MITIGATING SEISMICITY IN THE GREATER NORTH TEXAS AREA

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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/
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).
Multiple experiments (e.g., RMA, 1968; Rangley, 1976) confirmed the hypothesis that earthquakes can be triggered by an increase of fluid pressure, a result well-accounted for by the Hubbert-Rubey principle of effective stress.

(Hubbert & Ruby, 1959; Healy et al., 1968; Raleigh et al., 1967)

"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

Induced seismicity in Texas dates to 1918.
“Seismicity Caused by or Likely Related to Human Activity” NRC, 2012

Little Linkage Between Hydraulic Fracturing and Felt Earthquakes
CONTROL EXPERIMENT #1: ROCKY MOUNTAIN ARSENAL

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.

SUCCESSFUL EXAMPLES OF MITIGATION INVOLVE BETTER MONITORING AND MORE ACCESS TO DATA

PARADOX VALLEY, COLORADO

- Seismic monitoring with 10 stations began 8 years before injection.
- EQs began almost immediately after injection began in 1996.
- First significant EQs (M3.5) didn’t occur until 1999, ~3 years after injection began.
- “After reviewing data on injection volume, injection rate downhole pressure and percent days injecting, the Bureau of Reclamation noted, ‘Of the four parameters investigated, the downhole pressure exhibits the best correlation with the occurrence of near-well seismicity over time.’”
  (NRC REPORT)

Ellsworth, Science, 2013
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)
IT’S BEEN RECOGNIZED FOR ~40 YEARS THAT SMALL STRESS CHANGES TRIGGER EARTHQUAKES

-Stress changes over a 13 year period (1979-1992) near san andreas

-Most Earthquakes occur where positive increases in stress exist.

-Max stress changes are ~0.4 bars (<6 psi).

(Stein et al., 1992)
WHAT 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).
TEXAS HAS A ~100 YEAR HISTORY OF INDUCED SEISMICITY

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“The movements were accompanied by slight earthquakes which shook the houses, displaced dishes, spilled water, and disturbed the inhabitants generally.”

–The courts ruled that this was NOT “an act of God” but was “caused by an act of man, namely, the removal of large volumes of oil, gas, water, and sand from beneath the surface”
HIGHLIGHTS OF TEXAS INDUCED SEISMICITY

- Goose Creek 1918
- Snyder Area H2O Injection CO2 Injection (Davis and Pennington, 1989)
- West Texas (Complex result of industry activity) (Doser et al., 1992, Keller et al., 1987)
- FT Worth Basin (2008-Present) M 4.0 (2014) H2O Injection (Multiple Studies)
- Timpson M 4.8 H2O Injection (Frohlich et al., 2014)
- Mexia M 4 1932 Production (BEG Director Study)
- Fashing M 4.3 & M 4.8 Mostly Extraction Pennington et al., 1986)
- Alice M 3.9 (Combo) (e.g. Bilick, 1998)
- Goose Creek 1918 Production (Pratt & Johnson, 1924)
Did Injection Trigger Earthquakes?
The 7 Question Approach Outlined in NRC Report

(from Davis and Frohlich, 1993)

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

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
A Detailed Look at Earthquakes in the Fort Worth Basin

Prior to 2008:
1 possible event

Post 2008:
31 events > M3
>160 reports

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

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)
A Detailed Look at the 2008/2009 DFW Earthquake Sequence

Example from the 2008 DFW Earthquake Sequence

- 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 quakes were located
3. ARE EPICENTERS WITHIN 5 KM OF WELLS?

DFW Earthquakes occurred:

- Along linear trend about 2 km long
- At a common depth of ~4.4 km ± ~1 km (disposal well depth = 4.2 km)
- within a few hundred meters of injector.
Refined Locations Provided Opportunity to Explore Cause of Earthquakes

Earthquakes occur:
- Along linear trend about 2 km long
- Common depth of ~4.4 km
- Local Seismic Networks are Key
Texas Railroad Commission Disposal Well Data: Space-Time general correlation

- Earthquakes located within hundreds of meters of disposal well
- Earthquakes began shortly after the injector was initiated
- A mapped fault crosses the area
- No subsurface data on geology or material properties was made available
- Earthquakes continued into 2010 and moved away from injector

Frohlich, Potter, Hayward and Stump, 2010
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)
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

- Black triangles: SMU temporary stations
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**Local seismic networks are key**

**Required Data**
- High Resolution Local Seismic Monitoring.
- Vp & Vs Velocity Models.
Data needed to further constrain:

1. 2D seismic lines indicating fault offset versus depth.
2. Pore pressure models
May 20, 1950: One felt report, no instrumental data

Industry Cooperation in Study
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.

