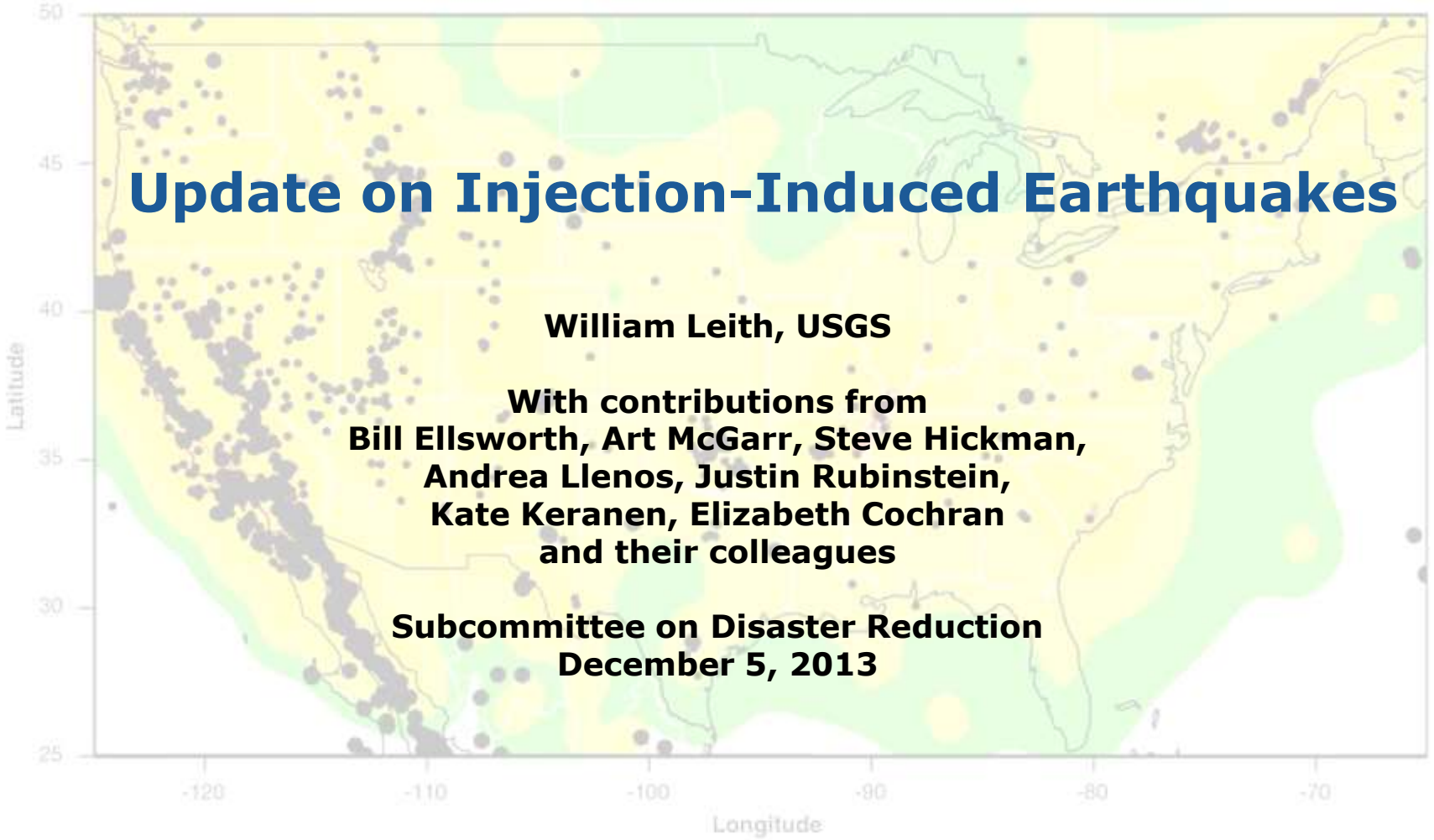


Update on Injection-Induced Earthquakes

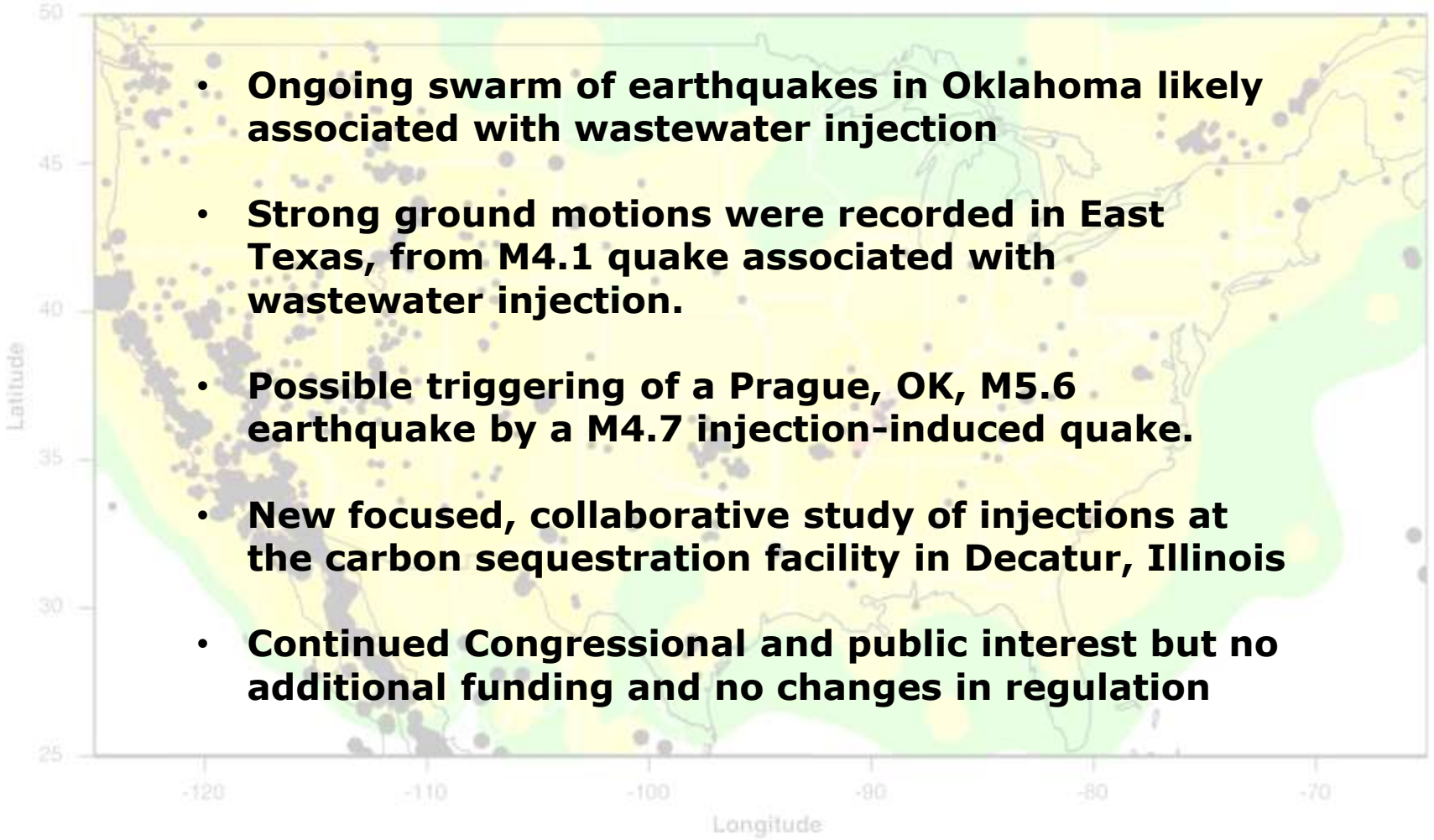
William Leith, USGS

With contributions from
Bill Ellsworth, Art McGarr, Steve Hickman,
Andrea Llenos, Justin Rubinstein,
Kate Keranen, Elizabeth Cochran
and their colleagues

Subcommittee on Disaster Reduction
December 5, 2013

USGS

Key Developments



- **Ongoing swarm of earthquakes in Oklahoma likely associated with wastewater injection**
- **Strong ground motions were recorded in East Texas, from M4.1 quake associated with wastewater injection.**
- **Possible triggering of a Prague, OK, M5.6 earthquake by a M4.7 injection-induced quake.**
- **New focused, collaborative study of injections at the carbon sequestration facility in Decatur, Illinois**
- **Continued Congressional and public interest but no additional funding and no changes in regulation**

USGS

Activities Entailing Fluid Injection at Depth

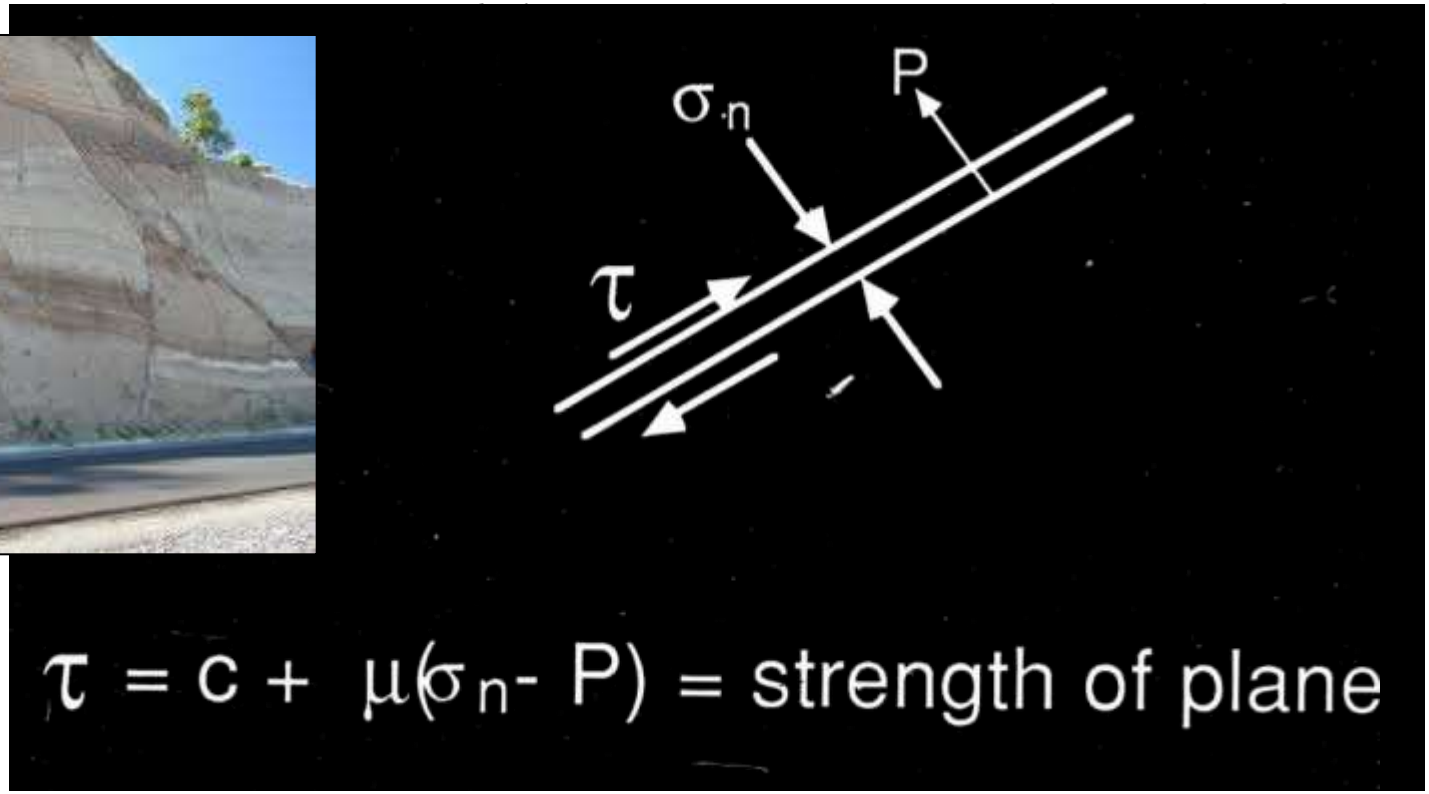
- Waste liquid disposal (chemicals and saline water)
- Enhancing oil and gas production (conventional)
- Tight shale gas and coal bed methane production (including disposal of wastewater)
- Geothermal production and Enhanced Geothermal Systems
- Carbon dioxide sequestration

USGS

How does fluid injection trigger earthquakes?

Increases in fluid pressure (P) at depth decrease the stress clamping the fault together, allowing the shear stress to dominate.

This phenomenon is well documented in laboratory experiments and has guided induced seismicity research for decades.



USGS

Research Challenges and Questions - 1

- What factors control the seismic response to an injection activity?
- Is it possible to predict in advance whether a given injection well will induce earthquakes large enough to be of concern?
- Can a small-scale injection activity trigger a large earthquake?
- How do induced earthquakes affect the National Seismic Hazard Maps?

USGS

Research Challenges and Questions - 2

- Why do triggered earthquakes occur in some places and not others?
- How large an earthquake can be induced?
- How should injection practices be altered to minimize the risk of inducing damaging earthquakes?
- Once a significant earthquake occurs, what operational changes should be implemented?
- How do the answers to these questions relate to regulation and permitting?

USGS

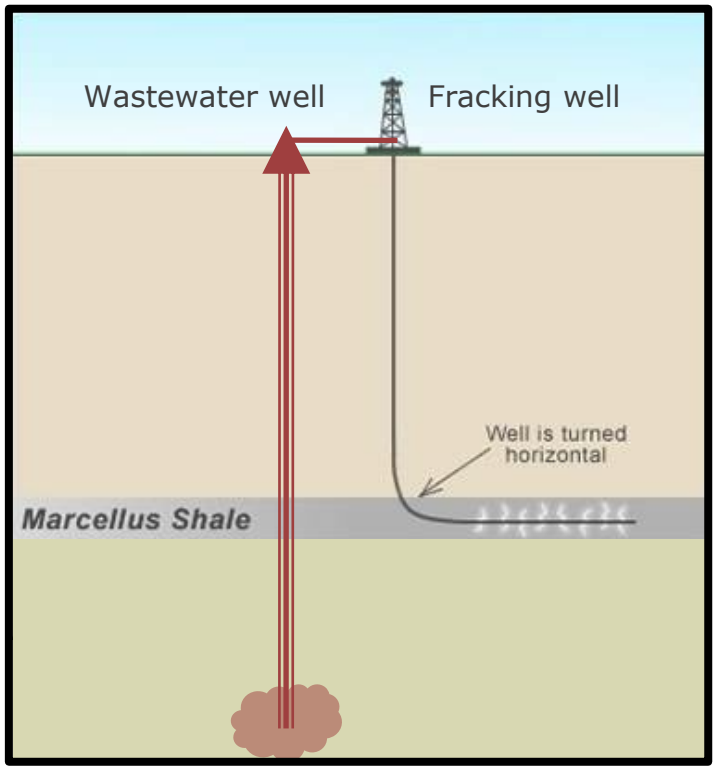
Who wants to know?

- Industry (business risk, liability)
  - Oil and gas producers
  - Oilfield service providers
  - Waste disposal companies
- Regulators (decision-making)
  - Permitting agencies
  - Local land-use jurisdictions
  - Earthquake safety regulators
- The public (adequate regulation?)
- Private facility owners

  (risk mitigation)
  - Dams, hospitals, power, etc.

