LEARNING FROM SEISMICITY IN THE DALLAS-FORT WORTH AREA

Acknowledgements:
Heather DeShon, Matt Hornbach, Chris Hayward, Beatrice Magnani, Cliff Frohlich, Jon Olson, North Texas Eqs Working Group, USGS

Brian Stump

Southern Methodist University

26 June 2015

KEY OBSERVATIONS FOR INDUCED SEISMICITY

- A small percentage of wastewater injection wells are associated with seismicity
- Earthquake rates have increased in the central US and pose an increased hazard regardless of cause
- Mitigation requires an improved physical understanding of causative processes

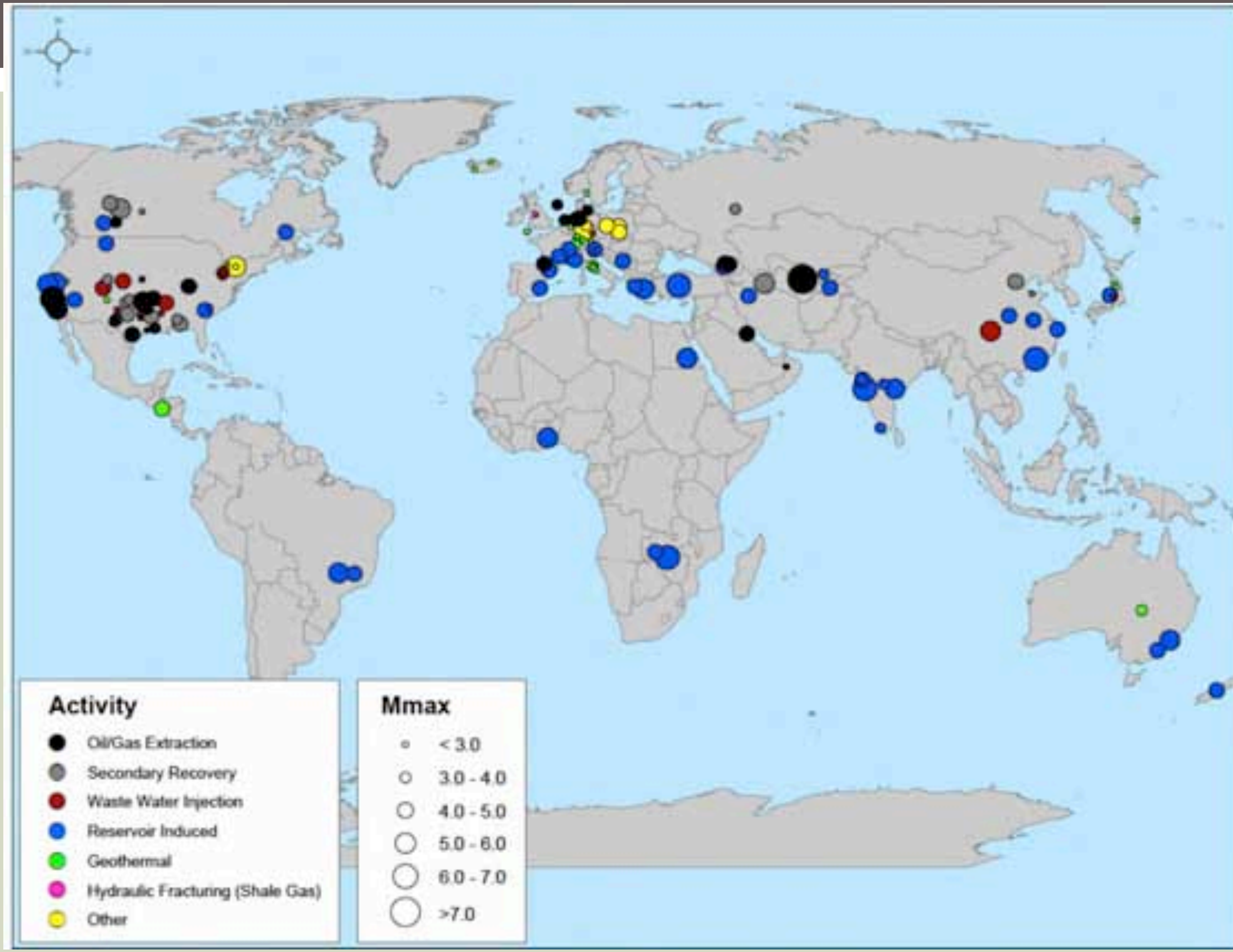
INJECTION-INDUCED SEISMICITY: A WELL ESTABLISHED PHENOMENA

- Multiple experiment (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

ROCKY MOUNTAIN ARSENAL
FLUID PRESSURES LOWERED FRICTIONAL RESISTANCE ALONG EXISTING FAULT SYSTEM

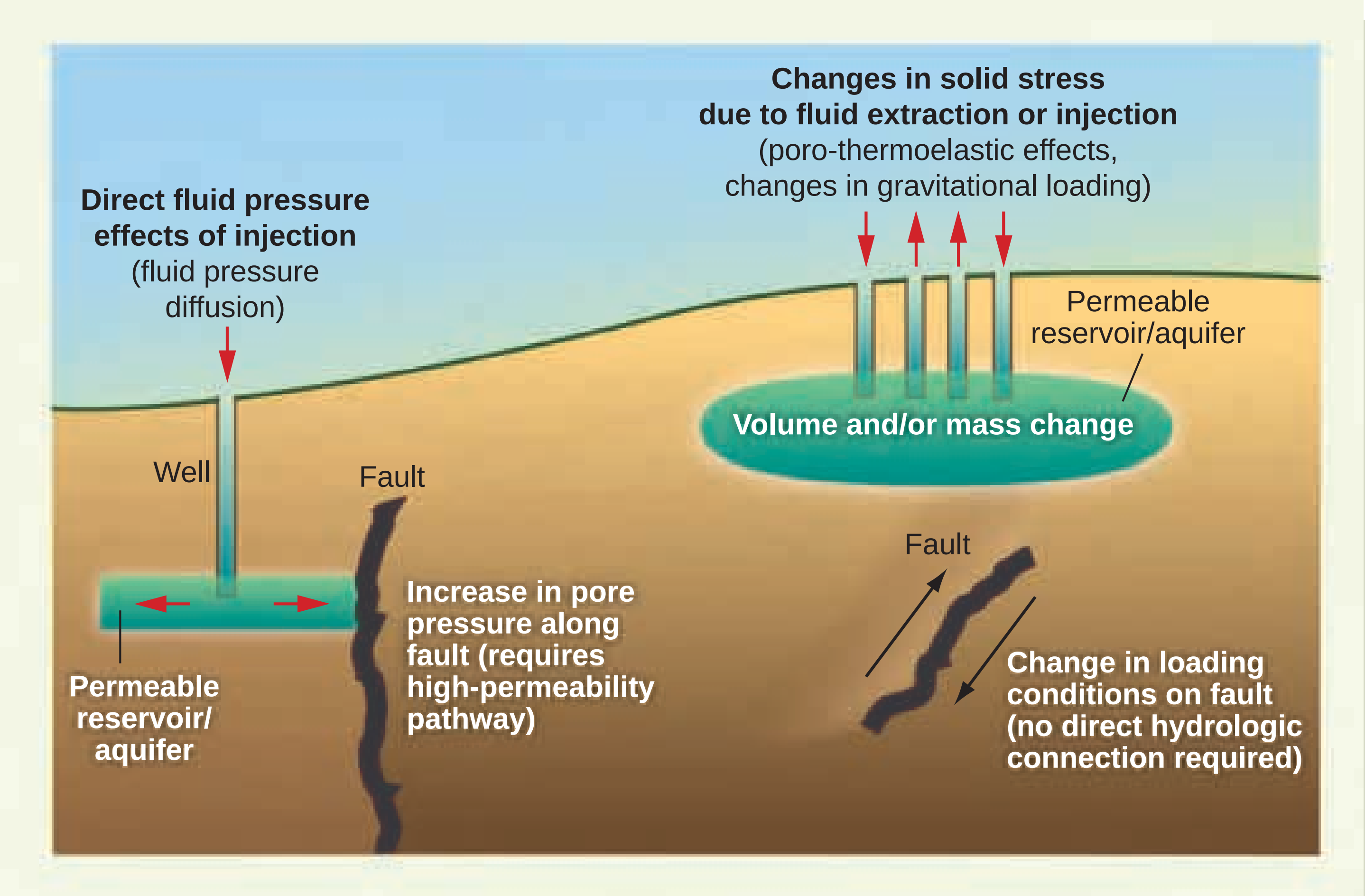
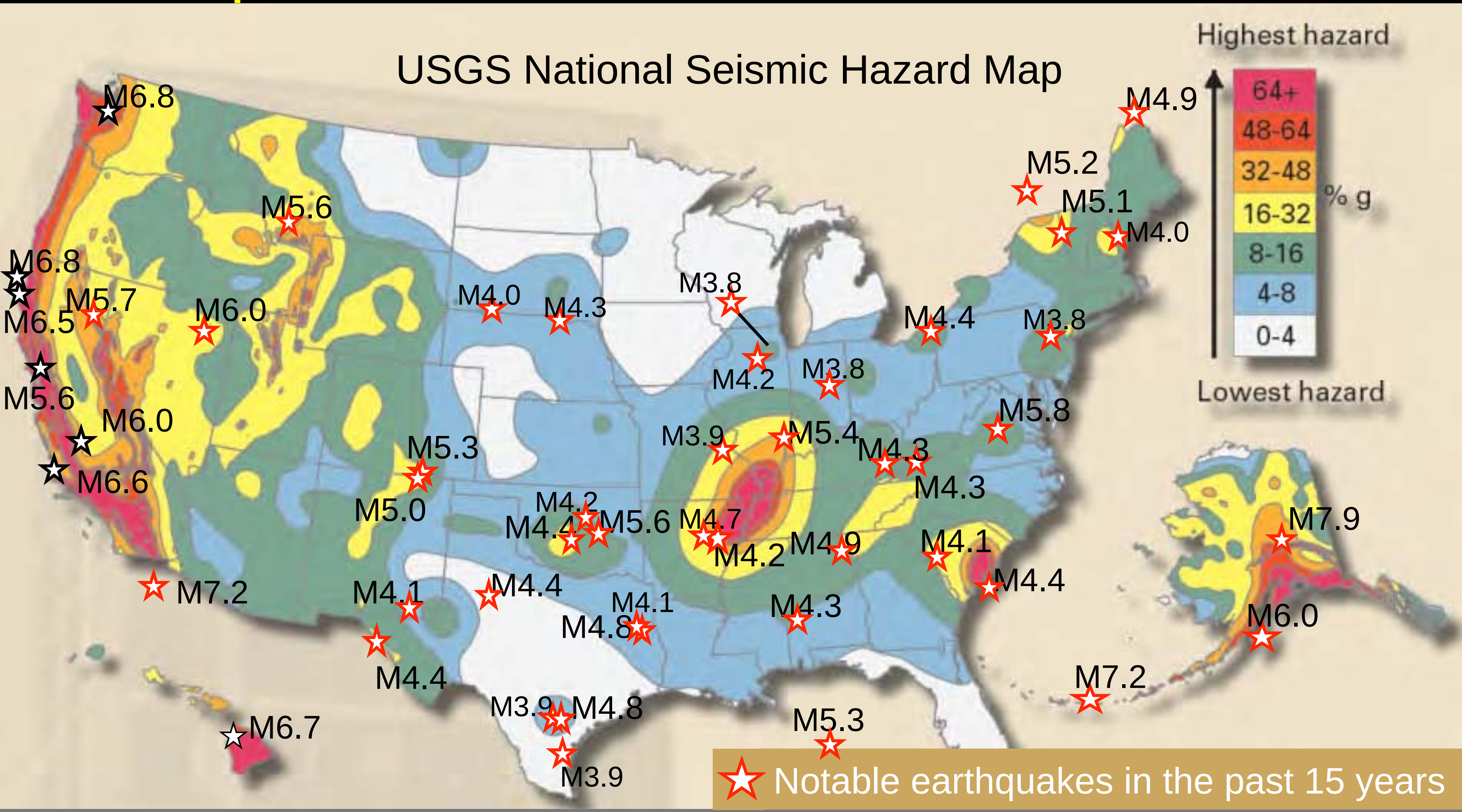


