Patterns of Induced Seismicity in Central and Northwest Oklahoma

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The Oklahoma Geological Survey is a state agency for research and public service located on the Norman Campus of the University of Oklahoma and affiliated with OU’s Mewbourne College of Earth and Energy. The Survey is chartered in the Oklahoma Constitution and is charged with investigating the state's land, water, mineral, and energy resources and disseminating the results of those investigations to promote the wise use of Oklahoma's natural resources, consistent with sound environmental practices.

We are not a regulatory authority
Mewbourne College staff engaged on seismicity issue

- **Oklahoma Geological Survey**
  - **Seismology:** Jacob Walter, State Seismologist, Jefferson Chang, Fernando Ferrer, Andrew Thiel, Isaac Woelfel
  - **Hydrogeology, Geology:** Kyle Murray
  - **Publications & Outreach:** Ted Satterfield, Molly Yunker

- **Conoco-Phillips School of Geology and Geophysics**
  - **Seismology:** Xiaowei Chen, Nori Nakata
  - **Geology:** Douglas Elmore, Matthew Pranter
  - **Geophysics:** Kurt Marfurt

- **Mewbourne School of Petroleum & Geological Engineering**
  - **Petroleum Engineering:** Zulfiquar Reza
OGS monitors ~100 seismometer stations
Human activity can induce earthquakes

Figure modified from: http://www.earthmagazine.org/article/ground-shaking-research-how-humans-trigger-earthquakes
6 Earthquakes, Injection, Oil Production

- M3.0+ OK Earthquakes
- AOI Injection
- OK Crude Oil Production x 10
7 Oil price, injection rate and OCC directed reductions

OCC Directive 1
3/25/2015
Effective 4/18/2015
8 Oklahoma Corporation Commission (OCC) Actions

- Redefinition into 7 subprovinces for analysis and possible future actions
2009-2012 M2.5+ earthquakes
2013 M2.5+ earthquakes
2014 M2.5+ earthquakes
2015 M2.5+ earthquakes
2016 M2.5+ earthquakes
2017 M2.5+ earthquakes
Petroleum development history affects seismicity
Full AOI M2.5+ earthquakes with new subprovinces
M2.5+ earthquakes, S, SE Cherokee Platform

![Map of M2.5+ earthquakes, S, SE Cherokee Platform]

![Chart showing M2.5+ earthquakes per day, injection (BWPD X 100,000), and injection over time]
Anadarko Shelf M2.5+ earthquakes
Central Cherokee Shelf M2.5+ earthquakes

The diagram shows the number of M2.5+ earthquakes per day, with injection data in blue and earthquake data in red. The peak in earthquake activity occurred around 2014-2015, coinciding with a period of increased injection activity.
South Part, C Cherokee, M2.5+ earthquakes,
E Half, S Central Cherokee Platform
Anadarko Basin M2.5+ earthquakes
Quantifying the limits of regional-scale earthquake mitigation measures

1. The Arbuckle Group SWD well locations predict M3.0+ earthquake occurrence within a ~1σ radius of gyration when the well centroid is geometrically weighted by SWD volume.

2. Arbuckle Group injection volume and earthquake occurrence between 2014 and 2016 are spatially cross-correlated to a length scale of 125 km.

3. Earthquake mitigation strategies implemented in late 2015 and 2016 are preferentially affecting the joint variability of SWD volume and small-magnitude earthquakes, while larger magnitude earthquakes (M3.0+) appear unaffected.

As a result, earthquake mitigation strategies may require further volume reductions and/or greater areal extent to increase effectiveness.
Problems with the Pollyea group conclusions

• Recommends greater extent to volume reductions, but ignores OCC directives of 2016, which ordered reductions to 40% of peak values in 2014 (although one of the orders was cited in the paper)

• Lumps all data together despite evident geologic boundaries that isolate different plays and different tectonic subprovinces such that they should be treated as separate statistical populations

• Graphically minimized the 2/3 reduction in earthquake frequency during 2016, which continued through 2017 in response to reductions

• Peer review failed to highlight these flaws
“The slight decrease in earthquake occurrence starting in 2016...”

