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(5/09)
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**ATTACHMENT 3**
**U.S. Department of Energy**
**FEDERAL ASSISTANCE REPORTING CHECKLIST**
**AND INSTRUCTIONS**

| 1. Identification Number:<br>**DE-FE0002056** | 2. Program/Project Title:<br>**Modeling CO2 Sequestration in Saline Aquifer and Depleted Oil Reservoir to Evaluate Regional CO2 Sequestration Potential of Ozark Plateau Aquifer System, South-Central Kansas** |
|---|---|

3. Recipient:
University of Kansas Center for Research

| 4. Reporting Requirements: | Frequency | No. of Copies | Addresses |
|---|---|---|---|
| **A. MANAGEMENT REPORTING**<br><br>☒ Progress Report<br>☒ Special Status Report | Q<br>A | Electronic Version to NETL> | *FITS@NETL.DOE.GOV* |
| **B. SCIENTIFIC/TECHNICAL REPORTING \***<br>(Reports/Products must be submitted with appropriate DOE F 241. The 241 forms are available at https://www.osti.gov/elink) | | | |
|     Report/Product            Form | | | |
| ☒ Final Scientific/Technical Report    DOE F 241.3<br>☒ Conference papers/proceedings/etc.\*  DOE F 241.3<br>☐ Software/Manual              DOE F 241.4<br>☒ Other (see special instructions)<br>    Topical                   DOE F 241.3<br>*\* Scientific/technical conferences only* | FG<br>A<br><br><br><br>A | Electronic Version to E-link> | *http://www.osti.gov/elink-2413*<br>*http://www.osti.gov/elink-2413*<br>*http://www.osti.gov/estsc/241-4pre.jsp* |
| **C. FINANCIAL REPORTING**<br><br>☒ SF-425, Federal Financial Report | Q, FG | Electronic Version To NETL> | *FITS@NETL.DOE.GOV* |
| **D. CLOSEOUT REPORTING**<br><br>☐ Patent Certification<br>☐ Property Certificate<br>☐ Other | FC<br>FC | Electronic Version To NETL> | *FITS@NETL.DOE.GOV* |
| **E. OTHER REPORTING**<br><br>☒ Annual Indirect Cost Proposal<br>☒ Annual Inventory Report of Federally Owned Property, if any<br>☐ Other | A<br>A | Electronic Version To NETL> | *FITS@NETL.DOE.GOV* |
| **F. AMERICAN RECOVERY AND REINVESTMENT ACT REPORTING**<br><br>☐ Reporting and Registration Requirements | | | *http://www.federalreporting.gov* |

**FREQUENCY CODES AND DUE DATES:**

    A - As required; see attached text for applicability.
    FG - Final; within ninety (90) calendar days after the project period ends.
    FC - Final - End of Effort.
    Q - Quarterly; within thirty (30) calendar days after end of the calendar quarter or portion thereof.
    S - Semiannually; within thirty (30) calendar days after end of project year and project half-year.
    YF - Yearly; 90 calendar days after the end of project year.
    YP - Yearly Property - due 15 days after period ending 9/30.

QUARTERY PROGRESS REPORT

Award Number: DE-FE0002056

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

"Modeling CO2 Sequestration in Saline Aquifer and Depleted Oil Reservoir
To Evaluate Regional CO2 Sequestration Potential of Ozark Plateau Aquifer System,
South-Central Kansas"

Project Director/Principal Investigator: W. Lynn Watney
Principal Investigator: Jason Rush

Fourteenth Quarter Progress Report

Date of Report: May 5, 2013

Period Covered by the Report: January 1, 2013 through March 31, 2013

Contributors to this Report: Saugata Datta, John Doveton, Martin Dubois,
Mina Fazelalavi, David Fowle, Paul Gerlach, Tom Hansen, Dennis Hedke,
Eugene Holubnayak, Larry Nicholson, Jennifer Raney, Jennifer Roberts, Jason Rush,
Ray Sorenson, John Victorine, Lynn Watney, John Youle, Dana Wreath

## EXECUTIVE SUMMARY

The project "Modeling $CO_2$ Sequestration in Saline Aquifer and Depleted Oil Reservoir to Evaluate Regional $CO_2$ Sequestration Potential of Ozark Plateau Aquifer System, South-Central Kansas" is focused on the Paleozoic-age Ozark Plateau Aquifer System (OPAS) in southern Kansas. OPAS is comprised of the thick and deeply buried Arbuckle Group saline aquifer and the overlying Mississippian carbonates that contain large oil and gas reservoirs. The study is collaboration between the KGS, Geology Departments at Kansas State University and The University of Kansas, BEREXCO, INC., Bittersweet Energy, Inc. Hedke-Saenger Geoscience, Ltd., Improved Hydrocarbon Recovery (IHR), Anadarko, Cimarex, Merit Energy, GloriOil, and Cisco.

The project has three areas of focus, 1) a field-scale study at Wellington Field, Sumner County, Kansas, 2) 25,000 square mile regional study of a 33-county area in southern Kansas, and 3) selection and modeling of a depleting oil field in the Chester/Morrow sandstone play in southwest Kansas to evaluate feasibility for $CO_2$-EOR and sequestration capacity in the underlying Arbuckle saline aquifer. Activities at Wellington Field are carried out through BEREXCO, a subcontractor on the project who is assisting in acquiring seismic, geologic, and engineering data for analysis. Evaluation of Wellington Field will assess miscible $CO_2$-EOR potential in the Mississippian tripolitic chert reservoir and $CO_2$ sequestration potential in the underlying Arbuckle Group saline aquifer. Activities in the regional study are carried out through Bittersweet Energy. They are characterizing the Arbuckle Group (saline) aquifer in southern Kansas to estimate regional $CO_2$ sequestration capacity. Supplemental funding has expanded the project area to all of southwest Kansas referred to as the Western Annex. IHR is managing the Chester/Morrow play for $CO_2$-EOR in the western Annex while Bittersweet will use new core and log data from basement test and over 200 mi2 of donated 3D seismic. IHR is managing the industrial partnership including Anadarko Petroleum Corporation, Cimarex Energy Company, Cisco Energy LLC, Glori Oil Ltd., and Merit Energy Company. Project is also supported by Sunflower Electric Power Corporation.

# PROJECT STATUS

| Task Name | Planned Start Date | Actual Start Date | Planned Finish Date | Actual Finish Date | % Complete |
|---|---|---|---|---|---|
| 1.0 Project Management & Planning | 12/8/2009 | 12/08/09 | 2/7/2014 | | 70% |
| 2.0 Characterize the OPAS (Ozark Plateau Aquifer System) | 1/1/2010 | 01/01/10 | 9/30/2013 | | 85% |
| 3.0 Initial geomodel of Mississippian Chat & Arbuckle Group - Wellington field | 1/1/2010 | 01/01/10 | 9/30/2010 | 09/30/10 | 100% |
| 4.0 Preparation, Drilling, Data Collection, and Analysis - Well #1 | 9/15/2010 | 12/15/10 | 3/31/2011 | 08/30/11 | 100% |
| 5.0 Preparation, Drilling, Data Collection and Analysis - Well #2 | 1/1/2011 | 02/20/11 | 6/30/2011 | 08/30/11 | 100% |
| 6.0 Update Geomodels | 5/1/2011 | 05/01/11 | 9/30/2011 | 10/31/12 | 100% |
| 7.0 Evaluate CO2 Sequestration Potential in Arbuckle Group Saline Aquifer | 8/1/2011 | 08/01/11 | 12/31/2011 | 10/31/12 | 100% |
| 8.0 Evaluate CO2 Sequestration Potential in Depleted Wellington field | 10/15/2011 | 10/15/11 | 7/30/2013 +++ | | 87% |
| 9.0 Characterize leakage pathways - risk assessment area | 1/1/2010 | 01/01/10 | 6/30/2012 | 10/31/12 | 100% |
| 10.0 Risk Assessment related to CO2-EOR and CO2 Sequestration in saline aquifer | 6/1/2012 | 06/01/12 | 9/30/2013 ** | | 85% |
| 11.0 Produced water and wellbore management plans - Risk assessment area | 1/1/2012 | 01/01/12 | 7/30/2013 | | 90% |
| 12.0 Regional CO2 sequestration potential in OPAS | 8/1/2012 | | 9/30/2013 | | 75% |
| 13.0 Regional source sink relationship | 1/1/2010 | 1/1//2010 | 9/30/2013 | | 80% |
| 14.0 Technology Transfer | 1/1/2010 | 01/01/10 | 2/7/1014 | | 80% |

| Milestone | Planned Completion Date | Actual Completion Date | Validation |
|---|---|---|---|
| HQ Milestone: Kick-off Meeting Held | 3/31/2010 | 03/31/10 | Completed |
| HQ Milestone: Begin collection of formation information from geologic surveys and private vendors | 6/30/2010 | 01/01/10 | Completed |
| HQ Milestone: Semi-Annual Progress Report on data availability and field contractors | 9/30/2010 | 07/30/10 | Submitted to Project manager |
| HQ Milestone: Establish database links to NATCARB and Regional Partnerships | 12/31/2010 | 12/31/10 | Completed |
| HQ Milestone: Annual Review Meeting attended | 3/31/2011 | 10/05/10 | Completed |
| HQ Milestone: Complete major field activities, such as drilling or seismic surveys at several characterization sites | 6/30/2011 | Note: This milestone was met collectively by all projects. No one project was held accountable to the milestone. | Completed |
| HQ Milestone: Semi-Annual Progress Report (i.e. Quarterly Report ending June 30, 2011) | 9/30/2011 | 09/30/11 | Completed |
| HQ Milestone: Yearly Review Meeting of all recipients; opportunities for information exchange and collaboration | 12/31/2011 | 11/15/11 | Attended meeting |
| HQ Milestone: Complete at least one major field activity such as well drilling, 2-D or 3-D seismic survey, or well logging | 3/31/2012 | 08/15/12 | Completed 3D seismic Cutt |
| HQ Milestone: Complete at least one major field activity such as well drilling, 2-D or 3-D seismic survey, or well logging | 6/30/2012 | 10/09/12 | Completed cutter well reach |
| HQ Milestone: Semi-annual report (i.e. Quarterly Report ending June 30, 2012) on project activities summarizing major milestones and costs for the project 9/30/2012 | 9/30/2012 | 09/30/12 | Completed |
| FOA Milestone: Updated Project Management Plan | 3/31/2010 | 03/31/10 | |
| FOA Milestone: Submit Site Characterization Plan | 5/28/2010 | | Completed |
| FOA Milestone: Notification to Project Manager that reservoir data collection has been initiated | 9/15/2010 | 01/01/10 | Completed |
| FOA Milestone: Notification to Project Manager that subcontractors have been identified for drilling/field service operations | 7/30/2010 | 01/01/10 | Completed |
| FOA Milestone: Notification to Project Manager that field service operations have begun at the project site | 7/1/2010 | 01/01/10 | Completed |
| FOA Milestone: Notification to Project Manager that characterization wells have been drilled | 6/3/2011 | 03/09/11 | Completed |
| FOA Milestone: Notification to Project Manager that well logging has been completed | 6/3/2011 | 03/09/11 | Completed |
| FOA Milestone: Notification to Project Manager that actvities on the lessons learned document on site characterization have been initiated | 7/15/2012 | | Completed |
| FOA Milestone: Notification to Project Manager that activities to populate database with geologic characterization data has begun | 12/31/2010 | 12/31/10 | Completed, email summary |
| KGS Milestone 1.1: Hire geology consultants for OPAS modeling | 3/31/2010 | 03/31/10 | 92% Completed* |
| KGS Milestone 1.2: Acquire/analyze seismic, geologic and engineering data - Wellington field | 6/30/2010 | 06/30/10 | Completed, quarterly rpt |
| KGS Milestone 1.3: Develop initial geomodel for Wellington field | 9/30/2010 | 09/30/10 | Completed, email summary |
| KGS Milestone 1.4: Locate and initiate drilling of Well #1 at Wellington field | 12/31/2010 | 12/25/10 | Completed, email summary |
| KGS Milestone 2.1: Complete Well#1 at Wellington - DST, core, log, case, perforate, test zones | 3/31/2011 | 08/30/11 | Completed, email summary |
| KGS Milestone 2.2: Complete Well#2 at Wellington - Drill, DST, log, case, perforate, test zones | 6/30/2011 | 08/30/11 | Completed, email summary |
| KGS Milestone 2.3: Update Wellington geomodels - Arbuckle & Mississippian | 9/30/2011 | 10/31/12 | completed |
| KGS Milestone 2.4: Evaluate CO2 Sequestration Potential of Arbuckle Group Saline Aquifer - Wellington field | 12/31/2011 | 10/31/12 | Completed |
| KGS Milestone 3.1: CO2 sequestration & EOR potential - Wellington field | 3/31/2012 | | 85% complete'++ |
| KGS Milestone 3.2: Characterize leakage pathways - Risk assessment area | 6/30/2012 | 10/31/12 | Completed |
| KGS Milestone 3.3: Risk assessment related to CO2-EOR and CO2-sequestration | 9/30/2012 | | 90% complete++++ |
| KGS Milestone 3.4: Regional CO2 Sequestration Potential in OPAS - 17 Counties | 12/7/2012 | | 70% complete |

## SUBTASKS COMPLETED WITHIN THE CURRENT QUARTER

**Task 7 -- Evaluation of sequestration potential in Arbuckle Group saline aquifer at Wellington Field through refined geomodel and employing initial simulations of small and larger scale CO2 injection**

Static and dynamic models of CO2 injection into the Arbuckle Group saline aquifer at Wellington Field were completed for use in the Class VI application as described in the 13th quarterly progress report. The focus of the modeling has been on a small scale field test of 40,000 tonnes, but commercial scale injection of 14 million tonnes in a single injection well was done to demonstrate larger scale capacity and containment by the Wellington Field structure.

**Task 10.  Risk assessment related to CO2-EOR and CO2-sequestration in saline aquifer**

A considerable amount of effort has been done in assessing risk locally and regionally analyzing well completions, structure, caprocks, and and pressures and injectivity lately the porosity and permeability within intervals the Arbuckle that are deemed most promising for injection. Of more recent interest has been earthquake hazards. Kansas' earthquake hazard is relatively low (Figure 1), i.e., active faults or those subject to activity are considered minor with respect to most areas of the U.S. outside of the north-central tier of states, Texas, and Florida.
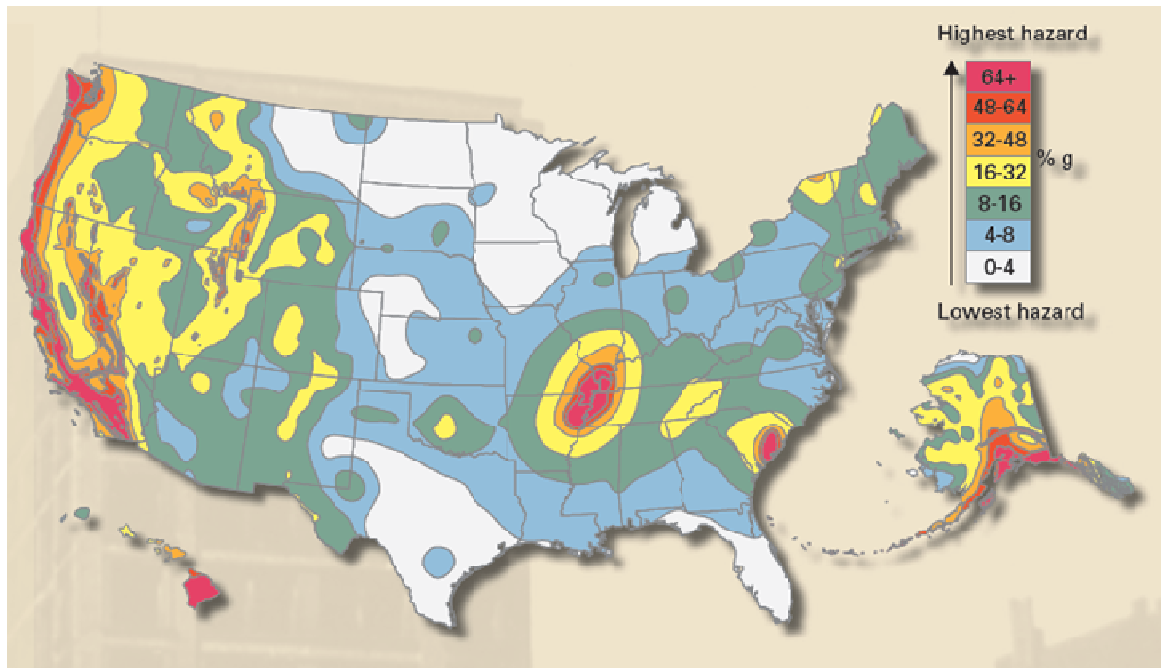


**Figure 1.    U.S. seismic hazard map. Colors on this map show the levels of horizontal shaking that have a 2-in-100 chance of being exceeded in a 50-year period. Shaking is expressed as a percentage of g (g is the acceleration of a falling object due to gravity).Source: 2008 United States National Seismic Hazard Maps, USGS, Menlo Park, CA.**

The sealing capacity of the the primary and secondary caprocks that bound the Mississippian and overly the Arbuckle saline acquifer were re-evaluated by examining the extent of underpressuring in the Mississippian. The Mississippian reservoir at Wellington Field is underpressured, which was previously inferred to represent the effective sealing of these caprocks.

