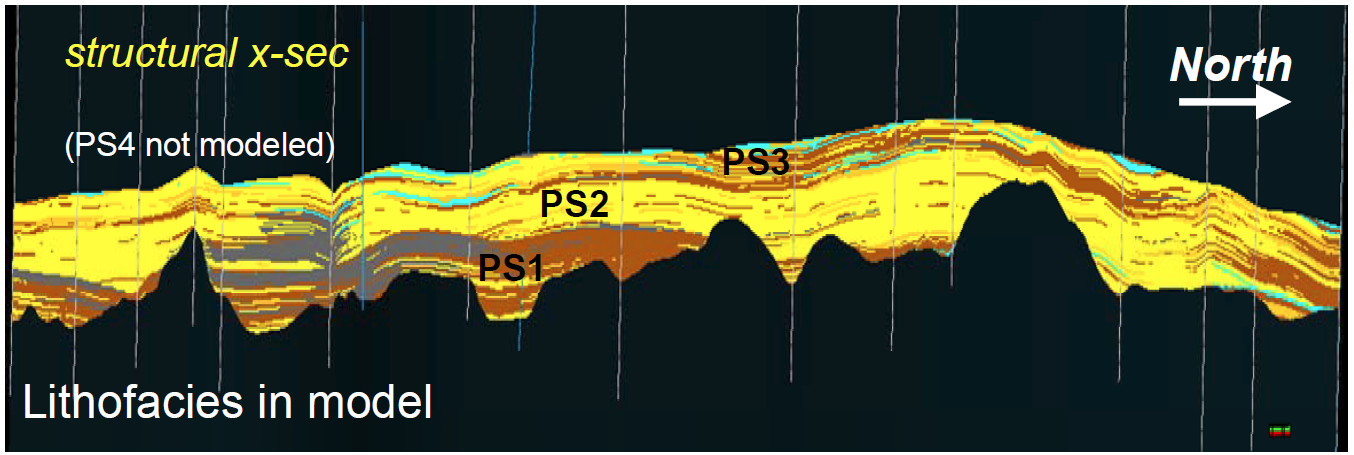
Dubois, Youle, and Williams, in prep.

Reservoir heterogeneity-- stratigraphically complex

-- Four Parasequences in North Eubank unit







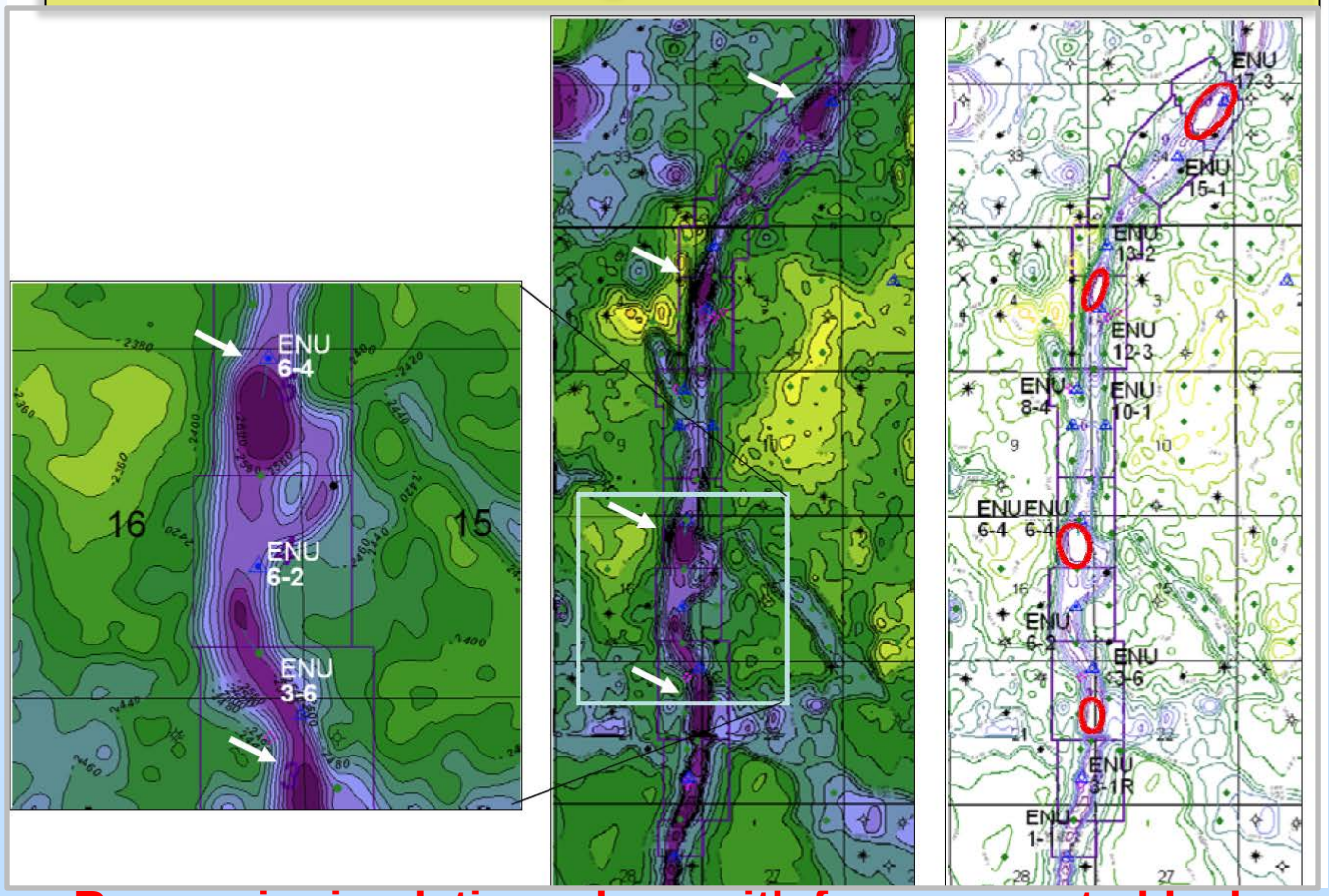
Sandstone = yellow; Sandy shale = brown; Gray = shale
Length of section ~ 5 miles

