SMALL SCALE FIELD TEST DEMONSTRATING CO_2 SEQUESTRATION IN ARBUCKLE SALINE AQUIFER AND BY CO_2-EOR AT WELLINGTON FIELD SUMNER COUNTY, KANSAS DE-FE0006821

W. Lynn Watney, & Jason Rush (Joint PIs)

Jennifer Hollenbach (Asst. Project Manager)

Kansas Geological Survey

Lawrence, KS 66047

U.S. Department of Energy

National Energy Technology Laboratory

Carbon Storage R&D Project Review Meeting

Mastering the Subsurface through Technology Innovation and Collaboration: Carbon Storage

Ellwood 1&2

3:25-3:50

Tuesday, August 16, 2016

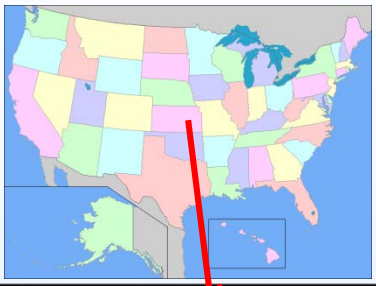
KANSAS GEOLOGICAL SURVEY The University of Kansas

KSCO2

NETL

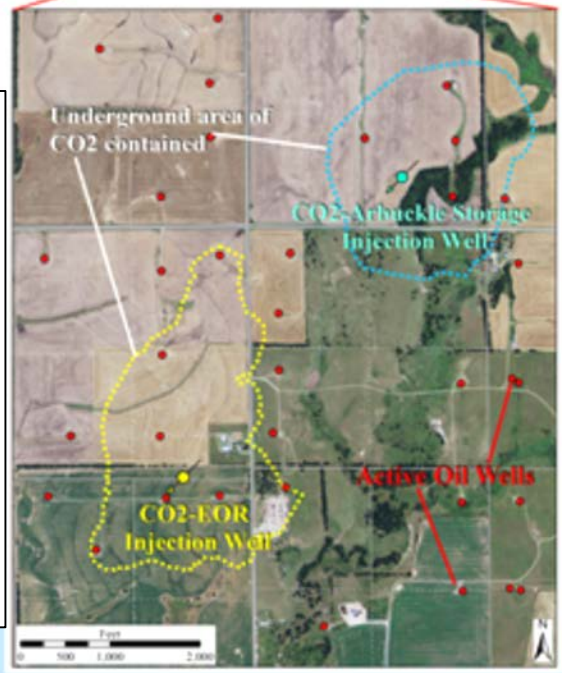
Presentation Outline

1. Project Overview
2. Benefits to the Program
3. Technical Status
4. Future Plans and Expectations



Wellington Field Sumner County Kansas

- **Oil field in rural area operating since 1929**
- **55 wells, 21 million barrels produced, 46,000 barrels annually**
- **Effective waterflood, ready for CO2-EOR**
- **<u>Phase I</u> – Completed June 21, 2016→ 20,000 tonnes CO2 injected into Mississippian dolomite for EOR**
- **<u>Phase II</u> – 26,000 tonnes CO2 into Arbuckle saline aquifer, pending Class VI permit (2017)**



Project Team

DOE-NETL Contract #FE0006821

Project established November 2011

Brian Dressel, P.M.

L. Watney (Proj. Manager, Joint PI), J. Rush (Joint PI), J. Hollenbach (Asst. Project Manager), T. Bidgoli, B. Campbell, J. Doveton, E. Holubnyak, M. Fazelalavi, C. Jackson, D. Newell, John Victorine

(static & dynamic modeling, petrophysics, well test analysis, install/maintain seismometer array, Structural, geochemical, geomechanical analysis, project management)

Dana Wreath, Adam Beren
(field operator and operations)

Tom Daley, Barry Freifeld
(CASSM, U-Tube for Arbuckle Class VI geosequestration)

KANSAS STATE UNIVERSITY — **Saugata Datta, Ian Andree** ***(USDW monitoring)***

T. Birdie ***(aquifer modeling, EPA Class VI permit)***

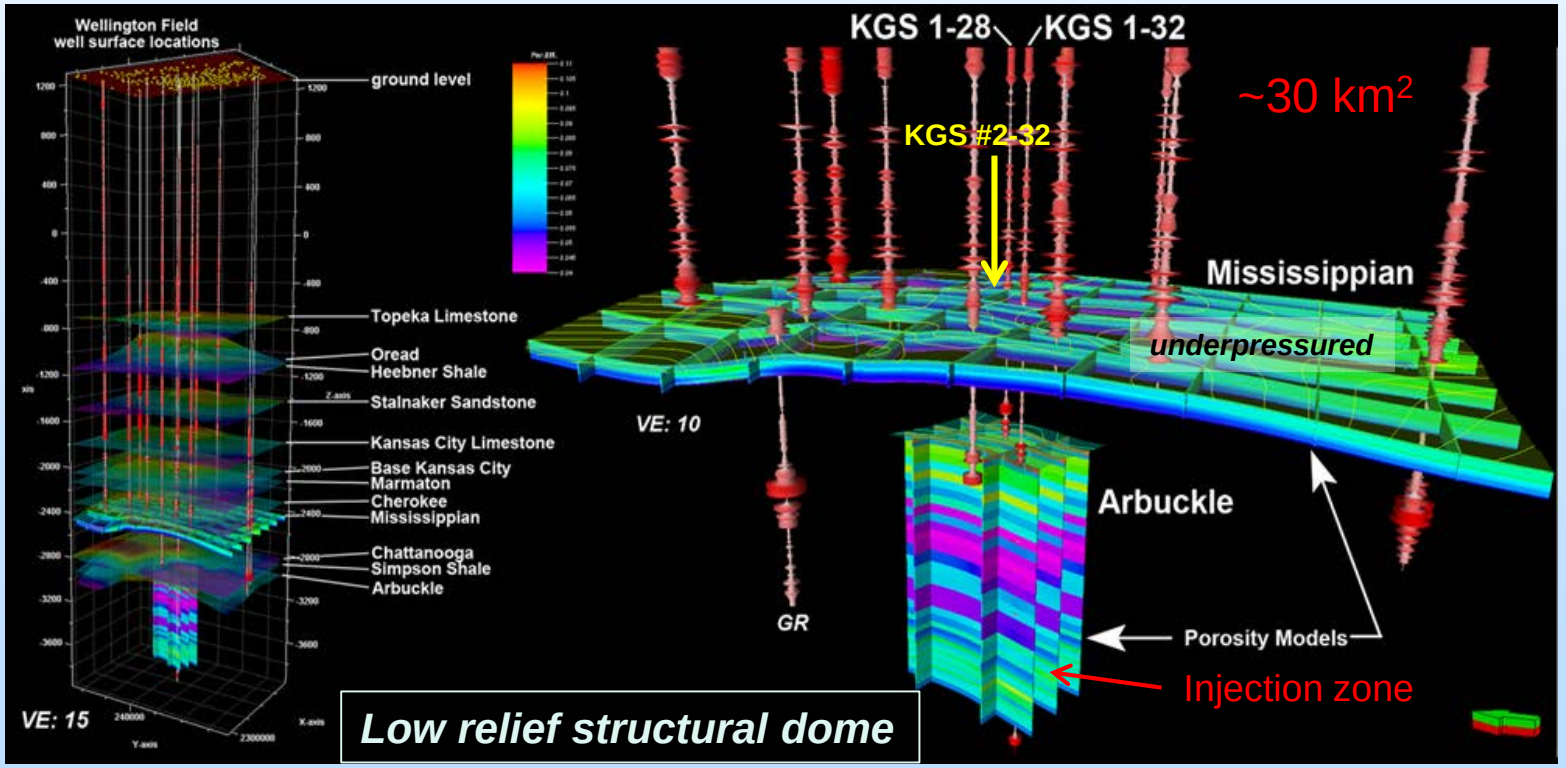
CO_2 supplier

Petrel
TechLog

Jennifer Roberts, Leigh Sterns, George Tsoflias, B. and K. Graham, A. Nolte, D. Schwab, B. Norwood
InSAR-cGPS, active and passive seismic, geochemistry

Benefits to the Program

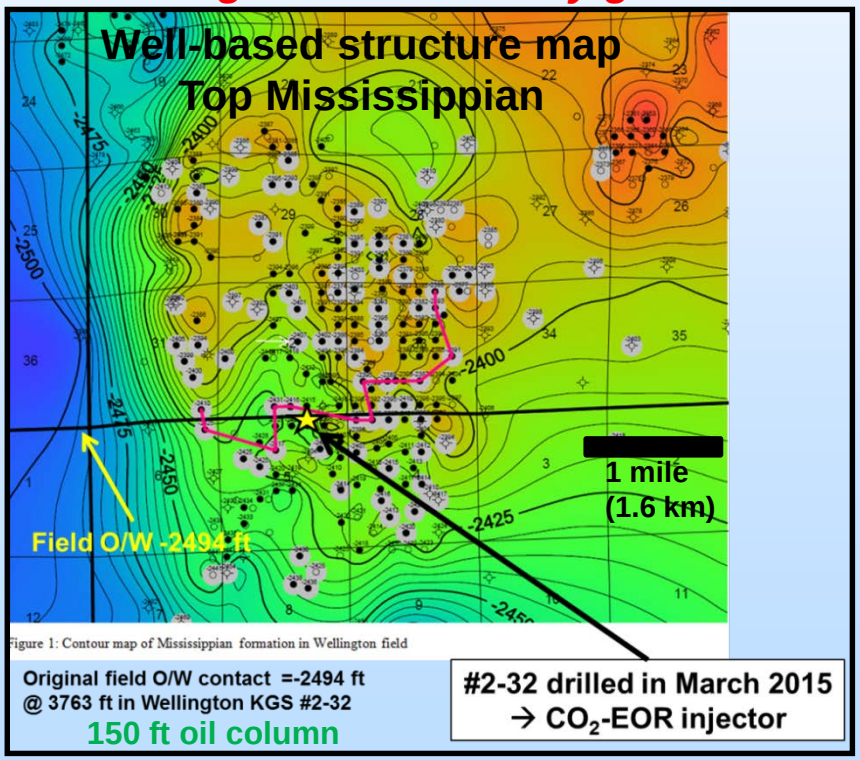
- **Demonstrate that 99 percent permanence of injected CO_2**
  - → 20,000 metric tons tonnes injected into KGS #2-32 into *Late Mississippian siliceous dolomite reservoir between January 9 and June 21, 2016 → CO_2 plume and EOR response as forecast by model* ***(Class II UIC permit)***
  - → 26,000 metric ton injection into underlying *Lower Ordovician Arbuckle Group dolomitic saline aquifer* ***(Pendiing Class VI UIC permit)***
- **Demonstrate reliable and cost effective MVA (*monitoring, verification, and accounting*) tools and techniques**
- **Develop best practices for effective and safe CO_2-EOR and CO_2 saline storage**



Technical Status

Task 15. Evaluate Potential to Move Oil and Optimize for Carbon Storage

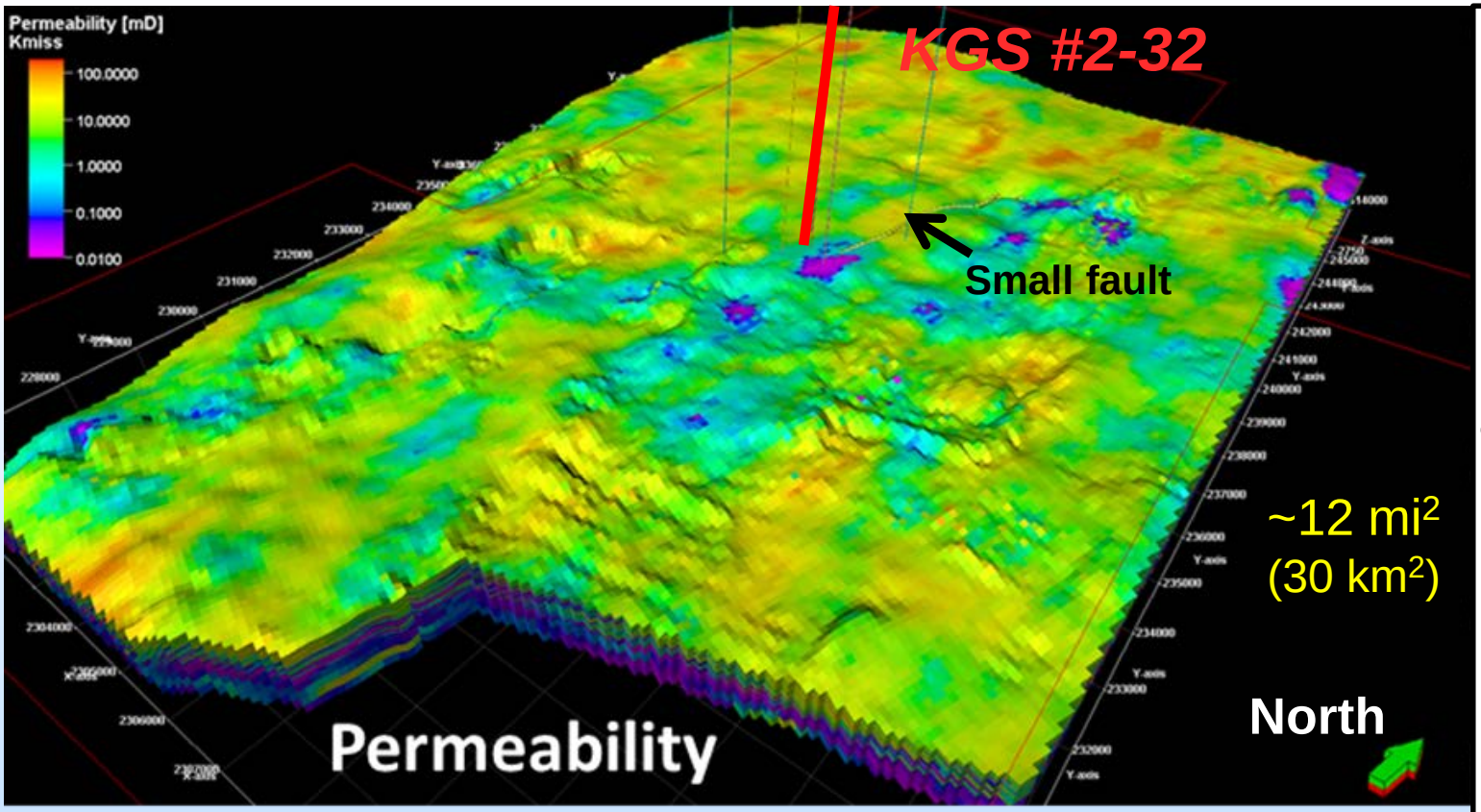
- Begin CO_2 injection into KGS #2-32 on January 9, 2016
- Completed injection on June 21, 2016
- 1,101 truckloads, 21,784 US tons, 19,803 metric tons, average of 120 tonnes per day, approximately 374,000 MCF of CO_2
- Total expenditures for purchasing CO_2 were $1,964,000. Our overall price for CO_2 was $90.16 per US ton from *Linde Group*
- ***Behaving as forecasted by gemodel/simulation***

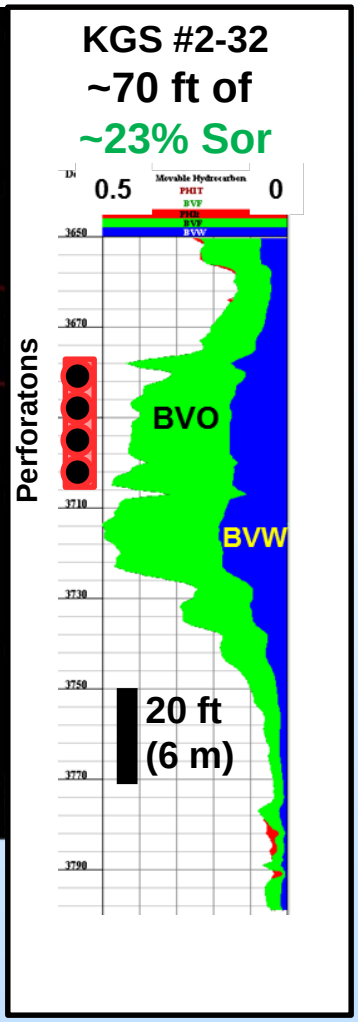


Monitoring technologies during Class II injection

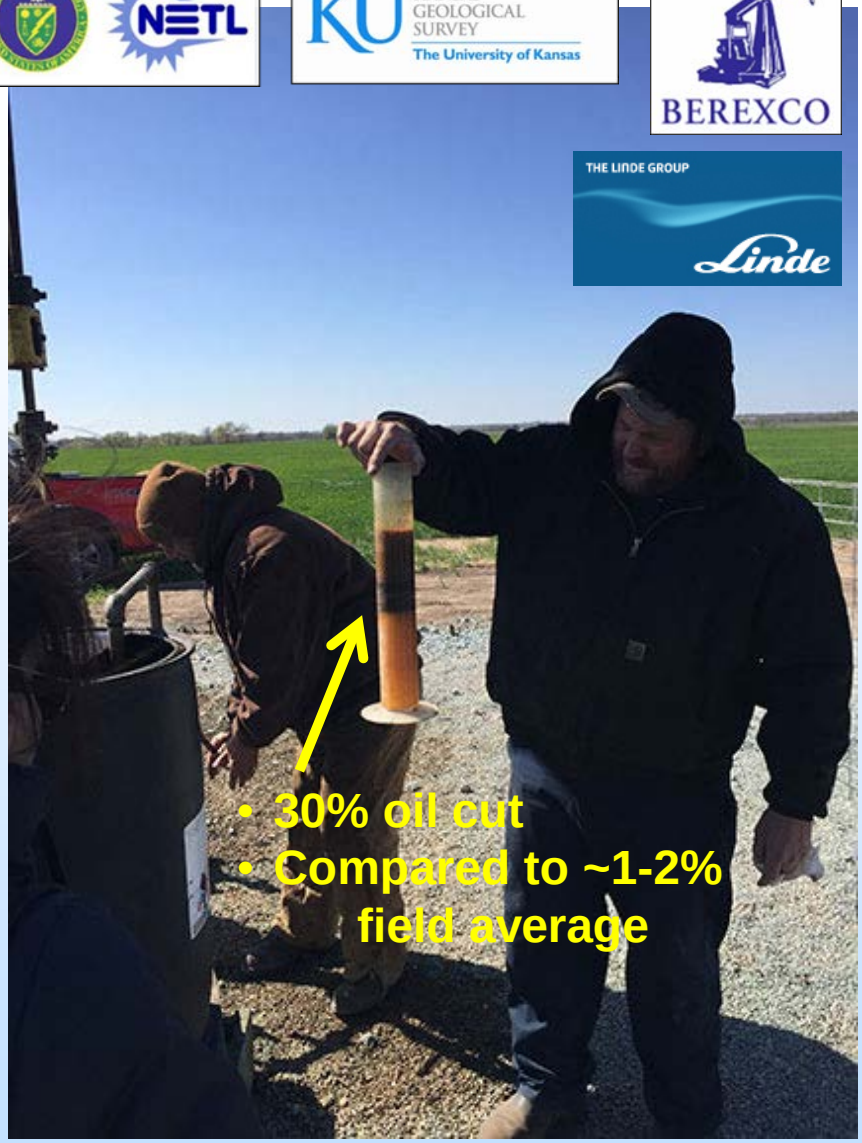
1) Surface water analysis
2) 18- seismometer array for passive seismic
3) cGPS and InSAR
4) Weekly analysis of 17 wells surrounding injector
5) Repeat 2D seismic survey (July 2016)
6) Post-CO_2 injection well performance around Class II well
7) Arbuckle pressure monitoring since April 2016