USGS

Fracking and Wastewater Injection



adapted from geology.com

Hundreds of thousands of frac jobs

Only a handful of felt events

None as large as magnitude 4 (so far)

30,000 deep wastewater wells in U.S.

Many with volumes > 10^6 m^3

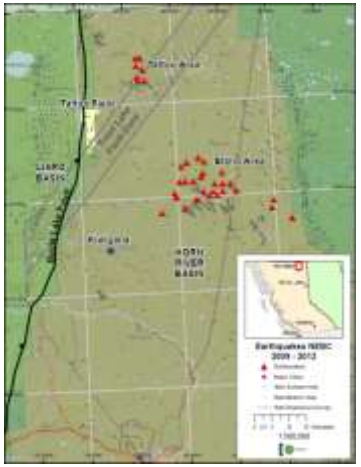
Few with detected seismicity

Magnitudes as large as M_w 5.6

USGS

Fracking and Earthquakes:
Investigation of Observed Seismicity in the Horn River Basin

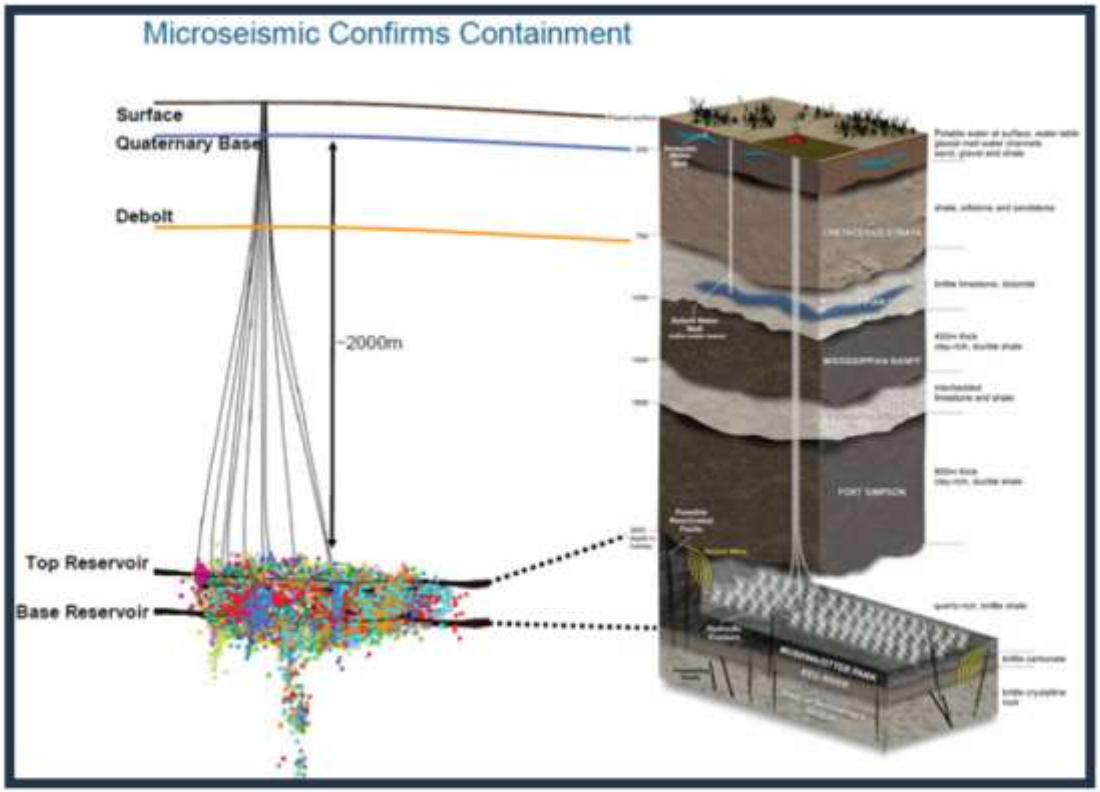
BC Oil and Gas Commission - August 2012



31 earthquakes; largest M_w 3.6

"The seismicity observed and reported by NRCan in the Horn River Basin between April 2009 and December 2011 was induced by fault movement resulting from injection of fluids during hydraulic fracturing."

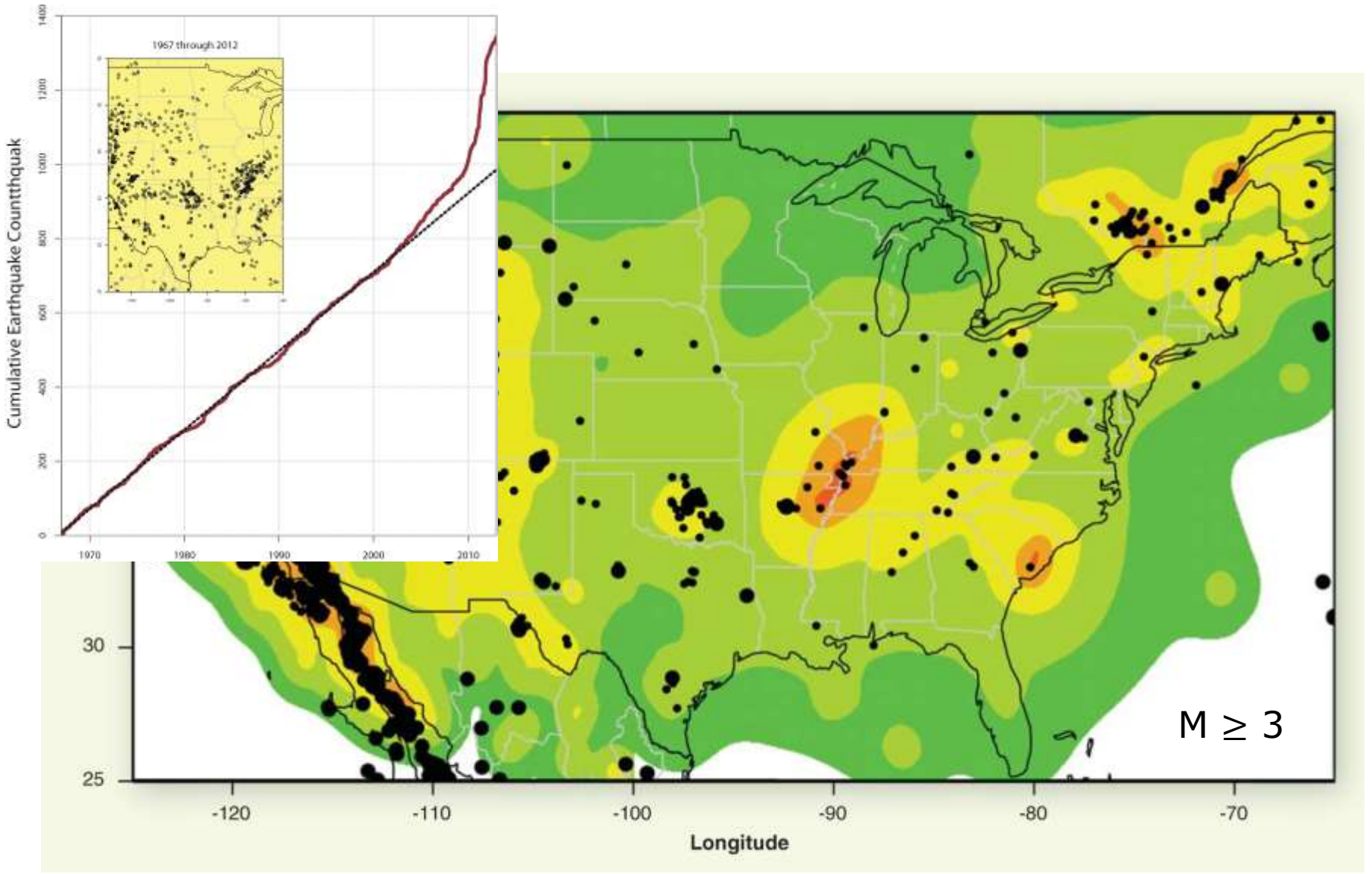
Figure 8: Cumulative microseismic plot for Kiwigana, coloured dots indicate contained micro-seismicity events caused by tensile and shear failure of intact shale. Trail of coloured dots suggest reopening or movement of pre-existing fault. Generalized stratigraphic column to right.



USGS

A by-product of the fracking operation is “produced water” (natural brine and fracking flowback)

High rate of earthquakes in the midcontinent since 2001



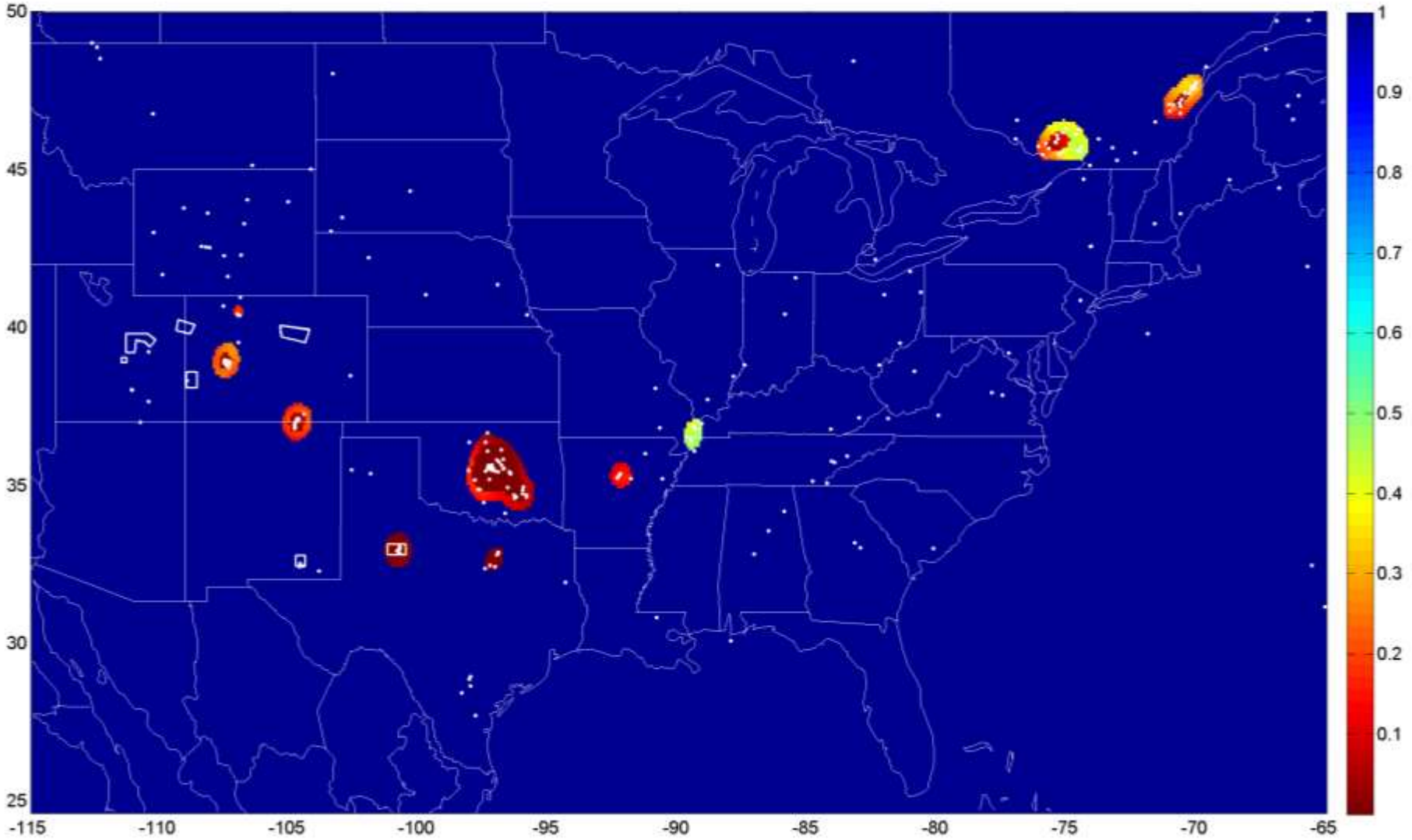
Ellsworth, W. L., 2012, Injection-Induced Earthquakes, *Science*, v. 341, doi: 10.1126/science.1225942

USGS

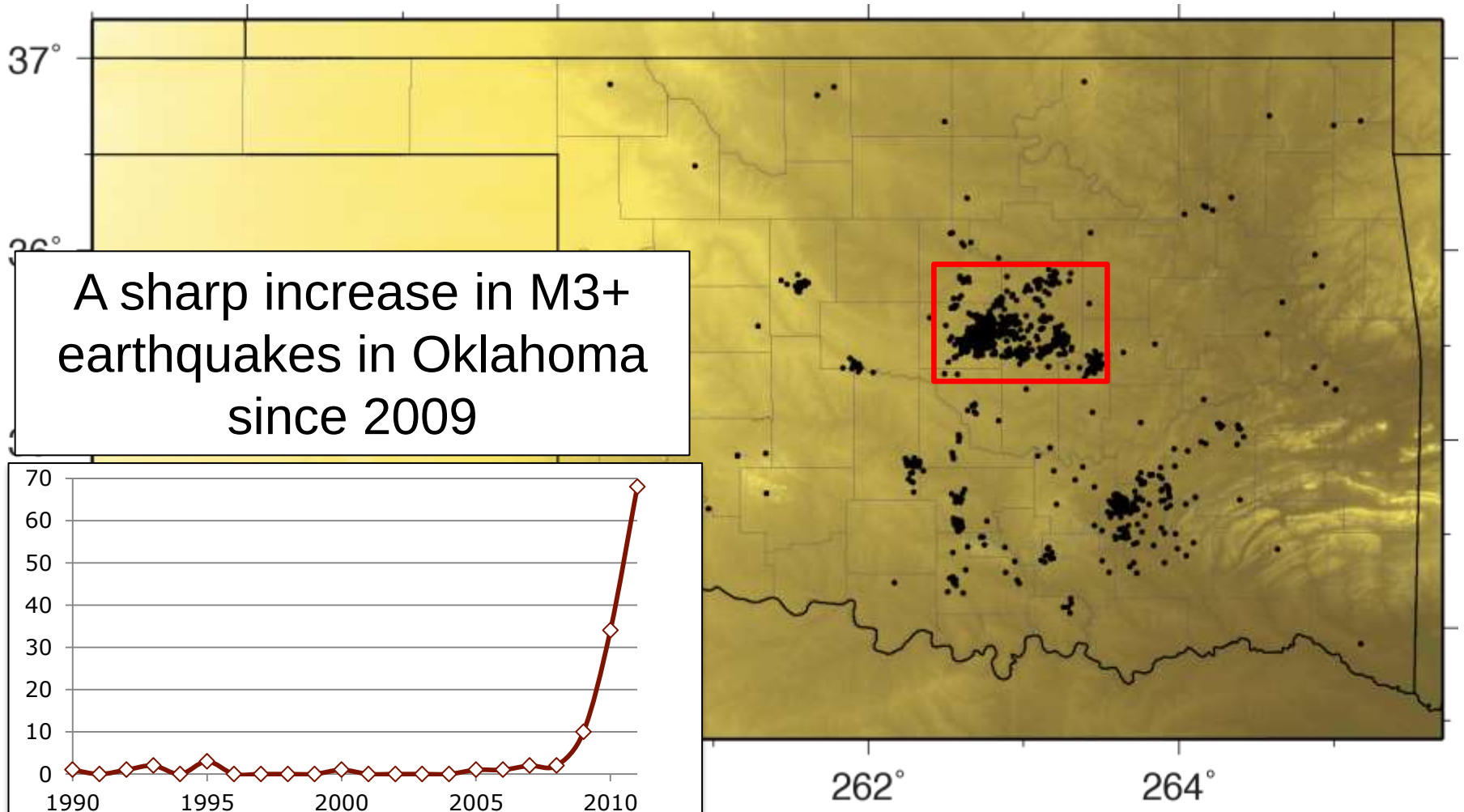
Areas with anomalous numbers of earthquakes, 2009-2012

relative to the forecast of the 2008 National Seismic Hazard Map

$P(N_{EQS}|NSHM)$ 2009-2013



Earthquakes in Oklahoma 2010-2011



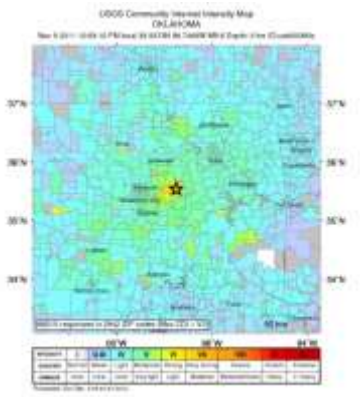
A sharp increase in M3+ earthquakes in Oklahoma since 2009

