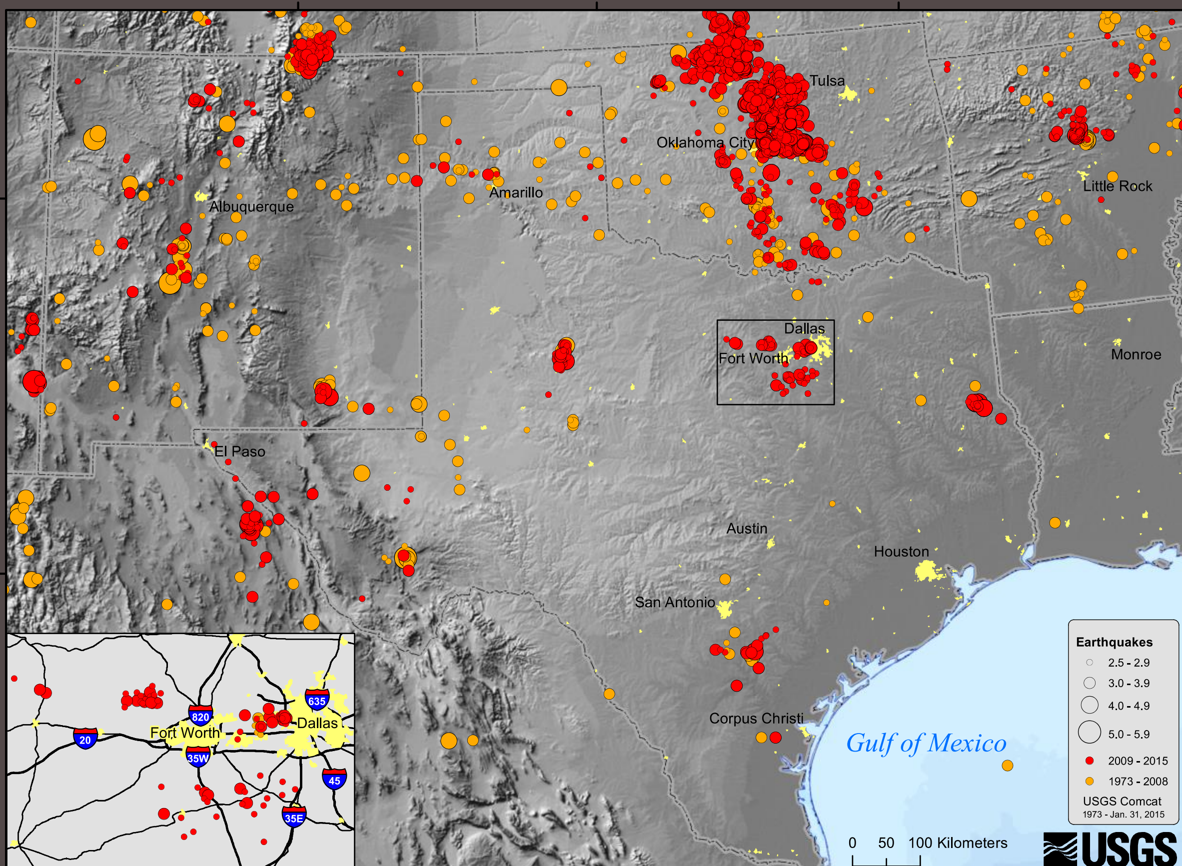
MITIGATING SEISMICITY IN THE GREATER NORTH TEXAS AREA



Matthew J. Hornbach[1]
Heather DeShon[1]
Brian Stump[1]
Chris Hayward[1]
Beatrice Magnani[1]
Cliff Frohlich[2]
Jon Olson[3]
Bill Ellsworth[4]
and the
NORth TeXas seismicity group[1, 2,3,4]

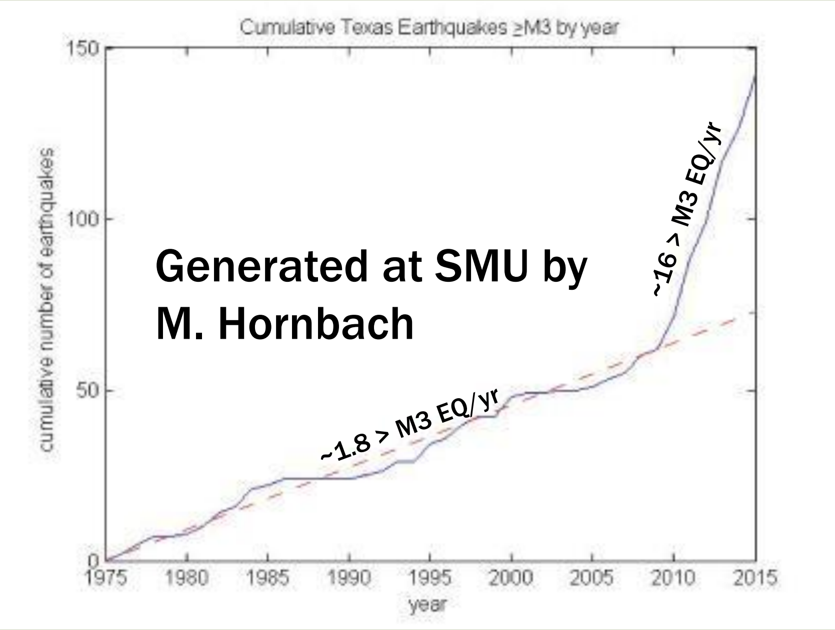
1 Southern Methodist University
Dept. of Earth Sciences
Dallas, Texas

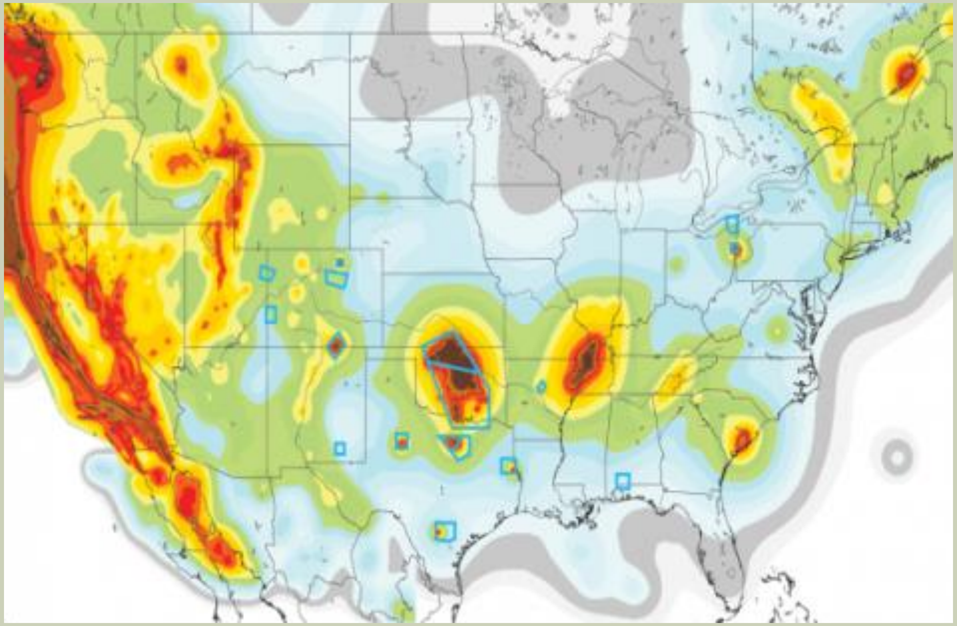
2 The University of Texas
Institute for Geophysics
Austin, Texas

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/

MECHANISMS FOR INDUCING EARTHQUAKES

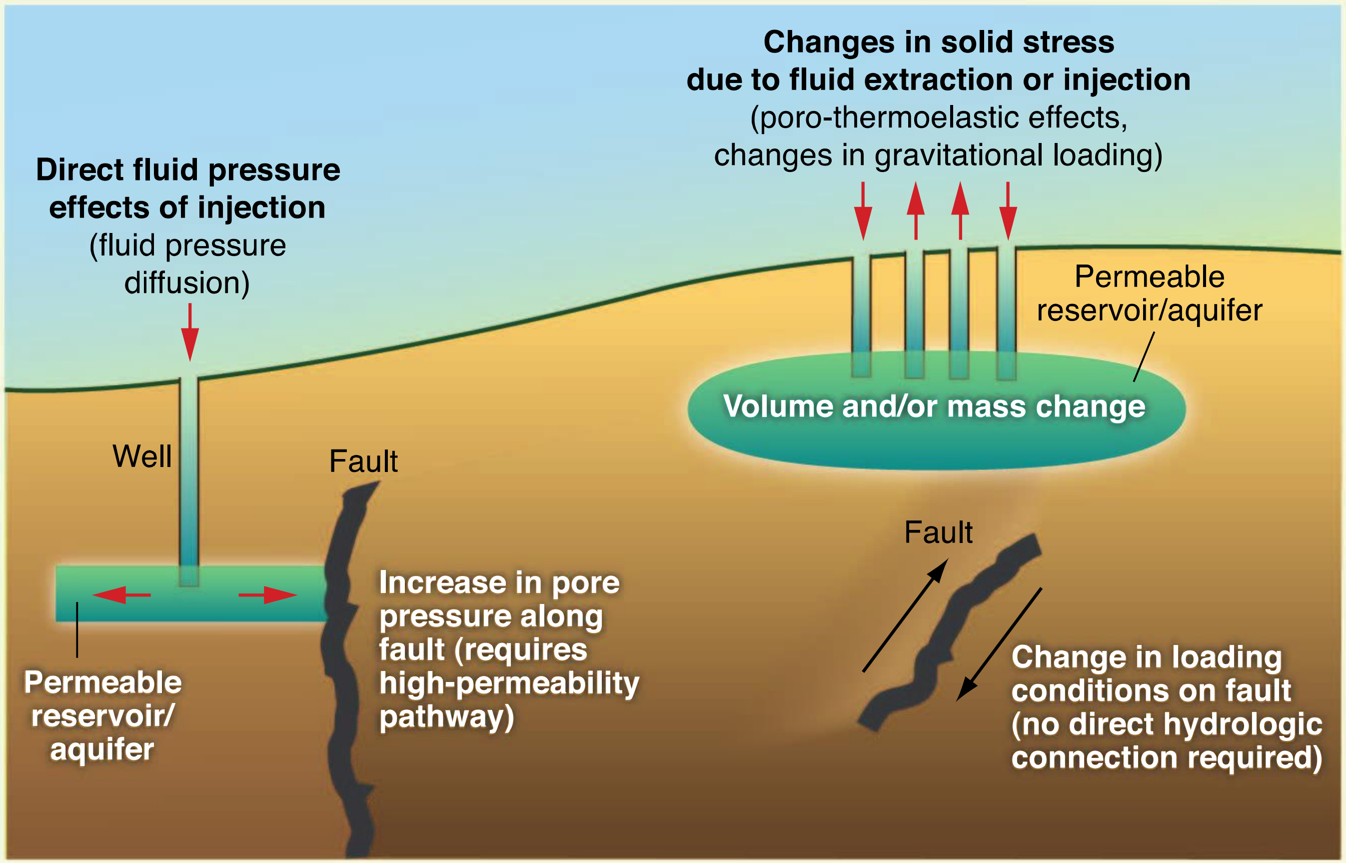


Fig. 3. Schematic diagram of mechanisms for inducing earthquakes. Earthquakes may be induced by increasing the pore pressure acting on a fault (**left**) or by changing the shear and normal stress acting on the fault (**right**). See (*4*).

Ellsworth, 2013

INJECTION-INDUCED SEISMICITY: A WELL ESTABLISHED PHENOMENA

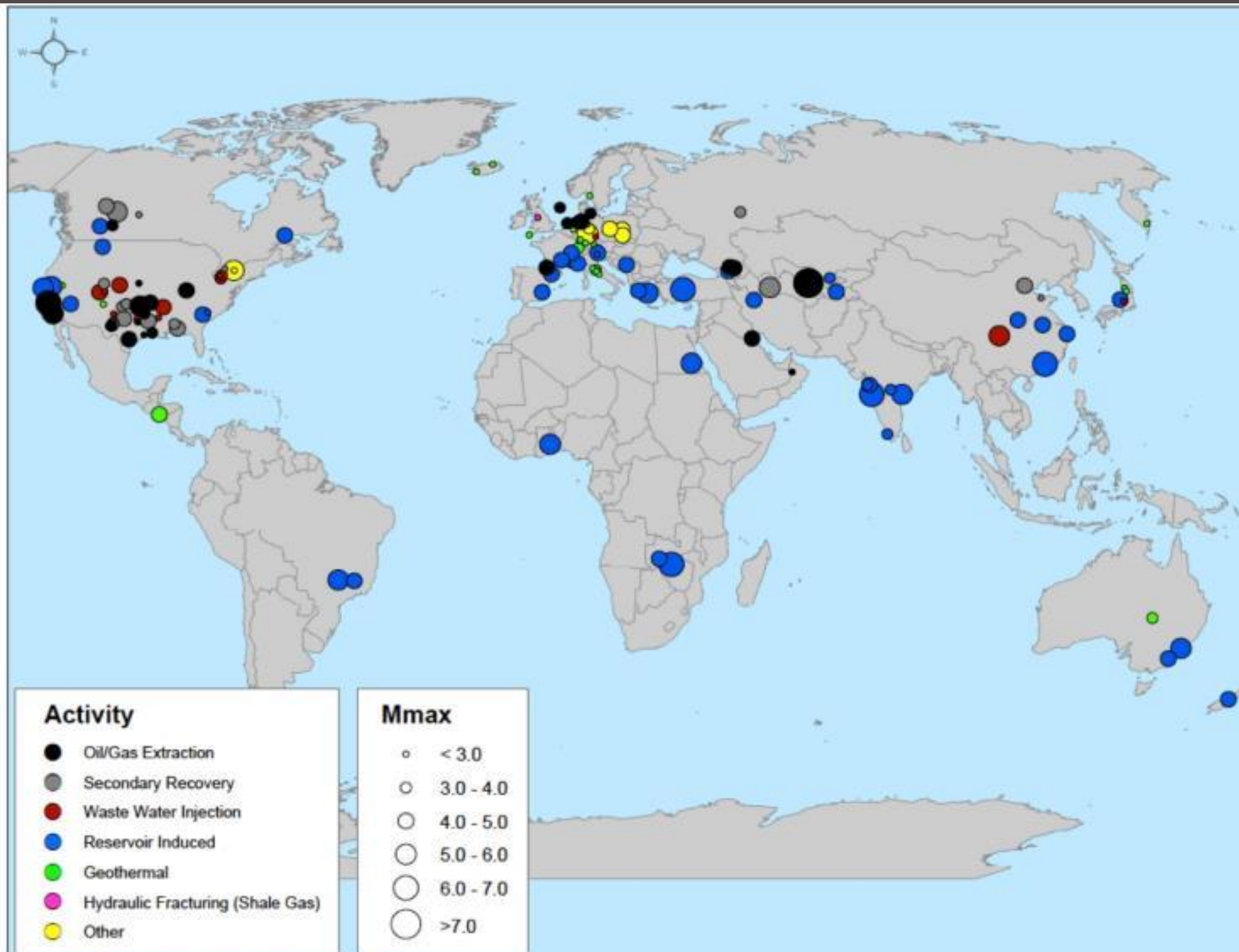
- Multiple experiment (e.g. RMA, 1968; Rangley,1976) confirmed the hypothesis that earthquakes can be triggered by an increase of fluid pressure, a result well-accounted for by the Hubbert-Rubey principle of effective stress.