Dubois, Youle, and Williams, in prep.

1. By 2011 water injection exceeded production by approximately one million barrels per year.
2. The reservoir system was significantly under-pressured, having an original BHP of 1572 psig.
3. A normal BHP would be 2350 psi (5500 ft deep x 0.43 psi/ft).
4. Rock fracture pressure is likely to be approximately 3500 psi if the fracture gradient is 0.65 psi/ft.
5. Fractures and conduits were not open until reservoir pressure exceeded approximately 2500 psi

Seismic depth maps, Top Meramec and location of probable sinkholes in North Eubank unit

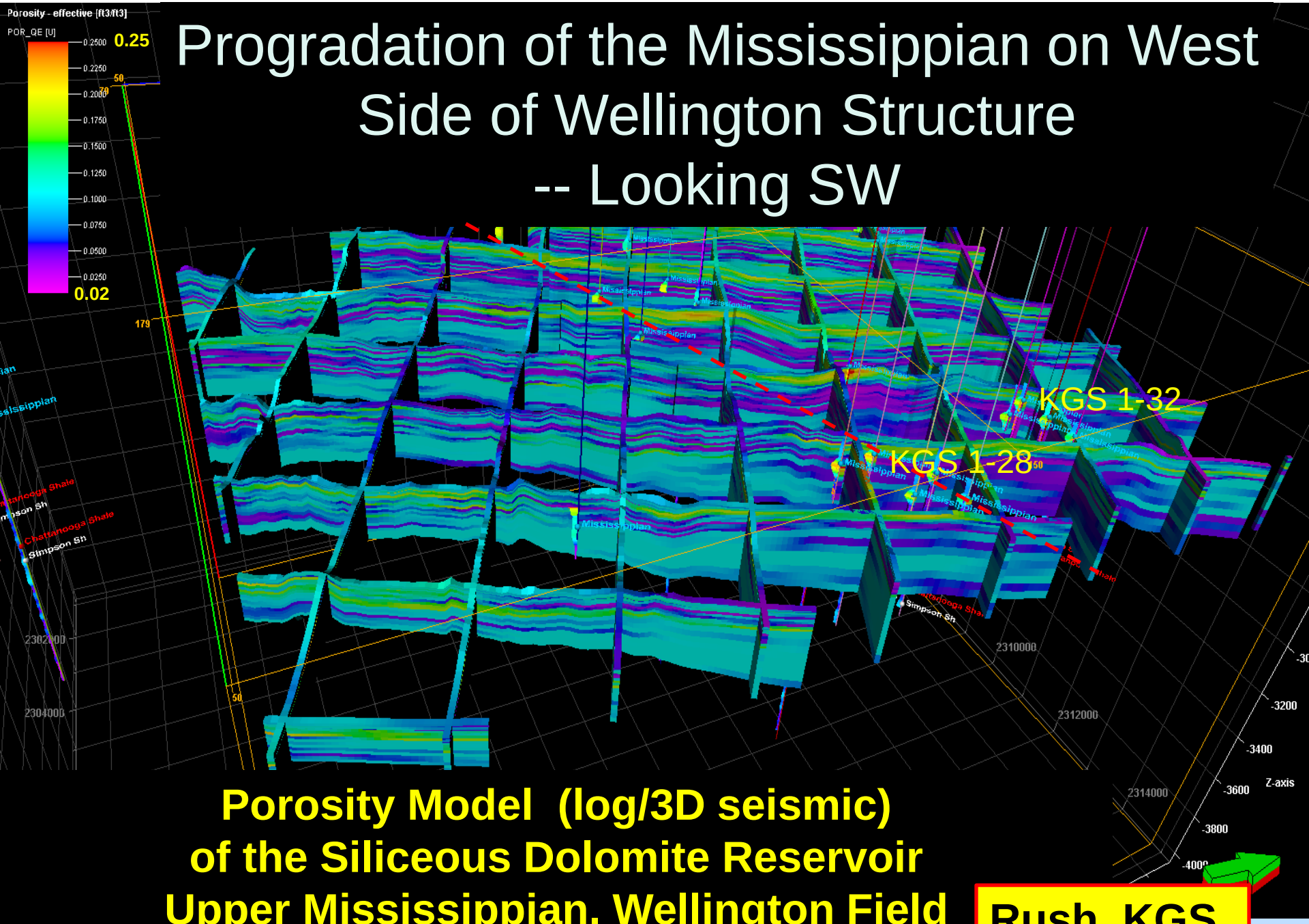
--- sinkholes possibly responsible for loss of injected water → **Will limit CO_2 injection pressures**