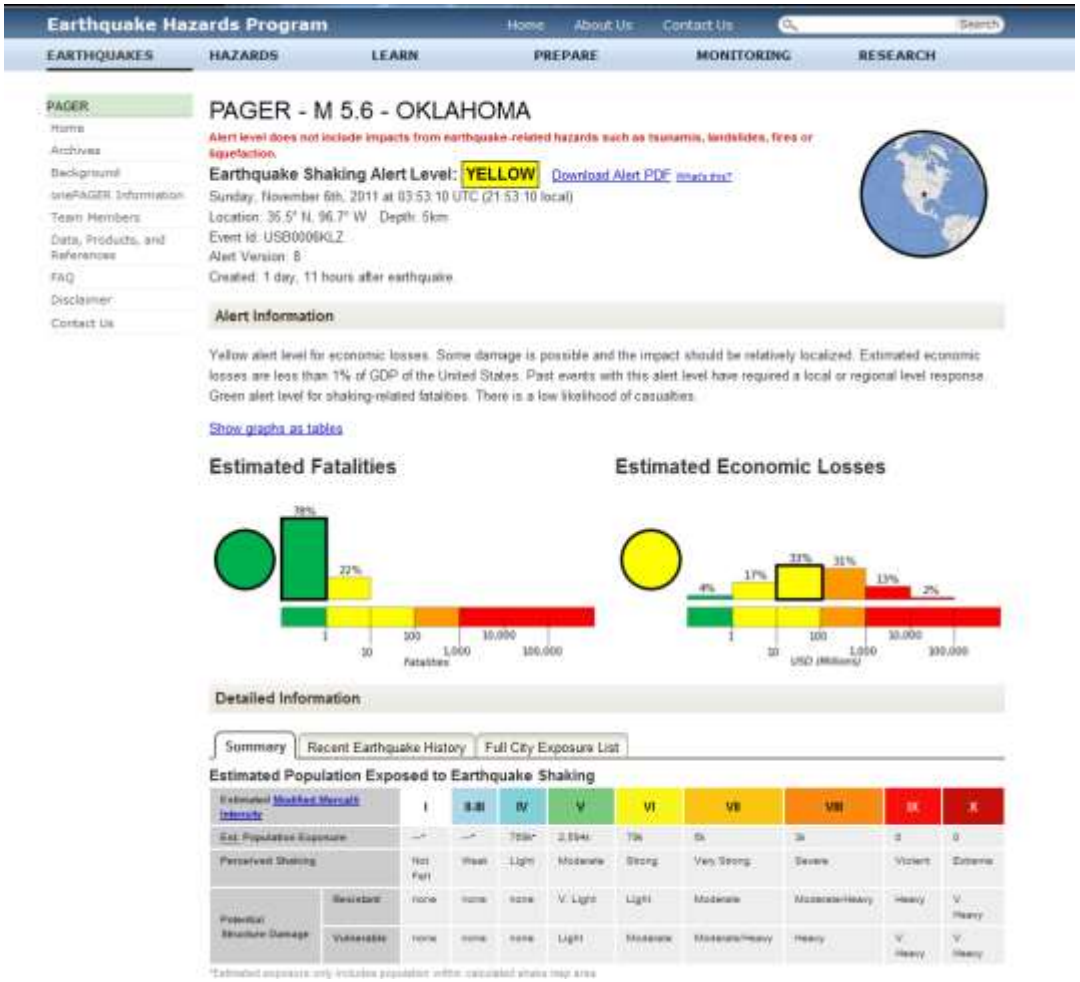
Ellsworth, 2013

2011 Prague, Oklahoma Earthquake

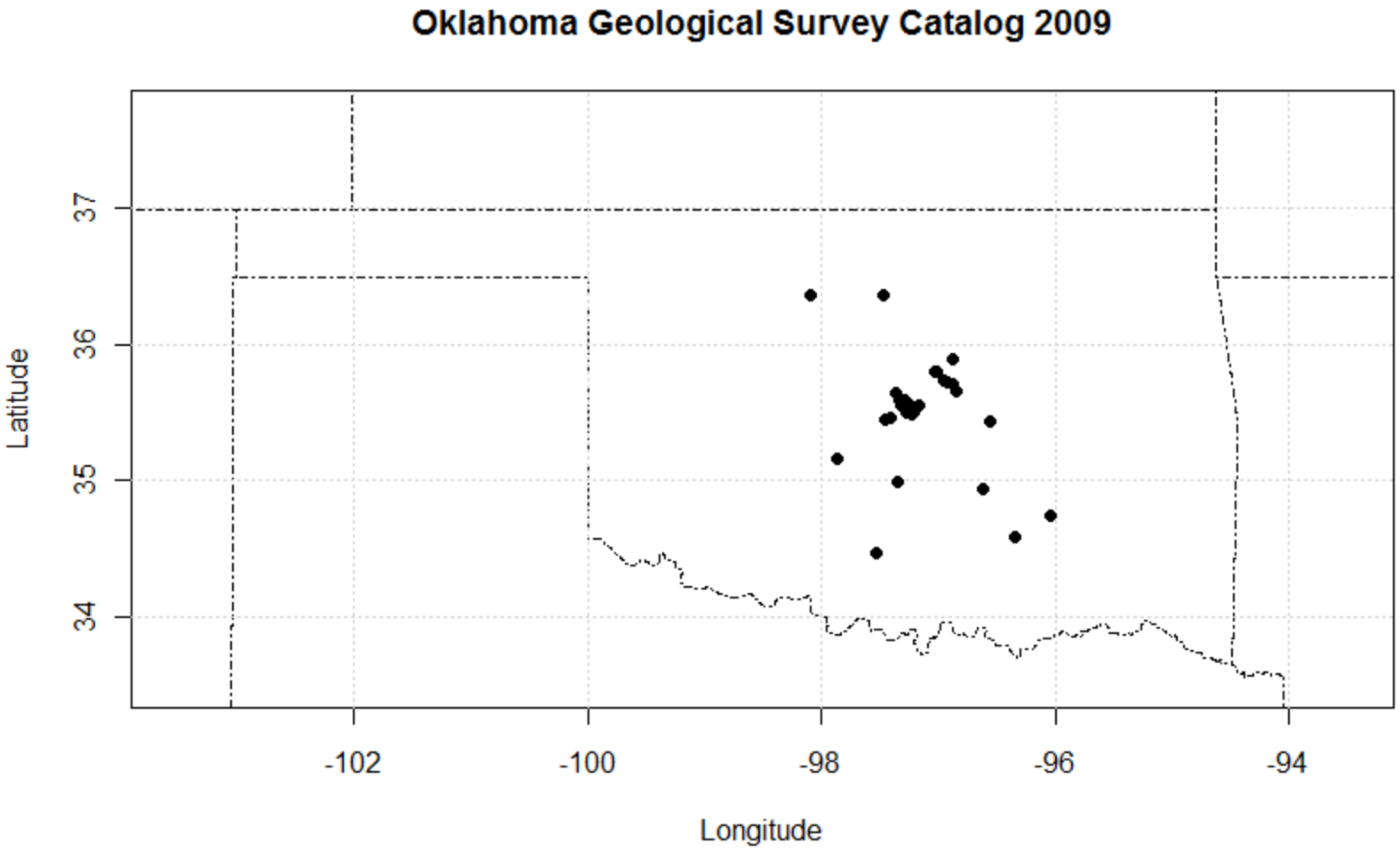
M_w 5.7

No fatalities; a few injuries; significant economic damage

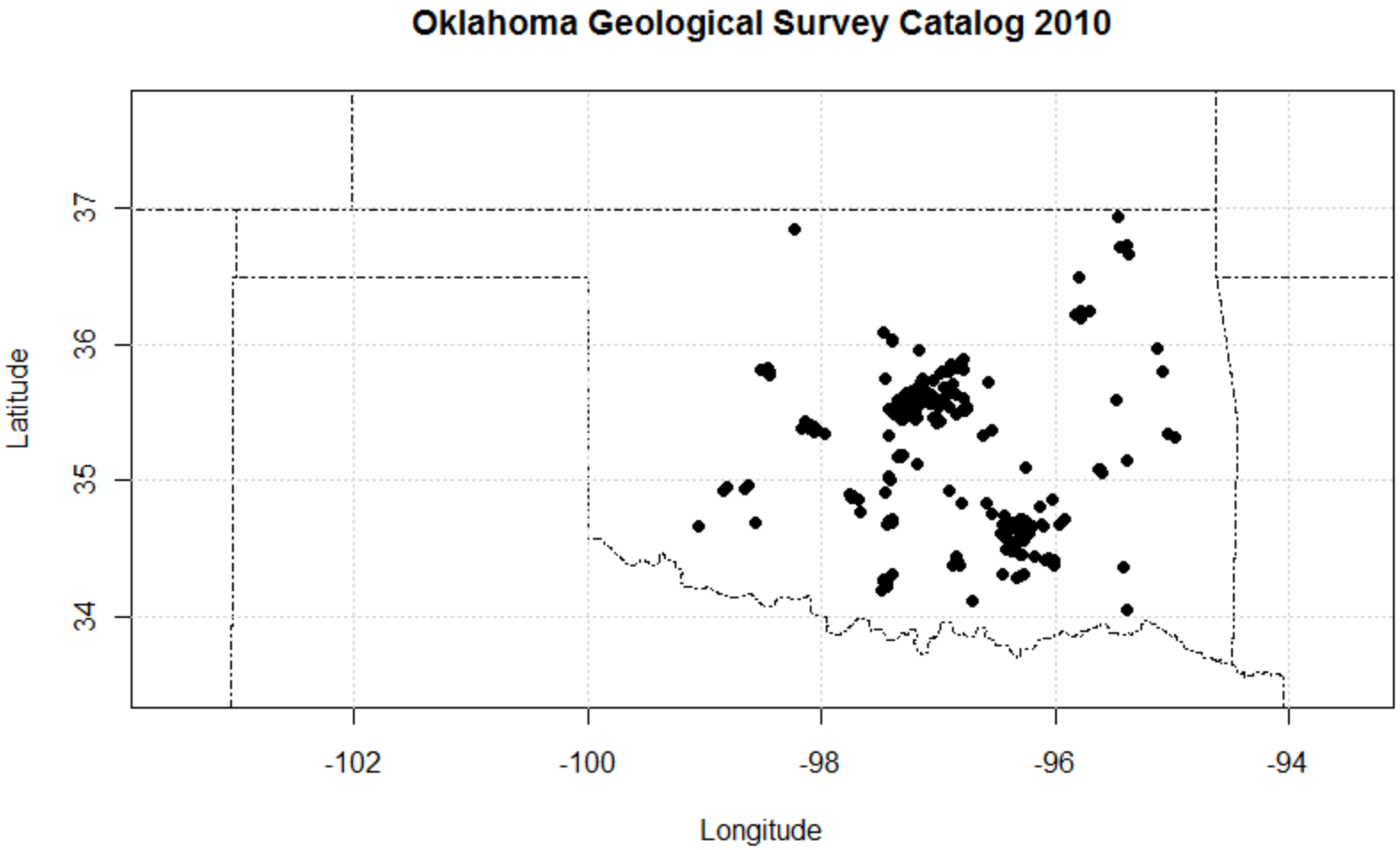




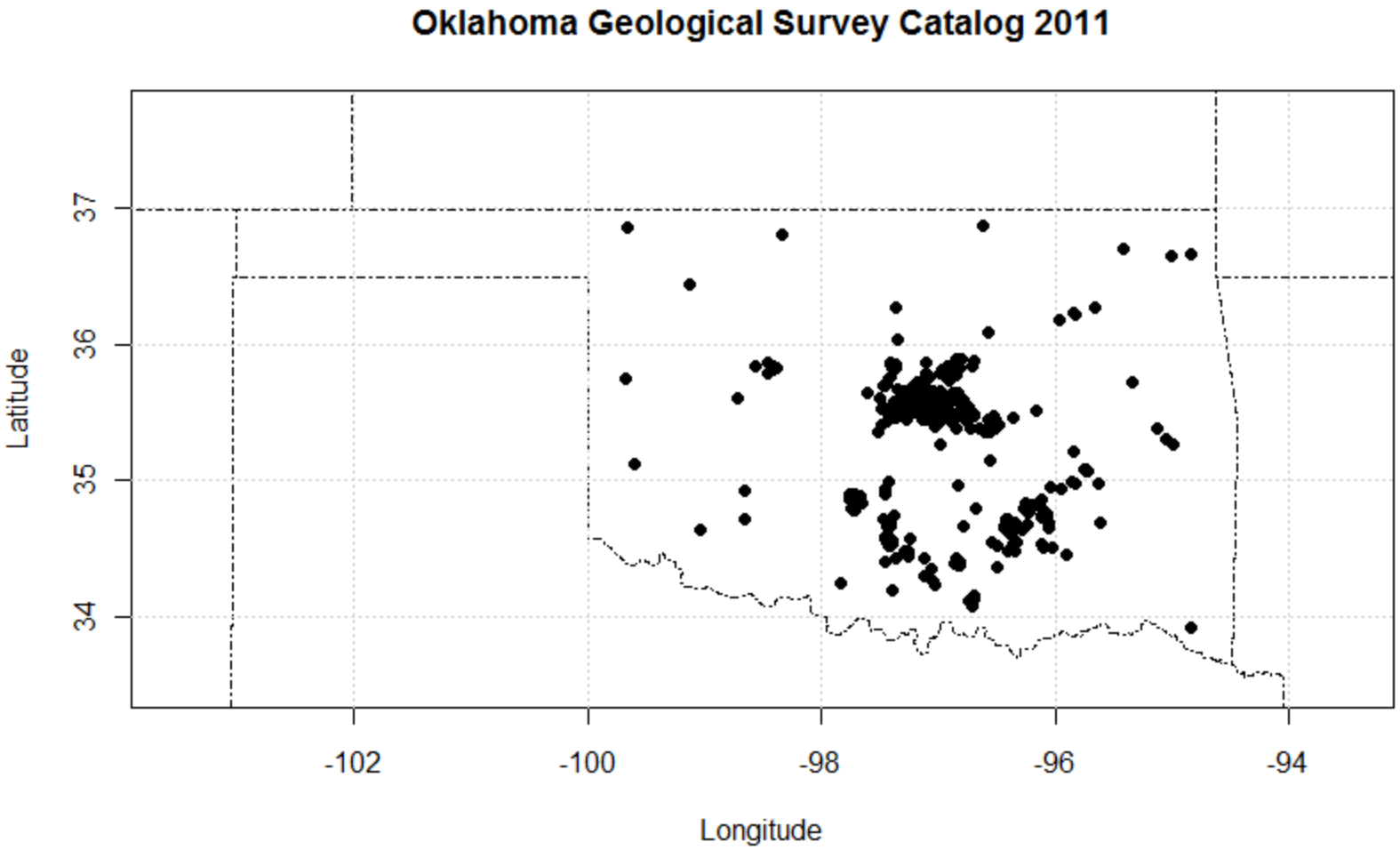
A moving target in Oklahoma



USGS


Oklahoma Geological Survey Catalog 2010
Latitude
37
36
35
34
-102
-100
-98
-96
-94
Longitude

