DOE F 4600.2
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U.S. Department of Energy
FEDERAL ASSISTANCE REPORTING CHECKLIST AND INSTRUCTIONS FOR RD&D PROJECTS

1. Identification Number:	2. Program/Project Title:
DE-FE0006821	**Small Scale Field Test Demonstration CO2 Sequestration**

3. Recipient:
University of Kansas Center for Research, Inc.

4. Reporting Requirements:	Frequency	Addressees
A. MANAGEMENT REPORTING		
☒ Research Performance Progress Report (RPPR)	Q	FITS@NETL.DOE.GOV
☒ Special Status Report	A	FITS@NETL.DOE.GOV
B. SCIENTIFIC/TECHNICAL REPORTING		
(Reports/Products must be submitted with appropriate DOE F 241. The 241 forms are available at www.osti.gov/elink)		
Report/Product — Form		
☒ Final Scientific/Technical Report — DOE F 241.3	FG	http://www.osti.gov/elink-2413
☒ Conference papers/proceedings* — DOE F 241.3	A	http://www.osti.gov/elink-2413
☐ Software/Manual — DOE F 241.4		
☐ Other (see special instructions) — DOE F 241.3		
** Scientific and technical conferences only*		
C. FINANCIAL REPORTING		
☒ SF-425 Federal Financial Report	Q, FG	FITS@NETL.DOE.GOV
D. CLOSEOUT REPORTING		
☒ Patent Certification	FC	FITS@NETL.DOE.GOV
☒ SF-428 & 428B Final Property Report	FC	FITS@NETL.DOE.GOV
☐ Other		
E. OTHER REPORTING		
☒ Annual Indirect Cost Proposal	O	See block 5 below for instructions.
☐ Audit of For-Profit Recipients		
☒ SF-428 Tangible Personal Property Report Forms Family	A	FITS@NETL.DOE.GOV
☒ Other – see block 5 below	A	FITS@NETL.DOE.GOV

FREQUENCY CODES AND DUE DATES:

A - Within 5 calendar days after events or as specified.
FG- Final; 90 calendar days after the project period ends.
FC- Final; End of Effort.
Y - Yearly; 90 calendar days after the end of the reporting period.
S - Semiannually; within 30 calendar days after end of project year and project half-year.
Q - Quarterly; within 30 days after end of the reporting period.
Y180 – Yearly; 180 days after the end of the recipient's fiscal year
O - Other; See instructions for further details.

5. Special Instructions:

Annual Indirect Cost Proposal – If DOE is the Cognizant Federal Agency, then the proposal should be sent to FITS@NETL.DOE.GOV . Otherwise, it should be sent to the Cognizant Federal Agency.

Other – The Recipient shall provide all deliverables as contained in Section D of Attachment 2 Statement of Project Objectives.

QUARTERLY PROGRESS REPORT

To
DOE-NETL
Brian Dressel, Program Manager
Award Number: DE-FE0006821

SMALL SCALE FIELD TEST DEMONSTRATING CO_2 SEQUESTRATION IN ARBUCKLE SALINE AQUIFER AND BY CO_2-EOR AT WELLINGTON FIELD, SUMNER COUNTY, KANSAS

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Date of Report: May 16, 2016
DUNS Number: 076248616

Recipient: University of Kansas Center for Research &
Kansas Geological Survey
1930 Constant Avenue
Lawrence, KS 66047

Project/Grant Period: 10/1/2011 through 9/30/2016
Eighteenth Quarterly Report
Period Covered by the Report: January 1, 2016 through May 16, 2016
Signature of Submitting Official:

Willard Lynn Watney

Digitally signed by Willard Lynn Watney
DN: cn=Willard Lynn Watney, o=University of Kansas, ou=Kansas Geological Survey, email=lwatney@kgs.ku.edu, c=US
Date: 2016.05.16 13:04:21 -05'00'

EXECUTIVE SUMMARY

PROJECT OBJECTIVES

The objectives of this project are to understand the processes that occur when a maximum of 70,000 metric tonnes of CO_2 are injected into two different formations to evaluate the response in different lithofacies and depositional environments. The evaluation will be accomplished through the use of both *in situ* and indirect MVA (monitoring, verification, and accounting) technologies. The project will optimize for carbon storage accounting for 99% of the CO_2 using lab and field testing and comprehensive characterization and modeling techniques.

CO_2 will be injected under supercritical conditions to demonstrate state-of-the-art MVA tools and techniques to monitor and visualize the injected CO_2 plume and to refine geomodels developed using nearly continuous core, exhaustive wireline logs, and well tests and a multi-component 3D seismic survey. Reservoir simulation studies will map the injected CO_2 plume and estimate tonnage of CO_2 stored in solution, as residual gas, and by mineralization and integrate MVA results and reservoir models shall be used to evaluate CO_2 leakage. A rapid-response mitigation plan will be developed to minimize CO_2 leakage and provide comprehensive risk management strategy. A documentation of best practice methodologies for MVA and application for closure of the carbon storage test will complete the project. The CO_2 shall be supplied from a reliable facility and have an adequate delivery and quality of CO_2.

SCOPE OF WORK

Budget Period 1 includes updating reservoirs models at Wellington Field and filing Class II and Class VI injection permit application. Static 3D geocellular models of the Mississippian and Arbuckle shall integrate petrophysical information from core, wireline logs, and well tests with spatial and attribute information from their respective 3D seismic volumes. Dynamic models (composition simulations) of these reservoirs shall incorporate this information with laboratory data obtained from rock and fluid analyses to predict the properties of the CO_2 plume through time. The results will be used as the basis to establish the MVA and as a basis to compare with actual CO_2 injection. The small scale field test shall evaluate the accuracy of the models as a means to refine them in order to improve the predictions of the behavior and fate of CO_2 and optimizing carbon storage.

Budget Period 2 includes completing a Class II underground injection control permit; drilling and equipping a new borehole into the Mississippian reservoir for use in the first phase of CO_2 injection; establishing MVA infrastructure and acquiring baseline data; establishing source of CO_2 and transportation to the injection site; building injection facilities in the oil field; and injecting CO_2 into the Mississippian-age spiculitic cherty dolomitic open marine carbonate reservoir as part of the small scale carbon storage project.

In Budget Period 3, contingent on securing a Class VI injection permit, the drilling and completion of an observation well will be done to monitor injection of CO_2 under supercritical conditions into the Lower Ordovician Arbuckle shallow (peritidal) marine dolomitic reservoir.

Monitoring during pre-injection, during injection, and post injection will be accomplished with MVA tools and techniques to visualize CO_2 plume movement and will be used to reconcile simulation results. Necessary documentation will be submitted for closure of the small scale carbon storage project.

PROJECT GOALS

The proposed small scale injection will advance the science and practice of carbon sequestration in the Midcontinent by refining characterization and modeling, evaluating best practices for MVA tailored to the geologic setting, optimize methods for remediation and risk management, and provide technical information and training to enable additional projects and facilitate discussions on issues of liability and risk management for operators, regulators, and policy makers.

The data gathered as part of this research effort and pilot study will be shared with the Southwest Sequestration Partnership (SWP) and integrated into the National Carbon Sequestration Database and Geographic Information System (NATCARB) and the 6th Edition of the Carbon Sequestration Atlas of the United States and Canada.

Project Deliverables by Task

1.5 Well Drilling and Installation Plan (Can be Appendix to PMP or Quarterly Report)
1.6 MVA Plan (Can be Appendix to PMP or Quarterly Report)
1.7 Public Outreach Plan (Can be Appendix to PMP)
1.8 Arbuckle Injection Permit Application Review go/no go Memo
1.9 Mississippian Injection Permit Application Review go/no go Memo
1.10 Site Development, Operations, and Closure Plan (Can be Appendix to PMP)
2.0 Suitable geology for Injection Arbuckle go/no go Memo
3.0 Suitable geology for Injection Mississippian go/no go Memo
11.2 Capture and Compression Design and Cost Evaluation go/no go Memo
19 Updated Site Characterization/Conceptual Models (Can be Appendix to Quarterly Report)
21 Commercialization Plan (Can be Appendix to Quarterly Report).
30 Best Practices Plan (Can be Appendix to Quarterly or Final Report)

ACCOMPLISHMENTS

CO2-EOR

1. Continuous CO_2 injection in the Mississippian reservoir began on January 9, 2015 and weekly reporting thereof.
2. Systematic weekly sampling of brine and gases at Wellington for up to 17 wells to understand the behavior of CO2 that is injected including quantifying interaction with the brine, oil, and reservoir rock, and accounting of the same.
3. Develop databases for field and lab analyses using Java-based web applications with functions including importing brine data and downloading of results. Developed means to

compare data by well and by date including 1) Wellington Field CO2 Brine Data Summary Page, 2) Fluid Level Data Summary Page, the latter including oil cut, % and metered CO2, fluid levels and estimated BHP.

4. Developed additional Java applications to analyze brine and gases including 1) compute correlation matrix and perform Principal Component Analysis on-the-fly for the brine data to identify correlations and outliers of analyses for QA/QC and interpretation and 2) to normalization brine analyses via charge balance of anions and cations so that ratio to within 2% of expected 1:1 ratio.
5. Built new and refine existing Java web applications to grid, map, and provide animated displays/movie of weekly changes in field and lab well-based measurements, displaying up to three variables using color cube algorithm.
6. Established clearly defined analytical procedures and protocols for brines and gases involving four labs at KGS and KU for cost saving, efficiency, on-site training, and overall QA/QC.
7. Have successfully used well based measurements to track CO2 and oil recovery including metered CO2 and incremental oil, oil cut and total fluid by well, and estimates of bottom hole pressure.
8. Have identified the location of the primary CO2 plume that still lies within the producing wells nearest the injection well, #2-32. CO2 produced amounts to less than 15% of the CO2 has been injected.
9. Volumetric analysis indicate that the bank of CO2 has extended to the entire ~70 ft thick porous and permeable portion of the Mississippian reservoir that also contains ~23% residual oil saturation.
10. Compositional fluid flow simulation recently performed has focused on the temperature effects of injecting cold CO2 suggest that a mixed phase plume has developed in the inner ring of wells within 660 ft of the CO2 injection well. CO2 varies from an inner core of cool liquid CO2 and warmer supercritical phase that likely has become miscible with oil.
11. New analyses of 3D seismic analysis include new sequence stratigraphic interpretation successfully integrating the 3D seismic, well log, and core. Model is consistent with progradation of high frequency parasequences exhibiting transgressive, maximum flooding, highstand and lowstand systems tracks comprising a single large depositional sequence encompassing the entire preserved Mississippian strata at Wellington Field.
12. The depositional model is consistent with a large regional cool water ramp that occupies large portions of southern Kansas and northern Oklahoma bordering the Anadarko and Arkoma basins.
13. Faulting along the ramp and at Wellington Field occurred syndepositionally with the Mississippian strata, locally influencing the progradational system and affecting reservoir lithofacies across a medial NE-SW trending fault in Wellington Field.
14. New AVO (amplitude vs. offset) analysis of the 3D indicates results consistent with the Petrel inversion of porosity. The AVO further indicates that the CO2 is confined to the

more higher porous contiguous portion of the reservoir surrounding the CO_2 injection well. Results also show the porosity barrier present along the syndepositional fault that bisects the field.

15. Increased pressure and presence of CO_2 noted in well #63 across a small medial fault located to the east of the injection well. The show of CO_2 indicates that the fault and associated lithofacies change act as a baffle between CO_2 injection well and this producer and are consistent with earlier pulse test and interpretation of 3D seismic imaging.
16. Seismology team has continued to build and refine earthquake catalog from Wellington seismometer array reporting weekly updates. *Magnitude of Completeness* established to verify that all events can be identified equal to or great than 1.4 M, a value that will continue to decrease over time as the catalog expands.
17. Capabilities of existing Java web applications pertaining to earthquakes have expanded to include 1) monthly summary of earthquakes as CO_2 Seismic Array Data Summary Page, and 2) 3D Animation/Movie of existing maps and 2D and 3D plots of earthquakes to illustrate by location, magnitude, and time. User can limit events to be shown by time and define what appears on the map.

Class VI – USEPA Geosequestration Permit

18. EPA made a preliminary determination that the USDW is absent in the AoR, additional questions received on April 22nd. KGS quickly responded to the request.
19. Submitted and received response from EPA refined conservative AoR model (Revised Section 5 of the Class VI permit).
20. Received request for information on faults, earthquakes recorded from Wellington array, and general induced seismicity in the area.
21. Refined and verified 18-seismometer array at Wellington with nearby earthquakes and update earthquake catalog on a weekly basis.
22. Workflow in place to report notable earthquakes within 24 hours to ensure location and magnitude.
23. Discussed and presented on induced seismicity in the context of a safe and effective CO_2 injection at Wellington in numerous venues.
24. Reviews made of portion of the draft Class VI permit.
25. The *Financial Responsibility Demonstration* was completed and uploaded to EPA on 5/5/16. Cost deemed to be manageable.
26. Information request from received from EPA on Friday April 29, 2016 concerning "*Well Construction and Operation, AoR and Corrective Action, Testing and Monitoring.*" The request pertains to receipt of updates and refined information in addition to that previously submitted. One question remains to be completed and document will be uploaded to EPA on 5/16/16.
27. EPA made a preliminary determination that the USDW is absent in the AoR with additional questions received on April 22nd. KGS responded to the request.

PROJECT SCHEDULE

Schedule for the CO2-EOR

The information from monitoring the CO2 injection in the Mississippian is being analyzed to determine the shutdown of the CO2 injection based on costs, effectiveness of the CO2, and planning toward extended waterflood and pressure maintenance to move the CO2 plume and oil bank to producing wells, and assess ultimately assess the efficiency of the EOR activity, to determine the amount of CO2 that has been sequestered and the fate of the CO2 that is stored.

Schedule and costs for Arbuckle CO2 injection --

Implementing BP3 and the Arbuckle injection is contingent receiving a draft of the Class VI Geosequestration Permit and schedule from EPA.

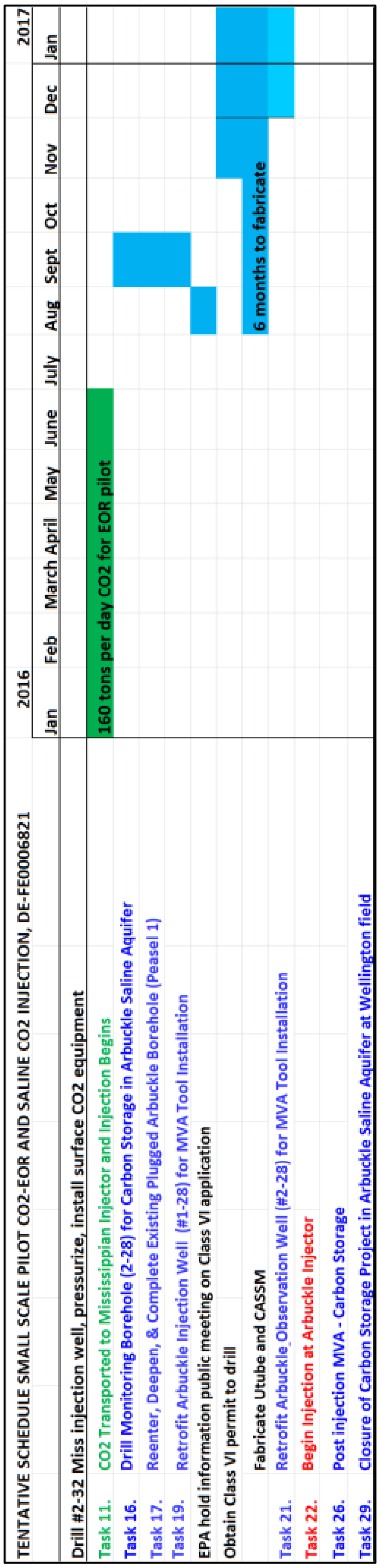
Continuation Application (CA), budget for BP3, and project extension will be filed after receipt of the draft Class VI permit.

The CA and related documents will include:

1) Summary of the status and findings from the CO2-EOR injection in the Mississippian reservoir;
2) Revised budget and PMP for the BP3 for Arbuckle injection and PISC based on recent updated costs including financial responsibility and post injection site care;
3) Present rationale for major milestone to proceed with preparations for the saline aquifer test injection - drilling #2-28, completing and testing #2-28 and #1-28, installing CO2 injection facilities, contracting for Phase II of the CO2 supply; costs to undertake monitoring, verification, and accounting of the CO2, synthesis and reporting;
4) Synopsis of the timeline, accomplishments, costs, and issues addressed during the course of the project;
5) Distill key elements of the draft Class VI permit, conveying obligations, financial assurance, and requirements of the post injection site care as it affects NETL-DOE;
6) Revise schedule and cost tables.

Wellington project currently is scheduled to end on September 30, 2016. A time extension of the project will be needed to accommodate the Arbuckle CO2 injection now estimated to begin in February 2017 after #2-28 is drilled and CASSM and U-Tube are fabricated, installed and tested in the 2^{nd} half of 2016 **(Figure 1**).

The completion date anticipated for the Arbuckle CO2 injection is anticipated to be the end of July 2017. The one year post injection site care as proposed to EPA would begin in August 2017 and continue through August 2018 (**Figure 1**).



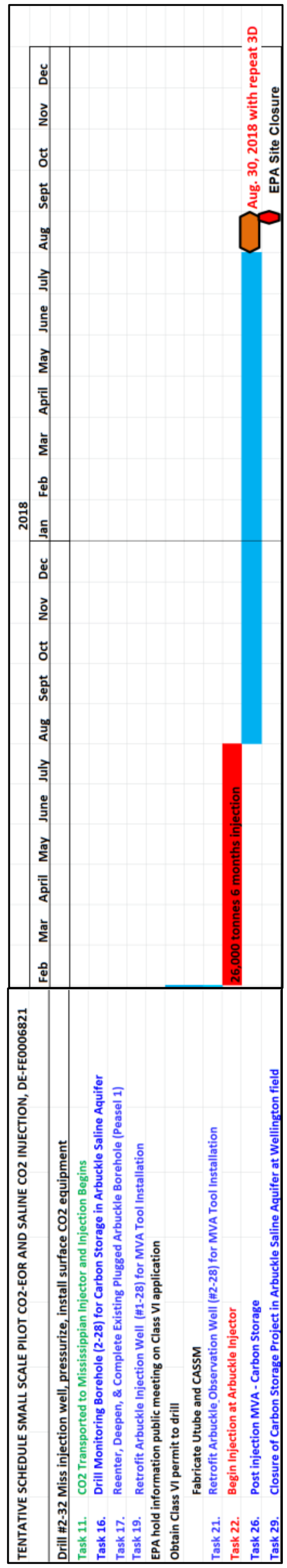


Figure 1. Revised timetable for DE-FE0006821 (on previous page).

ONGOING ACTIVITIES

MILESTONE STATUS REPORT

Task	Budget Period	Number	Milestone Description
Task 2.	1	1	Site Characterization of Arbuckle Saline Aquifer System - Wellington Field
Task 3.	1	2	Site characterization of Mississippian Reservoir for CO2 EOR - Wellington Field
Task 10.	2	3	Pre-injection MVA - establish background (baseline) readings
Task 13.	2	4	Retrofit Arbuckle Injection Well (#1-28) for MVA Tool Installation
Task 18.	3-yr1	5	Compare Simulation Results with MVA Data and Analysis and Submit Update of Site Characterization, Modeling, and Monitoring Plan
Task 22.	3-yr1	6	Recondition Mississippian Boreholes Around Mississippian CO2-EOR injector
Task 27.	3-yr2	7	Evaluate CO2 Sequestration Potential of CO2-EOR Pilot
Task 28.	3-yr2	8	Evaluate Potential of Incremental Oil Recovery and CO2 Sequestration by CO2-EOR - Wellington field

TASK 2. SITE CHARACTERIZATION OF ARBUCKLE SALINE AQUIFER SYSTEM – WELLINGTON FIELD

Delineation of Underground Source of Drinking Water (USDW) in the Vicinity of the Wellington CO_2 Sequestration Site

Additional analysis of the USDW was done to delimit and explain the USDW presence or absence in the area around Wellington Field for the Class VI permit. The synopsis is provided here.

The Wellington site in Sumner County, KS, lies near the eastern edge of the Hutchinson Salt beds in south central Kansas (**Figure 2**). The stratigraphy at the site is shown in **Figure 3**. Typically, there is a thin layer of Pleistocene or terrace deposit above the Upper Wellington Shale, which is typically 200 feet thick in the area. Underneath the Upper Wellington Formation are the approximately 50-100 feet thick (halite) Hutchison salt beds. Underlying the Hutchinson salt beds is approximately 200-250 feet of the Lower Wellington Shale consisting of beds of anhydrite and shale.

An extensive soil survey was conducted by the Unites States Department of Agriculture Soil Conservation Service (Fenwick et al, 1979) to map the soil composition in Sumner County. Based on the survey, Slate Creek and southern portions of Spring and Oak Creek contain alluvial sand/gravel in the surficial deposits, while the rest of area at the Wellington site contains clay mixed terrace deposits in the top soil (**Figure 4**). This distribution of soil types was confirmed by a review of well construction data in the WW-5 database of the Kansas Geological Survey (KGS) at the sites shown in **Figure 4**, and the soil data at these sites was used to construct two geologic cross sections shown in **Figures 5a-b**. As can be noted from cross-sectional logs, there are thick deposits of sand along Slate and Spring creeks, and mixed clay in the top soil in the rest of the area. A conceptualization of these two contrasting geologic settings is illustrated in **Figure**

6. The areas with mixed clay to sandy terrance at the top are expected to receive less recharge as compared to sandy areas along the two creeks which likely receive higher recharge from precipitation. Wells in the sandy areas are therefore expected to yield relatively more fresh water due the permeable formation and higher recharge as compared to wells constructed in the upland clay-rich terraces which and are “tighter” and receive less recharge from infiltration. As conceptualized in **Figures 7 and 8**, the creeks overlying sand/gravel deposits recharge the aquifer during spring when the creek stage is high, and groundwater flows back to the creek during drier periods when the stage is low. The diffuse salinity zone in the upper Wellington Shale is related to dissolution of halite and gypsum present in the shale and below in the Hutchison salt. Areas near streams with sand and gravel are a source of freshwater where recharge is high and thus dilute the high TDS water. Areas east of Wellington where the halite beds of the Hutchinson Salt in the process of undergoing dissolution due to their proximity to surface, TDS of groundwater is higher.

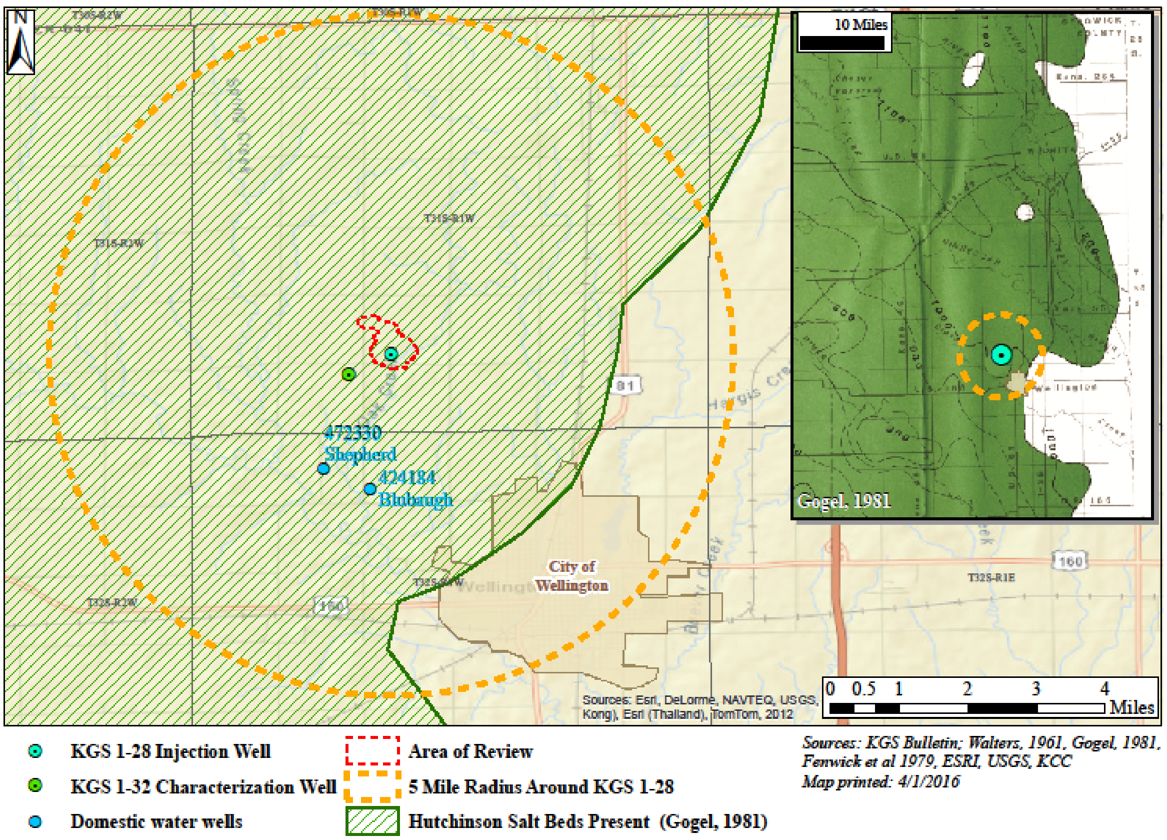


Figure 2. Location of Wellington sequestration site in relation to the Hutchinson salt beds in central Kansas.

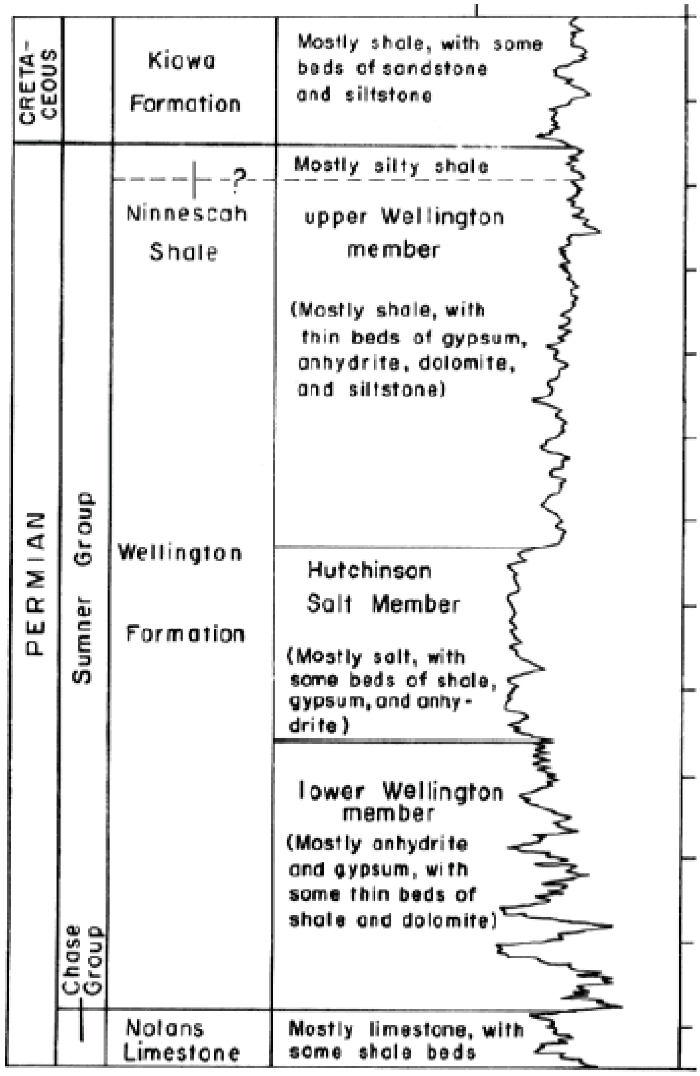


Figure 3. Stratigraphic relationship of bedrock in central Kansas (from Gogel, 1981)

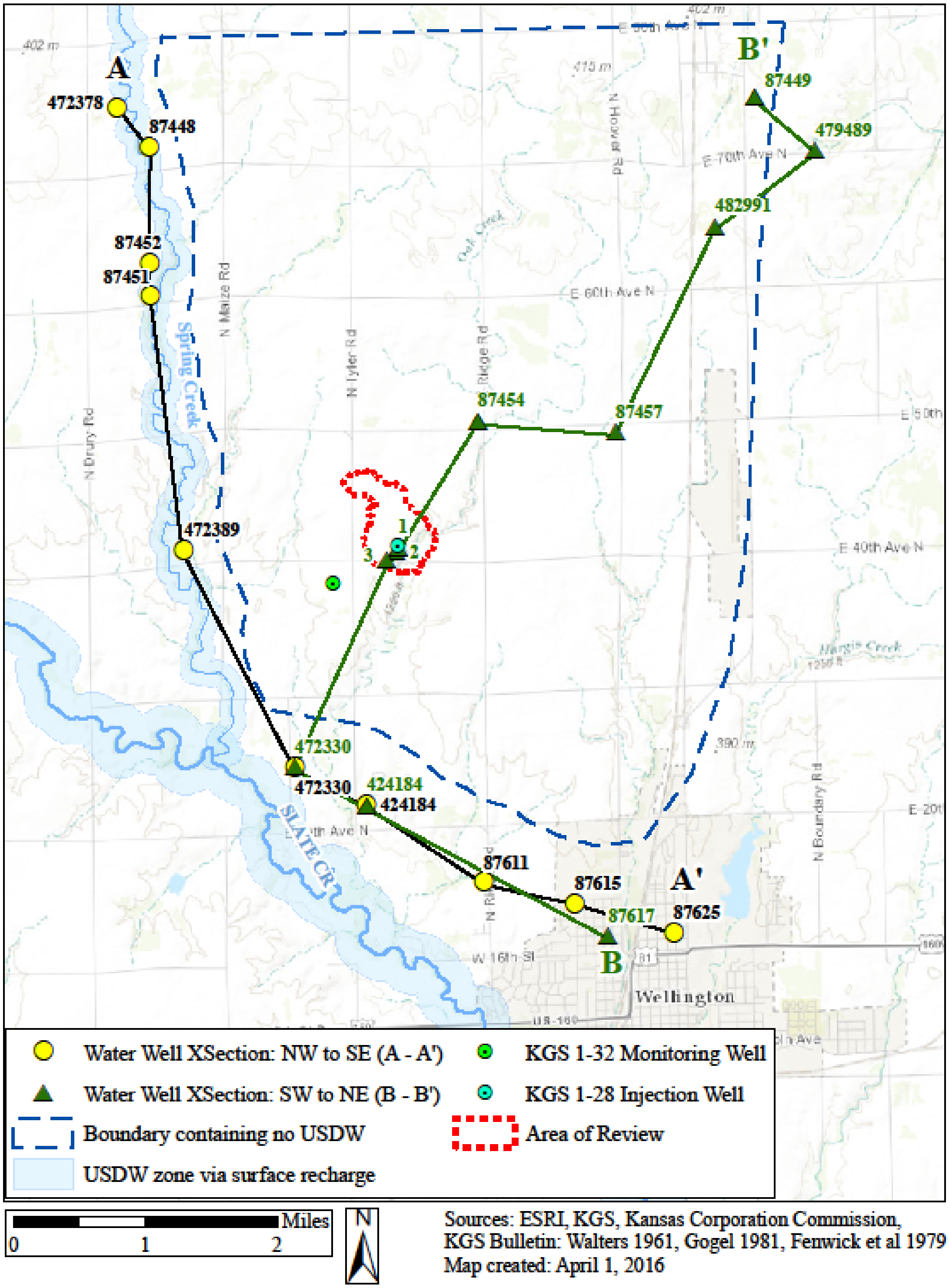


Figure 4. Index map of key wells and those used in cross sections.

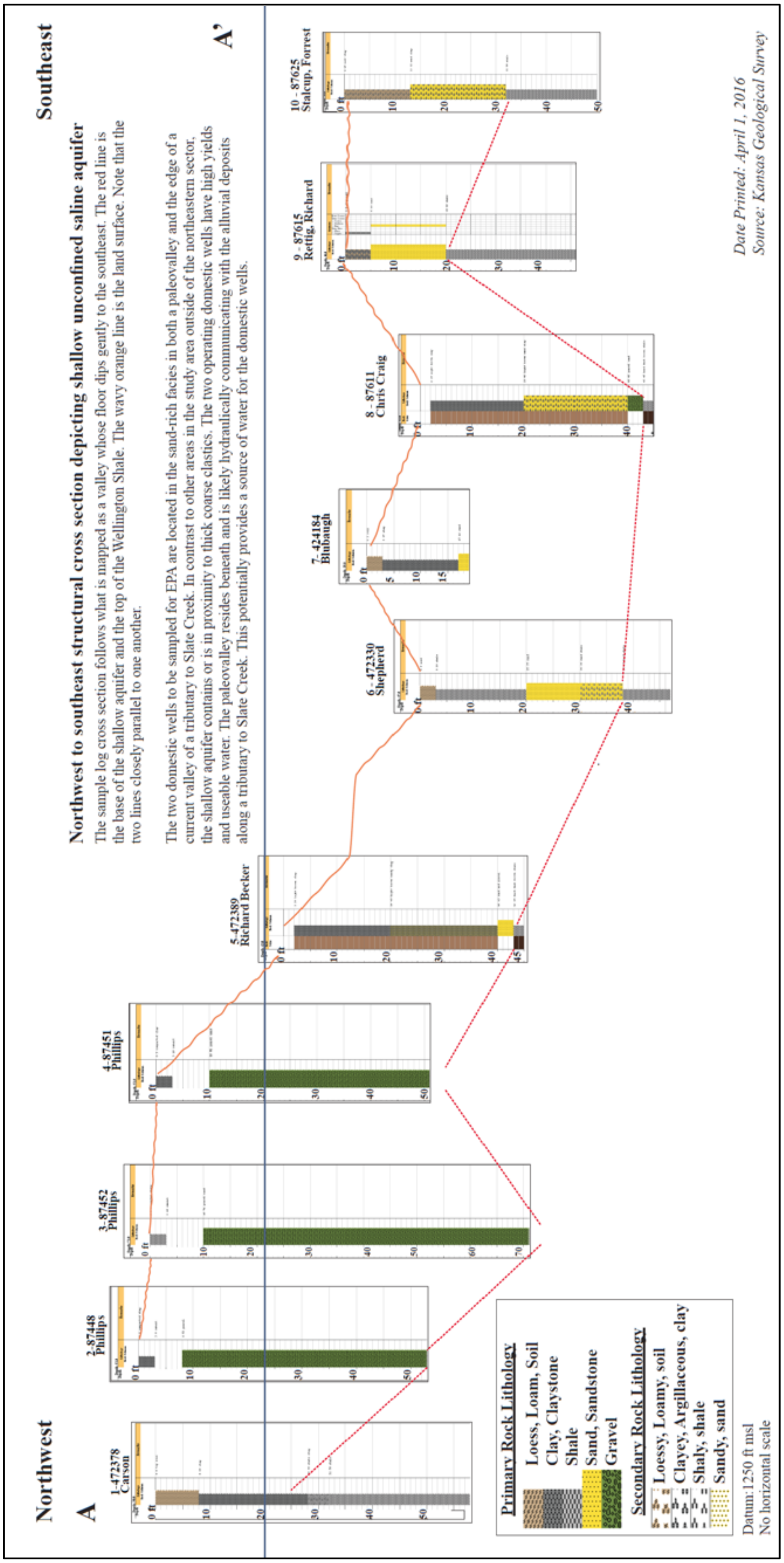
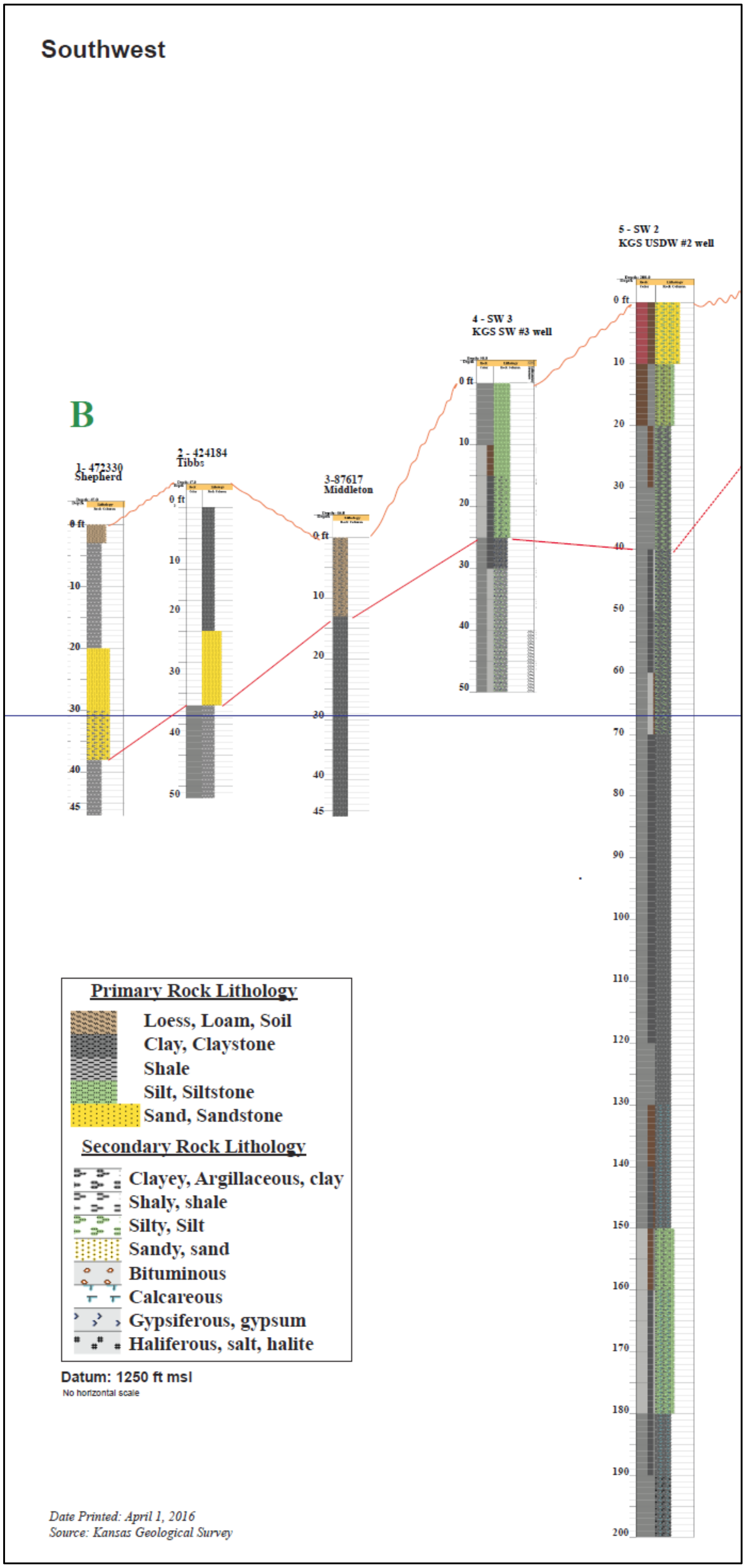
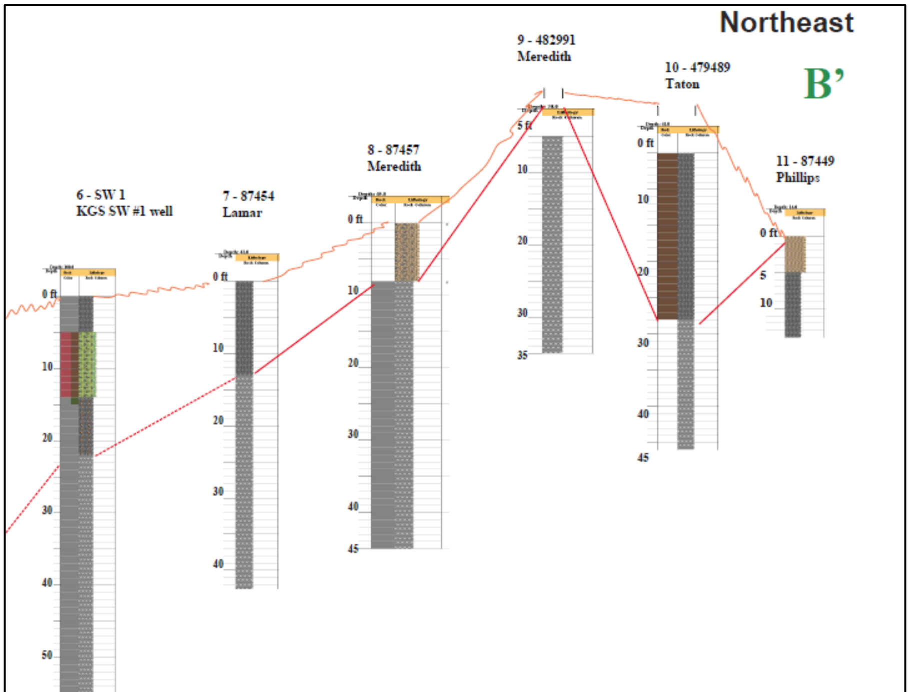


Figure 5a. Northwest – southeast geologic cross-section in study area emphasizing the presence of sand and gravel in the surficial soil along Slate and Spring creeks.


