

USGS Research into the Causes & Consequences of Injection-Induced Seismicity

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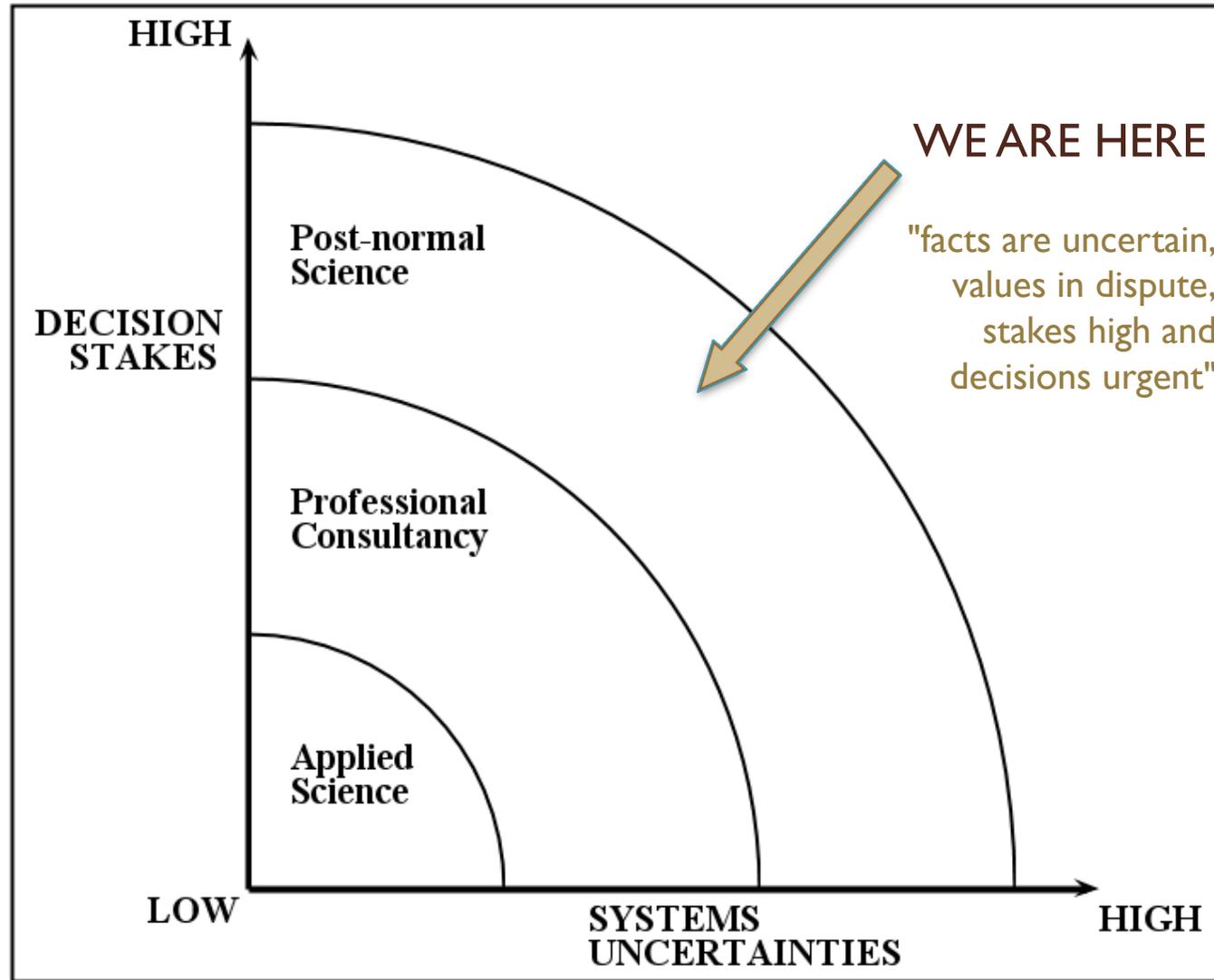
United States Geological Survey (USGS),
earthquakes, issued a "rare earthquake
warning" that a strong earthquake could
occur. The warning is not a
hype.

The Geological Survey on May 2 advising
that a strong earthquake could occur
in Oklahoma could signal that a larger

earthquake has occurred
remarkably since October 2013 –
the first since for a damaging magnitude



Induced earthquake environment



Funtowicz and Ravetz, 1991

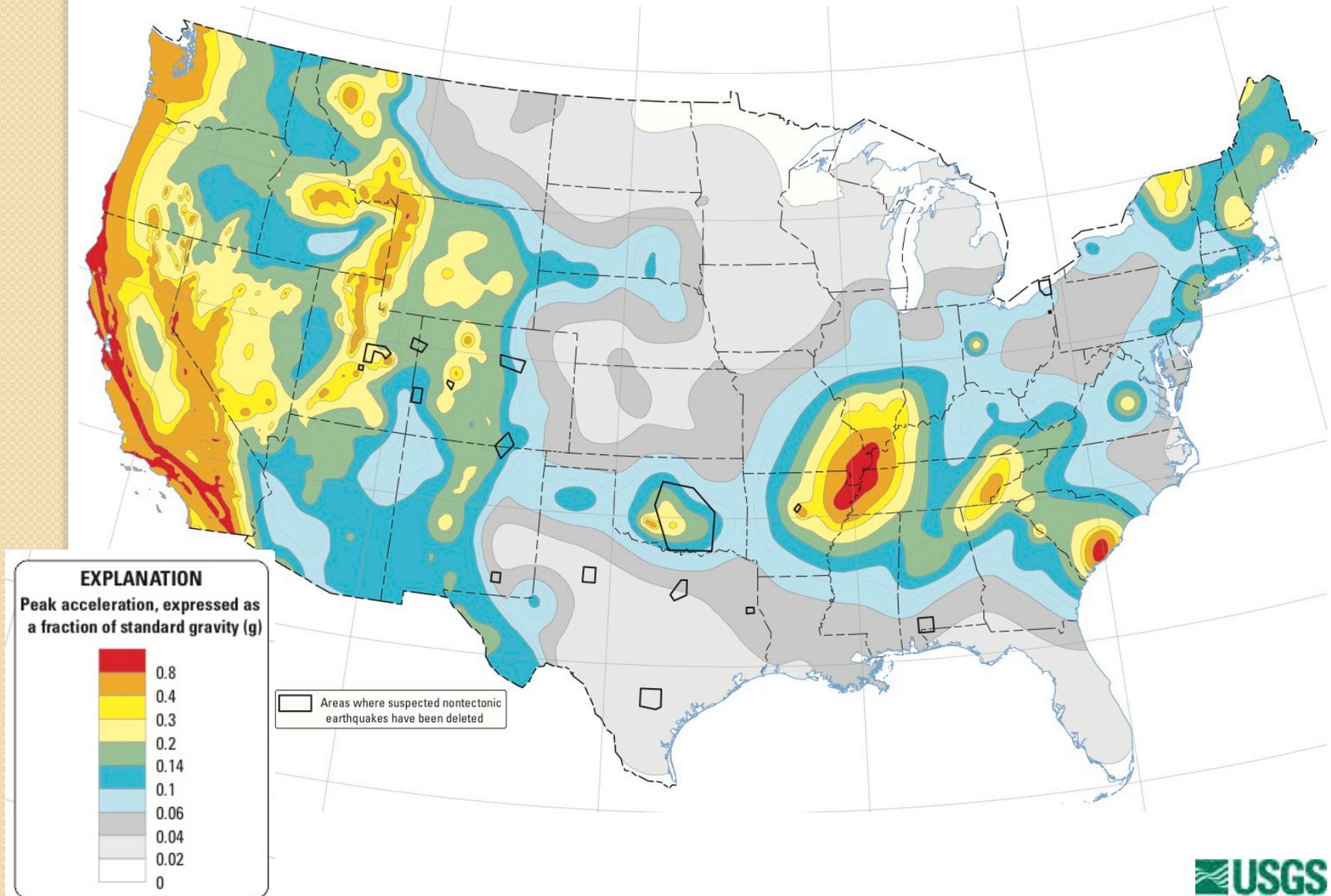
Injection-induced earthquakes: Who wants to know?