Fig. 3. Schematic diagram of mechanisms for inducing earthquakes. Earthquakes may be induced by increasing the pore pressure acting on a fault (**left**) or by changing the shear and normal stress acting on the fault (**right**). See (*4*).

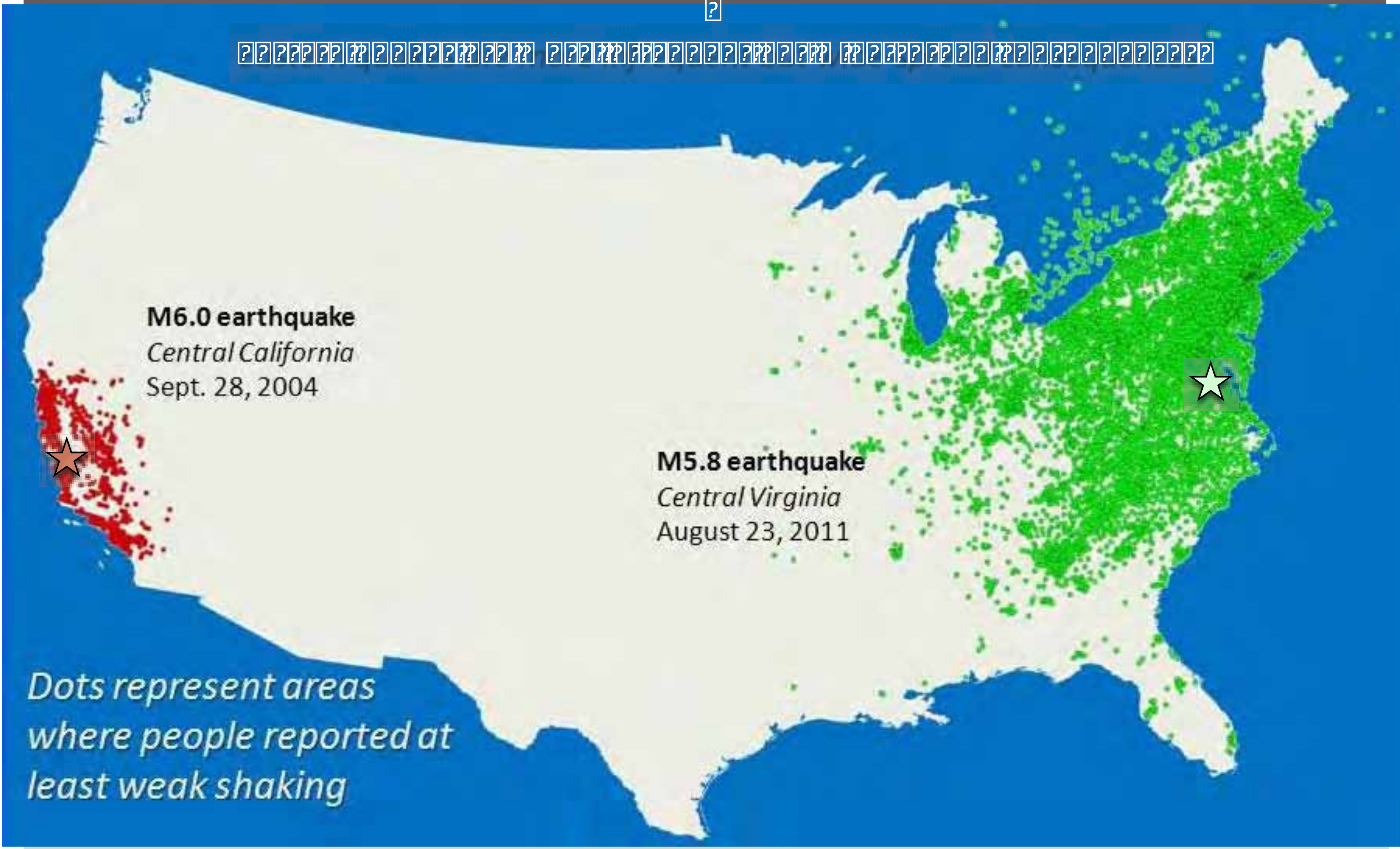
Ellsworth, 2013

Earthquakes are a national hazard

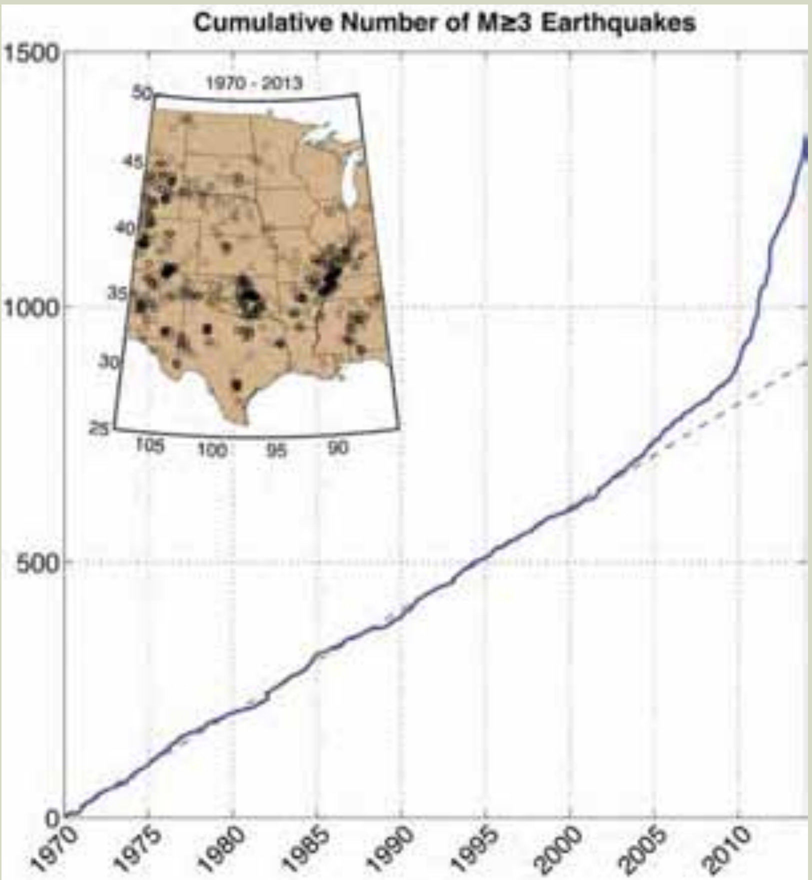


nehrp FEMA NIST National Institute of Standards and Technology NSF USGS science for a changing world

