The Past and Future Seismic Hazard in Oklahoma

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Andrew Thiel – Analyst/Outreach/Field
Isaac Woelfel – Field Technician

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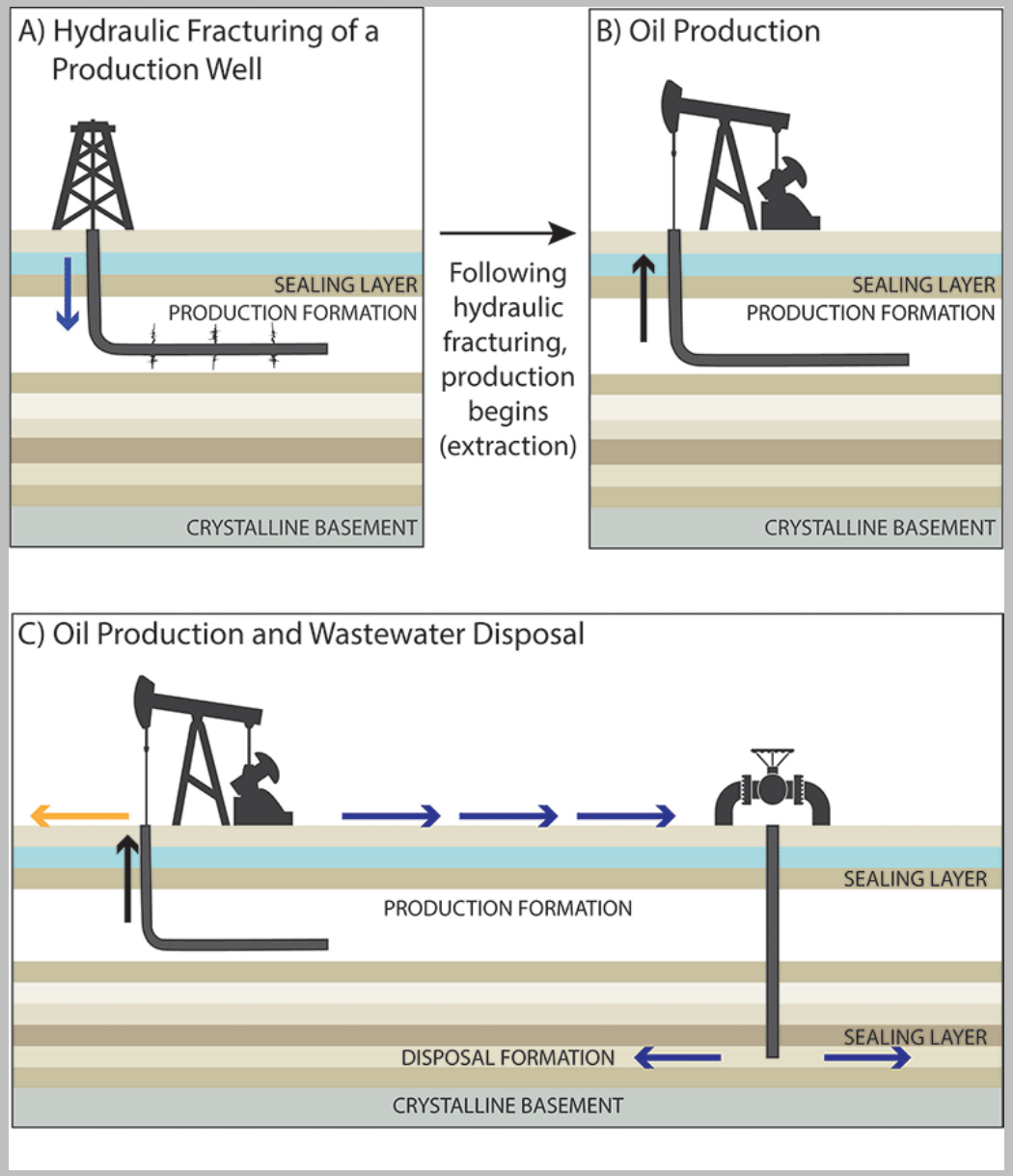
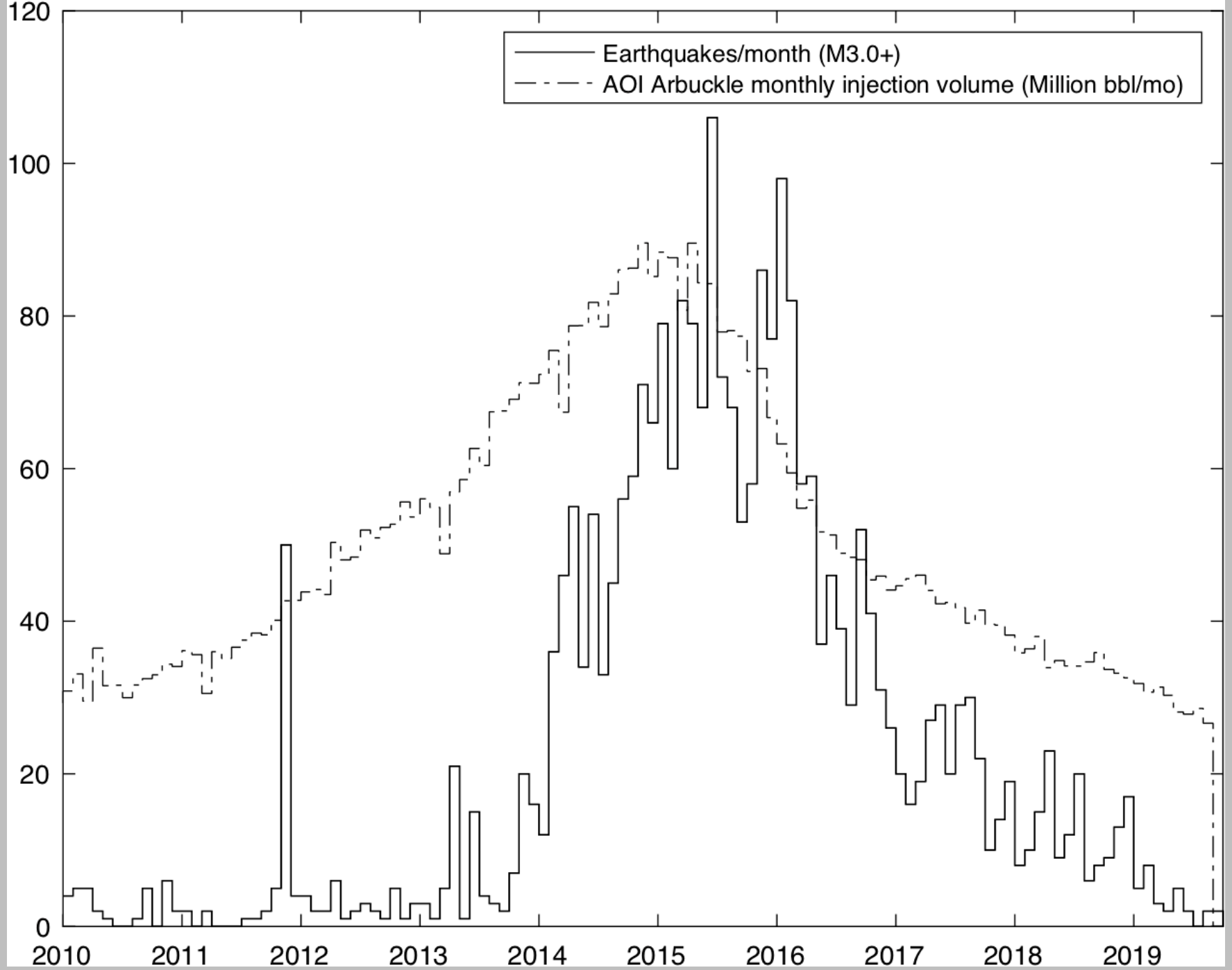
- November 2011 – Magnitude 5.7 near Prague, OK
- September 2016 – Magnitude 5.8 near Pawnee, OK
- November 2016 – Magnitude 5.0 near Cushing, OK

- Risk analysis suggests similar earthquake in Dallas metro area … ~$5 billion damage



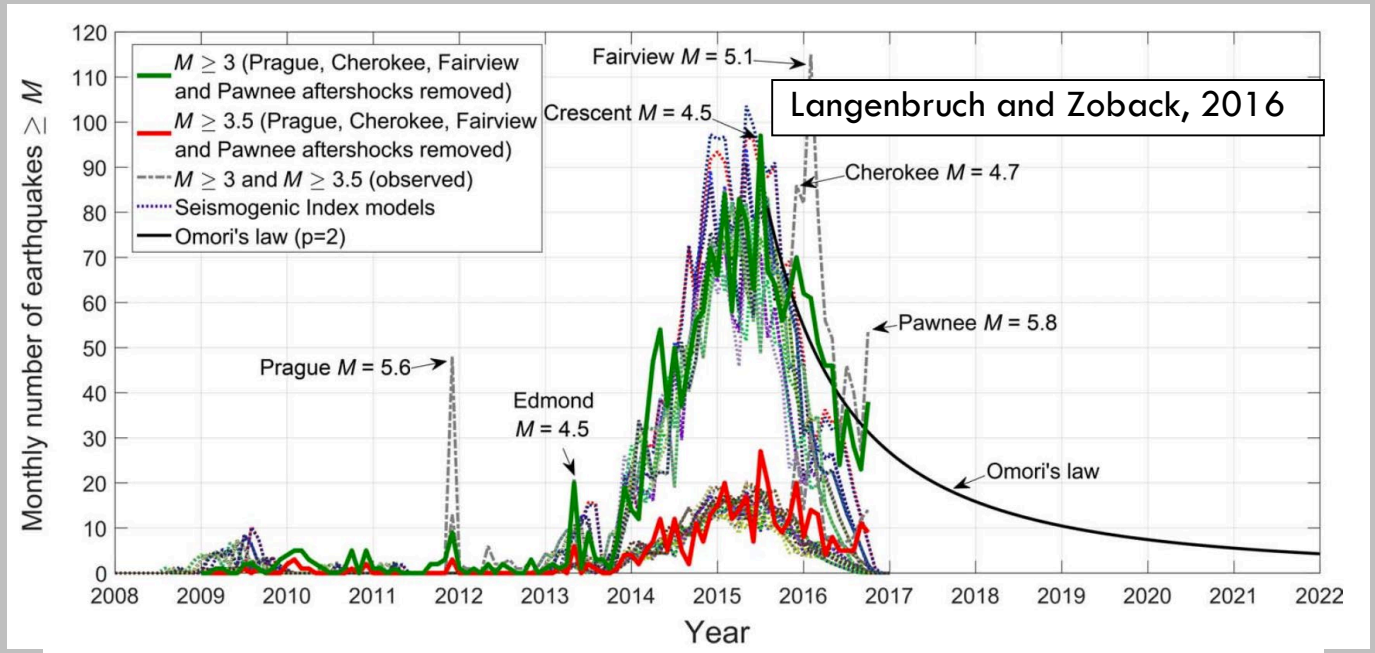
Arbuckle Group in Oklahoma

Rubinstein and Mahani, 2015

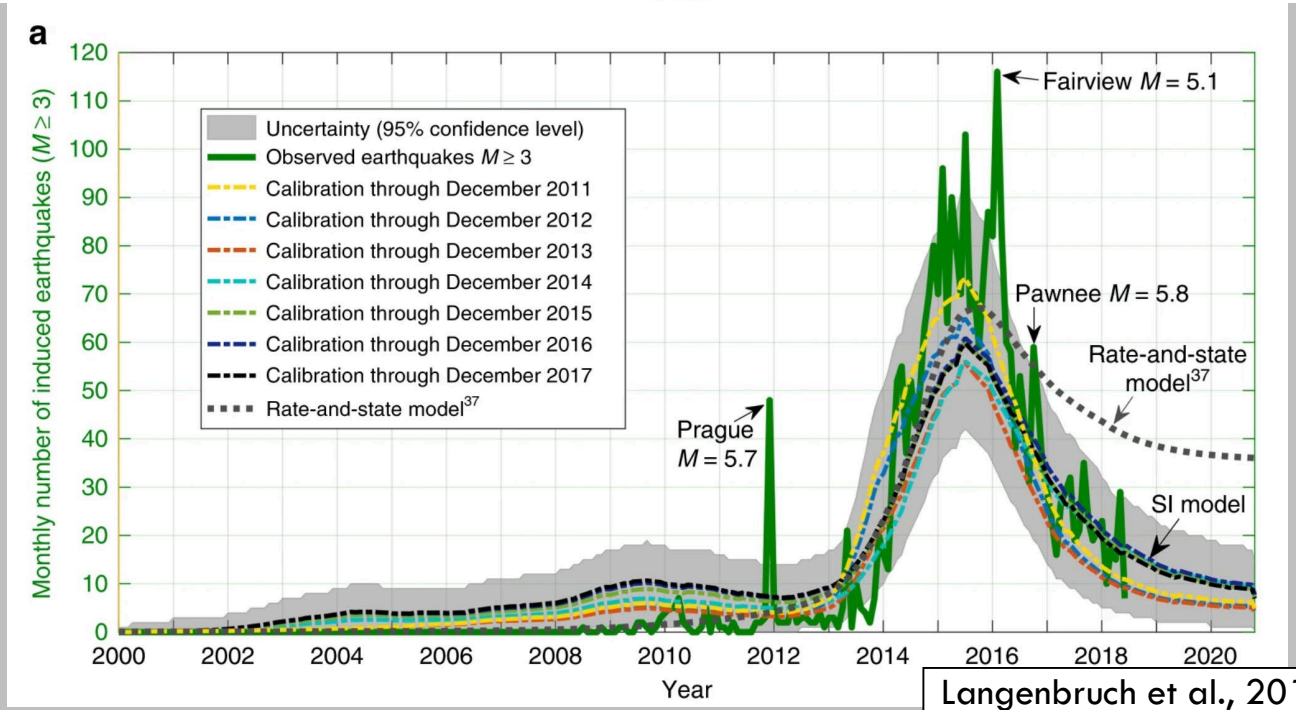


Walter et al., 2019

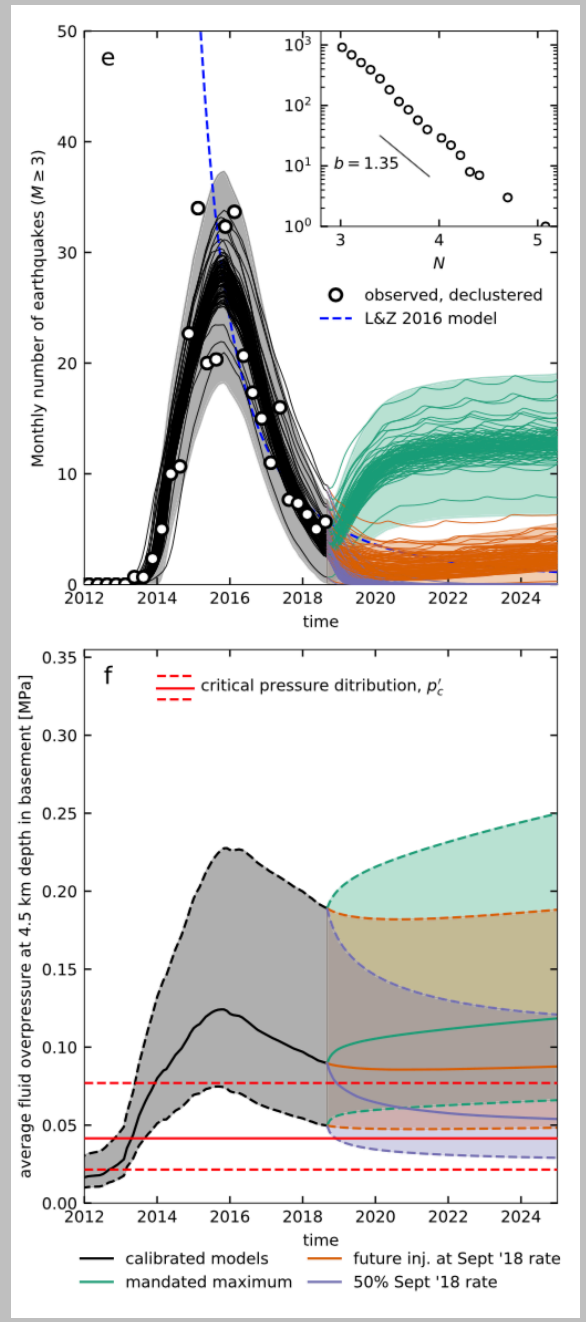
Forecasts for the future



Langenbruch and Zoback, 2016

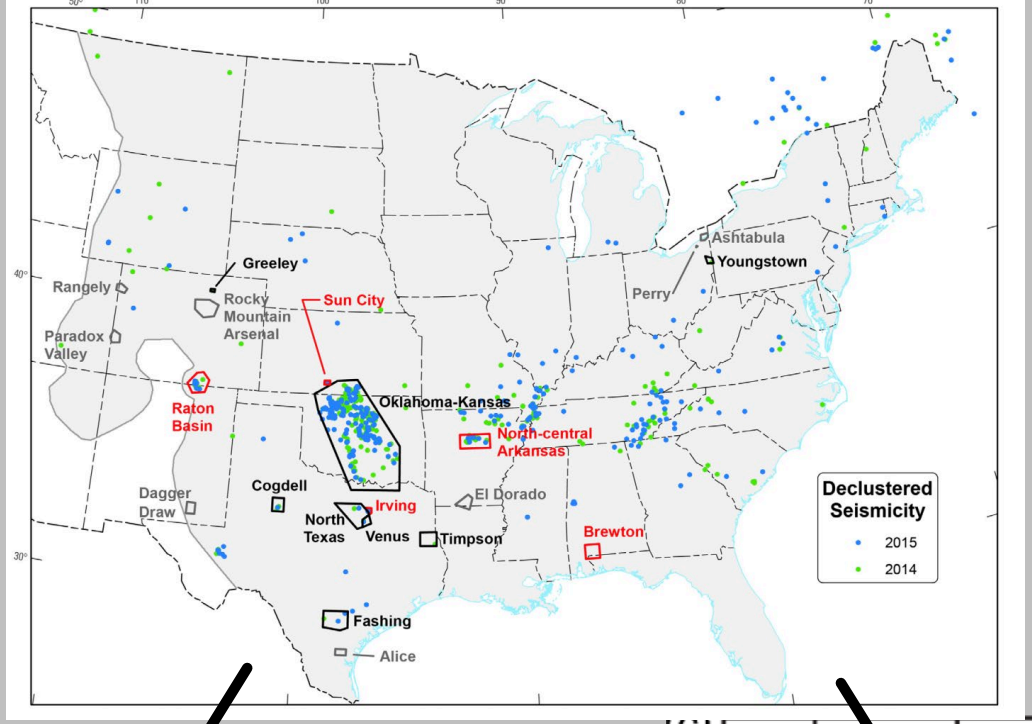


Langenbruch et al., 2019



Dempsey and Riffault, 2019

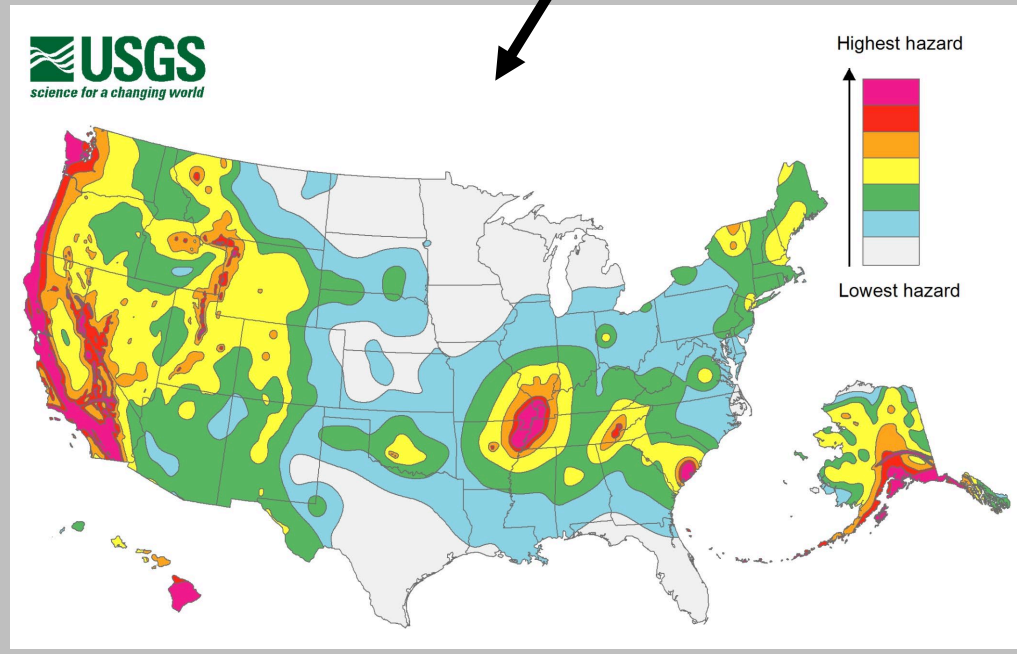
Petersen et al., 2016

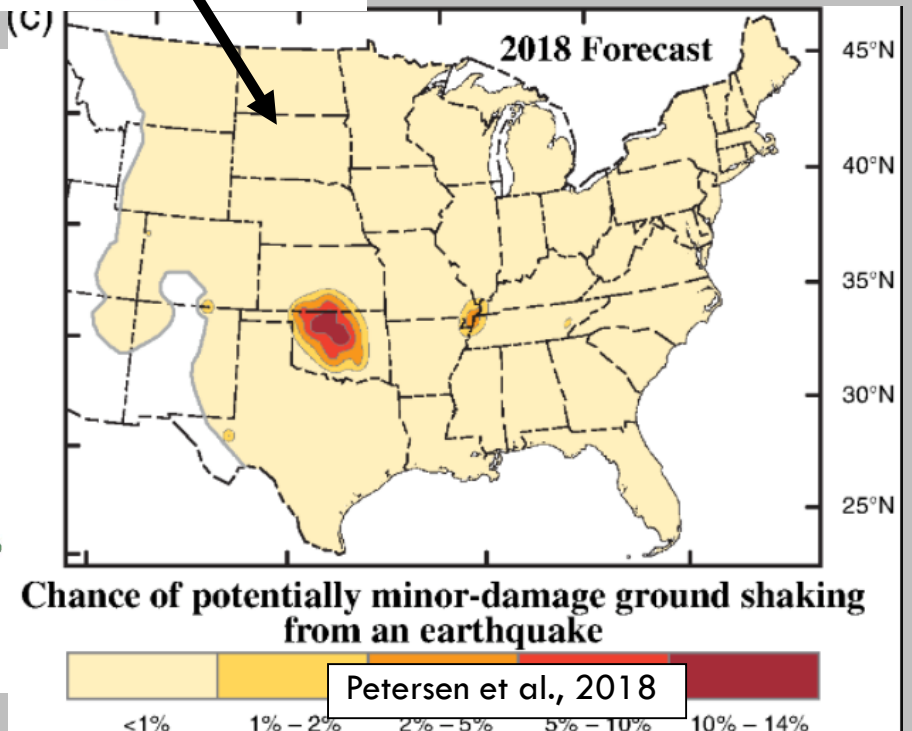


Fence off induced seismicity areas

Long-term hazard models won't include induced seismicity because decision made that it is a short-term hazard

Conflicting views of the hazard?