The final shut in pressures from 1051 drill stem tests in the upper Mississippian reservoir in Sumner County were divided by the measured depth from the surface for each well. The pressure gradient map indicates that under-pressurization prevails throughout the Mississippian in Sumner County (**Figure 2**). At most sites, the gradient is within the 0.2 -0.4 psi/ft range. There are very few sites with a freshwater hydrostatic gradient of 0.433 psi/ft or greater (or even 0.42 psi/ft, which was observed for DST's in the Arbuckle aquifer at KGS 1-28 and KGS 1-32). The few sites where the pressure gradient exceeds 0.433 psi/ft may be those associated with water flooding that has been implemented in the area.
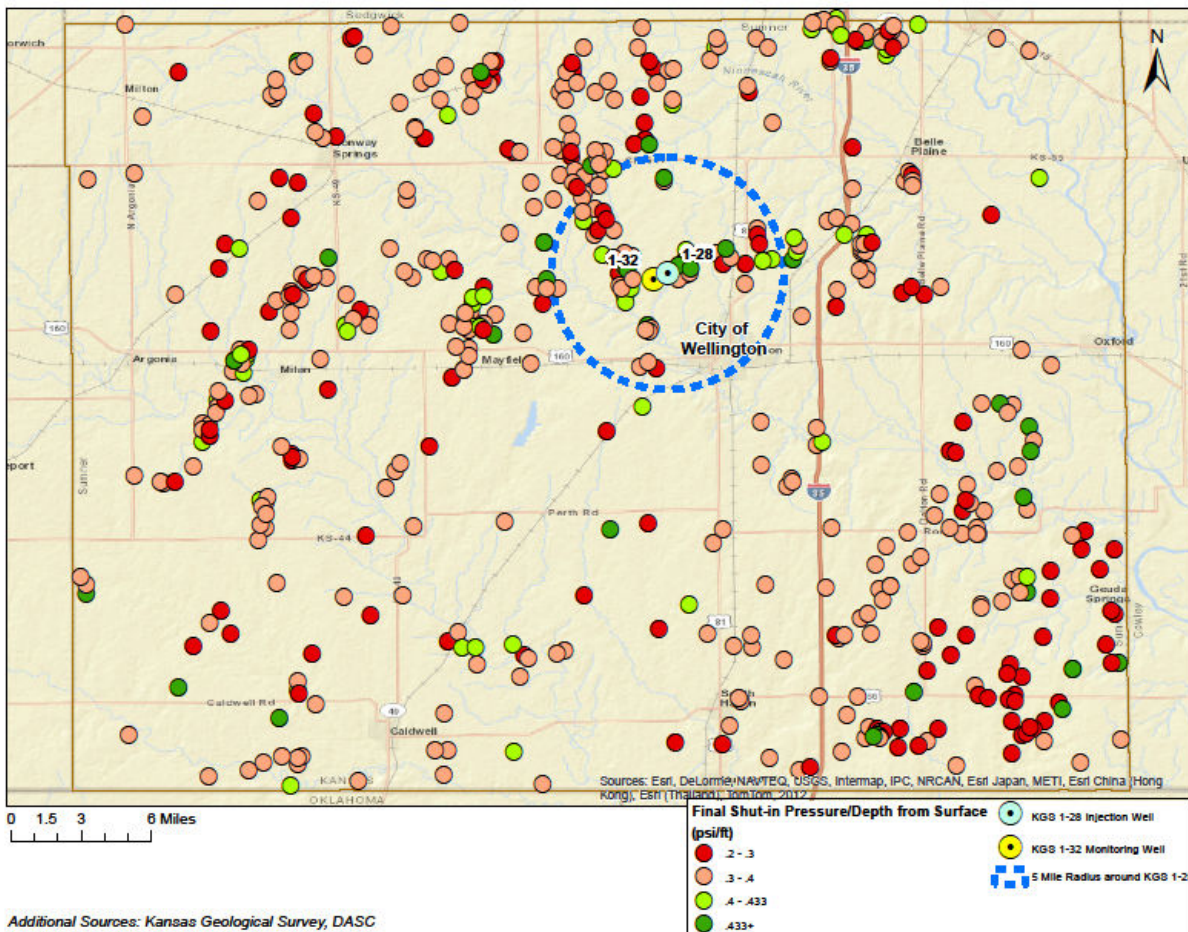


**Figure 2. Drill Stem Test based final shut pressure for the upper Mississippin strata in Sumner County divided by measured depth from surface depicted as color dots. Lowest pressure gradient (psi/ft) is in red (0.2-0.3 psi/ft) while highest pressure (>0.433) is in green. Pressures are clearly below a normal hydrostratic gradient of 0.433 psi/ft.**

Faulting in the area of Wellington Field was revisited by examining possible faults indicated by new seismic, attempting to understand the timing of the faults. The regional mapping of the structural configuration on the top of the Arbuckle Group and the Mississippian strata (Figure 3 and 4) suggests faulting is present northwest of Wellington Field.
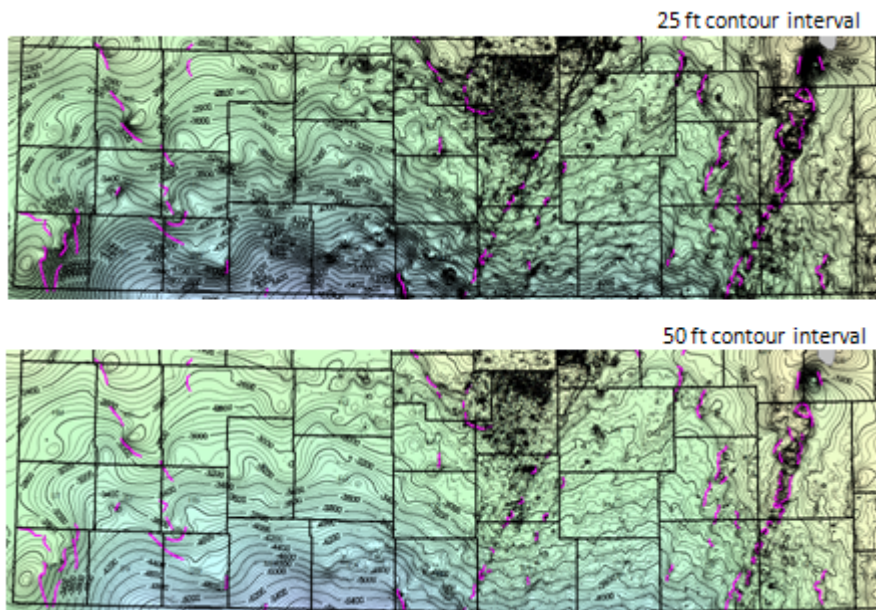


**Figure 3. Structural configuration on top of the Arbuckle Group in south-central Kansas. Purple lines suggest possible faults that are related to higher dip rates.**

Closest probably faulting to Wellington Field is ~3 mi. northwest of the Wellington KGS #1-28 well in Anson Southeast Field, another Missississippian field. Seismic maps and seismic profiles shown in Figures 5 and 6 show northeast-trending traces of the faults and plan view and 10 millisecond (msec) time offsets in profile. The offset at Arbuckle time (~720 msec) is linear and sharp while relief at the top of the Mississippian around 640 msec is ~5 msec. Offset at higher Pennsylvanian levels is diminisished that several msec. The lower impedance intervals bounding the generally underpressured Mississippian reservoir, while likely faulted, appear to have maintained pressure isolation from adjoining strata including the underlying Arbuckle
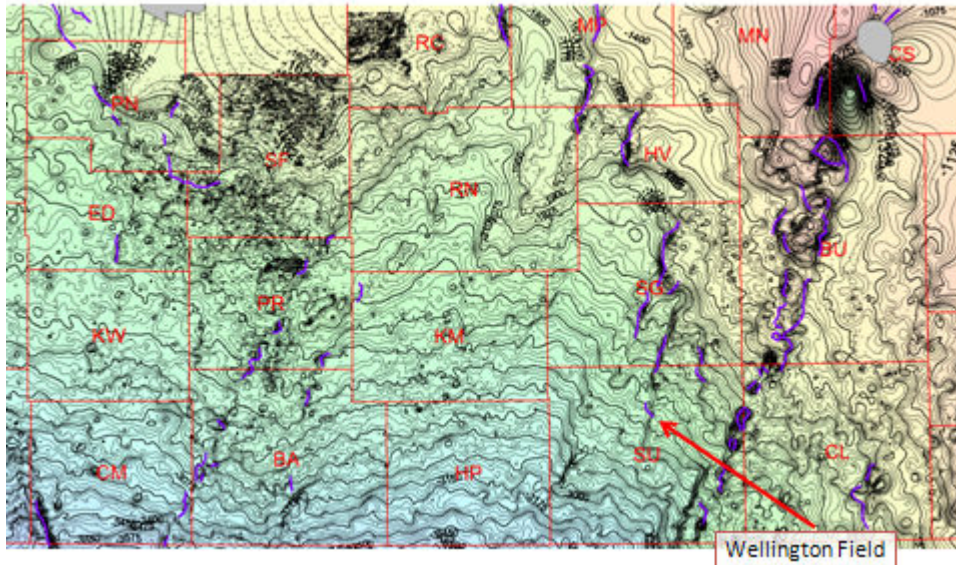
**Figure 4. Structural configuration on top of the Mississippian strata in the region around Wellington Field (tip of red arrow). The purple lines depict locations of higher dip rate suggesting faulting.**
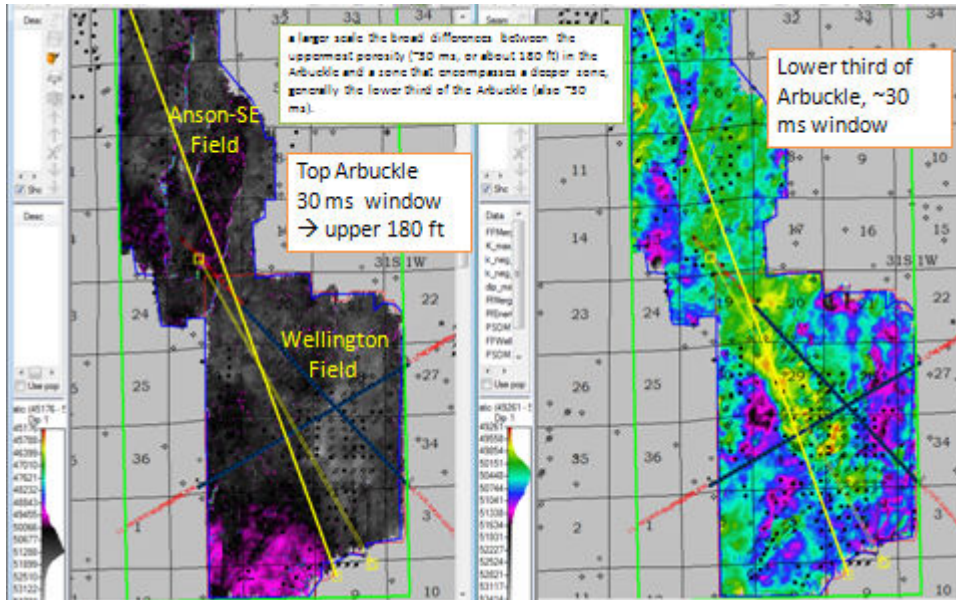


**Figure 5. Seismic impendance in the upper and lower porous intervals of the 3D seismic in the merge data including Anson Southeast and Wellington Field. Yellow index NW-SE oriented index line shows trace of the seismic profile in Figure 6.**
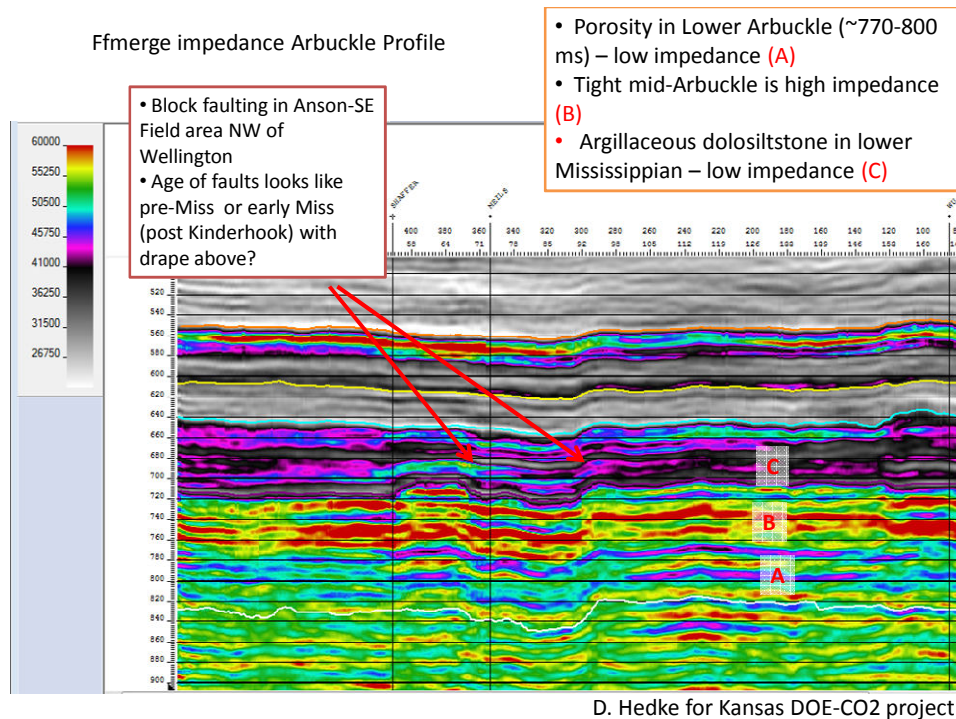
Ffmerge impedance Arbuckle Profile

- Block faulting in Anson-SE Field area NW of Wellington
- Age of faults looks like pre-Miss or early Miss (post Kinderhook) with drape above?

- Porosity in Lower Arbuckle (~770-800 ms) – low impedance (A)
- Tight mid-Arbuckle is high impedance (B)
- Argillaceous dolosiltstone in lower Mississippian – low impedance (C)

D. Hedke for Kansas DOE-CO2 project

**Figure 6. Northwest-southeast seismic profile of seismic impedance. Several horst and graben fault blocks are indicated. Label "A" is the lower impedance more porous and permeable lower Arbuckle. "B" is the tighter, more argillaceous baffle of the the middle mid Arbuckle, clearly exhibiting higher impedance. "C" is the low impedance interval in the lower Mississippian corresponding to argillaceous dolosiltite.**

The isopach of the Mississippian interval in the Anson SE and Wellington area is compared with the Top Arbuckle Structure in Figure 7 in a similar area as the maps and seismic discussed above. Anson SE has thicker Mississippian than Wellington Field with a NE-SW thin between the two fields. The two fields reside at a similar elevation relative to the Arbuckle, both on a southerly sloping Arbuckle surface.

An Arbuckle low SE of Anson SE Field is also a sharply defined Mississippian low, down to the west. A map of the configuration on the top of the Mississippian and an west-to-east cross section (Figure 8) illustrates a thick to thin Mississippian stratigraphic section corresponding to notable structural relief on the Arbuckle. The offset at the Top Arbuckle is 400 ft and at the top of Mississippian the relief is100 ft. Detailed correlations within the Mississippian are not clear, but the thinning appears to be related to both depositional thinning followed by  uplift and truncation along the east side onto a broad structural high.

The stratigraphic cross section of the interval above the top of Missiissippian to the Topeka Limestone indicate that little change has occurred in thickness or log character or derived lithololology. This is a clear indication of that the structural deformation is pre Pennsylvanian and has not affected this stratigraphically higher interval.

**Mississippian Isopach compared to subsea elevation of Arbuckle in Anson SE and Wellington Field areas**
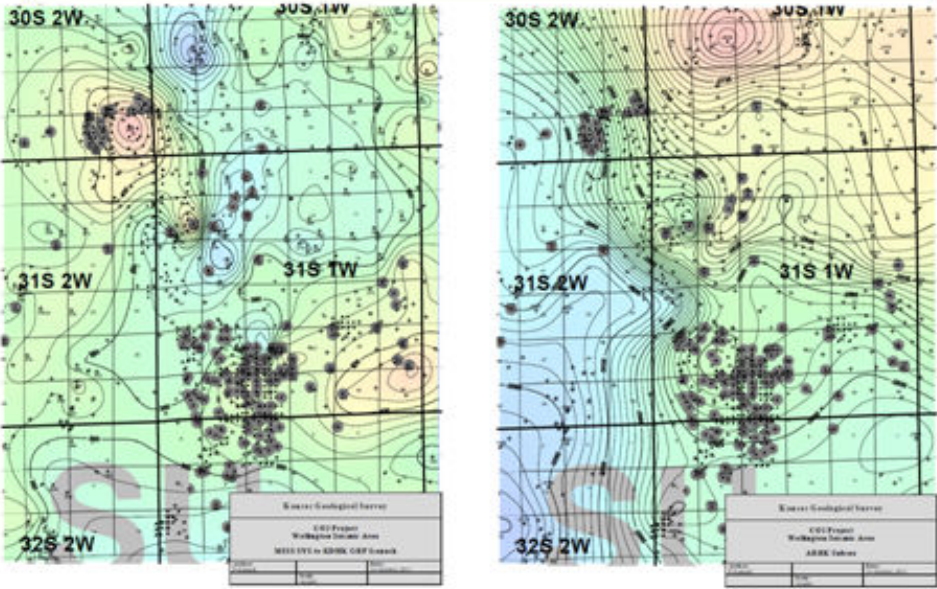
**Figure 7. Isopach of the Mississippian on left and the structural configuration of the Top of Arbuckle Group on the right.**
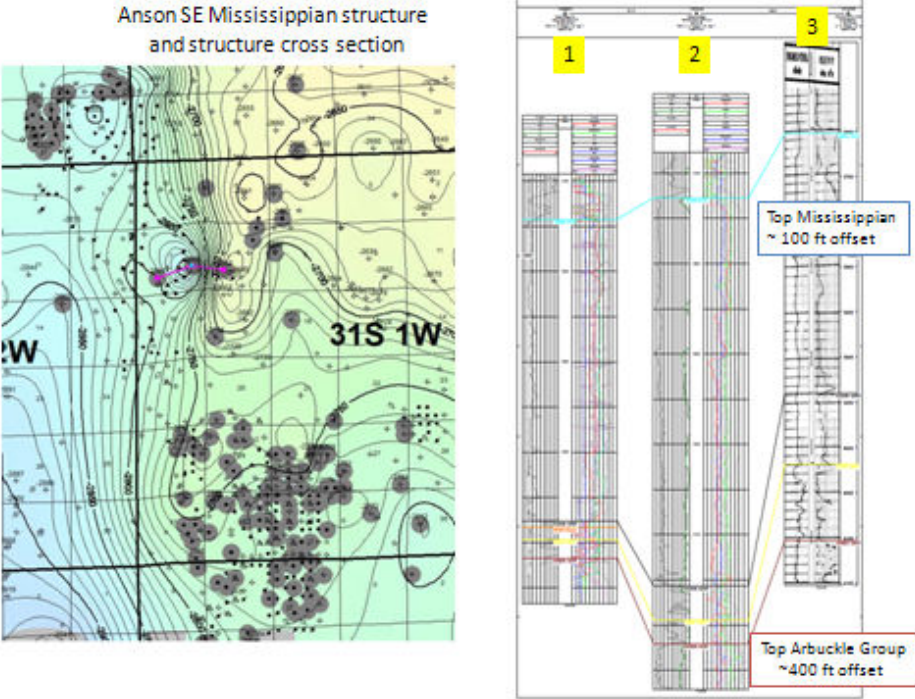


**Figure 8. (Left) Structural configuration Top Mississippian (20 ft C.I.) with cross section index and (right) structural crosss section focused on Mississippian interval showing constrasting offset between the Mississippian and the Arbuckle.**
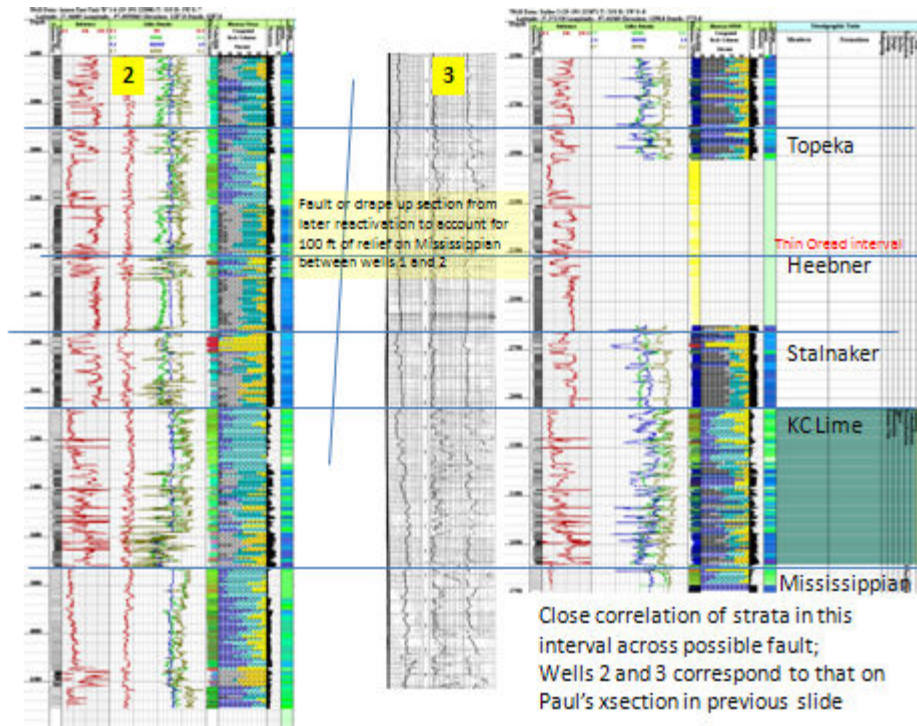
**Figure 9. Along same cross section as shown in Figure 8, but shallower zones above the Mississippian area shown up through the Upper Pennsylvanian Topeka Limestone.**

