

# Hindsight in 2020: A Decade of Seismicity versus HF, SWD, EORI, and CO<sub>2</sub> Injection in Oklahoma



*The*  
**UNIVERSITY**  
*of*  
**OKLAHOMA**

*Mewbourne College  
of Earth and Energy*

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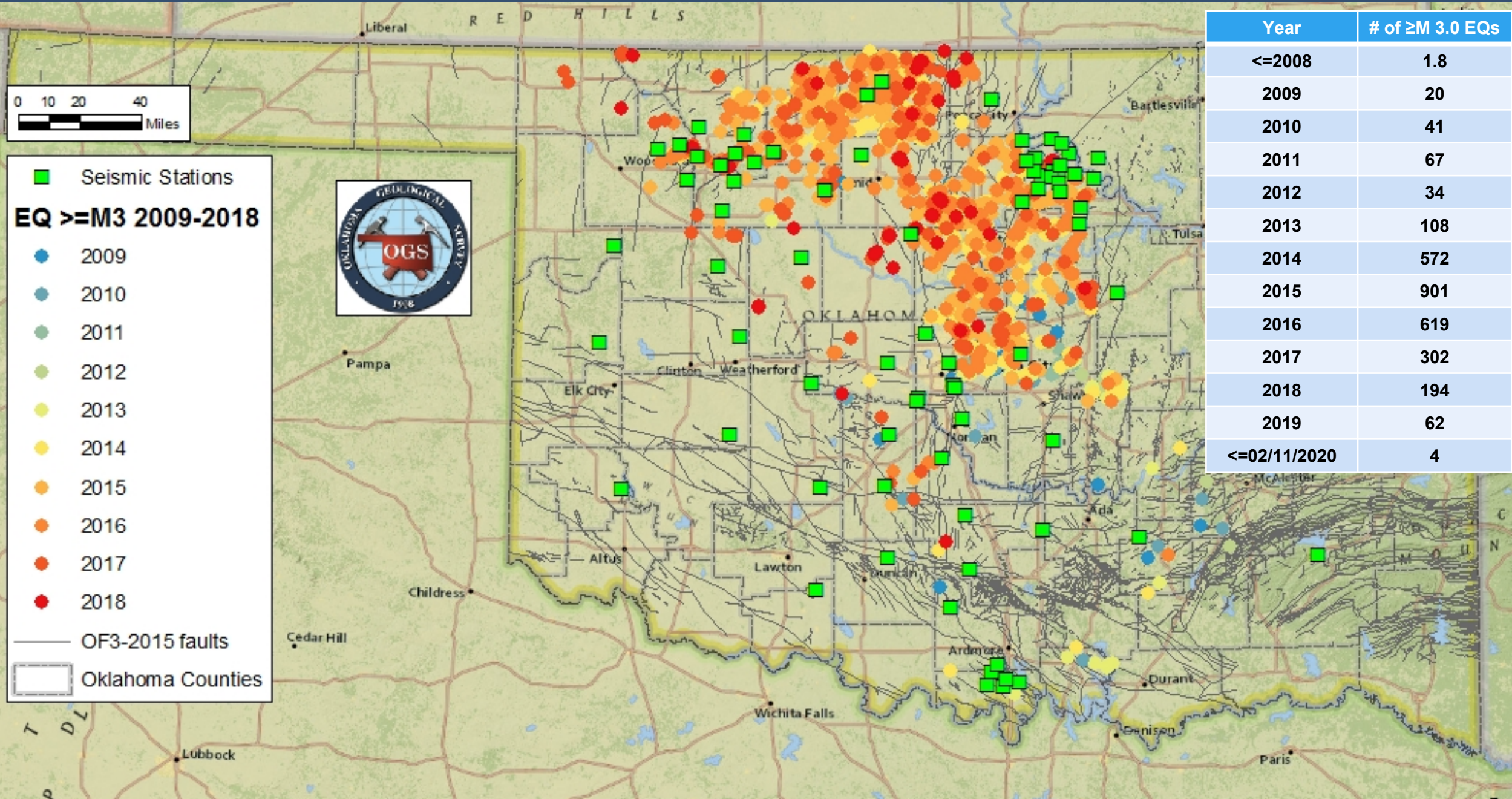
**KyleMurrayH2O@gmail.com**

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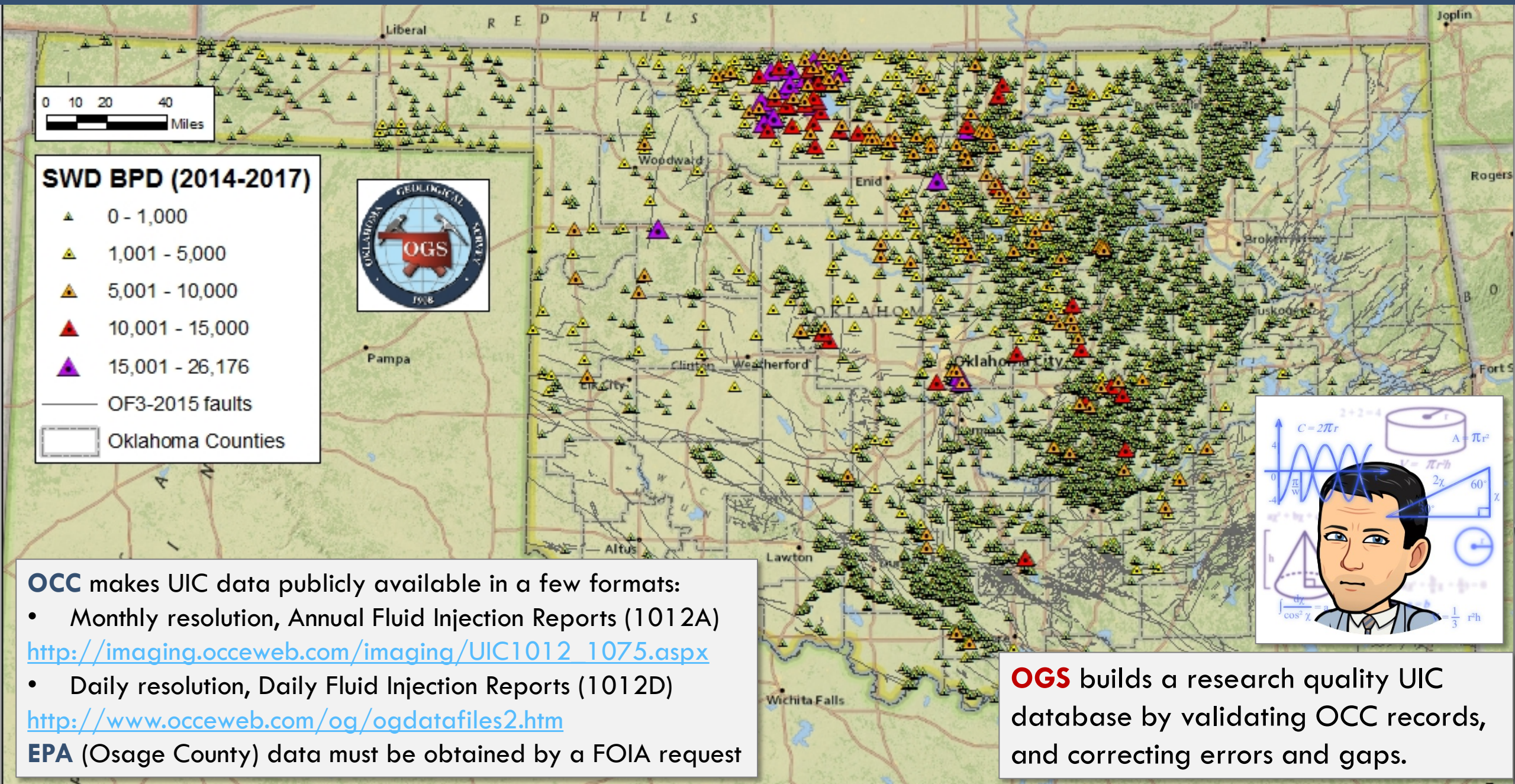


# Seismic Monitoring Network and Earthquakes in Oklahoma





# 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](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.



# Studies of Seismicity versus Fluid Injection

## Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 $M_w$ 5.7 earthquake sequence

Katie M. Keranen<sup>1</sup>, Heather M. Savage<sup>2</sup>, Geoffrey A. Abers<sup>2</sup>, and Elizabeth S. Cochran<sup>3</sup>

<sup>1</sup>ConocoPhillips School of Geology and Geophysics, University of Oklahoma, 100 E. Boyd Street, Norman, Oklahoma 73069, USA

<sup>2</sup>Lamont-Doherty Earth Observatory of Columbia University, PO Box 1000, 61 Route 9W, Palisades, New York 10964, USA

<sup>3</sup>U.S. Geological Survey, 525 S. Wilson Avenue, Pasadena, California 91106, USA

2013

## Groundwater

2013

## Hydrogeologic Controls on Induced Seismicity in Crystalline Basement Rocks Due to Fluid Injection into Basal Reservoirs

by Yipeng Zhang<sup>1</sup>, Mark Person<sup>2</sup>, John Rupp<sup>3</sup>, Kevin Ellett<sup>3</sup>, Michael A. Celia<sup>4</sup>, Carl W. Gable<sup>5</sup>, Brenda Bowen<sup>6</sup>, James Evans<sup>7</sup>, Karl Bandilla<sup>4</sup>, Peter Mozley<sup>1</sup>, Thomas Dewers<sup>8</sup>, and Thomas Elliot<sup>4</sup>

Scienceexpress

2014

## Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection

K. M. Keranen,<sup>1\*</sup> M. Weingarten,<sup>2</sup> G. A. Abers,<sup>3†</sup> B. A. Bekins,<sup>4</sup> S. Ge<sup>2</sup>

INSIGHTS | PERSPECTIVES

GEOPHYSICS

2015

## Coping with earthquakes induced by fluid injection

Hazard may be reduced by managing injection activities

By A. McGarr,<sup>1\*</sup> B. Bekins,<sup>2</sup> N. Burkardt,<sup>3</sup> J. Dewey,<sup>4</sup> P. Earle,<sup>4</sup> W. Ellsworth,<sup>1</sup> S. Ge,<sup>5</sup> S. Hickman,<sup>1</sup> A. Holland,<sup>6</sup> E. Majer,<sup>7</sup> J. Rubinstein,<sup>1</sup> A. Shookan<sup>5</sup>

are so many disposal wells that this contributes significantly to the total seismic hazard, at least in the mid-continent (1, 2, 6). EOR has been associated with earthquakes

RESEARCH ARTICLE

SEISMOLOGY

2015

## Oklahoma's recent earthquakes and saltwater disposal

F. Rall Walsh III\* and Mark D. Zoback

INDUCED SEISMICITY

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

2015

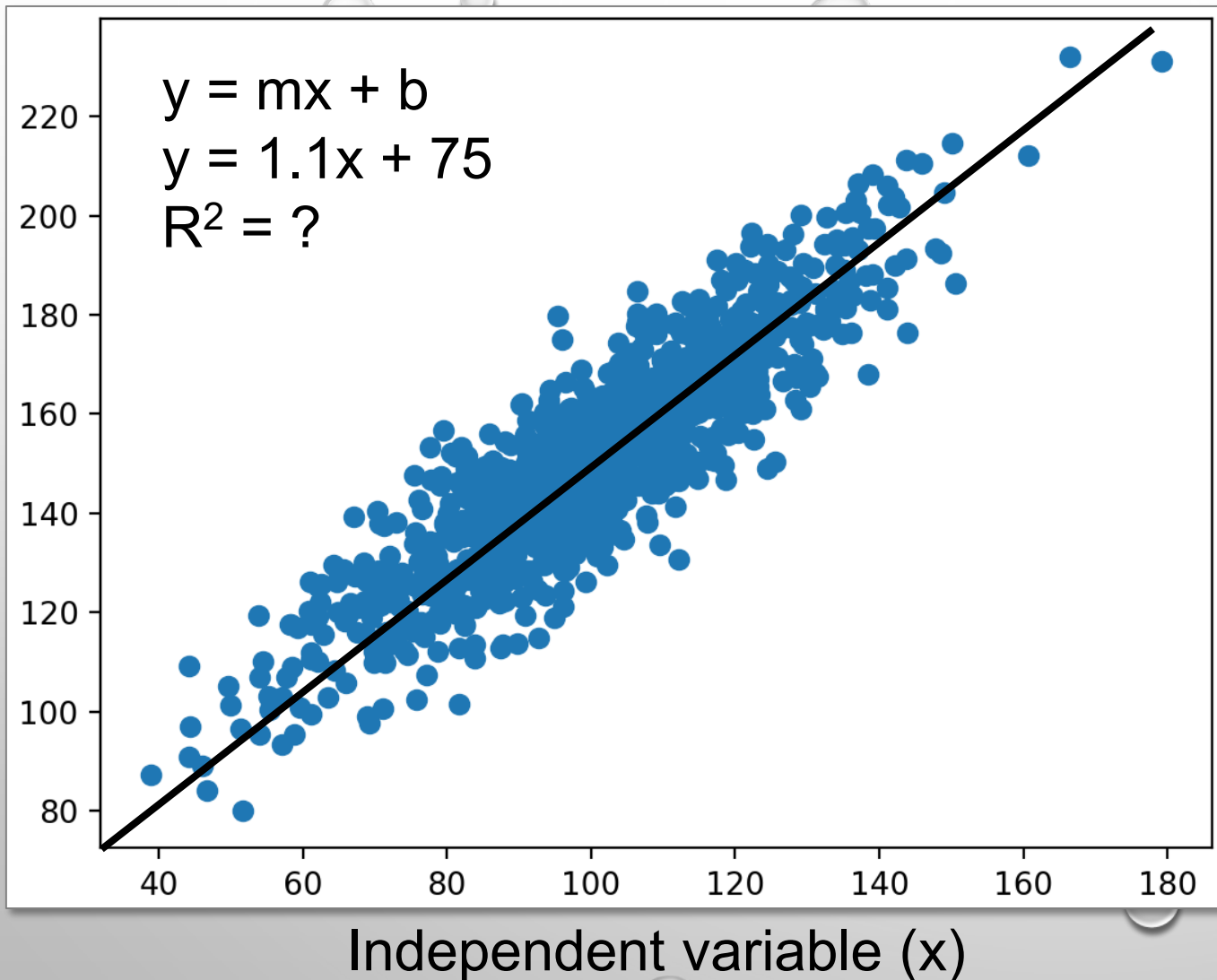
M. Weingarten,<sup>1\*</sup> S. Ge,<sup>1</sup> J. W. Godt,<sup>2</sup> B. A. Bekins,<sup>3</sup> J. L. Rubinstein<sup>3</sup>