national earthquake hazards reduction program

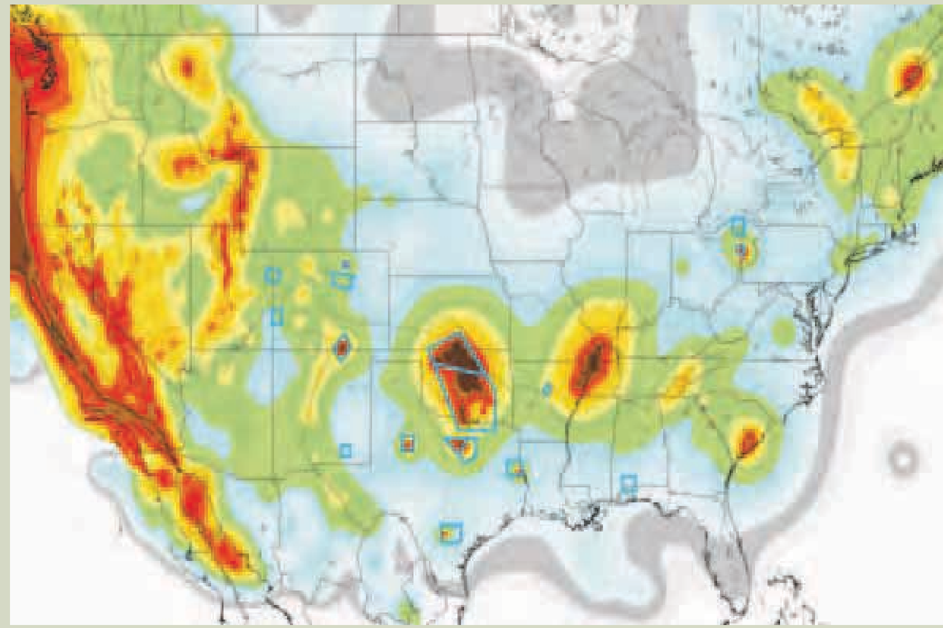

M6.0 earthquake
Central California
Sept. 28, 2004
M5.8 earthquake
Central Virginia
August 23, 2011
Dots represent areas
where people reported at
least weak shaking

INCREASE IN SEISMICITY AND HAZARD IN CENTRAL AND EASTERN US



Recent increase in annual seismicity in Central and Eastern US. Ellsworth, 2013.

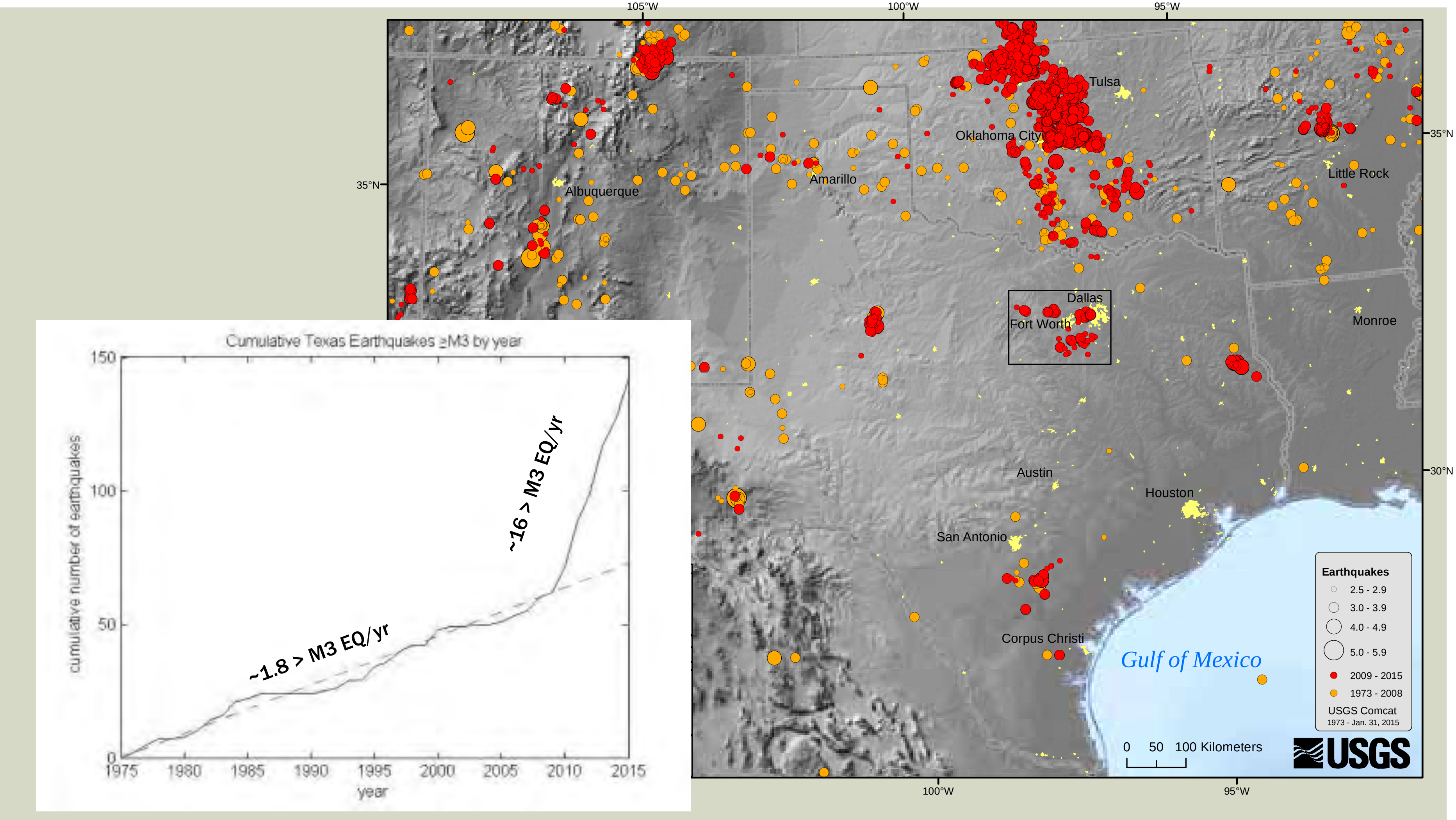
earthquake.usgs.gov/research/induced/



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/

HAZARD is independent of cause but mitigation strategies are not



http://earthquake.usgs.gov/earthquakes/states/texas/images/Texas-seis.pdf

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?

What data are helpful in addressing these questions?

BASIC DATA NEEDS

- Regional seismic data
- Local seismic networks
- Bottom hole pressure and permeability measurements.
- Brine production and brine sources (geochemical data).
- Better control on local subsurface structure.
- Fault properties and locations
- In-situ stresses
- Research support and collaboration

PATH FORWARD
NRC, 2012

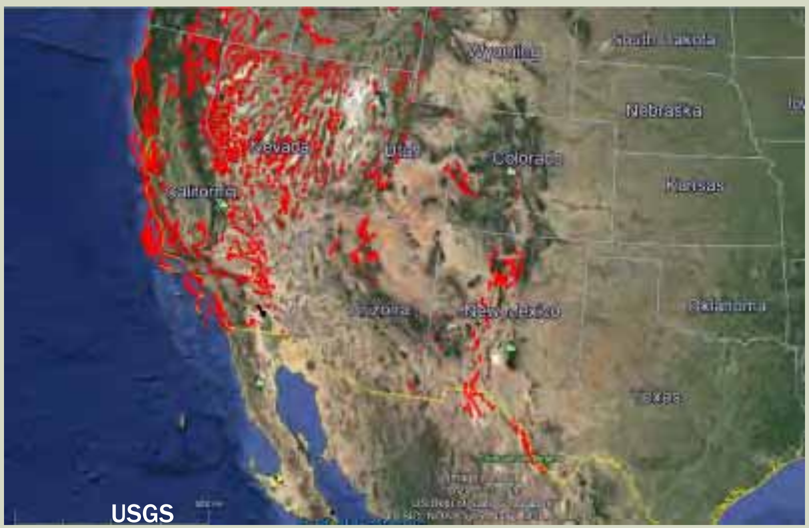
Current models employed to understand the predictability of the size and location of earthquakes through time in response to net fluid injection or withdrawal require calibration from data from field observations.

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.