Southwest
B
1- 472330 Shepherd
2 - 424184 Tibbs
3-87617 Middleton
4 - SW 3 KGS SW #3 well
5 - SW 2 KGS USDW #2 well
Primary Rock Lithology
Loess, Loam, Soil
Clay, Claystone
Shale
Silt, Siltstone
Sand, Sandstone
Secondary Rock Lithology
Clayey, Argillaceous, clay
Shaly, shale
Silty, Silt
Sandy, sand
Bituminous
Calcareous
Gypsiferous, gypsum
Haliferous, salt, halite
Datum: 1250 ft msl
No horizontal scale
Date Printed: April 1, 2016
Source: Kansas Geological Survey



Southwest to northeast structural cross section of the shallow unconfined aquifer in north-central Sumner County

The sample log cross section extends from what is inferred to be a paleovalley on the left, to an upland in the middle portion of the cross section, and another paleovalley on the northeast side. The basal contact of the surface aquifer and the contact with the Permian Wellington Shale is identified by the red line. The wavy orange line is the land surface. Note the basic conformance of the two.

The cross section spans an incised valley in the left most two wells. The three shallow water wells at Wellington, SW-3, -2, -1, and extending to the east comprise an older Pleistocene alluvial terrace as described below. The terrace continues eastward in the cross section until reaching the fourth well from the east side where the Pleistocene terrace laps onto the Wellington Shale. At this well location, only a thin mantle of soil/loess overlies the Wellington Shale. The Pleistocene terrace is again present in the next two wells as the elevation falls at the top of the Welllington Formation and surface topography. The far northeastermost well is another Pleistocene sand-rich paleovalley deposit inferred to have been incised into the Wellington Shale.

The northeasternmost well is topographically higher than the paleovalley deposits on west side of the cross section where gravel-rich sediment occurs. The lack of gravel in the northeastern paleovalley suggests that the two valleys are likely distinct units, i.e., the gravel-rich sediment is inferred to be located at the headland of a separate paleovalley.

Shallow water wells drilled at Wellington Field reside above the paleovalleys to the west and northeast. The sand and gravel, abundant and thick in the paleovalley, are replaced by red-brown discontinuous silt and thin fine sand layers and sticky plastic (gumbo) clay that is correlated to the Bethany series of soil and the underlying parent material that comprise the Pleistocene terrace alluvial deposit. The terrace is interpreted by Mandel (per. comm, July 23, 2015) as an early deposit of the ancestral Arkansas River preserved as a high terrace in north-central Sumner County. The Bethany series is described and mapped in the Soil Survey of Sumner County (USDA Soil Conservation Service).

As stated in the online version of the soil survey document -- (https://soilseries.sc.egov.usda.gov/OSD_Docs/B/BETHANY.html) the Bethany series consists of "...very deep, well drained soils that formed in loess or alluvium of Pleistocene age over shale of Permian age. These soils are on summits and backslopes of paleo-terraces in the Central Rolling Red Prairies (MLRA-80A). Slopes are 0 to 5 percent.

The Bethany series is a silt loam, to silt clay loam that varies from reddish brown to dark brown to dark grayish brown. Dr. Mandel confirmed that the Bethany series is generally clay-rich and is plastic and sticky when wet. This matches with the "gumbo" clay encountered when SW-1 was drilled kept the standard rotary bit from penetrating the clay rich layer at the bottom of this shallow aquifer.

The alluvial origin of the Pleistocene terrace presents a varied stratigraphy in the Wellington field area, e.g., the reddish silt, local sandy intervals, and clay deposits. As the cross section illustrates, the lateral and veritical complexity increases with the truncation of these older terrace/alluvial by deposits of younger alluvial valley comprised of coarser sediment. Water wells completed on the upland outside of the paleovalley and modern alluvial streams has limited yield affected by seasonal recharge with varying salinities. Limited recharge in these upland creates the potential for increased mixing with brines in the Wellington Shale.

The limited lateral hydraulic conductivity results is a perched aquifer comprised of the high terrace loamy deposits with variable yield, varying static fluid levels, and water quality. This portion of the shallow aquifer is not a major contributor to local water supply based on review of well records. While static water levels closely follow topography, these levels are constrained by the relatively thin Pleistocene terrace deposits that closely conform to the land surface.

Figure 5b. Southwest–Northeast geologic cross-section in study area emphasizing the presence of sand and gravel in the surficial soils near Slate Creek, and the mixed-clay deposits in the rest of the area.

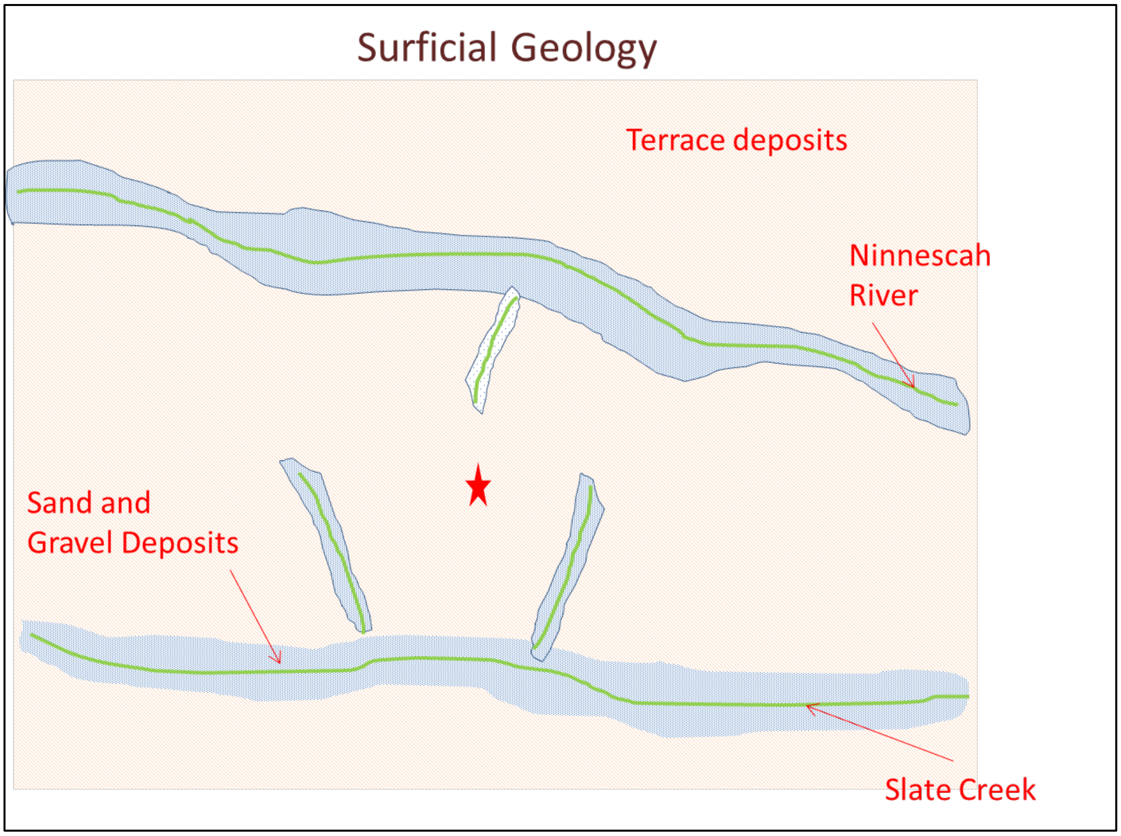
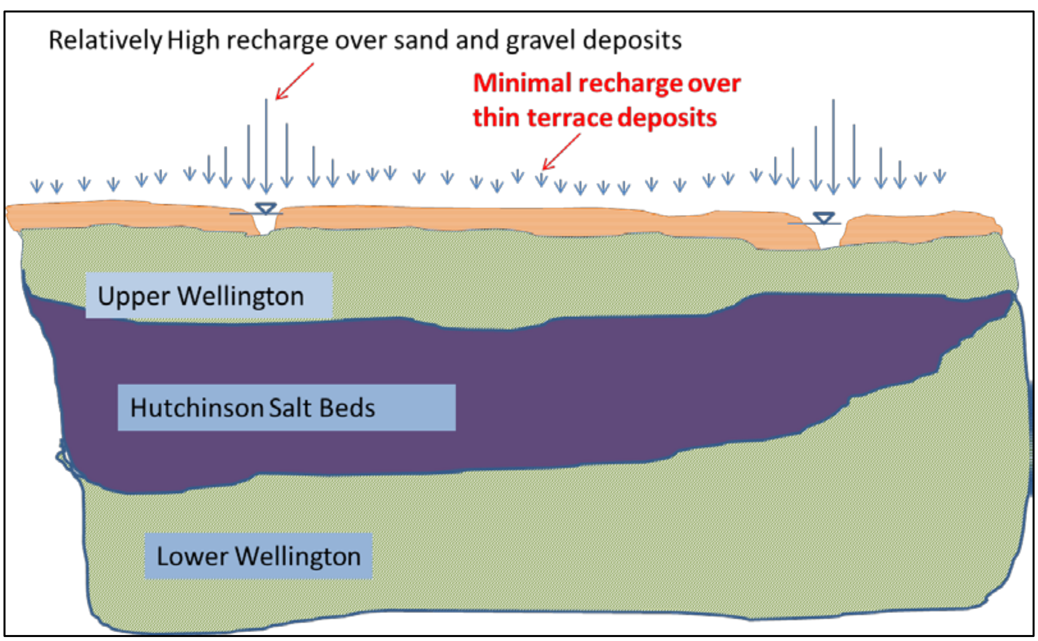


Figure 6. Interfluve area with thin, surficial Pleistocene terrace deposits and soil over Wellington in light tan color. Red star is location of Wellington Field. Generally, thick sand and gravel present in incised valleys that cut the older Pleistocene terraces. Incised valleys commonly lie beneath modern streams and alluvium and combine to form a viable shallow aquifer system.



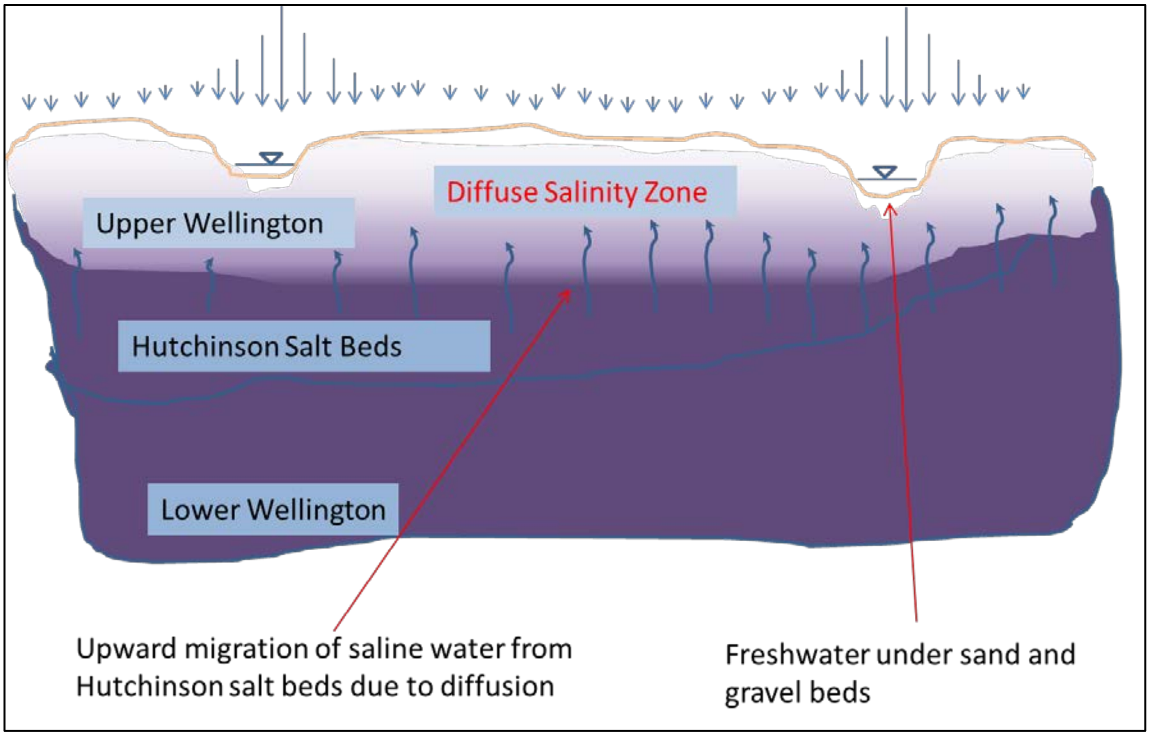


Figure 7. Conceptual models of how surface water recharge occurs between low recharge in older Pleistocene terrace deposits (upper diagram in brown) and along creeks and streams.

Received request from EPA for information on faults, earthquakes recorded from Wellington array, and general induced seismicity

Geologic Structure and Induced Seismicity Wellington CO_2 Sequestration Site Wellington, KS

Prepared and compiled by W. Lynn Watney, Tiraz Birdie, and Jennifer Hollenbach, and Tandis Bidgoli

Executive Summary

Based on a thorough review/processing of seismic data and incorporation of the same in the Petrel modeling software, a small fault, referred to as the medial fault has been identified west of the proposed Wellington injection well (KGS #1-28). This fault is approximately 7,000 feet long and extends from the base of the Arbuckle to the top of the Mississippian reservoir with a maximum vertical separation of 80 feet. The geologic characteristics of the fault are derived from the seismic data, the field-based injection test incorporated in the Petrel geo-model, and the resulting CMG multiphase Class VI fluid model. The associated geochemical and stable isotopic properties of the brines confirmed in both Arbuckle wells support the presence of separate, isolated hydrostratigraphic units in the Arbuckle.

The results of an analysis of reactivation potential indicate that an increase in pore pressure of at least 1,000 psi will be needed to cause movement of the fault. Based on results of the Class VI simulation model, a maximum increase in pore pressure of less than 30 psi is projected at the fault due to injection of 40,000 tons of CO_2 in the Arbuckle. This makes it highly unlikely for the fault to slip during geologic sequestration activities. In the unlikely event of an induced earthquake, the maximum potential magnitude would be approximately 4.0 (Wells and Coppersmith, 1994). However, it is unlikely that the entire length of the fault would move at one time (Wesnousky, 2006); thus, the earthquake intensity would rather be a fraction of the maximum magnitude and likely below the 2.5 magnitude that would not be felt, but would be detected and characterized by the 18-seismometer array in Wellington Field.

The Wellington seismometer array has been active since Fall 2014 and has an associated earthquake catalog processed since April 2015. The team managing the array has demonstrated its ability to verify the magnitude and hypocenter locations of faults, and is moving into modeling earthquake moment tensor solutions (Nolte, et al., 2016). The magnitude of completeness (Mc) of the current earthquake catalog, an important index for seismometer arrays, has been defined through a technique described by (Vorobieava, 2012). Mc is defined as the magnitude that can be confidently picked for all events of that magnitude and larger (Nolte et al., 2016). The current value of the magnitude of completeness is ~1.4 Mw, but over time, the Mc should continue to improve. The current minimum magnitude that can detected is 0.4 magnitude, in the microseismicity ($M<1$) range. This minimum magnitude can and is being confidently reported in the earthquake catalog. In addition, the accuracy of the hypocenter location has been confirmed by comparison of events recorded by the USGS monitoring system. In general, accuracy of the event data is considered to be highly resolved within 5 km of the Wellington array.

Independent engineering and geophysical monitoring and installation safeguards are in place to directly document downhole changes that will provide safeguards that CO_2 remains confined in the injection zone. Remedial measures are established and would be implemented in the event of a natural or operational catastrophe. The *Operating Plan for Safe and Efficient Injection* (*OPSEI*) provided to EPA in 2015 includes the *Wellington Seismic Action Plan* which list measures to be taken to prevent induced seismicity. The Wellington seismometer array would provide early detection and characterization of earthquakes including magnitude and depth, while downhole measurements pertaining to the injection itself would be used to analyze departures in CO_2 injection. These measurements include continuous recording of pressure and temperature, frequent measurements of in-situ fluid composition (U-Tube), and weekly measurements using the continuous active seismic monitoring system (CASSM).

Any changes in downhole fluid pressures (build up or a sudden loss) will be followed by analysis such as Hall Plot (Silin, et al., 2005; Fekete, 2014;UIC-NTW and EPA, 2015) as outlined in the report of the UIC-NTW and EPA, "*Minimizing and Managing Potential Impacts of Injection Induced Seismicity from Class II Disposal Wells: Practical Approaches*" (2015), pressure fall-off test, MIT, sampling of the overlying Mississippian reservoir, and shallow aquifer sampling to sufficiently understand the departure. The team has demonstrated many of these skillsets and ability to conduct and analyze the geoengineering-based monitoring being used in the analysis of the current CO_2 injection in the overlying Mississippian oil reservoir (Watney et al., 2016).

The medial fault lies only ~500 feet east of the Wellington Enhanced Oil Recovery (EOR) well (KGS #2-32) in the shallower Mississippian reservoir. The Class II injection well and vicinity around it that extends to at least 2000 ft radius, is being subjected to similar rates and volumes of CO_2 injection except approximately 23x higher differential bottomhole pressures (~700 psi) at the fault than estimated for the Class VI (30 psi). The upper permeable flow unit in the Mississippian at the site represents the top 70 feet of the 450 ft Mississippian interval, most of which is tight and thus isolated from the Arbuckle. Only the uppermost 30 ft of the most porous and permeable interval is perforated for CO_2 injection. In contrast, the lower Arbuckle hydrostratigraphic unit has approximately 140 feet of highly permeable strata and all of the interval would be perforated to optimize injectivity and limit the bottomhole pressure for volume and rate of CO_2 essentially the same as the Mississippian CO_2-EOR.

Water was injected into the Mississippian injection well started October 1, 2015 to repressurize the reservoir around the Mississippian well. At the end of March 2016, approximately 10,000 tons of CO_2 has been injected, which began on January 9, 2016. Differential pore pressures have been maintained at over 700 psi at the location of the injection well and the medial fault without causing any earthquakes in the field at or above the threshold magnitude of M2.5 established in the Wellington Seismic Action Plan submitted to the EPA (Nolte, et al., 2016).

The approach to geomodeling and simulation in the Mississippian reservoir closely parallels the workflow described in Section 4 of the Class VI application used to establish simulations of the Arbuckle to estimate the AoR. Although the model is only constrained by two Arbuckle wells (versus 17 wells in the Mississippian), the seismic inversion methods used to constrain porosity and permeability and other key rock properties are the same. Consequently, the fact that the current Mississippian CO_2 injection is behaving closely with that forecasted by the simulation, gives us confidence in the Arbuckle simulation and its predictions (Watney et al., 2016).

As documented previously in KGS's *Opinion Regarding Likelihood of Inducing Earthquakes Due to CO_2 Injection in the Wellington Oilfield* (Attachment to the Class VI application) the increase in seismic activity in south-central Kansas has been determined to be associated with saltwater disposal related to oil and gas recovery operations (Ellsworth, 2013; Keranen et al., 2013; Walsh and Zoback, 2015; Weingarten et al., 2015). The proposed quantity of fluid injection (40,000 tons, ~225,000 bbls annual injection and ~150 tons or 840 bbls/day) at Wellington is minuscule compared to the Class I and II operations in the area. For example, at a Class I site just north of the Wellington, approximately 2.5 million tons of brine has been injected annually in the Arbuckle for several decades without causing any noticeable earthquakes.

The core area of seismic concern in Harper and western Sumner counties was established on March 19, 2015 by the KCC (KCC Docket No. 15-CONS-770-CMSC) in response to the findings of the Kansas Induced Seismicity Task Force. On February 19, 2016 the Conservation Division of KCC issued a recommendation to replace the original Area of Seismic Concern with a new Proposed Area of Reduction (PAR), continuing the injection limitations currently implemented and expanding their geographic scope. Specifically, Class II brine disposal wells in the Arbuckle in the expanded area would be limited to 12,000 bbls per day within 55 days of the order. If enacted, the expanded area would include Wellington Field at the far eastern edge (KCC Staff Recommendation Docket No. 15-CONS-770-CMSC).

This proposed PAR recommendation is based on a report of *Kansas Earthquake Activity in 2015* provided to KCC by Kansas Seismic Induced Seismicity Task Force (Exhibit A of the staff recommendation). The conclusion from this review of seismicity indicated small, but noticeable expansion of earthquake activity occurred in 2015 (Figure 22).

The recommendation pending further action by the KCC would reduce injection of brine to 12,000 barrels per day in this region. This limited injection rate is 1/10th the rate of the proposed CO_2 injection at Wellington (equivalent to ~150 tons/day of CO_2). The team who is operating the Wellington seismometer array have accurately recognized the expansion of small, but numerous earthquakes to the areas west of Wellington through 2015 confirming the results of the regional KGS temporary array. Importantly, the expansion of the seismicity to Wellington began before repressurization of the Mississippian oil reservoir in October 2015. In spite of the small geographic expansion of the seismicity in 2015, the actions taken by the State of Kansas in March 2015 are believed to have contributed to a notable decline in the overall number and size of earthquakes. While the area of the earthquakes seemingly expanded in 2015, earthquakes of magnitude M2 noticeably reduced while in the larger, magnitude 3 and higher events in Kansas have stopped altogether since November 2015 (Figure 21) (Testimony Buchanan, January 20, 2016).

We are confident that our continuously operating seismometer array, engineering and geophysical monitoring will ensure that our injection is safe. We are prepared for CO_2 injection in the Class VI Arbuckle well and to some measure have demonstrated our capabilities with the Mississippian injection.

The information gained in the monitoring and assessment of CO_2 injection during this test will establish a number of important results that will provide stakeholders a growing foundation of critical data in this region that should contribute basic geoscience data to assist in future interpretations and models that can help the scientific, regulatory, and industry conduct safe injection. Moreover, these test injection will allow us to verify outcomes where volumetric (porosity x thickness) estimates of CO_2 storage were considerably higher than simulations due to a poor understanding of injectivity. The novel method used to populate the geomodel with what we believe are more reliable and robust estimates of permeability by rock types related back to well log responses itself is a worthy objective. We believe the risk of conducting this test is very small with the safeguards that are in place.

A major goal of the (DOE funded) Wellington project is to evaluate cost effective and dependable methodologies to avoid risks in CO2 injection including testing of advanced monitoring technologies to prevent earthquakes and leakage enable geologic sequestration as an climate change mitigation technology. The analysis and methodologies provided in the following sections elaborates on this aspect of the project.

Potential Fault Identification/Characterization and its Projected Impact on Induced Seismicity

Fracture and fault interpretation of the 3D seismic data in the Wellington Field has undergone significant refinement since the initial seismic acquisition and interpretation in 2011 including --

(1) pre-stack time migration to examine volumetric curvature and discontinuities in time,

(2) depth-migrated seismic volume used to develop the latest Petrel geomodel and CMG simulation,

(3) soon to be completed Discrete Fracture Network (DFN) model of the depth-migrated Petrel geomodel, and

(4) newly initiated study of the azimuthal AVO (amplitude with offset) attribute analysis.

The major conclusion of the work to date is that depth-migrated seismic, which is integrated with the well data, eliminated some longstanding inconsistencies between interpretations of time and depth seismic due to notable lateral variations in interval velocity. The body of work has, and is being, funded by DOE and other sources from KGS and KU that leverage the DOE funding. A new study is focused on current structural analysis of graduate-level research supervised by KGS and KU faculty. This and other related research will continue a pending continuation of the project. All data will eventually be made publically available.

The depth-migrated 3D Petrel model provides a consistent, reliable basis to perform a detailed structural interpretation and importantly, delineation and interpolation of detailed reservoir property data essential in modeling the behavior of fluids including CO_2. Discrete fracture network modeling (DFN) now confirms details of a small medial, laterally and vertically discontinuous fault that bisects Wellington Field (**Figures 8-11).** A horizontal amplitude slice near the base of the Arbuckle at ~5000 ft shows the lateral change in amplitude across the fault at the depth of the injection zone (**Figure 8**). The Class VI well, #1-28, lies ~530 ft east of the medial fault. The currently operating Mississippian CO_2-EOR well, #2-32, is located within ~500 ft west of the medial fault. The forecasted CO_2 plume defining the AoR in the Arbuckle is also shown by the turquoise blue outline. The medial fault terminates north of well #1-28 and south of #2-32.

The seismic amplitude slice near the top of the Mississippian at approximately 3750 feet in **Figure 9** shows a similar SW-NE curvilinear trace (orange line) of the fault as occurs in the Arbuckle. The fault terminates west of well #1-28 and within a few hundred feet southeast of the operating Class II CO_2-EOR well, #2-32. The lateral variations along the time slice map are indicative the changes in the properties of the horizons due to elevation change across the fault, ~80 ft of displacement.

West-to-east and south-to-north seismic profiles (**Figures 10 and 11**) indicate that the small displacement does not sufficiently offset the distinct stratigraphically hydrostratigraphic units in the Arbuckle. Stable isotopes, geochemistry, and microbial suggest no notable exchange of the brine between the hydrostratigraphic units over the millennia in at least the area of Wellington Field. Previous work on regional characterization of the Arbuckle and simulation of CO_2 storage for 10 commercial size sites also provide supports for this vertical compartmentalization of the Arbuckle. These models demonstrate that the earlier volumetric estimates (porosity X thickness) of CO_2 storage capacity are much higher than those based on simulation, with difference due to limitations on injectivity of the reservoir and lateral variations in permeability (Section 4 and Appendix E of the Class VI permit application; Final Report of DOE-NETL contract DE- FE0002056, 2015). Exchange of fluid could occur between hydrostratigraphic units under high pressure, we believe that this would be very unlikely since relatively low pressures are forecasted in the Arbuckle CO_2 injection. Also, pressure and fluid measurements in wells surrounding the Mississippian CO_2 injection indicate containment of the CO_2. Likewise, current low reservoir pressure in the Mississippian reservoir demonstrates that vertical leakage from the strata below including the Arbuckle has not been of any concern.

The west-to-east seismic crossline identifies a medial fault the lies within 530 ft of well #1-28 at the depth of the proposed Arbuckle injection at 5000 ft (**Figure 10**). The fault tips out at the top of the Mississippian at the oil reservoir from which the field is producing. Significant underpressuring of the Mississippian reservoir (900 psi at 3600 ft deep) resulting from oil withdrawal over the course of decades from the original discovery of the field in 1929 and lack of a strong natural water drive confirms that the lower Mississippian caprock and the Arbuckle saline aquifer are not in hydraulic communication in the AoR.

The south-to-north seismic profile (**Figure 11**) runs nearly parallel to the fault and near the northern terminus and therefore the displacement is minor. The fault tip, based on the seismic profile, is in the lower Mississippian as the fault approaches its northern terminus.

The extension of the fault into the basement is conjectural with the seismic data since velocity control into the basement is not available.

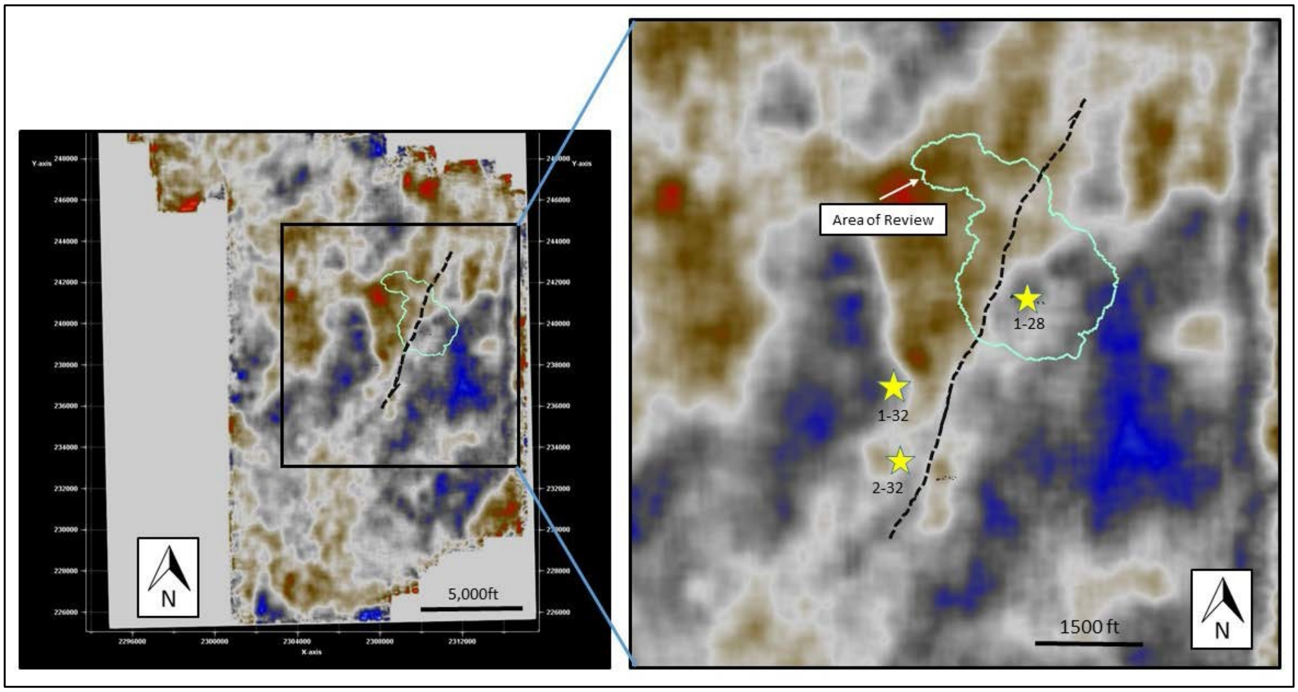


Figure 8. Map view of the near vertical medial fault near the Class II (#2-32) and Class VI (#1-28) injection wells in Wellington Field as shown on a horizontal amplitude slice of the 3D Petrel model at the base of the Arbuckle at ~5000ft. (the depth of the proposed Class VI injection). The width of the fault as shown on the map is proportional to the vertical offset. (Courtesy of D. Schwab, KGS/KU).

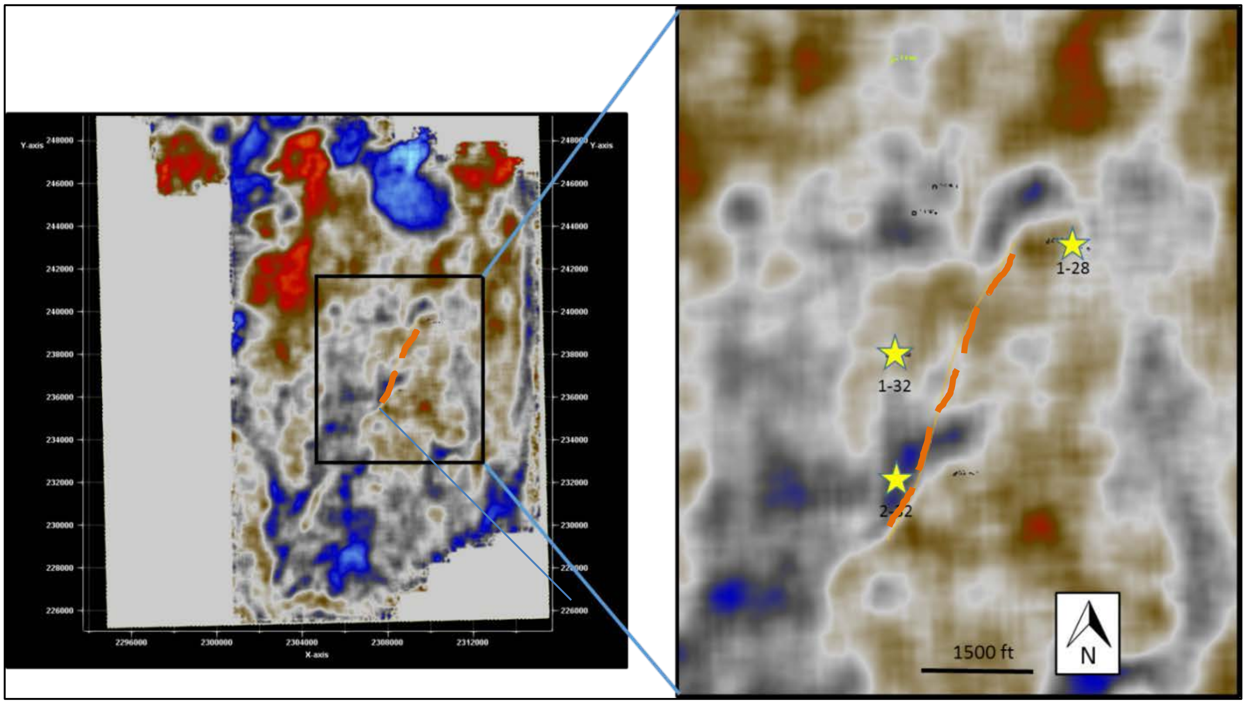


Figure 9. Seismic amplitude slice near the top of the Mississippian at around 3750 feet. The location of fault is the SW-NE curvilinear that delimits the discontinuous fault. The NW termination of the fault at the top of the Mississippian is due west of the Class VI injection well, #1-28. The southern termination is just southeast of the operating Class II CO_2-EOR well, #2-32. (Courtesy of D. Schwab, KGS/KU).