The uppermost stratigraphic interval that was mapped by the regional team is the lower Permian Hutchinson Salt and the underlying Top of Lower Permian Chase Group. The structure at the Top Chase Group shown in Figure 10 is very similar in shape and sense of the structure as mapped on the Top of Mississippian (Figure 7 left side). This suggests that the deformation continued but based on the shallow relief at 10 times less than the Mississisppian, the deformation is likely drape over deeper structure. The 50 ft of thinning of the Hutchinson Salt interval is likely due to dissolution of the halite in the uppermost section when it depth below the surface reached ~200 ft, as is common in central Kansas.
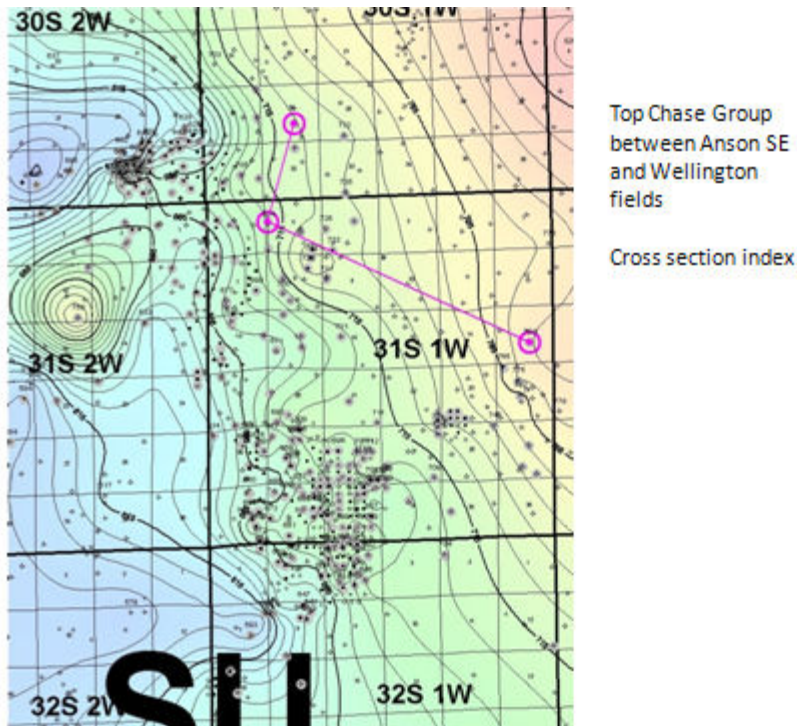
**Figure 9. Structural elevation on top of the Upper Permian Chase Group (C.I. = 2 ft, a factor of 10 times less thant the Mississippian) and a cross section index for section shown in Figure 10.**
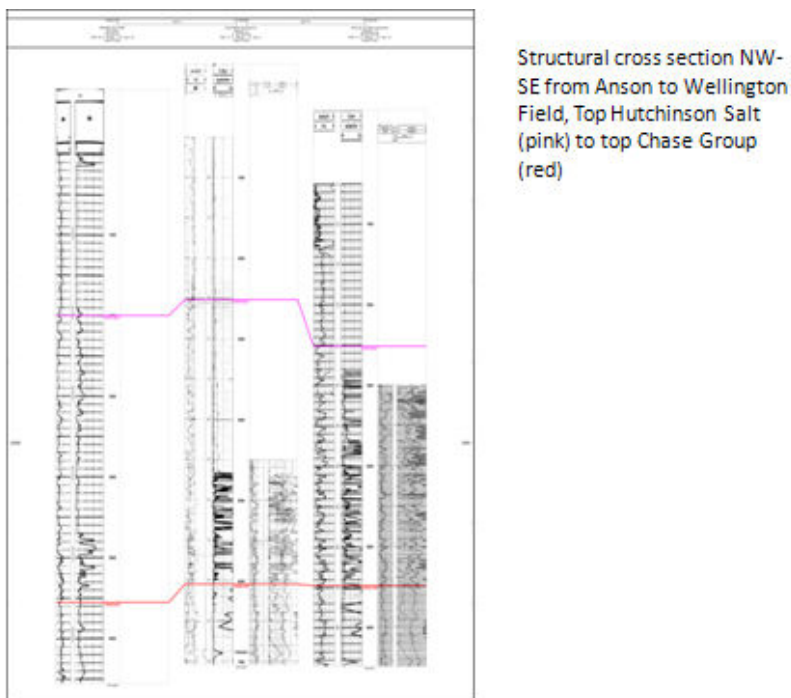


**Figure 10. The North to Southeast cross section depicts the stratigraphic interval between the top of the Hutchinson Salt and the Top of the Chase Group. Distance between tick marks along the margin of the logs is equal to 100 ft.**

13

**Task 12 -- Regional CO2 Sequestration Potential in OPAS - 17 Counties**

A total of **3292 wells** have been cataloged for the DOE-CO2 projects. Wells include type logs, key wells, field studies, and regional modeling sites. All wells have been inventoried and their status is known. This has allowed incomplete files to be identified and updated. The last of the log digitizing has been completed and LAS 2.0 files are being integrated with the stratigraphic formation tops and in some cases better version of the georeports to create a LAS 3.0 file. This information                                    is                                    reviewed                                    below.

The tabulation of creation of
489     Wells     in     DOE     CO2     LAS     3.0     DB     Table
122     Wells     NOT     in     Type     Log     LAS     3.0     DB     Table, strictly     CO2     Well
101     Wells     with     Geologist     Reports     in     DOE     CO2     LAS     2.0     DB     Table
293     Wells     with     Litho-Density     Logs     in     DOE     CO2     LAS     2.0     DB     Table
124 Wells with Litho-Density Logs and with PE Curve in DOE CO2 LAS 2.0 DB Table


**New Java Applets for Type Logs and cross section construction – verifying correlations and characterization of rocks and brines for estimating CO2 storage capacity**

The CO2 Project contains all of the wells that were identified for mapping the Arbuckle saline aquifer. Type wells were added to include best logs to correlate and characterize the entire stratigrpahic column.

**CO2 Project**
Summary Web Site: http://www.kgs.ku.edu/PRS/Ozark/Summary/
DB Tables: http://www.kgs.ku.edu/PRS/Ozark/Summary/DB_Tables.html
Profile CO2 Applet: http://www.kgs.ku.edu/PRS/Ozark/TYPE_LOG/Profile_CO2.html

**TYPE LOG Project**
Summary Web Site:  http://www.kgs.ku.edu/PRS/Ozark/TYPE_LOG/summary.html
DB Tables: http://www.kgs.ku.edu/PRS/Ozark/TYPE_LOG/DB_Tables.html
Profile Applet: http://www.kgs.ku.edu/PRS/Ozark/TYPE_LOG/Profile.html


An example of a cross section of three type logs each having  good georeports from the Davies Sample Log collection is shown in Figure 11. The sample descriptions have consistent detail and provide an important means to convey the lithology to aid in interpretation of the logs. The LAS 3.0 files from which the cross section was generated contain text descriptions for the user to access additional information about the lithology.
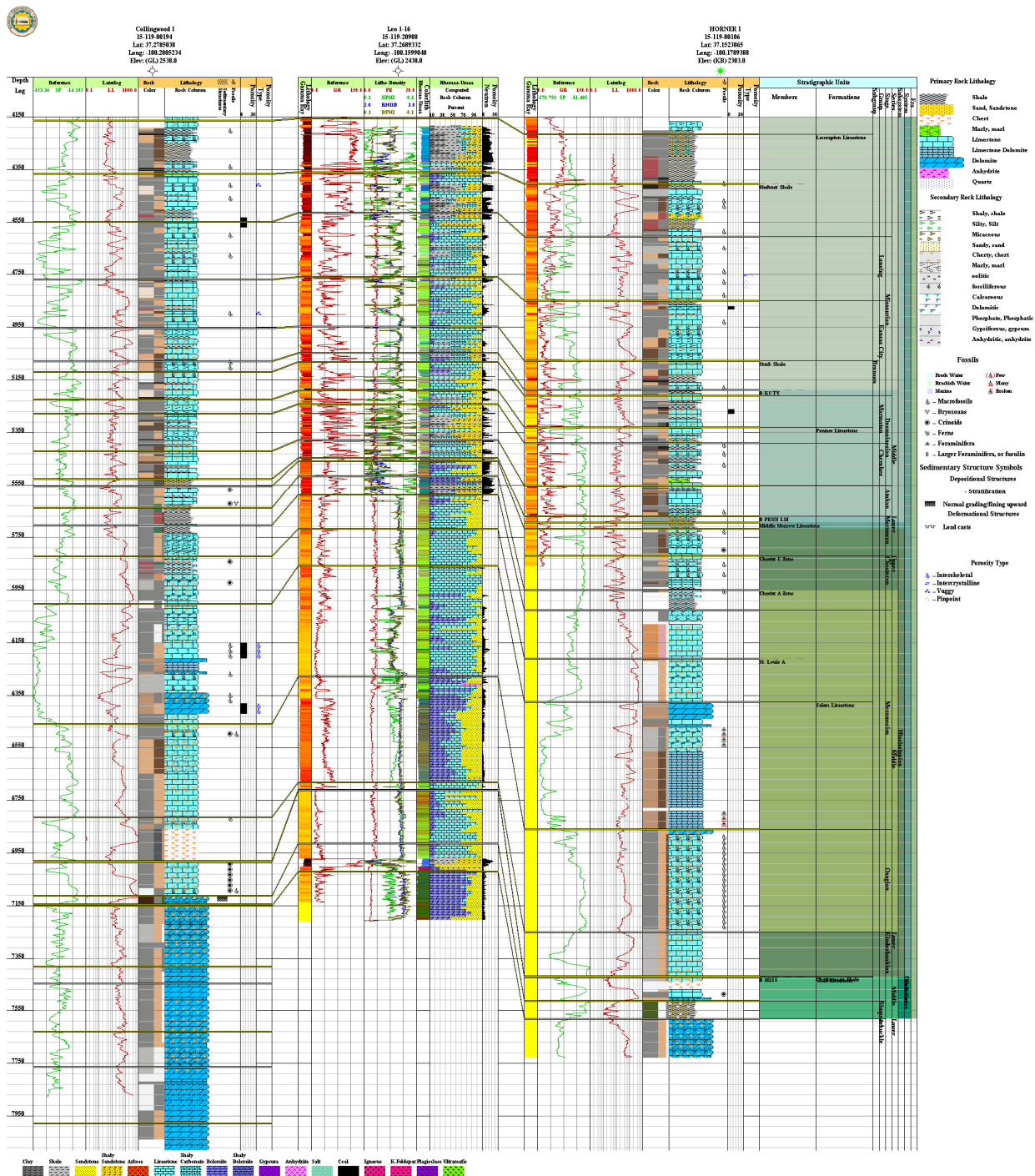
**Figure 11. Three well structural cross section comprised of digitized well logs and georeports (Davies Sample Log Service) . The interval extends from the Arbuckle into the Upper Pennsylvnian.**

The interfaces to access profiles of single wells and to create cross sections has been refined to facilate quick access to well information including stratigraphic correlations (Figure 12). This work has advanced significantly in the last quarter and has reached a penultimate stage of development. The final step will be to link these Java applications to the interactive mapper for the entire project, a task that is nearing completion.
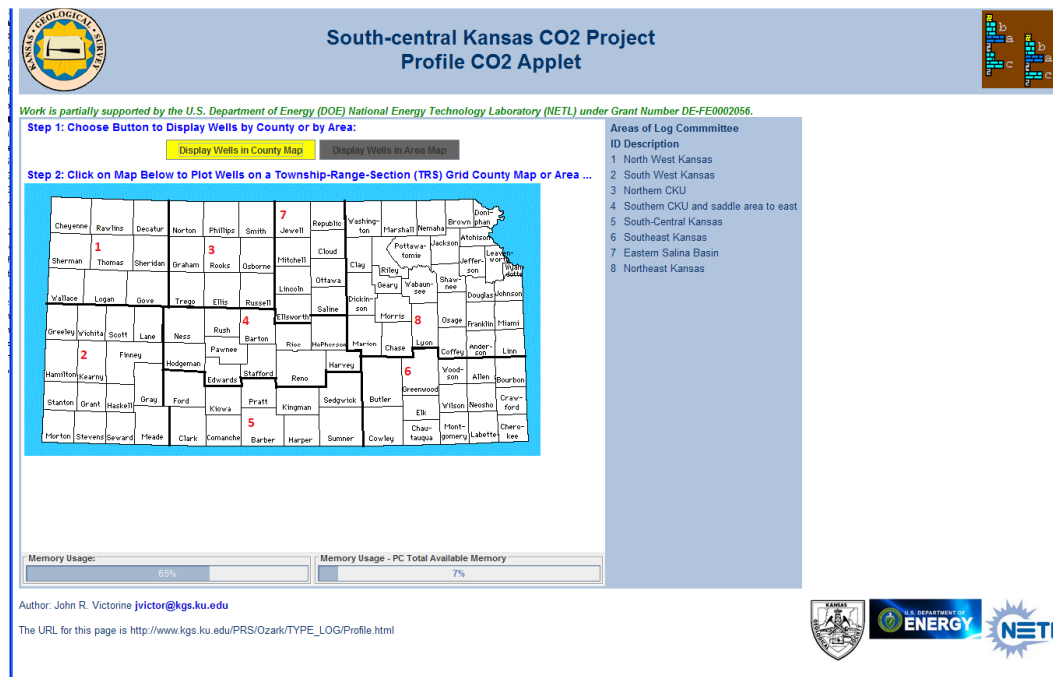


http://www.kgs.ku.edu/PRS/Ozark/TYPE_LOG/XSection.html

**Figure 12. Map introducing the well profile applet.**

The interface to modify the display of the well logs, georeports, and stratigraphic information has been refined (Figure 13). An annotated example of the cross section is shown in Figure 14. In the editing application for the type wells a reference and a well to be correlated are selected and the user is able to apply tops from the reference well to the new well (Figure 15). The user can only apply tops that exist in the stratigraphic table. However, the idea is to facilitate refining correlations, but doing such that the proposed changes are handled in an closely monitored manner.

The well header information is stored in the KGS Oracle database (Figure 16). The formation tops and logs curve names (mneumonics) is similarly stored online (Figure (17).
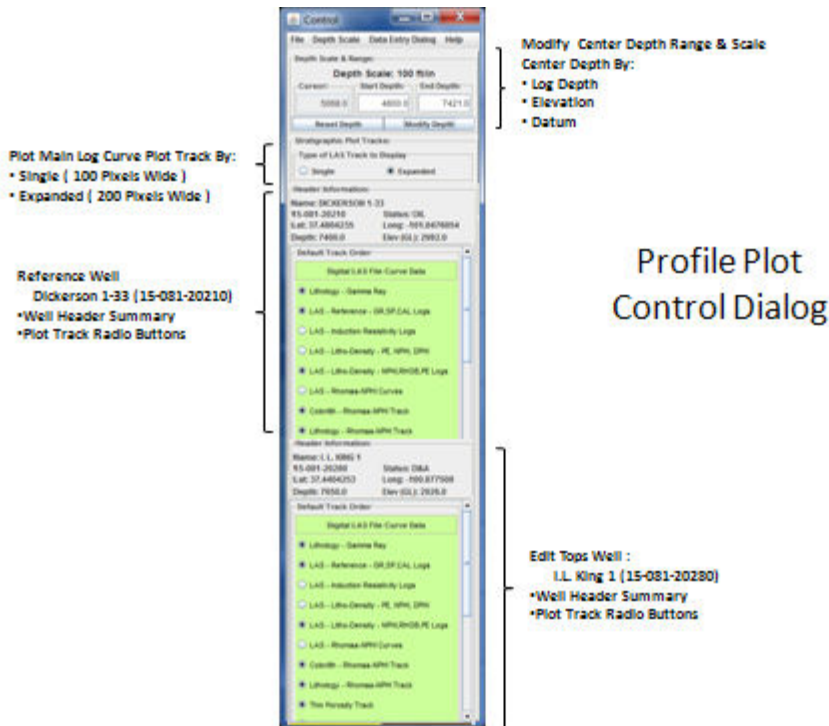
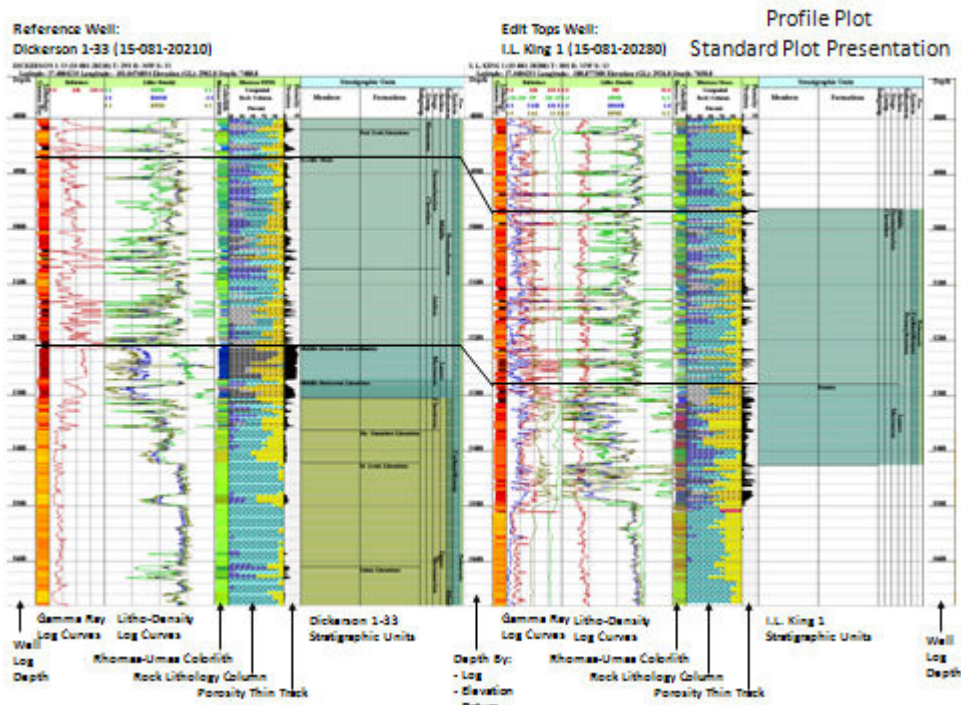**Figure 13. Control panel used to modify the wells that are displayed.**