Targeted area →High CO_2-EOR potential





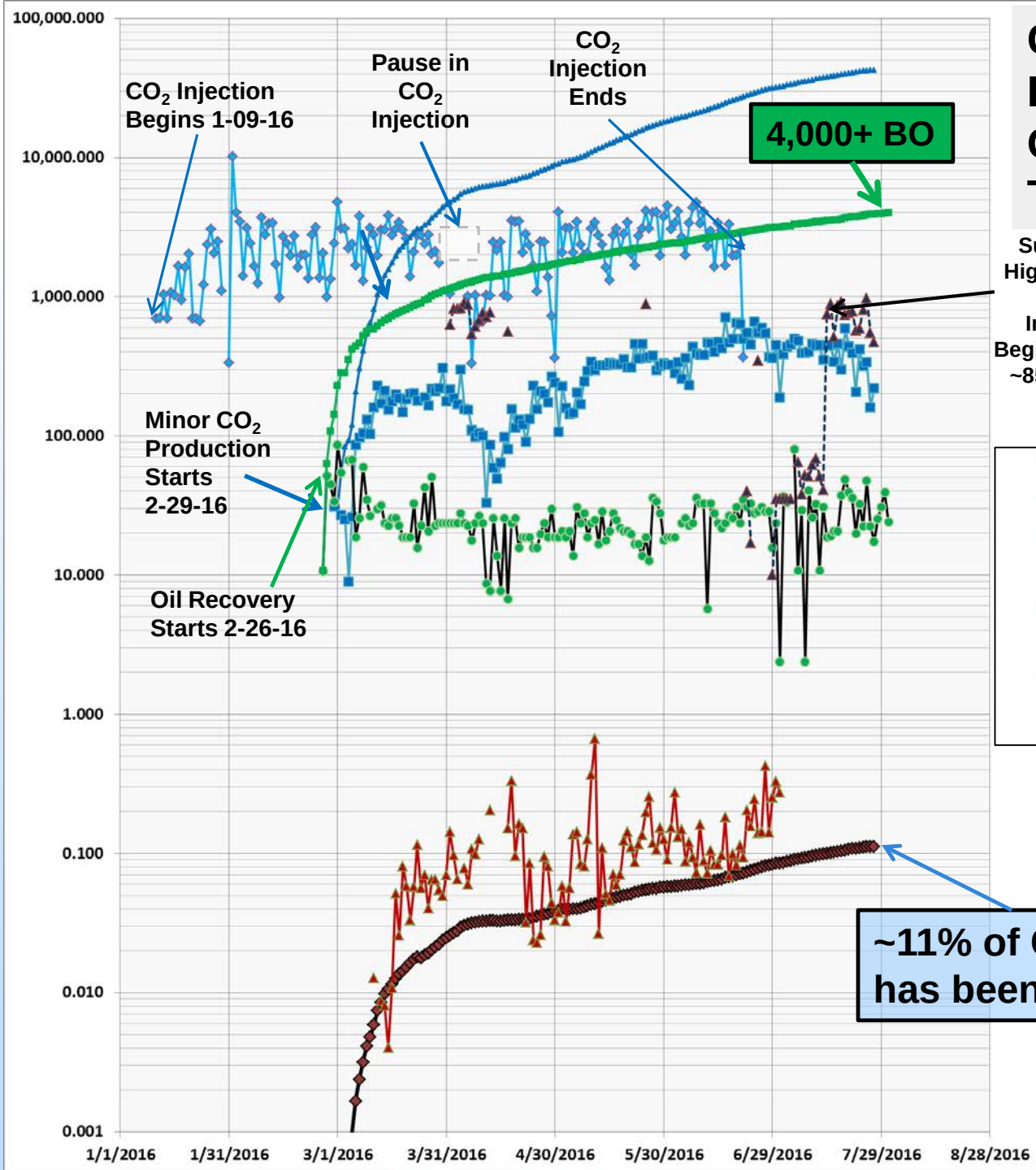
- Petrel map of permeability distribution in the Mississippian dolomite
- CO_2 injection well is red vertical line
- Lower permeability noted east and south of the injection well, Berexco Wellington KGS #2-32
- Residual oil saturation in cored injection well averages 23%



Wellington Field small scale CO_2-EOR
Jason Bruns above (Caanon Well Services) and Dana Wreath upper right (VP *Berexco, LLC*) with KGS staff

SCADA System installed on wells

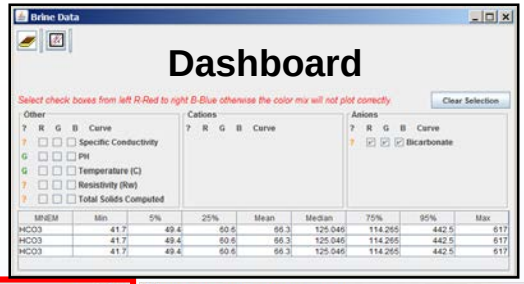
CO_2 Injected and Recovered & Oil Produced Through 7/31/16

