EIA 2017 Energy Conference
The Energy-Water Nexus and Induced Seismicity
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WATER-ENERGY NEXUS, PRESSURE MONITORING & PRODUCED WATER MANAGEMENT CHALLENGES

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OKLAHOMA GEOLOGICAL SURVEY 1908 OGS

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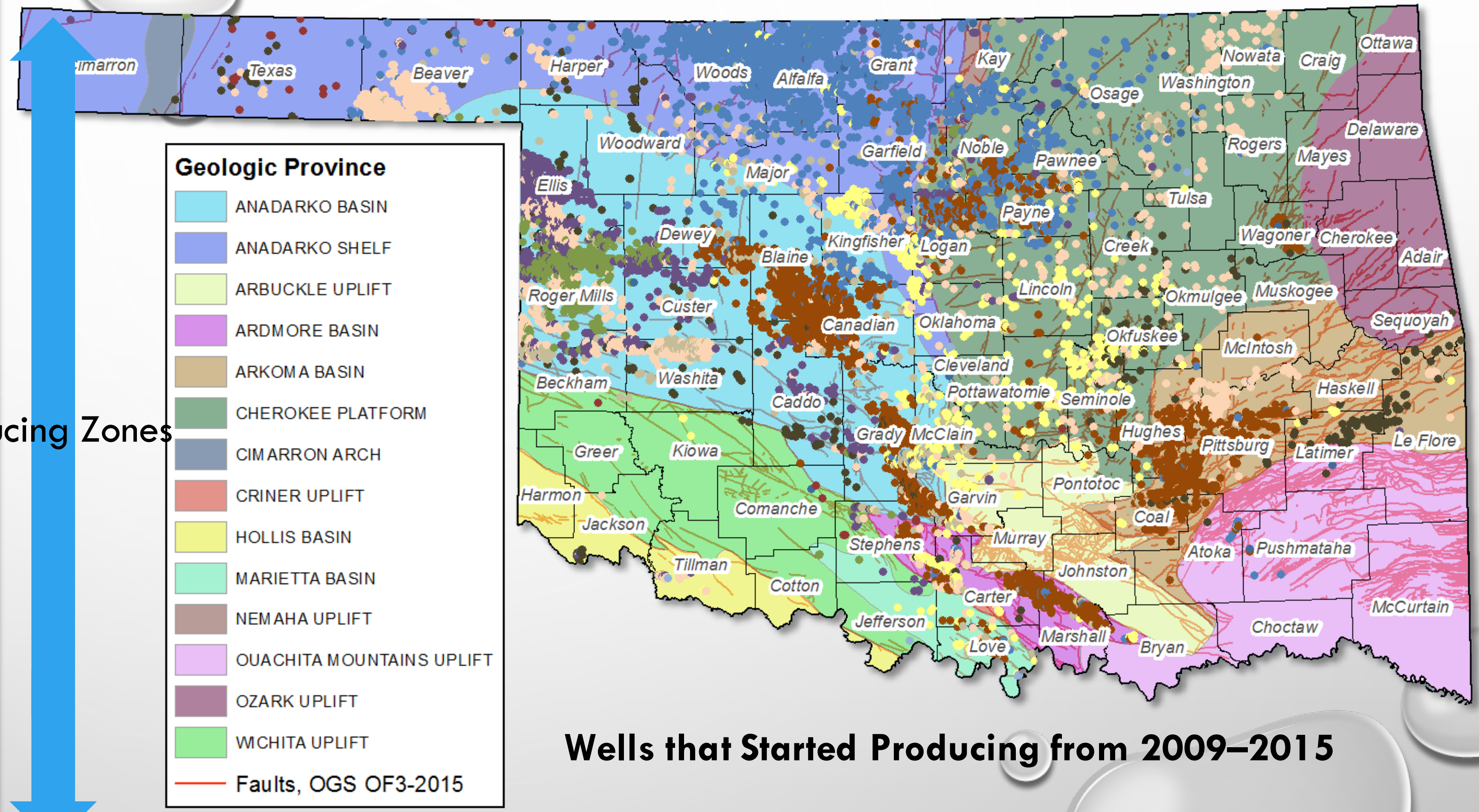
Geologic Zones Targeted for Production, Injection, & Disposal

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

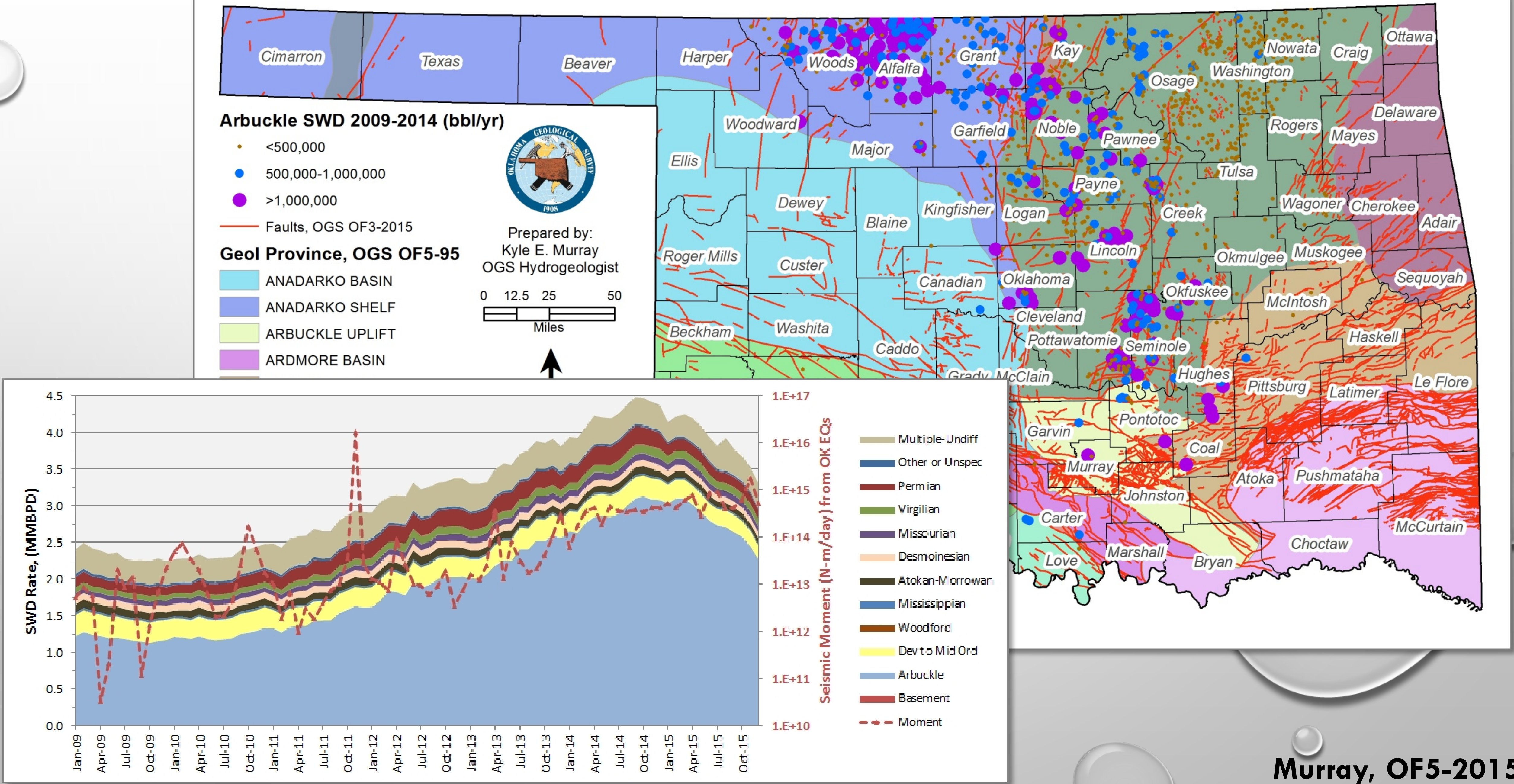


Wells that Started Producing from 2009–2015

Predominant Disposal Zone, avg of 2 km depth

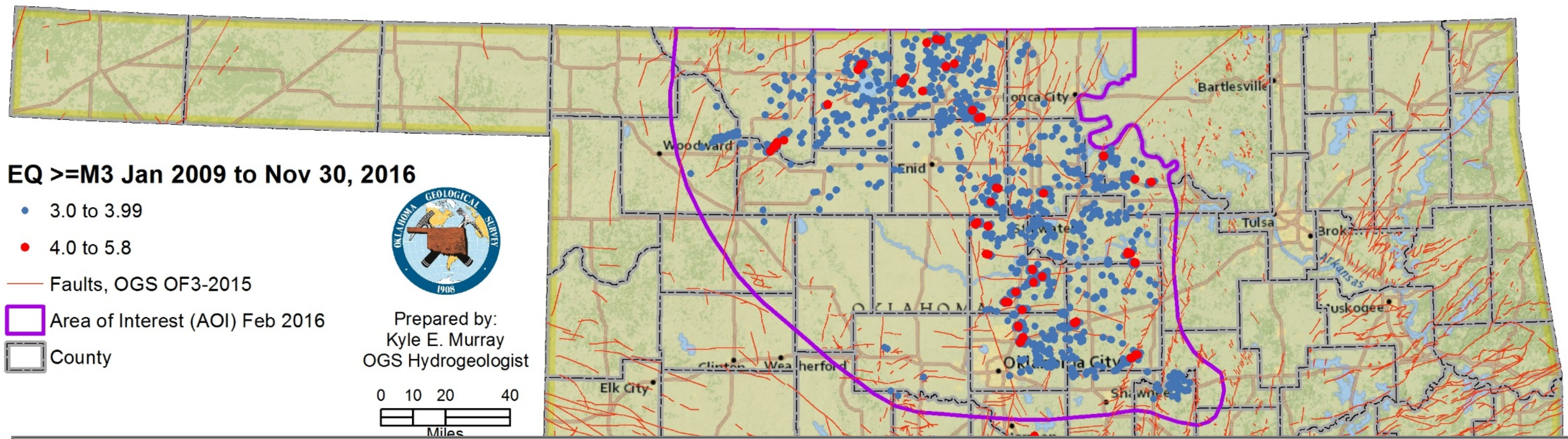
Earthquakes Down Here, avg of 5.5 km depth