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

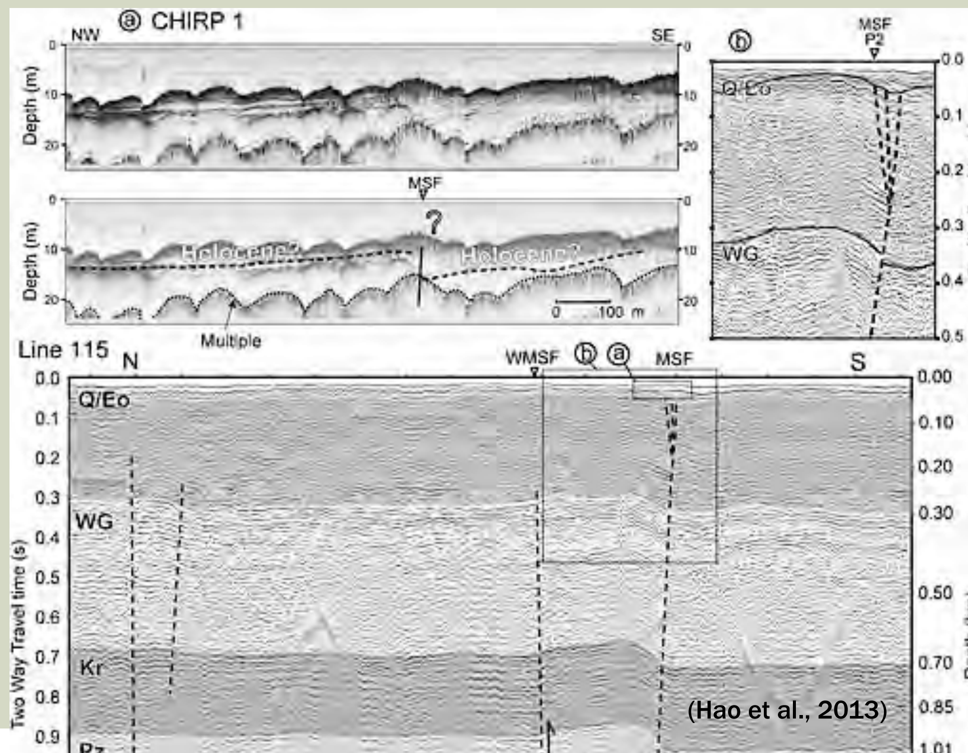
Useful data

- 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?

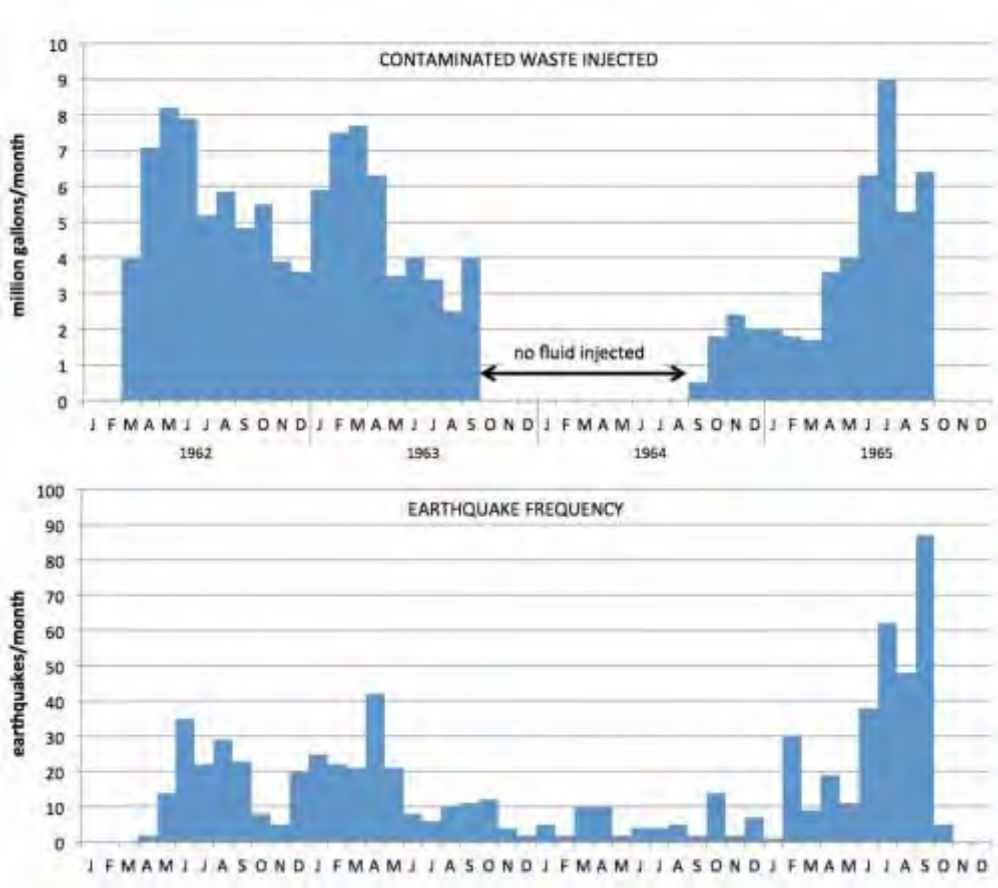
Example: Rocky Mountain Arsenal

(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.



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

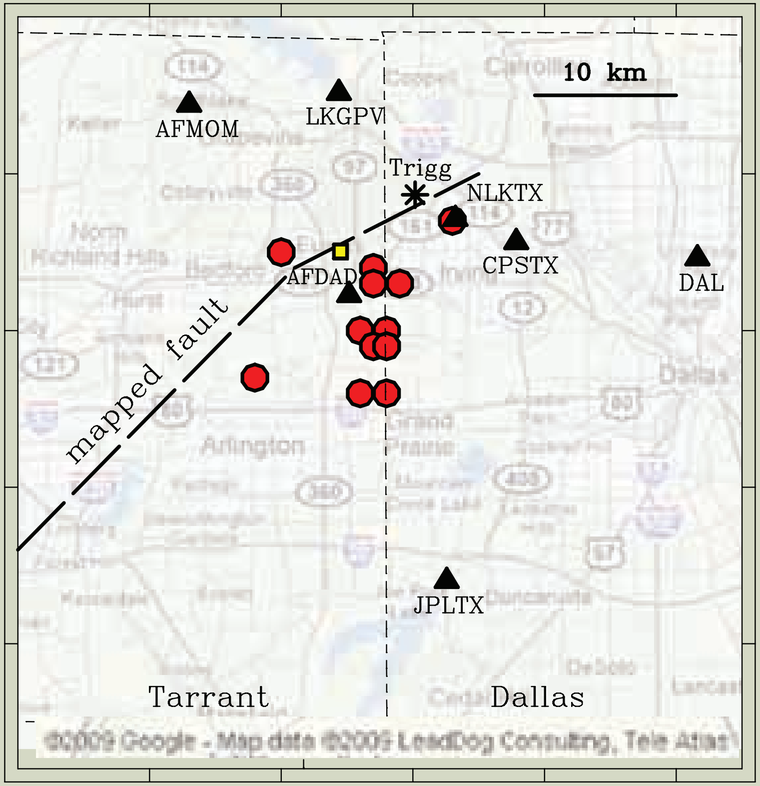
Required Data

- 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

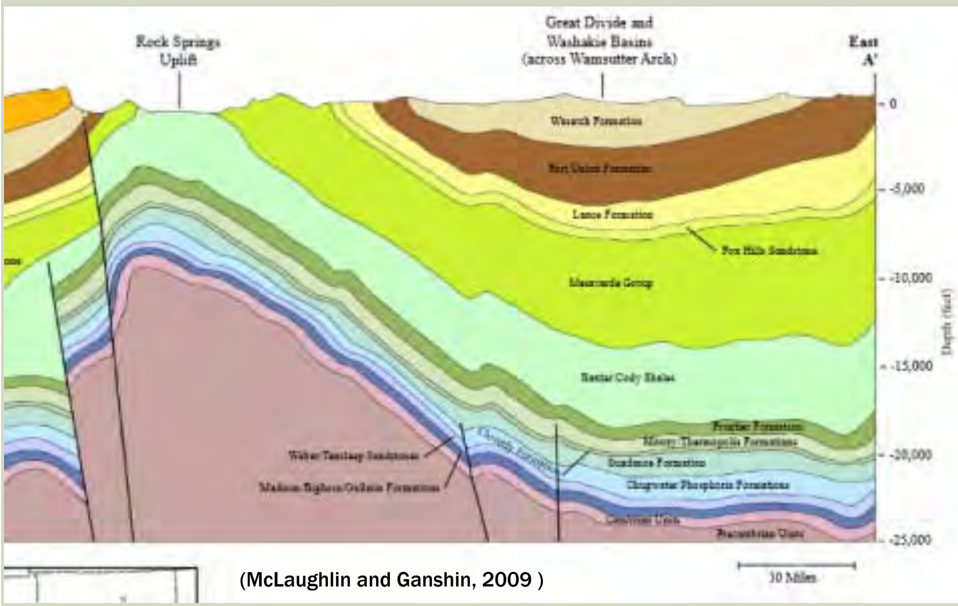
- High Resolution Local Seismic Monitoring.
- Vp & Vs Velocity Models.

5. ARE THERE GEOLOGIC STRUCTURES THAT MIGHT CHANNEL FLOW TO EARTHQUAKE SITES?

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.