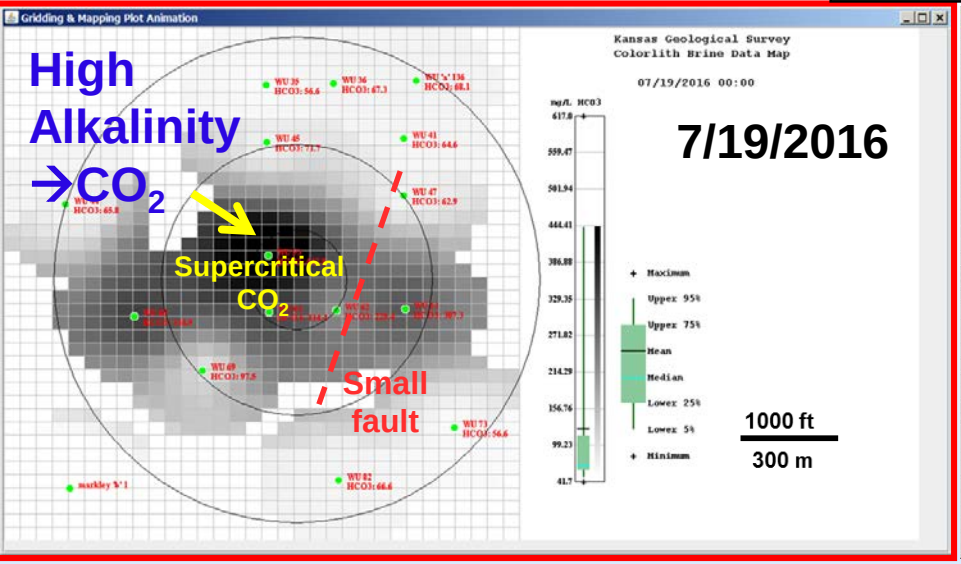


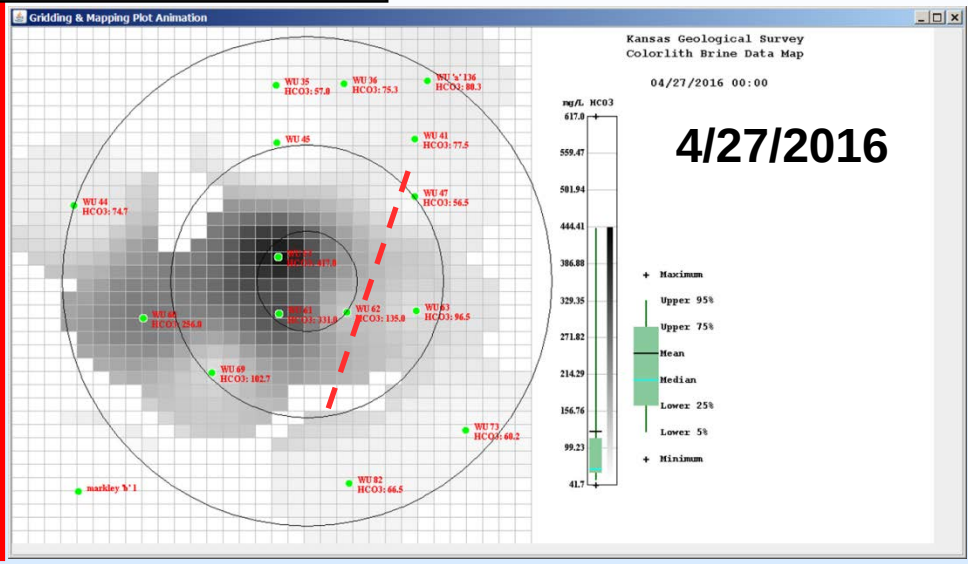
KSCO2

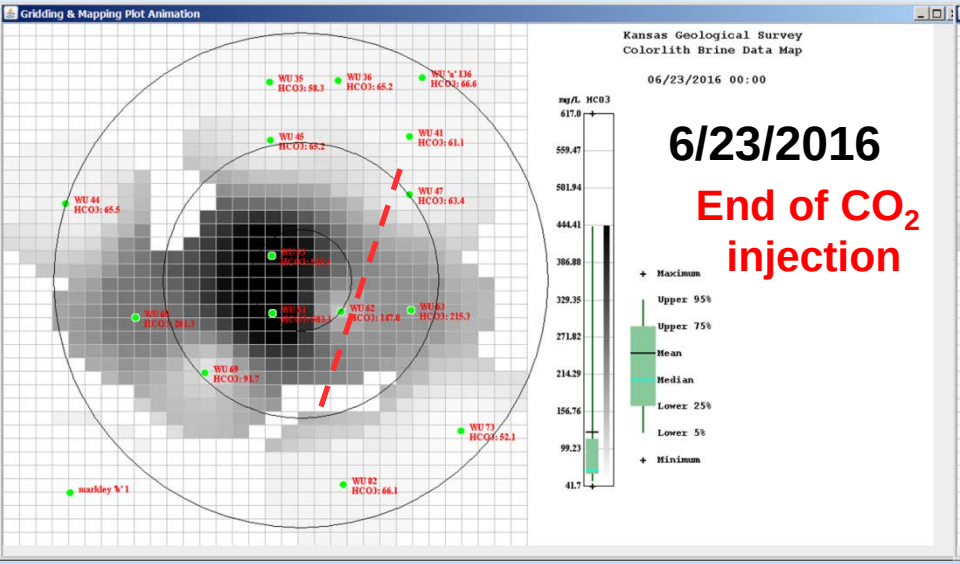
Time Lapse Alkalinity

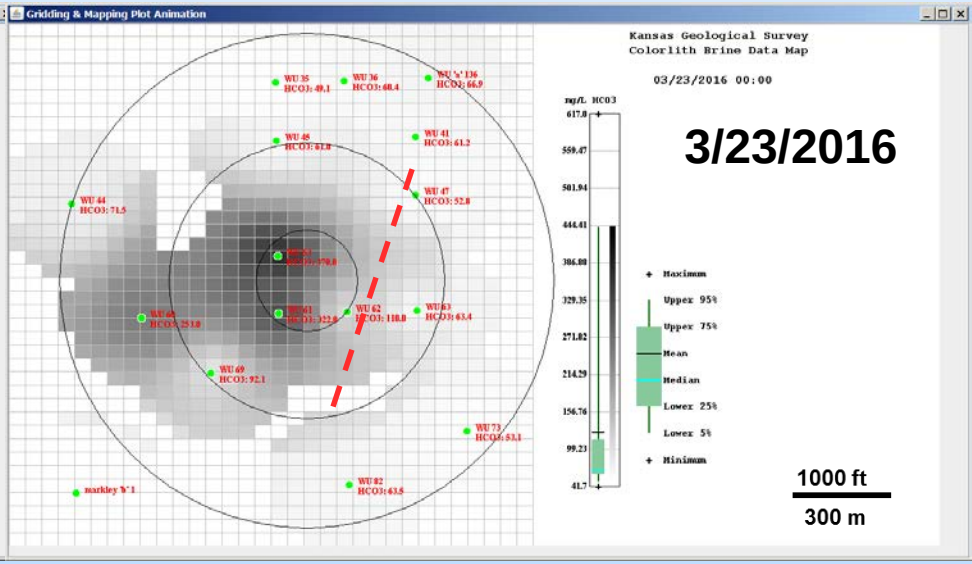
-- During and Post CO_2 Injection



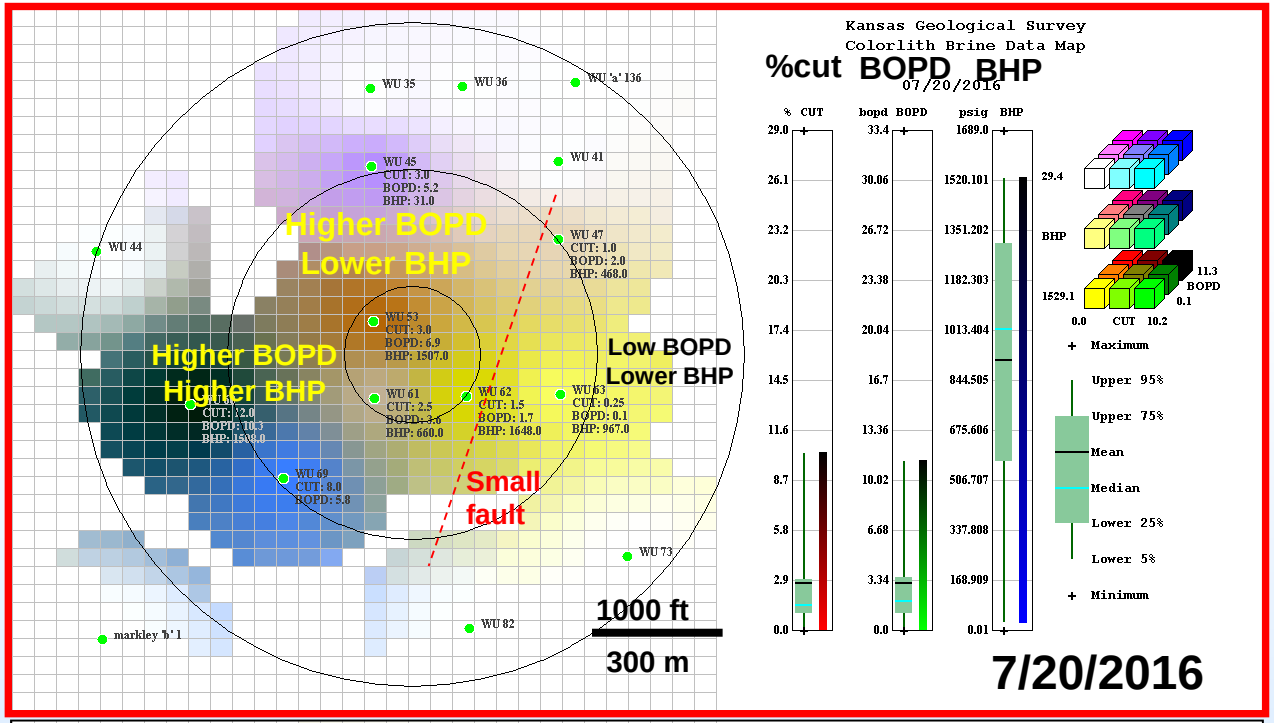


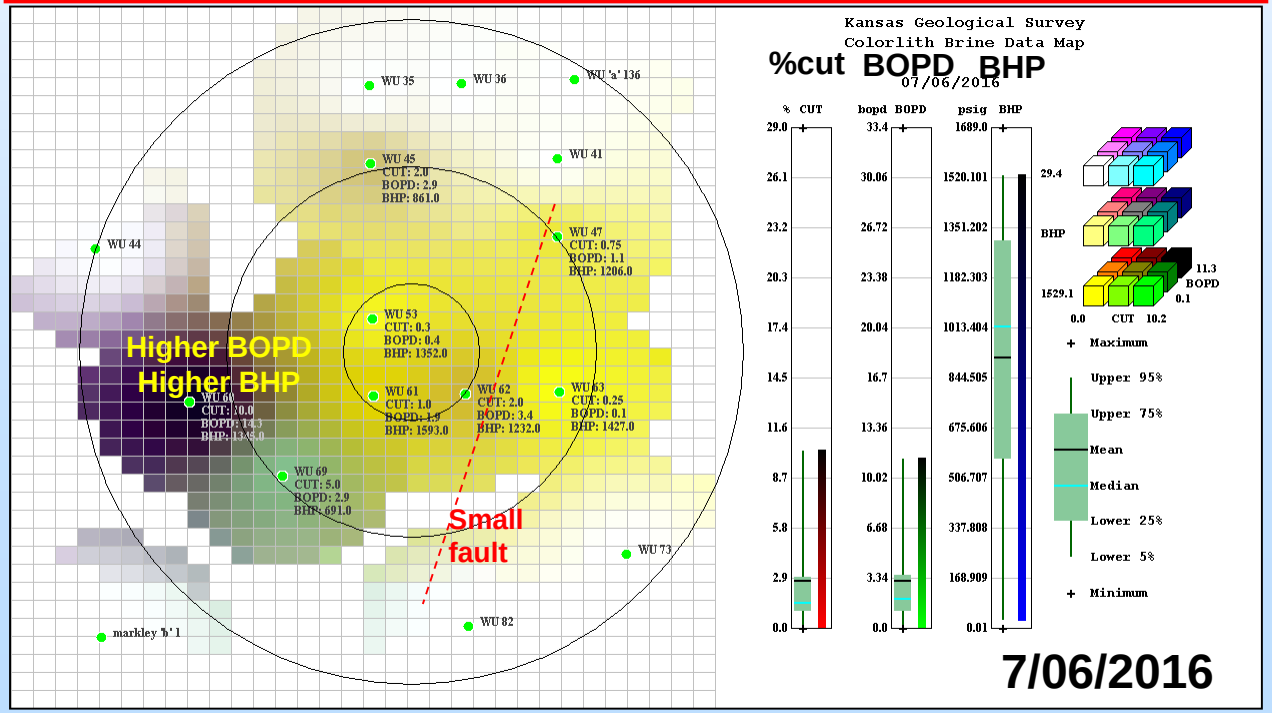






Time-Lapse of Production



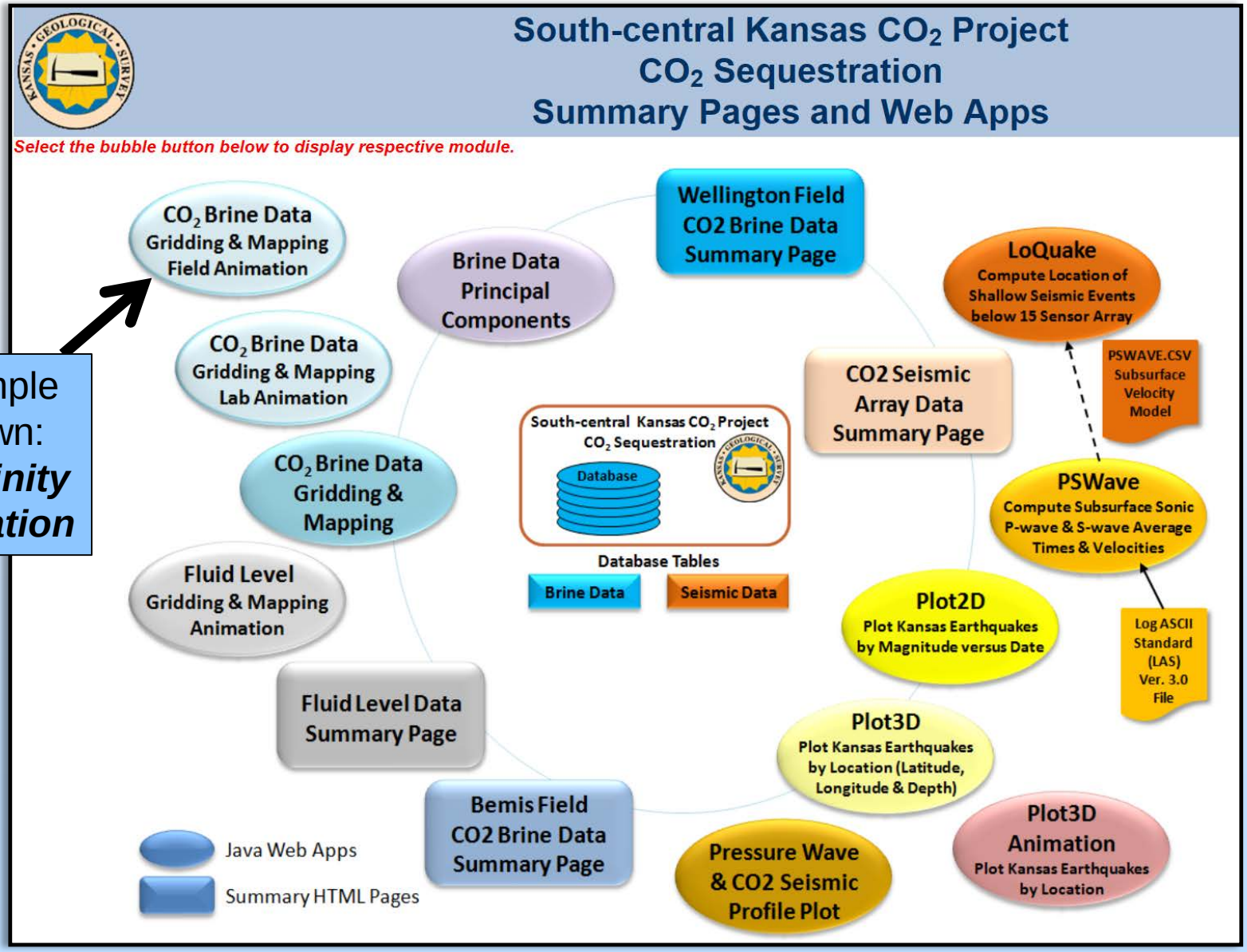


- % oil cut
- BOPD
- BHP (estimated from echometer)

- Supercritical core of CO2 and oil bank on perimeter
- Lack of CO_2 fingering
- Evidence for oil bank

Web Applications Built to Display and Analyze Data "*in Real-Time*" by the Team During Monitoring →

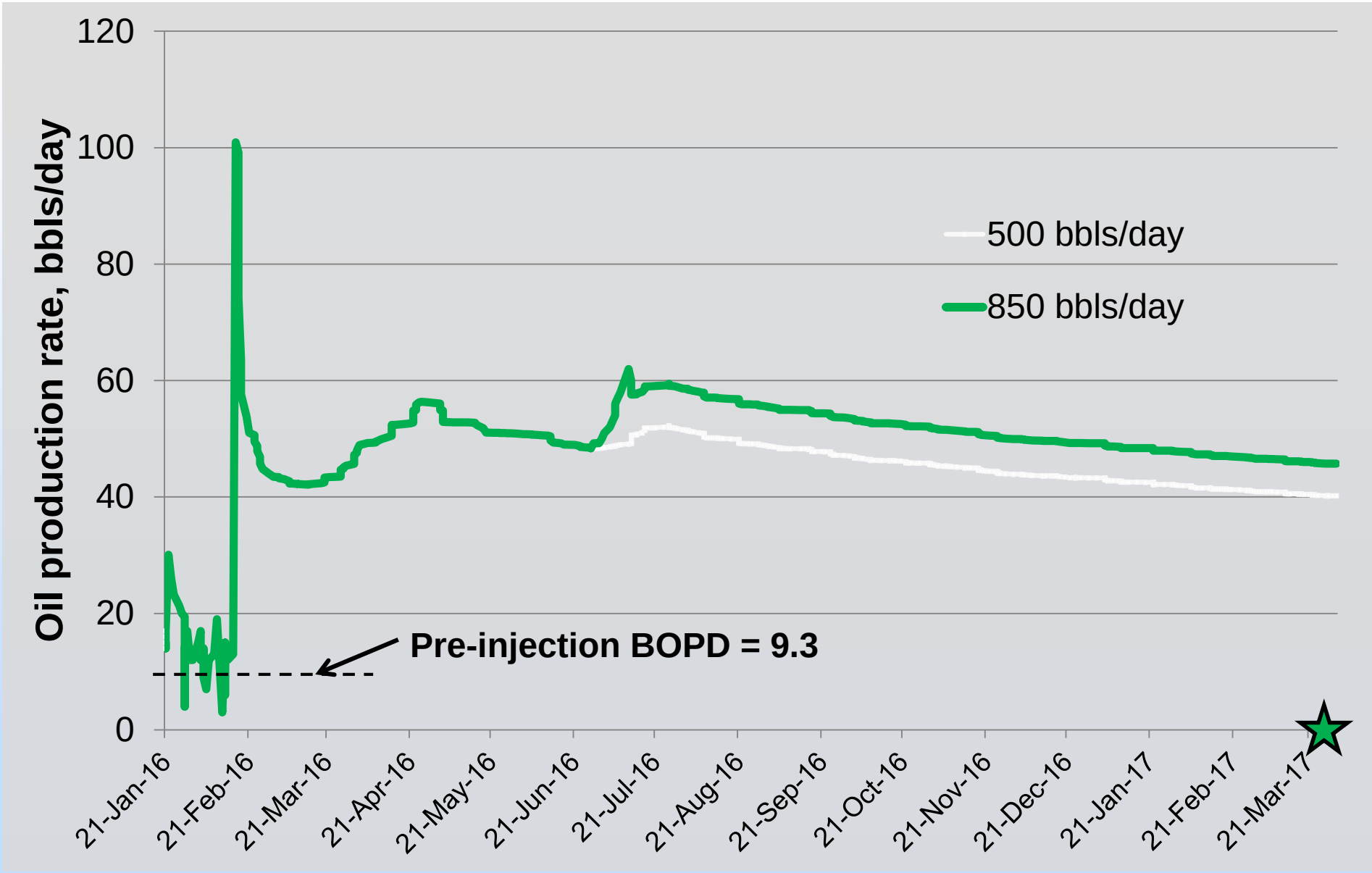
time lapse maps, cross plots, analytical tools, csv download



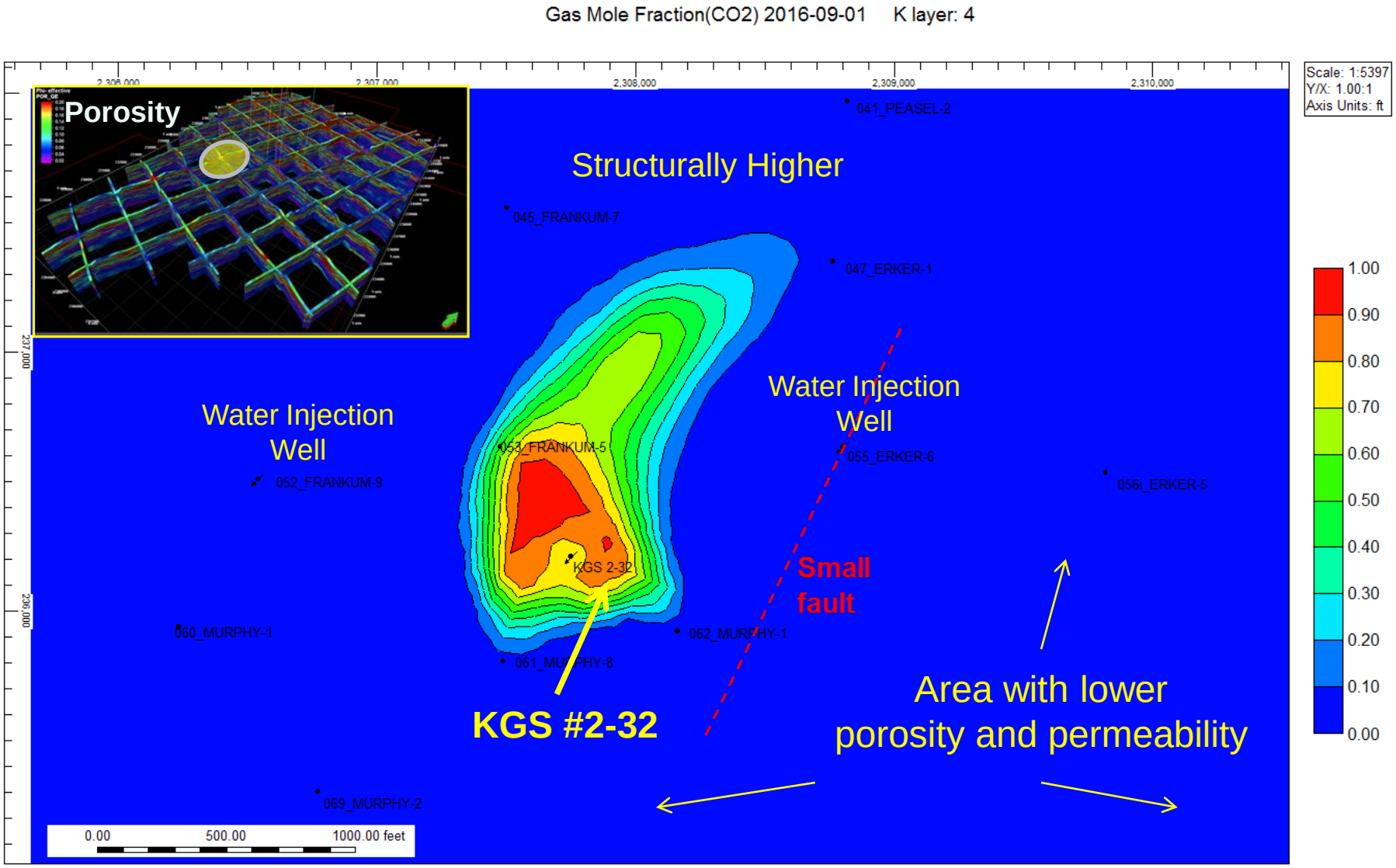
Example shown: ***Alkalinity animation***

Modeled Oil Production Rate (bbls/day)

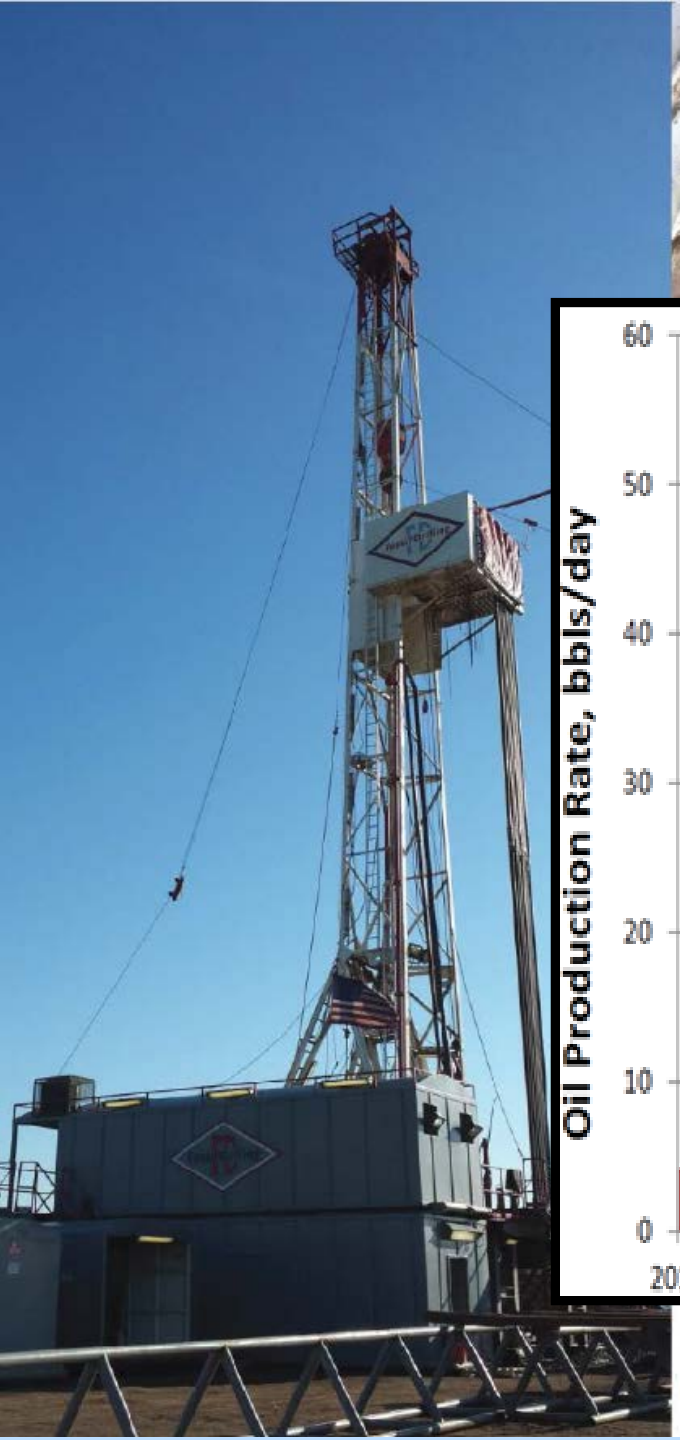
Compare 2-32 water injection post CO_2: 500 vs 850 bbls/day



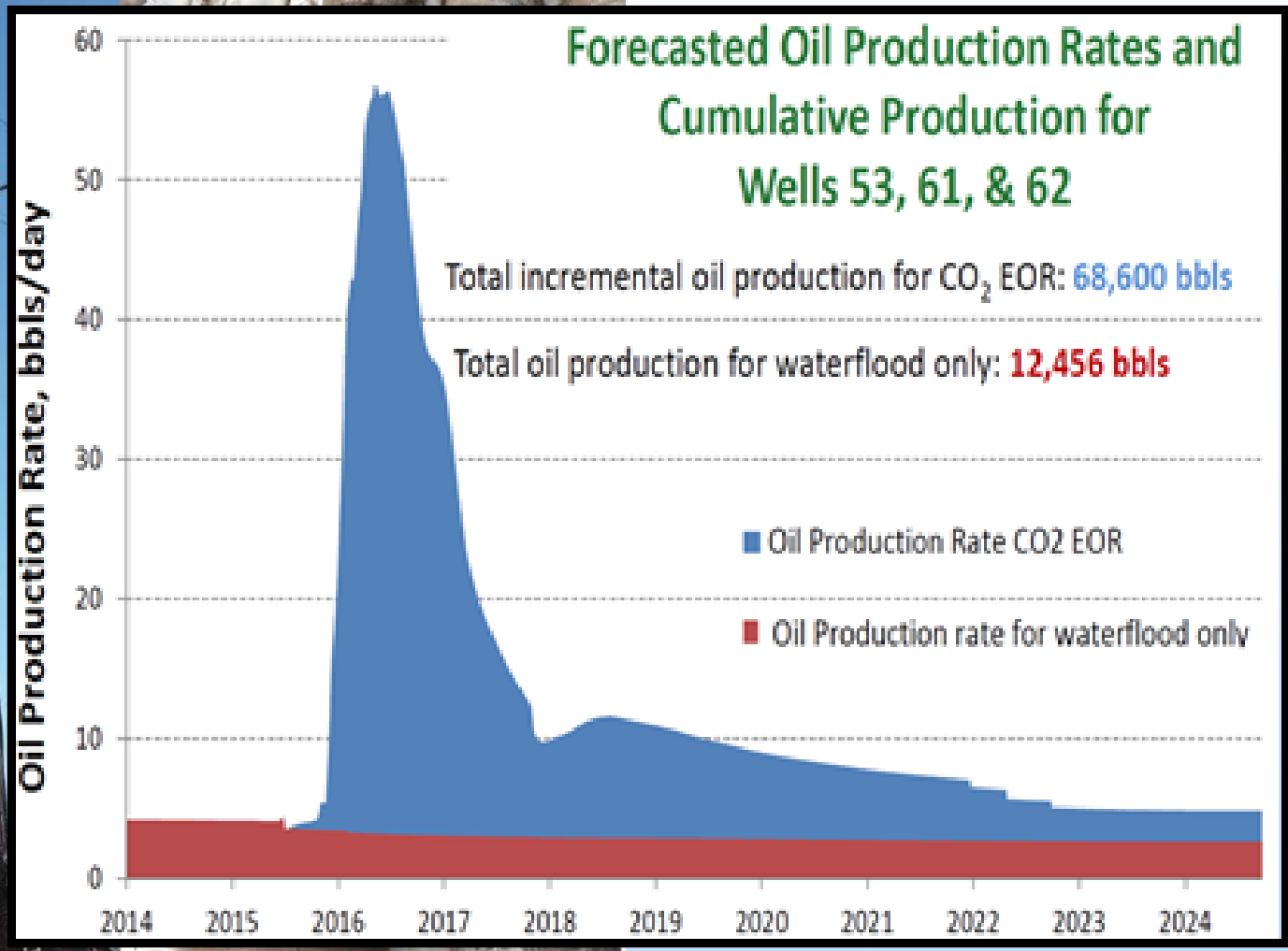
CO_2 Plume (mole fraction) Forecast for September 2016 in Mississippian Reservoir



