MITIGATING SEISMICITY IN AZLE AND THE GREATER NORTH TEXAS AREA

Matthew J. Hornbach
Heather DeShon
Brian Stump
Chris Hayward
Beatrice Magnani
Cliff Frohlich
Jon Olson
Bill Ellsworth
and the
NORth TeXas seismicity group

1 Southern Methodist University
Dept. of Earth Sciences
Dallas, Texas

2 The University of Texas
Institute for Geophysics
Austin, Texas

3 The University of Texas
Dept. of Petroleum and
Geosystems Engineering
Austin, Texas

4 United States Geological Survey
Menlo Park, Ca
EARTHQUAKE RISK HAS INCREASED SUBSTANTIALLY IN NORTH TEXAS SINCE LATE 2008

Recent increase in Texas seismicity (Most occur in the Fort Worth Basin)

For 2015, Texas seismicity is on track to be a factor of ~20 greater than historic levels.

Incorporating Induced Seismicity in the 2014 United States National Seismic Hazard Model – Results of 2014 Workshop and Sensitivity Studies

Pubs.usgs.gov/of/2015/1070/
"Seismicity Caused by or Likely Related to Human Activity" NRC, 2012

Little Linkage Between Hydraulic Fracturing and Felt Earthquakes
"Although only a very small fraction of injection and extraction activities at hundreds of thousands of energy development sites in the United States have induced seismicity at levels that are noticeable to the public" NRC, 2012

Studies on this topic in Texas date to 1918

Understanding the physical mechanisms remains an open question requiring data and collaboration from government, industry, and other subject-matter experts
Fig. 3. Schematic diagram of mechanisms for inducing earthquakes. Earthquakes may be induced by increasing the pore pressure acting on a fault (left) or by changing the shear and normal stress acting on the fault (right). See (4).
Did Injection Trigger Earthquakes?
The 7 Question Approach Outlined in NRC Report

(from Davis and Frohlich, 1993)

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Are the events the first known earthquakes of this character in the region?</td>
<td></td>
</tr>
<tr>
<td>2. Is there a clear correlation between injection and seismicity?</td>
<td></td>
</tr>
<tr>
<td>3. Are epicenters within 5 km of wells?</td>
<td></td>
</tr>
<tr>
<td>4. Do some earthquakes occur at or near injection depth?</td>
<td></td>
</tr>
<tr>
<td>5. Are there known geologic structures that may channel flow to sites of earthquakes?</td>
<td></td>
</tr>
<tr>
<td>6. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?</td>
<td></td>
</tr>
<tr>
<td>7. Are changes in fluid pressure at hypocentral distances sufficient to encourage seismicity?</td>
<td></td>
</tr>
</tbody>
</table>

A Score of 6 or greater = likely (RMA scored a 6)
A Score of 3-5 = possible-to-plausible
A Score of 2 or less = unlikely

What data are helpful in addressing these questions?
1. ARE THE EVENTS THE FIRST KNOWN EARTHQUAKES OF THIS CHARACTER IN THE REGION?

Useful data
- Instrument-Recorded Earthquakes.
- Pre-Instrumentation Earthquakes (Felt Reports).
- Surface Maps of Quaternary Deformation (geologic maps).
- Seismic Images Indicating Quaternary Deformation.

Quaternary deformation along the Meeman-Shelby Fault near Memphis, Tennessee, imaged by high-resolution marine and land seismic reflection profiles (Hao et al., 2013)
2. IS THERE A CLEAR CORRELATION BETWEEN INJECTION AND SEISMICITY?

Example: Rocky Mountain Arsenal

(1) Prior to injection, the area was not seismically active.

(2) The seismicity generally mimics the injection pattern, but not perfectly.

(3) Aftershocks in the region continued following injection (including after attempts to depressurize the reservoir).

(4) Largest EQ (M5) occurred year after injection stopped.

Required Data
- Well-constrained injection volumes and pressures.
- Higher-resolution (<1 km resolution, <M2) seismic monitoring.
3. Are epicenters within 5 km of wells? &
4. Do some earthquakes occur at or near injection depth?

Example from the 2008 DFW Earthquake Sequence

Local seismic networks are key

- Black triangles: SMU temporary stations
- Red circles: locations of quakes as reported by USGS
- Trigg well nearby where P and S velocities measured
- Yellow square: 1-km square area where Nov-Dec earthquakes were located

Required Data
- High Resolution Local Seismic Monitoring.
- Vp & Vs Velocity Models.
5. ARE THERE KNOWN GEOLOGIC STRUCTURES THAT MAY CHANNEL FLOW TO SITES OF EARTHQUAKES?

