Webinar for:
Regional Induced Seismicity Collaborative (RISC)
Norman, OK
Oct 11, 2018

SUBSURFACE PRESSURE IN SEISMOGENIC AREAS

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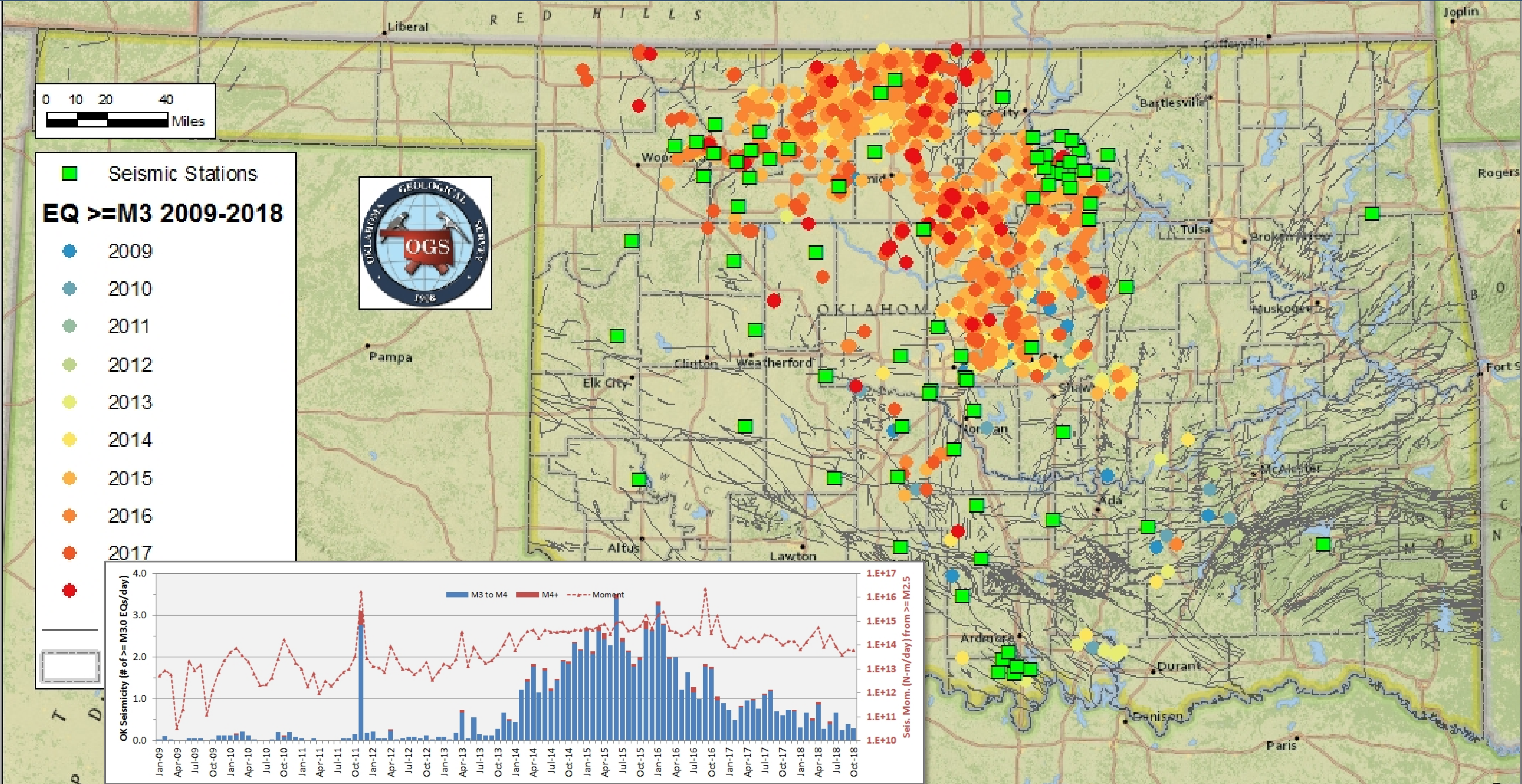
The UNIVERSITY of OKLAHOMA
Mewbourne College of Earth and Energy

OKLAHOMA GEOLOGICAL SURVEY 1908

Seismic Monitoring Network and Earthquakes in Oklahoma



OGS' First Crack at Putting Together 2011 UIC Data

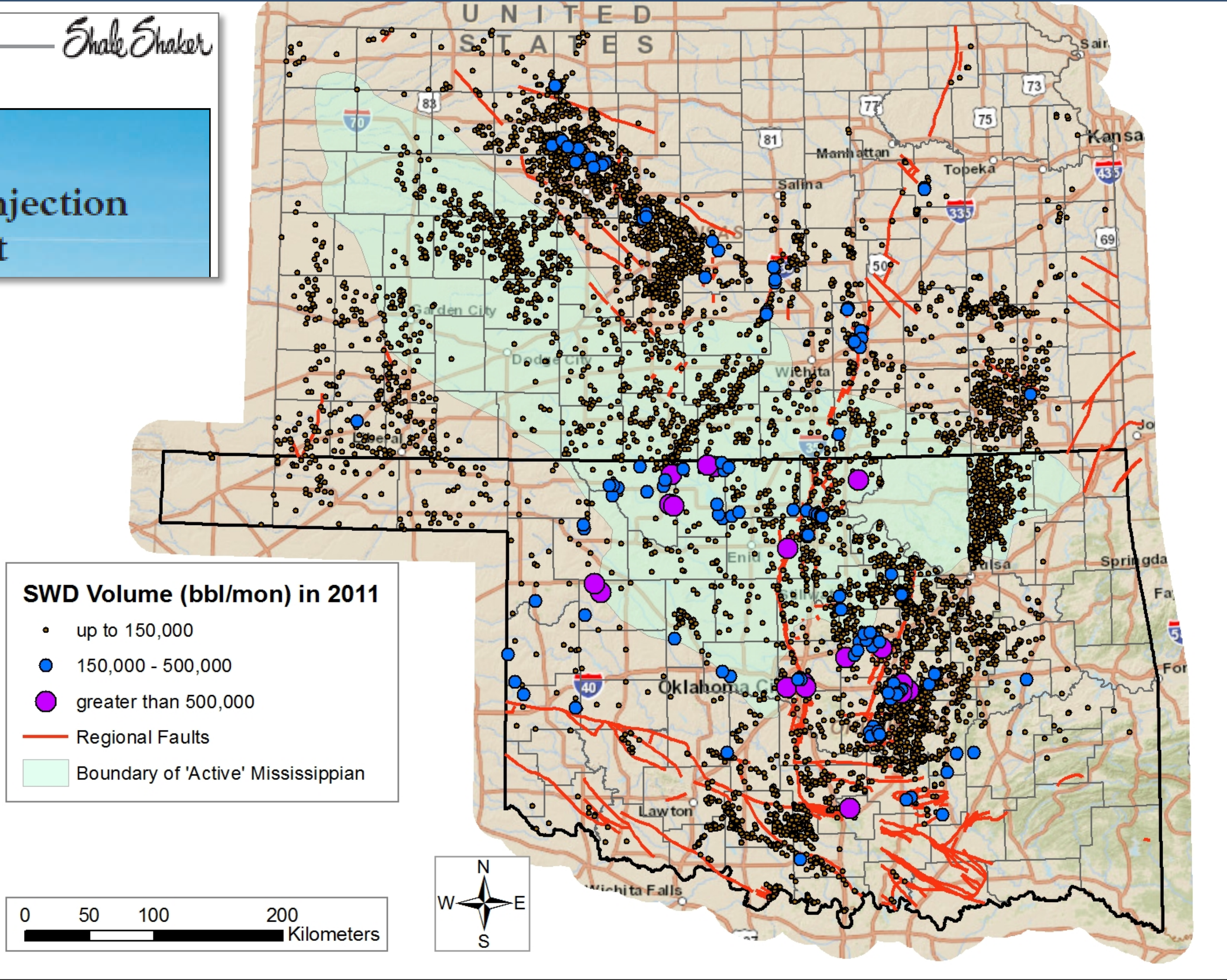
Resource Management

Shale Shaker

By Kyle E. Murray, Oklahoma Geological Survey | kyle.murray@ou.edu; Austin A. Holland, Oklahoma Geological Survey | austin.holland@ou.edu

Inventory of Class II Underground Injection Control Volumes in the Midcontinent

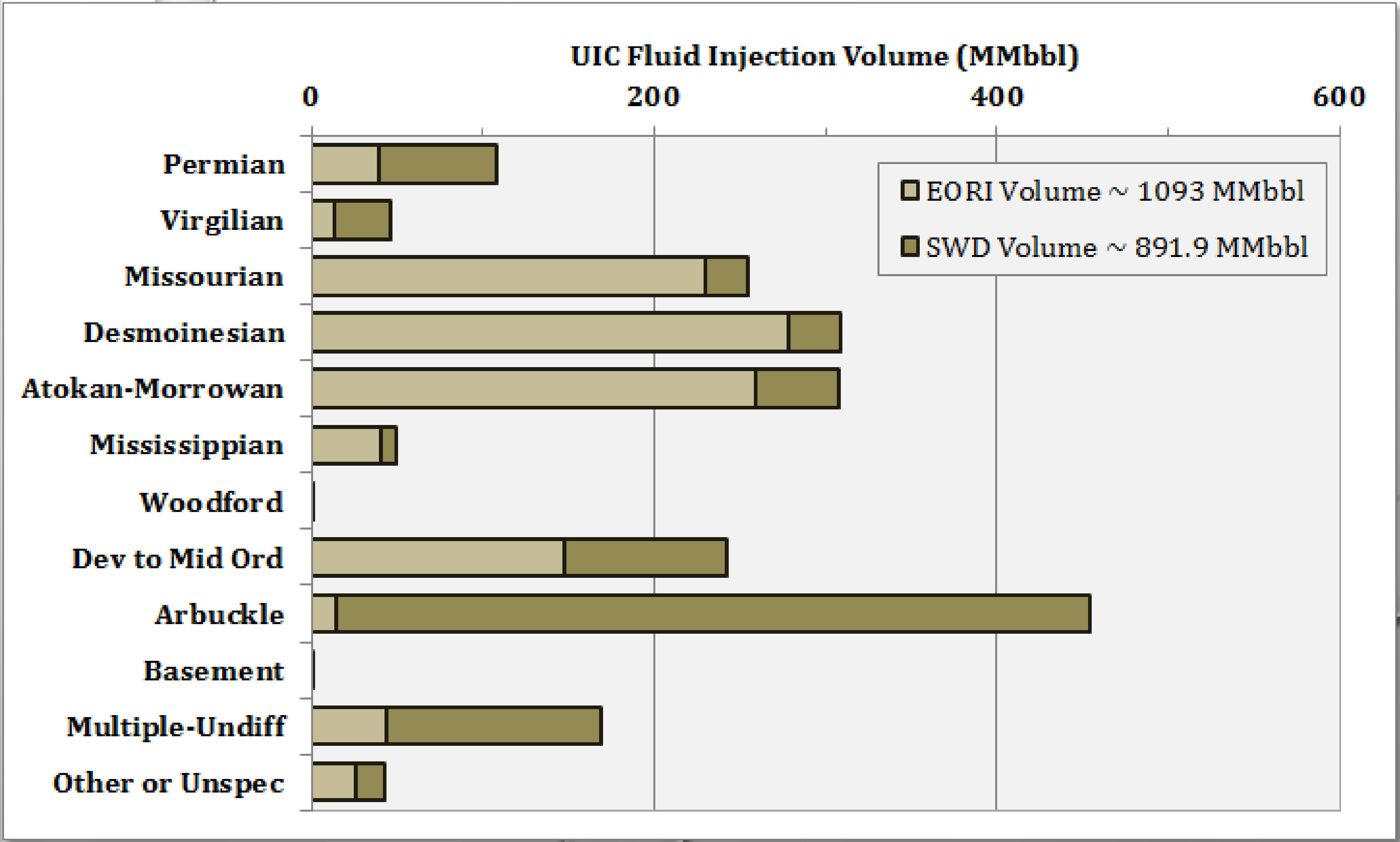
Murray, K.E., and Holland, A.A., 2014, Inventory of Class II Underground Injection Control Volumes in the Midcontinent: Shale Shaker, v. 65, no. 2, p. 98-106.



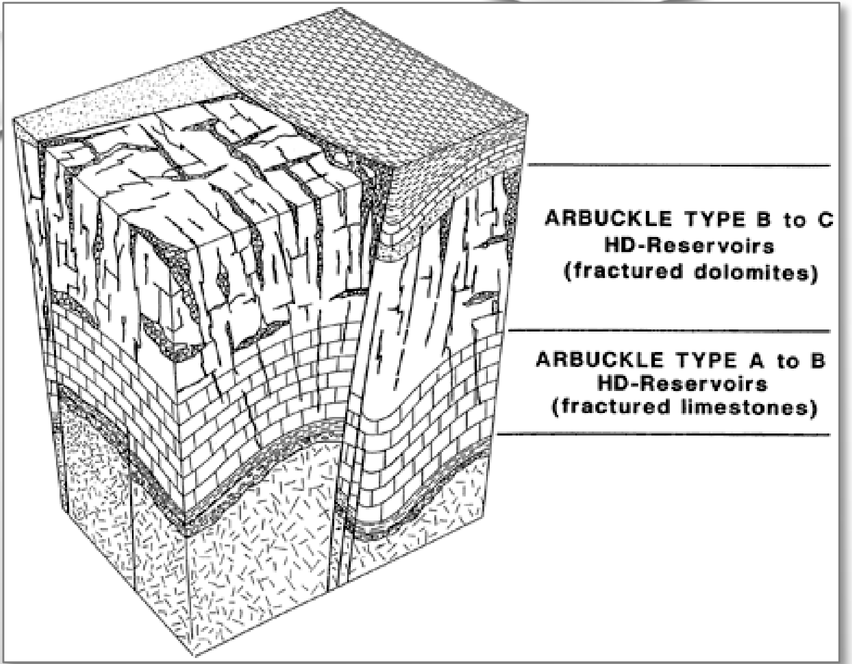
OGS' First Crack at Putting Together 2011 UIC Data

