

Is Maximum Magnitude ( $M_{max}$ )  
different for induced seismicity?

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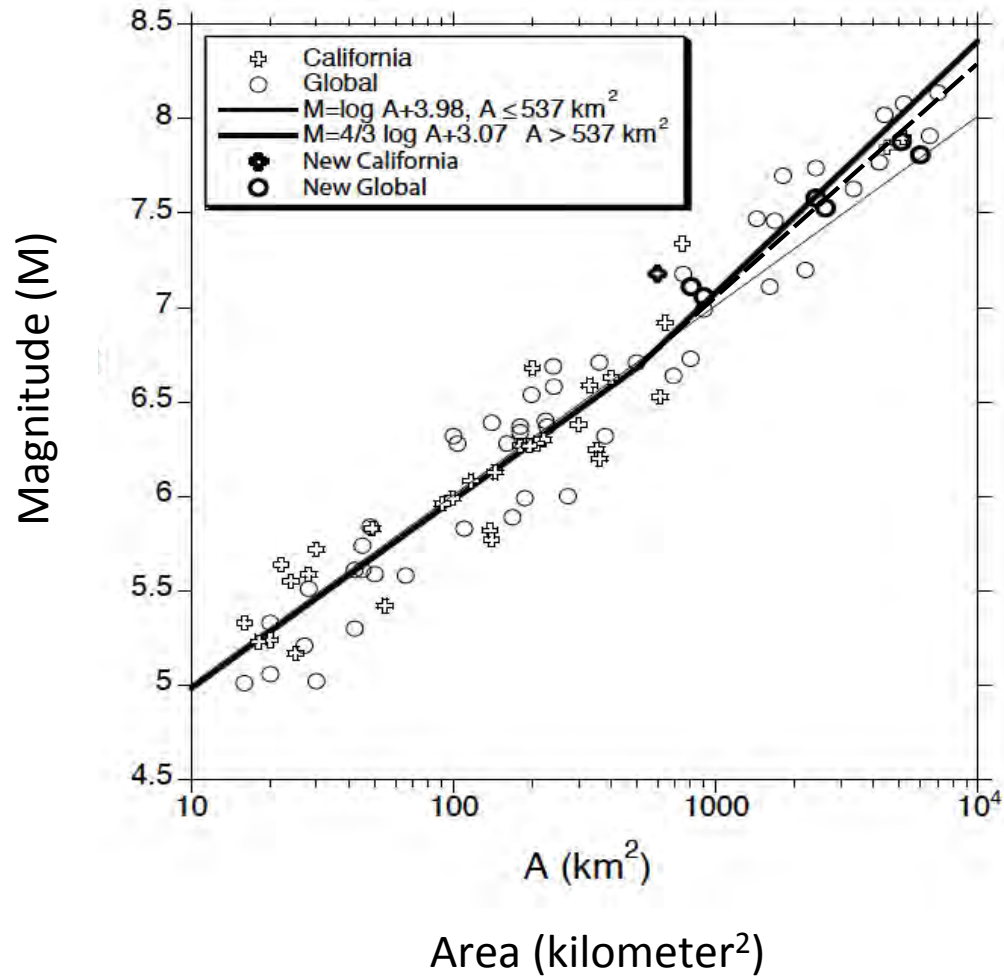
# Two hypotheses for what limits maximum magnitudes of fluid-induced earthquakes

- Hypothesis 1:  $M_{\max}$  limited according to the size of the largest nearby fault that is well oriented for slip in the ambient stress field.
- Hypothesis 2: Injection parameters limit  $M_{\max}$ .

