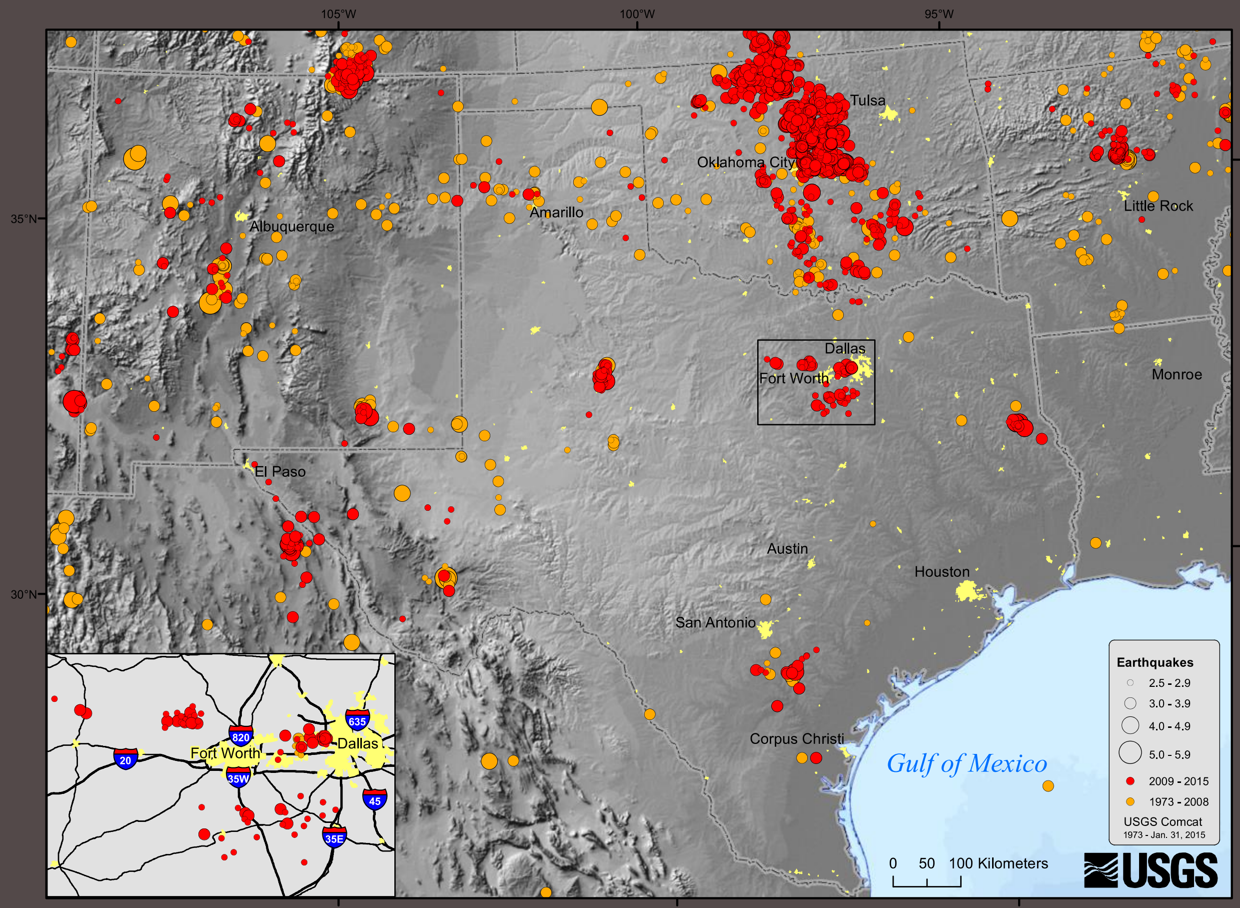
MITIGATING SEISMICITY IN AZLE AND THE GREATER NORTH TEXAS AREA



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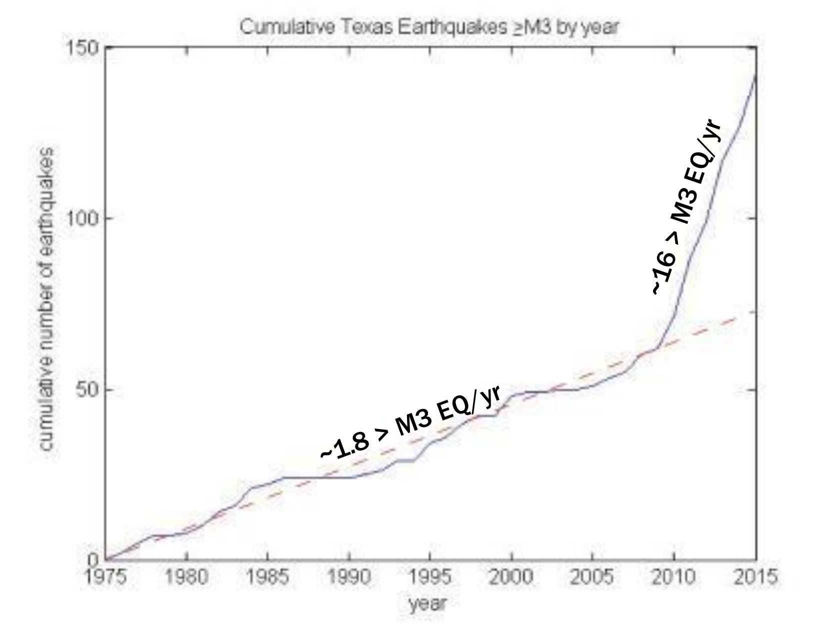
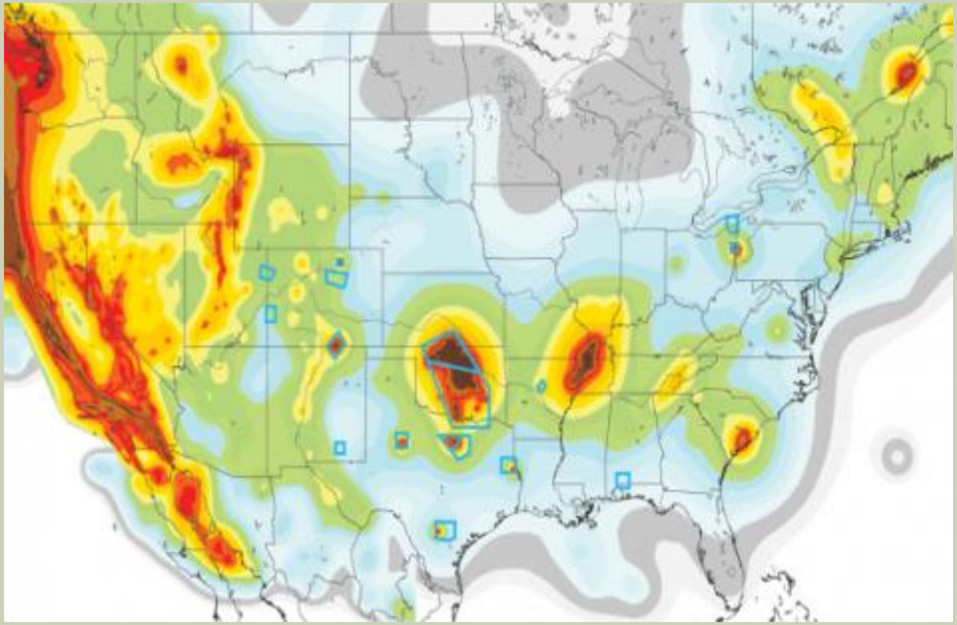
EARTHQUAKE RISK HAS INCREASED SUBSTANTIALLY IN NORTH TEXAS SINCE LATE 2008