# What stresses could be correlated to strain/seismic activity?

- **Hydraulic Fracturing Fluid Injection Rates**
- Oil Production Rates
- Gas Production Rates
- **Saltwater Disposal (SWD) Rates**
- **Enhanced Oil Recovery Injection (EORI) Rates**
  - Water (Salt, brackish, or fresh) injection
  - CO<sub>2</sub> gas injection

# Correlation of $y$ as a function of $x$ and $R^2$ ?

Dependent variable (y)



$r$  = Pearson product moment correlation coefficient

$$r = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{[N\sum x^2 - (\sum x)^2][N\sum y^2 - (\sum y)^2]}}$$

Where:

- $N$  = number of pairs of scores
- $\sum xy$  = sum of the products of paired scores
- $\sum x$  = sum of  $x$  scores
- $\sum y$  = sum of  $y$  scores
- $\sum x^2$  = sum of squared  $x$  scores
- $\sum y^2$  = sum of squared  $y$  scores

$r$  from -1 to 1

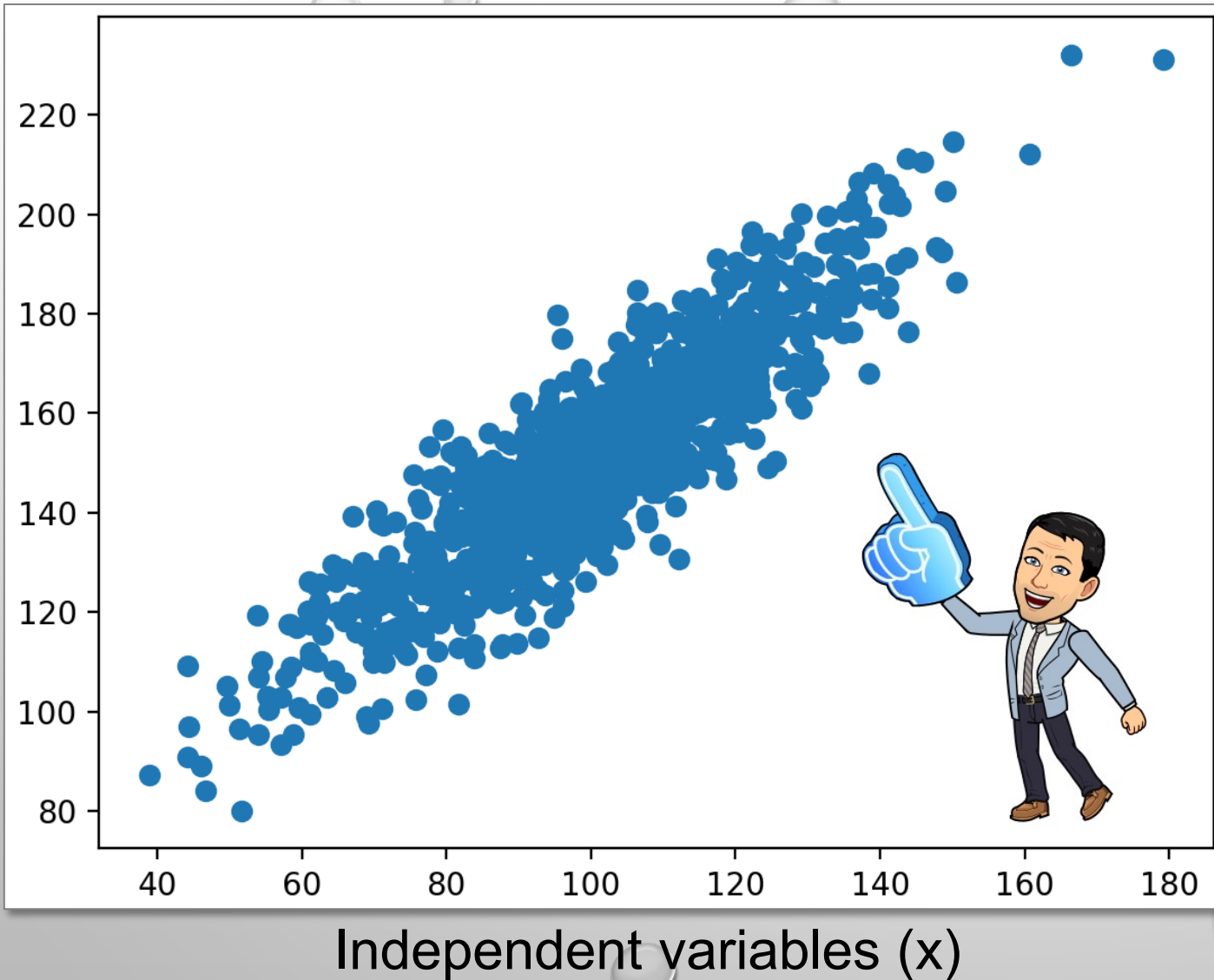
Excel formula computes:  
 $R^2$  or RSQ = Square of  $r$

so

$R^2$  from 0 to 1

# Correlation of EQ rate (y) as a function of injection rate (x) and $R^2$ ?

Dependent variable, Earthquakes (y)



Dependent Variable, EQ (y):

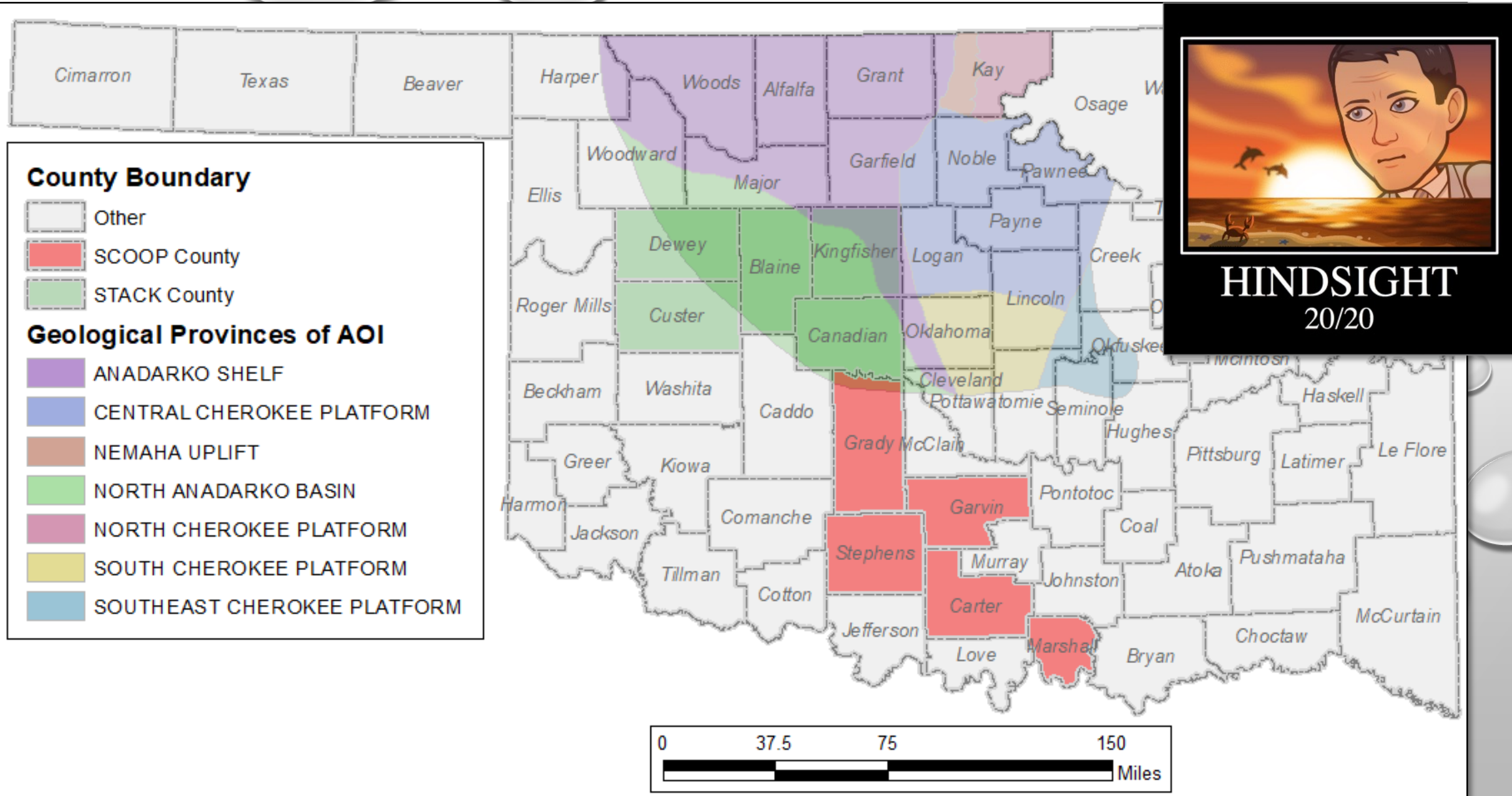
- 10 years or 120 months of data for correlation to:

Independent Variables (x):

- Hydraulic Fracturing Injection Rates by Fluid
- Saltwater Disposal (SWD) Rates by Zone
- Enhanced Oil Recovery Injection (EORI) Rates by Zone
  - BWPD
  - MCFCO<sub>2</sub>PD
- Oil Production by Zone
- Gas Production by Zone