Reservoir simulations done with four suspected leak points

Dubois, Youle, and Williams, in prep.

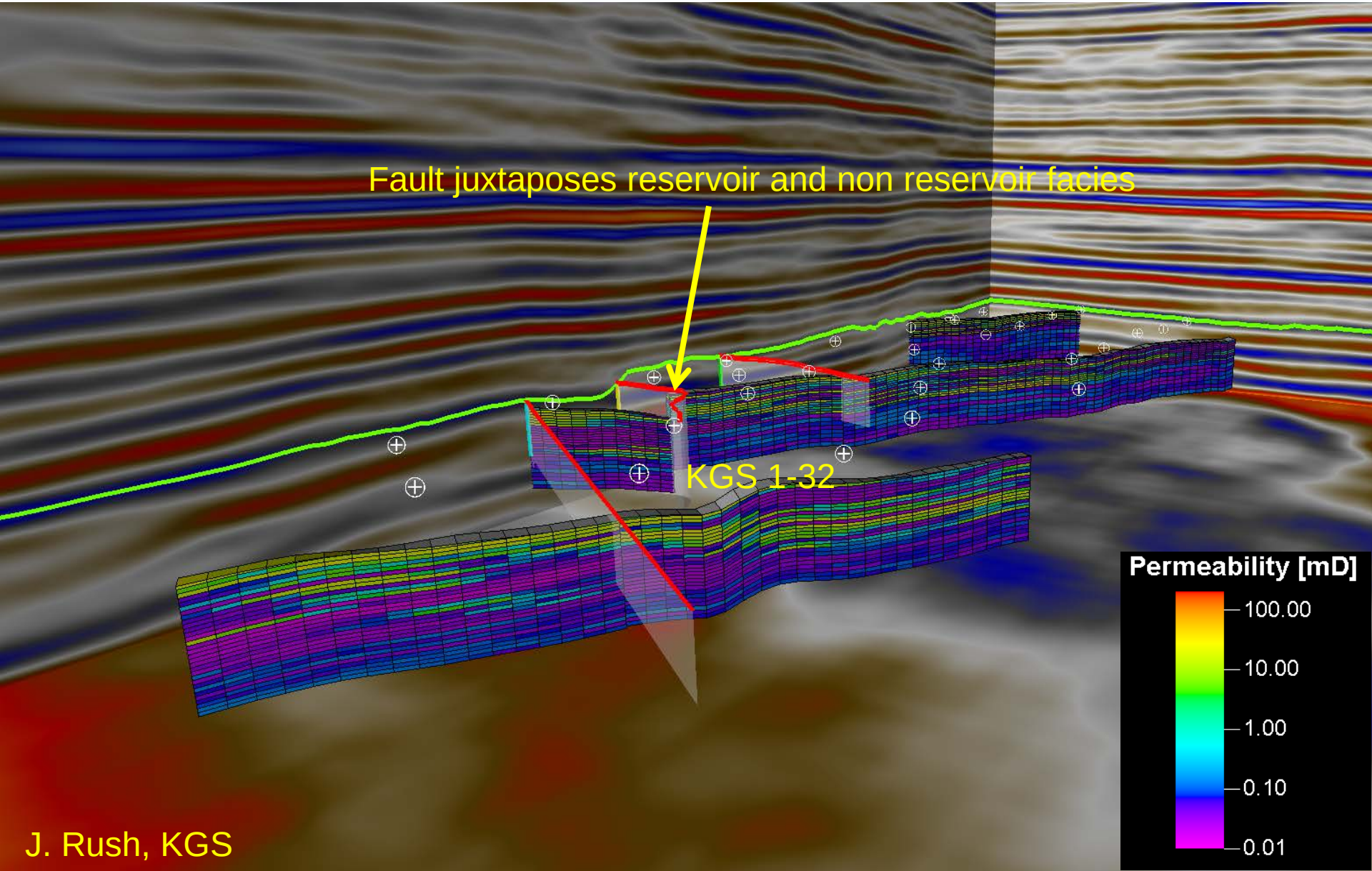
Progradation of the Mississippian on West Side of Wellington Structure -- Looking SW



