Induced Earthquakes: State of the Science 2018

Bill Ellsworth
Cornelius Langenbruch, Jens-Erik Lund-Snee,
Martin Schoenball[1], Clara Yoon[2], Matt Weingarten[3],
Greg Beroza and Mark Zoback

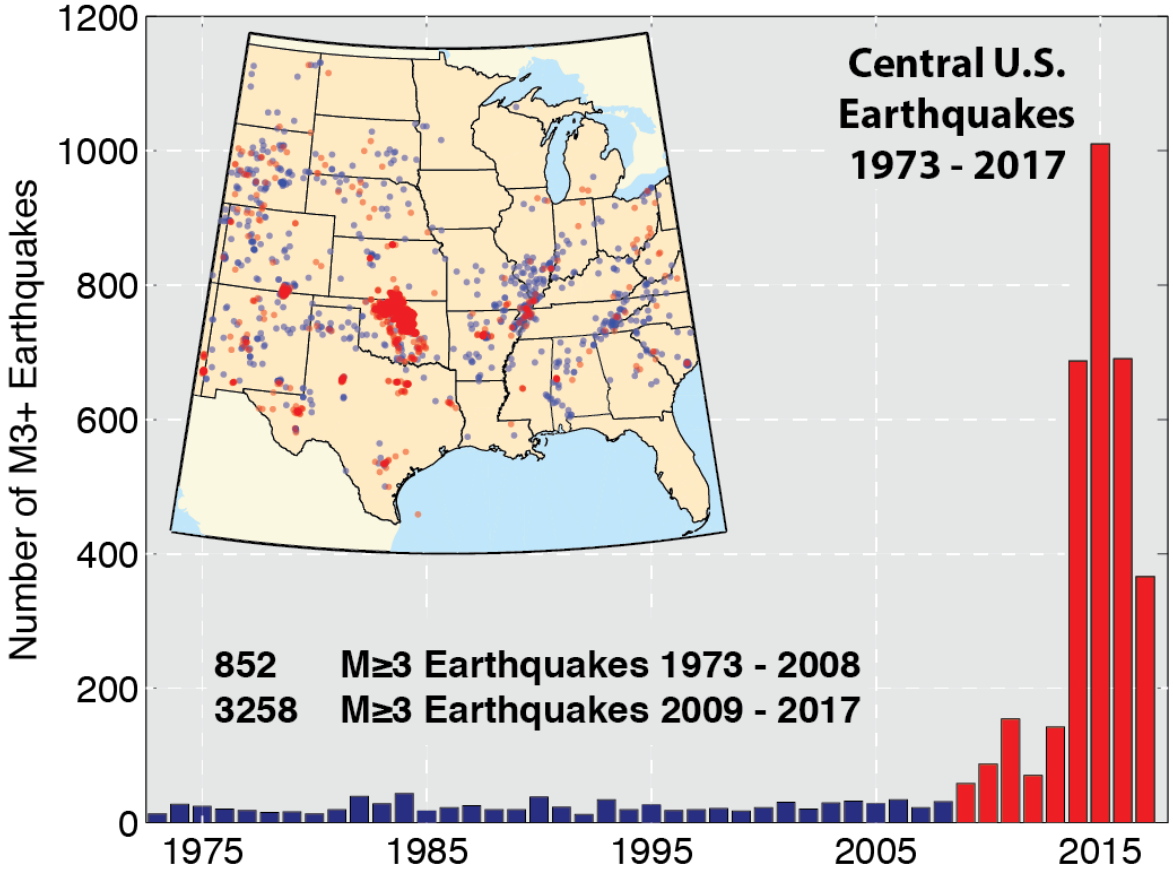
Stanford | Stanford Center for Induced and Triggered Seismicity
School of Earth, Energy & Environmental Sciences

[1] Now at Lawrence Berkeley National Laboratory
[2] Now at USGS, Pasadena
[3] Now at San Diego State University

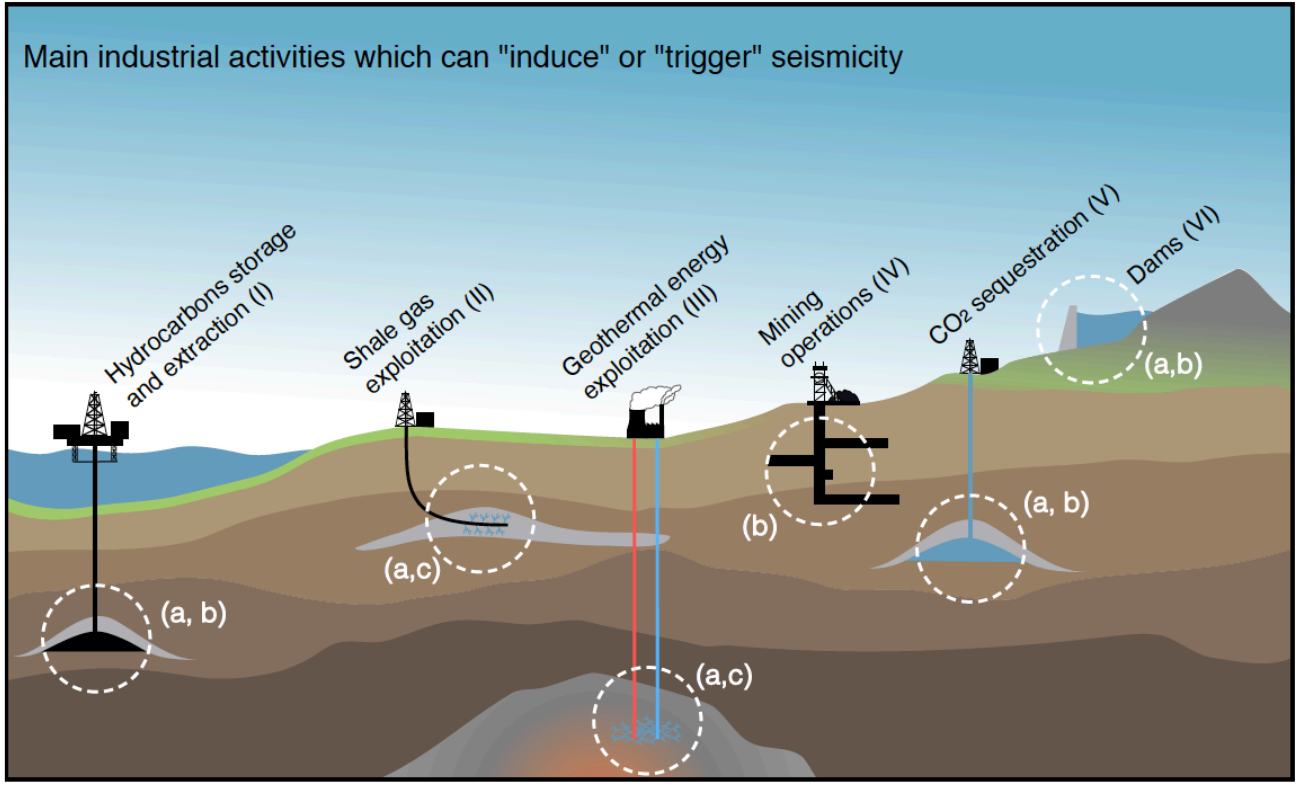
BANFF 2018 INTERNATIONAL
INDUCED SEISMICITY WORKSHOP
October 24 – 26, 2018 Banff,Alberta, Canada

Outline

- Mechanisms
- State of stress and perturbations
- High-pressure injection regime
- Low-pressure injection regime
- Physics-based prospective forecast

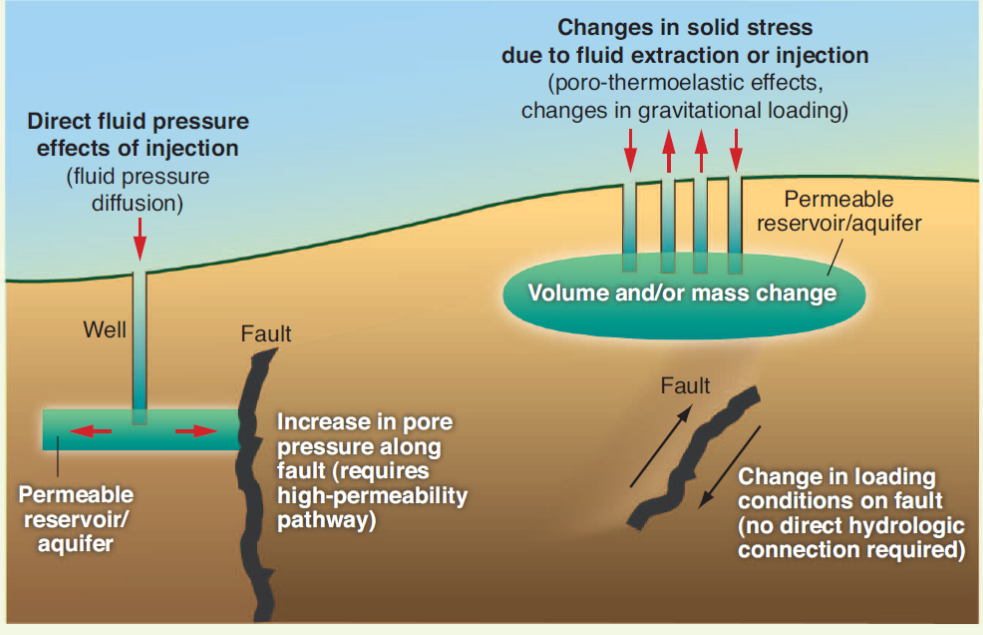


Mechanisms of Induced Earthquakes

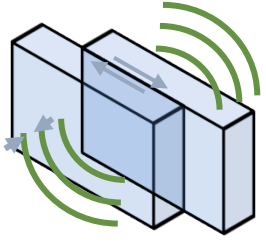


F. Grigoli, et al., 2017, Current challenges in monitoring, discrimination and management of induced seismicity related to underground industrial activities: a European perspective. *Reviews of Geophysics*, DOI: 10.1002/2016RG000542

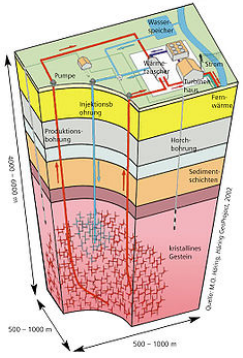
Inducing Earthquakes: Pore Pressure & Poroelasticity



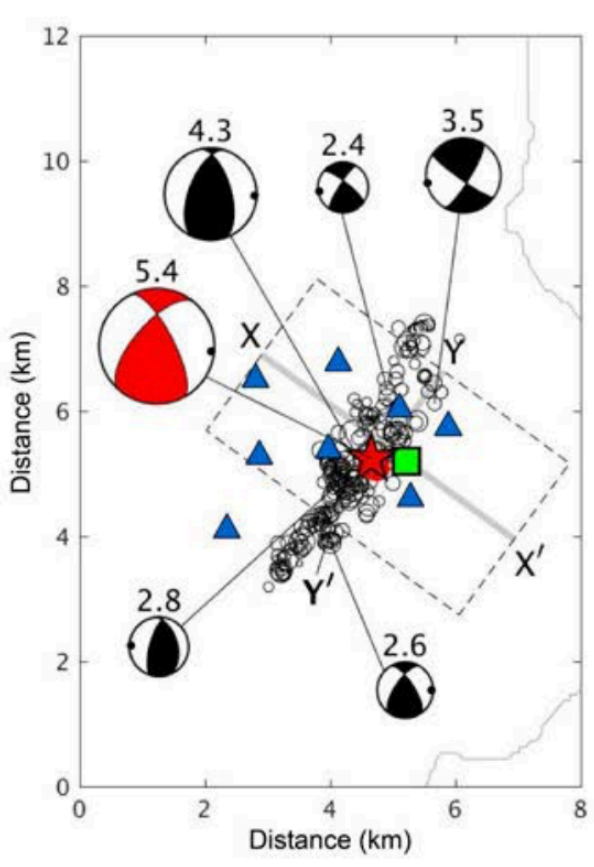
- Inactive faults can be reactivated by decreasing the effective normal stress
- $T_{crit} = \mu (\sigma_n - P)$

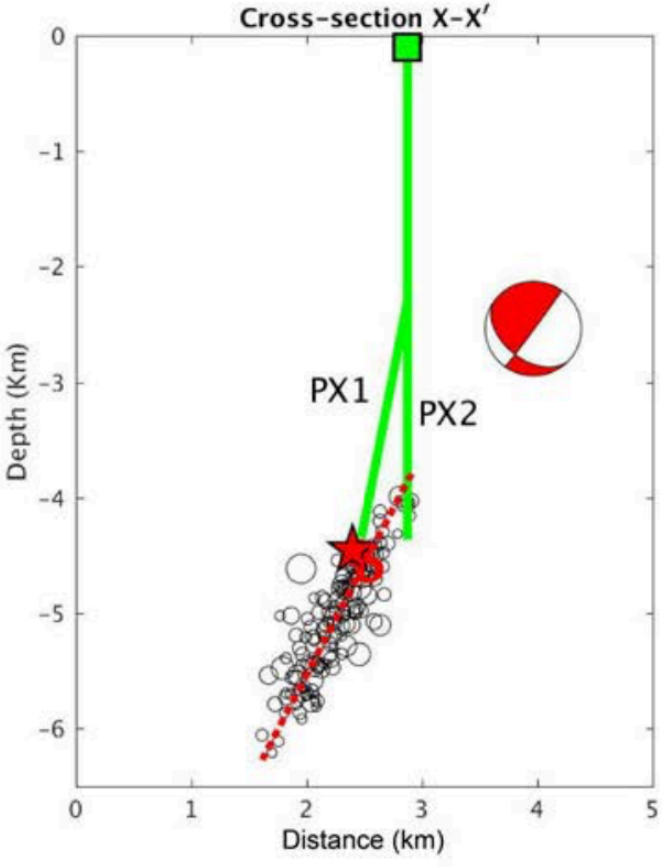


- Faults occur on a wide variety of scales and are found in virtually every geologic setting
- The Earth's crust is in a near critical failure state everywhere



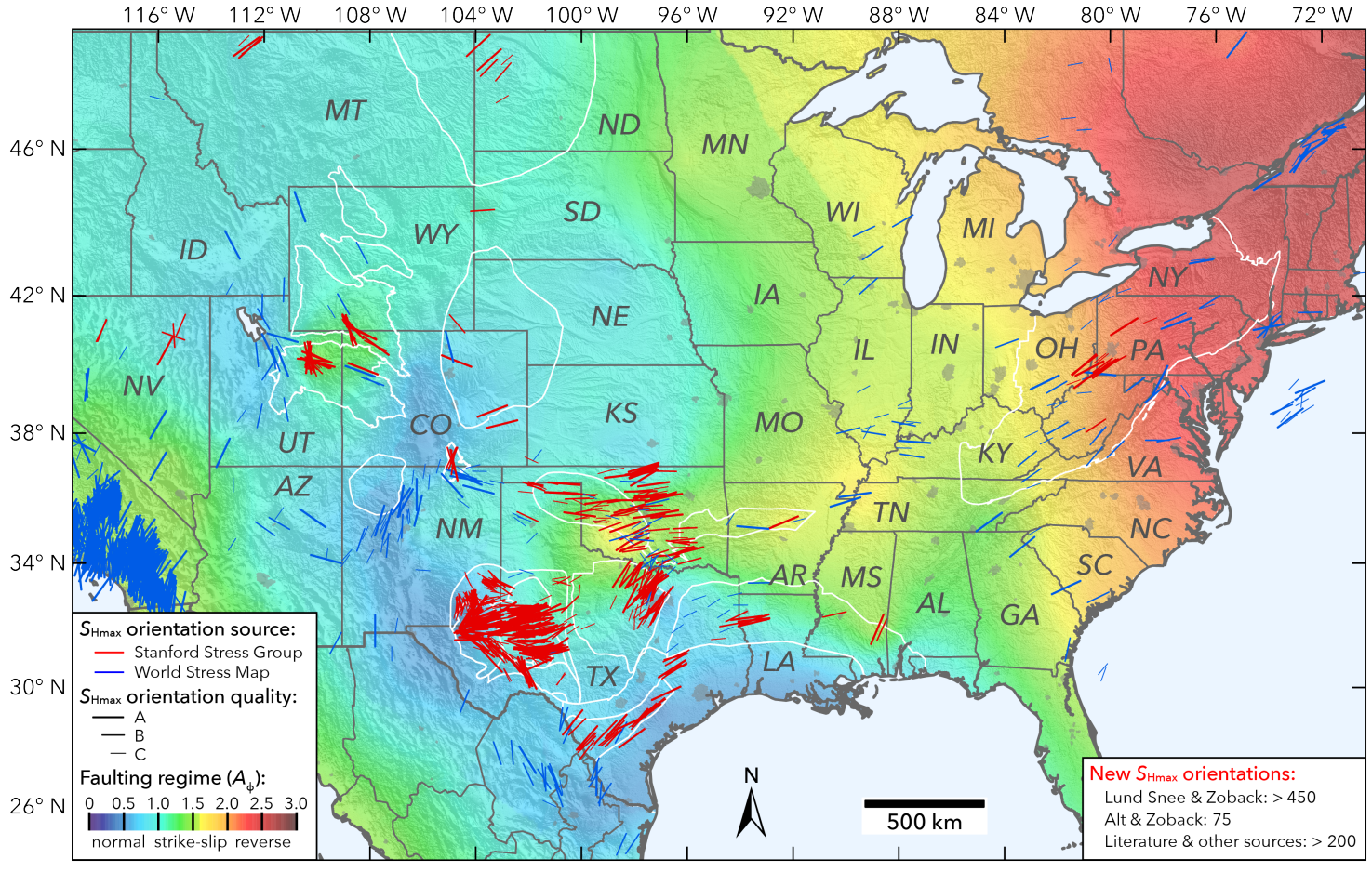
Pohang, Korea, Enhanced Geothermal System Project and the Mw 5.4 Pohang Earthquake