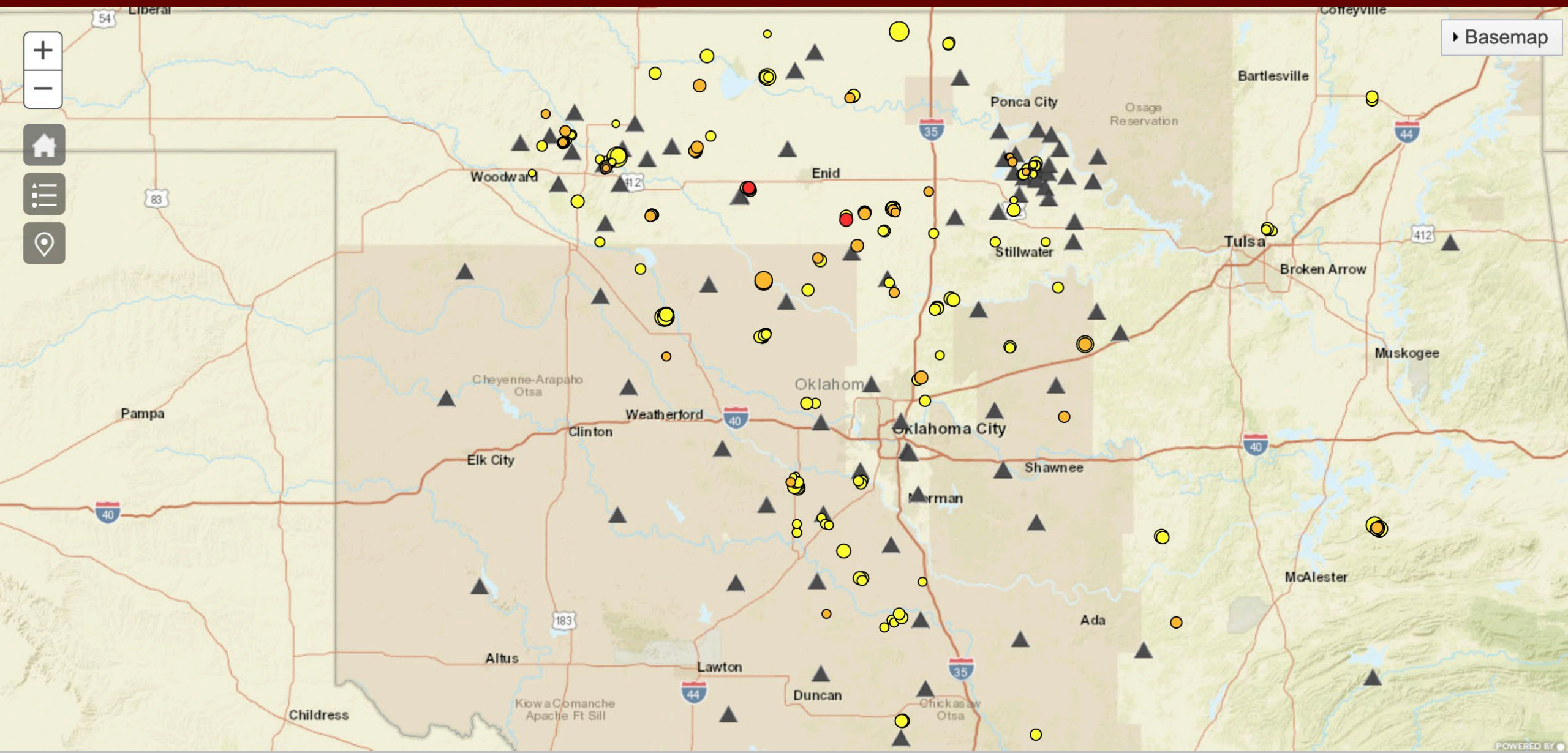




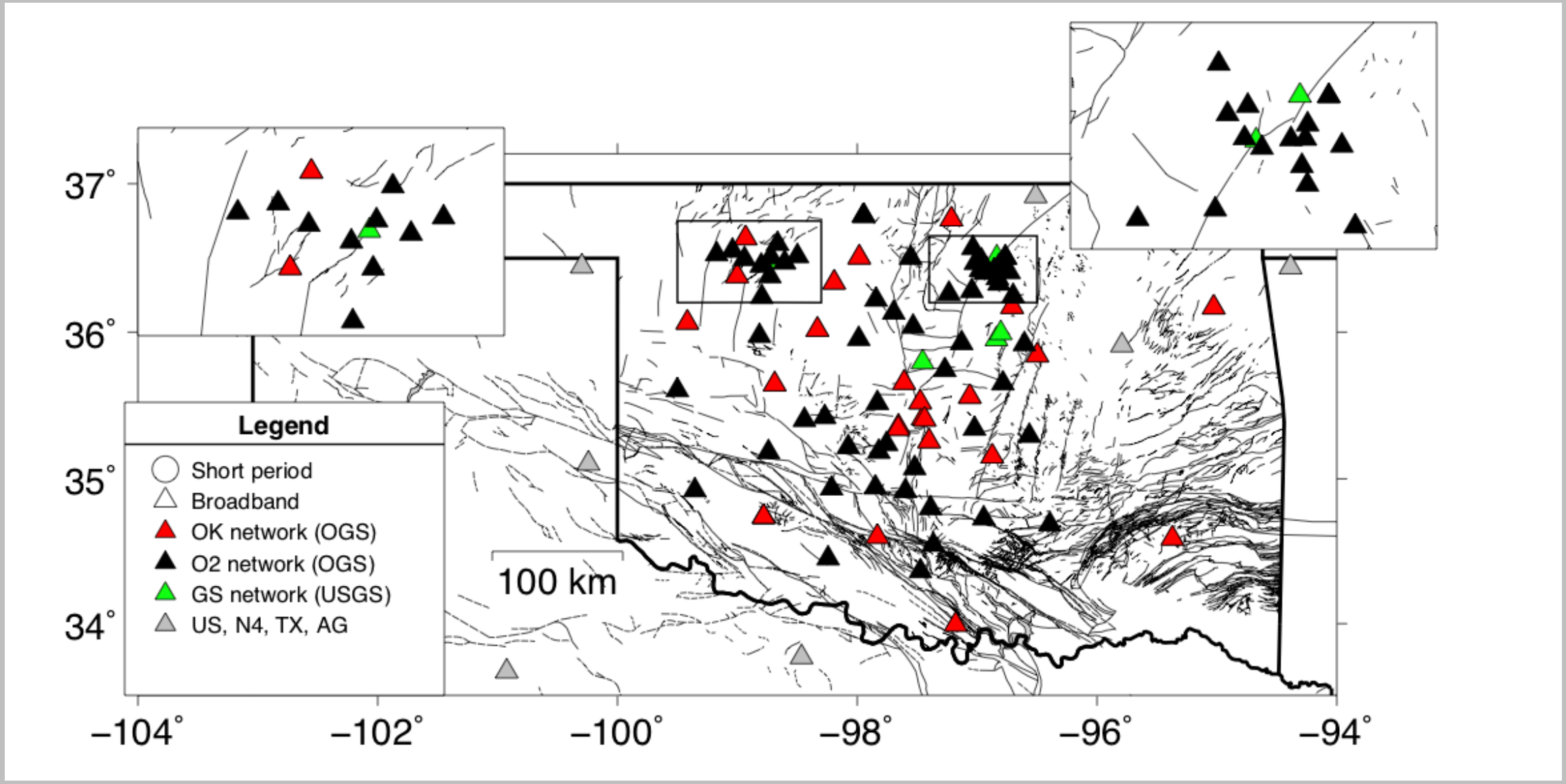
Petersen et al., 2018

ogsweb.ou.edu/quake_viewer/

Oklahoma Geological Survey Earthquake Viewer

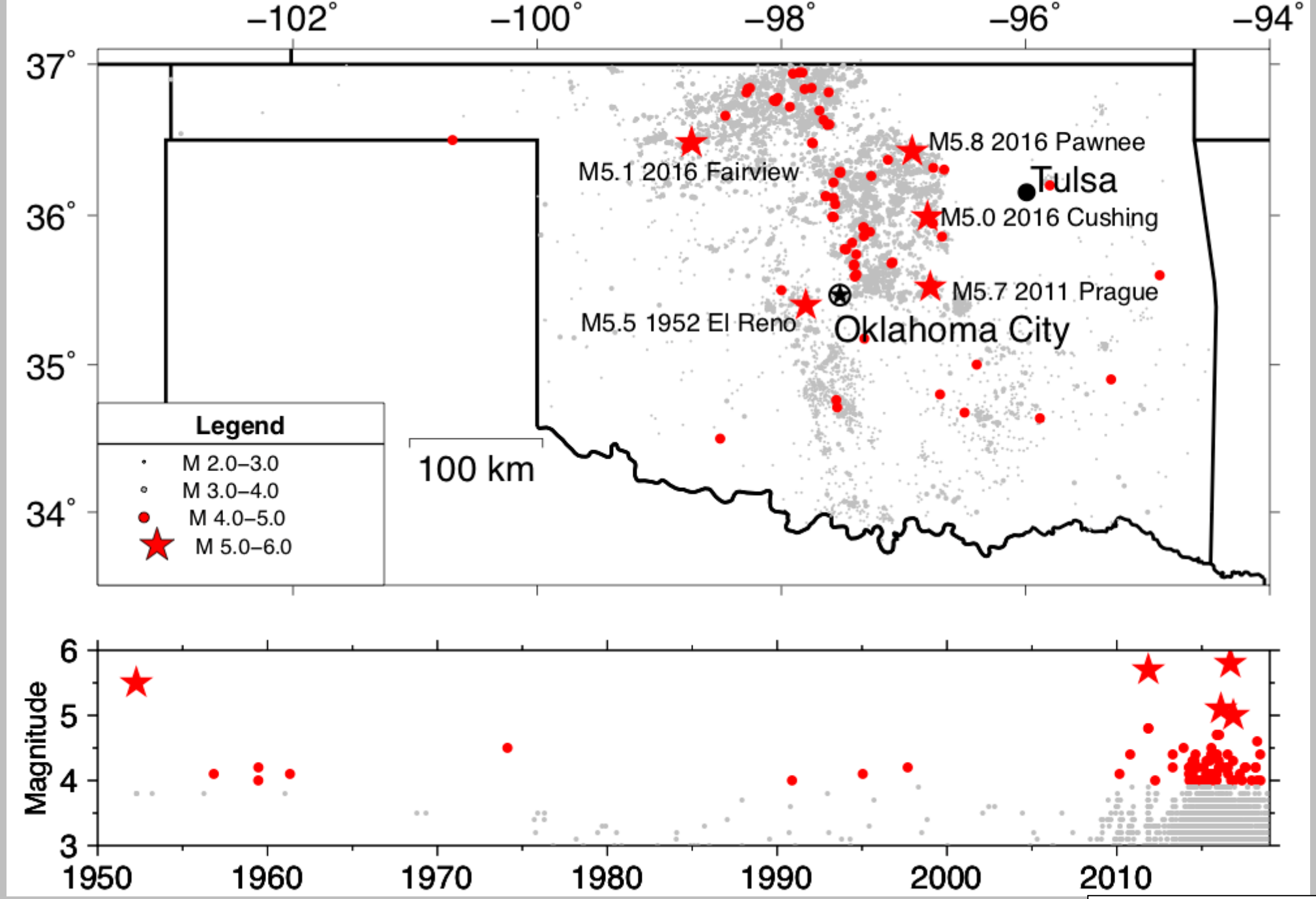


Download our scientific products: ogs.ou.edu



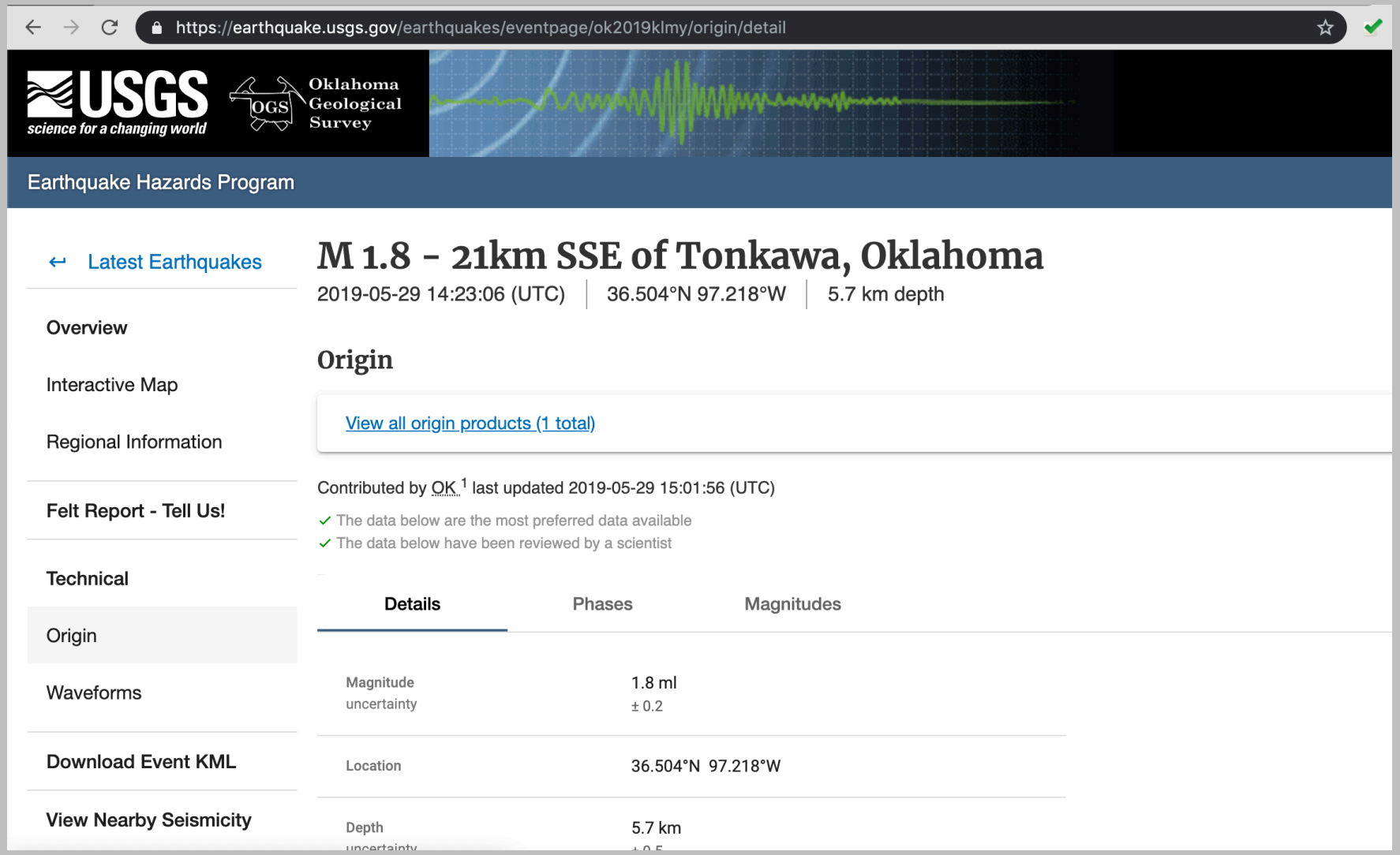
Stream our raw data in real-time

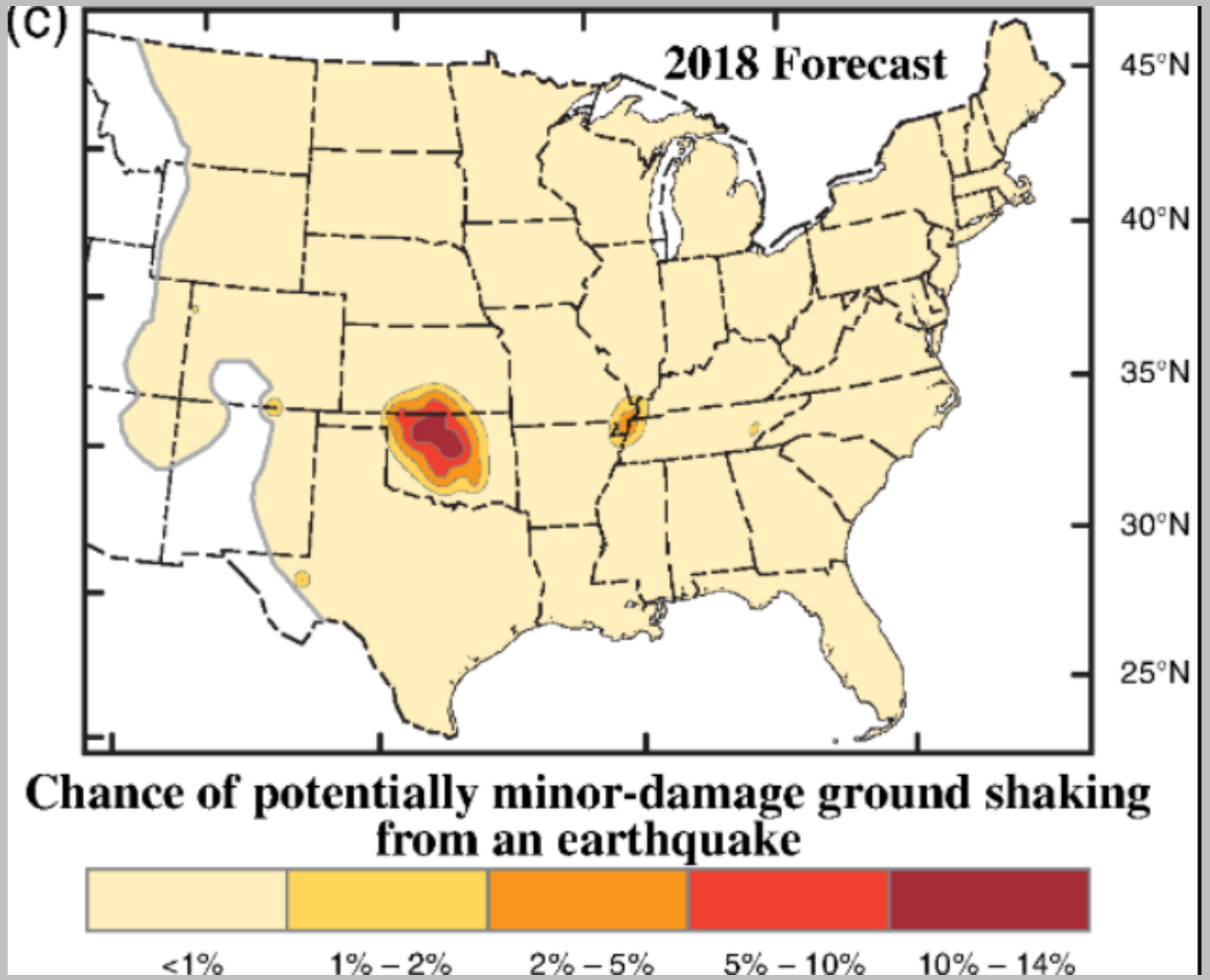
Walter et al., 2019



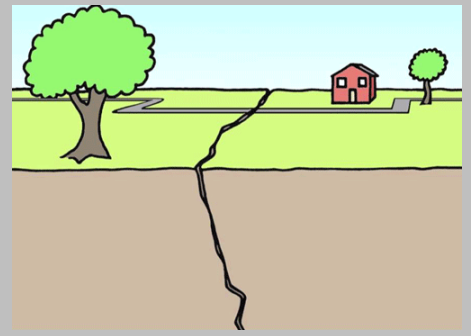
Walter et al., 2019

As of May 29, OGS is the authoritative regional network in the state, so USGS earthquakes are reported by OGS