- 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
 - Safety, adequate regulation?
- Private facility owners
(risk mitigation)
 - Dams, hospitals, power, etc.

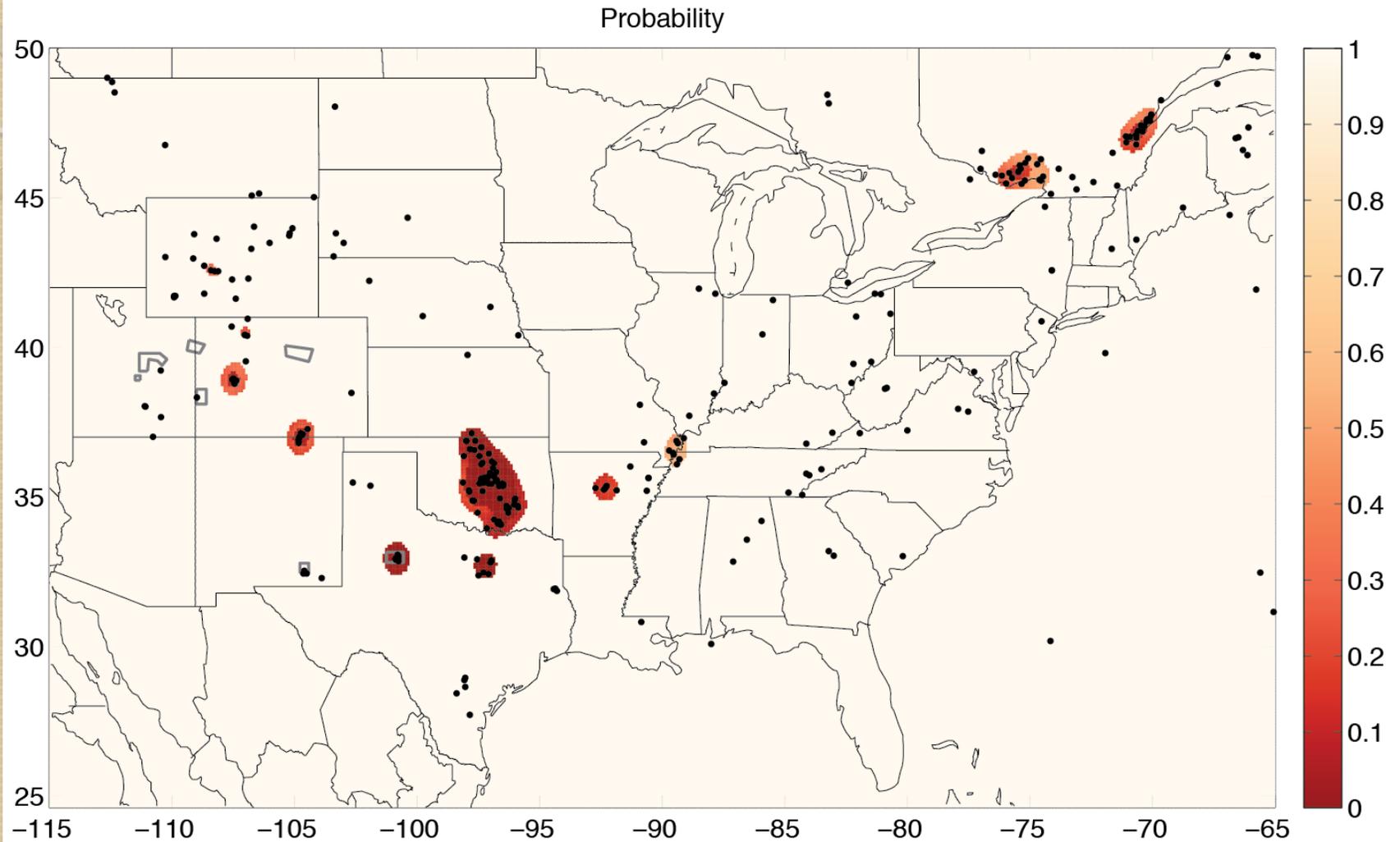


U. S. National Seismic Hazard Map (2014)

with areas of known or suspected induced seismicity removed from calculations

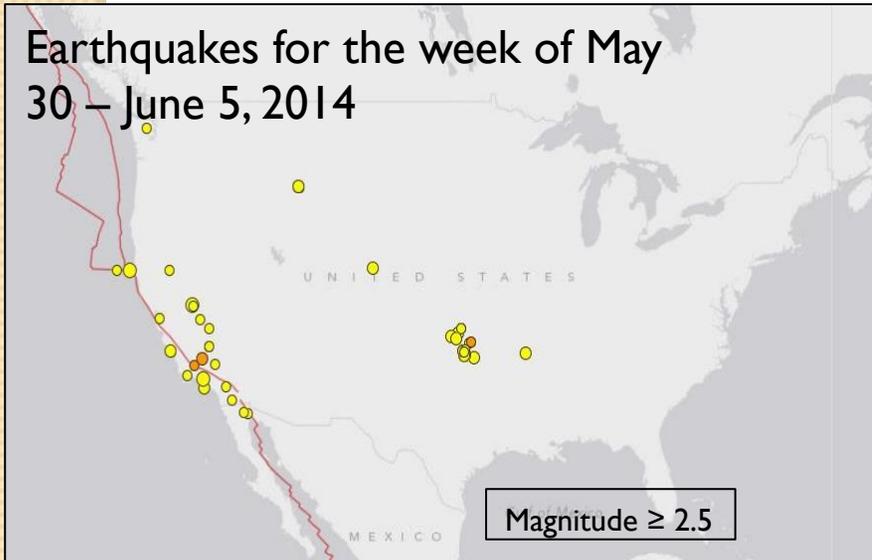


Excess earthquakes, 2009-2013

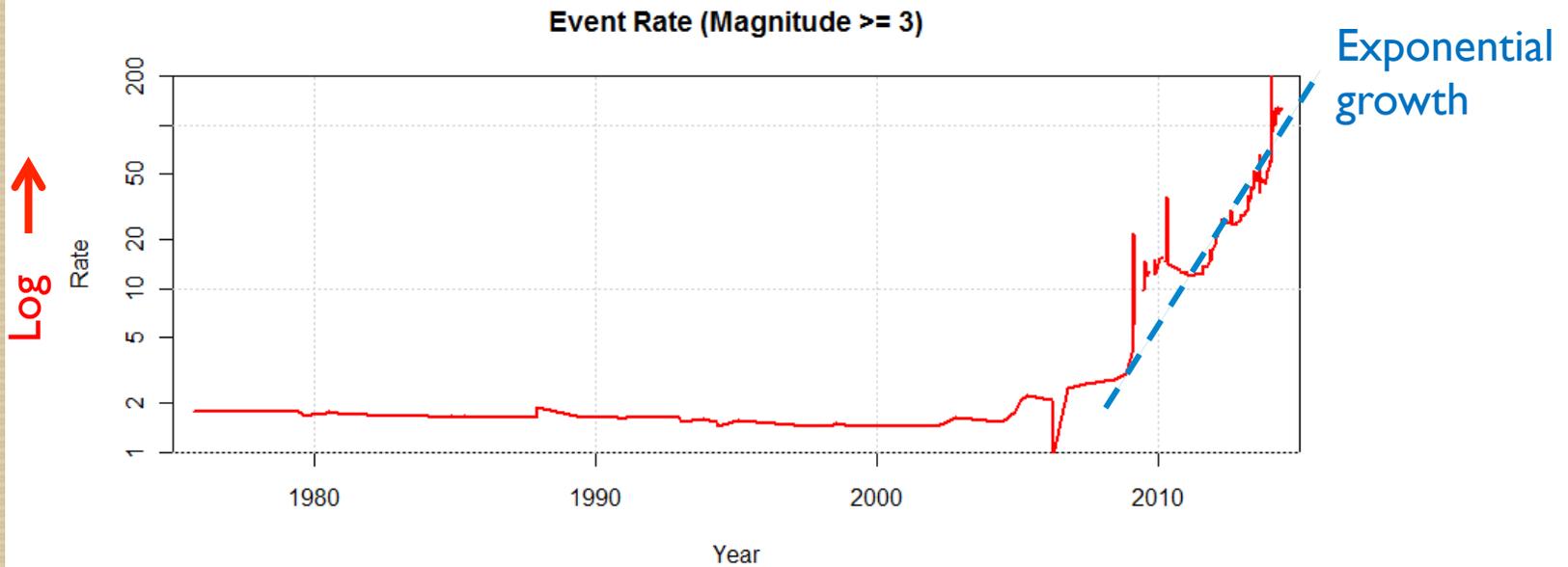


Content is preliminary and should not be considered a final USGS product.

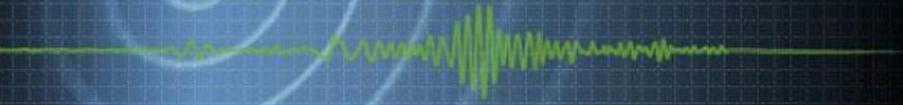
Earthquakes for the week of May 30 – June 5, 2014



Unprecedented increase in seismicity in Oklahoma...



... implies increased large-earthquake risk



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Record Number of Oklahoma Tremors Raises Possibility of Damaging Earthquakes

*Updated USGS-Oklahoma Geological Survey Joint Statement on Oklahoma Earthquakes
Originally Released: 10/22/2013 1:07:59 PM; Updated May 2, 2014*

The rate of earthquakes in Oklahoma has increased remarkably since October 2013 – by about 50 percent – significantly increasing the chance for a damaging magnitude 5.5 or greater quake in central Oklahoma.

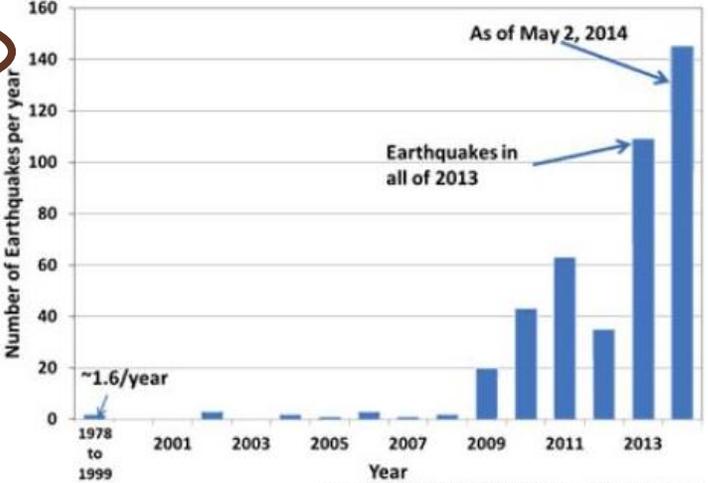
[View map of Oklahoma seismicity.](#)
[View animation of Oklahoma Seismicity.](#)

A new U.S. Geological Survey and Oklahoma Geological Survey analysis found that 145 earthquakes of magnitude 3.0 or greater occurred in Oklahoma from

January 2014 (through May 2; see accompanying graphic). The previous annual record, set in 2013, was 109 earthquakes, while the long-term average earthquake rate, from 1978 to 2008, was just two magnitude 3.0 or larger earthquakes per year. Important to people living in central and north-central Oklahoma is that the likelihood of future, damaging earthquakes has increased as a result of the increased number of small and moderate shocks.



