Patterns of Induced Seismicity in Central and Northwest Oklahoma

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AGI Webinar
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 the OU 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*
Earthquake Magnitude & Frequency

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Earthquakes</th>
<th>Energy Equivalents</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Largest recorded earthquakes</td>
<td>Krakatoa eruption</td>
</tr>
<tr>
<td></td>
<td>Vast destruction</td>
<td>World’s largest nuclear test (USSR)</td>
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<tr>
<td></td>
<td>Massive loss of life</td>
<td>Mount St Helens eruption</td>
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<tr>
<td>9</td>
<td>Great earthquake</td>
<td></td>
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<tr>
<td></td>
<td>Severe impact</td>
<td></td>
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<tr>
<td></td>
<td>Large loss of life</td>
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<tr>
<td>8</td>
<td>Strong earthquake</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Damage in $Billions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Some loss of life</td>
<td></td>
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<tr>
<td>7</td>
<td>Moderate earthquake</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Property damage</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Light earthquake</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Some property damage</td>
<td></td>
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<tr>
<td>5</td>
<td>Minor earthquake</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Felt by humans</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Injection induced earthquakes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Typical &lt;3.5 (Highest recorded = 5.6)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Frequency of Occurrence</td>
<td>Oklahoma city bombing</td>
</tr>
<tr>
<td></td>
<td>Avg. per year (est.)</td>
<td>Moderate lightning bolt</td>
</tr>
<tr>
<td>2</td>
<td>Magnitude 2.0 and below</td>
<td></td>
</tr>
</tbody>
</table>

- Chile (1960)
- Alaska (1964)
- Sumatra (2004)
- Chile (2010)
- New Madrid (1812)
- San Francisco (1906)
- Charleston SC (1886)
- Haiti (2010)
- Loma Prieta (1989)
- Northridge (1994)
- Long Island (1884)
- Loma Prieta (1989)
- Northridge (1994)
- Long Island (1884)
4 Measuring an Earthquake

- **Magnitude**
  - Scaled *estimate* of energy released as seismic waves,
  - Proportional to rupture area

- **Magnitude measured multiple ways** ($M_L, m_b, M_w, M_o, M_s$)
  - Estimates are uncertain, and rarely the same between different methods
  - Scales logarithmic (+1 unit of magnitude = ~10 times shaking & ~32 times the energy release)

- **Earthquake Intensity**
  - Varies with distance from the earthquake
  - Qualitative estimate (using *Modified Mercalli scale* ranging from I-XII)
5 OGS Monitors ~100 Seismometer Stations
6 Oklahoma Earthquakes, 2016

Earthquake map available at OGS website:
http://uok.maps.arcgis.com/apps/Minimalist/index.html?appid=3ebaf2b8de02406b94804cbdb5afbec8
7 Human Activity Can Induce Earthquakes

Figure modified from: http://www.earthmagazine.org/article/ground-shaking-research-how-humans-trigger-earthquakes
Earthquakes occur in basement, on optimally aligned faults.

2016 Earthquakes

- Average 5.8 ± 1.8

Active Fault Orientations 2014
Earthquakes occur in areas of large volume disposal wells.
Disposal contains <5% flowback water from hydraulic fracturing.

Oklahoma M2.5+ earthquakes

![Graph showing M2.5+ earthquakes and Arbuckle injection over time.](image)

- **M2.5+ Earthquakes per Day**
- **Arbuckle Injection**
- **30 Day Average**
- **90 Day Average**
12 State Actions on Induced Seismicity

• Governor creates Coordinating Council on Seismicity (2014)
• OCC directives reduce injection (2015)
• Oklahoma Geological Survey (OGS) position paper (2015)
• 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)
Oklahoma Corporation Commission (OCC) Actions

- Arbuckle Group injection wells in Area of Interest (AOI) submit weekly report of daily injection rate
- Wells in Precambrian basement plugged back or cut injection 50%
- Reductions and shut-in wells reduced overall injection by >900,000 BWPD since mid-2015
- Caps on injection rate in Western and Eastern AOI
Oil Price, Injection Rate and OCC Directed Reductions

- WTI Oil Price
- OCC Directed Reductions
- 684 Arbuckle Well Injection

Salt Water Disposal (Million Barrels per Day)
1. Reduce challenges to water re-use through targeted regulations and legislation:
   - Remove legal ambiguity about ownership of produced water
   - Establish bonding requirements for water impoundments without being an impediment
   - Make right-of-way for pipelines for recycled/re-used water easier to obtain
   - Request delegation from the U.S. EPA to Oklahoma for discharge permits

2. Facilitate re-use of produced water in oil and gas operations

3. Study feasibility of transferring Mississippi Lime produced water to STACK play.

4. Continue evaluation of evaporation as an alternative to injection.

5. Consider all environmental and stakeholder impacts, and data gaps before implementing long-term projects.
Earthquakes associated with hydraulic fracturing
17 STACK & SCOOP Play Areas

Woodford Plays

STACK

Meramec Play

SCOOP
OCC well completion guidance on seismicity

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

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

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

• Operations may resume if seismicity stops and mitigation approach considered adequate
19 The vision: a comprehensive high-quality seismic network

The map shows seismic activity across a region, marked by different symbols representing different magnitudes of earthquakes. The legend indicates symbols for M 3.0, M 4.0, M 5.0, and M 6.0 earthquakes. The map includes temporary networks, OGS network, and a proposed network. The timeline below the map shows the number of events per week from 2008 to 2017. The total cost is estimated to be around $4 million.
Acknowledgments

• OGS Staff Engaged on the Seismicity Issue
  • Seismology: Jacob Walter, Jefferson Chang, Fernando Ferrer, Andrew Thiel, Isaac Woelfel
  • Hydrogeology, Geology, Geophysics: Kyle Murray, Ella Walker, Jordan Williams, Kevin Crain, Steve Holloway,
  • Publications & Outreach: Ted Satterfield

• Major Additional Funding Sources
  • Research Partnership to Secure Energy for America (RPSEA)
  • Secretary of Energy and Environment (through Recovery Act)
  • Oklahoma Governor’s Emergency Fund
Backup Material
Summary: Induced Seismicity in Oklahoma

- No documented case of induced seismicity close to Oklahoma in earthquake rate or affected area
- Only 34% of earthquakes occur within 2 km of any known fault.
- It is not clear the density of faulting is greater in Oklahoma than elsewhere in the mid-continent
- Majority of recent earthquakes in central and north-central Oklahoma likely triggered by injection of produced water in SWD wells
- Hydraulic fracturing flowback water <5% of SWD volume in Arbuckle
- Drop in earthquake frequency since mid-2015 likely results from decreases in injection in Area of Interest driven by oil price and Corporation Commission directives
- Small number of lower magnitude earthquakes apparently associated with hydraulic fracturing manageable through a stoplight system
USGS One-Year Hazard Forecast

2016

Wichita

Oklahoma City

Tulsa

2017

Wichita

Oklahoma City

Tulsa

Chance of damage

- Highest chance: 10% - 12%
- 5% - 10%
- 2% - 5%
- 1% - 2%
- < 1%

Lowest chance
Different plays have different seismic history
Timing of Earthquakes and Hydraulic Fracturing Stages

(a) # Earthquakes/hr

(b) Pressure (psi)

(c) Rate (lpm)

Time (Month-Day of 2011)
Earthquakes, Oil and Water

- M2.8+ Earthquakes
- 684 Arbuckle Well Injection
- OK Oil Production x10
- 3 Month Moving Average

Graph showing the relationship between earthquakes per day and production/injection (million barrels/day) from 2011 to 2017.
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