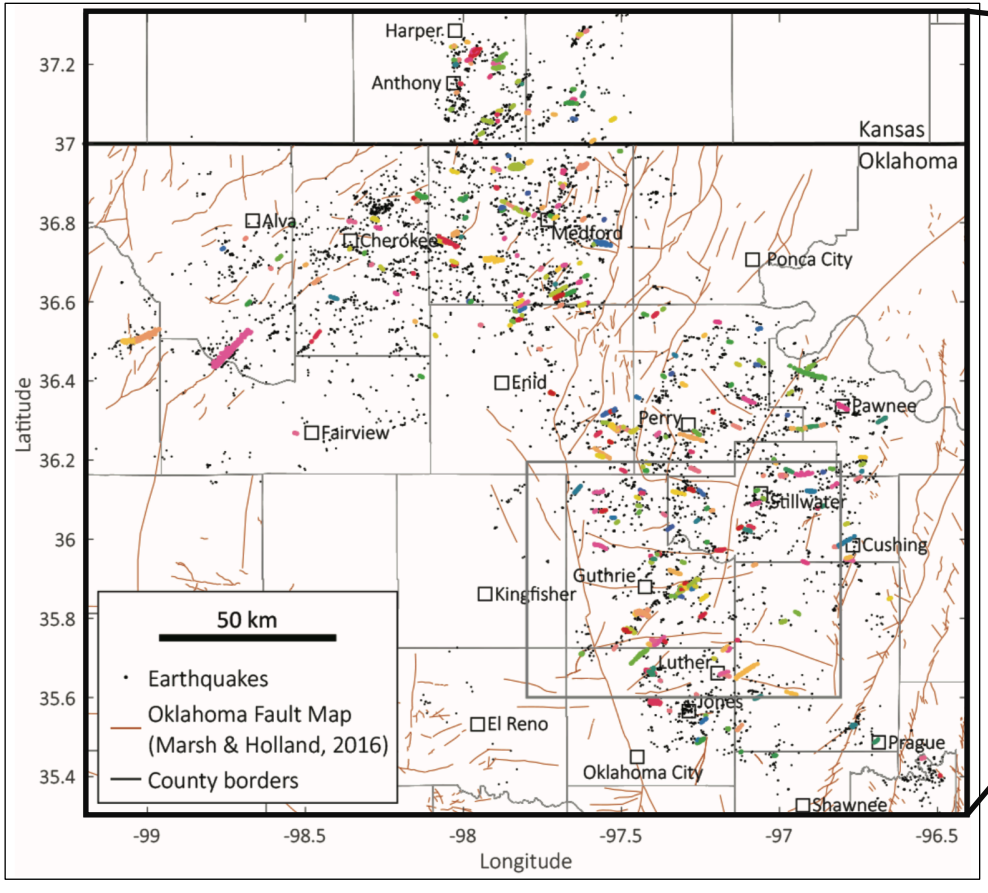
Kim et al., *Science* (2018)

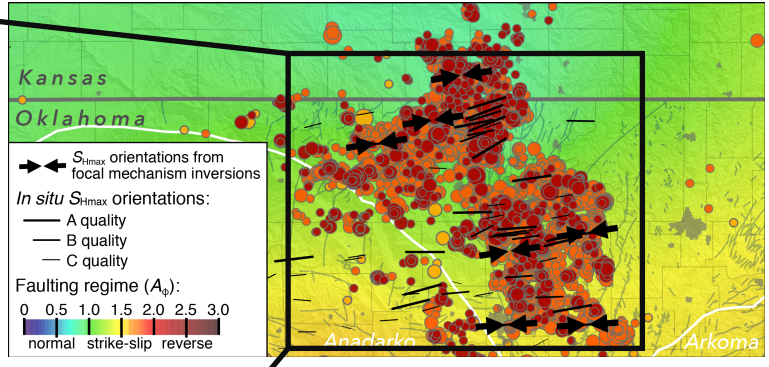
Near-Critical State of Stress in the Crust

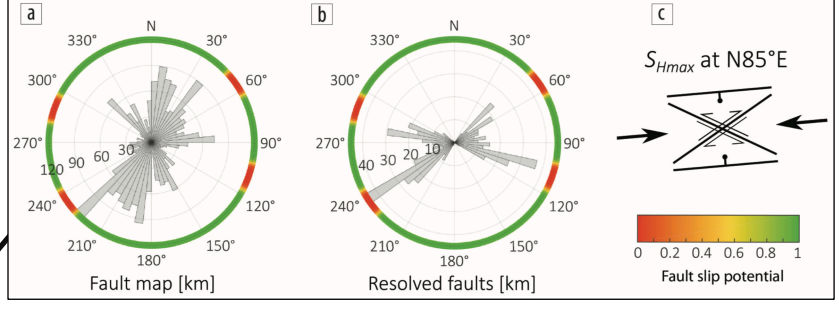


Lund-Snee and Zoback, in preparation

Mohr-Coulomb theory works!





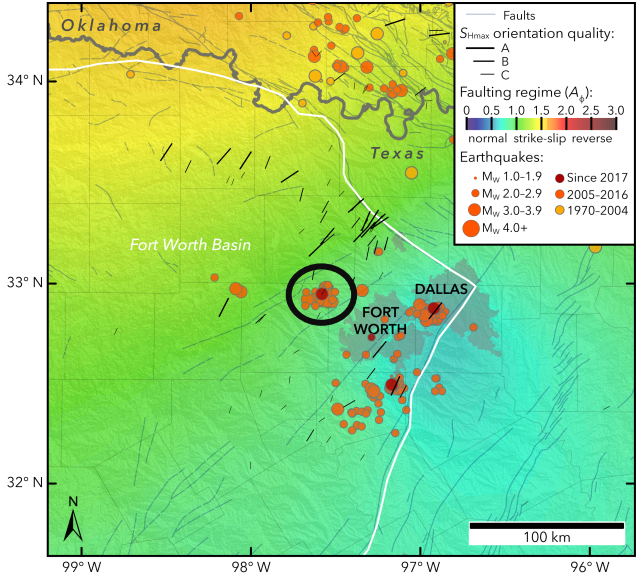


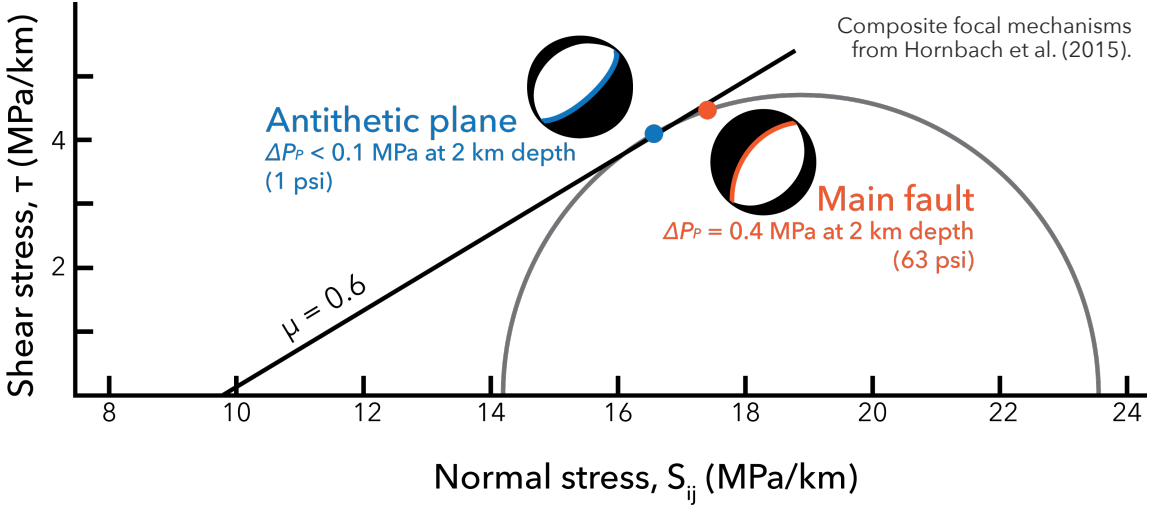
Inactive Activated

Schoenball et al. (2017, *TLE*)

Azle earthquakes (2013–2014) — Two M 3.6

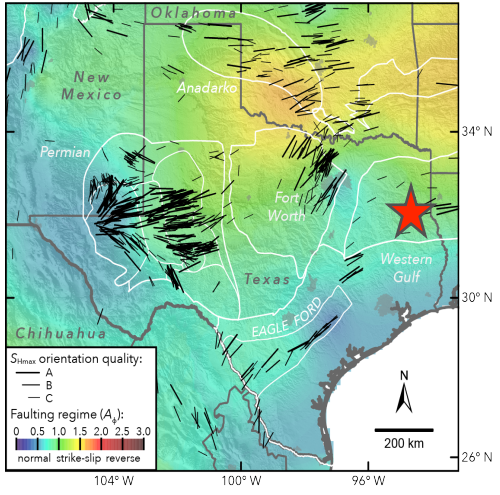
Very little ΔP_P needed to trigger slip

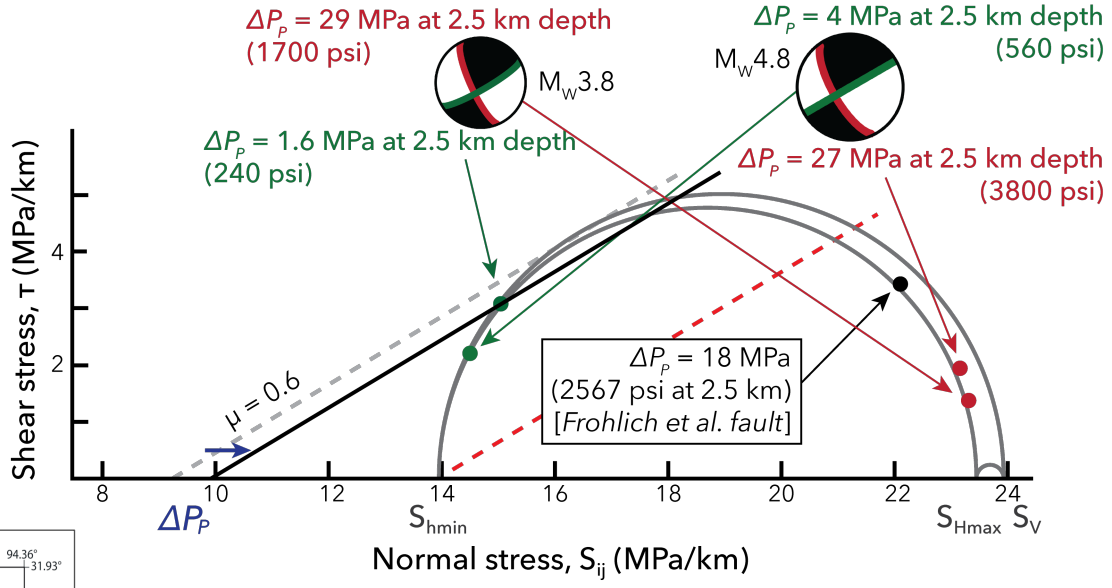


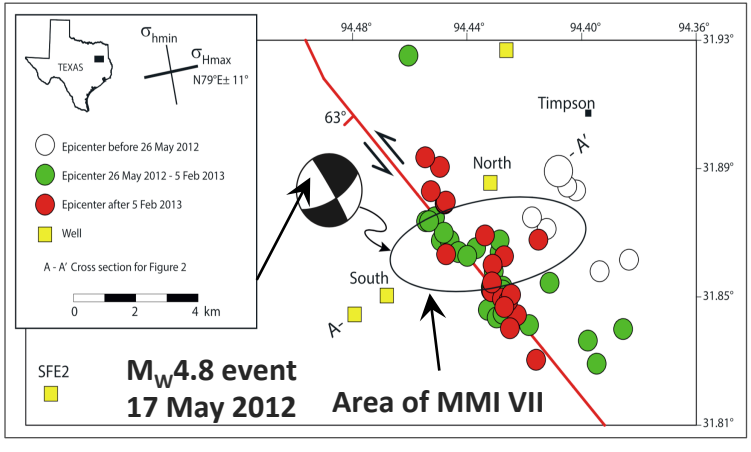


Hennings, et al. (submitted),
Lund Snee & Zoback (2016, *GRL*)

Timpson earthquakes (2008–2014, 2018)





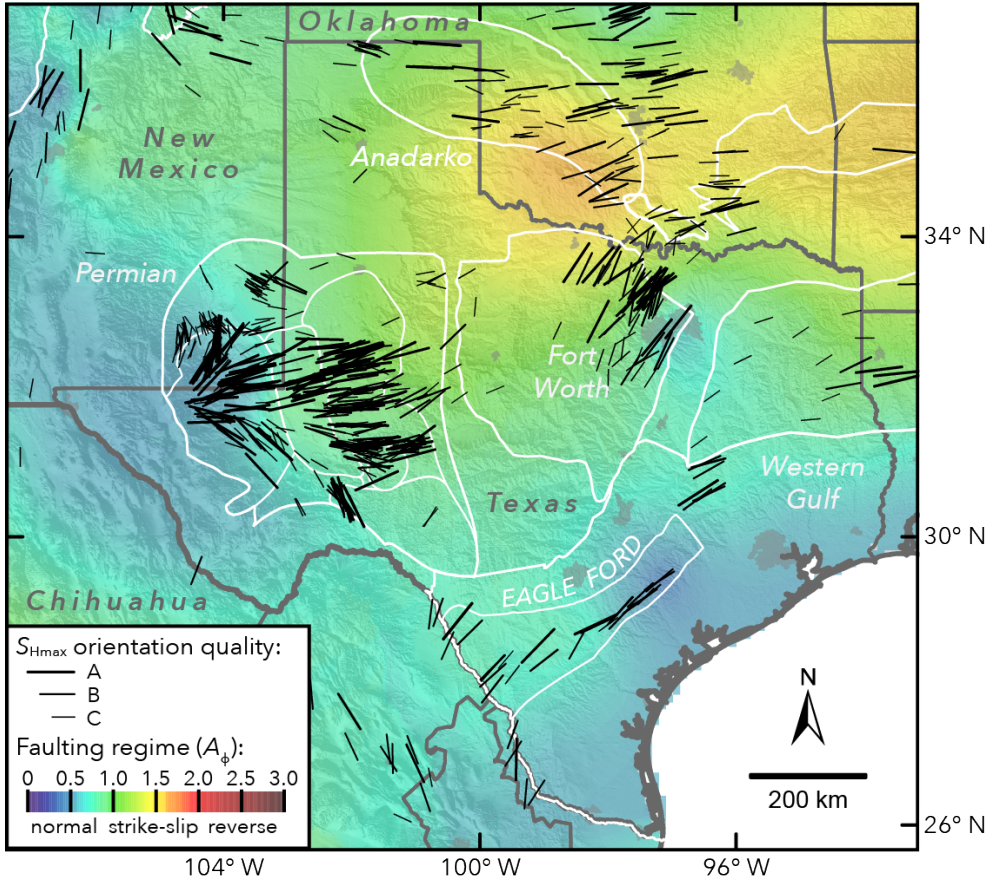


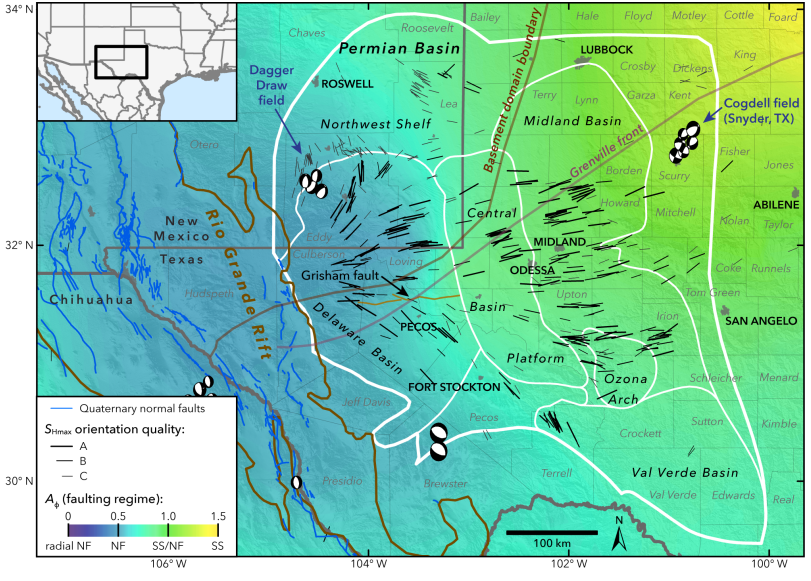
Poroelastic modeling constrained by InSAR indicates <2 MPa ΔP_P near hypocenters