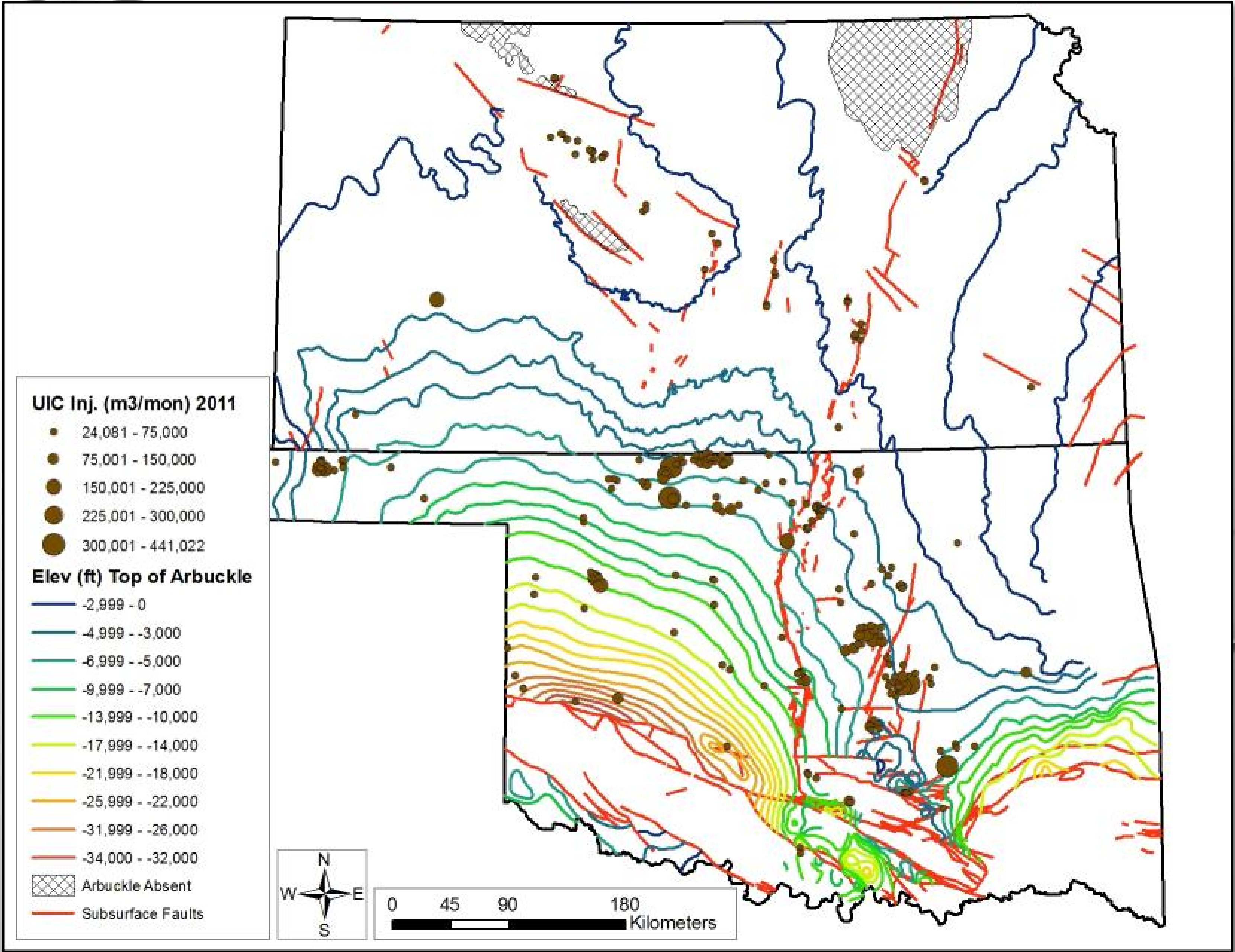
Zone	Group	Formation
Permian		Garber
	Chase	Brown Dolomite
	Council Grove	Pontotoc
	Admire	Belveal
Virgilian	Wabaunsee	Cisco Lime
	Shawnee	Pawhuska
		Endicott
	Douglas	Tonkawa
Missourian	Hoxbar	Lansing
		Cottage Grove
		Kansas City
		Hogshooter
		Layton
		Cleveland
Desmoinesian	Marmaton	Oswego
	Cabaniss	Skinner
	Krebs	Red Fork
		Burbank
		Bartlesville
		Hartshorne
Atokan-Morrowan	Atoka	Gilcrease
		Dutcher
	Morrow	Cromwell
	Springer	Wamsley
Mississippian	Chester	Manning
		Caney
	Meramec	Miss Lime
		Miss Chat
		St. Louis
		Mayes
	Osage	Sycamore
	Kinderhook	Kinderhook
Woodford	Upper Devonian	Woodford
Dev to Mid Ord	Middle Devonian	Misener
	Lower Dev - Silurian	Hunton
	Cincinnatian	Sylvan
		Viola
	Simpson	Bromide
		Wilcox
		McLish
		Oil Creek
Arbuckle	Arbuckle Group	West Spring Creek
		Kindblade
		Butterly Dolomite
Basement & Crystalline Rock	Cambrian	Reagan
	Pre-Cambrian	Granite

Key to Symbols
Sandstone
Carbonate
Shale
Coal
Granite



Top of the Arbuckle, Subsurface Faults & Largest Volume UIC wells





KS UIC data from KGS (2013) Well Database
KS Arbuckle Structure from Merriam and Smith (1961)
OK UIC data from OCC (2012) UIC Database
OK Arbuckle Structure from Evans et al (2012)

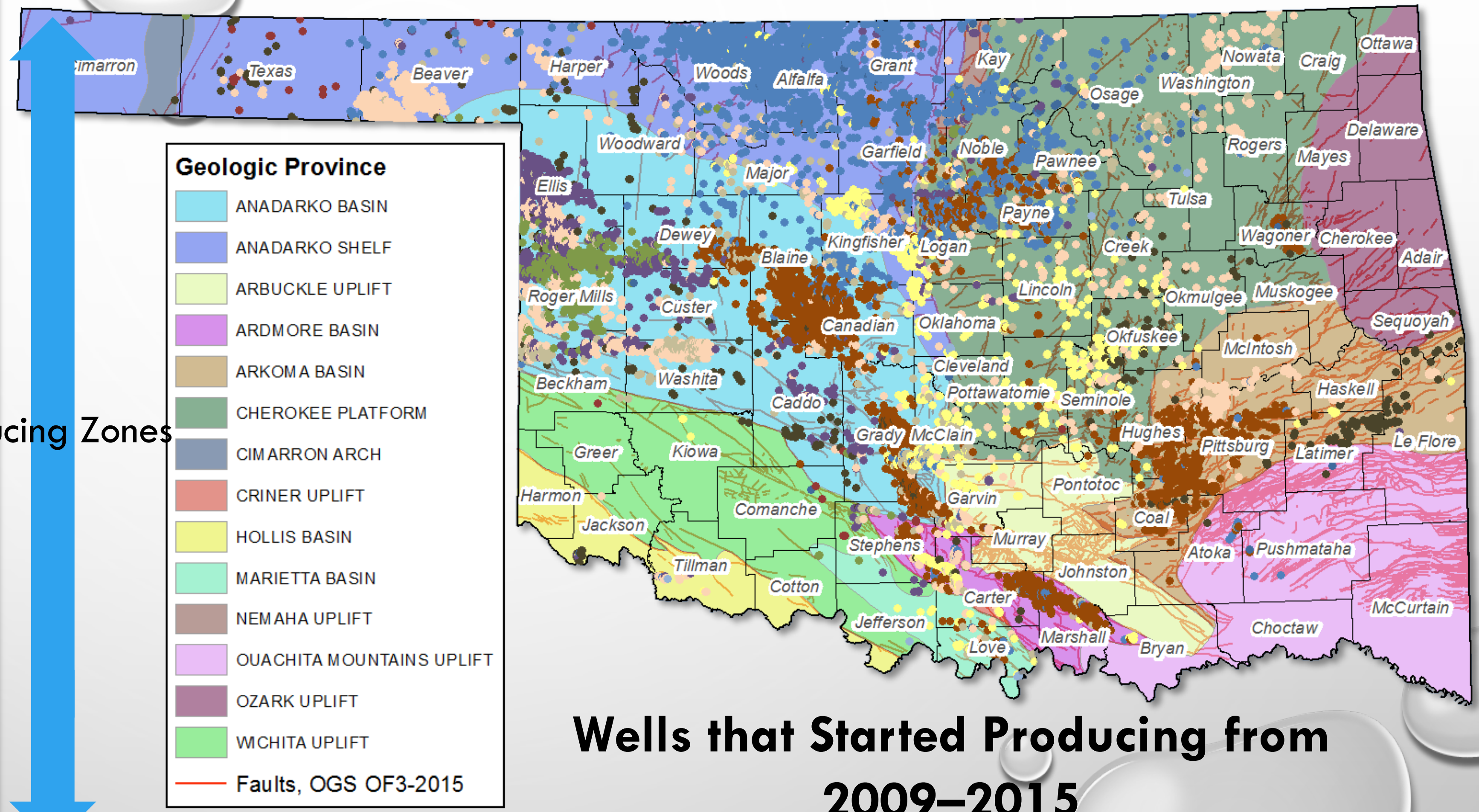
Zones for Production, Injection, & Disposal

Zone	Group	Formation
Multiple-Undiff		
Other or Unspec.		
Permian		Garber
	Chase	Brown Dolomite
	Council Grove	Pontotoc
	Admire	Belveal
Virgilian	Wabaunsee	Cisco Lime
	Shawnee	Pawhuska
		Endicott
	Douglas	Tonkawa
Missourian	Hoxbar	Lansing
		Cottage Grove
		Kansas City
		Hogshooter
		Layton
		Cleveland
Desmoinesian	Marmaton - Deese	Oswego
	Cabaniss - Deese	Skinner
	Krebs - Deese	Red Fork
		Burbank
		Bartlesville
		Hartshorne
Atokan-Morrowan	Atoka	Gilcrease
		Dutcher
	Morrow	Cromwell
	Springer	Wamsley
Mississippian	Chester	Manning
		Caney
	Meramec	Miss Lime
		Miss Chat
		St. Louis
		Mayes
	Osage	Sycamore
	Kinderhook	Kinderhook
Woodford	Upper Devonian	Woodford
Dev to Mid Ord	Middle Devonian	Misener
	Hunton	Frisco
		Bois d'Arc
		Henryhouse
		Chimneyhill
	Cincinnatian	Sylvan
		Viola
	Simpson	Bromide
		Wilcox
		McLish
		Oil Creek
Arbuckle	Arbuckle Group	West Spring Creek
		Kindblade
		Cool Creek
		McKenzie Hill
		Butterly dolomite
		Signal mountain
		Royer dolomite
		Fort sill limestone
Basement & Crystalline Rock	Cambrian	Reagan
	Pre-Cambrian	Granite

Granite Wash

Key to Symbols
Sandstone
Carbonate
Shale
Coal
Granite

Producing Zones



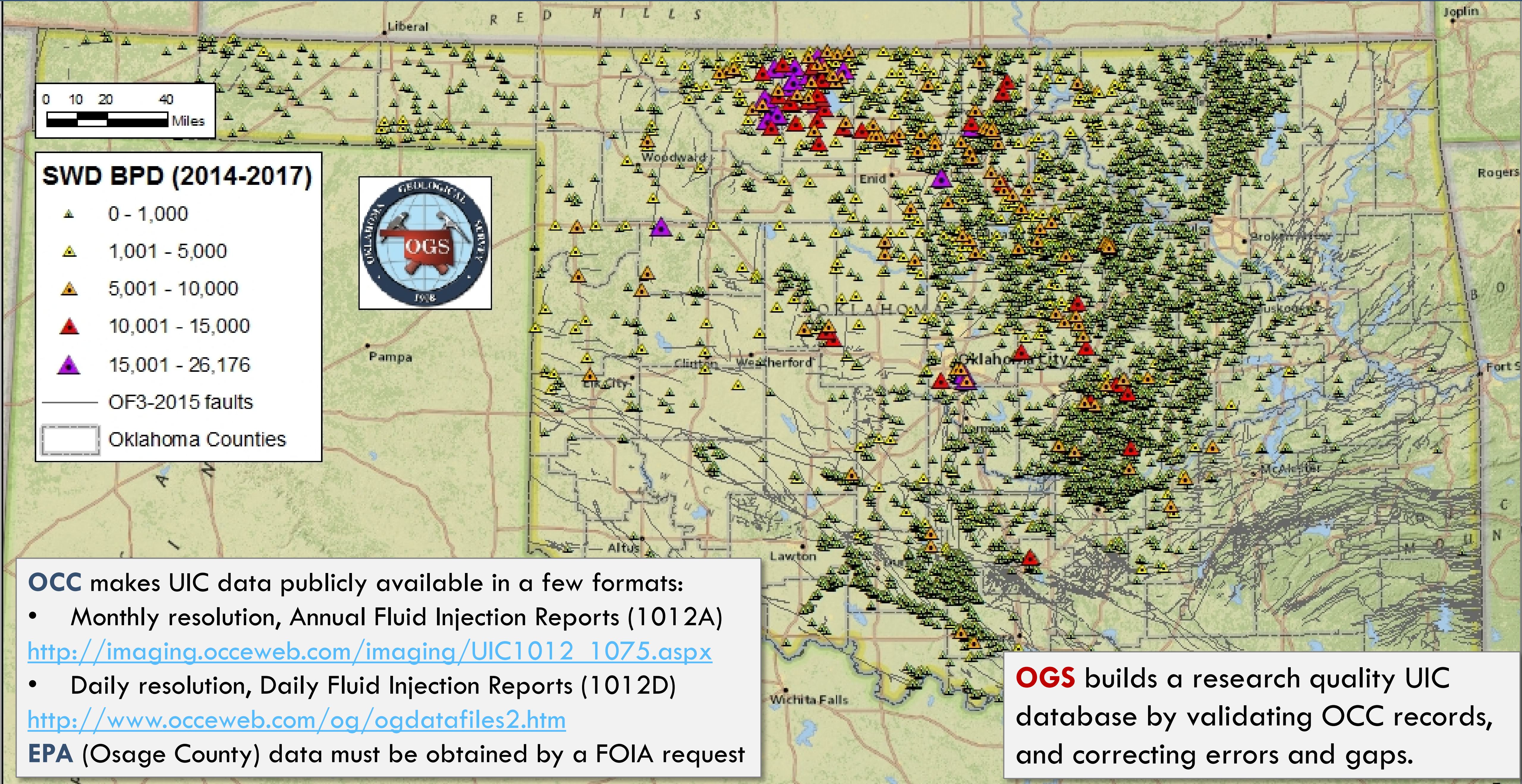
Wells that Started Producing from 2009–2015

(Murray, et al., 2018 in preparation)

Predominant Disposal Zone, avg of 2 km depth

Earthquakes Down Here, avg of 5.5 km depth

UIC Saltwater Disposal (SWD) or 2D volumes in Oklahoma



OCC makes UIC data publicly available in a few formats:

- Monthly resolution, Annual Fluid Injection Reports (1012A)

http://imaging.occeweb.com/imaging/UIC1012_1075.aspx

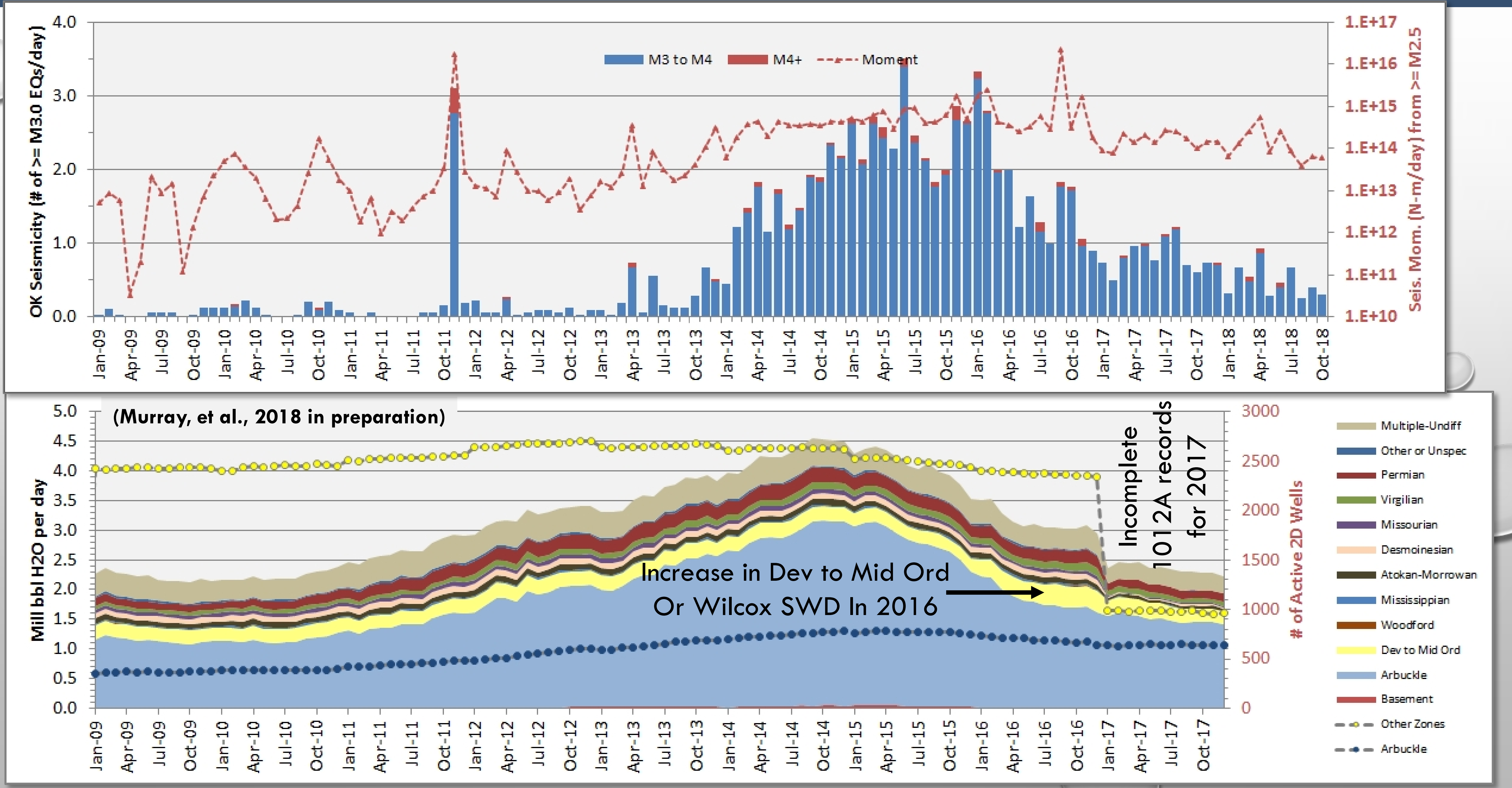
- Daily resolution, Daily Fluid Injection Reports (1012D)

http://www.occeweb.com/og/ogdatafiles2.htm

EPA (Osage County) data must be obtained by a FOIA request

OGS builds a research quality UIC database by validating OCC records, and correcting errors and gaps.

Statewide Earthquakes vs. SWD, 2009–2018



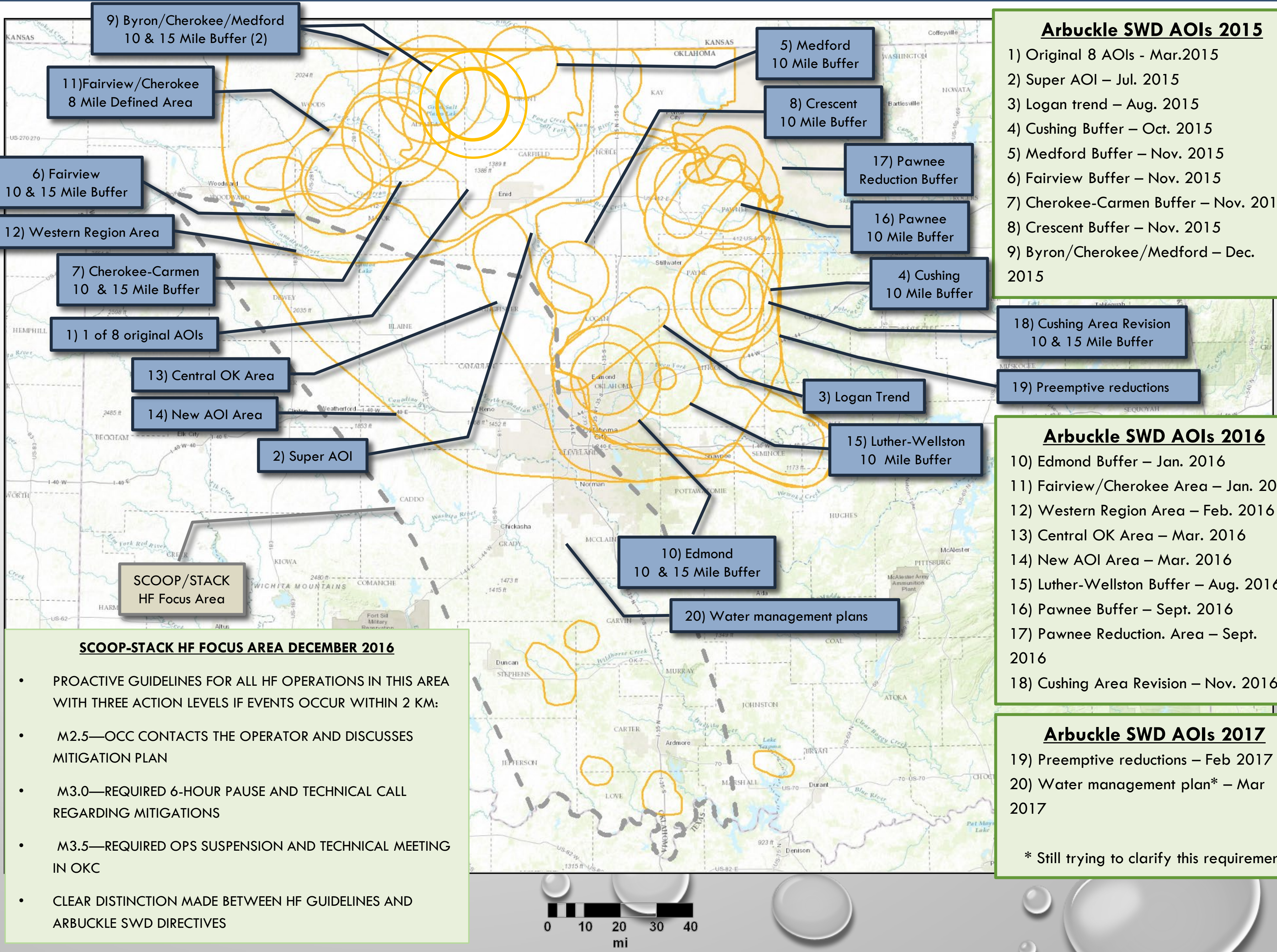
Oklahoma Corporation Commission's Regulatory Directives and Operational Rules, Mar 2017

Mitigating Induced Seismicity in Oklahoma:

The Oklahoma Corporation Commission (OCC) took direct action to mitigate induced seismicity in Oklahoma in early 2016. The OCC issued the following directives related to PW management to reduce seismicity in the Area of Interest (AOI) where intense earthquakes were recorded in central/north-central Oklahoma.

1. Reduction in maximum PW injection (SWD disposal) rate at the well level to ≤10,000 to 15,000 bbl/day per well
2. Reduction in regional-scale injection by 40% from the 2014 total injection
3. OCC (2014–present) requested that operators plug back SWD wells completed in the basement.

Scanlon et al., accepted



SCOOP-STACK HF FOCUS AREA DECEMBER 2016

- PROACTIVE GUIDELINES FOR ALL HF OPERATIONS IN THIS AREA WITH THREE ACTION LEVELS IF EVENTS OCCUR WITHIN 2 KM:
- M2.5—OCC CONTACTS THE OPERATOR AND DISCUSSES MITIGATION PLAN
- M3.0—REQUIRED 6-HOUR PAUSE AND TECHNICAL CALL REGARDING MITIGATIONS
- M3.5—REQUIRED OPS SUSPENSION AND TECHNICAL MEETING IN OKC
- CLEAR DISTINCTION MADE BETWEEN HF GUIDELINES AND ARBUCKLE SWD DIRECTIVES

Arbuckle SWD AOIs 2015

1) Original 8 AOIs - Mar.2015
2) Super AOI – Jul. 2015
3) Logan trend – Aug. 2015
4) Cushing Buffer – Oct. 2015
5) Medford Buffer – Nov. 2015
6) Fairview Buffer – Nov. 2015
7) Cherokee-Carmen Buffer – Nov. 2015
8) Crescent Buffer – Nov. 2015
9) Byron/Cherokee/Medford – Dec. 2015

Arbuckle SWD AOIs 2016

10) Edmond Buffer – Jan. 2016
11) Fairview/Cherokee Area – Jan. 2016
12) Western Region Area – Feb. 2016
13) Central OK Area – Mar. 2016
14) New AOI Area – Mar. 2016
15) Luther-Wellston Buffer – Aug. 2016
16) Pawnee Buffer – Sept. 2016
17) Pawnee Reduction. Area – Sept. 2016
18) Cushing Area Revision – Nov. 2016

Arbuckle SWD AOIs 2017

19) Preemptive reductions – Feb 2017
20) Water management plan* – Mar 2017

* Still trying to clarify this requirement

How is saltwater disposal related to seismicity in the mid-Continent?

INDUCED SEISMICITY

2015

High-rate injection is associated with the increase in U.S. mid-continent seismicity

M. Weingarten,[1*] S. Ge,[1] J. W. Godt,[2] B. A. Bekins,[3] J. L. Rubinstein[3]

An unprecedented increase in earthquakes in the U.S. mid-continent began in 2009. Many of these earthquakes have been documented as induced by wastewater injection. We examine the relationship between wastewater injection and U.S. mid-continent seismicity using a newly assembled injection well database for the central and eastern United States. We find that the entire increase in earthquake rate is associated with fluid injection wells. High-rate injection wells (>300,000 barrels per month) are much more likely to be associated with earthquakes than lower-rate wells. At the scale of our study, a well's cumulative injected volume, monthly wellhead pressure, depth, and proximity to crystalline basement do not strongly correlate with earthquake association. Managing injection rates may be a useful tool to minimize the likelihood of induced earthquakes.

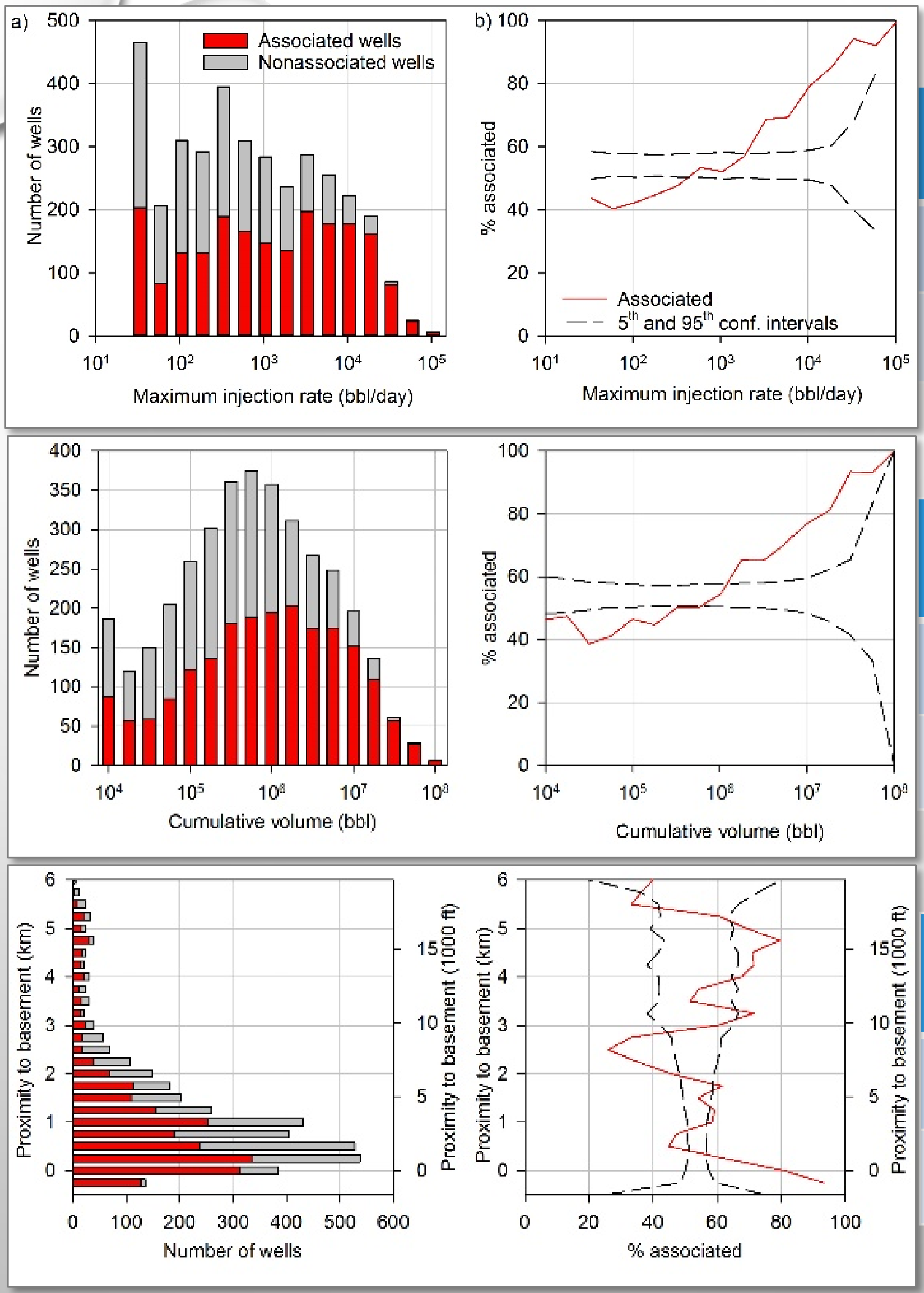
Cumulative injection
Monthly wellhead pressure
Depth
Proximity to basement
High-rate >300,000 BPM

Managing Basin-Scale Fluid Budgets to Reduce Injection-Induced Seismicity from the Recent U.S. Shale Oil Revolution

Seismological Research Letters-Accepted

By:
B.R. Scanlon
M.B. Weingarten
K.E. Murray
R.C. Reedy

Statistical Post-Audit: How is wastewater injection related to seismicity in Oklahoma?