Holubnyak (KGS)

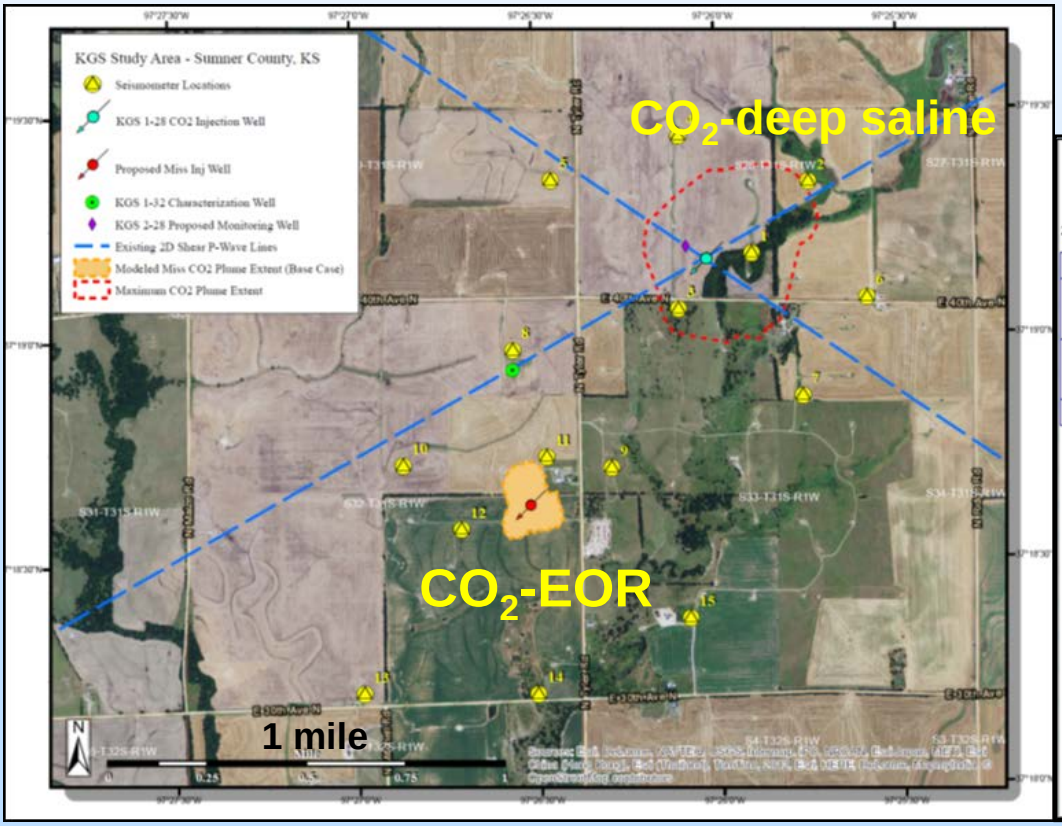


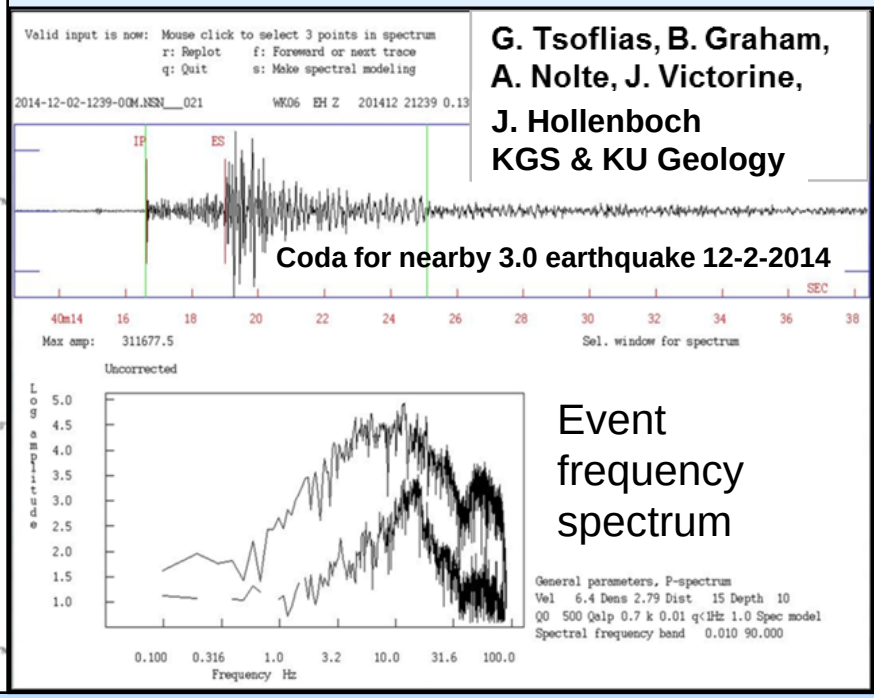
KSCO2


Forecasted Oil Production Rates and Cumulative Production for Wells 53, 61, & 62
Total incremental oil production for CO_2 EOR: 68,600 bbls
Total oil production for waterflood only: 12,456 bbls
Oil Production Rate CO2 EOR
Oil Production rate for waterflood only
Oil Production Rate, bbls/day
60
50
40
30
20
10
0
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024

• Milestone 3. Pre-injection MVA baseline recording

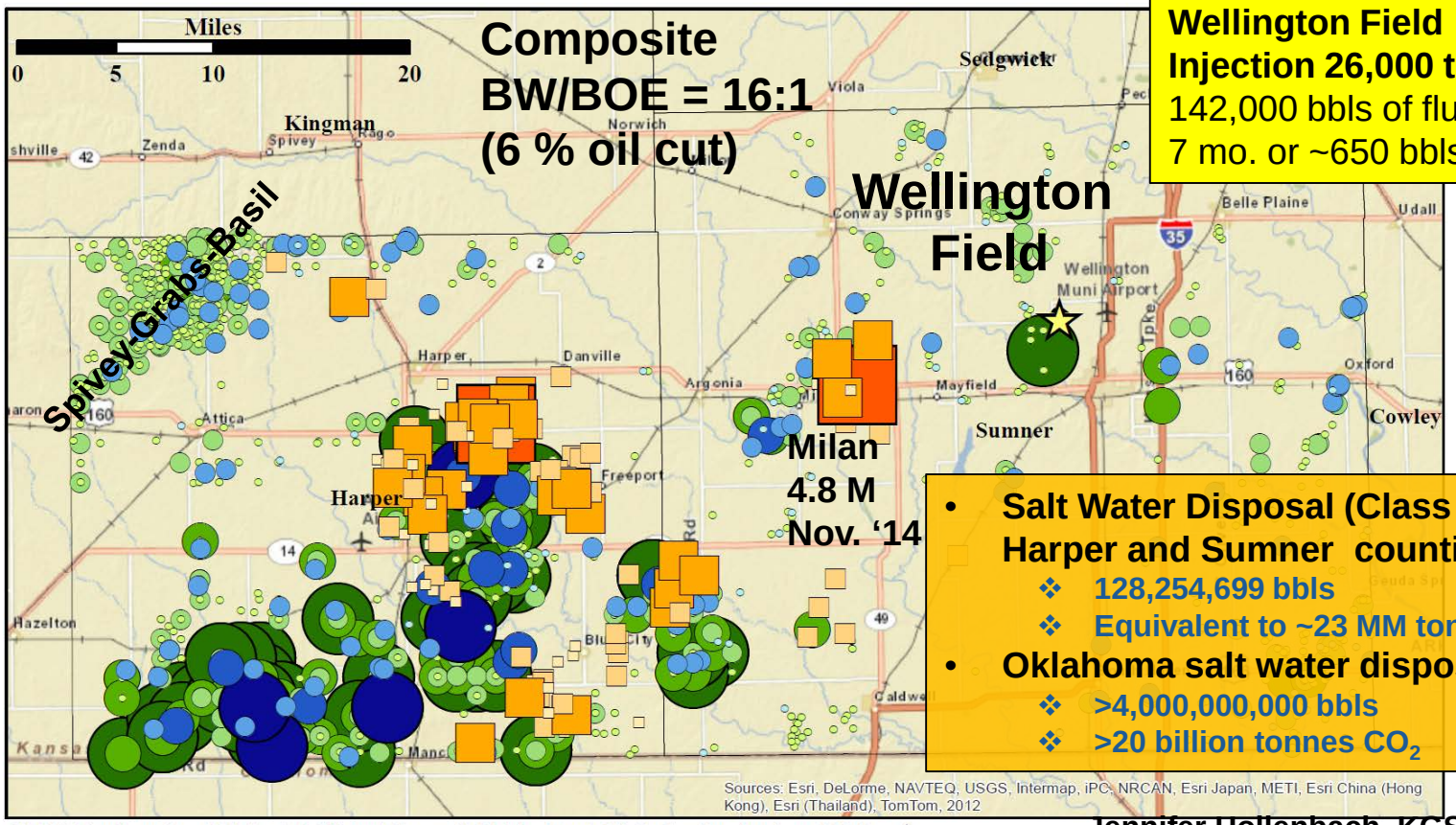
- ❑ 18 seismometer array since Fall 2014
- ❑ cGPS and inSAR for processing since August 2014
- ❑ Five shallow monitoring wells around KGS #1-28 and domestic wells in vicinity
- ❑ Weekly baseline geochemistry and production data from 17 wells during CO_2-EOR
- ❑ Static bottom hole pressure in lower Arbuckle from KGS #1-28 since April 2016





Induced Seismicity Southwest of Wellington Field

Total salt water injected by well (●), BOE produced by oil lease (●) and earthquakes (■) in 2014, Harper and Sumner Counties, Kansas



Wellington Field Arbuckle Injection 26,000 tonnes = 142,000 bbls of fluid over 7 mo. or ~650 bbls per day

- **Salt Water Disposal (Class II) in Harper and Sumner counties in 2014**
  - 128,254,699 bbls
  - Equivalent to ~23 MM tonnes CO_2
- **Oklahoma salt water disposal in 2014**
  - >4,000,000,000 bbls
  - >20 billion tonnes CO_2

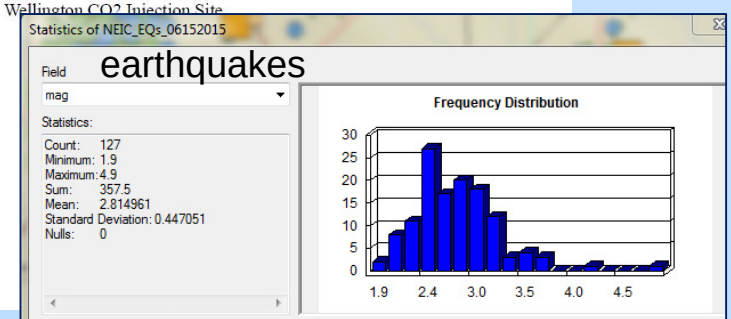
NEIC Earthquakes (2014)
Magnitude
1.9 - 2.5
2.5 - 3.0
3.0 - 4.0
4.0 - 5.0

Salt Water Disposal (2014)
Million BBLS
0.1
1.5
5.0
8.5

Total Oil & Gas Production (2014) (BOE)
Bbls
0 - 2,000
10,000
20,000
200,000

Wellington CO2 Injection Site

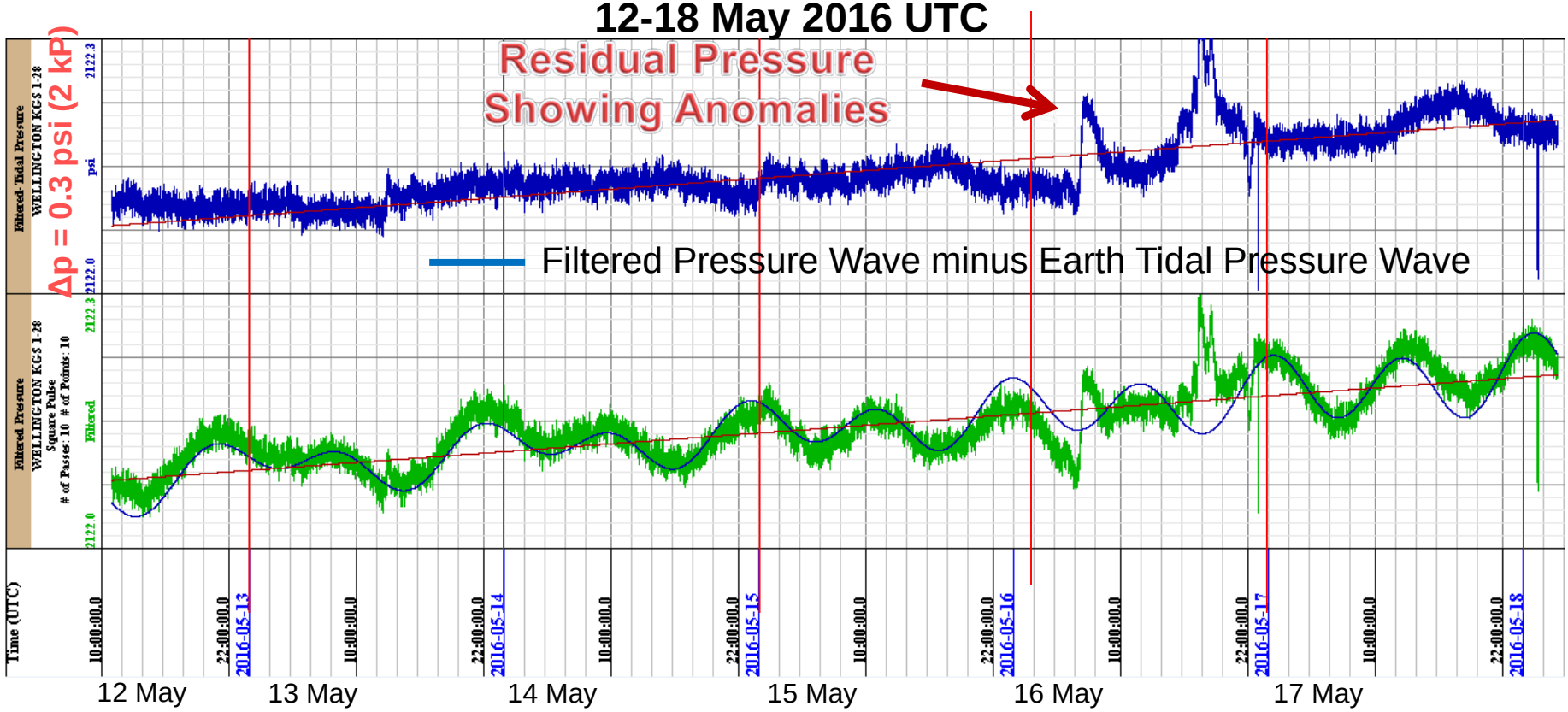
Min 1.9
Max 4.8
Mean 2.8
127 earthquakes in 2014



Jennifer Hollenbach, KGS

Bottom Hole Pressure Monitoring in Arbuckle KGS #1-28 (idle Class VI)

12-18 May 2016 UTC



Slope of the Filtered Pressure Wave
Start = 2121.77 psi; End = 2121.8 psi

Slope of the Filtered Pressure Wave plus Tidal Pressure Wave.
{ ϕ = 0.09 [PU]; C_w = 0.4437 1/[Gpa]; ϕ_{corr} = -180 ^{o}}

Noise Filtered Pressure Wave

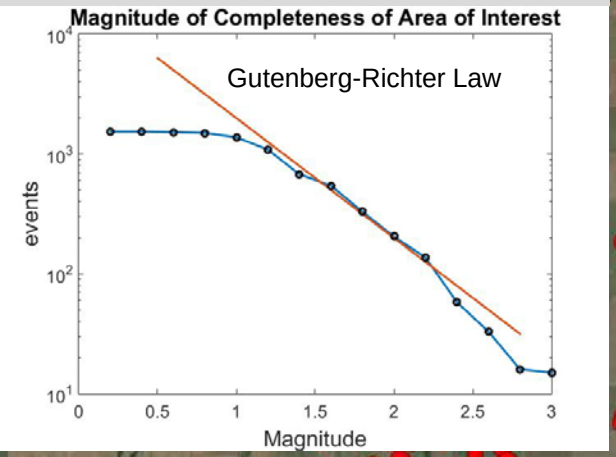
- On 4-25-16, BHP in lower Arbuckle was **+31.4 psig** higher than what was recorded on 8/23/11.
- Since April the pressure has risen to **+32.9 psi** (August 6) →
  1.5 psi in 103 days
  (0.0147 psi/day or **0.44 psi/mo**).
- **Increase in pressure forecast by simulation of 2-county brine disposal**

J. Victorine (KGS)

TRILOBITE TESTING, INC.