(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

CONTROL EXPERIMENT #1: ROCKY MOUNTAIN ARSENAL

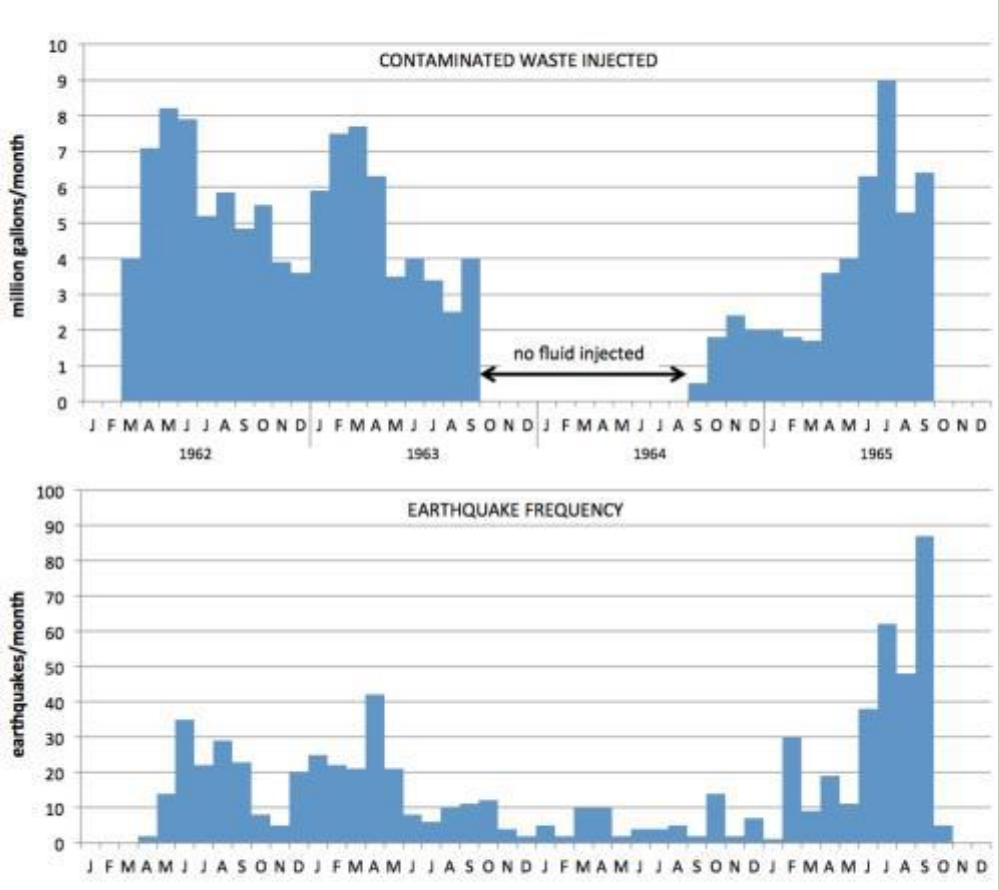
<u>Example: Rocky Mountain Arsenal</u>

(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.

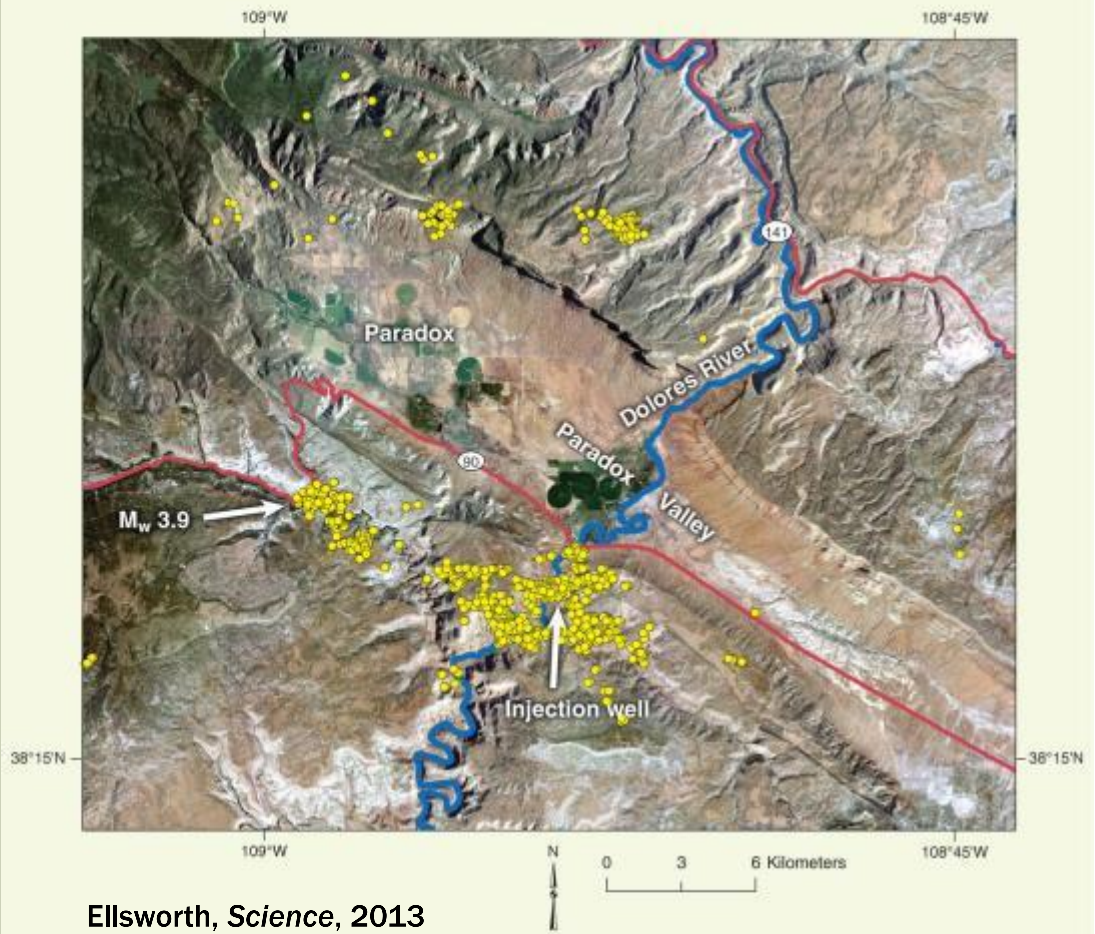


(from Hesiah & Bredehoeft, 1981; NRC Report, 2012)

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.
- 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)*

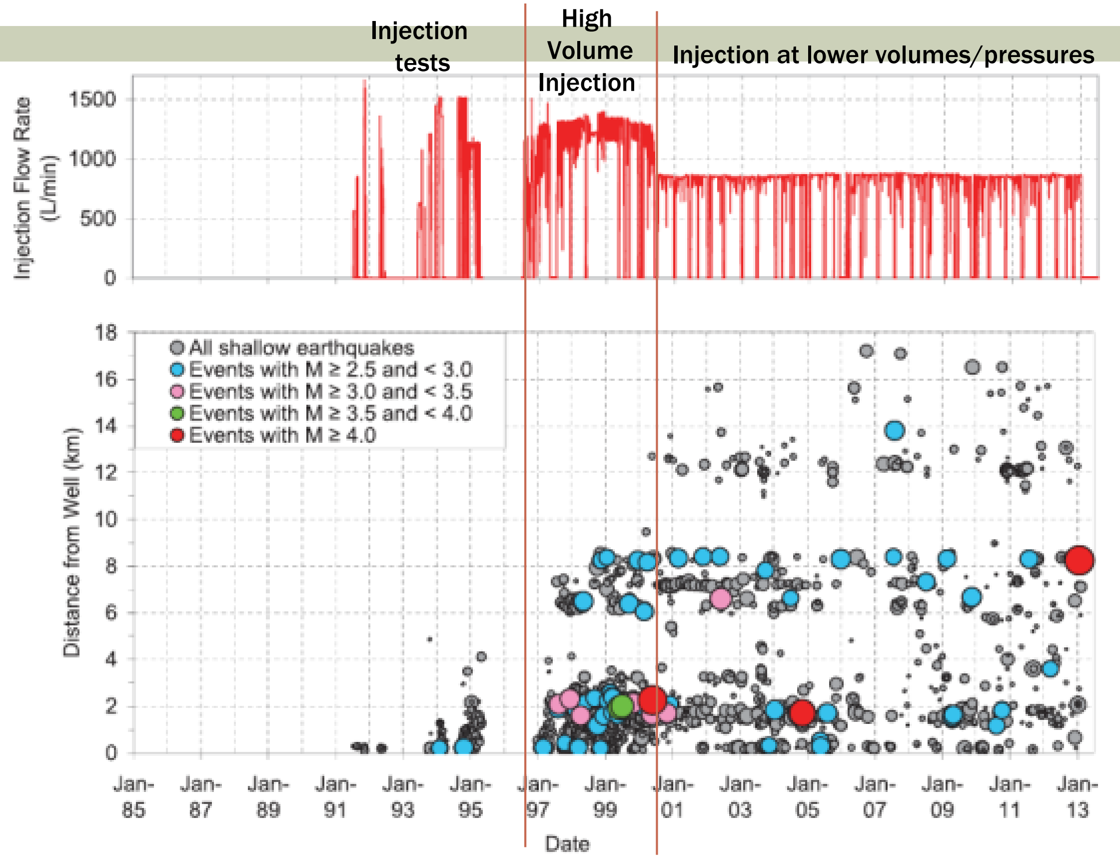


Ellsworth, *Science*, 2013

CONTROLLED EXPERIMENT #2: PARADOX VALLEY

PARADOX VALLEY, COLORADO

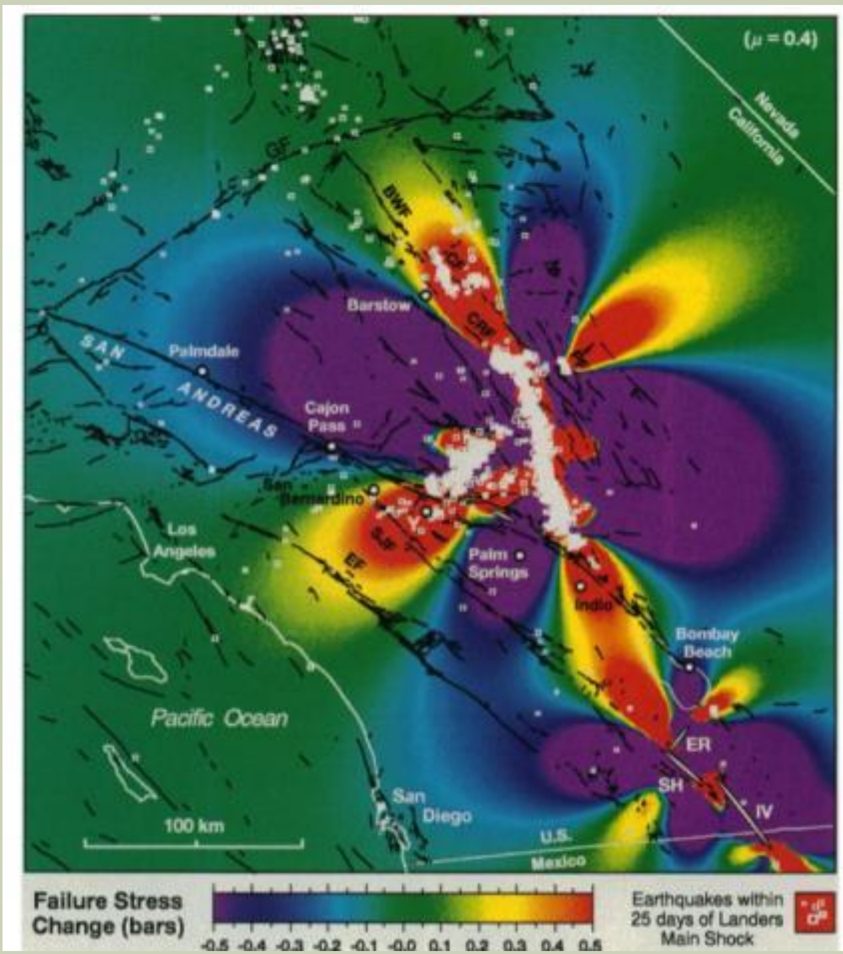
- BR adjusts injection strategies, to manage Bottom hole pressure.
- <u>EQ swarm monitoring combined with down hole pressure monitoring</u> provides invaluable tool for mitigating hazard and managing risk.
- Reducing injection volumes/pressures reduced bottom-hole pressures, which reduced earthquakes (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)

IT'S BEEN RECOGNIZED FOR ~40 YEARS THAT SMALL STRESS CHANGES TRIGGER EARTHQUAKES



(Stein et al., 1992)

–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).

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

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).

TEXAS HAS A ~100 YEAR HISTORY OF INDUCED SEISMICITY

580 *WALLACE E. PRATT AND DOUGLAS W. JOHNSON*

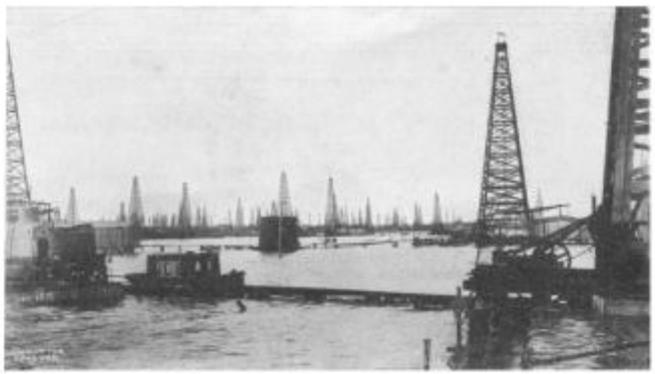


FIG. 4.—Looking east-southeast across Tabbs Bay, from a point east of Goose Creek. Gaillard Peninsula is to the right of this view.