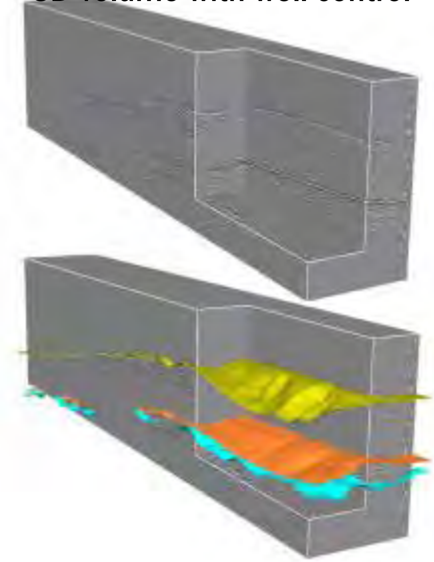
Typically Available (km resolution)



(McLaughlin and Ganshin, 2009)

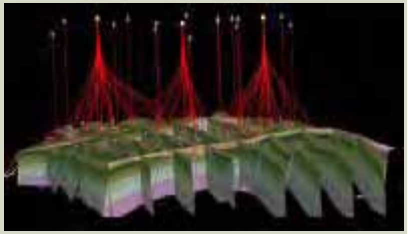
Typically Desired (m resolution)

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

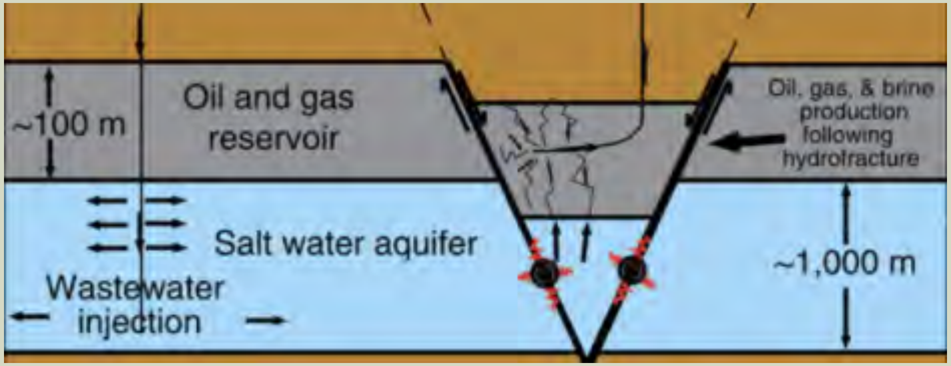
Location	EQ Induced Stress (psi)	Suspected Cause	Source(s)
Lacq Field, Fr.	~14.5 psi	Oil and Gas Activity	Segal et al., 1994
Elmore Ranch, Ca	1.5 – 4.5 psi	Adjacent fault rupture	Anderson and Johnson, 1999
Imogene Field, Tx	<59 psi	Oil and Gas Activity	Grasso, 1992; Grasso and Sornette, 1998
Kobe, Japan	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

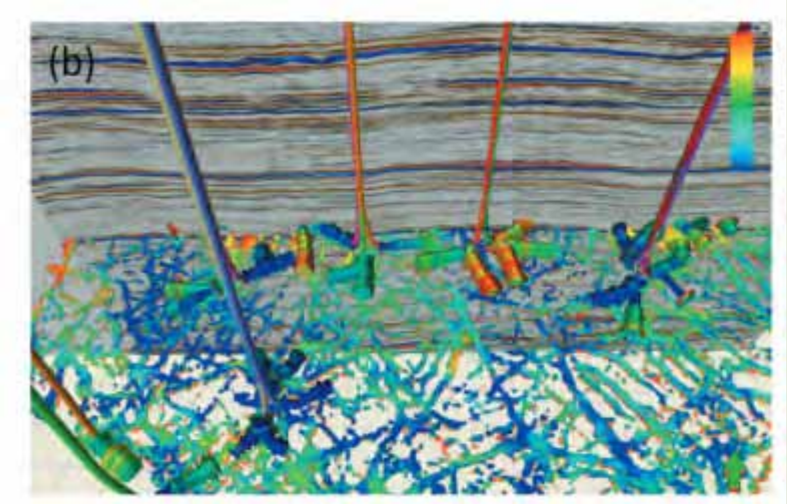
Studies also show a few psi *reduction* in stress *reduces* EQs (e.g. Stein & Lisowski, 1983).

Useful Data

- Bottom Hole Pressure measurements at injection sites

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



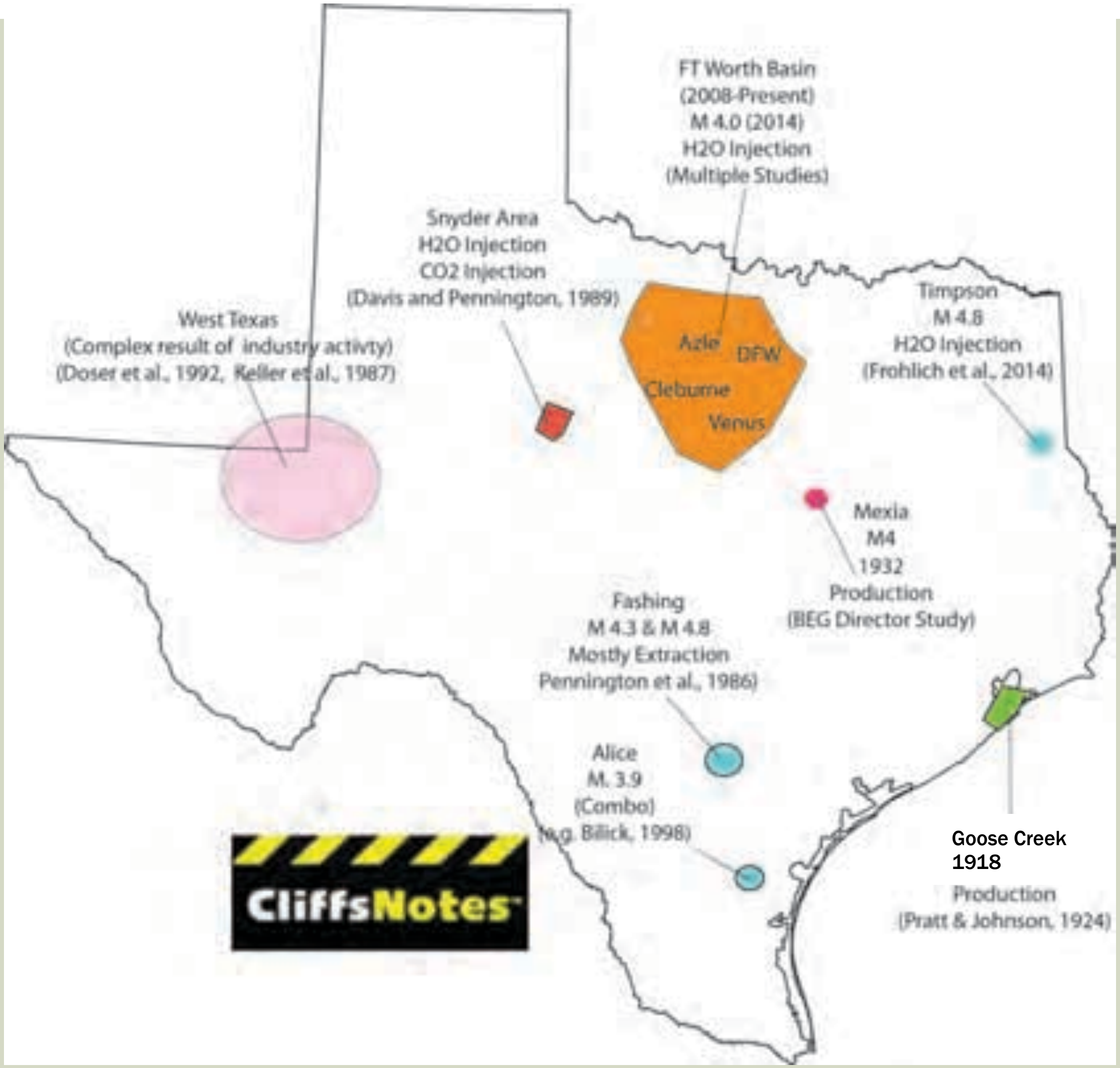


(e.g. Todorovic-Marinic et al., 2011)

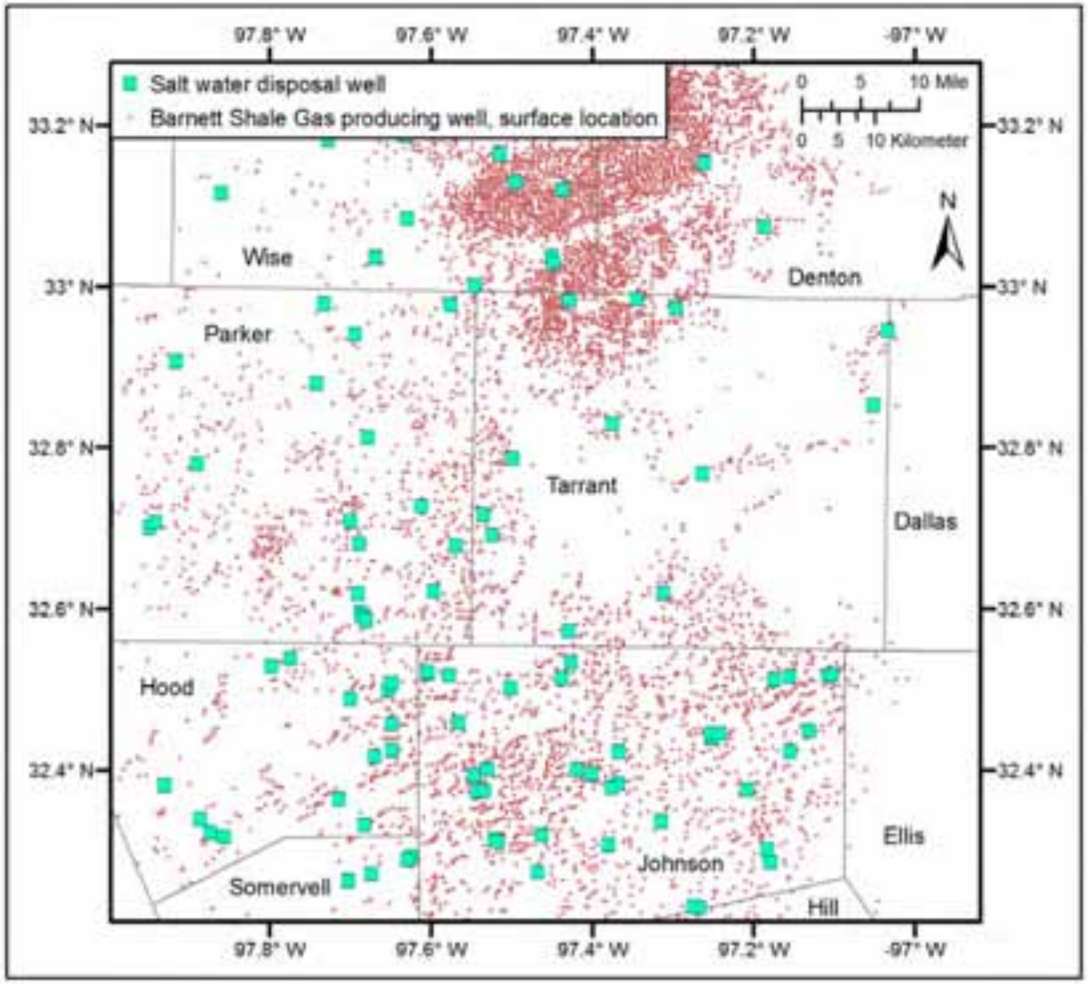
Useful Data for Estimating Flow, Pressure, and Seismicity on Faults