USGS


Oklahoma Geological Survey Catalog 2011
Latitude
37
36
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-102
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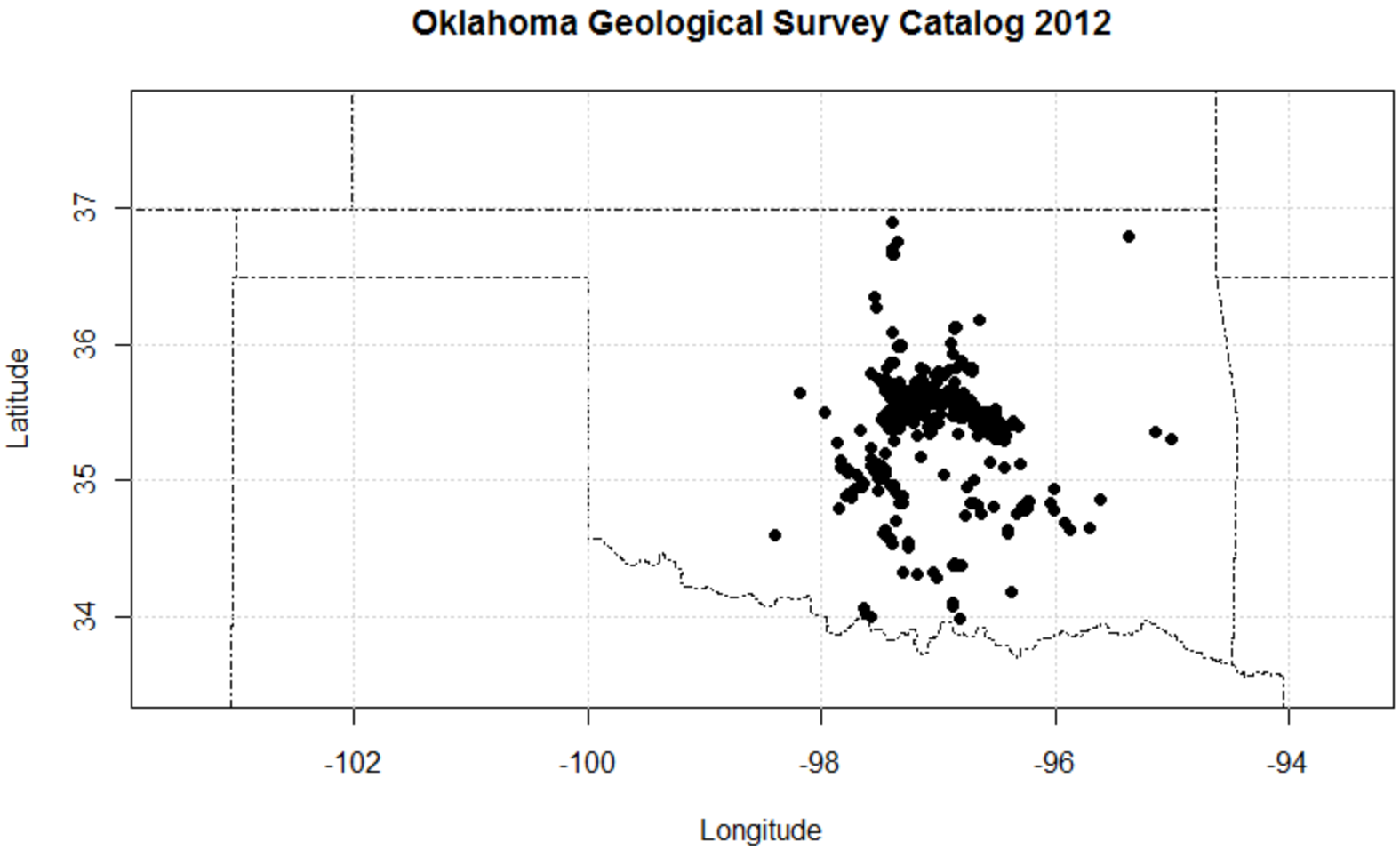
Longitude

USGS


Oklahoma Geological Survey Catalog 2012
Latitude
37
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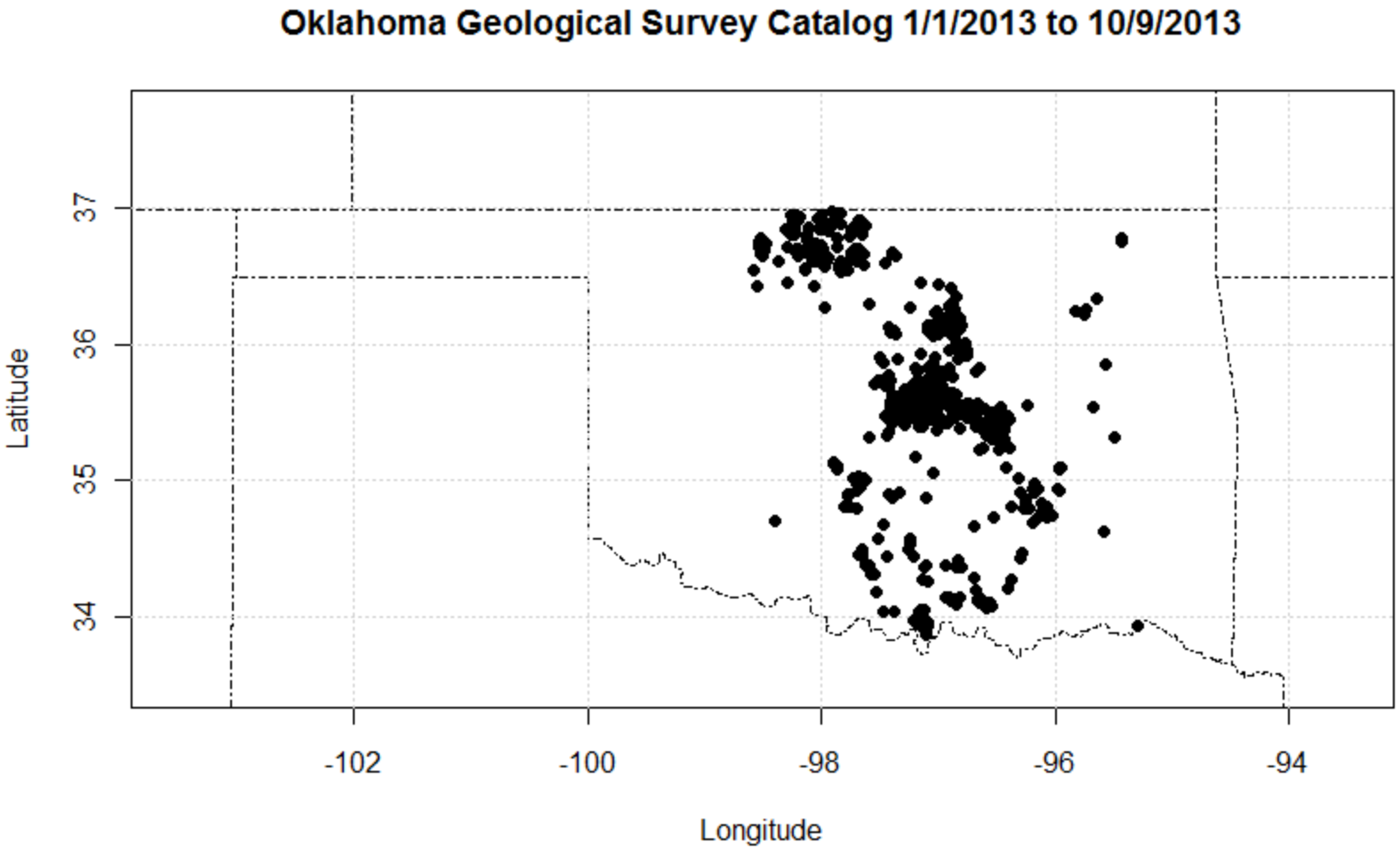
34
-102
-100
-98
-96
-94
Longitude

USGS


Oklahoma Geological Survey Catalog 1/1/2013 to 10/9/2013
Latitude
37
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-102
-100
-98
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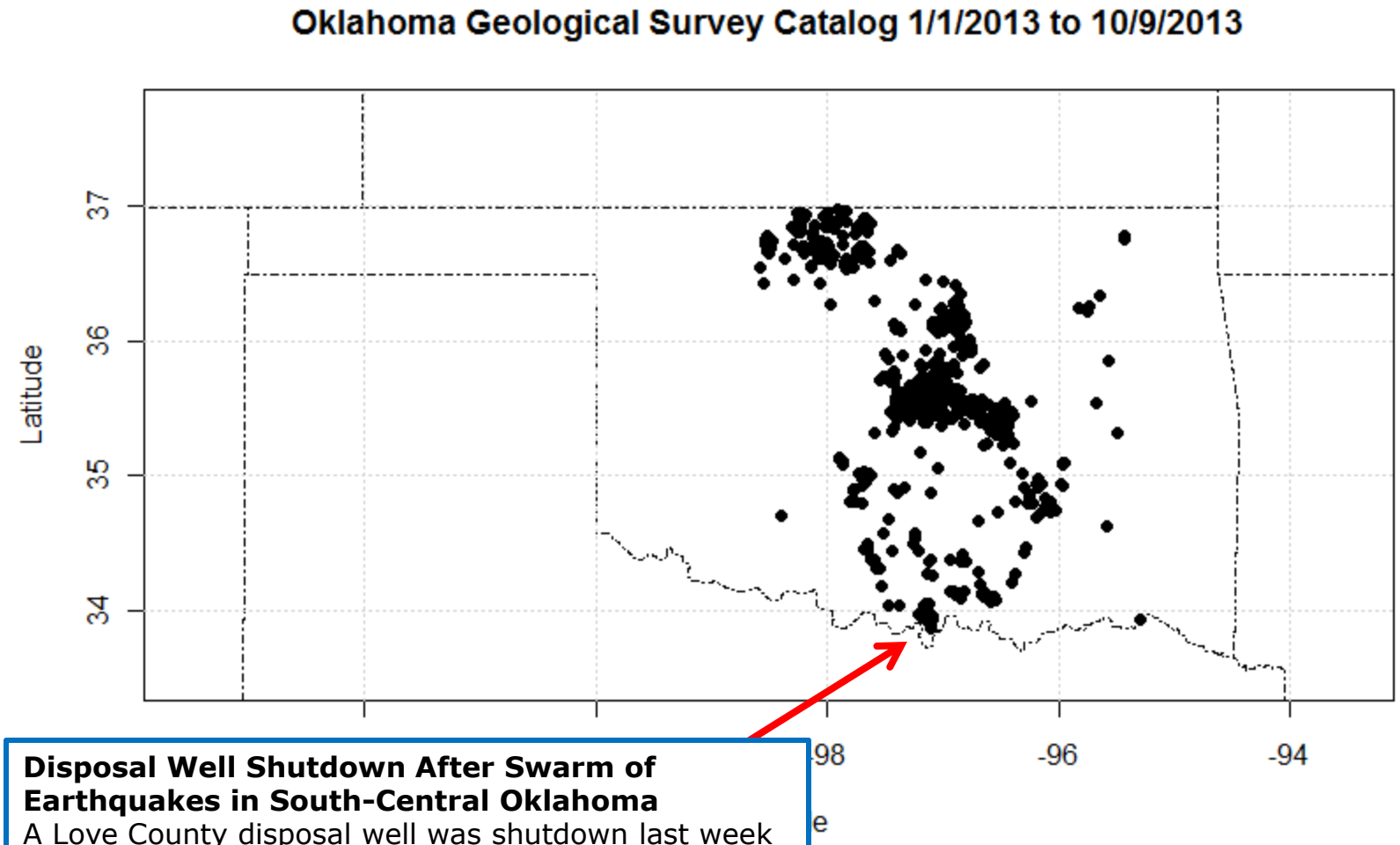
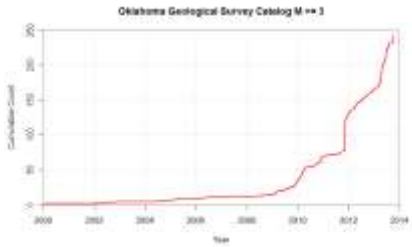
Longitude

USGS



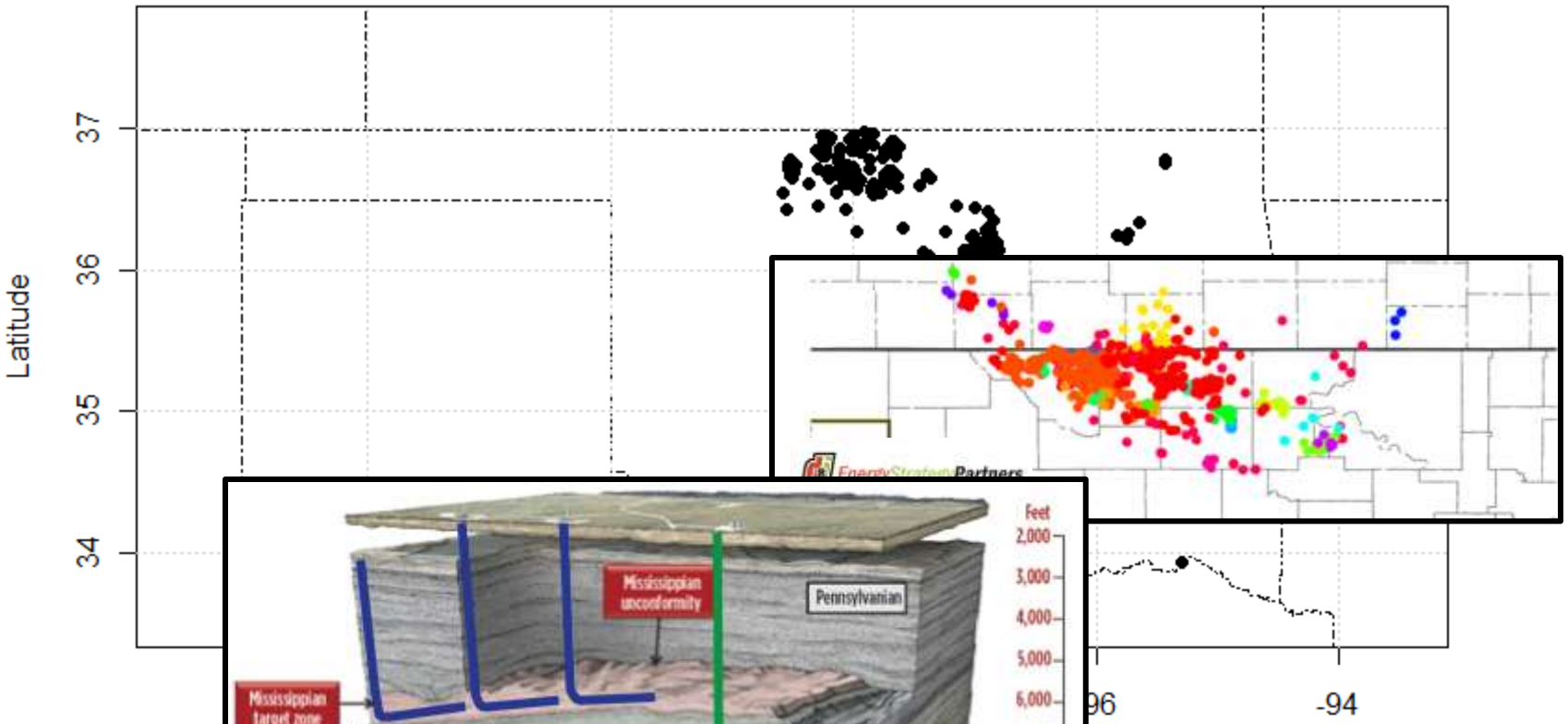
Disposal Well Shutdown After Swarm of Earthquakes in South-Central Oklahoma
A Love County disposal well was shutdown last week after a state seismologist suggested it might have triggered a swarm of damaging earthquakes that shook the area for weeks in September.