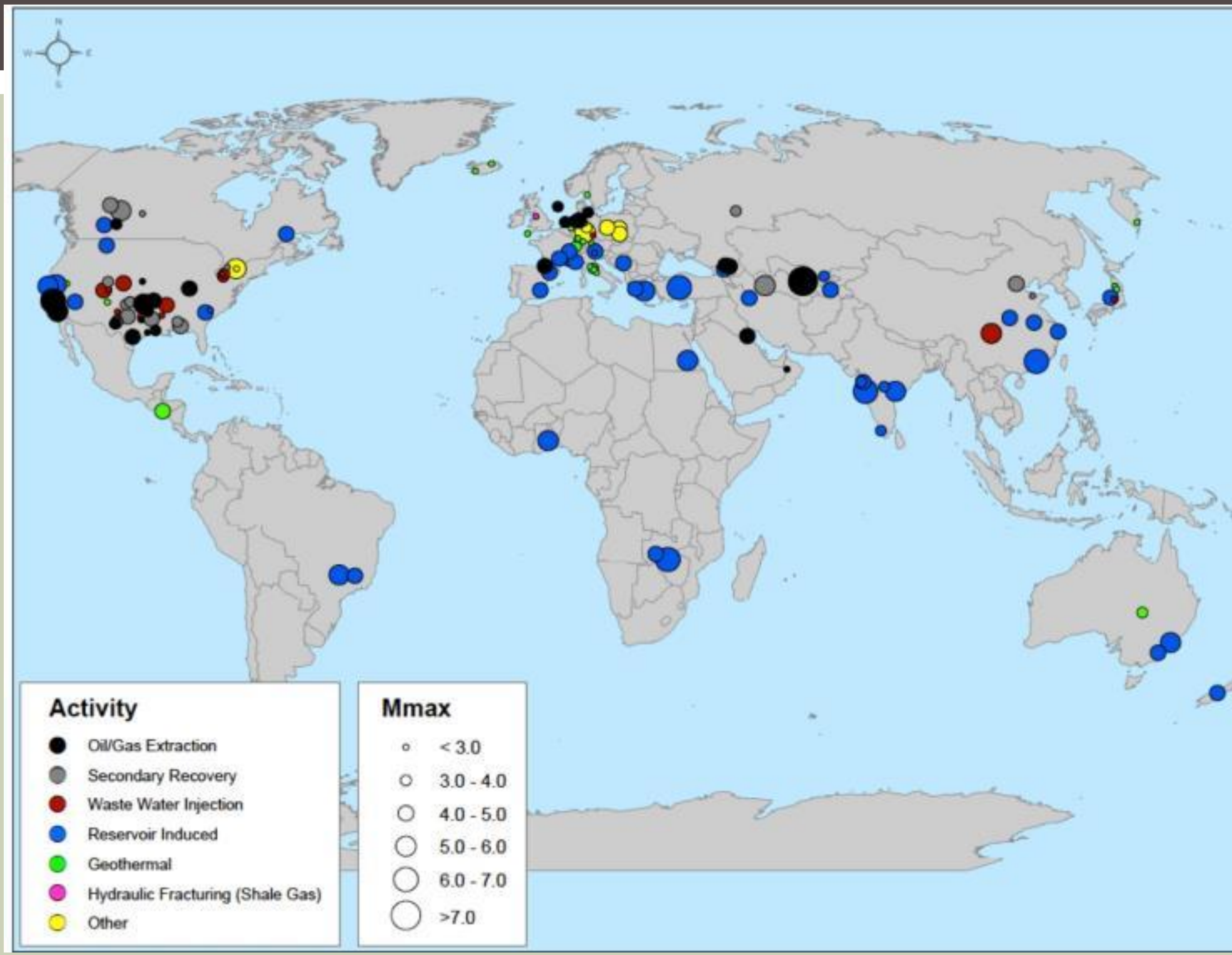
Recent increase in Texas seismicity (Most occur in the Fort Worth Basin)

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

INJECTION-INDUCED SEISMICITY: A WELL ESTABLISHED PHENOMENA

- "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

MECHANISMS FOR INDUCING EARTHQUAKES

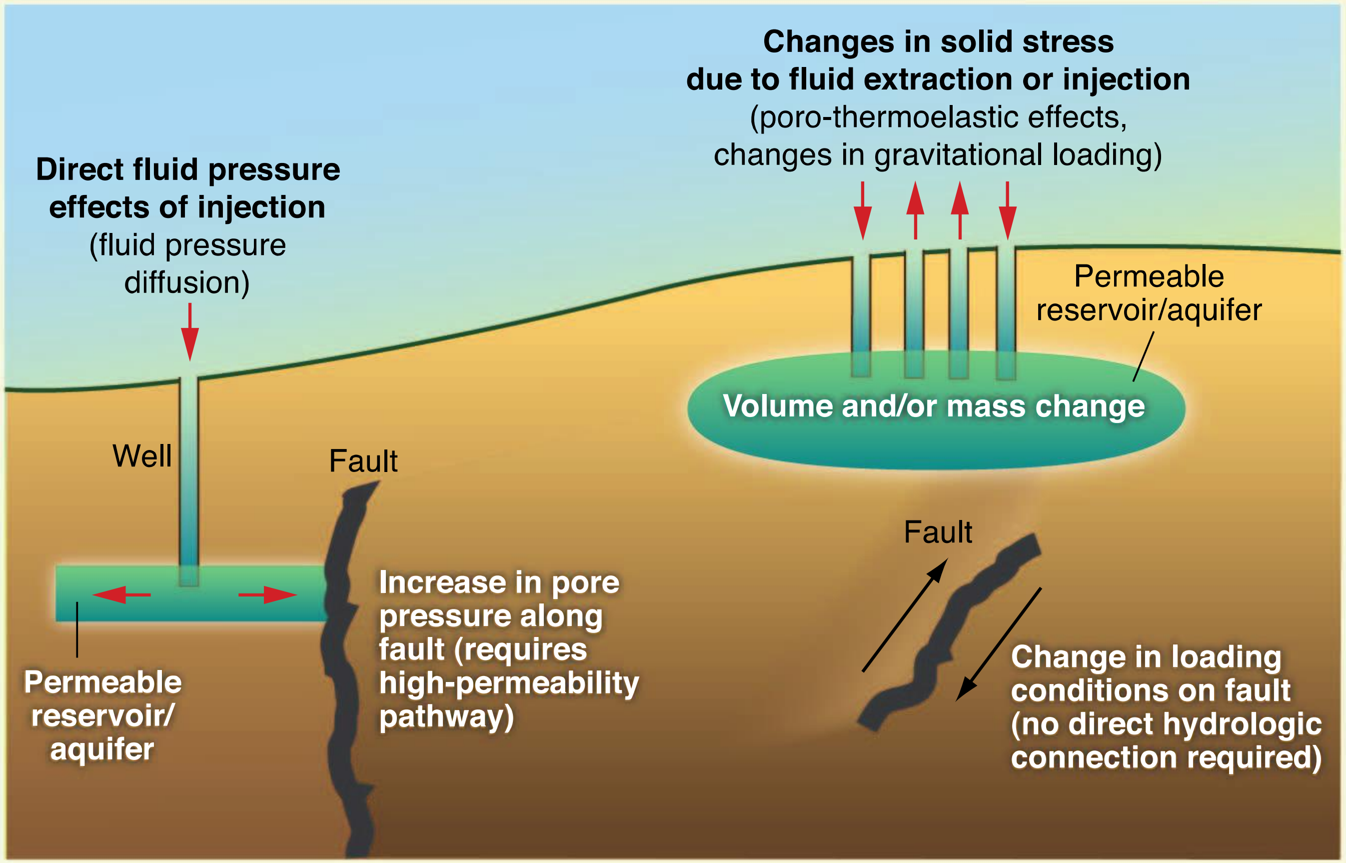


Fig. 3. Schematic diagram of mechanisms for inducing earthquakes. Earthquakes may be induced by increasing the pore pressure acting on a fault (**left**) or by changing the shear and normal stress acting on the fault (**right**). See (*4*).