Shirzaei et al. (2016, *Science*)

Frohlich et al. (2014, *JGR*)

Considerable stress variability in the south-central USA



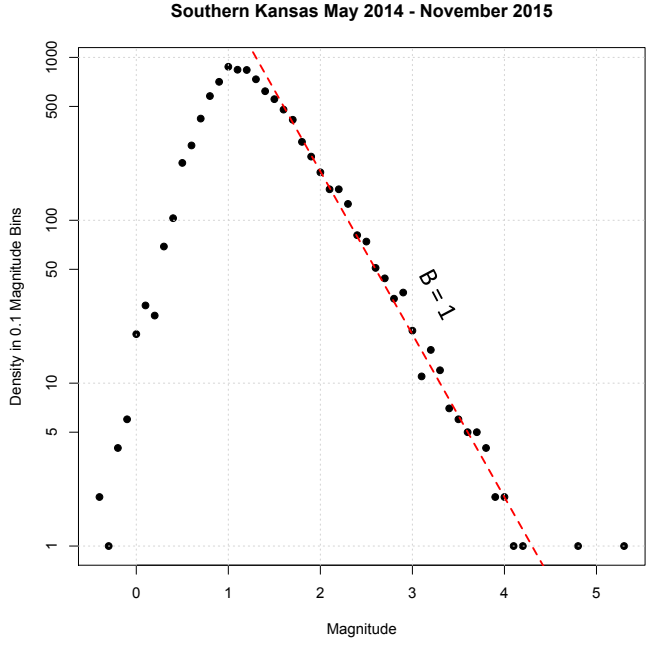


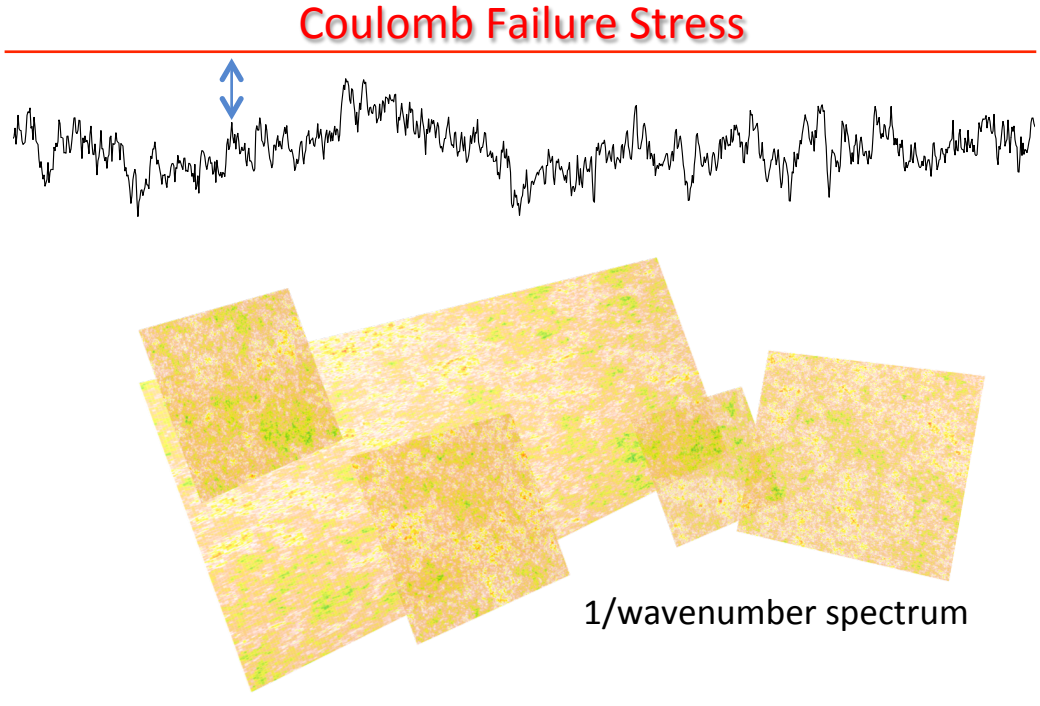
Lund Snee & Zoback (2016, 2018, and in prep.)
Alt & Zoback (2017, *BSSA*)
Hennings, Lund Snee, Zoback, et al. (submitted)

Basins from U.S. Energy Information Administration and Texas Bureau of Economic Geology

State of Stress in the Crust: Near-Critical but not Constant

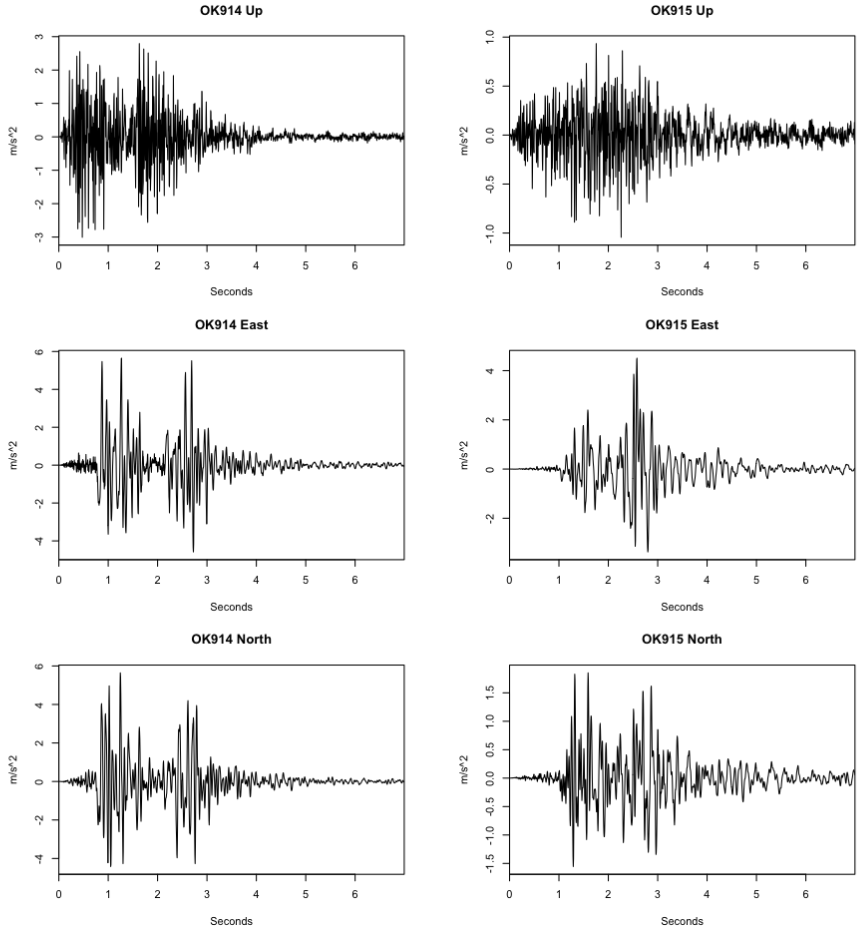
The pressures needed to initiate seismicity are small, as little as a few 10's of KPa to a few MPa, implying a critically stressed crust. Both natural and anthropogenic earthquakes follow normal Gutenberg-Richter statistic with b ≅ 1.





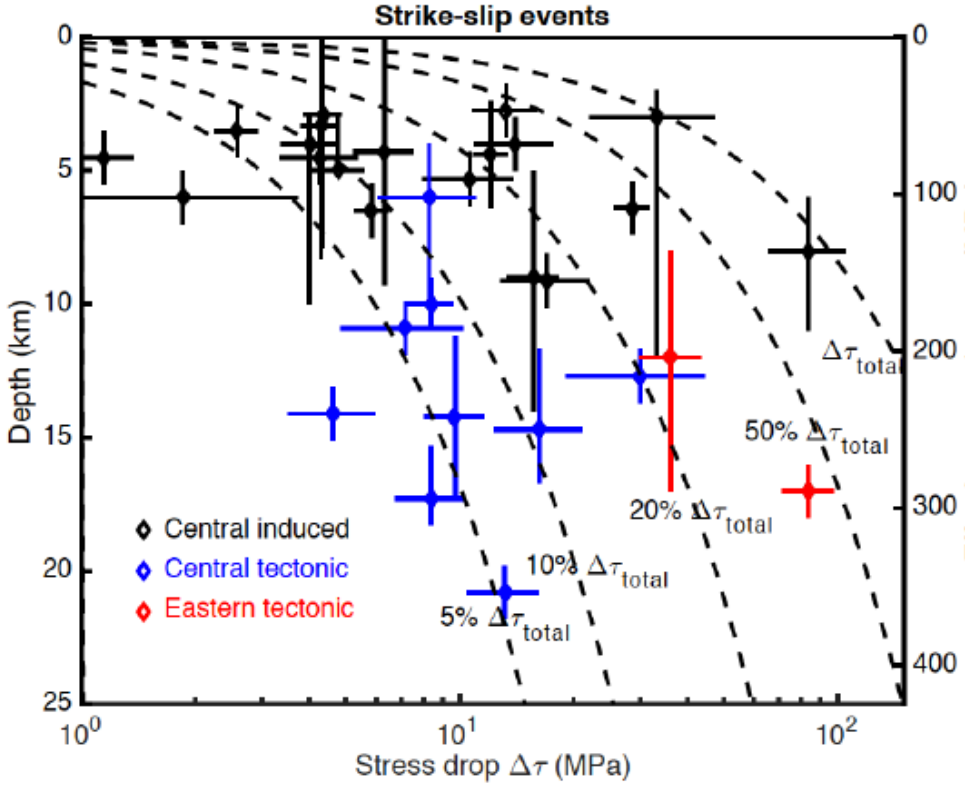
Induced Earthquakes are as strong as Tectonic Earthquakes

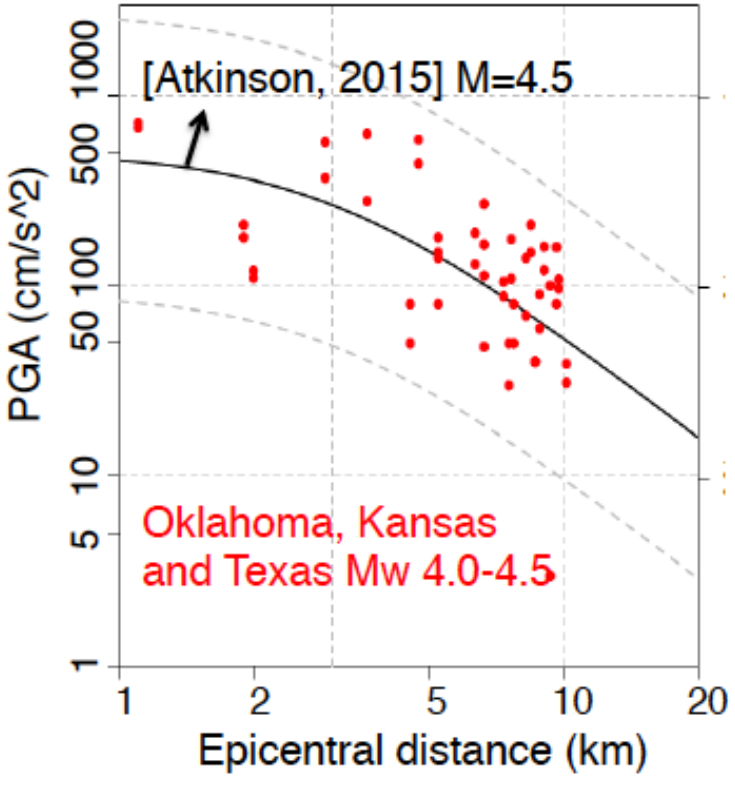
Downtown Cushing after 2016 Mw 5.0 (J. Beckel AP)



November 7, 2016 Cushing M_w 5.0

Induced Earthquakes are as strong as Tectonic Earthquakes



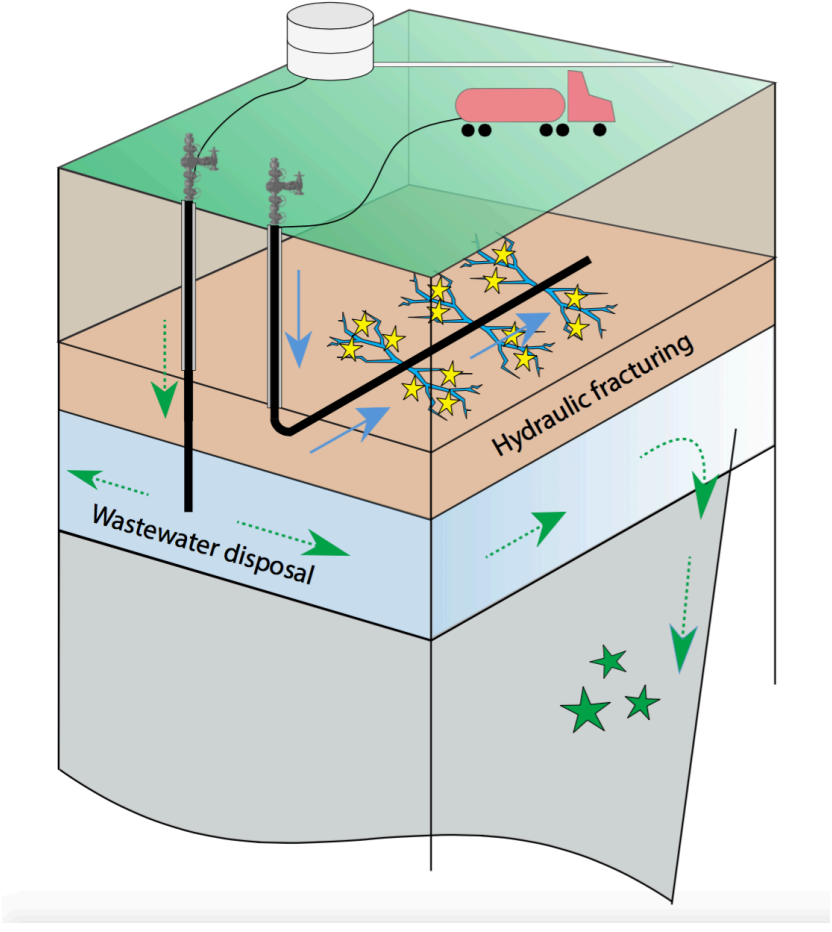


Huang, Ellsworth, Beroza (2017)