Pratt and Johnson, J. Geology, 1924

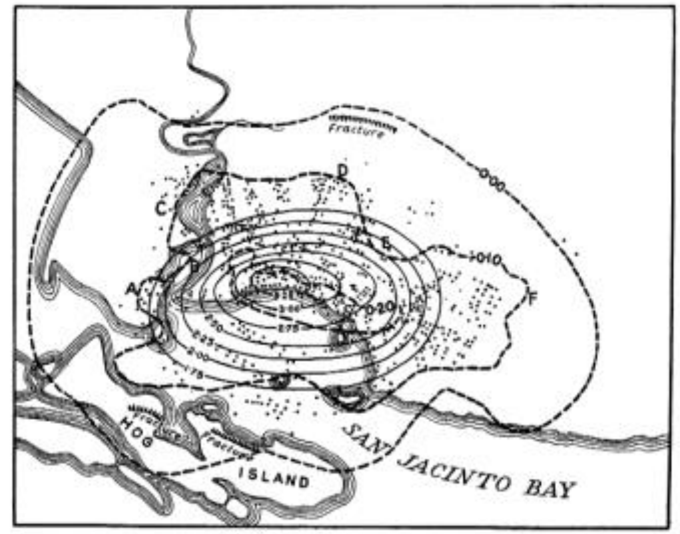
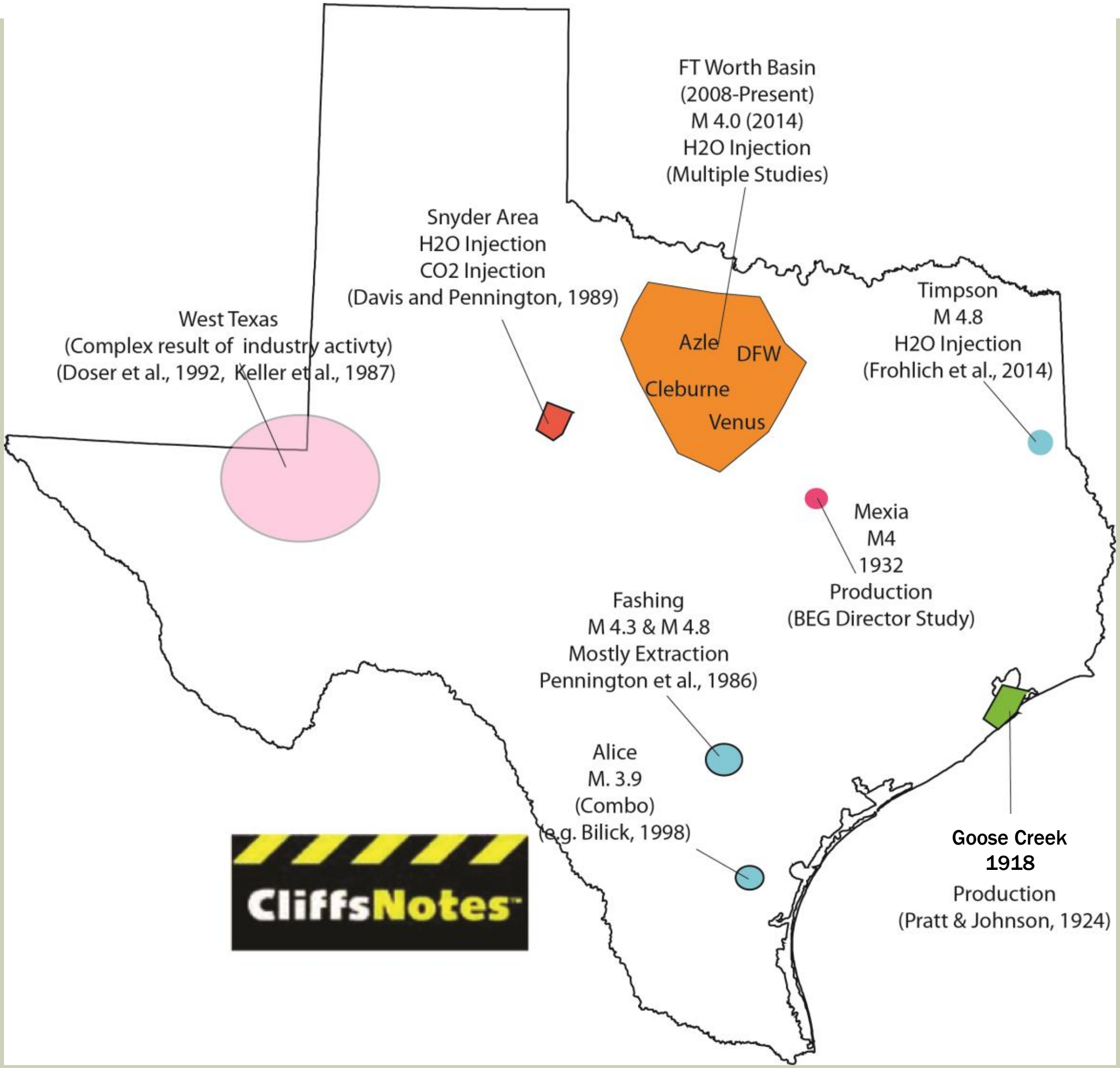


FIG. 7.—Contours of equal subsidence (in feet) for eight-year period shown in light solid lines; for one-year periods, in heavy broken lines. Dots represent wells.

“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



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

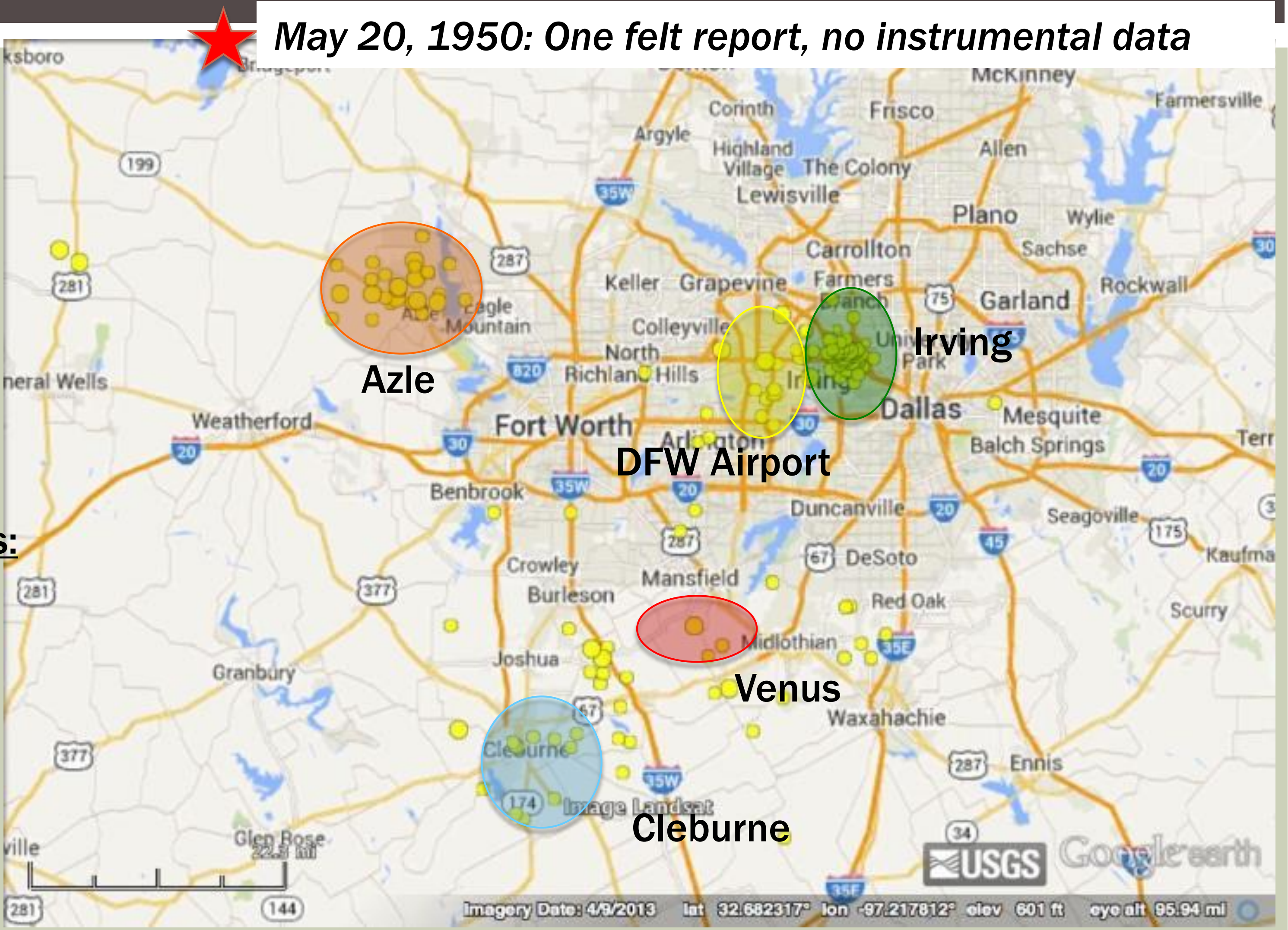
A Detailed Look at Earthquakes in the Fort Worth Basin

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

Prior to 2008:
1 possible event

Post 2008:
31 events ≥ M3
>160 reports

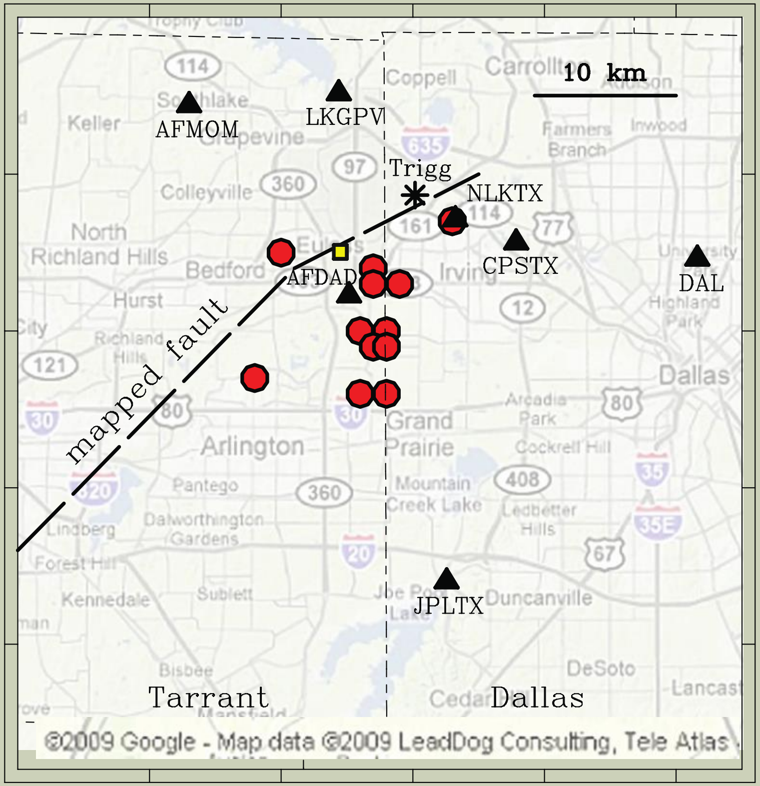
5 Temp. Networks:
DFW Airport (2008-)
Cleburne (2009-)
Venus (2011-)
Azle (2013-)
Irving (2014-)



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

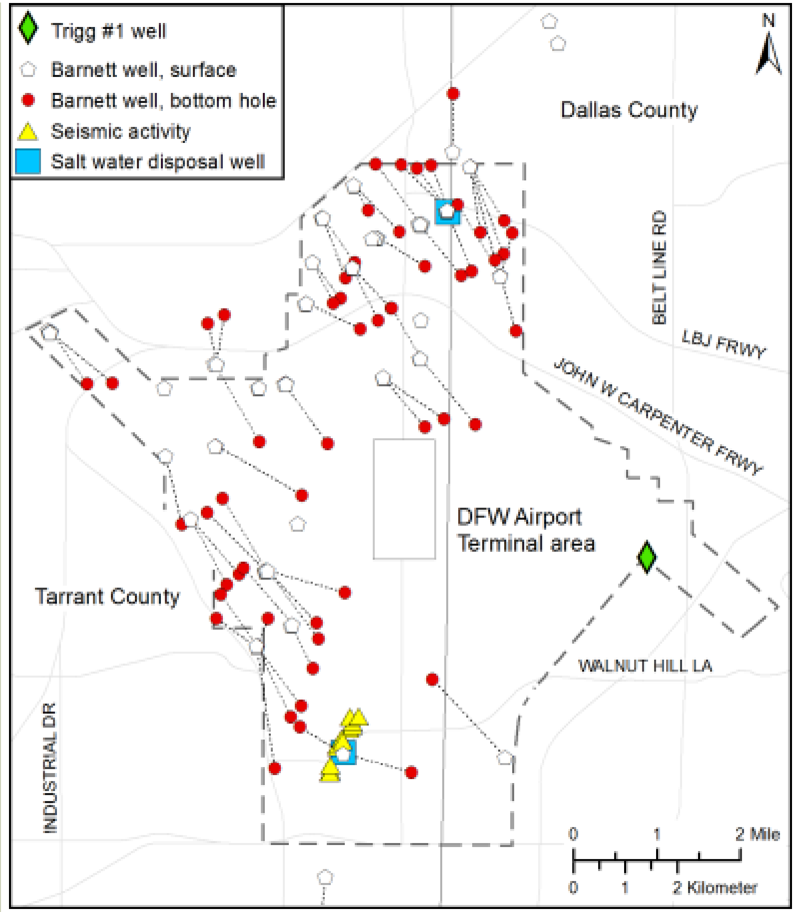


- Black triangles: SMU temporary stations
- Red circles: locations of quakes as reported by USGS
- Trigg well nearby where P and S velocities measured
- Yellow square: 1-km square area where Nov-Dec quakes were located

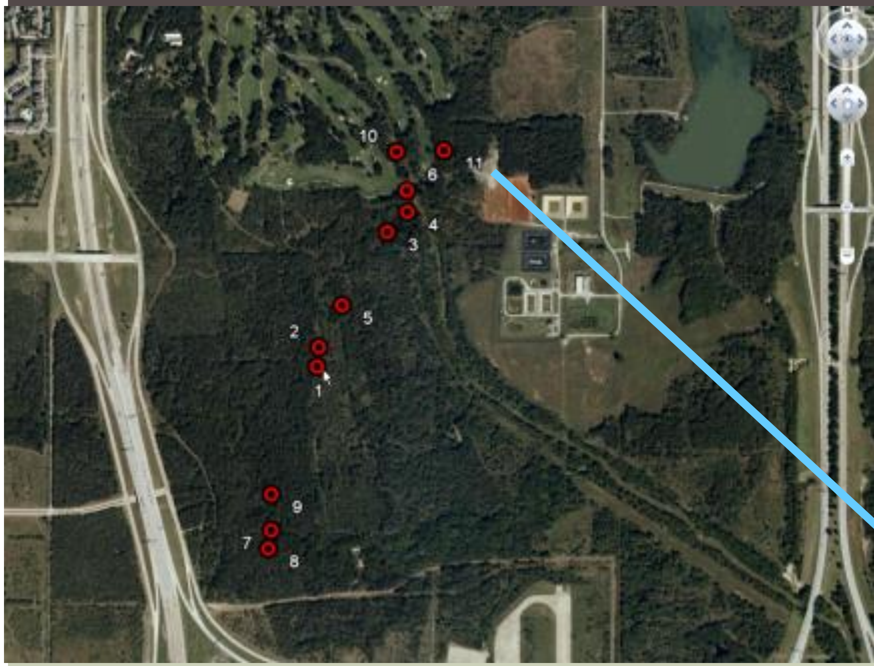
3. ARE EPICENTERS WITHIN 5 KM OF WELLS?