Ellsworth, 2013

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?

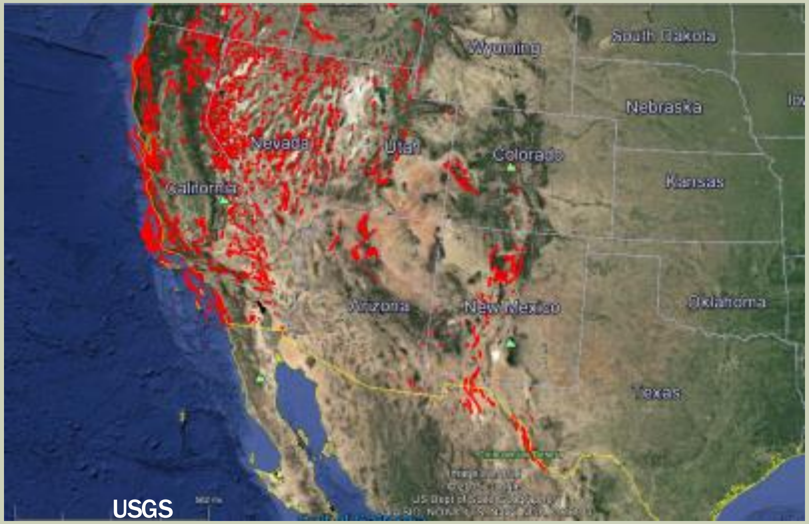
A Score of 6 or greater = likely (RMA scored a 6)
A Score of 3-5 = possible-to-plausible
A Score of 2 or less = unlikely

What data are helpful in addressing these questions?

1. ARE THE EVENTS THE FIRST KNOWN EARTHQUAKES OF THIS CHARACTER IN THE REGION?

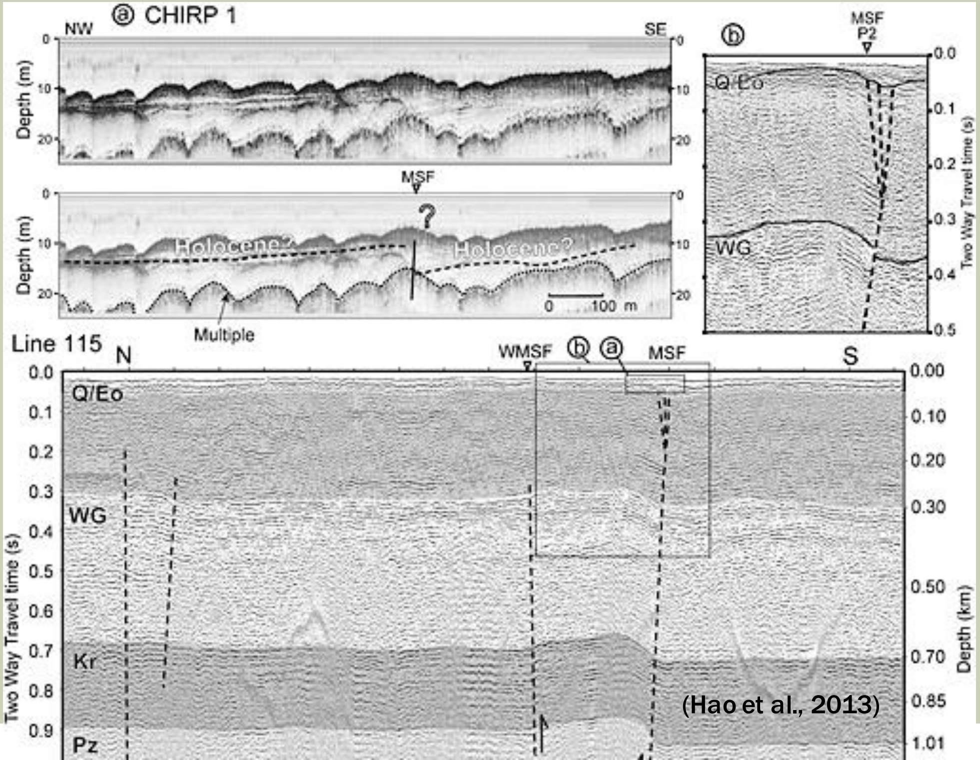
Useful data

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



Quaternary Fault Maps

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?

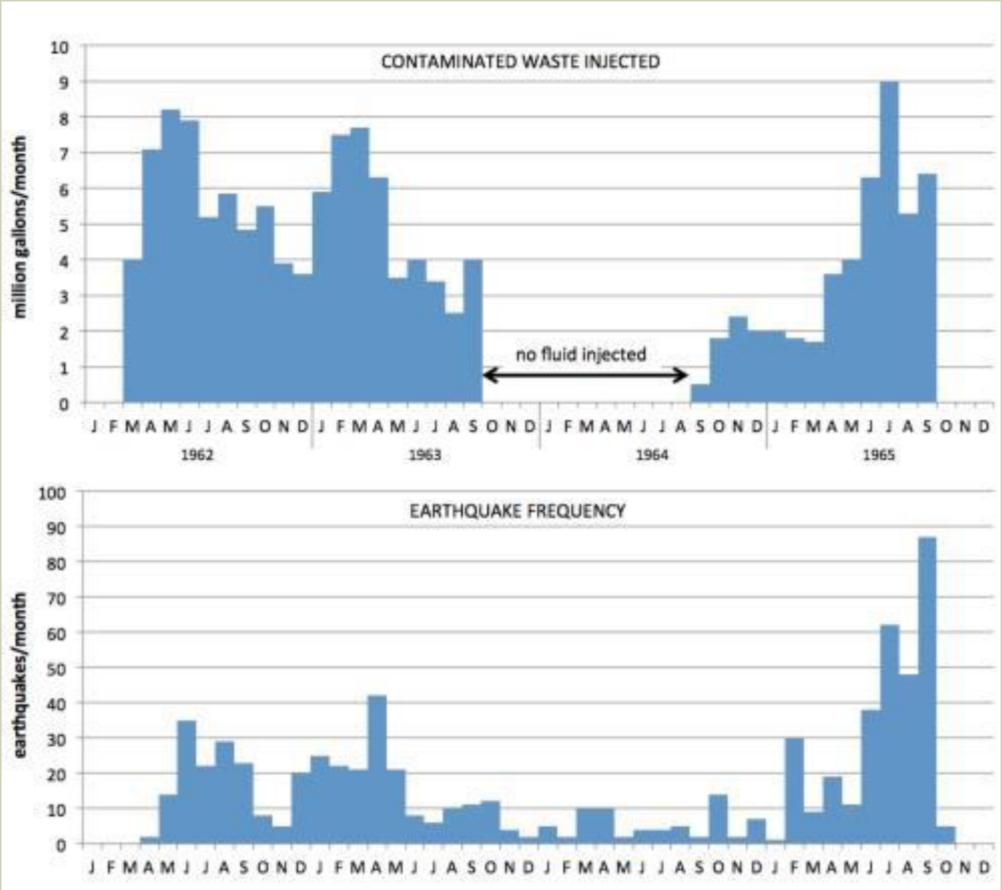
<u>Example: Rocky Mountain Arsenal</u>

(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.