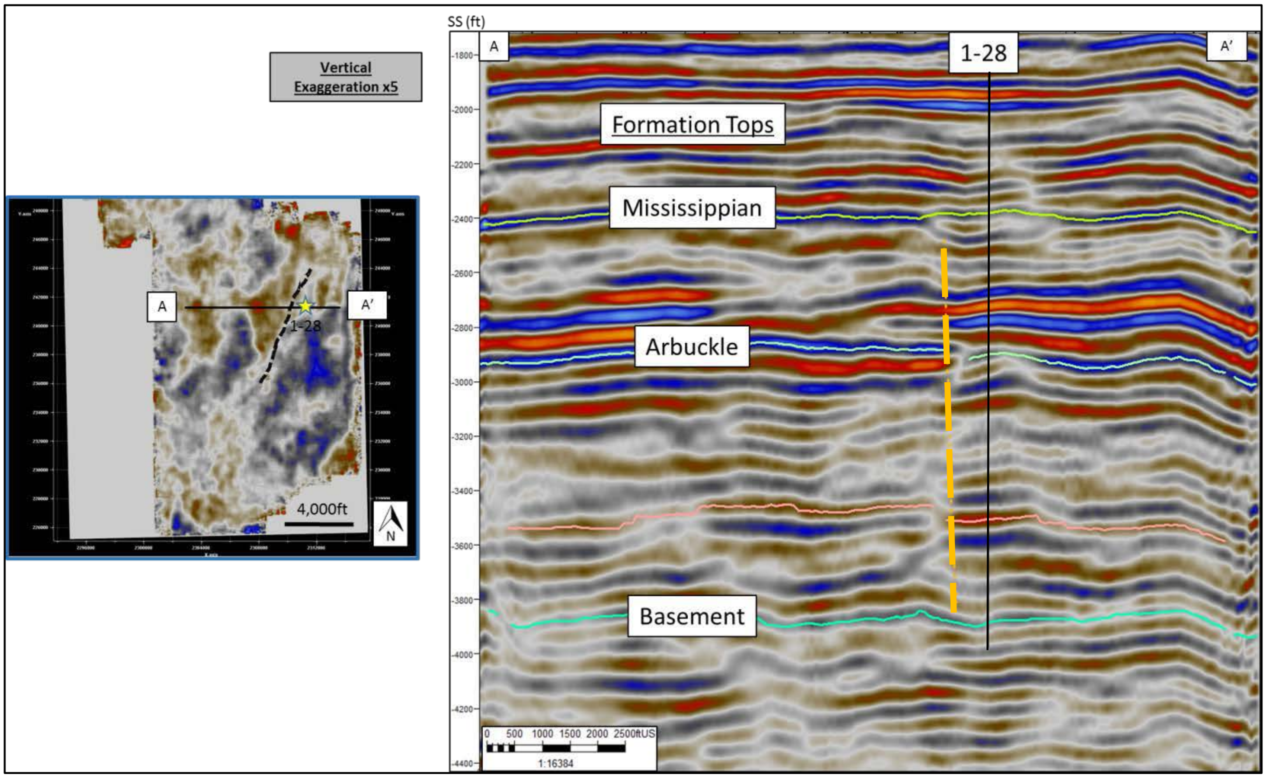


Figure 10. Medial fault as viewed in a west-to-east seismic amplitude profile with 5x exageration. Fault delineated as the orange dashed line is approximately 530 feet west of (Class VI) well #1- 28 at the injection interval of 5000 ft, depth intermediate between the arbitrary mid Arbuckle marker horizon (solid orange line) and the basement (turquoise line). The Arbuckle injection well is the vertical black line. (Courtesy of D. Schwab, KGS/KU).

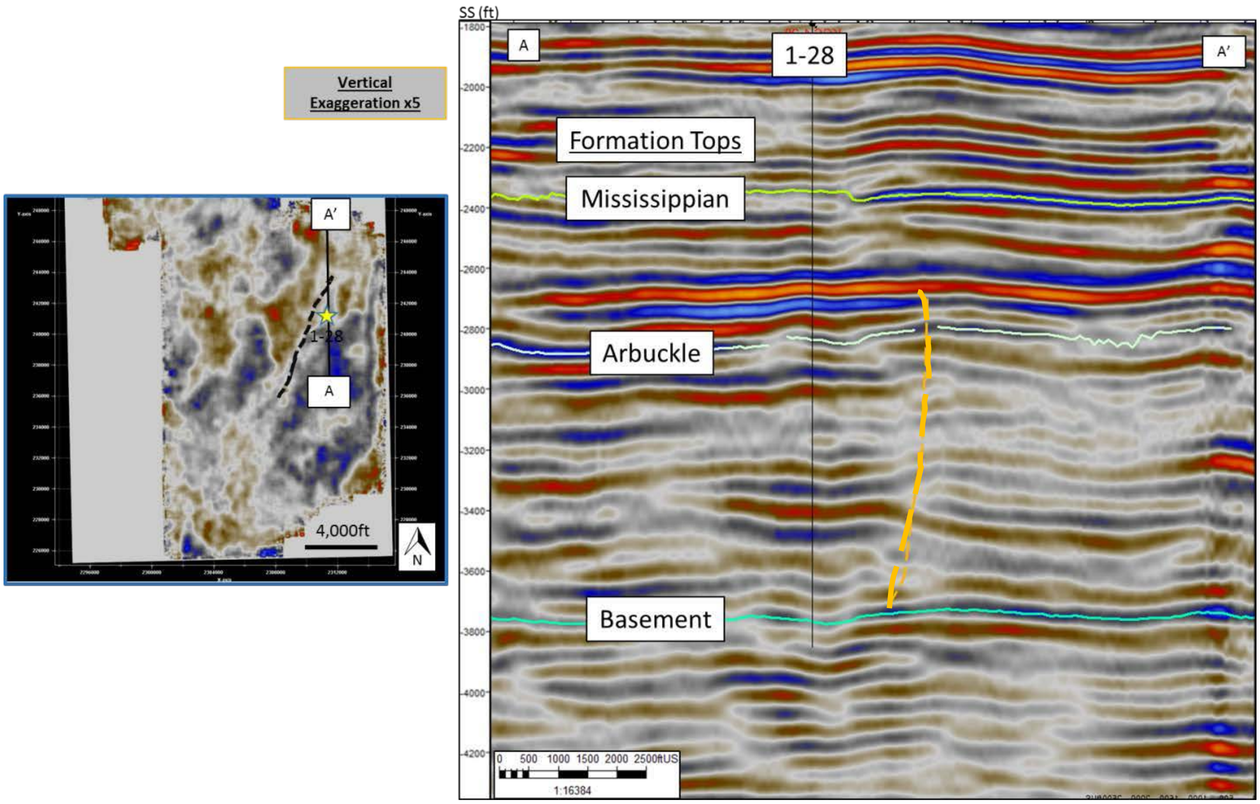


Figure 11. Medial fault as viewed in a south-to-north seismic amplitude profile vertical exaggeration of 5x. This south-to-north seismic profile runs nearly parallel to the fault and is located near the northern terminus of the fault. The fault line is a projection of where it crosses this section. Class VI injection well #1-28 is shown by the vertical black line. (Courtesy of D. Schwab, KGS/KU).

Reactivation Potential of Medial Fault

The general interest in developing a mechanical stratigraphy and characterization of fractures in 2011 and 2012 led to acquisition of the information used in the current analysis, including: (1) multi-component converted wave 3D seismic survey, (2) log core that sampled caprock, saline aquifer and the granite basement, (3) spectral sonic, density, and microresisitivity image logs, and 4) well testing. The recognition of the medial fault and the proximity of induced seismicity associated with brine disposal operations to the west encouraged the use of these data to evaluate the seismic hazard posed by the medial fault. Some of this information is included in Section 4 of the Class VI application.

Fault slip and dilation tendency analysis (Morris et al., 1996; Worum et al., 2004; Moeck et al., 2009) have provided critical pressures required to reactivate the medial fault based on the orientation of the fault relative to the principal stresses, a presumed coefficient of friction for the fault plane, pore fluid pressures, and style of faulting (e.g., normal versus strike-slip). These have been topics of considerable internal discussion and preliminary results shown here are still under internal review.

The slip tendency plot for faults in the area and the medial fault discussed above are visualized with fault planes (colored dots) on a Mohr circle shown in **Figure 12**. Based on the density log, step rate test, and image logs, the principal vertical and horizontal stresses were estimated as: Sv (5,308 PSI), Shmax (4,547 PSI), and Shmin (2,666 PSI) at a depth of 4869 ft (the middle of the proposed injection interval). The color scale is the Slip Tendency (ratio of shear stress to normal stress) and represents the coefficient of friction for fault planes at current reservoir conditions. Assuming a conservative coefficient of friction between 0.5 and 0.6, contact with the failure envelope would require an increase in pore pressure of 1,050 psi for a coefficient of friction of .5 and 1,350 psi for a coefficient of friction of 0.6. Substantially higher pore pressure increases would be required to reach failure on less optimally-oriented fault planes and fault segments (shown in greens and blues). It should be noted that based on the multiphase simulations conducted by the Wellington CMG model, a maximum pore pressure increase of only 15-20 psi is projected at the fault, which is substantially lower than that predicted for fault slip by the slip tendency analysis.

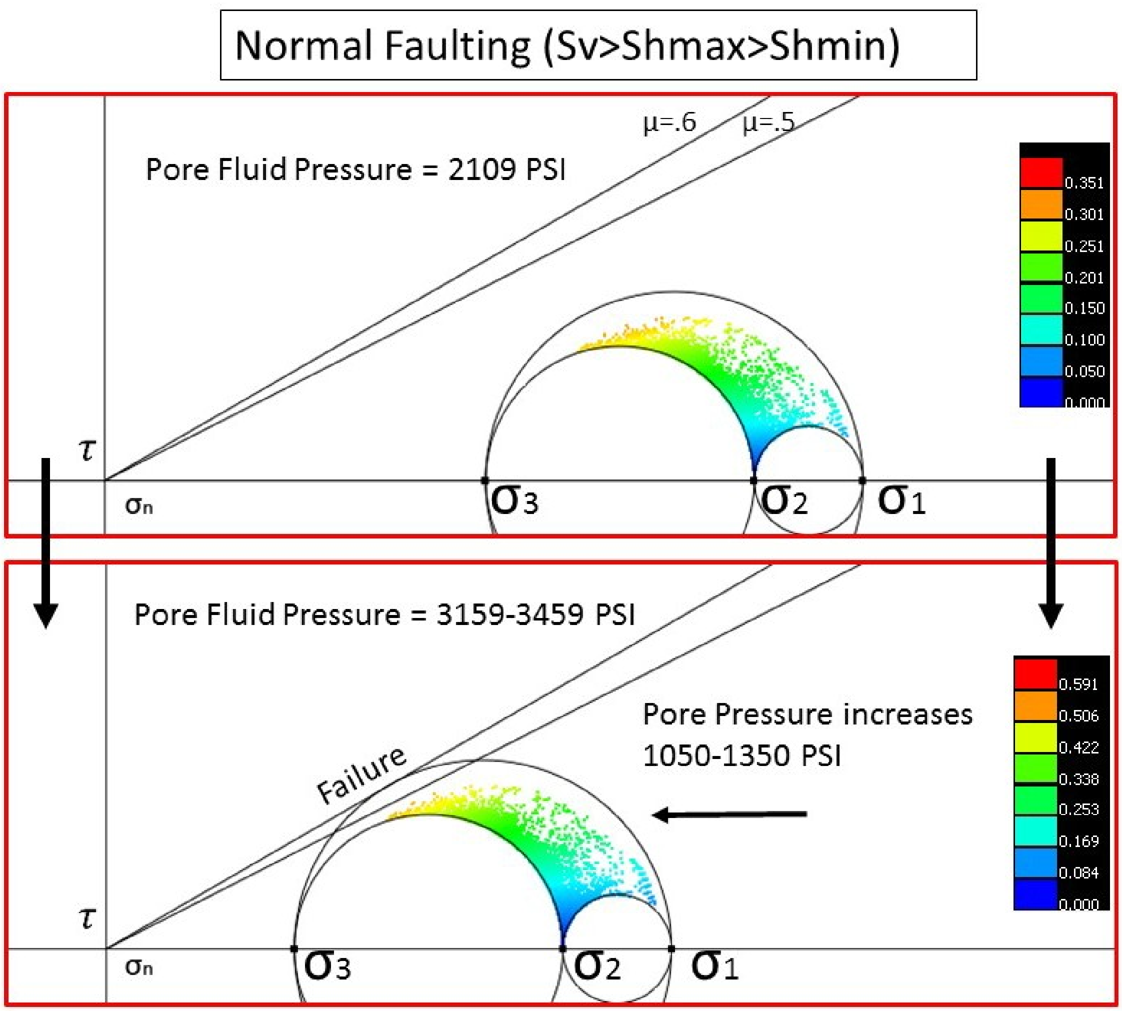


Figure 12. Slip tendency plot for faults within the study area as visualized with fault planes (colored dots) in a Mohr circle. A normal slip faulting stress environment was used to determine the slip tendency with estimates of principal stresses taken as Sv (5,308 PSI), Shmax (4,547 PSI), and Shmin (2,666 PSI) at a depth of 4,869 ft. The color scale is the Slip Tendency (ratio of shear stress to normal stress). Failure envelopes with coefficient of friction values of .5 and .6 are represented. (Courtesy of D. Schwab, KGS/KU).

Preliminary results summarized above on the 3D seismic mapping and reactivation potential of the faults were also reported by Bidgoli et al. (2015) at the AAPG Midcontinent Section Meeting in Tulsa, Schwab et al. (2015a) at the Geological Society of America Annual Meeting in Baltimore and Schwab et al. (2015b) at the AGU Fall Meeting in San Francisco. The work is part of the Master's thesis by Schwab at the University of Kansas, supported by the DOE contract DE-FE0006821 for small scale CO_2 injection at Wellington. The other recent presentation on estimated in-situ stresses, and slip and dilation tendency of faults was presented by Birdie et al. (2015) at South-Central Section, The Geological Society of America Meeting.

Representation of the Medial Fault in Class VI Model

In the geomechanical analysis described above, the potential of a fault to reactivate is dependent on the pore pressure acting on the fault plane. The pore pressure in the Arbuckle injection zone forecasted by the simulation of CO_2 injection is dependent on the hydrogeologic properties of the rocks at and near the fault. The Petrel model used in the simulation of the Area of Review (AoR) is considered robust given the constraints discussed initially on key properties derived from the comprehensive reservoir characterization. In particular, the (1) data demonstrating the lack of vertical communication between hydrostratigraphic units in the Arbuckle indicated by the results of multiple DST and perforation and swab tests (Section 4, Class VI application); (2) consistent reductions in permeability along both sides of the medial fault within the injection zone; and (3) sharp flexural bending along the medial fault. These data suggest simulation results constrained by the information available resulting in a reliable AoR.

The series of illustrations from the recently revised Section 5 of the Class VI permit are included in this document to show that the medial fault is sufficiently characterized by the information that is available to warrant its use in the forecast of the AoR. However, it is imperative that the *Wellington Operating Plan for Safe and Efficient Injecti*on be carefully implemented to monitor possible deviations and anomalies that fault and fracture systems may introduce. In particular, monitoring will be done to carefully recognize (1) abrupt changes in downhole pressure, (2) detection of CO_2 moving out of the injection zone using downhole continuous active seismic (CASSM), (3) examining Mississippian monitoring wells and use of 2D seismic to evaluate the loss of CO_2 into the Mississippian (4) detection and characterization of microearthquakes ($M<1$) and larger as described later this this document. This is precisely what is being done in the active CO_2 injection in overlying Class II Mississippian CO_2-EOR injection in well #2-32 previously shown in **Figures 8 and 9**. A brief summary of the Class II injection results obtained to-date will follow this section.

The model mesh of the Arbuckle model presented in **Figure 13** clearly shows the small down to the east declivity corresponding with the medial fault. As noted in the vertical slices of these figures, the displacement across the vertical fault is small (~80 ft) relative to the thickness of the hydrostratigraphic units comprising the Arbuckle. **Figure 14** is a 3D volume of the porosity used in the simulation. A 3D volume (**Figure 15**) and west-to-east cross section of the horizontal permeability in **Figure 16** shows significant reduction in the permeability by two orders of magnitude along and either side of the sharp flexure representing the medial fault and reduced permeability continuing eastward to and beyond well #1-28. Without carefully instituted injection and testing, additional properties for the fault are uncertain. The exact processes involved in the porosity and permeability reduction are not known at this time. The vertical permeability in **Figures 17 and 18** is similarly greatly reduced along and across the medial fault towards the east through KGS #1-28.

The notably north-south elongated CO_2 plume developed after 1-year of injection is strongly affected by the reduction of permeability immediately west of well #1-28 (**Figure 19**). The CO_2 plume extends initially north-northeast of the injection well and then bends to the northwest as it moves across the medial fault (**Figure 20**). The pressure field extends beyond the north end of the fault and near its tip on the south end and continues to the western portion of the mapped area (**Figure 20**).

Figure 20 includes the location of the well #2-32, the Class II CO_2-EOR injection well. This well is currently injecting CO_2 into the shallower Mississippian oil reservoir where nearly 10,000 metric tons have been injected to date. The injection well lies within an estimated 500 ft of the medial fault. This injection will be briefly summarized next in the interest of conveying how the medial fault was characterized and how the performance has been used to evaluate the veracity of the characterization and modeling effort, and the management and safety of this CO_2 flood.

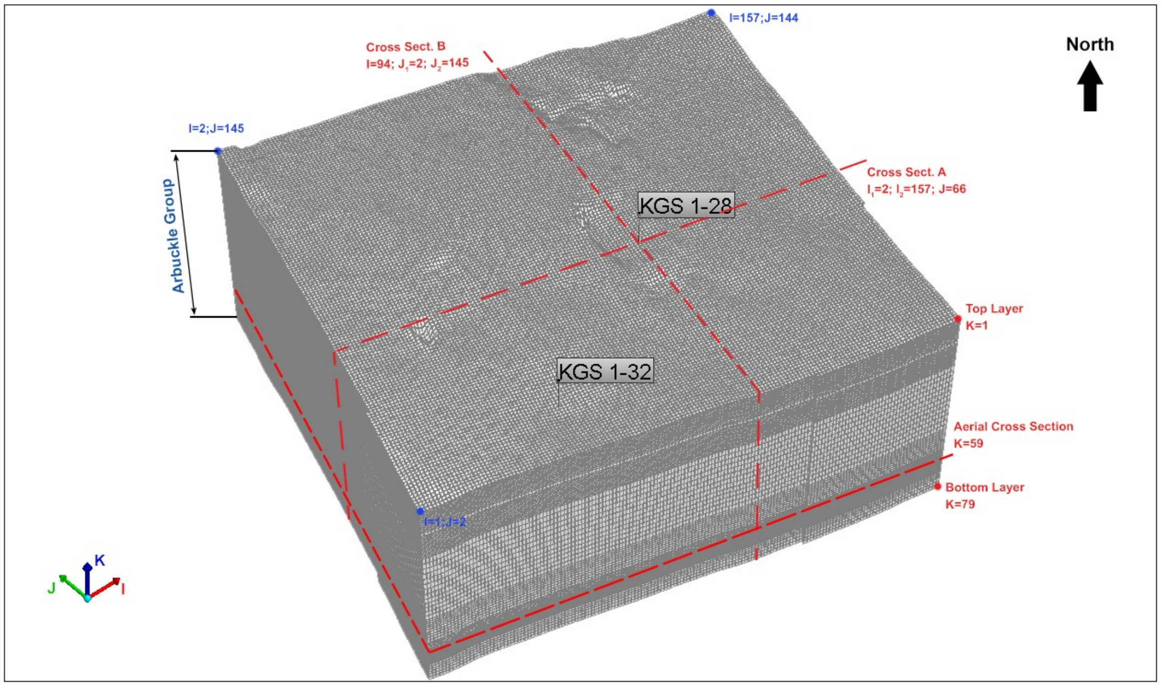


Figure 13. --Model mesh in 3-D showing location of Arbuckle injection and monitoring wells along with the east-west and north- south cross sections. Note the small declivity on the top of the Arbuckle produced by the medial fault.

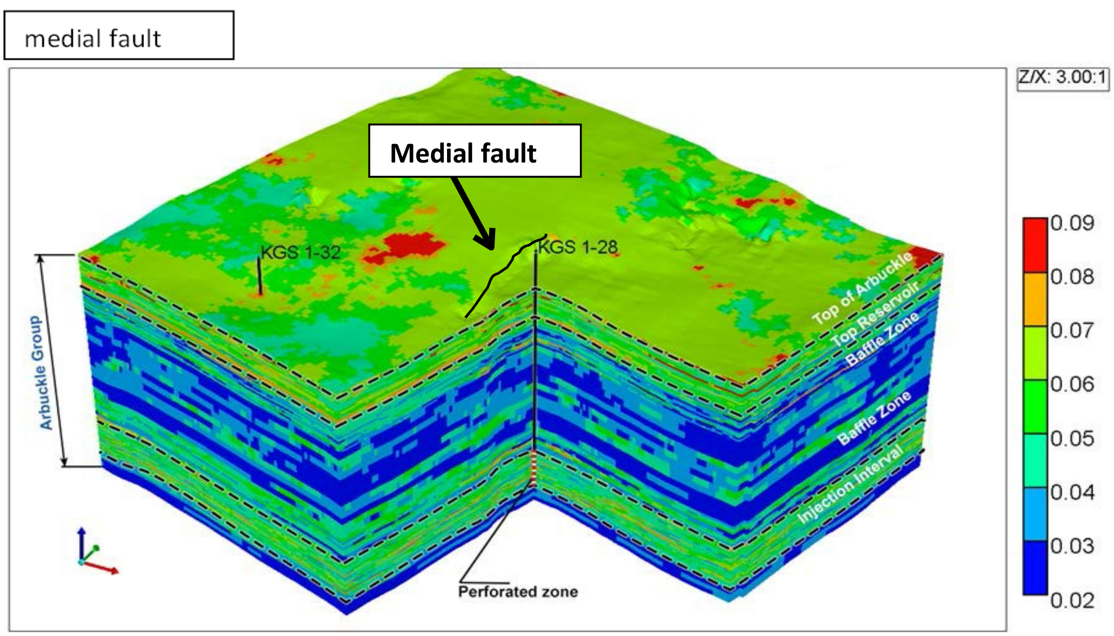


Figure 14. Upscaled porosity distribution in the Arbuckle Group based on the Petrel geomodel. Note the discontinuous relief on the surface of the Arbuckle west of KGS #1-28.

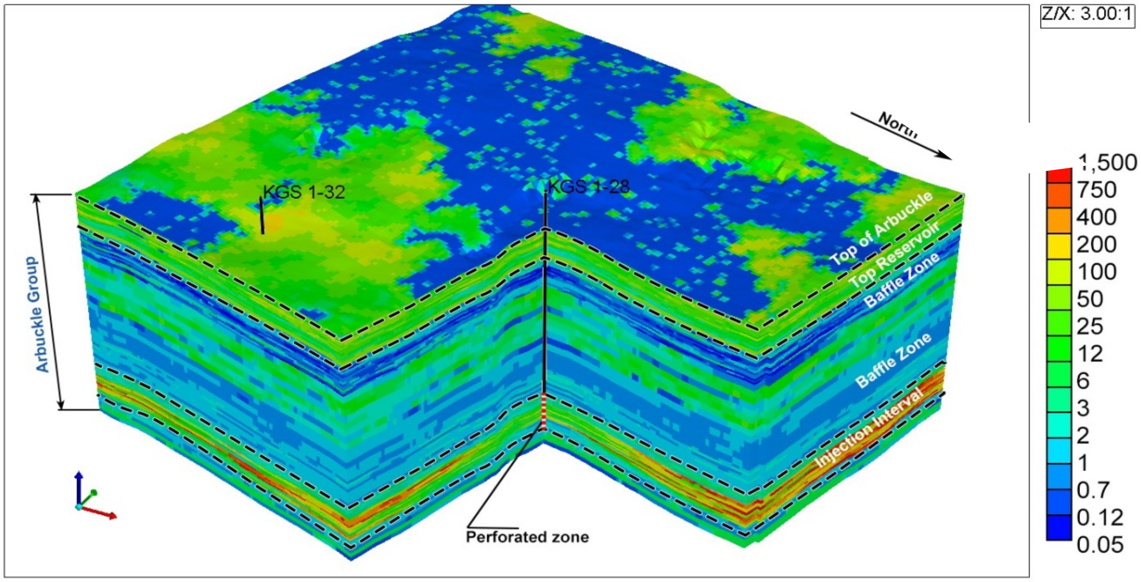


Figure 15. Upscaled horizontal permeability (mD) distributions in the Arbuckle Group derived from Petrel geo-model. The permeability is reduced in the injection zone in the vicinity of KGS #1-28.

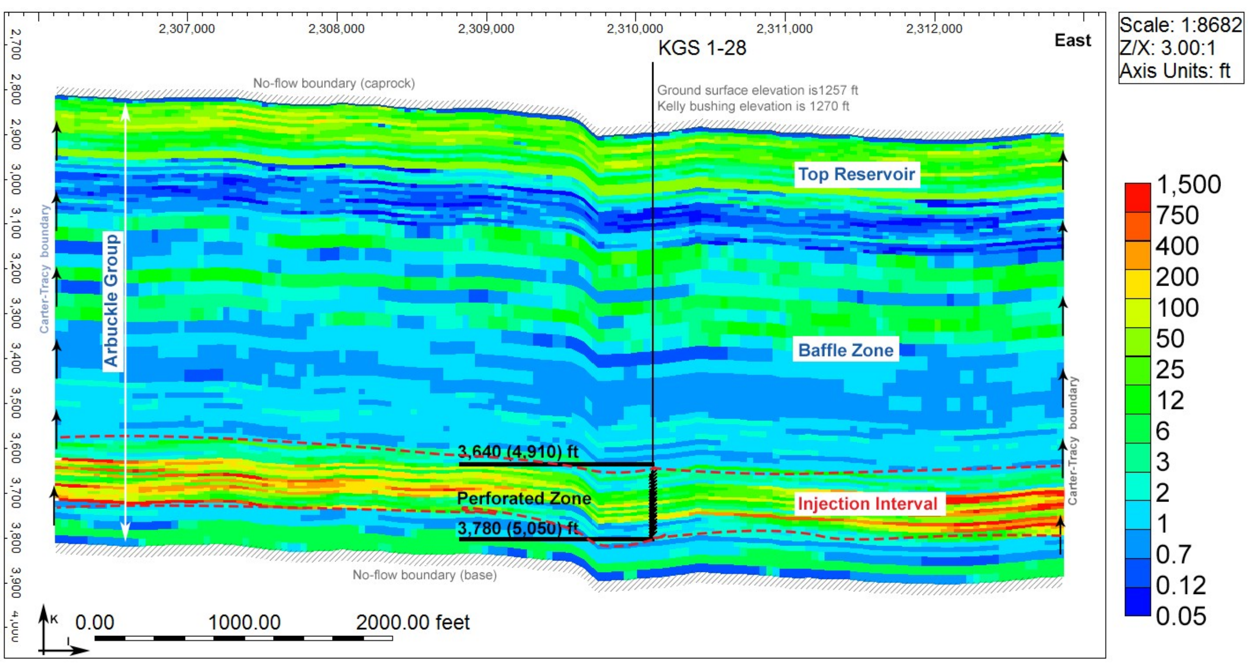


Figure 16. Horizontal permeability (mD) distribution within an east-west cross section through the injection well (KGS 1-28), vertical cross-section A-A'. Location of cross section shown in Figure 13.

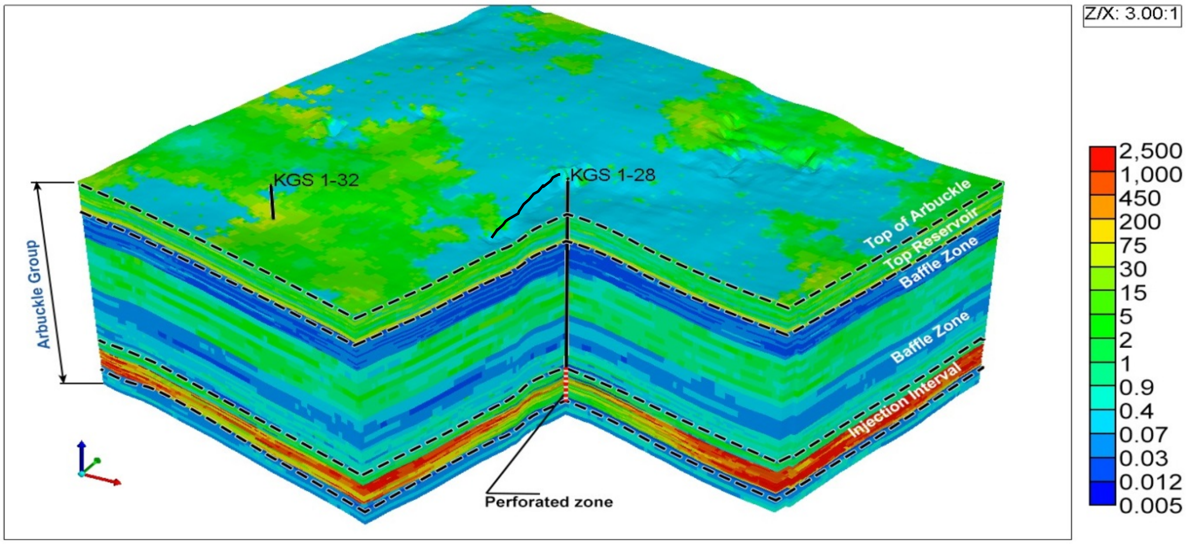


Figure 17. Upscaled vertical permeability (mD) distributions in the Arbuckle Group derived from Petrel geomodel.

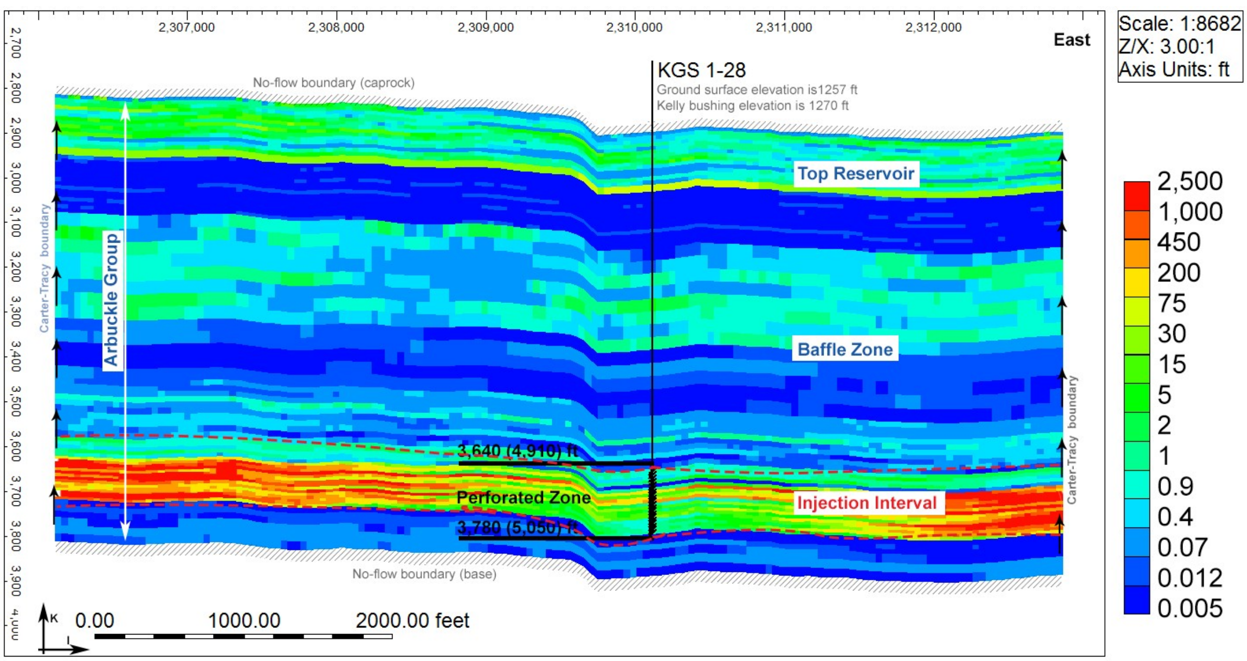


Figure 18. Vertical permeability (mD) distribution within an east-west cross section through the injection well (KGS 1-28), vertical cross-section A-A'. Location of cross section shown in Figure 13.

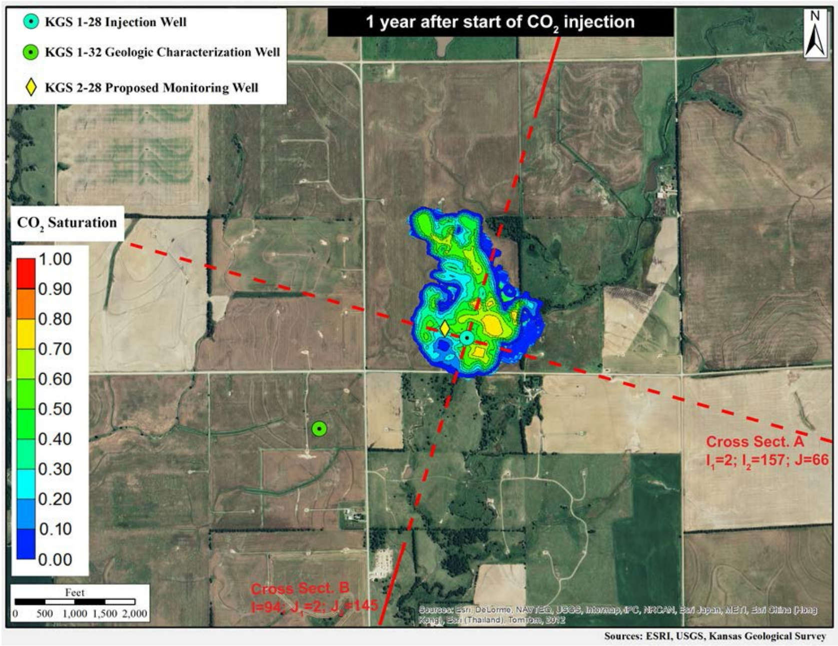


Figure 19. CO_2 saturation of the CO_2 plume after 1 year of CO_2 injection of 40,000 metric tons.

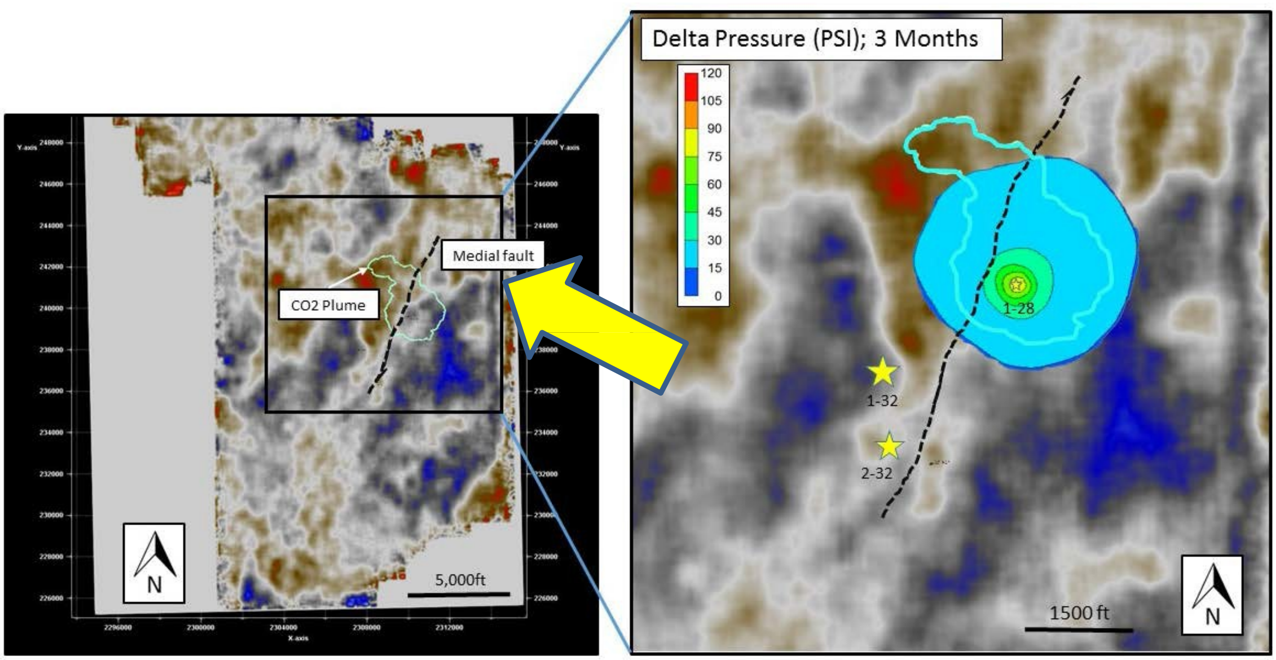


Figure 20. Delta pore pressure (filled color according to the scale bar) after 9 months injection of 40,000 metric tons of CO_2 in well #1-28. Outline (light blue solid line) of CO_2 saturation after 1 year of CO_2 injection. The medial fault is the black dashed line. Locations of the three KGS wells including the Class II CO_2-EOR injection well, #2-32, southwest of the Class VI well and near the medial fault shown in the figure.

Medial Fault and its influence on Class II Mississippian CO_2-EOR Injection

An extensive set of well logs and core was acquired during construction of the CO_2-EOR injection well (KGS #2-32). The data was analyzed for interpretation of the geology and hydrogeology to a similar extent as documented in the Class VI permit for the Arbuckle wells (KGS #1-28 and KGS #1-32). Whole cores were also collected and subject to Special Core Analysis (SCAL) to establish rock and fracture properties. Multi-well test was conducted to evaluate pressure connectivity between wells. As for the Arbuckle Class VI project, the site data was used to construct a (Petrel based) geomodel of the Mississippian reservoir using the same workflow as the Arbuckle Class VI model. The 3D Petrel model, which includes the medial fault in the Mississippian, suggests a reduction in both permeability and porosity near the fault. This reduction in porosity and permeability is attributed to depositional changes that occurred across a syndepositional fault that was active during the late Mississippian time prior to its quiescence post Mississippian (**Figures 21 and 22**). (Rush, et al., 2016). While the processes related to the reduction are different between the Arbuckle and the Mississippian, the property data along the medial fault is similar.