Earthquake catalog for Central Sumner County, near Wellington oil Field

- 827 events from April 2015 through July 2016 in area of interest
- Mw ranges from 0.4 – 2.7
- ~1.0 Mw Magnitude of Completeness for area of interest
- b-value of 1 for complete catalog
- Average accuracy within ~0.5 miles in X, Y, and Z



N

Riverdale

Area of Interest

STN01
WK02
WK05
WK03
WK06
WK08
WK07
WK10
WK12
WK11
WK15
WK13
WK14

Wellington Seismometer Array

STN02

Wellington

Milan

Mayfield

5 miles

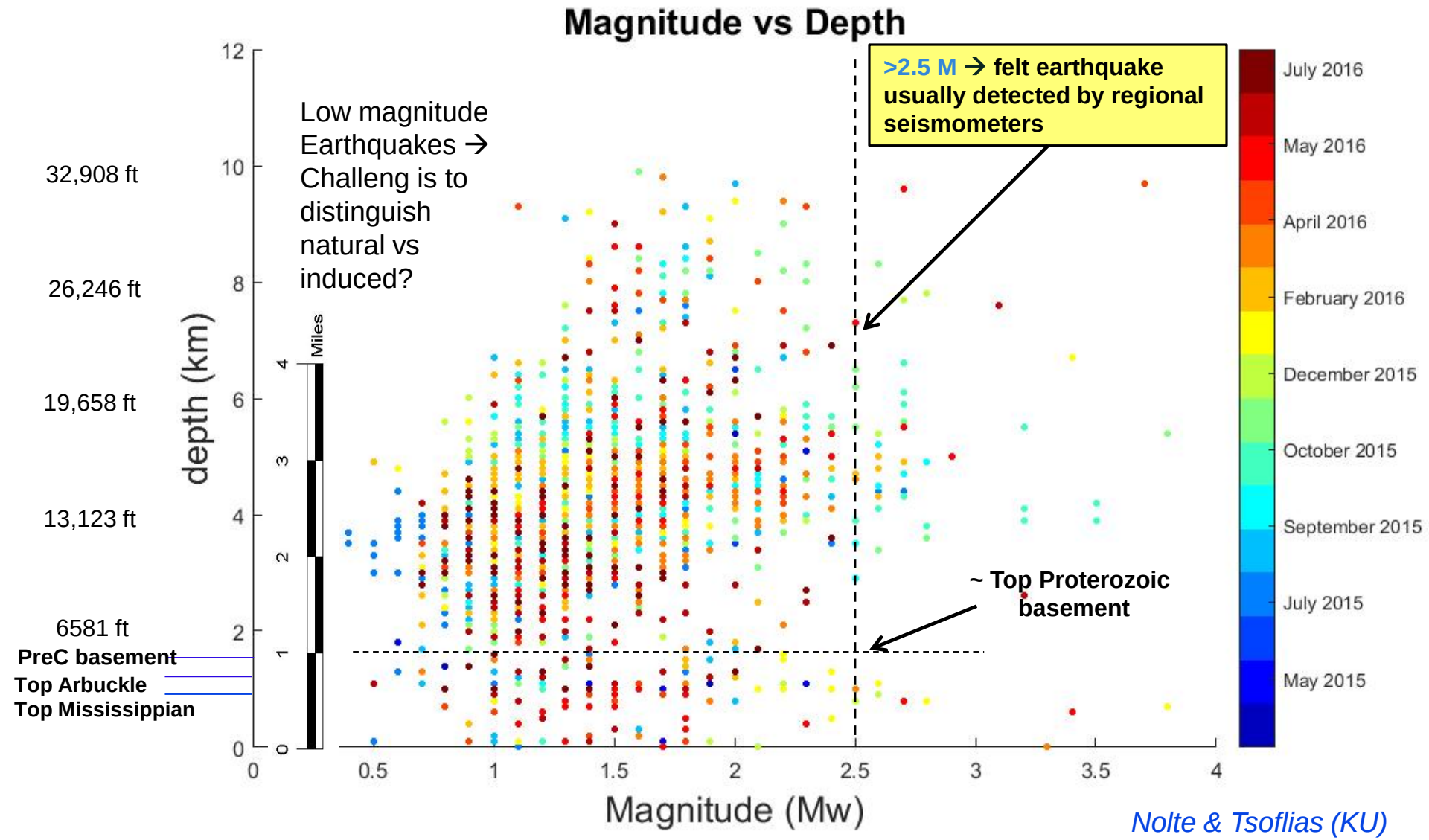
10 km

KS20

- Earthquake –size of circle based on magnitude
- Wellington seismometer array
- USGS seismometer array

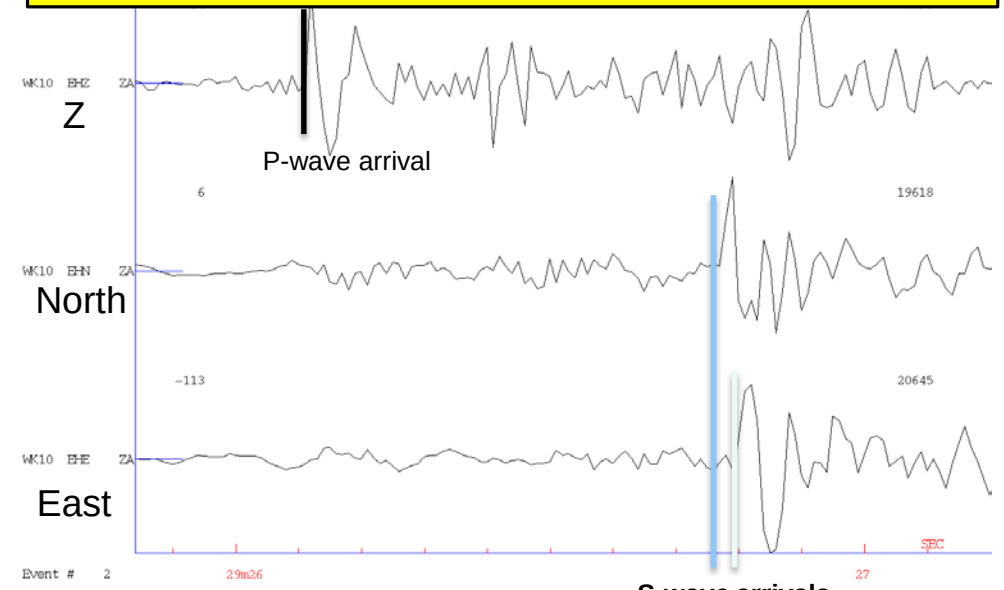
Nolte & Tsoflias (KU)

Earthquakes Recorded by the Wellington Seismometer Array



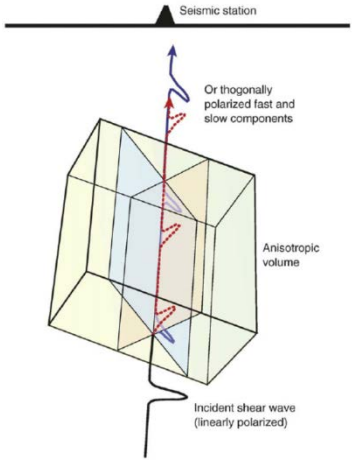
Nolte & Tsoflias (KU)

Example of shear wave splitting in local earthquake



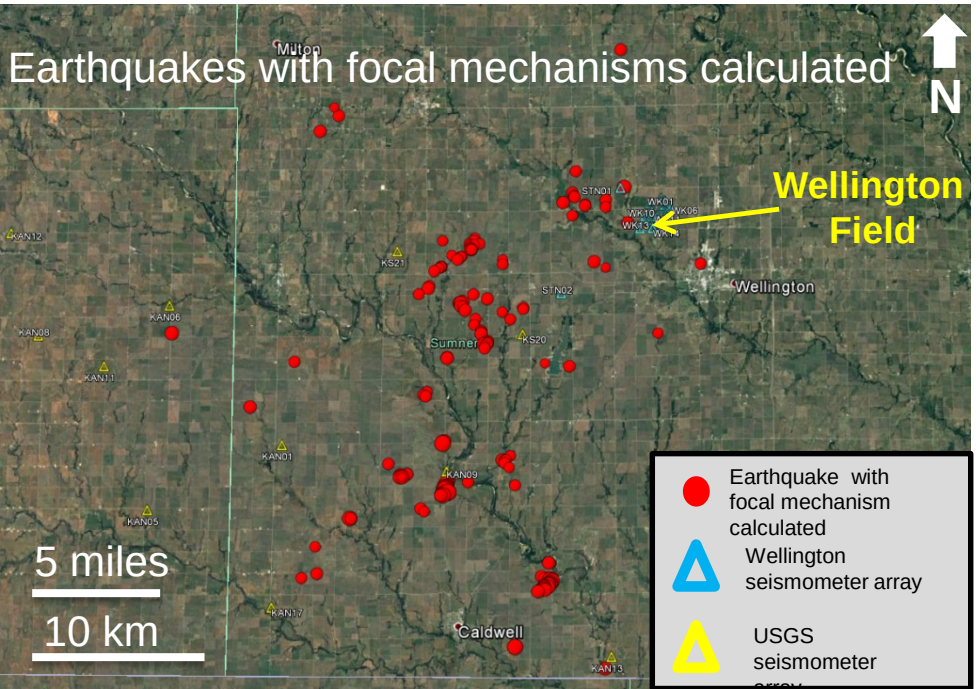
S-wave arrivals
Time difference is δt

- **Anisotropy can be identified through shear-wave splitting**
  - *Larger δt indicates higher anisotropy*
  - *Method can be used to identify fracture orientation*
  - ***Next step to ntegrate with geomechanical modeling!!***

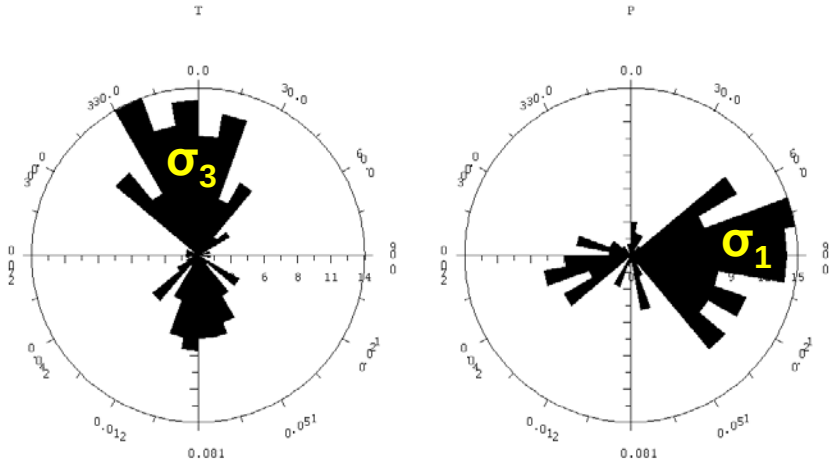


Schematic diagram of shear wave splitting due to upper mantle..

- Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/222413701_fig2_Fig-2-Schematic-diagram-of-shear-wave-splitting-due-to-upper-mantle-anisotropy-after [accessed Aug 11, 2016]



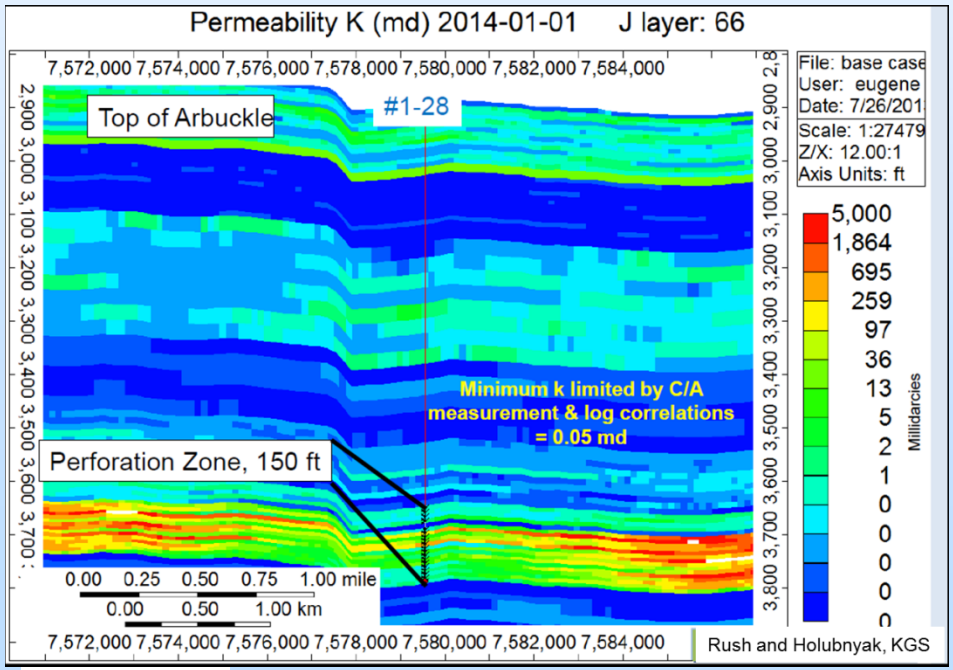
- **Focal mechanism inversion from 173 Mw ≥ 2 local earthquakes**
- Maximum horizontal stress at ~80 degrees
- Compared to 75 degrees derived from well logs

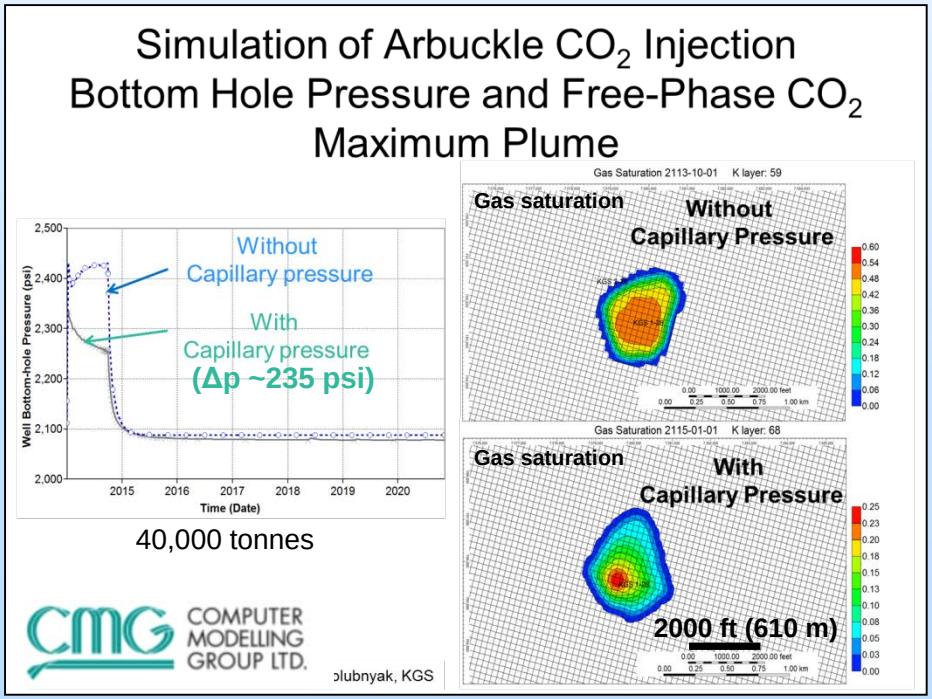


Nolte & Tsoflias (KU)

Technical Status

- **Milestone 2 - Submitted Class VI application, June 2014**
  - **Awaiting determination of Area of Review (AoR)** → Constructed STOMP model to run alongside CMG-GEM
  - **Successfully identified mechanism and cost to service financial assurance requirements for the Class VI permit** → inject 26,0000 tonnes of CO_2 (7 mo.) and a one-year Post Injection Site Care (**PISC**) to closure.
  - **Enhanced borehole seismic capability to measure sub M -2 to 3 magnitude events and combine with surface seismometer array**





Schlumberger **Petrel**

Status of Attachments in the Wellington Class VI Permit

- **Permit details are in the following 9 attachments**
- **7 Attachments near completion**

A. SUMMARY OF OPERATING REQUIREMENTS — **Draft Prepared**

B. AREA OF REVIEW AND CORRECTIVE ACTION PLAN — **Awaiting confirmation of Area of Review by EPA modelers**

C. TESTING AND MONITORING PLAN — **Draft Prepared**

D. WELL PLUGGING PLAN — **Draft Prepared**

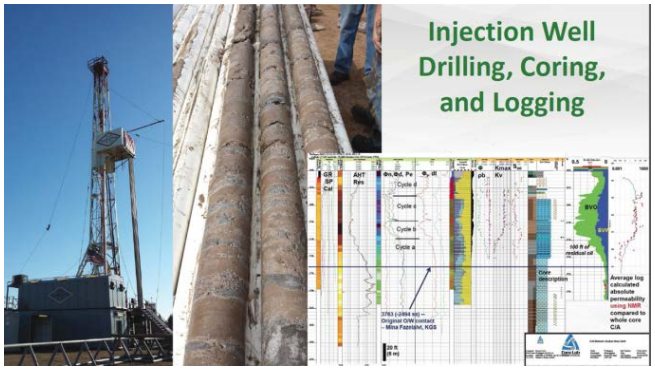
E. POST-INJECTION SITE CARE AND SITE CLOSURE PLAN — **Awaiting confirmation of Area of Review by EPA modelers**

F. EMERGENCY AND REMEDIAL RESPONSE PLAN — **Draft Prepared**

G. CONSTRUCTION DETAILS — **Draft Prepared**

H. FINANCIAL ASSURANCE DEMONSTRATION — **Preferred financial instruments established and costs estimated to guarantee financial obligations**

I. STIMULATION PROGRAM — **Draft Prepared**



Berexco/KGS Class VI Permit

The Kansas Team is Ready

KGS, Berexco, T. Birdie Consulting

KSCO2

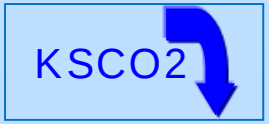
Accomplishments of the Wellington Project during BP2

ACTIVITIES CARRIED OUT TO DATE BY THE KANSAS TEAM

- Successful CO_2 injection in the Mississippian carried out by Berexco, LLC, Wichita, KS
- Injection done in a highly controlled and monitored environment
- Linde Group, a leader in CO_2 capture and supply, an excellent partner for the project, provided steady supply of CO_2
- Assisting in defining safe disposal and economic potential for Kansas reservoirs
- Rapid-response detection & mitigation procedures being tested are as part of a comprehensive operation & risk management plan
- Advanced monitoring technologies
- Wellington Field is proving to be a viable field laboratory

Future Plans and Expectations

- Continue post-injection monitoring of Mississippian wells and operation of seismometers and deep well pressure.
- Continue to acquire SAR satellite images and recording cGPS, operation of seismometer array, pressure monitoring, and surface and well sampling.
- Complete processing of the long offset repeat 2D seismic line acquired over the Mississippian injection site to validate CO_2 plume.
- Updated BP3 monitoring technologies and budget for the Arbuckle injection, ready to inject in the Arbuckle saline aquifer, pending receipt of Class VI permit in early 2017.
- Basis for Determination and Findings (D&F) filed to extend the project beyond September 30, 2016 in order to carry out Arbuckle injection.