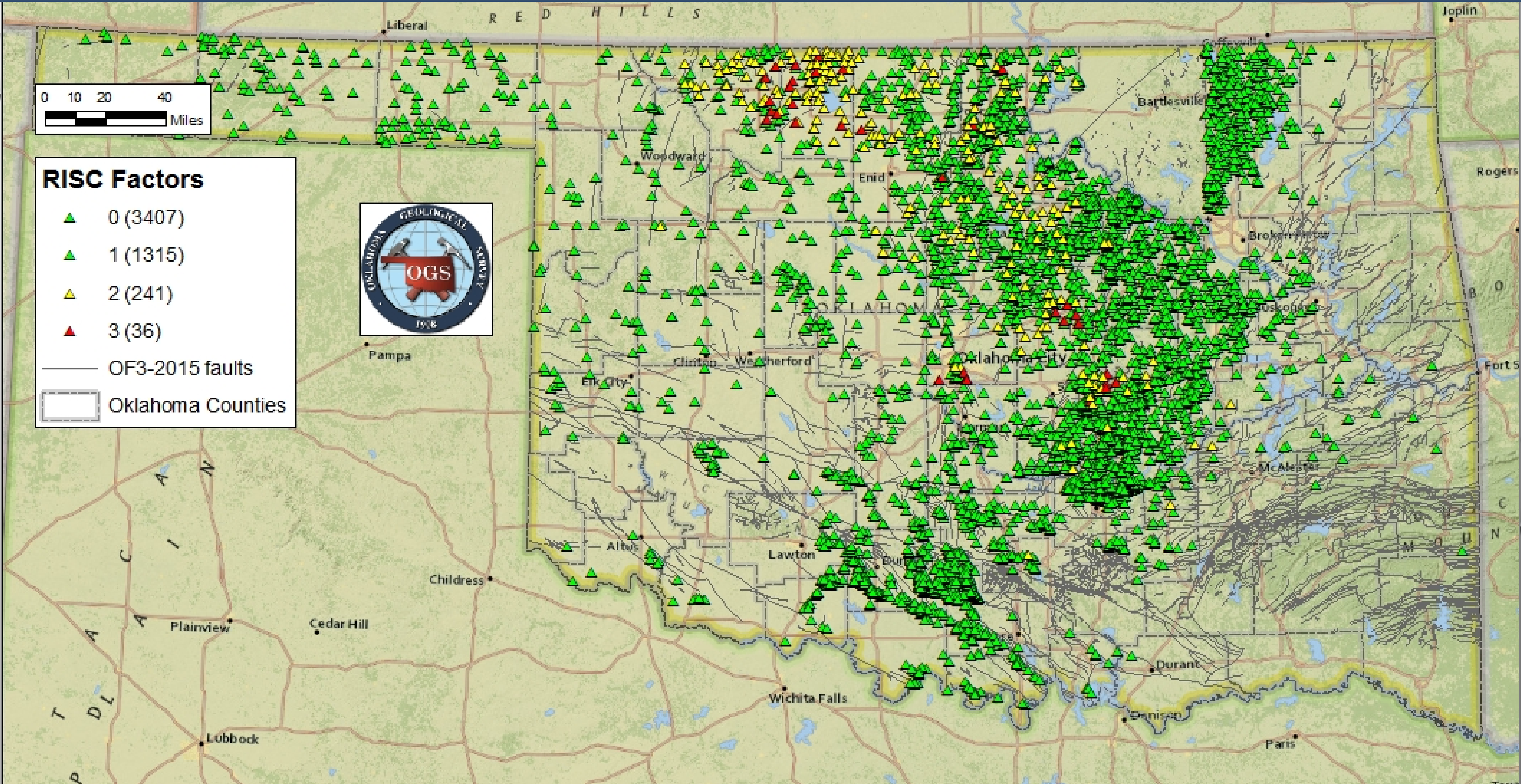


Maximum injection rate (bbl/day)	associated with ≥M 3.0+ EQ
<3000 bbl/day	40–60%
>10,000 bbl/day	80–95%

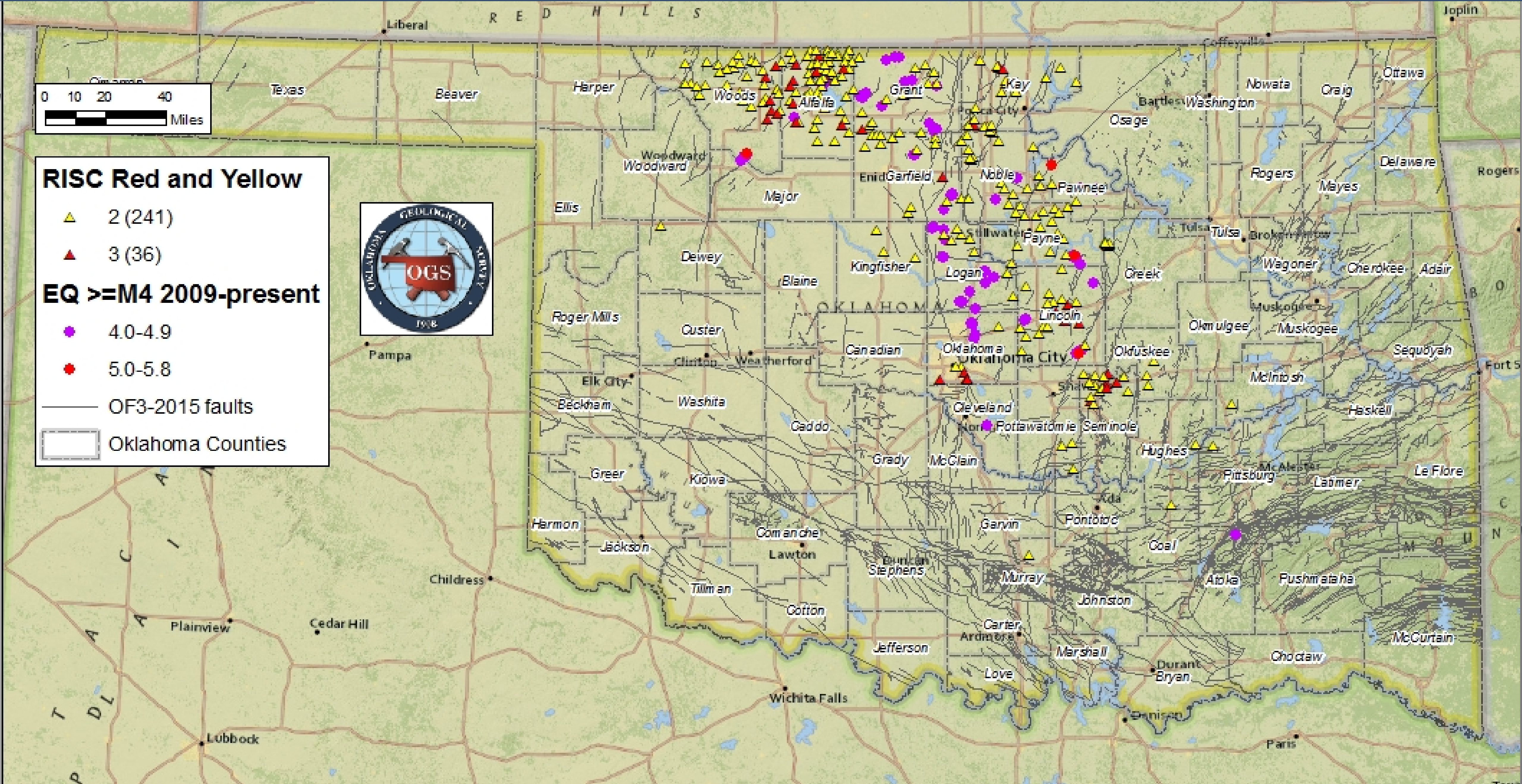
Cumulative volume from 2009 to 2016	associated with ≥M3.0+ EQ
2–3 MMbbl	65%
30–60 MMbbl	90%

Proximity to Basement	associated with ≥M3.0+ EQ
>0.5 km	55%
0.5 to –0.5 km	90%

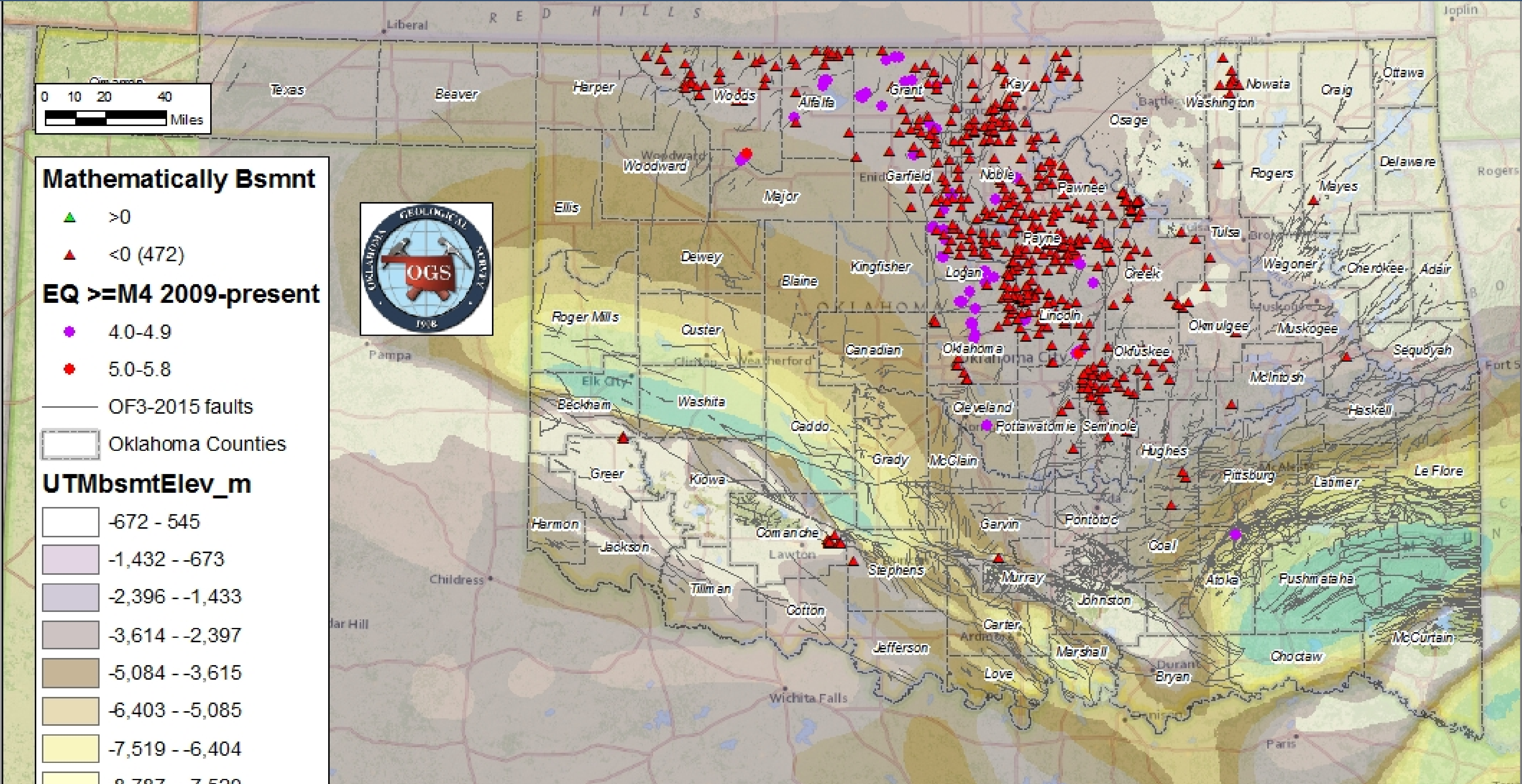
Spatial Distribution of Scanlon et al. Results, # of Associated Factors