- 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 INDUCED SEISMICITY LITERATURE IN TEXAS



Fort Worth Basin



Barnett Shale

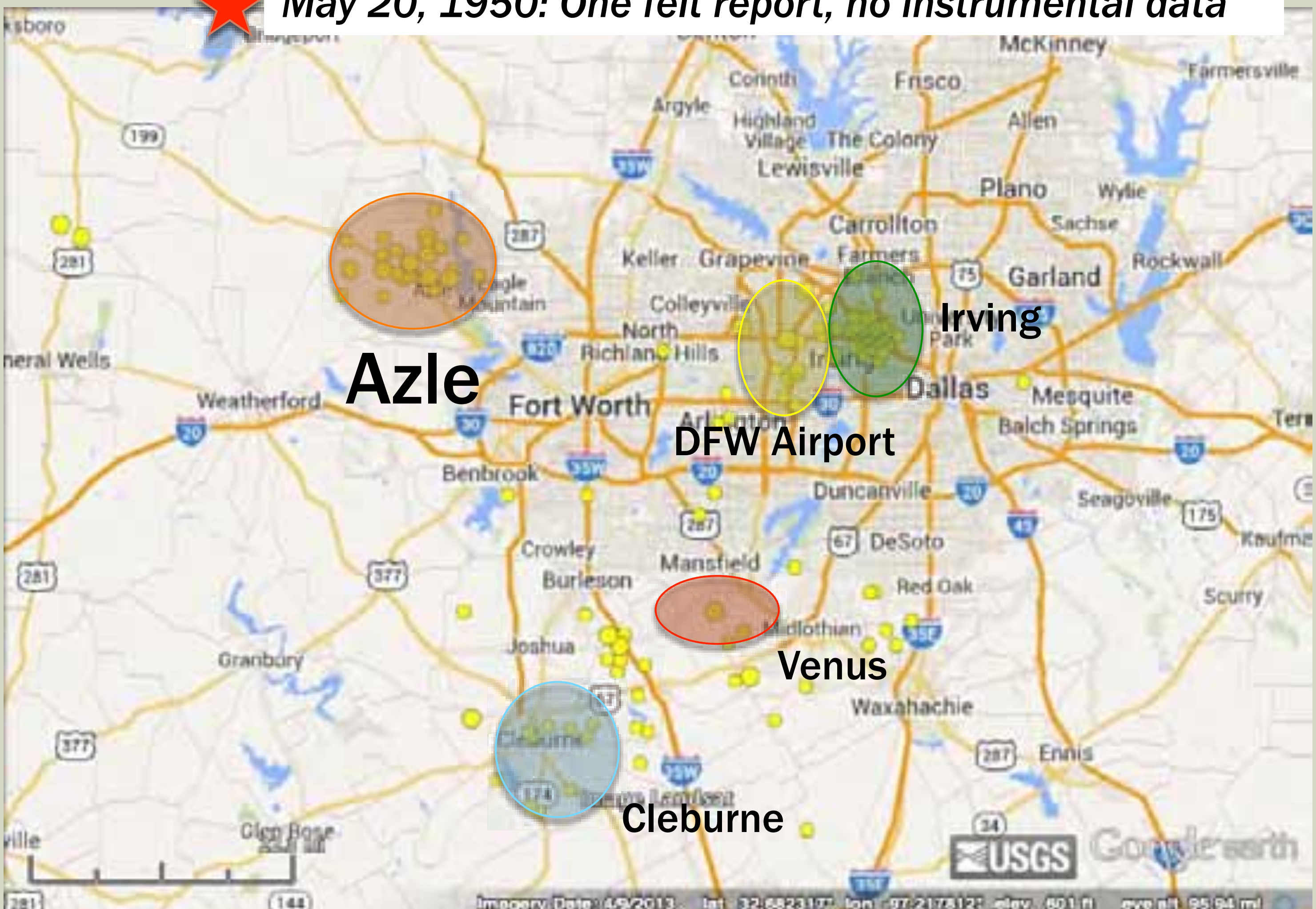
Regional gas production in the Fort Worth Basin and Waste Water Disposal sites.

Frohlich *et al*., 2010.

Vast majority of injectors have no associated seismicity

AZLE Earthquake Sequence 2014-2015

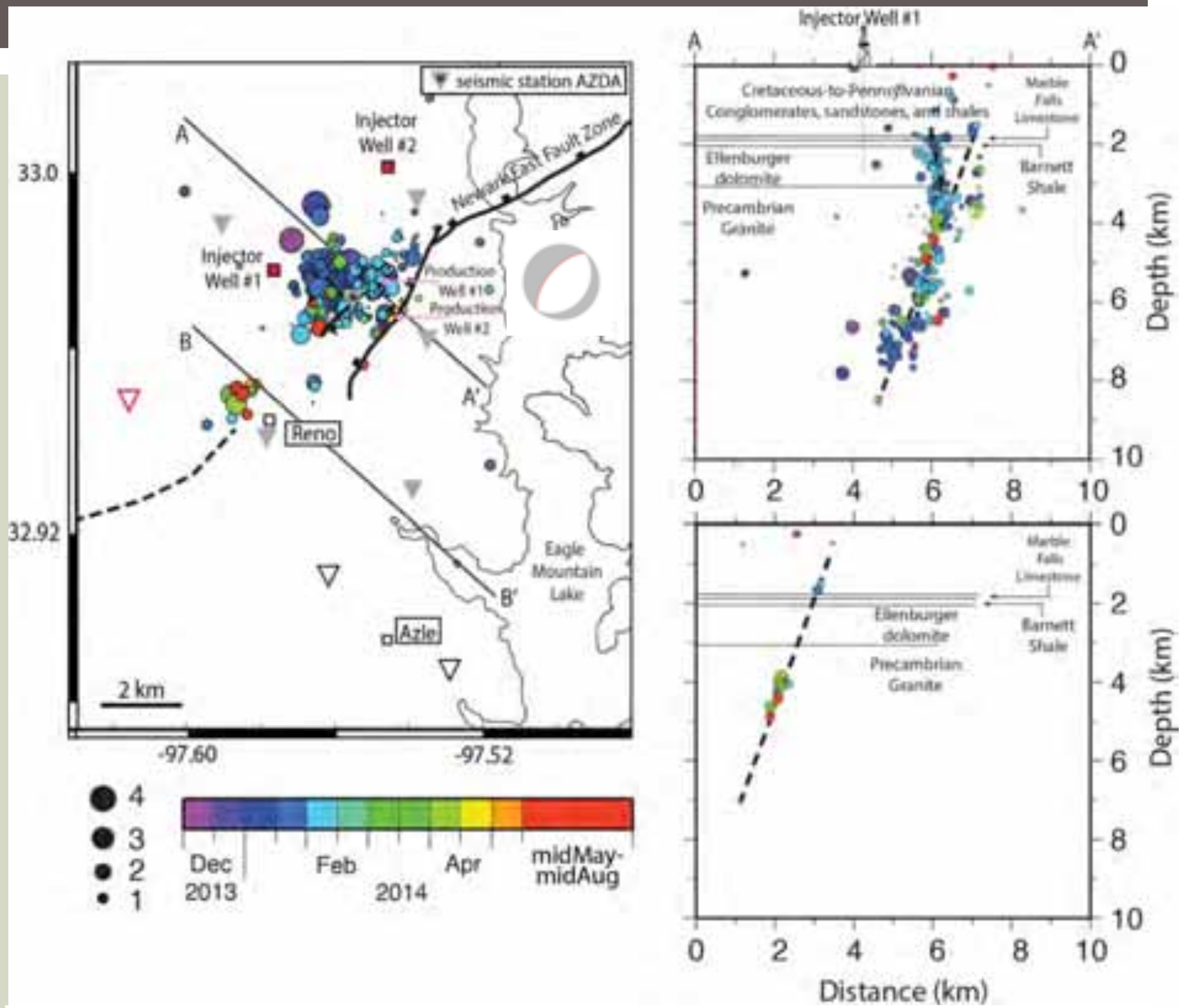
May 20, 1950: One felt report, no instrumental data