Oklahoma Earthquakes Magnitude 3.0 and greater



Year	Number of Earthquakes per year
1978 to 1999	~1.6
2001	2
2002	2
2003	2
2004	2
2005	2
2006	2
2007	2
2008	2
2009	20
2010	42
2011	62
2012	35
2013	109
2014 (as of May 2)	145

Source: USGS-NEIC ComCat & Oklahoma Geological Survey; May 2, 2014

Induced earthquakes – a primer

1. It is well established that moderate-size earthquakes can be triggered by fluid injection: it is established in theory, demonstrated in the laboratory, validated in field testing, and there are many places worldwide where injections have been stopped and the earthquakes stopped as well.
2. Fracking is rarely the cause of felt earthquakes (in the U.S!), and many injection-triggered earthquakes are unrelated to fracking at all.
3. Triggered earthquakes can cause significant damage.
4. Communities where earthquakes are being felt should be concerned, as should owners and operators of critical infrastructure near where large volumes are being injected.
5. Important data on injections are either not being collected at all, or are not readily available, or are not accurate. This compromises scientific progress and effective decision-making.

Induced earthquakes – some recent papers

McGarr, A. (2014), Maximum magnitude earthquakes induced by fluid injection, *Journal of Geophysical Research*.

Rubinstein, J.L., and others (2014), The 2001-Present Triggered Earthquake Sequence in the Raton Basin of Northern New Mexico and Southern Colorado, (BSSA).

Hough, S.E. (2014), Shaking from Injection-Induced Earthquakes in the Central and Eastern United States (BSSA).

Frohlich, C. and others (2014), The 17 May 2012 M4.8 earthquake near Timpson, East Texas: An event possibly triggered by fluid injection (JGR)

Ellsworth, W.L. (2013), Injection-induced earthquakes, *Science*.