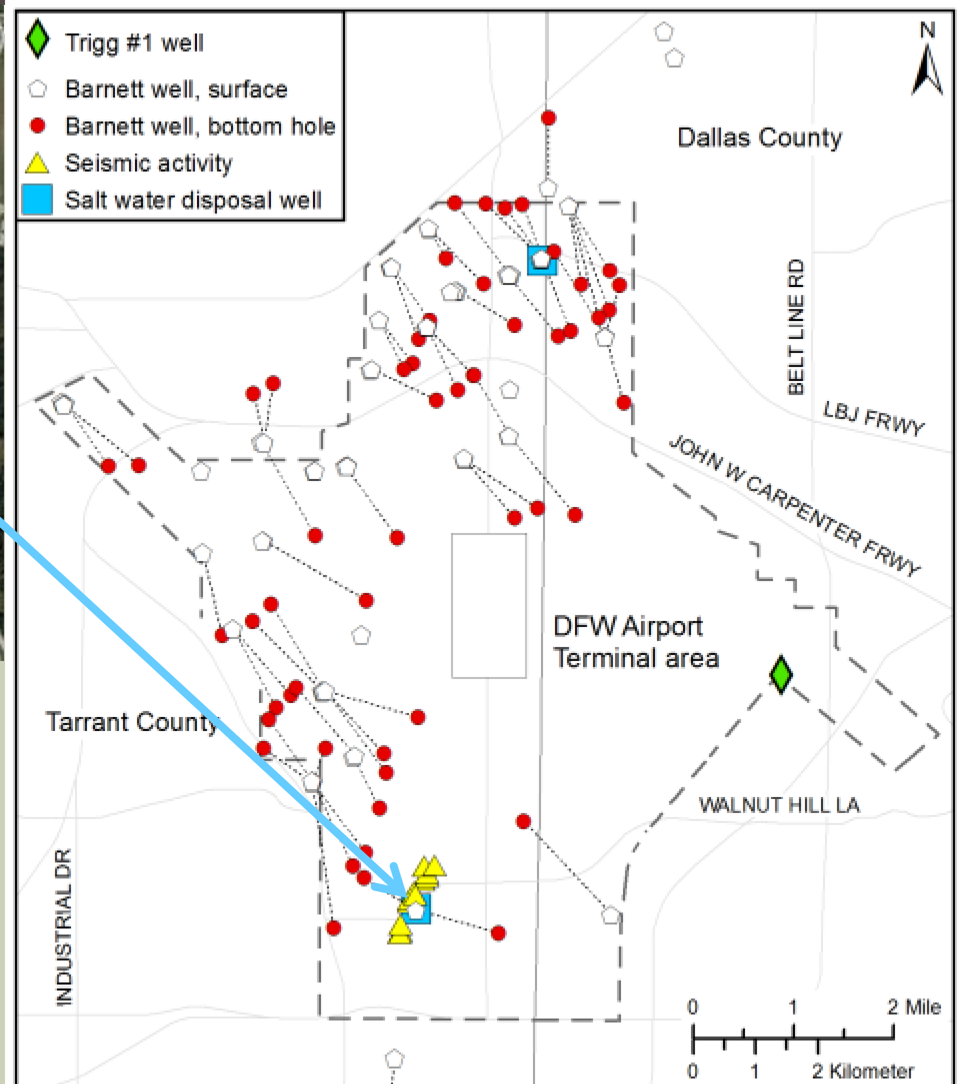
DFW Earthquakes occurred:

- **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

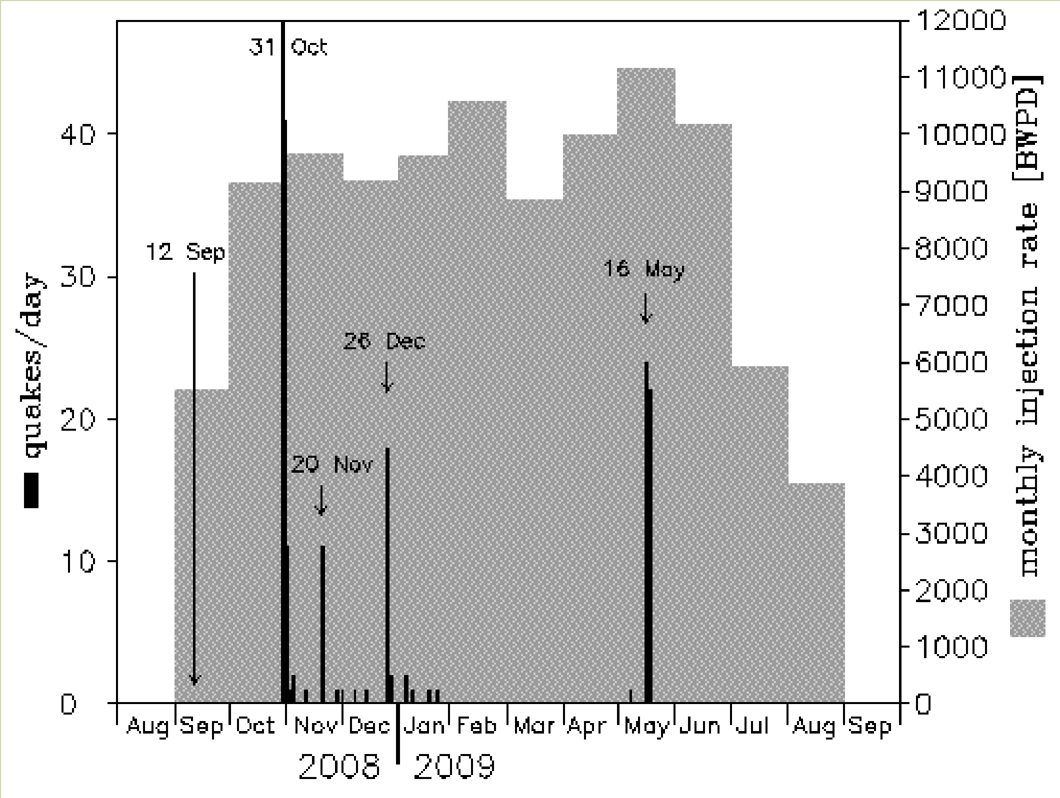




Earthquakes occur:

- 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



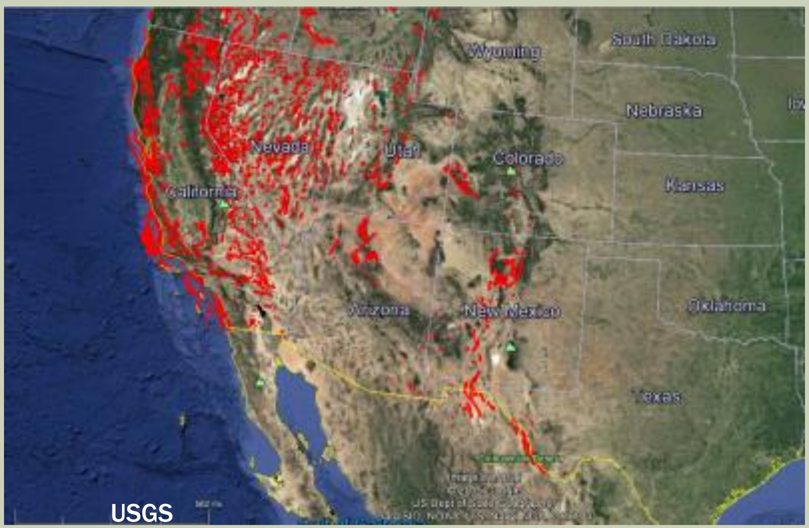
- Earthquakes located within hundreds of meters of disposal well
- Earthquakes began shortly after the injector was initiated
- A mapped fault crosses the area
- No subsurface data on geology or material properties was made available
- Earthquakes continued into 2010 and moved away from injector

Frohlich, Potter, Hayward and Stump, 2010

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

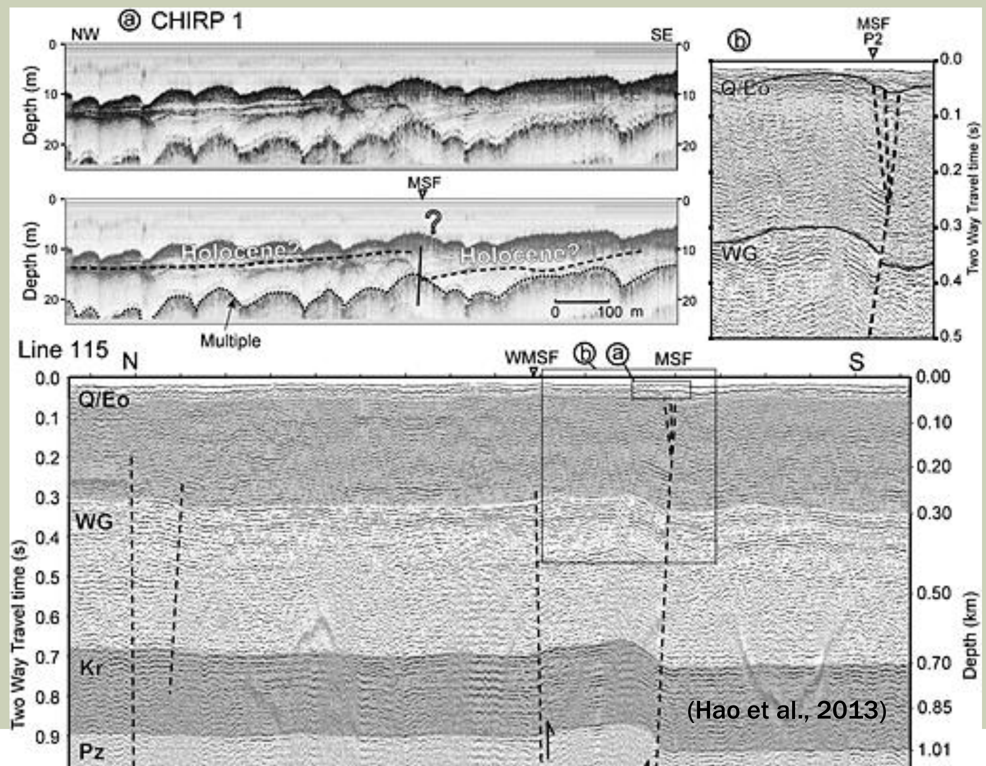
Useful data

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



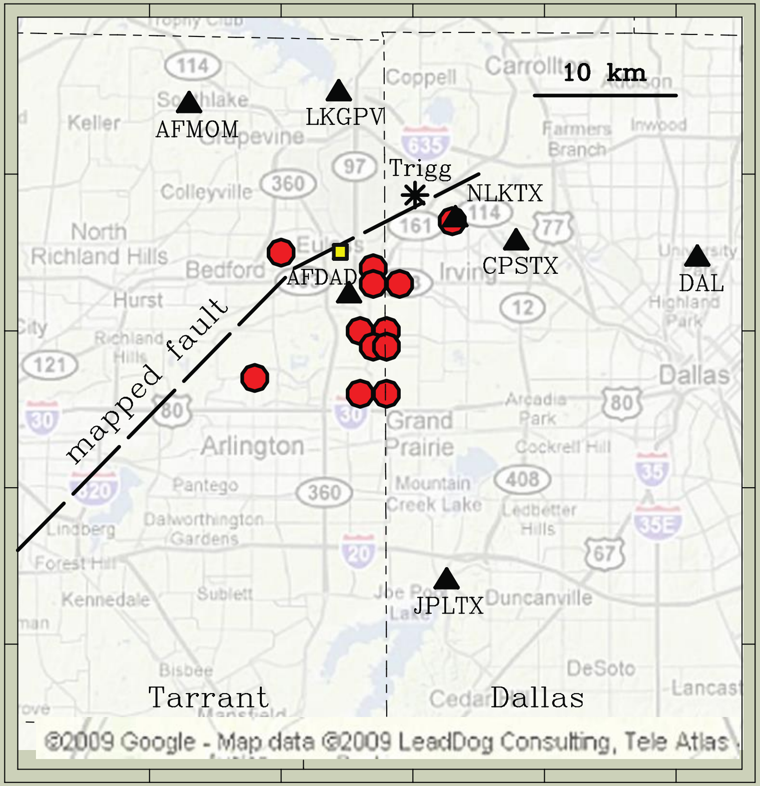
Quaternary Fault Maps

Quaternary deformation along the Meeman-Shelby Fault near Memphis, Tennessee, imaged by high-resolution marine and land seismic reflection profiles



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



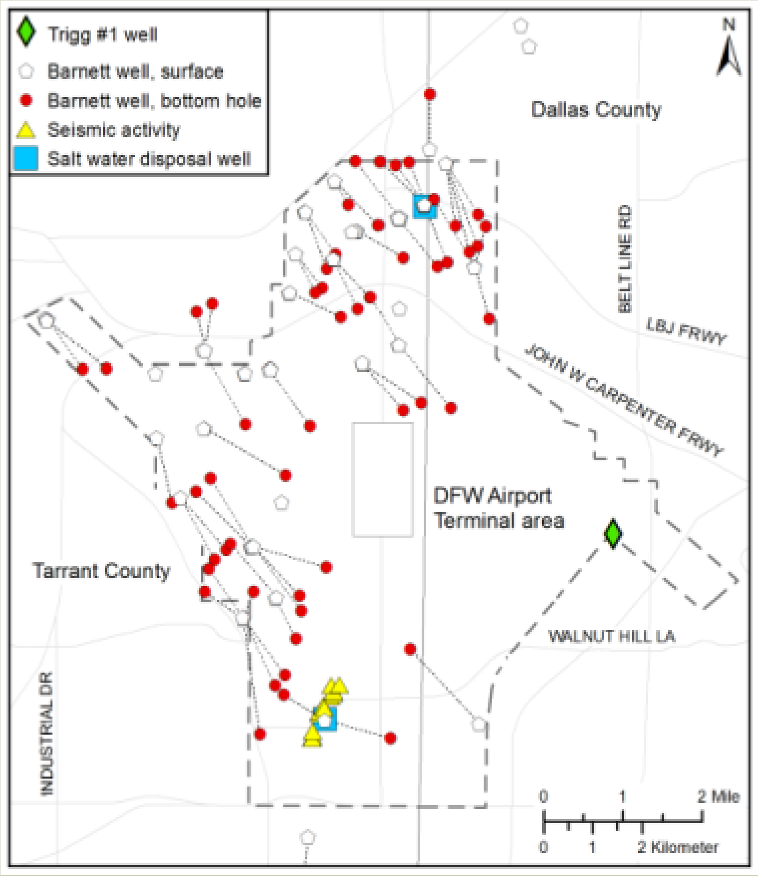
Local seismic networks are key

- 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.