**Figure 14. Plot of wells logs and stratigraphic correreations annotated with explanatory text.**

**Reference Well**

- Copy Tops from Reference Well and Paste in Edit Well
- Tops are fixed and can not be edited as reference well

**Edit Tops Well**

- Copy Tops from Reference Well and Paste in Edit Well
- Only Tops Source can modify depth or name
- User adding a new top is source.
- User not source may only evaluate
    - by clicking thumbs up or thumbs down
    - and setting their depth
- As mouse floats over tops position
    - Displays the name, depth range, status (Gold, Silver,...)
- Left Click on mouse to Edit or Evaluate Top

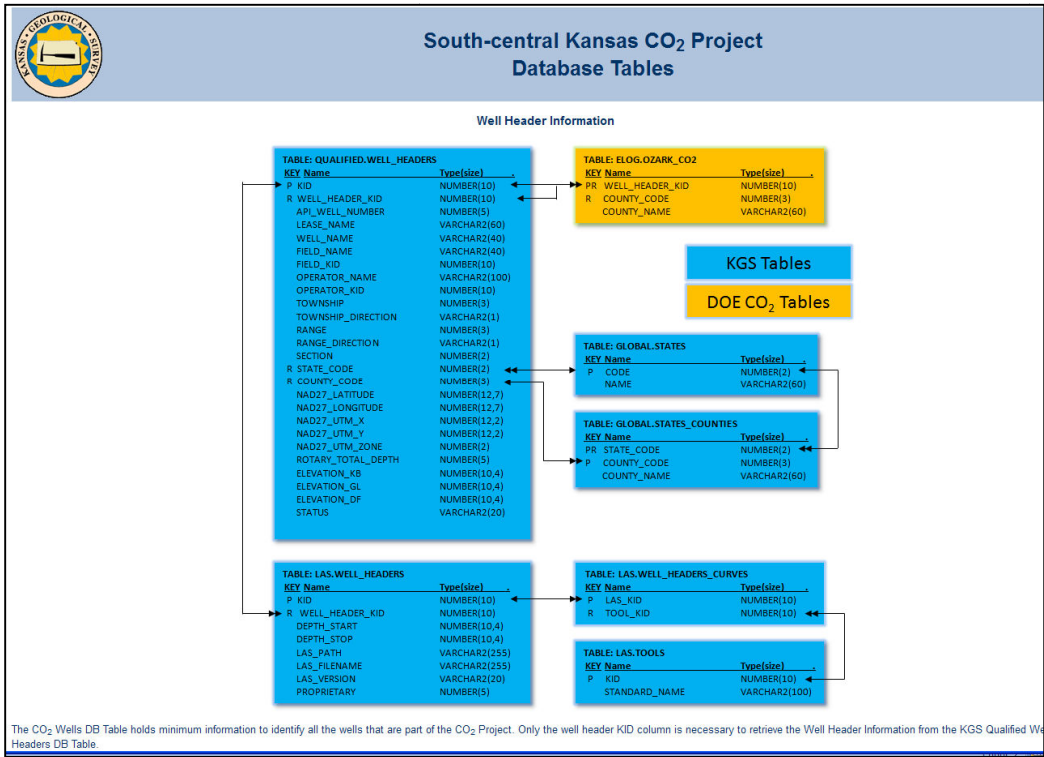**Figure 15. Adding and evaluating stratigraphic tops.**



**Figure 16. Data table example for well headers.**

**Well Tops Data**

TABLE: IQSTRAT.ZELLER
| KEY | Name | Type(size) |
|---|---|---|
| * | KID | NUMBER(10) |
| | SEQUENCE | NUMBER(10) |
| | RANK | VARCHAR2(12) |
| | NAME | VARCHAR2(60) |
| | TOP | NUMBER(12,6) |
| | BASE | NUMBER(12,6) |
| | SYSTEM | NUMBER(10) |
| | SERIES | NUMBER(10) |
| | SUBSYSTEM | NUMBER(10) |
| | SUBSERIES | NUMBER(10) |
| | STAGE | NUMBER(10) |
| | SUPERGROUP | NUMBER(10) |
| | SGROUP | NUMBER(10) |
| | SUBGROUP | NUMBER(10) |
| | FORMATION | NUMBER(10) |

TABLE: IQSTRAT.DOE_CO2_TOPS
| KEY | Name | Type(size) |
|---|---|---|
| R | ZELLER_KID | NUMBER(10) |
| R | WELL_HEADER_KID | NUMBER(10) |
| | API_NUMBER | VARCHAR2(32) |
| | NAME | VARCHAR2(60) |
| | DEPTH_TOP | NUMBER(8,2) |
| | DEPTH_BASE | NUMBER(8,2) |
| R | SOURCE_KID | NUMBER(10) |

TABLE: ELOG.OZARK_CO2
| KEY | Name | Type(size) |
|---|---|---|
| PR | WELL_HEADER_KID | NUMBER(10) |
| R | COUNTY_CODE | NUMBER(3) |
| | COUNTY_NAME | VARCHAR2(60) |

TABLE: IQSTRAT.TYPE_LOG_USERS
| KEY | Name | Type(size) |
|---|---|---|
| P | KID | NUMBER(10) |
| | NAME | VARCHAR2(80) |
| | EMAIL | VARCHAR2(80) |
| | INITIALS | VARCHAR2(4) |

Reference Tables

DOE CO₂ Tables

The CO₂ Tops DB Table is the primary table for holding the well tops for each well and the owner of the tops which was identified for each selected well in the CO₂ Project. The Zeller Database Table holds the Stratigraphic Units for the Type Log Project & CO₂ Project. The CO₂ Users Table holds all the Committee members for the CO₂ Project that are selecting & evaluating the tops.

**Final Log ASCII Standard (LAS) 3.0 File Information**

TABLE: ELOG.OZARK_CO2
| KEY | Name | Type(size) |
|---|---|---|
| PR | WELL_HEADER_KID | NUMBER(10) |
| R | COUNTY_CODE | NUMBER(3) |
| | COUNTY_NAME | VARCHAR2(60) |

| | | |
|---|---|---|
| GR_LOG | Gamma Ray Log Curve | |
| OHM_LOG | Resistivity Log Curve | |
| NEUTRON_LOG | Neutron Porosity Log Curve | |
| DENSITY_LOG | Density Log Curves | |
| PE_LOG | Photoelectric Factor Log Curve | |
| SONIC_LOG | Sonic Log Curves | |
| TH_LOG | Thorium Log Curve | |
| U_LOG | Uranium Log Curve | |
| K_LOG | Potassium Log Curve | |
| GR_CNT_LOG | Gamma Ray Count Log Curve | |
| NEUT_CNT_LOG | Neutron Count Log Curve | |

TABLE: IQSTRAT.DOE_CO2_LAS3
| KEY | Name | Type(size) |
|---|---|---|
| PR | WELL_HEADER_KID | NUMBER(10) |
| | FILE_PATH | VARCHAR2(255) |
| | FILE_NAME | VARCHAR2(255) |
| | DEPTH_START | NUMBER(10,4) |
| | DEPTH_STOP | NUMBER(10,4) |
| | FILE_STATUS | VARCHAR2(30) |
| | GR_LOG | VARCHAR2(4) |
| | OHM_LOG | VARCHAR2(4) |
| | NEUTRON_LOG | VARCHAR2(4) |
| | DENSITY_LOG | VARCHAR2(4) |
| | PE_LOG | VARCHAR2(4) |
| | SONIC_LOG | VARCHAR2(4) |
| | TH_LOG | VARCHAR2(4) |
| | U_LOG | VARCHAR2(4) |
| | K_LOG | VARCHAR2(4) |
| | GR_CNT_LOG | VARCHAR2(4) |
| | NEUT_CNT_LOG | VARCHAR2(4) |

DOE CO₂ Tables

This type Log LAS 3.0 file contains the Log ASCII Standard (LAS) 3.0 File Information for the final files containing the Log Data, Tops Data and the if present the Geologist Report Data. These files are part of the final deliverables for the CO₂ Project and are also part of the CO₂ Project mapper program to allow the user to build General Cross Sections with these files.
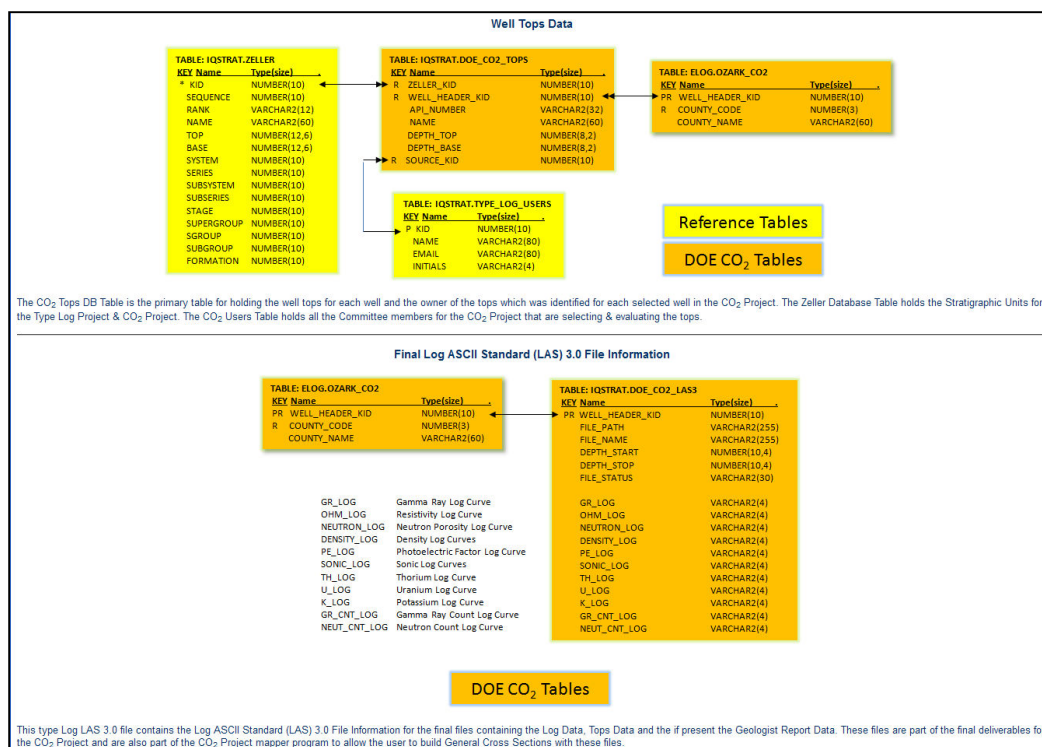
**Figure 17. Defines the stratigraphic classification and nomenclature accepted and used and well log definitions.**

## Compartments -- Static and Dynamic Modeling

Ten compartment areas (unfaulted, structural closure, and producing oil field above the Arbuckle saline aquifer) were previously identified during the regional mapping to build coarse grid static geomodels for simulation of commercial scale injection of CO2. Each site is around 4 townships in size and each have characteristics that are similar to Wellington with a large field above the saline aquifer.

Wellington Field log, core, and test data is being used to develop correlation between conventional logs and lithofacies descriptions in order to provide a lithofacies-based subdivision of flow or hydrostratigrahic units and provide estimates of permeabililty and other key properties needed for modeling CO2 injection including capillary pressure, relative permeability, mechanical properties, and reaction kinetics. The new Cutter KGS #1 well in southwestern Kansas will serve as the western calibration site once the core analysis is completed.

Each site will also involve a basic assessment of the local USDW to aid in the evaluation of risk involved in siting at that location. The integrated assessment will provide a framework for potentially more detailed investigations. Importantly, the lithofacies and flow units based characterization of each site and the properties that are attributed to them will be applied to refine the regional CO2 storage resource assessment in southern Kansas.

The basic stratigraphic layering has been defined and correlated through the mapped area. These units will be appropriately and consistently subdivided to create the flow units based on the exhaustive suite of logs, core, and test information at Wellington and Cutter Fields.

Additional wells have been digitized and we chose sites that had at least one basement tests with modern well logs. Wells used in the analysis will be available through the interactive mapper and the Java application toolset.

I've attached maps and grids for a calibration Wellington simulation area to serve as a means to model other sites. Since these files are for "format exchange" purpose, the "proposed area" is not important, just the ability to exchange.

**Information on Maps to set the stage for the geomodel and simulation**

The focus of the modeling will be the Arbuckle Group. The preliminary grid cell size will be 330 feet. The grids created in Geographix will be exported for simulation in ZMap plus format in Kansas South, State Plane 1927, SPCS 27.

**Update on locations of nonfaulted structural closure (NFSC) storage candidates**

The 10 areas to be modeled across the southern region annotated with the status of the current/near final digital and raster log data set which will be the basis for the modeling (Figure 18).

magenta diamonds = las file
grey triangles = raster file
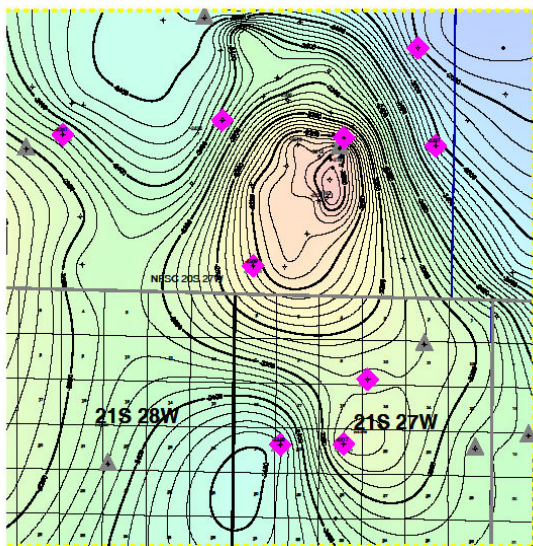
KANSAS GEOLOGICAL SURVEY

NFSC 23S 4W
ARBUCKLE SUBSEA

| Author: P Gerlach | Date: 6 July, 2012 |
| Scale: <scale> | |



KANSAS GEOLOGICAL SURVEY

CO2 Project

NFSC 25S-36W
ARBK Subsea

| Author: J GERLACH | Date: 28 March, 2013 |
| Scale: <scale> | |



KANSAS GEOLOGICAL SURVEY

CO2 PROJECT
NFSC 27S 10W
ARBK SUBSEA

| Author: J Gerlach | Date: 8 July, 2013 |
| Scale: <scale> | |



KANSAS GEOLOGICAL SURVEY

CO2 PROJECT
NFSC 30S 7E
ARBK SUBSEA

| Author: J GERLACH | Date: 18 July, 2013 |
| Scale: <scale> | |

**Figure 18. Structural maps at the top of the Arbuckle for the 10 NFSC areas in southern Kansas.**

**Task 13.        Regional Source-sink relationship**

CCUS – Carbon Capture, Utilization, and Storage

Kansas has major CO2-EOR potential with saline Aquifer sequestration as additional asset beneath oil fields in southern Kansas. The most viable method to manage CO2 storage will be by building on the existing infrastructure of a viable, local petroleum industry who at this time are primariliy interested in the use of CO2 for enhanced oil recovery.

The most promising candidates for CO2-EOR would be those fields that could use large amounts of CO2 to justify pipeline from point sources. The approach would be to first build the pipeline infrastucture around industry sources that are currently generating nearly pure CO2. This would be fertilizer/ammonia, ethanol, and possibly refineries. The map in Figure 19 highlights the larger fields that are large and ones in strategic locations to take advantage of a regional pipeline.
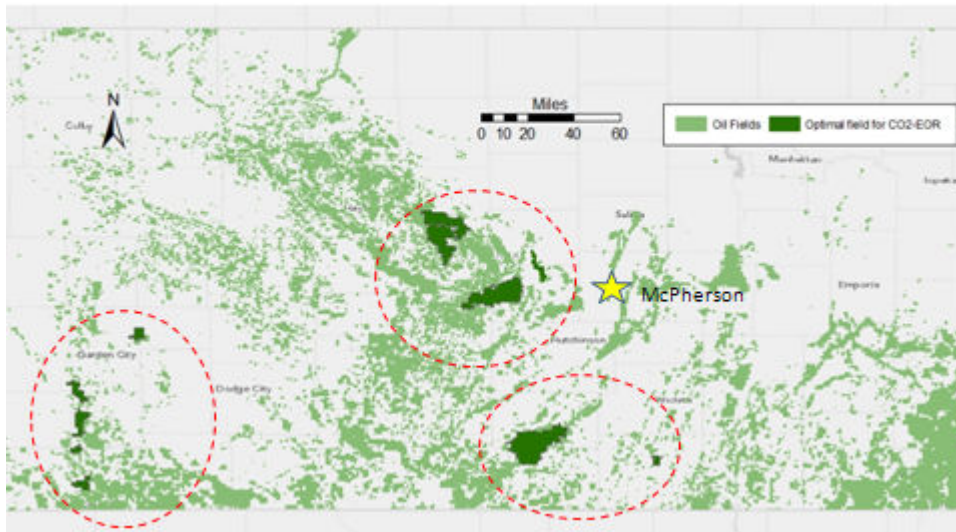


**Figure 19. Kansas oil fields with select fields highlighted in darker green showing those with large reserves or ones under current study that could be most ready for CO2. The yellow star is located at McPherson, the site of an oil refinery.**

Kansas is stranded from a reginal supply of CO2 and the most viable sources of CO2 would be ethanol plants. They are located on the Kansas oil field map that is also annotated with key oil fields (Figure 20). The red dotted circle identifies the fields currently being studied in the project. A pipeline scenario connects the ethanol plants with key fields located near the hypothetical pipeline.