Spatial Distribution of Scanlon et al. Results, >=2 Associated Factors

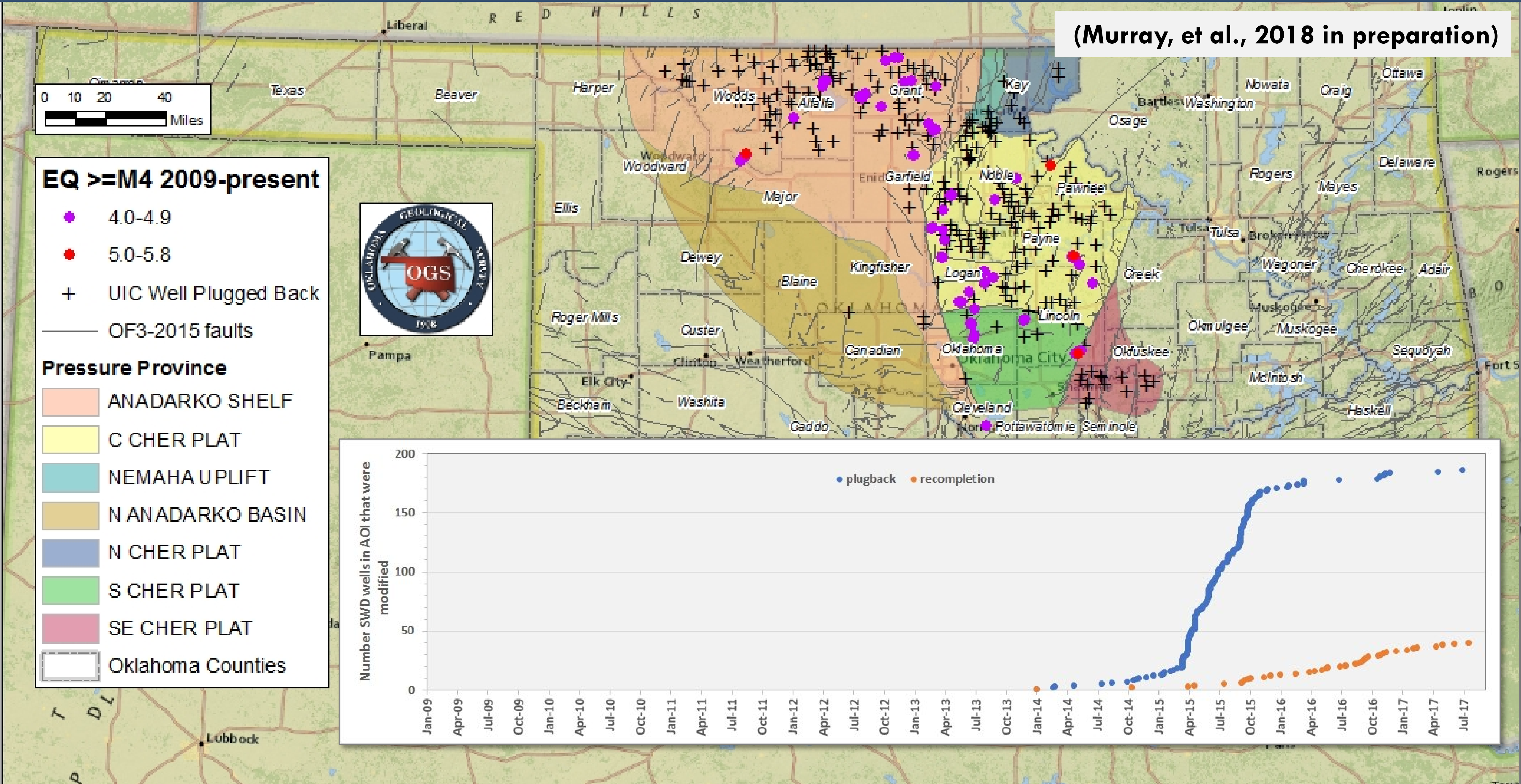


Wells that were "Mathematically" in Basement (Crain vs. Murray)

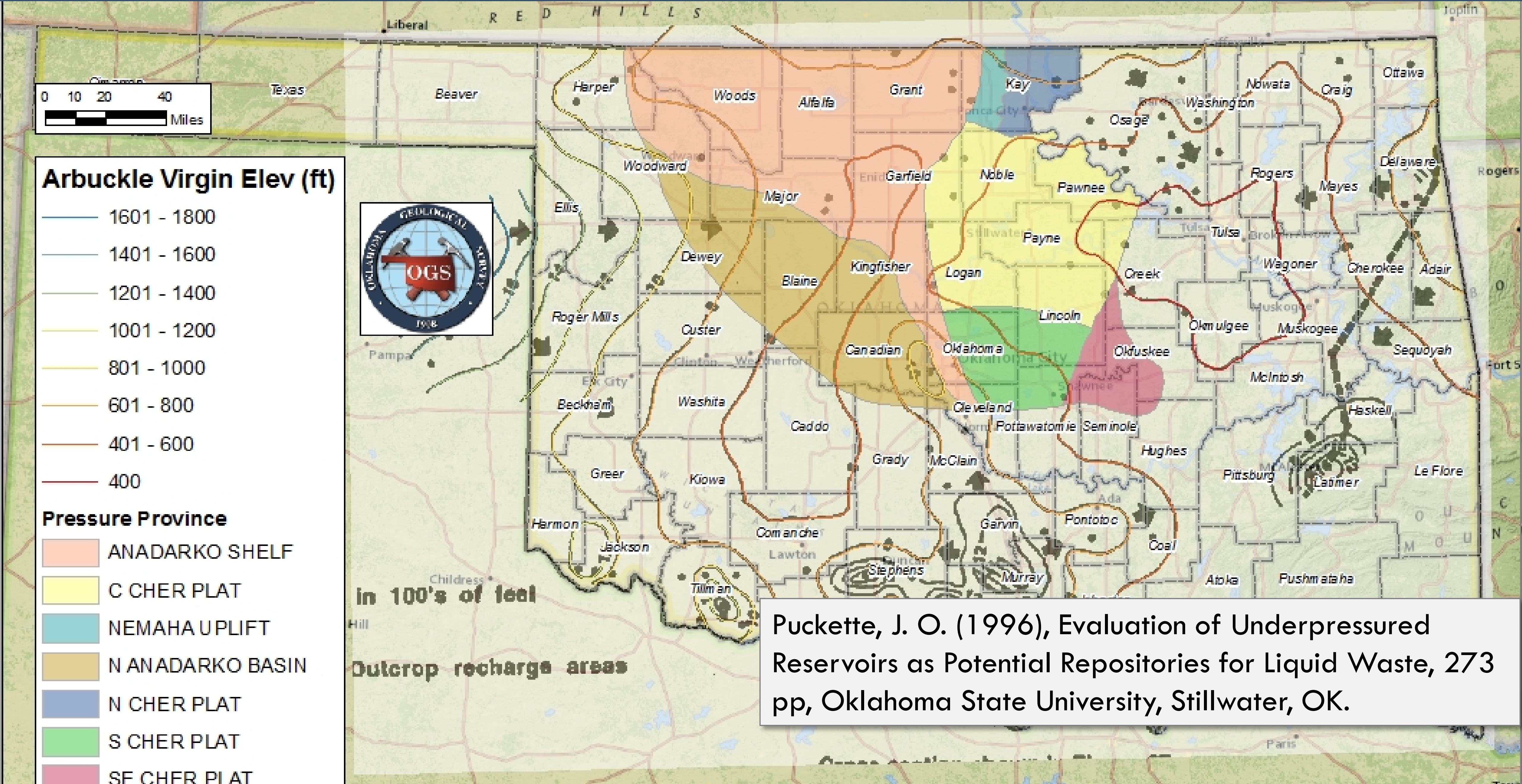


Plug-back Program, ~250 SWD wells

(Murray, et al., 2018 in preparation)

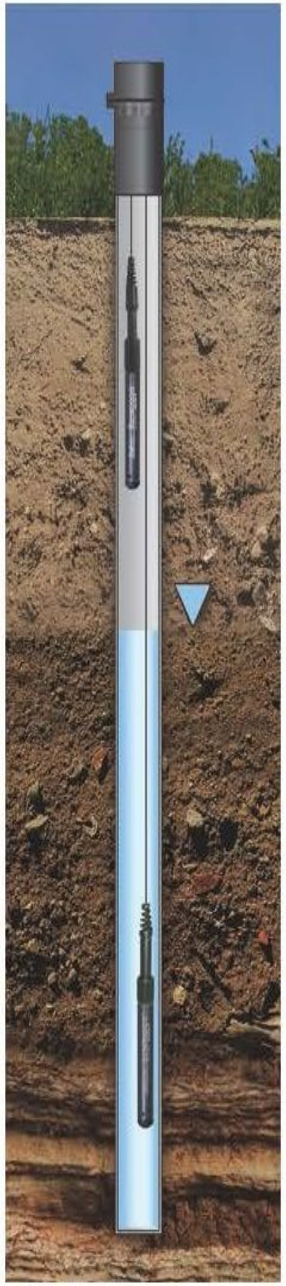


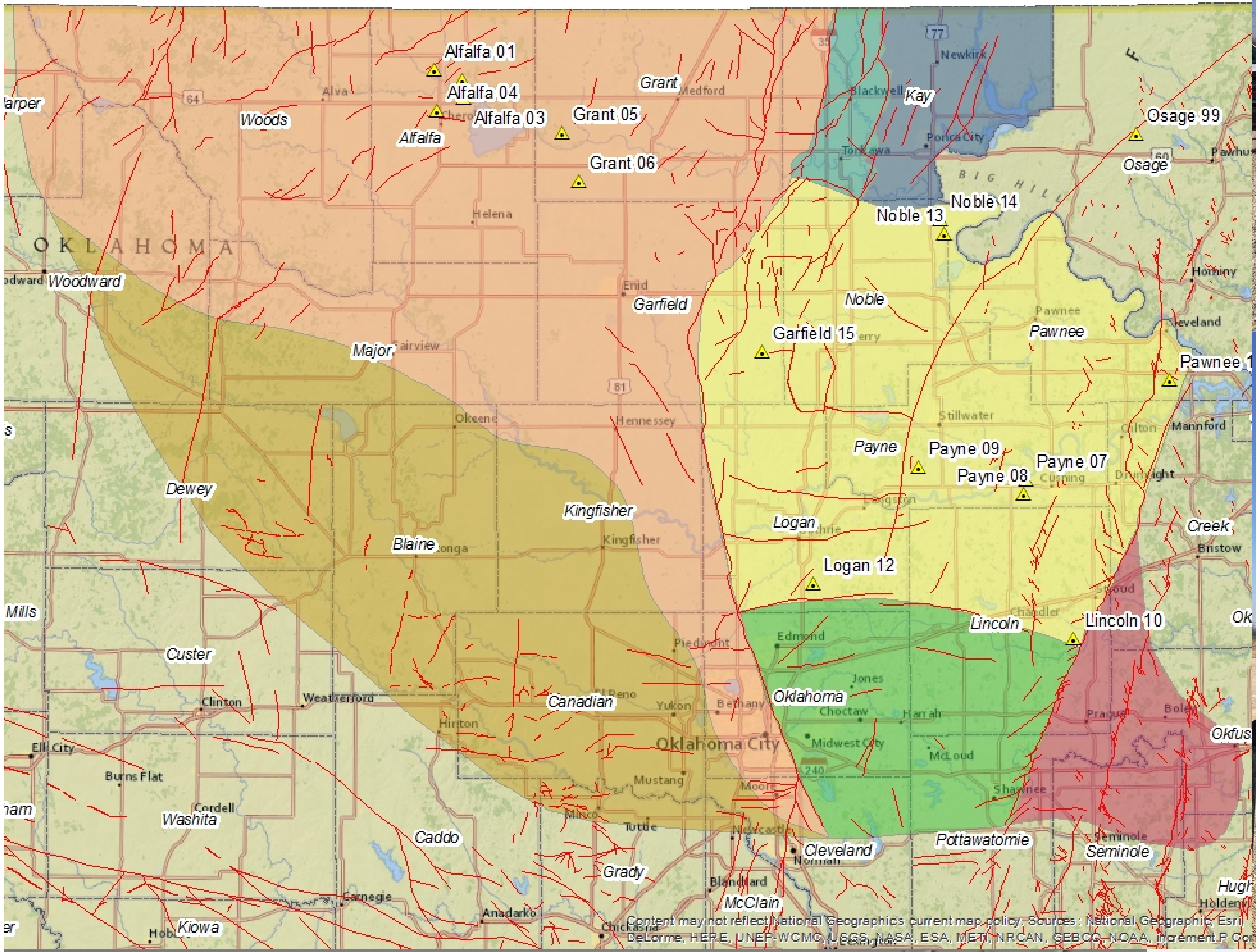
Virgin Pressure (Elevation Head) of the Arbuckle Group



Puckette, J. O. (1996), Evaluation of Underpressured Reservoirs as Potential Repositories for Liquid Waste, 273 pp, Oklahoma State University, Stillwater, OK.

Configuration & Deployment of Pressure Monitoring Network

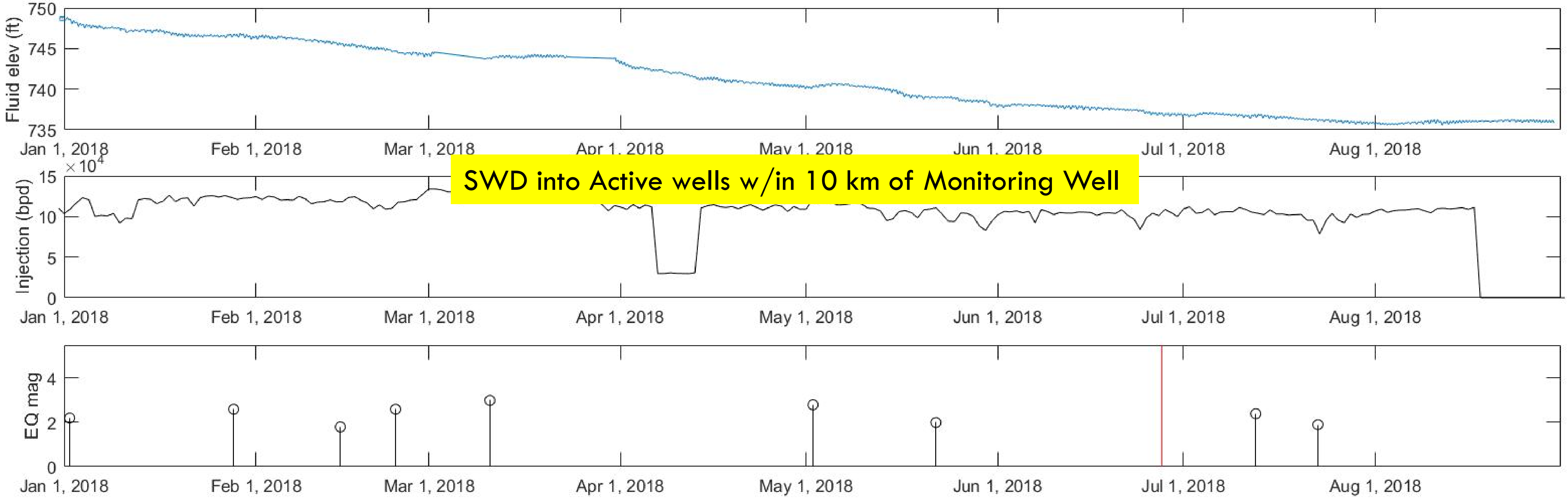




(Murray, et al., 2018 in preparation)