CONCLUSION WITH DFW EVENTS USING NRC APPROACH→ QUITE PLAUSIBLE INJECTION CAUSED EQS



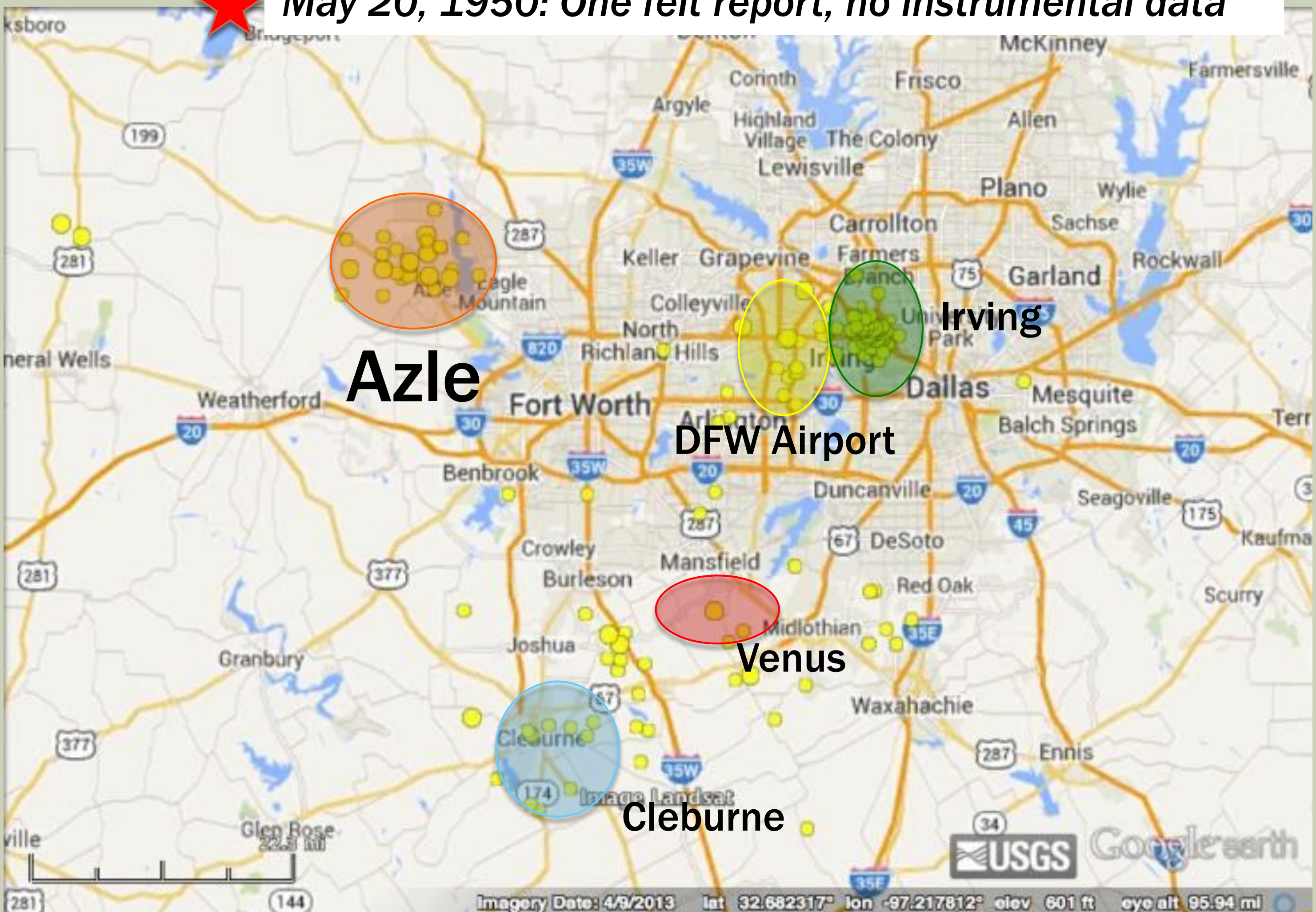
- Data needed to further constrain:

(1) 2D seismic lines indicating fault offset versus depth.

(2) Pore pressure models

AZLE Earthquake Sequence 2013-2014

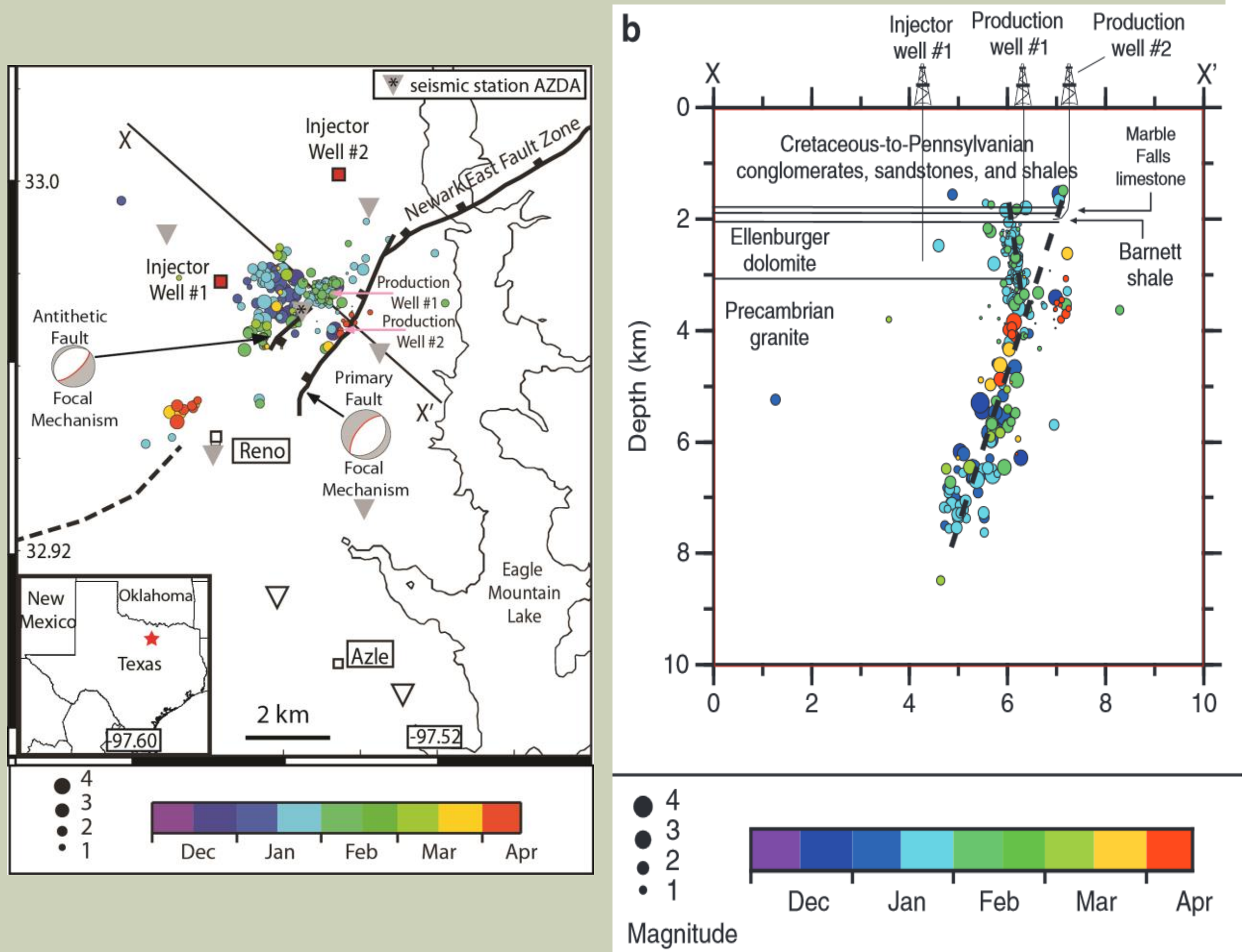
May 20, 1950: One felt report, no instrumental data



Industry Cooperation in Study

AZLE EVENT LOCATIONS THROUGH 26 AUG, 2014

- The last widely felt event was Jan 28th, 2014
- Last EQ recorded in May 2015
- Complex faulting
- The EQ sequences slowed as injection volumes reduced



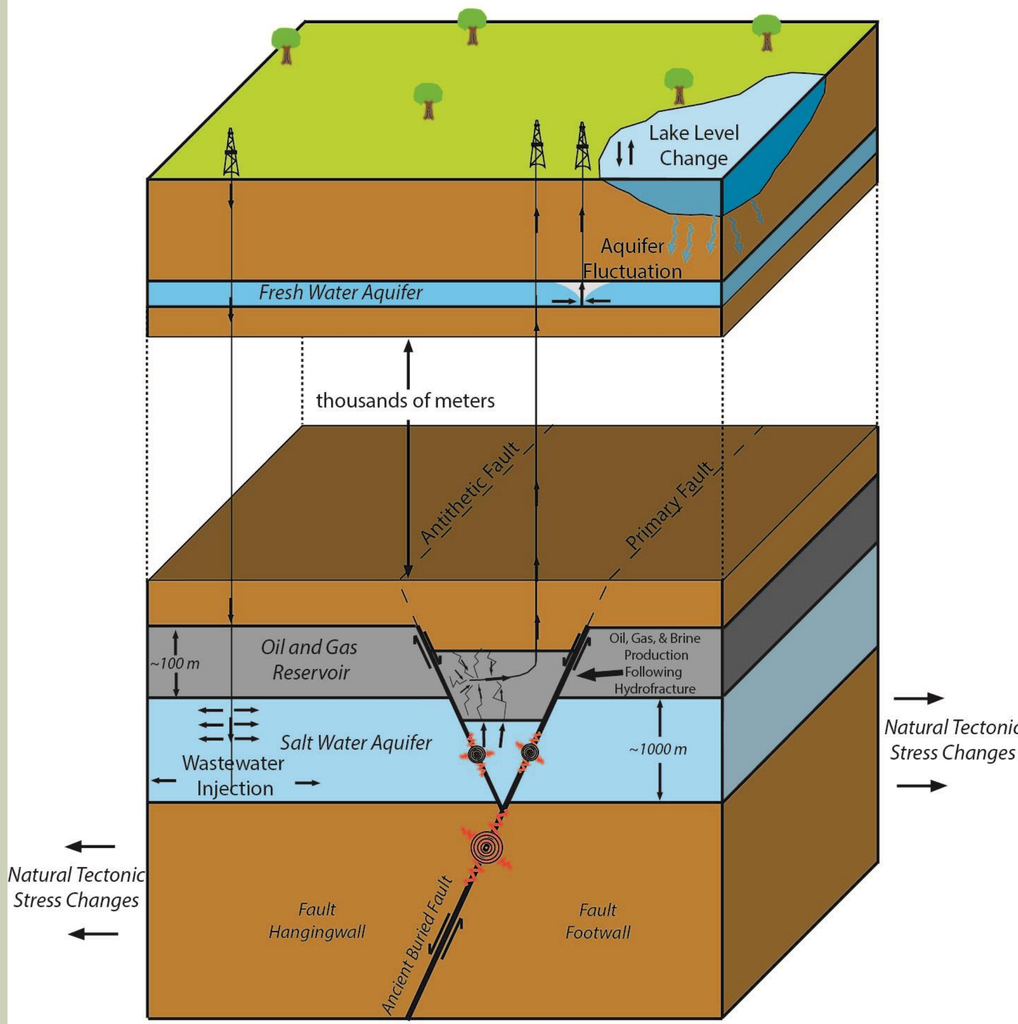
Hornbach, DeShon, *et al., 2015, Nature Communications*

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

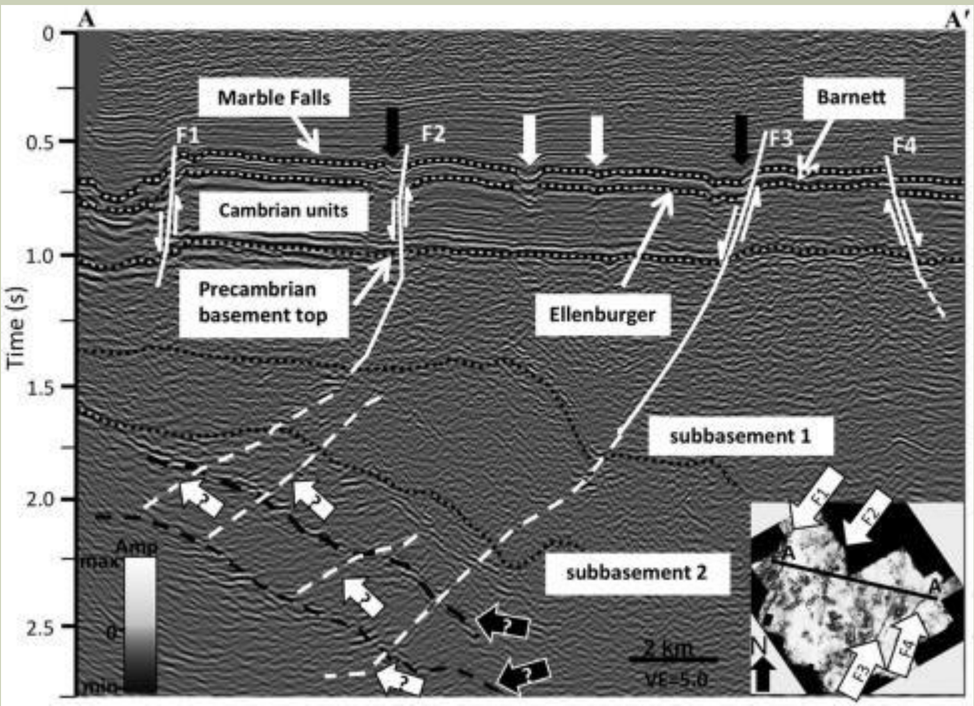
1. During the past 150 years of settlement, there had been no reported felt earthquakes in the Azle/Reno area prior to November, 2013.