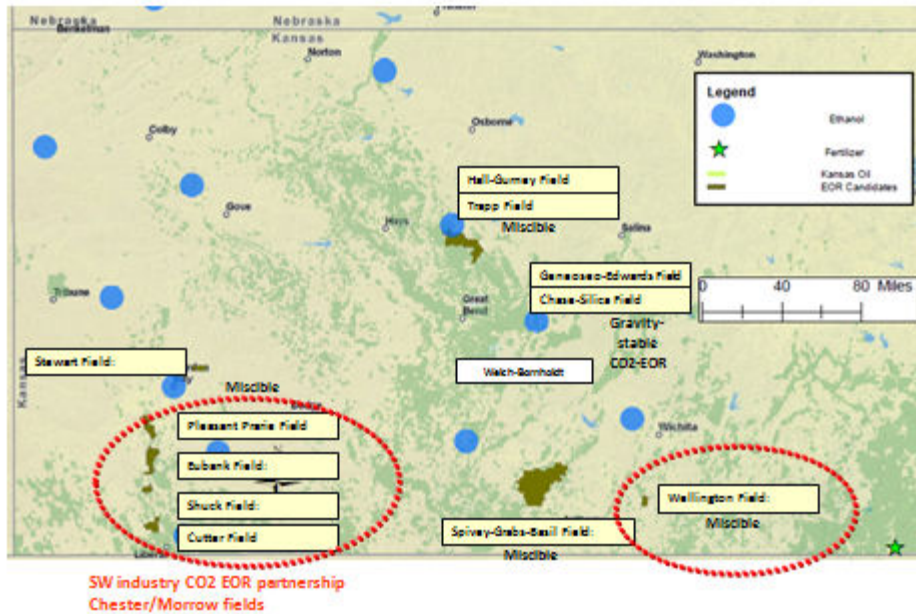## Ethanol Plants and Selected Oil Fields for CO2-EOR



**Figure 20. Kansas oil fields and ethanol plants highlighting fields that are part of the current study including Wellington and fields that are part of the SW industry CO2 EOR partnership.**
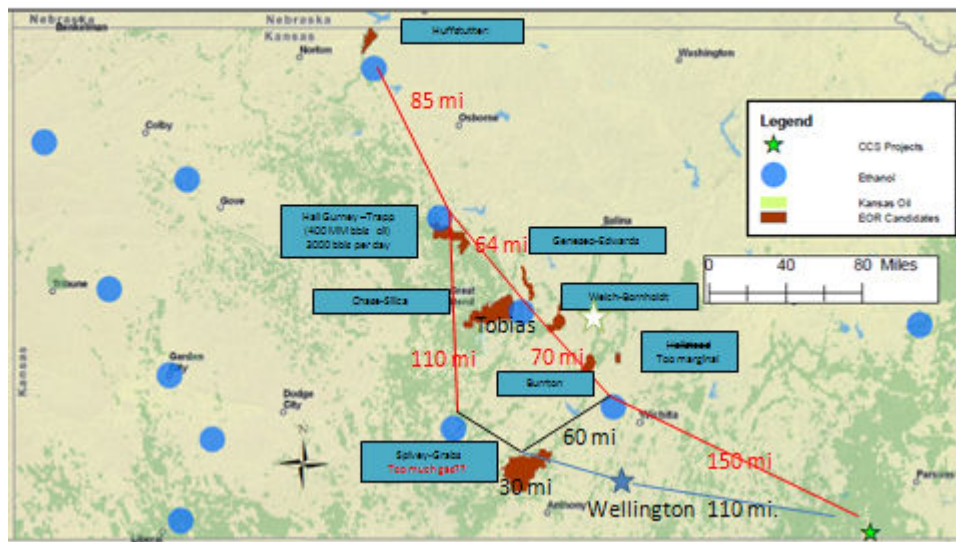
## CO2 Pipeline Scenario: Select CO2-EOR Candidates



**Figure 21. Ethanol, oil fields, and hypothetical CO2 pipeline system on eastern flank of the Central Kansas Uplift. Illustration was prepared jointly with the Clinton Climate Initiative staff.**

Total CO2 production from existing ethanol plants in Kansas is 1.7 million tonnes per year. Nearby Nebraska has ethanol plants that produce ~6 million metric tonnes per year. Together, Kansas and Nebraska ethanol plants could results in ~27 million barrels of incremental oil per year at 5 mcf CO2/bbl of oil. The total estimated technical CO2-EOR potential for Kansas is estimated at more than 750 million bbls according to the report on CO2-EOR Petential in the MGA Region that includes the Illionois/Indiana, Ohio, and Michigan oil producing regions (Figure 22).



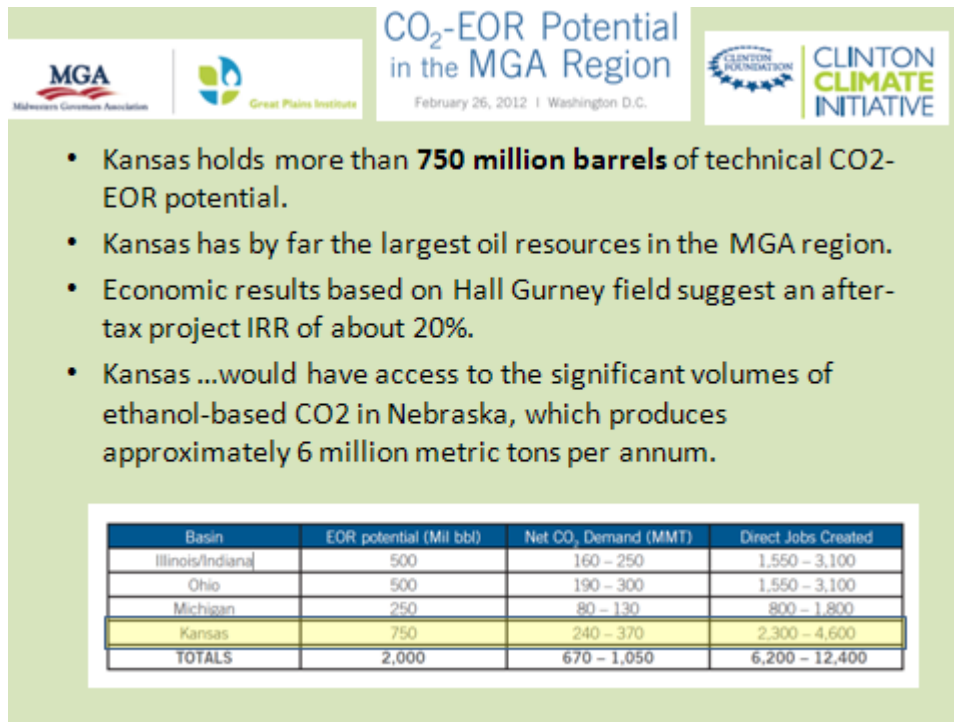| Basin | EOR potential (Mil bbl) | Net CO$_2$ Demand (MMT) | Direct Jobs Created |
|---|---|---|---|
| Illinois/Indiana | 500 | 160 – 250 | 1,550 – 3,100 |
| Ohio | 500 | 190 – 300 | 1,550 – 3,100 |
| Michigan | 250 | 80 – 130 | 800 – 1,800 |
| Kansas | 750 | 240 – 370 | 2,300 – 4,600 |
| TOTALS | 2,000 | 670 – 1,050 | 6,200 – 12,400 |

**Figure 22. Statistics on CO2-EOR in the area covered by the Midwest Governor's Association as noted in the report by the Clinton Climate Initiative on CO2-EOR Potential in the MGA Region, Feb. 26, 2012.**

The economics associated with CO2-EOR in Kansas are enhanced by favorable state tax incentives including a teriary oil recovery exemption to an 8% severance tax

## ONGOING ACTIVITIES - REGIONAL STUDY INCLUDING SOUTHWEST KANSAS

**Task 9. Characterize leakage pathways - Risk assessment area**

Petrophysical and engineering properties of the 110 ft thick lower Mississippian "Pierson" shaly dolomitic siltstone continue to be evaluated to determine its suitability to serve as a secondary caprock at Wellington field and other areas in southern Kansas where it is present (Figure 23). Mechanical, relative permeability, and capillary pressure analyses thus far do indicate the suitability of the interval to assist in trap vertically migrating CO2 from the Arbuckle. The Pierson Formation appears that it will augment the primary caprock of the Chattanooga and

Simpson shales. Total organic carbon has analyzed in the Pierson and values range up to 2% TOC (Figure 24). The geochemistry and microbial content are also being examined utilizing in situ CO2 experiments this past fall at NETL Pittsburgh. Susan Carrol and Megan Smith at LLNL have also sampled a suite of core plugs from the Wellington KGS #1-32. The sampling was done in cooperation with Saugata Datta at KSU and Eugene Holubnyak. LLNL consist of running in situ experiments with CO2 injection and running tomographic images to image and measure changes in the pore geometry.
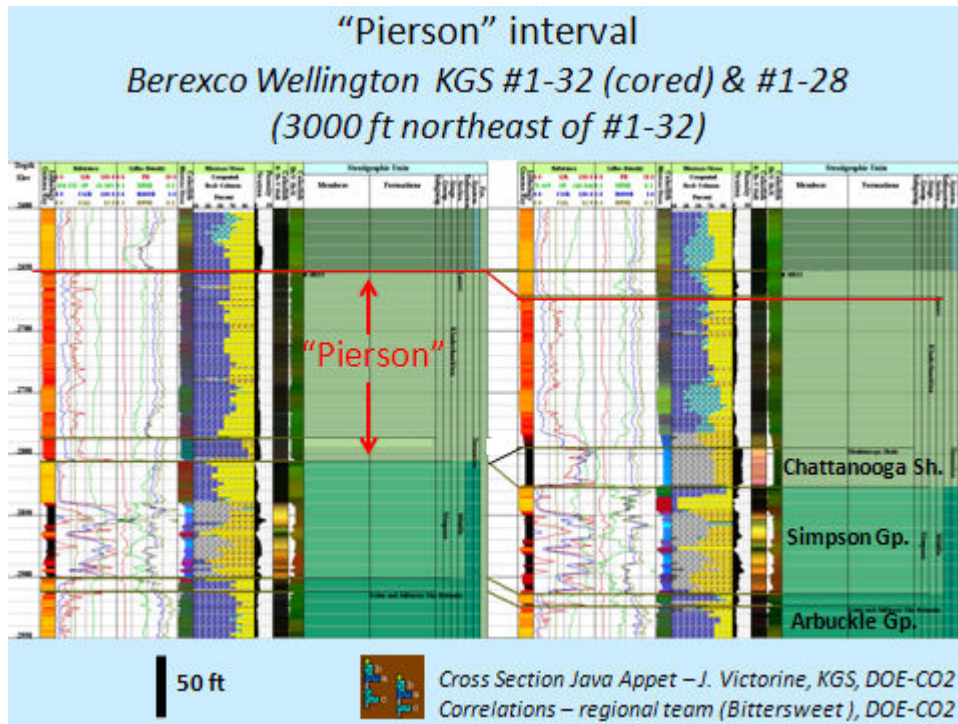


**Figure 23. Pierson Formaton defined in the lower Mississippian, present in the core well #1-32 and nearby well #1-28 in Wellington Field.**

| Client ID | Well Name | State | County | Top depth (ft) | Formation | Sample Type | Prep | TOC. wt. % | Verified | Lab Id | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Berexco LLC Wellington KGS No. 1-32 | | | 3695.40 | | Core | NOPR | 0.10 | | 3402822662 | Penn sh |
| | Berexco LLC Wellington KGS No. 1-32 | | | 3738.25 | | Core | NOPR | 0.39 | | 3402822664 | MSSP |
| | Berexco LLC Wellington KGS No. 1-32 | | | 3754.00 | | Core | NOPR | 0.19 | | 3402822666 | MSSP |
| | Berexco LLC Wellington KGS No. 1-32 | | | 3784.50 | → | Core | NOPR | 1.87 | TOC | 3402822668 | MSSP |
| | Berexco LLC Wellington KGS No. 1-32 | | | 3937.25 | | Core | NOPR | 0.94 | | 3402822670 | MSSP |
| | Berexco LLC Wellington KGS No. 1-32 | | | 3968.75 | | Core | NOPR | 1.28 | | 3402822672 | MSSP |
| | Berexco LLC Wellington KGS No. 1-32 | | | 3982.00 | → | Core | NOPR | 0.60 | TOC | 3402822674 | MSSP |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4024.00 | | Core | NOPR | 0.21 | | 3402822676 | MSSP |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4048.50 | | Core | NOPR | 1.11 | | 3402822678 | MSSP |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4059.75 | | Core | NOPR | 0.69 | | 3402822680 | MSSP |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4065.50 | → | Core | NOPR | 1.59 | TOC | 3402822682 | M-D Chat Sh |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4099.60 | | Core | NOPR | 0.17 | | 3402822684 | SMPS |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4110.00 | | Core | NOPR | 0.19 | | 3402822686 | SMPS |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4117.00 | | Core | NOPR | 0.22 | | 3402822688 | SMPS |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4134.50 | | Core | NOPR | 0.10 | TOC | 3402822690 | SMPS |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4143.00 | | Core | NOPR | 0.09 | | 3402822692 | SMPS |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4153.50 | | Core | NOPR | 0.04 | TOC | 3402822694 | SMPS |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4161.60 | | Core | NOPR | 0.11 | | 3402822696 | SMPS |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4234.00 | | Core | NOPR | 0.01 | | 3402822698 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4239.40 | | Core | NOPR | 0.02 | | 3402822700 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4272.00 | | Core | NOPR | 0.01 | TOC | 3402822702 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4307.20 | | Core | NOPR | 0.01 | TOC | 3402822704 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4365.00 | | Core | NOPR | 0.21 | | 3402822706 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4394.50 | | Core | NOPR | 0.07 | | 3402822708 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4410.00 | | Core | NOPR | 0.60 | TOC | 3402822710 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4431.30 | | Core | NOPR | 0.03 | | 3402822712 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4435.50 | | Core | NOPR | 0.01 | TOC | 3402822714 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4530.00 | | Core | NOPR | 0.32 | | 3402822716 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 4682.25 | | Core | NOPR | 0.02 | | 3402822718 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 5118.00 | | Core | NOPR | 0.06 | | 3402822720 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 5124.00 | | Core | NOPR | 0.08 | | 3402822722 | ABCK |
| | Berexco LLC Wellington KGS No. 1-32 | | | 5147.20 | | Core | NOPR | 0.16 | | 3402822724 | REGN |
| | Berexco LLC Wellington KGS No. 1-32 | | | 5160.50 | | Core | NOPR | 0.39 | TOC | 3402822726 | REGN |

**Figure 24. Several samples of the lower Mississippian have Total organic content approaching 2%. This is relatively high for a dolomitic siltstone.**

Close examination of the Pierson Formation reveals few fractures and uniform bedded strata revealed by the helical CT scans of core (Figure 25). The thin bedding is also clear from the images for a portion of the logging suite (Figure 26).
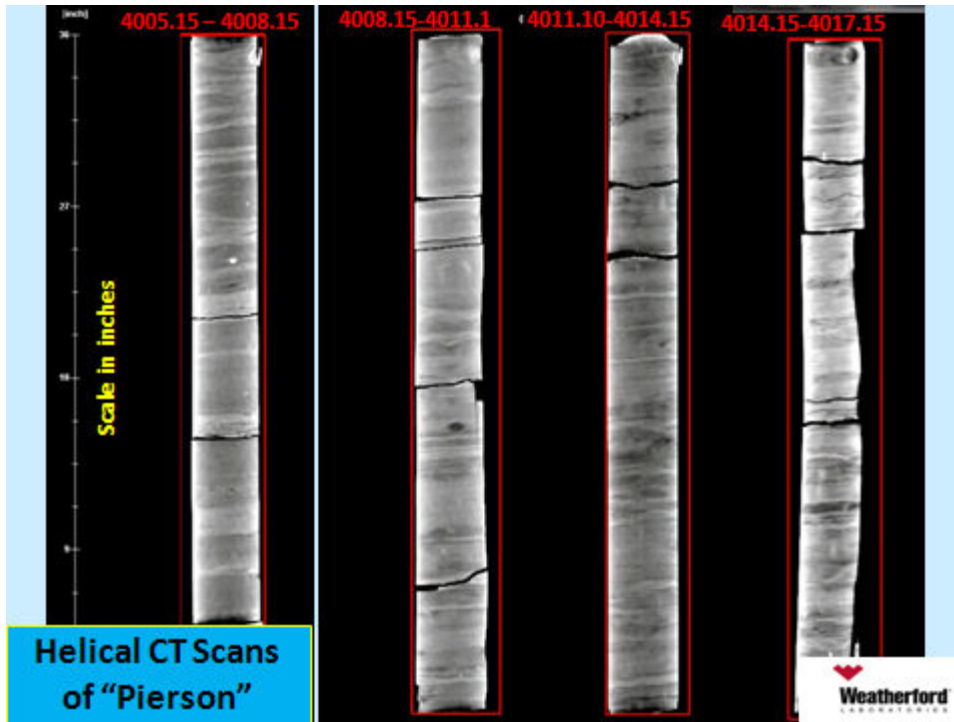
27

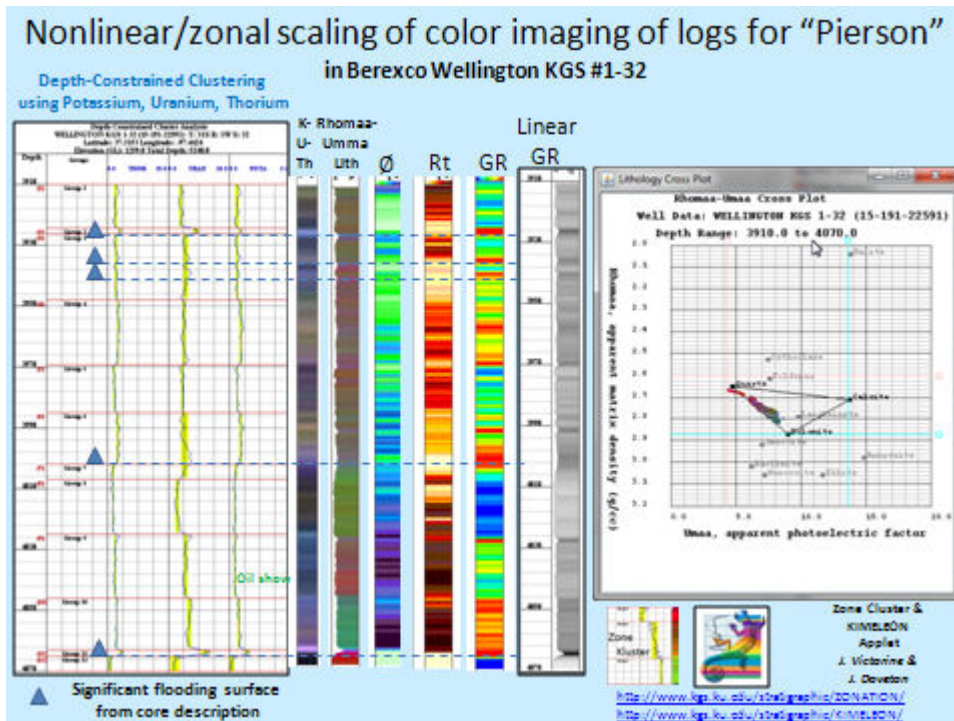**Figure 25. Scans of the Pierson Formation.**



**Figure 26. (Left) Spectral gamma ray profile of the 110 ft thick Pierson Formation in Wellington #1-32. (Center) Images of well logs showing the thin bedded stratigraphy of this interval. (Right) Rhomma-Umma compositional plot showing a uniform range in composition between dolomite and silca (silt-sized quartz grains).**