Useful Data
- Basin to Basin-Scale structural interpretations.
- High Resolution permeability measurements.
- High Resolution regional and local seismic monitoring.
- 2D/3D active source seismic data or associated interpretations.

Typically Available (km resolution)

Typically Desired (m resolution)

(McLaughlin and Ganshin, 2009)

(Hornbach et al., JGR, 2008)
6. ARE CHANGES IN FLUID PRESSURE AT WELL BOTTOMS SUFFICIENT TO ENCOURAGE SEISMICITY?

Multiple Peer-Reviewed Studies Confirm Stress Increases of ~1.5 psi Trigger Earthquakes
(See, for example, Parsons, 2002; Hardebeck et al., 1998; Harris, 1998, King et al., 1994, NRC 2012, and additional examples below).

Examples of Peer-Reviewed Measured Stress Changes that Trigger Earthquakes

<table>
<thead>
<tr>
<th>Location</th>
<th>EQ Induced Stress (psi)</th>
<th>Suspected Cause</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lacq Field, Fr.</td>
<td>~14.5 psi</td>
<td>Oil and Gas Activity</td>
<td>Segal et al., 1994</td>
</tr>
<tr>
<td>Elmore Ranch, Ca</td>
<td>1.5 – 4.5 psi</td>
<td>Adjacent fault rupture</td>
<td>Anderson and Johnson, 1999</td>
</tr>
<tr>
<td>Imogene Field, Tx</td>
<td>&lt;59 psi</td>
<td>Oil and Gas Activity</td>
<td>Grasso, 1992; Grasso and Sornette, 1998</td>
</tr>
<tr>
<td>Kobe, Japan</td>
<td>2.9 psi</td>
<td>Adjacent fault rupture</td>
<td>Toda et al, 1998.</td>
</tr>
<tr>
<td>Global</td>
<td>0.1 – 7 psi</td>
<td>Large ocean tides</td>
<td>Cochran et al., 2004</td>
</tr>
<tr>
<td>Gasli Field,Uzb.</td>
<td>5.8 - 7.3 psi</td>
<td>Oil and Gas Activity</td>
<td>Adushkin et al., 2000</td>
</tr>
<tr>
<td>Kettleman Field, Ca</td>
<td>~1.5 psi</td>
<td>Oil and Gas Activity</td>
<td>Segal 1985; McGarr, 1991</td>
</tr>
<tr>
<td>Homestead Valley, Ca</td>
<td>~44 psi</td>
<td>Adjacent fault rupture</td>
<td>Stein and Lisowski, 1983</td>
</tr>
<tr>
<td>Loma Prieta, Ca.</td>
<td>5.8 - 7.3 psi</td>
<td>Distant Earthquakes</td>
<td>Reasenberg and Simpson, 1992</td>
</tr>
</tbody>
</table>

Studies also show a few psi reduction in stress reduces EQs (e.g. Stein & Lisowski, 1983).

Useful Data
- Bottom Hole Pressure measurements at injection sites
7. ARE CHANGES IN FLUID PRESSURE AT HYPOCENTRAL DISTANCES SUFFICIENT TO ENCOURAGE SEISMICITY?

Useful Data for Estimating Flow, Pressure, and Seismicity on Faults

- Bottom Hole Pressure measurements at injection sites
- Regional 3D Structure and Permeability
- Fluid Properties (for example fluid phases)
- Regional brine injection and brine production data from the reservoir.
- Regional stress field

(e.g. Todorovic-Marinic et al., 2011)
A Detailed Look at Earthquakes in the Fort Worth Basin

May 20, 1950: One felt report, no instrumental data

Prior to 2008:
1 possible event

Post 2008:
31 events > M3
>160 recorded

5 Temp. Networks:
DFW Airport (2008-)
Cleburne (2009-)
Venus (2011-)
Azle (2013-)
Irving (2014-)

Earthquakes Report by National Earthquake Information Center since 2008 (2.0 – 4.0)
The last widely felt event was Jan 28th, 2014

Last EQ recorded in May 2015

Complex faulting

The EQ sequences slowed as injection volumes reduced

Hornbach, DeShon, et al., 2015, *Nature Communications*
CAUSAL FACTORS

- Natural Tectonic Stress Changes
- Ground Water Changes
- Lake Level Changes
- Industry Activity
  - SWD Injection
  - Brine Production

Hornbach et al., 2015, Nature Comm.
IT IS IMPROBABLE THAT THE AZLE EARTHQUAKES ARE TRIGGERED NATURALLY

1. During the past 150 years of settlement, there had been no reported felt earthquakes in the Azle/Reno area prior to November, 2013.