Industry Cooperation in Study

AZLE EVENT LOCATIONS THROUGH 26 AUG, 2014

- The last widely felt event was Jan 28th, 2014
- Seismicity rate was highly variable
- The sequence has slowed, last recorded event January 2015
- Faulting appears complex

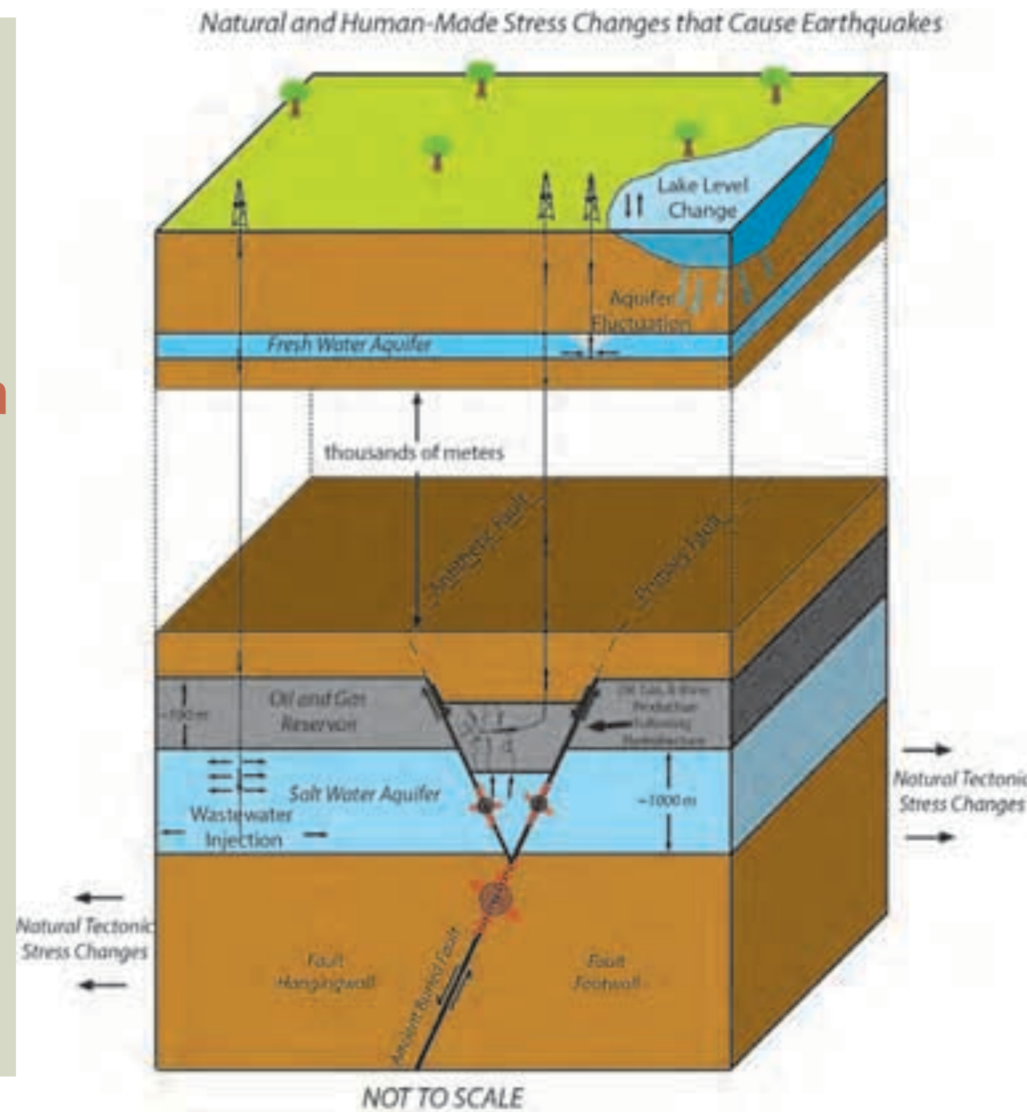


Hornbach, DeShon, *et al., 2015, Nature Communications*

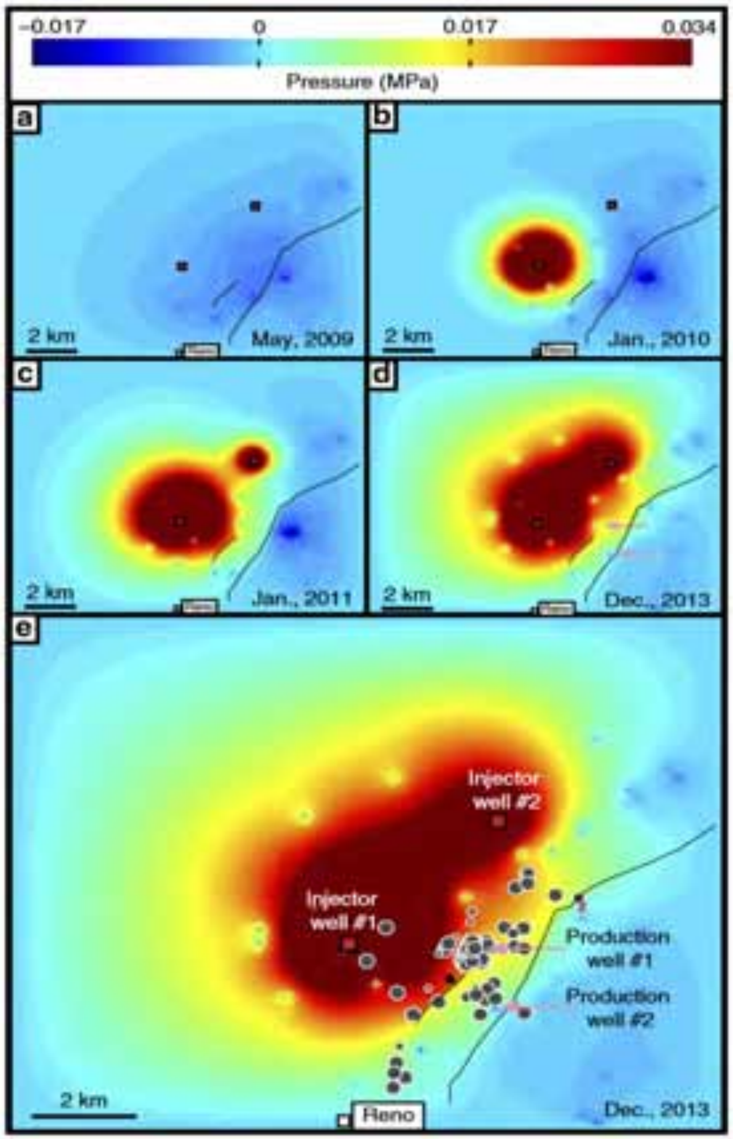
CAUSAL FACTORS

- Natural Tectonic Stress Changes
- Ground Water C[illegible]
- L[illegible] Le[illegible] Changes
- Industry Activity
  - SWD Injection
  - Brine Production

<1 kPa on the fault



SWD INJECTION AND BRINE PRODUCTION
MOST LIKELY CAUSE



- Pressure modeling confirms it is plausible injection/production caused pressure changes sufficient to trigger earthquakes.
- Pressure modeling indicates pressure changes associated with drought were 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.

LINKAGE TO PRODUCTION ACTIVITIES?