A structural log cross section that extends southwestward from Wellington Field ~100 miles is shown in Figure 27. The Pierson Formation log response and lithology persists, but thins to the Harper County well location while the Chattanooga Shale thickens to the southwest. It appears the area in the vicinity of the cross section as adequate capock above the Arbuckle saline aquifer.
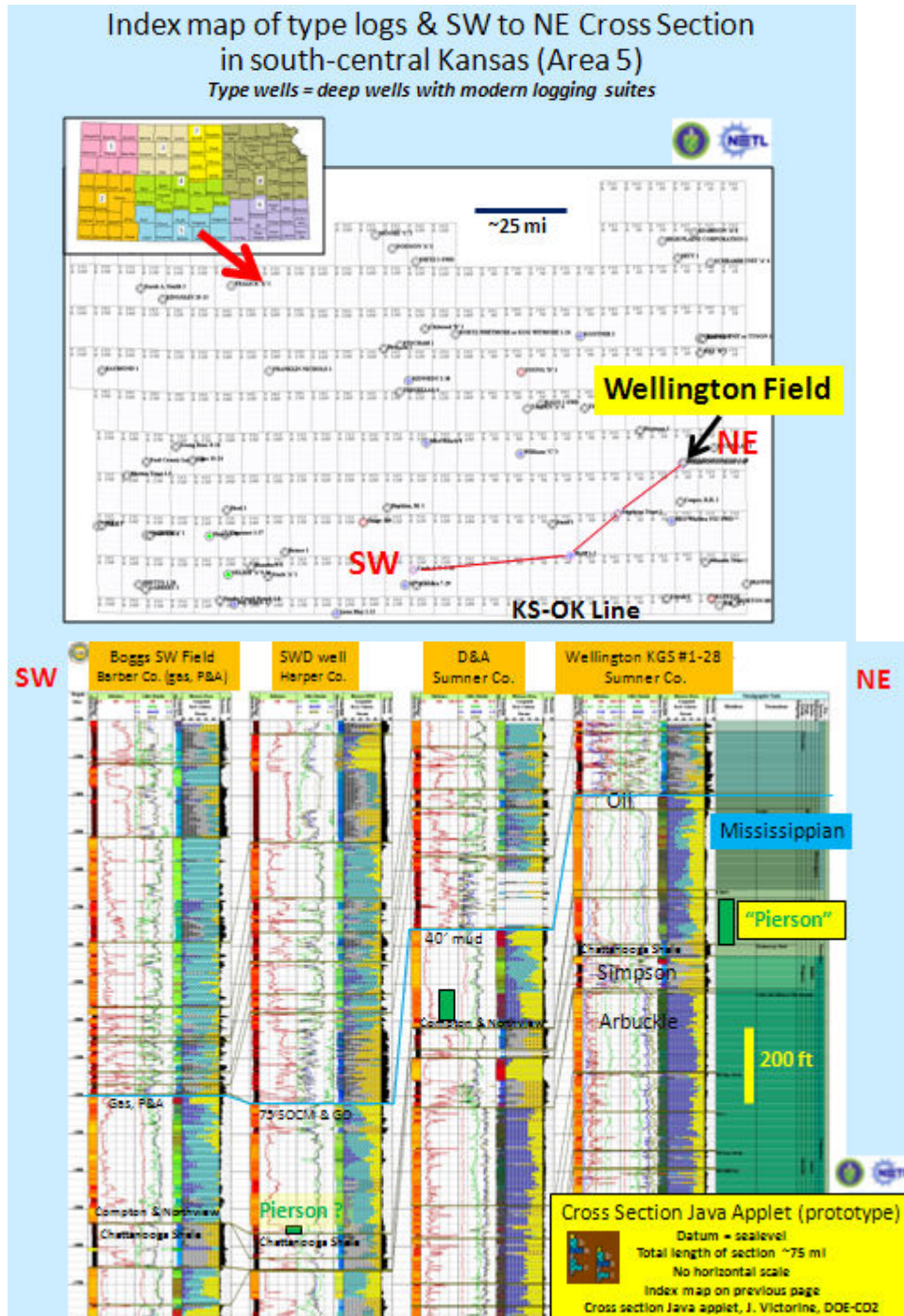


**Figure 27. Index map and structural cross section highlighting the presence of the Pierson Formation. The Pierson thins southwestward over a span of ~100 miles.**

**Task 18. Update Geomodels and Conduct Simulation Studies in Southwestern Kansas**

The activities during the quarter were focused on finishing simulation modeling at Eubank Field and establishing the geomodel and parameters for simulation of Shuck Field. Eubank Field is an incised valley filled with Chester age sandstone reservoir. The seismic is used to define the valley which is upu to 1400 ft wide and 140 to 200 ft deep in the area of Eubank Field (Figure 28).
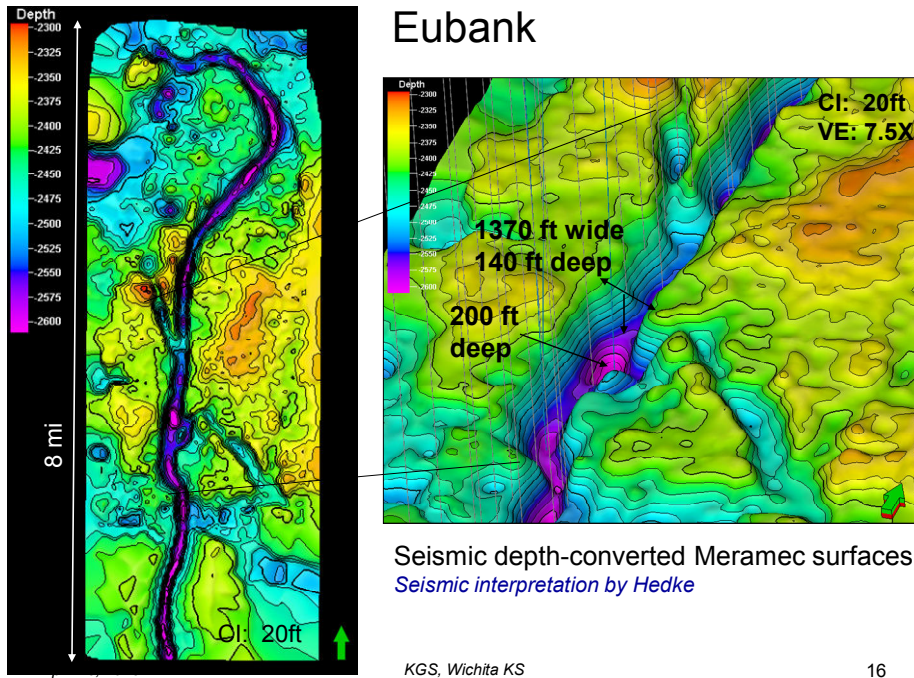


**Figure 28. Stucture map on the top of the Meramec Limestone clearly showing the location of the incised valley. Eubank Field extends along few miles of the valley.**

Locally, the incised valley appears to cross a karst/sinkhole features that is shown in Figure 29. Other locations along the valley similarly have closed depressions.

## Eubank – depth ties
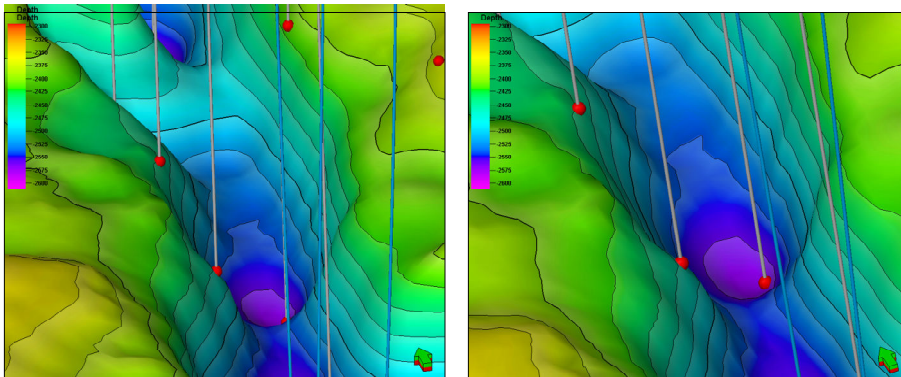


Valley walls and irregular floor tied to well measured tops – same view, different perspective.  Red dots are Meramec tops intersected by the depth-converted Meramec seismic surface. Isolated lows in valley floor, confirmed by well penetration, may be karst-related sink holes.

**Figure 29. Depth-converted seismic tie closely to the valley walls and floor indicating a very accurate depth conversion.**

As the Chesterian seas onlapped the exposed Meramecian surface, the valley was filled by a fluvial-estuarine system from south to north. The incision still may have been occurring north of the Chester shoreline during fill south of the shoreline. The oldest Chester fill is to the south, youngest is to the north. Depositional environments are more marine and tidal-influenced to the south. More fluvial influence to the north (Figure 30).

## IVF Depositional Environment

**Shuck and Eubank** valley-fill sediments are primarily tidal-dominated estuarine-type deposits, although some are more related to Dalrymple et al's (1992) wave-dominated estuary system (Youle).

**Pleasant Prairie South** has more fluvial influence but still some tidal influence (Senior).
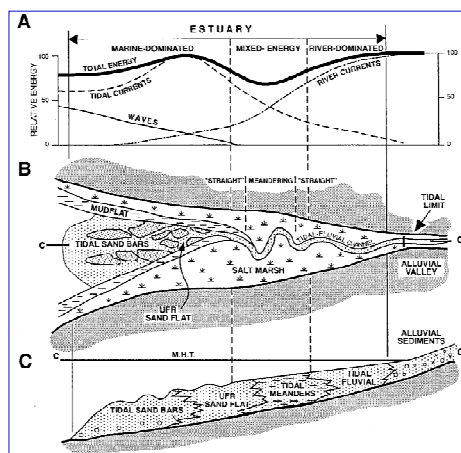


Dalrymple et al (1992) tide-dominated estuary model
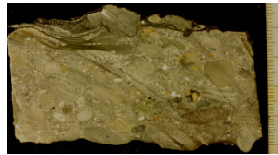
Figure 30. IVF depositional environment.

The depositional facies and petrofacies of the Chester sanstone in Eubank Field are described in Figure 31.



- **Depositional facies** are lithofacies defined in core deposited in a similar depositional environment
- **Petrofacies** are lithofacies identifiable on wireline logs. Multiple depositional facies may be in same petrofacies class
- **Youle defined five petrofacies** in Eubank and Shuck that can be defined by log signatures

**Petrofacies 5** (main pay lithofacies) Figure 24. Estuary Bar sandstone depositional facies, very-fine to fine-grained sandstone lithofacies. Owens 3A core (MD 5465-5475).

**Petrofacies 4** (below left)
Estuary Bar facies sandstones (Petrofacies 5) interbedded with shalier Estuary Bar Margin depositional facies, slightly shaley fine-grained sandstone lithofacies (Petrofacies 4). Facies are depositionally linked - deposited in immediately adjacent settings. (Hugoton Energy Black 4-3 core 5481-5491)

**Petrofacies 3** (above)
Marine Transgressive Conglomerate lag depositonal facies, conglomerate lithofacies, lies on top of parasequence boundary FS P4. Lithoclasts of limestone, sandstone and shale in sandy bioclastic packstone. Grades upward into the Marine Shale facies **(Petrofacies 1).** (Hugoton Energy Black 4-3 core 5422.8)

**Petrofacies 2** (left)
"Salt Marsh" facies depositional facies, sandy shale lithofacies. Soft sediment deformation and root traces noted. (APC Owens 3A 5595-5601)

**Petrofacies 1**
Marine shale – not identified in core but recognizable on logs

April 16, 2013          KGS, Wichita KS          22

**Figure 31. Eubank depositional facies and petrofacies.**

Parasequences are recognized in the core that often compartmentalize the reservoir into stacks of fining upward sandstone and shaly intervals (Figure 32). These boundaries are also interpreted from well logs (Figure 33).

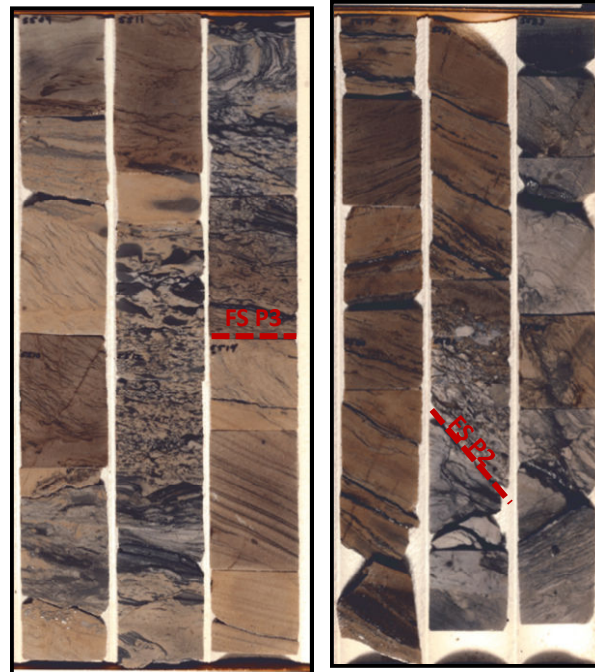**Parasequence Boundaries recognized in core**

*Key parasequence boundaries marking acceleration in Chester sea onlap are recognized in core and correlated with wireline logs in wells without core.*

(Left) **Flooding Surface for PS3 at 5514.** Maximum flooding surface for PS3 is appx. 10 ft above this surface. (core 5509-5515)

(Right) **PS2 Flooding surface at 5581.5**, Estuary Bar and Bar Margin facies of PS 2 lying sharply above intertidal to supratidal "Salt Marsh" facies. (core 5579-5586)

*(work by Youle)*

**Figure 32. Parasequence boundaries recognized in core.**

## Eubank North, Parasequences in logs and model
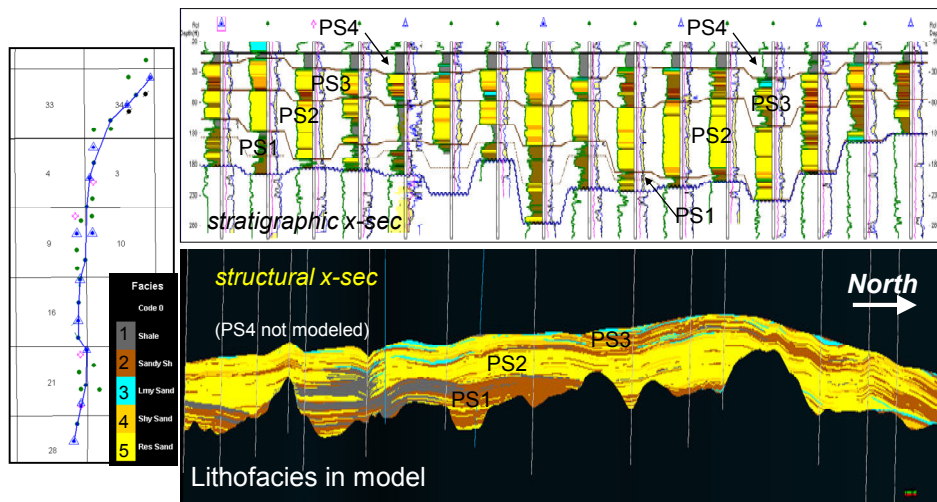


Four parasequences in North Eubank unit area. Wireline x-sec is not to scale. Model x-sec has true horizontal scale along similar path, but crosses "bumps" in straight line between wells rather than center of valley.

**Figure 33. Stratigrahic cross section along the axis of the incised valley at Eubank North showing inferred lithologies and parasequences, PS1 through PS4. Cross section is datumed on top of PS4.**

Figure 34 shows the depositional episodes in North Eubank Field from PS1 through PS3, the main period of sandstone fill in the incised valley.
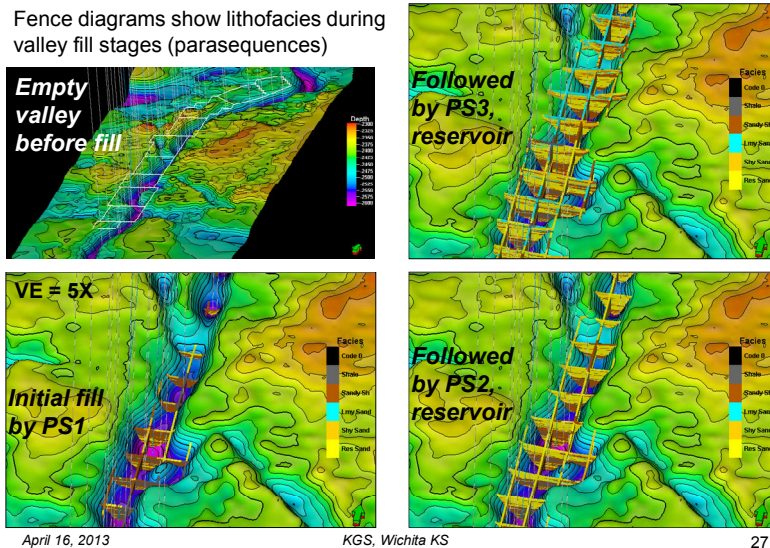


**Figure 35. North Eubank Field incised valley fill succession.**

Latest findings suggest that the sandstone reservoirs in the series of fields studied appears to be connected. Local barriers to updip flow to the north are structural in nature. Pleasant Prairie and Eubank IVF traps occur where the valley "crosses" post-Chesterian faulted structures related to the Ouchita Orogeny and the development of the Anadarko Basin. Northern closure to the Shuck field appears to be due to a very localized karst (Sorenson, personal communication).

Oil that have accumulated along the length of the valley are very similar and are primarily of Woodford Shale in origin, having migrated out of the Anadarko Basin. A minor component of the oil is Ordovician in age (Kim et al, 2010). In addition, the Chester IVF system may have been a primary route for the Woodford oil charging the reservoirs in the much of western Kansas (Sorenson, personal communication).

Generous operator contributions of data has allowed this comprehensive study of Chester IVF system. Post-Meramec incision was filled by tidally dominated estuarine sediments to south and more fluvial to the north.Trapping mechanism is structural in nature for the three fields studied Shuck, Eubank North Unit, and Pleasant Prairie South were prolific in primary and water flood phases. Based on relatively simple modeling and simulation, the fields should be good $CO_2$ flood candidates provided a source of $CO_2$ can be found.Substantial model and flow simulation improvements are advisable prior to implementing $CO_2$ floods based on these studies.

**Task 17.    Acquire (New) Data at a Select Chester/Morrow Field to Model CO2 sequestration Potential in the Western Annex**

Core analysis of the Cutter KGS #1 is underway at Weatherford Labs in Houston. The initial P-wave interpretation of the new multicomponent seismic acquired at Cutter has been received and work has begun on the processing and interpreting the shear wave data.