Acknowledgements & Disclaimer

Acknowledgements

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

Disclaimer

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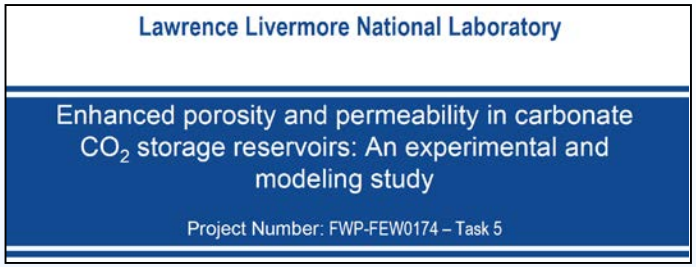
Synergistic Activities

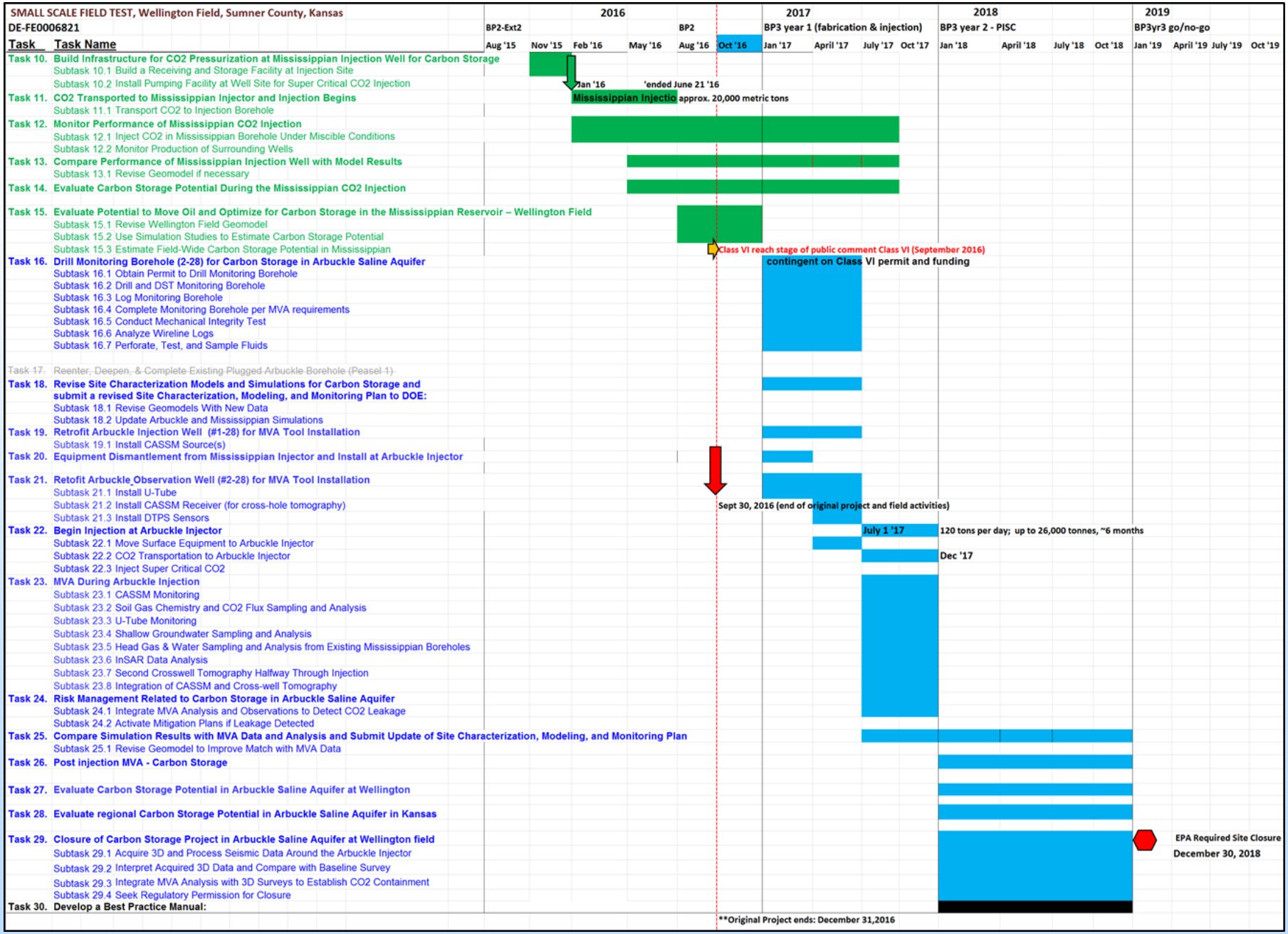
- Collaboration with Susan Carroll, PI, LLNL



  - Task addition → *Experimental calibration of NMR well logs to determine pore connectivity in the injection zone at the Wellington CO_2 storage demonstration site, Kansas*
- Data rich site with considerable data sharing with all data publically available
    - Carbonate and caprock cores, modern wireline logs, tests -> KU, KSU et students and faculty; industry consortium
    - Water and oil samples
    - Multicomponent 3D → new processing techniques → KU, KSU, BEG
    - Earthquake catalog being built from operating IRIS/KGS 18-seismometer array
    - Monitoring and risk analysis from operational plan for safe and effective injection and adaptation by EPA for this project
    - Test NRAP tools
- Extensive Web (Java) application tools and development, petrophysical application focus, data archiving
  - Need more users and explore incorporation into NATCARB

Appendix

Schedule – Wellington Small Scale Injection



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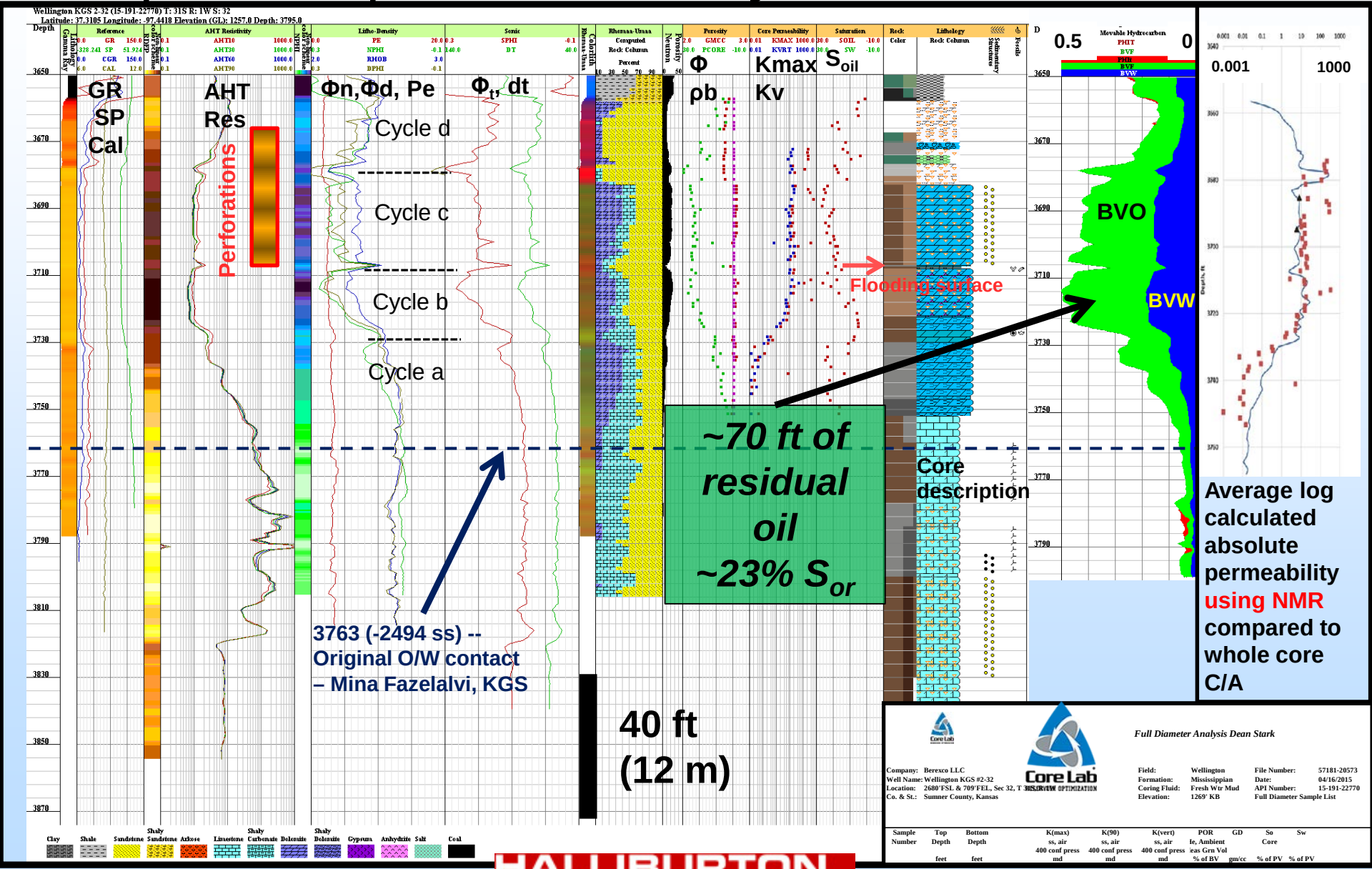
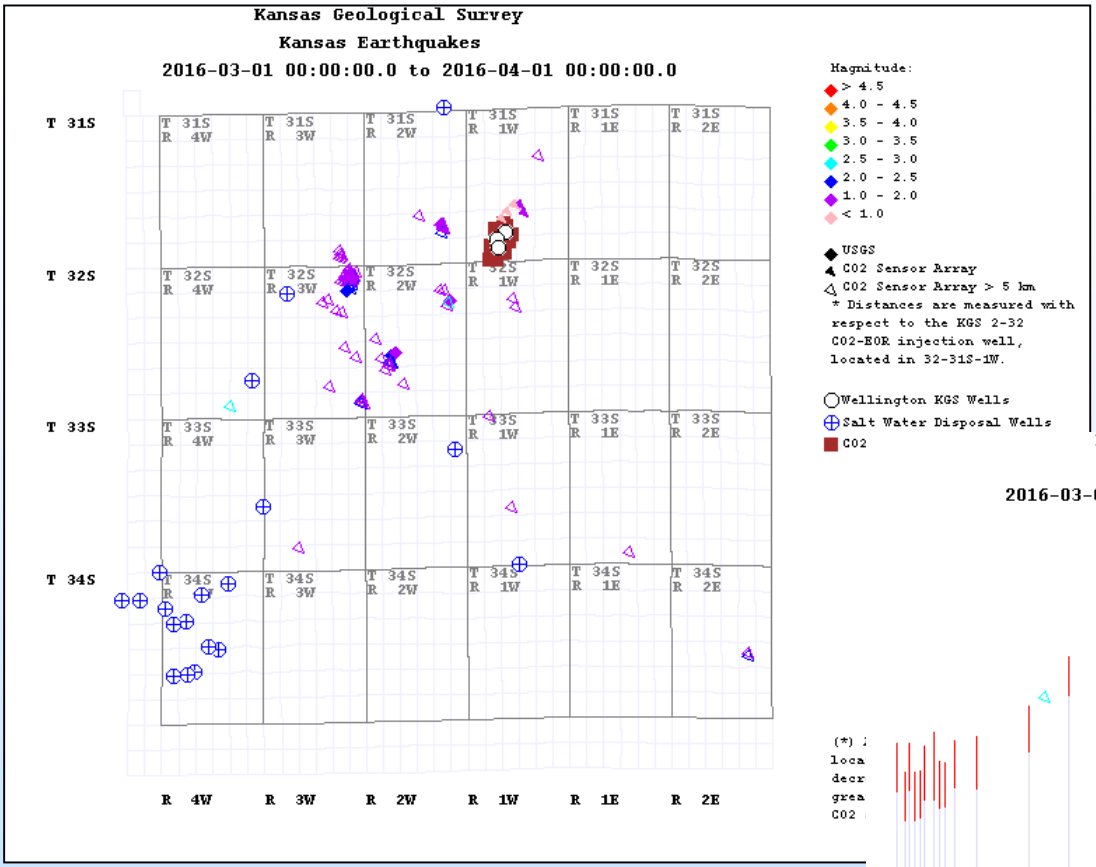
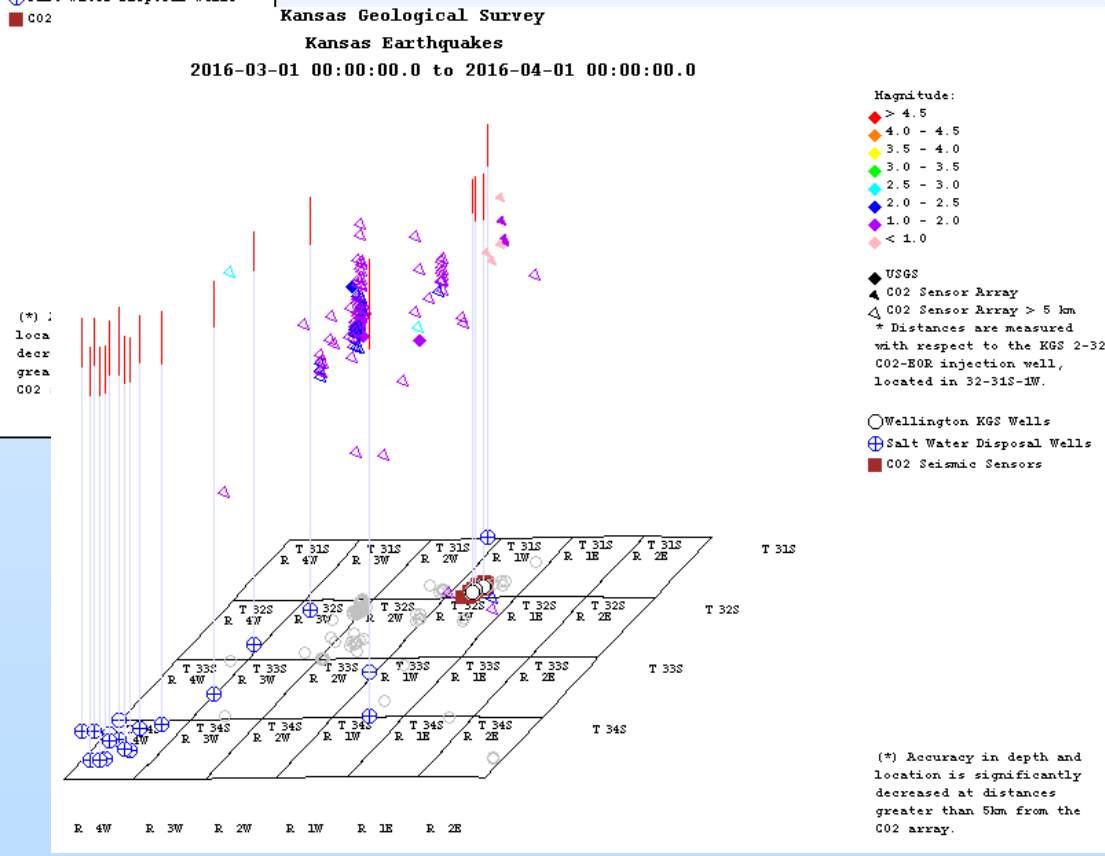
- Advanced Subsurface Characterization for CO_2 Geologic Sequestration and Induced Seismicity Evaluations, by Tiraz Birdie, Lynn Watney, Aimee Scheffer, Jason Rush, Eugene Holubnyak, Mina Fazelalavi, John Doveton, Jennifer Raney, Saugata Datta, Dennis Hedke, and Jennifer Roberts. Carbon Management Technology Conference, November 19th 2015. (Acrobat PDF, 2.5 MB)

KGS #2-32 Mississippian reservoir interval, composition plot, core analysis, and moveable oil