SWD in Oklahoma, 2009–2015 w/ map of Arbuckle SWD, 2009–2014



Murray, OF5-2015

Earthquakes of Magnitude ≥3.0 from 1/1/2009 to 5/7/2017

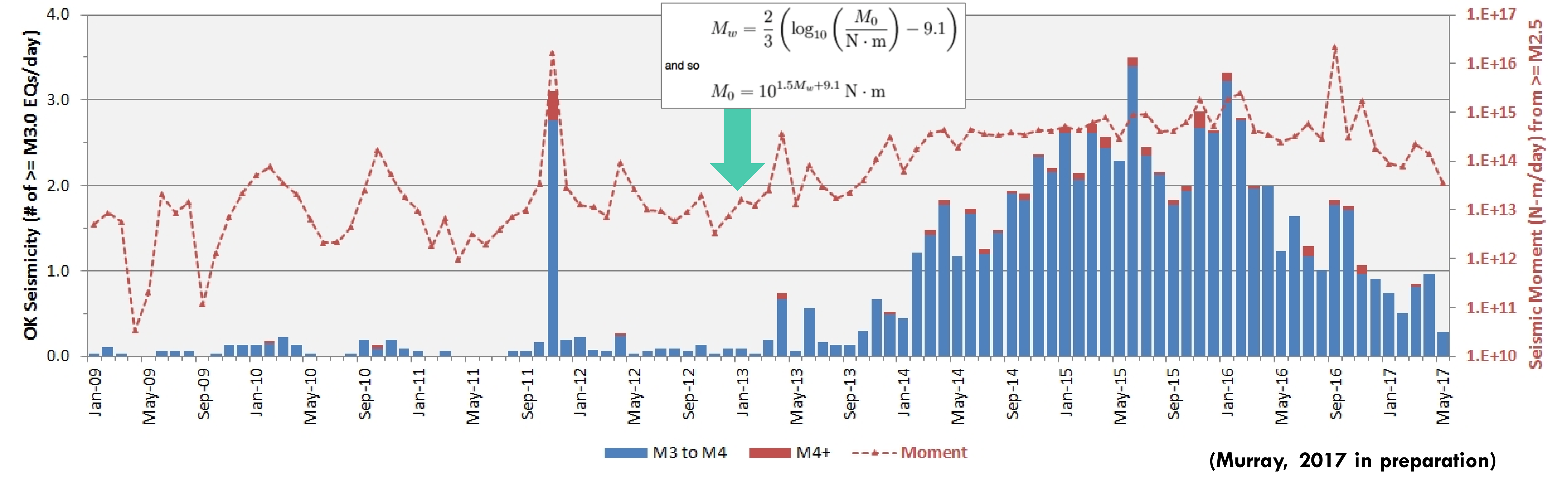


3 Sep 2016 M5.8 Pawnee
1 Nov 2016 M4.3 Pawnee
6 Nov 2016 M5.0 Cushing

$$M_w = \frac{2}{3}\left(\log_{10}\left(\frac{M_0}{\mathrm{N\cdot m}}\right) - 9.1\right)$$

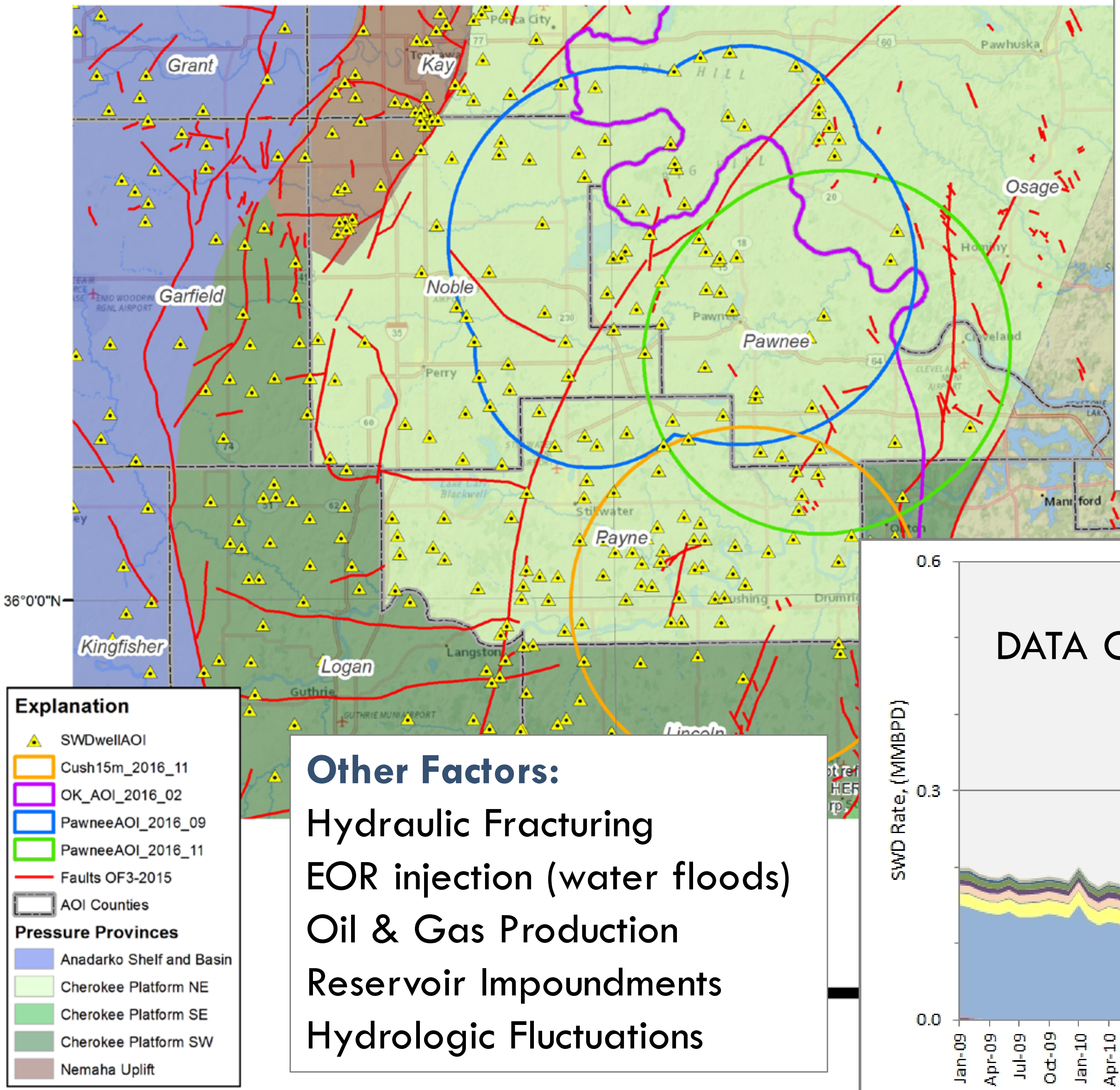
and so

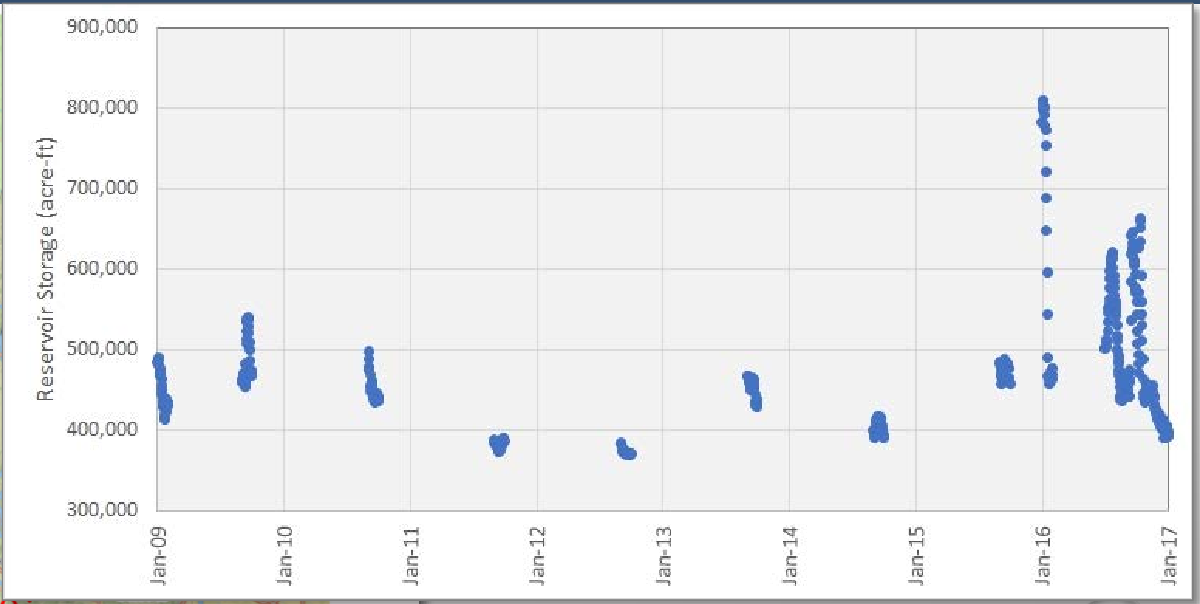
$$M_0 = 10^{1.5M_w+9.1}\ \mathrm{N\cdot m}$$



(Murray, 2017 in preparation)

OCC & EPA Volume Reduction Areas after Pawnee & Cushing





Other Factors:

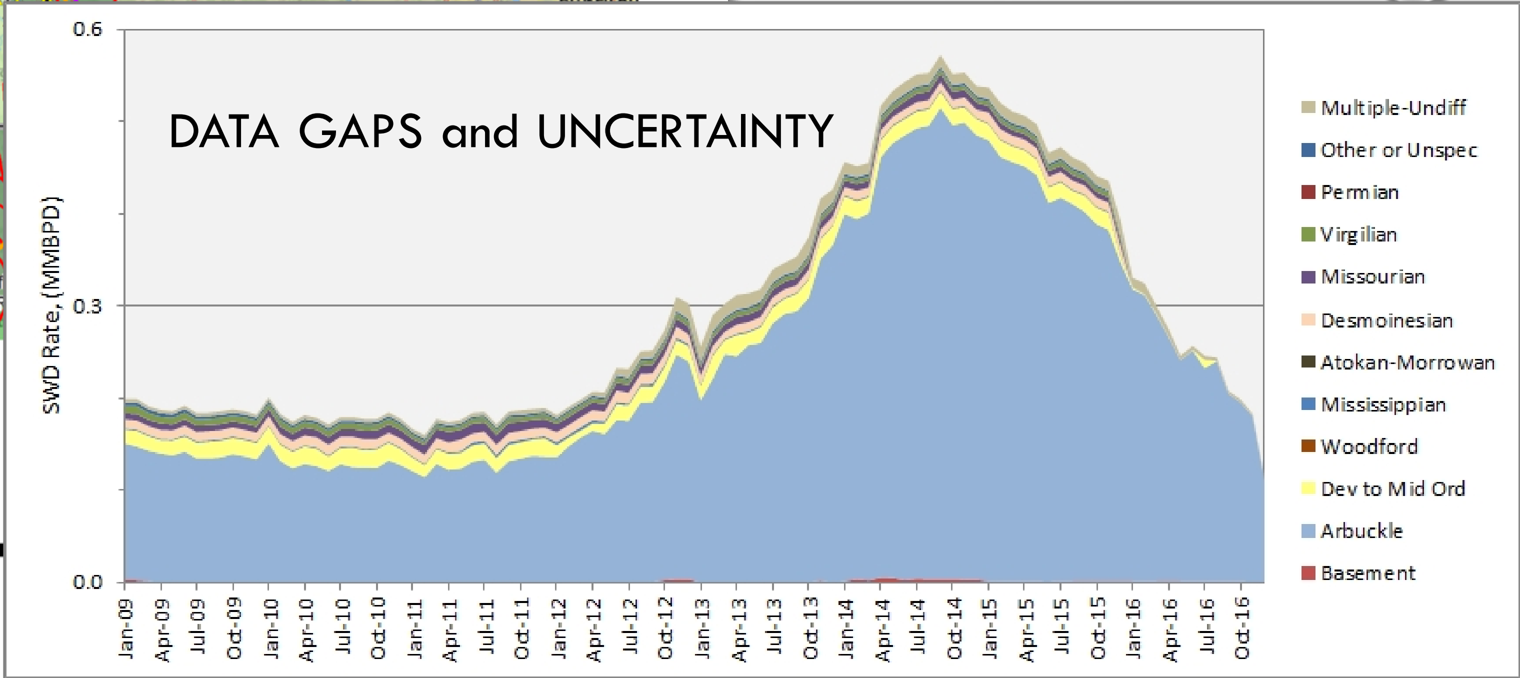
Hydraulic Fracturing

EOR injection (water floods)