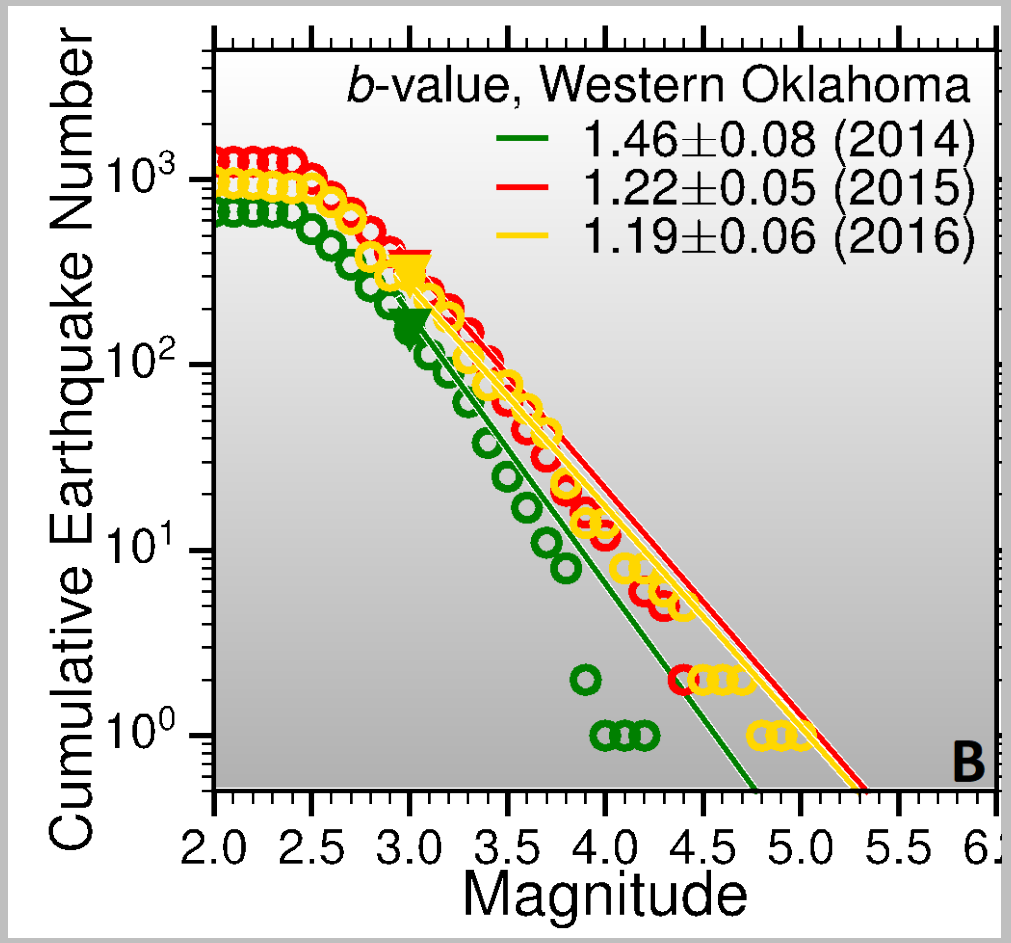




Petersen et al., 2018



You might want to know the probability of having an earthquake, so just like a dice game one would want to know how many sides to the die (maximum magnitude) and outcomes of previous rolls (seismicity rate/magnitudes)



Goebel et al., 2017

Earthquake catalog

↓

Decluster

↓

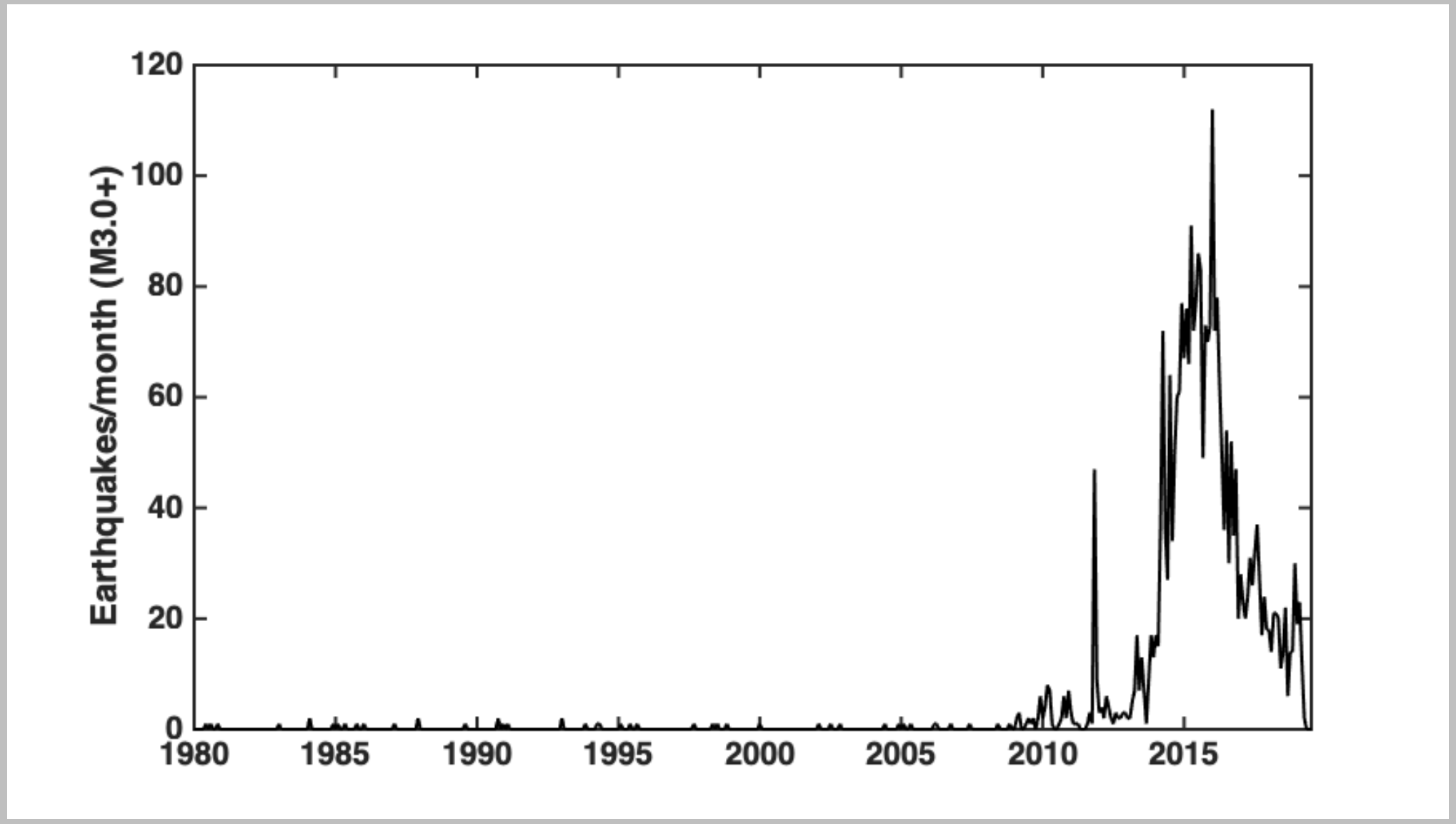
Earthquake rate

↓

Ground-motion model

↓

Hazard model



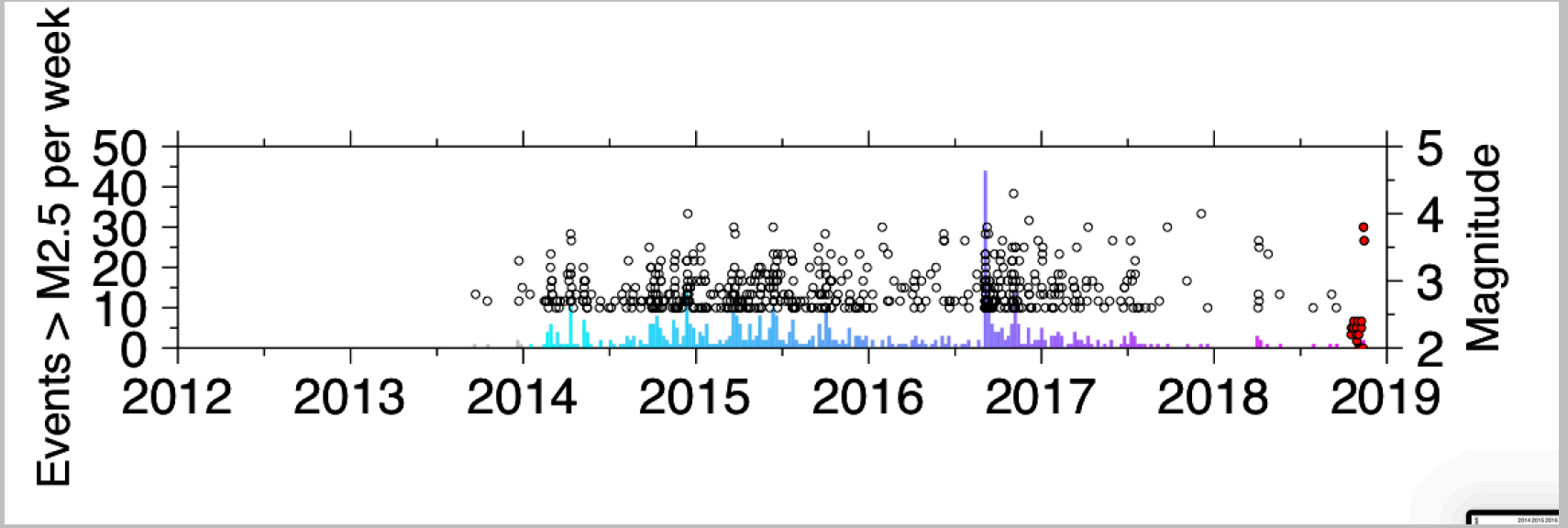
Probabilistic seismic hazard modeling (PSHA) uses past seismicity rates and rates of background events, but what is a good statistical representation of earthquakes over geologic time or even recorded time?

- What is declustering?

- Want only seismicity which obeys a stationary Poisson process
- Must define spatiotemporal criteria relative to mainshock to define "dependent" events
- Example:
  - *Gardner & Knopoff (1974):*

$$t = \begin{cases} 10^{0.032*M+2.7389}, & \text{if } M \geq 6.5 \\ 10^{0.5409*M-0.547}, & \text{else} \end{cases} \quad [days]$$

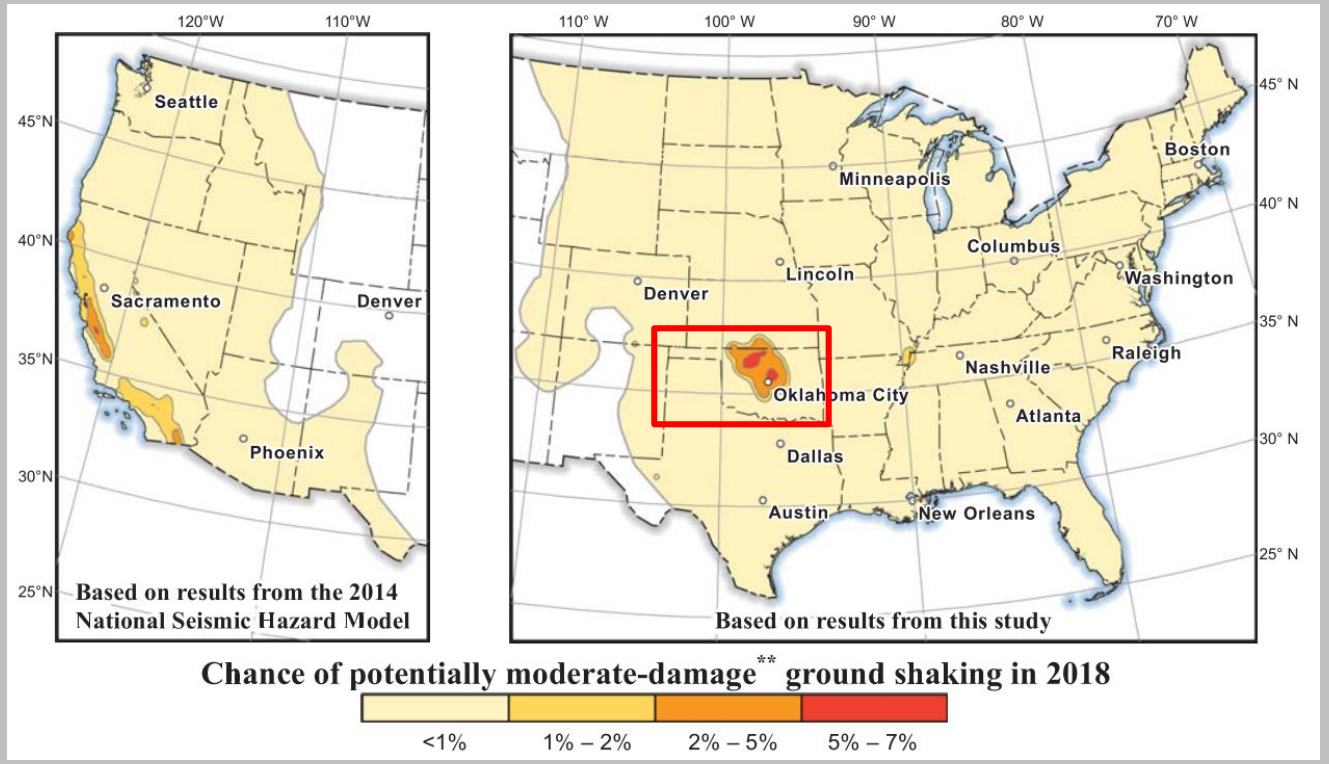
$$d = 10^{0.1238*M+0.983} \quad [km]$$



Are Oklahoma aftershocks the same as other aftershocks?

Zach Rosson
MS Student

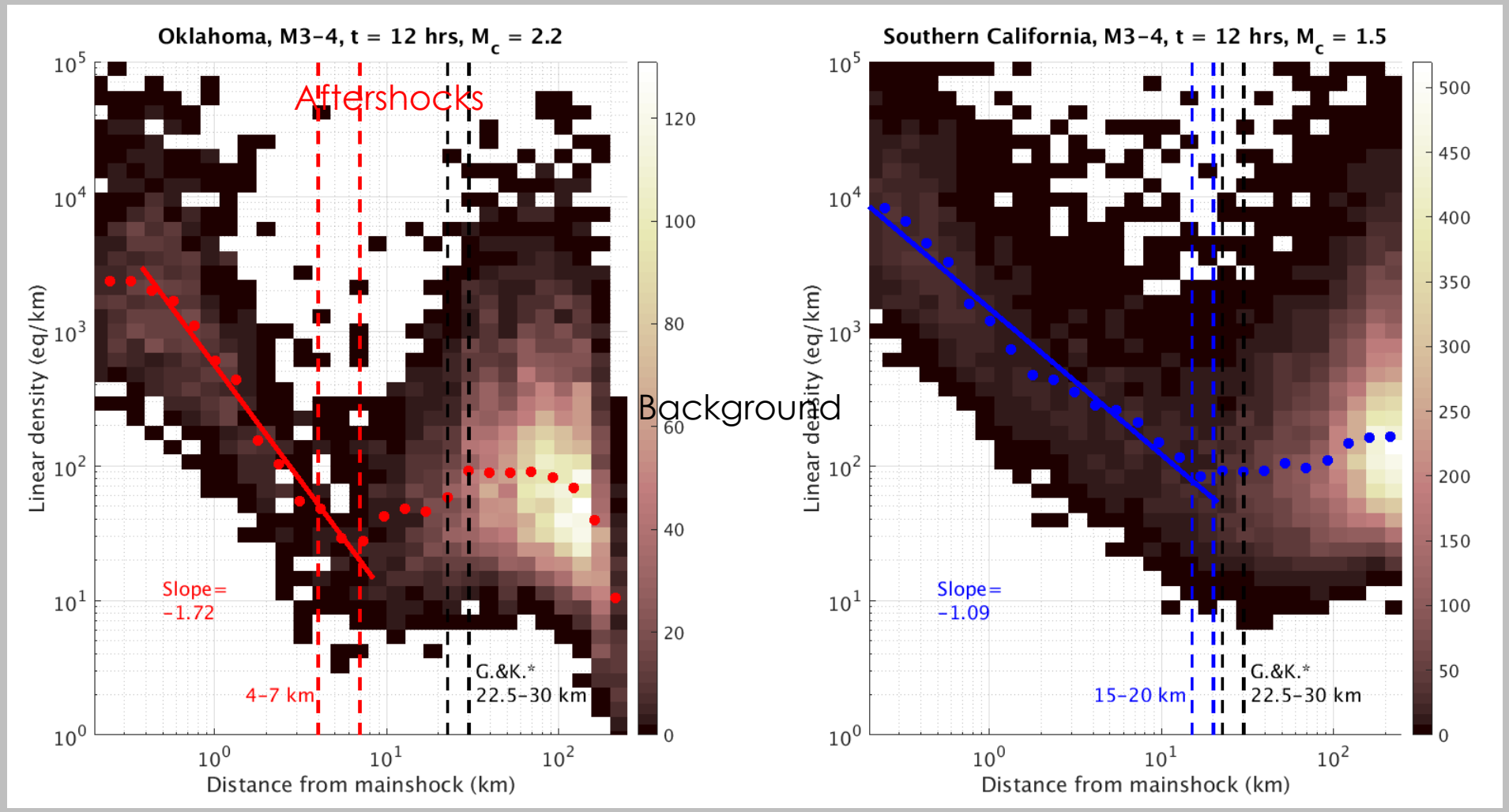
Zones of induced seismicity	Weight based on scientific consensus—considered induced	1-year count M2.7+ through fall 2015		2-year count M2.7+ through fall 2015		Start year–end year (if applicable)	Largest earthquake (M, date)
		dec.	full	dec.	full		
Zones that have had M2.7 and greater earthquake activity in years 2014–2015							
Oklahoma-Kansas	1.0—yes	149	3,528	292	5,991	2006–present	5.6, Nov. 2011



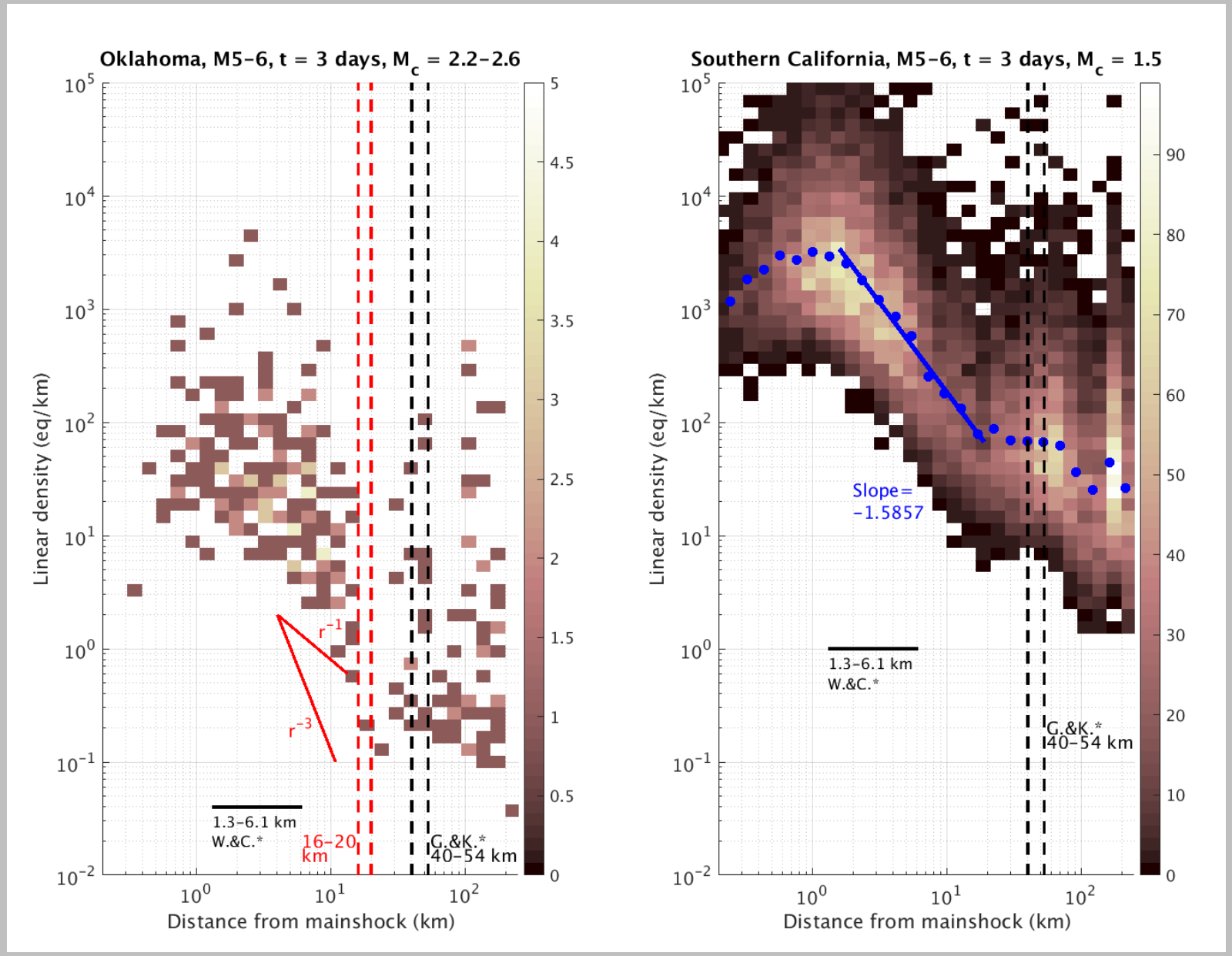
(Peterson et al., 2018)