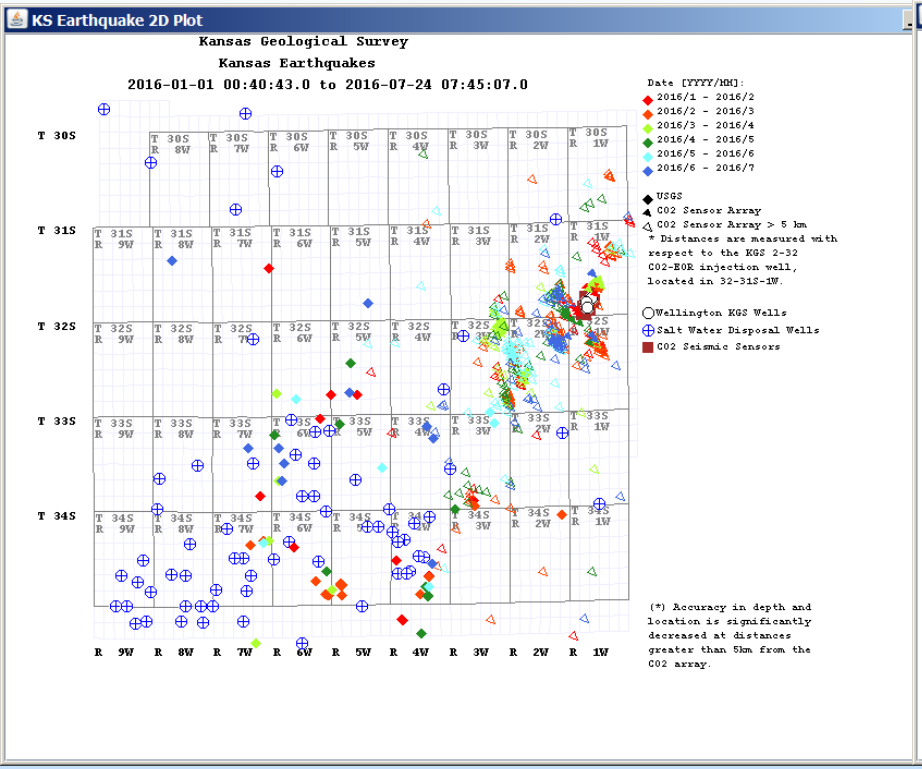


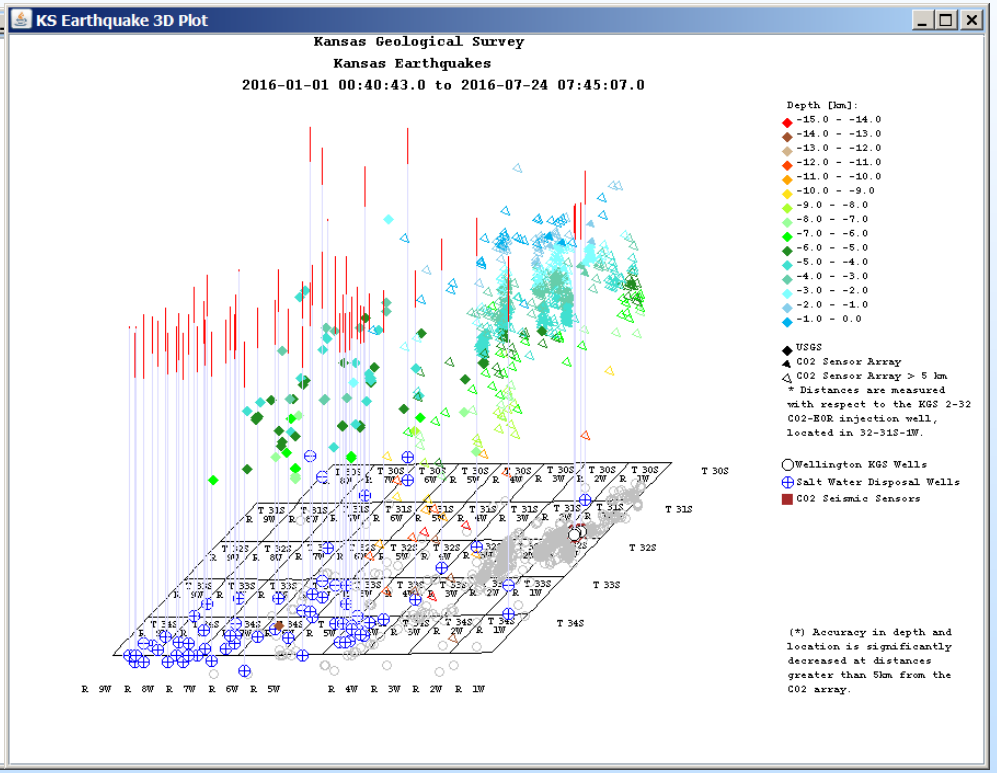
Refined March 2-16 Events

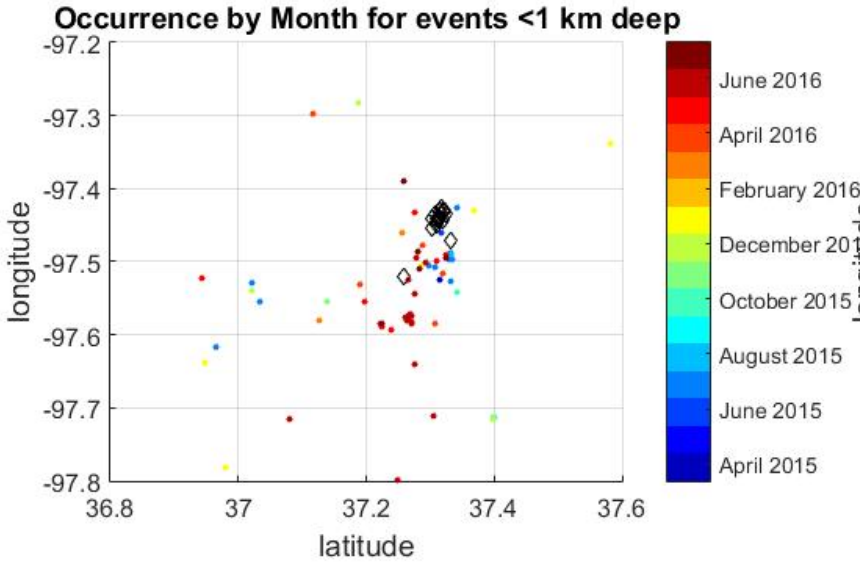


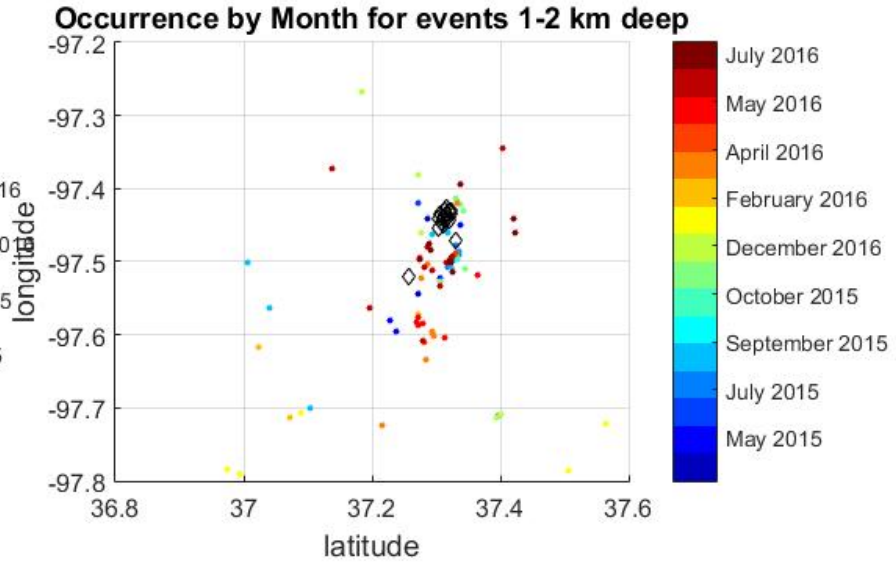


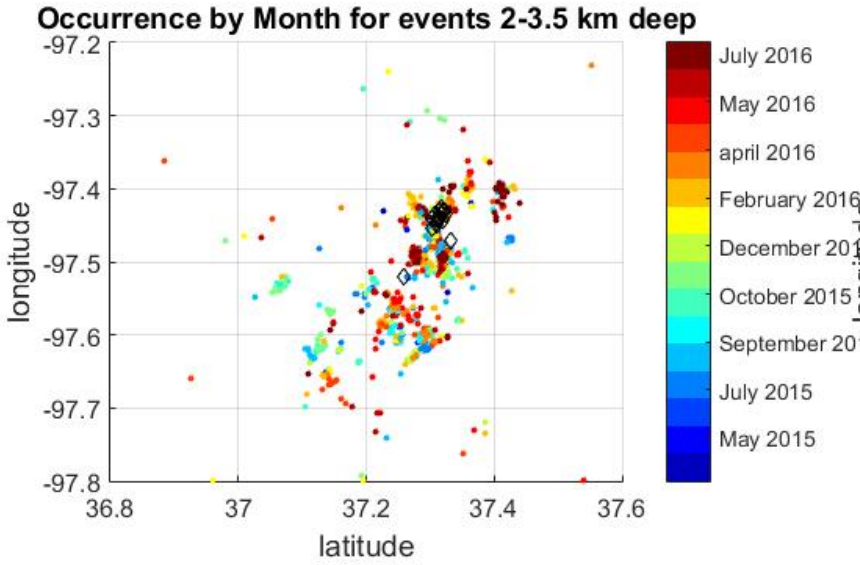
2016 events

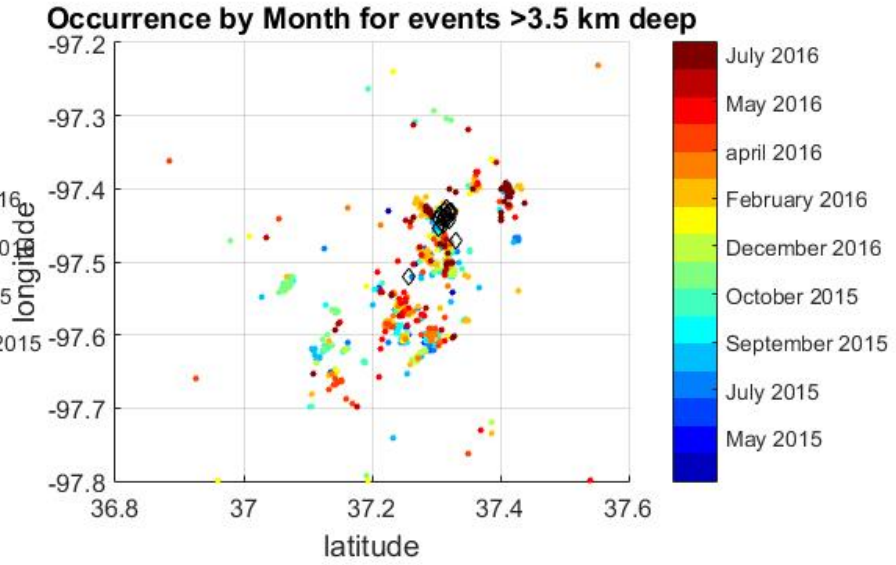

KS Earthquake 2D Plot
Kansas Geological Survey
Kansas Earthquakes
2016-01-01 00:40:43.0 to 2016-07-24 07:45:07.0
Date [YYYY/MM]:
2016/1 - 2016/2
2016/2 - 2016/3
2016/3 - 2016/4
2016/4 - 2016/5
2016/5 - 2016/6
2016/6 - 2016/7
USGS
CO2 Sensor Array
CO2 Sensor Array > 5 km
* Distances are measured with respect to the KGS 2-32 CO2-EOR injection well, located in 32-31S-1W.
Wellington KGS Wells
Salt Water Disposal Wells
CO2 Seismic Sensors
(*) Accuracy in depth and location is significantly decreased at distances greater than 5km from the CO2 array.


KS Earthquake 3D Plot
Kansas Geological Survey
Kansas Earthquakes
2016-01-01 00:40:43.0 to 2016-07-24 07:45:07.0
Depth [km]:
-15.0 - -14.0
-14.0 - -13.0
-13.0 - -12.0
-12.0 - -11.0
-11.0 - -10.0
-10.0 - -9.0
-9.0 - -8.0
-8.0 - -7.0
-7.0 - -6.0
-6.0 - -5.0
-5.0 - -4.0
-4.0 - -3.0
-3.0 - -2.0
-2.0 - -1.0
-1.0 - 0.0
USGS
CO2 Sensor Array
CO2 Sensor Array > 5 km
* Distances are measured with respect to the KGS 2-32 CO2-EOR injection well, located in 32-31S-1W.
Wellington KGS Wells
Salt Water Disposal Wells
CO2 Seismic Sensors
(*) Accuracy in depth and location is significantly decreased at distances greater than 5km from the CO2 array.


Occurrence by Month for events <1 km deep
longitude
latitude
-97.2
-97.3
-97.4
-97.5
-97.6
-97.7
-97.8
36.8
37
37.2
37.4
37.6
June 2016
April 2016
February 2016
December 2016
October 2015
August 2015
June 2015
April 2015


Occurrence by Month for events 1-2 km deep
longitude
latitude
-97.2
-97.3
-97.4
-97.5
-97.6
-97.7
-97.8
36.8
37
37.2
37.4
37.6
July 2016
May 2016
April 2016
February 2016
December 2016
October 2015
September 2015
July 2015
May 2015


Occurrence by Month for events 2-3.5 km deep
longitude
latitude
-97.2
-97.3
-97.4
-97.5
-97.6
-97.7
-97.8
36.8
37
37.2
37.4
37.6
July 2016
May 2016
april 2016
February 2016
December 2016
October 2015
September 2015
July 2015
May 2015


Occurrence by Month for events >3.5 km deep
longitude
latitude
-97.2
-97.3
-97.4
-97.5
-97.6
-97.7
-97.8
36.8
37
37.2
37.4
37.6
July 2016
May 2016
april 2016
February 2016
December 2016
October 2015
September 2015
July 2015
May 2015

Monitoring based Rapid Response Plan

Monitoring Activity

Wellhead Pressure	Seismometers	cGPS	InSAR	CASSM	2D & 3D Seismic
Continuous			Weekly		2x

Response Action

Hall Plot Analysis	Pressure Fall-Off Test	MIT	Miss. Sampling	U-Tube Sampling	USDW Sampling	Pause Injection

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

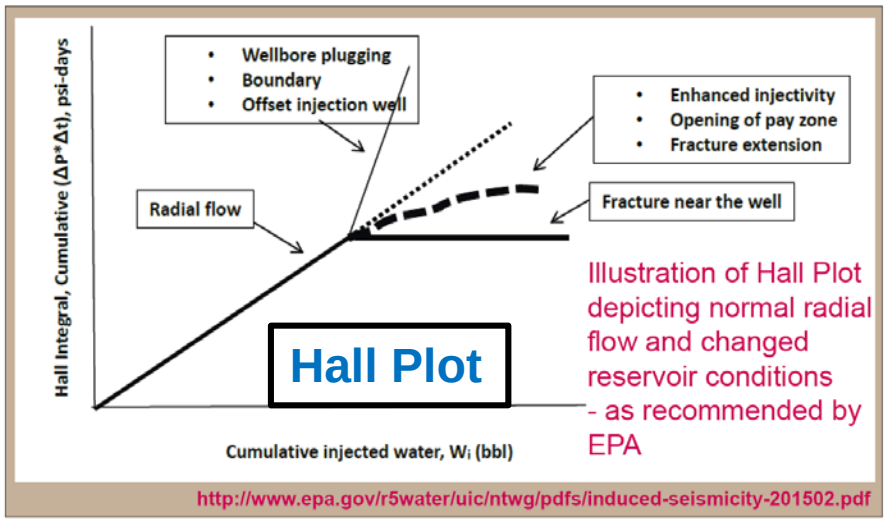


Illustration of Hall Plot depicting normal radial flow and changed reservoir conditions - as recommended by EPA

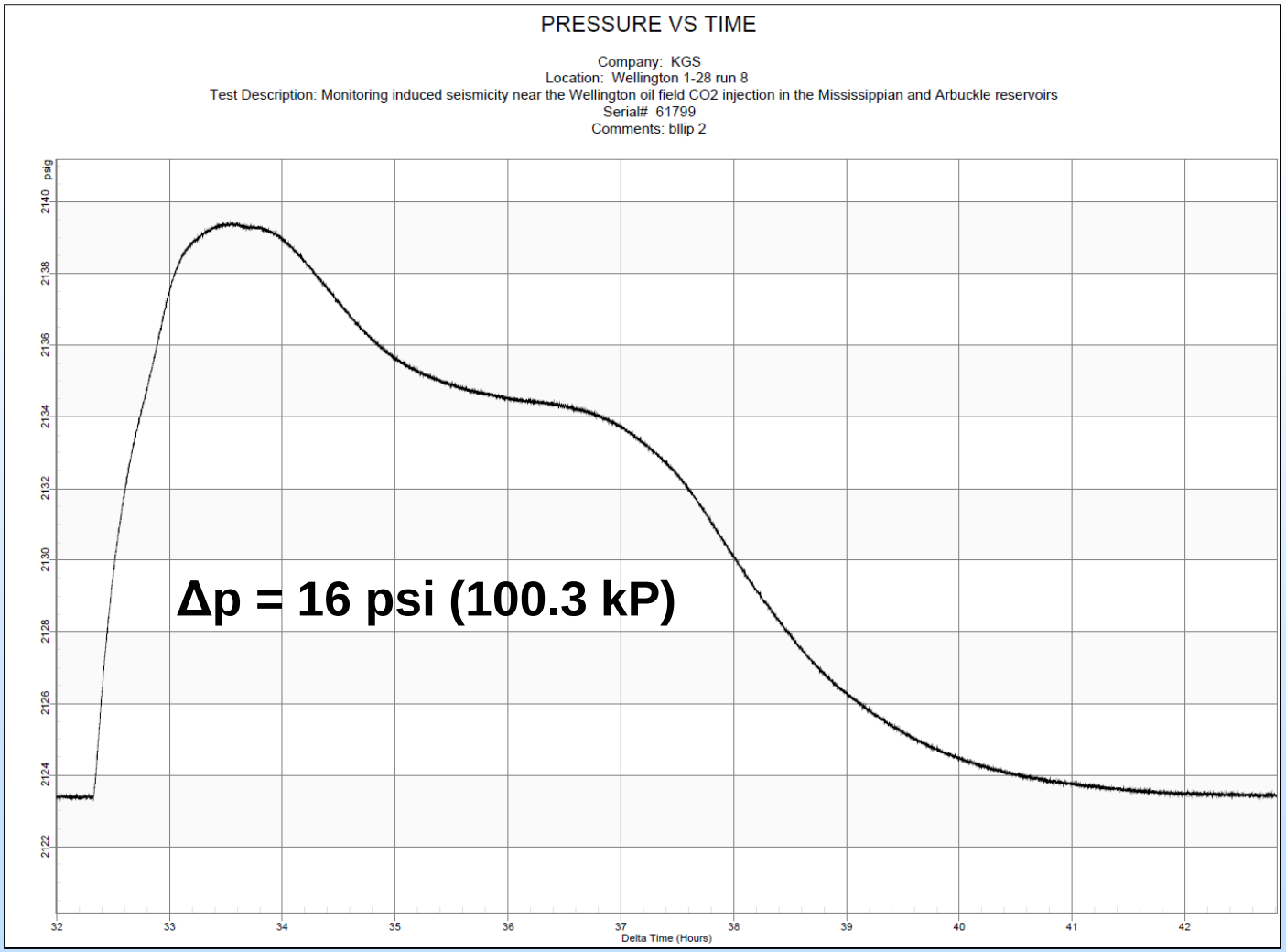
http://www.epa.gov/r5water/uic/ntwg/pdfs/induced-seismicity-201502.pdf

Under review by EPA

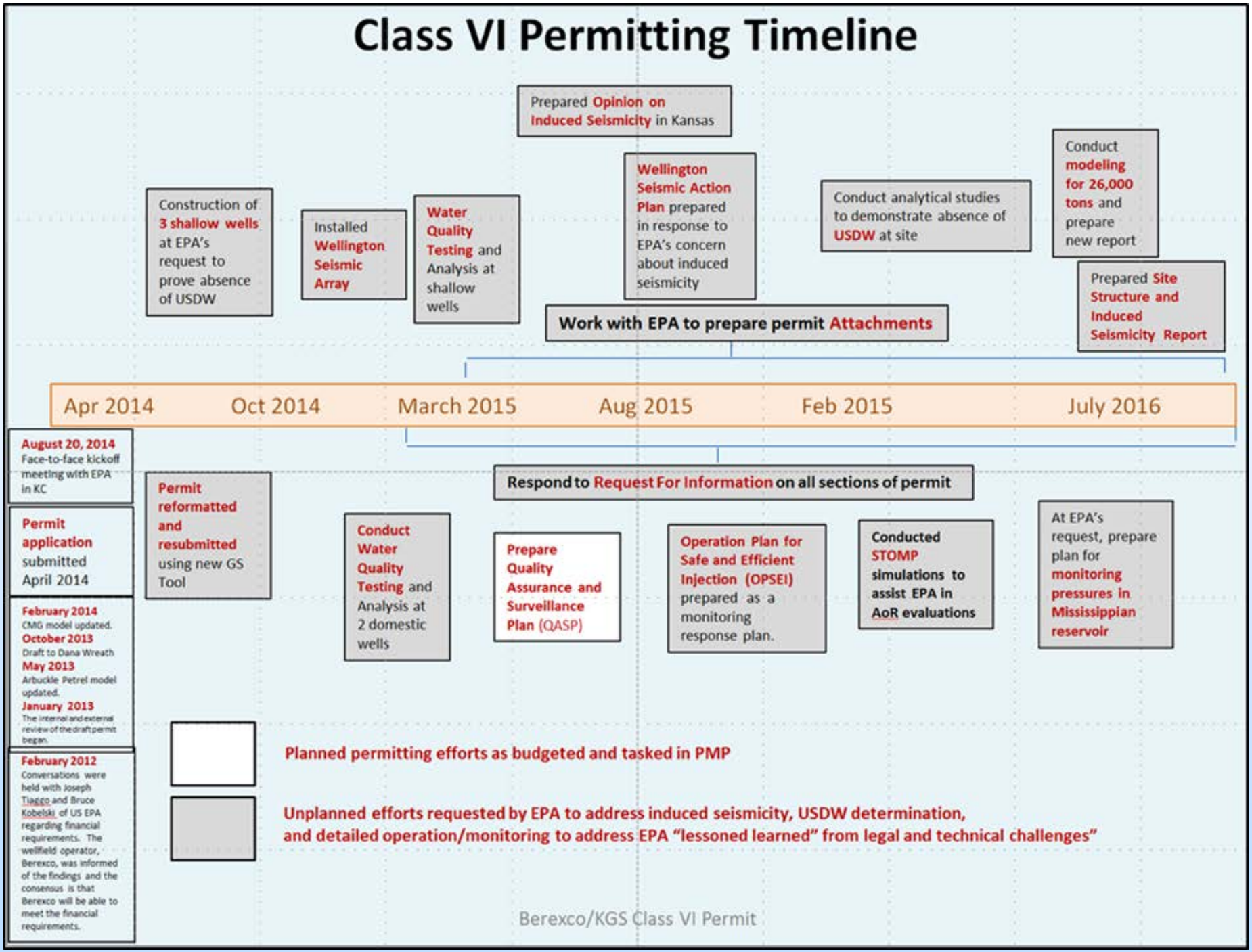
Operational plan for safe and efficient CO2 injection to Draft emergency and remedial response plan for Class VI permit