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

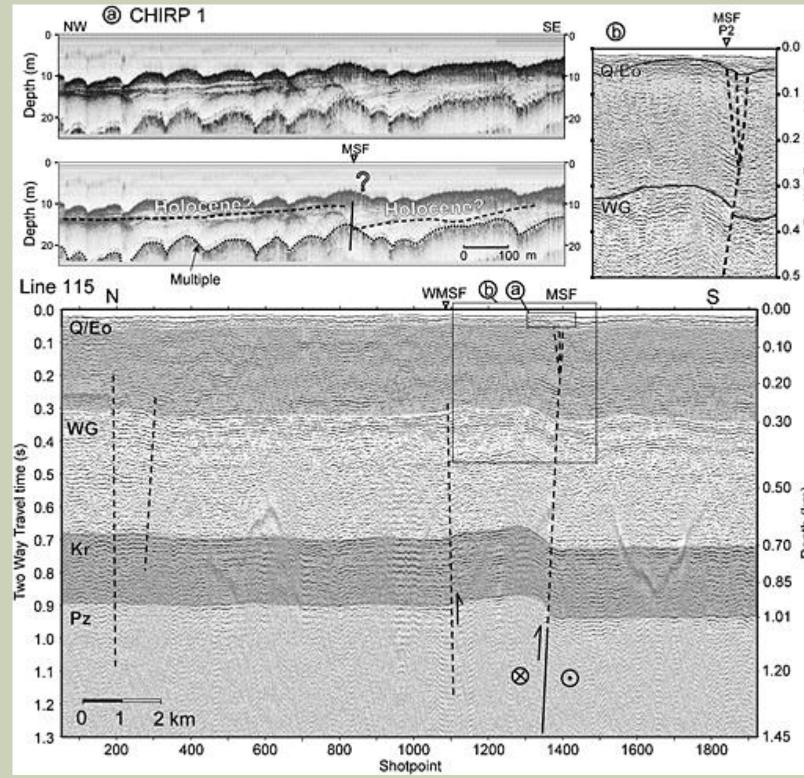
3. Publicly available regional seismic data show no significant fault offsets in sediment deposited more than ~300 million years ago in the Fort Worth Basin. Additionally, Gutenburg-Richter Law Modeling suggest we should observe significant (~35 m) offset at surface if these faults have a M3 event only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

FT. WORTH BASIN VS. NEW MADRID



Khatiwada et al., 2013



Quaternary deformation along the Meeman-Shelby Fault near Memphis, Tennessee, imaged by high-resolution marine and land seismic reflection profiles

Published interpretations indicate no faulting beyond Marble Falls

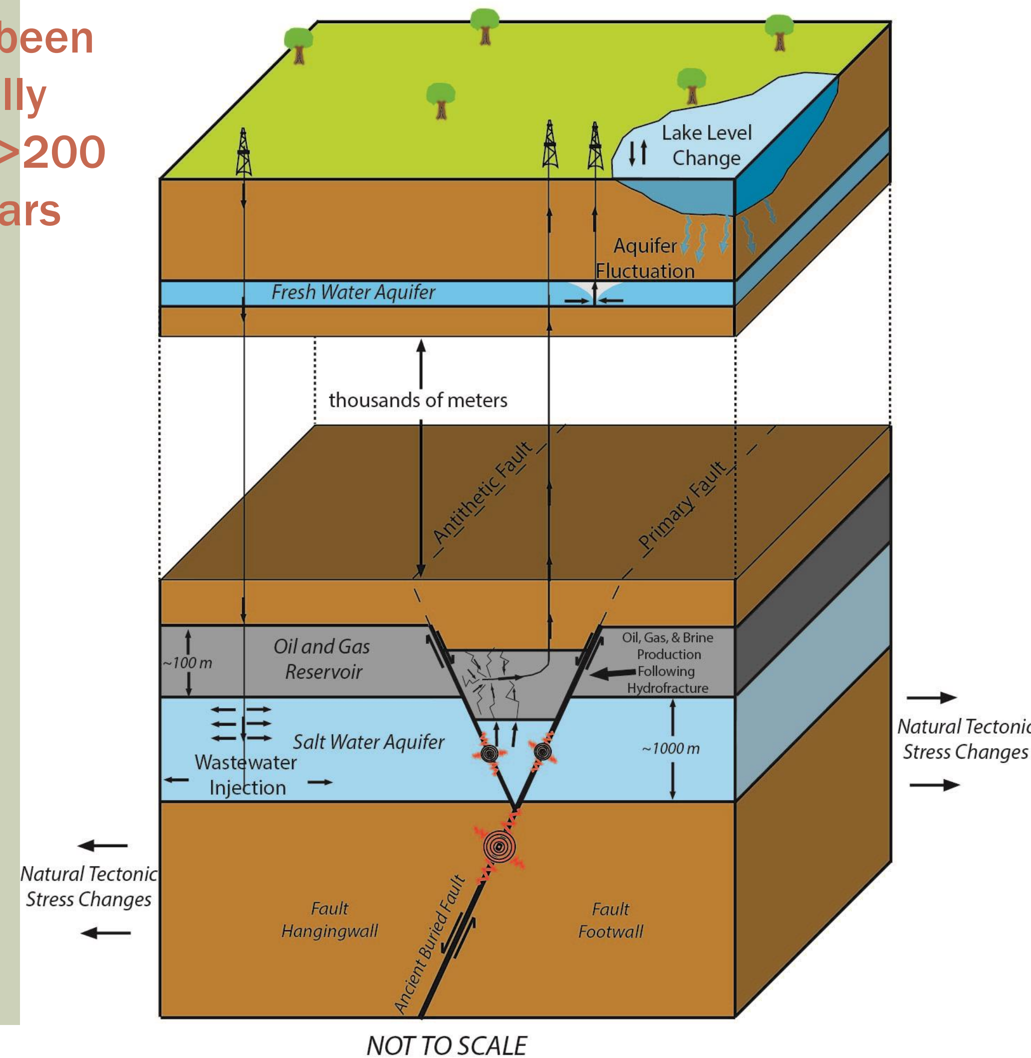
CAUSAL FACTORS

- 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

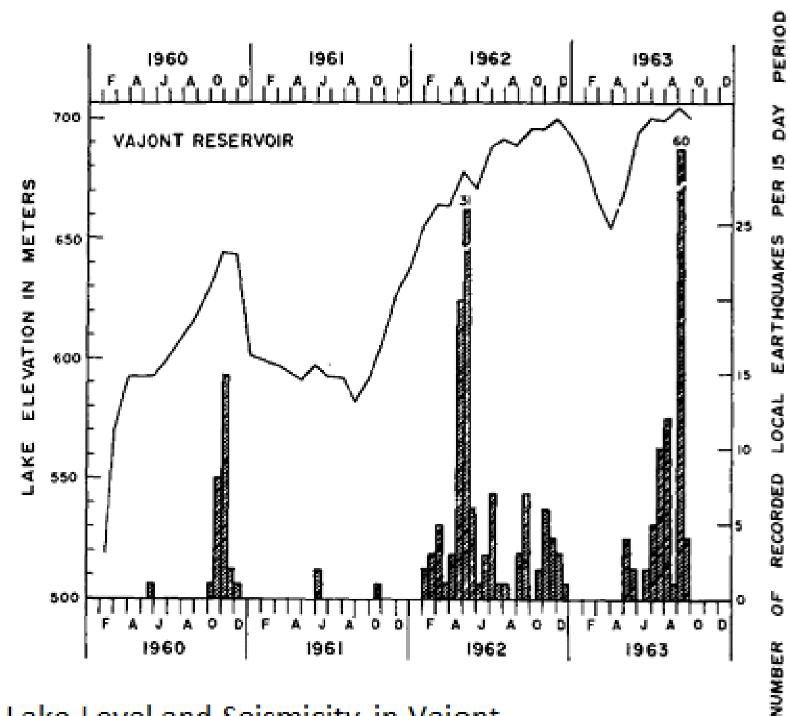
Natural and Human-Made Stress Changes that Cause Earthquakes



Hornbach et al., 2015, Nature Comm.

ASSESSING WATER TABLE CHANGES

What we typically observe with reservoir-induced seismicity:

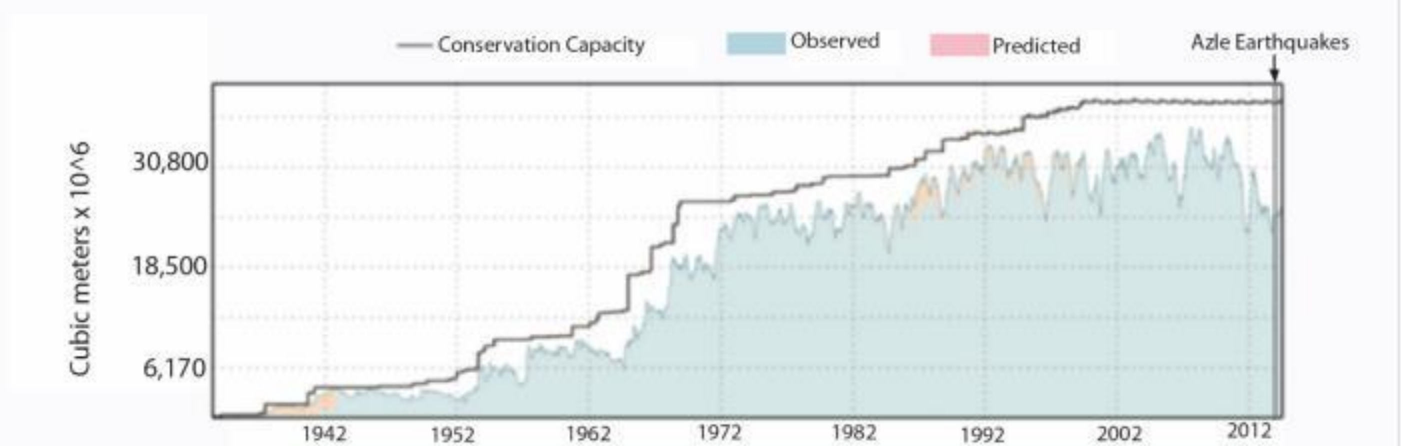


Variations in Lake Level and Seismicity in Vajont Reservoir,Greece (See Galanopoulus, 1967; Gupta et al., 1972)

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

ASSESSING WATER TABLE CHANGES

What we observe at Eagle Mountain Lake:



Water volume stored in Eagle Mountain Lake since dam construction in 1932

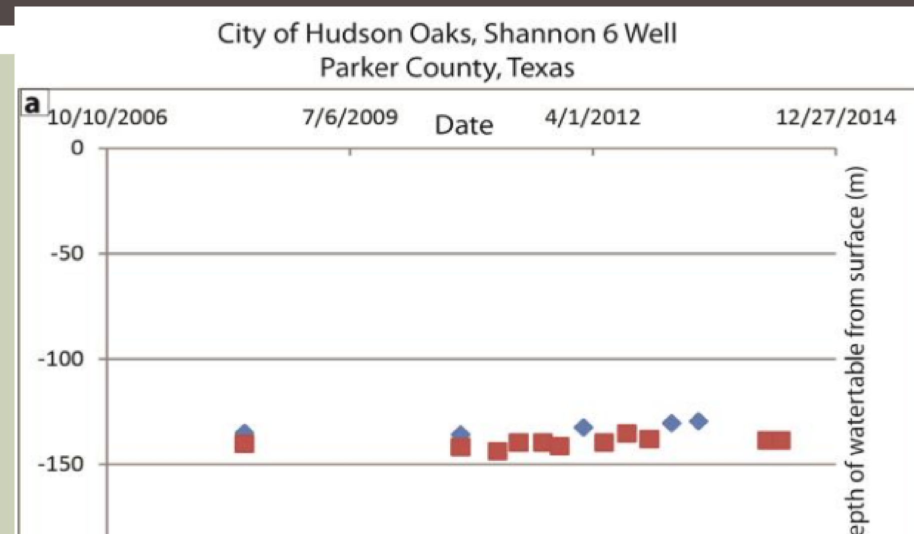
1.) The greatest stress/lake level change occurred ~50 years ago—no felt EQs occurred.
2.) Lake Levels were not at record high or record low levels during Azle Earthquakes.