Spatial aftershock decay – Analysis/results

- Stack all mainshocks and the distances to their aftershocks
- Compute nearest-neighbor linear density *(Silverman, 1986; Felzer and Brodsky, 2006)* between adjacent, stacked aftershocks
- Fit inverse power law to aftershock decay

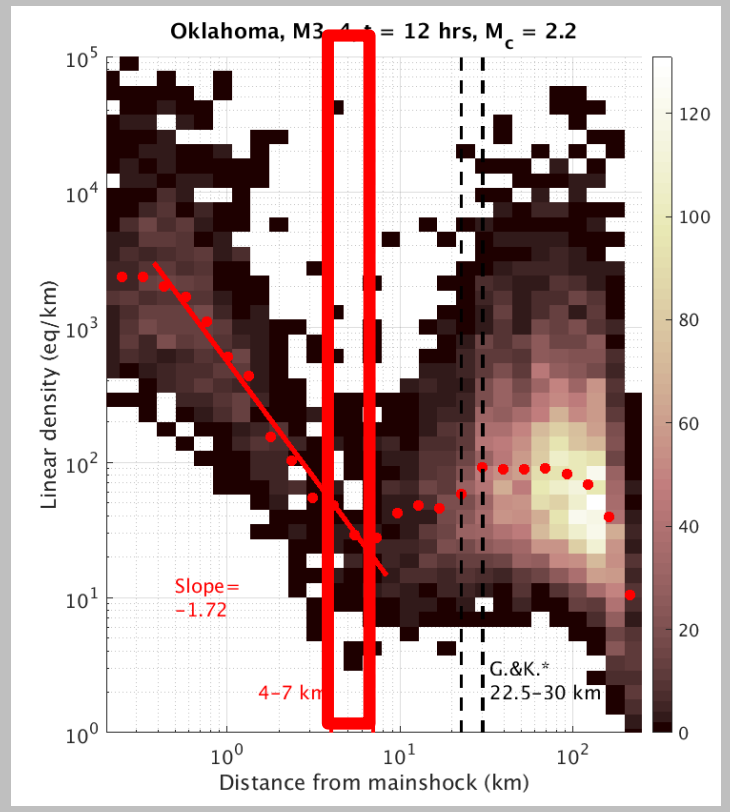


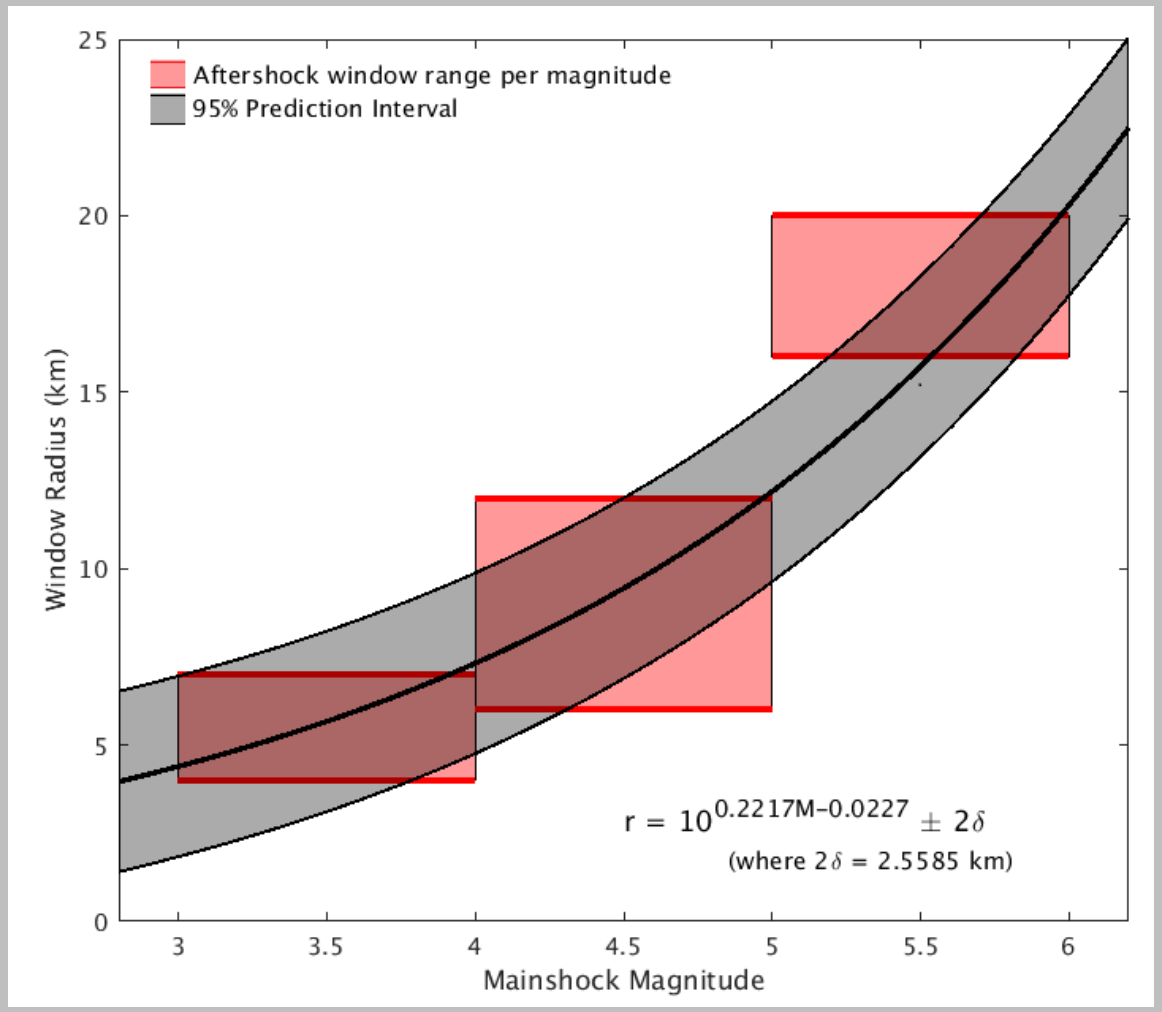
Rosson et al. (GRL), 2019

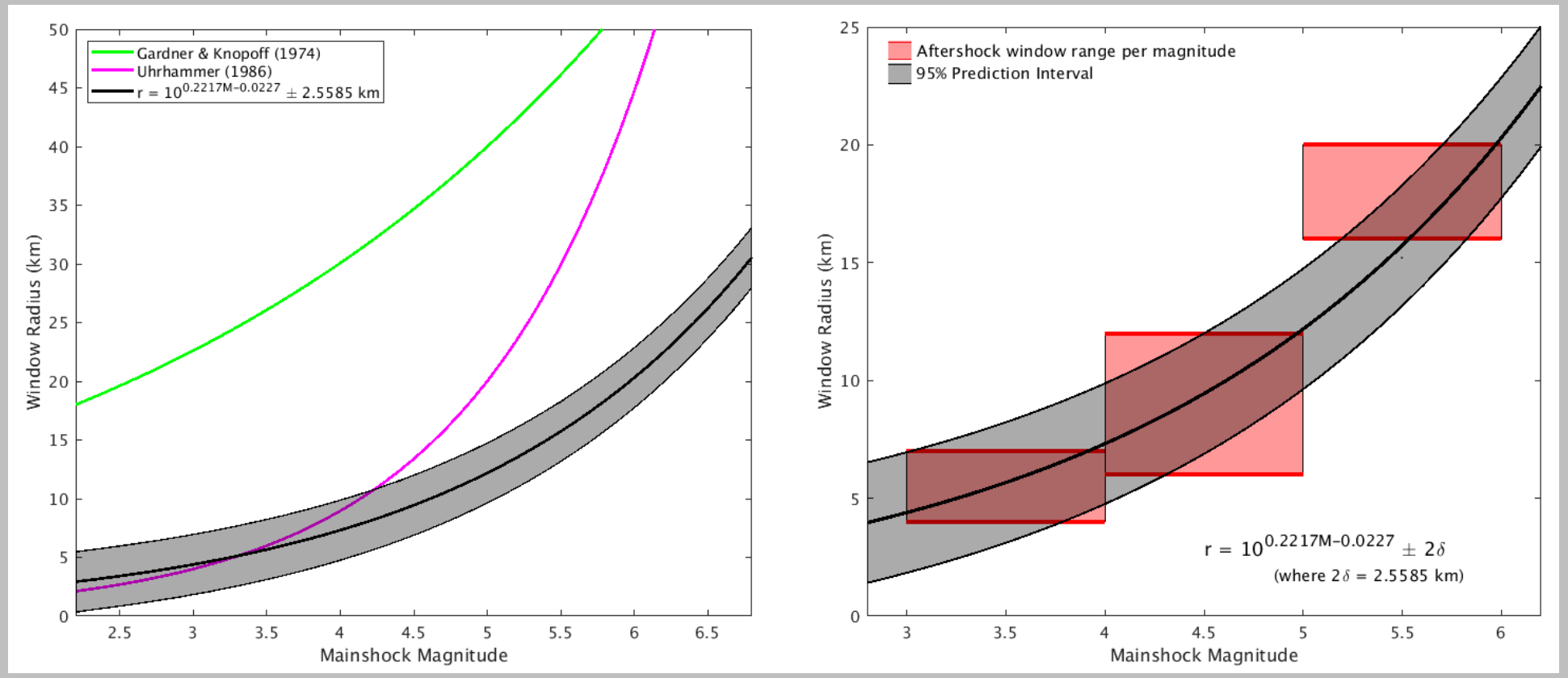


Rosson et al. (GRL), 2019

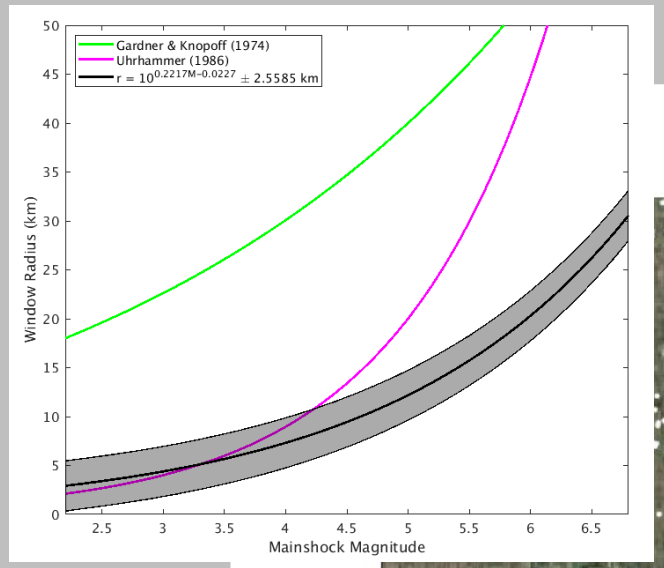
Proposed declustering

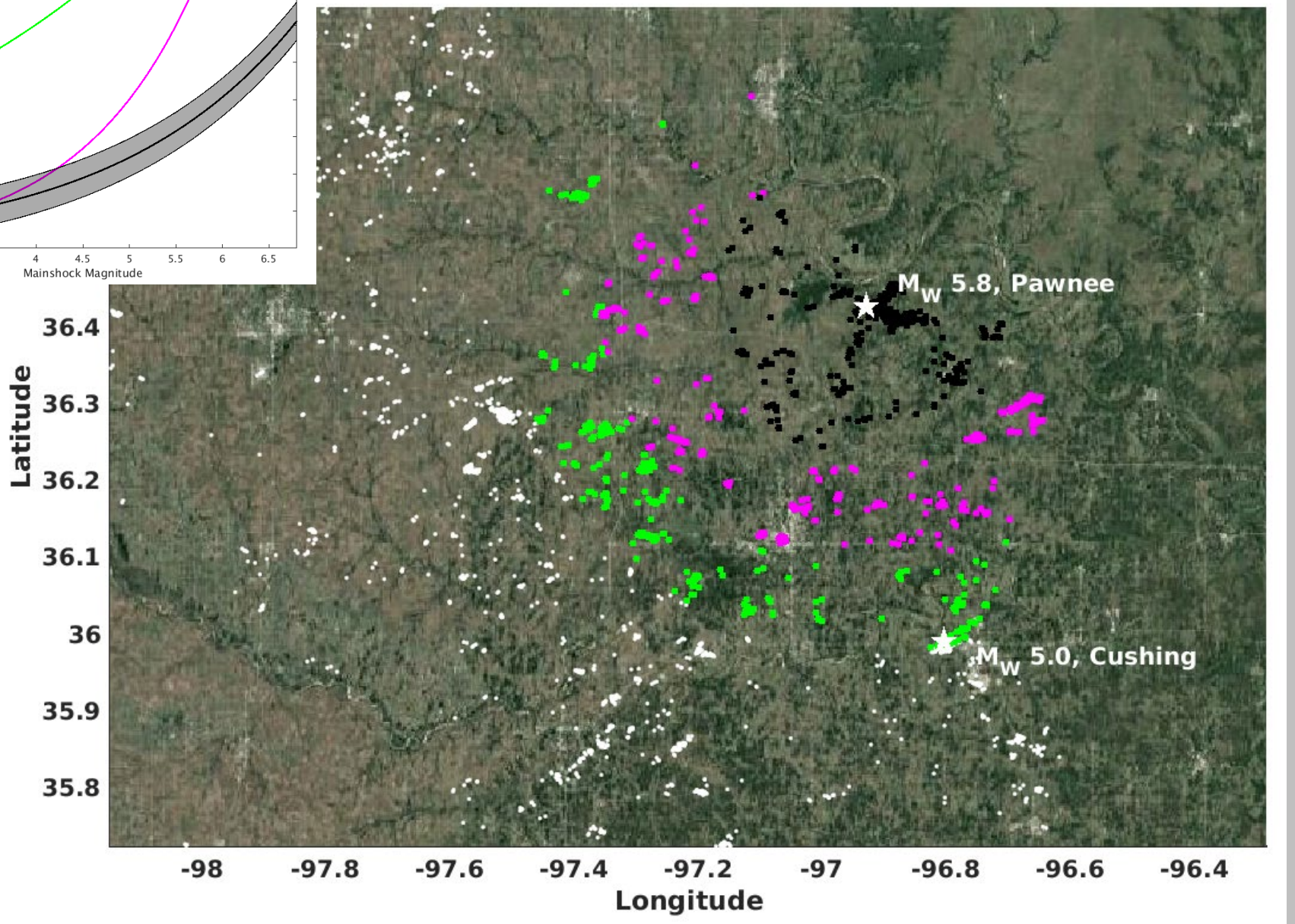






Rosson et al. (GRL), 2019

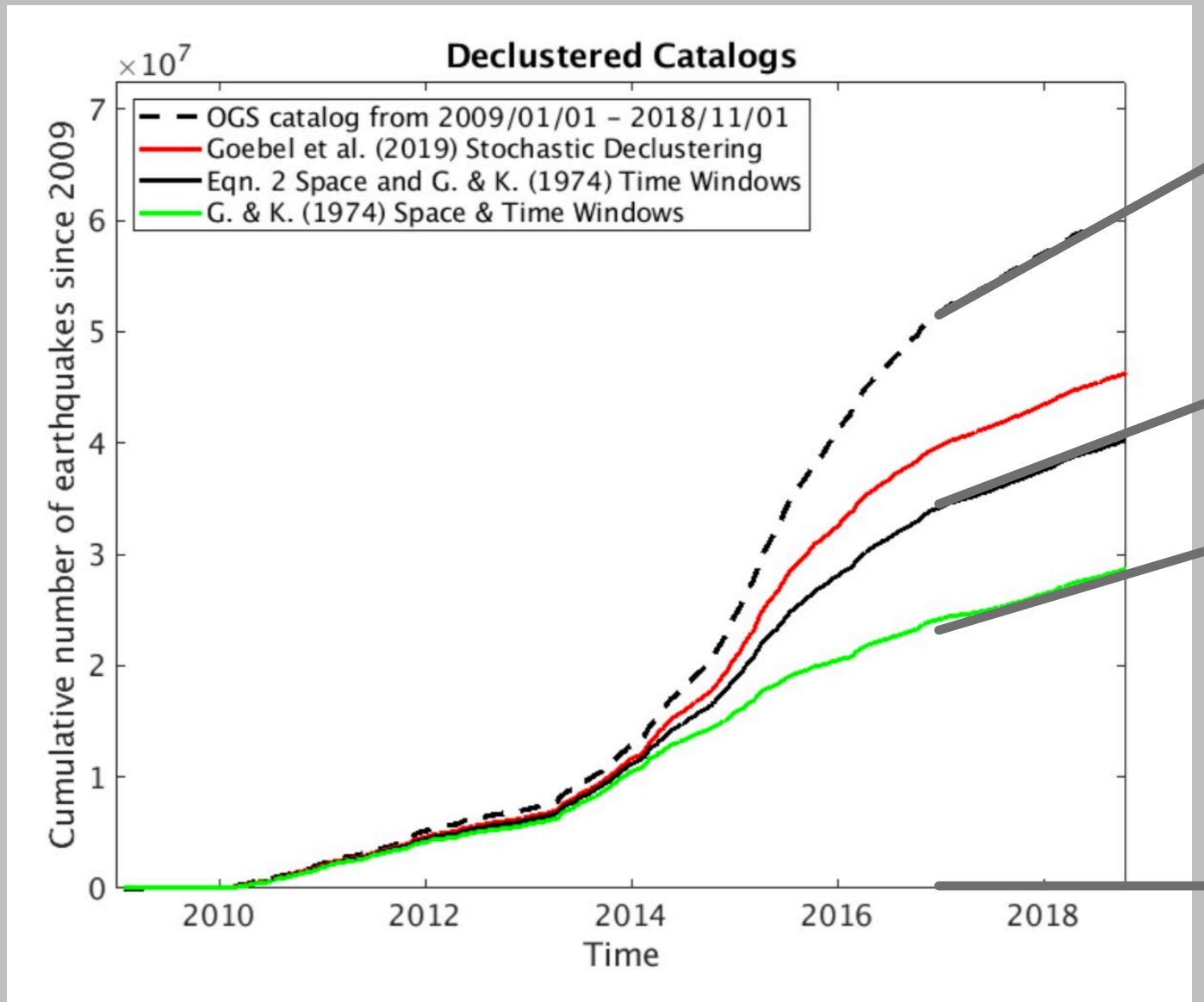




September 2016
Pawnee M5.8

50 km away

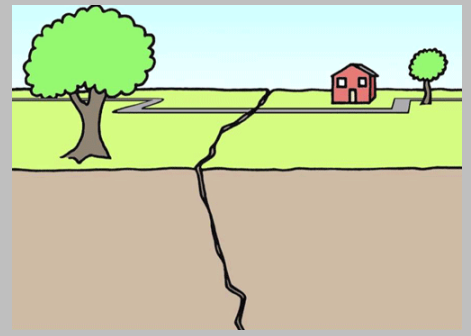
November 2016
Cushing M5.0



All slightly different rates, all very much above the background rate

Thus, the chance for a large earthquake in Oklahoma is still statistically higher than pre-unconventional times

Rosson et al. (GRL), 2019



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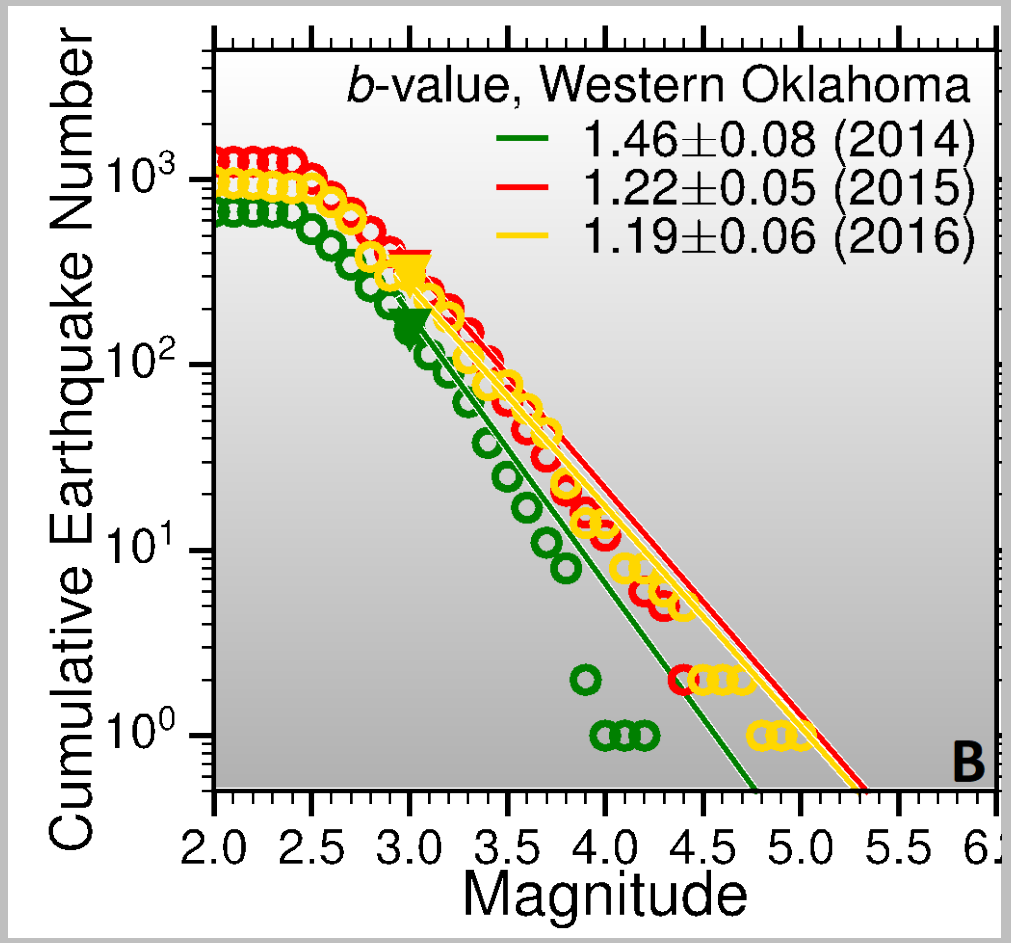