A second similarity between the Mississippian and Arbuckle modeling is that the reservoir heterogeneity is incorporated in the Petrel model in a robust manner as is being demonstrated by the accuracy of the forecasts of the performance of the Mississippian CO_2-EOR pilot injection. Since commencement of injection on January 9, 2016, surrounding wells are being measured weekly for pressure, fluids produced, oil cut, and CO_2 and samples taken for cation and anion analysis of brine and GC analysis of casing head gas. The third similarity is that the daily rate of CO_2 injection ~ 150 tons and the total volume to be injected (~ 26,000 tons) are essentially the same as what is intended for the Arbuckle Class VI injection. As of March 31, 2016, nearly 10,000 metric tons have been injected through a 30 ft perforated interval and CO_2 and oil produced have behaved very closely to that forecasted, with measurable, yet minor volumes (~1% of the CO_2 injected) of the CO_2 reaching the wells immediately around the Class II injection well, #2-32 (**Figures 23 and 24**).

A distinct contrast between the Mississippian and Arbuckle activities is in the pore pressure change due to the CO_2 injection. In the Mississippian, bottomhole pressure has been increased by up to 600 psi). During this period, there have been no earthquakes of magnitude 2.5 or larger in Wellington Field as detected in either the Wellington, Kansas, or USGS seismometer networks. We anticipate that pressures will increase to over 800 psi in the Mississippian by the end of CO_2 injection in July 2016, by which time approximately 26,000 tons of CO_2 will have been injected in the Mississippian reservoir.

The 700 psi increase in the Mississippian reservoir is 23 times higher than the projected pressure at the medial fault the during the Class VI injection in the Arbuckle. It is safe to conclude at this midpoint of the Mississippian injection with the containment of the CO_2 around the inner monitoring wells with initial oil recovery (1000 barrels) underway as predicted without significant venting of CO_2 that the characterization and modeling of the Mississippian is reliable and that the matrix dominated characterization of the Mississippian dolomite (**Figure 24**). Thus far, no measureable earthquakes are attributable to this injection. With anticipated containment of CO_2 in the Arbuckle at much lower pressures, well below the estimated critical pressure to induce seismicity, we are highly confident that producing a detrimental earthquake is highly remote.

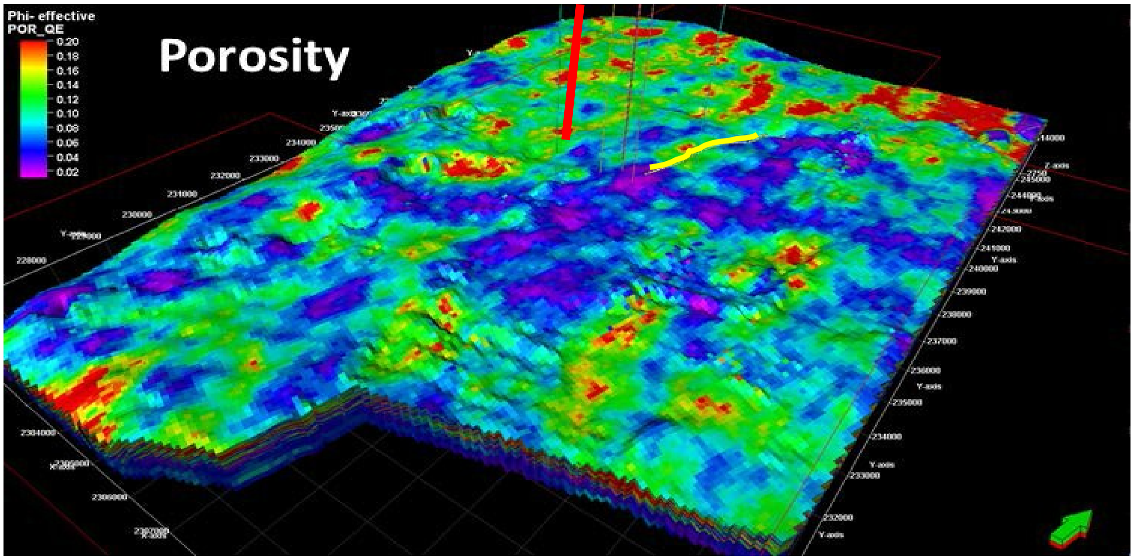


Figure 21. Petrel-based porosity map of the Mississippian reservoir at Wellington Field. CO_2 injection well is red colored vertical line near middle of the map. Low porosity noted east and south of the injection well, KGS #2-32. Very thin north-northwest trending yellow line is the trace of the medial fault.

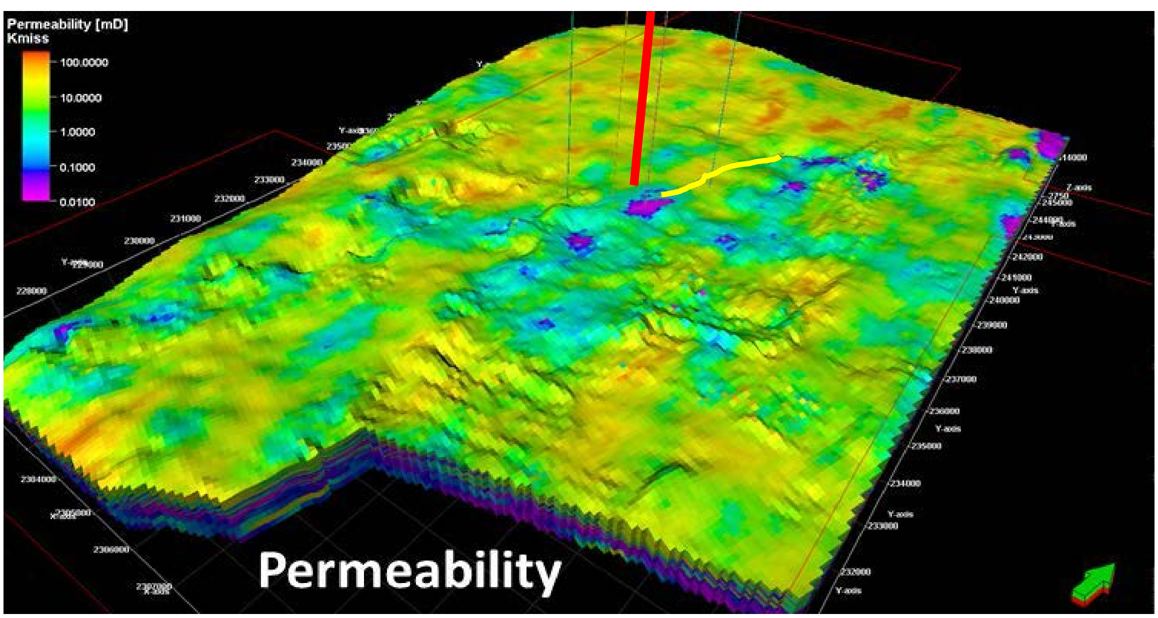


Figure 22. Petrel-based map of permeability for the Mississippian oil reservoir. CO_2 injection well is red colored vertical line near middle of the map. Lower permeability noted east and

south of the injection well, KGS #2-32. Very thin north-northwest trending yellow line is the trace of the medial fault.

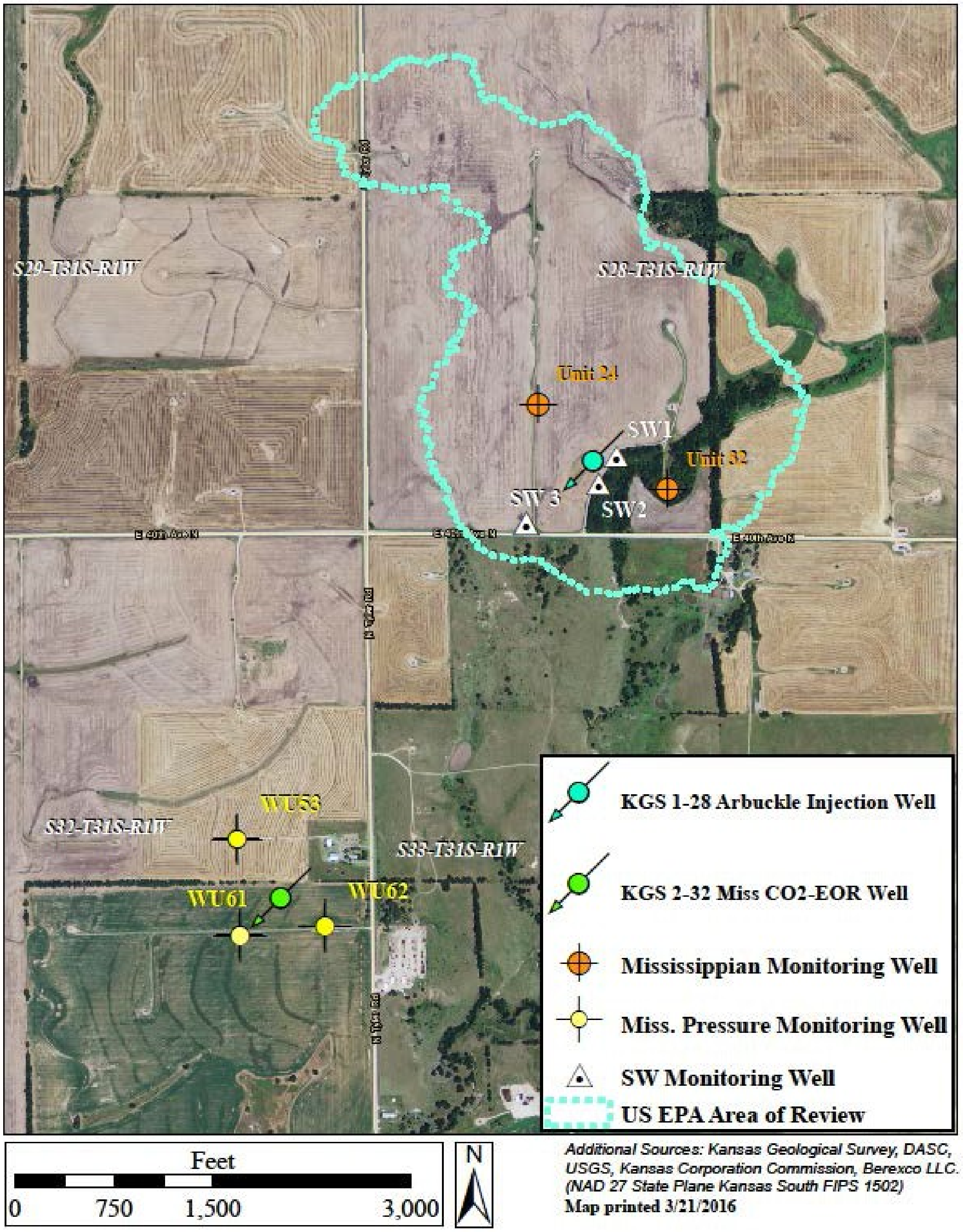


Figure 23. Location of observation wells that are continuously monitored for pressure at the Wellington Enhanced Oil Recovery (EOR) site.

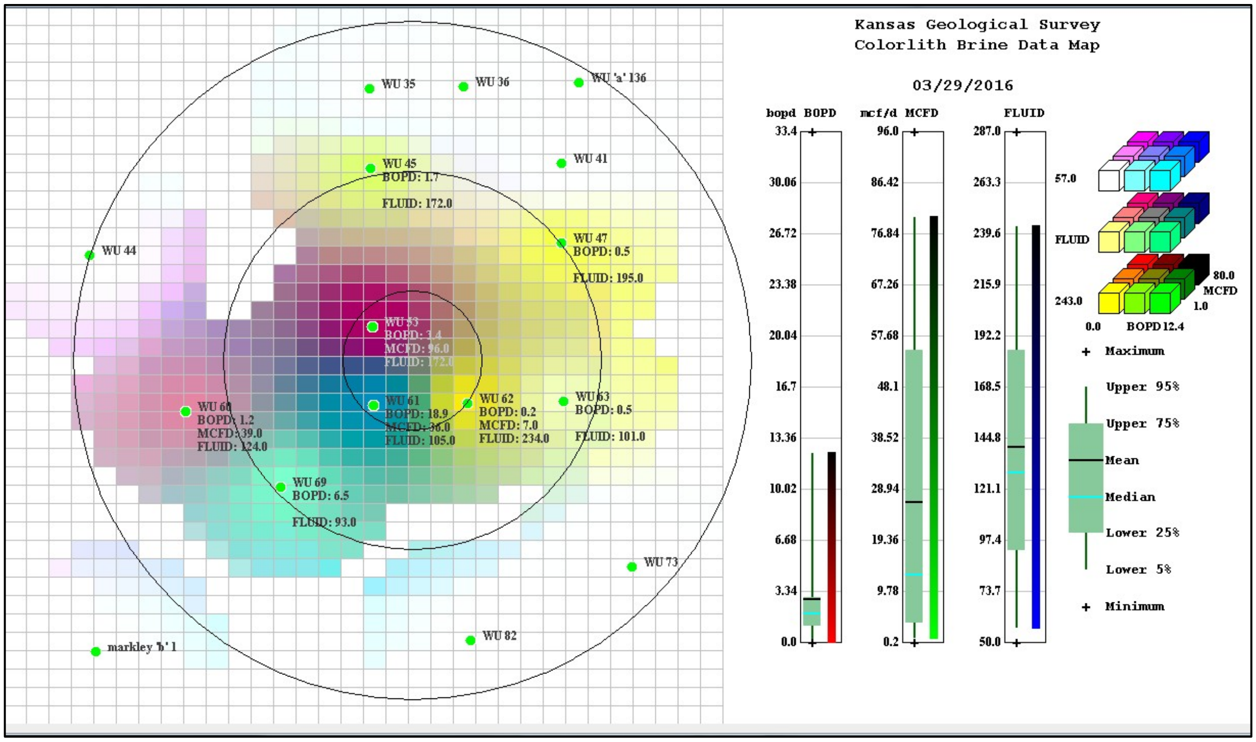


Figure 24. Well monitoring of the CO_2-EOR injection on March 24th indicates minimal CO_2 venting (approximately 2% of the total CO_2 injected) is limited to inner ring wells immediately surrounding the CO_2 injection well and well #60 in a few hundred feet to the southwest of the injection well. Oil production is well above the average from the inner ring wells and wells #60 and #69 immediately southwest of the injection well. In contrast, well #63 on the east side of the medial fault and east of the CO_2 injection well has not as yet responded to the CO_2 injection.

Summary of Potential Impacts of Medial Fault on Induced Seismicity

Stable oxygen and hydrogen isotopes and contrasts in cations and anion abundance within the Arbuckle hydrostratigraphic units and pronounced underpressuring in the Mississippian oil reservoir relative to the Arbuckle and overlying strata suggests that the medial fault is not in communication with shallower intervals. Reduced porosity and permeability in the proposed injection interval on either side of the medial fault is believed to be the extent of the influence of the fault with the information that is available. Advanced geologic characterization using seismic, wireline logs, and core analyses has been incorporated in the model. Therefore, the fault hydrogeologic properties are adequately represented in the CMG simulation model.

1. Geomechanical analysis suggests that the likelihood of movement along the medial fault is extremely low with injection pressures well below that required to move the fault.

2. The rate and total volume of CO_2 that is injected (<1000 barrels per day, 225,000 barrels

annually) falls considerably below what is considered by regulators to be a high volume well (12,000 barrels per day and ~4 million barrels annually) by Class I and II standards.

3. Mississippian injection of brine and CO_2 during EOR at KGS #2-32, which is of similar magnitude as that planned for the Arbuckle project, has not produced any earthquake of M2.5 or larger, which is a (Class VI) threshold magnitude.

Region Wide Induced Seismicity
Induced Seismicity in South-central Kansas

Abnormally high levels of seismicity rapidly increased in parts of north-central Oklahoma beginning in 2013 with development of the Mississippian Lime Play that was accompanied by exceeding large quantities of brine disposal in the deep saline Arbuckle aquifer system. By 2014, abnormally high seismicity increased abruptly by 20-fold in south-central Kansas including Harper and western Sumner counties following extension of the oil play and disposal wells that began in Kansas in 2012. By 2014, brine disposal rates in south-central Kansas were over 7 times annual disposal volumes for the prior decade (Figure 18). Over 120 million barrels of brine were disposed in the Arbuckle in Harper and Sumner counties in 2014 (**Figure 25**), with wells initially permitted to dispose up to 80K barrels per day. Tubing pressures reported from these high volume wells were up to 450 psi. The number of earthquakes and very large volumes of brine delivered by a few large wells in a focused area was a clear, historical departure from previous seismicity and disposal in Kansas.

Earthquakes continued to steadily increase into early 2015 before the Kansas Corporation Commission issued an order on March 19, 2015 to operators in areas of high seismicity in Harper and western Sumner counties to reduce rates of injection in these areas to less than 8,000 barrels per day and tubing pressures to an average of 250 psi a 100 days after issuance of the order (**Figure 26)** (http://estar.kcc.ks.gov/estar/ViewFile.aspx/15-770%20Order.pdf?Id=05630050-78a3-4800-a08b-852023775305a). Oil production and related brine injection also fell in late 2014 with major fall in the oil price (**Figure 27**) and together appear to have contributed to the continuing decrease in seismicity (**Figure 28**). Larger earthquakes above 3 and 4 magnitude have steadily decreased and no earthquakes in Kansas exceeding 3.0 have been recorded since mid-November 2015. A USGS temporary seismometer network was installed west of Wellington in 2014. This added USGS network is of interest to the Wellington project due to its location. Information such as earthquake waveforms (CODA) have be used from the USGS array to compare with data recorded in the Wellington array. These data were used initially to confirm magnitude and depths

On February 19, 2016 the Conservation Division of the Kansas Corporation Commission issued a Staff Recommendation Docket No. 15-CONS-770-CMSC in support of a Proposed Area of Reduction (PAR) to replace the current Areas of Seismic Concern that was issued by KCC on March 19, 2015. The rationale is that data from the KGS temporary seismic network noted an increase in seismicity through 2015 that occurred outside of the original Areas of Seismic Concern (Figure 19). Accordingly, the KCC has issued a Proposed Area of Reduction (PAR) --

The Wellington seismometer array has recorded this expansion of small earthquakes west of Wellington Field as well as the clustering of earthquakes similar to ones earlier that led to the original Area of Seismic Concern.

KCC recommendations for the PAR include --

All Arbuckle injection wells located within the PAR, but outside of the original areas of concern should be subject to the following scheduled reductions:

a) 16,000 barrels per day per well within 10 days of the Order in this docket.
b) 12,000 barrels per day per well within 55 days of the Order in this docket.

On February 19, 2016 the Conservation Division of KCC issued a recommendation to replace the original Area of Seismic Concern with a new Proposed Area of Reduction (PAR) continuing the injection limitations currently implemented and expanding their geographic scope. Specifically, Class II brine disposal wells in the Arbuckle in the expanded area would be limited to 12,000 bbls per day within 55 days of the order. If enacted, the expanded area would include Wellington Field at the far eastern edge (KCC Staff Recommendation Docket No. 15-CONS-770-CMSC).

This proposed PAR recommendation is based on a report of the Kansas Earthquake Activity in 2015 by Kansas Seismic Induced Seismicity Task Force (Exhibit A of the staff recommendation). The conclusion is that there has been a small but noticeable expansion of earthquake activity in 2015 (**Figure 29**).

The recommendation pending further action by the KCC would reduce injection of brine to 12,000 barrels per day in this region (**Figure 30**). This limitation on injection is 1/10th the rate of the proposed CO_2 injection at Wellington (equivalent to ~150 tons/day of CO_2). The team who are operating the Wellington seismometer array have accurately recognized the expansion of the small but numerous earthquakes to the areas west of Wellington through 2015 confirming the results of the regional KGS temporary array. Importantly, the expansion of the seismicity to Wellington began before repressurization of the Mississippian oil reservoir in October 2015 (**Figure 31**). In spite of the small geographic expansion of the seismicity in 2015, the actions taken by the State of Kansas in March 2015 are believed to have contributed to the decline in the overall number of events exceeding M2 including noticeable reductions in the larger, 3 magnitude and above in Kansas (**Figure 28**) (Testimony Buchanan, January 2016).

We remain confident that our continuously operating seismometer network and engineering monitoring proposed for the Class VI Arbuckle well and to some extent being demonstrated with the Mississippian injection, will ensure that our injection is safe. Moreover, the information gained will allow us to contribute further to the understanding and the management of disposal in an area with induced seismicity.

The far northeastern edge of the PAR does extend just to the outline of Wellington Field (**Figure 30**). Our maps derived from and the supporting documentation described above for the Wellington seismometer array attests to its capability to provide an accurate research grade earthquake data. A proactive stance will include repositioning two of the broadband seismometers immediately west and east of the field to be able to refine locations and properties of nearby earthquakes including resolution of fault planes and slip vectors.

In addition to providing guidance on where the expansion of the seismicity is occurring, the KGS has performed preliminary simulations of the brine injection from large volume disposal wells in Harper and western Sumner Counties. The simulations suggest a development of an elevated regional pressure field in the Arbuckle that closely corresponds to the expanded area of low-magnitude seismicity (Bidgoli et al, 2015). Refinements to the preliminary simulations will be improved with input from the ongoing testing and monitoring at Wellington (e.g. downhole pressure monitoring to commence soon at KGS 1-28 to see if static pressures have changed since 2011.).

Berexco and the KGS will soon initiate a 1-month long continuous measurement of bottomhole pressure at the open perforations in the proposed Class VI injection well, #1-28. The data in absolute pressure will be compared with earlier data collected prior to the induced seismicity to test simulations by the KGS to evaluate pressure spatial and temporal pressure changes resulting from monthly brine disposal volumes in the Arbuckle. The simulations based on actual rock property assessment from well log data calibrated from the Wellington small scale project suggests that a large pressure field has developed in the Harper and eastern Sumner County area in the Arbuckle and/or the upper basement. The continued bottomhole pressure testing will build on this new information to assess temporal changes. The information and interpretations would be put in context of literature on this type of hydrologic testing. The results would be made available to DOE, EPA, state regulators, and the induced seismicity task force.

The seismometer data coupled with our engineering monitoring and active seismic imaging set for the actual injection will help us ensure that we are not the causing earthquakes above 2.5 magnitude, but will closely monitor all the information toward understanding the mechanisms and dynamic behavior of what is attributed to induced seismicity. The rate and volume of our small-scale CO_2 injection results in a small, transient pressure field.

The recently released USGS report, *2016 One-Year Seismic Hazard Forecast for the Central and Eastern United States,* further highlights the concerns for hazards created by induced seismicity in Oklahoma and southern Kansas (Petersen et al., 2016).

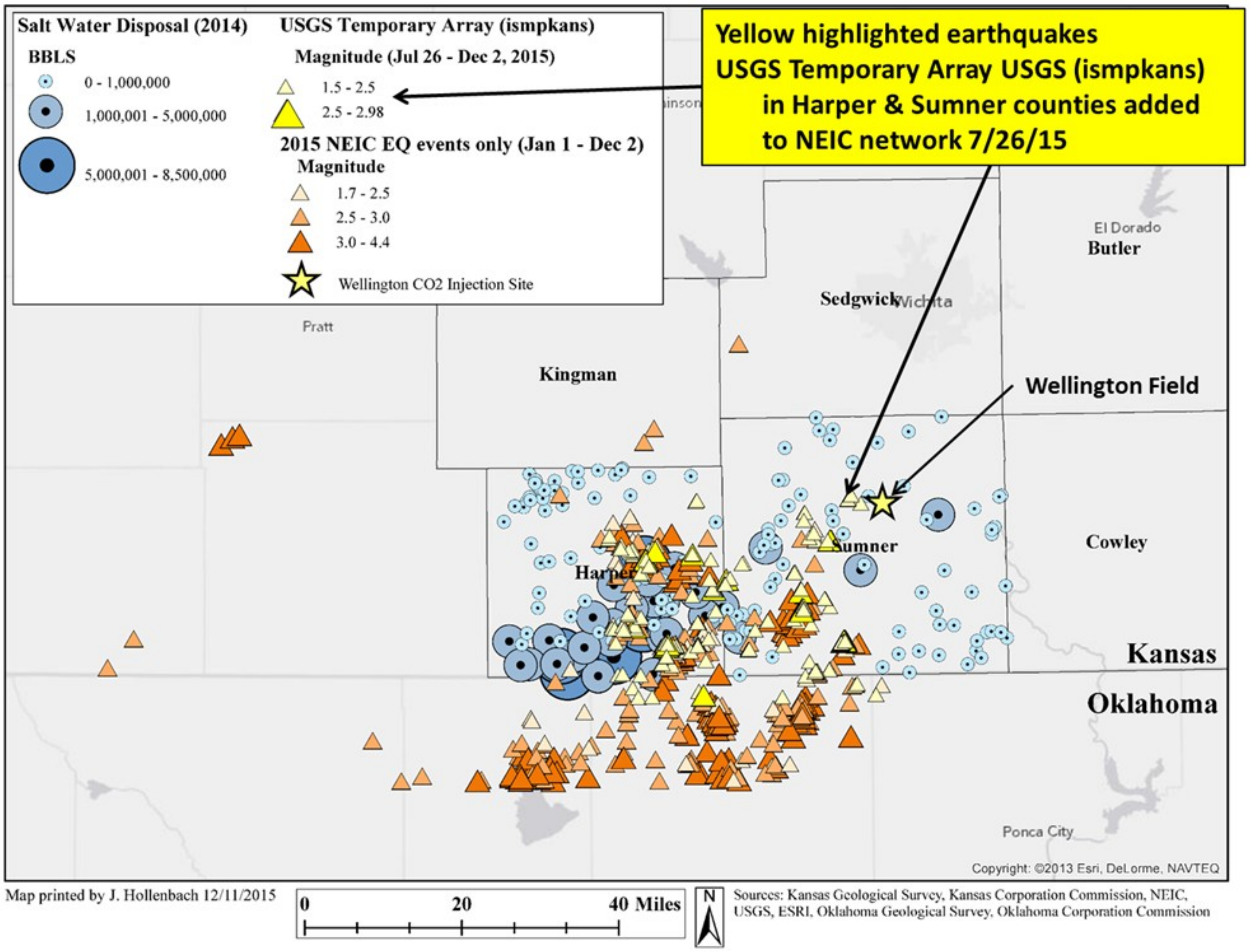


Figure 25. Map of south-central Kansas and northern most portion of north-central Oklahoma. Brine disposal wells shown in Kansas for 2014 with volumes of disposal noted by size of blue circles. Earthquakes shown by orange triangles from NEIC catalog for period January 1, 2015 to December 2, 2015, but not including those from USGS temporary array released on 7/26/2015. The events from the temporary array are shown in yellow triangles. Larger triangles are larger earthquakes.

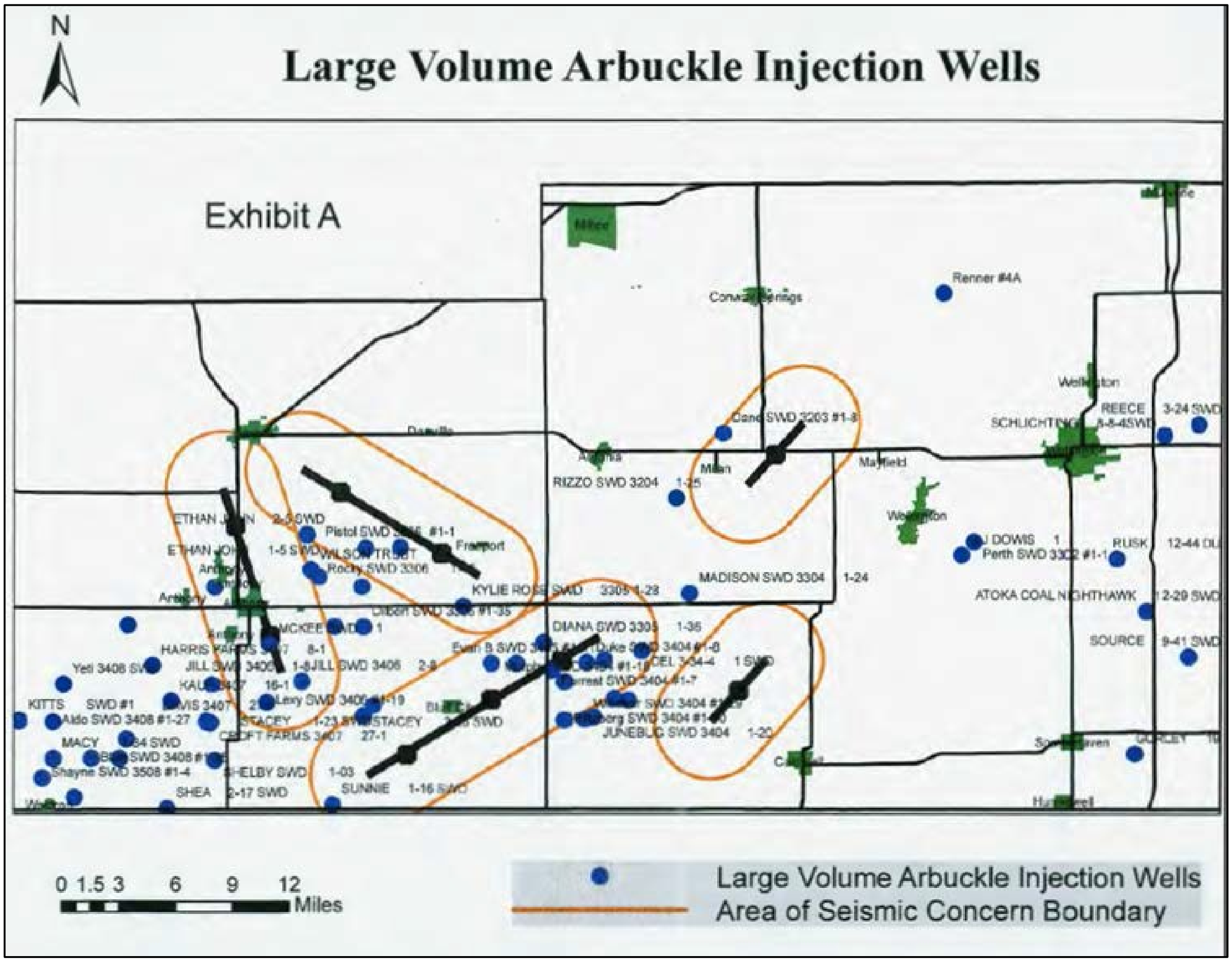


Figure 26. Reduction of rates of injection into the Arbuckle applicable to wells in defined areas of increased seismic activity in Harper and Sumner Counties in KCC Order Reducing Saltwater (Docket No. 15-CONS-770-CMSC).

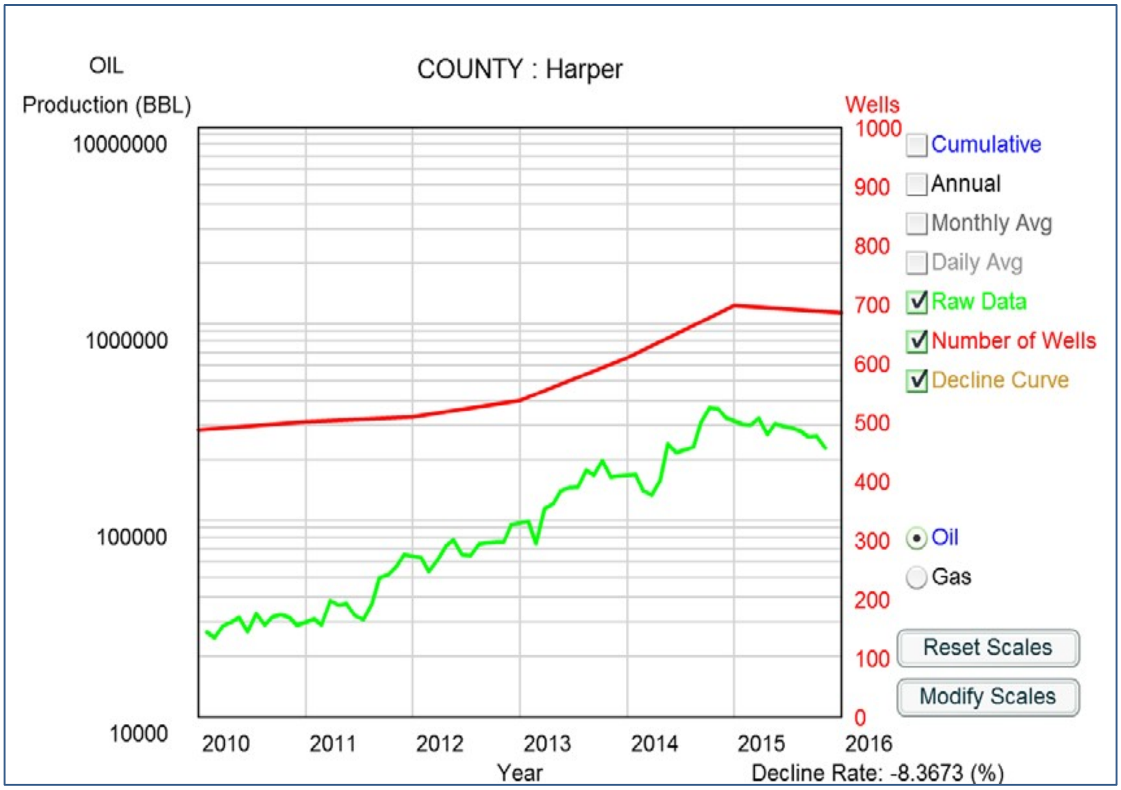


Figure 20. Oil production in Harper County began to decline in late 2014 along with production wells and, in turn, contributed to a decrease in brine disposal (http://maps.kgs.ku.edu/plots/PlotProduction.html?sType=COUNTY&sKID=77).

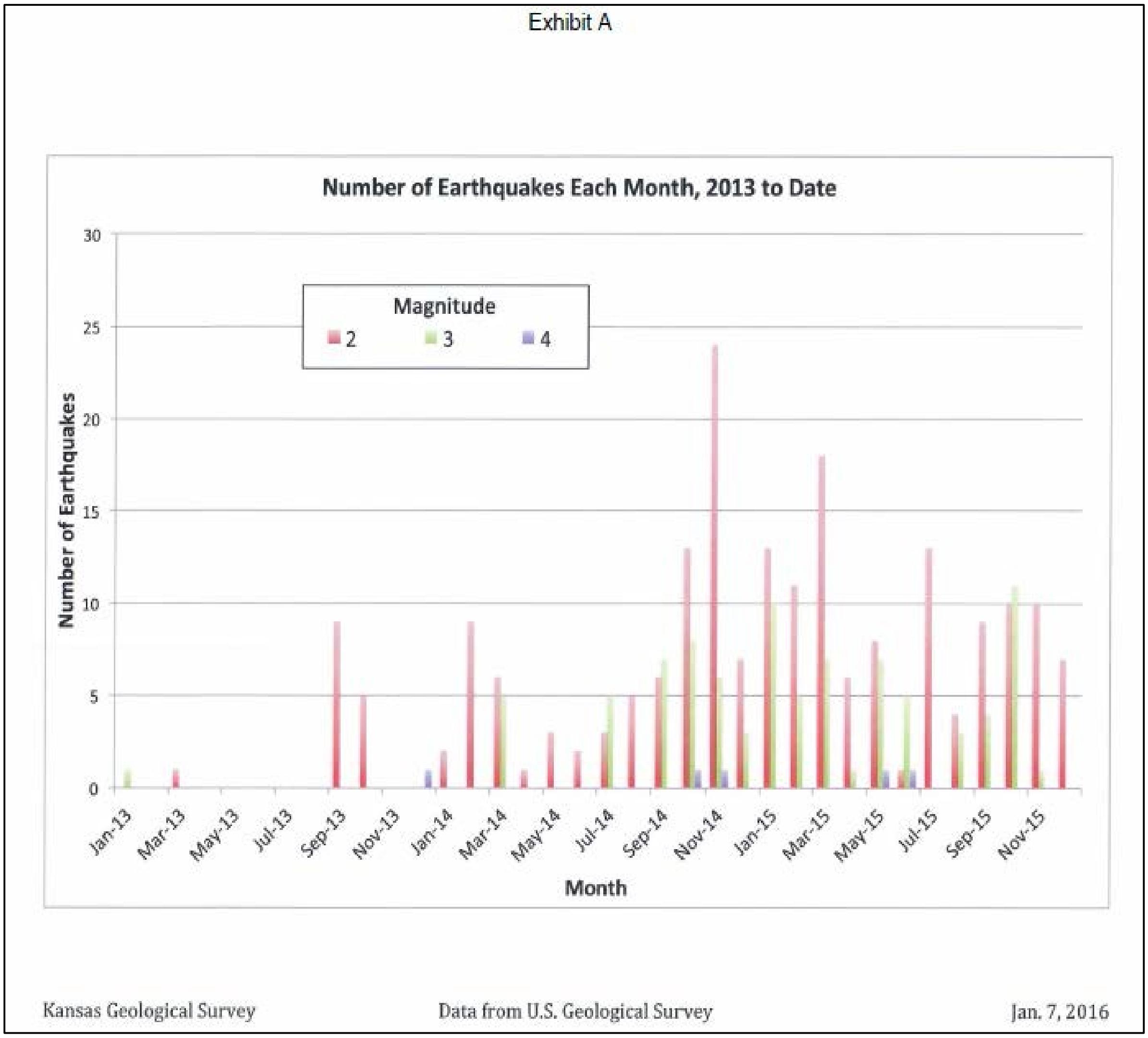


Figure 28. Decrease in the number of earthquakes in Kansas M2 and above since early 2015 (Exhibit A from (Testimony Rex Buchanan to Kansas Legislature, January 20, 2016; KCC Staff Recommendation Docket No. 15-CONS-770-CMSC).