## Geological Provinces and Plays or Study Areas



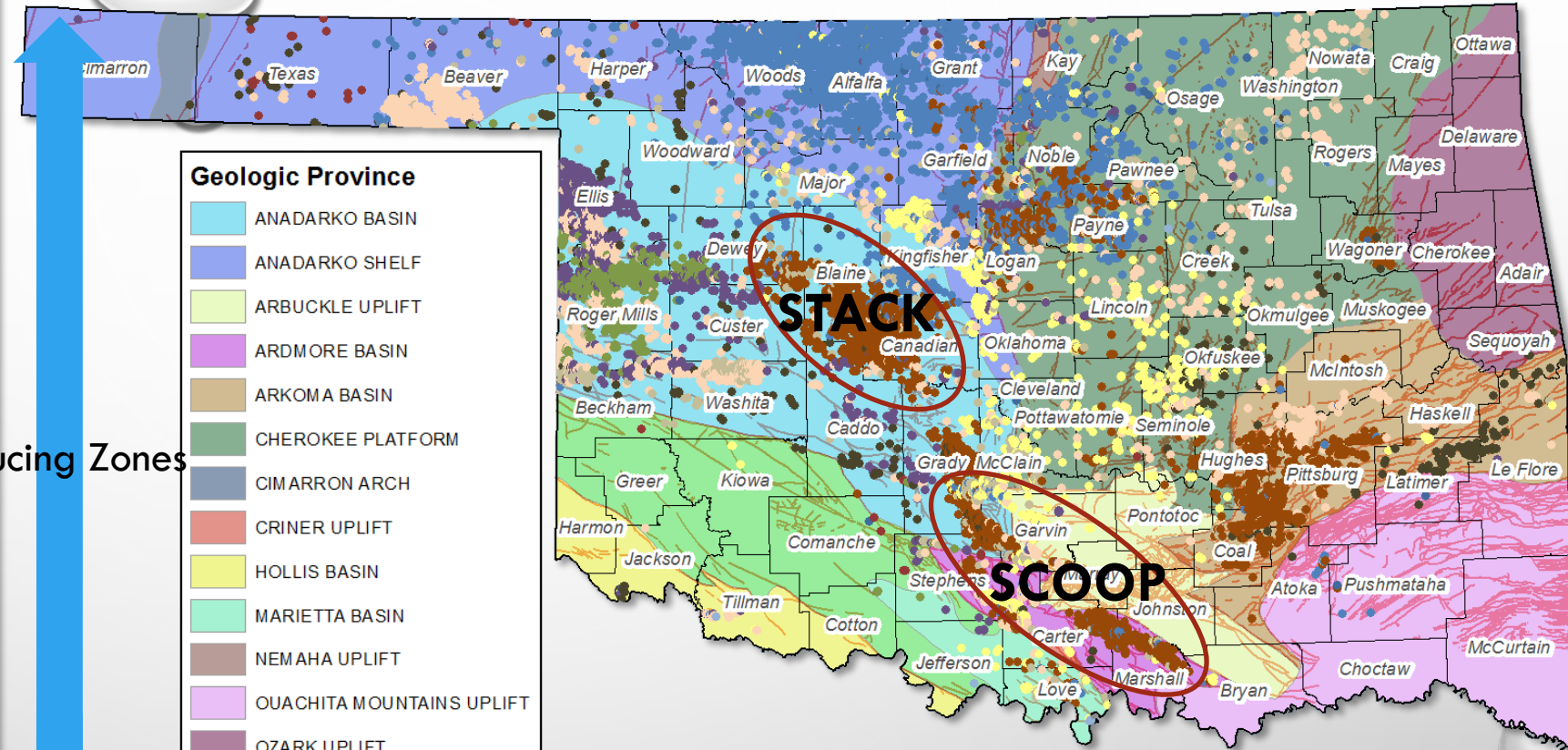
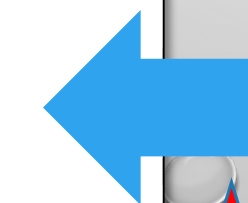


# Zones for Production, Injection, & Disposal

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

Granite Wash

Producing Zones

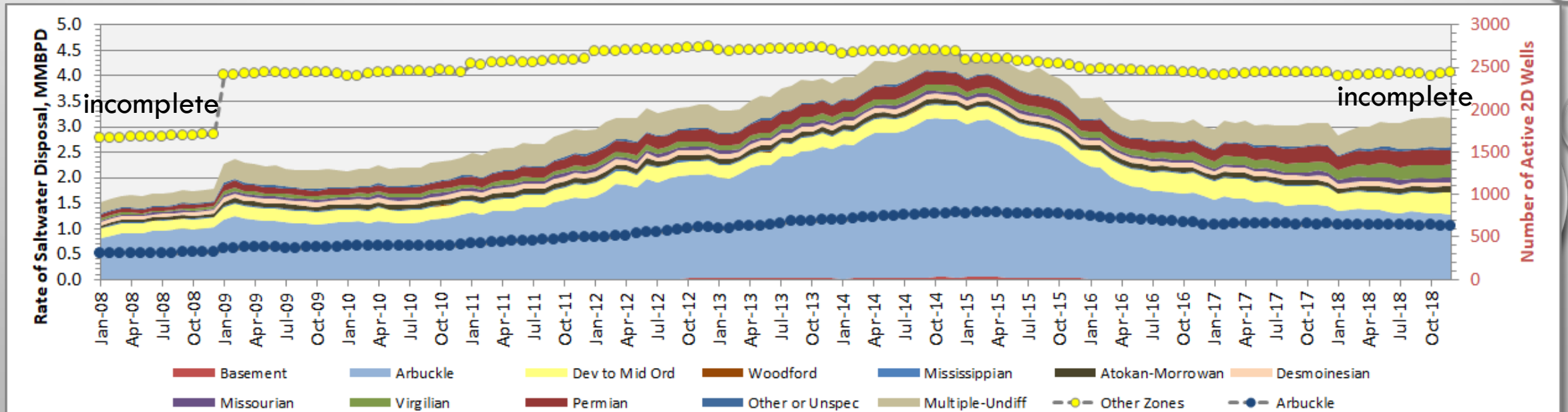
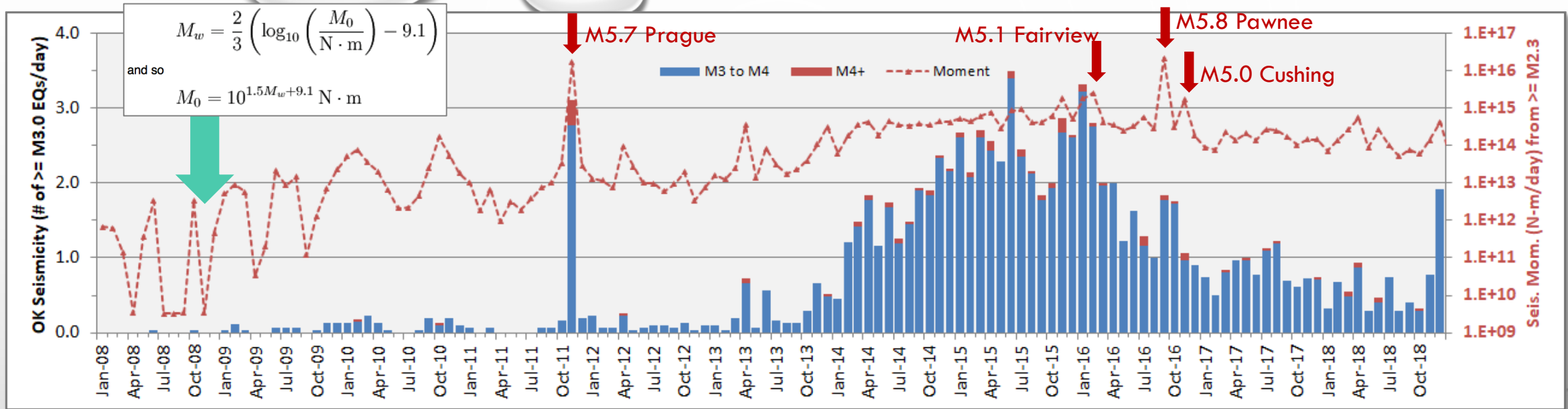


Wells that Started Producing from 2009–2015

Predominant Disposal Zone, avg of 2 km depth

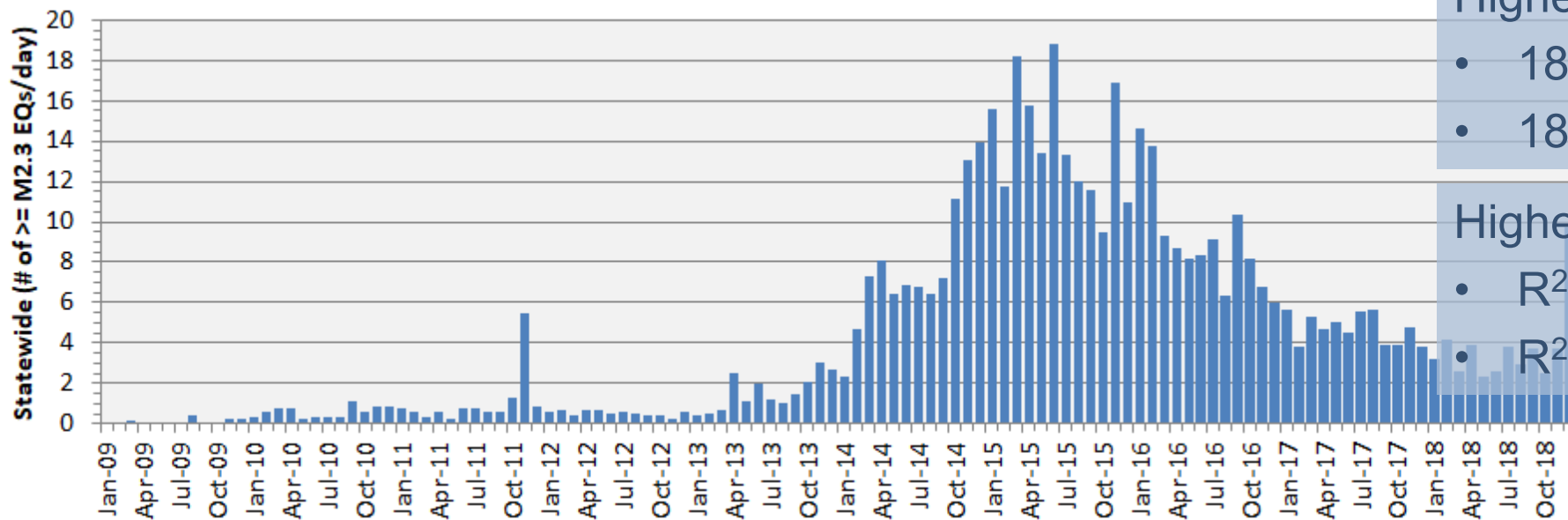
Earthquakes Down Here, avg of 5.5 km depth

# Statewide Earthquakes vs. SWD, 2008–2018





# Dependent Variable: EQ rate or # $M \geq 2.3$ per day in the State of OK

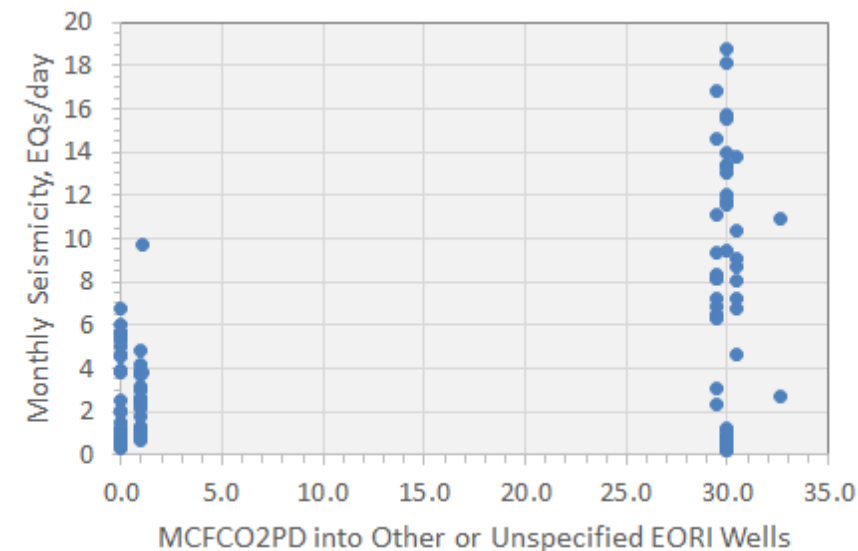
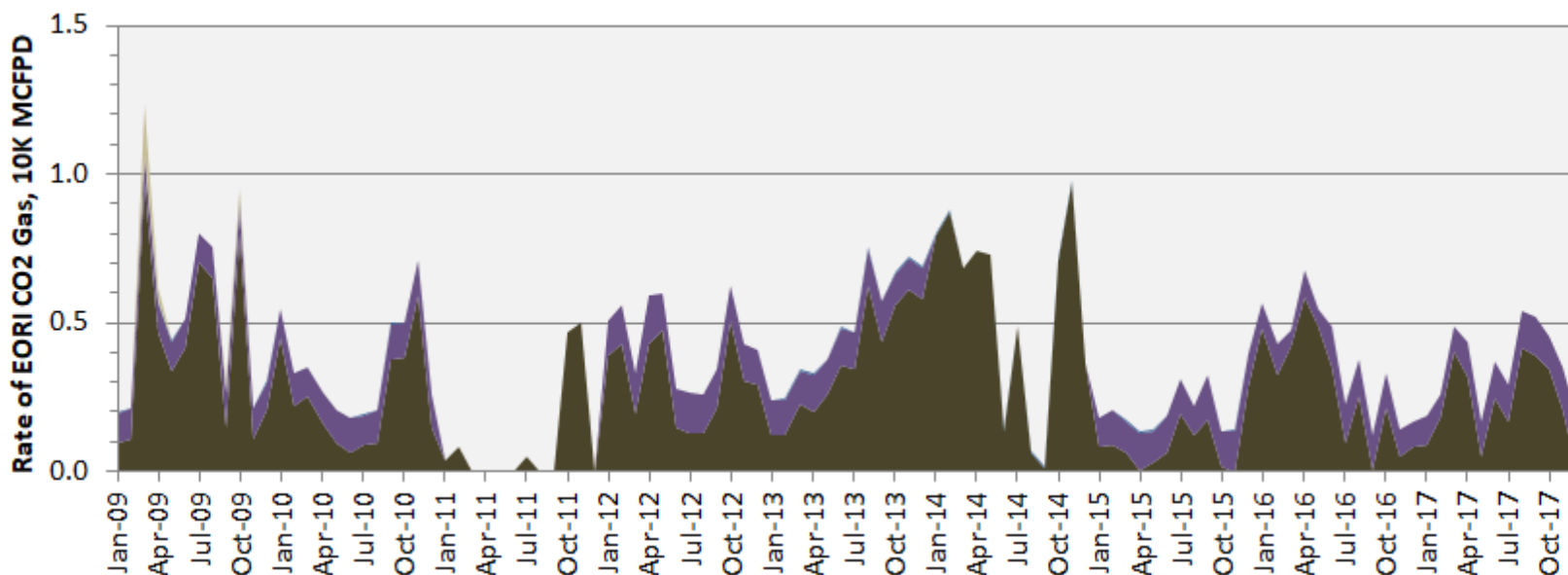