Goebel et al., 2017

Earthquake catalog

↓

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↓

Earthquake rate

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Ground-motion model

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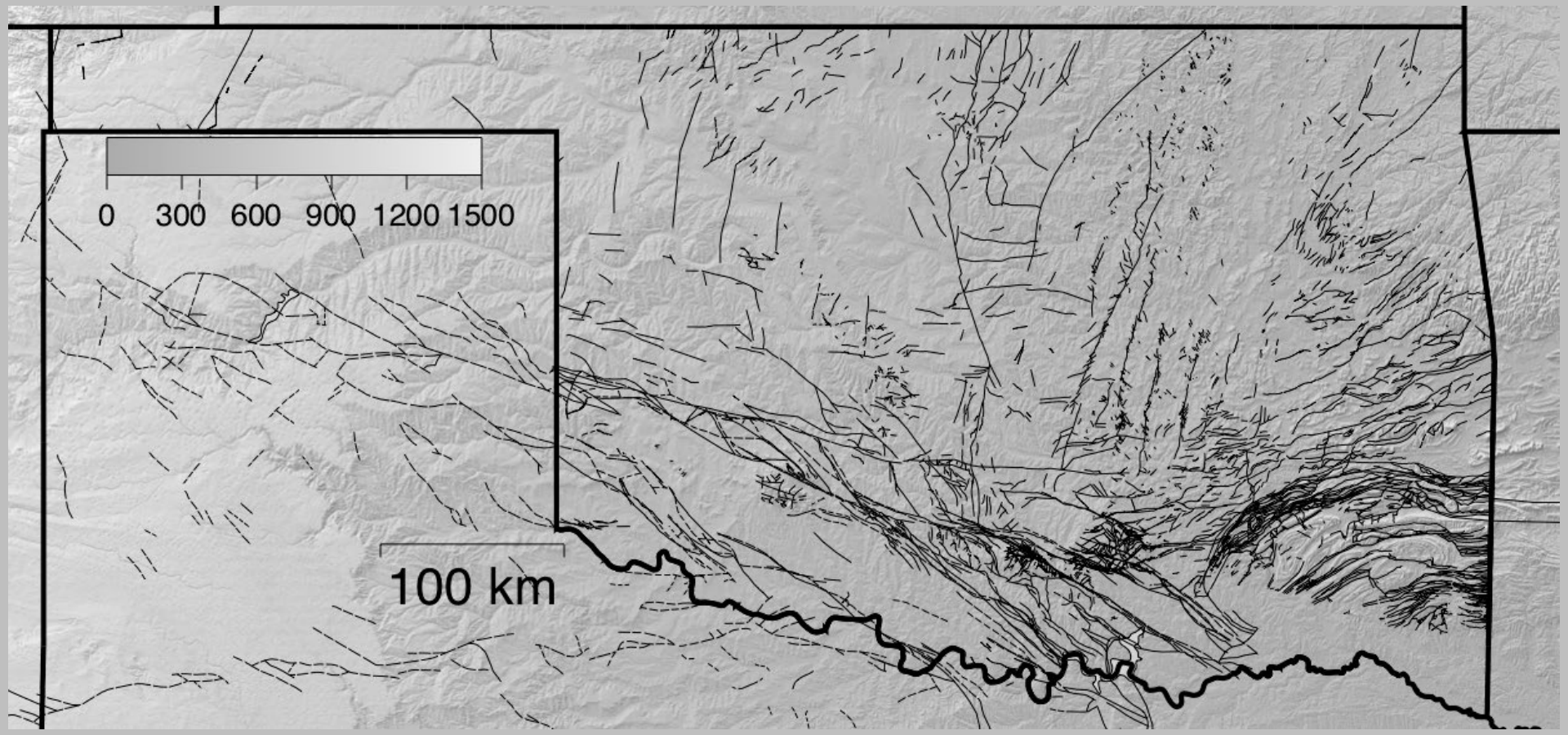
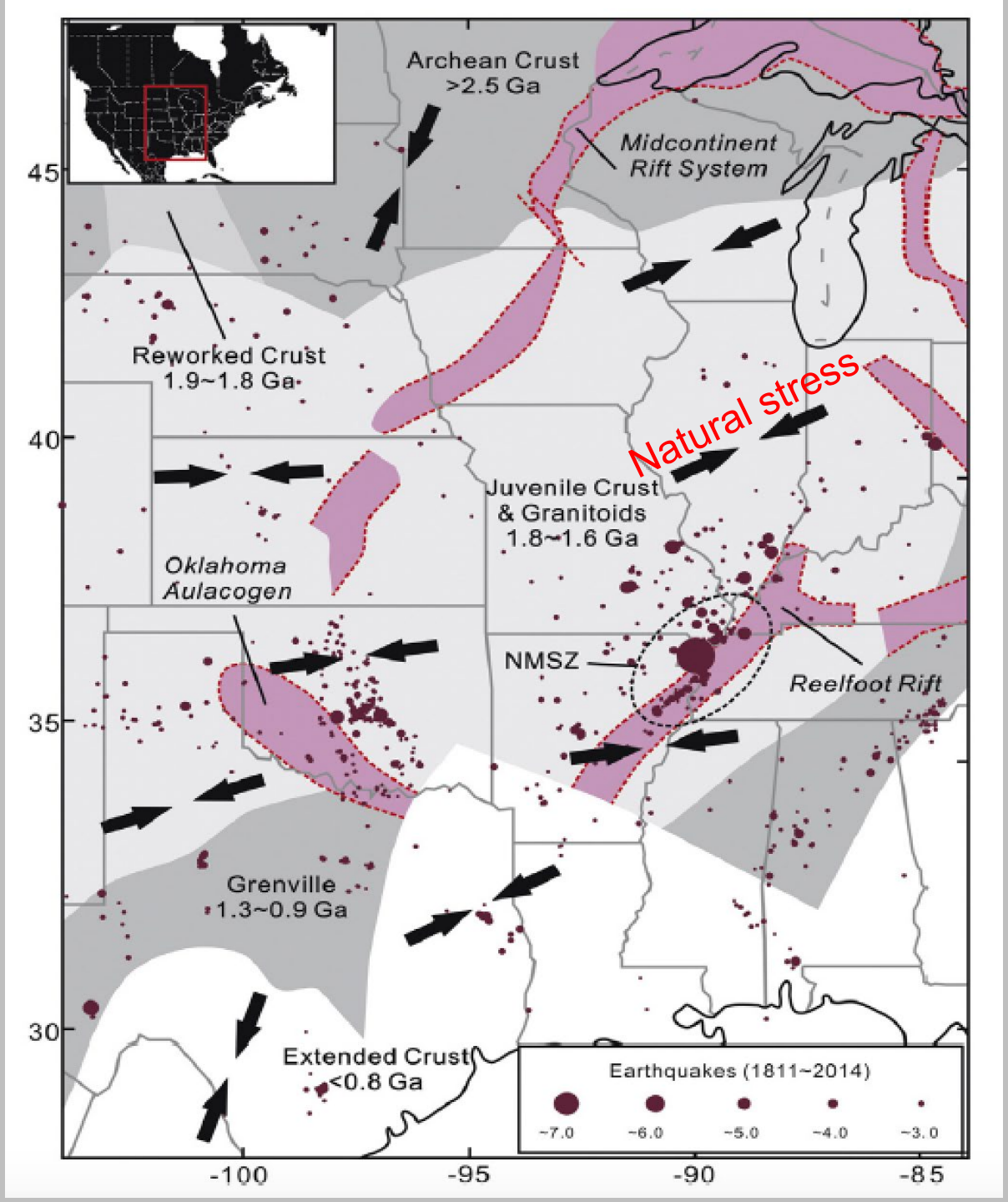
Hazard model

Statistical seismology informs us of the hazard based on what we know about past earthquakes

ogs.ou.edu

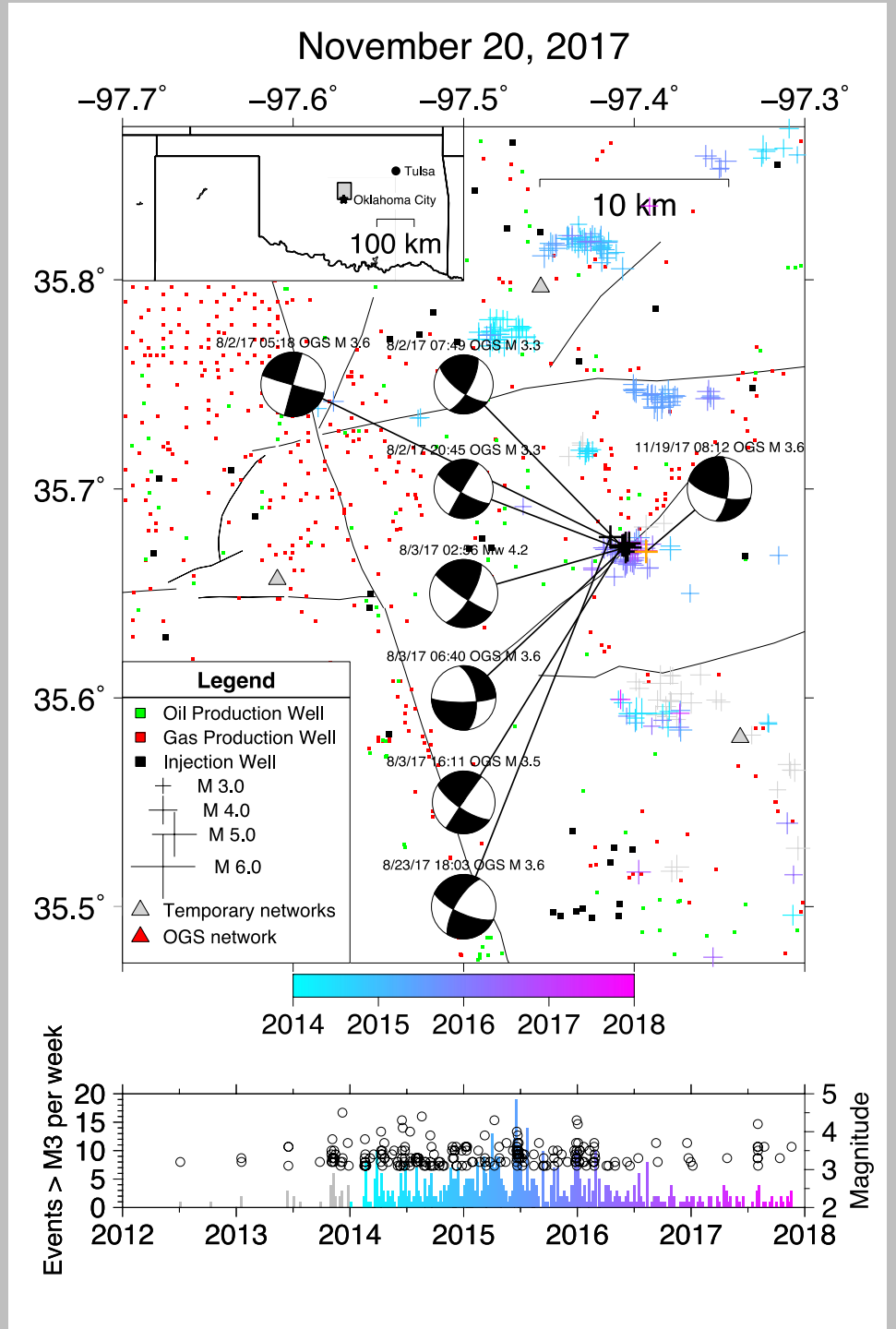


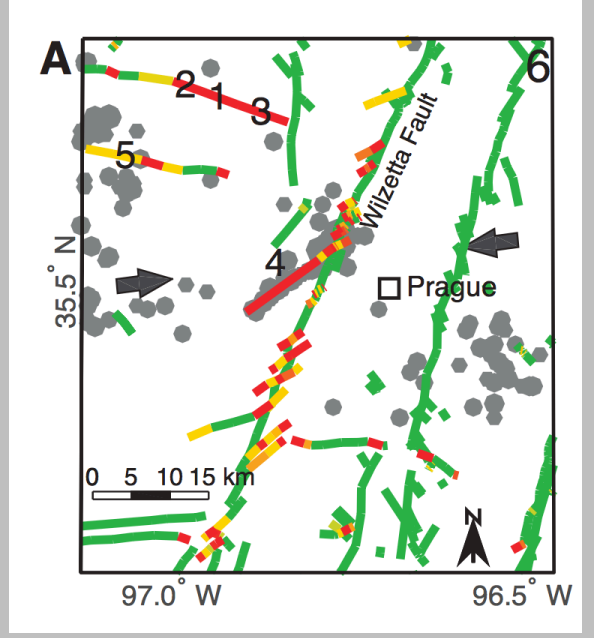
Complexity of faults and smaller features not captured



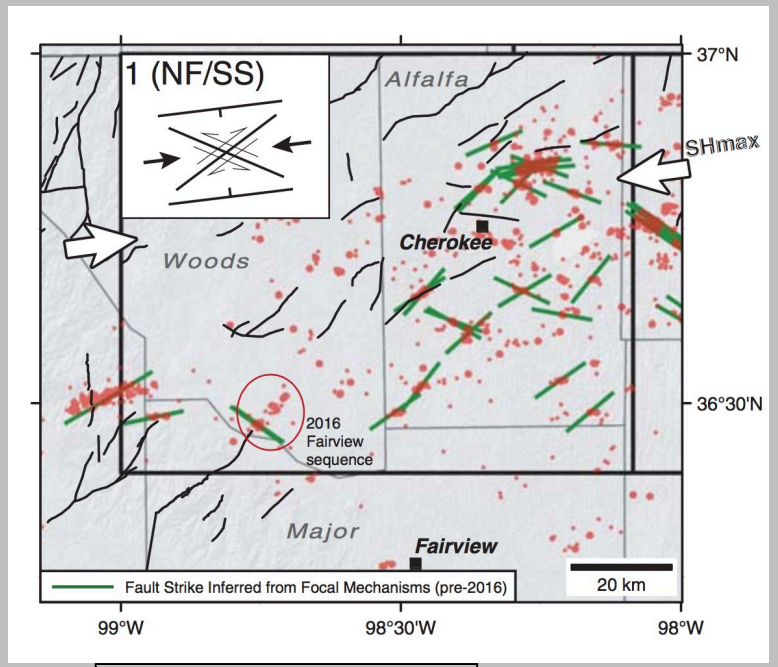
REGIONAL STRESS DIRECTION

Stress development in heterogenetic lithosphere: Insights into earthquake processes in the New Madrid Seismic Zone *(Zhan et al., 2016)*



