SUBSURFACE PRESSURE IN SEISMOGENIC AREAS

Kyle E. Murray, Ph.D. Hydrogeologist
KyleMurrayH2O@gmail.com
Kyle.Murray@ou.edu
https://twitter.com/KyleMurrayH2O
http://kylemurray.oucreate.com/

Webinar for:
Regional Induced Seismicity Collaborative (RISC)
Norman, OK
Oct 11, 2018
OGS’ First Crack at Putting Together 2011 UIC Data

Inventory of Class II Underground Injection Control Volumes in the Midcontinent

OGS’ First Crack at Putting Together 2011 UIC Data

<table>
<thead>
<tr>
<th>Zone</th>
<th>Group</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permian</td>
<td>Chase</td>
<td>Garber</td>
</tr>
<tr>
<td></td>
<td>Council Grove</td>
<td>Pontotoc</td>
</tr>
<tr>
<td></td>
<td>Admire</td>
<td>Belvair</td>
</tr>
<tr>
<td></td>
<td>Wabashnee</td>
<td>Cisco Lime</td>
</tr>
<tr>
<td></td>
<td>Shawnee</td>
<td>Pawhuska</td>
</tr>
<tr>
<td></td>
<td>Douglas</td>
<td>Twin Lakes</td>
</tr>
<tr>
<td>Desmoinesian</td>
<td>Hoxbar</td>
<td>Lansing</td>
</tr>
<tr>
<td></td>
<td>Cremonics</td>
<td>Skinney</td>
</tr>
<tr>
<td></td>
<td>Red Fork</td>
<td>Rushbank</td>
</tr>
<tr>
<td></td>
<td>Bath Project</td>
<td>Lanesville</td>
</tr>
<tr>
<td></td>
<td>Miss Lime</td>
<td>Miss Chat</td>
</tr>
<tr>
<td></td>
<td>St. Louis</td>
<td>St. Louis</td>
</tr>
<tr>
<td></td>
<td>Mayes</td>
<td>Mayes</td>
</tr>
<tr>
<td></td>
<td>Osage</td>
<td>Sycamore</td>
</tr>
<tr>
<td></td>
<td>Kinderhook</td>
<td>Kinderhook</td>
</tr>
<tr>
<td>Desmoinesian</td>
<td>Atoka</td>
<td>Gilcrese</td>
</tr>
<tr>
<td></td>
<td>Morrow</td>
<td>Dutcher</td>
</tr>
<tr>
<td></td>
<td>Springers</td>
<td>Wamsley</td>
</tr>
<tr>
<td></td>
<td>Chester</td>
<td>Caney</td>
</tr>
<tr>
<td>Mississippi</td>
<td>Meramec</td>
<td>Seacliff</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dev to Mid Ord</td>
<td>Upper Devonian</td>
<td>Woodford</td>
</tr>
<tr>
<td></td>
<td>Middle Devonian</td>
<td>Musser</td>
</tr>
<tr>
<td></td>
<td>Lower Dev - Silurian</td>
<td>Huntley</td>
</tr>
<tr>
<td></td>
<td>Cincinnati</td>
<td>Sylvan</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arubackle</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Arubackle Group</td>
<td>Kindblade</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basement &amp; Crystalline Rock</td>
<td>Cambrian</td>
<td>Reagan</td>
</tr>
<tr>
<td></td>
<td>Pre-Cambrian</td>
<td>Granite</td>
</tr>
</tbody>
</table>

UIC Fluid Injection Volume (MMbbl)

- **Permian**: EORI Volume ~ 1093 MMbbl
- **Virgilian**: SWD Volume ~ 891.9 MMbbl
- **Missourian**
- **Desmoinesian**
- **Atokan-Morrowan**
- **Mississippian**
- **Woodford**
- **Dev to Mid Ord**
- **Arbuckle**
- **Basement**
- **Multiple Undiff**
- **Other or Unspec**
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)
Wells that Started Producing from 2009–2015

Granite Wash Earthquakes Down Here, avg of 5.5 km depth
Predominant Disposal Zone, avg of 2 km depth

(Murray, et al., 2018 in preparation)
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

(Murray, et al., 2018 in preparation)

Increase in Dev to Mid Ord
Or Wilcox SWD in 2016

Incomplete 1012A records for 2017
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
How is saltwater disposal related to seismicity in the mid-Continent?

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

M. Weingarten, S. Ge, J. W. Godt, B. A. Bekins, J. L. Rubinstein

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.
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?