Keranen, K.M., and others (2013), Potentially induced earthquakes in Oklahoma: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence (*Geology*)

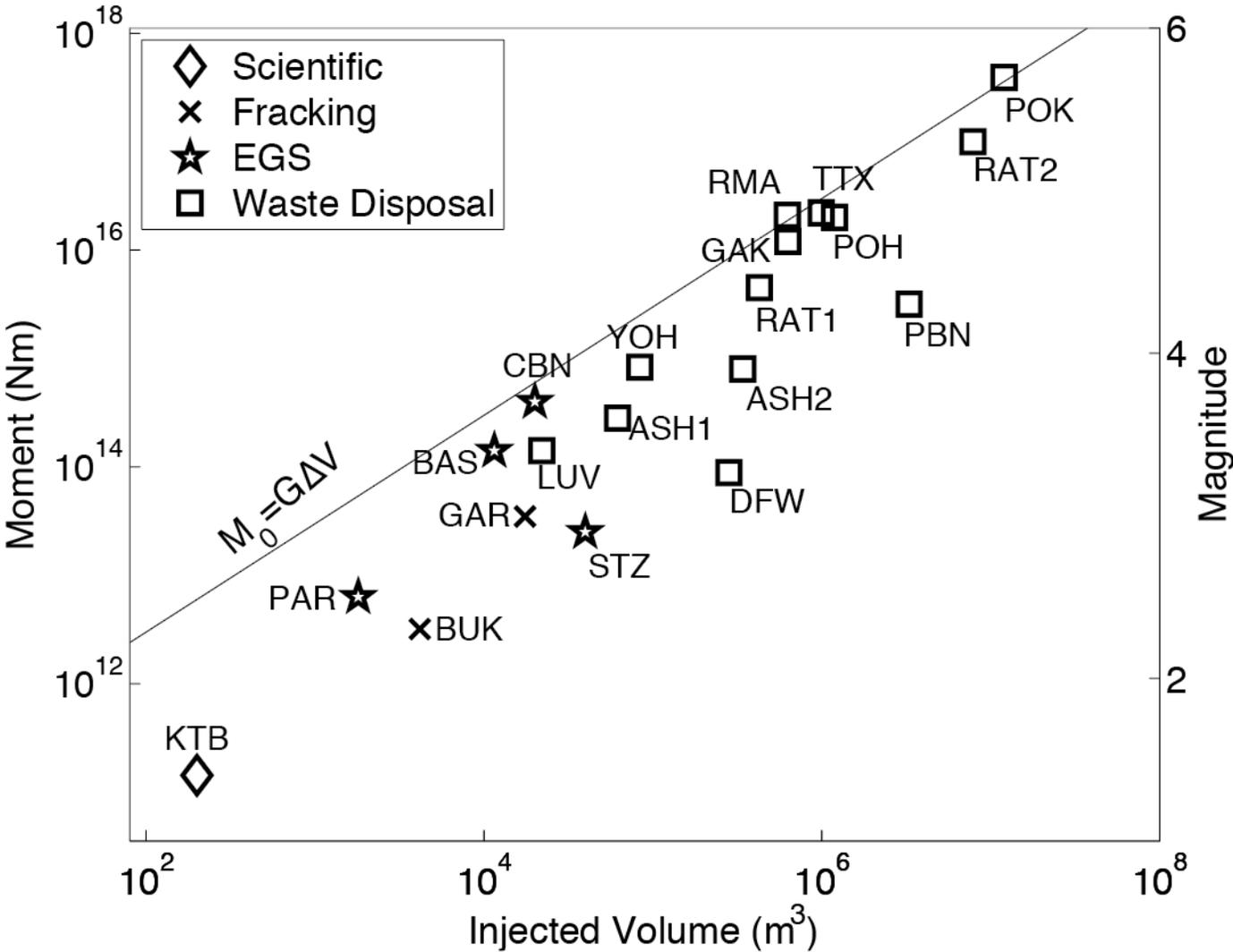
Llenos, A.L. and A.J. Michael (2013), Modeling earthquake rate changes in Oklahoma and Arkansas: Possible signatures of induced seismicity (BSSA).

Sumy, D.F., and others (2013), The mechanisms and stress triggering of earthquakes during the November 2011 M5.7 Oklahoma earthquake sequence (JGR).

Kim, W-Y (2013), Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio (JGR).

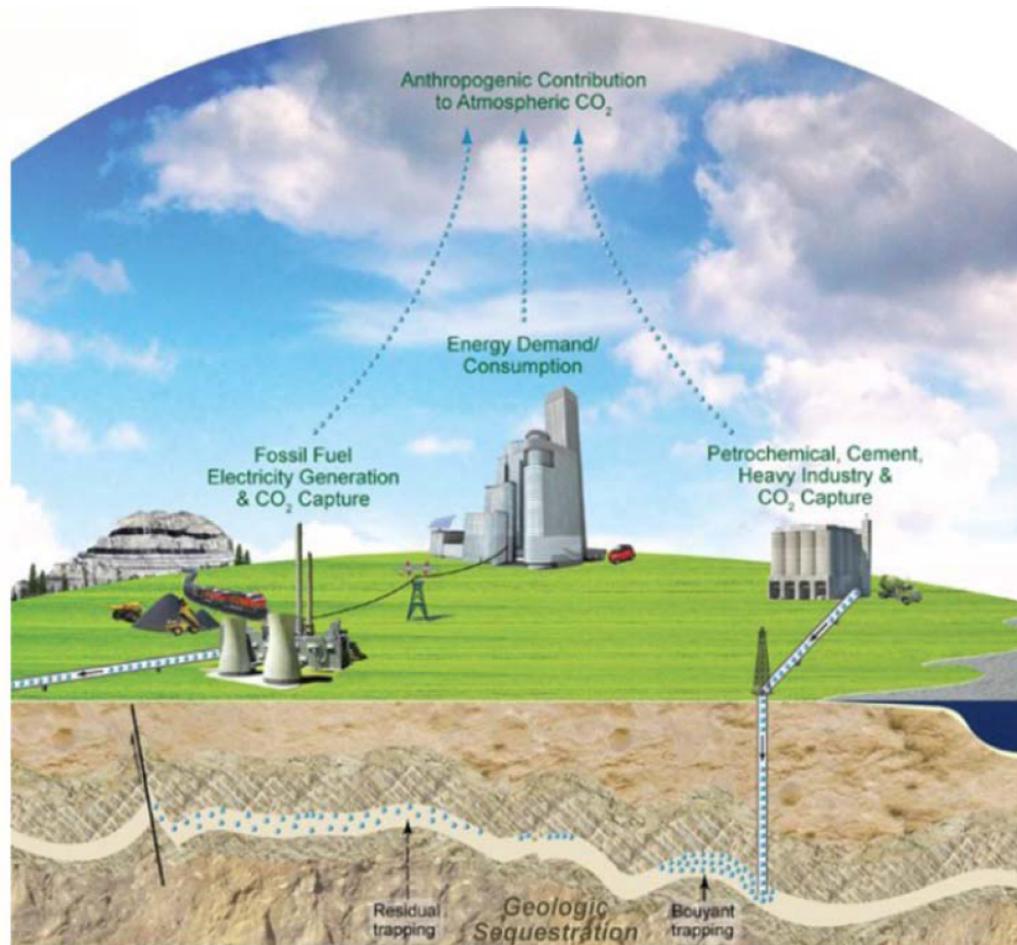
Frohlich, C. (2013), Induced Earthquakes Are Not All Alike: Examples from Texas Since 2008 (EOS Trans. AGU)