## Highest Seismicity Rates in OK

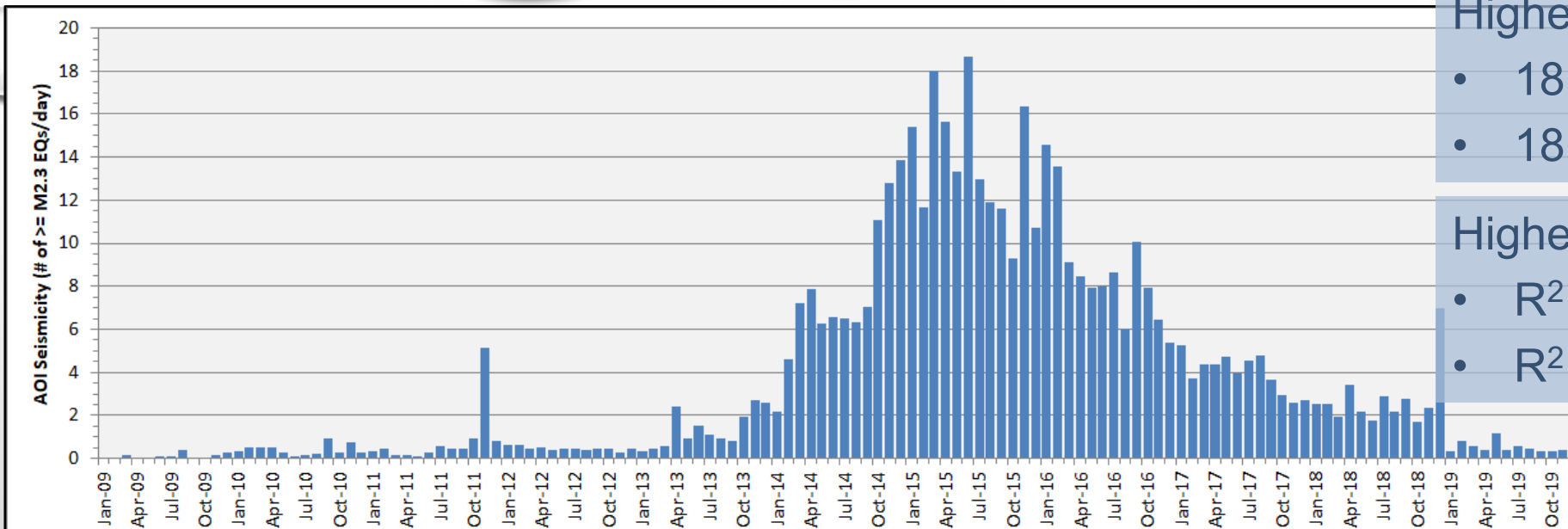
- 18.8 EQ/day Jun 2015
- 18.2 EQ/day Mar 2015

## Highest Pearson CCs, CO<sub>2</sub> in OK

- $R^2$  of 0.1625 for Other CO<sub>2</sub>
- $R^2$  of 0.0915 for Missourian CO<sub>2</sub>



# Dependent Variable: EQ rate or # $M \geq 2.3$ per day in the AOI

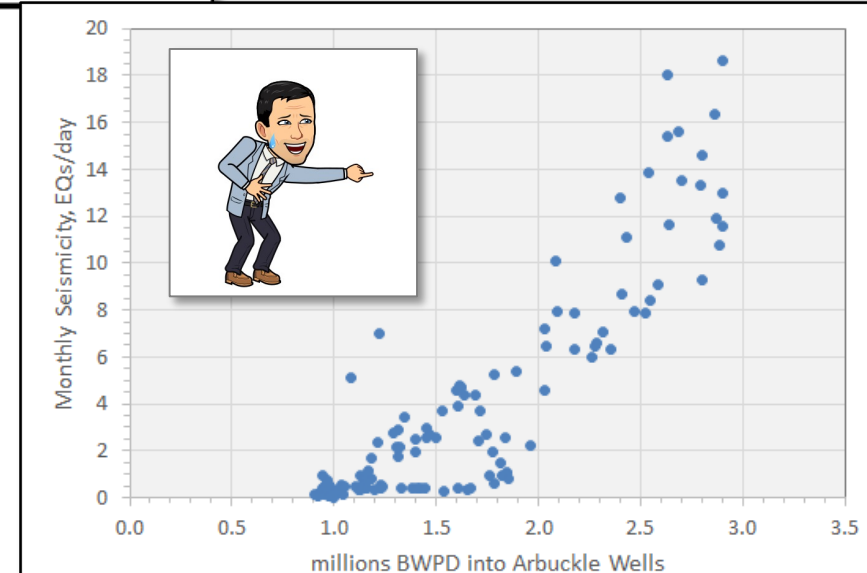
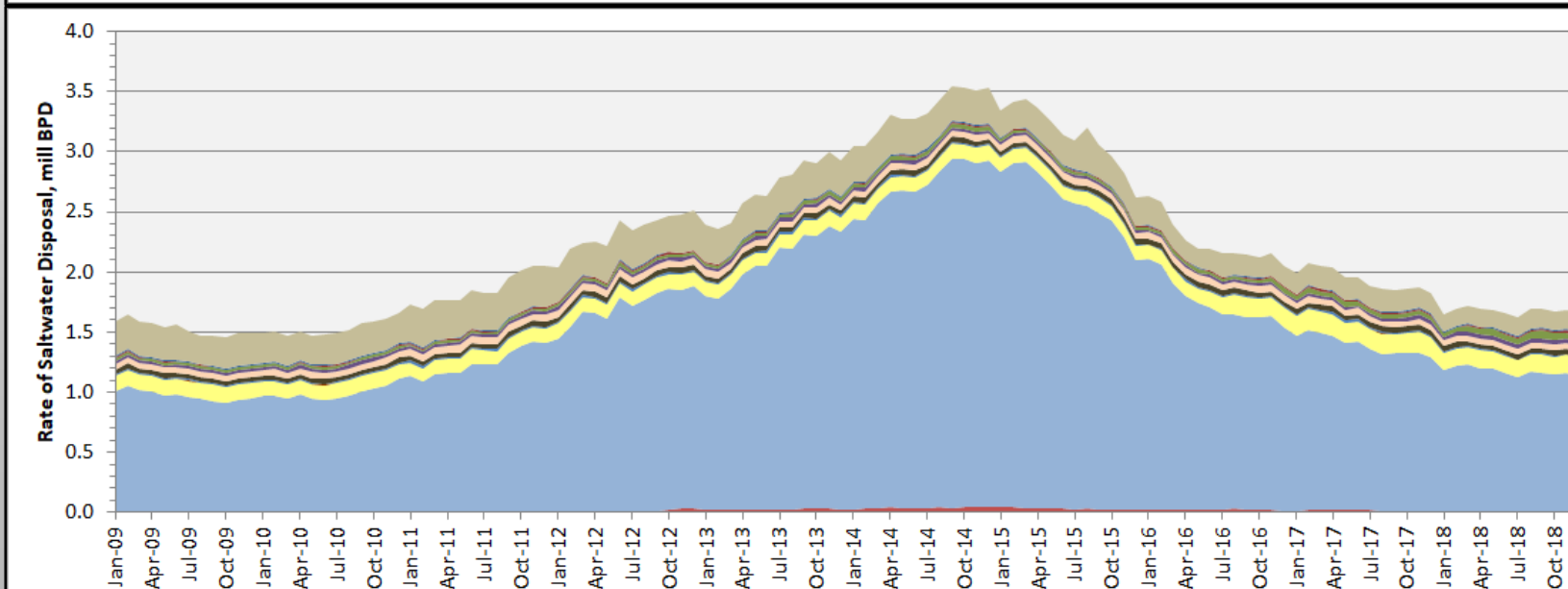


## Highest Seismicity Rates in AOI

- 18.7 EQ/day Jun 2015
- 18.0 EQ/day Mar 2015

## Highest Pearson CCs for AOI

- $R^2$  of 0.7877 for Arbuckle SWD
- $R^2$  of 0.7372 for Basement SWD





# Dependent Variable: EQ rate or # $M \geq 2.3$ per day in the STACK

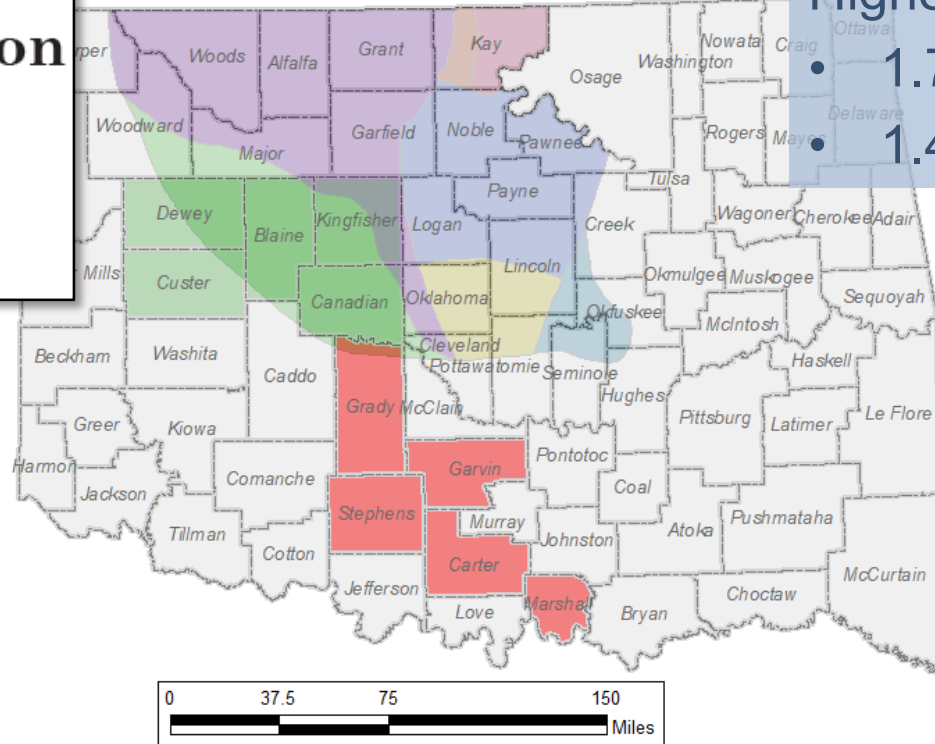
## Decadal Profile of Oilfield Fluid Production and Injection in the STACK, Oklahoma