Exhibit A

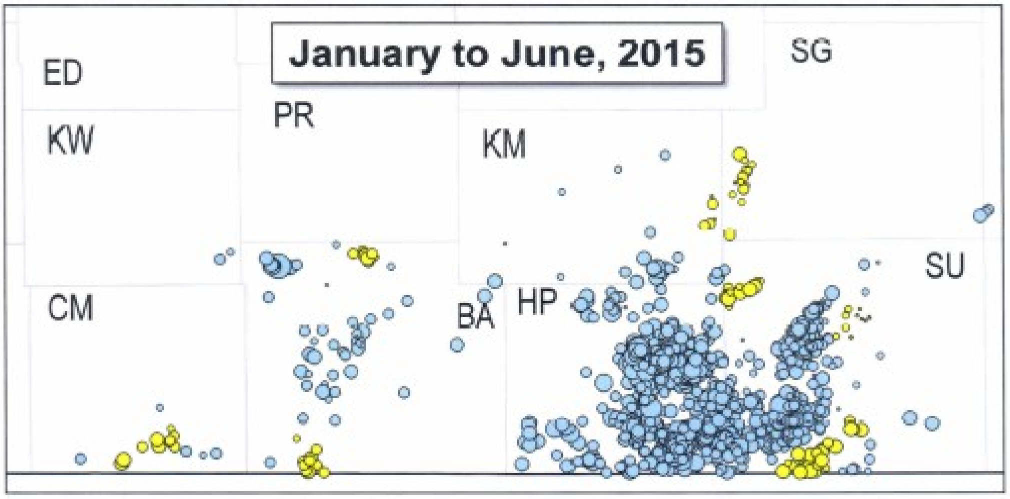


Figure 3. 1690 earthquakes were located by the KCC/KGS network in south-central Kansas from January to June, 2015. Yellow indicates areas with very little activity during the first half of the year that increased significantly during the second half of the year.

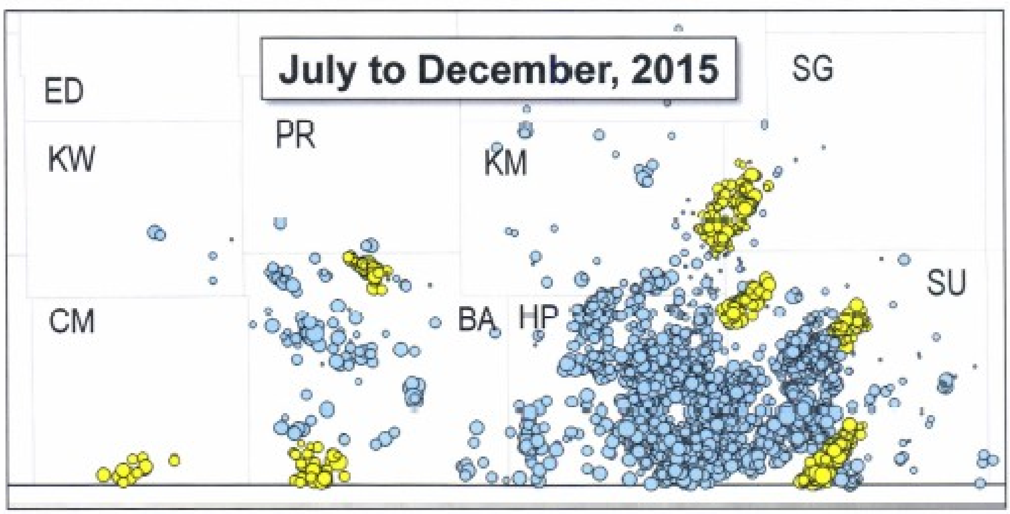


Figure 4. 3085 earthquakes were located by the KCC/KGS network in south-central Kansas from July to December, 2015. Yellow indicates cluster areas with very little activity during the first half of the year that increased significantly during the second half of the year.

Figure 29. Changes in earthquakes from KGS temporary seismometer network recording a small but noticeable expansion of the earthquakes in south-central Kansas between January-June 2015 and July-December 2015 (Exhibit A from (KCC Staff Recommendation Docket No. 15-CONS- 770-CMSC).

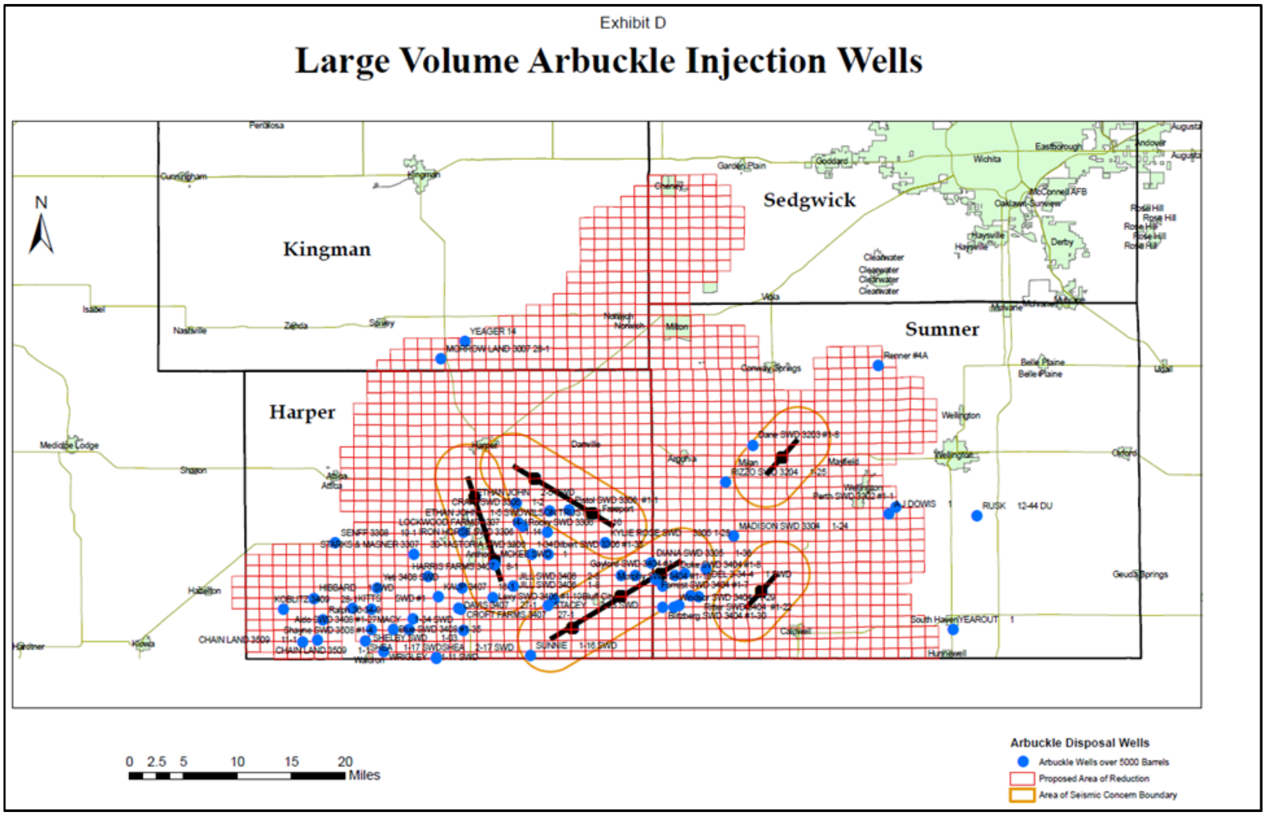


Figure 30. The outline of the Proposed Area of Reduction (PAR) recommended by the Conservation Division of the Kansas Corporation Commission (Exhibit A from (KCC Staff Recommendation Docket No. 15-CONS-770-CMSC).

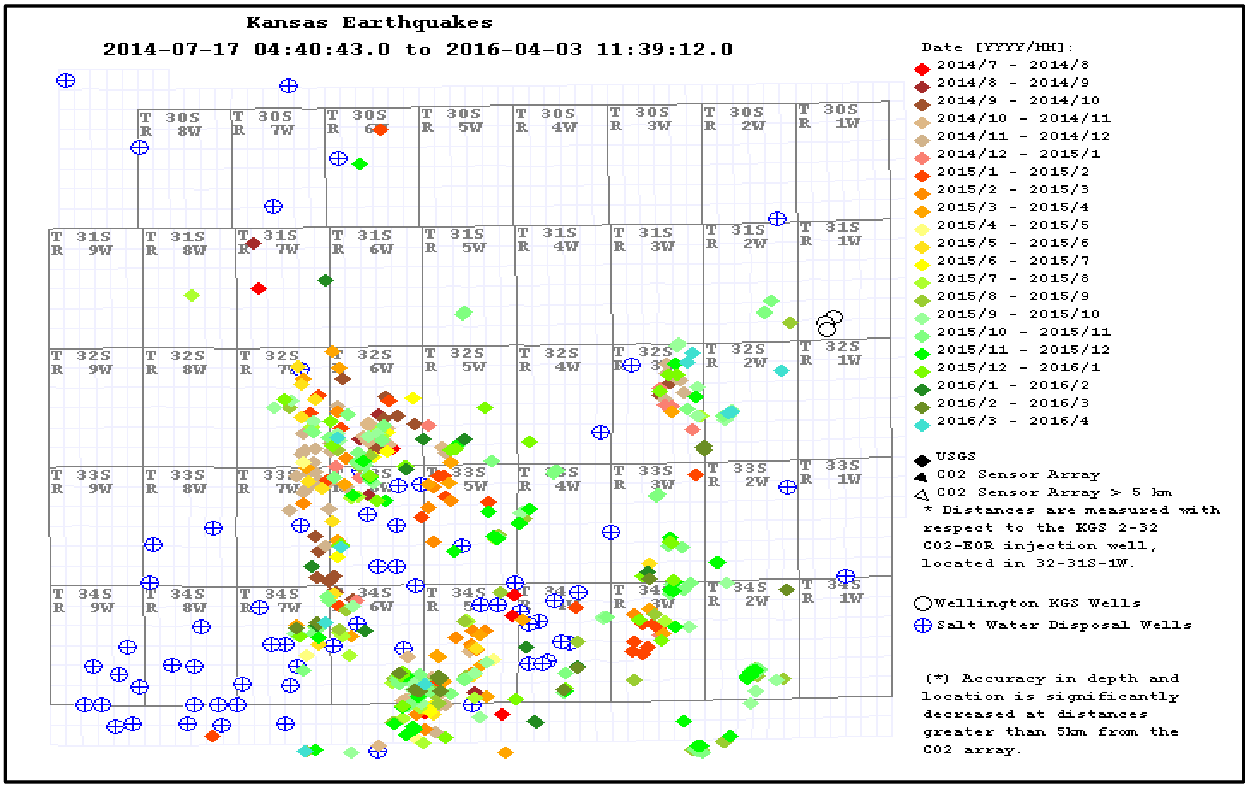


Figure 31. Java based map showing dates of earthquakes in south-central Kansas from the NEIC catalog between July 17, 2014 and April 3, 2016. Three KGS wells drilled in Wellington field are shown by three open circles in T31s-R1w in northeast corner of the map. Map generated by KGS Java Applet, Kansas Earthquakes 3D Plot -- *http://www.kgs.ku.edu/PRS/Ozark/Software/KS_Earthquake_3DPlot/index.html*

Induced Seismicity in Wellington Area

The Wellington 18-seismometer array has recorded 254 events from April 2015 to late March of 2016, the extent of the current catalog. Magnitudes range from Mw 0.2 to Mw 2.6 (**Figure 33**) from Nolte, et al., 2016). Earthquakes prior to 4-18-15 are being added to the catalog as time permit. The magnitude scale used is the moment magnitude (Mw) which is the standard for local (less than 10 km) and induced seismicity. The moment magnitude is calculated from the energy spectra of the event, which requires higher frequency data than other magnitudes, but has a linear magnitude curve at close distances that other magnitudes such as local (Richter) or coda magnitudes do not have. The energy spectrum calculated from an event is then used along with attenuation factors to correct for the distance away from the event the stations are. While smaller events have been recorded, events above the detection limit have been utilized for analysis of the seismic trends. The seismometer array is part of existing research at Wellington and in its current configuration, hypocenters and magnitudes assigned to earthquakes within 5 km of the array are considered most reliable (**Figure 34**). This activity is administered by a KGS-KU team of faculty, staff, and two graduate and one undergraduate student. This work is supported by multiple groups including DOE and the Kansas Interdisciplinary Carbonate Consortium.

Many small earthquakes generally in the range of 1.0 magnitude completely surround Wellington Field on either side of the 5 km ring of reliability (**Figures 33 and 34**). The earthquakes are typically in clusters in both time and space, described further in the narrative below.

A total of 14 small earthquakes have been recorded ranging in magnitude from 0.2 to 1.4 (**Figure 34**). Small earthquakes below 0.7 magnitude are within a mile radius of well #1-28. A cluster of earthquakes resides on the northeastern corner between Wellington and Wellington East fields. The magnitudes of these earthquakes span 0.1 to 1.4. While, seismological and geologic research on these earthquakes derived from the Wellington array is in progress, preliminary details are conveyed below in the interest in clarity and to provide a basis for discussion.

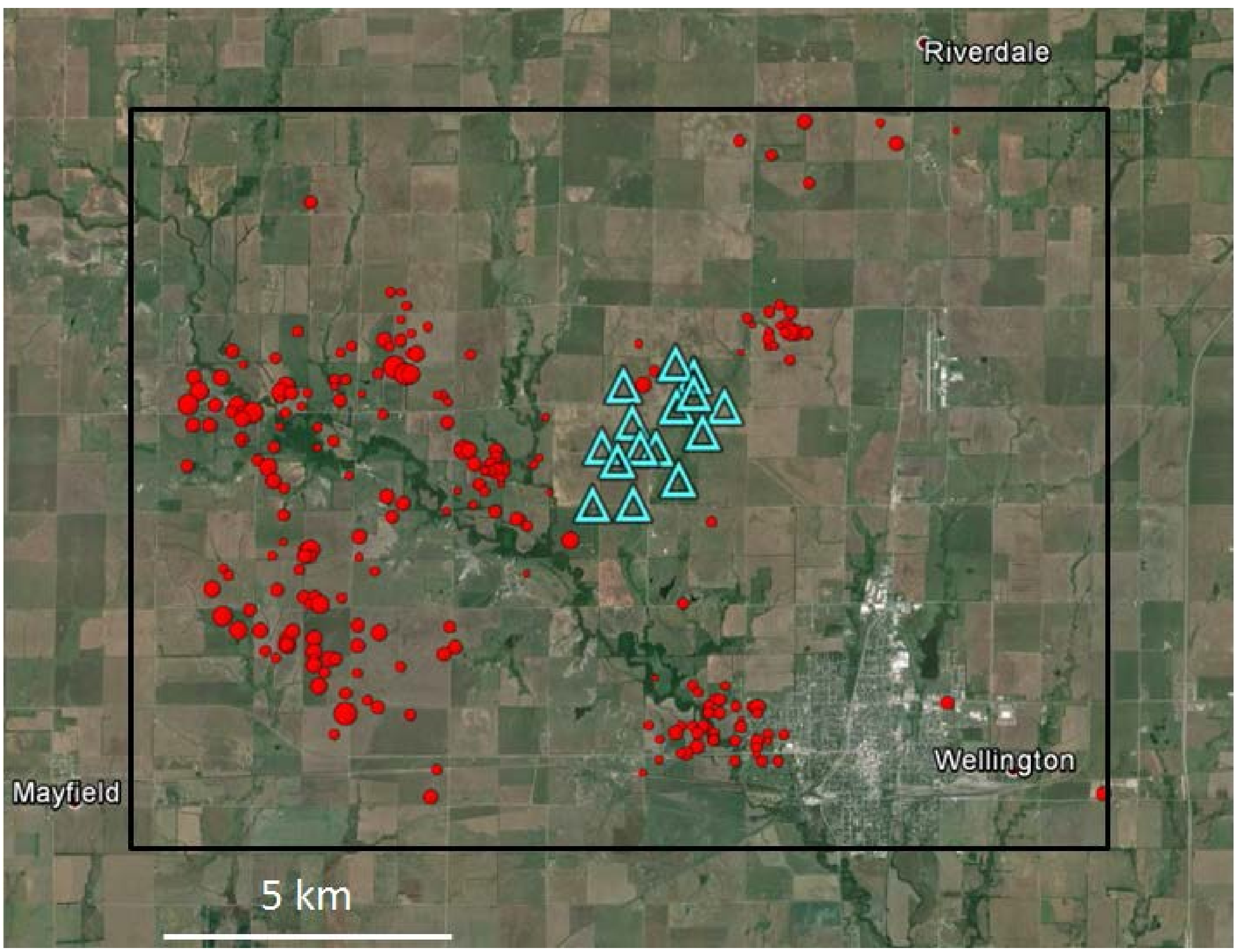
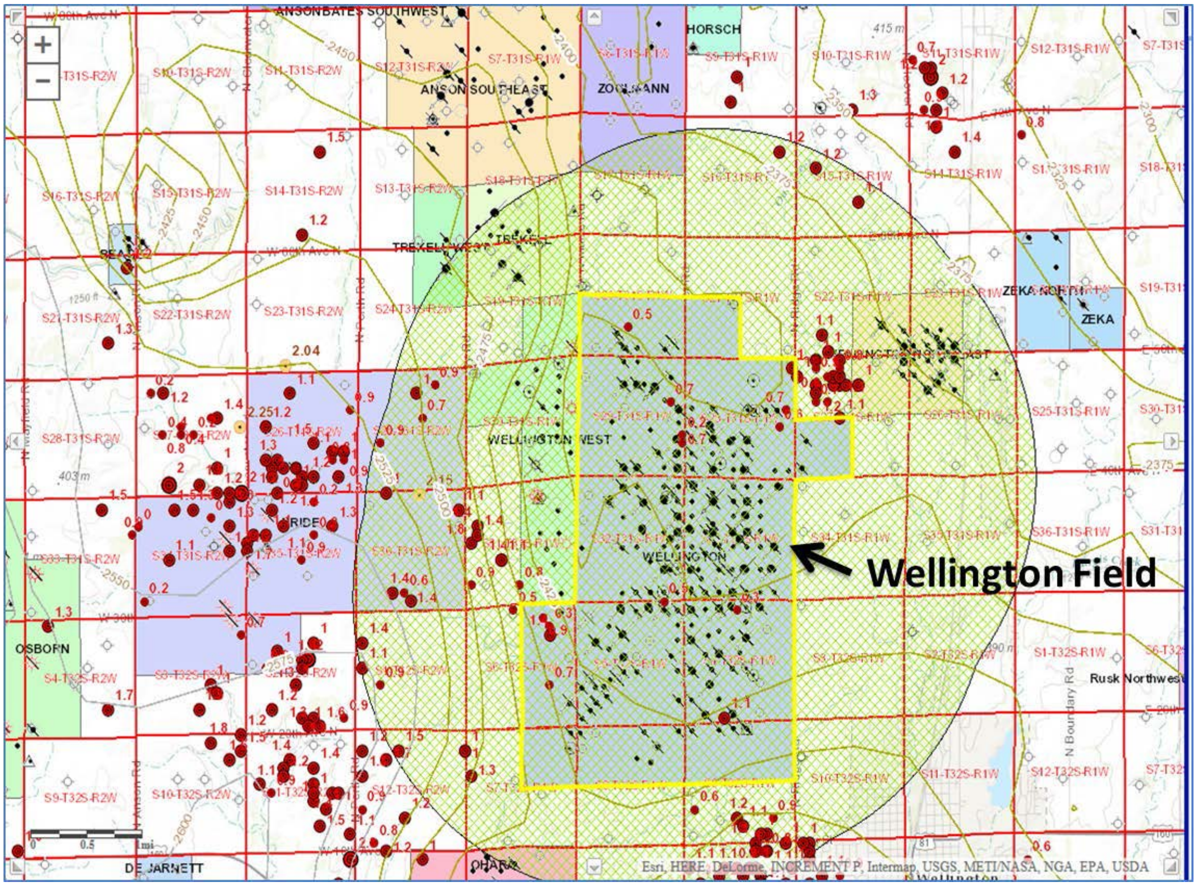


Figure 33. Map showing all events within the approximate area of interest. Wellington stations are the blue triangles and earthquakes are the red circles with diameter proportional to event magnitude. All events in this area were used to calculate a preliminary Magnitude of Completeness (from Nolte et al., 2016).



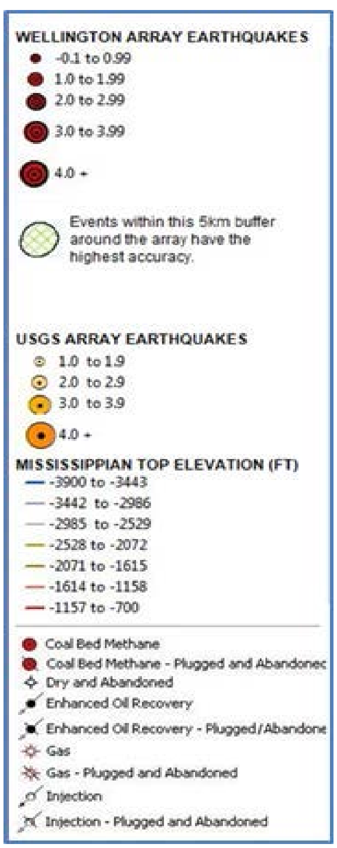


Figure 34. Map of Wellington Field (with yellow outline) and nearby oil fields showing location of earthquakes (red dots) detected with the Wellington seismometer array. Illustration is from the *Kansas Interactive Online Geology Mapper (KIOGM)* accessed through the KGS (http://maps.kgs.ku.edu/co2/). Earthquakes are labeled with magnitudes. Yellow green stippled oval area surrounding Wellington Field denotes 5 km radius of reliability beyond the edges of the Wellington seismometer array. Legend is to the left of the caption.

Magnitude of Completeness --The magnitude of completeness (Mc) is a critical component of an earthquake catalog (Nolte et al., 2016). The Mc is the earthquake magnitude for which an array can confidently pick all events of that magnitude and larger in a certain area. Usually the Mc is calculated at the end of the study period, however, the Wellington array is being used to monitor the CO_2 injections and must report events larger than M_W 2.5 to regulators. The Mc for the Wellington array is ~1.4 M_W. This confirms that a M_W 2.5 or larger event can be detected, since the array can confidently pick all events within a local area of M_W 1.4 and larger. A magnitude of completeness is calculated by using the Gutenberg-Richter frequency-magnitude distribution (Vorobieava, 2012). This law states that for every event of magnitude 2, there are 10 magnitude 1 events and 100 magnitude 0 events. This relationship is represented by the equation:

$$\log(N) = A - bM \qquad (1)$$

Where N is the number of events of magnitude M and A and b are coefficients. It is expected that b should be equal to 1 as defined by the Gutenberg-Richter law. Comparing the predicted event/magnitude relationship using equation (1) to the observed event/magnitude data it can be determined where the event number diverges from the expected value. This can be seen in **Figure 35**, where the orange line (predicted) diverges from the blue line (observed). The deviation begins at approximately Mw 1.4 and is most obvious at Mw 1.2. This deviation range will become smaller as the catalog continues to grow and the Mc will be more accurate (**Figure 36**).

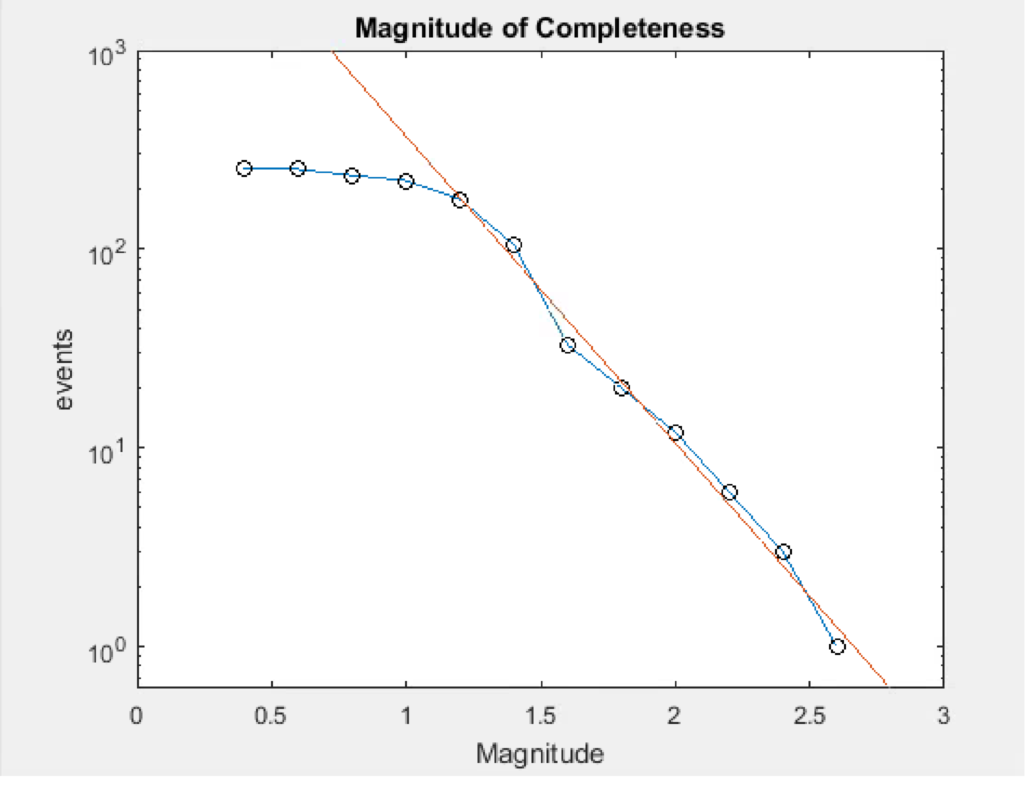
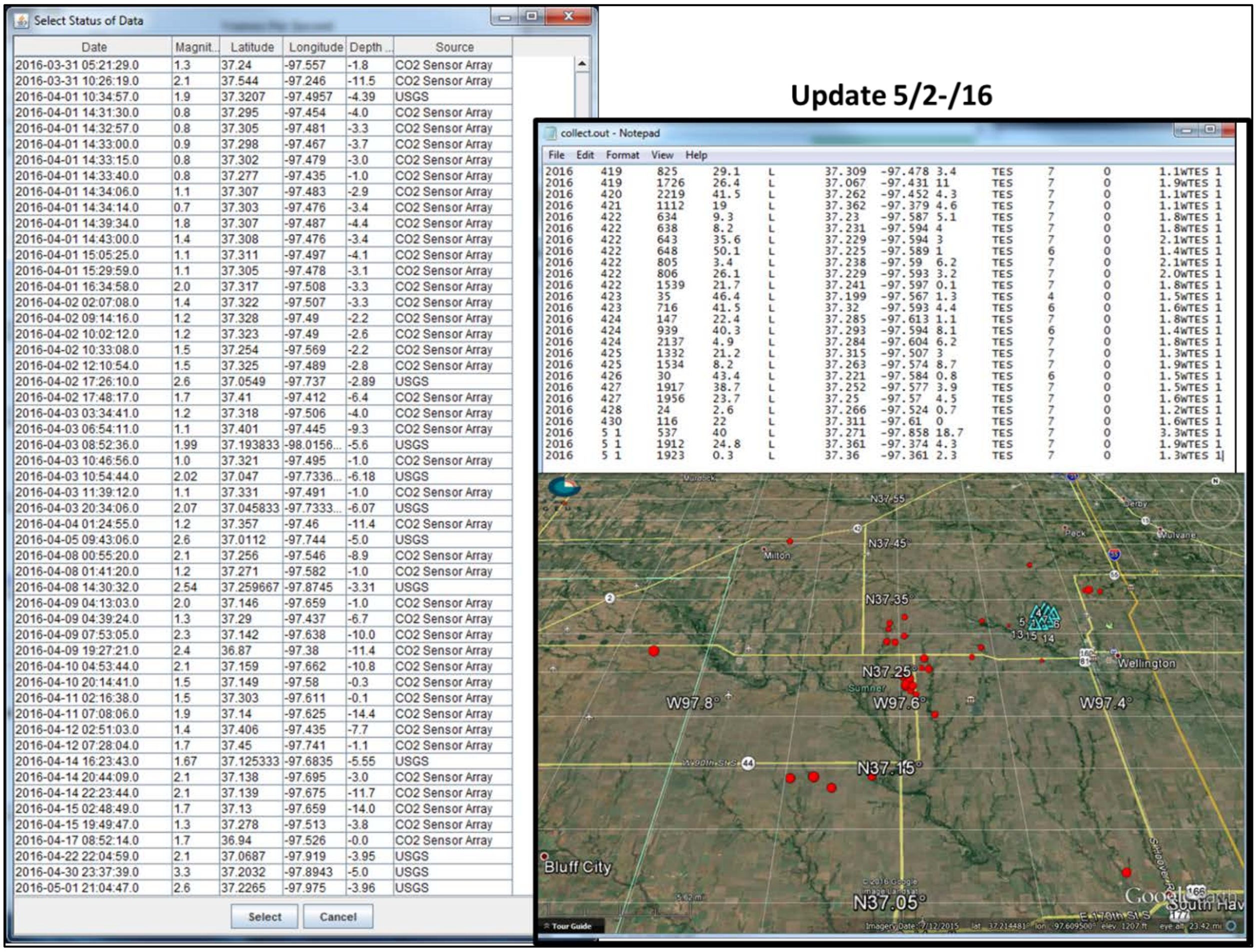


Figure 35. Graph showing the Magnitude of completeness, calculated from the Gutenberg-Richter law. The blue line with circles represents events recorded from the seismometer array and orange line represents predicted events using equation 1 from the Gutenberg-Richter law.



Date	Magnit...	Latitude	Longitude	Depth ...	Source
2016-03-31 05:21:29.0	1.3	37.24	-97.557	-1.8	CO2 Sensor Array
2016-03-31 10:26:19.0	2.1	37.544	-97.246	-11.5	CO2 Sensor Array
2016-04-01 10:34:57.0	1.9	37.3207	-97.4957	-4.39	USGS
2016-04-01 14:31:30.0	0.8	37.295	-97.454	-4.0	CO2 Sensor Array
2016-04-01 14:32:57.0	0.8	37.305	-97.481	-3.3	CO2 Sensor Array
2016-04-01 14:33:00.0	0.9	37.298	-97.467	-3.7	CO2 Sensor Array
2016-04-01 14:33:15.0	0.8	37.302	-97.479	-3.0	CO2 Sensor Array
2016-04-01 14:33:40.0	0.8	37.277	-97.435	-1.0	CO2 Sensor Array
2016-04-01 14:34:06.0	1.1	37.307	-97.483	-2.9	CO2 Sensor Array
2016-04-01 14:34:14.0	0.7	37.303	-97.476	-3.4	CO2 Sensor Array
2016-04-01 14:39:34.0	1.8	37.307	-97.487	-4.4	CO2 Sensor Array
2016-04-01 14:43:00.0	1.4	37.308	-97.476	-3.4	CO2 Sensor Array
2016-04-01 15:05:25.0	1.1	37.311	-97.497	-4.1	CO2 Sensor Array
2016-04-01 15:29:59.0	1.1	37.305	-97.478	-3.1	CO2 Sensor Array
2016-04-01 16:34:58.0	2.0	37.317	-97.508	-3.3	CO2 Sensor Array
2016-04-02 02:07:08.0	1.4	37.322	-97.507	-3.3	CO2 Sensor Array
2016-04-02 09:14:16.0	1.2	37.328	-97.49	-2.2	CO2 Sensor Array
2016-04-02 10:02:12.0	1.2	37.323	-97.49	-2.6	CO2 Sensor Array
2016-04-02 10:33:08.0	1.5	37.254	-97.569	-2.2	CO2 Sensor Array
2016-04-02 12:10:54.0	1.5	37.325	-97.489	-2.8	CO2 Sensor Array
2016-04-02 17:26:10.0	2.6	37.0549	-97.737	-2.89	USGS
2016-04-02 17:48:17.0	1.7	37.41	-97.412	-6.4	CO2 Sensor Array
2016-04-03 03:34:41.0	1.2	37.318	-97.506	-4.0	CO2 Sensor Array
2016-04-03 06:54:11.0	1.1	37.401	-97.445	-9.3	CO2 Sensor Array
2016-04-03 08:52:36.0	1.99	37.193833	-98.0156...	-5.6	USGS
2016-04-03 10:46:56.0	1.0	37.321	-97.495	-1.0	CO2 Sensor Array
2016-04-03 10:54:44.0	2.02	37.047	-97.7336...	-6.18	USGS
2016-04-03 11:39:12.0	1.1	37.331	-97.491	-1.0	CO2 Sensor Array
2016-04-03 20:34:06.0	2.07	37.045833	-97.7333...	-6.07	USGS
2016-04-04 01:24:55.0	1.2	37.357	-97.46	-11.4	CO2 Sensor Array
2016-04-05 09:43:06.0	2.6	37.0112	-97.744	-5.0	USGS
2016-04-08 00:55:20.0	2.1	37.256	-97.546	-8.9	CO2 Sensor Array
2016-04-08 01:41:20.0	1.2	37.271	-97.582	-1.0	CO2 Sensor Array
2016-04-08 14:30:32.0	2.54	37.259667	-97.8745	-3.31	USGS
2016-04-09 04:13:03.0	2.0	37.146	-97.659	-1.0	CO2 Sensor Array
2016-04-09 04:39:24.0	1.3	37.29	-97.437	-6.7	CO2 Sensor Array
2016-04-09 07:53:05.0	2.3	37.142	-97.638	-10.0	CO2 Sensor Array
2016-04-09 19:27:21.0	2.4	36.87	-97.38	-11.4	CO2 Sensor Array
2016-04-10 04:53:44.0	2.1	37.159	-97.662	-10.8	CO2 Sensor Array
2016-04-10 20:14:41.0	1.5	37.149	-97.58	-0.3	CO2 Sensor Array
2016-04-11 02:16:38.0	1.5	37.303	-97.611	-0.1	CO2 Sensor Array
2016-04-11 07:08:06.0	1.9	37.14	-97.625	-14.4	CO2 Sensor Array
2016-04-12 02:51:03.0	1.4	37.406	-97.435	-7.7	CO2 Sensor Array
2016-04-12 07:28:04.0	1.7	37.45	-97.741	-1.1	CO2 Sensor Array
2016-04-14 16:23:43.0	1.67	37.125333	-97.6835	-5.55	USGS
2016-04-14 20:44:09.0	2.1	37.138	-97.695	-3.0	CO2 Sensor Array
2016-04-14 22:23:44.0	2.1	37.139	-97.675	-11.7	CO2 Sensor Array
2016-04-15 02:48:49.0	1.7	37.13	-97.659	-14.0	CO2 Sensor Array
2016-04-15 19:49:47.0	1.3	37.278	-97.513	-3.8	CO2 Sensor Array
2016-04-17 08:52:14.0	1.7	36.94	-97.526	-0.0	CO2 Sensor Array
2016-04-22 22:04:59.0	2.1	37.0687	-97.919	-3.95	USGS
2016-04-30 23:37:39.0	3.3	37.2032	-97.8943	-5.0	USGS
2016-05-01 21:04:47.0	2.6	37.2265	-97.975	-3.96	USGS

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2016	419	825	29.1	L	37.309	-97.478	3.4	TES	7	0	1.1WTES 1
2016	419	1726	26.4	L	37.067	-97.431	11	TES	7	0	1.9WTES 1
2016	420	2219	41.5	L	37.262	-97.452	4.3	TES	7	0	1.1WTES 1
2016	421	1112	19	L	37.362	-97.379	4.6	TES	7	0	1.1WTES 1
2016	422	634	9.3	L	37.23	-97.587	5.1	TES	7	0	1.8WTES 1
2016	422	638	8.2	L	37.231	-97.594	4	TES	7	0	1.8WTES 1
2016	422	643	35.6	L	37.229	-97.594	3	TES	7	0	2.1WTES 1
2016	422	648	50.1	L	37.225	-97.589	1	TES	6	0	1.4WTES 1
2016	422	805	3.4	L	37.238	-97.59	6.2	TES	7	0	2.1WTES 1
2016	422	806	26.1	L	37.229	-97.593	3.2	TES	7	0	2.0WTES 1
2016	422	1539	21.7	L	37.241	-97.597	0.1	TES	7	0	1.8WTES 1
2016	423	35	46.4	L	37.199	-97.567	1.3	TES	4	0	1.5WTES 1
2016	423	716	41.5	L	37.32	-97.593	4.4	TES	6	0	1.6WTES 1
2016	424	147	22.4	L	37.285	-97.613	1.1	TES	7	0	1.8WTES 1
2016	424	939	40.3	L	37.293	-97.594	8.1	TES	6	0	1.4WTES 1
2016	424	2137	4.9	L	37.284	-97.604	6.2	TES	7	0	1.8WTES 1
2016	425	1332	21.2	L	37.315	-97.507	3	TES	7	0	1.3WTES 1
2016	425	1534	8.2	L	37.263	-97.574	8.7	TES	7	0	1.9WTES 1
2016	426	30	43.4	L	37.221	-97.584	0.8	TES	6	0	1.5WTES 1
2016	427	1917	38.7	L	37.252	-97.577	3.9	TES	7	0	1.5WTES 1
2016	427	1956	23.7	L	37.25	-97.57	4.5	TES	7	0	1.6WTES 1
2016	428	24	2.6	L	37.266	-97.524	0.7	TES	7	0	1.2WTES 1
2016	430	116	22	L	37.311	-97.61	0	TES	7	0	1.6WTES 1
2016	5 1	537	40	L	37.271	-97.858	18.7	TES	7	0	3.3WTES 1
2016	5 1	1912	24.8	L	37.361	-97.374	4.3	TES	7	0	1.9WTES 1
2016	5 1	1923	0.3	L	37.36	-97.361	2.3	TES	7	0	1.3WTES 1

Figure 36. Example of the earthquake catalog of the Wellington Array (aka CO2 Sensor Array). Full catalog is on the left, upper right are the weekly additions, and the Google Earth map on the lower right shows the epicenters of the weekly additions as of 5-1-16.