Maximum magnitude scales with volume



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

Carbon Capture and Sequestration



EXPLANATION

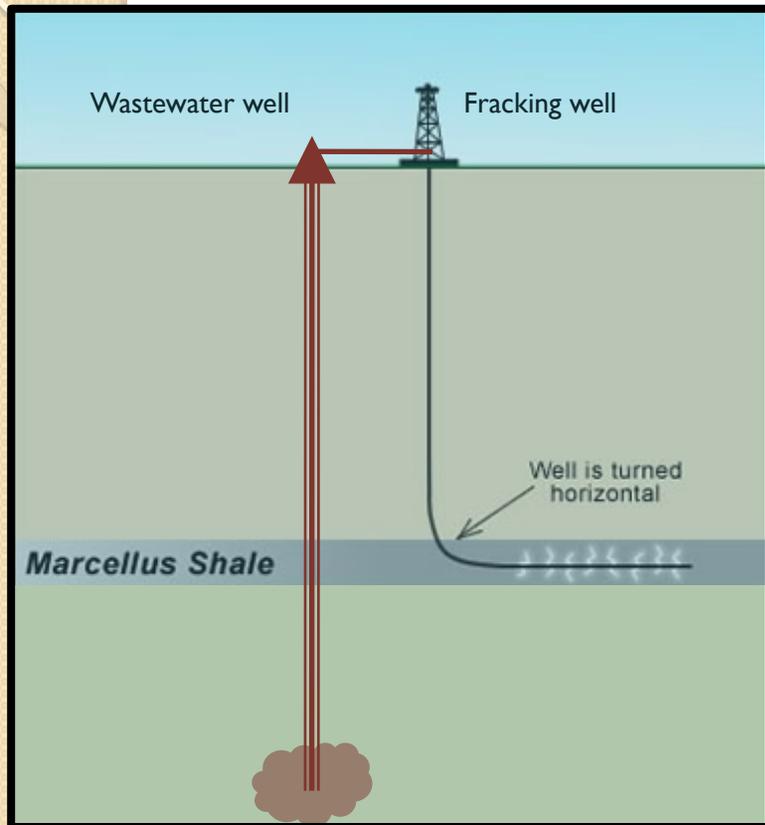
 CO ₂ flow direction	 Gas
 Oil and gas flow direction	 Oil
 CO ₂ storage volume	 Seal formation
 Oxygen	 Storage formation

“The proposed injection volumes of liquid CO₂ 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 CO₂ 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.”

Fracking and Wastewater Injection



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 $> 10^6$ m³

Few with detected seismicity

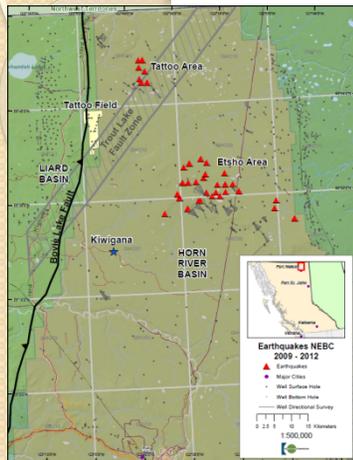
Magnitudes as large as M_w 5.6



Fracking and Earthquakes:

Investigation of Observed Seismicity in the Horn River Basin

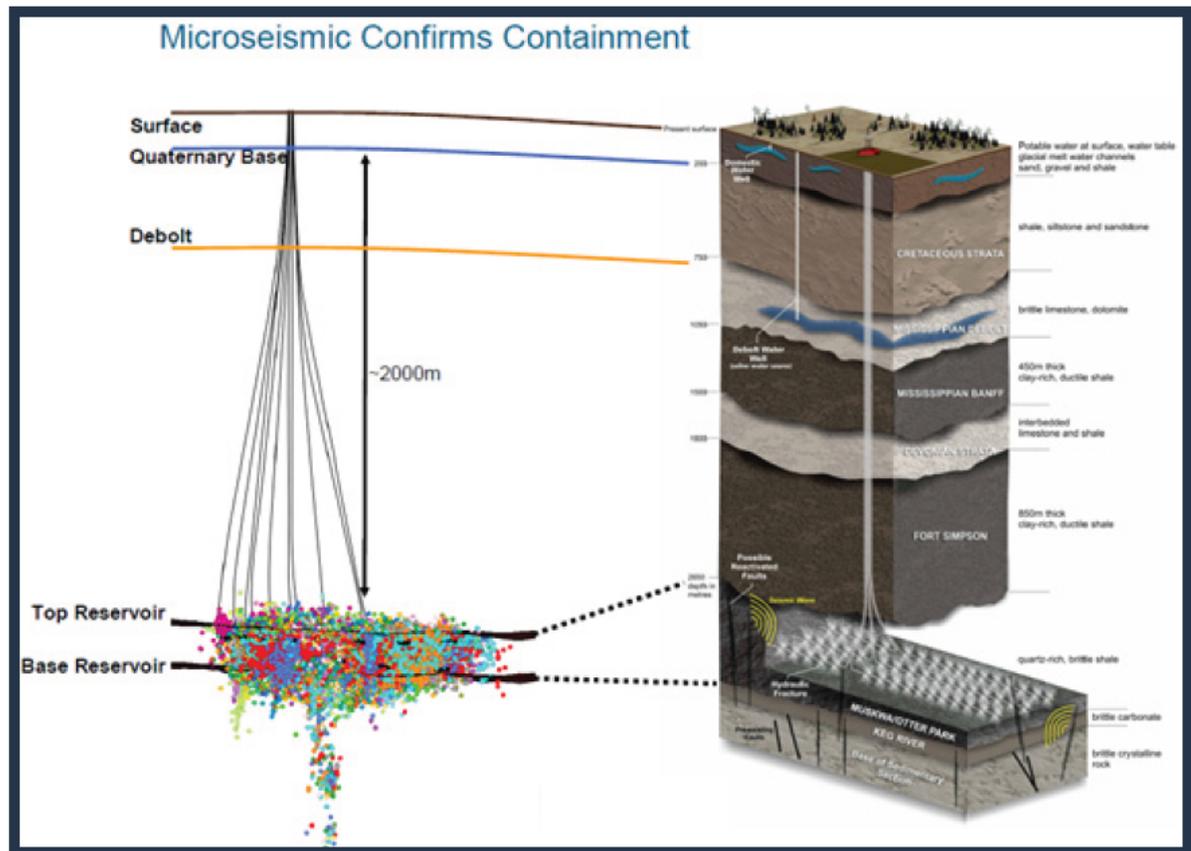
BC Oil and Gas Commission - August 2012



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.