Alfalfa 03 with radius of 10 km

Fluid Elevation in Inactive SWD Monitoring Well



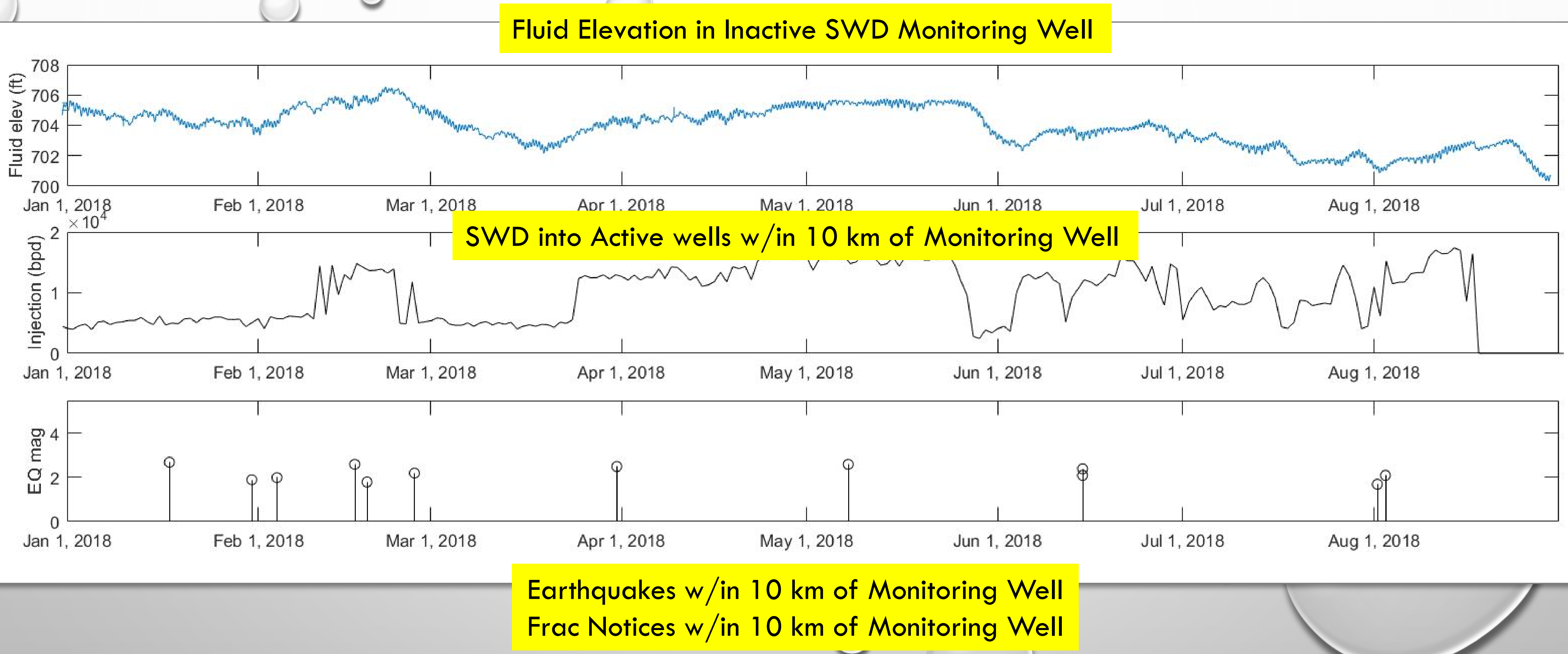
SWD into Active wells w/in 10 km of Monitoring Well

Earthquakes w/in 10 km of Monitoring Well

Frac Notices w/in 10 km of Monitoring Well

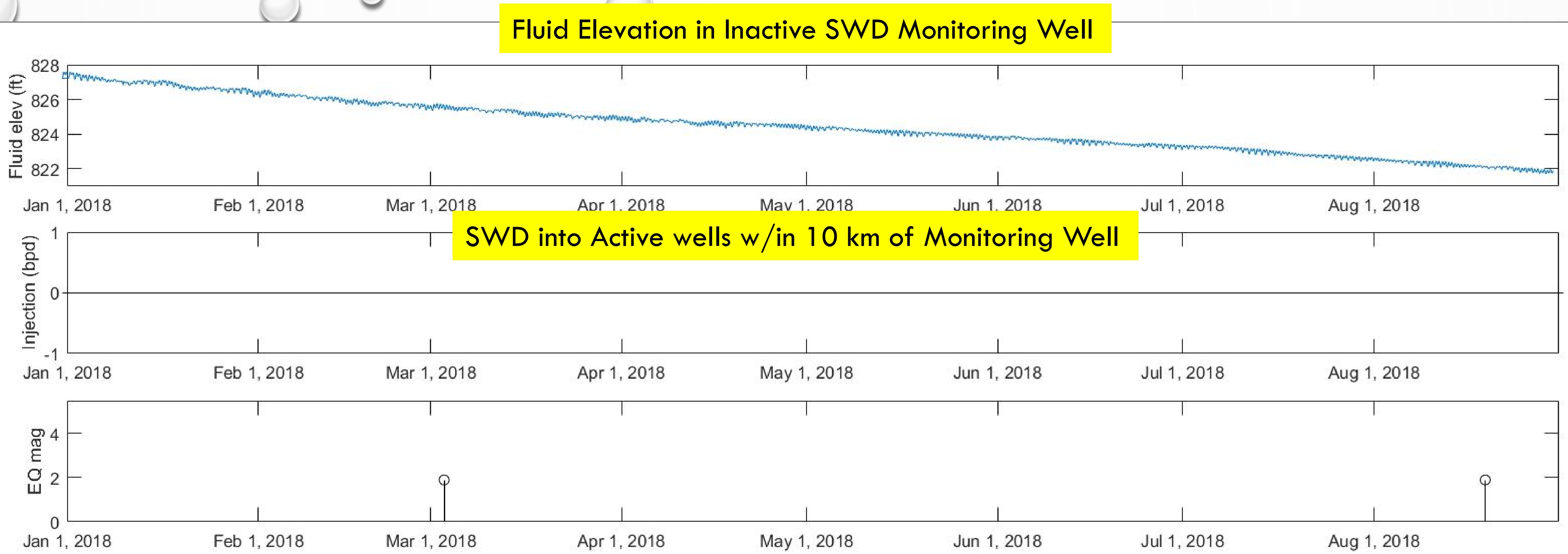
(Murray, et al., 2018 in preparation)

Payne 09 with radius of 10 km



(Murray, et al., 2018 in preparation)

Logan 12 with radius of 10 km

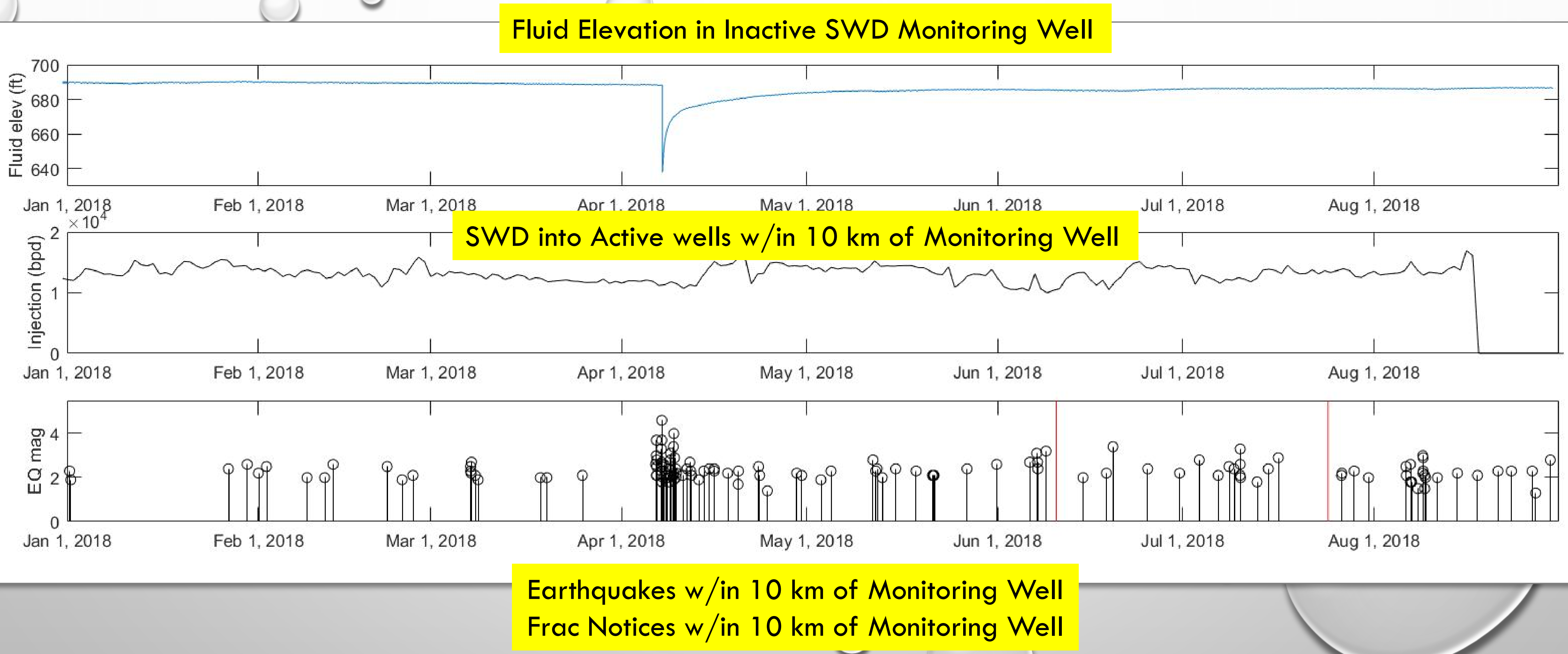


Kroll, K. A., E. S. Cochran, and K. E. Murray (2017), Poroelastic Properties of the Arbuckle Group in Oklahoma Derived from Well Fluid Level Response to the 3 September 2016 Mw 5.8 Pawnee and 7 November 2016 Mw 5.0 Cushing Earthquakes, Seismological Research Letters, 88(4), 963-970.

Perilla-Castillo, P. J. (2017), Rock properties derived from analysis of solid earth tide strain observed in continuous pressure monitoring of the Arbuckle Group of Oklahoma, 65 pp, University of Oklahoma, Norman, OK.

Williams, J. A. (2017), Geologic, permeability, and fracture characterization of the Arbuckle Group in the Cherokee Platform, Oklahoma 62 pp, Emporia State University, Emporia, KS.

Garfield 15 with radius of 10 km



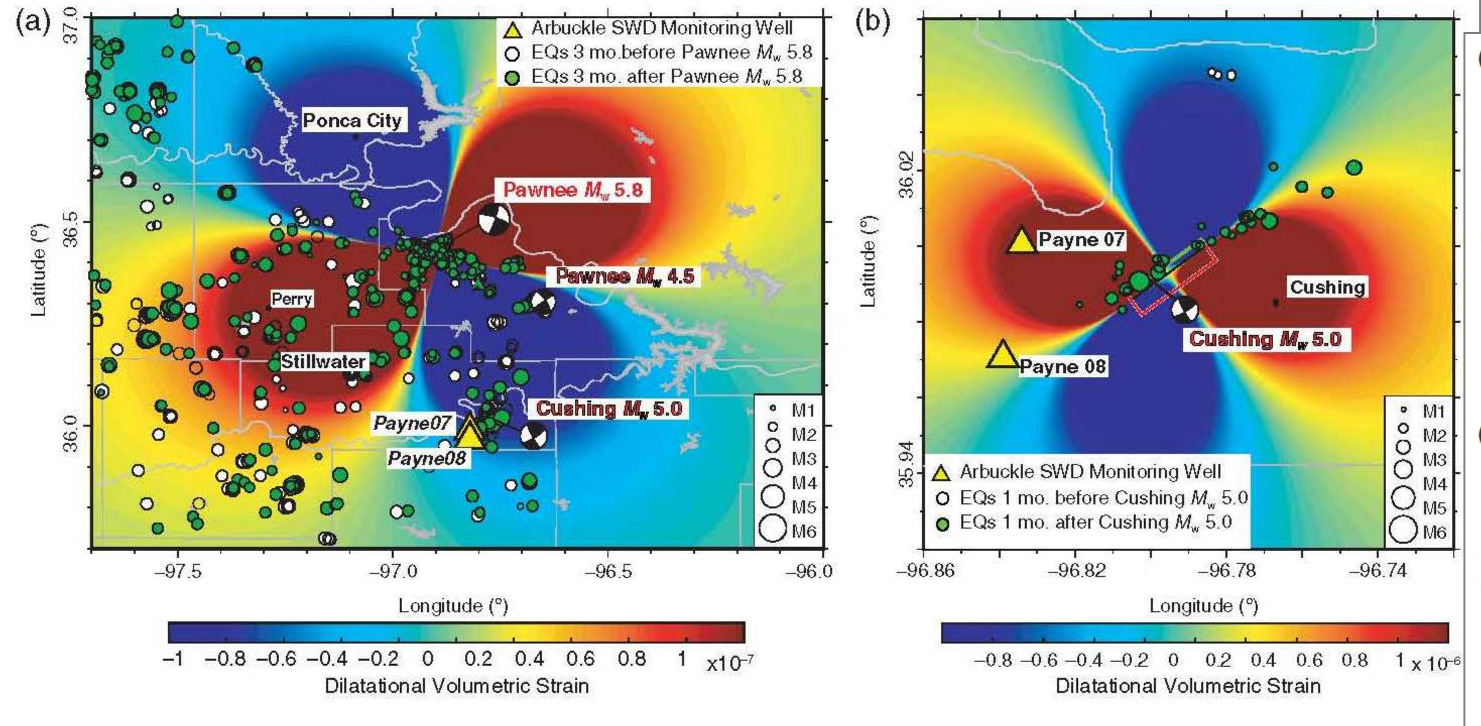
(Murray, et al., 2018 in preparation)

Seismic event (Stress) vs. Fluid level fluctuations (Strain)