Summary of Earthquake Activity –

1. Seismicity in south-central Kansas increased 20-fold in 2014 following the introduction of high volume, high rate brine disposal wells in 2012 as part of the Mississippian Lime Play. Regional analysis suggests a relationship between Class II injection and earthquakes. This conclusion was presented to the Kansas House Standing Committee on Energy and Environment by Rex Buchanan (KGS Director) on January 26, 2015.
2. Since early 2015 after a downturn in the oil industry and the KCC order issued in March 19, 2015 reducing the rates of disposal of brine in areas of elevated seismicity in Harper and western Sumner County, the number of large earthquakes has notably decreased.
3. Smaller earthquakes below 2.0 magnitude have persisted and become more aerially widespread, including movement eastward into the immediate vicinity of Wellington in late 2015 and 2016.This movement was recognized by the KGS temporary seismometer network and the Wellington seismometer array.
4. The number of events analyzed from the Wellington seismometer array totals 254 from April 2015 to the end of March. The Wellington array however has been active and recording data since the fall of 2014, but the catalog with vetted earthquakes goes back to only this initial date of 4-18-2105. As the research project continues at the KGS and KU, the earthquake catalog will continue to be extended back in time.
5. Fourteen small earthquakes with magnitudes of 0.2 to 1.4 have occurred within the outline of Wellington Field as recorded by the Wellington seismometer array. As shown by the series of maps and plots, there are considerably more earthquakes outside the Wellington well field than within the wellfield itself.
6. A large number of small sub 2.5 earthquakes in the Wellington area were recorded in the early to mid 2015 by the Wellington seismometer array as the events moved into the Wellington area. Small earthquakes have also been previously recorded west of the field in January 2015 as reported by Rex Buchanan (Director, KGS) to the Kansas House Standing Committee on Energy and Environment (**Figure 29**).
7. The KCC recommended a Proposed Area of Reduction (PAR) that has widened that area of concern about high rate brine disposal leading to induced seismicity. The recommendation is warranted by results of the Wellington seismometer array presented in this report. While the danger of creating felt earthquakes by the small scale CO_2 injection is minimal, Berexco and KGS are taking a proactive position with seismometer realignment and bottomhole pressure testing to evaluate regional simulations that might provide insights to a possible mechanism for the expansion of induced seismicity, albeit at low levels. The information gained from the exceptional monitoring opportunity will likely pay dividends for scientists, regulators, and industry to refine procedures to manage disposal safely and effectively.

Operating Plan for Safe Injection -- Two documents previously filed with the EPA addressed earlier concerns about the potential for inducing earthquakes at Wellington – 1) *KGS's Opinion Regarding Likelihood of Inducing Earthquakes Due to* CO_2 *Injection in the Wellington Oilfield* and 2) *Operating Plan for Safe and Efficient Injection (OPSEI)*. The first document highlights the relationship between the recent spate of earthquakes and injection in Class II wells related with oil and gas operations. The second document addresses the monitoring and installation safeguards in place to ensure that CO_2 remains confined in the injection zone and the remedial measures to be implemented in the event of a natural or operational catastrophe. The OPSEI also includes the Wellington Seismic Action Plan which list measures to be taken to prevent induced seismicity including system of early detection and mapping of earthquakes (magnitude and depth) accompanied by downhole data pertaining to the injection that will be used to analyze departures in CO_2 injection using standard engineering protocol.

The OPSEI based monitoring and rapid response plan as provided to the EPA is summarized in **Figure 37**. For example, any changes in downhole fluid pressures (build up or a sudden loss) associated with the medial fault would trigger a rapid response which involve a pause in injection and a review of all monitoring data including seismic activity, followed by necessary analysis (such as Hall Plot). The team has the demonstrated skillset to conduct and analyze the geoengineering-based monitoring. Any departures or earthquakes above 2.5 would be assessed and the EPA alerted when thresholds, which have been set in the operational plan, are reached.

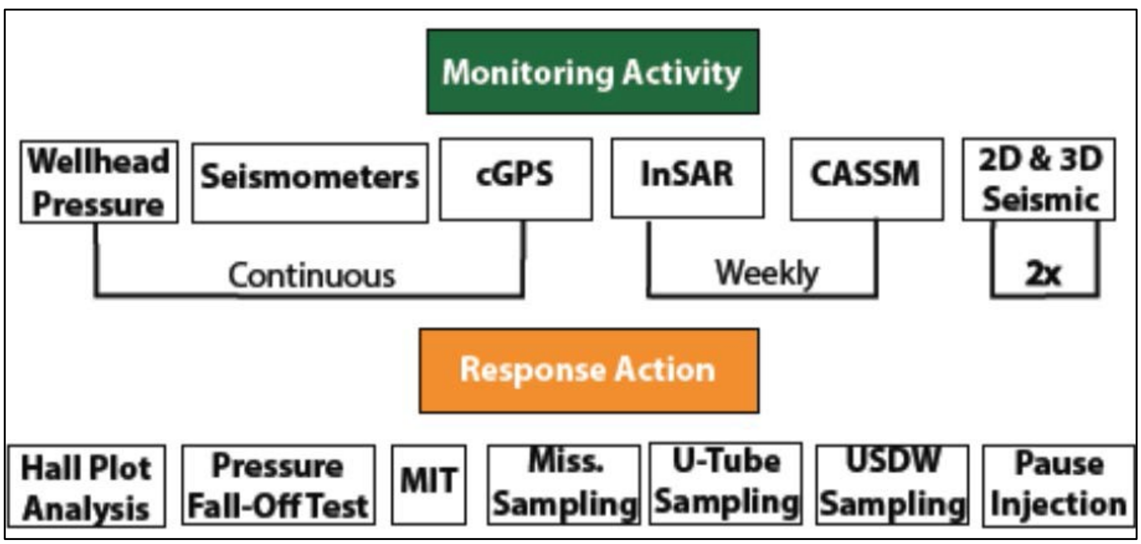

Figure 37. Partial list of monitoring activities and response action in the Wellington Operating Plan for Safe and Efficient Injection (OPSEI).

The USGS seismometer network is reporting earthquakes larger than 2.5. The Wellington seismic array, developed specifically for the Wellington project, is capable of detecting very small earthquakes of ~0.5 magnitude. The workflow and methods used follow standard protocol, and results have been validated using USGS NEIC catalog for larger earthquakes. Efforts continue to refine information learned about the earthquakes including fault mechanism, related geology, and evaluating the linkage with large scale Class II brine disposal via simulations. This network will be relied upon to control CO_2 injection so as to avoid larger earthquakes.

The seismometer array has collected data continuously since the fall of 2014. The earthquake catalog is updated weekly and events are analyzed and reported within 24 hrs. The methodology of picking small earthquakes in the 0-1 magnitude range is now routine and the depths of earthquakes are highly resolved within a 5 km radius of the Wellington array. Larger events (>2.5), recorded by the USGS are frequently used to check the accuracy of magnitude assignment and location. Also, steps are being taken to improve and refine the array, such as relocating two of seismometers to sites outside of the array to improve identification of hypocenters of smaller events near the field and to establish their focal mechanism. The KGS/KU teams who work on the array meet regularly and convey results to others members of the Class VI team. Weekly data are uploaded to NSF-IRIS (who has loaned the equipment) and the data also stored locally and made accessible to the public with internal web-based maps and plots.

Continued Research Education and Knowledge Dissemination -- The KGS-KU team actively participates in numerous meetings to address the topic of induced seismicity and undertaking safe and efficient injection. Induced seismicity has been openly discussed relative to the CO_2 injection activity at Wellington Field. A graduate level seminar, *GEOL 771 Advanced Geophysics: Induced Seismicity and Fluid Injection*, has been taught in Spring 2015 and 2016 by KGS/KU scientists Bidgoli, Tsoflias, Taylor, and Watney. This seminar has evaluated results from the Wellington array, geologic and engineering characterization, and relevant geology of the Midcontinent and seismology. The dialogs between the team and stakeholders will continue in earnest.

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Continuous pressure monitoring in the lower Arbuckle prior to CO2 injection

Large rate and high volume brine disposal in the area believed to be responsible for the induced seismicity. Simulations by the KGS suggests a regional pressure field has developed in the Arbuckle saline aquifer and pressures may be finding faults in the basement that are critically stressed that have become reactivated (Bidgoli et al., 2015; please refer to references above) (**Figure 38**). In order to test the simulation bottom hole pressure measurements in the Arbuckle were needed to verify the simulation. Slightly elevated pressures were forecasted for the Wellington Field area, ~20 psi. Small earthquakes, mainly microseismicity, increased in Wellingon area in early 2015 and the question was posed whether there is accompanying pressure change. Downhole pressure measurement was discussed with Kansas Induced Seismicity Task Force, but an idle well was needed to run the test.

Surface based measurements used to estimate bottom hole pressure are deemed inadequate to test the simulation. If a pressure field is established, this type of pressure measurement could potentially be used to evaluate whether an area might have the propensity for induced earthquakes especially if accompanied by clusters of small microearthquakes that might herald a larger quake.The assumption in the case of the testing in the Arbuckle is that the observed pressure is being transmitted at depth in the basement where faults are critically stressed, requiring a small force to move. To date the vast majority of earthquakes have occurred in the shallow basement.

Installing a pressure transducer at the open perforations in the lower Arbuckle in Wellington KGS 1-28 became a high priority once the microseismicity in the Wellington area become apparent. KGS funds were used to contract the installation of a high resolution pressure transducer that was placed in KGS #1-28 on April 25th (**Figures 39 through 42**). The objective is to determine if a pressure increase is noted compared to the last activity in this well, which was a pulse test in the lower Arbuckle perforations in August 2011. This earlier access to the well was done well before to onset of seismicity in the area. The extended pressure recording in 1-28 following the pulse test obtained what is considered a stable pressure.

Trilobite Testing out of Hays conducted the original tests in #1-28 and the other DOE funded. They received the job to install the pressure gauge at 5000 ft at precisely the depth where the last pressure measurements were made. The instrument is programmed to sample every second with an accuracy of 0.1 psi. The sensitivity is roughly 10x greater than the accuracy, permitting very small pressure fluctuations to be recorded. The temporal changes in pressure itself could be very revealing.

A cable carries pressure data to the surface recorder, where the data is stored (**Figures 39 and 40**). A USB port at the surface recorder is used to export the data for analysis. The pressure gauge needs to be reprogramed every 14 days from the surface, essentially with each download of data.

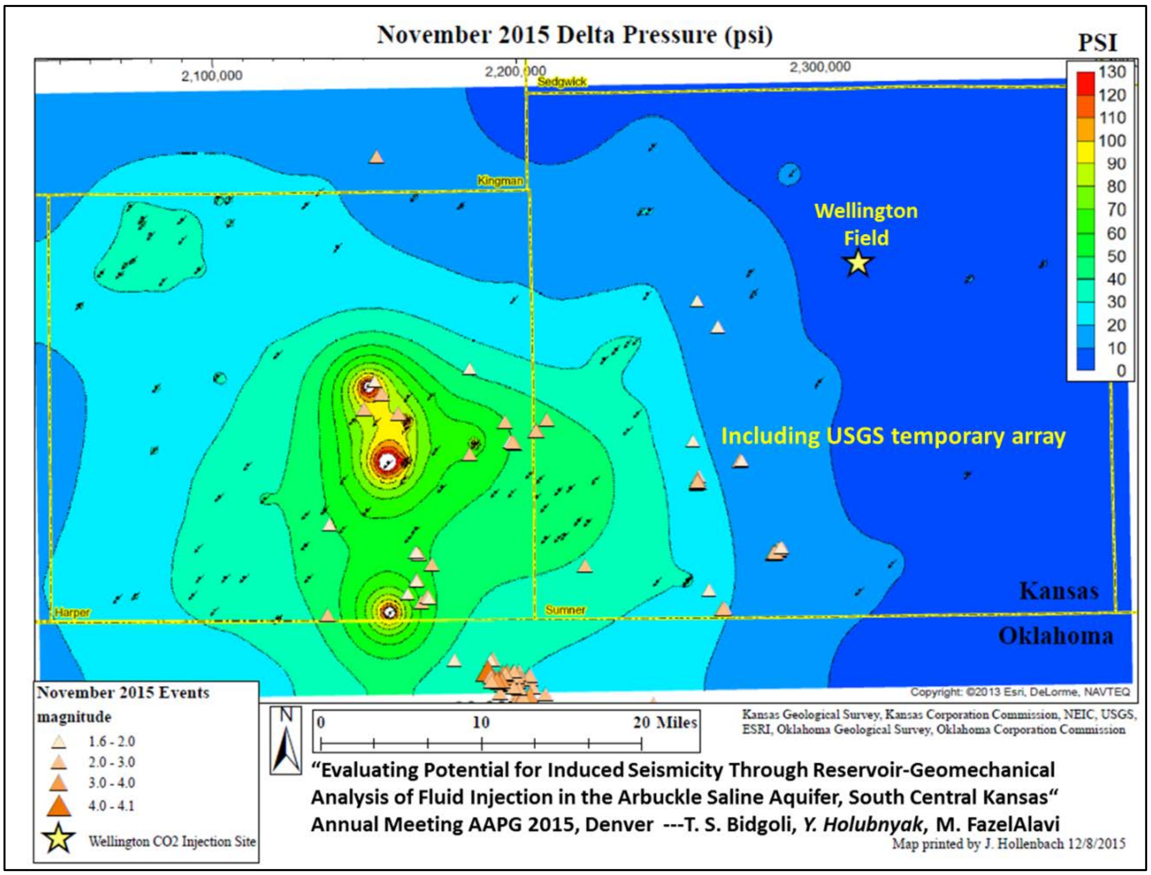


Figure 38. Regional pressure produced in Arbuckle from large volume and rate brine disposal prior to 2014. Higher pressure in inner core of brine disposal.

Figure 39. Wellington KGS #1-28 equipped with pressure transducer to continuously record small pressure changes in the lower Arbuckle

Figure 40. Pressure readout along with time stamp and delta T.

The wellbore diagram of well #1-28 shows the location of the perforations where pressure measurements are now being obtained (**Figure 41**). The first pressure readout from April 25th to May 5, 2016 shows small diurnal tidal oscillations (**Figure 42**). Also, a long term, small increase in pressure is noted over the duration of these measurements. Two clear spikes in pressure are noted and are being analyzed. It is possible that disposal wells that use large surface pressures (400+ psi) to start up to overcome frictional loss, may be creating these pulses. Obviously, a large amount of work has yet to be done.

Small high frequency, low amplitude pressure variations are being compared with earthquakes to determine if there is an association between pressure changes and the detection of actual earthquakes from this method of pressure sampling in the lower Arbuckle. Co-seismic events have been recognized in shallow aquifers for even small earthquakes. Thus, it appears possible that earthquakes can transmit small pressure changes.

The key finding at this point is that the bottomhole pressure at #1-28 has increased over 30 psi compared to the same measurement in August 2011. Carefully looking at the new data and the extended pressure measurements in 2011 before induced seismicity appeared in the area leads to a conclusion that the Arbuckle has been repressurized in Wellington Field. While not an indication of earthquakes, the simulation of regional brine disposal would suggest that the area has a greater potentially for seismicity due to the elevated pressures, it the pressures are indeed transmitted into basement faults.

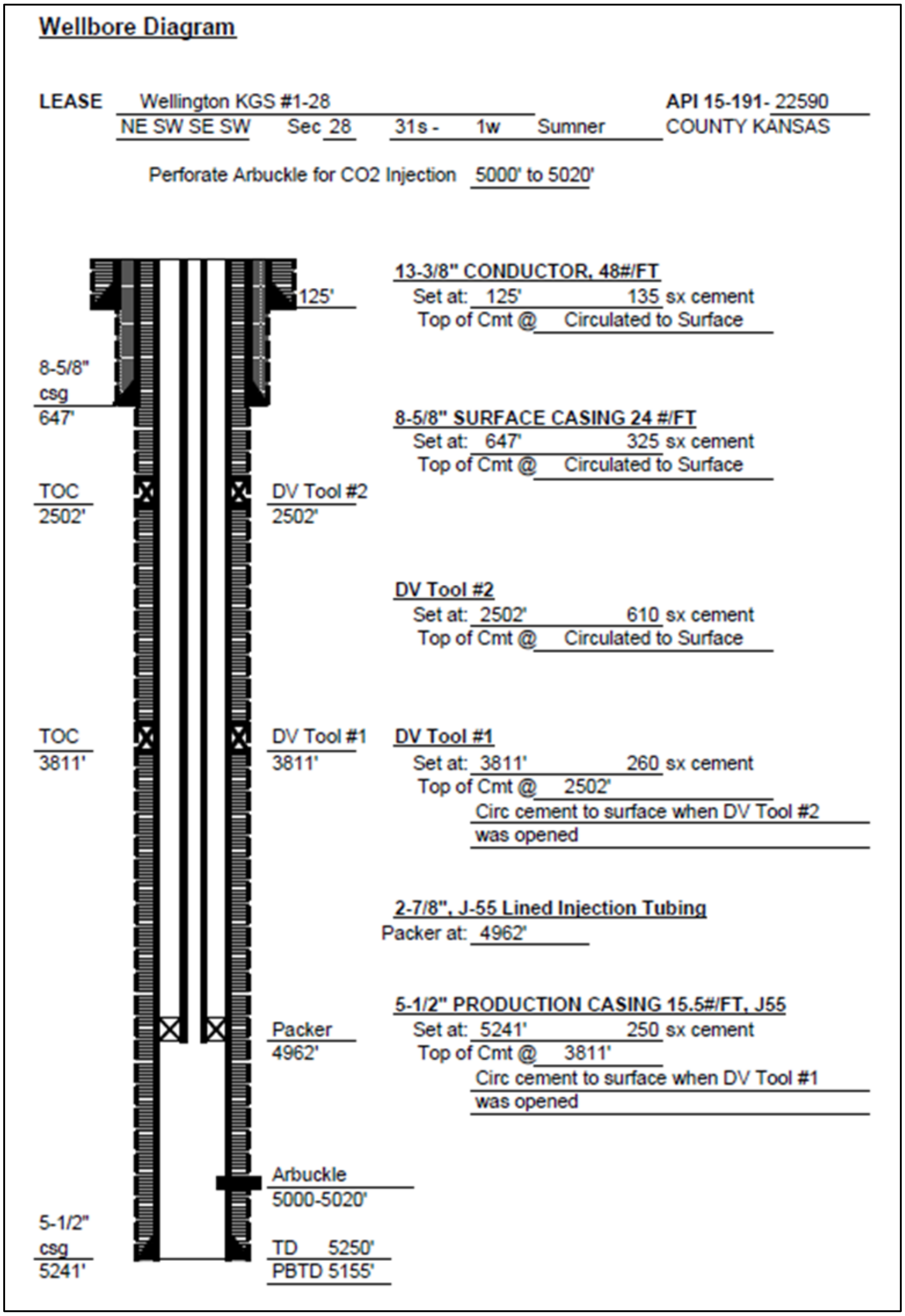


Figure 41. Wellbore schematic of well #1-28 showing perforation at depth of 5000 to 5020 ft.

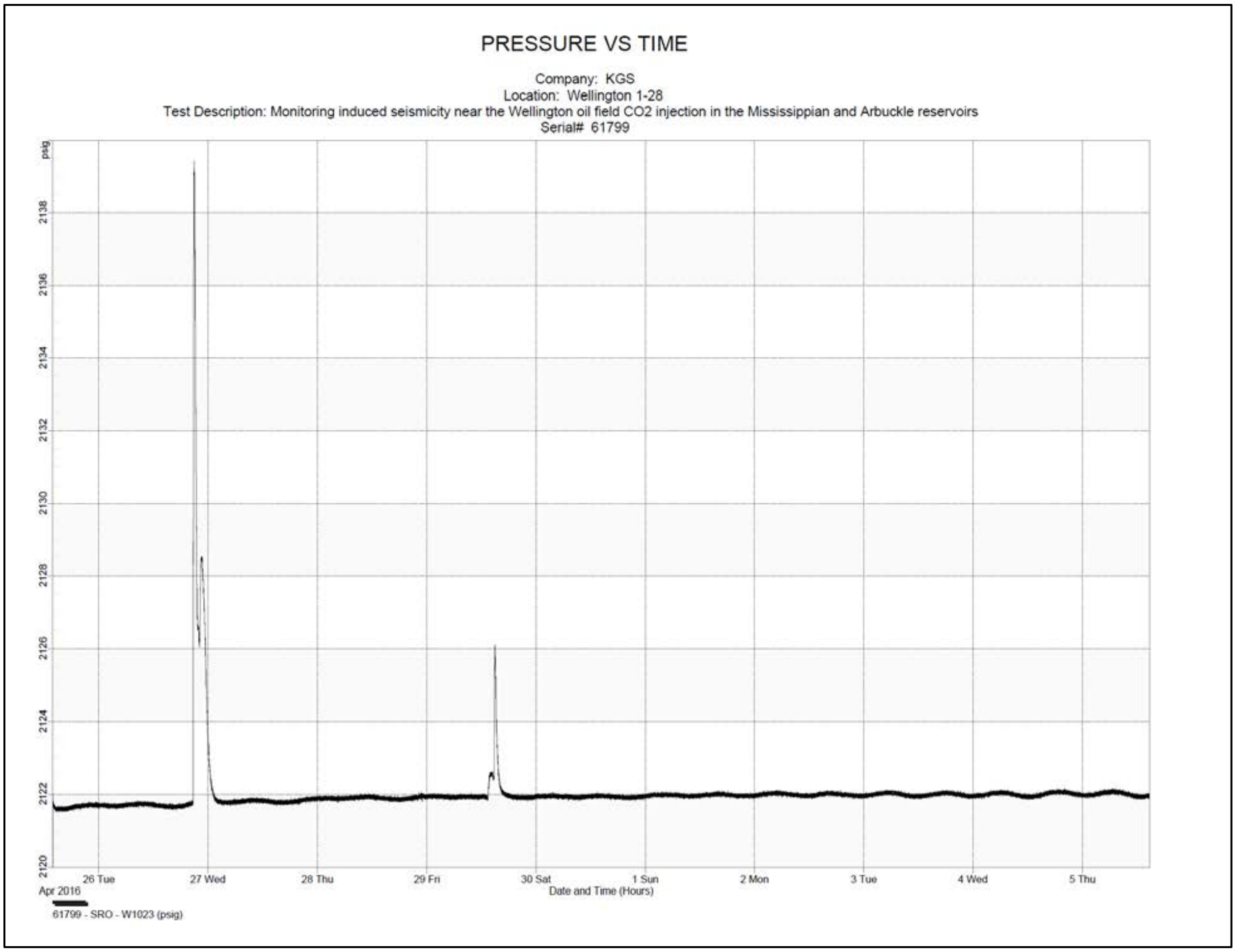


Figure 42. Initial record of pressure vs. time from April 25 to May 5, 2016 in well #1-28 from lower Arbuckle at 5000 ft depth. Pressures are measured every second and data is transmitted by cable to surface recorder.

Update on performance and monitoring of CO_2 injection into the Mississippian spiculitic (cherty) dolomite at Wellington Field, Kansas

(as included in the proceedings of the Kansas Interdisciplinary Carbonate Consortium at KU)

By Watney, W.L.[1], Rush, J.[1], Holubnyak, Y.[1], Fazelalavi, M.[1], Hollenback, J.[1], Jackson, C.[1], Campbell, K. Graham, B., Nolte, A., Victorine, J.[1], Doveton, J.[1], Tsoflias, G.[2], Roberts, J.[2], Whittemore, D.[1], and Wreath, D.[3]

1) KICC, Kansas Geological Survey, University of Kansas, Lawrence, KS
2) KICC, Department of Geology, University of Kansas, Lawrence, KS
3) Berexco, LLC., Wichita, KS

Key Findings

- CO_2 injection into the Mississippian oil reservoir at Wellington Field commenced on January 9, 2016

- A total 9,500 tonnes (163,000 MCF) of CO_2 were injected by March 31 with only 4,600 MCF of CO_2 produced since venting started on March 1.
- Incremental oil production began on Feb. 26 and totaled 1,098 barrels on March 31.
- A supercritical CO_2 plume and adjoining miscible oil bank continue to build in the immediate vicinity of the injection well, Berexco Wellington KGS #2-32.
- The geomodel and composition simulations have provided a useful forecast of the injection

Significance

The goal of the Wellington Small Scale CO_2 injection is to evaluate the efficacy of injecting CO_2 for enhanced oil recovery in a Late Mississippian siliceous dolomite and for saline aquifer storage in the Lower Ordovician Arbuckle Group dolomite. Phase I, the CO_2-EOR pilot injection began on January 9, 2016 and as of March 31, nearly 10,000 tons of CO_2 have been injected into the oil reservoir. The results of this test will contribute toward the ultimate goal of evaluating geologic carbon management in Kansas by 1) establishing best practices for characterization and simulation of the reservoirs, 2) evaluating monitoring techniques to ensure safe and effective CO_2 injection and account for the CO_2 that is injected, 3) applying results to evaluate commercialization in Kansas.

Methods Used for the CO_2-EOR at Wellington

1) Drill, evaluate, and complete CO_2 injection well
2) Revise seismic interpretation and renew geomodel
3) Update simulation and forecast incremental oil and CO_2 sequestered
4) Construct CO_2 injection facility
5) Repressurize the pilot area and begin CO_2 injection, monitoring, and accounting
6) Transition to waterflooding to continue moving oil and sequestration of CO_2 and monitor and assess

Results

First generation geomodel

Porosity models of the Mississippian reservoir using well control alone indicated reservoir continuity across Wellington Field agreeing with an excellent waterflood history (**Figures 43 and 48**).

Updated reservoir quality and distribution

Three-dimensional seismic imaging and new logging, coring, and testing of the CO_2 injection well reveal important refinements in the reservoir important in the design of the CO_2 flood. Complex low-angle, progradational patterns of the siliceous spiculitic dolomite Mississippian reservoir with local antecedent and syndepositional structures locally impact both quality and continuity of the reservoir (**Figures 45 and 46**). A northeast trending low porosity and permeability trend passing immediately east of the new injection well represents the distal end of a westward progradational lobe toeing out alongside a small (~15 m offset) syndepositional fault.

CO_2 injection performance meeting expectations

The continuous injection of CO_2 began on January 9, 2016. With nearly 10,000 metric tons of CO_2 injected by March 31st and close monitoring of gases and liquids produced, only minor amounts of CO_2 have broken through to the nearby producing wells beginning on February 28 (**Figure 48**). Initial oil recovery began on March 1st with over 1,000 barrels total recovery as of March 31. Some dissolved CO2 has moved west of the injection pattern, but not eastward across the low porosity-permeability trend (**Figure 48**). The 18-seismometer network has detected minor seismicity in the area, but none that can be attributed to the CO_2 injection.

Acknowledgements

This project's primary sponsor is DOE-NETL (*Contract DE-FE0006821*) with support of cost sharing partner and field operator, Berexco, LLC. KICC has provided valuable support for students who have contributed to many facets of the project since it was established in 2009.

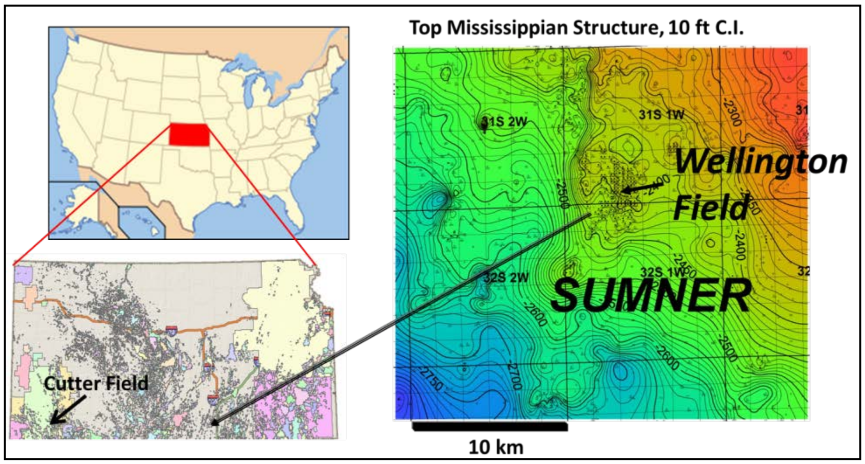


Figure 43. Location map of Wellington Field, Sumner County, Kansas.

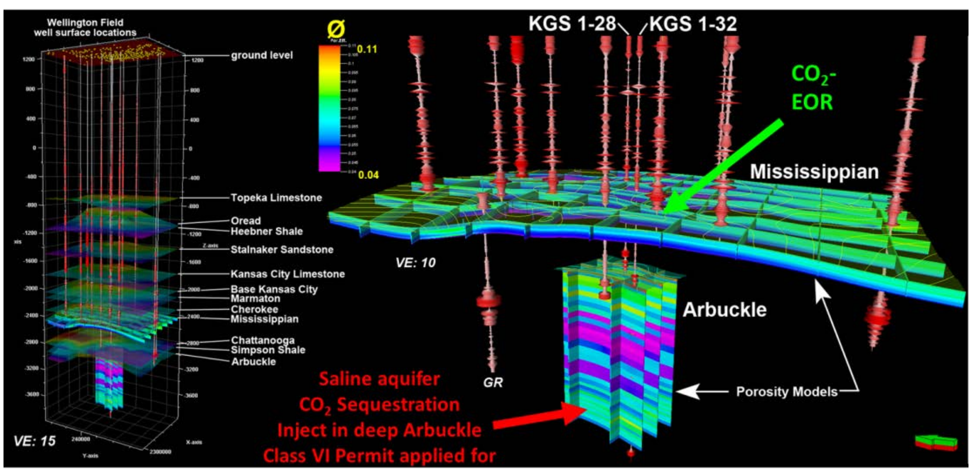


Figure 44. Porosity distribution in the Mississippian and underlying Arbuckle Group in Wellington Field as depicted in an early version of Petrel geomodel (J. Rush, KGS)

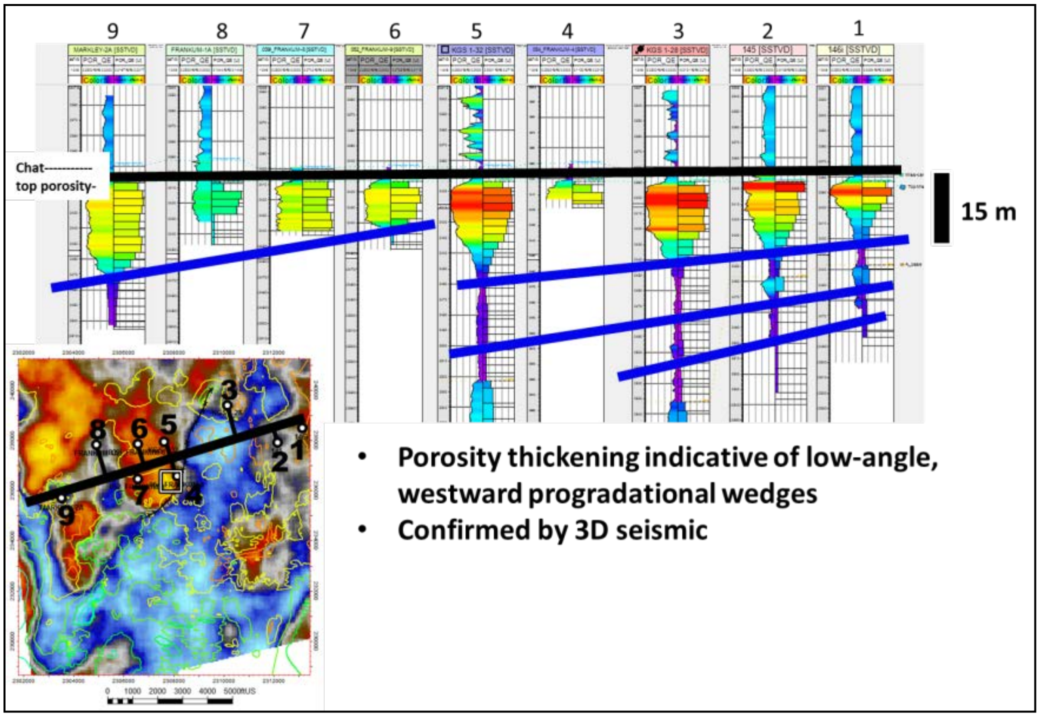


Figure 45. West to east gamma ray and porosity cross section with datum at the top of the Mississippian oil reservoir crossing near the CO_2-EOR injection well (well #6).

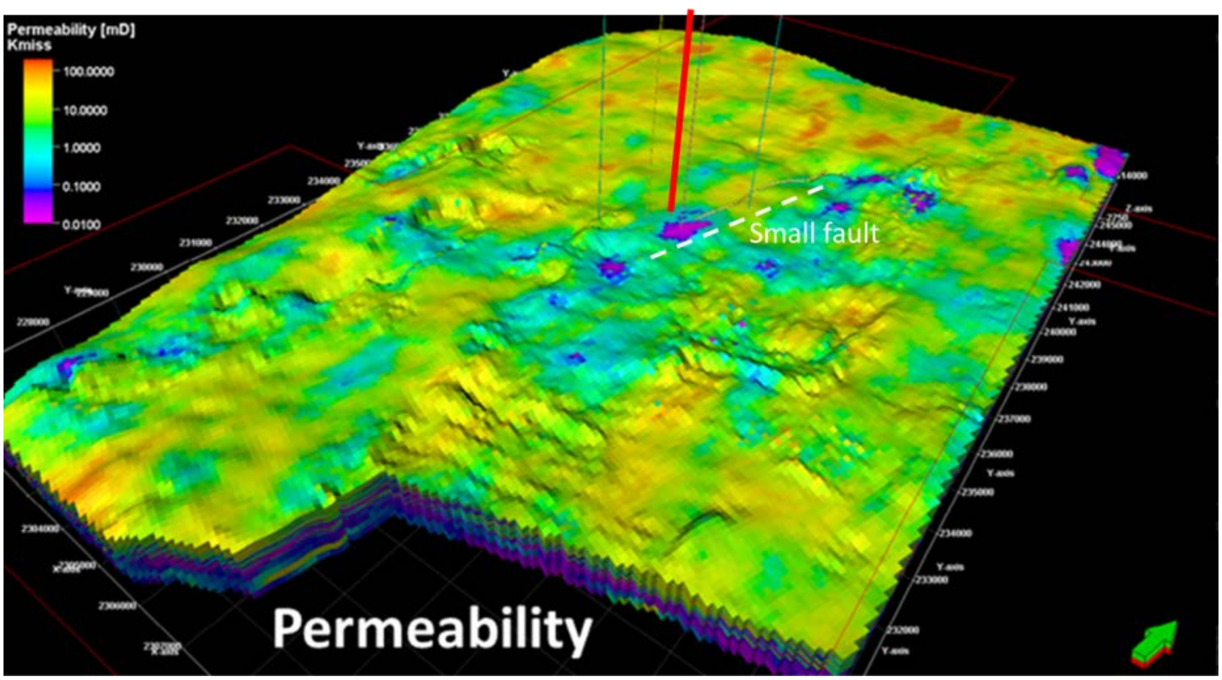


Figure 46. Petrel geomodel showing permeability distribution near the CO_2-EOR injection well, Berexco KGS #2-32, identified by the red vertical line (Rush, Holubnyak, and Fazelalavi).

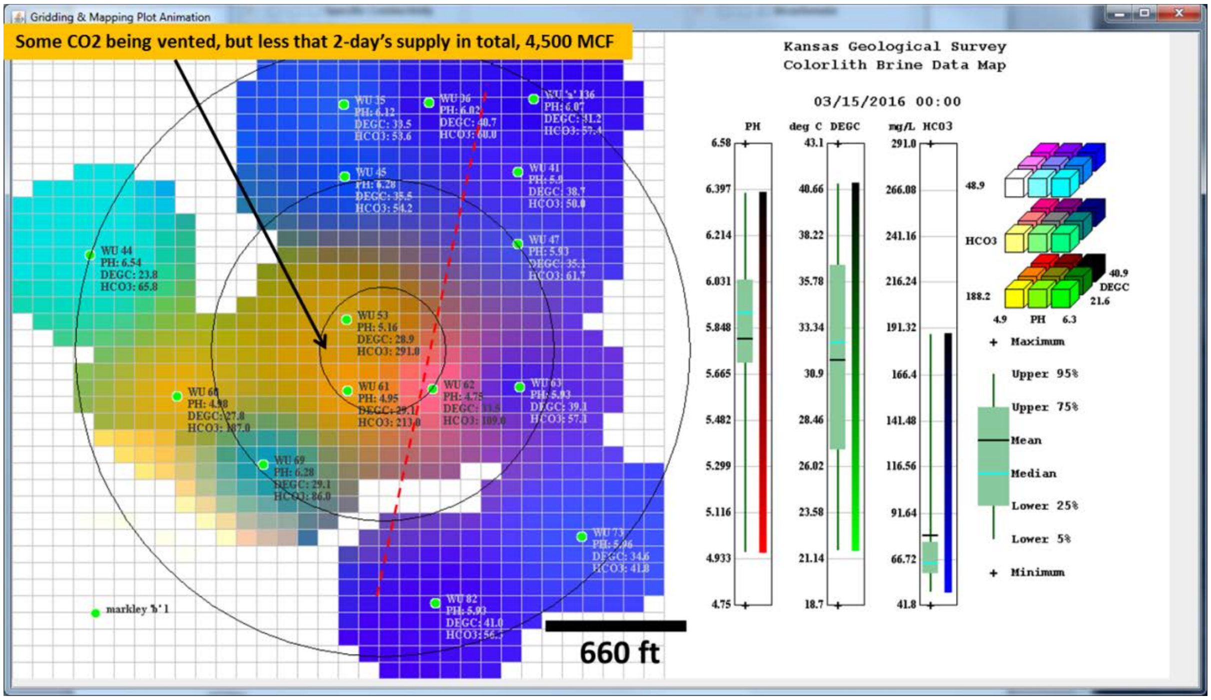


Figure 47. Colorlith map of pH, temperature, and alkalinity from weekly sampling of the brine within the CO_2-EOR (ring map). Inner ring is retaining most of the CO_2 (Campbell, Jackson, Whittemore, Roberts, Hollenack, Victorine, Blazer).