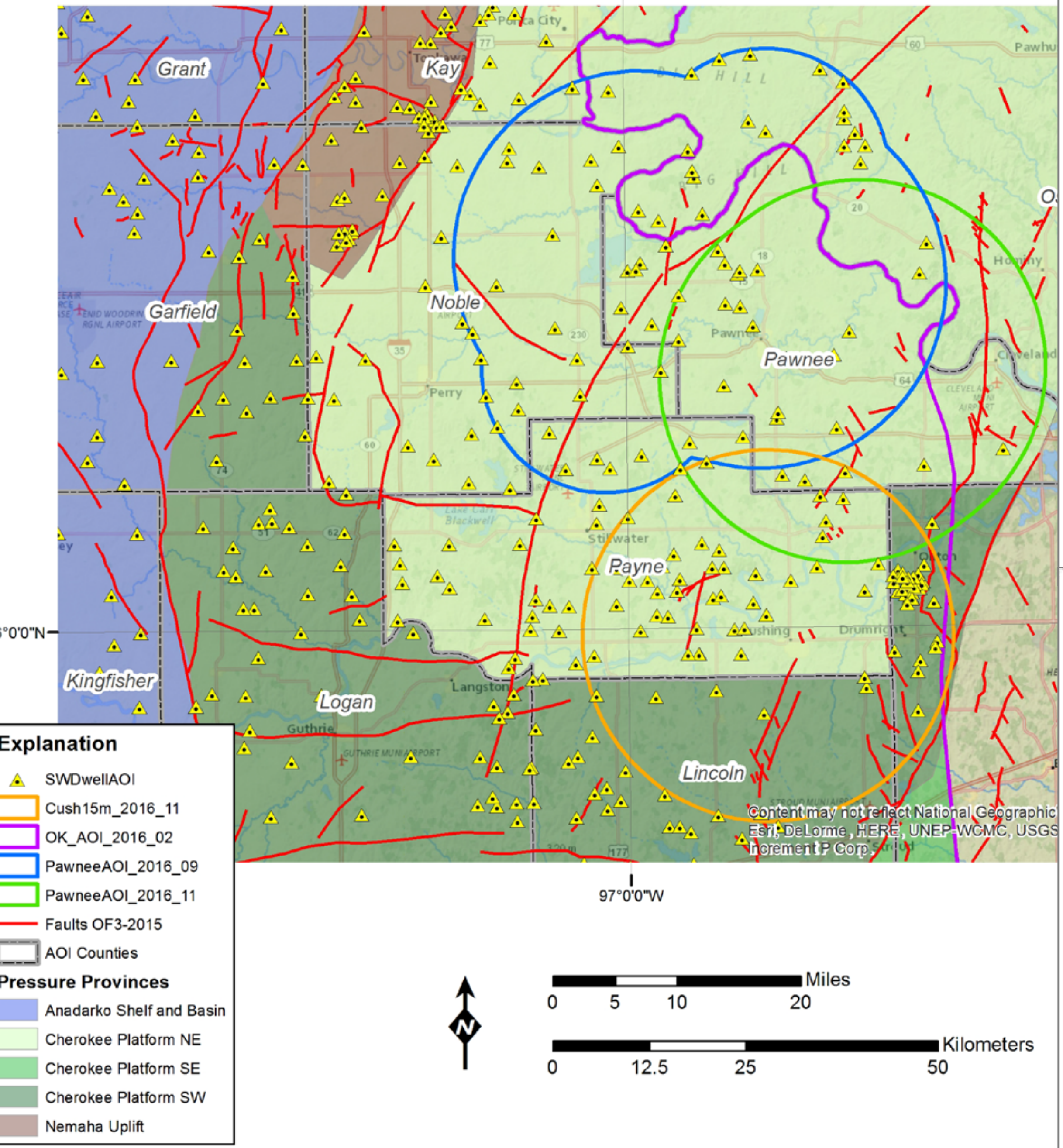
Oil & Gas Production

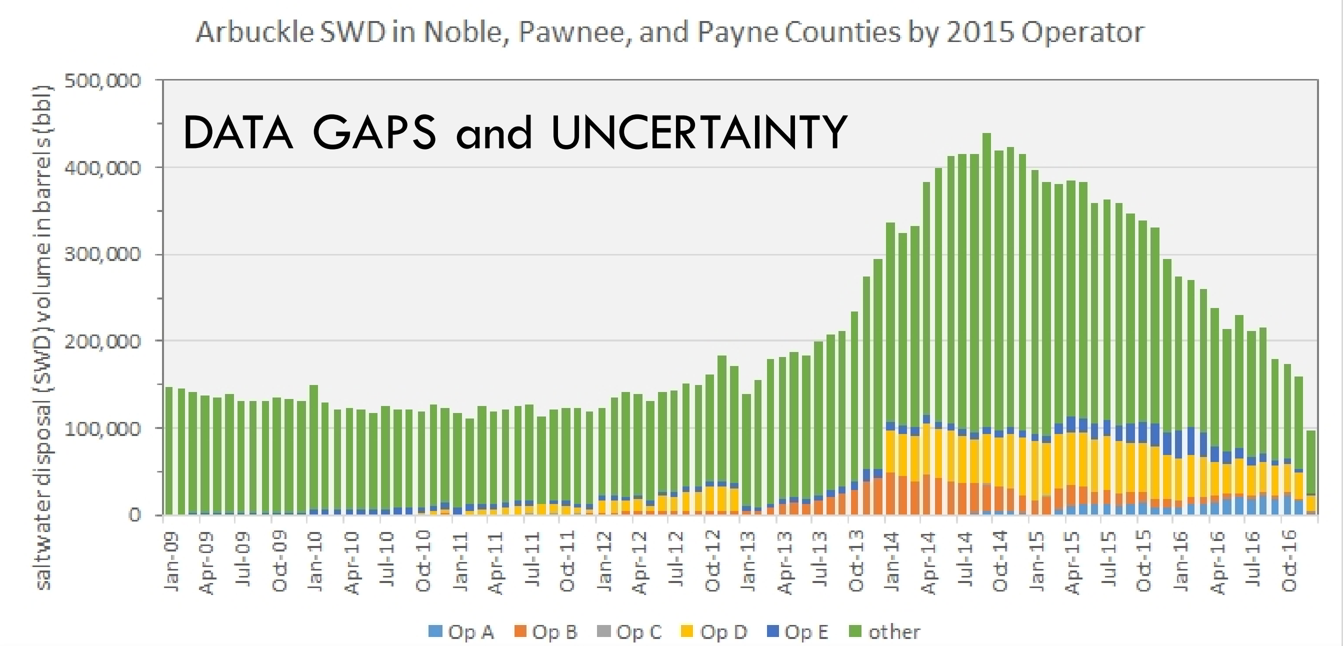
Reservoir Impoundments

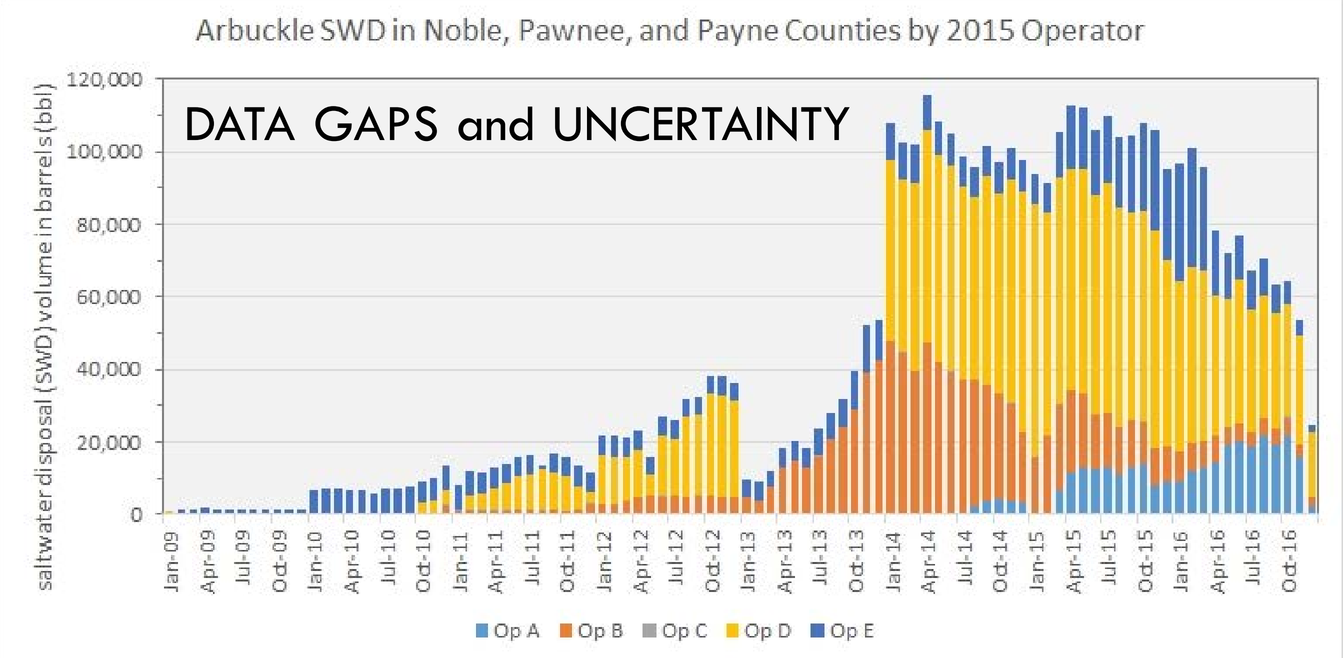
Hydrologic Fluctuations



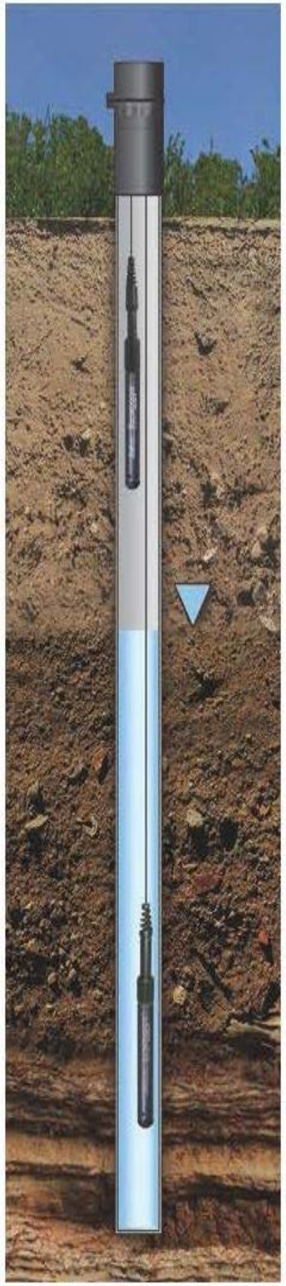
Arbuckle SWD History in Noble, Pawnee, and Payne Counties