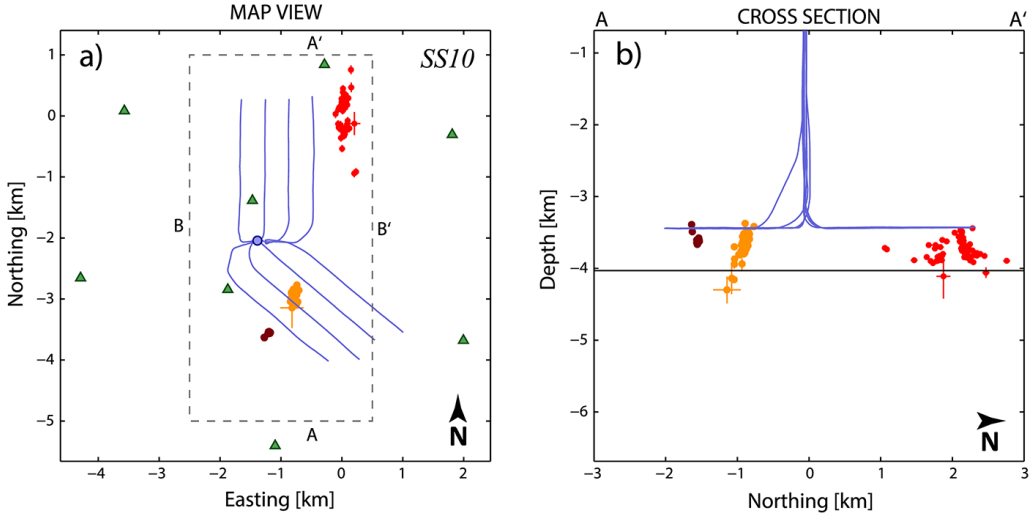
Key points: State of Stress

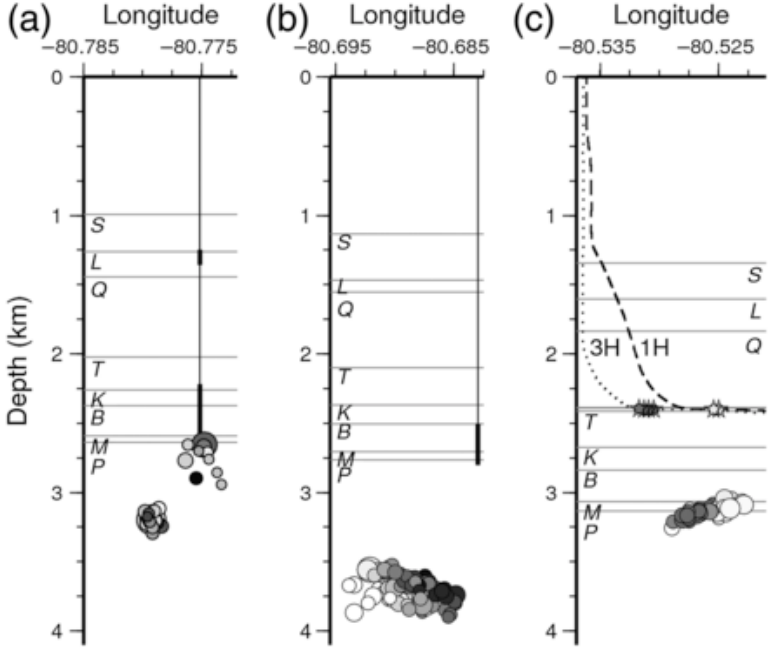
- Stress in the crust is at a near-critical state.
- Mohr-Coulomb theory can explain fault activation in many (but not all) cases.
- Induced earthquakes follow the Gutenberg-Richter magnitude-frequency relation.
- Induced earthquake magnitude-frequency statistics imply a (nearly) self-similar strength heterogeneity spectrum.
- When induced earthquakes occur, they release tectonic stress and are as strong as natural earthquakes in the same region.

Fracking Induced Earthquakes



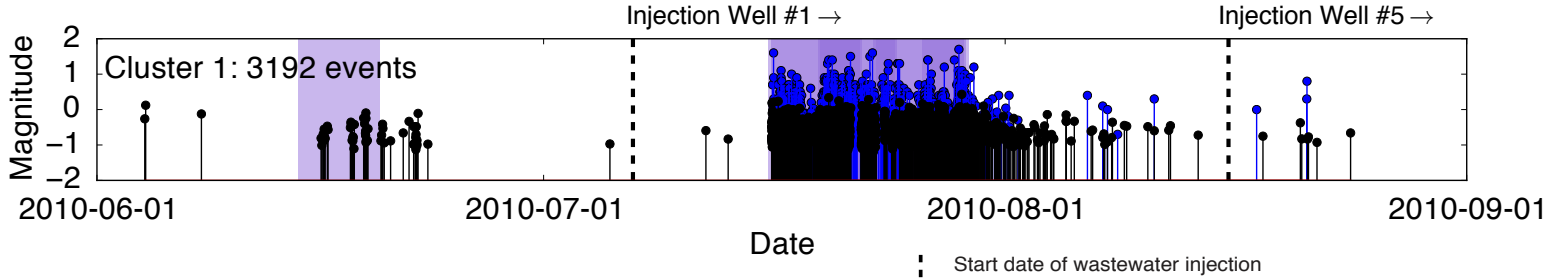
Fracking Induced Earthquakes

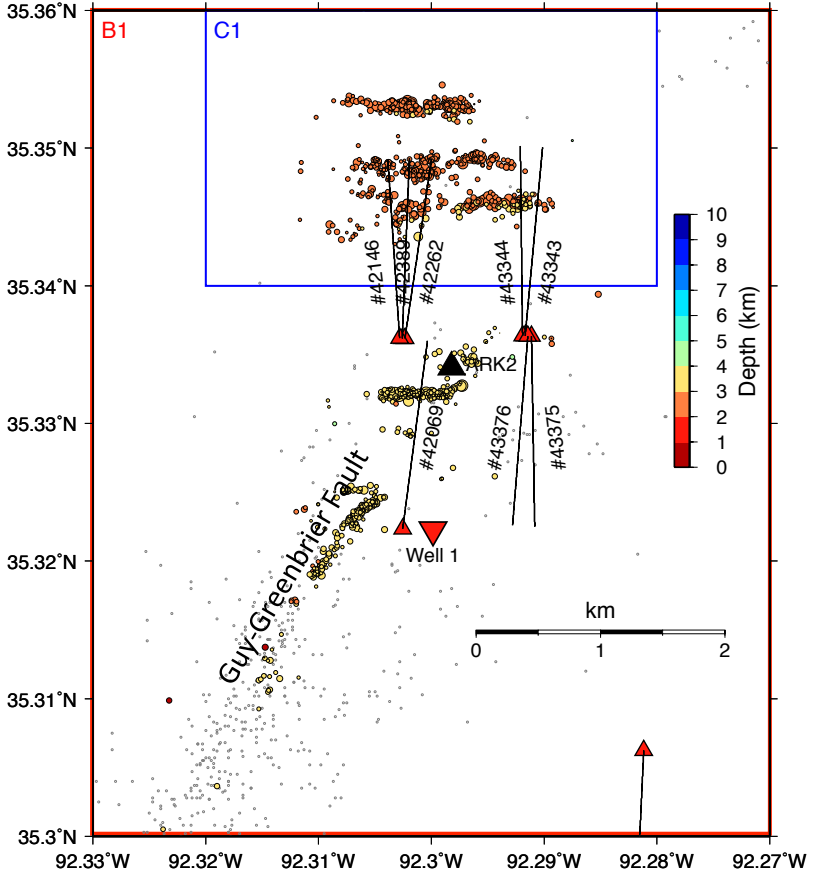




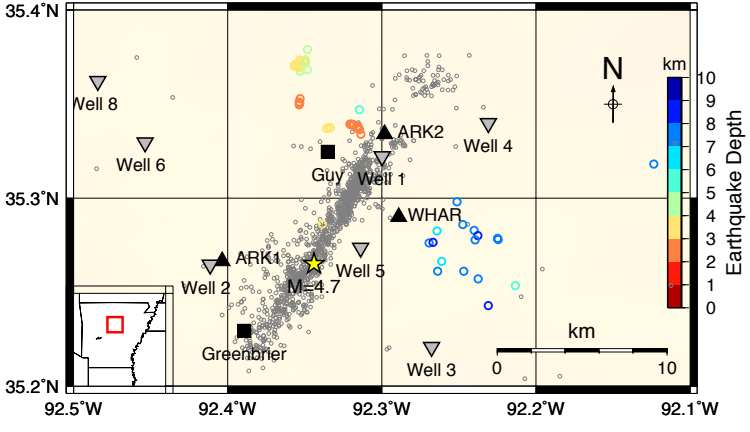
Schultz, R., Wang, R., Gu, Y.J., Haug, K. and Atkinson, G., 2017. A seismological overview of the induced earthquakes in the Duvernay play near Fox Creek, Alberta. Journal of Geophysical Research: Solid Earth, 122(1), pp.492-505.

Skoumal, R.J., Brudzinski, M.R. and Currie, B.S., 2015. Microseismicity induced by deep wastewater injection in Southern Trumbull County, Ohio. *Seismological Research Letters*, *86*(5), pp.1326-1334.

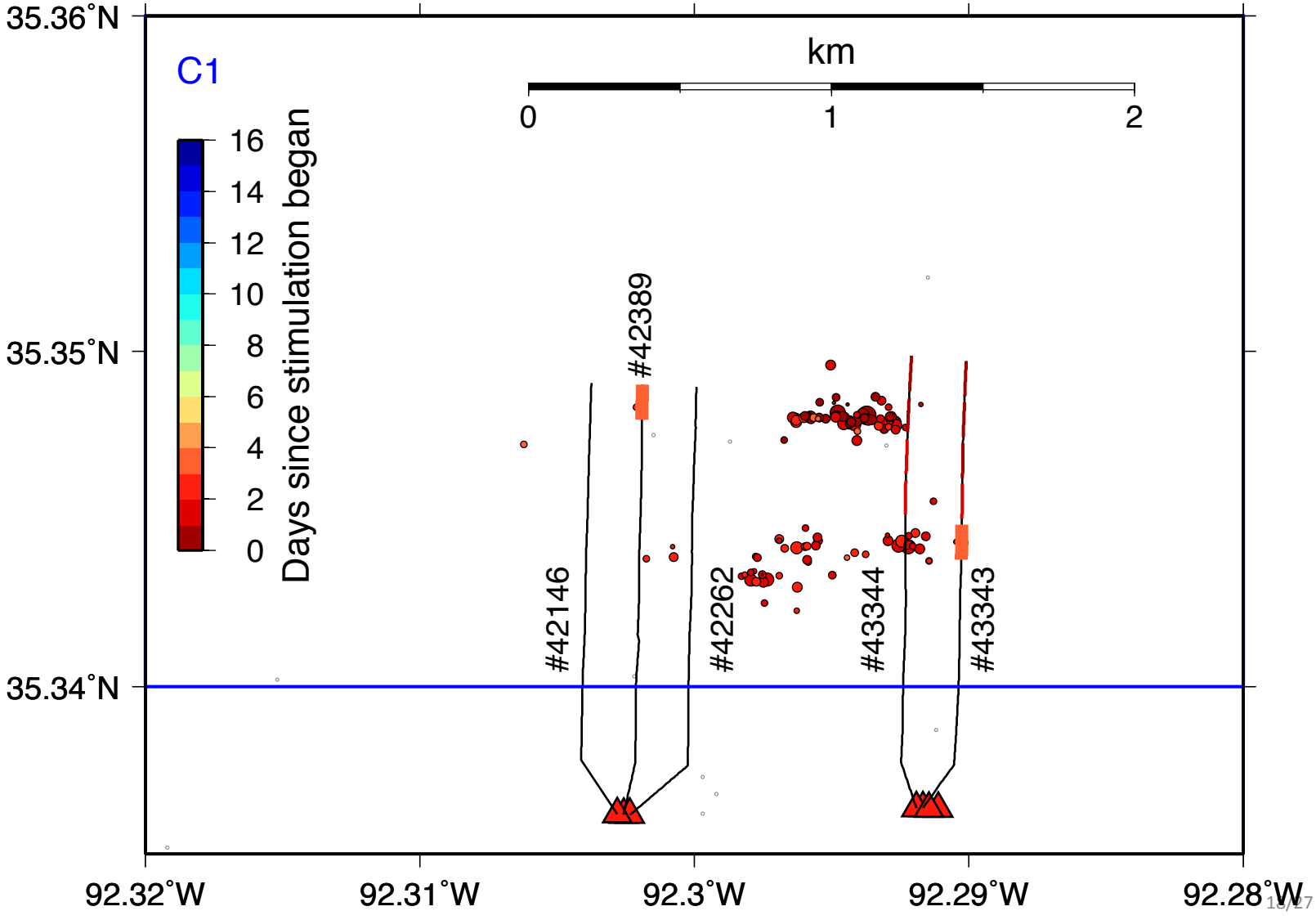




Fracking-induced earthquakes in Guy, Arkansas during the initial stages of activity



Yoon, Clara E., et al. "Seismicity During the Initial Stages of the Guy-Greenbrier, Arkansas, Earthquake Sequence", JGR, 2017.


C1
km
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14
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10
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6
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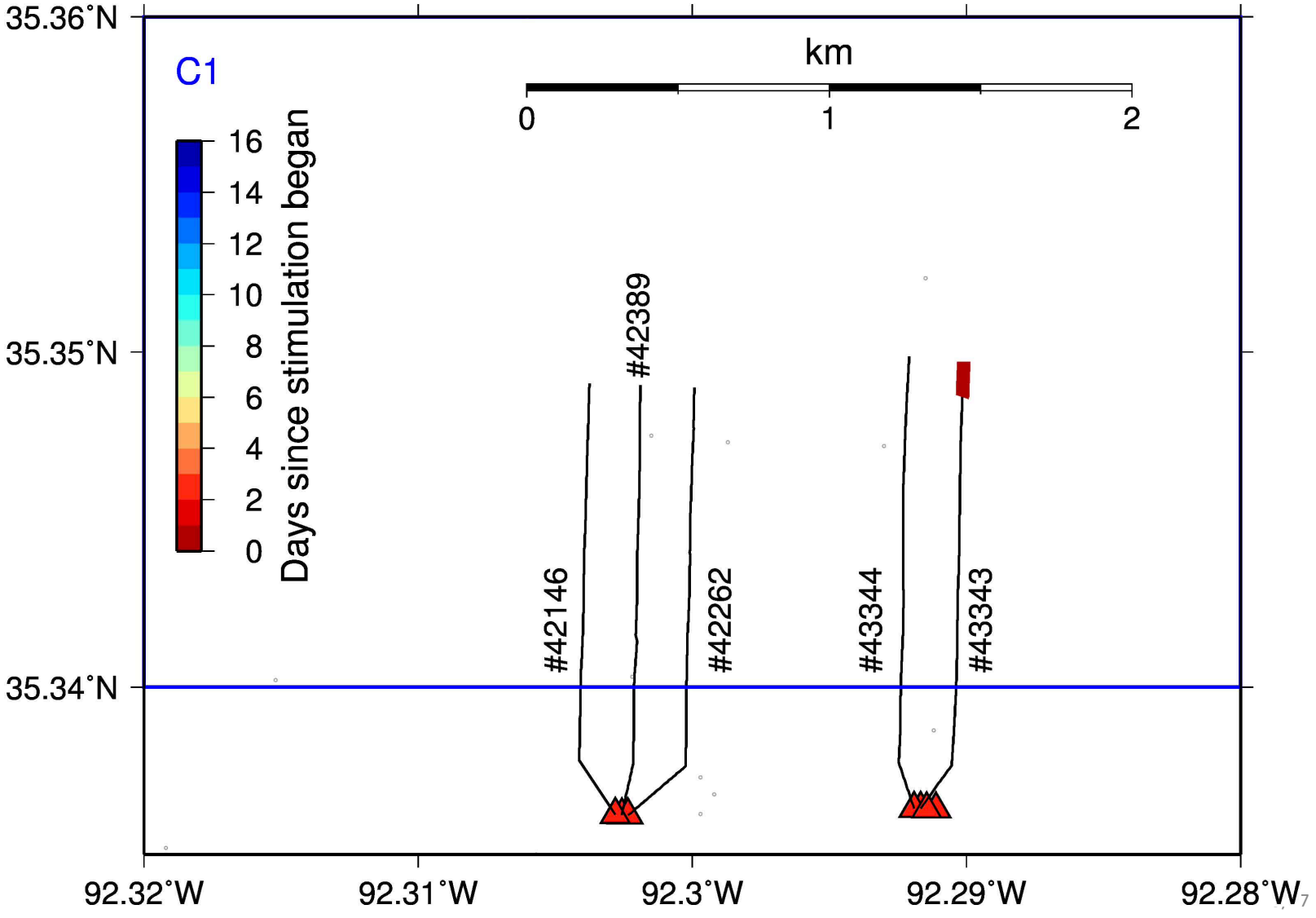
2
0
Days since stimulation began
#42389
#42146
#42262
#43344
#43343
35.36˚N
35.35˚N
35.34˚N
92.32˚W
92.31˚W
92.3˚W
92.29˚W
92.28˚W