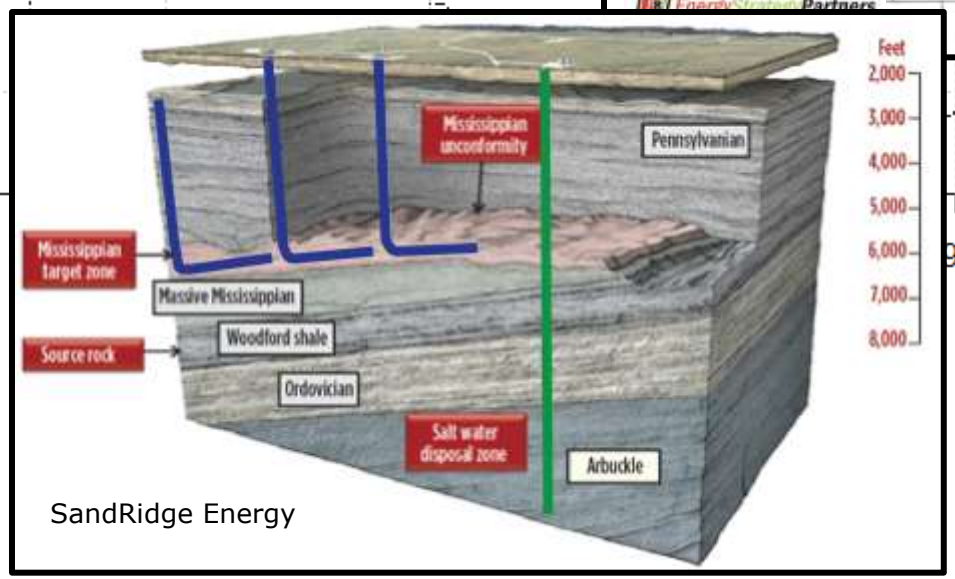
USGS



N. Oklahoma - Mississippi Lime Play

Oklahoma Geological Survey Catalog 1/1/2013 to 10/9/2013

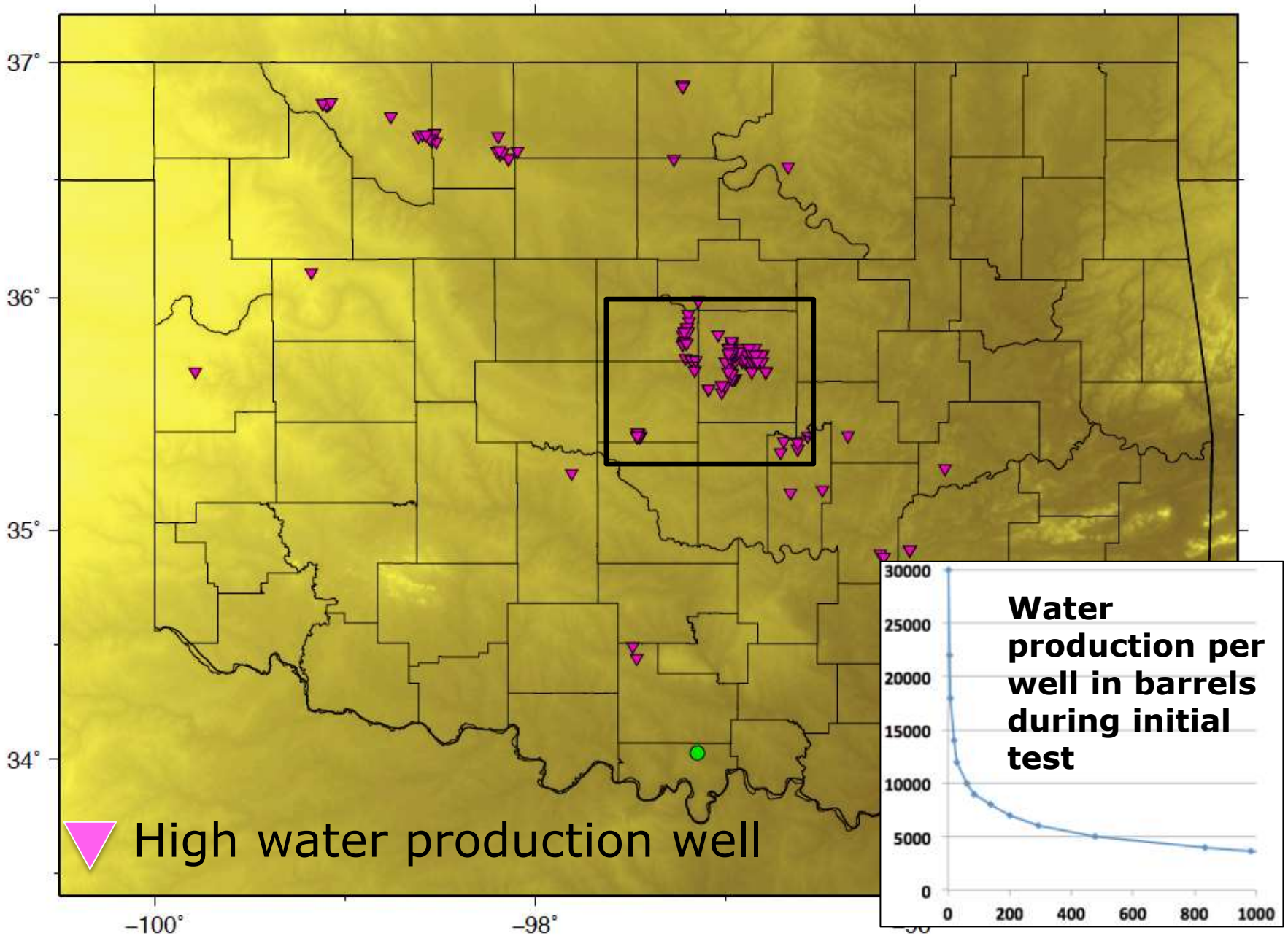




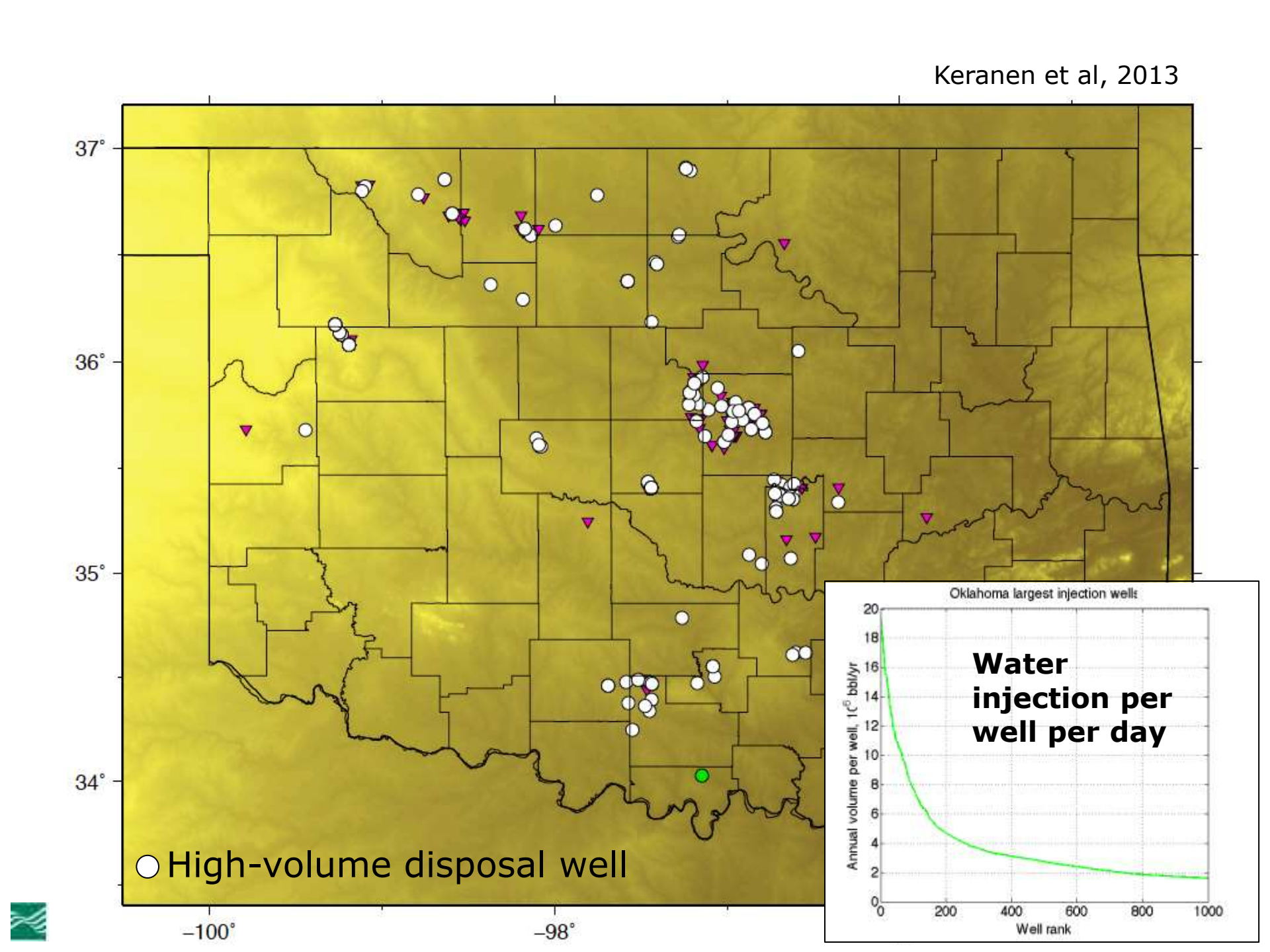
SandRidge Energy

USGS

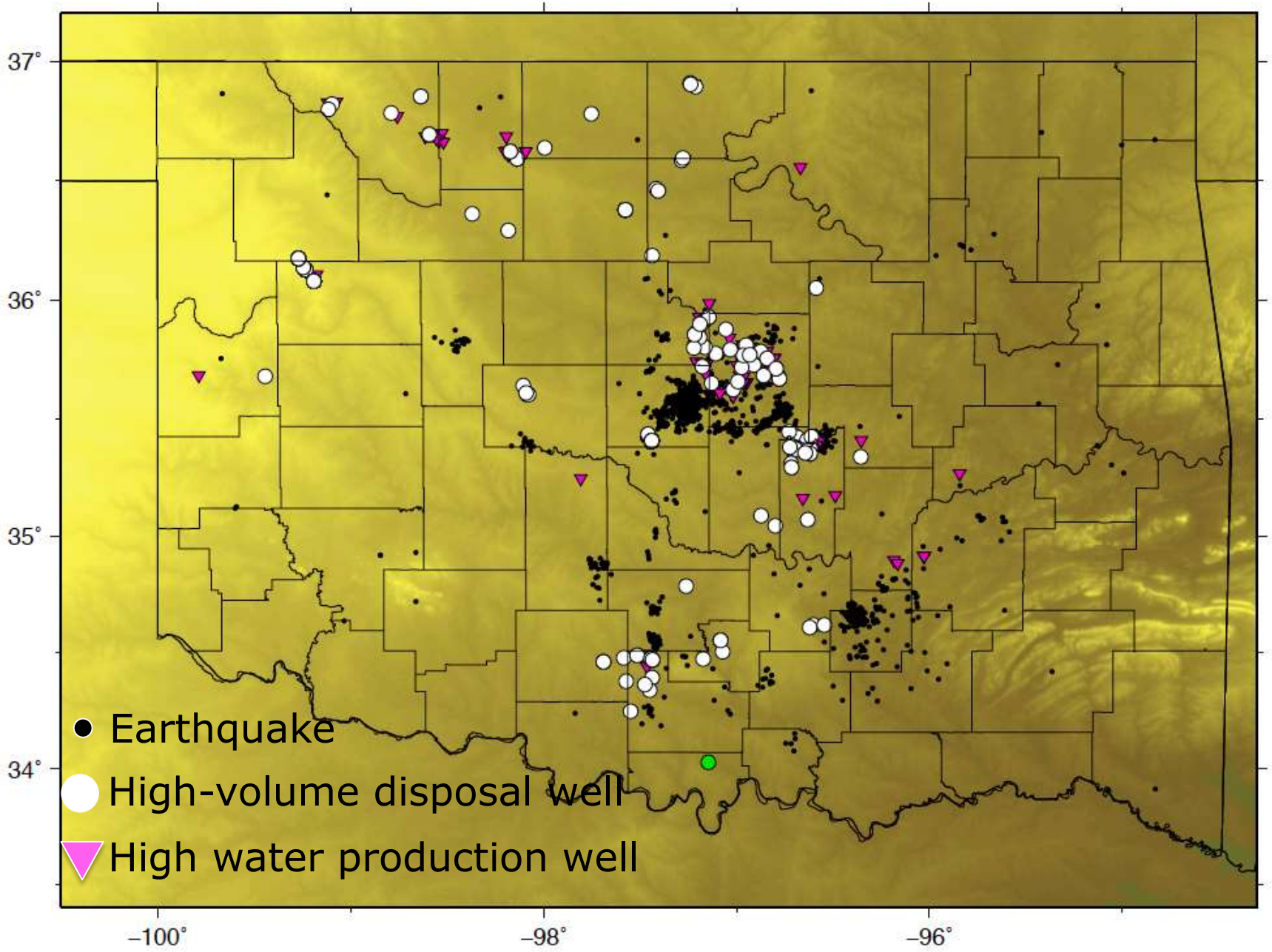
Keranen et al, 2013



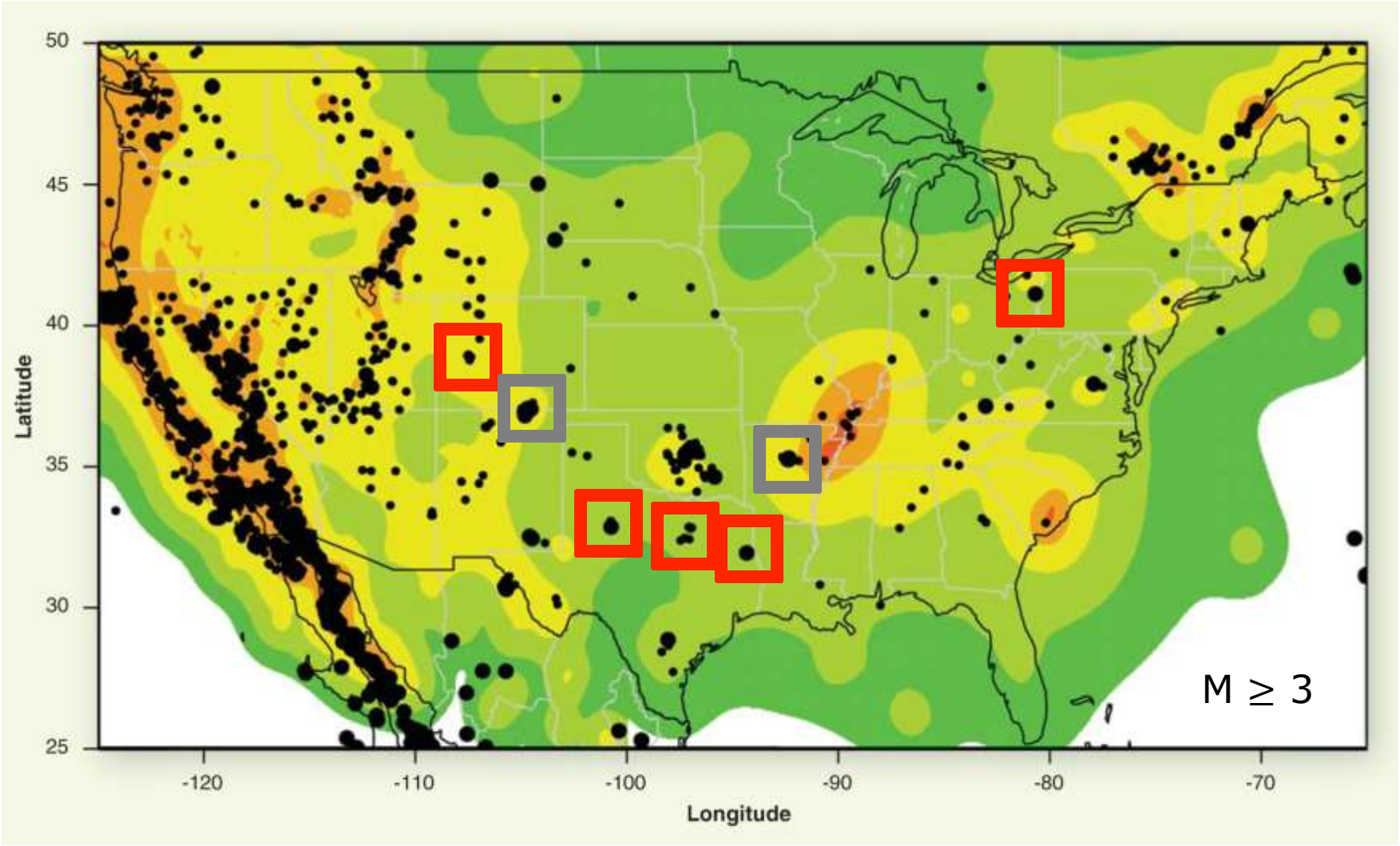
Keranen et al, 2013



Keranen et al, 2013

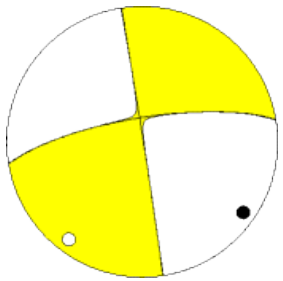


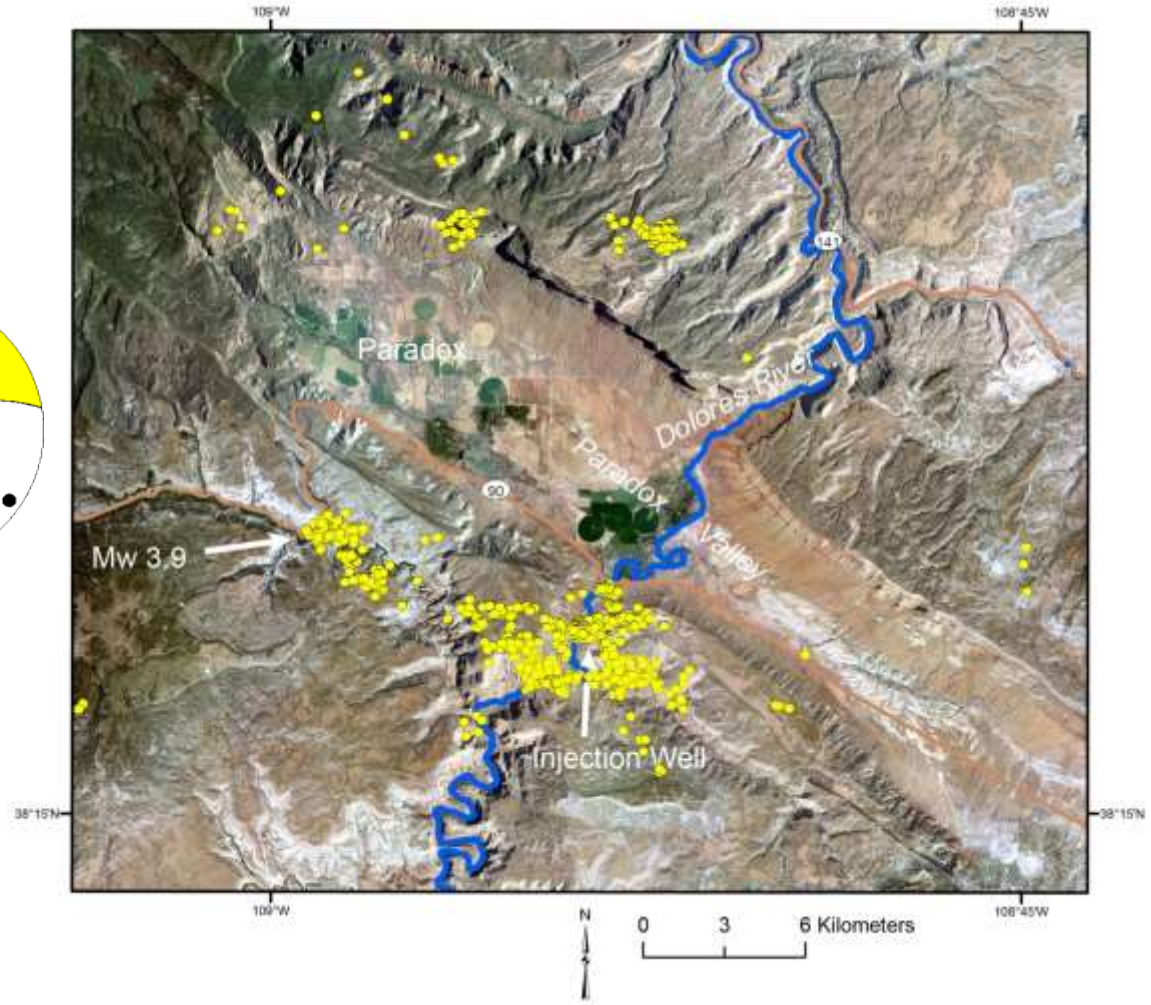
Earthquake Hazard and Seismicity
2009 - 2012



USGS

January 25, 2013 M_w 3.9 Paradox Valley Earthquake





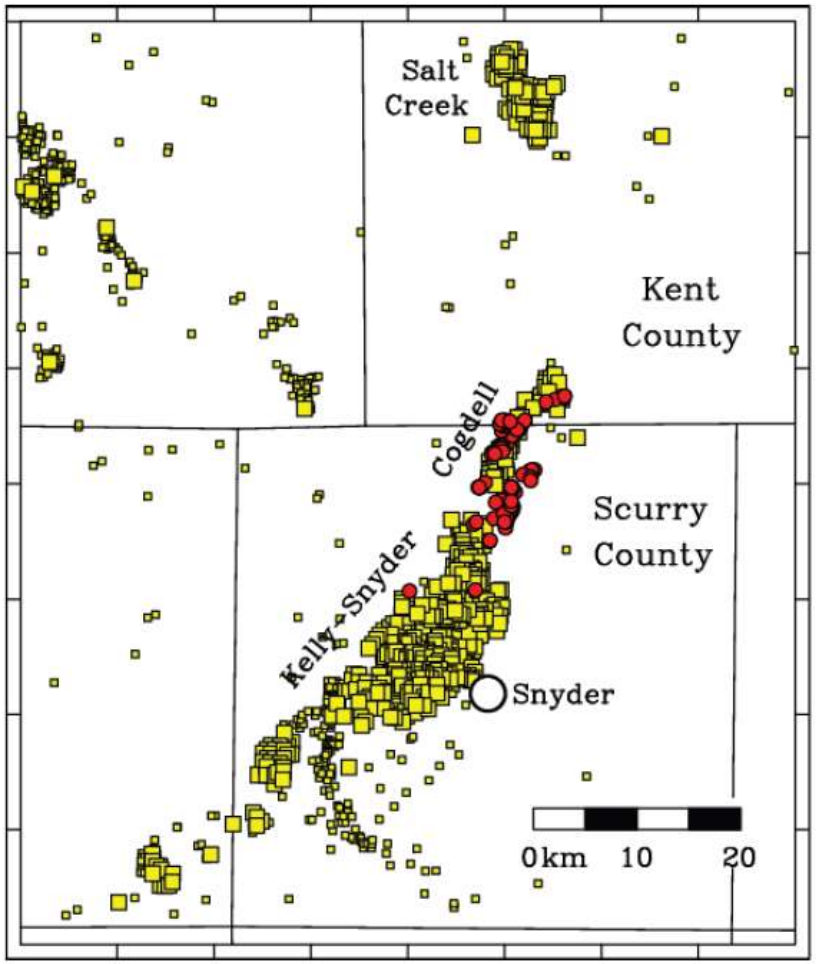
- 8 km from well
- Small magnitude activity within 1 year of start of injection
- M_w 3.9 delayed 16 years after injection began
- Bureau of Reclamation reconsidering future of injection

USGS

Earthquakes Induced by Enhanced Oil Recovery