2. There is no clear evidence for fault surface expressions indicative of large-scale active faulting in the region.

3. Publicly available regional seismic data show no significant fault offsets in sediment deposited more than ~300 million years ago in the Fort Worth Basin. Additionally, Gutenberg-Richter Law Modeling suggest we should observe significant (~35 m) offset with depth if these faults have a M3 event only once every 10,000 years.

4. The seismicity pattern in Azle is not consistent with the typical foreshock-main-shock-aftershock sequence observed in most tectonic earthquake sequences, but is consistent with earthquake swarm patterns often associated with induced seismicity.
Assumptions:
• Uniformly accumulated displacement since the Pennsylvanian (300Ma).
• $M_{\text{max}}$ 5.6 (based on current seismicity)
• Longest return intervals ~100,000 years

Displacement calculations – three cases:
1. The Azle sequence displaced the fault by ~1.2mm.
2. A G-R sequence with single $M_{\text{max}}$ of 5.0 would slip the fault ~48mm.
3. A G-R sequence with single fault-filling $M_{5.6}$ would slip the fault ~380mm.
Results:
1. One Azle seq. ~4m offset.
2. One $M_{max} 5.0$ seq. ~140m offset.
3. One $M_{max} 5.6$ seq. ~1200m offset.
CAUSAL FACTORS

- Natural Tectonic Stress Changes
- Ground Water Changes
- Lake Level Changes
- Industry Activity
  - SWD Injection
  - Brine Production

Unlikely. The region has been tectonically inactive for >200 million years.

Hornbach et al., 2015, Nature Comm.
CAUSAL FACTORS

• Natural Tectonic Stress Changes
• Ground Water Changes
• Lake Level Changes
• Industry Activity
  • SWD Injection
  • Brine Production

No anomalous water levels <1 kPa (<0.1 psi) on the fault

Hornbach et al., 2015, Nature Comm.
Pressure modeling indicates injection/production caused pressure changes sufficient to trigger earthquakes.

Pressure changes associated with drought are likely orders of magnitude lower.

Faults near the Azle/Reno area, though historically inactive, appear near-critically stressed.

Currently, industry activities appear to represent the largest quantifiable stress driver on the fault system.
## AZLE EARTHQUAKES: INDUCED OR NATURAL?

**Conclusion:** It is likely that industry activity triggered the Azle/Reno EQs.

<table>
<thead>
<tr>
<th>(Davis and Frohlich, 1993)</th>
<th>Azle Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Are the events the first known earthquakes of this character in the region?</td>
<td>YES</td>
</tr>
<tr>
<td>2. Is there a clear correlation between injection and seismicity?</td>
<td>YES</td>
</tr>
<tr>
<td>3. Are epicenters within 5 km of wells?</td>
<td>YES</td>
</tr>
<tr>
<td>4. Do some earthquakes occur at or near injection depth?</td>
<td>YES</td>
</tr>
<tr>
<td>5. Are there known geologic structures that may channel flow to sites of earthquakes?</td>
<td>YES</td>
</tr>
<tr>
<td>6. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?</td>
<td>YES</td>
</tr>
<tr>
<td>7. Are changes in fluid pressure at hypocentral distances sufficient to encourage seismicity?</td>
<td>YES</td>
</tr>
</tbody>
</table>
“Current models employed to understand the predictability of the size and location of earthquakes through time in response to net fluid injection or withdrawal require calibration from data from field observations.”

“The success of these models is compromised in large part due to the lack of basic data at most locations on the interactions among rock, faults, and fluid as a complex system.”
BASIC DATA NEEDS
(AS ALREADY OUTLINED IN THE AZLE STUDY)

- Better Regional seismic data (TEXNET could improve this)
- High quality, local seismic networks (TEXNET could improve this)
- Bottom hole pressure and permeability measurements.
- Brine production data and brine sources (geochemical data).
- Better control on local subsurface structure.
- Fault properties
- In-situ stresses
SUCCESSFUL EXAMPLES OF MITIGATION INVOLVE BETTER MONITORING AND MORE ACCESS TO DATA

PARADOX VALLEY, COLORADO

- BR adjusts injection strategies, to manage Bottom hole pressure.

- EQ swarm monitoring combined with down hole pressure monitoring provides invaluable tool for mitigating hazard and managing risk.

- Reducing injection volumes/pressures reduced bottom-hole pressures, which reduced earthquakes (similar to what we observe in Azle).

- After changing injection strategies, reducing injection volume:
  --- felt seismicity is reduced with time.
  --- events spreads more than 8 km away (as stress diffusion models predict).
  --- big events still occur (Like RMA).

- Constraining “acceptable” seismicity requires high quality seismic/pressure data and a detailed risk analysis.

(From Block et al., 2013)