Ohio Earthquakes Linked To Fracking, A First For Region

AP | By JULIE CARR SMYTH

Posted: 04/11/2014 7:55 pm EDT | Updated: 04/11/2014 7:59 pm EDT

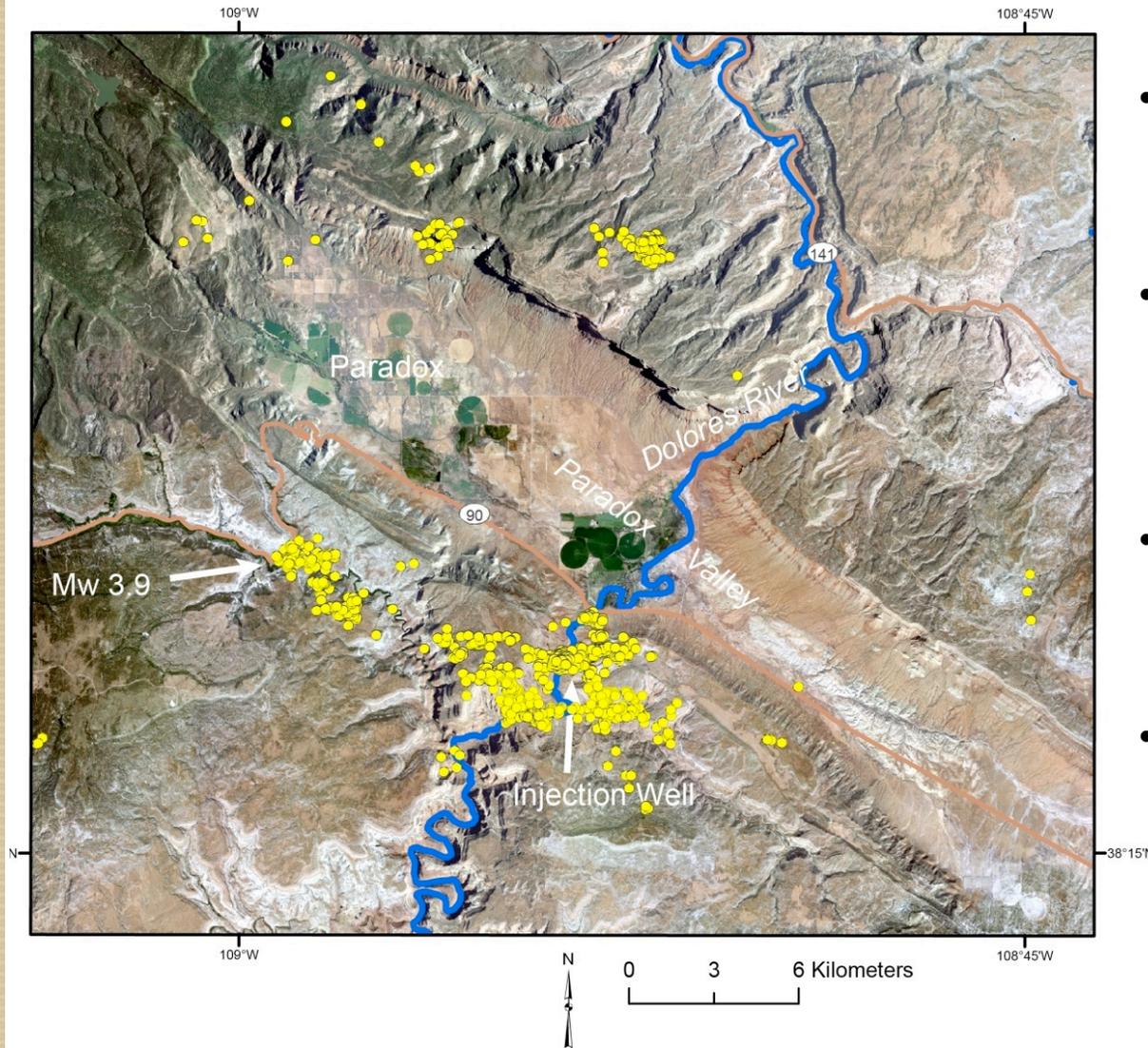


20k	6499	719	1	565	1267
Like	Share	Tweet	Pin it	Email	Comment



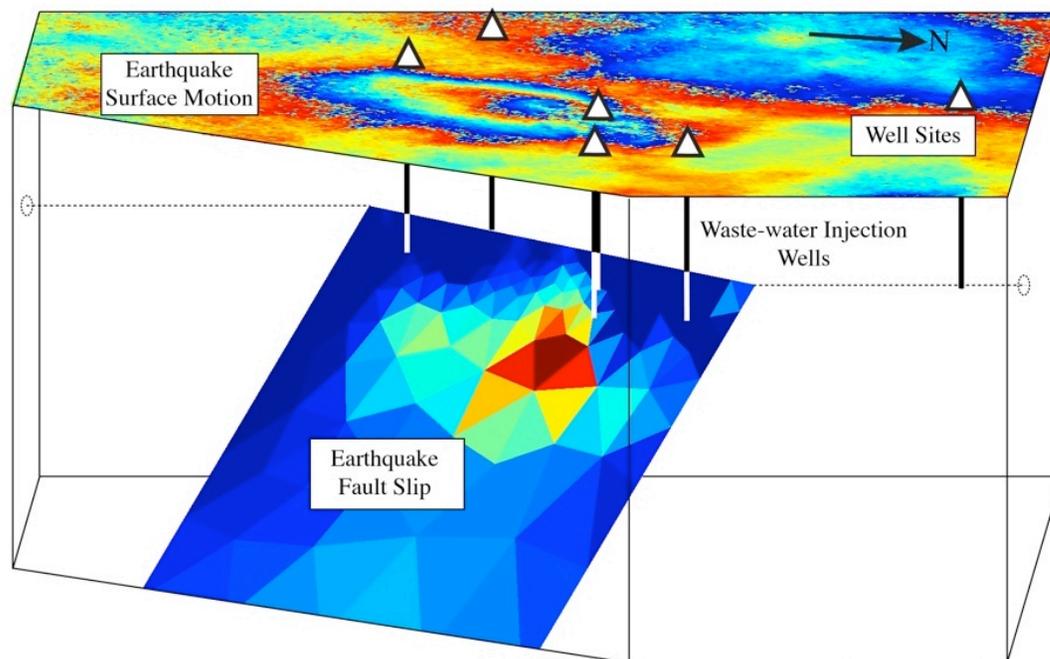
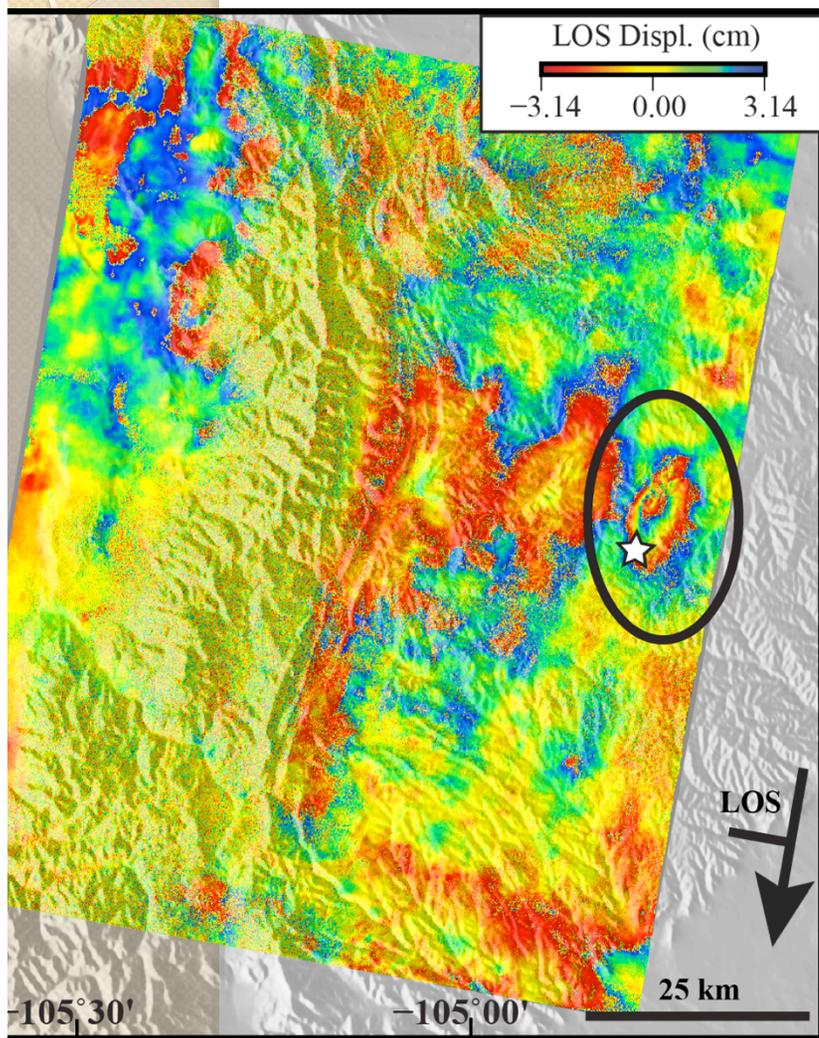
COLUMBUS, Ohio (AP) — Geologists in Ohio have for the first time linked earthquakes in a geologic formation deep under the Appalachians to hydraulic fracturing, leading the state to issue new permit conditions Friday in certain areas that are among the nation's strictest.