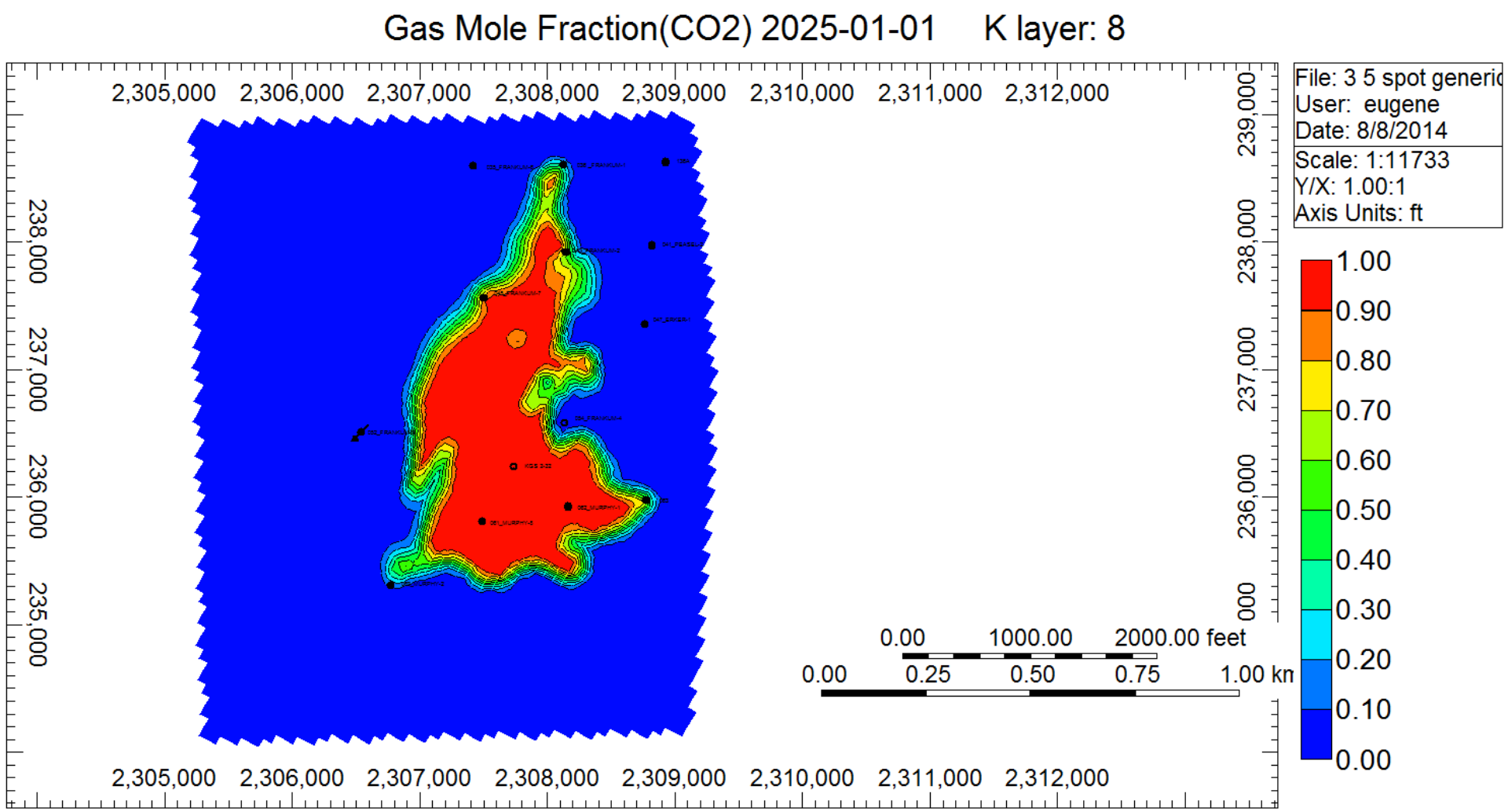
Porosity Model (log/3D seismic) of the Siliceous Dolomite Reservoir Upper Mississippian, Wellington Field