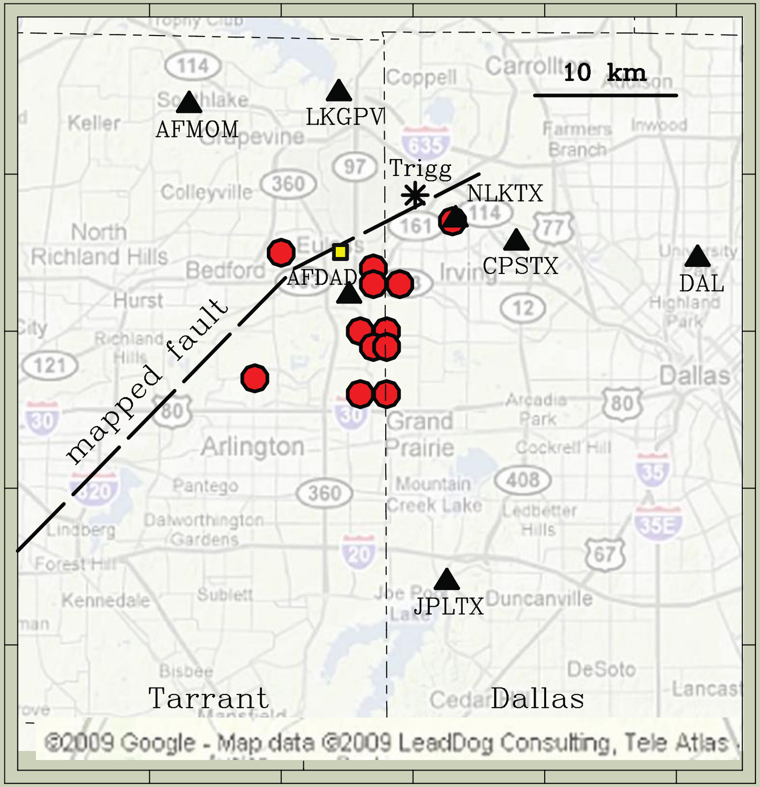
(from Hesiah & Bredehoeft, 1981; NRC Report, 2012)

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

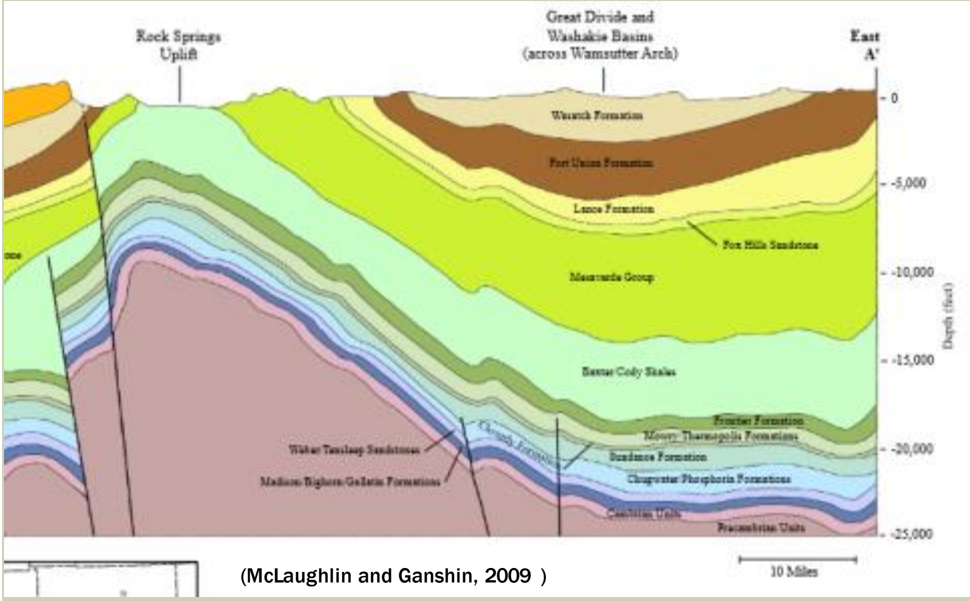
- High Resolution Local Seismic Monitoring.
- Vp & Vs Velocity Models.

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.

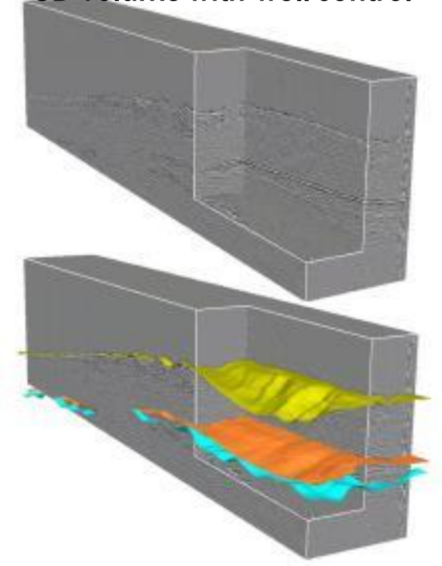
Typically Available (km resolution)



(McLaughlin and Ganshin, 2009)

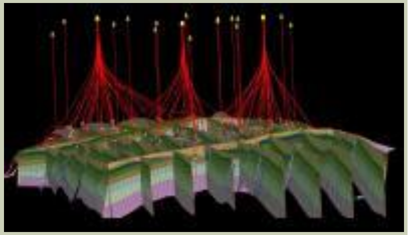
Typically Desired (m resolution)

3D volume with well control



(Hornbach et al., JGR, 2008)

2D/3D perm models



(from Paradigm Geophysical)

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

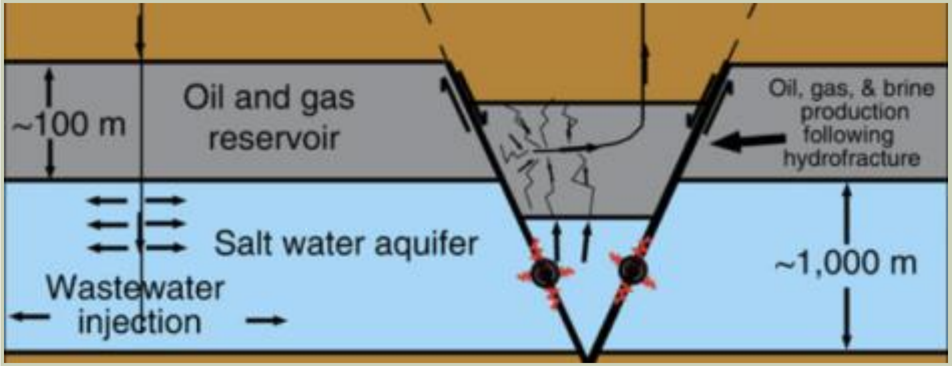
Location	EQ Induced Stress (psi)	Suspected Cause	Source(s)
Lacq Field, Fr.	~14.5 psi	Oil and Gas Activity	Segal et al., 1994
Elmore Ranch, Ca	1.5 – 4.5 psi	Adjacent fault rupture	Anderson and Johnson, 1999
Imogene Field, Tx	<59 psi	Oil and Gas Activity	Grasso, 1992; Grasso and Sornette, 1998
Kobe, Japan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

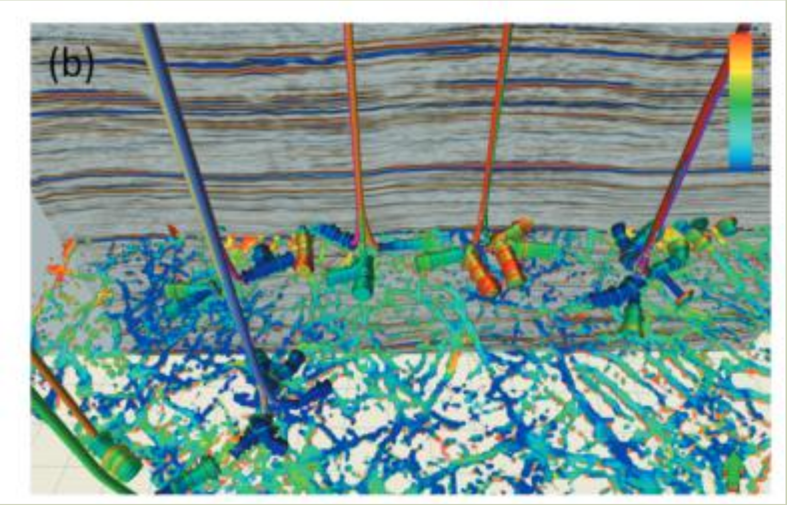
Studies also show a few psi *reduction* in stress *reduces* EQs (e.g. Stein & Lisowski, 1983).