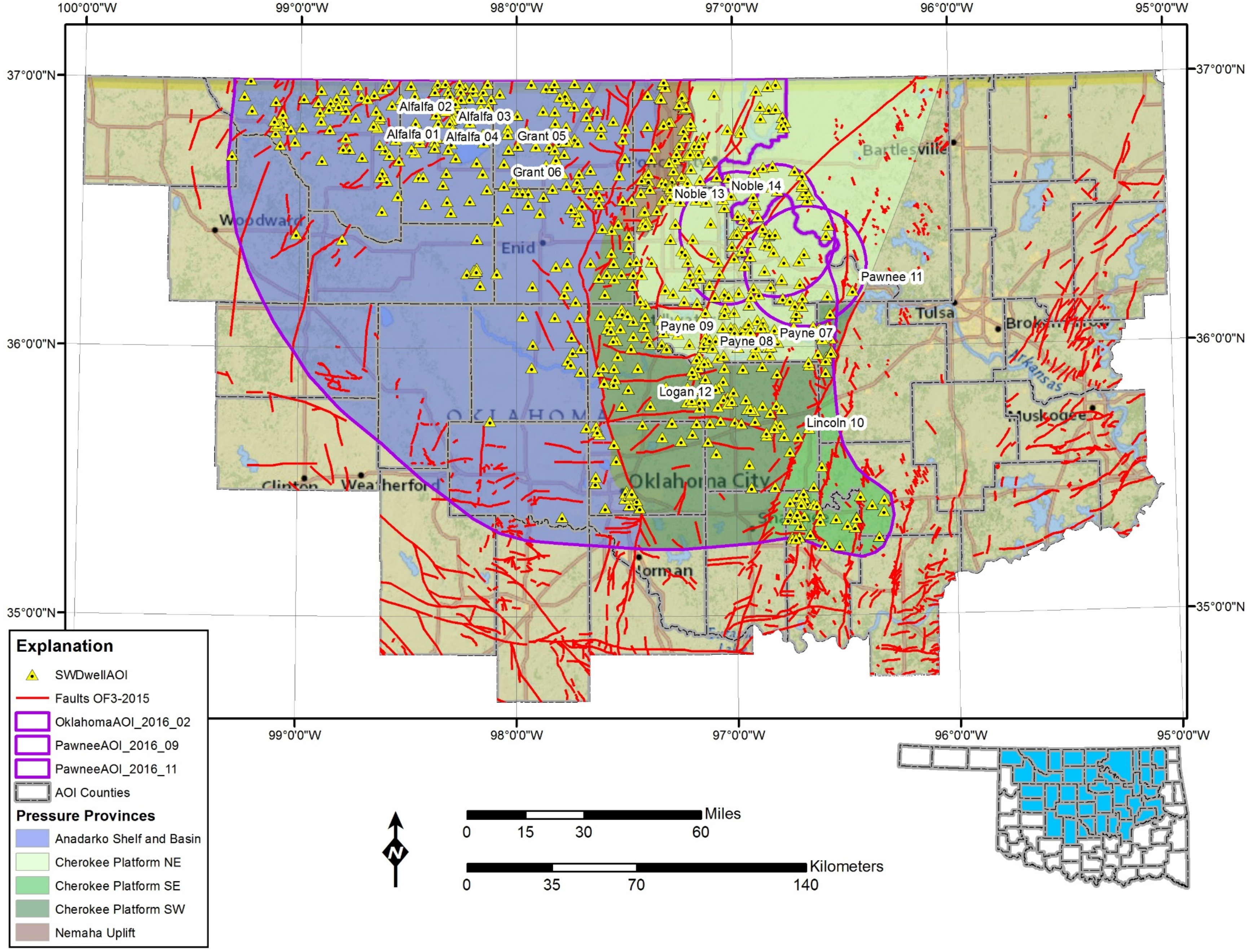




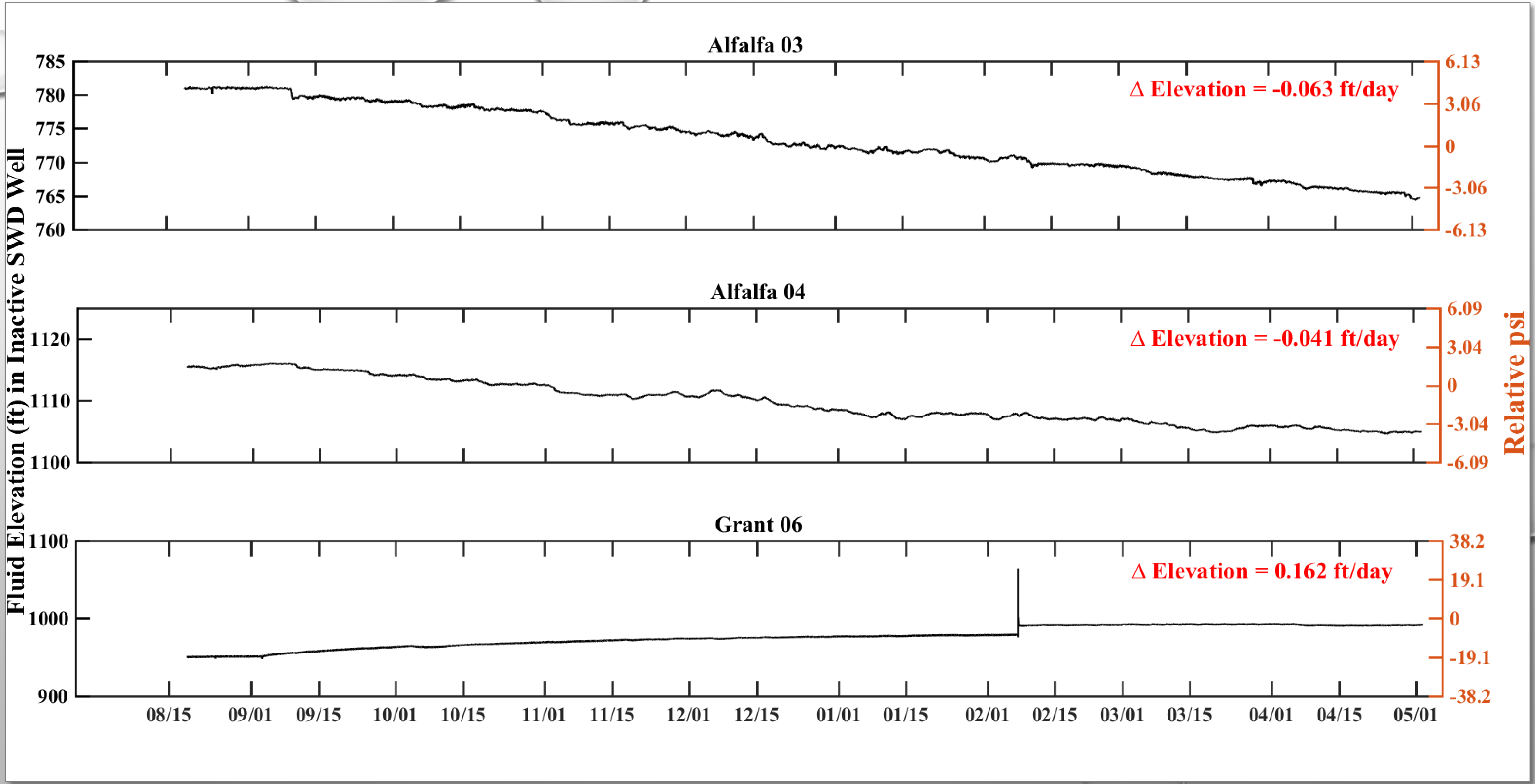
Arbuckle Pressure Monitoring, Wellhead Configuration and Deployment



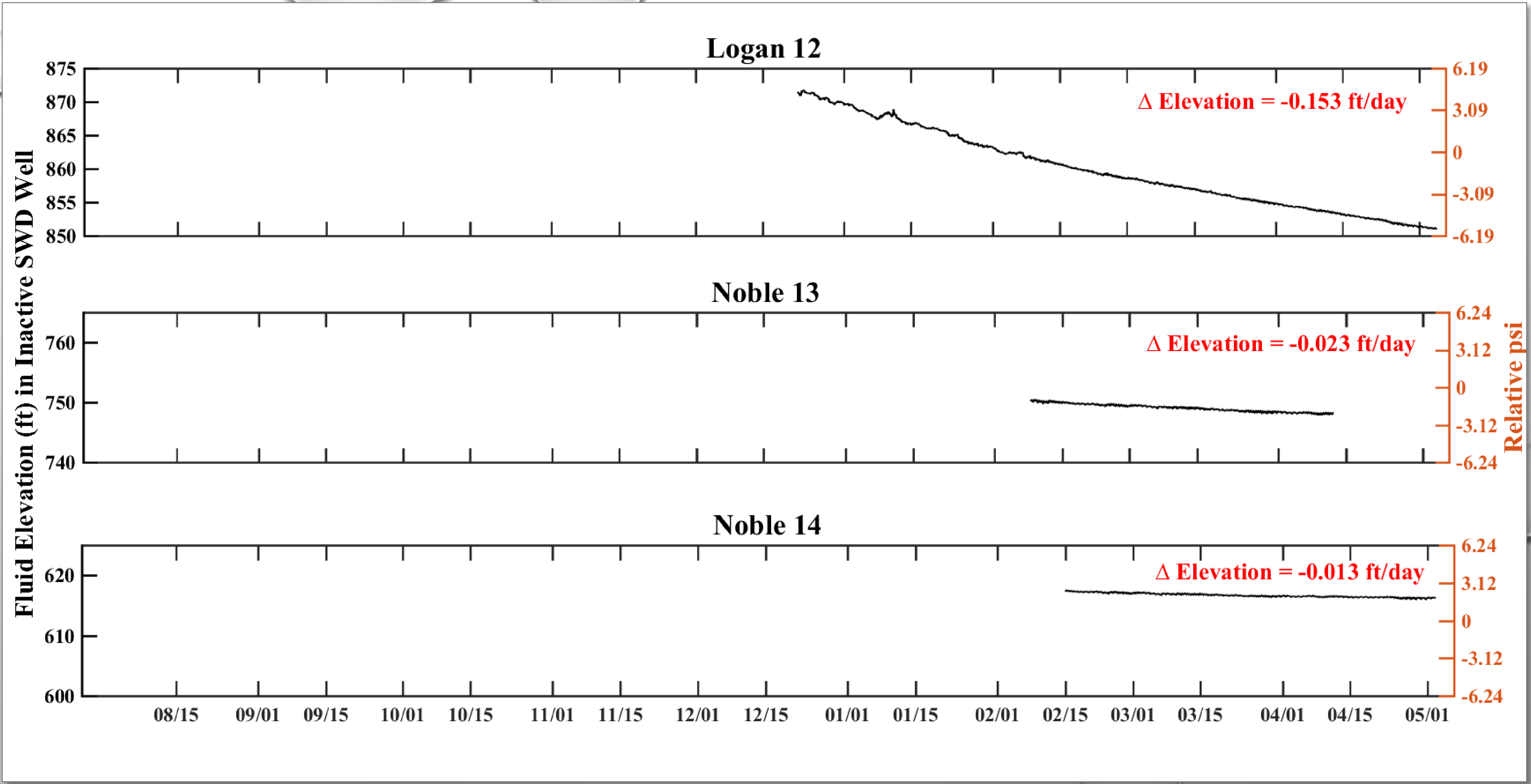
Arbuckle Pressure Monitoring, instrumented wells are labeled



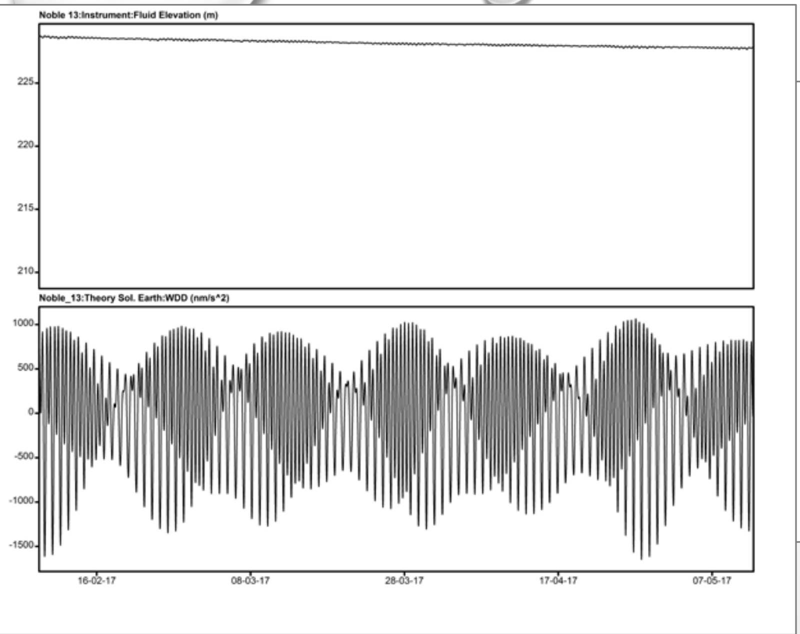
Anadarko Shelf wells w/o injection effects (Alfalfa 03, Alfalfa 04, Grant 06)