Rush, KGS

Wellington Field looking NW

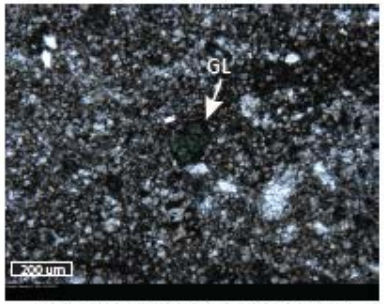


CO2 plume from simulation of small scale field test injection (26,300 tonnes)

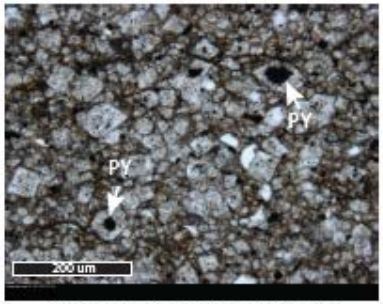


E. Holubnayak, KGS

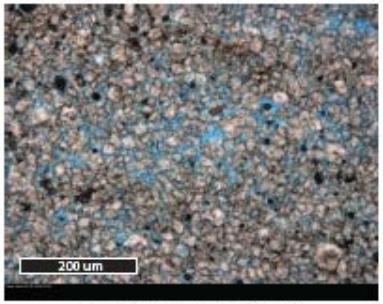
Diagenetic facies and textures



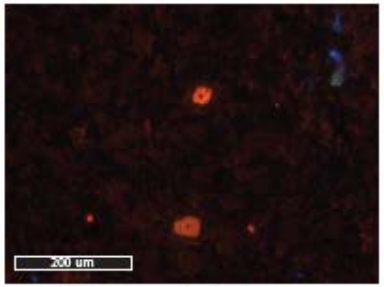
Argillaceous dolomite (WL 1-32, 4026.4 ft)



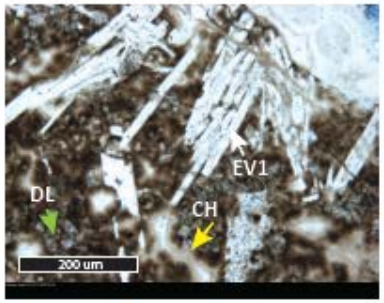
Argillaceous dolomite (WL 1-32, 4049 ft)



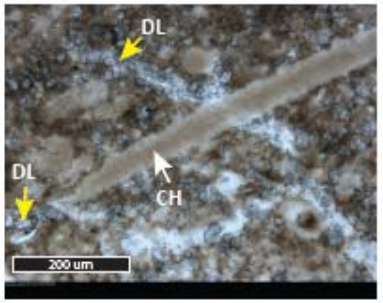
Dolomite (WL 1-32, 3892.25 ft)



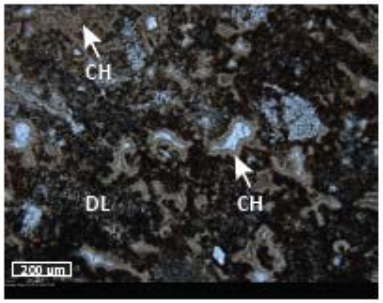
Dolomite on cathodoluminescence (WL 1-32, 3807 ft)



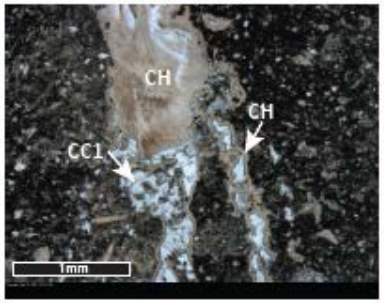
Nodular chert (WL 1-32, 3680.7 ft)



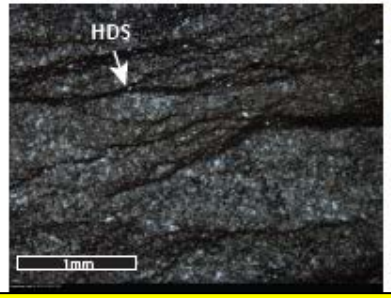
Nodular chert (WL 1-32, 3671.8 ft)