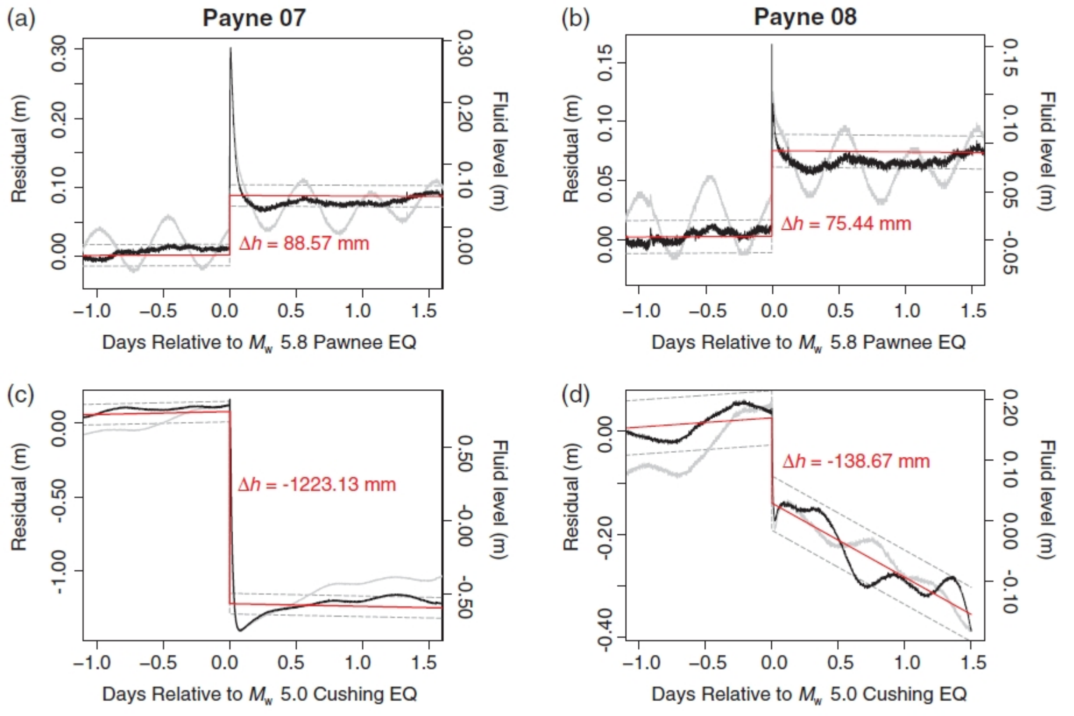
Poroelastic Properties of the Arbuckle Group in Oklahoma Derived from Well Fluid Level Response to the 3 September 2016 M_W 5.8 Pawnee and 7 November 2016 M_W 5.0 Cushing Earthquakes

by Kayla A. Kroll, Elizabeth S. Cochran, and Kyle E. Murray

Seismological Research Letters Volume 88, Number 4 July/August 2017

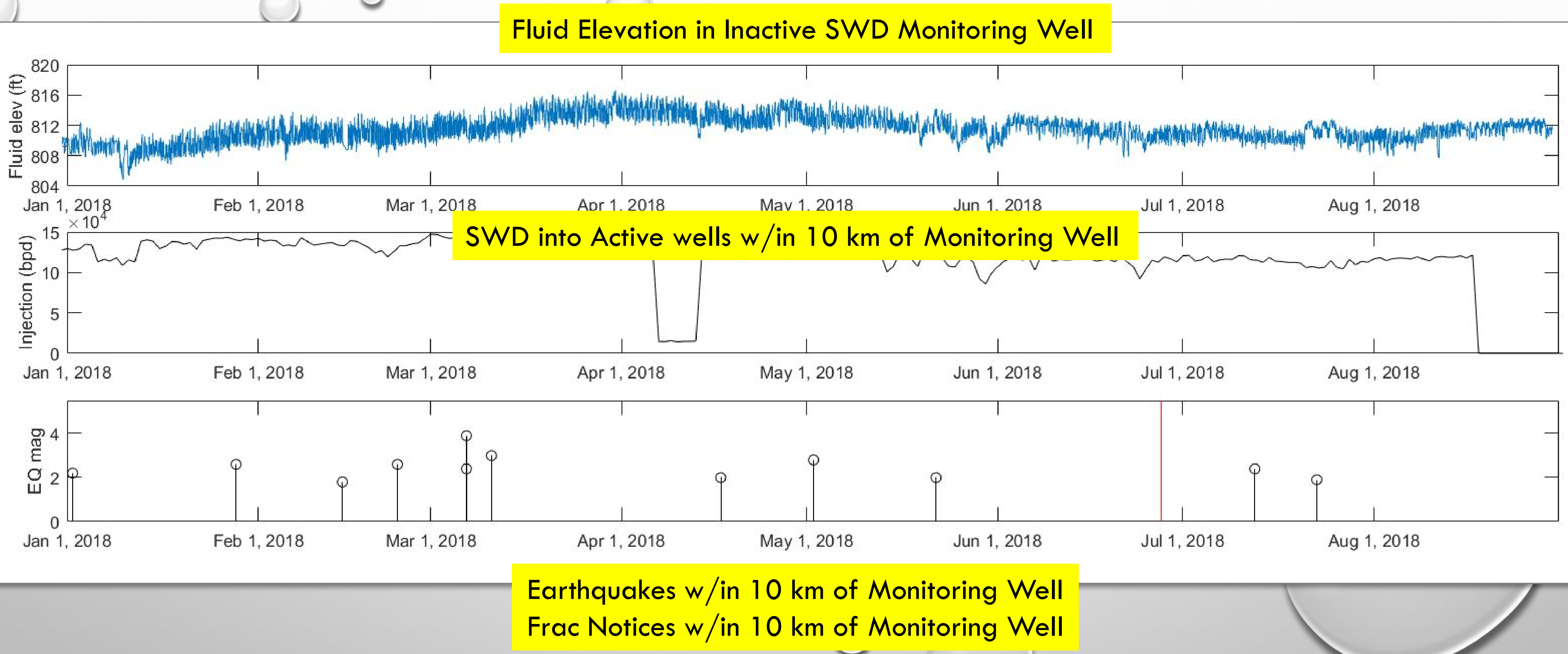


▲ **Figure 1.** Seismicity and volumetric strain change map associated with the 3 September 2016 M_w 5.8 Pawnee and 7 November 2016 M_w 5.0 Cushing, Oklahoma, earthquakes, computed for a receiver depth of 1.5 km. (a) Seismicity during the three months before (open circles) and after (green circles) the Pawnee earthquake, scaled by magnitude. Focal mechanisms for the three largest events provided by the National Earthquake Information Center (NEIC, see Data and Resources) catalog. (b) Seismicity during the month before and month after the Cushing earthquake. Background color in both figures is the static volumetric strain change computed with the Coulomb v.3.3 software, assuming the NEIC focal mechanism solution as the source orientation (see Data and Resources; Lin and Stein, 2004; Toda *et al.*, 2005, 2011).



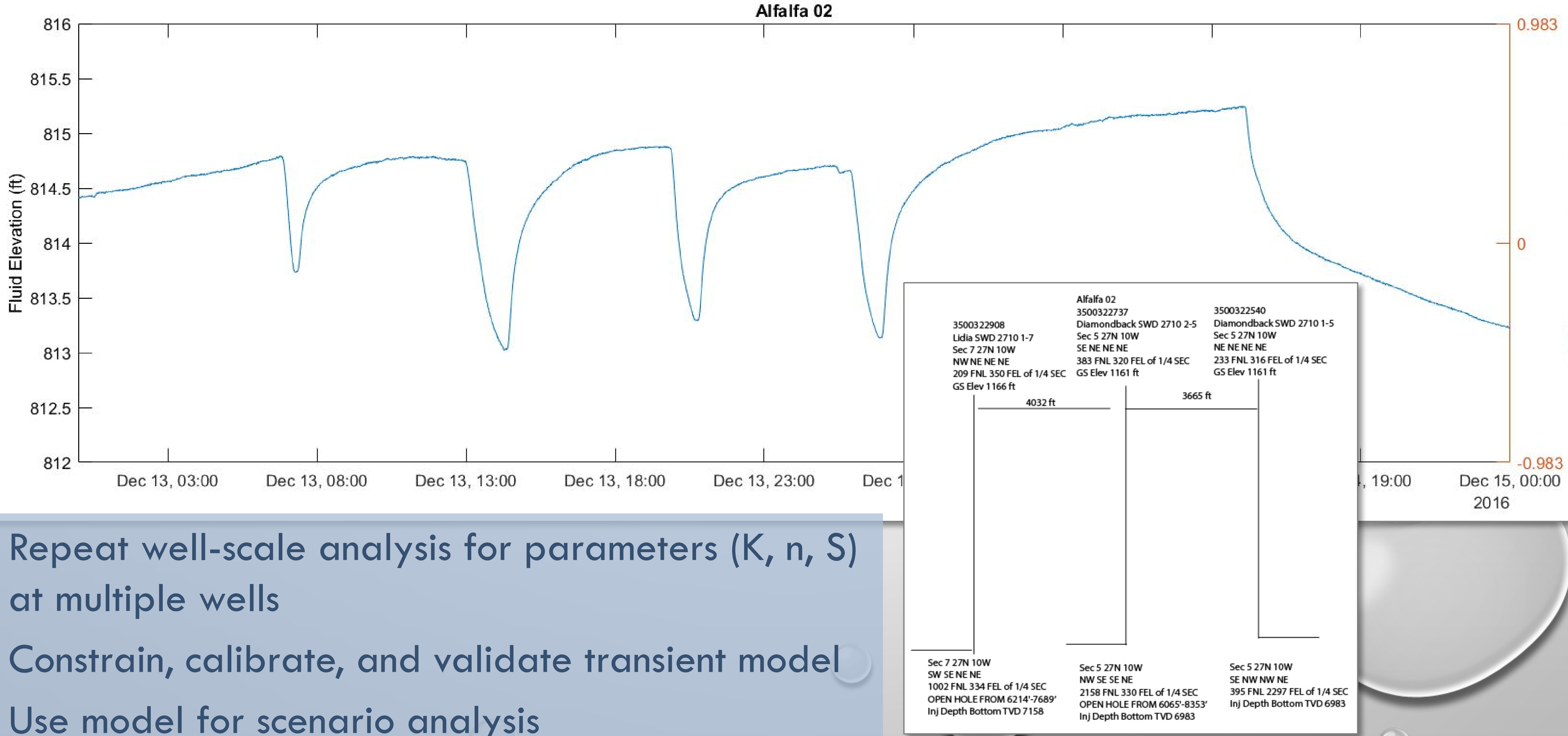
▲ **Figure 2.** Residual fluid level response (black, left axes scale) of the Arbuckle Group after removing barometric and solid Earth tide effects around the time of the M_w 5.8 Pawnee (top) and M_w 5.0 Cushing (bottom), Oklahoma, earthquakes, and relative fluid level before removing tidal signal (gray, right axes scale). The Heaviside fit to the residual coseismic offset is shown in red with the amplitude Δh indicated along with the 95% confidence intervals (gray dashed). Both wells show a positive fluid level increase due to the Pawnee event, and a larger amplitude fluid level decrease due to the Cushing event.

Alfalfa 02 with radius of 10 km



(Murray, et al., 2018 in preparation)

Observed Head at Alfalfa 02 w/ Injection Effects from nearby well

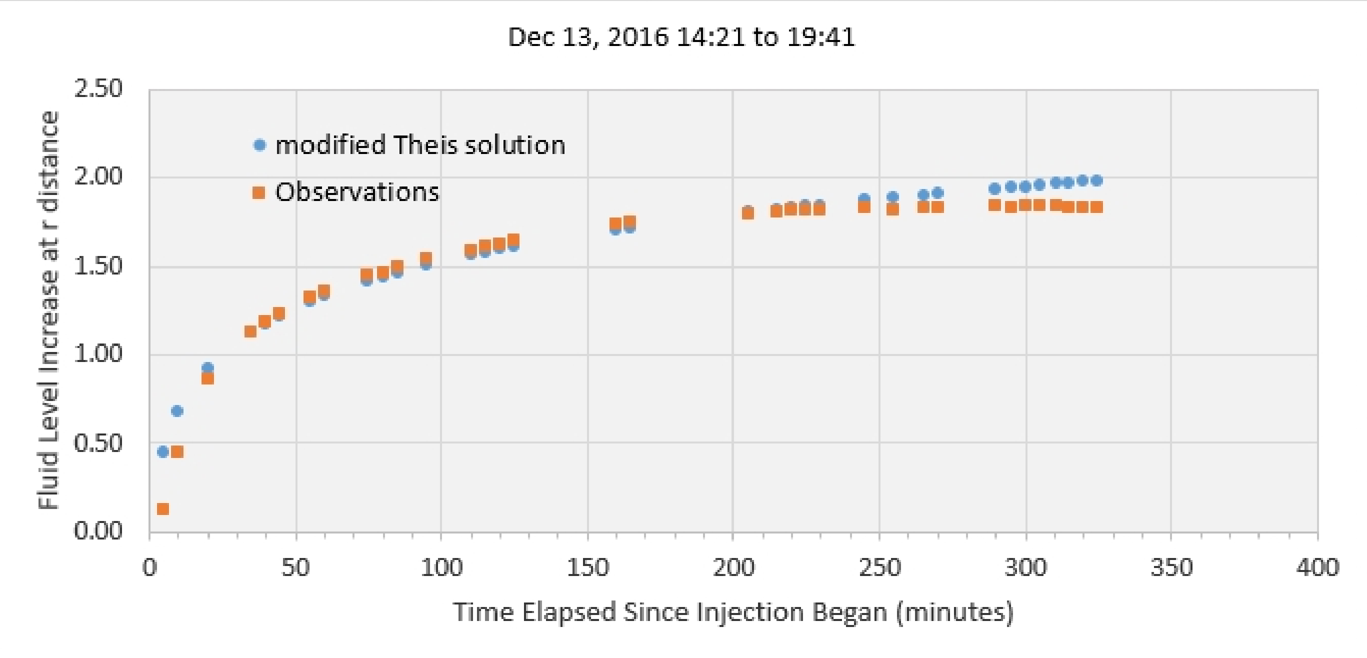


- Repeat well-scale analysis for parameters (K, n, S) at multiple wells
- Constrain, calibrate, and validate transient model
- Use model for scenario analysis