Monitoring and Rapid Response Plan is designed **to alert the team of anomalies while injecting CO_2, based on prioritizing the monitoring technologies --**

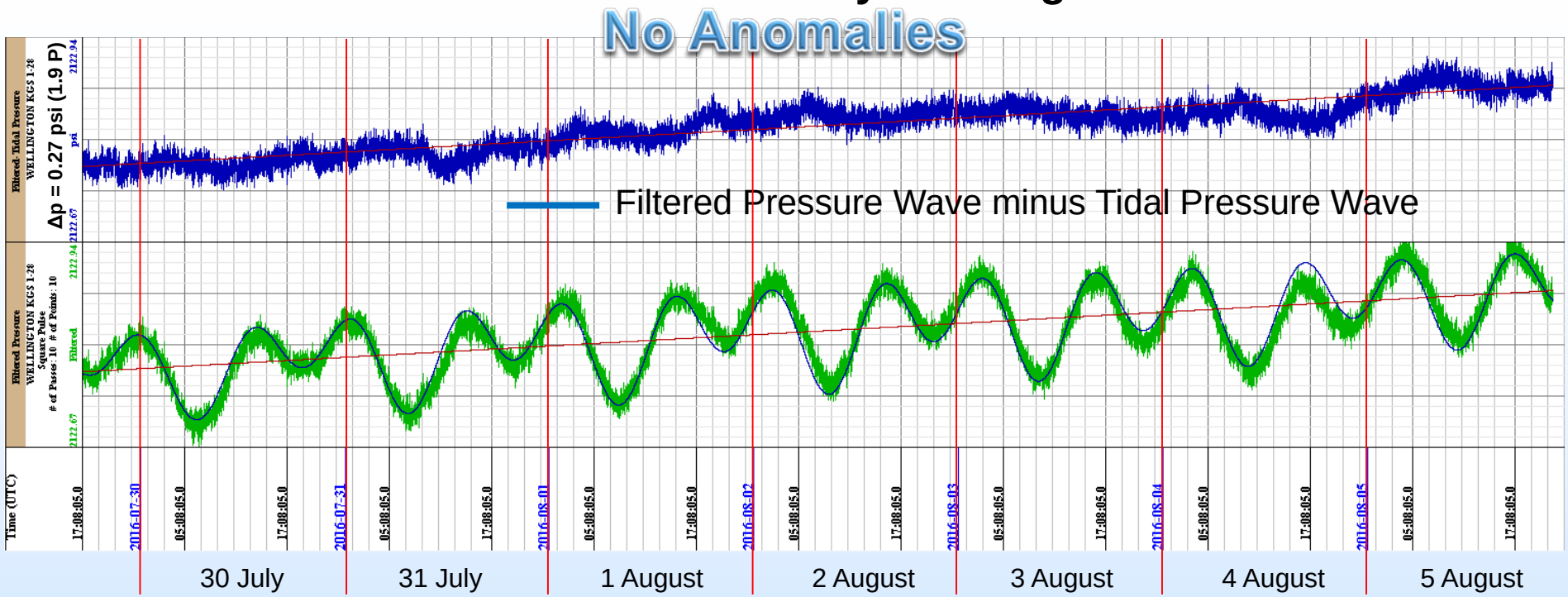
1) *Reliability of the data and approaches used to analyze*
2) *Frequency that data is acquired during injection*
3) *Sensitivity and precision of the monitoring method → detect small changes in CO_2 plume behavior*
4) *Location and therefore resolution of the data*
5) *Detection of spatial extent of the CO_2 plume*
6) *Ability to detect movement above and below the injection zone.*


PRESSURE VS TIME
Company: KGS
Location: Wellington 1-28 run 8
Test Description: Monitoring induced seismicity near the Wellington oil field CO2 injection in the Mississippian and Arbuckle reservoirs
Serial# 61799
Comments: bllip 2
psig
2140
2138
2136
2134
2132
2130
2128
2126
2124
2122
Δp = 16 psi (100.3 kP)
32
33
34
35
36
37
38
39
40
41
42
Delta Time (Hours)

Class VI Permitting Timeline



Pressure Measurement – 29 July to 5 August 2016 UTC



Slope of the Filtered Pressure Wave
Start = 2122.77 psi; End = 2122.88 psi

Slope of the Filtered Pressure Wave
plus Tidal Pressure Wave.
{ ϕ = 0.09 [PU]; C_w = 0.4437 1/[Gpa]; ϕ_{corr} = -13 ^{o} }

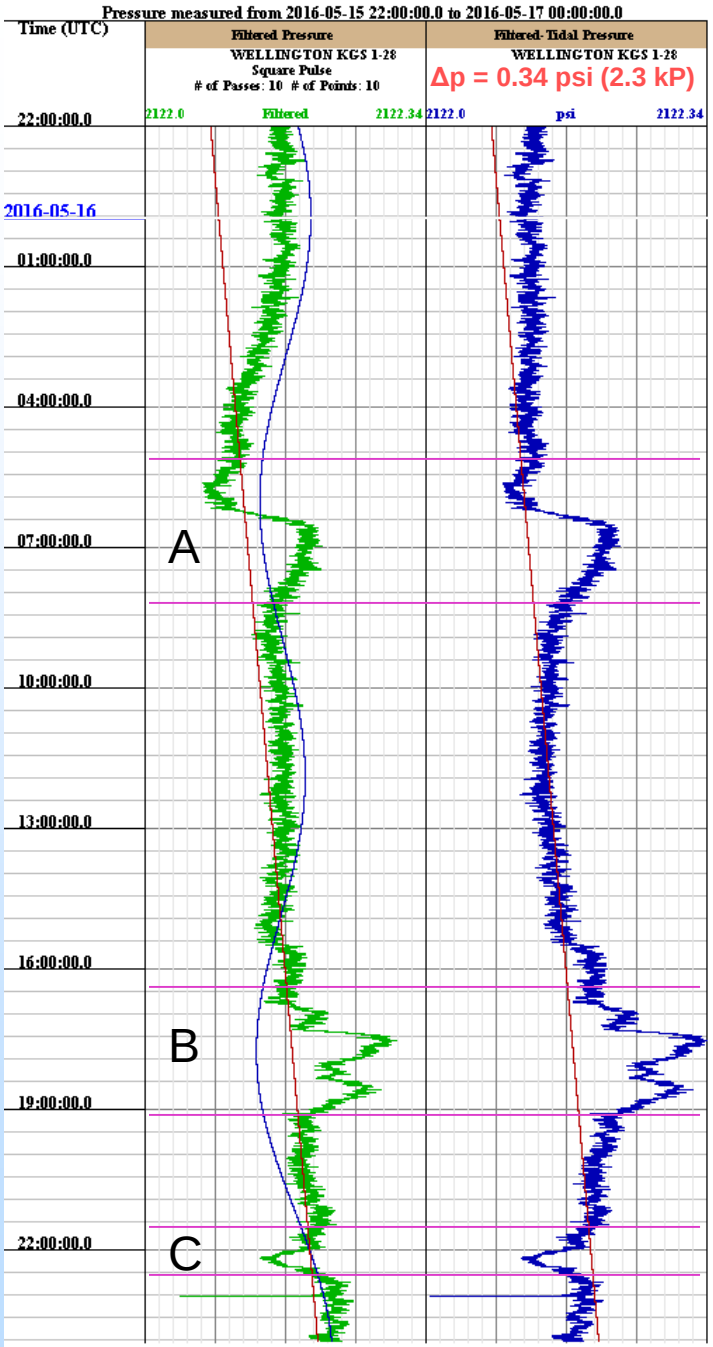
Filtered Pressure Wave

	Sun			Moon		
UTC (0.0)	Apparent R.A.	° above Horizon	Distance A.U.	Apparent R.A.	° above Horizon	Distance km
7/28/2016,	08 30 50.59,	71.4,	1.015442,	03 12 08.50,	67.0,	369726.0
7/29/2016,	08 34 45.53,	71.2,	1.015337,	04 09 30.01,	69.4,	370288.0
7/30/2016,	08 38 39.89,	70.9,	1.015228,	05 08 00.82,	70.7,	371462.0
7/31/2016,	08 42 33.67,	70.7,	1.015113,	06 07 01.28,	70.8,	373309.0
8/01/2016,	08 46 26.84,	70.4,	1.014992,	07 05 35.56,	69.6,	375854.0
8/02/2016,	08 50 19.42,	70.2,	1.014866,	08 02 46.93,	67.4,	379066.0
8/03/2016,	08 54 11.39,	69.9,	1.014733,	08 57 53.10,	64.4,	382835.0
8/04/2016,	08 58 02.75,	69.6,	1.014596,	09 50 34.78,	60.7,	386978.0
8/05/2016,	09 01 53.50,	69.4,	1.014453,	10 40 55.42,	56.8,	391243.0
8/06/2016,	09 05 43.65,	69.1,	1.014304,	11 29 15.74,	52.8,	395339.0
8/07/2016,	09 09 33.18,	68.8,	1.014150,	12 16 06.99,	48.8,	398957.0

1.496 X 10^{11} [m] = 1 Astronomical Unit [AU]

TRILOBITE TESTING, INC.

Bottom Hole Pressure Monitoring
KGS #1-28 (idle Class VI)



Details of May 16 Anomaly as documented for pressure catalog

Pressure Events: 16 May 2016 16:00 to 17:00 (UTC)

A: "piston like" pull up then down

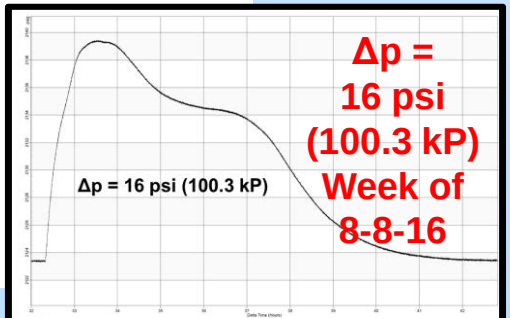
dip	05:40 to 06:10	Min: 05:41:18	2122.042 psi
pulse	06:10 to 08:00	Max: 06:42:42	2122.235 psi
Base:	21:40		2122.161 psi

Δp = .235 psi (6.4 kP)

B: 4 pulses

(1)	16:40 to 17:15	Max: 16:59:42	2122.254 psi
(2)	17:15 to 18:05	Max: 17:35:00	2122.341 psi
(3)	18:05 to 18:20	Max: ~18:15:08	2122.261 psi
(4)	18:20 to 19:00	Max: 18:35:36	2122.292 psi
Base:	19:00		2122.225 psi

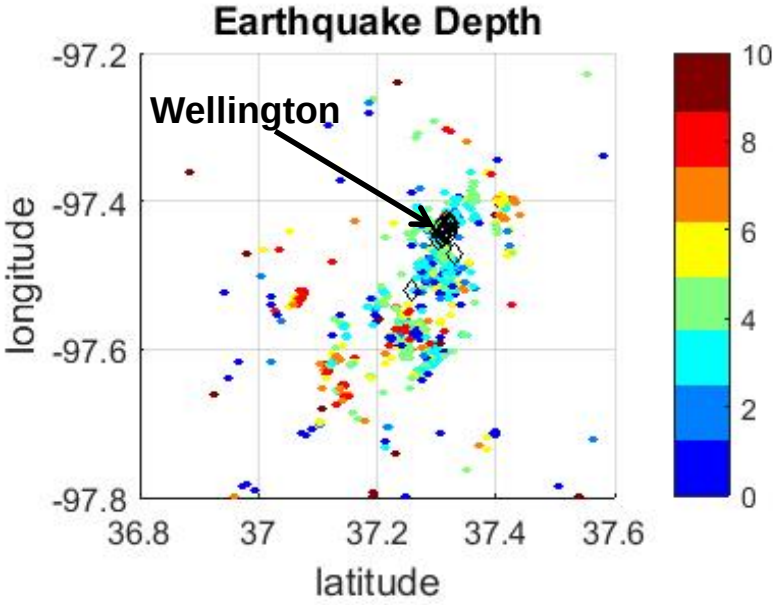
C: dip 22:00 to 22:30 Min: 22:10:14 2122.111 psi

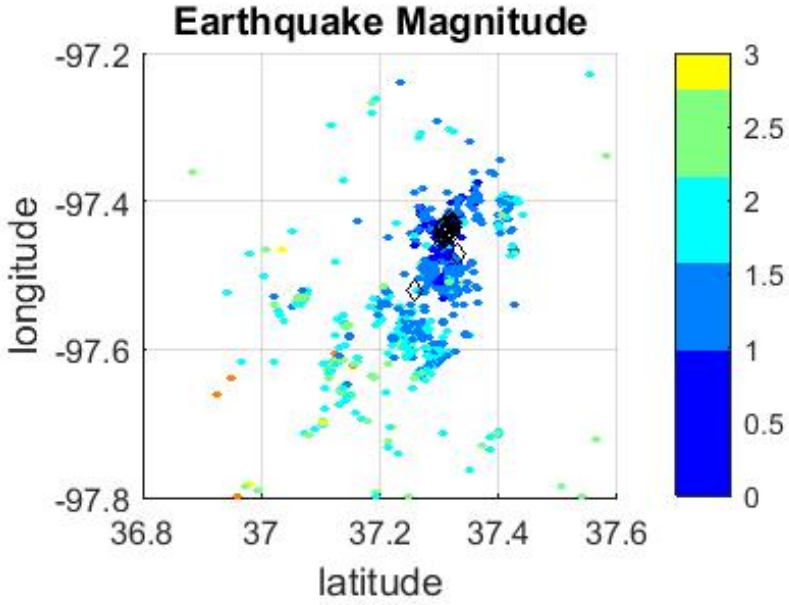


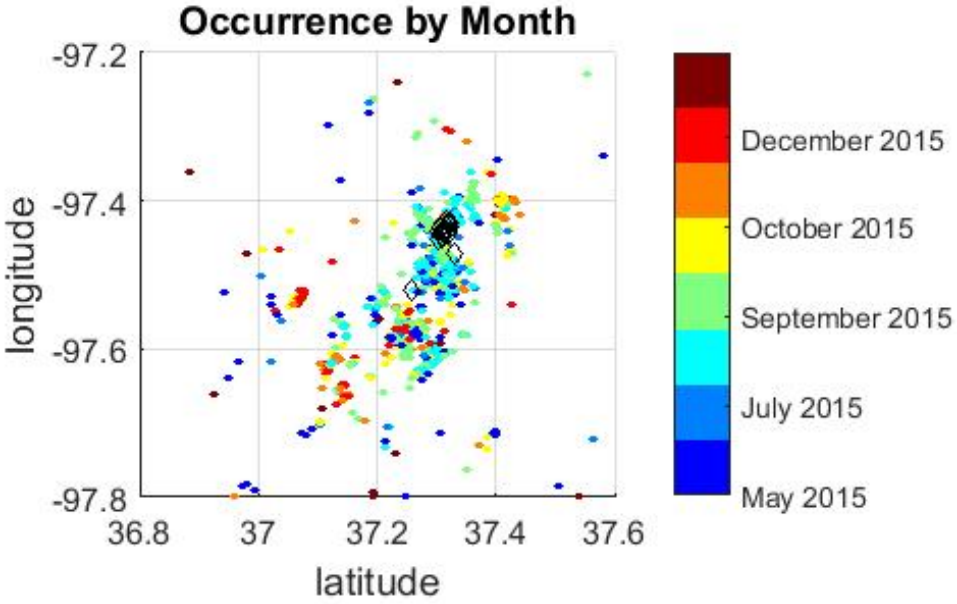
Δp = 16 psi (100.3 kP) Week of 8-8-16

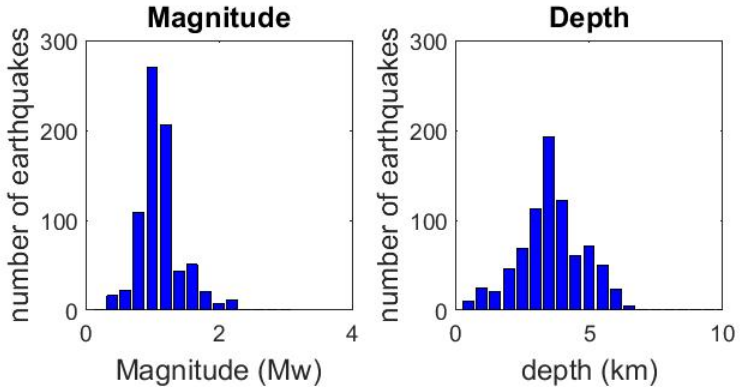
TRILOBITE TESTING, INC.

Spatial and Temporal Relationships of Earthquake Catalog









2 events of Mw 2.5 or greater in area of interest

Diamonds indicate locations of Wellington Seismometer Array

Nolte & Tsoflias (KU)

Pressure (psi) -- Mississippian reservoir September 2016