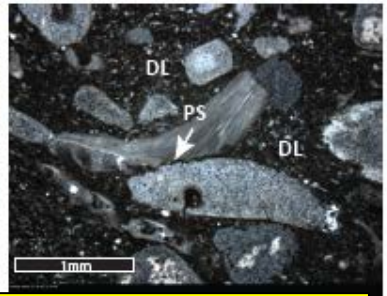


Nodular cherty dolomite (WL 1-32, 3680.7 ft)

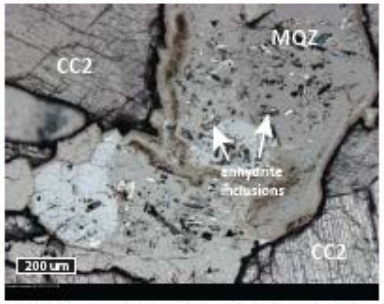


Argillaceous dolomite (WL 1-32, 3867 ft)

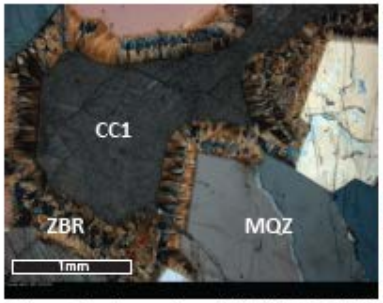




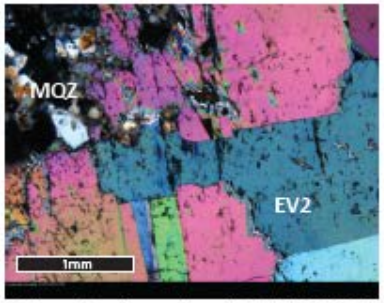
Silica-replaced evaporite nodule (WL 1-32, 4049.4 ft)



Silica-replaced evaporite nodule (WL 1-32, 3790 ft)



Silica-replaced evaporite nodule (WL 1-32, 3857.5 ft)