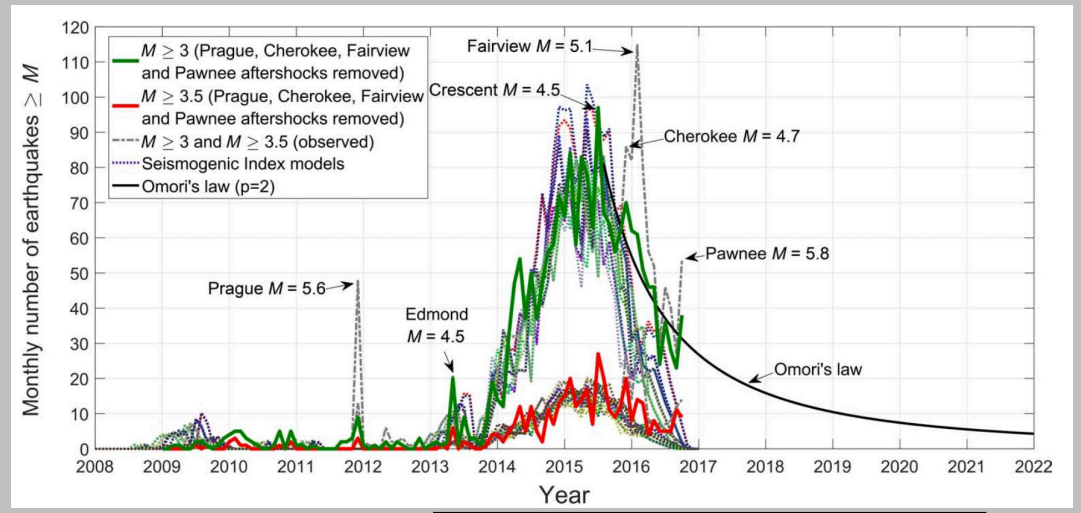


Walsh and Zoback, 2016

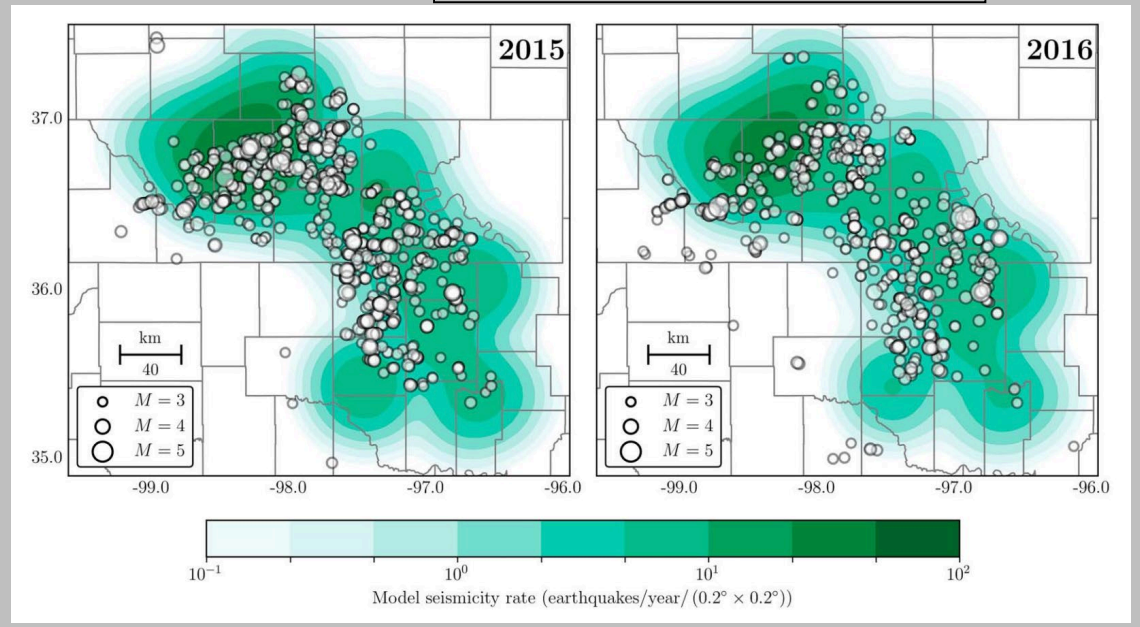


Alt and Zoback, 2017

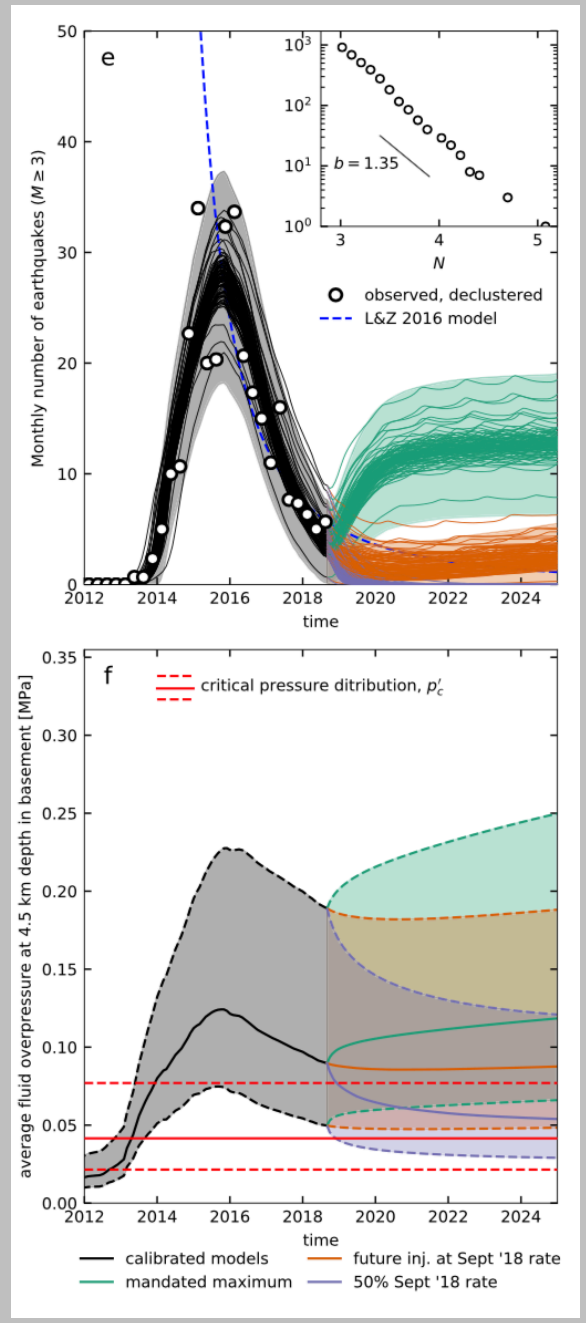
Seismicity and pore pressure models



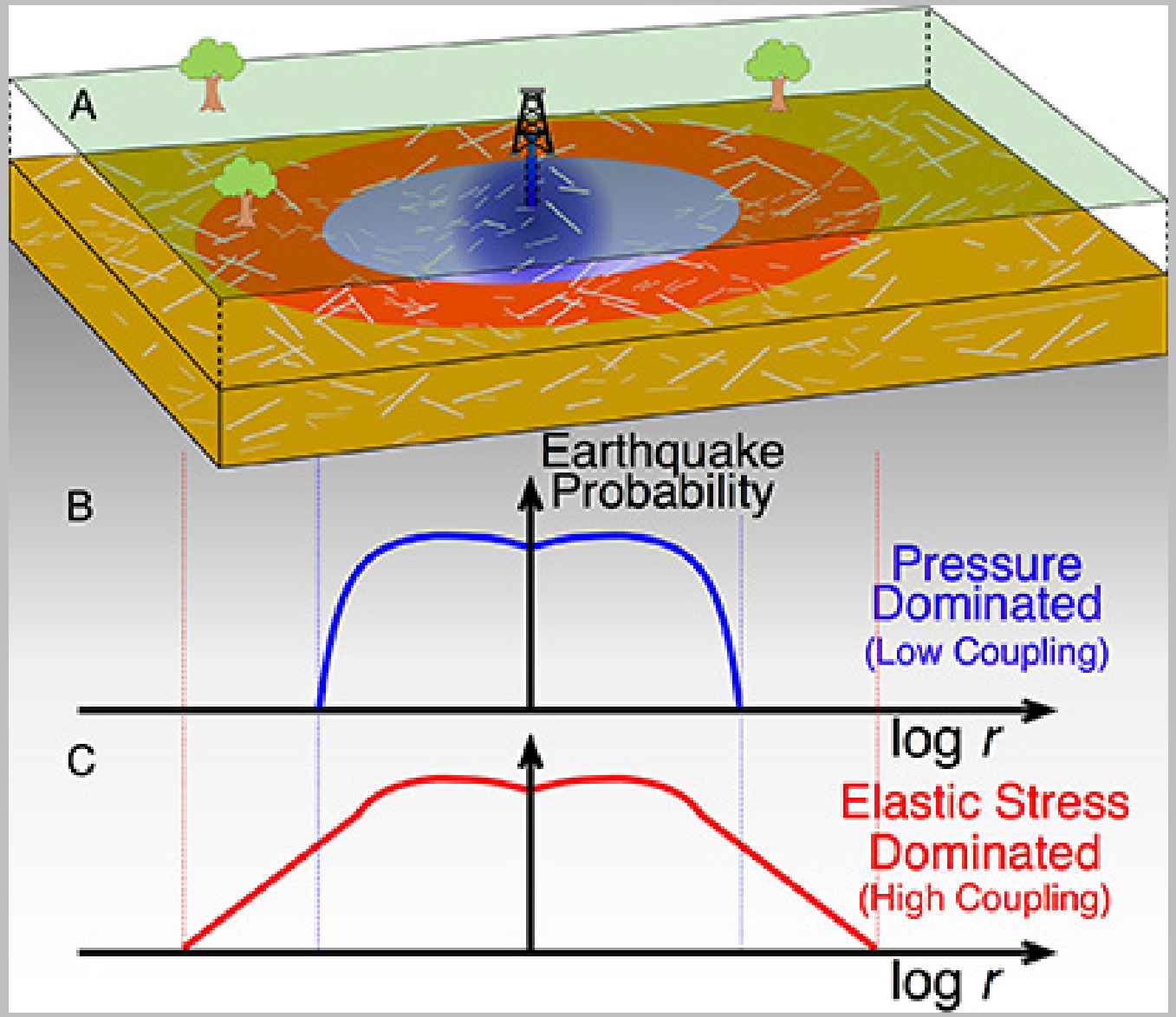
Langenbruch and Zoback, 2016



Norbeck and Rubinstein, 2018

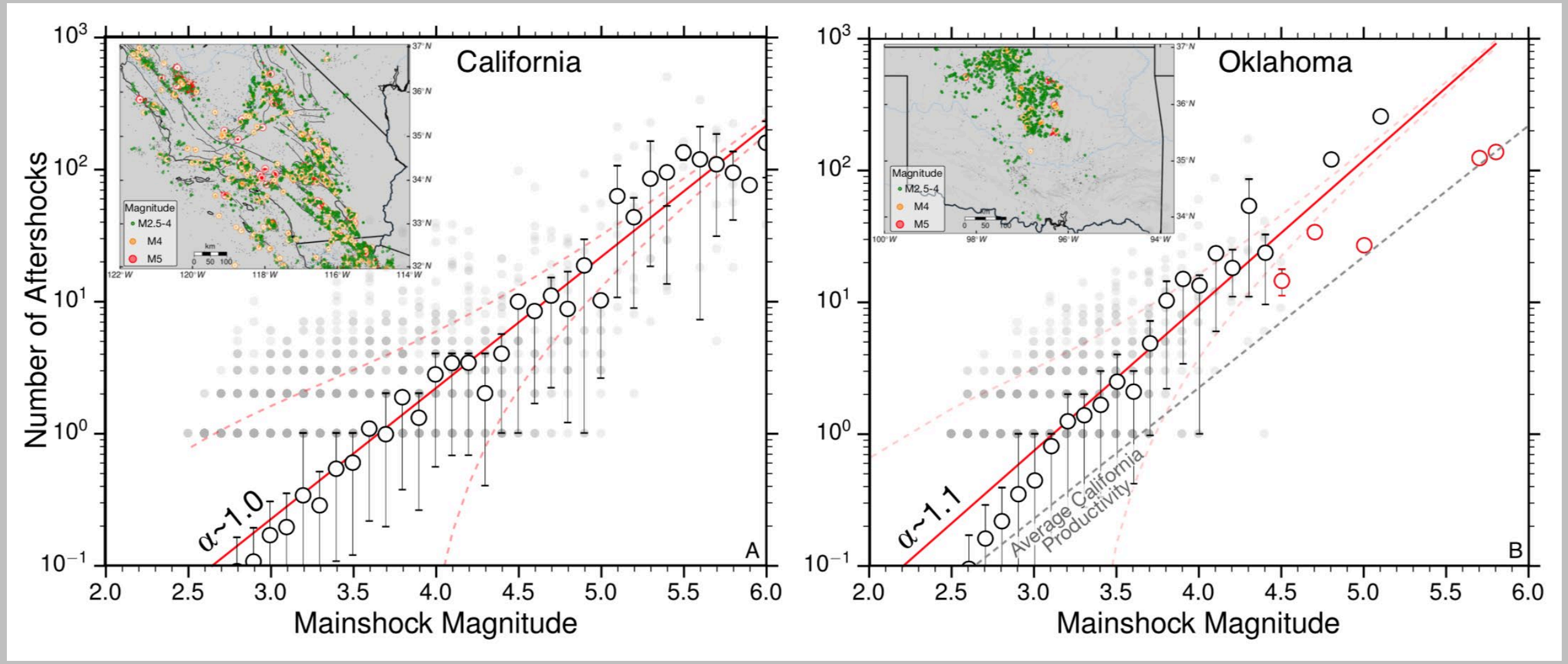


Dempsey and Riffault, 2019

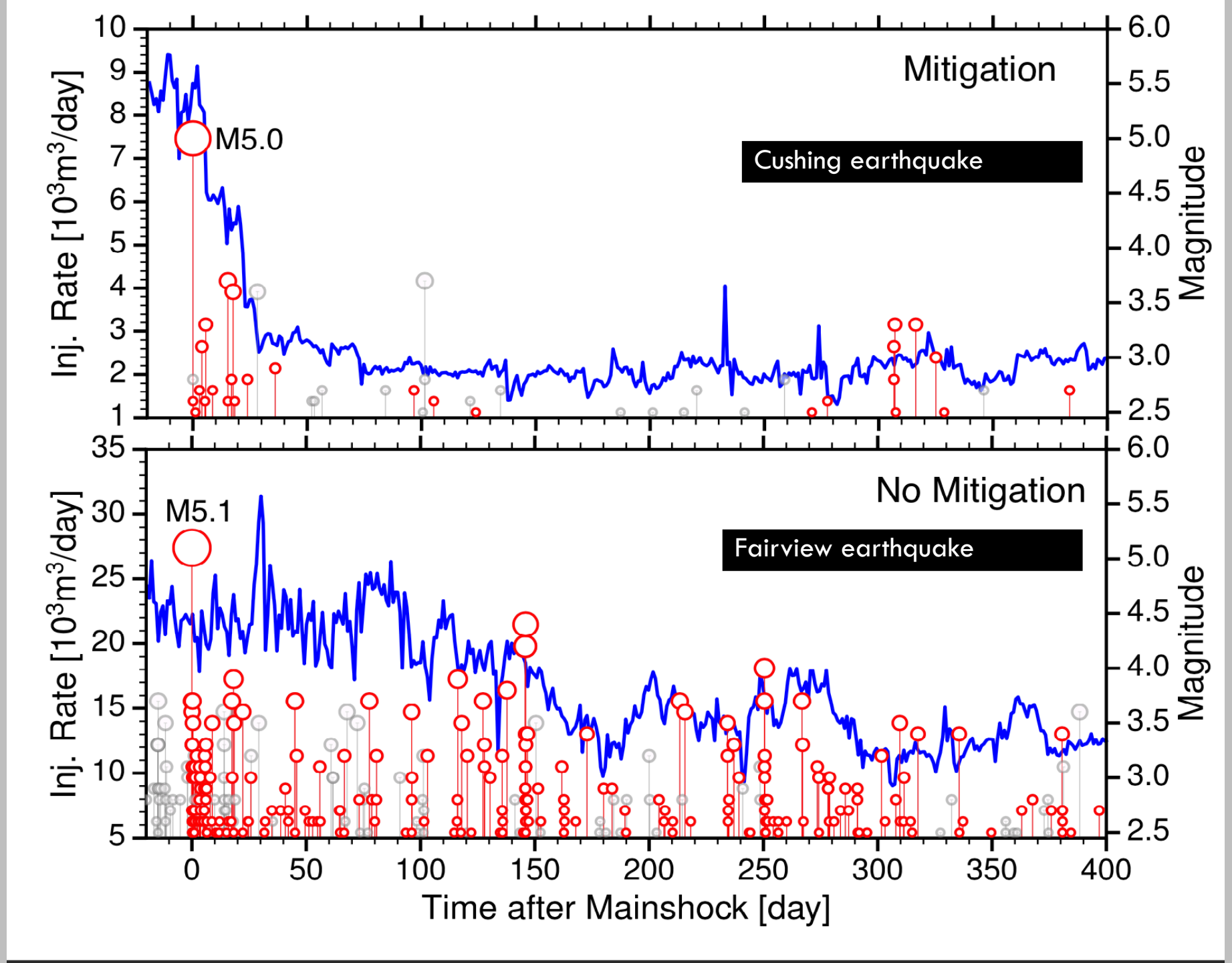


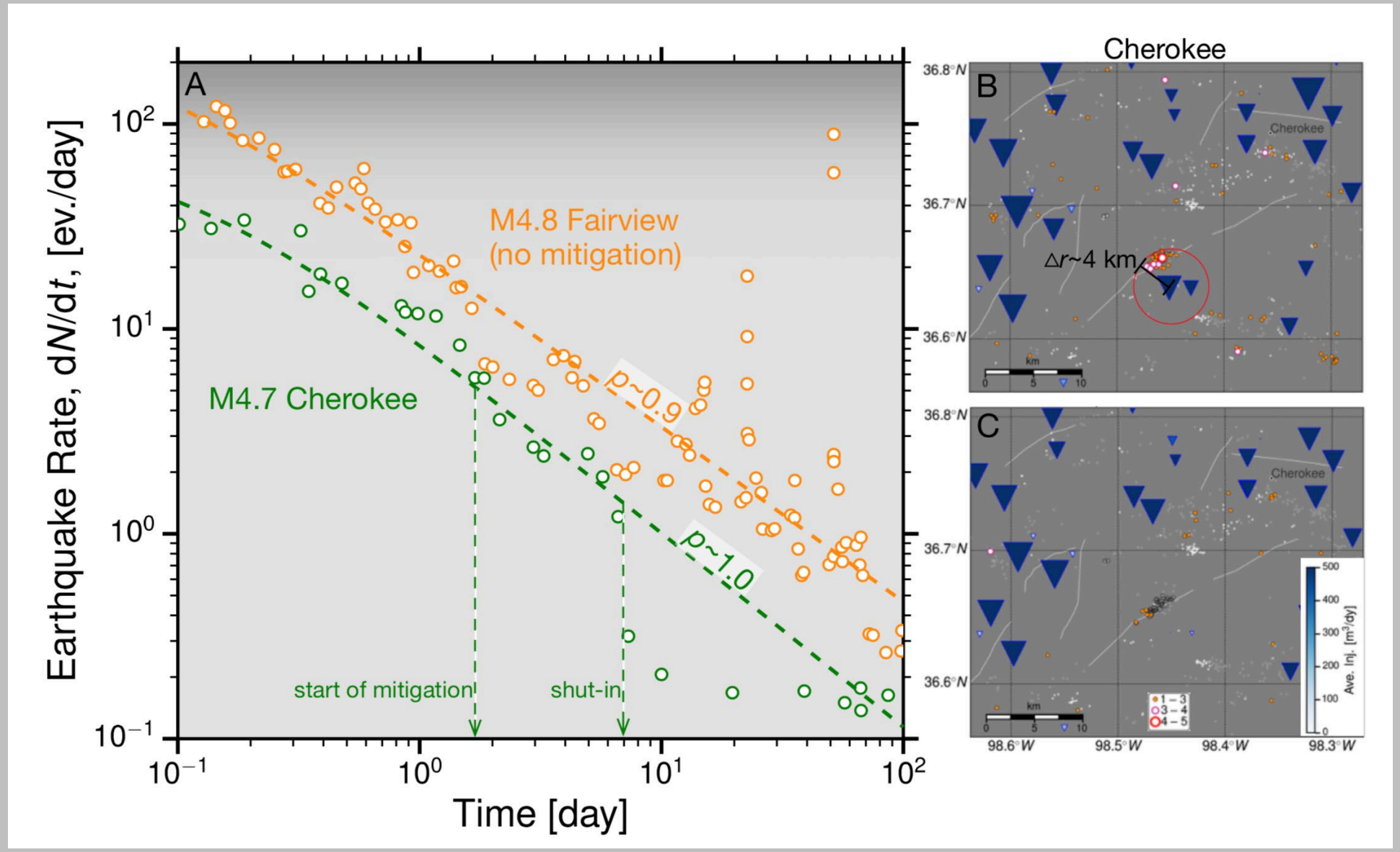
Goebel and Brodsky, 2018


OKLAHOMA EARTHQUAKES
OCC: SHUTTING DOWN WELLS, REDUCING VOLUME
THE LATEST
FOX 23 NEWS
5:01
62°



Goebel et al., 2019


Mitigation
M5.0
Cushing earthquake
No Mitigation
M5.1
Fairview earthquake
Inj. Rate [10³m³/day]
Magnitude
Time after Mainshock [day]
0
50
100
150
200
250
300
350
400


A
M4.8 Fairview
(no mitigation)
M4.7 Cherokee
p~0.9
p~1.0
start of mitigation
shut-in
Earthquake Rate, dN/dt, [ev./day]
Time [day]
Cherokee
B
C
Δr~4 km
36.8°N
36.7°N
36.6°N
98.6°W
98.5°W
98.4°W
98.3°W
km
1 – 3
3 – 4
4 – 5
Ave. Inj. [m³/dy]

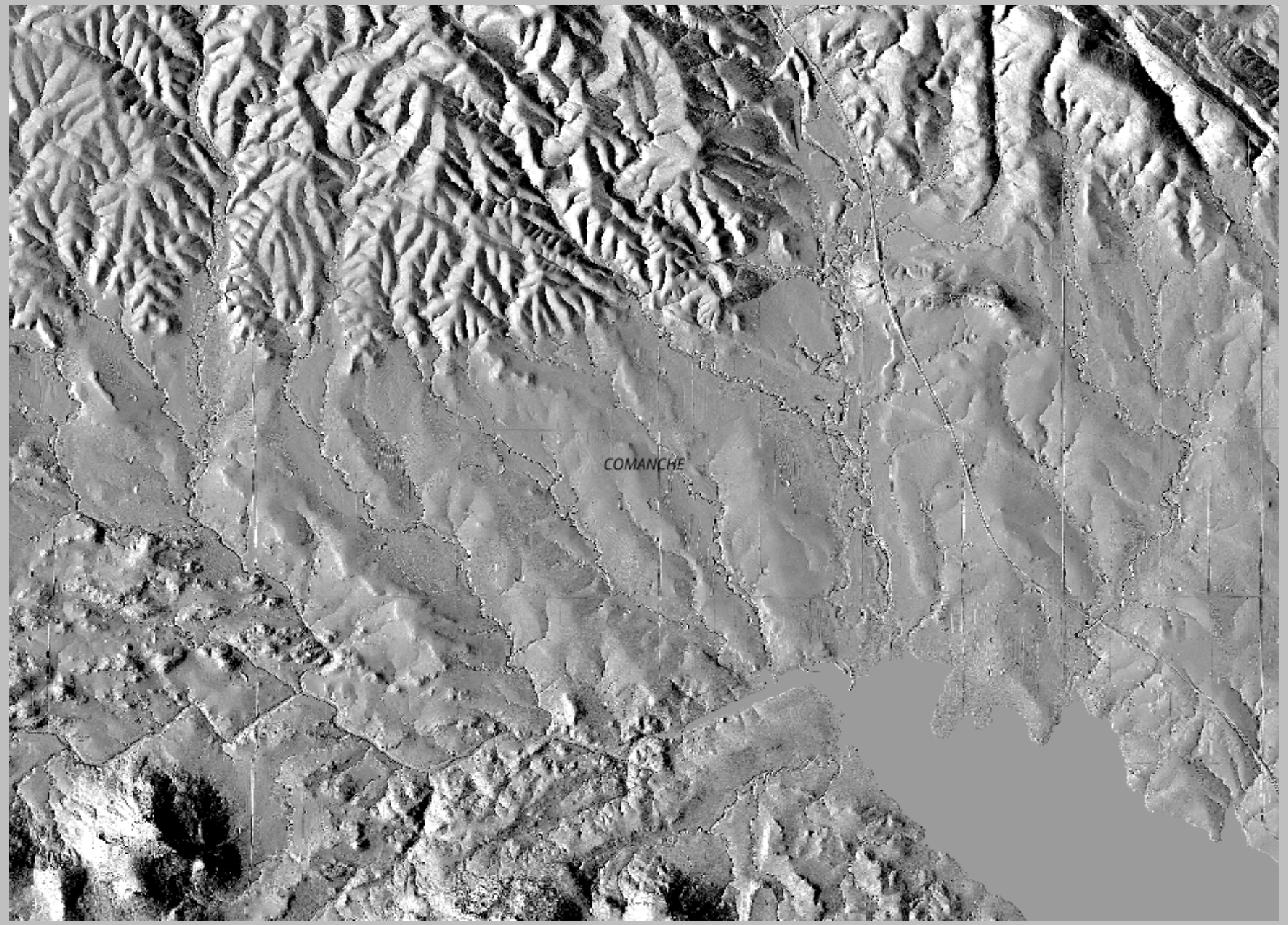
Consider geologic time

AREAL VIEW OF THE MEERS FAULT

THE MOST PROMINENT HOLOCENE FAULT SCARP EAST OF THE ROCKY MOUNTAINS!