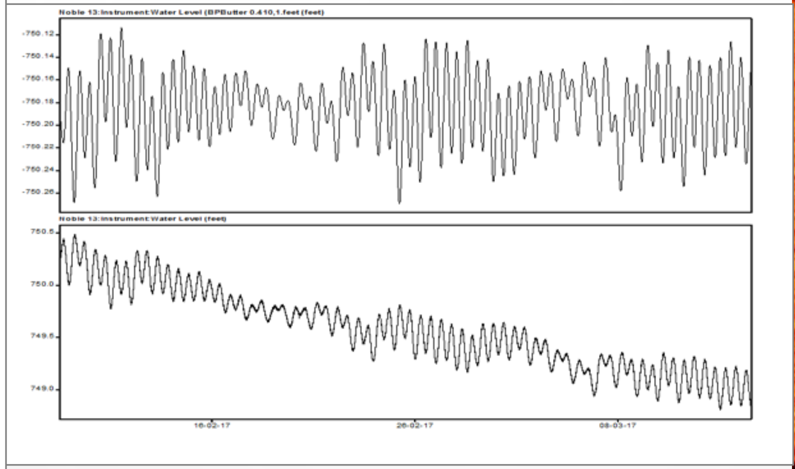


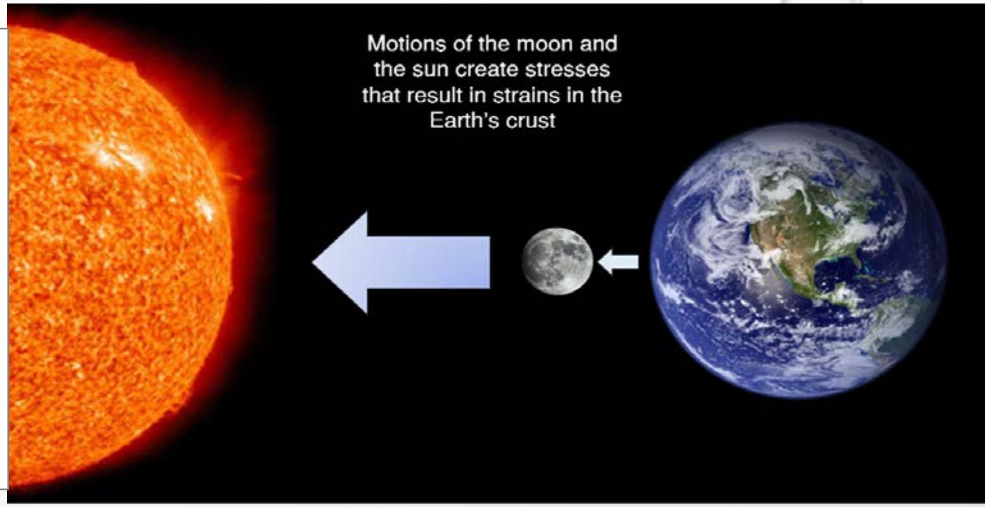
Cherokee Platform wells w/o injection effects (Logan 12, Noble 13, Noble 14)



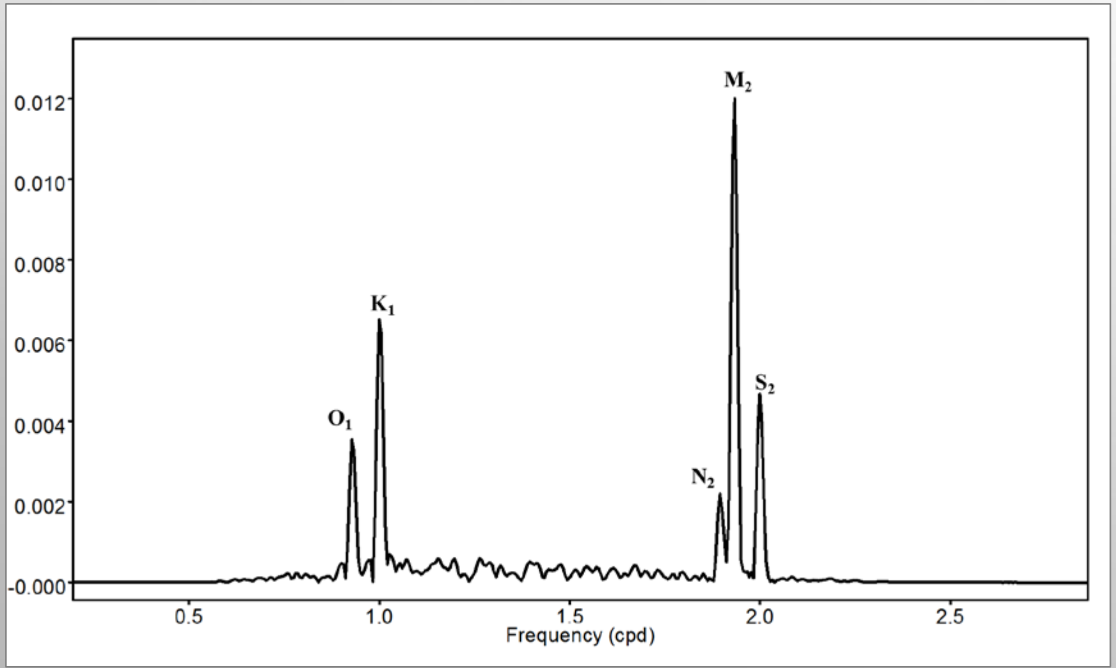
Solid Earth Tide Analysis with Tsoft (Van Camp and Vauterin, 2005)







Schematic diagram of the gravitational effects of the Sun and the Moon in the Earth's crust.



- 95% of the solid earth tidal strain is the result of five main tidal components
- Some of the tidal components are influenced by atmospheric and earth tide stresses; however, it is more reliable to use components O_1 and M_2

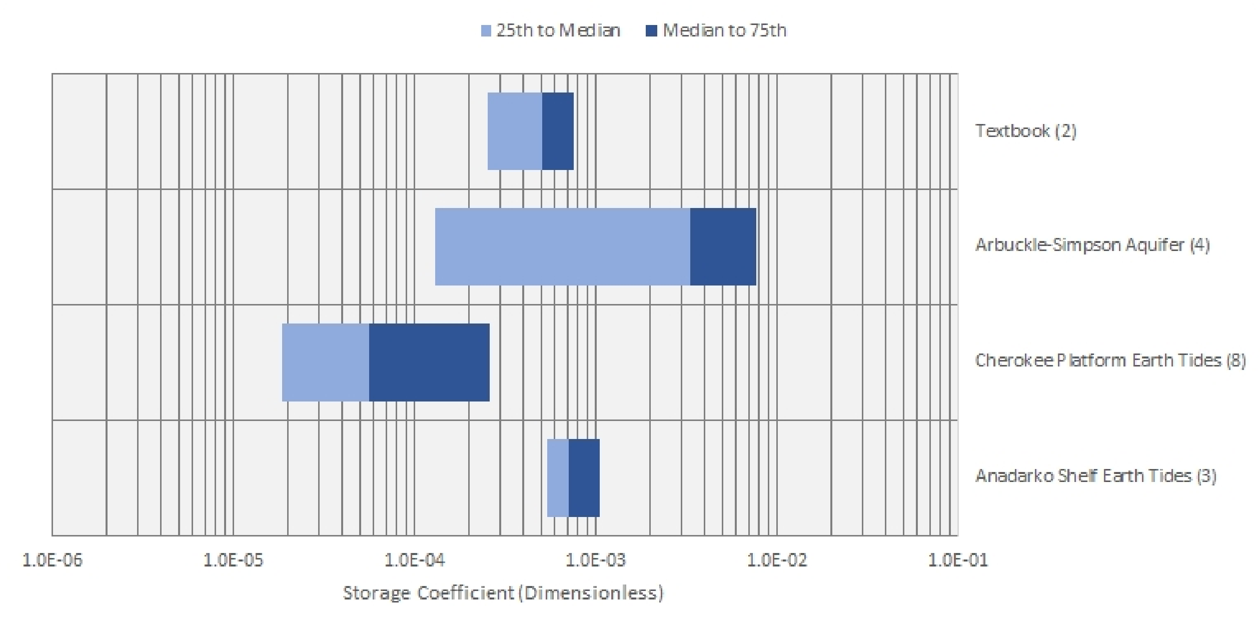
Table 2
Major Harmonic Components of the Tidal Potential (Munk and MacDonald 1960)

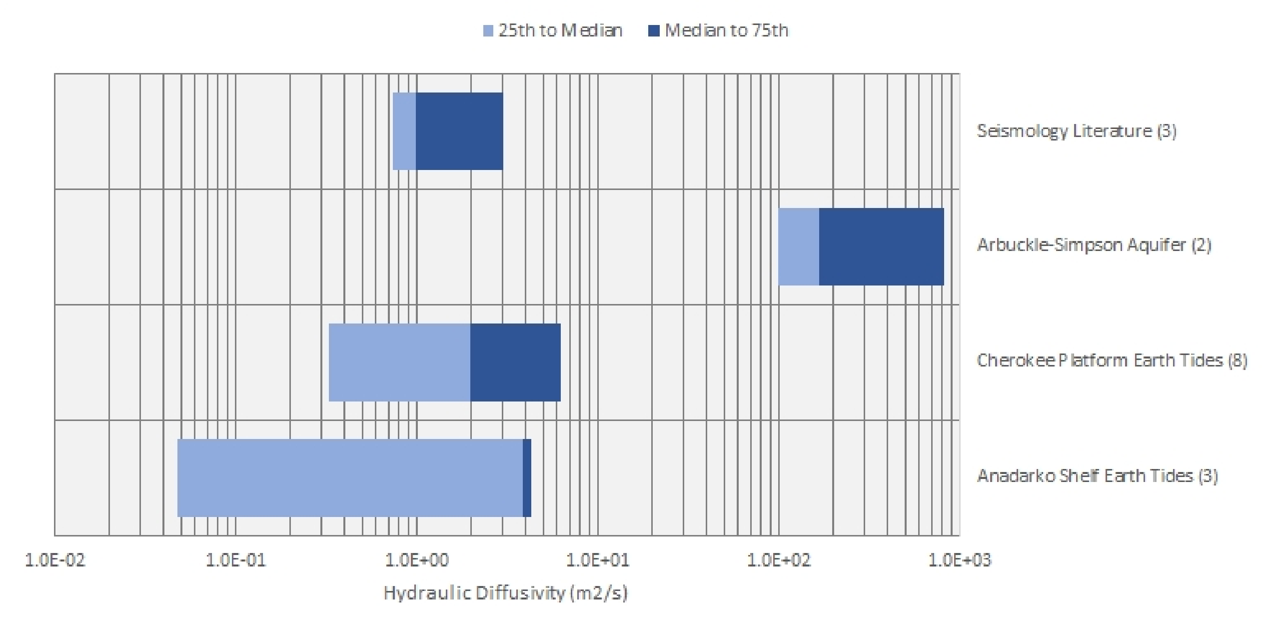
Tidal component	Period (d)	Frequency (cpd)	Description
O_1	1.0758	0.9295	Principal lunar
K_1	1.3721	1.0029	Lunar-solar
M_2	0.5175	1.9324	Principal lunar
S_2	0.5000	2.0000	Principal solar
N_2	0.5275	1.8957	Lunar elliptic