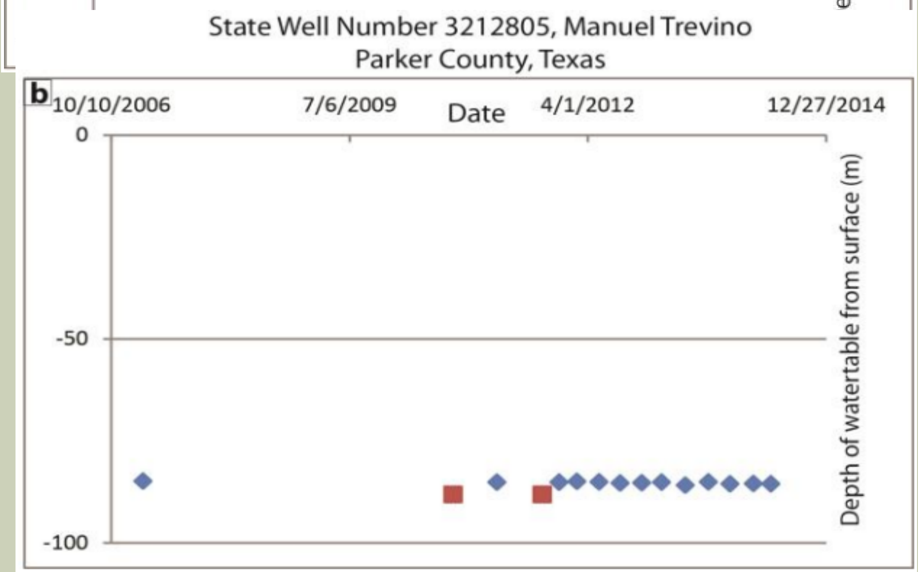
GROUND WATER FLUCTUATIONS ARE ALSO MINIMAL

<u>**Trinity Aquifer measurements near Azle:**</u>
(provided by Upper Trinity Groundwater Conservation District)

Blue Diamonds: static measurements

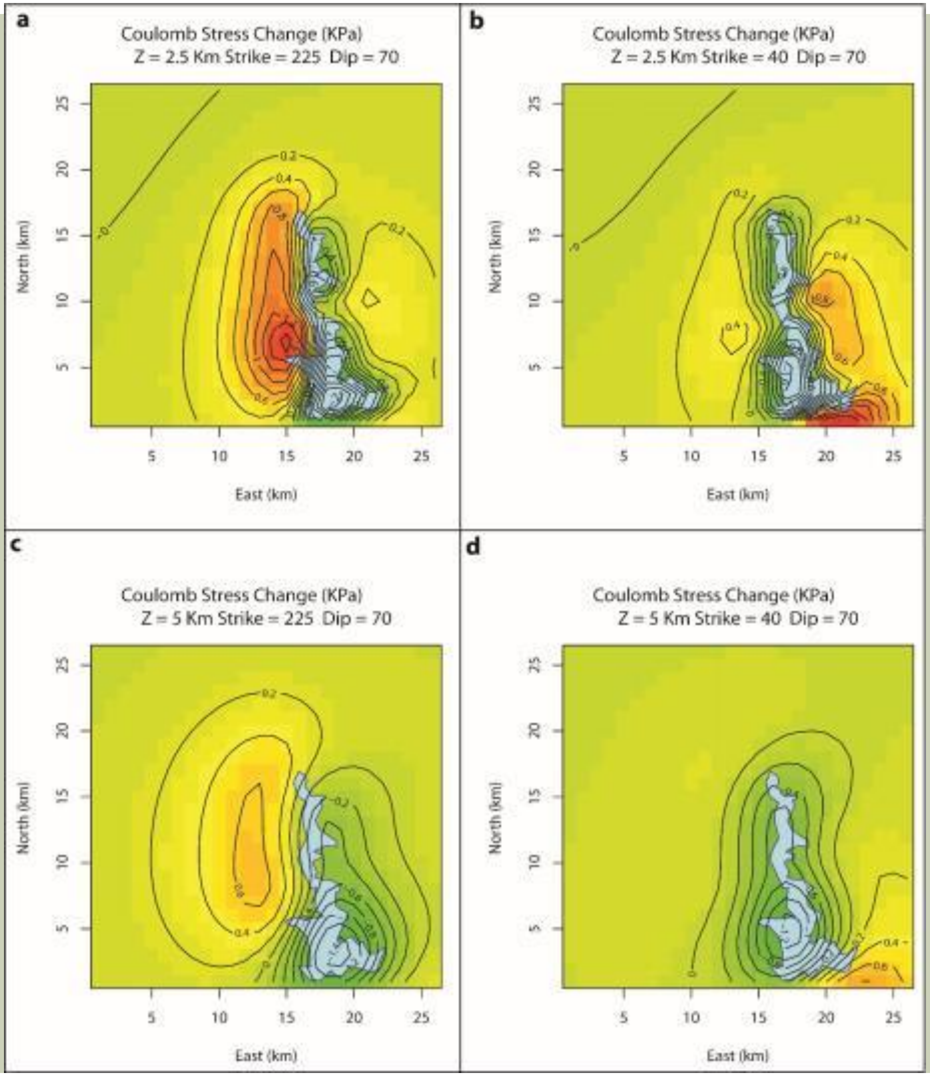
Red squares: measurements while pumping





ESTIMATED STRESS CHANGES CAUSED BY RECENT LAKE-LEVEL AND GROUND WATER CHANGE IN THE AZLE/RENO ARE TINY (COMPARABLE TO TIDAL STRESSES)

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

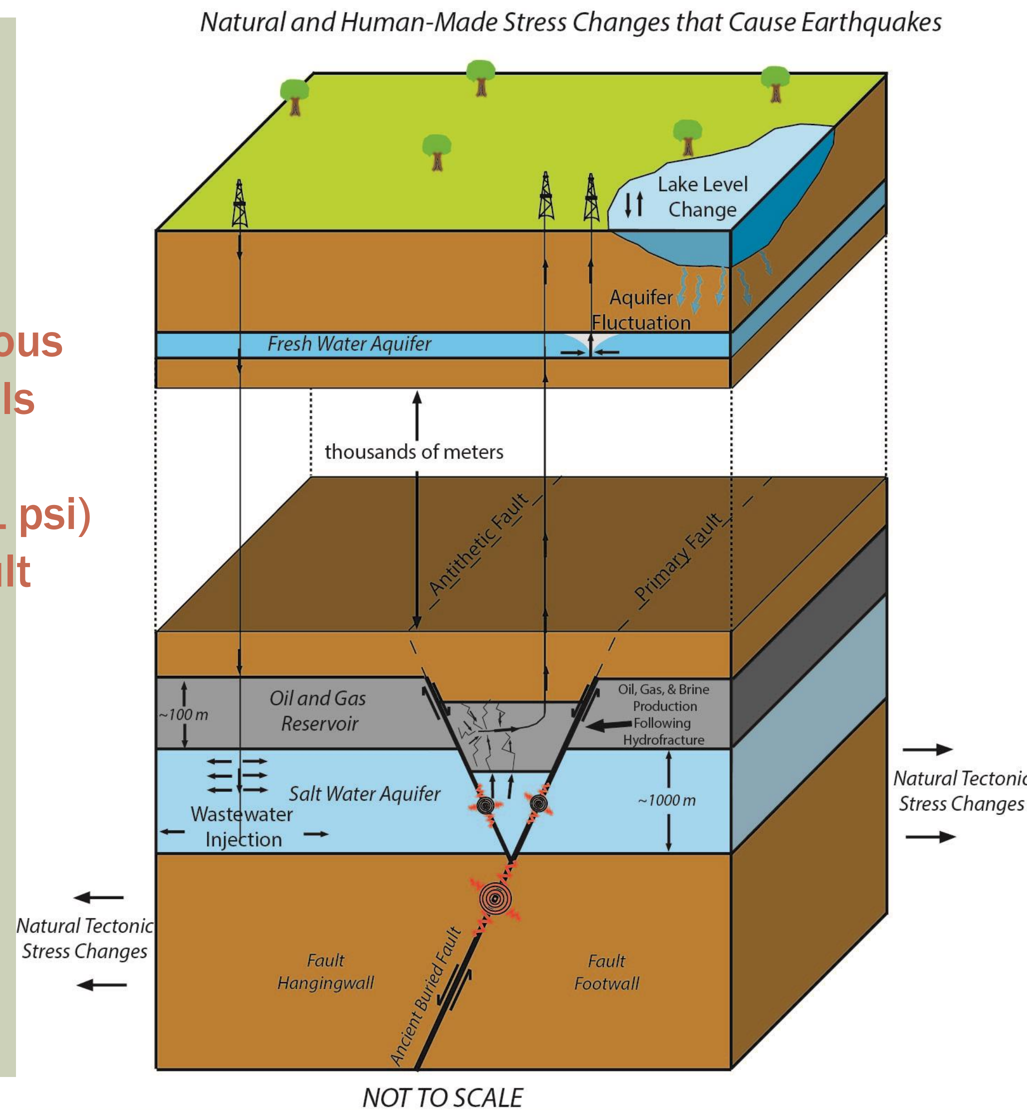


CAUSAL FACTORS

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

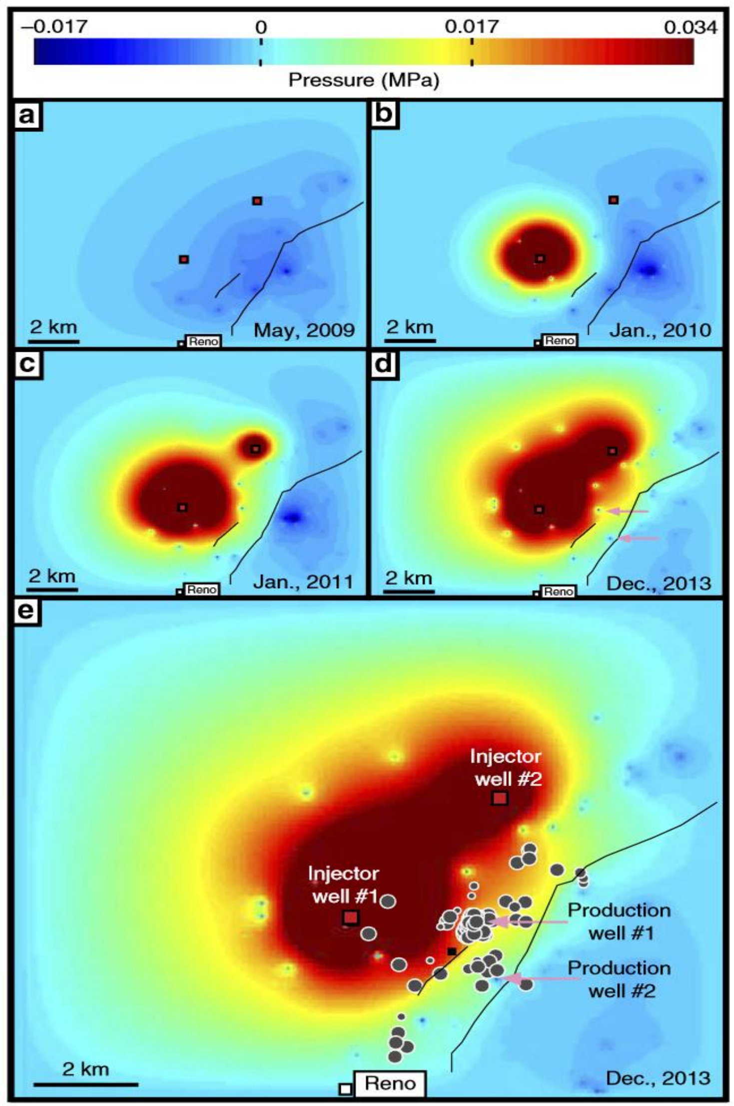
No anomalous water levels

<1 kPa (<0.1 psi) on the fault



Hornbach et al., 2015, Nature Comm.

QUANTIFYING SUBSURFACE INJECTION/PRODUCTION PRESSURES



<u>Basic Model Parameters (for ~75 different models)</u>

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)

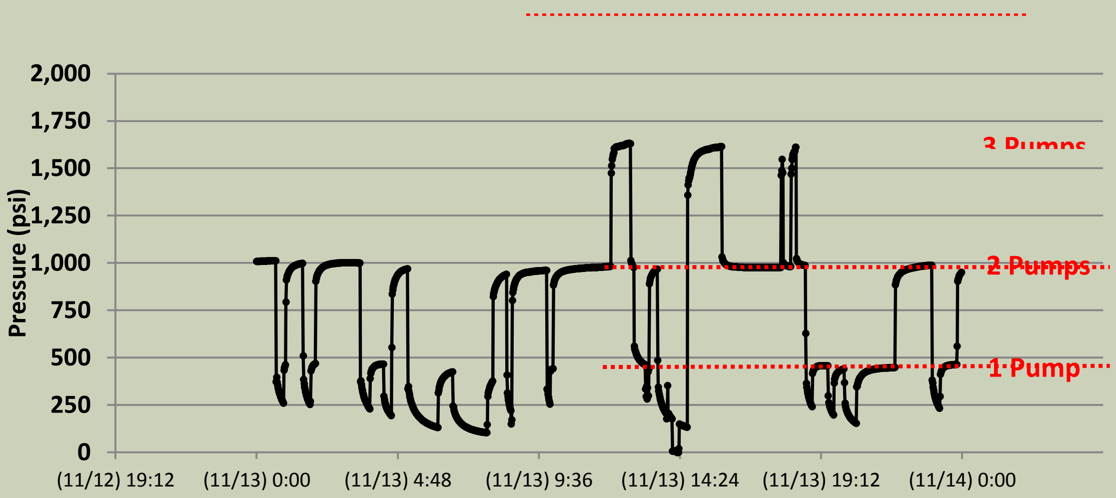
Ellenburger Permeability: 3 mD to 100 mD.

Shale/Basement Permeability = .001 mD

Fault Permeability = 0.1 mD to 100 mD

PERMEABILITY: DERIVED DIRECTLY FROM INDUSTRY-PROVIDED PRESSURE/ FALL-OFF TESTS

Number of Pumps Running	Approximate Pressure (psi)	Approximate Rate (bbl/d)
1	~450	8,000
2	~1,000	16,000
3	~1,600	22,000



Methods include Cooper-Jacob method (hydrogeology), and Horner Method (Petroleum Engineering)

–Both methods resulted in permeability values with endmember ranges from 3-100 mD

BOTTOM HOLE PRESSURE ESTIMATES

Derived by accounting for frictional energy loss using Darcy-Weisbach equation using TRC available data:

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

Pf= pressure loss due to friction
fd = 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):

$$P_b = P_o - \frac{\mu Q}{2\pi k H} \ln\left(\frac{R_b}{R_0}\right)$$

Pb = Pressure above hydrostatic
Po = 0, at a distance Ro from well
Mu = fluid viscosity
k = permeability
H = reservoir thickness
Q = average fluid flux
Rb = Casing radius
Ro = radial distance where P is zero.

Darcy's Law Approach usually produced lower values.