Useful Data

- Bottom Hole Pressure measurements at injection sites

7. ARE CHANGES IN FLUID PRESSURE AT HYPOCENTRAL DISTANCES SUFFICIENT TO ENCOURAGE SEISMICITY?





(e.g. Todorovic-Marinic et al., 2011)

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

HISTORY OF TEXAS INDUCED SEISMICITY

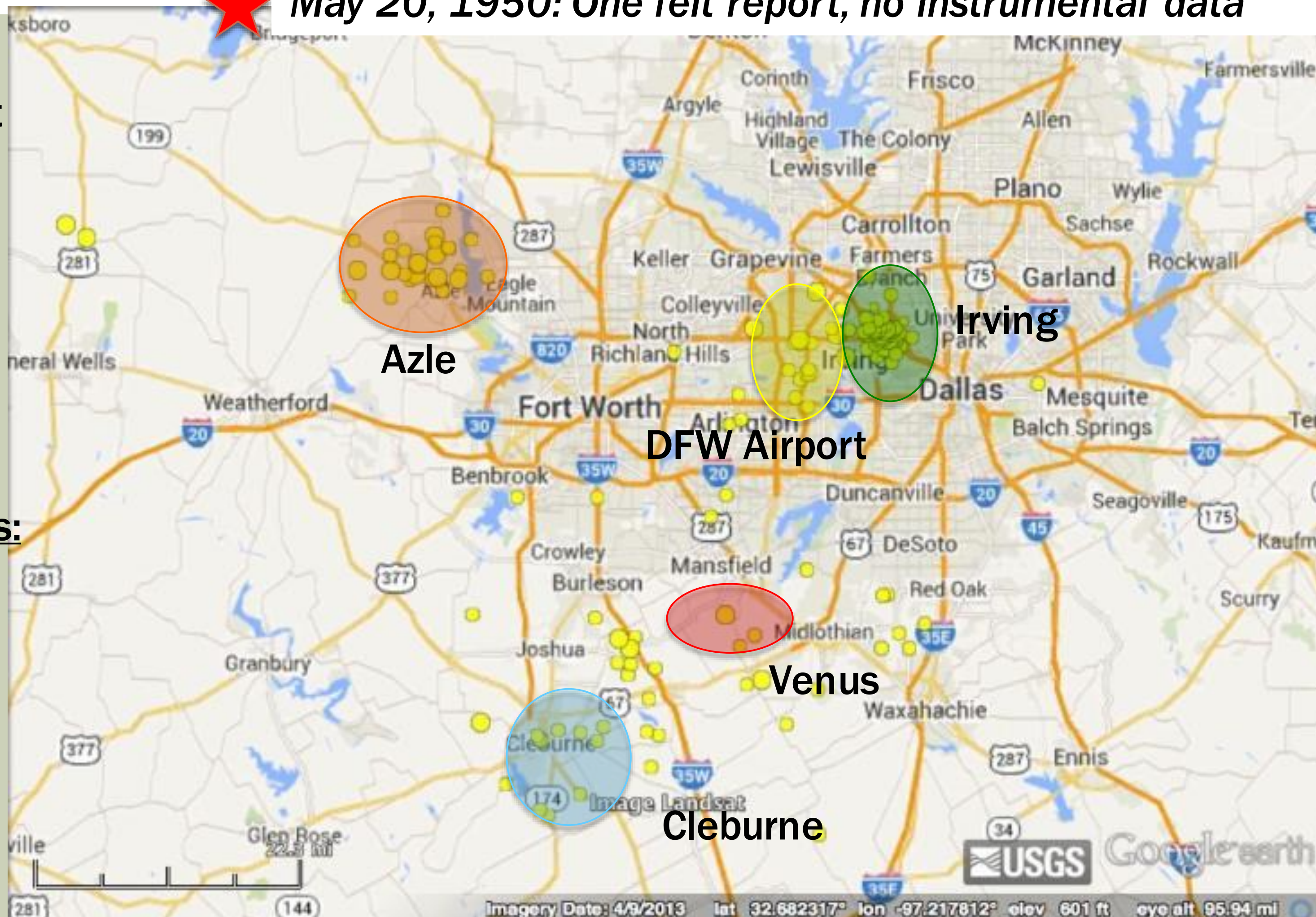
A Detailed Look at Earthquakes in the Fort Worth Basin

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

Prior to 2008:
1 possible event

Post 2008:
31 events ≥ M3
>160 recorded

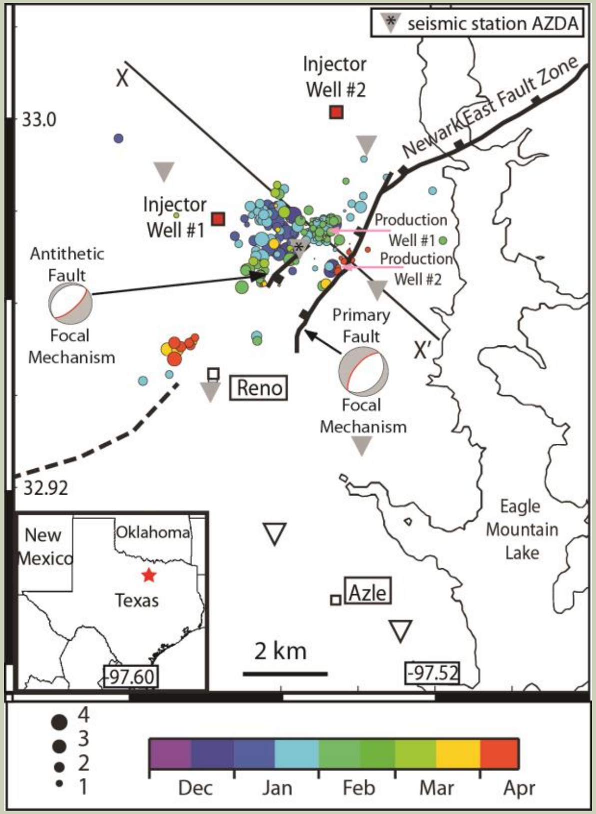
5 Temp. Networks:
DFW Airport (2008-)
Cleburne (2009-)
Venus (2011-)
Azle (2013-)
Irving (2014-)

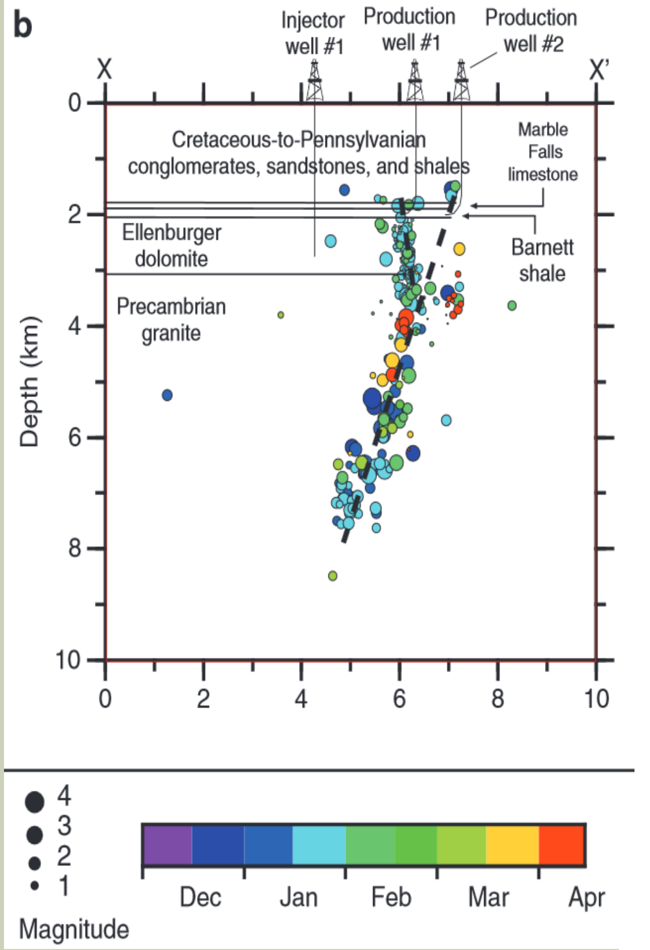


Earthquakes Report by National Earthquake Information Center since 2008 (2.0 – 4.0)