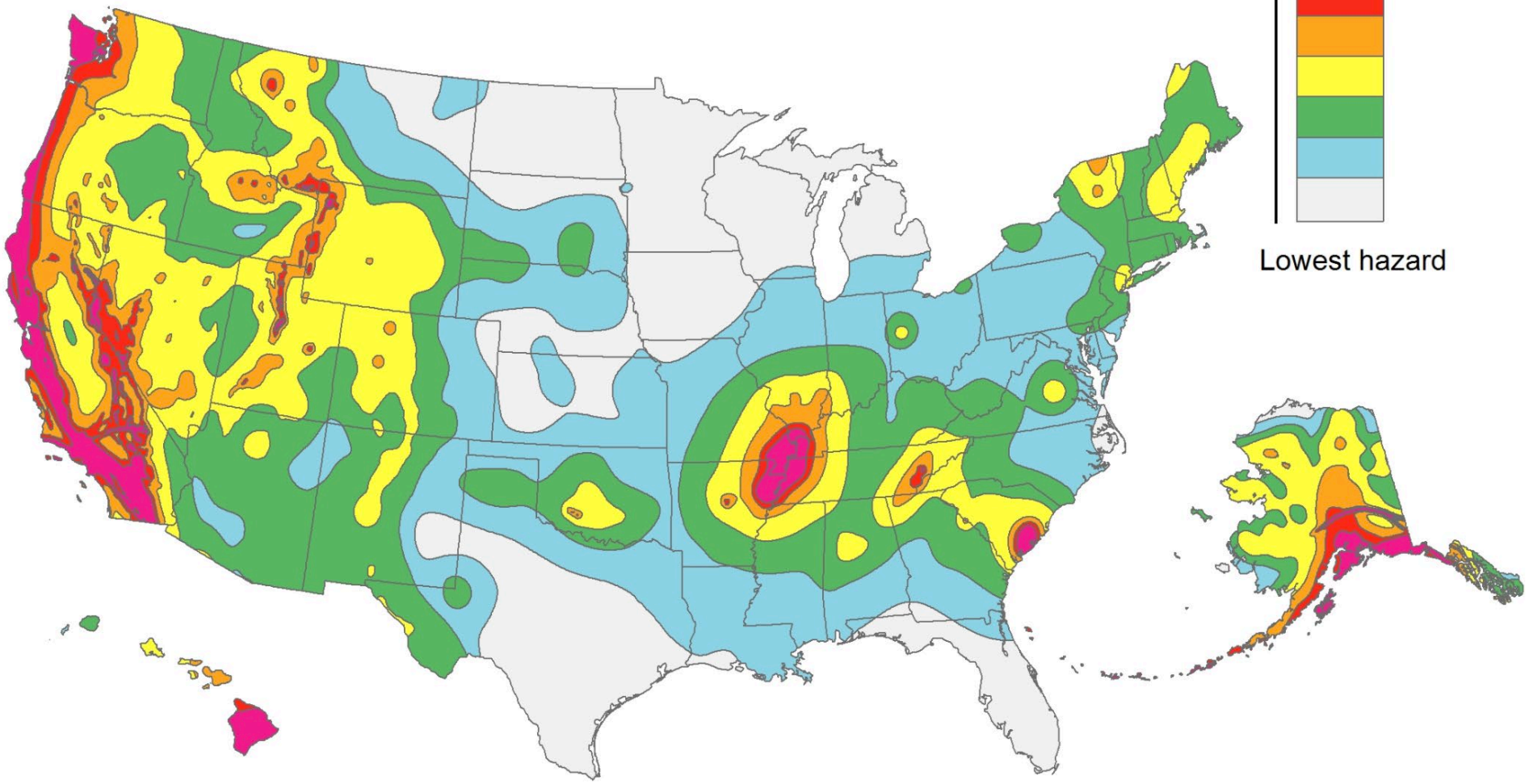
LARGE (~ 7 MAGNITUDE OCCURRED EVENTS, ~1300, ~2600, AND MAYBE ~5000 YEARS AGO)

Photo by D.B. Slemmons, Univ. of Nevada, Reno, *in* Madole, 1988.


COMANCHE

USGS
science for a changing world

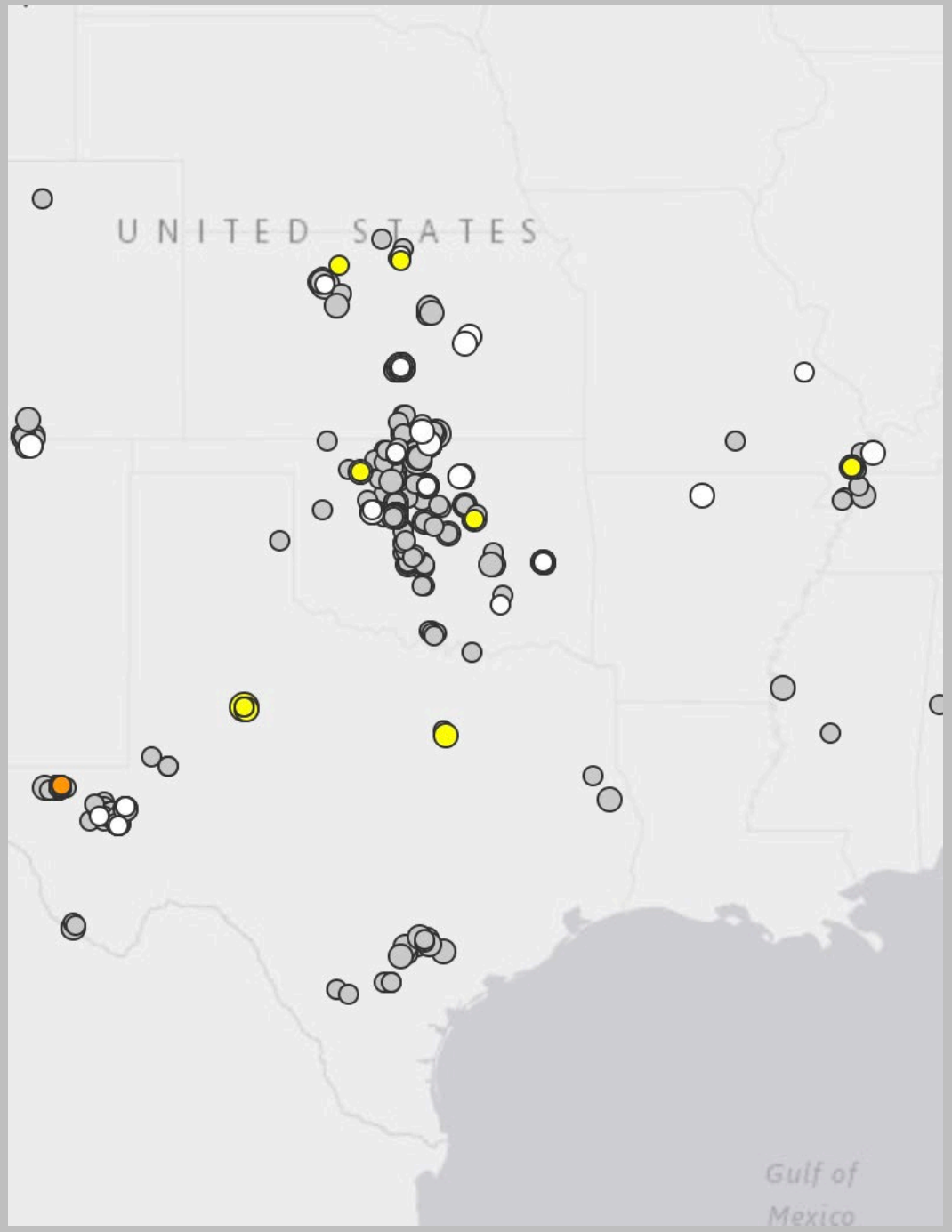
Seismic hazard “before” induced earthquakes

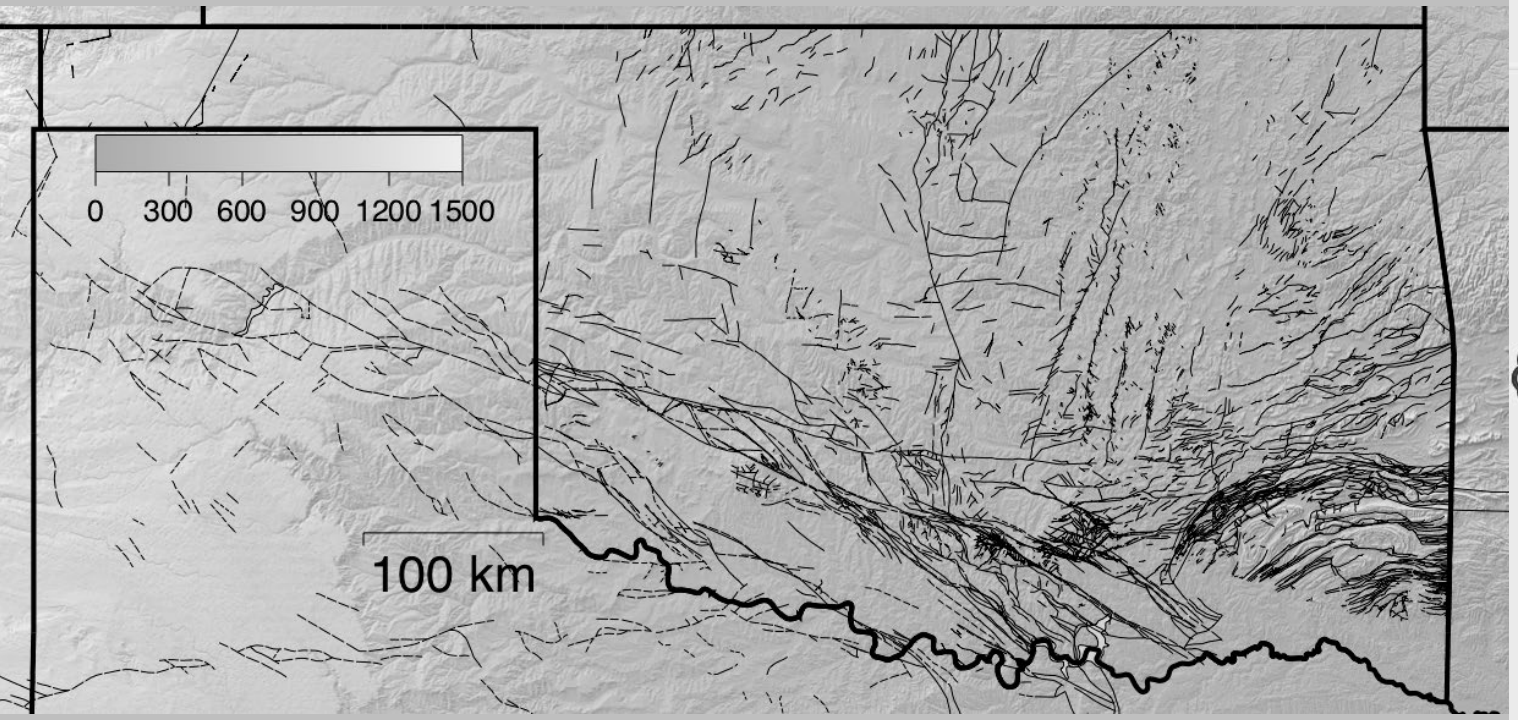


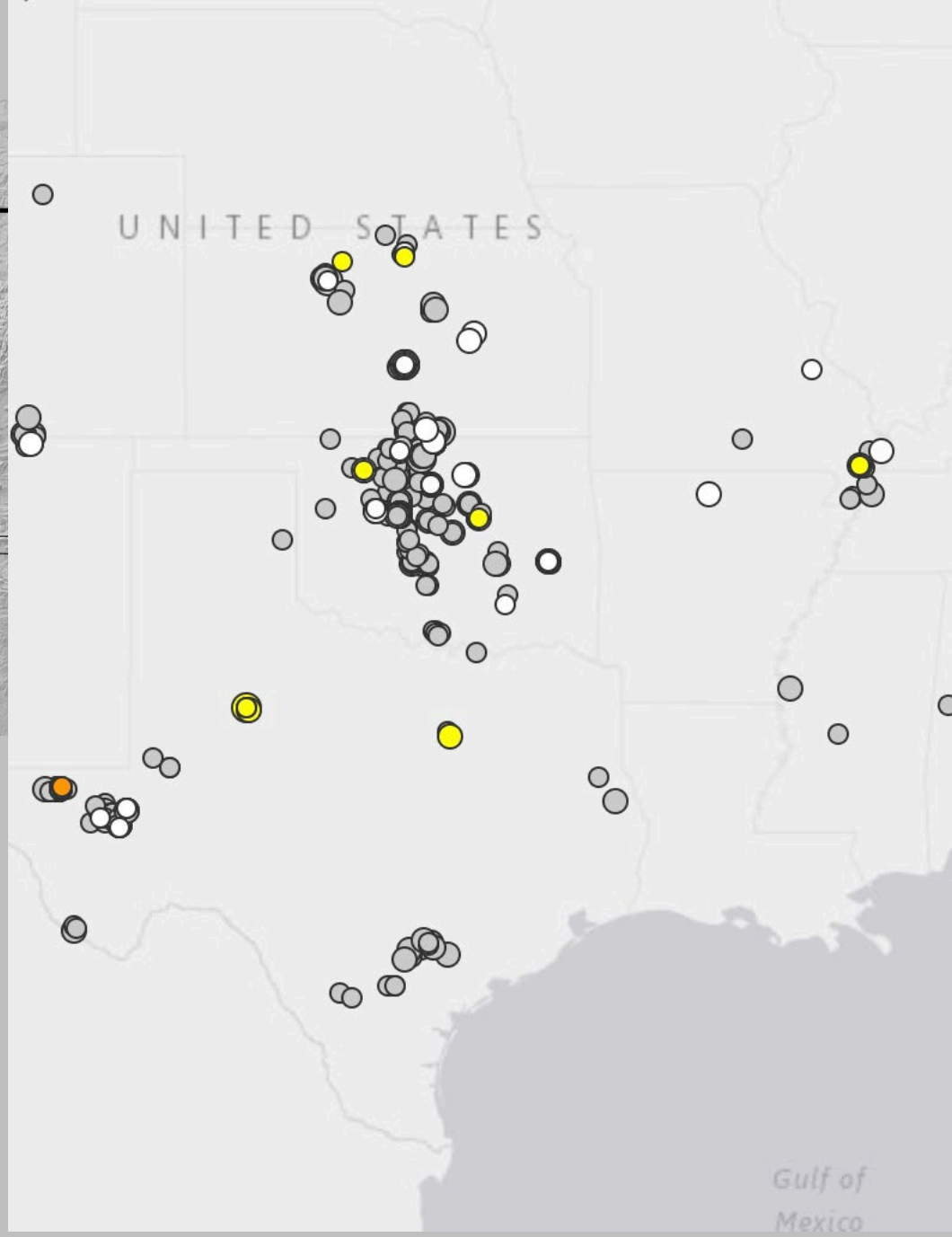
Midcontinent seismicity since January 1, 2019 (earthquakes > M2.5)

Earthquakes occur everywhere in the world, in unexpected places and those places lead to the most damage

Midcontinent may be more active than the East Coast, but everywhere east of California is lumped into "Central and Eastern US" in federal hazards program

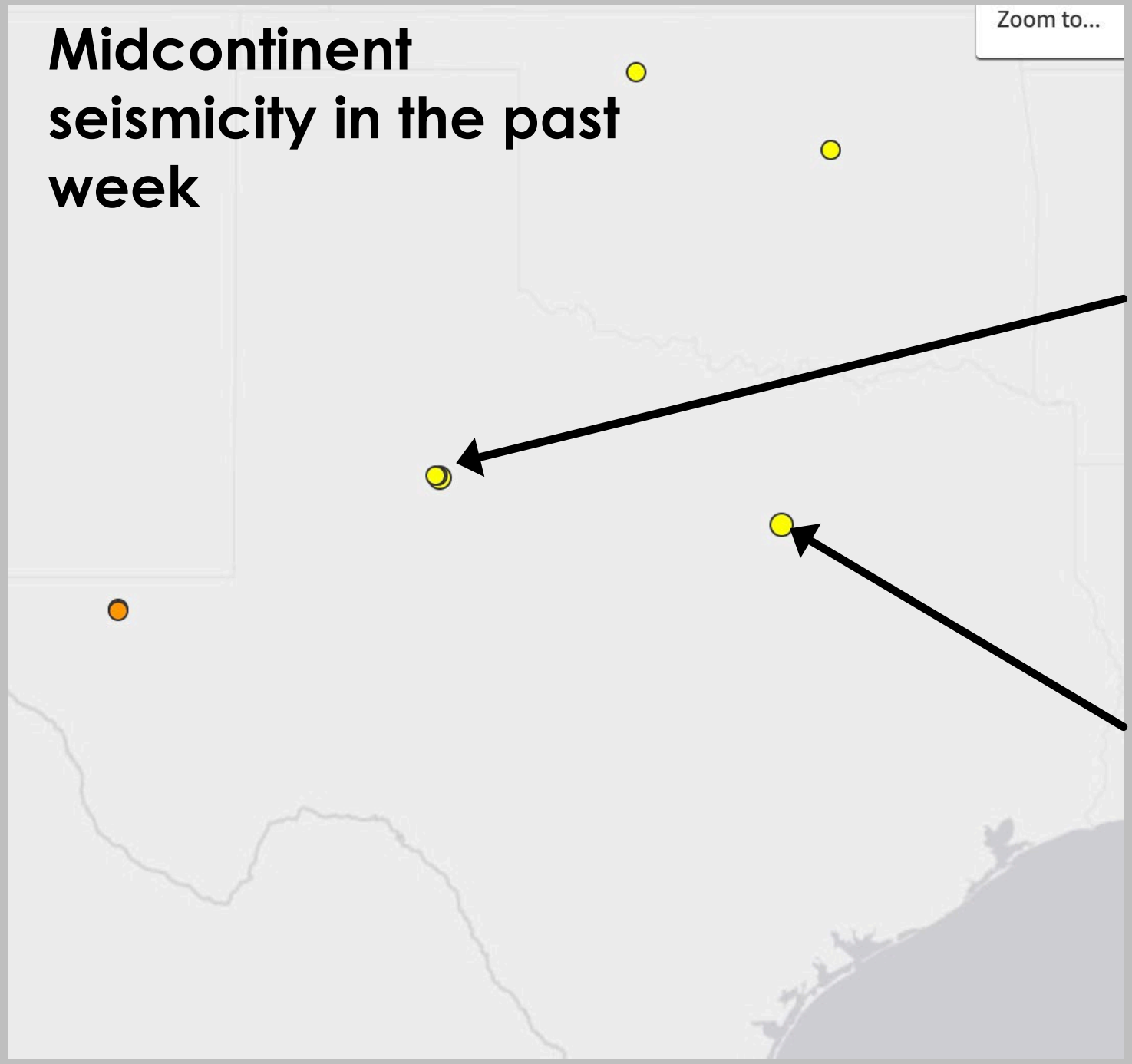






Perhaps the midcontinent is more seismically active than assumed?

Midcontinent seismicity in the past week



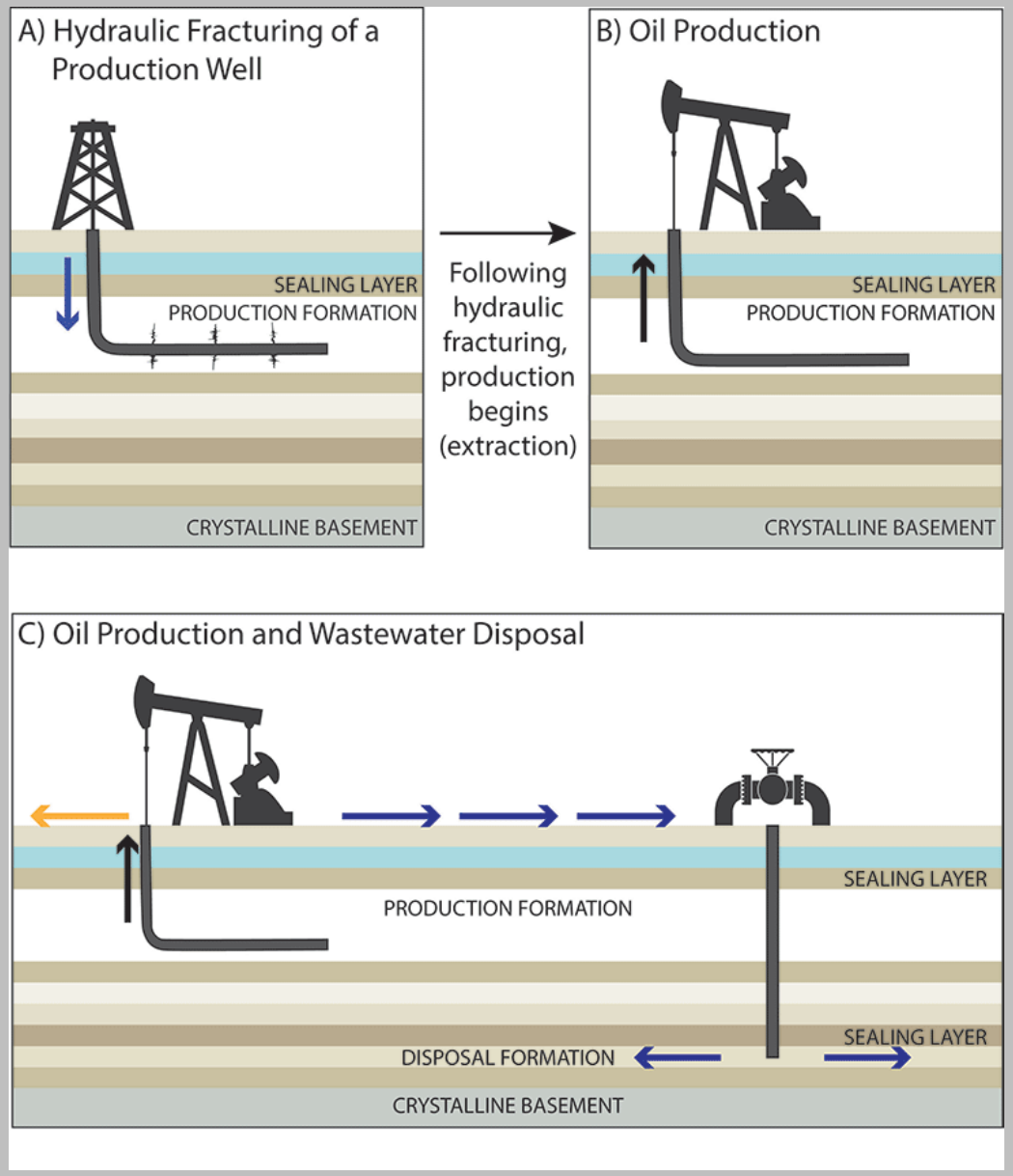
M4.0 Snyder-Cogdell Field, induced earthquakes since the 1970s, CO2 waterflood operation

M3.2 Venus, TX site of the 2015 M4.0 Venus earthquake (Scales et al., 2018), wastewater disposal

Great Central US Shakeout happened –
Did you miss out?

