Geology and Seismicity

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The University of Texas at Austin
Texas Seismicity – USGS/ANSS catalog M>=3.0

Savvidis, unpublished
Seismograph stations currently operating in the Fort Worth Basin.
USGS has reported 204 M1.8+ earthquakes in this region since 2008.
SMU has reported over 1500 small earthquakes ranging from M<0 to M4 since beginning network operations in late 2013.
Heather DeShon (SMU)
Fort Worth Basin Seismicity - Azle

Azle 2013–2016

Azle earthquakes 2014-16, DeShon.

Azle conceptual model, Hornbach (2015)
Fort Worth Basin Seismicity – Venus and Irving

Venus earthquakes 2015-16, DeShon.

Irving earthquakes (2014-16), DeShon.
Texas Seismicity  Walter et al., in prep
~50,000 injection wells permitted since 1930’s
~34,000 active injection wells associated with enhanced oil production
~8,000 permitted disposal wells (UIC Class II)
Texas Geology

Many known subsurface fault systems that are poorly documented publically

12+ distinct tectonic areas
- Anadarko Basin
- Amarillo Uplift
- Palo Duro Arch
- Midland Basin
- Delaware Basin
- Trans-Pecos/Marathon
- Val Verde
- Gulf Coast
- Talco/Mexia/Balcones
- East Texas Basin
- Sabine Uplift
- Ft Worth Basin
- Llano/Bend Arch

Ewing, in press
Induced Seismicity Mechanisms

**KEY FACTORS:**

- Fault systems
- In situ stress
- Pressure perturbation
- Reservoir hydraulic capacity and continuity
- Fault reactivation

These factors are dynamically coupled...

*Scientific American, Anna Kuchment, 2016*
Faults - most of the recent earthquakes are occurring along undocumented faults
Faults – not simple planes

Moab Fault, Hennings

Schopfer et al., 2006
Faults – not simple planes

Schopfer et al. (2006)
Earthquake magnitude, fault size, rupture distance

Adapted from Zoback and Gorelick, 2012
Required Basics - Stress

\[ S_v > S_{H_{\text{max}}} > S_{h_{\text{min}}} \]

\[ S_{H_{\text{max}}} > S_v > S_{h_{\text{min}}} \]

\[ S_{H_{\text{max}}} > S_{h_{\text{min}}} > S_v \]
Texas Stress Map

$L_{shmax} > S_v > L_{shmin}$

$L_{shmax} > L_{Sv} > L_{Shmin}$

Lund Snee and Zoback, in review
Injection and Pore Pressure

Fort Worth Basin area injection

Cumulative Monthly Injection Volumes and Average Monthly Rates per Well, Texas Oil & Gas Districts 5, 7B, and 9 (January 1983-June 2015)

Lemons and Hennings, unpublished
Injection and Pore Pressure

Wellbore pressure given by:

$$p_w = p_{init} + \frac{Q \mu}{4\pi kh} \left( \frac{r_w^2}{4\eta t} \right)$$

Reservoir pressure given by:

$$p_w = p_{init} + \frac{Q \mu}{4\pi kh} \left( \frac{r^2}{4\eta t} \right)$$

Penetration of $\Delta p$-isobar given by:

$$r_{\Delta p} = \sqrt{\frac{4 k t}{C_T \mu}} \left( \frac{\Delta p}{Q \mu} \right)$$

Tyrrell, SPE, 2016
Injection and Pore Pressure
Injection Intervals are Hydrologically Complex

Elebiju et al., 2010

Abad, 2013
Pore Pressure Perturbations May Spread Far and Fast

Hsieh and Bredehoeft (1981)

Hornbach et al. (2016)
Need to Move from Associative to Mechanistic Analyses

Frohlich et al. (2016)

Fan et al. (2016)
Need to Include Comprehensive Geological Controls

Fort Worth Basin 3D model

Top Ellenburger surface

Characterization of injection intervals
### Synthesis of Key Factors (fictitious example)

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Hazard Factor</th>
<th>High</th>
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</thead>
<tbody>
<tr>
<td><strong>faults</strong></td>
<td></td>
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<tr>
<td>fault movement history</td>
<td>few</td>
<td>not since Archean</td>
<td>lots</td>
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<tr>
<td>fault size</td>
<td>small</td>
<td>big</td>
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<tr>
<td>fault geometry</td>
<td>non-planar</td>
<td>planar</td>
<td></td>
</tr>
<tr>
<td>fault complexity</td>
<td>complex</td>
<td>simple</td>
<td></td>
</tr>
<tr>
<td>fault cohesion</td>
<td>high</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>fault friction</td>
<td>high</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>fault rupture style</td>
<td>creeps</td>
<td>slips fast</td>
<td></td>
</tr>
<tr>
<td><strong>stress architecture</strong></td>
<td></td>
<td></td>
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<tr>
<td>stress magnitude</td>
<td>isotropic</td>
<td>anisotropic</td>
<td></td>
</tr>
<tr>
<td><strong>disposal zone character and pore pressure</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>disposal zone connectivity</td>
<td>low</td>
<td>high</td>
<td></td>
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<tr>
<td>disposal zone volume</td>
<td>low</td>
<td>high</td>
<td></td>
</tr>
<tr>
<td>disposal zone/basement strat connectivity</td>
<td>not connected</td>
<td>connected</td>
<td></td>
</tr>
<tr>
<td>disposal zone/basement fault connectivity</td>
<td>not connected</td>
<td>connected</td>
<td></td>
</tr>
<tr>
<td>pore pressure</td>
<td>low</td>
<td>high</td>
<td></td>
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<tr>
<td><strong>fault reactivation potential</strong></td>
<td>low</td>
<td>critical</td>
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</table>
TexNet Seismic Network and CISR Research