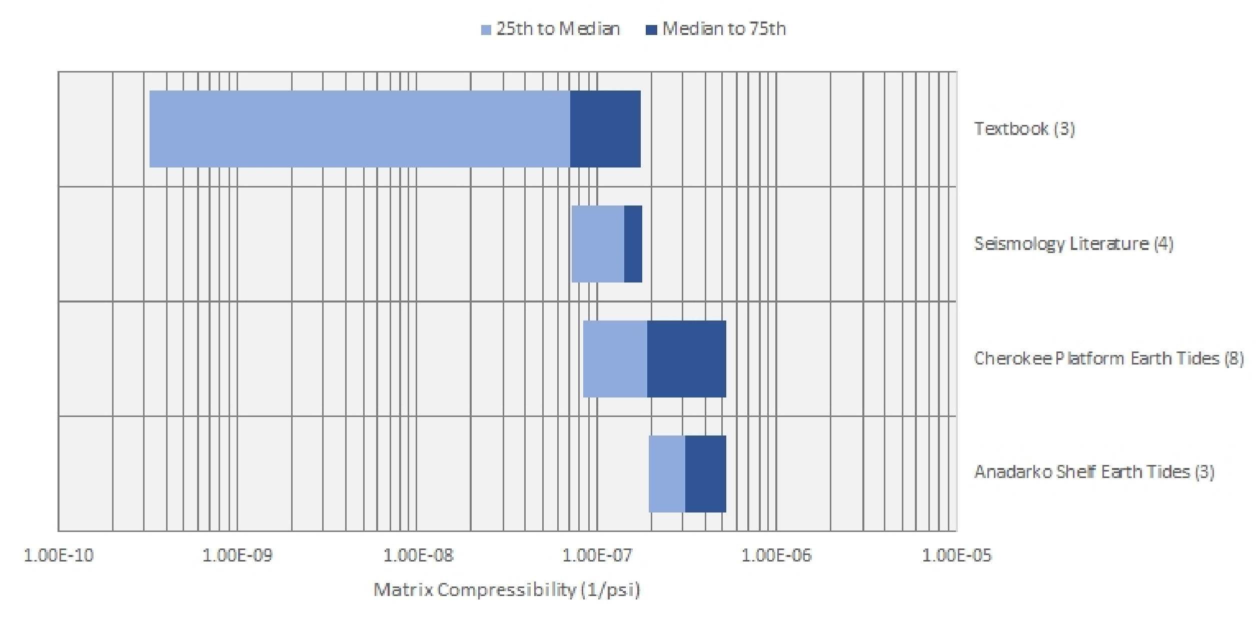
Preliminary Results (Arbuckle ROCK PROPERTIES) from Solid Earth Tide Analysis

	Property	Amplitude	Unit Thickness	Unit Thickness	Storativity	Permeability	Matrix Compressibility	Hydraulic Diffusivity
	Units	m	feet	m	dimensionless	mD	psi	m^2/s
Alfalfa 03	O1	0.0054	2467	752	1.1E-03	2.9E+01	6.2E-07	3.9E+00
Alfalfa 03	M2	0.0128	2467	752	4.6E-04	1.6E+01	2.5E-07	4.9E+00
Alfalfa 04	O1	0.0028	1008	307	8.2E-04	2.2E+01	4.9E-07	5.0E-02
Alfalfa 04	M2	0.0037	1008	307	6.1E-04	1.2E+01	3.7E-07	4.0E-02
Grant 06	O1	0.0027	2622	799	1.1E-03	1.5E+03	2.2E-07	4.2E+00
Grant 06	M2	0.0037	2622	799	5.7E-04	7.9E+02	1.2E-07	4.0E+00
Payne 07	O1	0.0042	901	275	2.1E-05	6.2E+01	5.3E-07	5.2E+00
Payne 07	M2	0.0130	901	275	2.8E-06	3.6E+01	1.7E-07	9.4E+00
Payne 08	O1	0.0038	755	230	3.0E-05	7.8E+01	5.6E-07	3.9E+00
Payne 08	M2	0.0100	755	230	1.1E-05	5.0E+01	2.1E-07	6.6E+00
Payne 09	O1	0.0035	638	194	1.8E-05	3.2E+01	8.0E-08	2.3E+00
Payne 09	M2	0.0230	638	194	2.7E-06	2.0E+01	1.2E-08	9.2E+00
Lincoln 10	O1	0.0032	1578	481	2.6E-03	2.9E+01	5.0E-07	8.0E-02
Lincoln 10	M2	0.0053	1578	481	1.0E-03	2.1E+01	2.0E-07	1.5E-01
Pawnee 11	O1	0.0055	550	168	2.1E-04	1.6E+02	3.5E-07	7.8E-01
Pawnee 11	M2	0.0140	550	168	5.7E-05	8.8E+01	9.3E-08	1.7E+00
Logan 12	O1	0.0039	1226	374	6.7E-04	7.1E+01	5.8E-07	2.5E-01
Logan 12	M2	0.0110	1226	374	1.6E-04	4.0E+01	1.4E-07	5.9E-01
Noble 13	O1	0.0250	1291	393	4.6E-05	1.9E+02	5.4E-08	1.0E+01
Noble 13	M2	0.0200	1291	393	5.7E-05	1.0E+02	6.8E-08	4.6E+00
Noble 14	O1	0.0037	1017	310	2.8E-04	3.5E+01	6.0E-07	2.5E-01
Noble 14	M2	0.0127	1017	310	8.2E-05	2.3E+01	1.7E-07	5.7E-01

Arbuckle ROCK PROPERTIES from Solid Earth Tide Analysis vs Other Studies

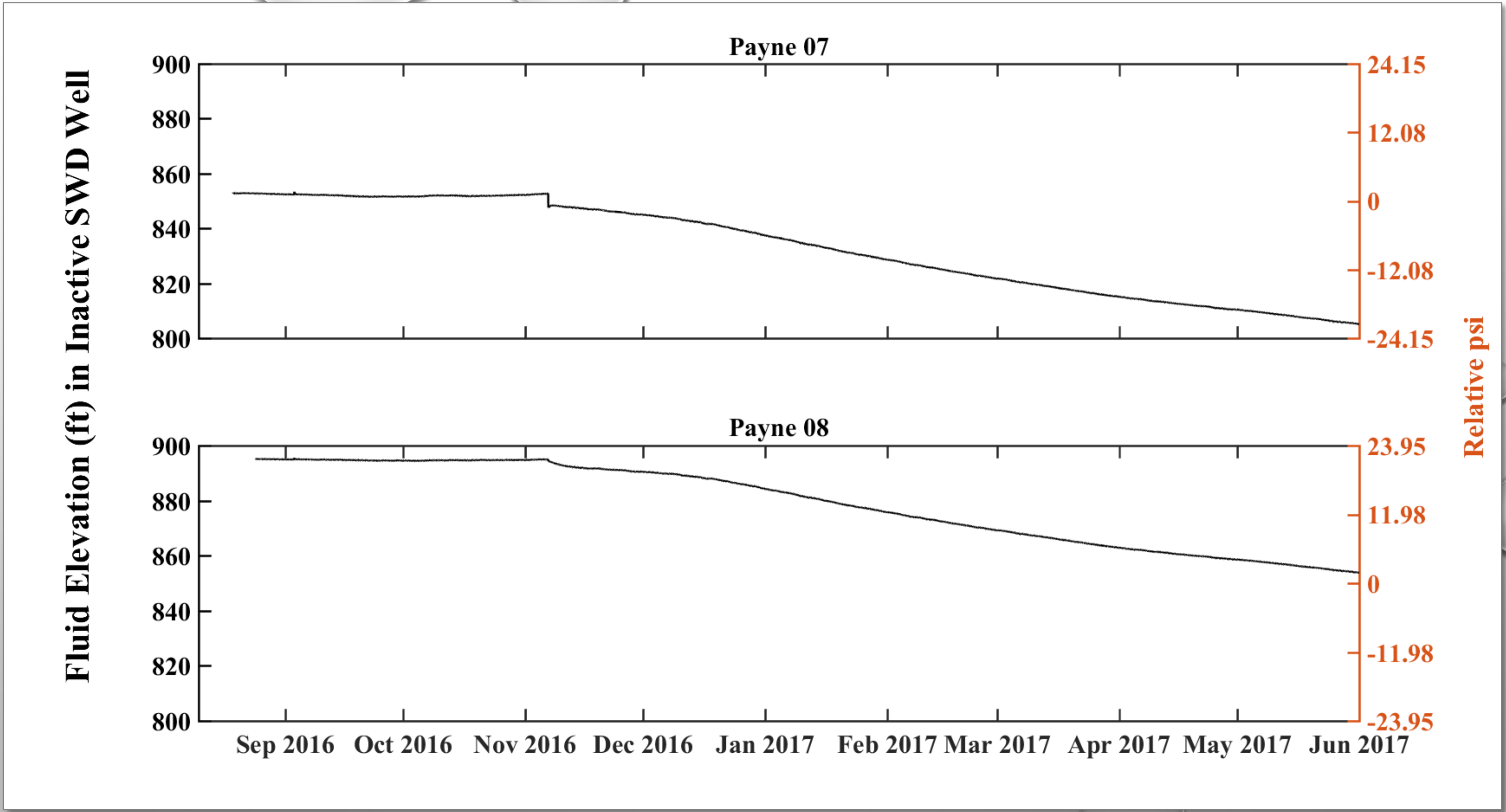






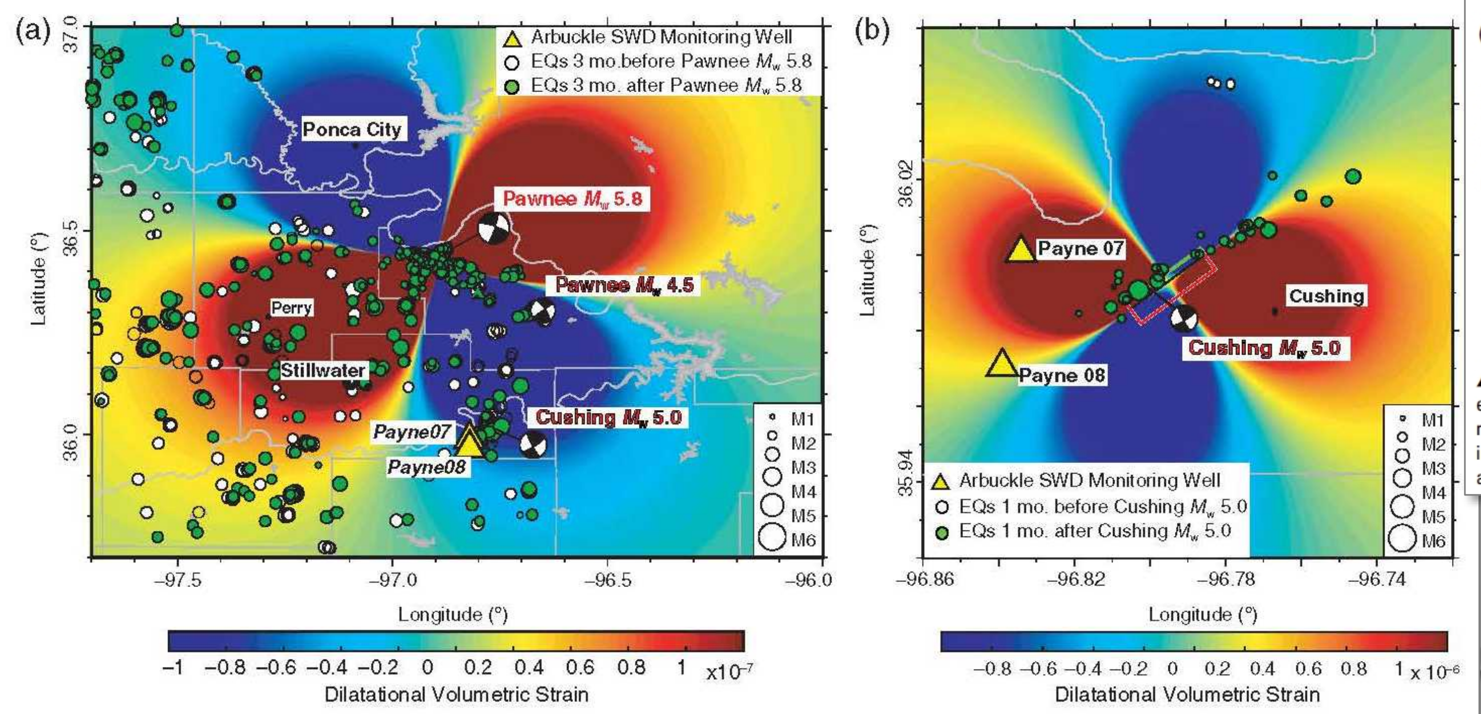
- Storage Coefficient is Lower than most previous studies suggest
- Water is not stored in the Arbuckle
- Pressure migrates away (laterally or vertically?) from injection point very quickly