By  
Dr. Kyle Murray

Hydrogeologist, Oklahoma Geological Survey

### Geological Provinces of OK

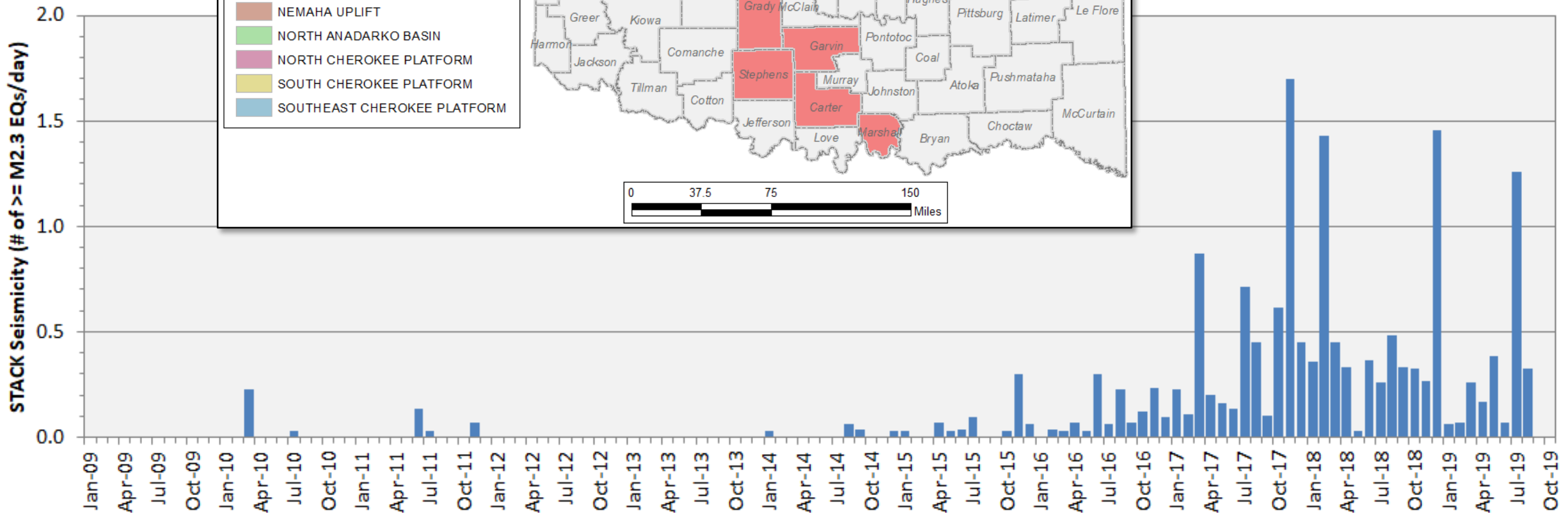
- ANADARKO SHELF
- CENTRAL CHEROKEE PLATFORM
- NEMAHA UPLIFT
- NORTH ANADARKO BASIN
- NORTH CHEROKEE PLATFORM
- SOUTH CHEROKEE PLATFORM
- SOUTHEAST CHEROKEE PLATFORM



### Highest Seismicity Rates in STACK

• 1.7 EQ/day Nov 2017

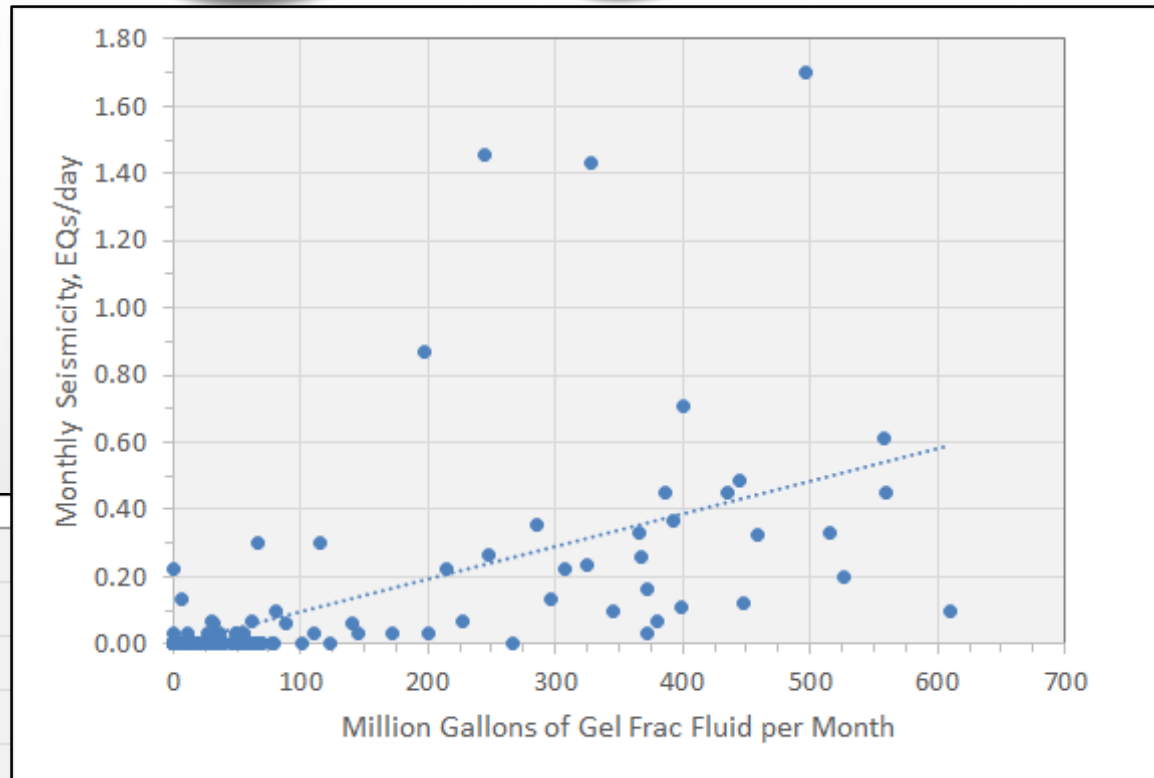
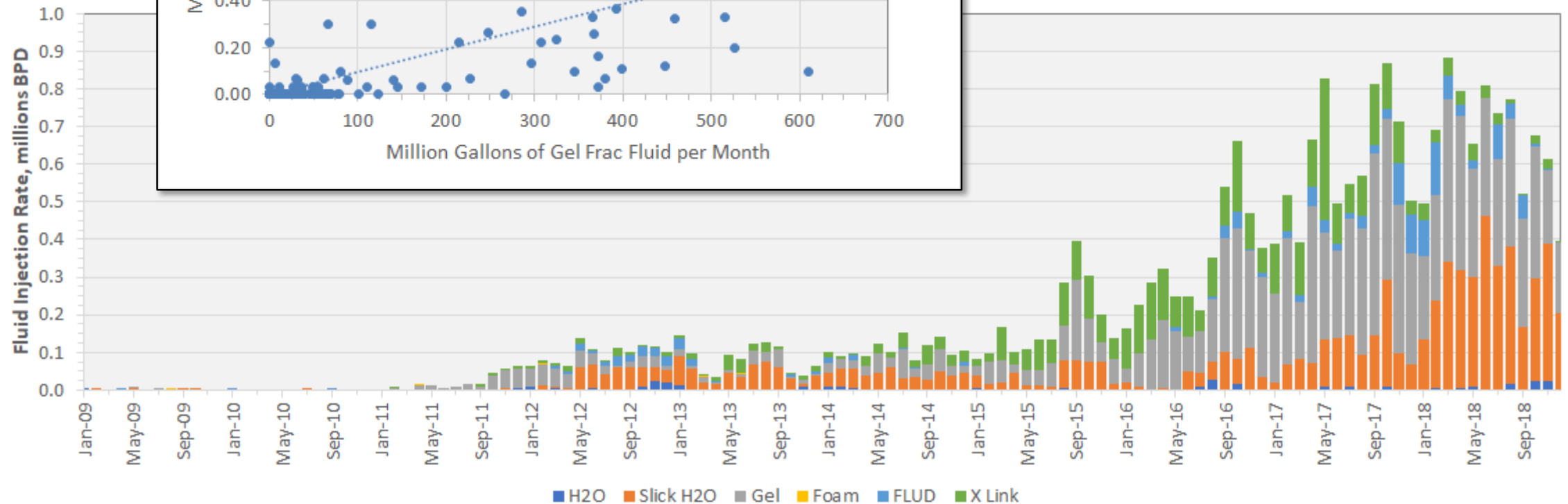
• 1.45 EQ/day Dec 2018