# Magnitude–Log Area Relation

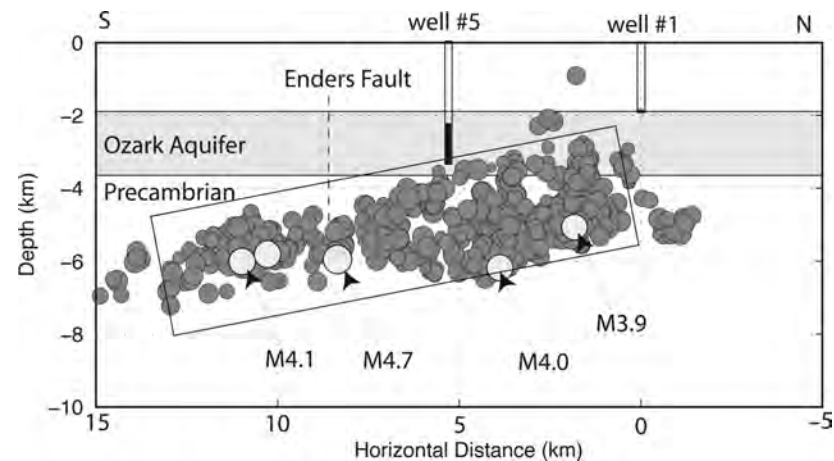
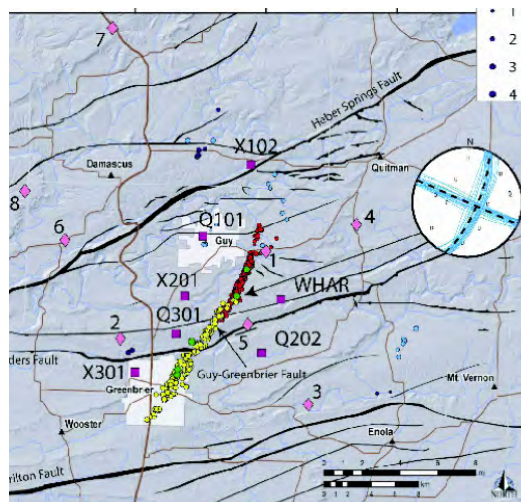
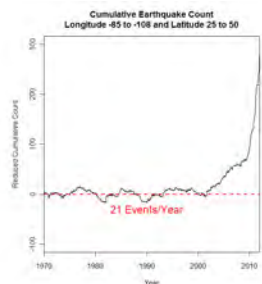
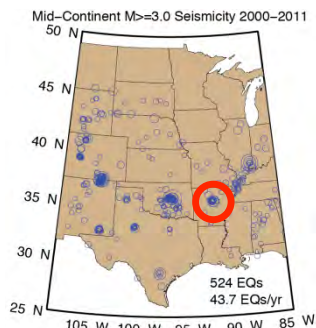
for continental strike-slip earthquakes

Hanks and Bakun, BSSA (2008, 2014)

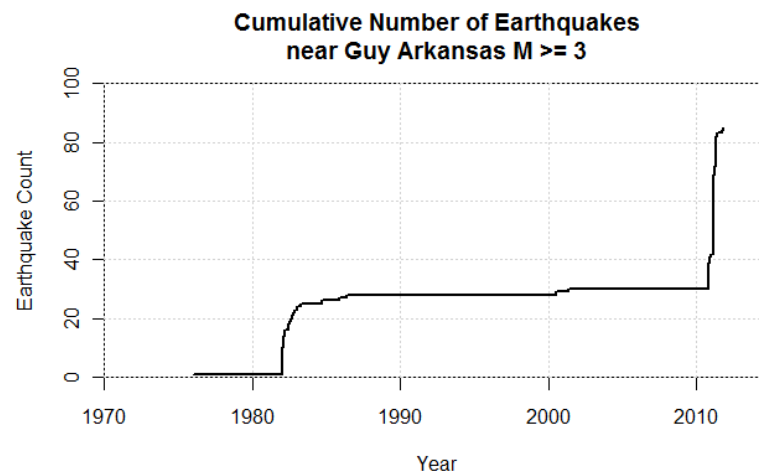


# Injection-induced earthquakes are similar to natural earthquakes

- Focal mechanisms are consistent with ambient pre-existing state of stress. Suggests that stresses causing induced earthquake fault slip are tectonic in origin.
- Well located hypocenters often reveal previously-unmapped fault planes.
- Seismograms of fluid-induced earthquakes are similar to those from tectonic earthquakes.



- 7/2010 injection in well #1 begins.
- 8/2010 injection in well #5 begins.
- 9/2010 “continuous” swarm of earthquakes starts.
- 2/27/2011 M 4.7
- 3/3/2011 injection halted.