Cogdell Oil Field, West Texas

Seismicity detected during Passage of USArray

Earthquakes in **RED**
Injection wells in **Yellow**



Active in late 1970s and early 1980s during water flooding

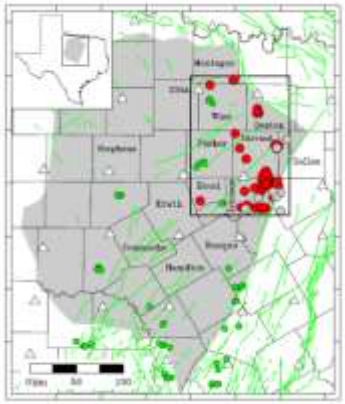
Resumption of seismicity in 2006 after **CO_2 injection** began

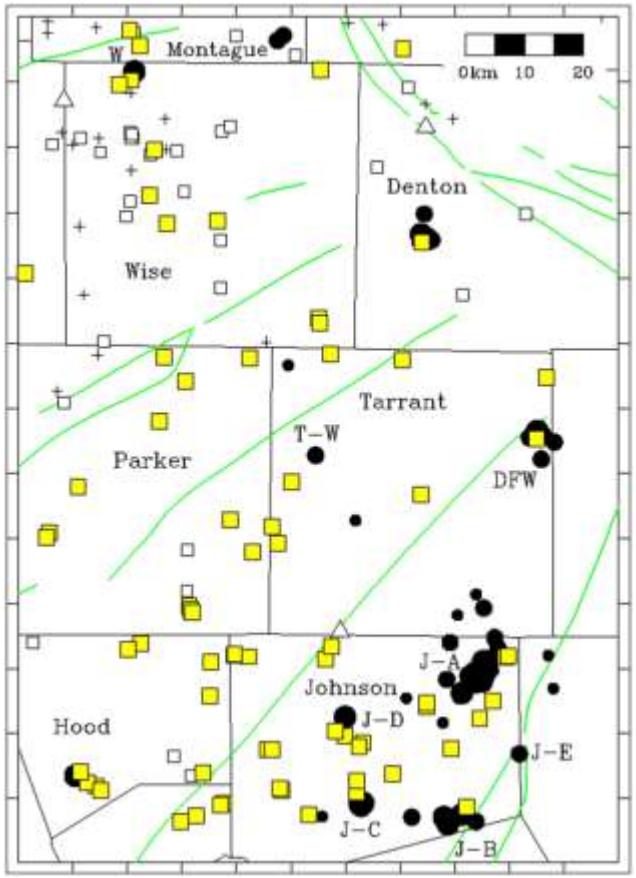
Largest event M_w 4.4

Gan, W., and Frohlich, C, in press, Are recent earthquakes in the Cogdell oil field, Texas, triggered by CO_2 injection?. *Proc. Natl. Academy of Science.*

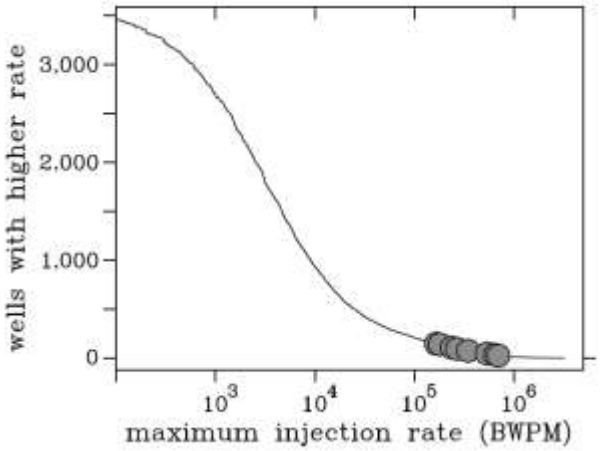
USGS

Earthquakes and Waste Water in the Barnett Shale





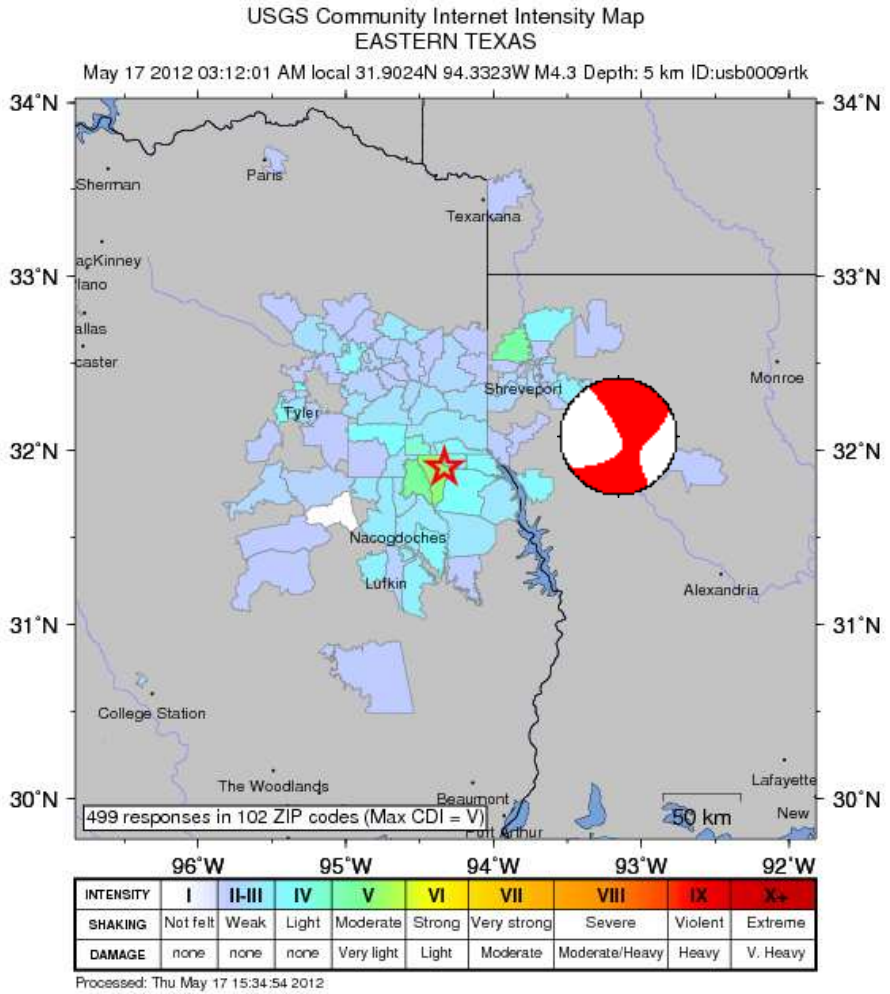
Detailed analysis using USArray Transportable Array showed seismicity to be associated with high-volume waste water injection wells



Frohlich, C., 2012, *Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas*. Proc. Natl. Acad. Sci.