# Monthly Fluid Injection for Hydraulic Fracturing in the STACK

Highest Pearson CCs for STACK

- $R^2$  of 0.4608 for Gel Frac
- $R^2$  of 0.3732 for Flud Frac

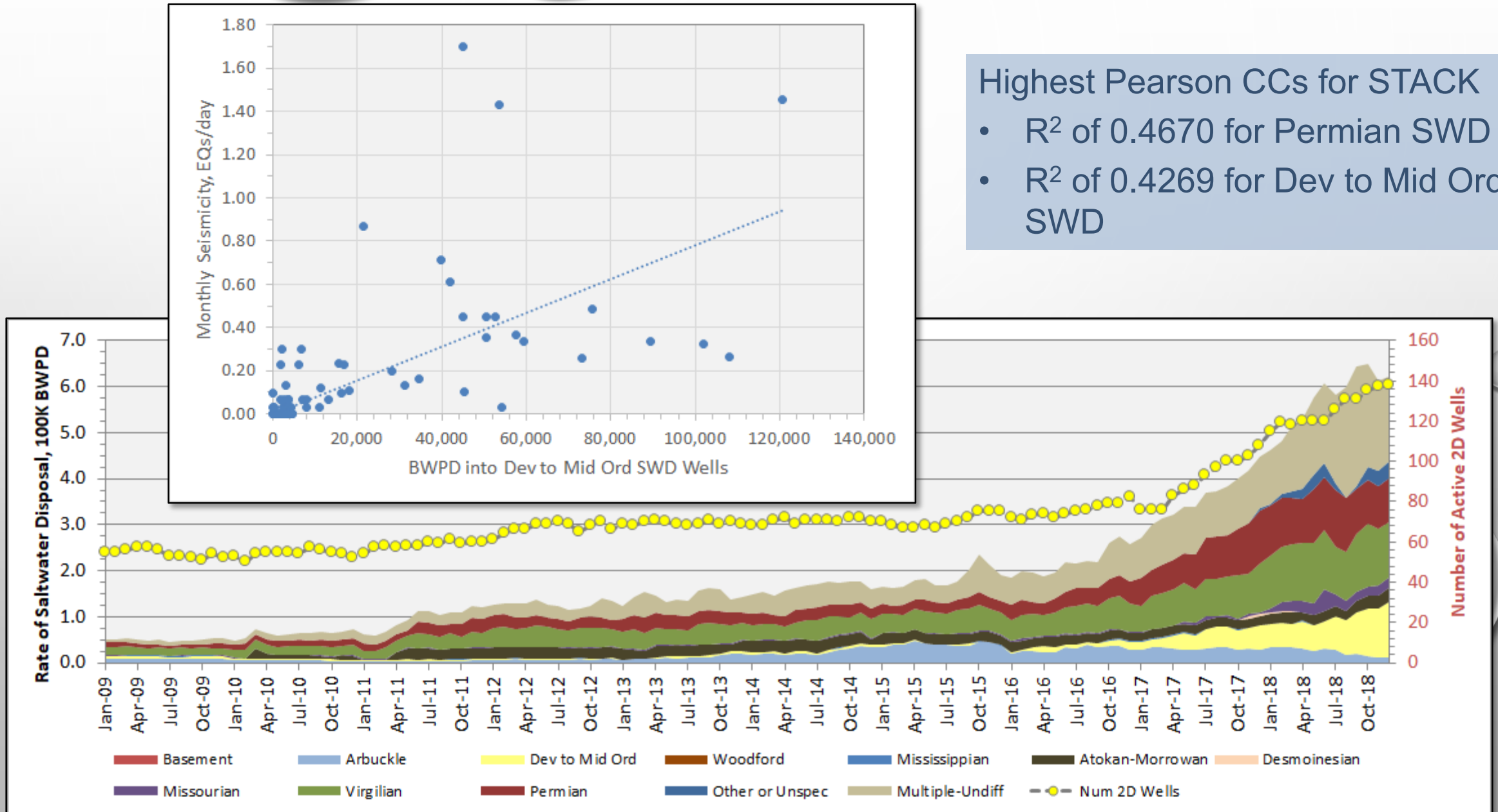




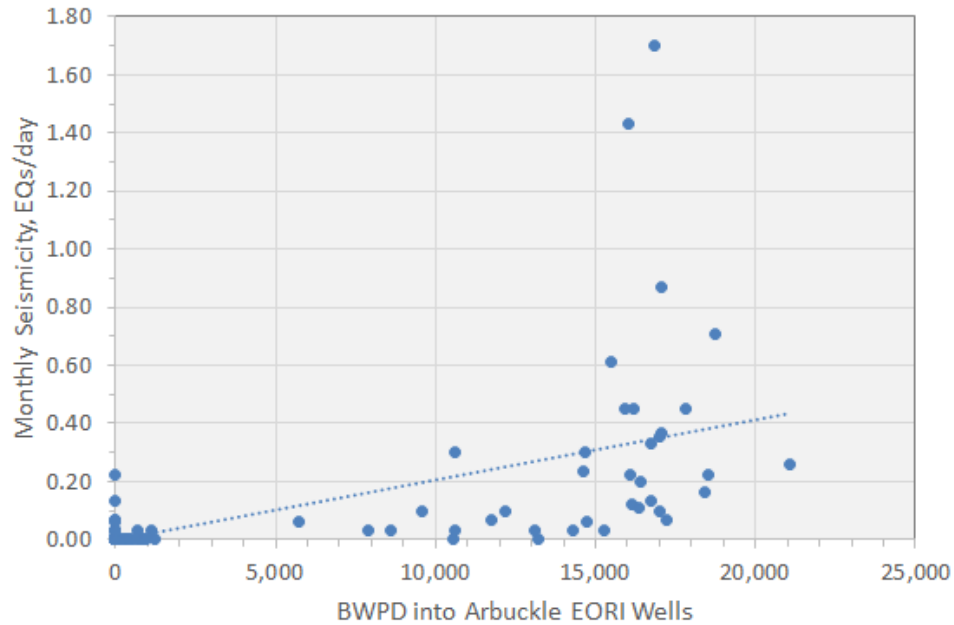
# Monthly SWD Injection in the STACK

Highest Pearson CCs for STACK

- $R^2$  of 0.4670 for Permian SWD
- $R^2$  of 0.4269 for Dev to Mid Ord SWD

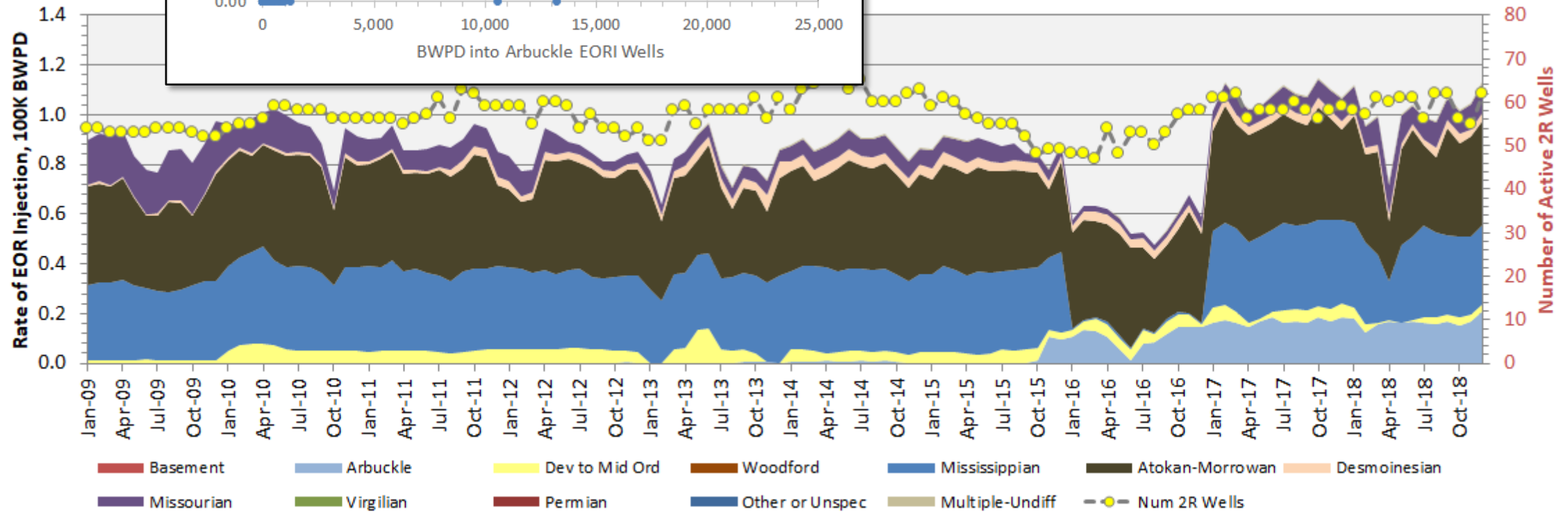


# Monthly EOR BWPD Injection in the STACK



Highest Pearson CCs for STACK

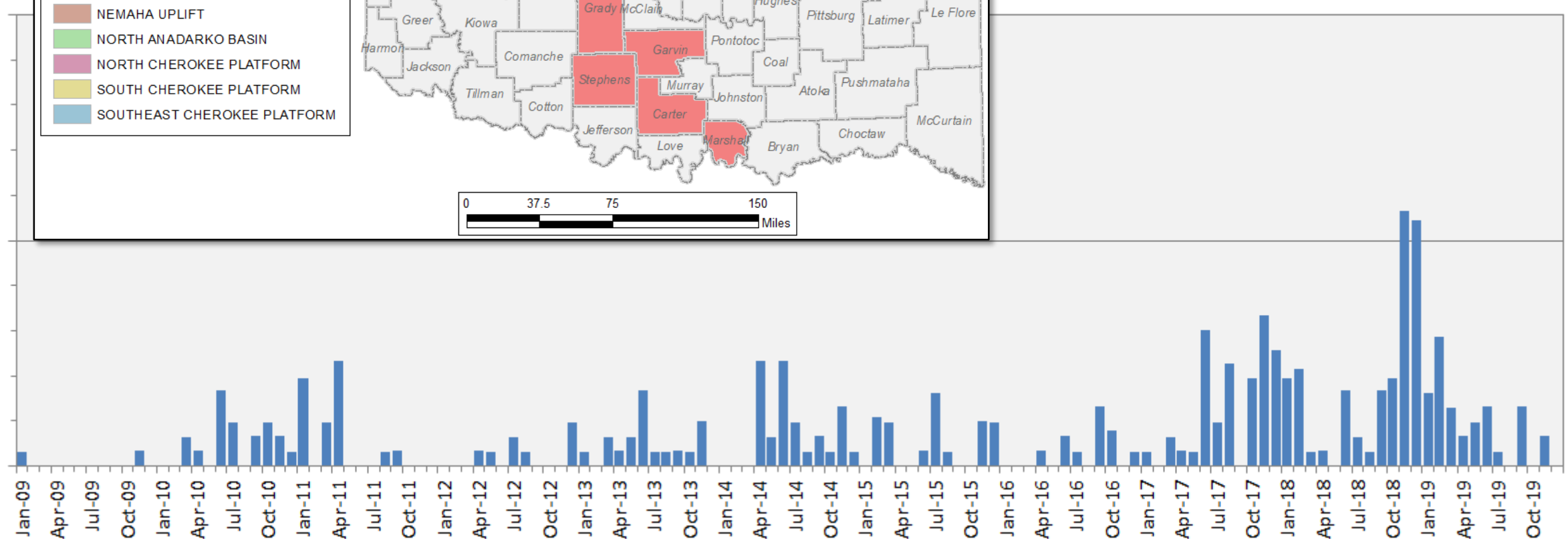
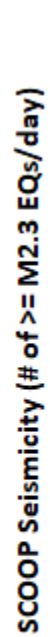
- $R^2$  of 0.4158 for Arbuckle EORI
- $R^2$  of 0.1519 for Multiple-Undiff. EORI