The testing of the Cutter KGS #1 well has been defined and will commence in early June. A total of 13 intervals are identified for testing illustrated in Figures 36 and 37. The intervals range from five samples (#1-#5) in the Lower Ordovician Arbuckle, #6 in the Lower Ordovician Simpson Sandstone, #7 in the Upper Orodvician Viola Limestone, #8 Osagean Mississippian, #9 Warsaw Mississippian, #10 St. Louis Mississippian, #11 Chester Mississippian, #12 Lower Pennsylvanian Upper Morrowan Sandstone. For each interval the casing will be perforated and the interval swabbed to obtain clean connate brine. Trilobite Testing will apply a means to record pressure buildup for the lower zones so as to permit estimation of the permeability to compare with the core analysis and the nuclear magnetic resonance log. The number of samples will be dependent on the cost, which will be closely monitored. Two sampling teams will be on site to obtain the brine, K-State for the geochemistry and KU for the microbial analysis. Both groups continue to work closely together. Each sampling intervals has corresponding core.
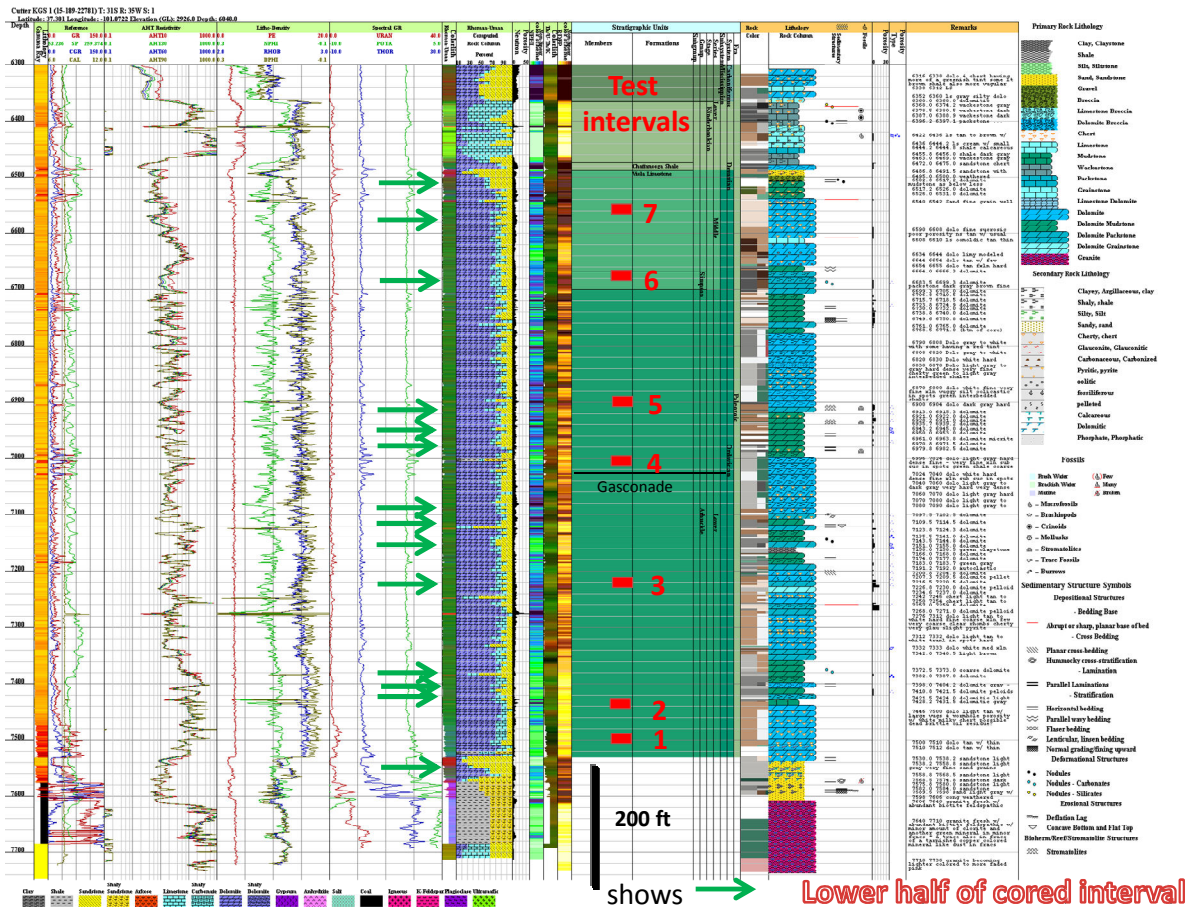


**Figure 35. Composite logs and core description of the lower half of the cored interval in the Cutter KGS #1 showing the locations #1 through #7 that will be perf and swabbed to aquire brine samples. Yellow highlighted list in right are zone of fluorescence interpreted as hydrocarbon shows.**
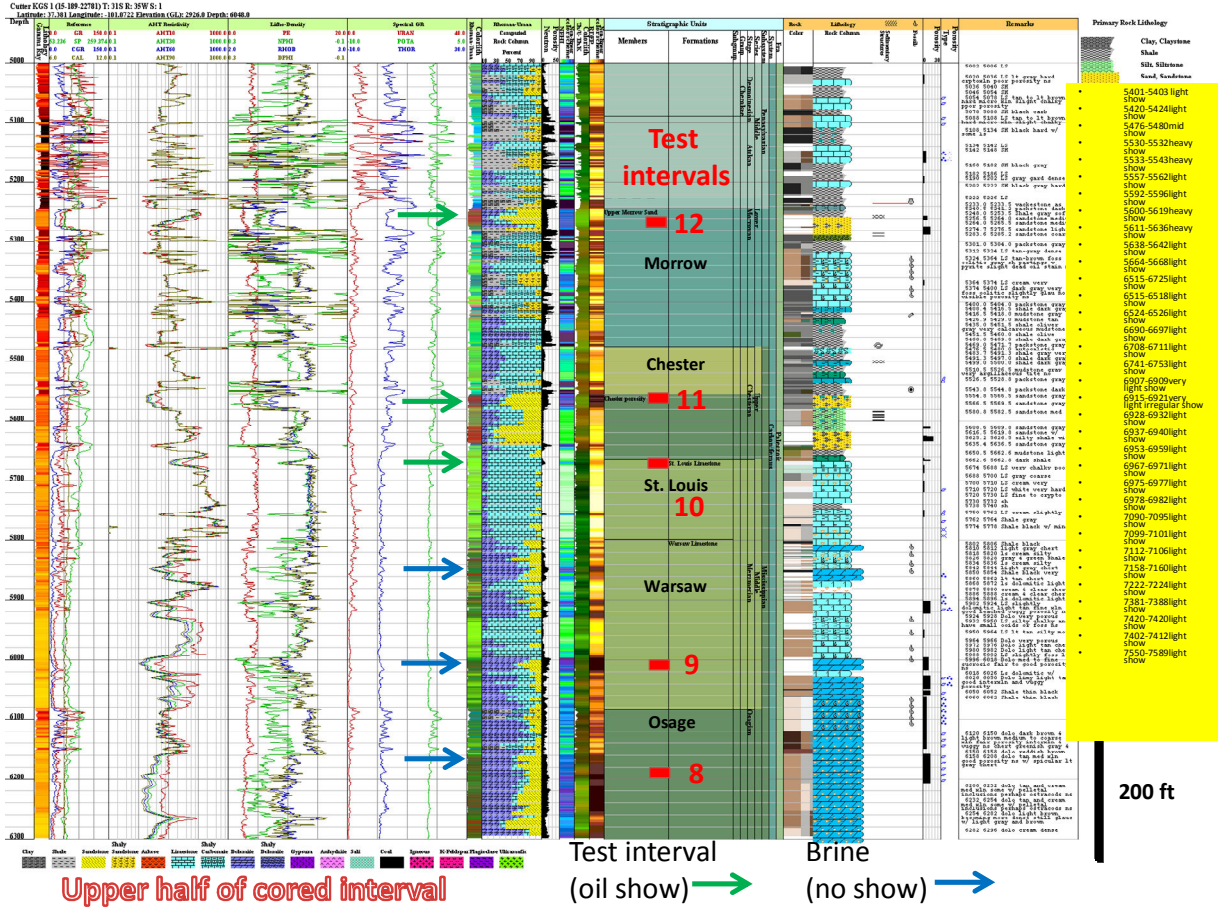
**Figure 36. Composite logs and core description of the upper half of the cored interval in the Cutter KGS #1 showing the locations #8 through #12 that will be perf and swabbed to aquire brine samples. Yellow highlighted list in right are zone of fluorescence interpreted as hydrocarbon shows.**

An example of the test procedure is shown in Figure 37.

**Figure 37. Test procedures for #1-#3 in the lowermost Arbuckle Group.**

## ONGOING ACTIVITIES - WELLINGTON FIELD

**Task 3. Geomodel of Mississippian Chat & Arbuckle Group - Wellington field**

The magnetic resonance imaging log (MRIL) calibrated to core and test data has served as a vital tool to derive essential parameters for our modeling efforts. The report included below by Mina Alavi used the MRIL to evaluate the integrity of the primary and secondary caprock immediately overlying the Arbuckle Group at Wellington Field.

**Sealing Integrity of Barriers above Arbuckle**

### I - Introduction

It is planned to inject 40,000 tons of $CO_2$ in Arbuckle formation and containment of injected $CO_2$ in Arbuckle formation is an issue. There are several vertical barriers above Arbuckle formation which can prevent vertical movement of injected $CO_2$ from Arbuckle to other

formations or to the surface. Two of these main barriers are; Arbuckle cap rock which is called Chattanooga Shale, the tight zones in Mississippian formation from 3915 to 4005ft. CO2 entry pressure in each of these barriers is calculated, increase in Arbuckle pressure due to CO2 injection will be estimated and it will be shown that these barriers can prevent CO2 migration from Arbuckle to upper formations.

## II - Arbuckle Cap Rock

Chattanooga shale is above Arbuckle formation at it constitutes NMR Entry pressure in the Chattanooga shale was calculated in well 1-32 and 1-28. Entry pressure is where capillary pressure at which the non-wetting phase enters the biggest pores, that is the pressure at which the wetting phase saturation is 85 %(Volokin et al., 2001). Techlog converts pore size (T2 distribution) to pore throat radius using a proportionally constant Kappa (K) and therefore to capillary pressure. Capillary pressure and pore throat radius relationship can be expressed as:

$$P_c = \frac{2\sigma cos\theta}{r_{neck}}$$

Where,

$P_c$=Capillary pressure
$\sigma$=Interfacial tension of Mercury-air
$r_{neck}$= pore radius

Kappa value of 9 was used in the Chattanooga shale and Kappa value of 15 was used in the tight carbonate zone in lower Mississippian. Kappa value is usually 4 but can be ranged from 1 to 10 in sandstone for different core samples (Volokitin et al., 2001). In this article, Kappa value of 3 is the optimum scale that minimizes the error between NMR capillary pressure and core capillary pressure data. Kappa value of 4 was used at first but the results showed that NMR capillary pressure curves don't match very well with the generalized Pc curves of chat conglomerate in Mississippian in the Spivey-Grab field (Watney et al., 2001). NMR capillary pressure curves matched better with Generalized Pc curves when Kappa value of 9 was used in sandstone. Kappa value in Carbonate reservoir is ranged from 10-20. NMR capillary pressure curves matched better with the generalized Pc curve in the Wellington West field (Bhattacharya et al., 2003) when Kappa value of 15 was used in the Carbonate zone. Kappa values can be adjusted when SCAL data become available.

According to NMR, mercury entry pressure for this shale interval is from 1 to 55 bars. Maximum entry pressure is about 55 bars in well 1-32 which is equivalent to 64 psi in CO2-brine system. Also based on Mercury injection, entry pressure in Chattanooga shale in well 1-28 is from 0.5 to 250 bars. The maximum value is about 250 Bars which is equivalent to 293 psi in CO2-brine system. Entry pressure is higher in well 1-28 and this difference is due to the pore size distribution that exists in both well. This indicates pore sizes are smaller in 1-28 than 1-32 and therefore the entry pressure is higher. Entry pressure of cap rock is largely a function of its pore size and this can be variable laterally and vertically. Smaller pore size has a higher entry pressure. Figure 1 and 2 are output of NMR entry pressure in Chattooga shale in well 1-32 and 1-28 respectively.

The following equation was used to convert entry pressure from mercury-air system to CO2-brine system:

$$Pe_{CO2/brine} = P_{e-Hg/air.} \frac{\gamma_{CO2/brine}.COS\theta_{CO2/brine}}{\gamma Hg/air.COS\theta_{Hg/air}}$$ (Equation 1)

Where,

$Pe_{CO2/brine}$ is entry pressure in the reservoir system which in this case is $CO2/brine$

$Pe_{Hg/air}$ is entry pressure in mercury-air system

$\gamma_{CO2/brine}$ and $\gamma_{Hg/air}$ are interfacial tension of CO2/brine and Hg/air respectively

$COS\boldsymbol{\theta}_{CO2/brine}$ and $COS\boldsymbol{\theta}_{Hg/air}$ are contact angles of reservoir CO2/brie/solid and Hg/air/solid system

Interfacial tension of 30 dyne/cm and 485 dyne/cm were used for CO2-brine and Mercury air system respectively. Also, contact angle of 0 and 140 were used for CO2-brine and Mercury-air system respectively.

Average pressure increase of Arbuckle reservoir was estimated after injecting 40,000 tons of CO2. First, Arbuckle rock and water contraction per one psi pressure increase was estimated using the following equation:

$$(C_{f*}BV)*(1-\emptyset)+(C_w * BV * \emptyset)$$ (Equation 2)

Where,

$C_f$ is rock compressibility per psi

$C_w$ is water compressibility per psi

BV is bulk volume

$\emptyset$ is Average porosity

The following parameters were used to estimate rock and water contraction per psi in Arbuckle:

$C_f$= 4E-6

$C_{w=}$ 3E-6

$\emptyset$=0.06

BV= 1.33E+12

The amount of contraction of Arbuckle rock and water is 5.24E+06 ft$^3$ /psi using equation 2. Volume of CO2 which will be injected was estimated using density of CO2 at reservoir condition, 0.58 g/cm$^3$. Volume of CO2 at reservoir condition is 2.44E+06 ft$^3$. Having the volume of CO2 at reservoir condition and rock and water contraction per psi, Average pressure increase in the reservoir after injection of CO2 was estimated. This value is 0.46 psi.

At the start of CO2 injection, Arbuckle and Chattanooga shale pressure are in equilibrium at their initial pressure. After completion of CO2 injection, average pressure in Arbuckle will be higher than Chattanooga shale pressure by 0.46 psi. During injection and immediately after injection, pressure at the depth and location of injection will be higher than the average pressure. But after few years pressure in Arbuckle area and depth will be equalized and pressure at every location will be close to the average which will be only 0.46 more than the initial pressure. Since entry

pressure of Chattanooga shale is 64 psi and exceeds average pressure increase in Arbuckle, $CO_2$ cannot enter or pass Chattanooga shale in the long term when injection pressure is equalized. Therefore few years after injection, escape of $CO_2$ from cap rock would not be possible.

To investigate sealing integrity of Chattanooga shale during injection, it is necessary to know pressure in Arbuckle reservoir immediately below Chattanooga shale at the location of injection well during injection. If pressure in this location remains below initial pressure plus 64 psi which is the entry pressure, Chattanooga shale will be sealing in this period.

However another mechanism which is important should also be considered when assessing sealing integrity of cap rocks. Assume that pressure in Arbuckle immediately below cap rock increases by 200 psi which is more than the entry pressure and $CO_2$ reaches just below cap rock. Even under this condition, $CO_2$ cannot enter cap rock or pass through it. Since cap rock is 100% saturated with water and $CO_2$ saturation in cap rock is zero, only water phase in Arbuckle can flow into cap rock and the flow of water will increase its pressure. Because increases in Arbuckle pressure will be gradual, cap rock pressure will increase simultaneously. It can be said that pressure of shale layers immediately above Arbuckle will have the same increase in pressure that exists in Arbuckle just below these layers. If $CO_2$ phase pressure and water phase pressure in Arbuckle are equal, $CO_2$ cannot enter cap rock because cap rock pressure would be equalized with water phase pressure of Arbuckle. Only if $CO_2$ pressure is higher than water phase pressure in Arbuckle by entry pressure of cap rock, $CO_2$ will be able to enter cap rock. This condition cannot occur unless a large column of $CO_2$ is developed and accumulates below cap rock.

Gravity difference between water and $CO_2$ at reservoir condition is 0.23 psi per ft of depth. Entry pressure of Chattanooga shale is about 64 psi. If the column of $CO_2$ is small e.g. 10 ft, pressure difference between $CO_2$ and water phase will be small e.g. 2.3 psi which is less than entry pressure. In this condition $CO_2$ cannot enter or pass the cap rock. However if a $CO_2$ column with a thickness of 400 ft develops below cap rock by injection of large masses of $CO_2$ (billion tons), $CO_2$ phase pressure will be 92 psi more than water phase pressure. At this condition $CO_2$ will enter Chattanooga shale and pass through it to upper formations. Because volume of $CO_2$ injection in Arbuckle compared to the area of the reservoir is negligible, $CO_2$ column below cap rock will be small and cap rock integrity against migration of $CO_2$ remain theoretically guaranteed.