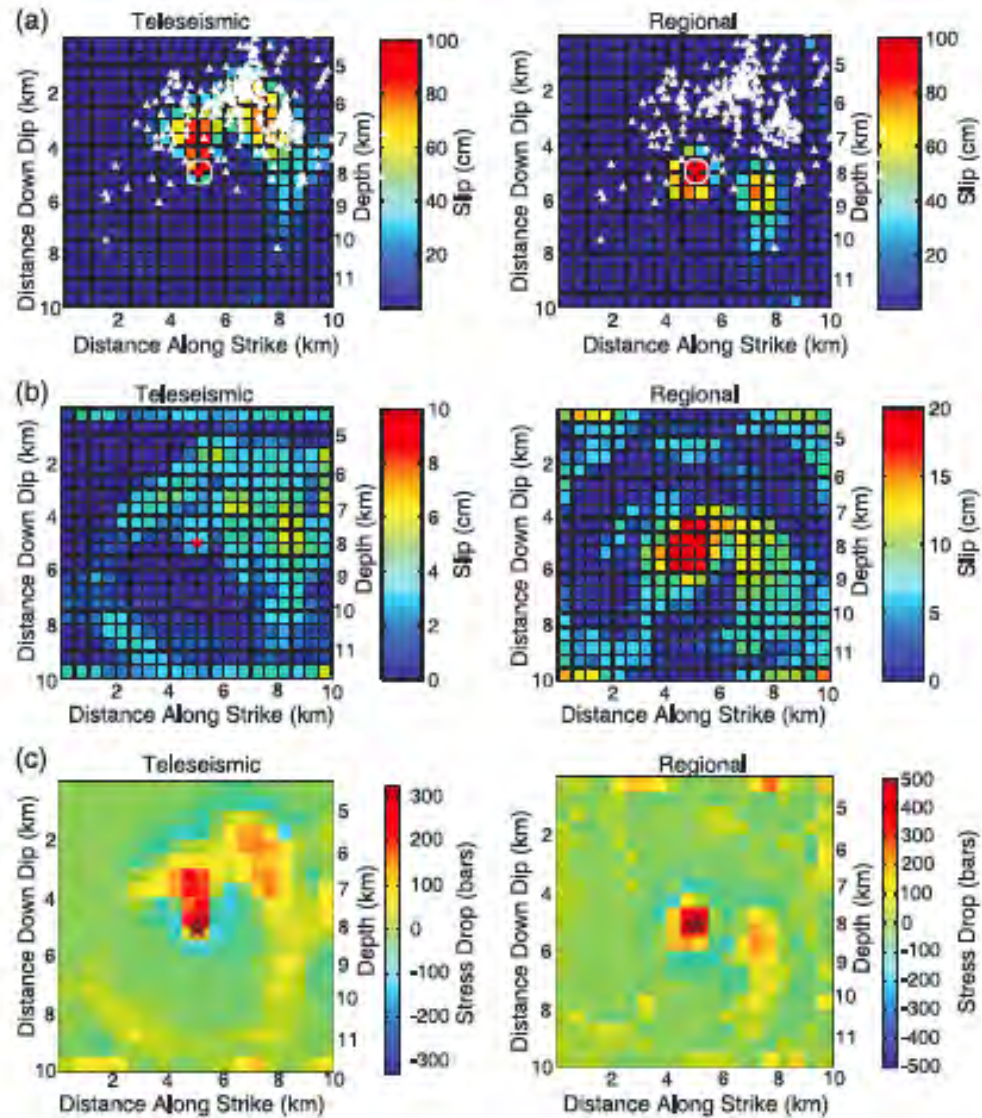


Horton, S., 2012, *Disposal of Hydrofracking Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquake*; *Seismological Research Letters*, v. 83.

# Guy-Greenbrier earthquakes

- Injection terminated after M4.7 event in March 2011 to avoid larger earthquake.
- Based on fault area, Horton estimated  $M_{max}5.6$ .
- Fault area  $41 \text{ km}^2$  determined by putting the rectangle, seen in slide 5, around most of the hypocenters.
- $M_{max}4.7$  is consistent with injected volume, adjacent to fault, of 629,000 cubic m.