C1
km
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Days since stimulation began
#42146
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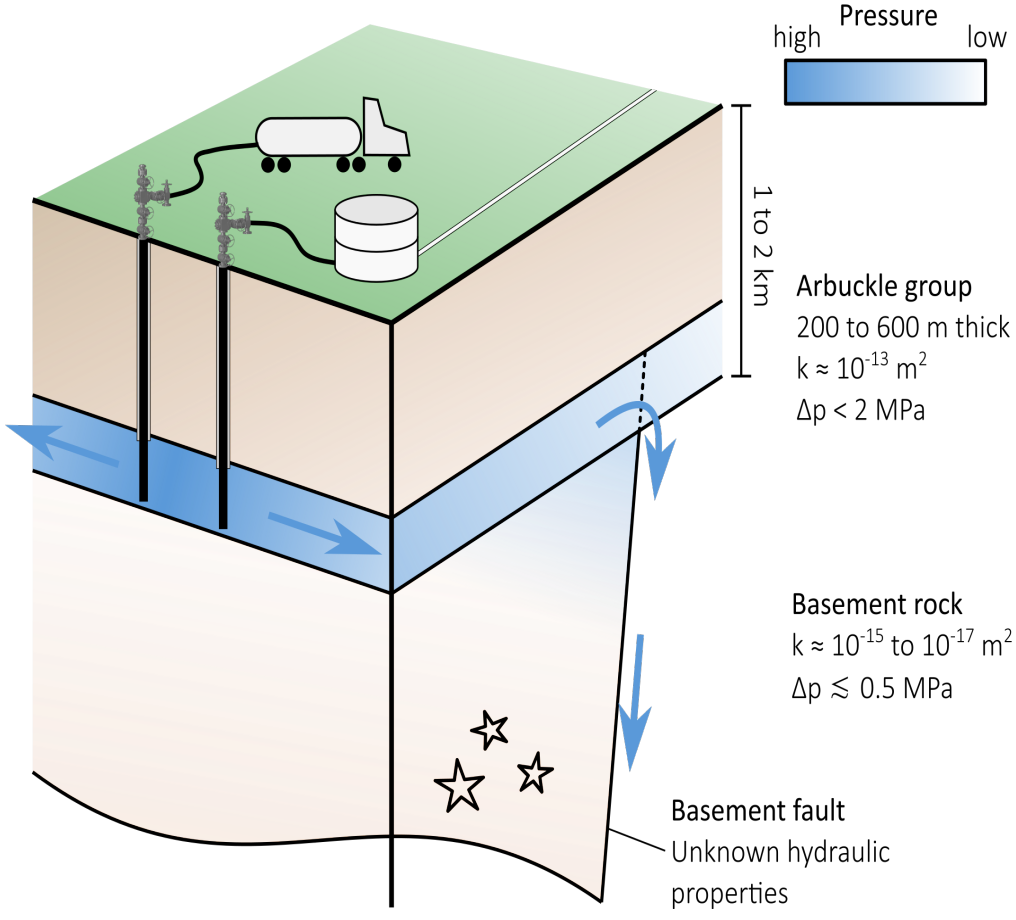
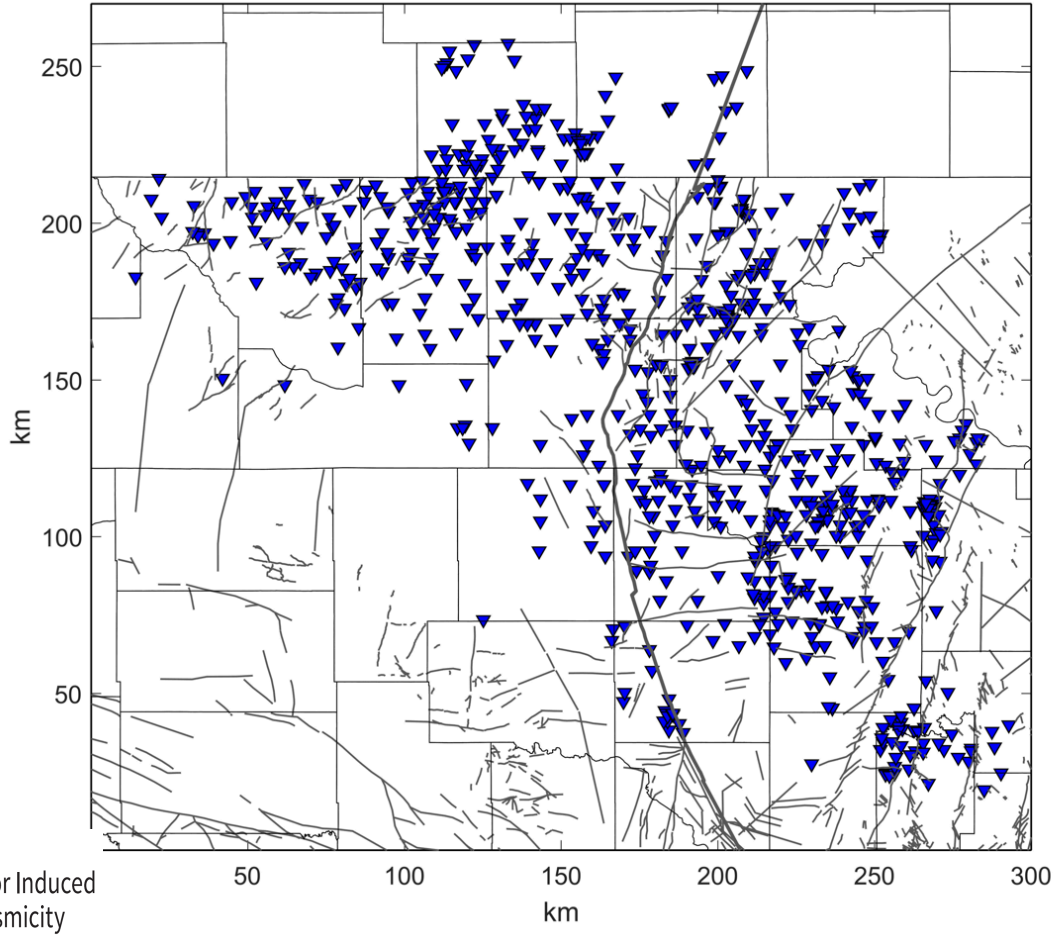
35.36˚N
35.35˚N
35.34˚N
92.32˚W
92.31˚W
92.3˚W
92.29˚W
92.28˚W

Wastewater Disposal Induced Earthquakes



Induced Earthquakes in Oklahoma are principally caused by wastewater disposal



Arbuckle wells
(basal formation)

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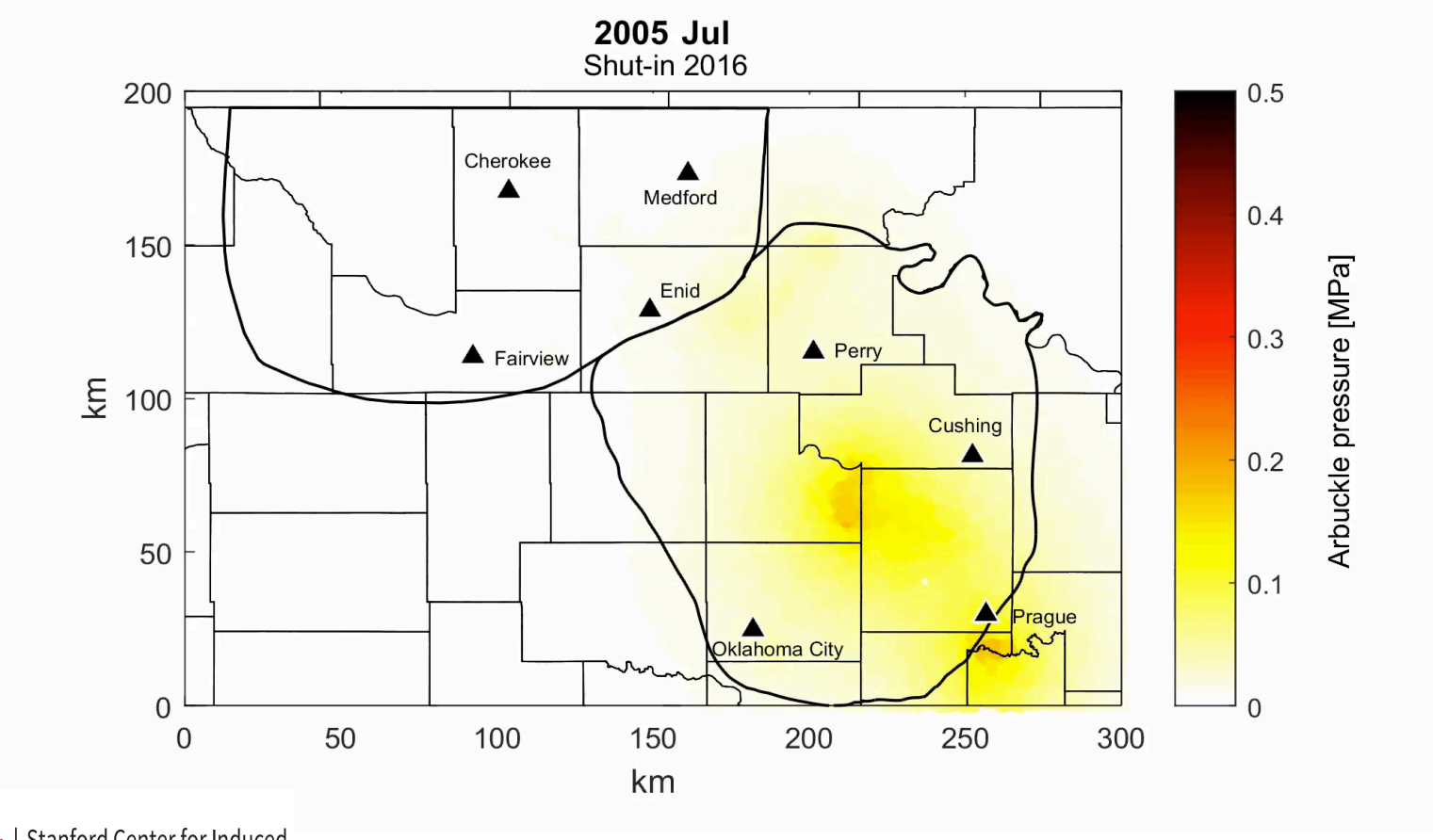
Induced Earthquakes in Oklahoma are principally caused by wastewater disposal



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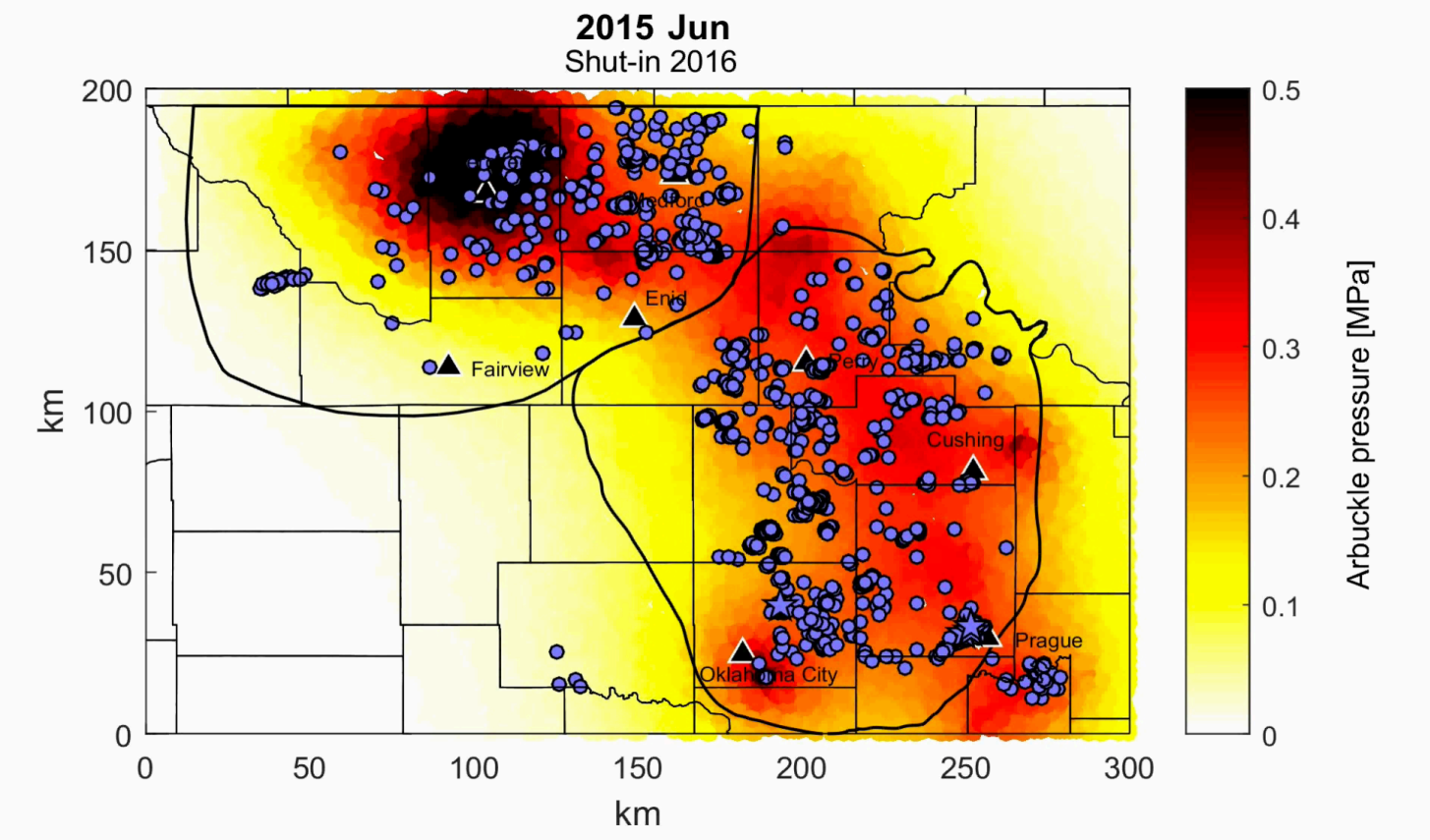
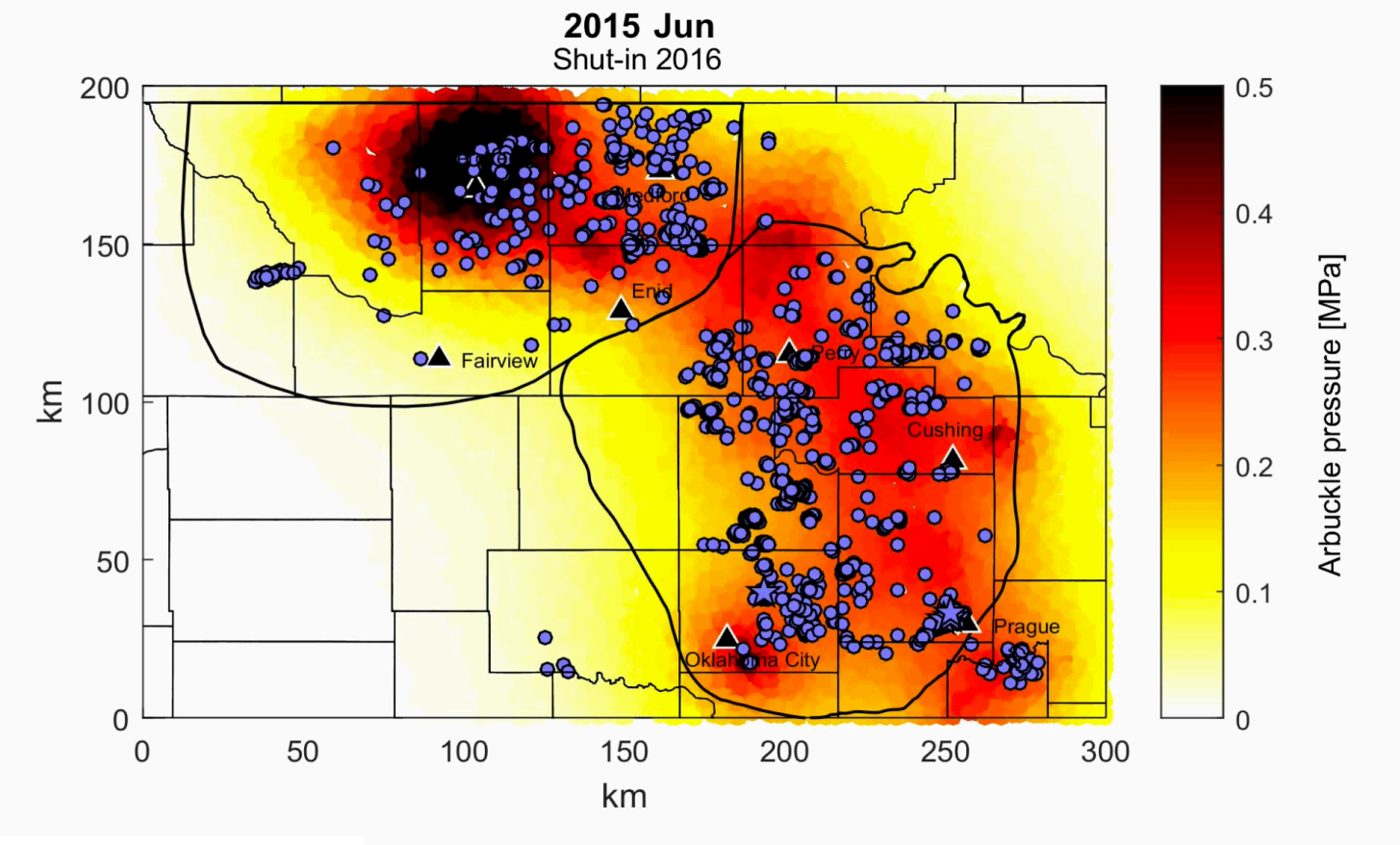
The small fluid pressure perturbation is very broadly distributed due to the high diffusivity of the Arbuckle Formation