Questions from 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
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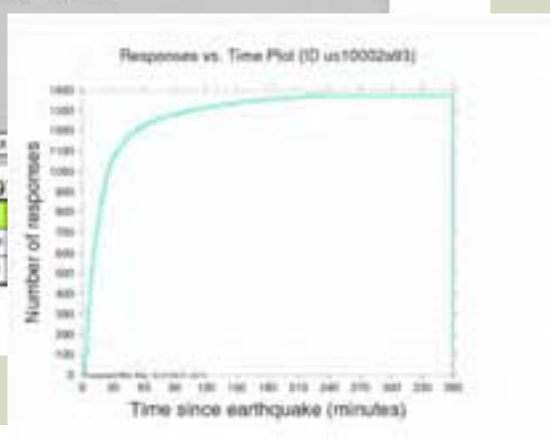
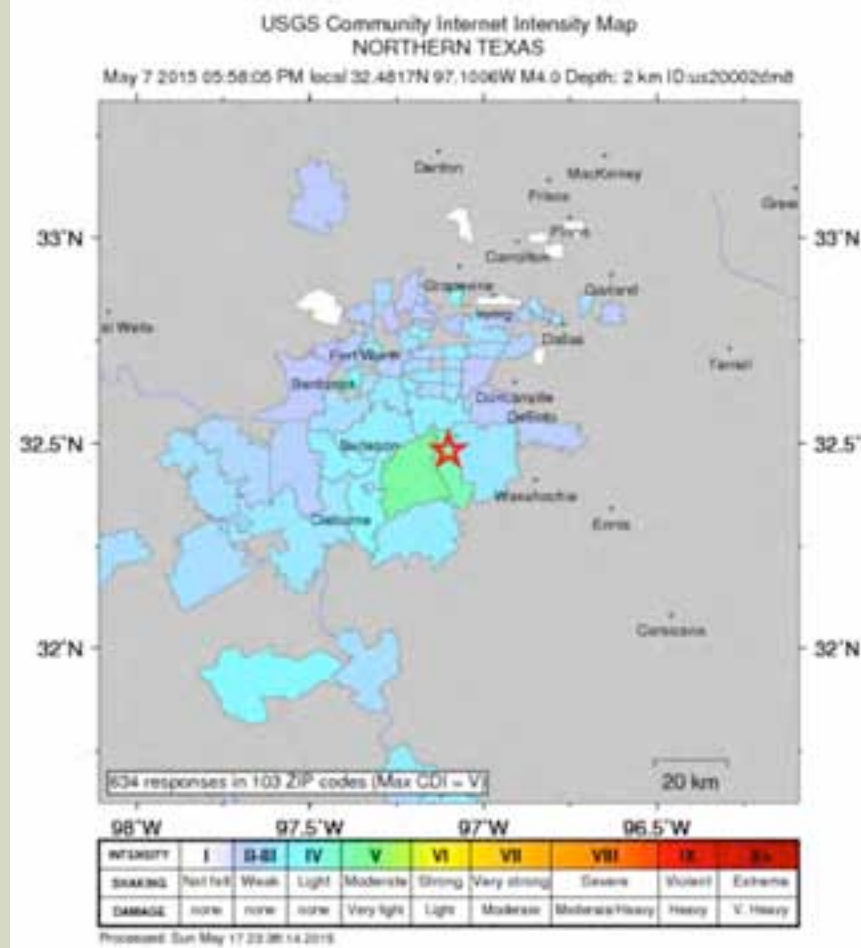
<u>Better</u> subsurface data to constrain structures, faults and material properties. This type of data needed to produce physical models to assess the cause of earthquakes.

EVENTS CONTINUE
Magnitude 3.3 (18 May) and 4.0 (7 May)





earthquake.usgs.gov/earthquakes/

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NRC, 2012

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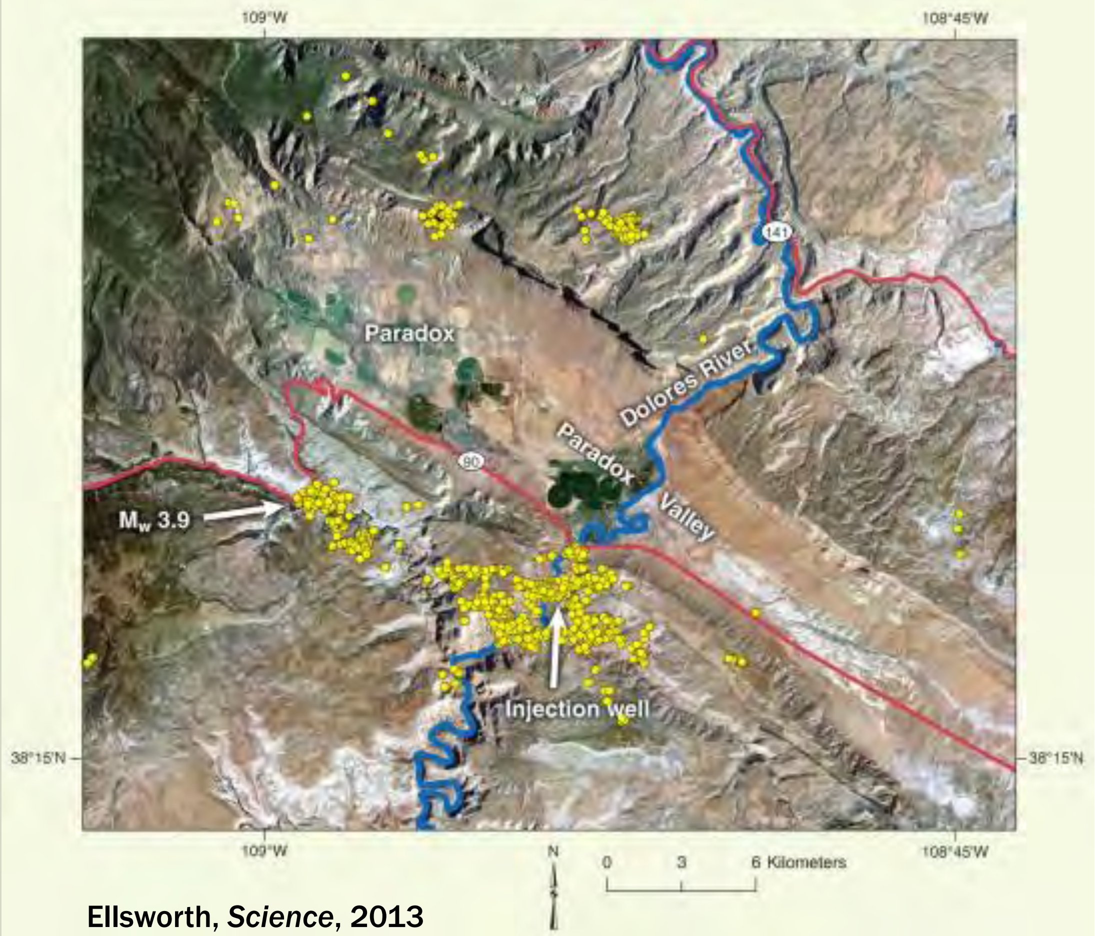
CONCLUDING REMARKS

- ***Proof of Induced Seismicity may be difficult to obtain.*** Absolute proof may not be necessary for consideration of prudent operational changes.
- ***No agreed upon physical model for linkage between commercial activities and earthquakes.*** A range of physical models may be in operation depending on individual conditions.
- ***Need for reservoir engineers, geologists and geophysicists to work together to attack these problems.*** Data sharing provides a step in assessment of these issues. Seismic monitoring is only one part of this assessment.

MITIGATION INVOLVE BETTER MONITORING AND MORE DATA ACCESS

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.
- May 2000. M 4.3 event occurs. Bureau of Reclamation begins data review.
- *"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 <u>downhole pressure exhibits the best correlation with the occurrence of near-well seismicity over time</u>.'"* *(NRC REPORT)*



Ellsworth, *Science*, 2013

MITIGATION INVOLVE BETTER MONITORING AND MORE DATA ACCESS

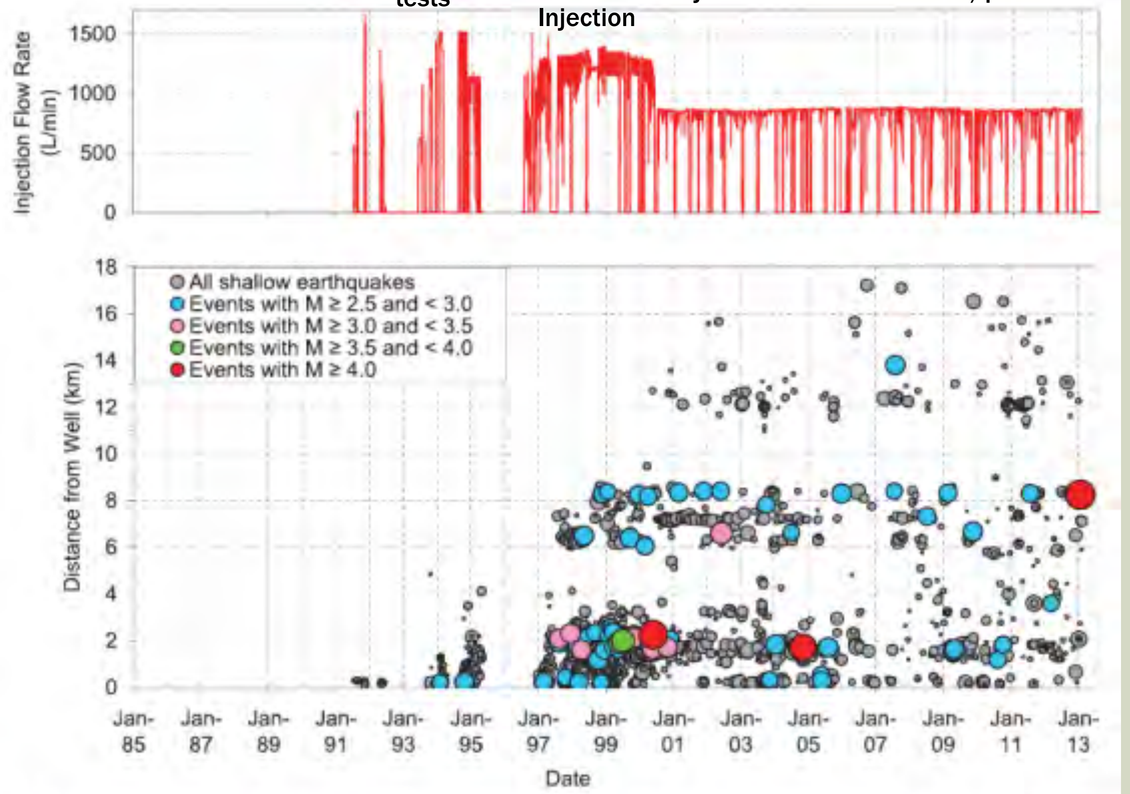
PARADOX VALLEY, COLORADO

- 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.

Injection tests

High Volume Injection

Injection at lower volumes/pressures



▲ **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)