January 25, 2013 M_w 3.9 Paradox Valley Earthquake

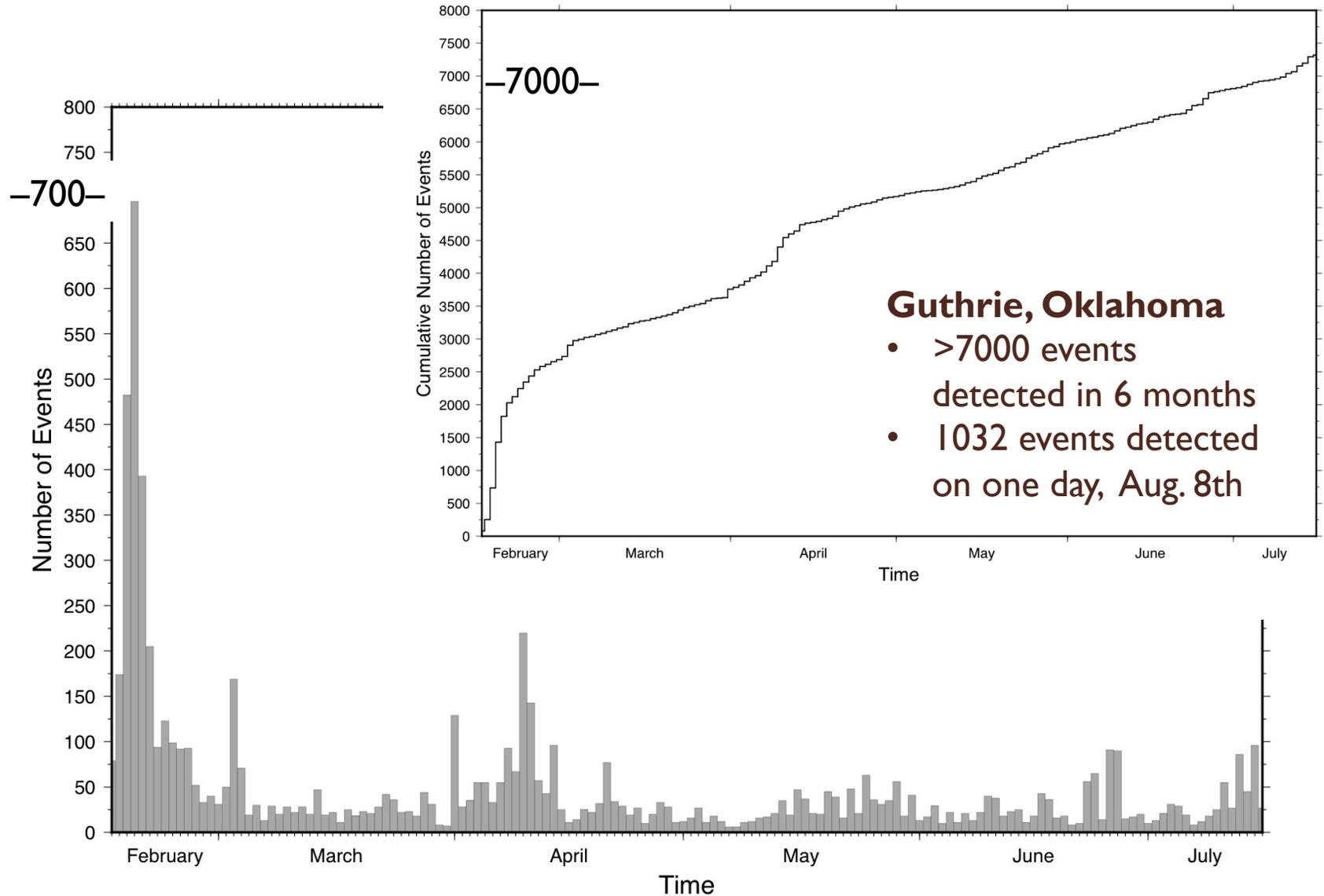


- Triggering up to **8 km** from brine disposal well
- Small magnitude activity within 1 year of start of injection
- M_w 3.9 delayed **16 years** after injection began
- Bureau of Reclamation reconsidering future of injection

Ground subsidence associated with the 2011 M5.3 Trinidad Earthquake (from InSAR)



Induced earthquakes at Guthrie, Oklahoma

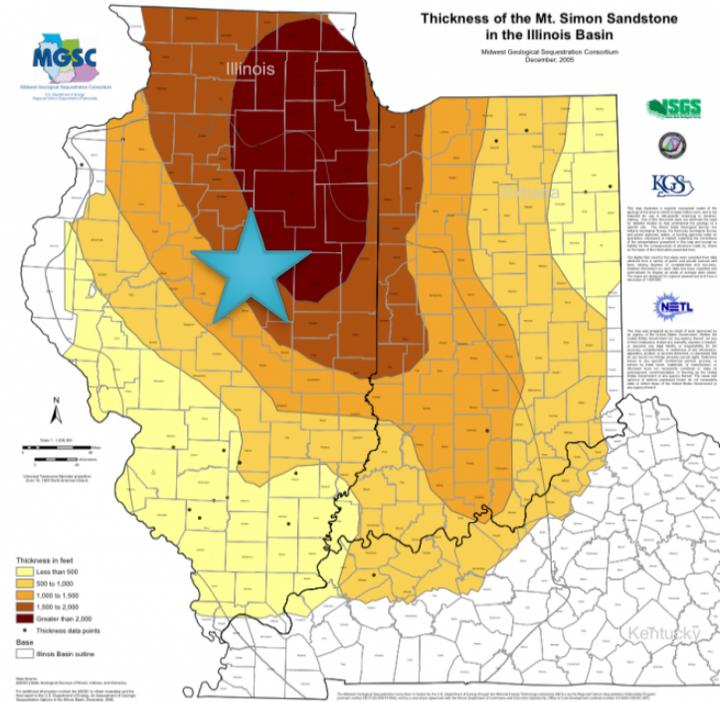


Courtesy of Harley Benz, USGS (benz@usgs.gov)

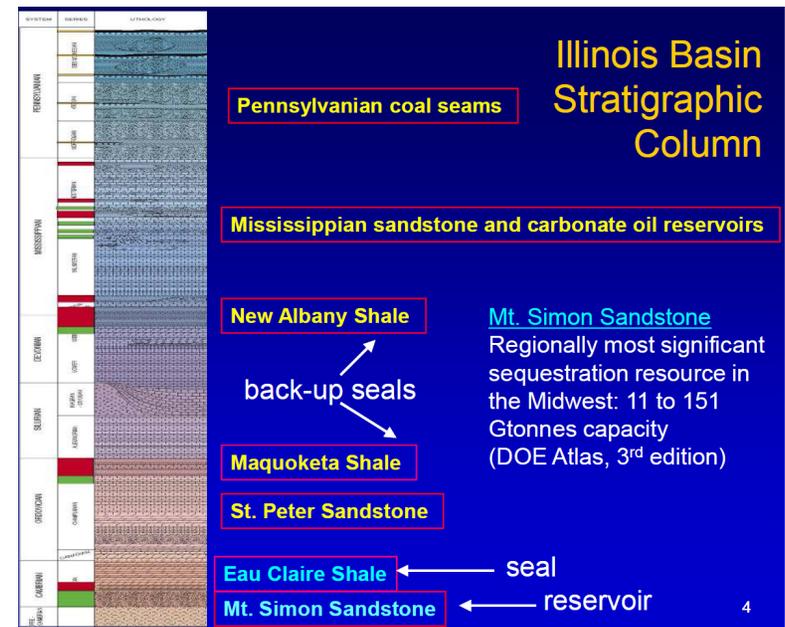


Decatur CCS Project:

- Injection of 1 000 tonnes/day CO₂ 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 (pop. ~100,000)
- Permitting to increase injection to commercial scale (~3000 tons/day) 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 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 data sharing and scientific cooperation with the ISGS and ADM.