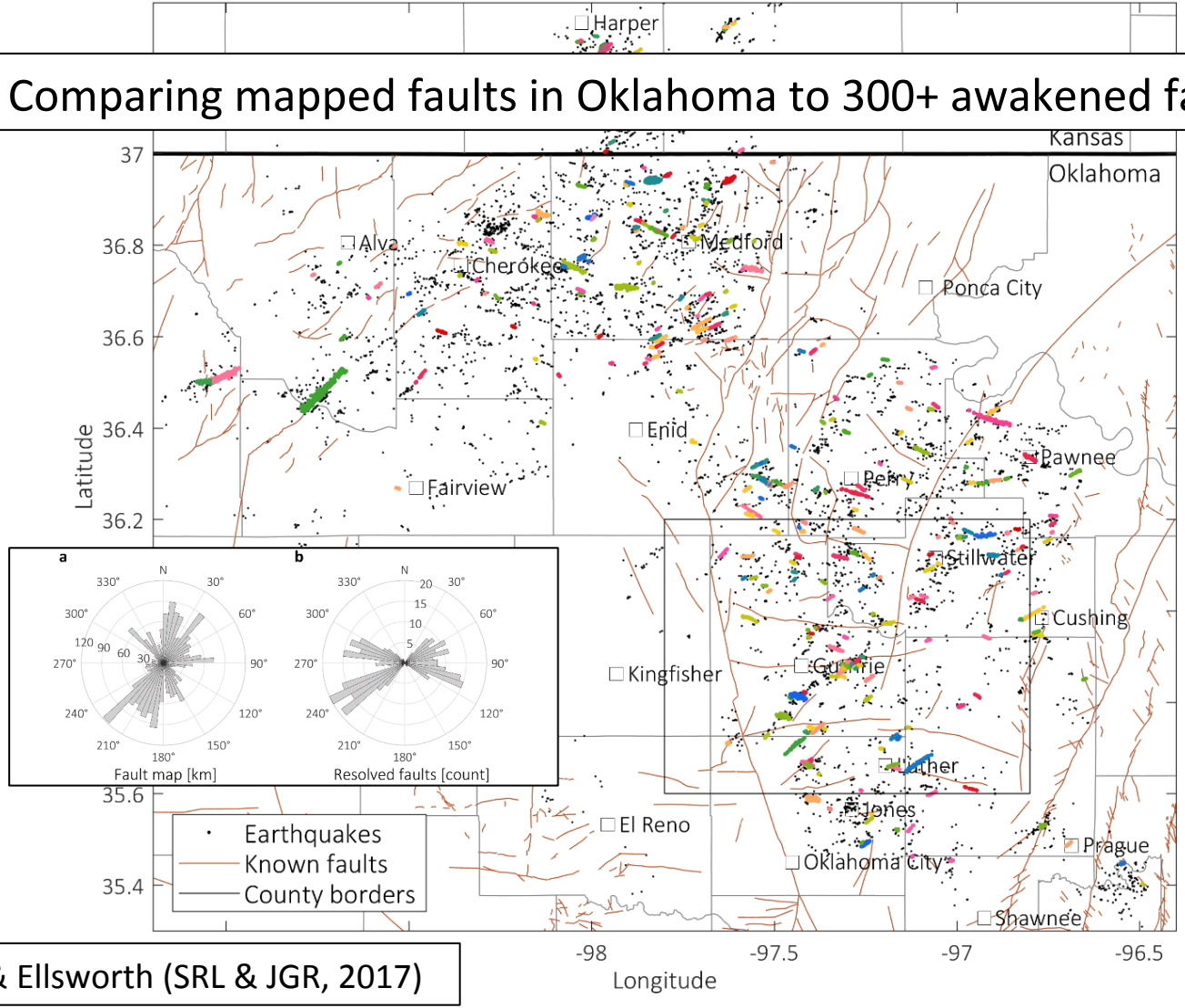


The induced earthquakes frequently occur 10 to 20 km from the nearest high-rate injection wells

How do faults wake up when fluid pressures rises?



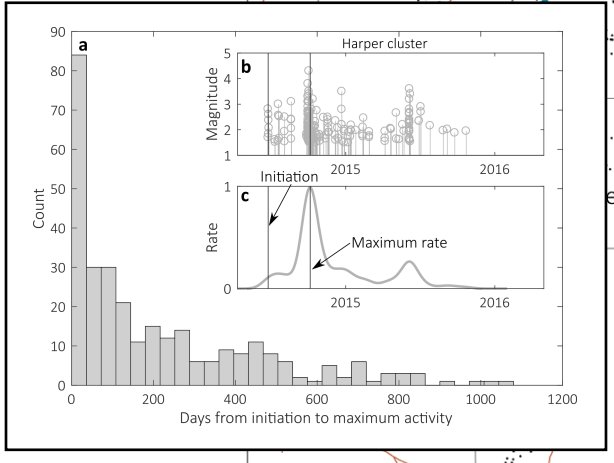
Comparing mapped faults in Oklahoma to 300+ awakened faults

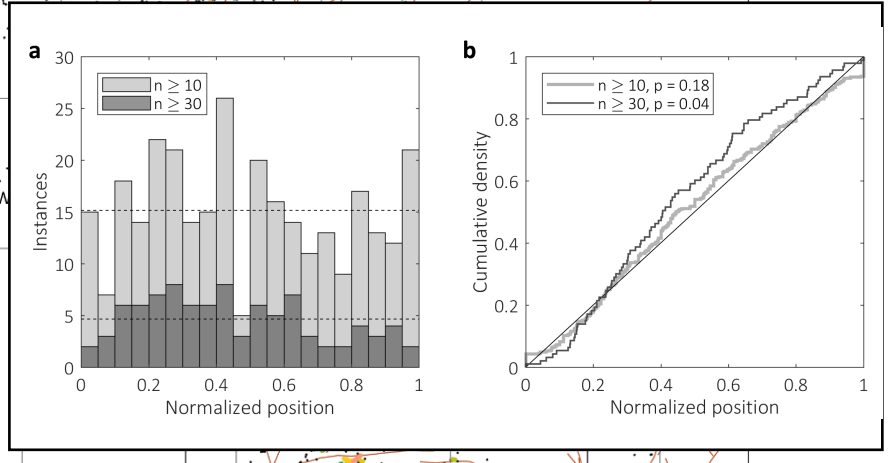


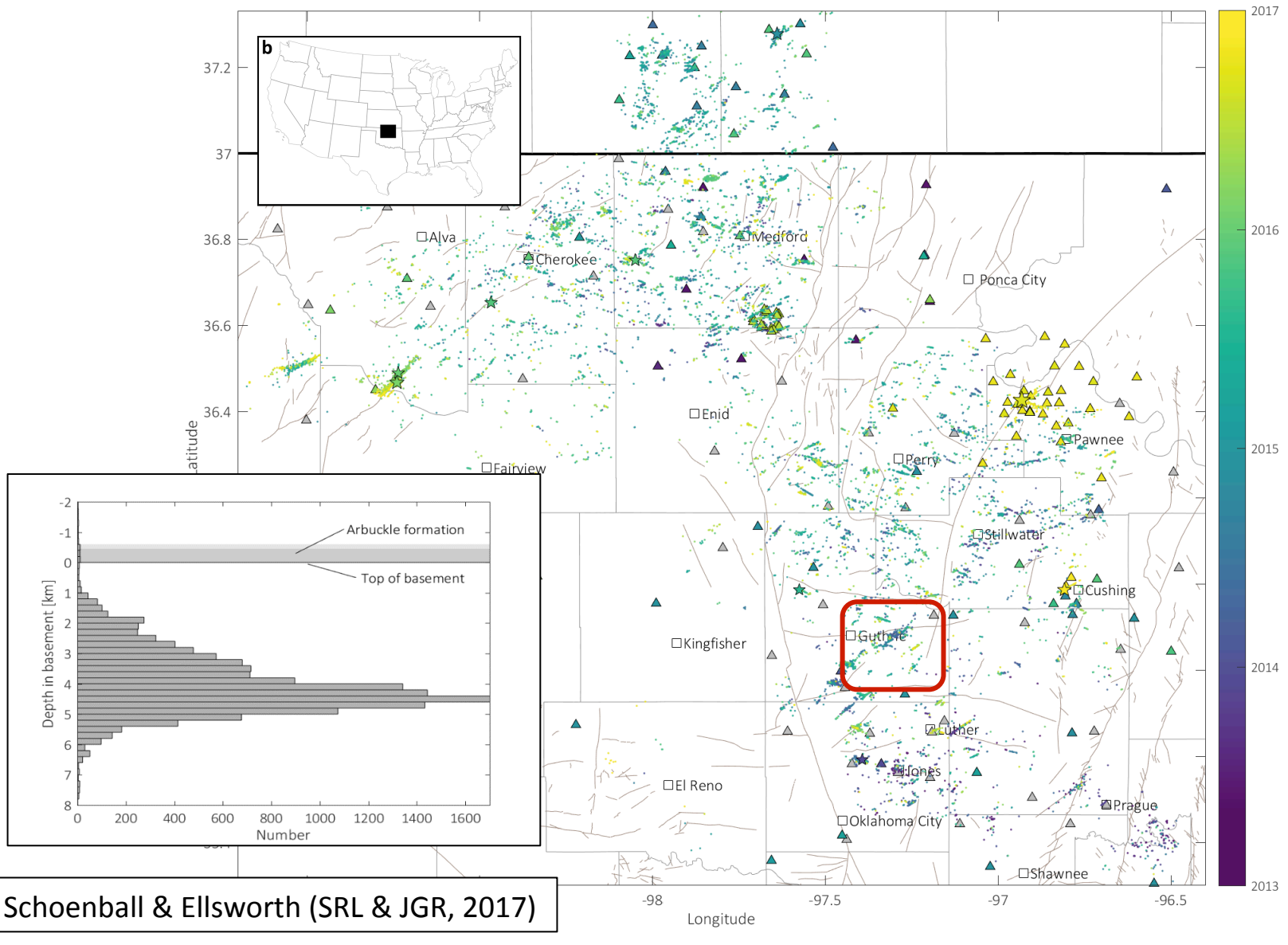
Schoenball & Ellsworth (SRL & JGR, 2017)

Seismicity evolution as a fault wakes up: Peak activity

No Oklahoma sequence begins with an earthquake > M 3.6 even with the very high M_c = 2.8 for this catalog

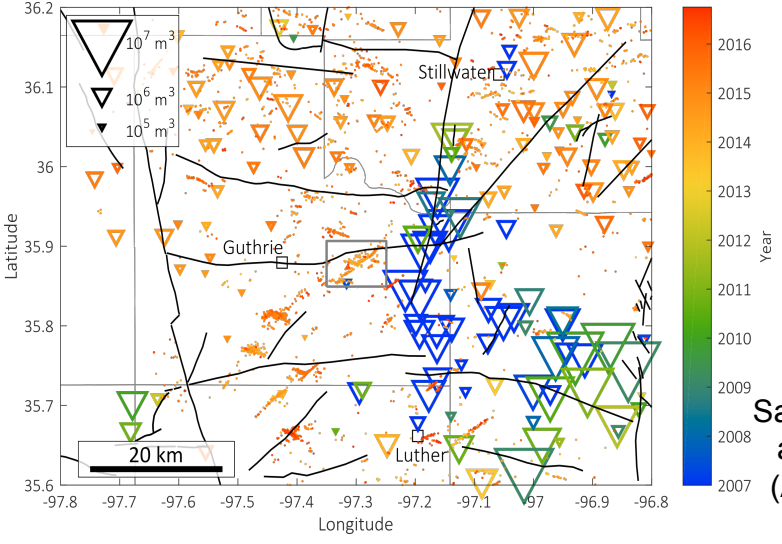






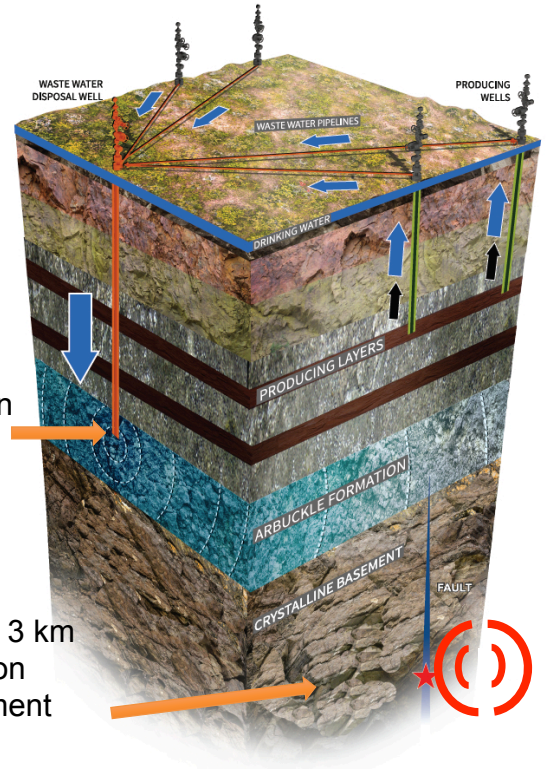
Schoenball & Ellsworth (SRL & JGR, 2017)

Induced Earthquakes near Guthrie-Langston, Oklahoma



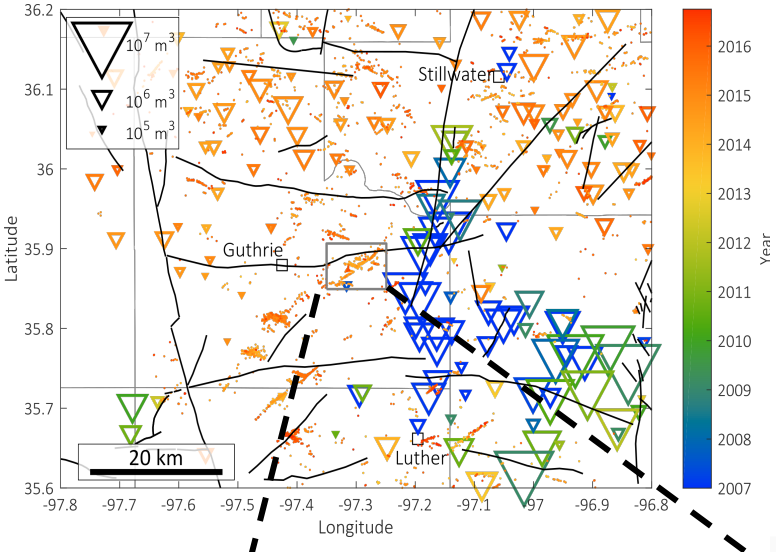
Disposal wells identified by year of peak injection

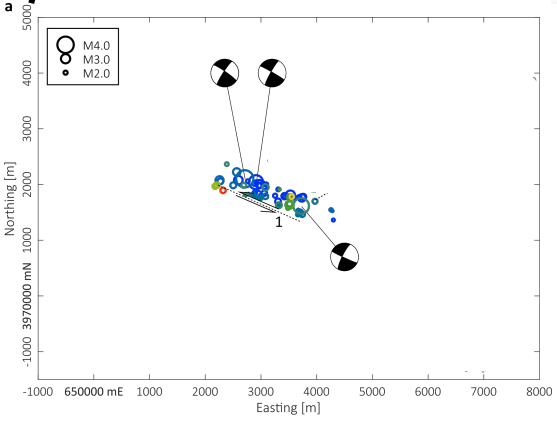
Saltwater Injection at 1.6 – 2.5 km (Arbuckle group ≈1Darcy)