QUANTIFYING SUBSURFACE INJECTION PRESSURES

Models Use Conservative Numbers and a Broad Range of Model Parameters

Well #1 mean excess bottom hole pressure in (psi)	Well #2 mean excess bottom hole pressure in (psi)	mean effective permeability (m^2)	Thickness of high perm. zone (m)	Producers included?	Boundary Conditions	Specific Storage (m^{-1})	Excess pressure on fault at AZDA, Jan. 1st, 2014 (psi)
77	25	3x10^-14	1000	yes	closed	5 x 10^-6	1.2
77	25	3x10^-14	1000	yes	closed	13x10^-6	2.9
77	25	3x10^-14	1000	no	closed	7.3x10^-6	1.6
638	431	3x10^-14	300	no	closed	7.3x10^-6	20.3
351	236	3x10^-14	300	no	closed	7.3x10^-6	11.6
351	236	3x10^-14	300	yes	open	7.3x10^-6	3.9
351	236	3x10^-14	1000	yes	closed	13x10^-6	4.3
351	236	3x10^-14	1000	no	closed	5 x 10^-6	7.3
351	236	3x10^-14	1000	no	open	5x10^-6	1.5
351	236	1x10^-14	1000	yes	closed	1x10^6	15.9
351	236	1x10^-14	1000	yes	closed	13x10^-6	14.5
351	236	1x10^-14	1000	yes	closed	7.3x10^-6	16.0
84	41	5x10^-14	1000	yes	open	7.3x10^-6	2.9
351	236	5x10^-14	1000	yes	closed	7.3 x 10^-6	14.5
351	236	10x10^-14	1000	yes	open	7.3 x 10^-6	2.5

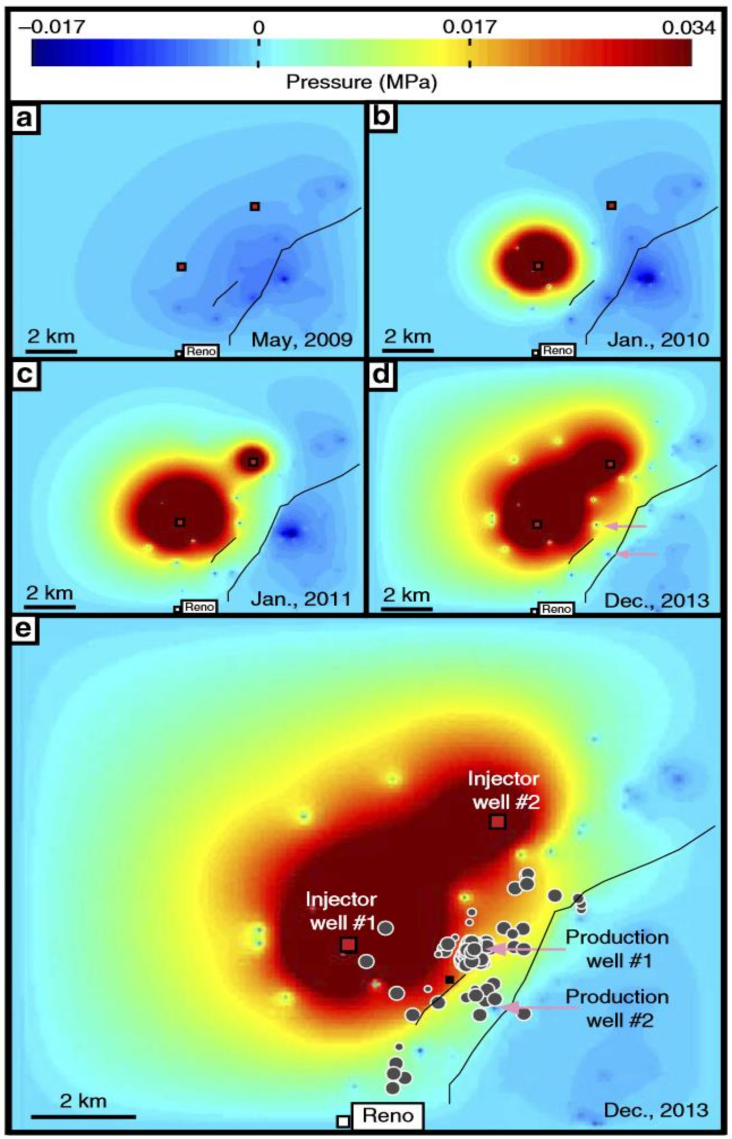
--Pressures on the fault are consistently 10X to 100X greater than those predicted by water level variations.

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

-- Narrower flow zones generate highest pressures.

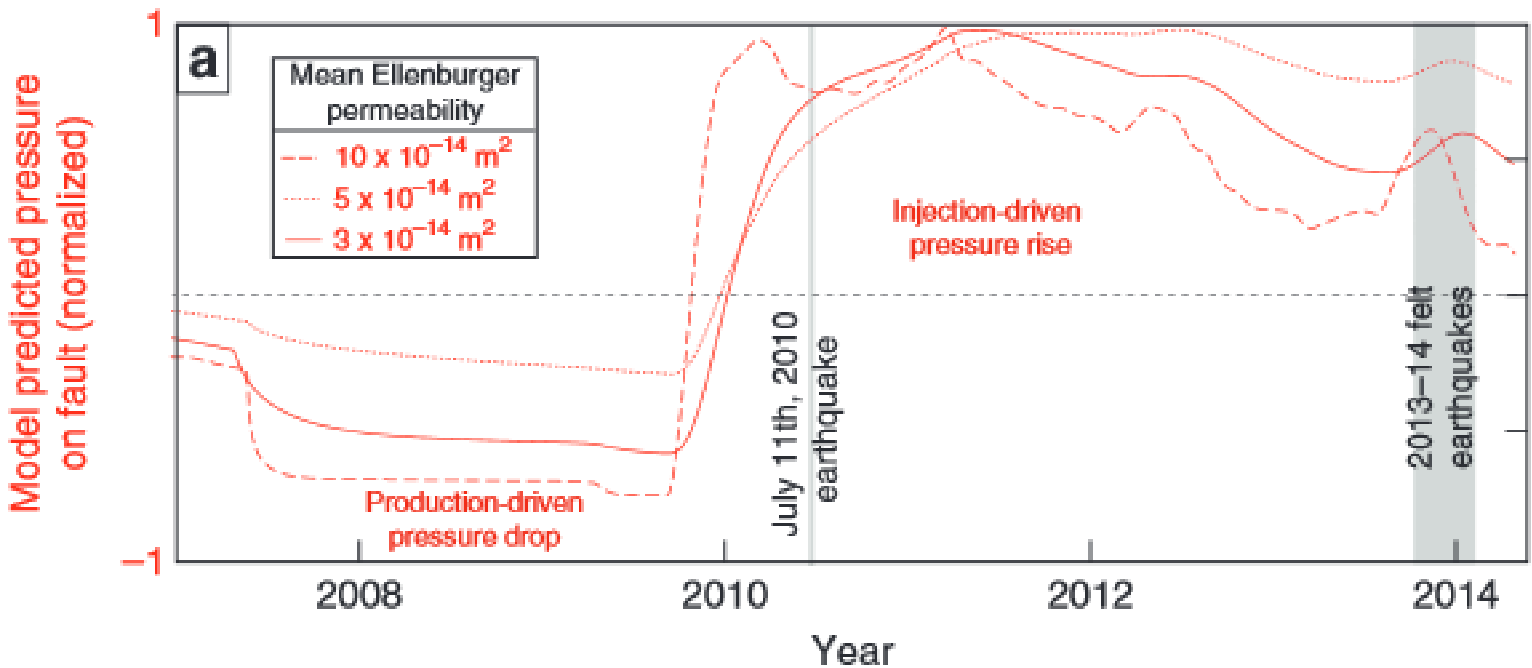
--We welcome and encourage more data to improve/refine these results.

QUANTIFYING SUBSURFACE INJECTION/PRODUCTION PRESSURES



- 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



AZLE EARTHQUAKES: INDUCED OR NATURAL? NRC-ENDORSED QUESTIONS.

	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?	Somewhat (new data indicates 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.

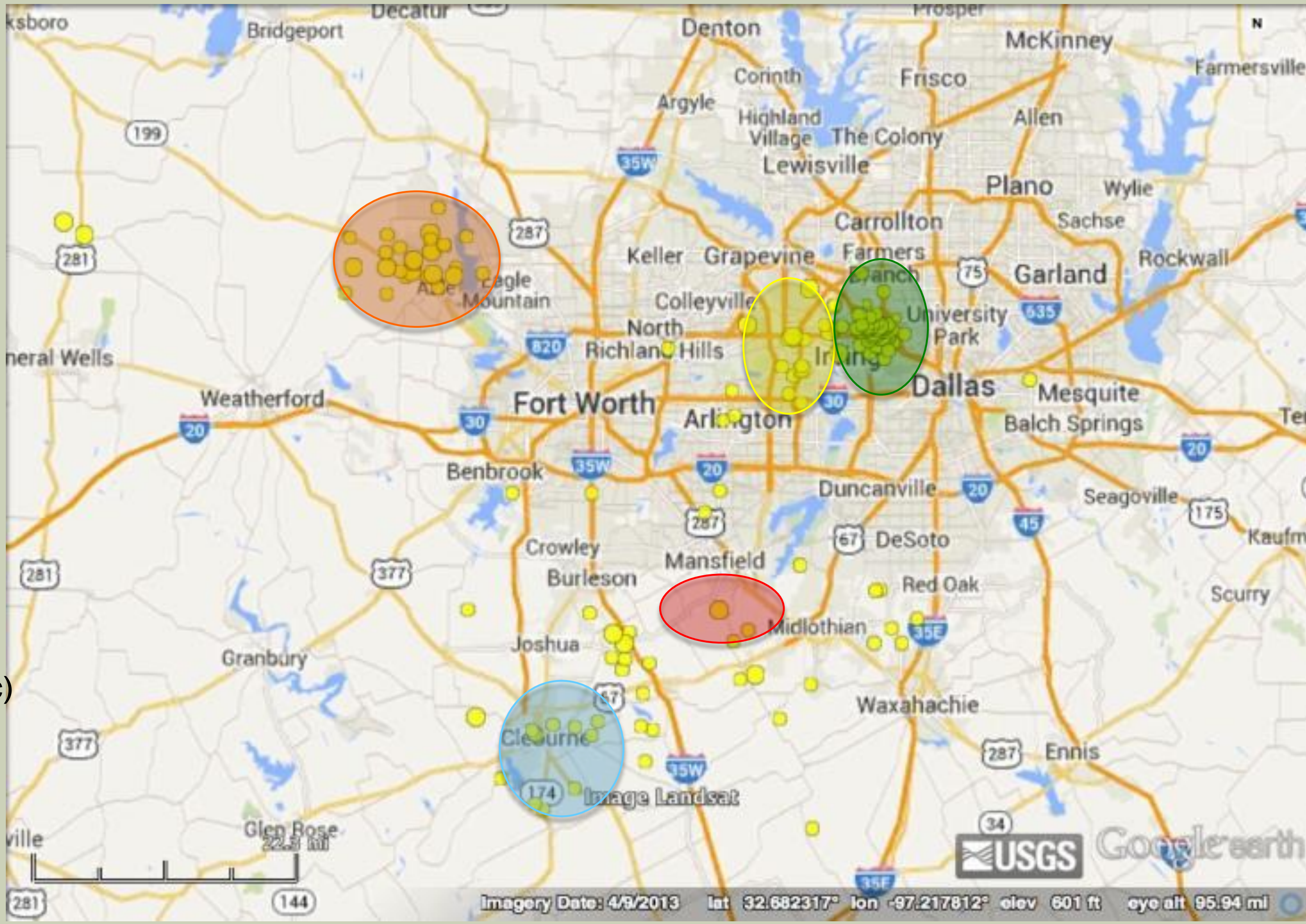
WAYS TO MOVE FORWARD

<u>3 Dense arrays</u>:

1. Azle/Reno
2. Irving
3. Venus

<u>Other data</u>:

-TRRC P/V Data.
-UTGCD Data.
-private industry data.
(fall off tests, seismic)



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

CONCLUDING REMARKS

- ***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 <u>Force</u> 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 <u>10 billion pounds</u>.

–We are not talking about breaking rock (fracking),. It's already broken, and the faults are loaded. This is simply reactivation

WHY NOT APPLY MULTI-PHASE FLOW IN THE MODEL?

--We'd be glad to apply multiphase flow if we had any evidence that it was important at this site.

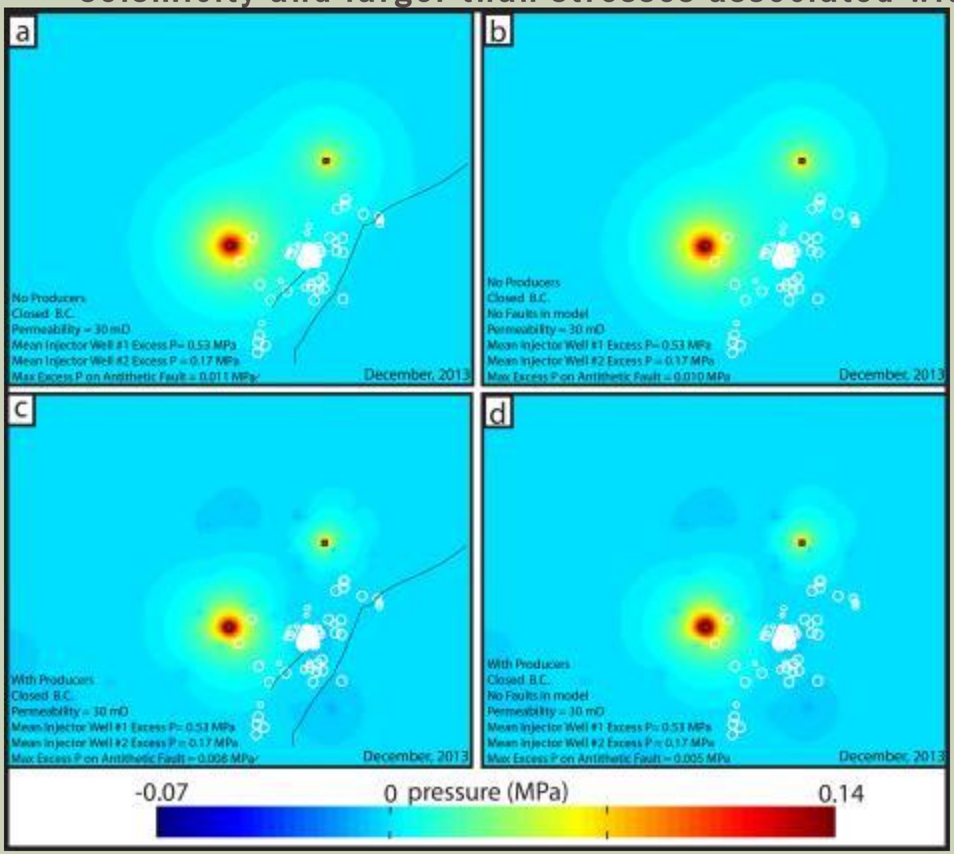
--To our knowledge, there <u>isn't a single well</u> currently producing gas in the Ellenburger in the Azle/Reno Area.

--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

THE AUTHORS ALWAYS APPLY LOW PERMEABILITY ZONES ON THE FAULTS

- **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 ground water changes near the surface.

ESTIMATES OF PRODUCTION DATA FROM 70 WELLS.

- 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.