Cherokee Platform wells w/ poroelastic effects (Payne 07&08)

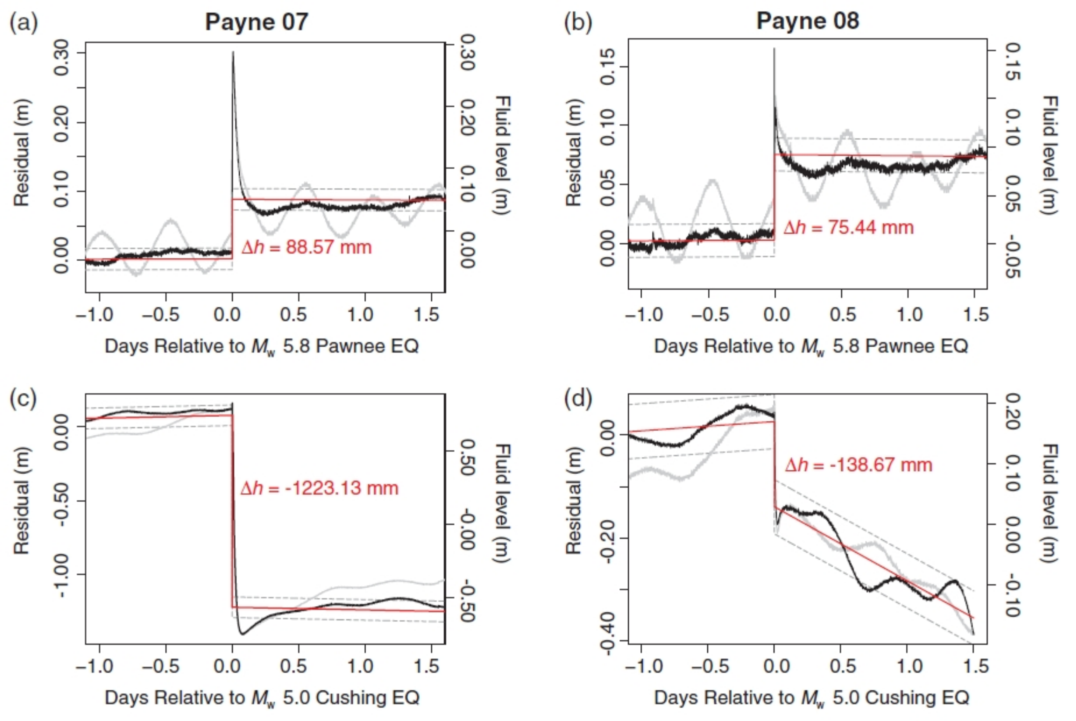


Seismic event (Stress) vs. Fluid level fluctuations (Strain)

Motivation:
Derive poroelastic properties of the Arbuckle from co-seismic fluid level responses



▲ **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.

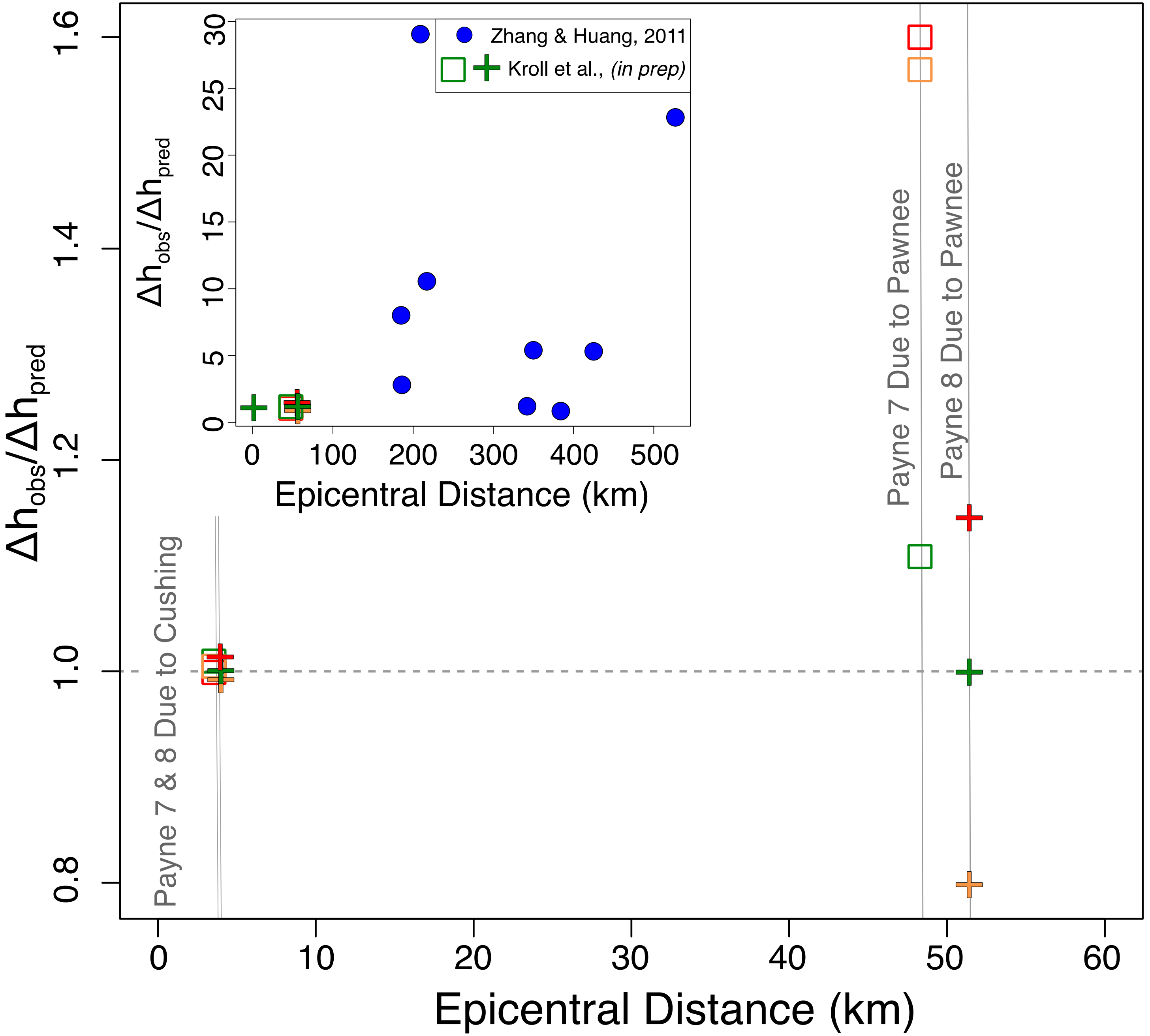
Kroll, K. A., Cochran, E. S., and Murray, K. E., 2017, Poroelastic properties of the Arbuckle Group in Oklahoma derived from well fluid level response to the 3 September 2016 Mw5.8 Pawnee and 7 November 2016 Mw5.0 Cushing Earthquakes: Seismological Research Letters, p. 8.

Which conditions best explain response in wells?

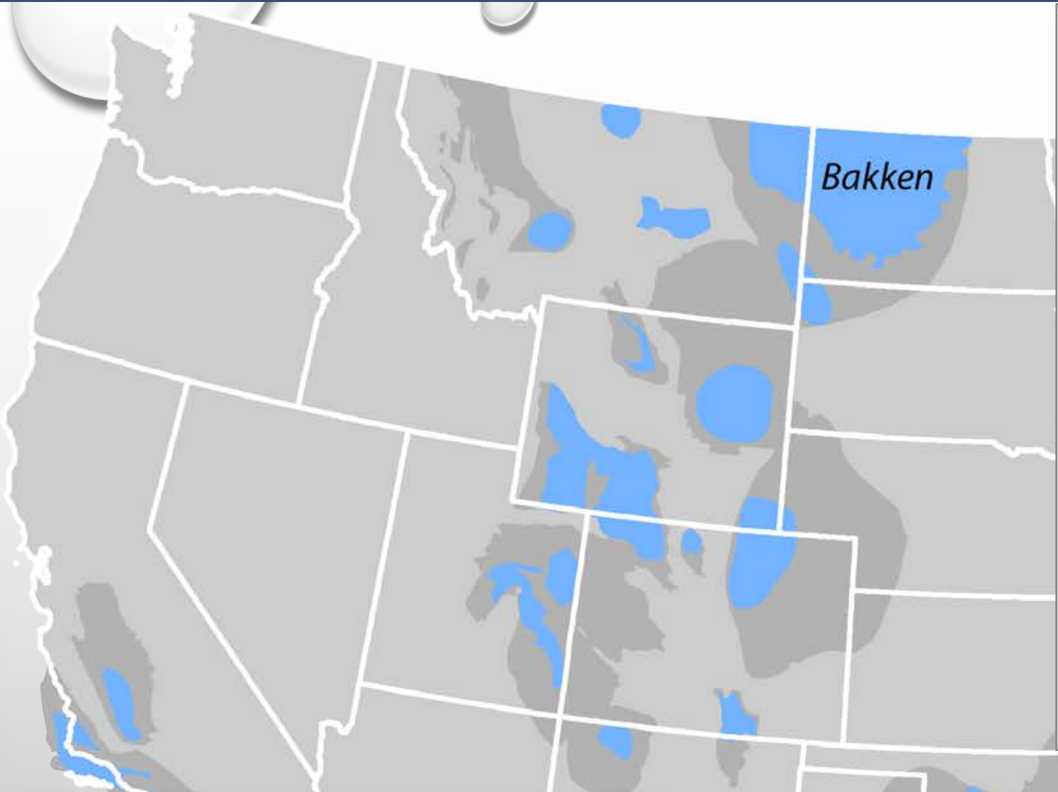
Hypothesis 1:
Reservoir properties static through time and space