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 at surface if these faults have a M3 event only once every 10,000 years (Magnani et al.,2015)

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.
Published interpretations indicate no faulting beyond Marble Falls.
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.
What we typically observe with reservoir-induced seismicity:

1.) Earthquakes usually occur following rapid variation in lake level.
2.) Most occur within 5 years of impoundment (e.g. Simpson, 1976).

Variations in Lake Level and Seismicity in Vajont Reservoir, Greece (See Galanopoulos, 1967; Gupta et al., 1972).
What we observe at Eagle Mountain Lake:

1.) The greatest stress/lake level change occurred ~50 years ago—no felt EQs occurred.
2.) Lake Levels were not at record high or record low levels during Azle Earthquakes.
GROUND WATER FLUCTUATIONS ARE ALSO MINIMAL

Trinity Aquifer measurements near Azle:
(provided by Upper Trinity Groundwater Conservation District)

Blue Diamonds: static measurements

Red squares: measurements while pumping
ESTIMATED STRESS CHANGES CAUSED BY RECENT LAKE-LEVEL AND GROUND WATER CHANGE IN THE AZLE/RENO AREA ARE TINY (COMPARABLE TO TIDAL STRESSES)

Stresses caused by recent lake or groundwater change are less than 1 KPa (<0.15 psi)
CAUSAL FACTORS

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

Hornbach et al., 2015, Nature Comm.
Basic Model Parameters (for ~75 different models)

Approach: 4th order finite-difference diffusion, single phase flow. (e.g. USGS’s MODFLOW)

Dimensions: ~10 km x ~12 km x ~1.5 km

Cell Dimensions: 10m x 10 m x 10 m (hi res)
100m x 100m x 100m (low res)
50m x 50 m x 50m (standard)

Boundary Conditions: Open and Closed.

Production wells: >100 analyzed. 70 integrated into the model that produce water year-to-year.

Bottom Hole Pressures: (1) Dupuit-Thiem equation (conservation of mass)
(2) Frictional Loss Calculation.
(mean excess values range from 25 – 640 psi)

Ellenburger Permeability: 3 mD to 100 mD.

Shale/Basement Permeability = 0.001 mD

Fault Permeability = 0.1 mD to 100 mD
Methods include Cooper-Jacob method (hydrogeology), and Horner Method (Petroleum Engineering)

- Both methods resulted in permeability values with endmember ranges from 3-100 mD
Derived by accounting for frictional energy loss using Darcy-Weisbach equation using TRC available data:

\[
P_f = f_d \rho_w \frac{L V^2}{D 2}
\]

\( P_f \) = pressure loss due to friction  
\( f_d \) = Darcy friction coefficient  
\( \rho_w \) = density of fluid  
\( L \) = Length of pipe  
\( D \) = Diameter of pipe  
\( V \) = average fluid velocity.

Derived using radial solution of Darcy’s Law (Dupuit-Thiem, conservation of mass):

\[
P_b = P_o - \frac{\mu Q}{2\pi kH} \ln\left(\frac{R_b}{R_o}\right)
\]

\( P_b \) = Pressure above hydrostatic  
\( P_o = 0 \), at a distance \( R_o \) from well  
\( \mu \) = fluid viscosity  
\( k \) = permeability  
\( H \) = reservoir thickness  
\( Q \) = average fluid flux  
\( R_b \) = Casing radius  
\( R_o \) = radial distance where \( P \) is zero.

Darcy’s Law Approach usually produced lower values.
---Pressures on the fault are consistently 10X to 100X greater than those predicted by water level variations.