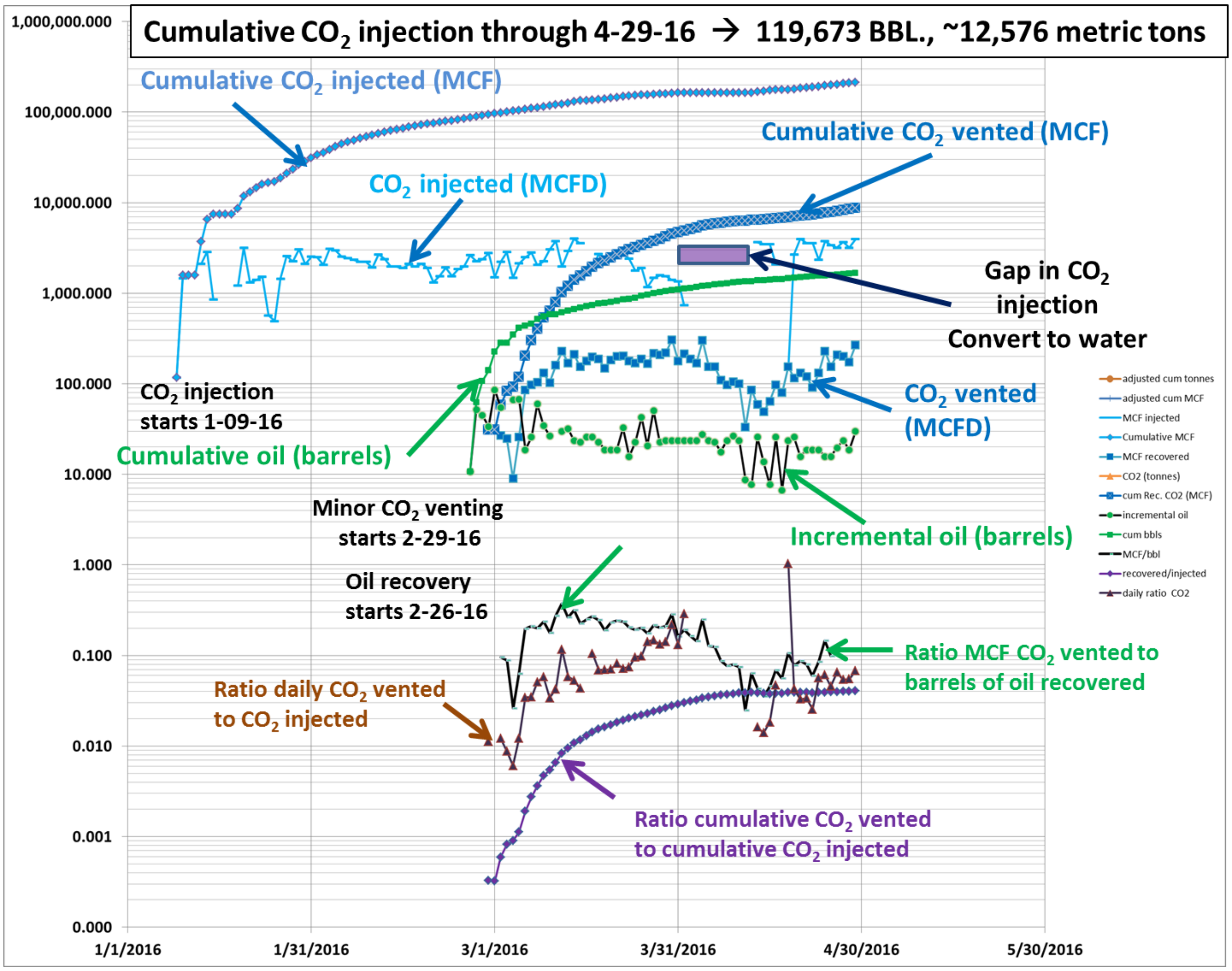


Figure 48. Combined semi-log plot of the CO_2 injected and recovered and the oil produced from the Wellington CO_2-EOR through the end of April, 2016

CO_2-EOR Datasheet and time lapse maps

While CO2 injected has remained steady except for short period of water injection, venting of CO2 has increased very slowly since it began to be produced on 2-29-16. CO2 recovery to 267 MCFD on April 29, representing 9% of the CO2 injected on a daily basis (**Figure 48**). The CO2 recovery has since decreased slightly and venting now totals 147 MCF on May 7. Most of the CO2 and oil remain within the inner ring wells #53, #61, and #62 surrounding the injection well, #2-32, with a small of amount of CO2 being produced from well #60 to the west in the outer ring (**Figure 49**).

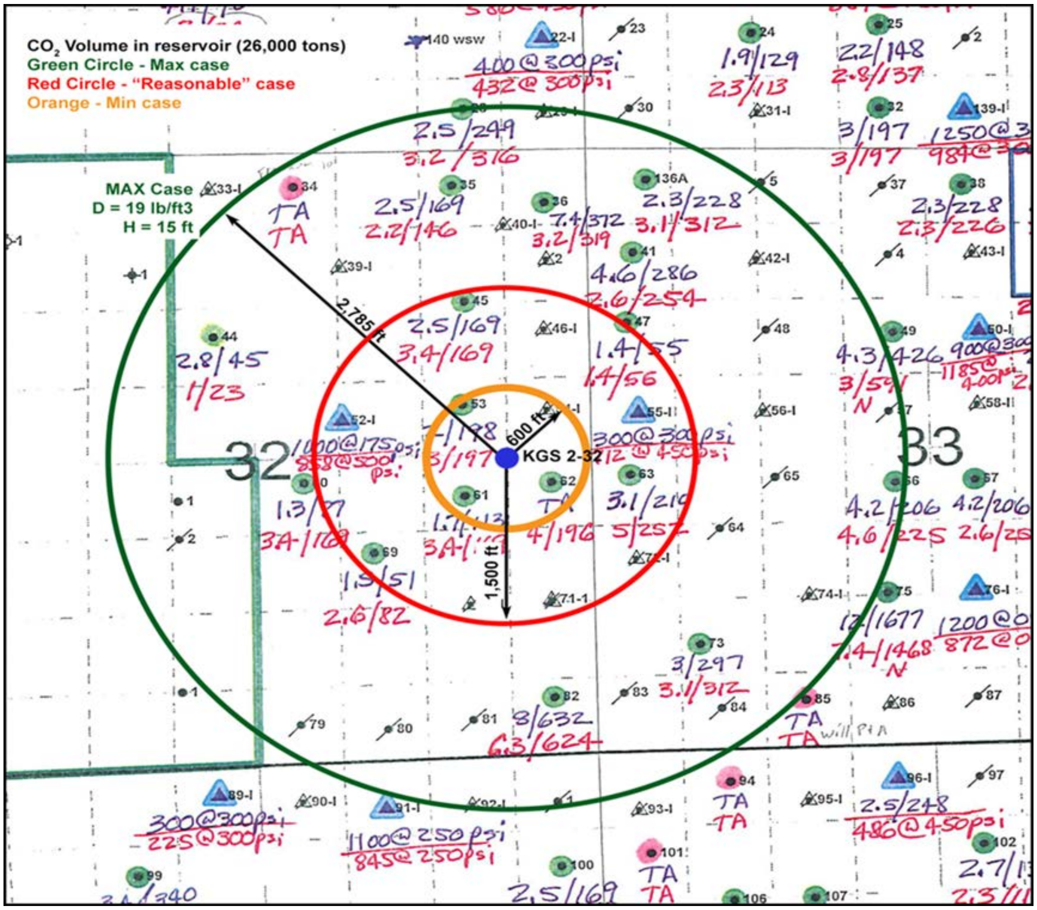


Figure 49. Ring map of Wellington Field. Ring system is used to establish a system to determine CO2 and oil production changes and to aid in sampling is discussing response.

Field measurements of pH, temperature, and HCO3 as of May 10 indicate some the CO2 had reached a well farther west, #44 in the outer ring. Well #69 still has shows of CO2 in the casinghead gas and pH and temperature indicate the gas is present in small amounts beneath this well (**Figure 47**). Recently, well #63 in the inner ring to the east of the injection well and across the small fault has begun to respond. A test rate test from the injection well carried out before repressurization of the reservoir indicated a similar mutted pressure response, so this late response to CO2 is not unexpected. This also demonstrates that the fault and related lithofacies change on either side of fault due to its syndepositional nature act as a baffle to the CO2 migration. This may be more so the changes the lithofacies than the fault itself. Also, no unusual migration of CO2 is otherwise noted along the fault.

Tubing pressure has increased slightly, comparable to levels experienced at the end of January. daily injected volumes of CO_2 has risen to levels of mid March (**Figures 50 and 51**). Also, oil production is on a gentle increase of 9 bbls per day since March 24 (**Figure 52).** CO_2 recovery is holding rather steady around 200 MCF per day, amounting to 7% of the CO_2 injected on a daily basis (**Figure 53**). Ratio of daily CO_2 recovered to injected was at 29% before brine was injected on April 2nd (**Figure 53**). When CO_2 injection was resumed on April 13th, the ratio had declined to 2%, attesting to the impact of an interlude of brine injection (**Figure 53**). The ratio of cumulative CO_2 recovered vs. injected since January 9th has remained about 5% since April 16th (**Figure 53**). It will be important to continue to closely watch this ratio in terms of optimizing the sweep efficiency of the CO_2.

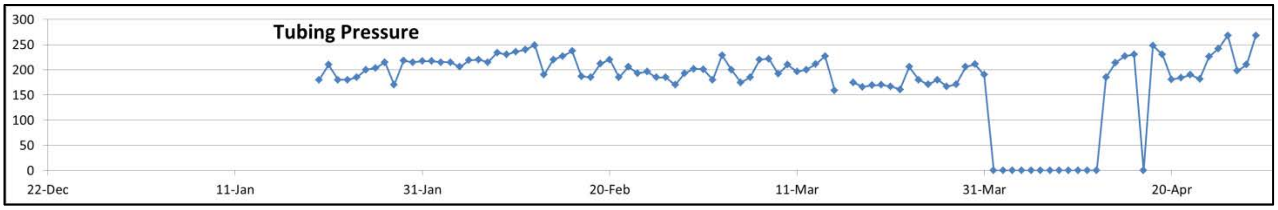


Figure 50. Tubing pressure has increased since CO_2 injection was restarted (zero tubing pressure) on April 13th.

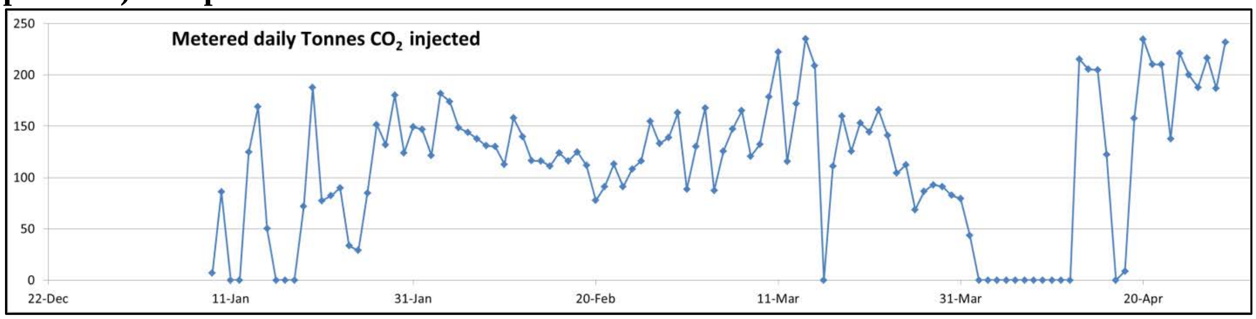


Figure 51. Daily metered CO_2 injected tonnes/day.

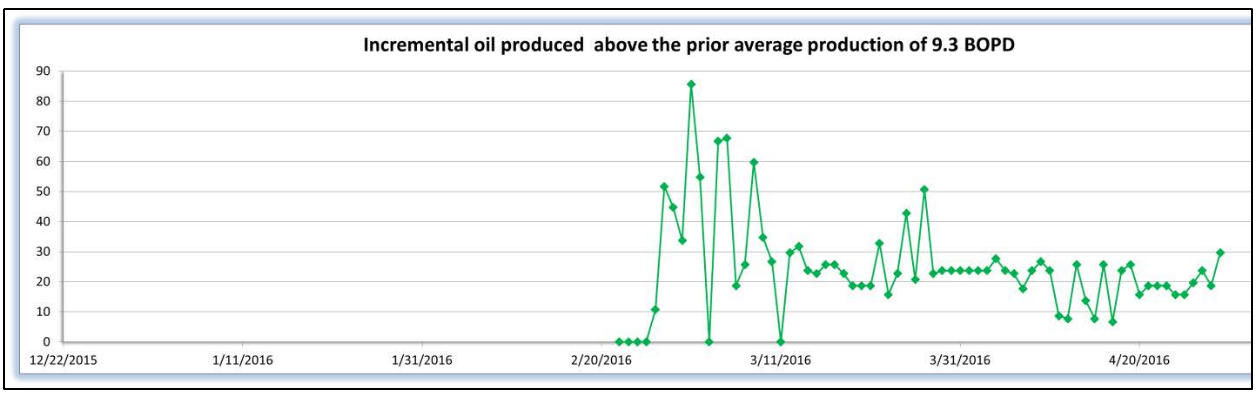


Figure 52. Incremental oil recovery from the Nelson East tank battery. The slight increase in oil recovery in late April may have been in response to the increased CO_2 injection since late April.

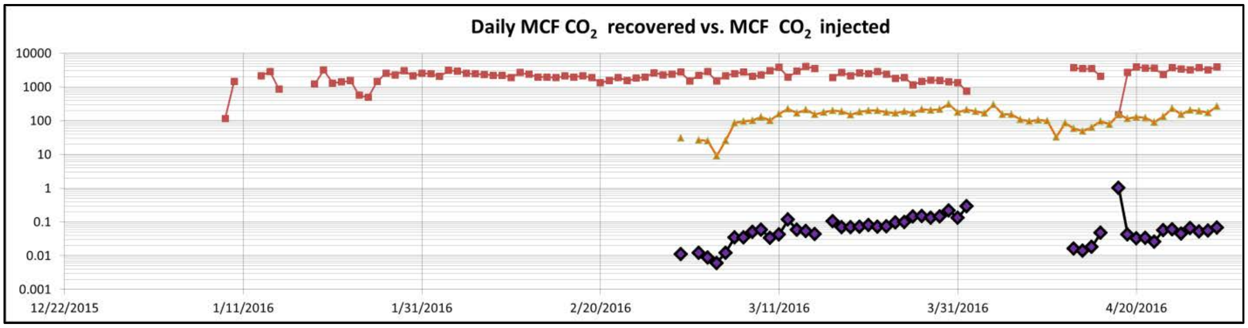


Figure 53. Daily oil recovered (red) compared to cumulative CO2 injected vs. recovered (gold), that is compared to the ratio between the daily CO2 recovered and injected.

Weekly monitoring indicates that the CO_2 plume has started limited expansion to the east of the injection well. The western expansion of the CO_2 is indicated by the field-based alkalinity measurements, remaining high in the two inner ring wells, #53 and #61, and continuing increase in well #60 in the outer ring (**Figure 54**). Brine pH taken on 4-20-16 shows pH decrease in well #63 on east side of monitored area indicating a clear expansion of the influence by CO_2 (**Figure 55**). It was just noted today 5/2/16 that well #63 began to vent a small amount of CO_2, between 3 and 5 MCFD. This expansion of the CO_2 to well #63 is indicated in the map of the estimated bottom hole pressure (**Figure 56**). Well #63 lies on the opposite side of a small fault (less than 75 ft displacement, considered to be syndepositional fault due to the facies change across the fault. The well had pressure communication with the injection well during a pressure test in mid-2015, but the pressures were muted. Also, pressure response was again lagging during repressurization of the reservoir from 900 psi to 1600 psi that extended from October 1, 2015 to late December, 2015. All of this points to a baffle and reduced permeability between the injection well and #63. At the same time, no CO_2 appears to have moved along the fault since wells along the trace of the fault have not responded to the CO_2 injection.

The map showing current vented CO_2, oil cut, and bottomhole pressure in **Figure 57** indicate a clear base of where the CO_2 and oil actually are located, in the inner ring wells. While CO_2 is venting in very small amounts from well #60 to the west of the CO_2 injection well, the incremental oil has stayed in inner ring near the CO_2 injection well (**Figure 57**).

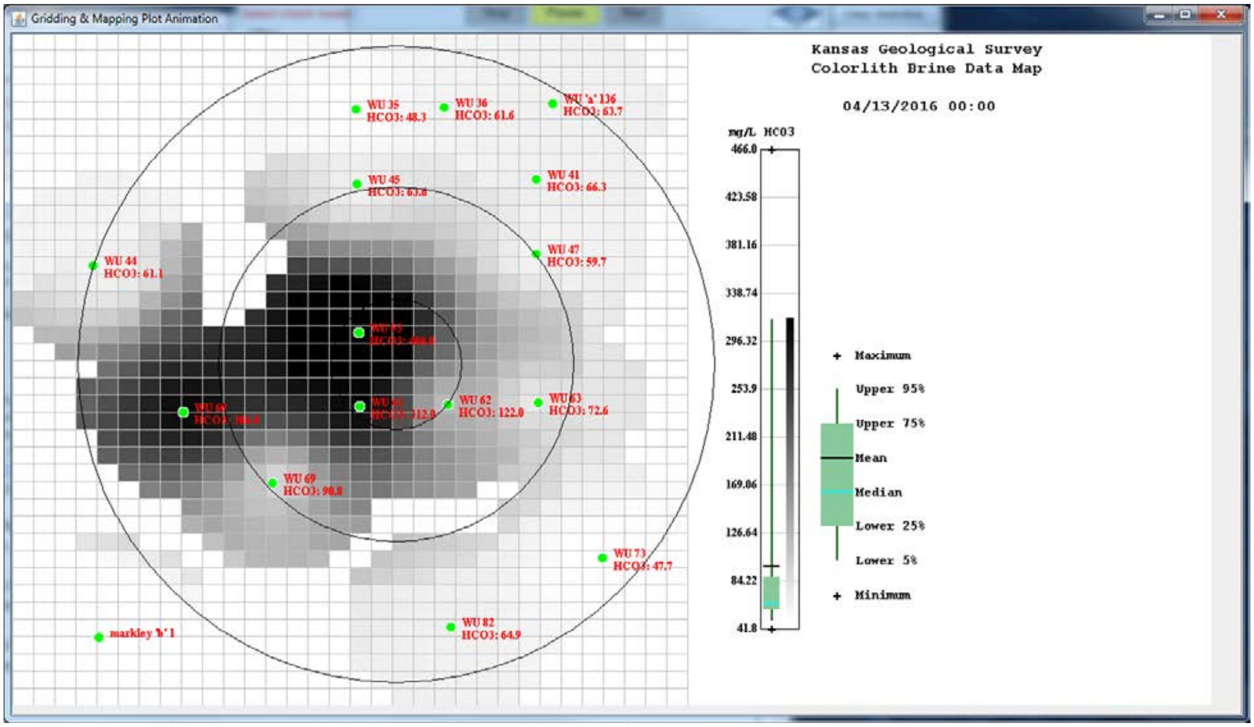


Figure 54. Field based alkalinity.

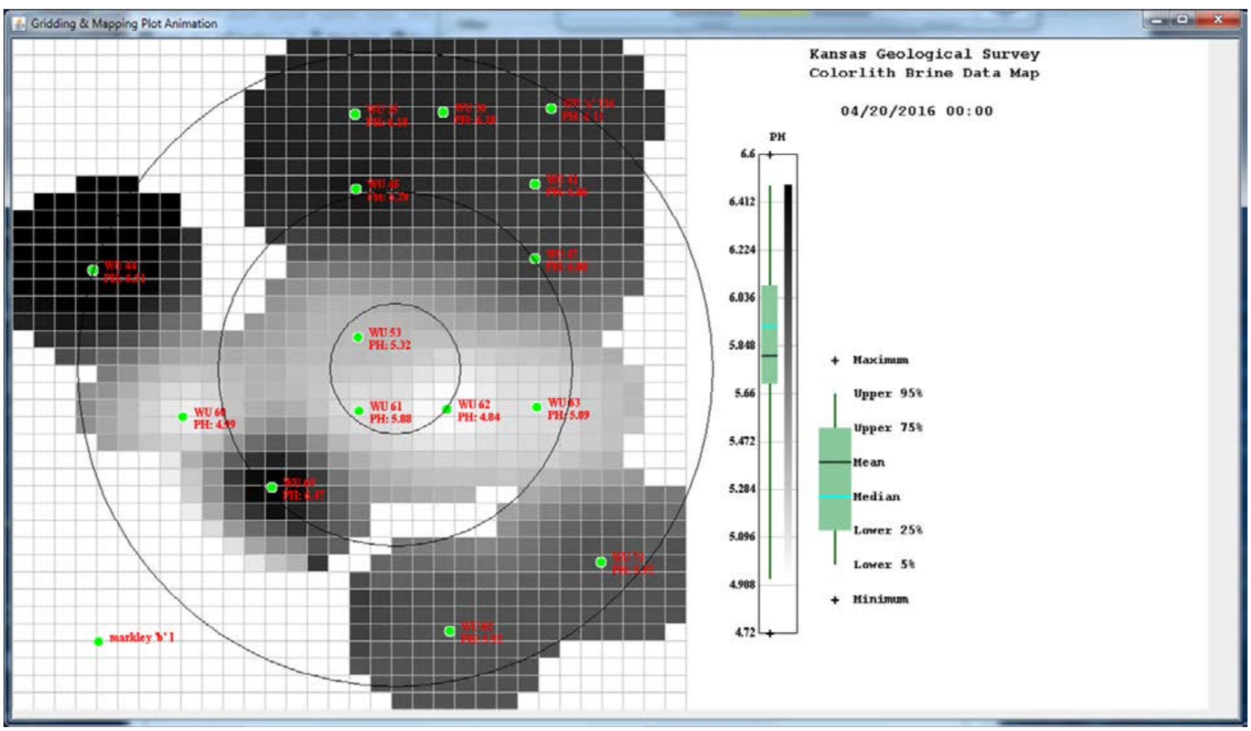


Figure 55. Brine pH taken on 4/20/16 indicates that pH began to fall in well #63 located to the east of the CO2 injection well.

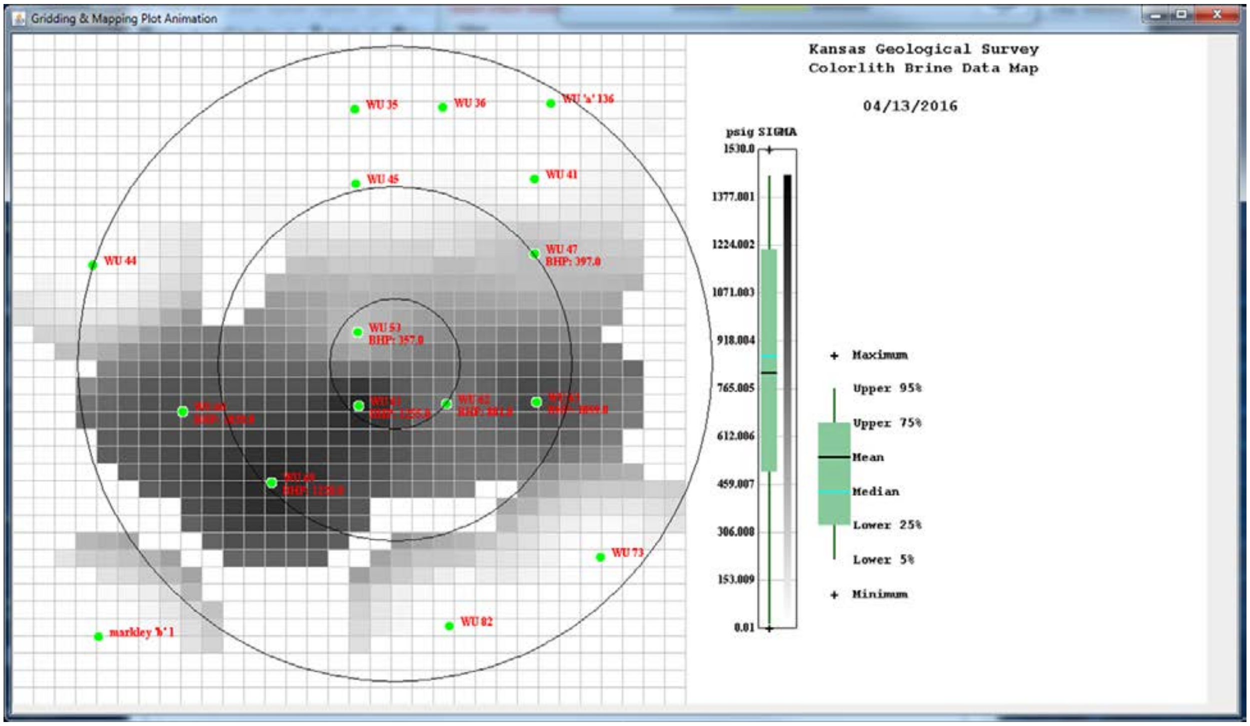


Figure 56. Estimated bottom hole pressure.

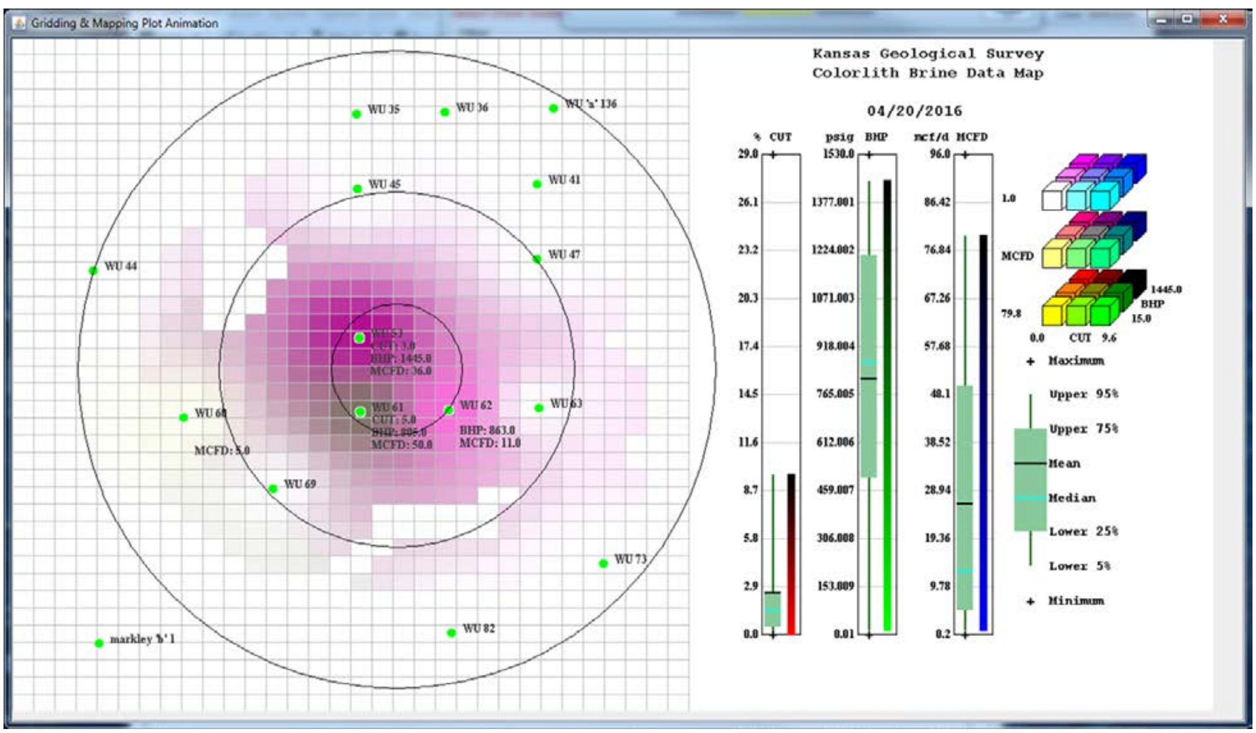


Figure 57. Combined vented CO_2, oil cut, and bottomhole pressure.

Simulation of phase change of CO_2 around the CO_2 injection well

Simulation of phase and pressures of the CO_2 injected into the Mississippian reservoir suggests the creation of a core column of CO_2 in the immediate vicinity of the CO_2 injection well. The modeled column of CO_2 depicts what is believed to be a phase change from liquid to supercritical CO_2 due to the effects of warming of the cold CO_2 that is injected (**Figure 58**). The CO_2 spans the entire thickness of porous and permeable dolomite reservoir extending below the 30 ft long perforations in the uppermost Mississippian (**Figure 59**) to an equal thickness of reservoir below the perforations.

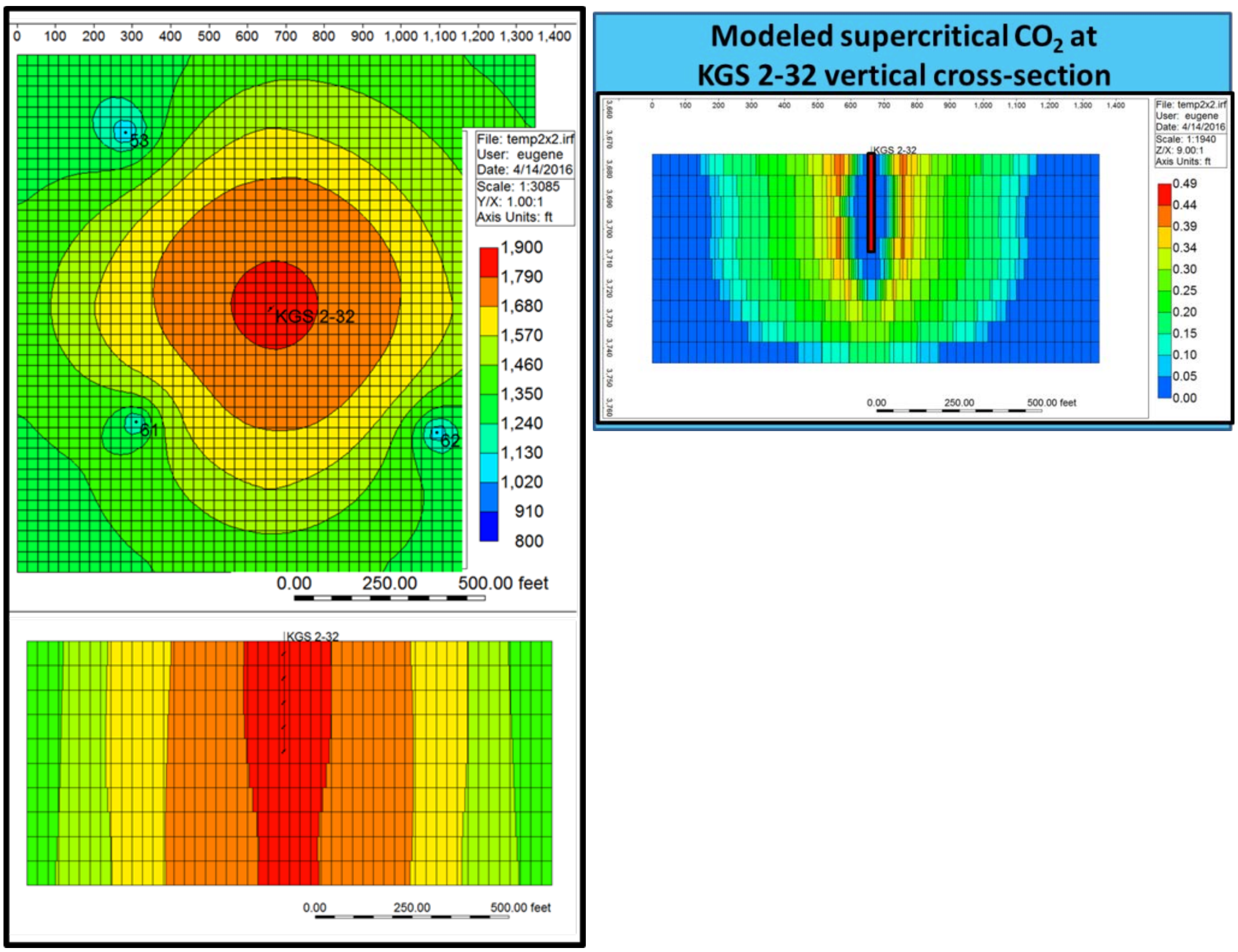


Figure 58. Simulation of phase and pressures of the CO_2 injected into the Mississippian reservoir

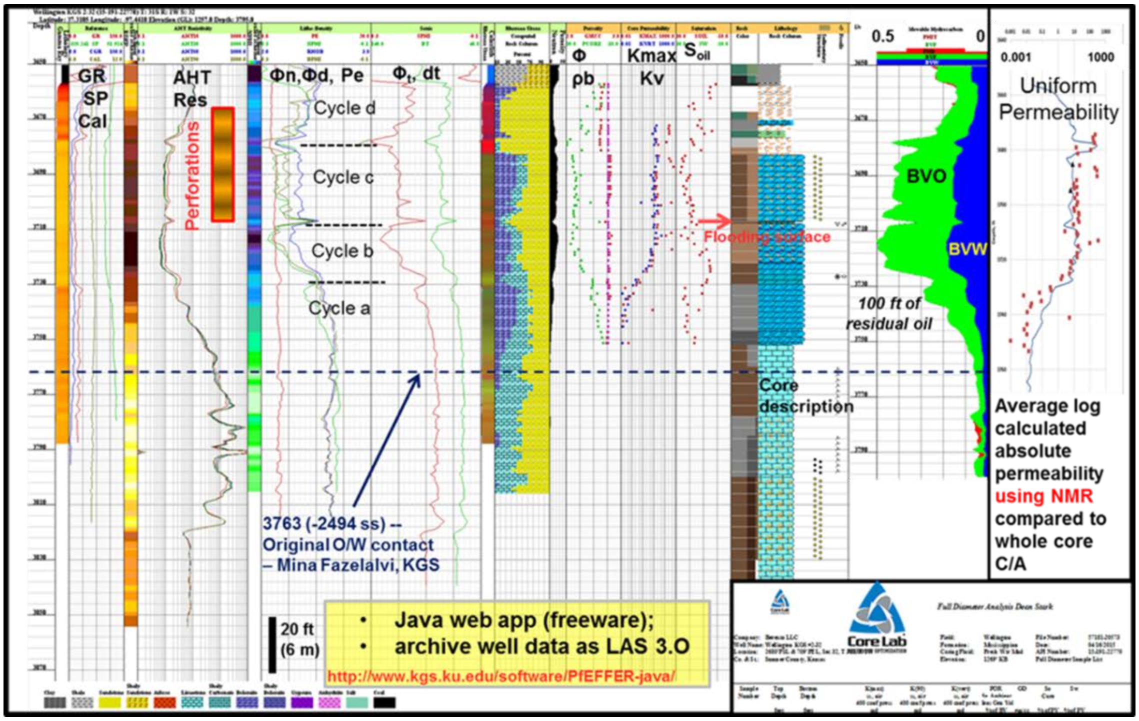


Figure 59. Wellbore profile the CO_2 injection well, Wellington KGS #2-32.

Further constraints in reservoir to help explain the location of the CO2

As previously mentioned the CO2 is contained in the inner ring of wells with shows of CO2 in the casinghead gas only in locations in nearby wells on the west side of the small medial fault that bisects the field (**Figure 60**). The internal stratigraphy of the Petrel geomodel was examined from a sequence stratigraphic viewpoint and in so doing recognized the progradational nature of the oil reservoir. Two views of west-to-east depth-migrated seismic cross section, a structural version above and a section with a stratigraphic datum on the top of Pierson (**Figure 61**) illustrates the discontinuity on the east side of the projected location of the CO2 injection well #2-32. The lithofacies change and the fault itself are acting as a baffle to the CO2 plume with only recent increases noted in pressure and CO2 show in well #63 shown in **Figure 56**. This condition is expected to continue and will have to maintain pressure and serve to confine the CO2 plume and oil bank on the west side of the fault.

Figure 62 is another west to east depth migrated seismic sections displaying inverted porosity rather than amplitude. The section is a stratigraphic with a datum at the top of the Pierson the MFS. The line of section is north of the structural block that contains the small fault and the CO2-EOR injection site. Without the fault, the progradational nature of the highstand systems track (HST) is clearly evident. The dip on the clinoforms is approximately 3 degrees. This same dip is indicated in the microresistivity imaging logs for the HST. It is evident in the type of strata that local compartmentalization can be created by lateral stratigraphic as lithofacies appear to change along the clinoform, grainier and porous on the proximal side and at the toplap at the top of the Mississippian encounters more subaerial weathering and autoclastic brecciation, the chert rich breccias with limited porosity. It is possible that the shows of CO2 that have extended beyond the CO2 plume may by the result of migration along the thin fractured vuggy breccias at the top of the Mississippian (high frequency cycle D as described in core and logs in the CO2 injection well, #2-32 as shown in **Figure 59**).