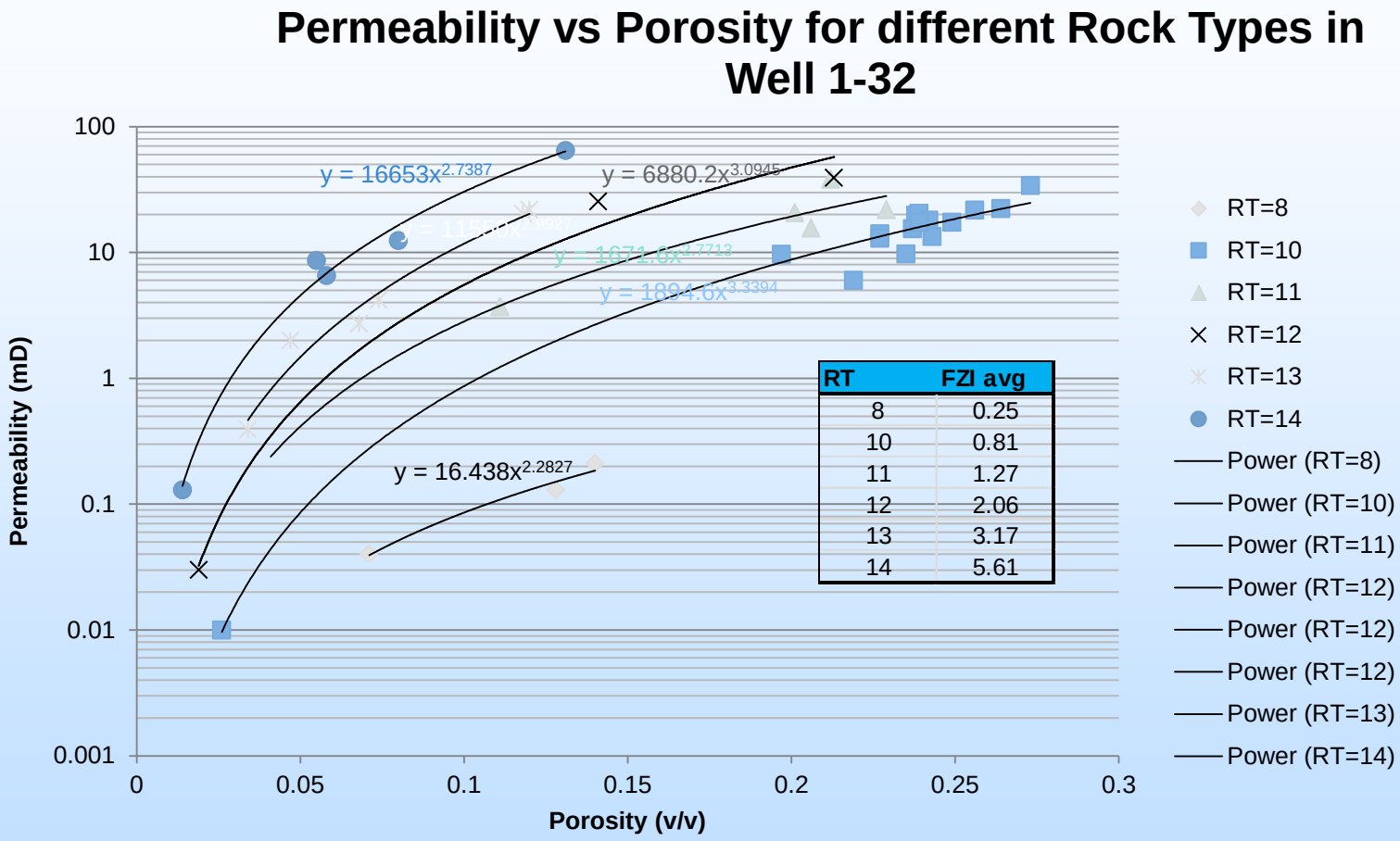


Silica-replaced evaporite nodule (WL 1-32, 3689 ft)

Petrography, Berexco Wellington KGS #1-32
Thin sections from the Mississippian oil reservoir
-- dolomite, silica, minor amounts of anhydrite, organic matter, pyrite

Luis G. Montalvo 1, Luis Gonzalez 1, Lynn Watney 2, 2014,
1) Department of Geology, University of Kansas, Lawrence, KS, 2) Kansas Geological Survey

Upper Mississippian Reservoir Quality



Schlumberger

Techlog Wellbore Software Platform

M. Fazelalavi, KGS

Accomplishments to Date

- KGS Milestone 1.2: Acquire/analyze seismic, geologic and engineering data - Wellington field -- COMPLETED
- KGS Milestone 1.3: Develop initial geomodel for Wellington field -- COMPLETED
- KGS Milestone 1.4: Locate and initiate drilling of Well #1 at Wellington field -- COMPLETED
- KGS Milestone 2.1: Complete Well #1 at Wellington - DST, core, log, case, perforate, test zones -- COMPLETED
- KGS Milestone 2.2: Complete Well #2 at Wellington - Drill, DST, log, case, perforate, test zones -- COMPLETED
- KGS Milestone 2.3: Update Wellington geomodels - Arbuckle & Mississippian -- COMPLETED
- KGS Milestone 2.4: Evaluate CO_2 Sequestration Potential of Arbuckle Group Saline Aquifer - Wellington field -- COMPLETED
- KGS Milestone 3.1: CO_2 sequestration & EOR potential - Wellington field – 98%
- KGS Milestone 3.2: Characterize leakage pathways - Risk assessment area -- COMPLETED
- KGS Milestone 3.3: Risk assessment related to CO_2-EOR and CO_2-sequestration -- COMPLETED
- KGS Milestone 3.4: Regional CO_2 Sequestration Potential - 33 Counties – 99%

Summary

- **Key findings**
  1. Initial estimates of CO_2 P10 & P90 storage in the Arbuckle aquifer are being refined using dynamic modeling at 10 regional sites and single MegaModel spanning southern Kansas.
  2. Use of a reservoir approach to assessing regional storage should improve the estimation of geologic CO_2 storage capacity to within ±30%.
  3. Coring, extensive fluid sampling, well testing, and multicomponent 3D seismic provide a rich basis in Wellington and Cutter fields to serve as calibration sites for the regional models.
  4. Field studies serve as potential template for commercial deployment of CCS in Kansas with an oil field overlying a thick saline aquifer on a structure suited for staged carbon storage that can be accomplished by the local petroleum industry.
  5. Calibration was accomplished with multiple, independent methods that addressed the reservoirs at all scales.
  6. Approaches used by petroleum industry permitted extending key reservoir properties → vertical and horizontal permeability→ rational flow units → closely conforming with regional stratigraphic correlations.

- **Future Plans**
  - Complete the final report.