--- Pressure on fault is typically near or above 0.01 MPa (1.5 psi).

--- Narrower flow zones generate highest pressures.

---We welcome and encourage more data to improve/refine these results.
• Pressure modeling indicate injection/production caused pressure changes (1.5–50 psi) sufficient to trigger earthquakes.

• Pressure changes associated with drought or lake level changes are likely orders of magnitude lower.

• Faults near 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.
SEISMICITY AND ESTIMATED FLUID PRESSURE AT FAULT

- Mean Ellenburger permeability
  - $10 \times 10^{-14} \text{ m}^2$
  - $5 \times 10^{-14} \text{ m}^2$
  - $3 \times 10^{-14} \text{ m}^2$

- Model predicted pressure on fault (normalized)
- Injection-driven pressure rise
- Production-driven pressure drop
- July 11th, 2010 earthquake
- 2013–14 felt earthquakes
# AZLE EARTHQUAKES: INDUCED OR NATURAL?
## NRC-ENDORSED QUESTIONS.

<table>
<thead>
<tr>
<th>Question</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>Somewhat (new data indicates 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>
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</table>

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

3. Dense arrays:
   1. Azle/Reno
   2. Irving
   3. Venus

Other data:
- TRRC P/V Data.
- UTGCD Data.
- Private industry data.
  (fall off tests, seismic)
“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
100% Proof of Induced Seismicity will be difficult to obtain. Nonetheless, absolute proof is not be necessary for consideration of prudent operational changes.

Models and EQ mitigation are not currently limited by model approach but by DATA. Modeling and mitigation will only be as robust as the data provided.

Need for reservoir engineers, geologists and geophysicists across industry, academia, regulatory agencies, to work together to solve these problems. Data sharing represents a critical step in assessment of these issues. Seismic monitoring is only one part of this assessment.
HOW CAN “FOOTBALL” PRESSURES CAUSE EARTHQUAKES?

Although Pressures Necessary for Failure are Small, Total Force on the Fault can be Large.

5 psi is a small force over an area of just 1 square inch.

5 psi on the surface of a typical door is a force > 17,000 lbs.

A pressure change of 5-10 psi will topple multi-story buildings (e.g. Ngo et al., 2007).

Faults below Azle/Reno are at least 1 mile long and half a mile tall. A mean increase in pressure of only 5 psi applied to it produces an excess force of at least 10 billion pounds.

–We are not talking about breaking rock (fracking). It’s already broken, and the faults are loaded. This is simply reactivation
--We’d be glad to apply multiphase flow if we had any evidence that it was important at this site.

--To our knowledge, there isn’t a single well currently producing gas in the Ellenburger in the Azle/Reno Area.

--If so much gas exists in the Ellenburger, why aren’t companies producing it? completion would be much less expensive than with the barnett!

--That said, we welcome any data provided to enhance the model
This is patently FALSE and a mis-statement by someone who did not carefully read the study. See supplementary figure 9 which provides a clear example of subsurface pressures where no faults in the model exist. Even in this case, pressure are still consistent with those that cause seismicity and larger than stresses associated with groundwater changes.

Supplementary Figure 9. Estimate for excess pressure in the Ellenburger, December 2013, based on model results assuming average pressures of 0.57 MPa and 0.17 MPa exist at Injector Well #1 and Injector Well #2, respectively. These injection pressures are low end-member estimates. For all models, the Ellenburger is 1000 m thick. (a) only brine injection occurs; (b) only brine injection occurs and no subsurface faults exist; (c) brine injection and water production occur, and (d) brine injection and water production occur and no faults exist. The existence of faults and no production wells results in the largest pressure development at earthquake locations. The scenario with no faults and brine production results in the lowest pressure development in the area of earthquakes locations. Even for the lowest pressure case, model-predicted pressure is still ~1 order of magnitude higher than the expected pressure changes caused by lake level and groundwater changes near the surface.
We use rough estimates, not by choice, but because these are all that is available.

We welcome industry providing additional data that will improve models.

We analyzed more than 70 wells. Out of a total of 130 wells analyzed, only 70 wells produced significant water year after year. All were near the fault. Since others did not produce water, we didn’t use them.