# Mineral Virginia, M5.8 (Hartzell et al., 2013)

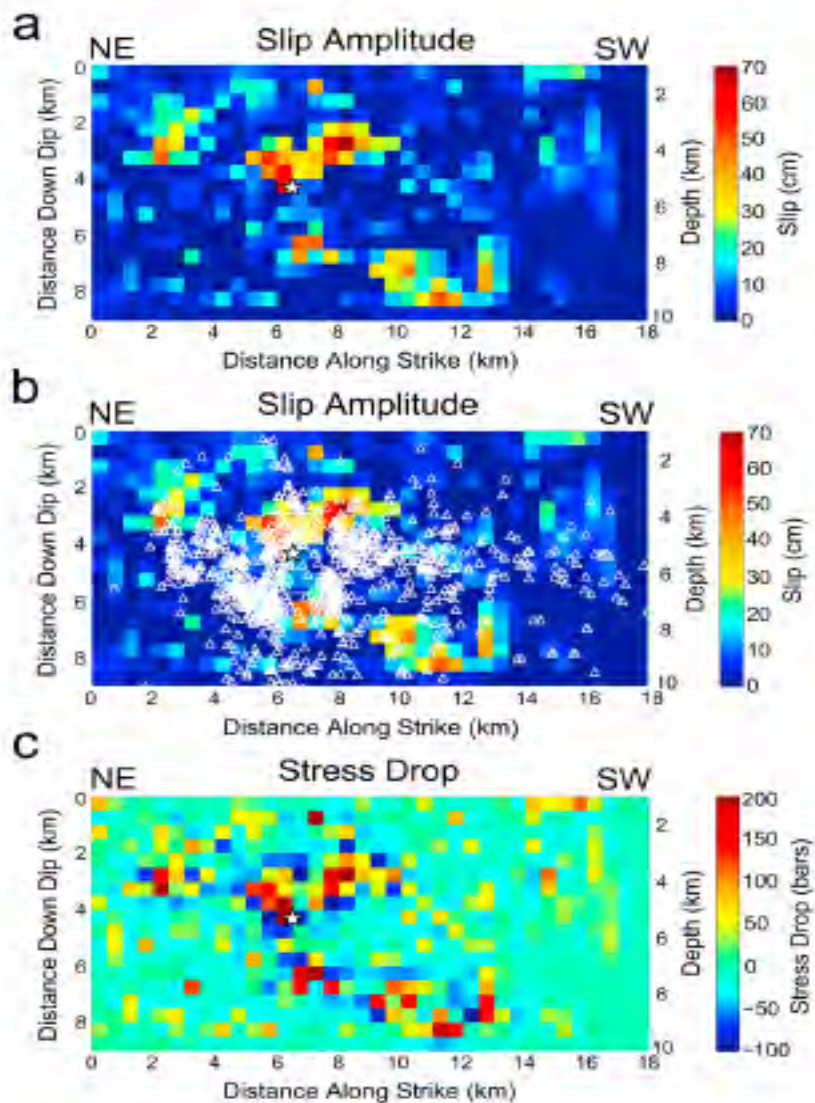


# 23 August 2011 Mineral, VA

- $M_w=5.8$
- Fault area  $100 \text{ km}^2$  from the finite slip model in the previous slide.
- Natural tectonic earthquake
- From fault area, expected M6