Pollyea and others, 2018
Newsweek journalism puts nation’s survival at risk by causing massive cluelessness
Anomalous seismicity potentially associated with completion operations (hydraulic fracturing)

Comparison of FracNotice (since 10/2016) and OGS Catalog

- Earthquakes within 2 km and 5 days of start of hydraulic fracturing job
- 7% of hydraulic fracturing operations may generate an earthquake
- Eliminating double counting (multiple earthquakes/wells in an area) 4% result in an earthquake
- As of April 7, 2017
OCC well completion guidance on seismicity

• Action following anomalous seismic activity ≤2 km from completion operations

• Stoplight system, if Oklahoma Geological Survey reports magnitude ≥2.5M; ≥3.0M; ≥3.5M earthquake

• Escalating review of operator’s internal mitigation procedures by Oil & Gas Conservation Division of OCC

• Operations may resume if seismicity stops and mitigation approach considered adequate

• Procedure exercised successfully 27 times
Summary

- Frequency of earthquakes related to deep injection of produced water
  - Rose to 20-50X background during 2009-mid 2013 (20-100 M3.0+/year)
  - Rose to >600X background by 2015 (2014 – 579; 2015 – 903)
  - Declined sharply in 2016 in response to OCC actions, and to price drop (623)
  - Flat in 2017 (304); apparently lower in 2018(?)
- Earthquakes related to completion operations, especially in the SCOOP and STACK plays, have responded to actions to limit, and even stop additional seismicity
- Regulatory response is increasingly tied to enhanced understanding of regional variations in seismicity
- Research has considerably enhanced understanding of rock properties and seismic characteristics of response to deep injection
Backup Material
Well completions, earthquakes, major faults

Mississippian wells

Hunton wells

Earthquakes
Earthquakes occur in areas of large volume disposal wells

Murray 2015, OGS OF5-2015

SWD well volumes (bbl/mon) in 2014

- up to 150,000
- 150,000 - 500,000
- greater than 500,000

Regional Faults

Prepared by:
Kyle E. Murray
OGS Hydrogeologist
Disposal contains <5% flowback water from hydraulic fracturing

OK earthquakes occur in basement, on optimally aligned faults.

2016 Earthquakes

- Average 5.8 ± 1.8

Active Fault Orientations 2014

- Maximum Horizontal Stress

OGS OF1-2015
Continuous measurement of hydrostatic head in 15 shut-in UIC Class II (salt water disposal) wells completed in the Arbuckle Group provides insight into induced seismicity.
State actions on induced seismicity

- Governor creates Coordinating Council on Seismicity (2014)
- Secretary of Energy funds $200,000 seismicity projects (2015)
- Governor’s Water for 2060 Produced Water Working Group (2015)
- RPSEA funded stations added to OGS network (2016)
- Governor’s Emergency Fund $1,387,000 to OCC, OGS (2016)
- New tracking system for earthquakes and injection for OCC (2016)
### Earthquake magnitude & frequency