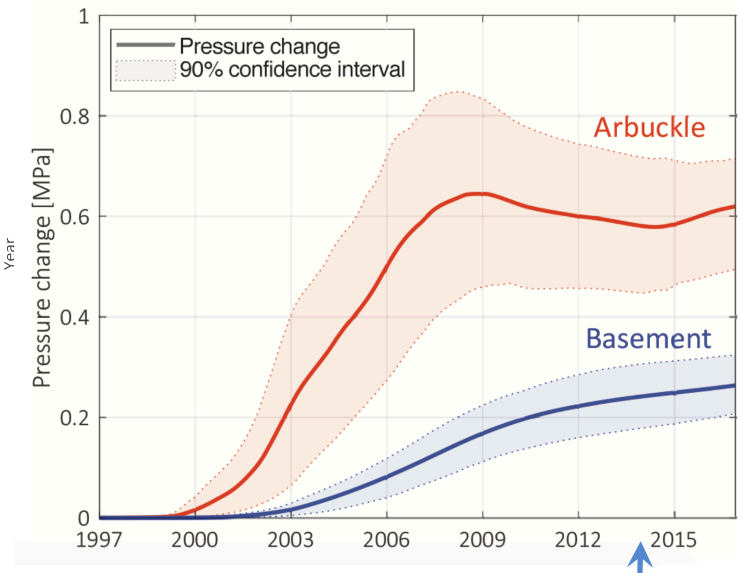


Seismicity about 3 km below injection (granitic basement ≈1mDarcy)

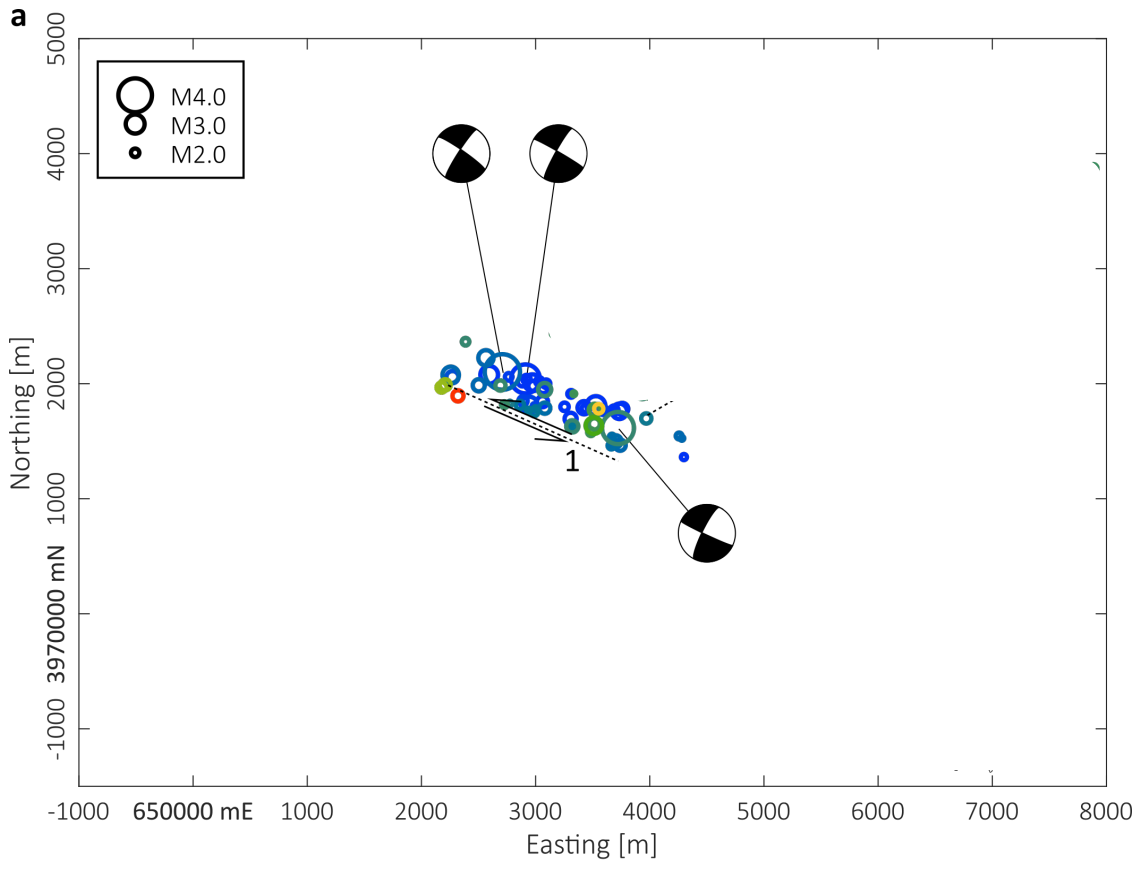
Induced Earthquakes near Guthrie-Langston, Oklahoma







Seismicity first detected


a
M4.0
M3.0
M2.0
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Northing [m]
5000
4000
3000
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1000
3970000 mN
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650000 mE
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4000
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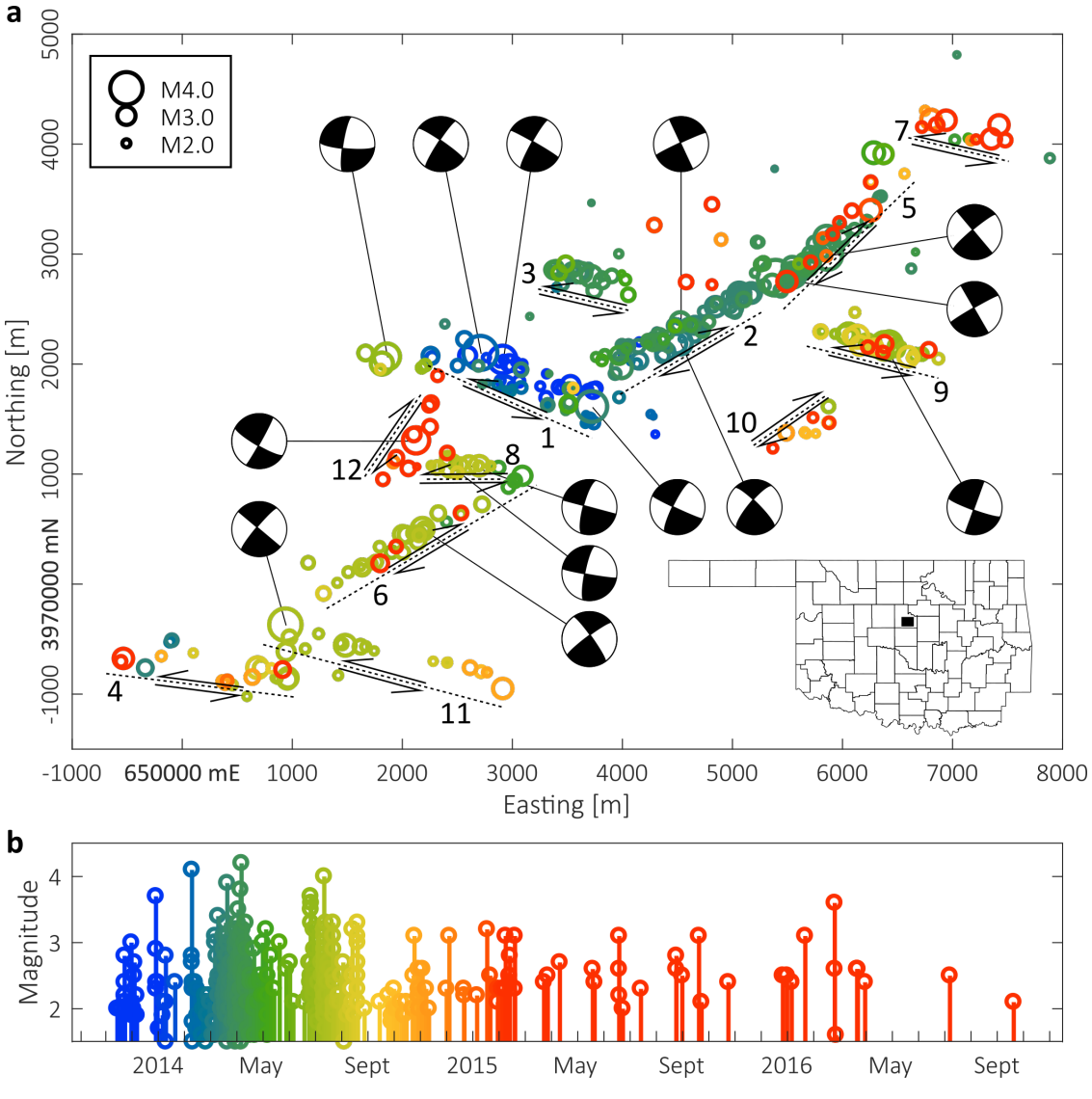
6000
7000
8000
Easting [m]


a
M4.0
M3.0
M2.0
Northing [m]
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3970000 mN
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650000 mE
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Easting [m]
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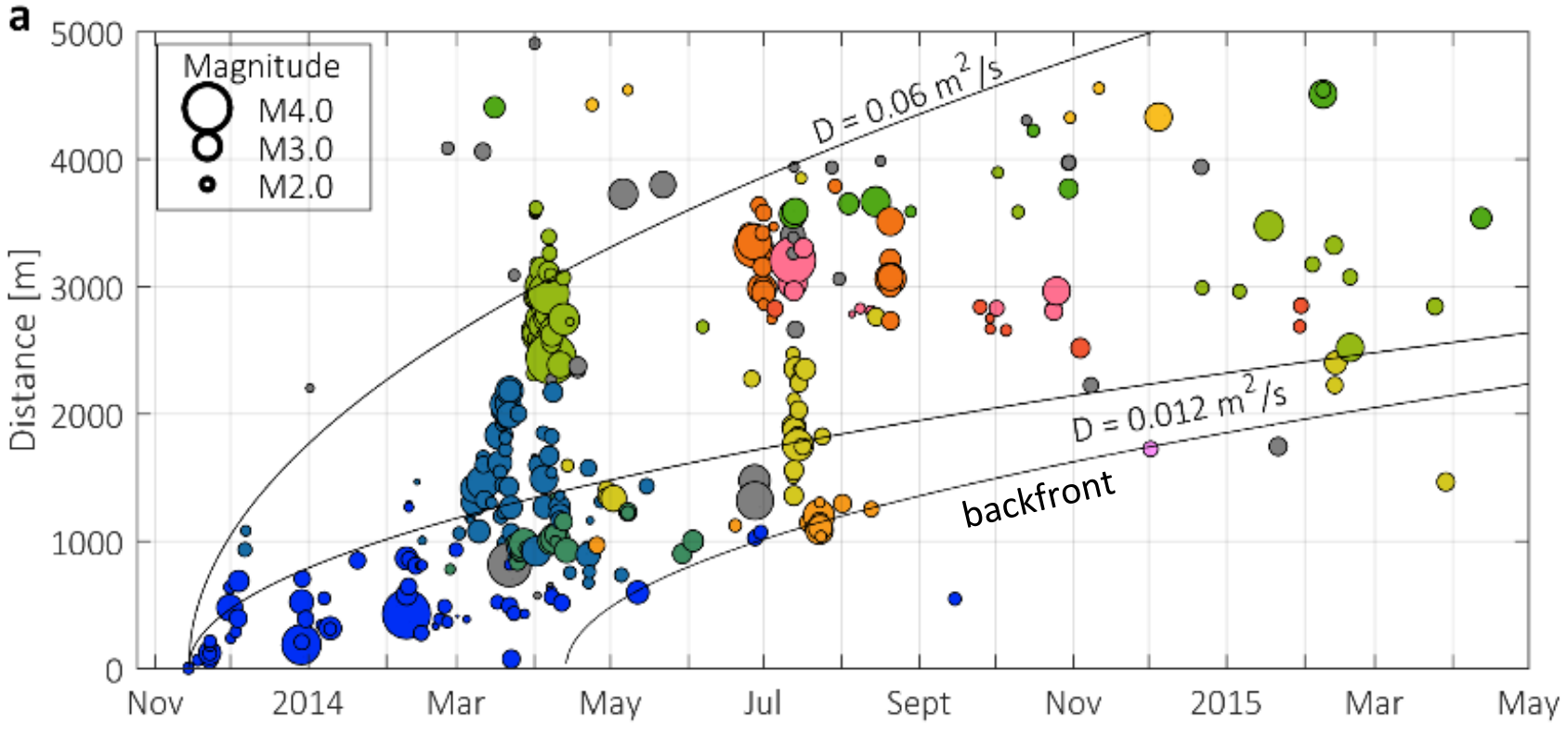
May
Sept
2016
May
Sept

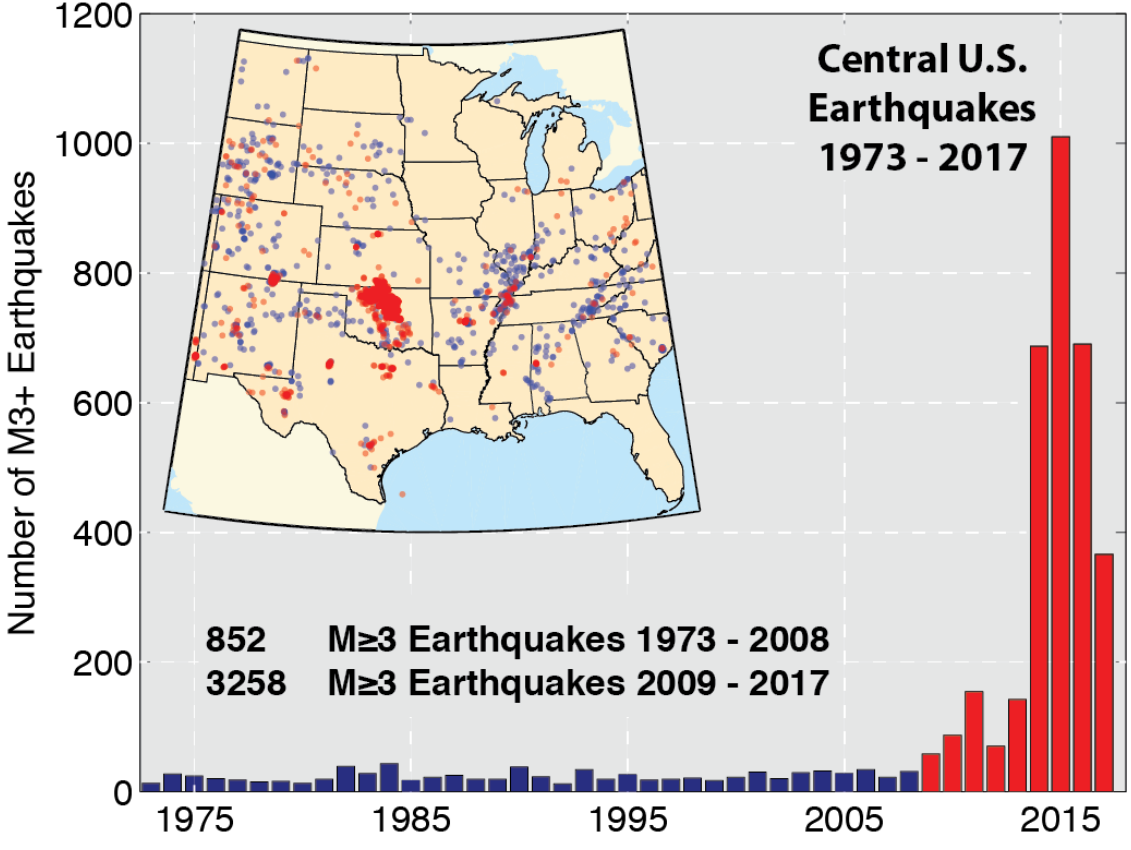
“Seismic Diffusivity” and Pore Pressure Diffusion

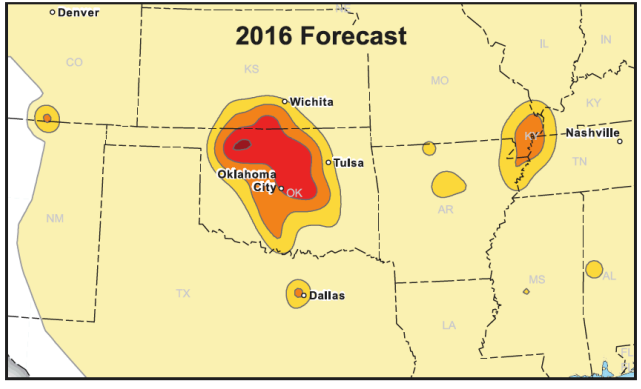


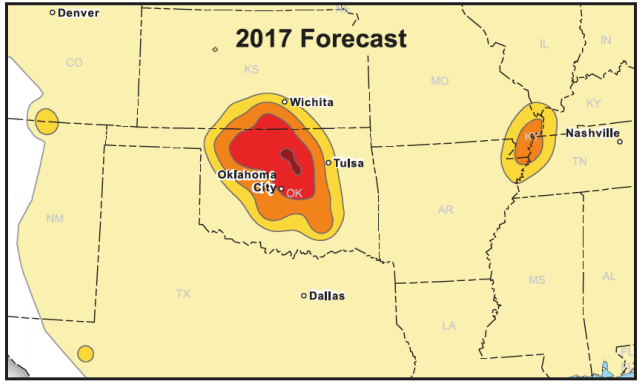
Key points: Injection Induced Earthquakes

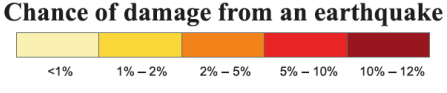
- Pressure can migrate quickly and over large distances through fractures and other permeable pathways.
- Ancient faults with favorable orientations in the tectonic stress field can be reactivated by small (10s to a few hundred of KPa) pressure increase.
- Once initiated by anthropogenic stressing, earthquake sequences may propagate along faults through earthquake to earthquake interactions.
- Many sequences initiate months before peak activity, and none starts with an earthquake larger than M3.6.
- Seismic monitoring can identify faults as they wake up before strong earthquakes are triggered.