AZLE EVENT LOCATIONS THROUGH 26 AUG, 2014

- 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





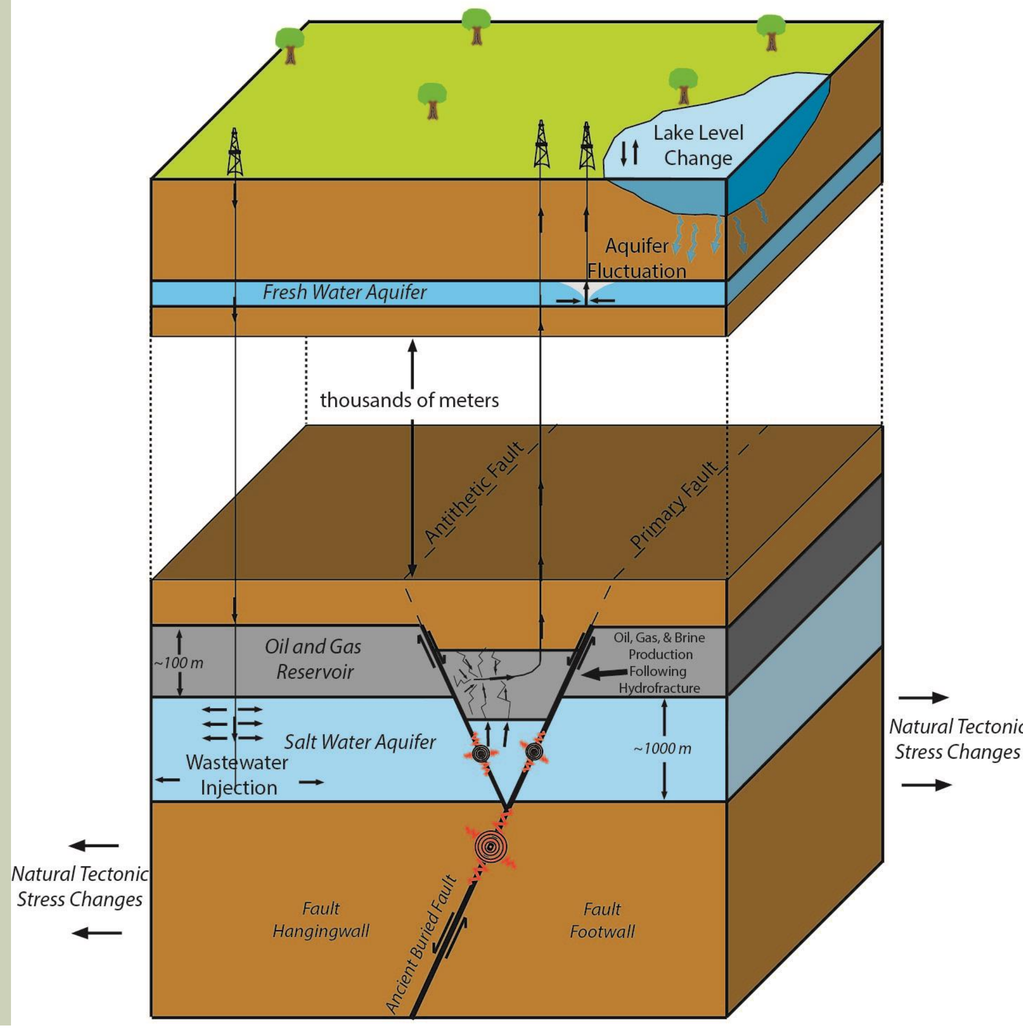
Hornbach, DeShon, *et al., 2015, Nature Communications*

CAUSAL FACTORS

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

Hornbach et al., 2015, Nature Comm.

Natural and Human-Made Stress Changes that Cause Earthquakes



NOT TO SCALE

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, Gutenburg-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.

FAULT OFFSET MODELING

Assumptions:

- Uniformly accumulated displacement since the Pennsylvanian (300Ma).
- M_{max} 5.6 (based on current seismicity)
- Longest return intervals ~100,000 years

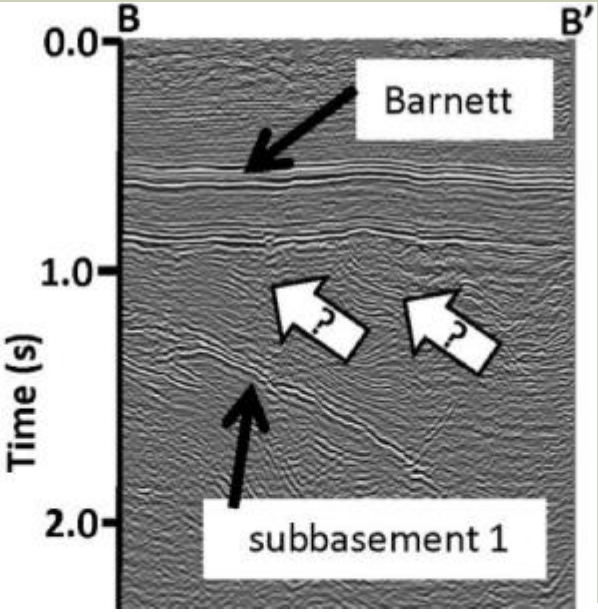
Displacement calculations– three cases:

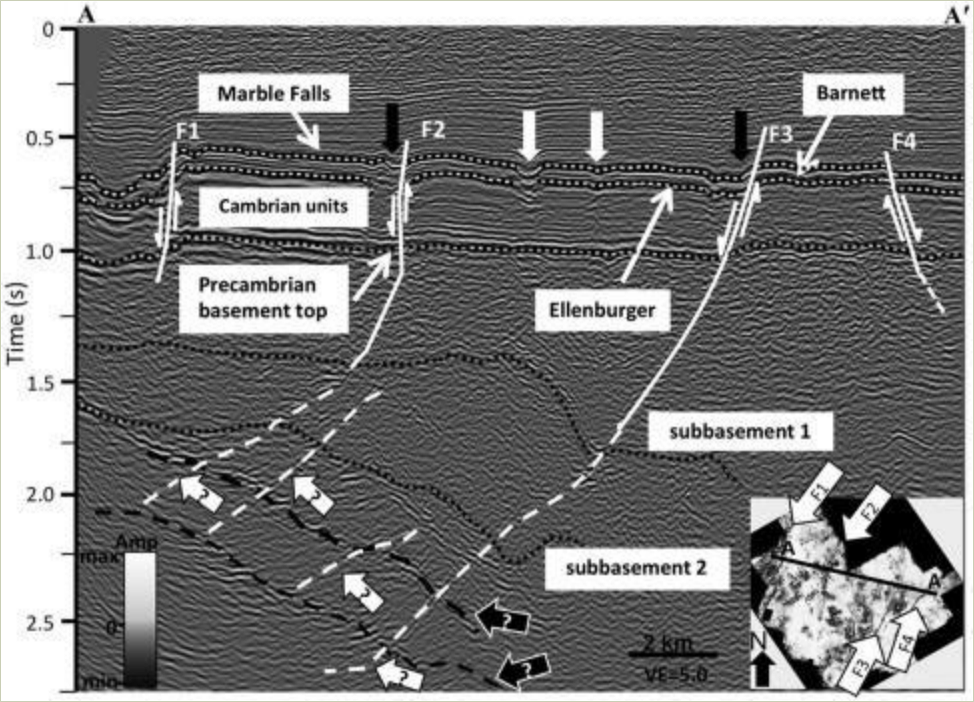
1. The Azle sequence displaced the fault by ~1.2mm.
2. A G-R sequence with single M_{max} of 5.0 would slip the fault ~48mm.
3. A G-R sequence with single fault-filling M5.6 would slip the fault ~380mm.