USGS

Investigating the 17 May 2012 M4.8 Earthquake near Timpson, East Texas



Five Principal Earthquakes

M_w 3.9 May 10, 2012
M_w 4.8 May 17, 2012

M_w 4.1 January 25, 2013

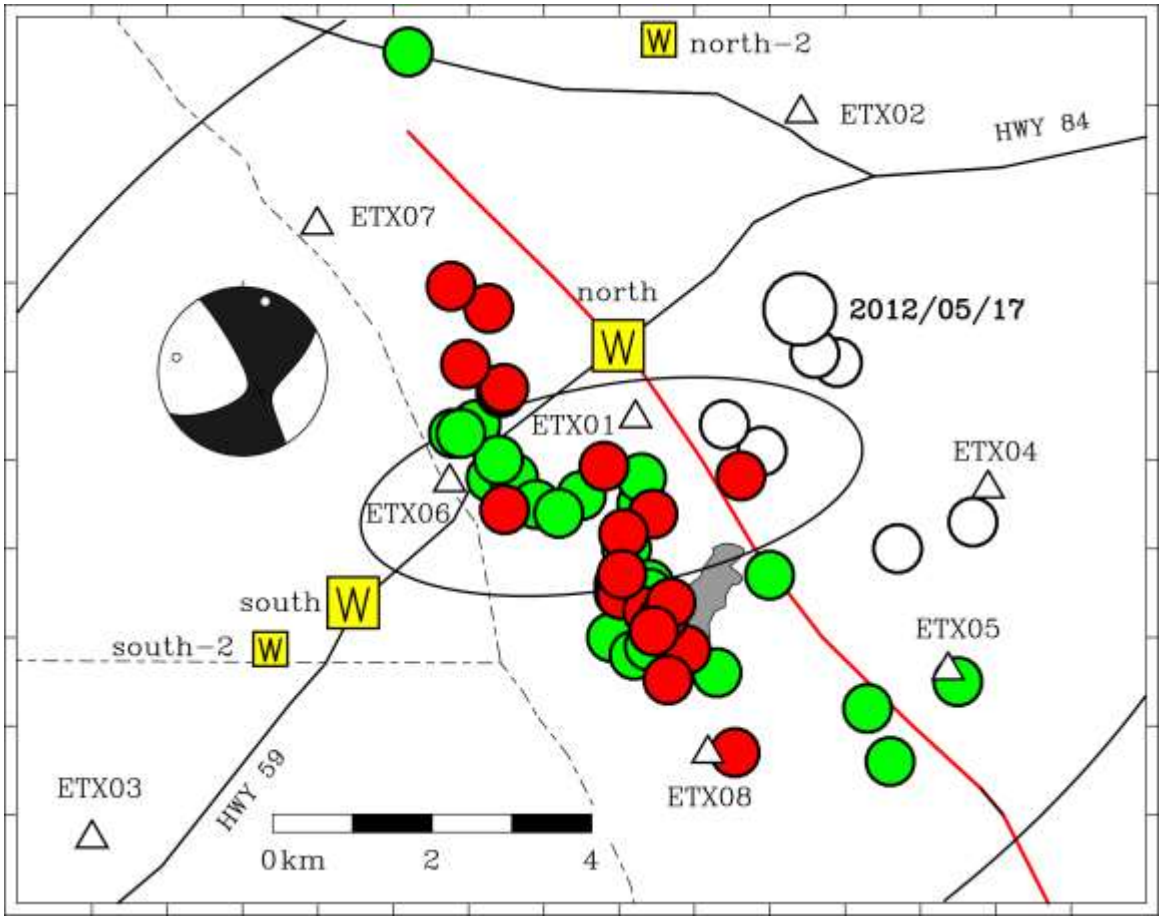
M_w 4.0 September 2, 2013
M_w 4.1 September 2, 2013

Frohlich, C., Ellsworth, W., Brown, W. Brunt, M., and Luetgert, J, submitted, The 17 May 2012 M4.8 earthquake near Timpson, east Texas: An event possibly triggered by fluid injection, *J. Geophys. Res.*

USGS

Timson Earthquakes

Earthquake Location Results from Temporary Networks

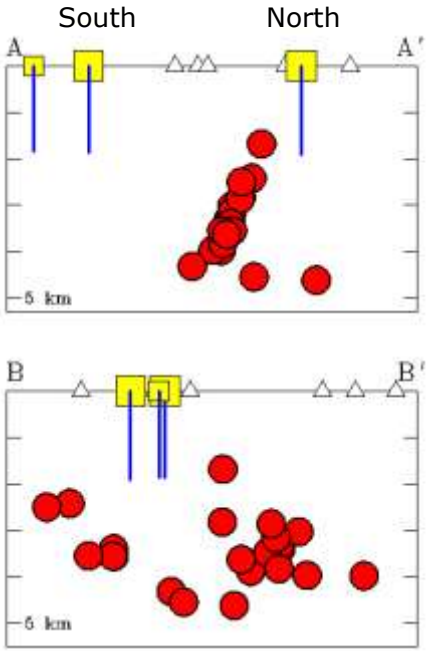


NEIC Location

Frohlich, C., Ellsworth, W., Brown, W. Brunt, M., and Luetgert, J, submitted, The 17 May 2012 M4.8 earthquake near Timpson, east Texas: An event possibly triggered by fluid injection, *J. Geophys. Res.*

USGS

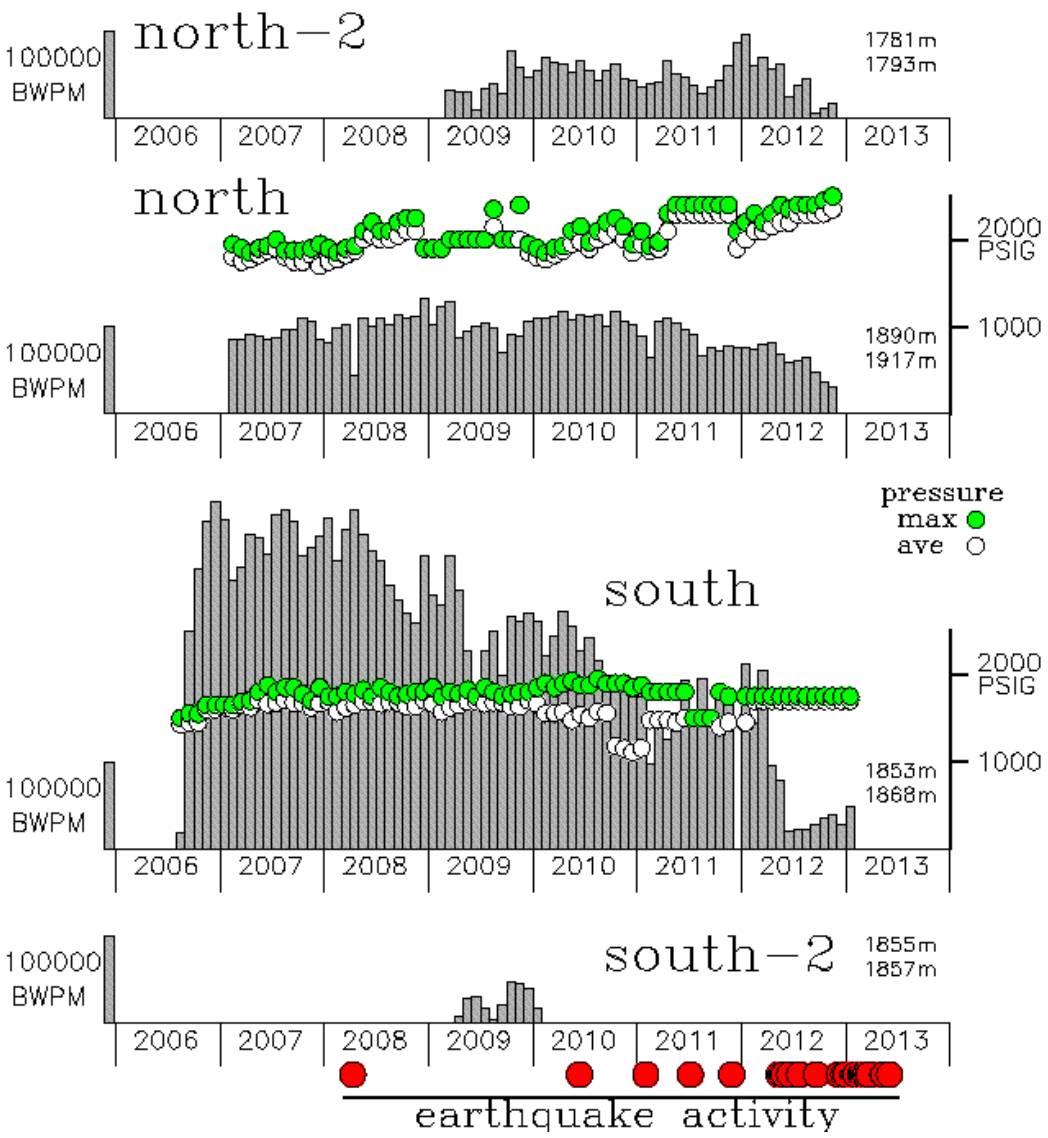
Timson Wastewater Injection Wells



Cumulative Volumes

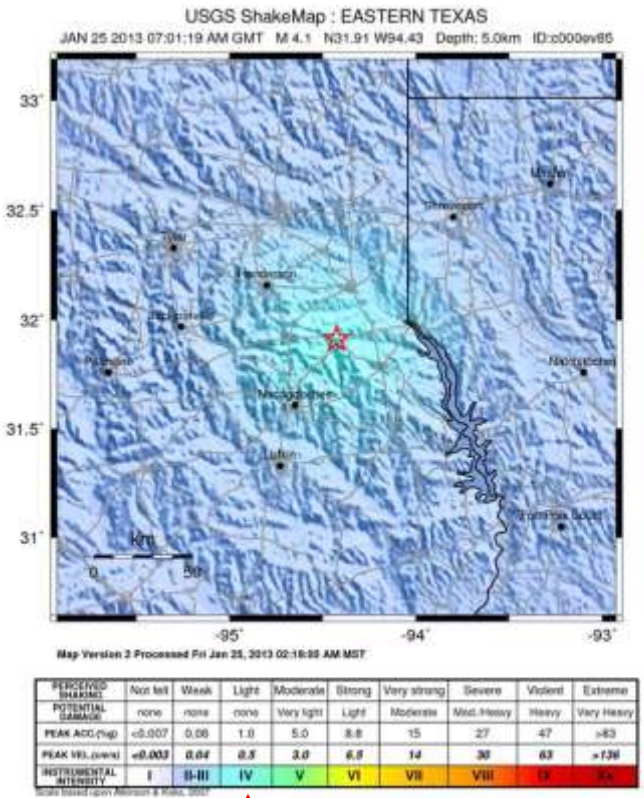
North: 1 million m^3

South: 3 million m^3



Timson M_w 4.1 January 25, 2013

ShakeMap Prediction



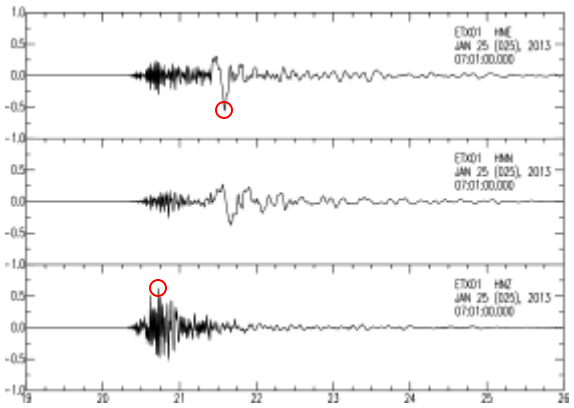
Predicted values from GMPEs too small!