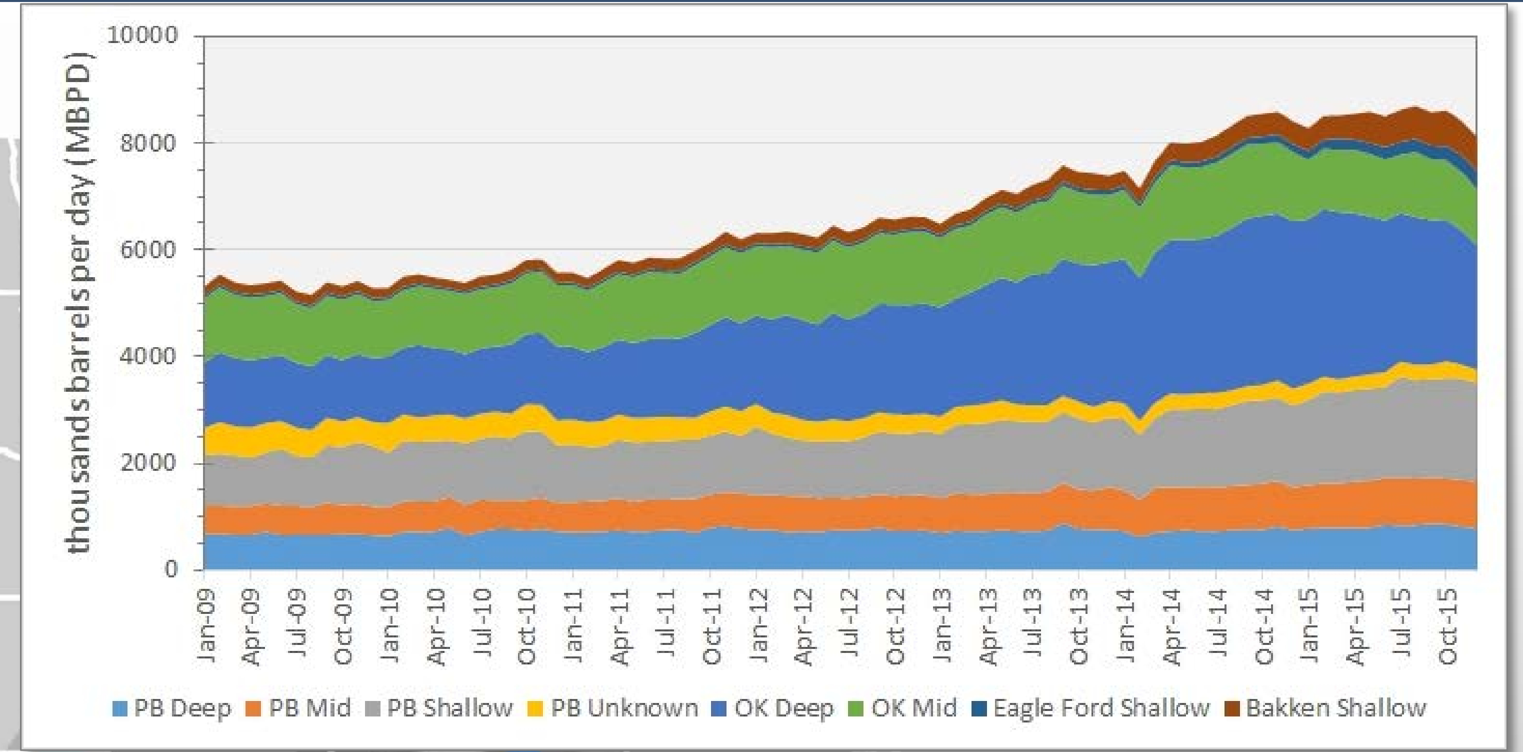
Hypothesis 2:
Spatially heterogeneous, static in time

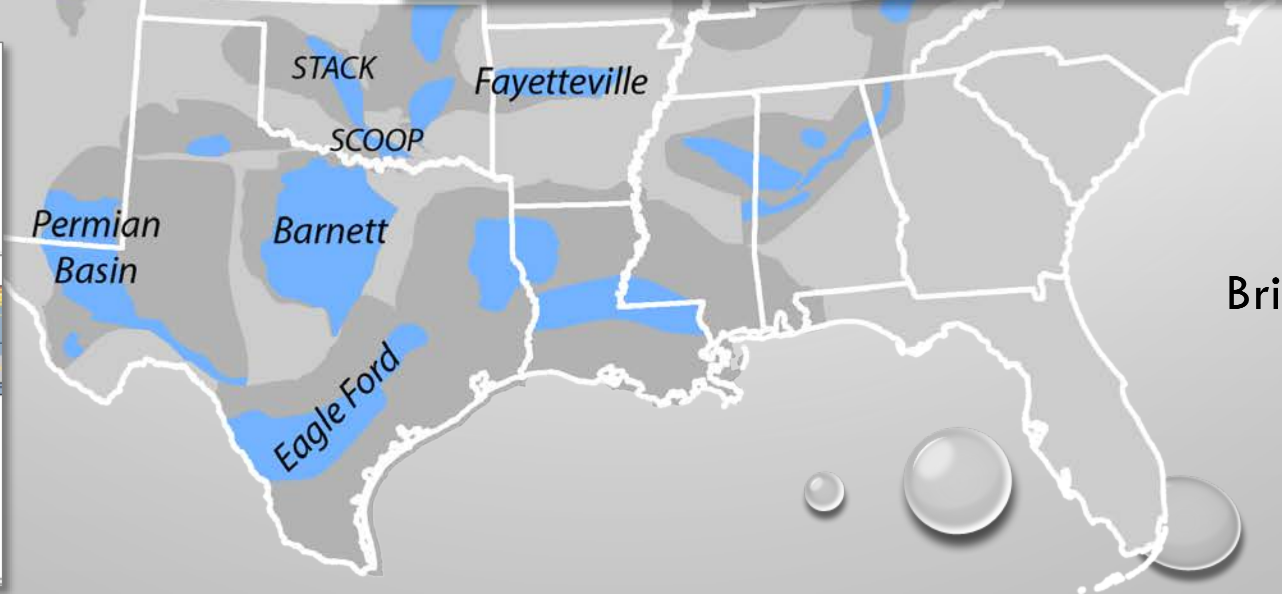
Hypothesis 3:
Spatially static, heterogeneous in time

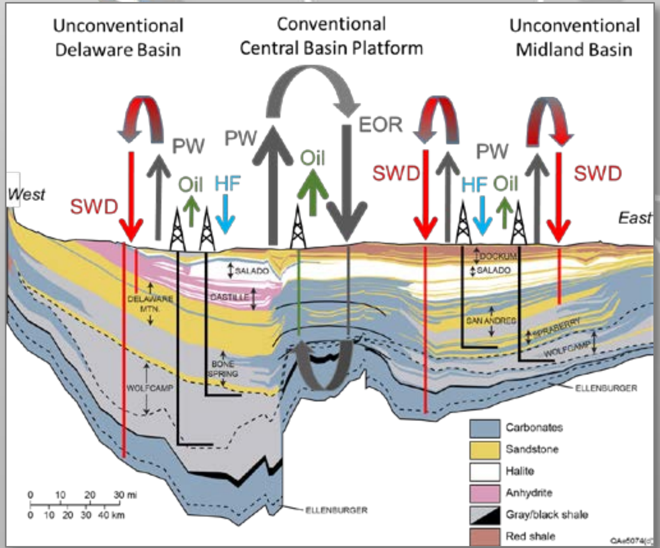


Saltwater Disposal (SWD) in Permian Basin, Oklahoma, Eagle Ford, & Bakken





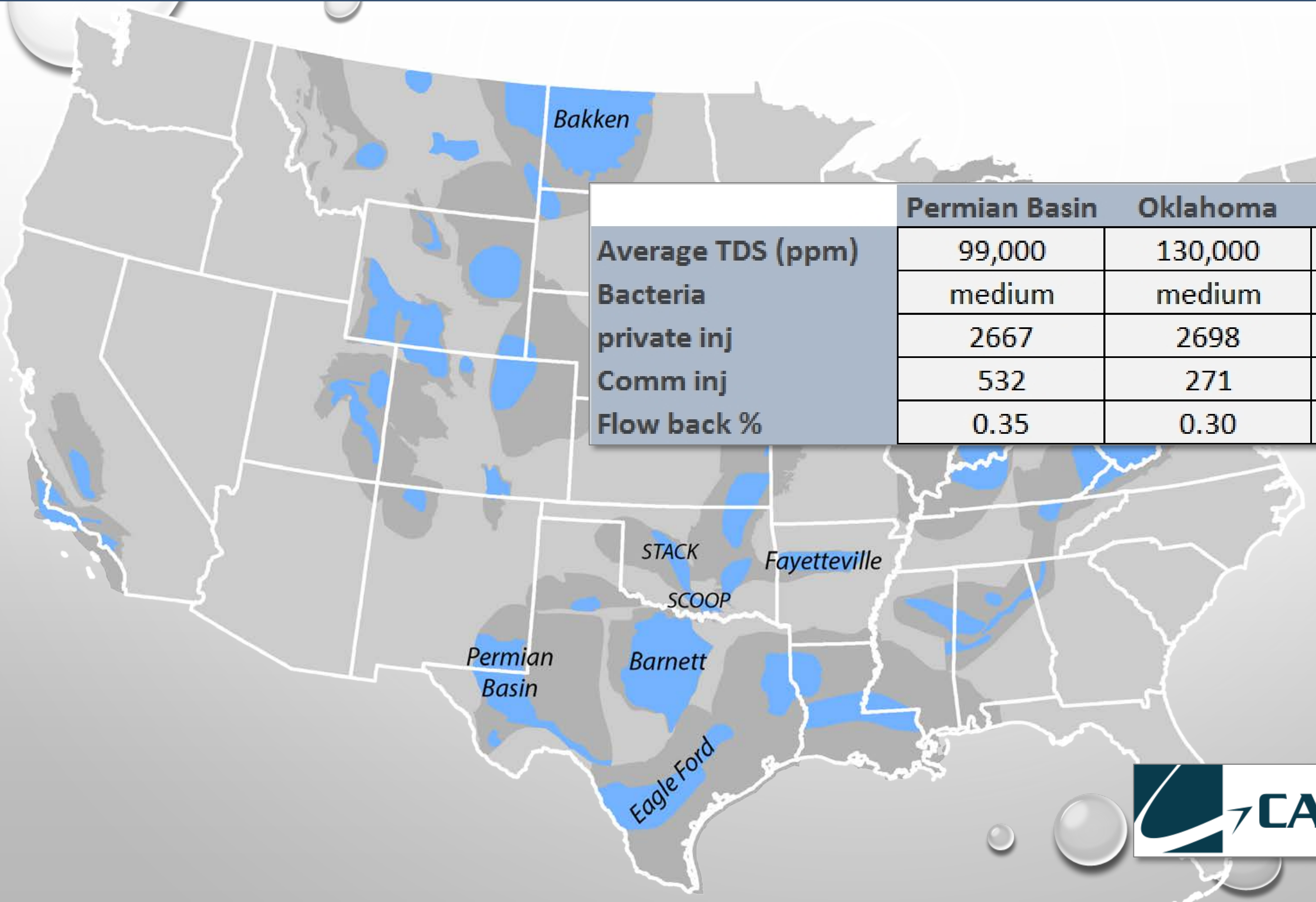




Collaborators:
Bridget Scanlon & Bob Reedy

Bureau of Economic Geology

Produced H_2O and SWD in Permian Basin, Oklahoma, Eagle Ford, & Bakken



	Permian Basin	Oklahoma	Eagle Ford	Bakken
Average TDS (ppm)	99,000	130,000	54,000	253,000
Bacteria	medium	medium	medium	low
private inj	2667	2698	459	362
Comm inj	532	271	232	54
Flow back %	0.35	0.30	0.07	0.25

Collaborator:
Laura Capper

CAP RESOURCES

Closing Remarks

- **Thoughtful water management can provide a variety of benefits:**
  - Increase value and assets
  - Reduce drilling, exploration, and sourcing costs
  - Minimize waste handling costs
  - Avoid liabilities such as induced seismicity or environmental contamination
- **Successful produced water treatment depends on:**
  - Inexpensive source of energy to drive treatment process
  - Reasonable plan for managing concentrated brine and other wastes

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