### III – Second barrier (Tight Zones in Mississippian)

Another barrier exists in lower Mississippian formation. NMR module was run to get the entry pressure in the lower Mississippian. Entry pressure is from 33 to 150 bars from 3915 to 4005 ft according to mercury injection. Entry pressure is shown in Figure 3. Maximum entry pressure is about 150 bars which is equivalent to 176 psi in $CO_2$- brine system. This high entry pressure implies low permeability, small pore size and therefore small pore throat size exist in this interval. This barrier can prevent vertical movement of $CO_2$ by the same mechanism which was discussed before.
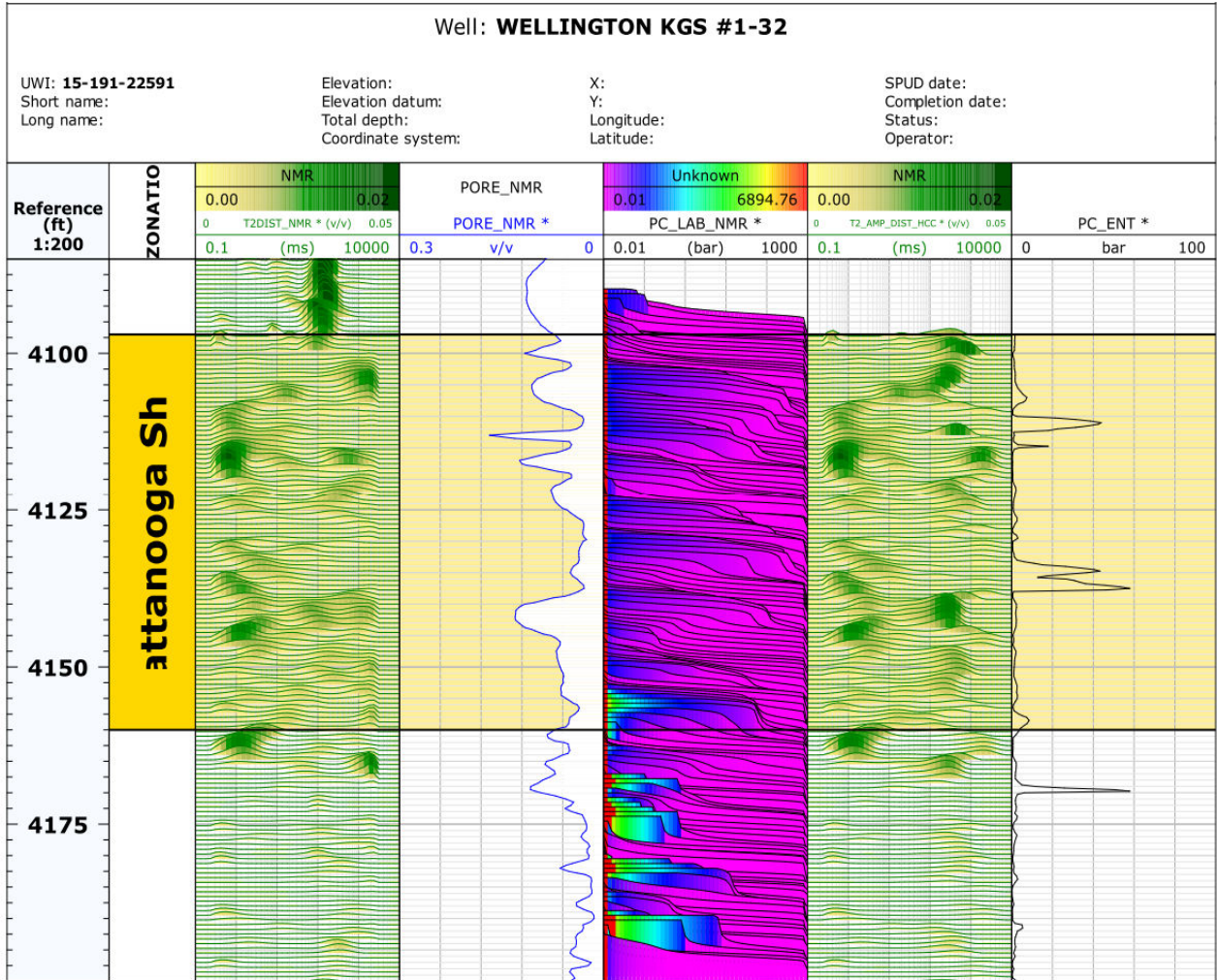
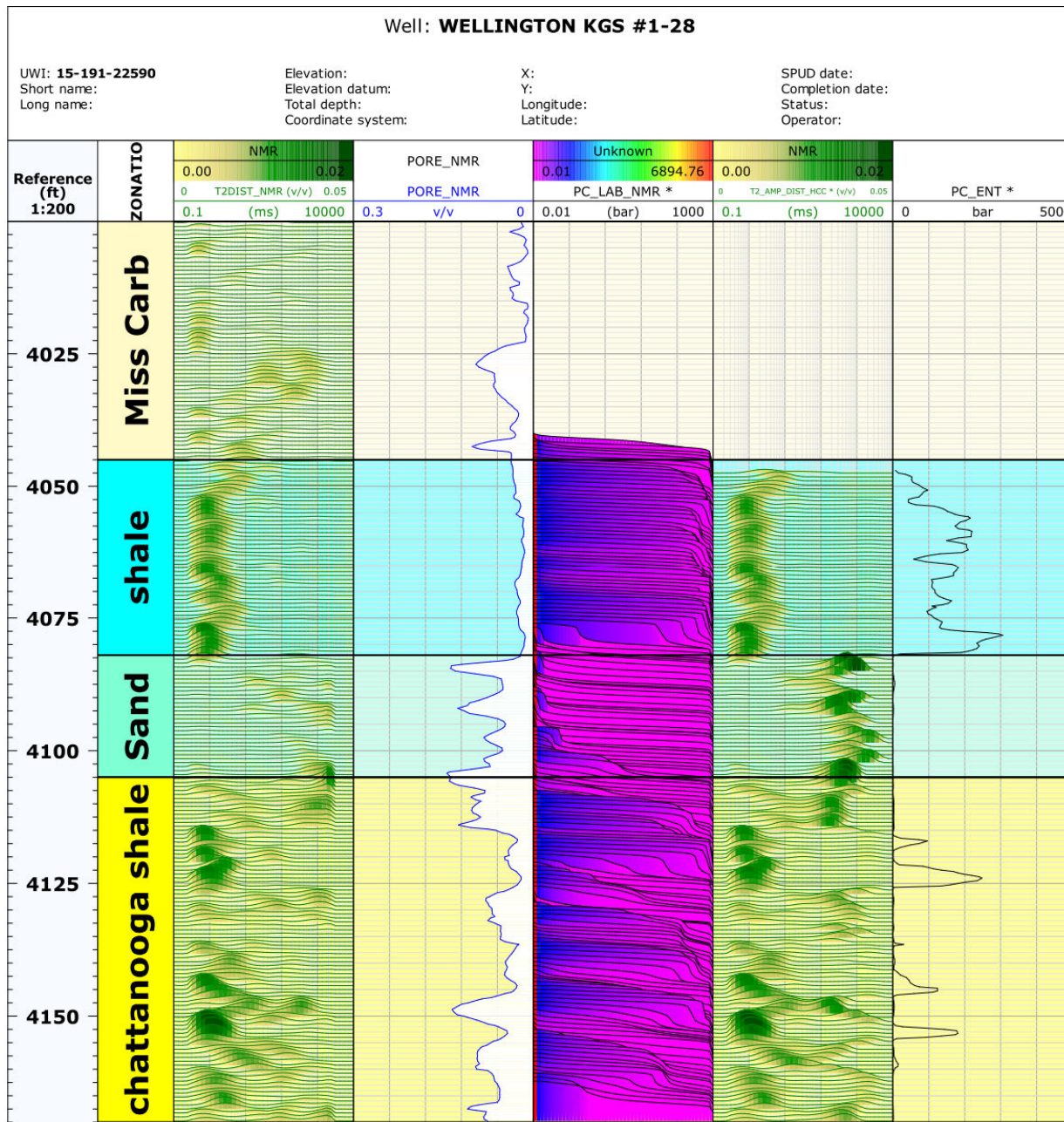**Figure 1: NMR entry pressure in Chattanooga caprock in well 1-32**

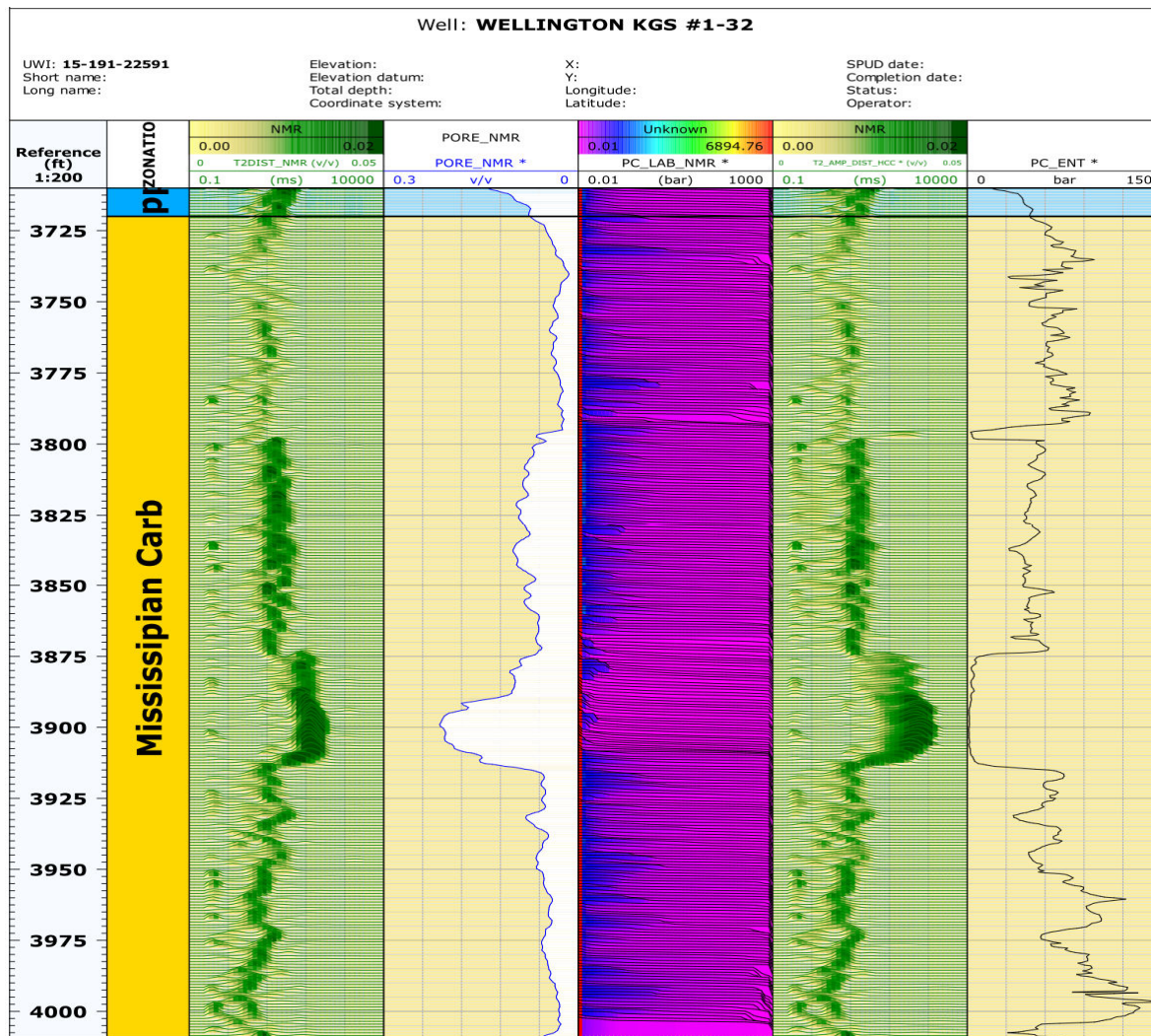**Figure 2: NMR entry pressure in Chattanooga caprock in well 1-28**

**Figure 3: NMR entry pressure in tight Mississippian zone in well 1-32**

## PRESENTATIONS AND PUBLICATIONS

January 8th, Tulsa Geological Society, Carbon Storage in Kansas  - Lynn Watney

January 25th, Richmond Kansas High School -- Oil and gas in Kansas and CCUS -- Lynn Watney

January 31st, AAPG Mississippian Forum, Oklahoma City, OK, Mississippian Carbonate and Chert Reservoirs in Kansas: Integrating Log, Core, and Seismic Information -- Lynn Watney (based primarily on Wellington Field)

February 18-19, Applied Geoscience Conference, Houston, TX, Mississippian Exploration: Stratigraphy, Petrology, and Reservoir Properties -- Lynn Watney (based on new data from Wellington Field, considerations for CCUS, and regional mapping)

**Eleven papers accepted for AAPG Mid-Continent Section Meeting, October 12-15, 2013, involving activities supported by DOE, to be acknowledged in the presentations:**

Seismic attribute analysis of the Mississippian chert at the Wellington field -- Aryrat Sirazhiev

Core transect across Shuck Pool: A Chesterian incised valley fill succession in Seward County, KS -- John Youle

The Geologic History of Kansas, 2013 or Updating the Work of a Legend - Paul Gerlach

Online Development of New Kansas Type Logs -- Paul Gerlach

In Situ Validation of PSDM Seismic Volumetric Curvature as a Tool for Paleokars Heterogeneity Studies: Results from an Extended-Reach Lateral at Bemis-Shutts -- Jason Rush

Reservoir Engineering Aspects of Pilot Scale CO2 EOR Project in Upper Mississippian Formation at Wellington Field in Southern Kansas - Eugene Holubnyak

Dynamic Modeling of CO2 Geological Storage in the Arbuckle Saline Aquifer at Wellington Field -- Eugene Holubnyak

CO2 Enhanced oil recovery and CO2 sequestration potential of the Mississippian Chester -- Martin Dubois

Systematic and episodic structural deformation in southern Kansas and implications for CCUS -- Lynn Watney

Evaluating CO2 Utilization and Storage in Kansas -- Lynn Watney

Core workshop -- Wellington KGS #1-32, Sumner County, and Cutter KGS #1, Stevens County, Kansas -- Lynn Watney


**KEY FINDINGS**

1. Underpressuring of the Mississippian spans Sumner County and is not limited to only the Mississippian reservoir at Wellington Field.

2. Faulting of the pre-Pennsylvanian strata is indicated in the Anson Southeast area several miles to the northwest of the Wellington KGS #1-28. A detailed examination of this area indicates that the faults were intermittently active prior to the early Pennsylvanian and subsequent deformation of the related structures were post tectonic and limited to what in indicated as drapping of the strata. The integrity of the seals either below or above the Mississippian have not been compromised such that underpressuring is maintained and the oil that have accumulated in the fields. The historical earthquake activity has placed the area under low risk category according to the USGS.

3. The Lower Permian age Huthinson Salt (halite) and associated anhydrite beds, ~200 ft thick, that underlie the halite thin several miles east of Wellington Field as the more soluble halite comes within ~200 ft of the land surface. The units immediately underlie the USDW of the upper Wellington Shale. The water quality in the maginal USDW remains good for local domestic wells.

4. The regional analysis of the carbon storage has taken major steps toward finalizing the digital log database. Stratigraphic tops are complete and Java software has been developed to allow review and verificatioin of the correlations. Java tools were also

developed to map out the the progress on finalizing formation tops and assembling supportive data such as georeports useful for verifying log assigned petrofacies.

5. Analysis of the 10 nonfaulted sites with structural closure with larger oil field and thick underlying Arbuckle saline aquifer began in ernest to apply petrophysical correlations from Wellington and Cutter Fields to construct static and dynamic models of commercial scale $CO_2$ injection and evaluate associated local risks.

6. Regional source-sink for $CO_2$ has developed scenarios for potential pipeline infrastructure to ethanol and fertilizer plants, and refinery. Moreover, the Kanasa model of coupling oil field and underlying saline aquifer appears to be viable, attracting carbon trading in aquifer and realize current value of $CO_2$-EOR to improve economics, and finally to more effectively address risks with the oil field infrastructure and potential for an economical long-term monitoring program.

7. SW Kansas Industry $CO_2$-EOR Initiative intermediate findings are very promising.

8. Continued petrophysical analysis, particularly with the MRIL tool, will provide us with a more robust means to model and predict $CO_2$ plume behavior.

9. All activities at Cutter Field are meeting expectations – core obtained, seismic deployment and initial interpretations, successful logging.


## PLANS

1. Conduct testing of the Cutter KGS #1.
2. Complete the processing of the new seismic at Cutter Field.
3. Complete the final geomodel of the Mississippian at Wellington Field and begin simulation for $CO_2$-EOR.
4. Work toward verifying the regional stratigraphic correlations and implement new Java web applications with the interactive mapper.
5. Begin static and dynamic modeling of the 10 regional sites to evaluate commercial scale $CO_2$ injection into the Arbuckle saline aquifer for use in refining estimates of overall $CO_2$ sequestration capacity for NATCARB.


## SPENDING PLAN

COST PLAN/STATUS

| | BP 1 Starts: 12/8/09 Ends: 2/7/11 | | | | | BP2 Starts 2/8/11 Ends 8/7/12 | | | | | | BP3 Starts 8/8/12 Ends 2/7/14 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Baseline Reporting Quarter | 12/8/09-12/31/09 Q1 | 1/1/10-3/31/10 Q2 | 4/1/10-6/30/10 Q3 | 7/1/10-9/30/10 Q4 | 10/1-12/31/10 Q5 | 1/1/11-3/31/11 Q6 | 4/1/11-6/30/11 Q7 | 7/1/11-9/30/11 Q8 | 10/1/11-12/31/11 Q9 | 1/1/12-3/31/12 Q10 | 4/1/12-6/30/12 Q11 | 7/1/12-9/30/12 Q12 | 10/1/12-12/31/12 Q13 | 1/1/13-3/31/13 Q14 |
| **Baseline Cost Plan (from SF-424A)** (from 424A, Sec. D) | | | | | | | | | | | | | | |
| Federal Share | $1,007,622.75 | $1,007,622.75 | $1,007,622.75 | $1,007,622.75 | $0.00 | $0.00 | $0.00 | $1,169,543.00 | $1,169,543.00 | $1,169,543.00 | $1,169,543.00 | $316,409.00 | $316,409.00 | $316,409.0( |
| Non-Federal Share | $277,260.75 | $277,260.75 | $277,260.75 | $277,260.75 | $0.00 | $0.00 | $0.00 | $303,182.75 | $303,182.75 | $303,182.75 | $303,182.75 | $81,854.50 | $81,854.50 | $81,854.5( |
| Total Planned (Federal and Non-Federal) | $1,284,883.50 | $1,284,883.50 | $1,284,883.50 | $1,284,883.50 | $0.00 | $0.00 | $0.00 | $1,472,725.75 | $1,472,725.75 | $1,472,725.75 | $1,472,725.75 | $398,263.50 | $398,263.50 | $398,263.5( |
| Cumulative Baseline Cost | $1,284,883.50 | $2,569,767.00 | $3,854,650.50 | $5,139,534.00 | $5,139,534.00 | $5,139,534.00 | $5,139,534.00 | $6,612,259.75 | $8,084,985.50 | $9,557,711.25 | $11,030,437.00 | $11,428,700.50 | $11,826,964.00 | $12,225,227.5( |
| **Actual Incurred Costs** | | | | | | | | | | | | | | |
| Federal Share | $4,019.93 | $84,603.97 | $494,428.37 | $111,405.52 | $238,675.97 | $1,902,936.55 | $625,853.17 | $275,754.50 | $523,196.12 | $453,026.11 | $238,793.52 | $1,282,545.00 | $1,314,156.54 | $395,454.3( |
| Non-Federal Share | $0.00 | $43,980.04 | $40,584.78 | $13,195.88 | $526,210.30 | $35,887.34 | $414,511.02 | $20,247.24 | $16,687.00 | $61,683.20 | $150,646.51 | $221,053.41 | $121,637.40 | -$65,989.7( |
| Total Incurred Costs-Quarterly (Federal and Non-Federal) | $4,019.93 | $84,603.97 | $535,013.15 | $124,601.40 | $764,886.27 | $1,938,823.89 | $1,040,364.19 | $296,001.74 | $539,883.12 | $514,709.31 | $389,440.03 | $1,503,598.41 | $1,435,793.94 | $329,464.5( |
| Cumulative Incurred Costs | $4,019.93 | $88,623.90 | $623,637.05 | $748,238.45 | $1,513,124.72 | $3,451,948.61 | $4,492,312.80 | $4,788,314.54 | $5,328,197.66 | $5,842,906.97 | $6,232,347.00 | $7,735,945.41 | $9,171,739.35 | $9,501,203.9( |
| **Variance** | | | | | | | | | | | | | | |
| Federal Share | $1,003,602.82 | $923,018.78 | $513,194.38 | $896,217.23 | -$238,675.97 | -$1,902,936.55 | -$625,853.17 | $893,788.50 | $646,346.88 | $716,516.89 | $930,749.48 | -$966,136.00 | -$997,747.54 | -$79,045.3( |
| Non-Federal Share | $277,260.75 | $233,280.71 | $236,675.97 | $264,064.87 | -$526,210.30 | -$35,887.34 | -$414,511.02 | $282,935.51 | $286,495.75 | $241,499.55 | $152,536.24 | -$139,198.91 | -$39,782.90 | $147,844.2( |
| Total Variance-Quarterly Federal and Non-Federal) | $1,280,863.57 | $1,156,299.49 | $749,870.35 | $1,160,282.10 | -$764,886.27 | -$1,938,823.89 | -$1,040,364.19 | $1,176,724.01 | $932,842.63 | $958,016.44 | $1,083,285.72 | -$1,105,334.91 | -$1,037,530.44 | $68,798.9( |
| Cumulative Variance | $1,280,863.57 | $2,437,163.06 | $3,187,033.41 | $4,347,315.51 | $3,582,429.24 | $1,643,605.35 | $603,241.16 | $1,779,965.17 | $2,712,807.80 | $3,670,824.24 | $4,754,109.96 | $3,648,775.05 | $2,611,244.61 | $2,680,043.5( |