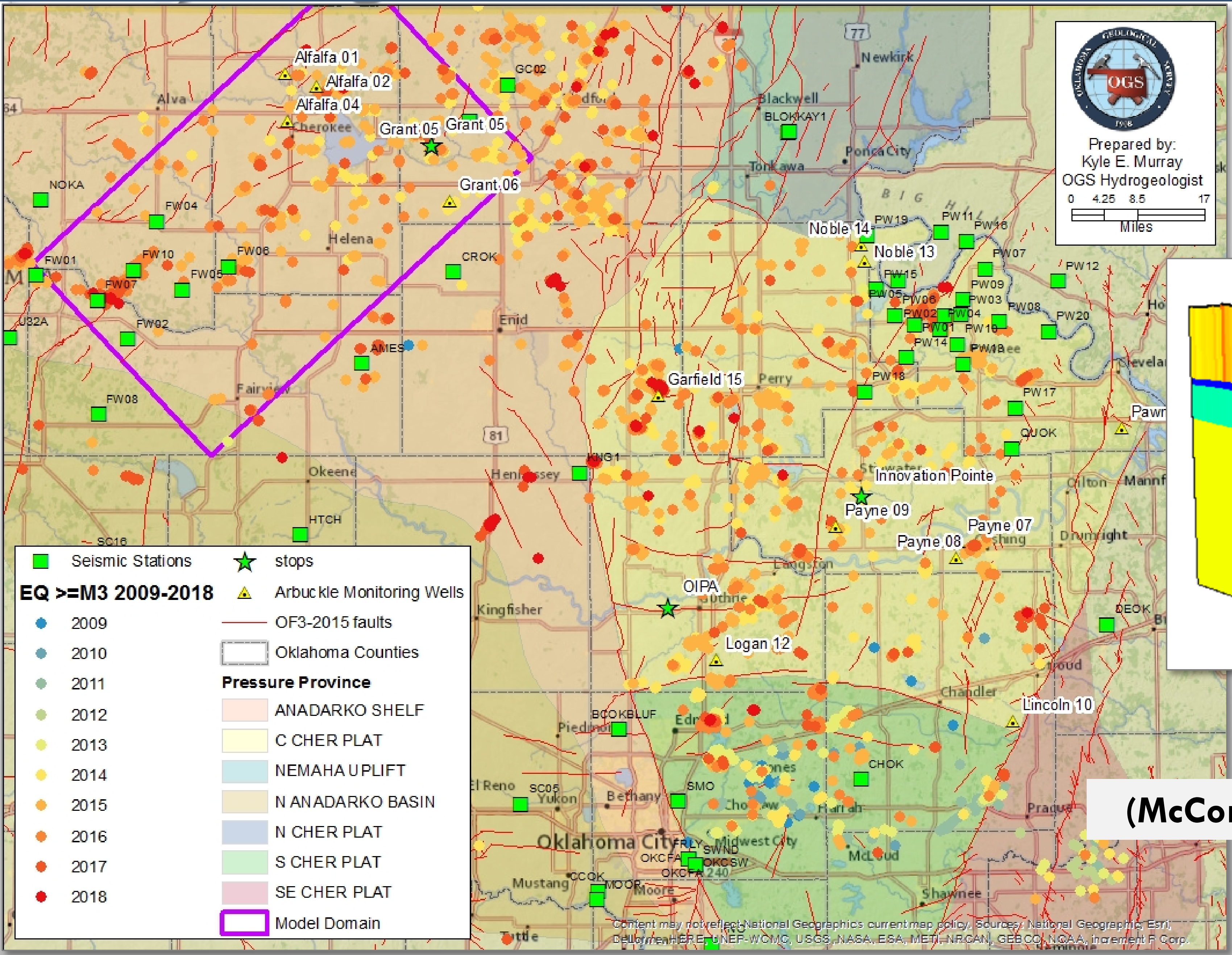
(Murray, et al., 2018 in preparation)

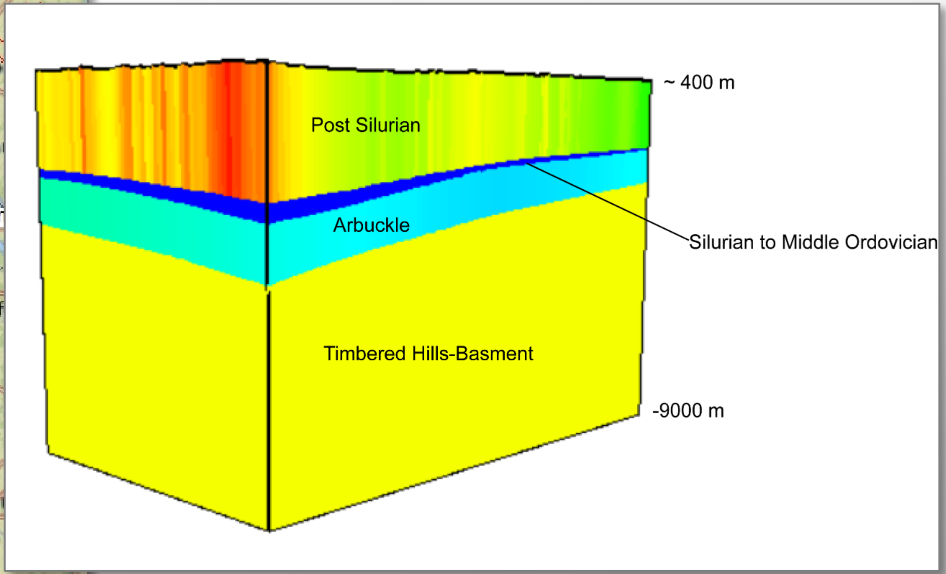
Modified Theis Solution for Estimating Hydraulic Properties

measured in well or based on well completion, field data									
adjust to calibrate									
calculated value									
published values									
textbook									
	1/(psi-1 * 6894.75)=m2/N								
	6894.757293								
	cw	m1	p (psi)	m2	C (g/L NaCl)	m3	T (deg F)	m4	
cw (psi-1)	318592.206	7.033	3218.8335	541.5	0.1	-537	200	403300	Osif (1988)
				ppm NaCl ->	100000				
		Distance between 2D Inj and 2D obs, ft	400.0	~3665 ft					
TDS of H2O		porosity, n	0.050		0.05 to 0.15, Carrell, 2014				
		Hydraulic Conductivity, K, ft/day	7.0						
inj TVD top	6115	compress of reservoir, Beta p, m2/N	1.65378E-11		1/Ku = 1.65378E-11 (Kroll et al., 2017); 10-8 to 10-10 m2/N, Carrell, 2014; 3.02E-7 psi-1 Perilla, 2017				
inj TVD bot	6983								
Press. Gradient, psi/ft	0.4915	compress of fluid, Beta f, m2/N	4.55E-10		Osif, 1988 a function of temp, NaCl salinity, pressure				
		Reservoir/Aquifer Thickness, b, ft	868.0	<868 ft					
antecedent BPD	15391	Transmissivity, T, ft^2/day	6076.0						
injection BPD	20649	Storage Coefficient, S	1.16E-04	m2/s					
delta BPD during inj	5259	Diffusivity, D (ft^2/day)	5.24E+07	56.390	ft2/day * unit conversions (1.07516E-6) = m2/s; 0.005 m2/s Barbour et al, 2017				
		Injection Rate, ft^3/day	29528						
		Specific Storage, Ss, ft-1	1.33E-07	4.38E-07	m-1 * unit conversions (0.3048); 1.39 E-6 m-1 Perilla, 2017				
		density of fluid, kg/m3	1136	2311.665532	psi/ft * unit conversions (2311.665532)				
		specific weight, kN/m3	11143						



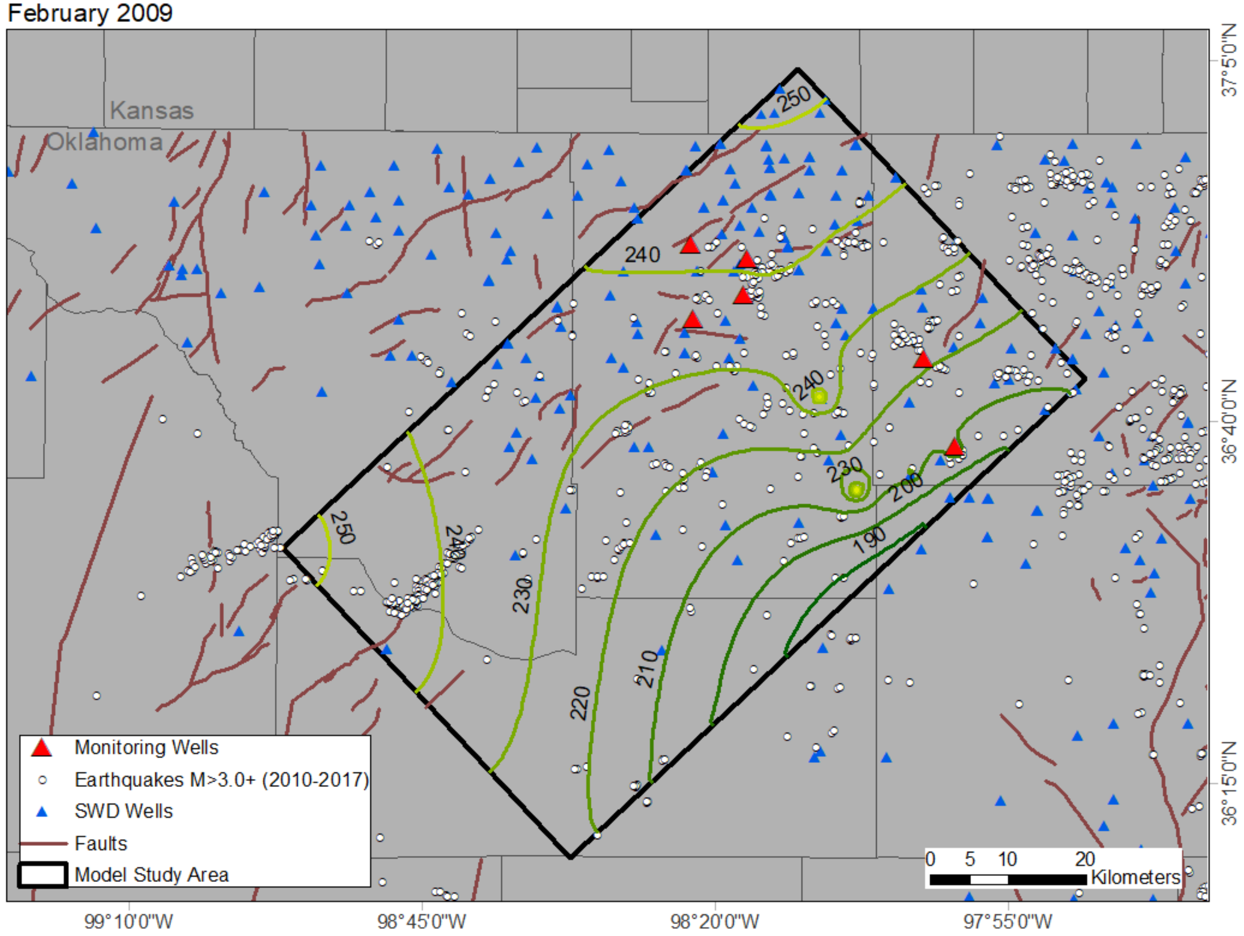
Calibrated Model of Stress (Injection) & Strain (Observed Head)

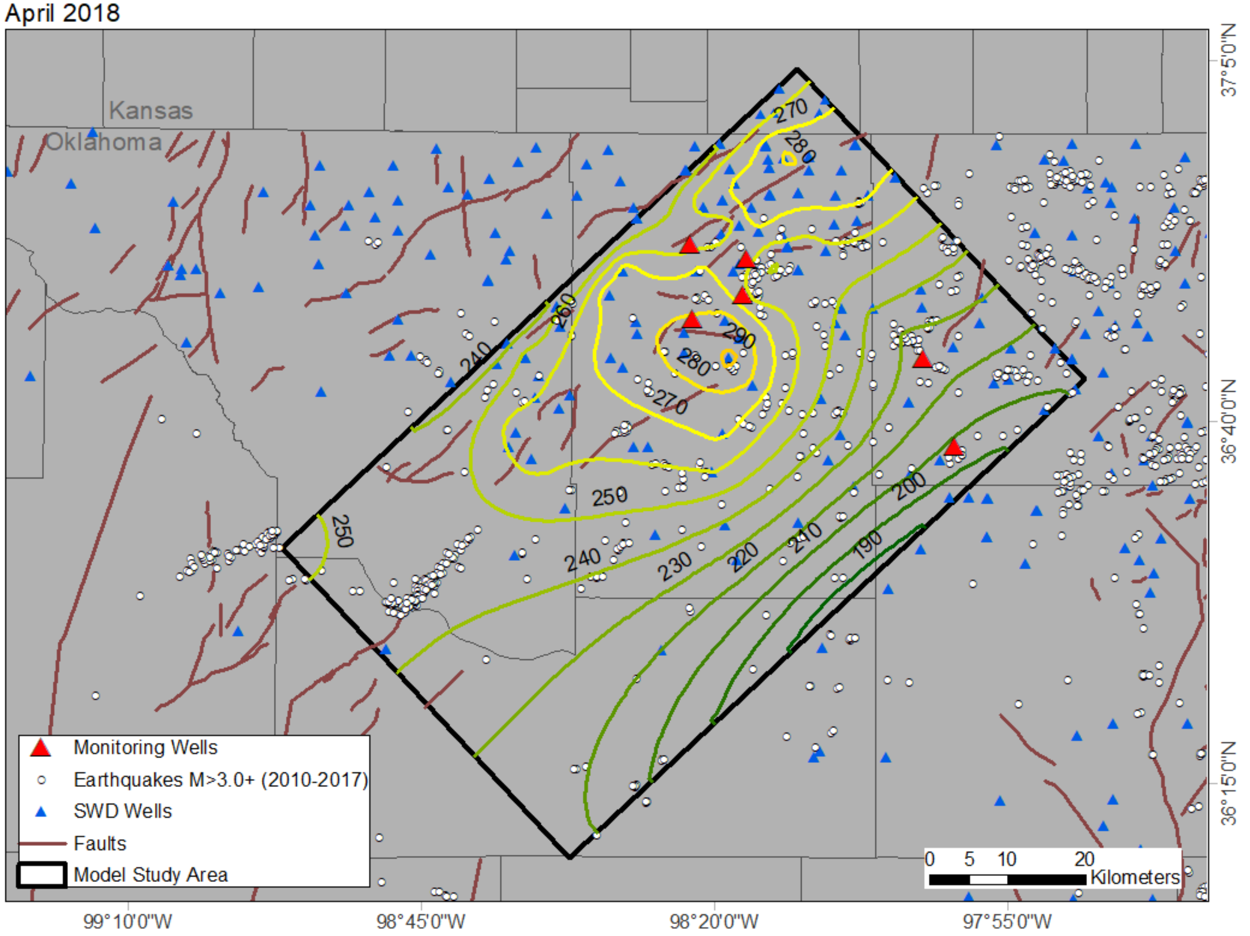




(McConville & Murray, 2018 in preparation)

Transient Model Results – Feb 2009 vs. Apr 2018





Future Research RE: Subsurface Pressure in Seismogenic Areas (OK)

- Conduct injection tests with high-res monitoring
  - Define Hydraulic Properties
  - Relate Microseismicity to Injection Scenarios
- Improve Top Arbuckle and Top Basement Maps
- Refine Arbuckle "Initial Conditions" (Puckette, 1996)
- Instrument Basement Wells (DISCO)
  - Define Hydraulic Properties
  - Establish Pressure Regime/Trends
- Construct Integrated Hydrogeologic/Geomechanical/Seismological Model
- Provide Up-To-Date Decision Support Tool for Operators & Regulators