TECTONIC OFFSET MODELED VS. OBSERVED

Results:

1. One Azle seq. ~4m offset.
2. One Mmax 5.0 seq. ~140m offset.
3. One Mmax 5.6 seq. ~1200m offset.





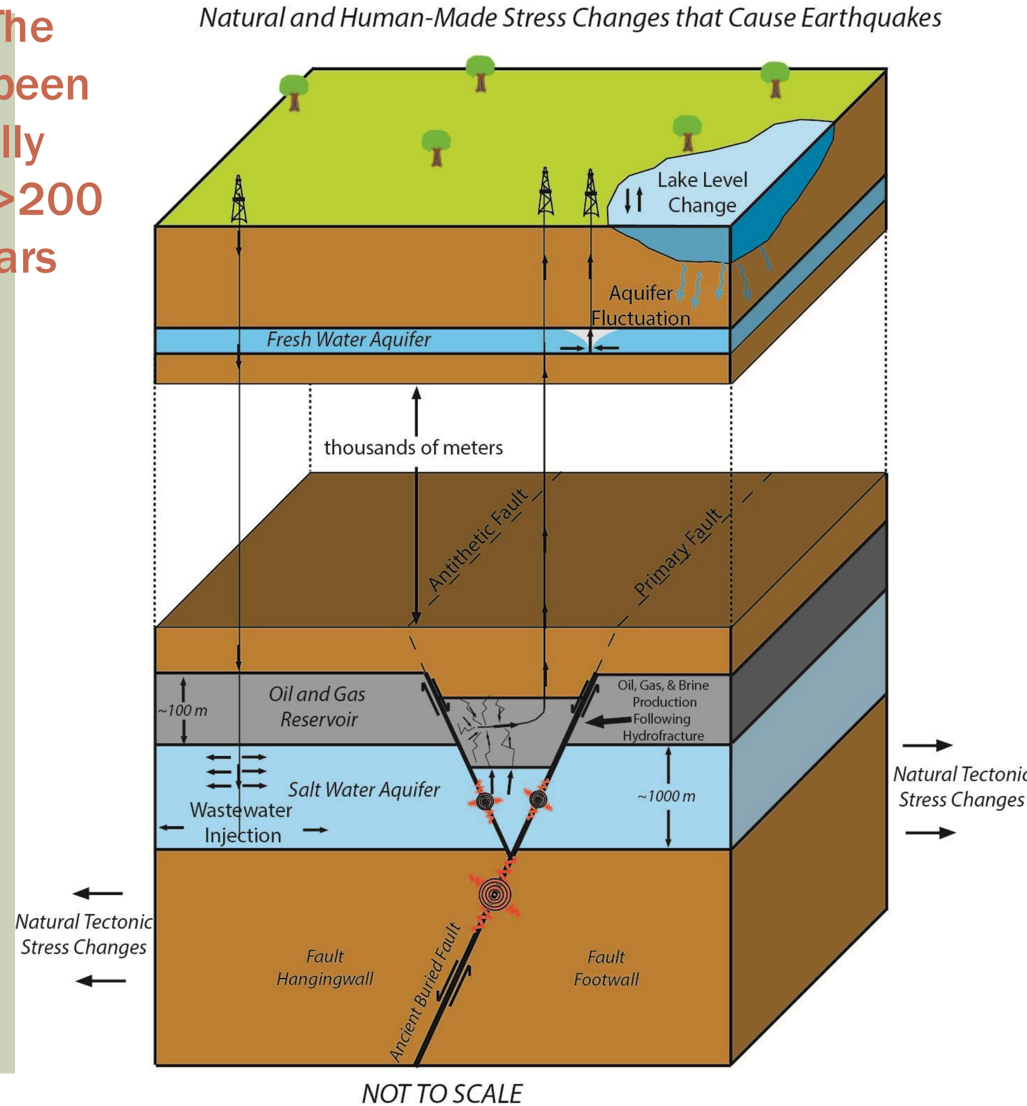
Khatiwada et al., 2013

CAUSAL FACTORS

- Natural Tectonic Stress Changes

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

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



Hornbach et al., 2015, Nature Comm.

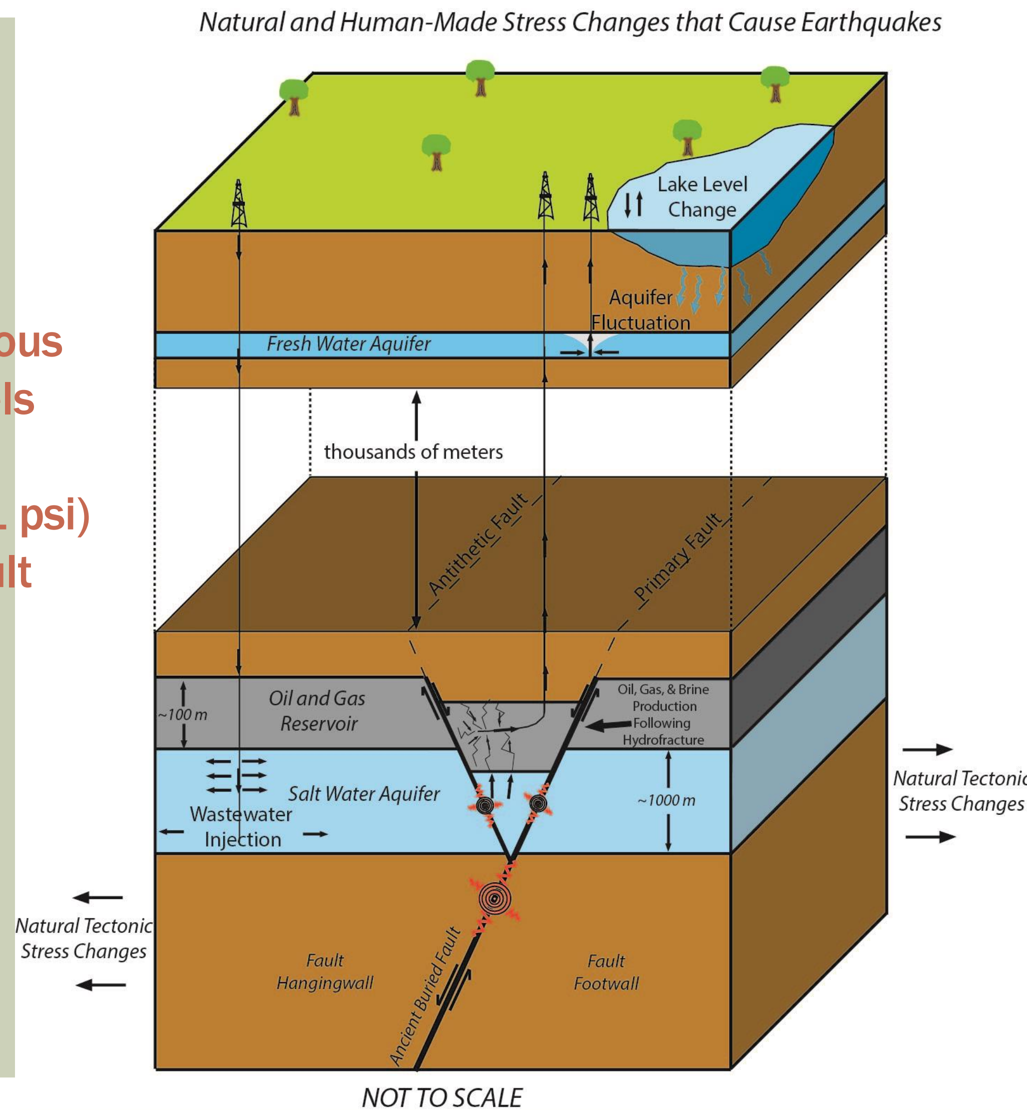
CAUSAL FACTORS

- Nat tonic Str ges
- Ground Water C
- L Le Changes
- Industry Activity
  - SWD Injection
  - Brine Production