Observed Ground Motions

Acceleration

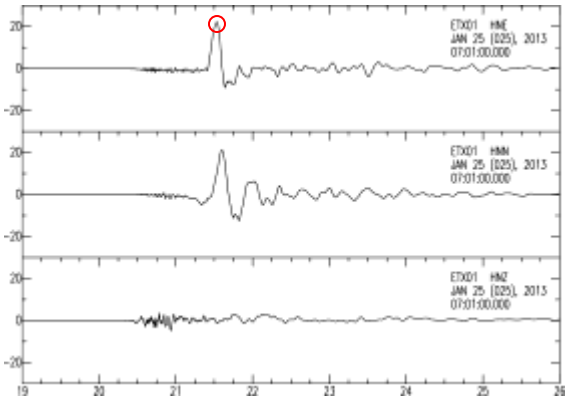
55% g

62% g



Velocity

22 cm/s



USGS

USGS

30 Days, Magnitude 2.5+ Worldwide

1173 earthquakes - Download

Updated: 2013-12-03 16:21:29 UTC-05:00

Showing event times using Local System Time (UTC-05:00)

18 earthquakes in map area

3.6	2km NNW of Azle, Texas 2013-11-19 19:40:35 UTC-05:00	5
3.6	16km N of Mineral Wells, Texas 2013-11-28 02:58:36 UTC-05:00	5
3.3	7km W of Azle, Texas 2013-11-25 02:43:03 UTC-05:00	5.0 km
3.2	2km ENE of Azle, Texas 2013-11-29 01:14:08 UTC-05:00	5.0 km
3.0	1km ESE of Azle, Texas 2013-11-26 09:24:03 UTC-05:00	5.0 km
3.0	5km SSE of Springtown, Texas 2013-11-09 14:54:31 UTC-05:00	5.0 km
2.9	4km ESE of Springtown, Texas 2013-11-07 23:32:57 UTC-05:00	4.8 km
2.9	3km SW of Reno, Texas 2013-11-23 04:43:32 UTC-05:00	4.7 km
2.8	22km SSW of Jacksboro, Texas 2013-11-28 03:41:07 UTC-05:00	5.0 km
2.8	5km E of Springtown, Texas 2013-11-26 15:03:28 UTC-05:00	3.4 km
2.8	3km WNW of Azle, Texas 2013-11-19 13:03:36 UTC-05:00	5.0 km
2.8	1km W of Briar, Texas 2013-11-11 03:30:54 UTC-05:00	5.0 km
2.7	2km ESE of Reno, Texas 2013-12-03 10:44:32 UTC-05:00	5.0 km
2.7	0km SSE of Reno, Texas 2013-11-25 20:55:22 UTC-05:00	5.0 km

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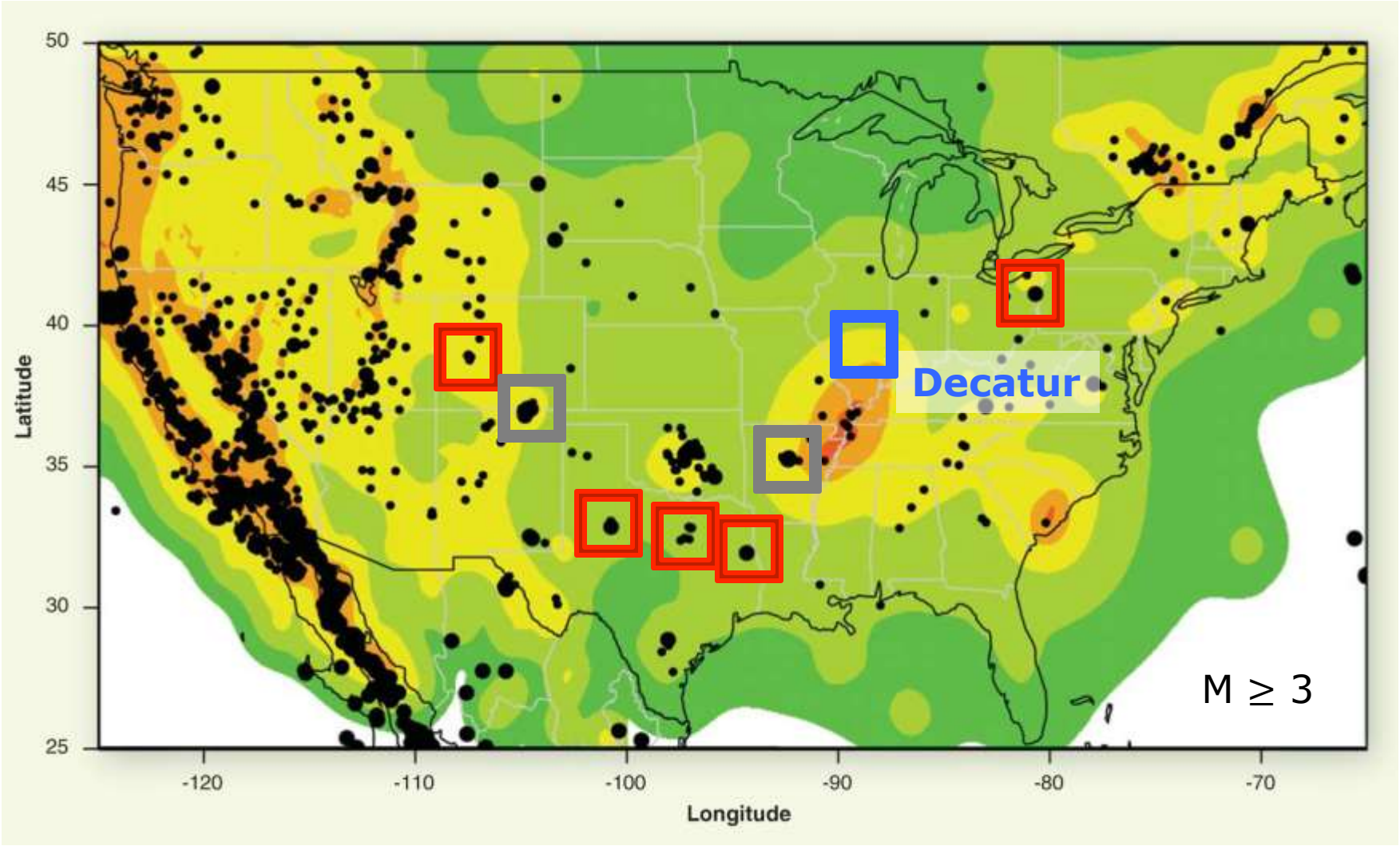
North Texas quakes prompt calls for inquiry into gas drilling as possible cause

USGS

Earthquakes near Azle, TX, Nov-Dec. 2013

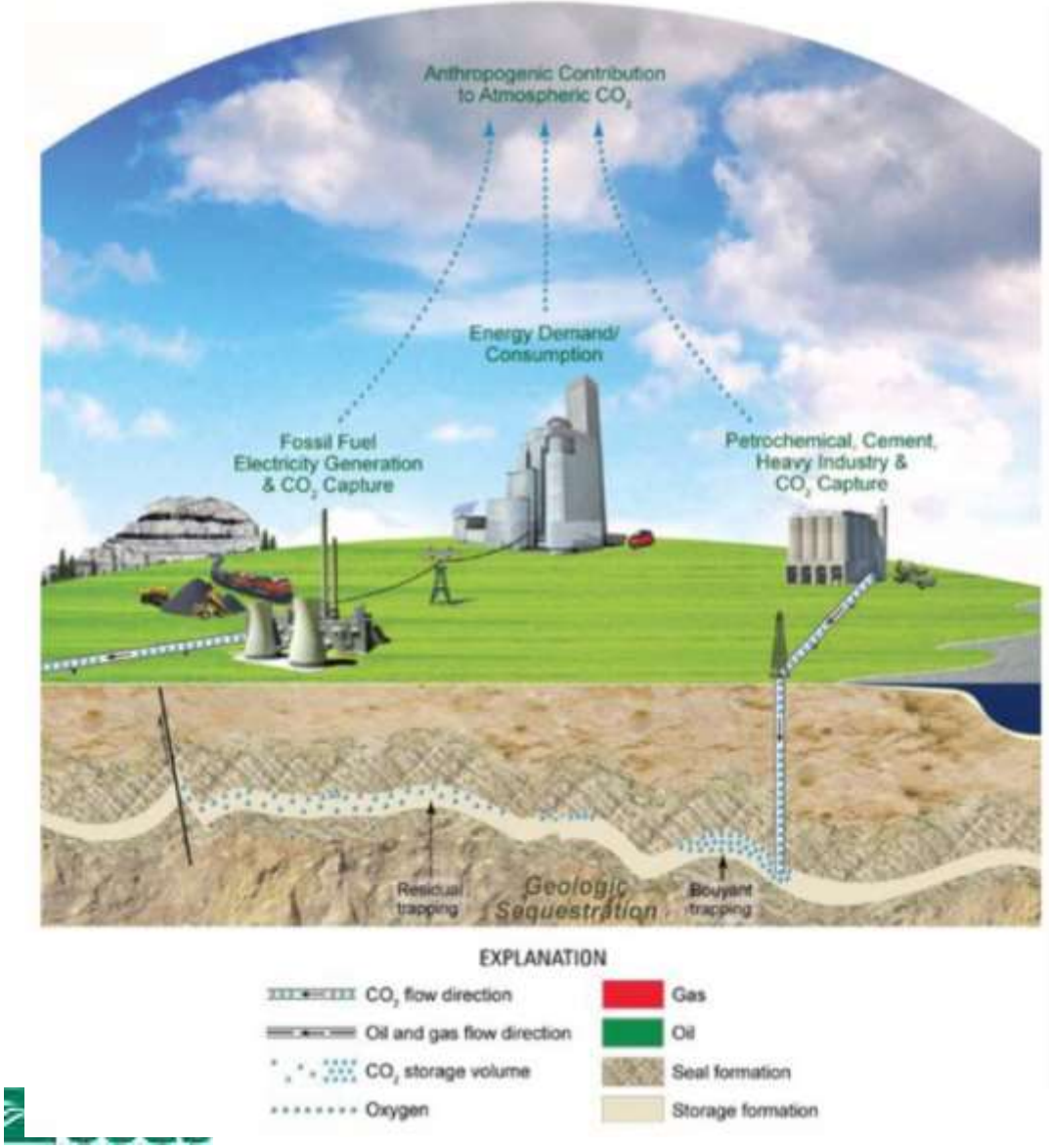
Earthquake Hazard and Seismicity
2009 - 2012



Ellsworth, W. L., 2012, Injection-Induced Earthquakes, *Science*, v. 341, doi: 10.1126/science.1225942

Hitzman et al., *Induced Seismicity Potential in Energy Technologies*
National Research Council, 2012

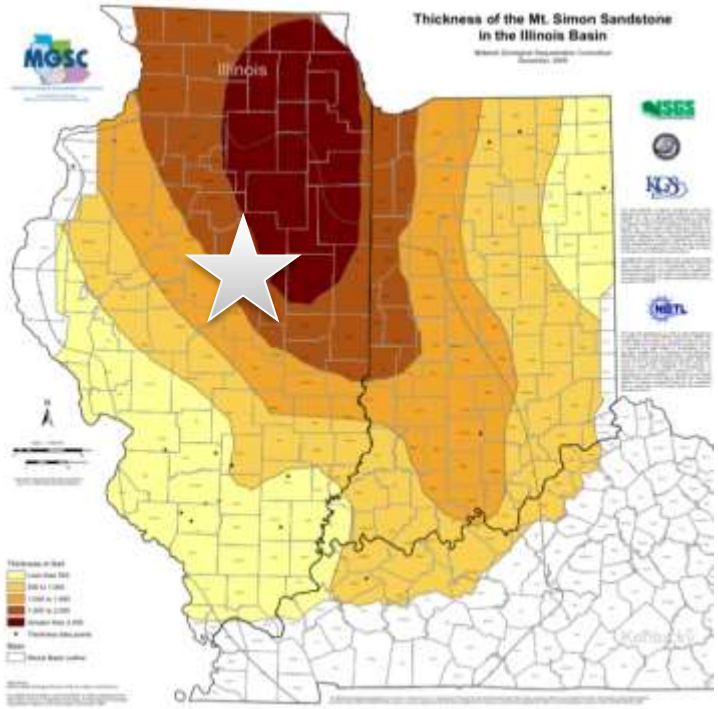
Carbon Capture and Sequestration



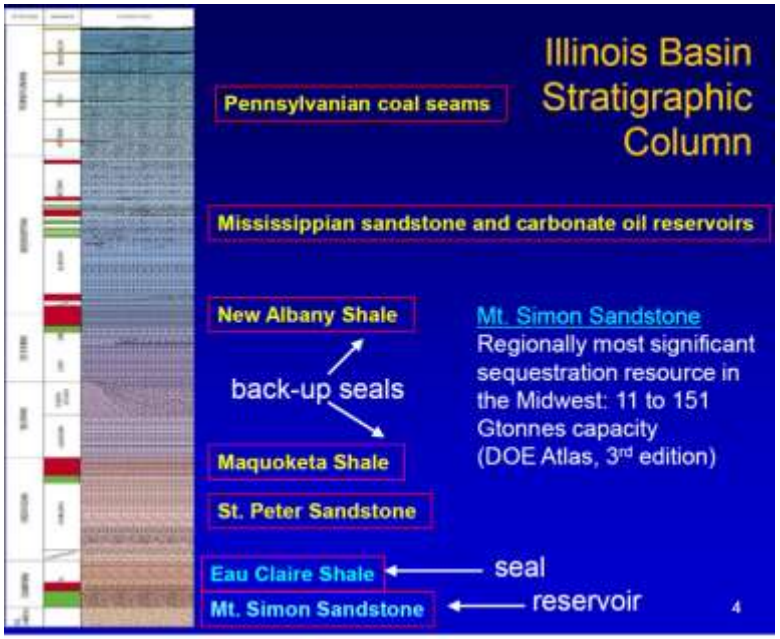
"The proposed injection volumes of liquid CO_2 in large-scale sequestration projects are much larger than those associated with other energy technologies. There is no experience with fluid injection at these large scales and little data on seismicity associated with CO_2 pilot projects. If the reservoirs behave in a similar manner to oil and gas fields, these large net volumes may have the potential to impact the pore pressure over vast areas . . such large spatial areas may have potential to increase both the number and magnitude of seismic events."

Background on Decatur CCS Project:

- Injection of 1000 tonnes/day CO_2 at Archer Daniels Midland ethanol production plant began in November 2011, into Mount Simon Sandstone at 2.1 km depth, resting directly on top of pre-Cambrian basement. Site is located in city of Decatur IL (population ~100,000).
- Permitting to increase injection to commercial scale (~3000 tonnes/day) is underway through U.S. EPA.
- The Illinois State Geological Survey manages the ongoing *Illinois Basin - Decatur Project* (IBDP) while ADM manages the *Illinois Industrial Carbon Capture and Storage* project (ICCS), which will add ~2000 tonnes/day capacity.
- Funding from DOE and industry collaborators: ADM and Schlumberger. Schlumberger already operates a 31-level borehole geophone array at this site, with plans for additional stations.
- USGS has set up an independent, 12-station seismic network at Decatur, with terms on data sharing and scientific cooperation at Decatur now being negotiated with the ISGS and ADM.



courtesy of Illinois State Geological Survey



USGS Seismic Monitoring Network at Decatur

Three 500-ft-deep borehole + surface stations (DEC01, 02, 03) and nine surface stations
Field work end of Oct 2013: installed final station (DEC06), optimized entire network

USGS

Some Conclusions and Observations

- Fluid injection, but not fracking, is primarily responsible for the recent increase in midcontinent seismicity, through the well-understood effective stress mechanism.

- Although very few injection wells have seismicity associated with them, ancient faults have ruptured in triggered earthquakes with magnitudes up to M_w 5.6.

- We currently have very limited predictive capability due to:
  - Uncertainty in the stress state and pore pressure
  - Rudimentary knowledge of flow paths
  - Poor knowledge of potentially capable faults
  - Poor detection and location capabilities of seismic networks
  - Difficulty in predicting how large an earthquake will grow

- Injection parameter data are typically inadequate for scientific study.

USGS

Additional Resources at USGS

Update on Manmade Earthquakes
http://www.usgs.gov/blogs/features/usgs_top_story/man-made-earthquakes/

FAQ on earthquakes induced by fluid injection
http://www.usgs.gov/faq/?q=taxonomy/term/9833

Earthquake swarm continues in central Oklahoma
http://www.usgs.gov/newsroom/article.asp?ID=3710&from=rss

Shale, Hydraulic Fracturing and Induced Earthquakes (4/4/12)
http://gallery.usgs.gov/videos/533

Injection Induced Earthquakes (taped presentation, 12-2-13)
http://media.wr.usgs.gov/colloquium/WRC_02dec13.mp4

Injection Induced Earthquakes (review article, Science, 2013)
http://pubs.er.usgs.gov/publication/70048668

Modeling earthquake rate changes in Oklahoma and Arkansas: possible signatures of induced seismicity
http://pubs.er.usgs.gov/publication/70048493

Significant Induced Earthquakes in the Central and Eastern U.S. Since 2008
http://earthquake.usgs.gov/hazards/about/workshops/CEUS-WORKSHP/2.22.2012/Rubinstein2012InducedEqs.pdf

USGS