Appendix

– These slides will not be discussed during the presentation, but are mandatory

ORGANIZATIONAL STRUCTURE

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

DOE project -- DE-FE002056

Principal Investigators

Jason Rush -- Joint PI
W. Lynn Watney - Joint PI

UNIVERSITY OF KANSAS

Kansas Geological Survey

Co-Principal Investigators

Kerry D. Newell -- stratigraphy, geochemistry
Jason Rush -- Petrel geomodeling and data integration
Richard Miller -- geophysics
John Doveton-- log petrophysics and core-log modeling
Jianghai Xia -- gravity-magnetics modeling & interpretation
Marios Sophocleous --geohydrology

Key Personnel

John Victorine -- Java web app development
David Laflen -- manage core & curation
Mike Killion -- modify ESRI map service for project
Jennifer Raney -- asst. project manager
Debra Stewart, Dan Suchy -- data management
Yevhen 'Eugene' Holubnyak, Petroleum Engineer
Fatemeh "Mina" FazelAlavi, Engineering Research Assistant

KU Department of Geology

Co-Principal Investigators

Evan Franseen --sedimentology, stratigraphy
Robert Goldstein -- diagenesis, fluid inclusion
David Fowle -- reactive pathways, microbial catalysis
Jennifer Roberts -- reactive pathways, microbial catalysis
George Tsoflias -- geophysics

Grad Research Assistants

Aimee Scheffer (graduated) -- biogeology & geochemistry
Breanna Huff -- biogeology
Christa Jackson -- biogeology and geochemistry
Ayrat Sirazhiev (graduated) -- geophysics
Yousuf Fadolalkarem -- geophysics
Brad King -- diagenesis

SUBCONTRACTS

Berexco, Beredco Drilling -- *Wichita, KS*

Wellington Field access; drilling, coring, completion and testing; modeling and simulation

Key Personnel

Dana Wreath - manager, reservoir and production engineer
Randy Koudele - reservoir engineer
Bill Lamb - reservoir engineer

Bittersweet Energy, Inc., *Wichita, KS*

Tom Hansen, Principal, Wichita, Geological Supervision - regional data, Arbuckle hydrogeology
Paul Gerlach -- regional data acquisition, 2 yrs.
Larry Nicholson -- regional data acquisition, 2 yrs.
Anna Smith -- regional data acquisition, 2 yrs.
Ken Cooper, Petrotek Engineering, Littleton, CO- engineer, well injection, hydrogeology
John Lorenz, Scott Cooper, FractureStudies, Edgewood, NM -- core fracture study

Kansas State University

Seismic and Geochemical Services

Co-Principal Investigators

Saugata Datta -- reactive pathways and reaction constants
Abdelmoneam Raef -- seismic analysis and modeling

Grad Research Assistants

Robin Barker (graduated)
Derek Ohl - seismic analysis and modeling
Randi Isham -- seismic
Brent Campbell - aqueous geochemistry

Southwest Kansas CO2 EOR Initiative - Chester Morrow

Martin Dubois, IHR, LLC -- team lead, geomodeling
John Youle, Sunflower Energy -- core and depositional models
Ray Sorenson, consultant -- data acquisition and advising
Eugene Williams, Williams Engineering -- reservoir modeling

Services

LOGDIGI, LLC, *Katy, TX* - wireline log digitizing
David G. KOGER, *Dallas, TX* - remote sensing data and analysis
Weatherford Laboratories, *Houston, TX* -- core analyses
CMG - Simulation Services, *Calgary, Alberta* --greenhouse gas simulation and software
Halliburton, *Liberal, KS* -- wireline logging services
Hedke-Saenger Geoscience, LTD., *Wichita, KS* - geophysical acquistion, interpret & design
Susan E. Nissen, *McLouth, KS* -- Geophysical Consultant, volumetic curvature
Lockhart Geophysical, *Denver, CO* -- acquis & interpret 2D shear wave, gravity & mag
Fairfield Industries, Inc., *Denver, CO* -- 2D, 3D multicomponent seismic processing
Paragon Geophysical Services, *Wichita, KS* -- 3D seismic acquisition
Echo Geophysical, *Denver, CO* -- 3D seismic processing
Converging Point - QC seismic acquisition
Noble Energy, *Houston, TX; Denver, CO* -- collaborating co., fields adjoining Wellington

Gantt Chart

Bibliography

List peer reviewed publications generated from project per the format of the examples below

- Journal, one author:
  - Gaus, I., 2010, Role and impact of CO2-rock interactions during CO2 storage in sedimentary rocks: International Journal of Greenhouse Gas Control, v. 4, p. 73-89, available at: XXXXXXX.com.
- Journal, multiple authors:
  - MacQuarrie, K., and Mayer, K.U., 2005, Reactive transport modeling in fractured rock: A state-of-the-science review. Earth Science Reviews, v. 72, p. 189-227, available at: XXXXXXX.com.
- Publication:
  - Bethke, C.M., 1996, Geochemical reaction modeling, concepts and applications: New York, Oxford University Press, 397 p.