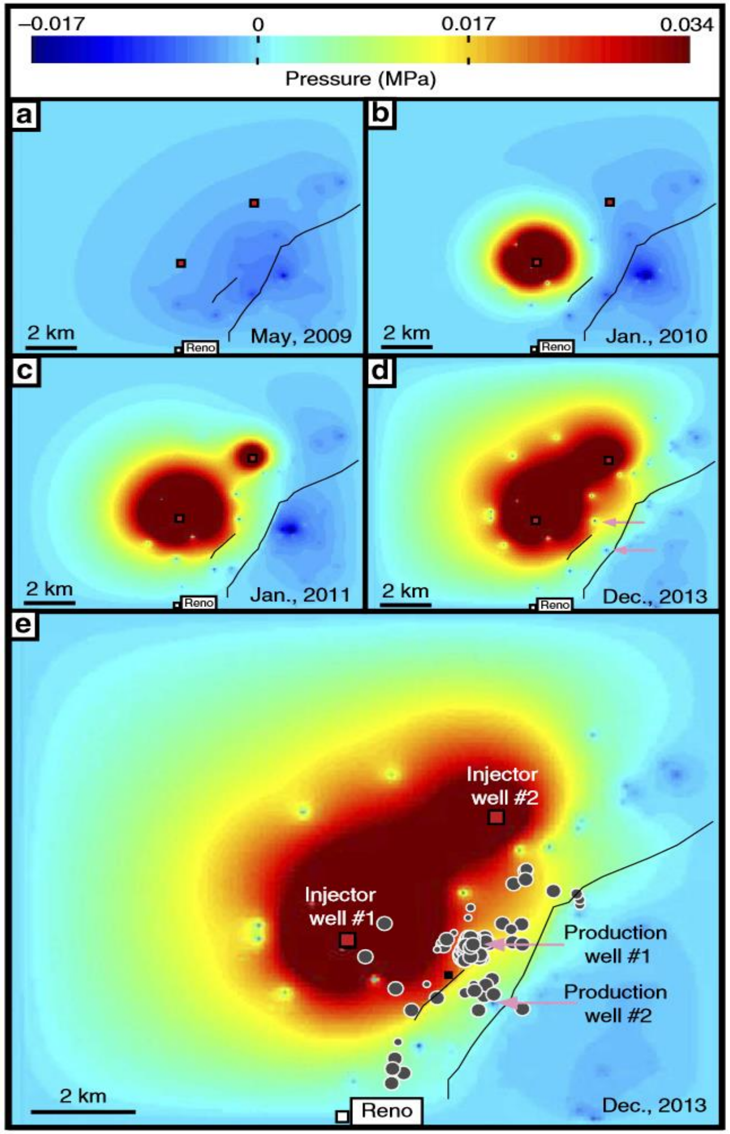
No anomalous water levels

<1 kPa (<0.1 psi) on the fault

Hornbach et al., 2015, Nature Comm.



QUANTIFYING SUBSURFACE INJECTION/PRODUCTION PRESSURES



- Pressure modeling indicate injection/production caused pressure changes sufficient to trigger earthquakes.
- pressure changes associated with drought 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.

AZLE EARTHQUAKES: INDUCED OR NATURAL?

(Davis and Frohlich, 1993)	Azle Answers
1. Are the events the first known earthquakes of this character in the region?	YES
2. Is there a clear correlation between injection and seismicity?	YES
3. Are epicenters within 5 km of wells?	YES
4. Do some earthquakes occur at or near injection depth?	YES
5. Are there known geologic structures that may channel flow to sites of earthquakes?	YES
6. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?	YES
7. Are changes in fluid pressure at hypocentral distances sufficient to encourage seismicity?	YES

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

PATH FORWARD
NRC, 2012

"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."

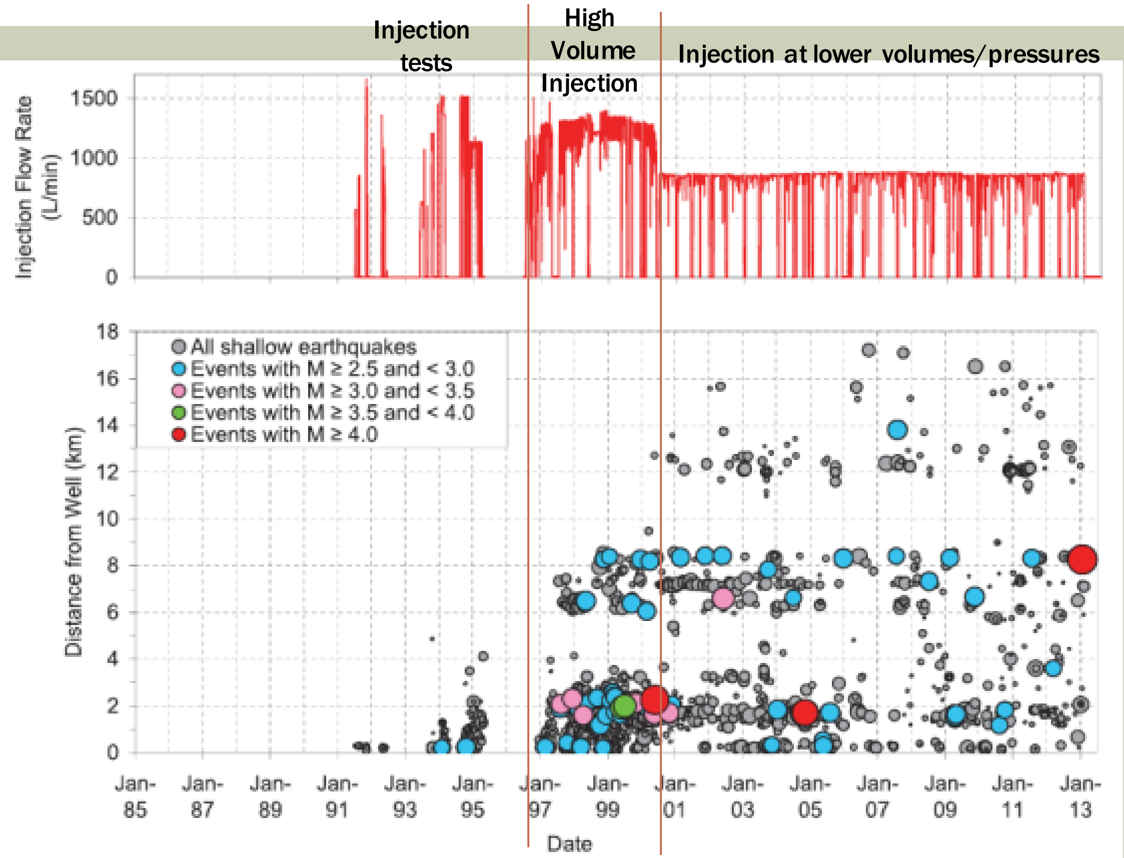
BASIC DATA NEEDS (AS ALREADY OUTLINED IN THE AZLE STUDY)

- 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.
- <u>EQ swarm monitoring combined with down hole pressure monitoring</u> 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.



▲ **Figure 6.** Scatter plot of earthquakes having M ≥0.5 and locating less than 8.5 km deep (relative to the ground-surface elevation at the injection wellhead), plotted as a function of date and distance from the PVU injection well (lower plot). Each circle represents a single earthquake, with the width of the circle scaled by the event magnitude. The upper plot shows the daily average injection flow rate over the same time period.

(From Block et al., 2013)