**Dependent Variable: EQ rate or #  $M \geq 2.3$  per day in the SCOOP**

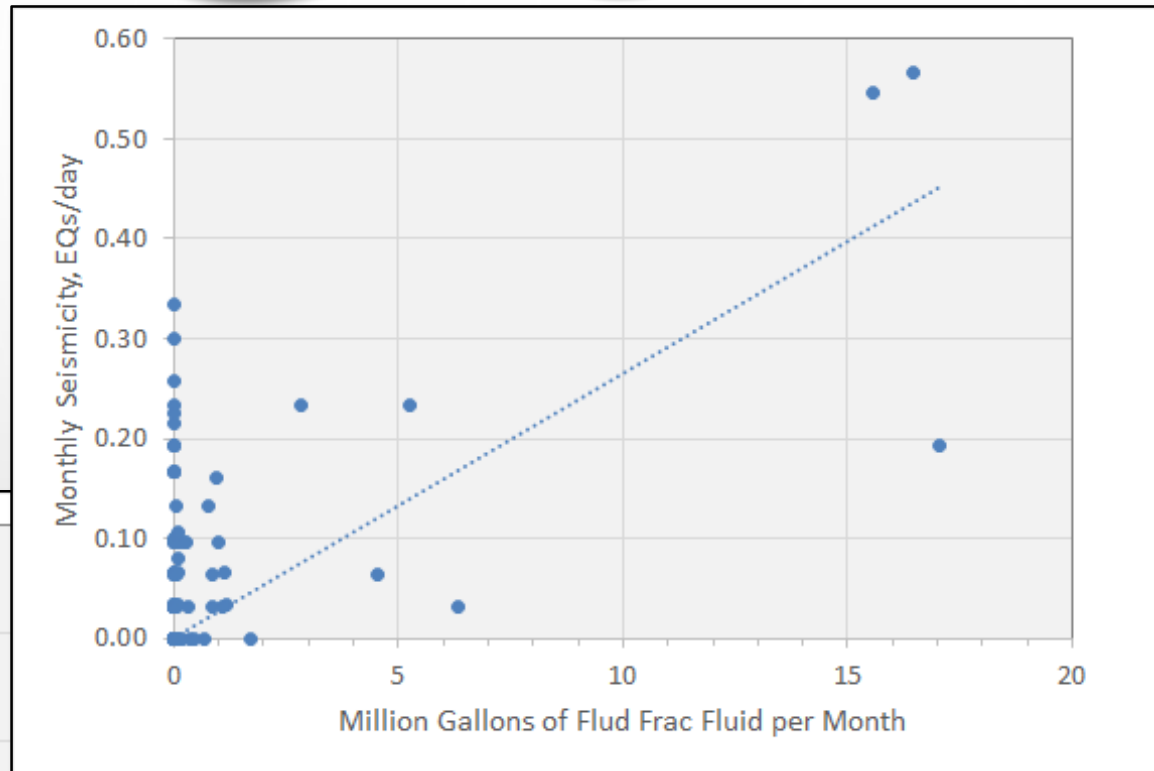
## Highest Seismicity Rates in SCOOP

- 0.57 EQ/day Nov 2018
- 0.55 EQ/day Dec 2018



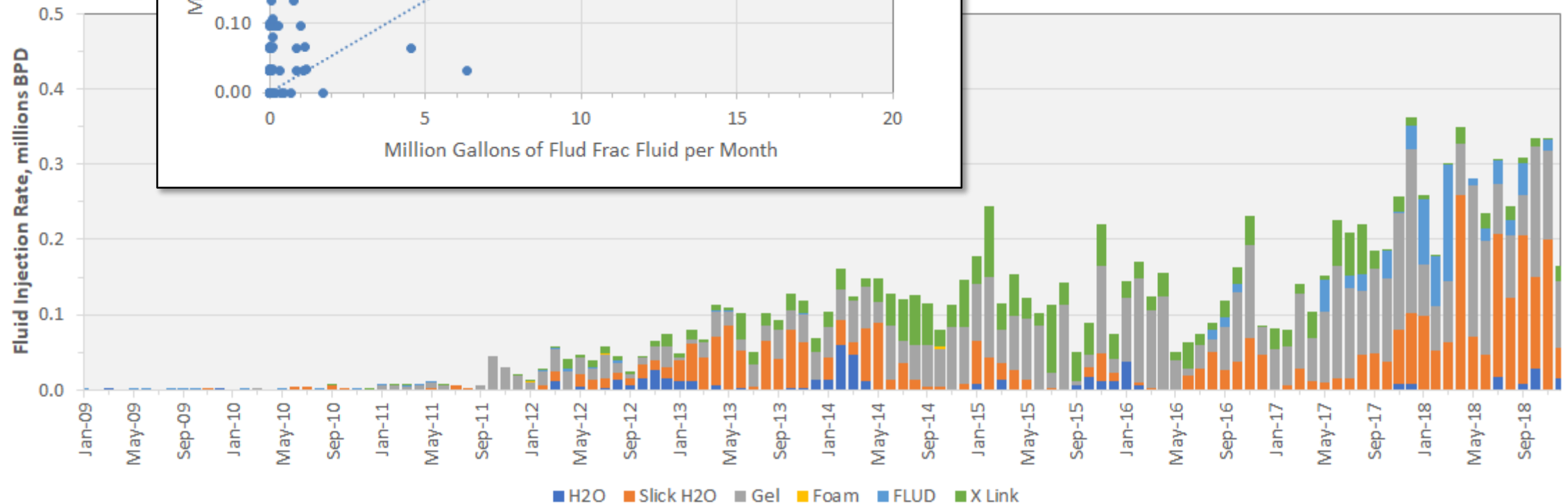


# Monthly Fluid Injection for Hydraulic Fracturing in the SCOOP

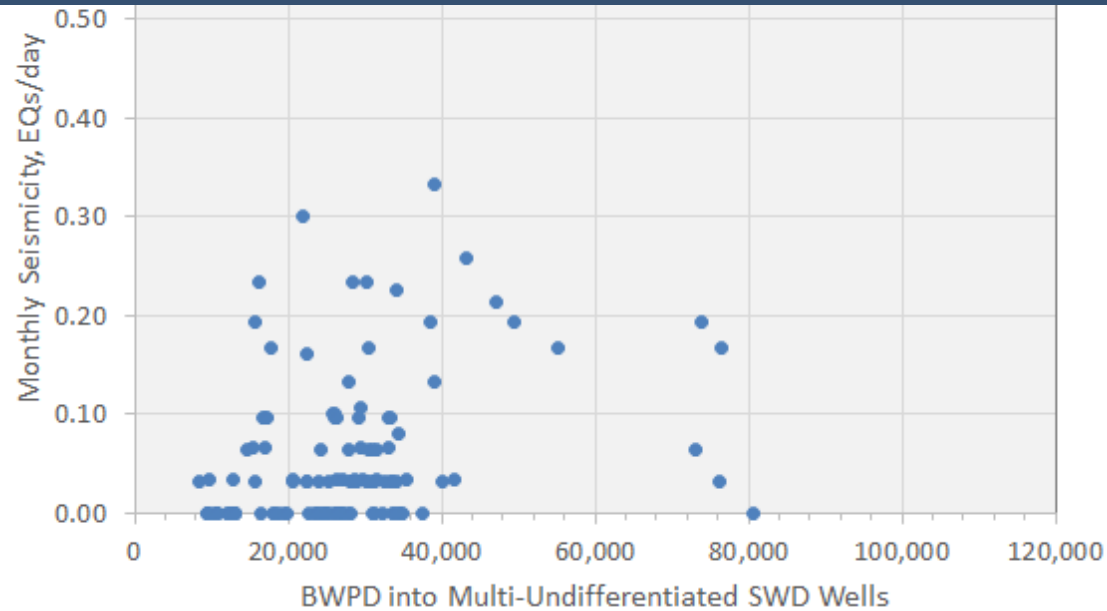


Highest Pearson CCs for SCOOP

- $R^2$  of 0.3632 for Fluid Frac
- $R^2$  of 0.2782 for Gel Frac

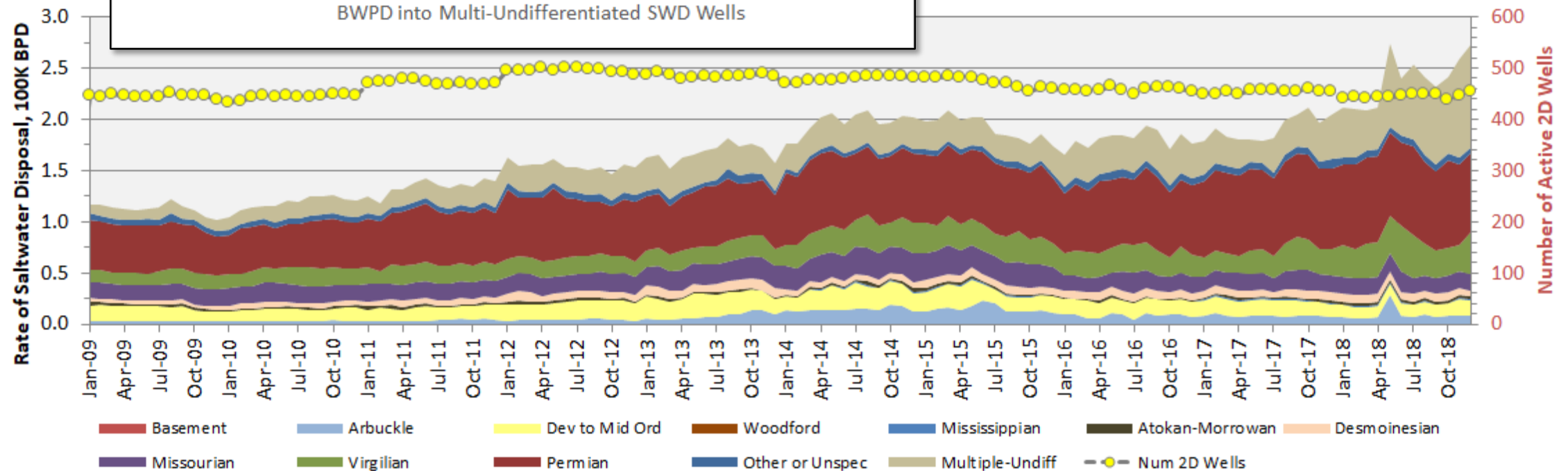


# Monthly SWD Injection in the SCOOP

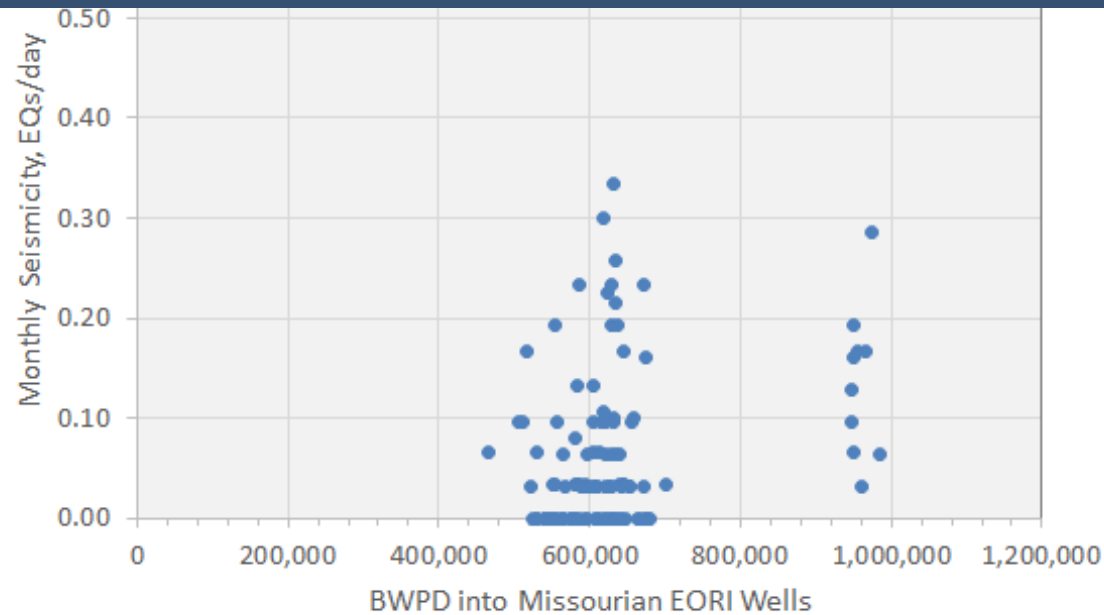


Highest Pearson CCs for SCOOP

- $R^2$  of 0.2986 for Multi-Undiff. SWD
- $R^2$  of 0.1868 for Perm SWD

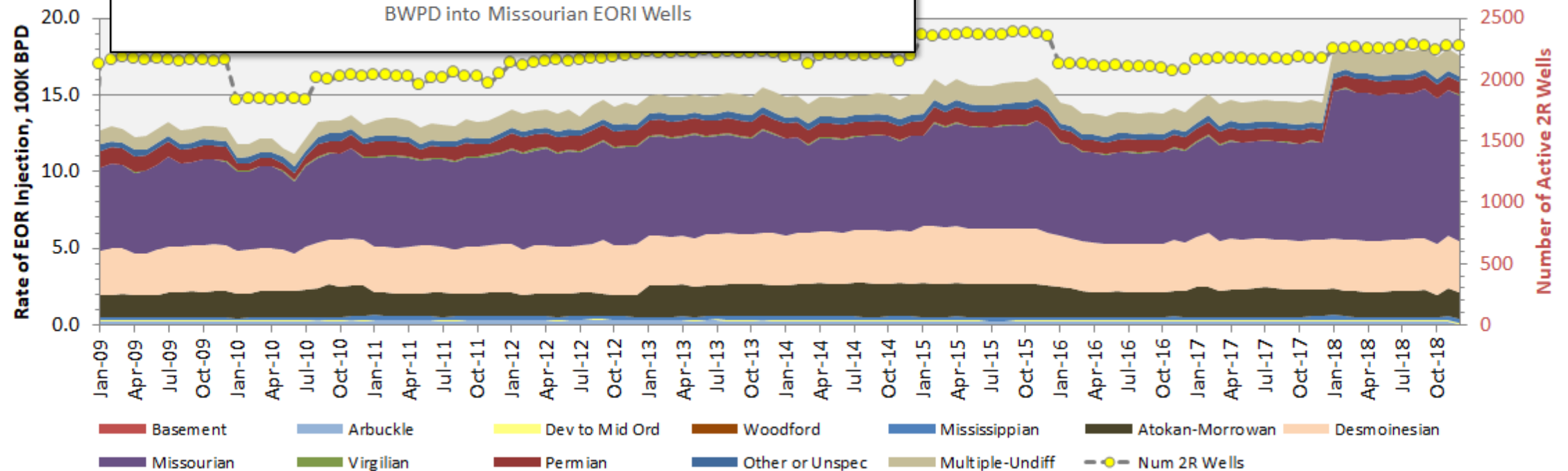


# Monthly EOR Injection in the SCOOP



Highest Pearson CCs for SCOOP

- $R^2$  of 0.2058 for Missourian EORI
- $R^2$  of 0.1585 for Dev to Mid Ord EORI





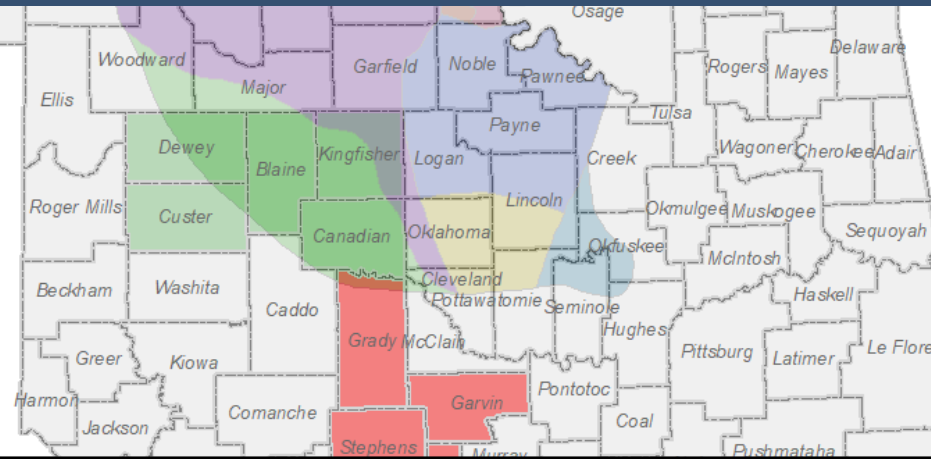
# Dependent Variable: EQ rate or # $M \geq 2.3$ per day in the S Cher. Plat.