October 17 10:17 AM

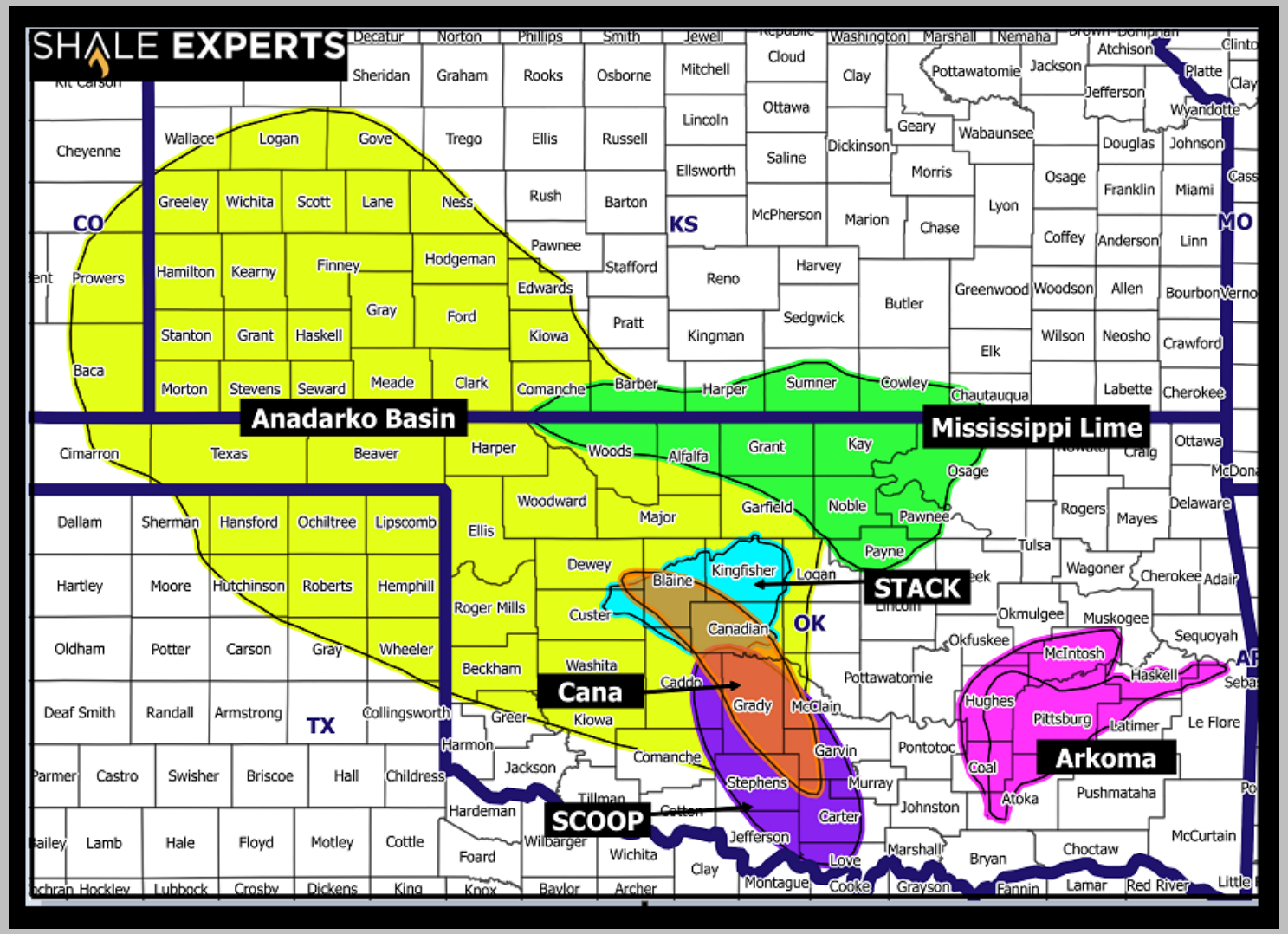
Your organization can participate:
www.shakeout.org

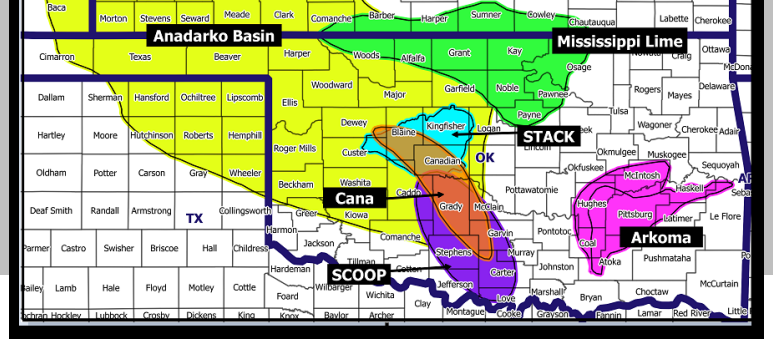


Arbuckle Group in Oklahoma

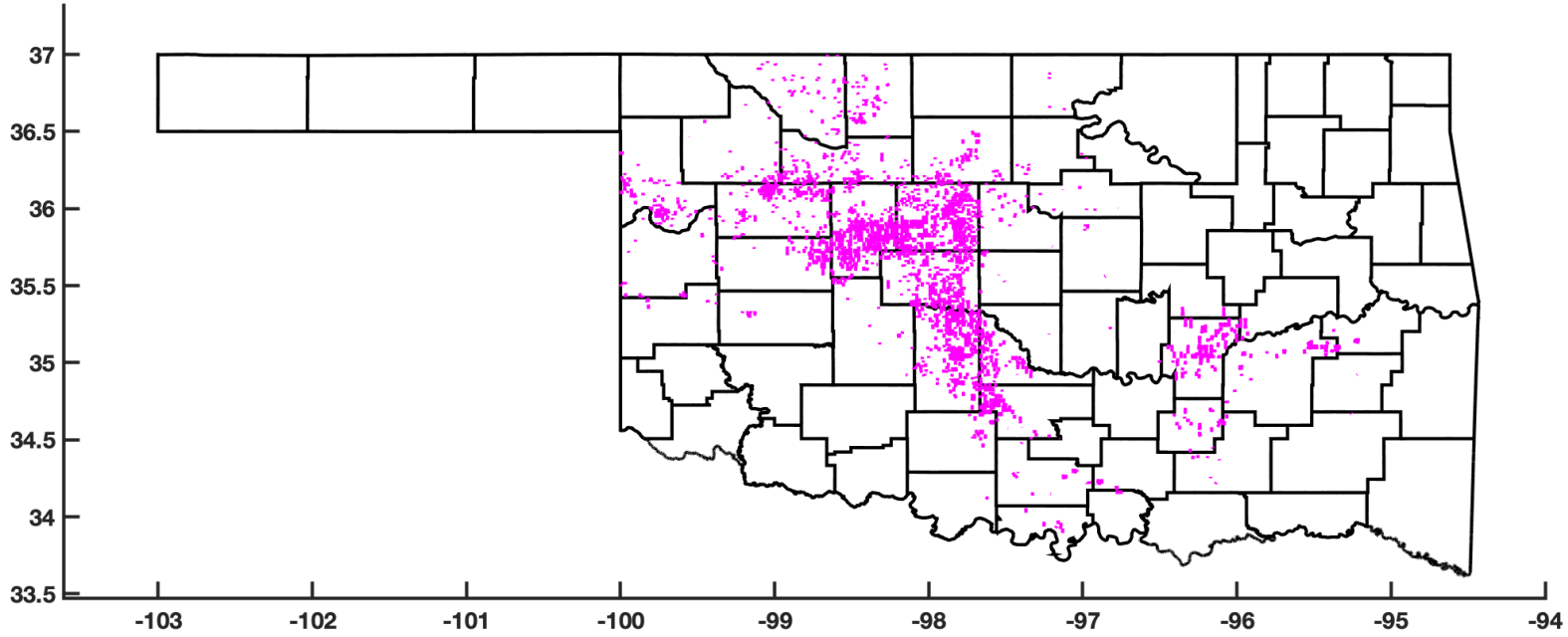
Rubinstein and Mahani, 2015

SCOOP/STACK enters the picture …

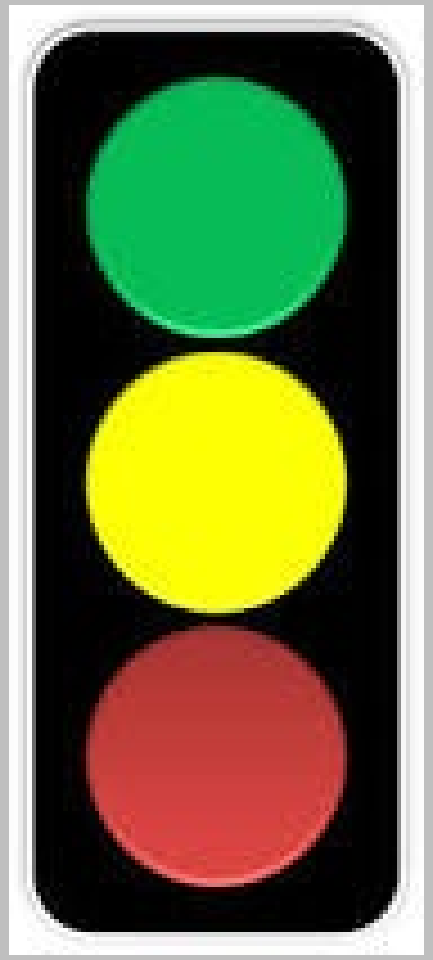




FracNotice available since Oct 2016



Oklahoma Corporation Commission Protocol for earthquakes associated with well completions (issued Dec 20, 2016, since updated, with more updates likely)



SUMMARY OF WELL COMPLETION SEISMICITY GUIDANCE

Terms: Oil and Gas Conservation Division (OGCD)
Oklahoma Geological Survey (OGS)

Action following anomalous seismic activity within 1.25 miles of hydraulic fracturing operations:

- **If magnitude, as determined by the OGS, is greater than or equal to 2.5M:**
  - **OGCD contacts designated representative for the operator with active completion operations within a 2 km radius of located seismic events.**
  - **Implementation of the operator's internal mitigation practices commences.**
  - **Operation continues.**

- **If magnitude is greater than or equal to 3.0M:**
  - **Operator initiates a pause of operations for no less than 6 hours.**
  - **Technical conference/call held between the OGCD staff and operator about operator mitigation practices.**
  - **Upon agreement between operator and OGCD regarding mitigation practices and reduced seismic activity, operator permitted to resume with revised completion procedure.**

- **If magnitude is greater than or equal to 3.5M:**
  - **Operator suspends operations**
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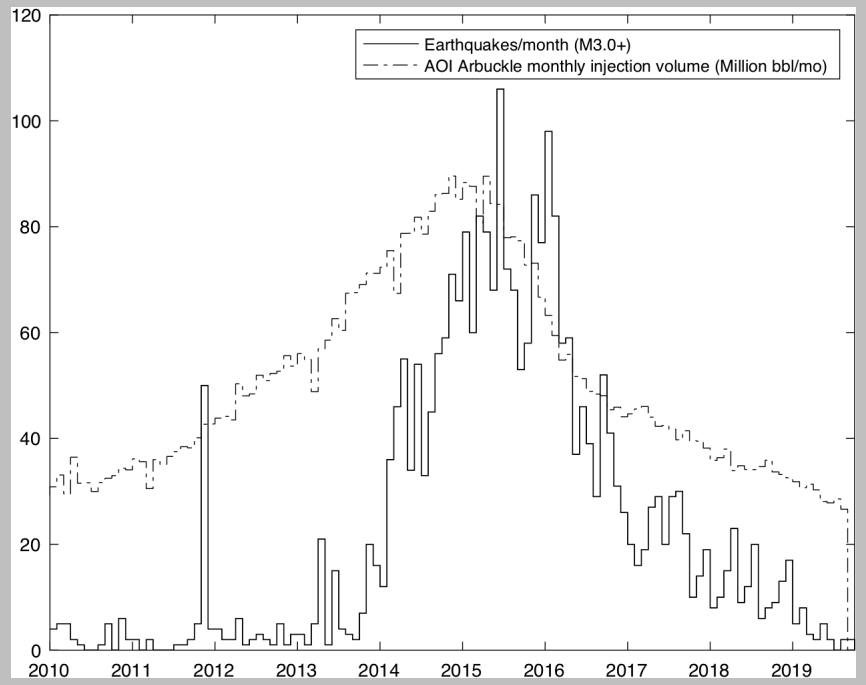
Hydraulic fracturing – injection occurs over days, mitigation on hours



Wastewater injection - injection for several years, mitigation for several years?

Rapid mitigation appears to successfully reduce aftershock productivity

Unconventionals in Oklahoma

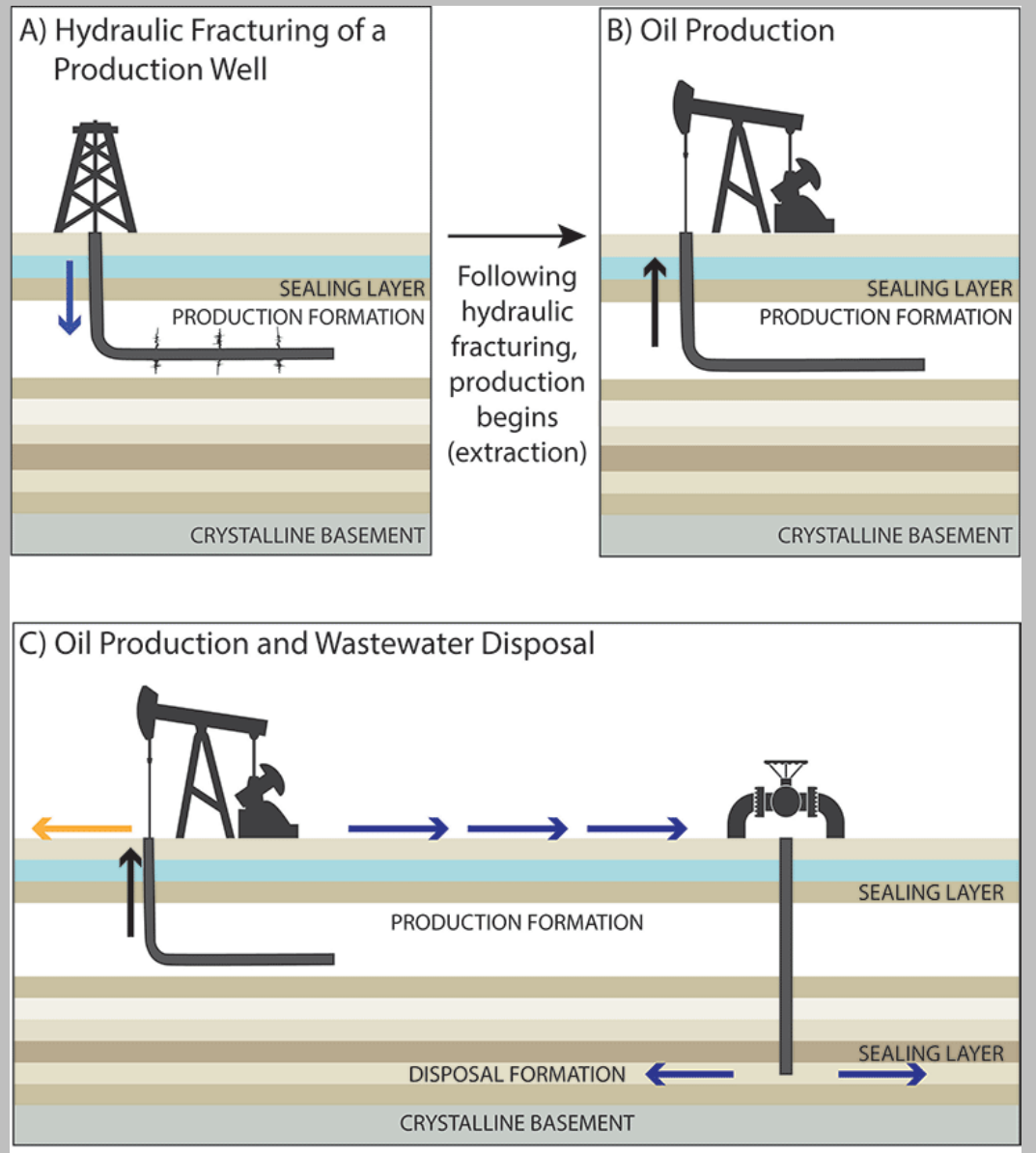
Horizontal drilling (~95% of new wells are horizontals - coupled with legislative change to allow 2 mi long laterals vs 1 mi long laterals previously)

Completion-triggered seismicity during hydraulic fracturing

Geology includes rocks with substantial produced water

Wastewater disposal-induced earthquakes

Arbuckle Group in Oklahoma



Rubinstein and Mahani, 2015

Unconventionals in Oklahoma

Horizontal drilling (~95% of new wells are horizontals - coupled with legislative change to allow 2 mi long laterals vs 1 mi long laterals previously)

Completion-triggered seismicity during hydraulic fracturing

<5% of completed wells and largest events only M3.6

Geology includes rocks with substantial produced water

Wastewater disposal-induced earthquakes

Large earthquakes are rare, but have incurred ~$10 million damage total (claims paid in Oklahoma), likely an underestimate of actual damage

($74 million in gross production taxes collected in September 2019)

Conclusions – takeaway points:

- Longer term hazard remains elusive to estimate but likely elevated chance of a moderately damaging (or several?) earthquakes in the next decade

- Short term challenges related to hydraulic-fracture triggered seismicity – hazard and risk associated with these actions?

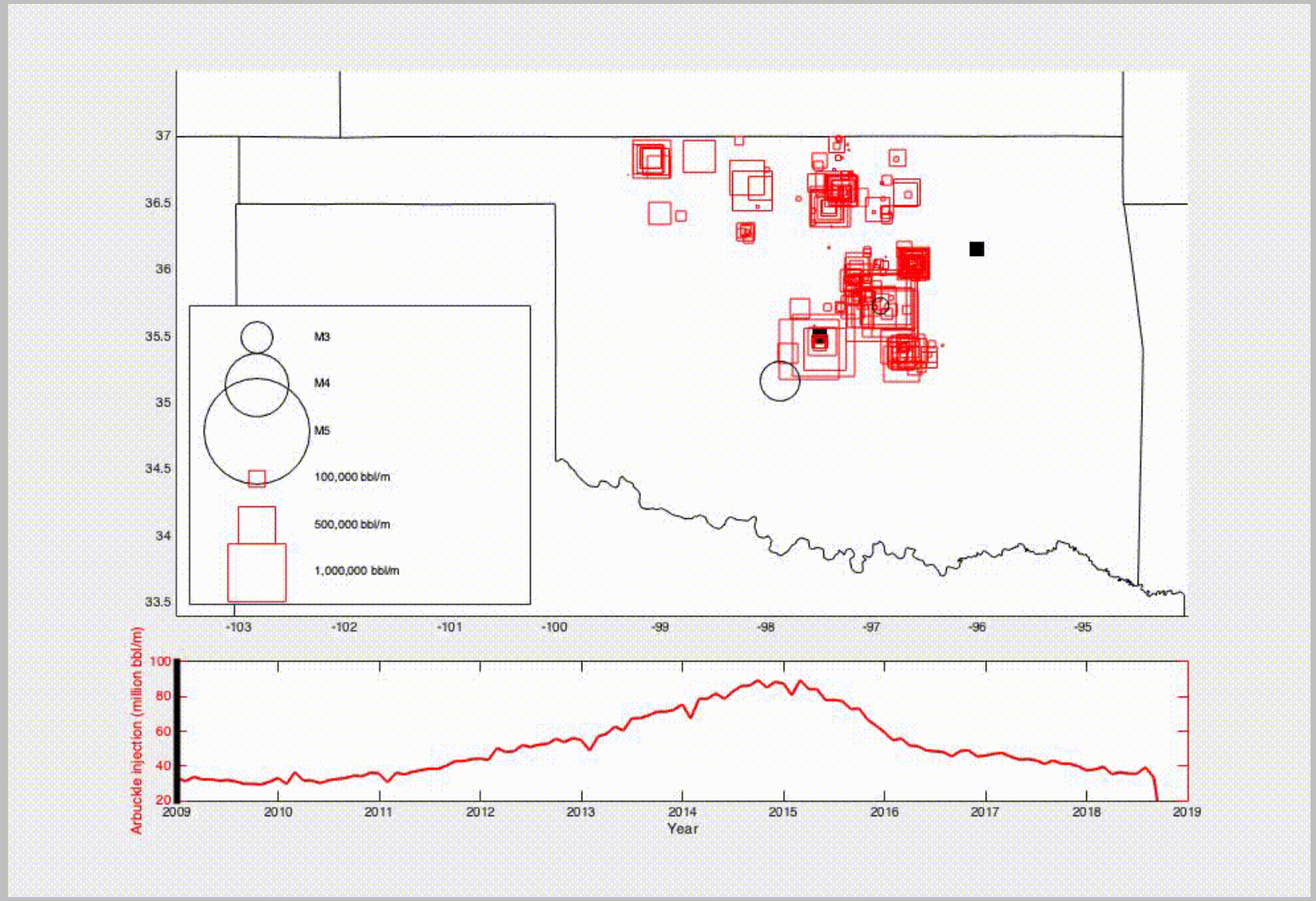
- **Science we can use:** State agencies support scientists working toward understanding mechanics of induced seismicity

- **How can we better serve our stakeholders?:** Local and regional scientists so incredibly important to our communities and often only access some citizens have to science. Follow-up questions: jwalter@ou.edu

Acknowledgements

The State of Oklahoma through the Secretary of Earth and Energy, DOE RPSEA funding for network upgrades in early mid-2010s, collaboration funding provided by DOE for Regional Induced Seismicity Collaboration (RISC), Current DOE NETL research funding

QUESTIONS?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M3
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M5
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Arbuckle injection (million bbl/m)
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60
40
20
2009
2010
2011
2012
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2015
2016
2017
2018
2019
Year