<table>
<thead>
<tr>
<th>Maximum injection rate (bbl/day)</th>
<th>associated with ≥M 3.0+ EQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;3000 bbl/day</td>
<td>40–60%</td>
</tr>
<tr>
<td>&gt;10,000 bbl/day</td>
<td>80–95%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cumulative volume from 2009 to 2016</th>
<th>associated with ≥M3.0+ EQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2–3 MMbbl</td>
<td>65%</td>
</tr>
<tr>
<td>30–60 MMbbl</td>
<td>90%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proximity to Basement</th>
<th>associated with ≥M3.0+ EQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;0.5 km</td>
<td>55%</td>
</tr>
<tr>
<td>0.5 to –0.5 km</td>
<td>90%</td>
</tr>
</tbody>
</table>
Spatial Distribution of Scanlon et al. Results, # of Associated Factors

RISC Factors
- 0 (3407)
- 1 (1315)
- 2 (241)
- 3 (36)

OF3-2015 faults

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

RISC Red and Yellow
- 2 (241)
- 3 (36)

EQ >=M4 2009-present
- 4.0-4.9
- 5.0-5.8

OF3-2015 faults

Oklahoma Counties
Wells that were “Mathematically” in Basement (Crain vs. Murray)
Plug-back Program, ~250 SWD wells

(Murray, et al., 2018 in preparation)
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

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)
Logan 12 with radius of 10 km

Fluid Elevation in Inactive SWD Monitoring Well

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


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

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

Poroplastic 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

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 v3.3 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 Hewittville 8x to the residual coseismic offset is shown in red with the amplitude $\Delta h$ (indicated along with the 86% 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

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

- measured in well or based on well completion data
- adjusted value
- published values
- textbook

\[ \psi_{0,1} * 6894.75 \text{ m}^2 \text{N} \]

<table>
<thead>
<tr>
<th>( \Delta x )</th>
<th>( m_1 )</th>
<th>( m_2 )</th>
<th>( k/15 )</th>
<th>( C ) (g/L NaCl)</th>
<th>( m_3 )</th>
<th>( T ) (deg F)</th>
<th>( m_4 )</th>
<th>( C_{st} ) (1988)</th>
</tr>
</thead>
<tbody>
<tr>
<td>318952.206</td>
<td>7.083</td>
<td>2628.9335</td>
<td>0.1</td>
<td>-537</td>
<td>200</td>
<td>403300</td>
<td>100000</td>
<td></td>
</tr>
</tbody>
</table>

Distance between 2D-Inj and 2D obs. Ft: 400 ft
Reservoir/Formation Thickness, b, ft: 3655 ft
Hydraulic Conductivity, K, ft/day: 7.0
Compress of Reservoir, Beta p, m2/N: 185378E-11
Transmissivity, T, ft^2/day: 60750
Storage Coefficient, S: 1.16E-04
Specific Storage, Sr, ft^-1: 1.33E-07
Density of fluid, kg/m^3: 1036
Specific weight, kN/m^3: 1143

TDS of H2O

| inj TVD Top | Compress of fluid, Beta f, m2/N: 4.5E-10
|------------|--------------------------------|
| 6115       | Reservoir/Formation Thickness, b, ft: 868 ft
| 6886       | Transmissivity, T, ft^2/day: 60750
| 0.4915     | Storage Coefficient, S: 1.16E-04

Delta BPD during inj

- Injection BPD: 15391
- Water Injection BPD: 20849

- Diffusivity, D, ft^2/day: 5.24E07
- Storage Coefficient, S: 1.16E-04
- Specific Storage, Sr, ft^-1: 1.33E-07
- Density of fluid, kg/m^3: 1036
- Specific weight, kN/m^3: 1143

- Inflow/Outflow: 23520
- Inflow Rate, ft^3/day: 23520
- Effective Porosity: 0.1
- Reservoir Temperature: 120 deg F

- \( C_{st} \) (1988) as a function of temp, NaCl salinity, pressure

Dec 13, 2016 14:21 to 19:41

modified Theis solution

Observations

- Observations

- \( C_{st} \) (1988) unit conversions: 0.005 m2/s Barbour et al., 2017

- \( C_{st} \) (1988) unit conversions: 0.002 m2/s Perilla, 2017
Calibrated Model of Stress (Injection) & Strain (Observed Head)

(McConville & Murray, 2018 in preparation)
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)
- Define Hydraulic Properties
- Establish Pressure Regime/Trends

Construct Integrated Hydrogeologic/Geomechanical/Seismological Model

Provide Up-To-Date Decision Support Tool for Operators & Regulators

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