# M5.65 Prague, OK, earthquake (Sun and Hartzell, 2014)

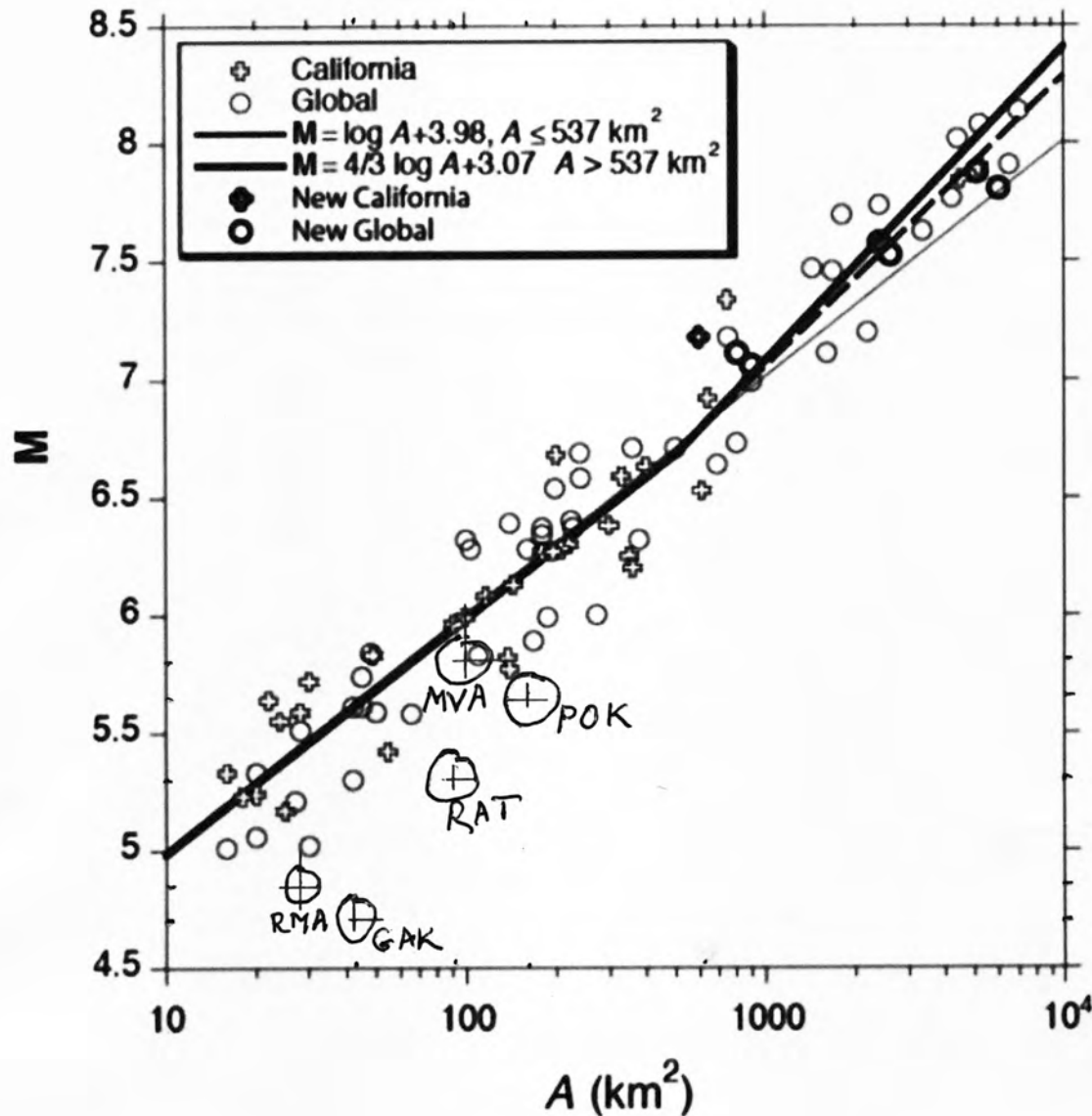


# 6 Nov., 2011 Prague, OK

- $M_w=5.65$
- Fault area from the slip model in the previous slide= $162 \text{ km}^2$
- $M(\text{fault area})=6.2$
- Difference between  $M_w$  and  $M(\text{fault area})$  similar to results from intensity analysis reported by Hough (BSSA, 2014).