## County Boundary

- Other
- SCOOP County
- STACK County

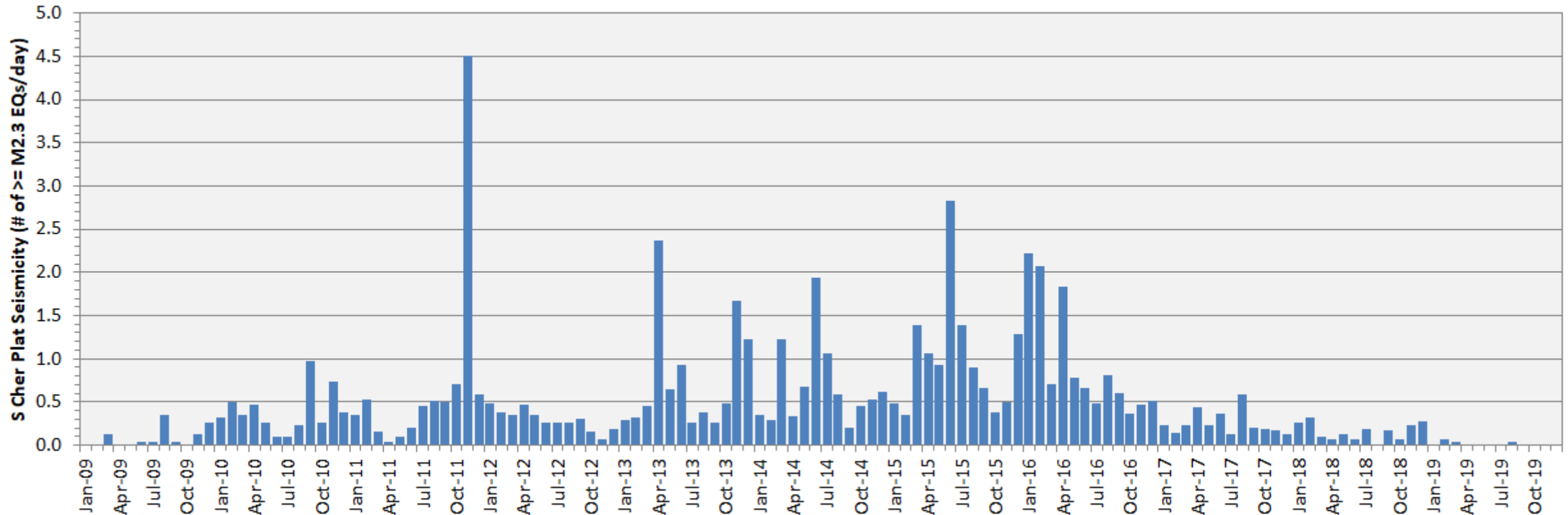
## Geological Provinces of AOI

- ANADARKO SHELF
- CENTRAL CHEROKEE PLATFORM
- NEMAHA UPLIFT
- NORTH ANADARKO BASIN
- NORTH CHEROKEE PLATFORM

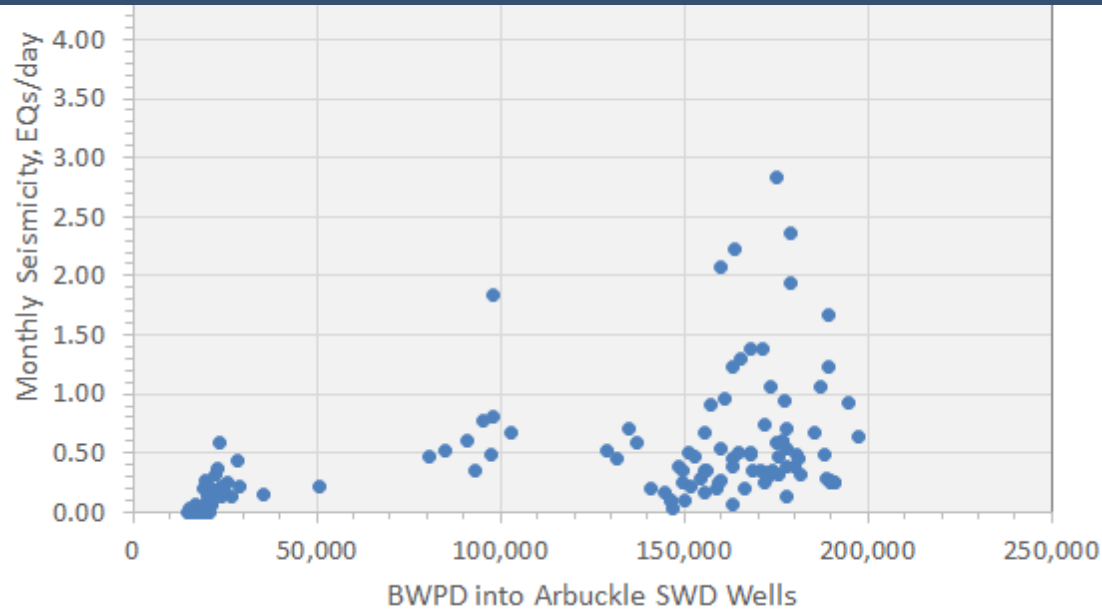


## Highest Seismicity Rates in South Cherokee Platform

- 4.50 EQ/day Nov 2011 (Prague)
- 2.83 EQ/day Jun 2015

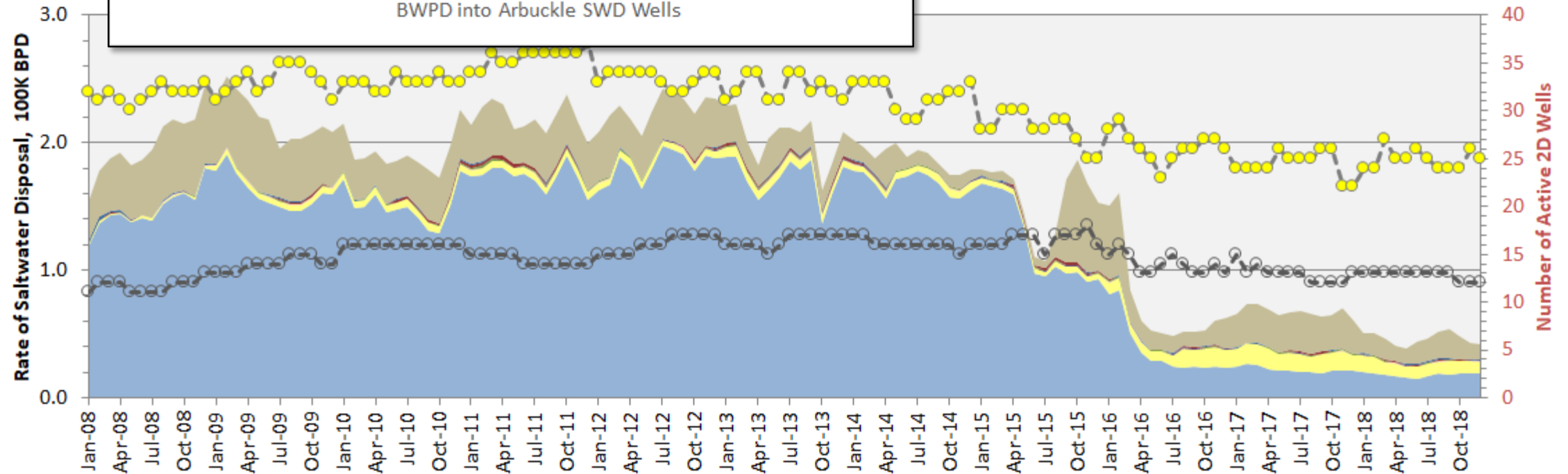


# Monthly SWD Injection in the South Cherokee Platform

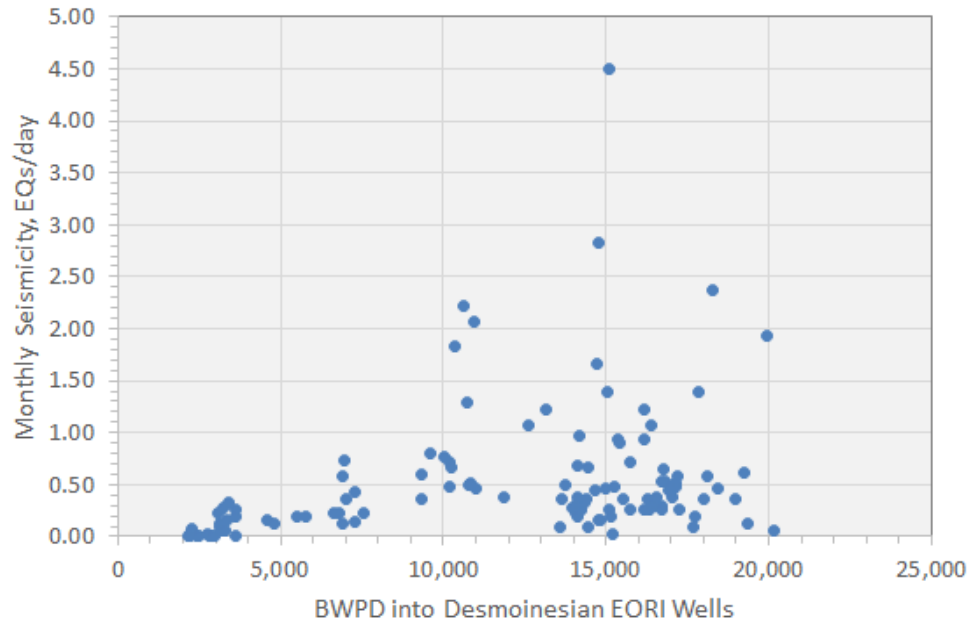


Highest Pearson CCs for South Cherokee Platform

- $R^2$  of 0.1688 for Virgilian SWD
- $R^2$  of 0.1505 for Arbuckle SWD

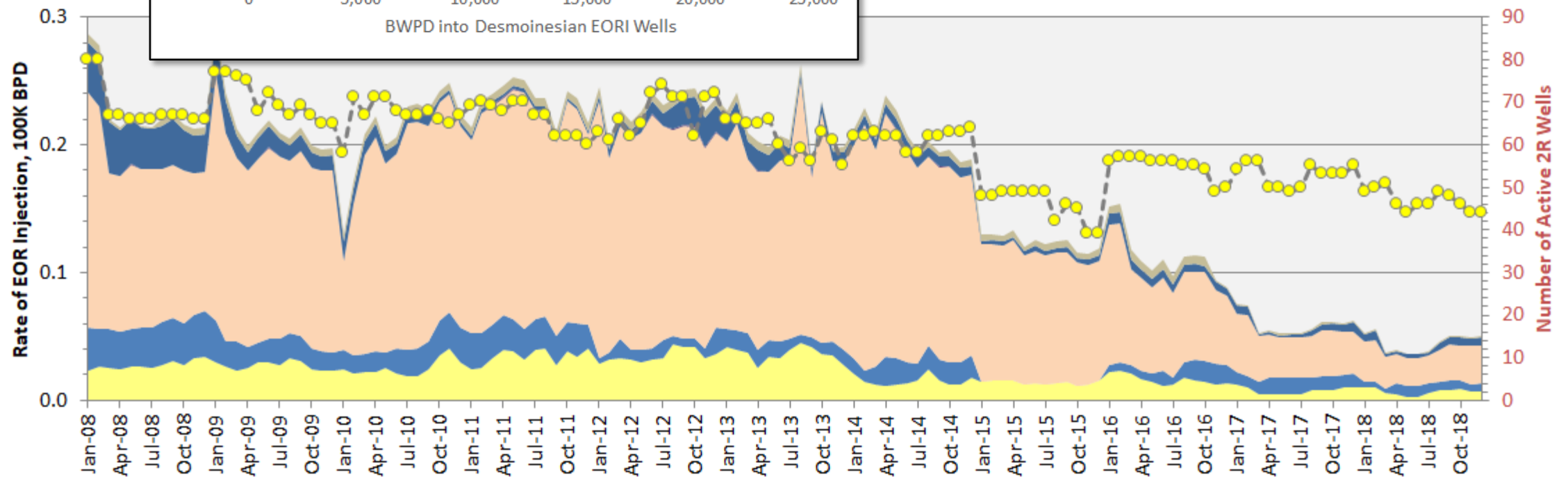


# Monthly EOR Injection in the South Cherokee Platform



Highest Pearson CCs for South Cherokee Platform

- $R^2$  of 0.0914 for Desmoinesian EORI
- $R^2$  of 0.0904 for Missourian EORI





# Summary and Conclusions

## \*AOI

$R^2$  of 0.7877 for Arbuckle SWD

$R^2$  of 0.7372 for Basement SWD

## STACK

$R^2$  of 0.4670 for Permian SWD

$R^2$  of 0.4646 for Miss Oil Production

## SCOOP

$R^2$  of 0.3632 for Flud Frac

$R^2$  of 0.3425 for Miss. Gas

## \*South Cherokee Platform

$R^2$  of 0.1688 for Virgilian SWD

$R^2$  of 0.1505 for Arbuckle SWD

*\*haven't done  $R^2$  for other injection or production*

## Statewide EQ versus CO<sub>2</sub>

$R^2$  of 0.1625 for Other or Unspecified Zone

- Many human activities that correlate to seismicity are cross-correlated
- Additional analyses and modeling studies are required to understand the mechanisms that have the greatest effect on subsurface stresses
- ***New project Funded by OWRB:***  
*Database Compilation and GeoSpatial Analysis of Produced Water Quality in Oklahoma*

# Upcoming Special Issues and Publications

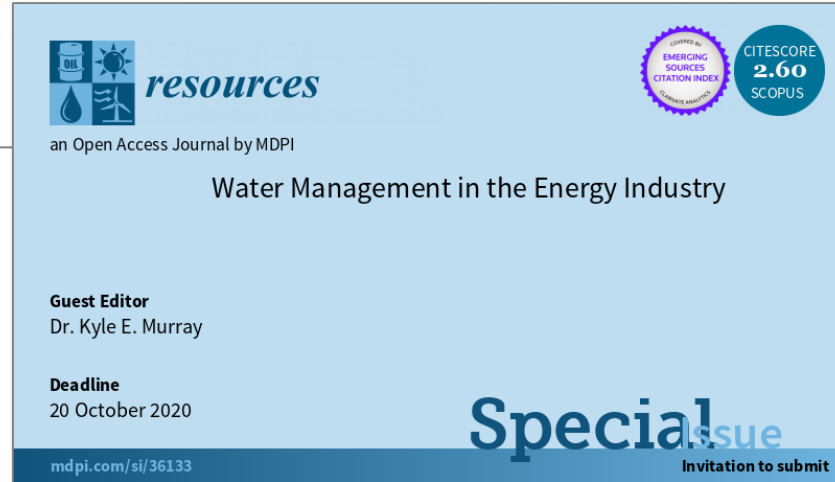
## Special Issue Editor

**Dr. Kyle E. Murray**   [E-Mail](#)   [Website](#)

*Guest Editor*

University of Oklahoma, Norman, United States

**Interests:** groundwater; hydrogeology; wastewater reuse; water-energy nexus; subsurface geoscience



## Geological Society of America Memoir

### Midcontinent Earthquakes: The Scientific and Regulatory Response to Induced Seismicity

*Volume Editors:*

**Michael Young** – TX Bureau of Economic Geology

**Rex Buchanan** – KS Geological Survey

**Kyle Murray** – OK Geological Survey