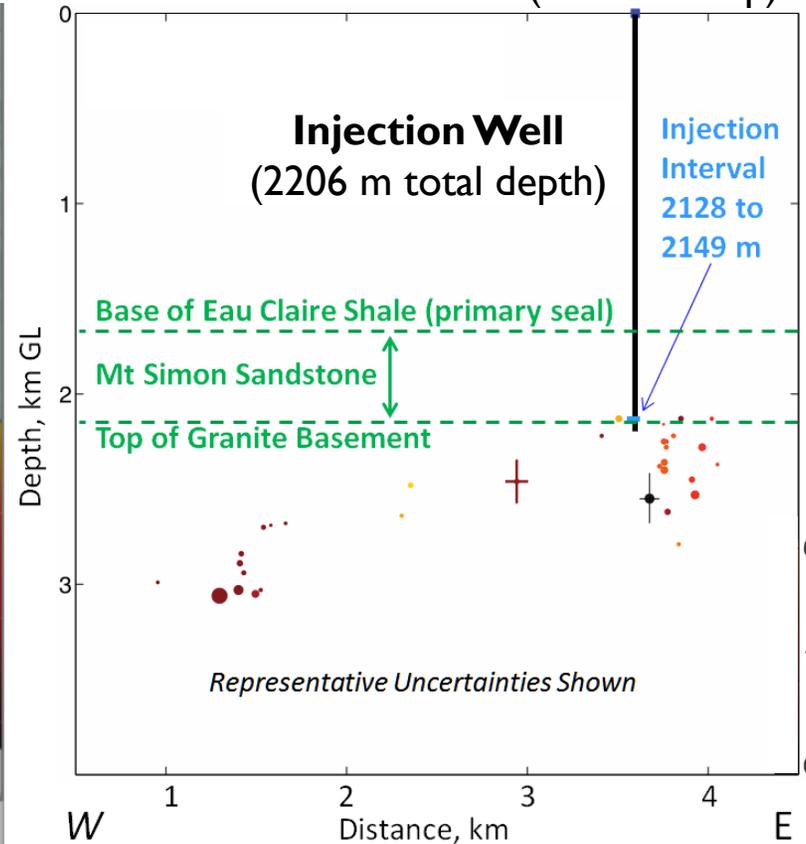
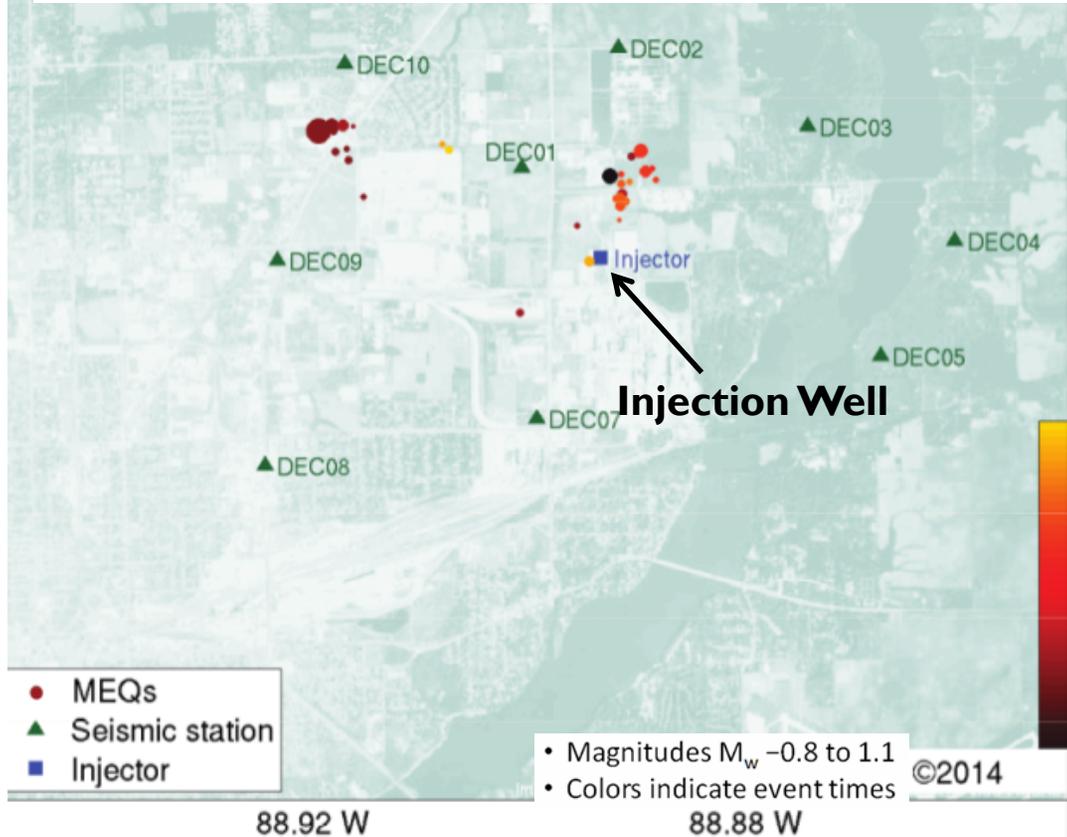


courtesy of Illinois State Geological Survey

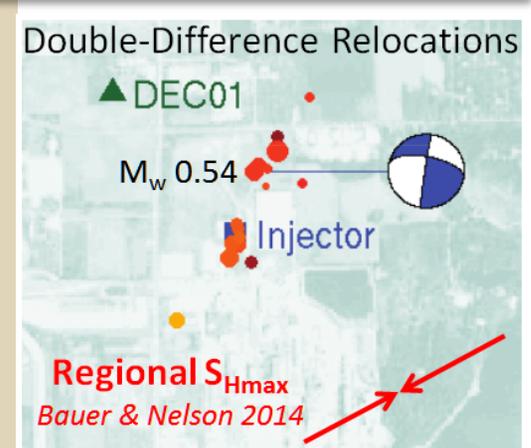


A valuable partnership at the Decatur CCS pilot site

Injection Well
(2206 m deep)



- 12-station network installed by USGS in 2013 (*green triangles*), using surface and shallow borehole sensors.
- Events to date are very small (M_w -0.8 to 1.1) and group into two clusters: Close to injection well and 1.8 to 2.6 km to the W-NW.
- Most microearthquakes are in granite basement, well below the caprock, and are unlikely to have compromised seal integrity.
- Earthquake relocations, a preliminary focal mechanism and regional stress directions suggest that some of this activity is due to reactivation of basement faults that are well oriented for slip.



Some Conclusions and Observations

- Fluid injection is primarily responsible for the recent increase in midcontinent seismicity through the well-understood effective stress mechanism. Fracking is only rarely the cause of felt earthquakes.
- Although very few injection wells have seismicity associated with them faults have ruptured in induced earthquakes with magnitudes up to M_w 5.6.
- Maximum magnitude appears to scale with total injected volume.
- We currently have very limited predictive capability due to:
 - Uncertainty in the stress state and pore pressure
 - Rudimentary knowledge of, or data on, 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.