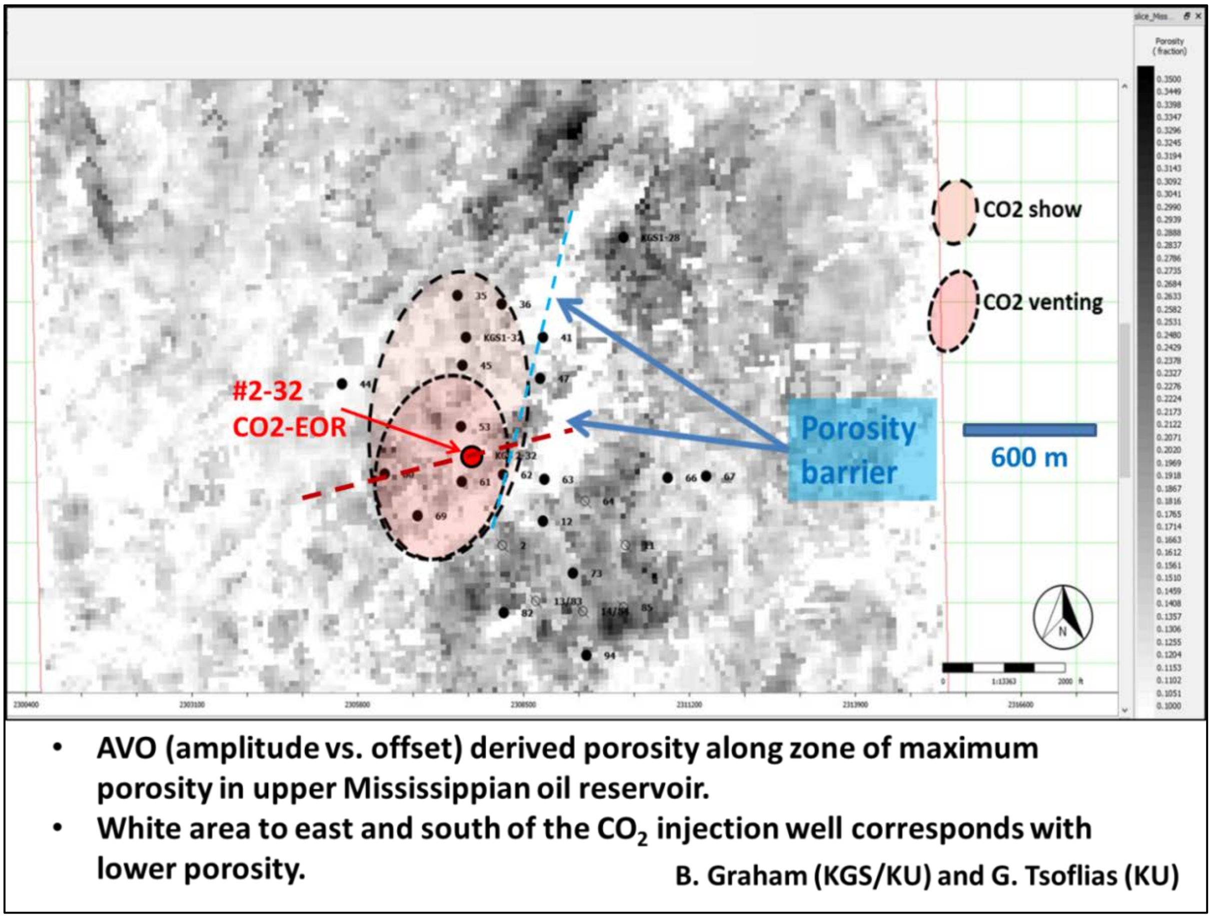


Figure 60. AVO map of the porosity along the maximum porosity illustrating the low porosity (area of more solid white) bordering the east and south sides of the CO2 plume outlined in black dashed line.

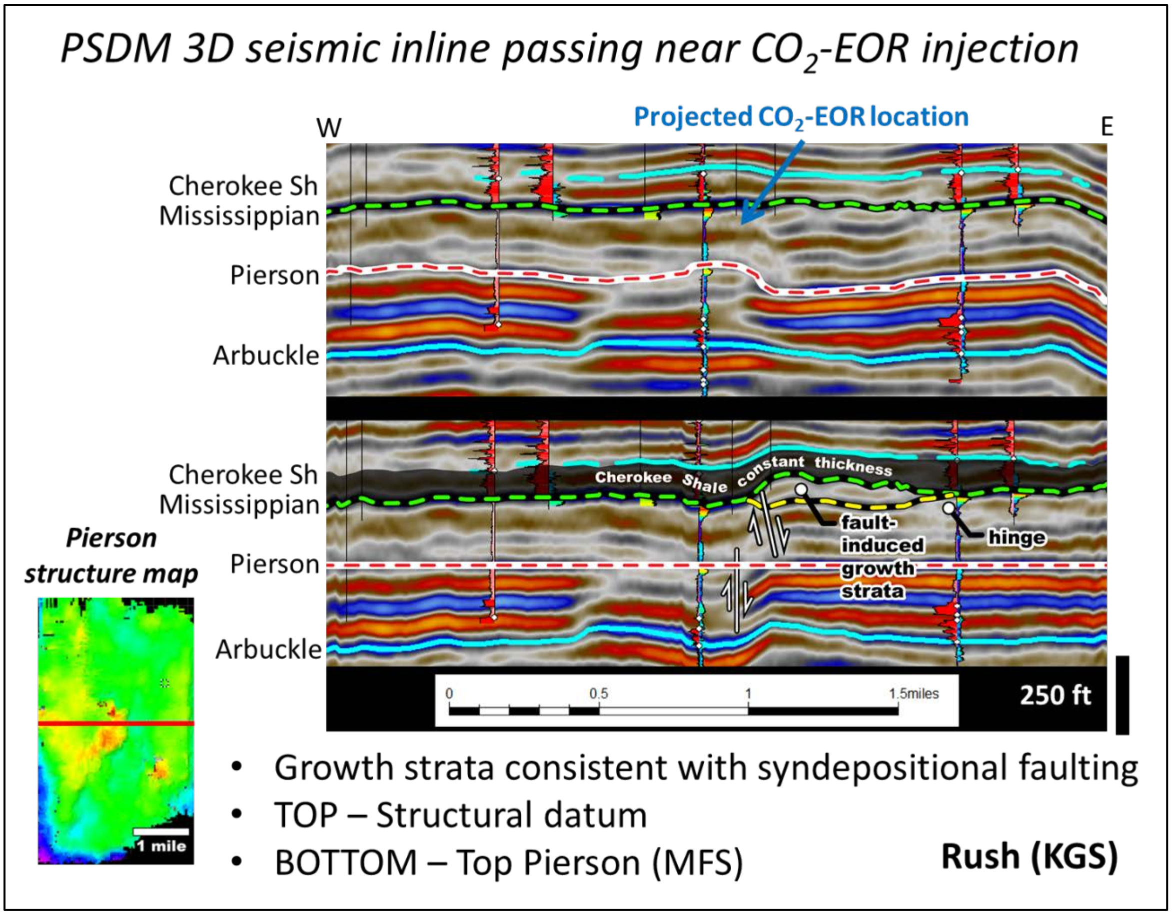


Figure 61. Depth-migrated seismic west-to-east cross sections crossing the small fault and CO2 injection site. Fault is interpreted as syndepositional and terminates at the top of the Mississippian. The Pierson datum on the lower cross section is a maximum flooding surface (MFS) capping a transgressive systems tract characterized by long, thin continuous seismic reflectors and rock that indicates deeper water organic-rich argillaceous dolosiltite. Overlying the MFS is a high stand systems track consisting of thicker inclined seismic reflectors comprised of mostly porous spiculitic packstone and grainstone indicative of shallower water deposition.

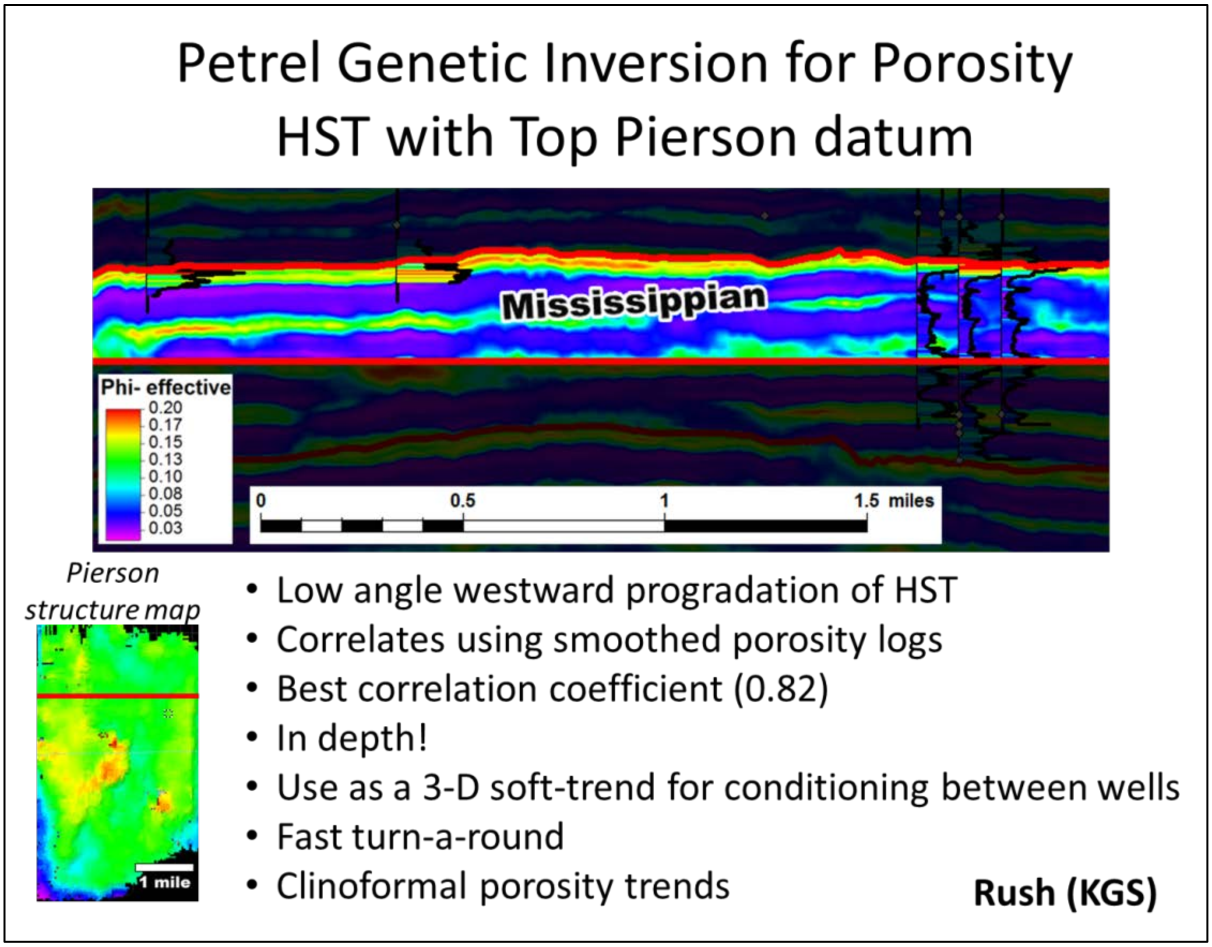


Figure 62. West-to-east cross section with stratigraphic datum at the top of Pierson the MFS underlying the high stand systems track (HST) existing the westerly dipping clinoforms. Note folding across the structure inferred from thinning and arching of the Pierson strata below, again suggesting syndepositional movement, in keeping with many examples of structural reactivation that affected most all of the strata in Kansas (Watney, 1980, Baars and Watney, 1991, Watney et al., 2001, and Watney et al., 2008).

The geochemical studies of the sampled brines and gases will provide considerable insight into the manner in which CO2 is sequestered in the cherty spiculitic dolomite reservoir. The Mississippian dolomite is considerably different than the Arbuckle dolomite being 1) finely crystalline, 2) zoned crystals of dolomite that are Fe-bearing and non ferroan, and 3) Mississippian dolomites are non-stokiometric pure Mg-Ca carbonate, but contain impurities including Fe and Mn, as indicated in geochemical lab test, XRD, petrographic characterization (**Figure 63**). Pore size of the Mississippian dolomites in smaller exposing more surface area to minerals to react with CO2 **(Figure 63a**). Besides the dolomite and silica, accessory minerals include glauconite, pyrite, and anhydrite (**Figure 64**), providing addition reaction sites for the CO2.

Lab experiments conducted on the Mississippian dolomite indicate that supercritical CO2 did readily react when samples were ground to exposure more service area with the dolomite and framboidal pyrite showing notable dissolution. . Also, secondary precipitation of iron oxides were noted (**Figure 65**).

The general profile of the Mississippian oil reservoir is considerably more uniform than the Arbuckle since the parasequences are thicker and the pore space does not vary as much as the Arbuckle. The geochemical results of the field injection will be closely analyzed to understand the how and how much CO2 is sequestered in the Mississippian.

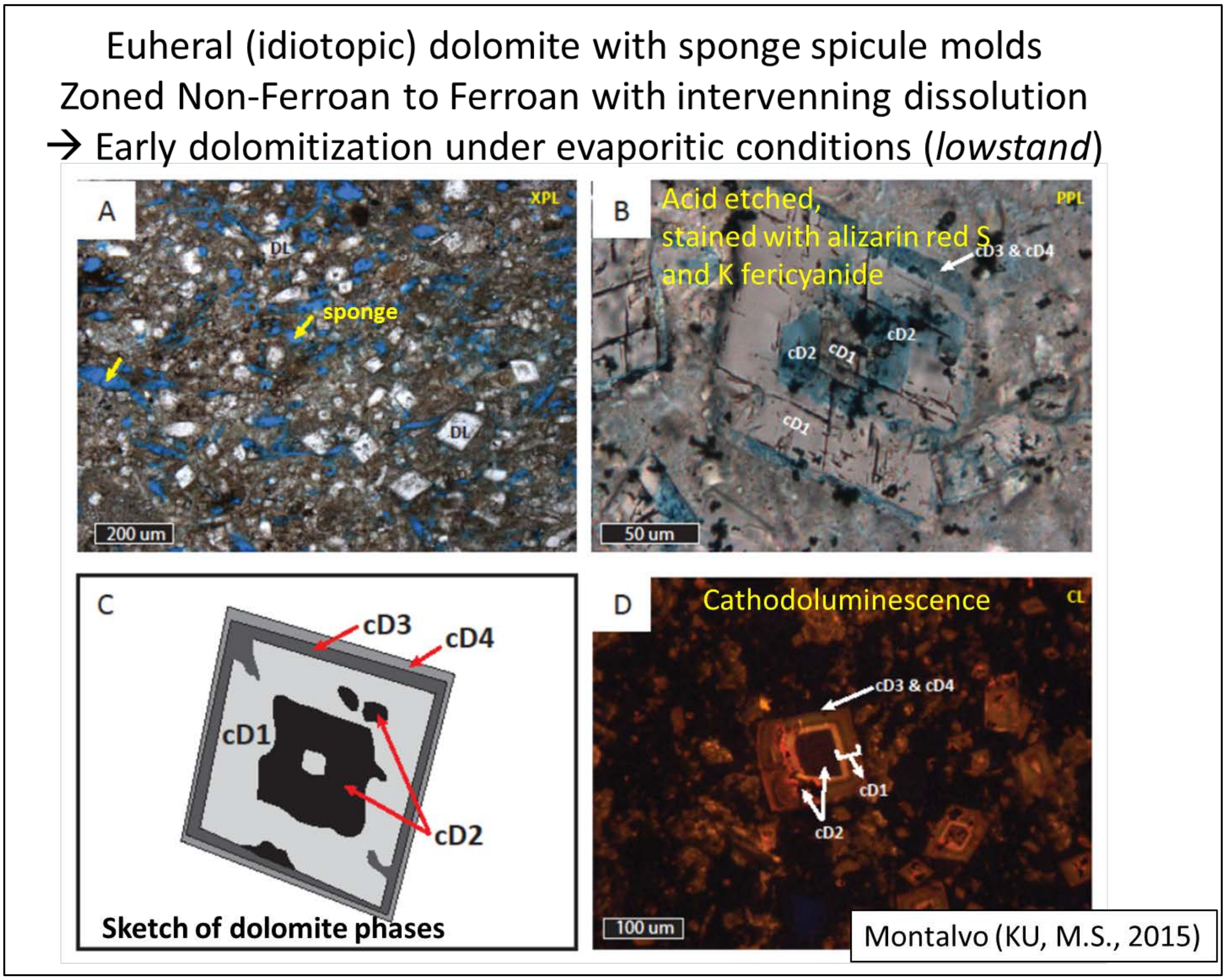


Figure 63. Thin section petrography, staining, and cathodoluminensce were used to characterize the Mississippian dolomite.

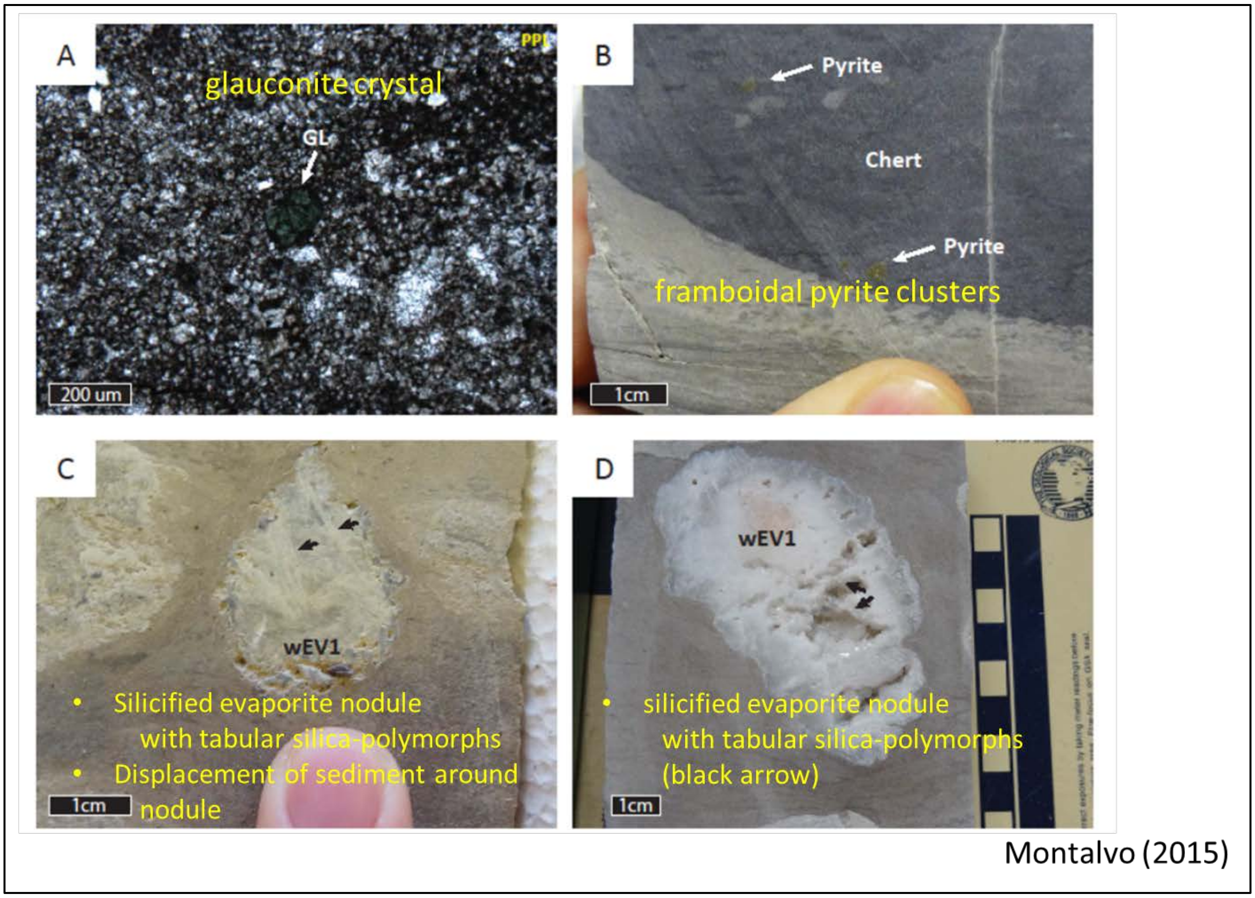
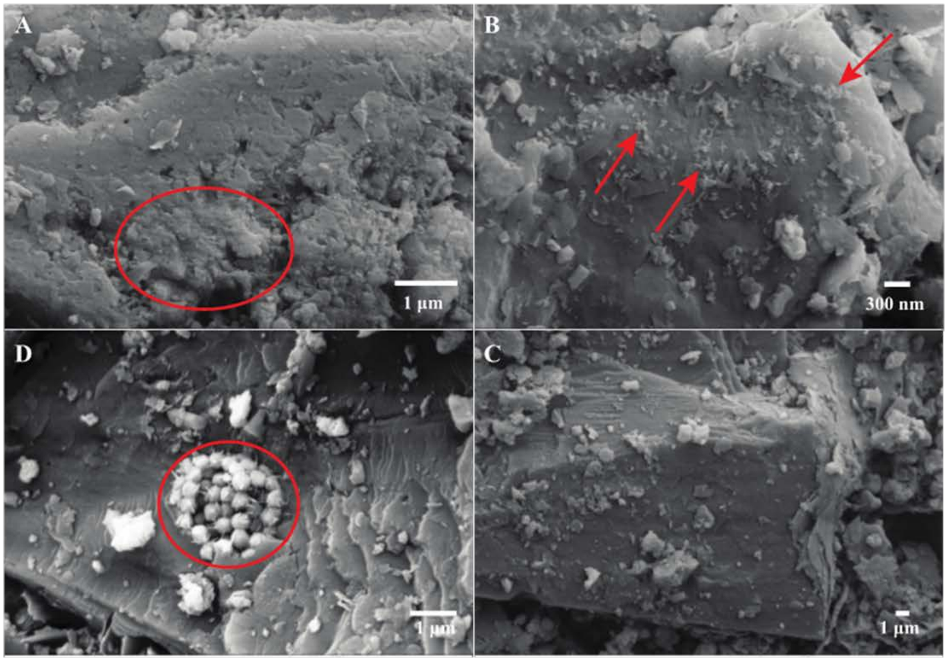


Figure 64. Accessory minerals present in the Mississippian oil reservoir include pyrite, glauconite, and anhydrite, the later distributed as nodules in part replaced by silica.



- (A) **Supercritical CO_2 reacted** -- Dolomite Dissolution, Framboidal Pyrite, and Secondary Precipitation of Iron Oxides in Abiotic Cowley Experiments.
- (B) Secondary precipitation of Fe-oxides can be seen in CO_2-reacted "Cowley Facies"
- (C) **Nitrogen-reacted control experiments** show no signs of dolomite dissolution or Fe-oxyhydroxide precipitation.
- (D) Framboidal pyrite crystals, circled in red, are present in unreacted "Cowley Facies", and may be dissolved upon exposure to CO_2.
- Images were taken using the secondary electron detector of a LEO field emission scanning electron microscope.

Christa Jackson, (KU M.S. 2015) and Jennifer Roberts, Geology, KICC

Figure 65. Scanning electron microscopy was conducted on samples of Mississippian dolomite that were subjected to supercritical CO2. Dissolution of dolomite and pyrite and precipitation of iron oxides were noted.

Several photos are shown of the injection site in **Figures 66 and 67**. Operations have gone smoothly for the field crew, Berexco, LLC, and the CO2 supplier, Linde Group.

Figure 66. The upper left photo at the Wellington site shows the Linde storage tanks. The manifold and hoses from the storage tanks and a small pump are shown in the upper right photo. The CO2 injection well #2-32 is shown in the lower left photo with the triplex pump behind the wellhead. is brine on site in case it is needed for the injection well. The triplex pump is shown on the lower left with the cylinders behind the heads where the CO2 is located, thus coated with white frost.

Figure 67. Left photo shows larger oil cut when the incremental oil began to be produced from the wells nearest the CO2 injection well. Oil cuts typically were 1 to ½ percent compared to the 30% noted in the photo. Upper right photos shows the East Nelson tank battery with the gun barrel in the foreground that separates oil from water and in light brown, the gas separated added as CO2 began to be produced with the oil and water. Normally, gas production is insignificant in this field. The lower right photo shows the meter for the CO2 being injected at the wellhead. The meters at the injection and producing wells are part of the SCATA (Supervisory Control And Data Acquisition) system and can be accessed and controlled online.

SUMMARY

1. The mobilized oil recovered to date represents only a very small fraction of the pore volume believed to reflect at portion of the CO_2 that has moved and been vented at the producing wells. The dates of the venting of measureable CO_2 and incremental oil were essentially simultaneous at the end of February 2016, a month and a half after continuous CO_2 injection started.

2. Venting of CO_2 remains only around 5% of the CO_2 that is injected, ~200 MCFD. The conversion to brine injection for 2 weeks in April led to a reduction of the CO_2 that was vented, but venting of CO_2 has again have returned to the same low level.
3. The remaining CO_2 appears to be accumulating around a slowly expanding area within the inner ring of producing wells. This is suggested by the time-series maps and the simulation of the CO_2 phase behavior around the injection well. An injection profile test done early during the CO_2 injection also suggested that the CO_2 was moving downward.
4. There is considerable pore volume in the lower portion of the Mississippian reservoir that is also below the perforated interval of the CO_2 injection well. Similarly, producing wells are also perforated in the uppermost Mississippian. The implication is that the recovery of the oil and CO_2 will be more complex than simply injection of brine following CO_2. Pressure maintenance will be required around the pilot area as well as keeping the inner ring wells pumped at a level to drive the CO_2 and oil to these wells.
5. CO_2 has finally reached well #63 located to the east of the injection well. The delay is not unanticipated with the diminished response to pressurization before CO2 injection and a subdued response during a pressure pulse test in May 2015. Interpretation of 3D seismic also indicates a northeast-to-southwest area of reduced permeability and porosity in the vicinity of well #63 that appears to be responsible for the delayed response. The small fault associated with the area of reduce porosity and permeability has no other effects on the CO2 injection compares to normal variations in reservoir properties as conveyed by the existing seismic data and interpretations.
6. Induced seismicity of small, but notable rates reached Wellington Field in early 2015 prior to repressurization and CO2 injection in the Mississippian reservoir. The Wellington seismometer array has documented this advance with a dependable earthquake catalog that is updated on a weekly basis.
7. Steps have been taken by Kansas regulators to limit rates and volumes of brine injection into the Arbuckle in the area due to this expansion of earthquakes and the development of earthquake clusters as noted with the Wellington array and the temporary array of the KGS.
8. The Wellington array has provided important surveillance of this seismicity, but more important, will provide new scientific understanding of the properties of earthquakes, including geomechanical information that will augment other well based and seismic information from Wellington. The objective will be to address what comprises safe and effective injection and understand the mechanisms of induced seismicity to further limit or prevent induced seismicity in the future.
9. Introduction of continuous downhole pressure monitoring in the Arbuckle in the idle well #1-28 shows considerable promise to establish that static pressure in the lower Arbuckle has risen since the well was last tested in August 2011. The resolution of the pressure transducer is also investigating the potential to short term pressure perturbations that may be from start-up of larger brine disposal wells or co-seismic events when earthquakes occur. The well information will be compared with updates to the regional brine simulations and is currently being compared in time with events from the Wellington earthquake catalog.

FUTURE PLANS

Evaluation of Performance of the CO2-EOR

CO2 injection will eventually change to waterflood and pressure maintenance to manage the CO2 plume and oil bank so that the latter can be moved to nearby producing wells. With the relatively small amount of CO2 vented and oil recovered, 12,000 tonnes (200,00 MCF) CO2 injected and 9,000 MCF recovered (4.5% of the total injected), steps will be taken to determine when the CO2 injection will be changed to water injection.

The forecast will be made on a technical basis reviewing the

1) well production, pressures, and fluid recovery;
2) geochemical data -- The well and fluids data is analyzed on a weekly basis and will be integrated and summarized with analytical tools to determine the current conditions of the CO2 plume and oil bank.
3) update of reservoir simulation - forecasts will factor into how the plume and oil bank can be best managed.
4) seismicity has been recorded at micro levels in the immediate vicinity of the field and the depths of the earthquakes have been restricted to the shallow basement; earthquakes are unrelated to the current injection, arriving in early 2015 before the Mississippian reservoir was represssurized and before CO2 injection began.
5) Satellite Synthetic Aperture Radar (SAR) scenes continue to be acquired on a monthly basis and will be integrated via InSAR processing to determine if ground deformation has occurred; in fall 2015, the conclusion was that the noise level was too high to resolve surface deformation.
6) repeat 2D seismic survey is being considered to firm up the location and properties of the CO2 plume prior to ending CO2 injection (**Figure 68**). The timeliness of the repeat 2D is helping to manage the plume while assuring EPA of the capability of using repeat seismic to image the CO2 plume for the Arbuckle injection. The seismic line would also provide additional understanding of the fault and how CO2 is interacting with it. Sufficient offset will be obtained to use results for AVO analysis, a primary processing technique that would be used to close the project when the CO2 injection in the Arbuckle has been completed. The baseline survey is the original 3D seismic survey so it would be acquired and processed in the same manner.

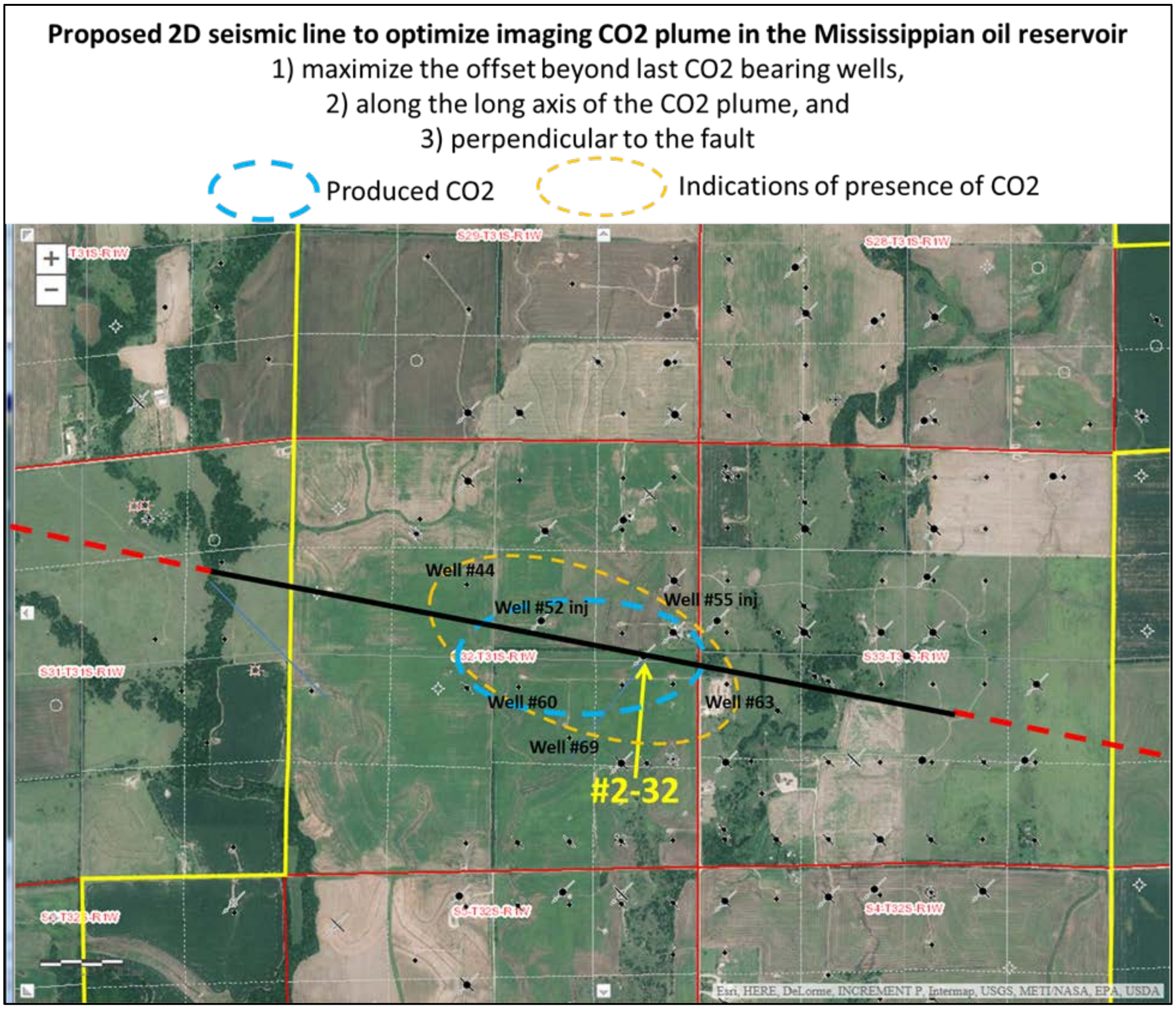


Figure 68. A repeat 2D seismic survey is being considered. The final processed line is shown as the black solid line. In order to get the long offsets needed for AVO the actual survey footprint (i.e. locations occupied by the vibroseis trucks on land) will have to extend 4,000 feet longer on both ends of the black line, approximated by the red dashed line segments.

PRODUCTS

Publications, conference papers, and presentations

1) Presentation made on induced seismicity and conducting safe and effective injection at Kansas Next Step Oil and Gas Seminar, Hays, KS on 4-6-16

2) Berexco sponsored field trip to Wellington for KU Engineers was held on 4-19-16. Fifteen students and faculty from the KU Petroleum and Chemical Engineering Department along with members of Berexco and KGS.
3) Presentation on CO2 Utilization and Storage in Kansas to KU 66th Annual Environmental Engineering Conference on April 19th. Here is the link to the presentation
4) CO2-EOR project update to KU Interdisciplinary Carbonate Consortium.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

A project organization chart follows (**Figure 69**. The work authorized in this budget period includes office tasks related to preparation of reports and application for a Class VI permit to inject CO_2 into the Arbuckle saline aquifer.

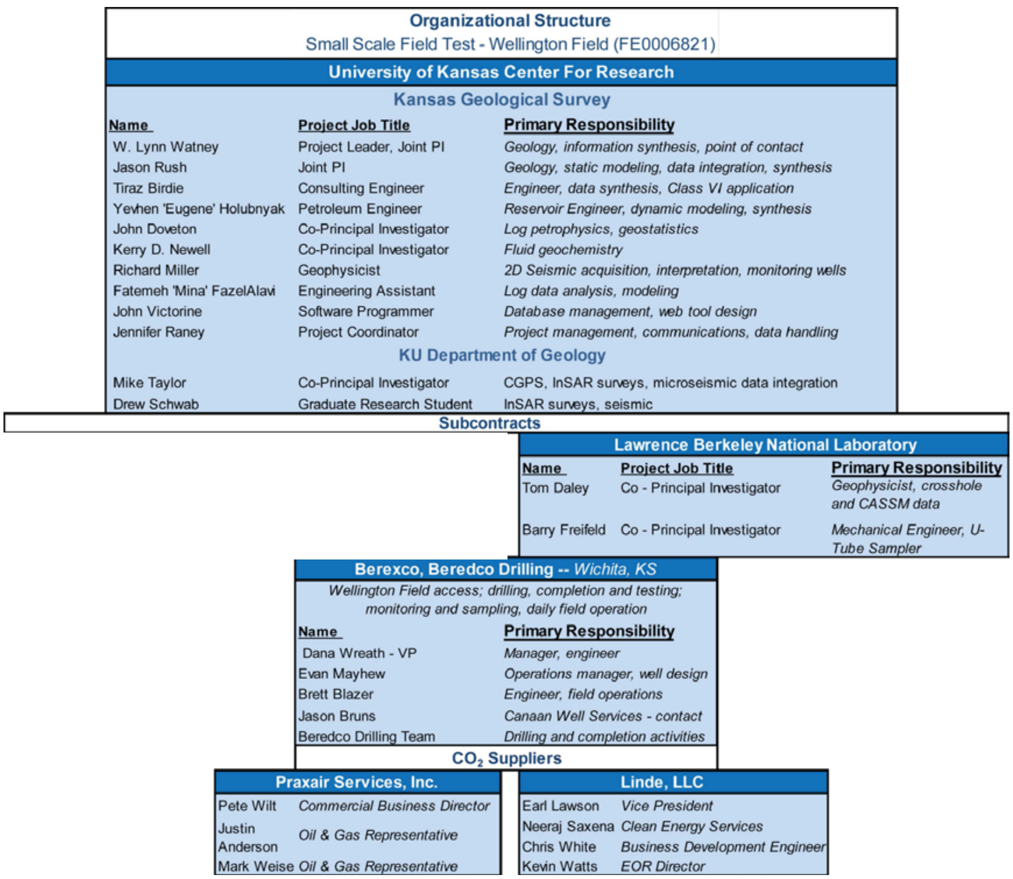


Figure 69. Organizational Chart.

IMPACT

The response of the CO2-EOR is very promising. With the exception of a RFI on well completion from EPA, documents for the Class VI application have been submitted.

CHANGES/PROBLEMS

Funds are very tight due to the no cost time extensions necessary to permit review and response to for the Class VI permit.

BUDGETARY INFORMATION

Cost Status Report

Baseline Reporting Quarter	1/1/16 - 3/31/16 Q18	4/1/16 - 6/30/16 Q19	7/1/16 - 9/30/16 Q20
Baseline Cost Plan (from SF-424A)			
Federal Share	$325,087.75	$325,087.75	$325,087.75
Non-Federal Share	$0.00	$0.00	$0.00
Total Planned (Federal and Non-Federal)	$325,087.75	$325,087.75	$325,087.75
Cumulative Baseline Cost	$13,333,560.28	$13,658,648.03	$13,983,735.78
Actual Incurred Costs			
Federal Share	$271,440.25	$0.00	$0.00
Non-Federal Share	$0.00	$0.00	$0.00
Total Incurred Costs-Quarterly (Federal and Non-Federal)	$271,440.25	$0.00	$0.00
Cumulative Incurred Costs	$3,549,458.46	$3,549,458.46	$3,549,458.46
Variance			
Federal Share	$53,647.50		
Non-Federal Share	$0.00		
Total Variance-Quarterly Federal and Non-Federal)	$53,647.50		
Cumulative Variance	**$9,784,101.82**		