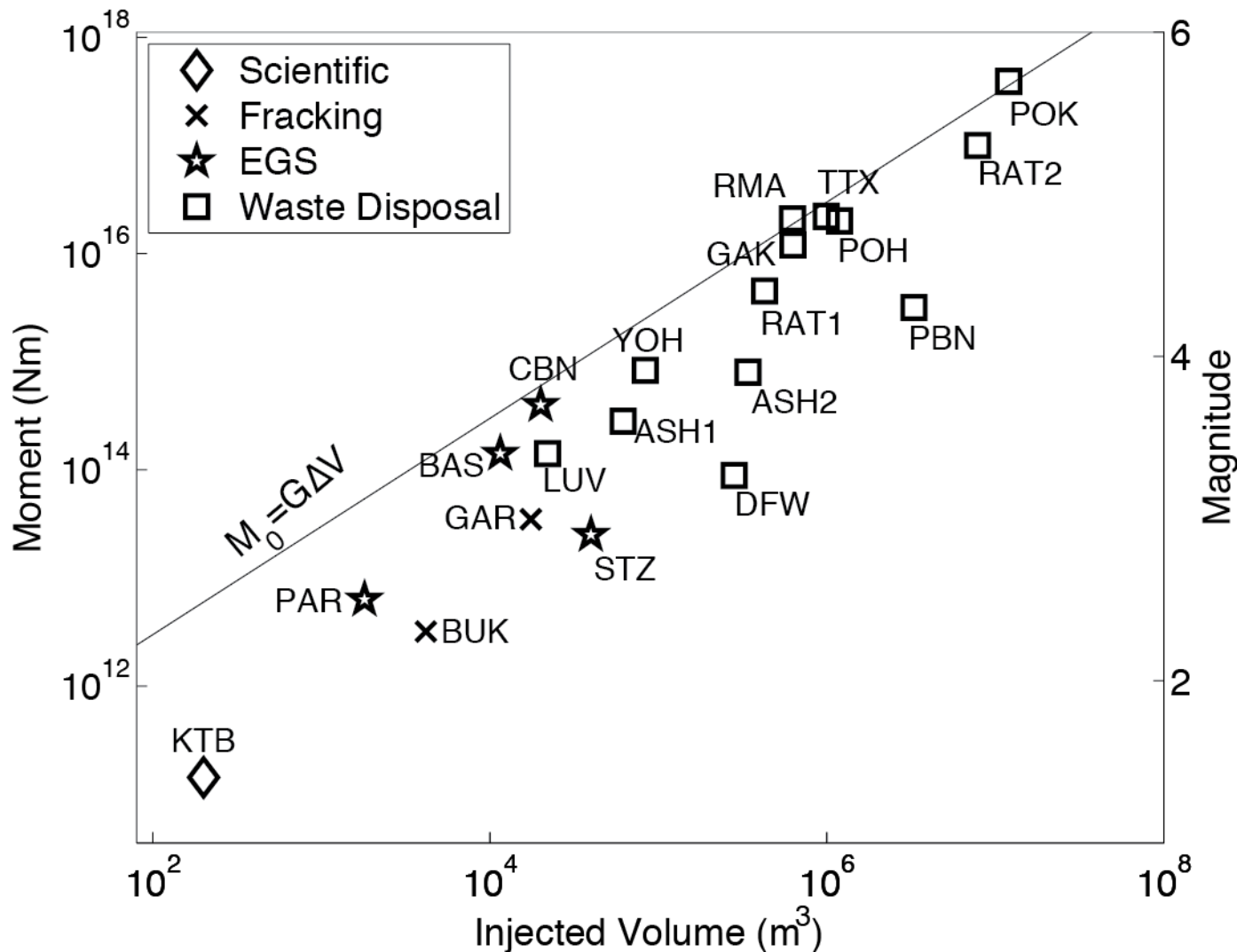
# Hanks and Bakun, BSSA (2014)

For their size, induced earthquakes tend to have larger rupture areas.



MVA: Mineral, Virginia  
POK: Prague, Oklahoma  
RAT: Raton Basin, Colorado  
RMA: Denver, Colorado  
GAK: Guy, Arkansas

# Higher Injection Volumes = Possibility of Bigger Quakes



KTB: eastern Bavaria, Germany  
 BUK: Bowland shale, UK  
 GAR: Garvin County, OK  
 STZ: Soultz, France  
 DFW: Dallas-Fort Worth Airport, TX  
 BAS: Basel, Switzerland  
 ASH1: Ashtabula, OH, July, 1987  
 CBN: Cooper Basin, Australia  
 ASH2: Ashtabula, OH, January 2001  
 YOH: Youngstown, OH  
 PBN: Paradox Valley, CO  
 RAT1: Raton Basin, CO, September 2001  
 GAK: Guy, AR  
 POH: Painesville, OH  
 RMA: Denver, CO  
 TIX: Timpson, TX  
 RAT2: Raton Basin, CO, 2011  
 POK: Prague, OK

(McGarr, 2014)

# Questions for discussion

- How do we define “critically-stressed faults”?
- If  $M_{\max}$  for fluid-injection induced earthquakes is controlled by size of nearby fault, how do we find it and how large is it?
- If  $M_{\max}$  is controlled by injection volume, what about multiple nearby injection wells?
- To what extent can monitoring with a local seismic network identify wells with big earthquake response?