**TexNet**
Will monitor, locate, and catalog seismicity across Texas, capable of detecting and locating earthquakes with magnitudes $\geq$M2.0 using the new backbone network and improve investigations of ongoing sequences by deploying temporary seismic monitoring stations and conducting site-specific assessments.

**Center for Integrated Seismicity Research**
CISR will conduct fundamental and applied research to better understand naturally occurring and potentially induced seismicity and the associated risks, and to discern strategies for communicating with stakeholders and responding to public concerns regarding seismicity.
The TexNet Seismic Network
<table>
<thead>
<tr>
<th>TexNet and CISR Research (13+ active projects)</th>
</tr>
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<tbody>
<tr>
<td>UT Bureau of Economic Geology</td>
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<tr>
<td>UT Institute for Geophysics</td>
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<tr>
<td>UT Petroleum and Geosystems Engineering</td>
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<td>UT Psychology</td>
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<tr>
<td>UT Moody College of Communications</td>
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<tr>
<td>UT Civil, Architectural, and Environmental Engineering</td>
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<tr>
<td>TAMU Petroleum Engineering</td>
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<tr>
<td>SMU Geology and Geophysics</td>
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</tbody>
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### TexNet and Seismology
- permanent and portable seismic networks
- velocity models
- EQ locations, calibrated magnitudes, catalog, maps
- EQ focal mechanisms
- advanced source characterization

### Geologic & Hydrologic Description
- stress magnitude characterization (SCITS)
- fault system characterization
- disposal zone geomodels
- site to basin fluid budgets

### Geomechanics and Reservoir Modeling
- static fault sensitivity analysis
- basin-scale reservoir models for Pp estimation
- site-specific poroelastic scenario models
- site-specific reservoir flow models
- coupled fault rupture and permeability models

### Seismic Hazard and Risk Assessment
- Vs30 database and TX Vs map
- ground motion models
- seismic vulnerability estimates

### Seismic Risk Social Science
- data on risk perceptions of EQs
- characterization of stakeholder beliefs, values, and reactions to seismic risk
- communication strategy effectiveness and tools

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**TexNet**

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**CISR**

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**TAMEST Shale Task Force**
TexNet and CISR Research Timeline

**State-Wide and General Topics**
1. network procurement and installation
2. network management and data stream
3. R&D products to improve network performance
4. EQ compilations and characterizations
5. fault mapping and disposal zone characterizations
6. seismic risk communication and outreach

**Ft Worth Basin Integrated Study**
1. local seismic networks and EQ studies
2. basin-scale fluid budgets and pore pressure
3. stress characterization (Stanford)
4. fault characterization
5. 3D basin geo and hydrologic and modeling
6. fault reactivation analysis and mapping
7. reservoir modeling of seismicity mechanics
8. assessment of basin seismogenic potential

**Greater West Texas Basin Integrated Study**
1. local seismicity base-line studies and analyses
2. *integrated geological characterization
3. assessment of basin seismogenic potential

**Eagle Ford Operating Area Integrated Study**
1. local seismicity base-line studies and analyses
2. *integrated geological characterization
3. assessment of basin seismogenic potential

**Panhandle Seismicity Study**
1. seismicity analysis (existing and TA stations)
2. *integrated geological characterization
3. assessment of basin seismogenic potential

*integrated geological characterization
Closing Thoughts

* a physical understanding of possible linkages between oil and gas operations and earthquakes is the first real step to mitigating these effects *

Data Needs

- better earthquake data in areas of natural and induced activity
- better controls on fault presence and characteristics, can’t rely only on EQ seismicity
- better controls on disposal zone pore pressure and pressure history from down-hole data

Collaboration Needs

- fluid flow simulations for pore pressure estimation need to be far more comprehensive and include realistic geological controls and boundary conditions
- subsurface integrated and mechanistic models that are shared and revisited by interdisciplinary groups
- models for fault-triggering mechanisms based on more complete physical descriptions
- development of resource assessments for disposal capacity of select Texas basins