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Earthquakes</th>
<th>Energy Equivalents</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1</td>
<td>Krakatoa eruption</td>
<td>World’s largest nuclear test (USSR)</td>
</tr>
<tr>
<td>1</td>
<td>Mount St Helens eruption</td>
<td>Hiroshima atomic bomb</td>
</tr>
<tr>
<td>18</td>
<td>Moderate lightning bolt</td>
<td>Oklahoma city bombing</td>
</tr>
<tr>
<td>150</td>
<td>Average tornado</td>
<td>Moderate lightning bolt</td>
</tr>
<tr>
<td>1,500</td>
<td>Long Island (1884)</td>
<td>Injection induced earthquakes (Typical &lt;3.5)</td>
</tr>
<tr>
<td>10,000</td>
<td>Loma Prieta (1989)</td>
<td>Injection induced earthquakes (Typical &lt;3.5)</td>
</tr>
<tr>
<td>100,000</td>
<td>Northridge (1994)</td>
<td>Injection induced earthquakes (Typical &lt;3.5)</td>
</tr>
<tr>
<td>10,000</td>
<td>Chile (2010)</td>
<td>Injection induced earthquakes (Typical &lt;3.5)</td>
</tr>
<tr>
<td>150</td>
<td>Sumatra (2004)</td>
<td>Injection induced earthquakes (Typical &lt;3.5)</td>
</tr>
<tr>
<td>150</td>
<td>Alaska (1964)</td>
<td>Injection induced earthquakes (Typical &lt;3.5)</td>
</tr>
<tr>
<td>100,000</td>
<td>Chile (1960)</td>
<td>Injection induced earthquakes (Typical &lt;3.5)</td>
</tr>
</tbody>
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Largest recorded earthquakes
- Vast destruction
- Massive loss of life

Great earthquake
- Severe impact
- Large loss of life

Strong earthquake
- Damage in $Billions
- Some loss of life

Moderate earthquake
- Property damage

Light earthquake
- Some property damage

Minor earthquake
- Felt by humans

Injection induced earthquakes
- Typical <3.5 (Highest recorded = 5.8)

Frequency of Occurrence
- Avg. per year (est.)

Magnitude 2.0 and below = typical micro-seismic events
Frequency vs magnitude
(Gutenberg-Richter relationship)
Lagenbruch & Zoback, *How will induced seismicity in Oklahoma respond...*

- Statistically based model
  - “predicts that widely felt $M \geq 3$ earthquakes in the affected areas, as well as the probability of potentially damaging larger events, should significantly decrease by the end of 2016 and approach historic levels within a few years.”

- Comment by Goebel and others critiques model and parameter values, suggests substantially higher rate, slower decline

- Reply stands by model results as better reflecting rates to date
Barbour and others, *Effects of varying injection rates*…

- Combined effect of stress changes associated with high-rate and long term fluid injection may have influenced timing & location of Pawnee earthquake.
- Diffusion principal mechanism transmitting pore-fluid pressure changes in basement rock; effects of rock-fluid strain coupling are significant.
- Seismicity rate calculations sensitive to rate of change of Coulomb failure stresses and predict increases >1 order of magnitude above background.
- Predicted seismicity rate increase resembles lagged smoothed version of injection-rate history.
- Observed seismicity leading up to main shock follows cumulative density function of rates predicted by variable-rate injection simulation.
- If seismicity rates are affected by poroelastic stress changes, they may remain elevated for >1 year after shut-in of injection wells;
- Accurate geomechanical properties of subsurface essential in understanding hazards associated with injection-induced seismicity, especially in low strain-rate environments.
Kroll and others, *Poroelastic properties of Arbuckle Group… from well fluid level response*

- Report fluid level changes in two monitoring wells in response to the 3 September 2016 Mw 5.8 Pawnee and the 7 November 2016 Mw 5.0 Cushing earthquakes.

- Both direction and amplitude of observed fluid level step can be predicted from computed volumetric strain change and a reasonable set of poroelastic parameters.

- Modeling results indicate that poroelastic parameters differ at the time of the Pawnee and Cushing earthquakes, with a moderately higher Skempton’s coefficient required to fit the response to the Cushing earthquake.

- May indicate that dynamic shaking resulted in physical alteration of the Arbuckle at distances up to ~50 km from the Pawnee earthquake.
A comprehensive network for Oklahoma

~$3.5 million cost to install, phased over 3 years ~$400k to operate for 5 years*
*Operating costs may be absorbed by OGS core budget if we are successful in getting Maintenance and Operations budget back to FY16 levels (was $200k/yr, FY17 is $90k/yr)