Seismicity is declining, but still far above background. How long will it last?



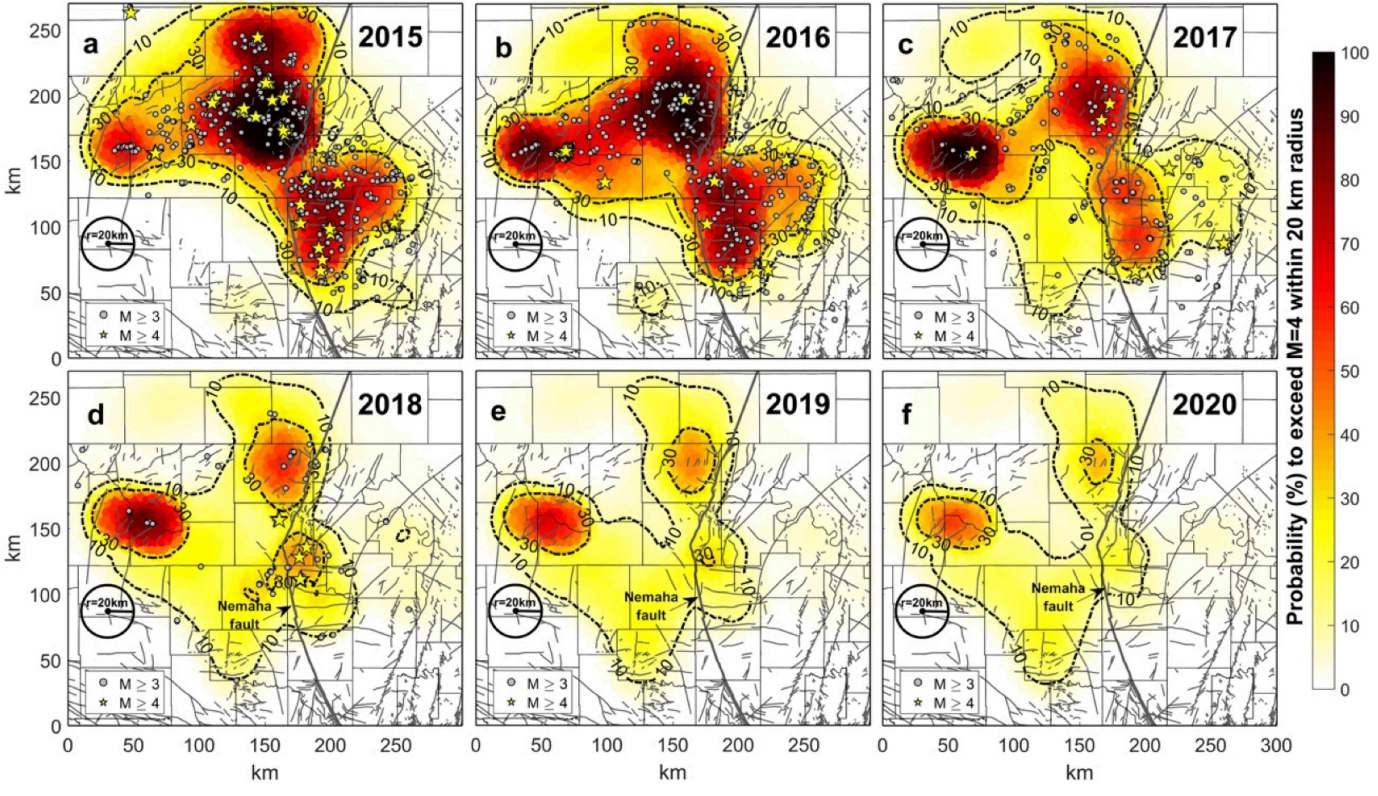






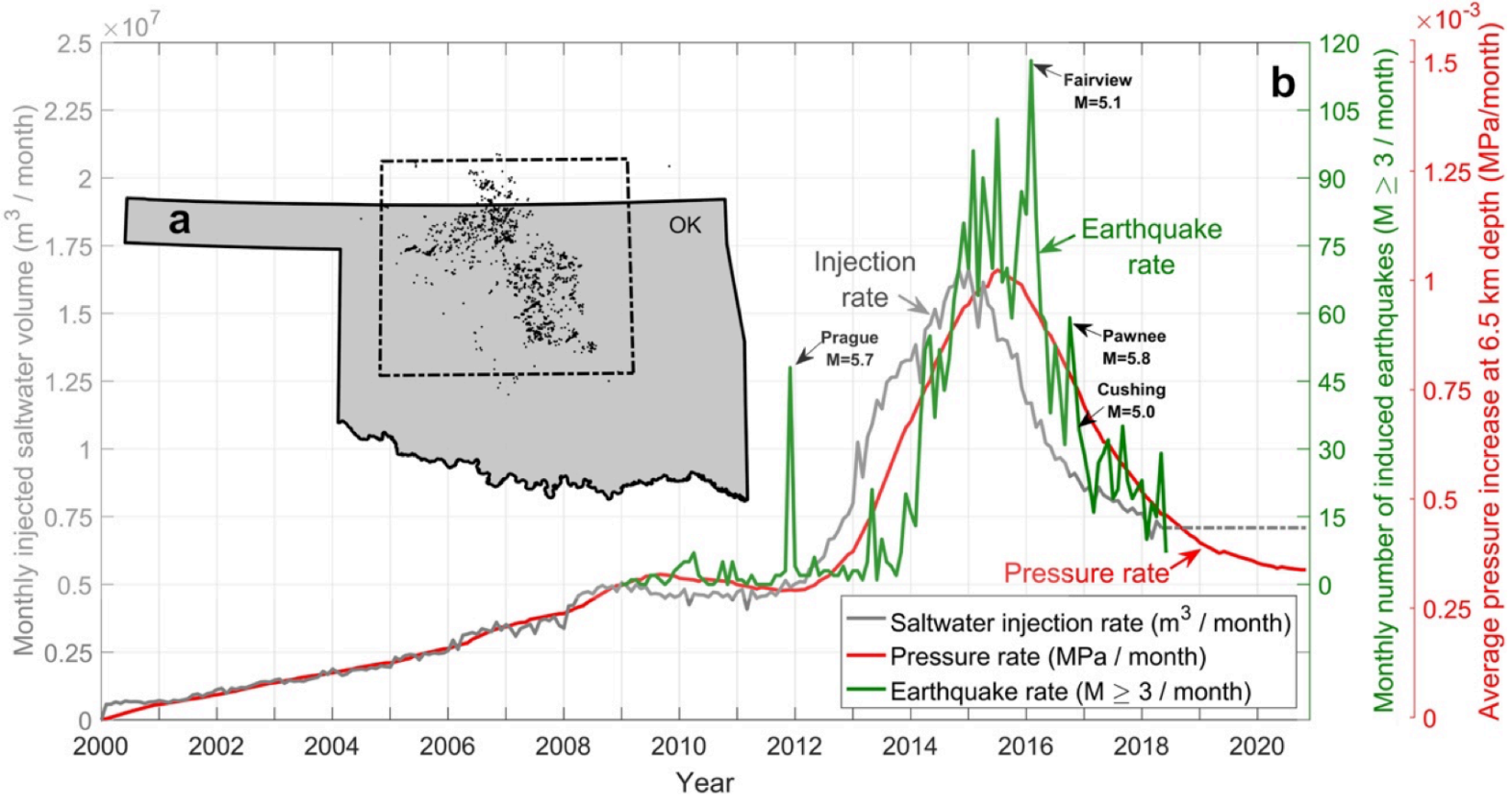
Physics-based forecasting of man-made earthquake hazards in Oklahoma and Kansas

Cornelius Langenbruch, Matthew Weingarten & Mark Zoback

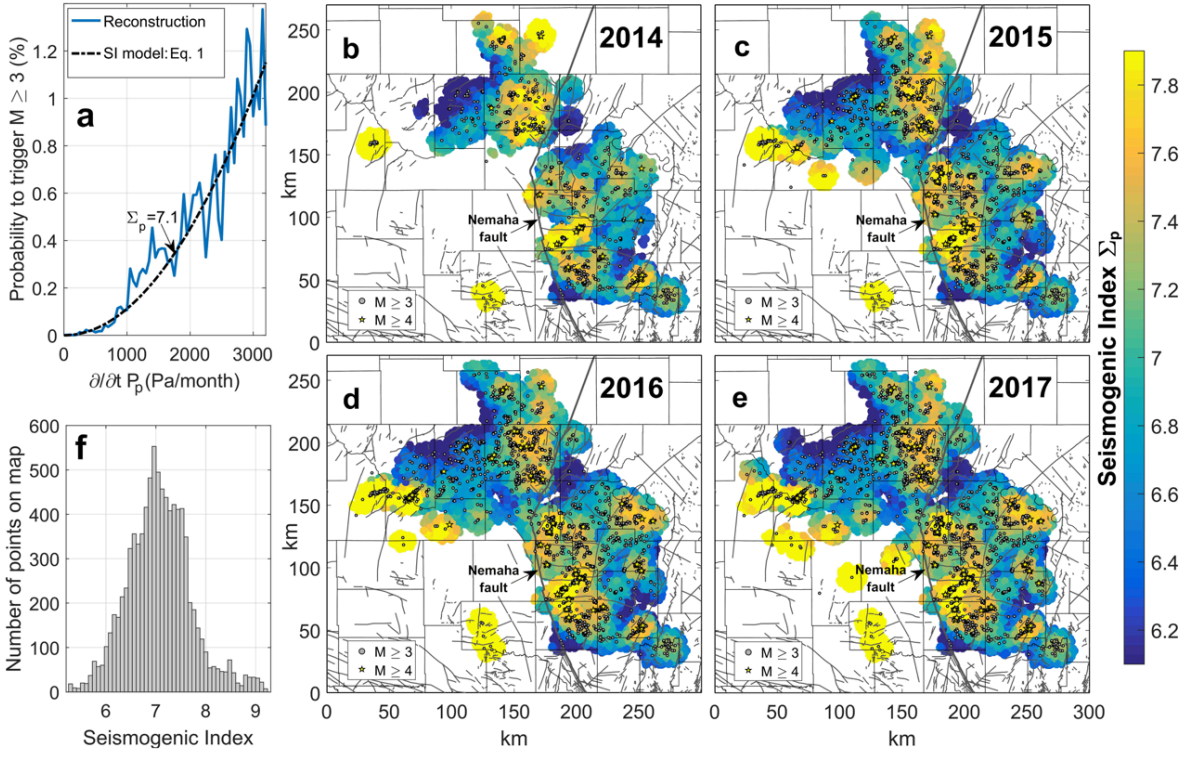


Langenbruch, C., Weingarten, M. and Zoback, M.D., 2018. Physics-based forecasting of man-made earthquake hazards in Oklahoma and Kansas. *Nature communications*, *9*(1), p.3946.

Injection rates and pressures are falling
-- and the earthquake rate is falling too

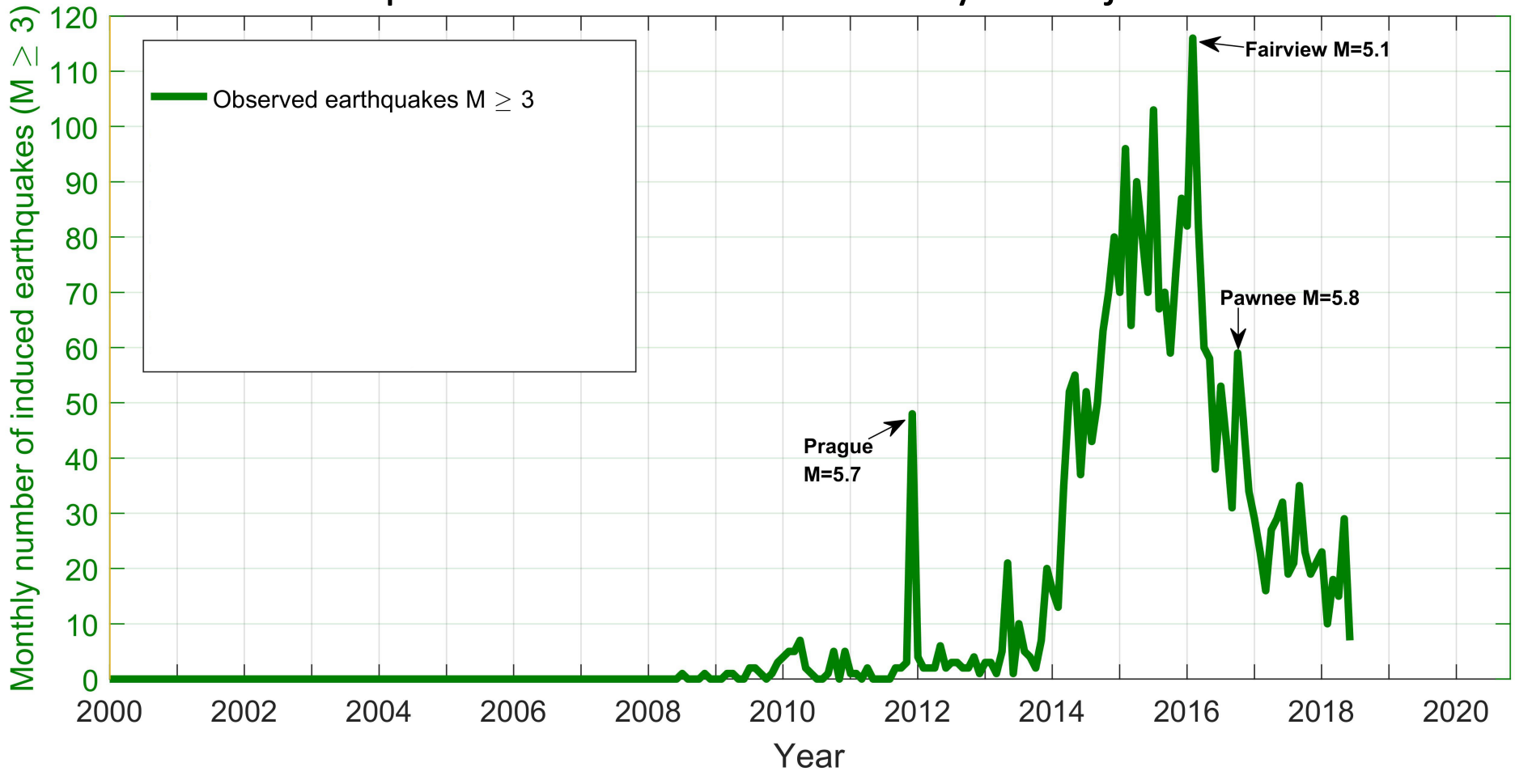


Adaptation of the Seismogenic Index Model to Wastewater Disposal

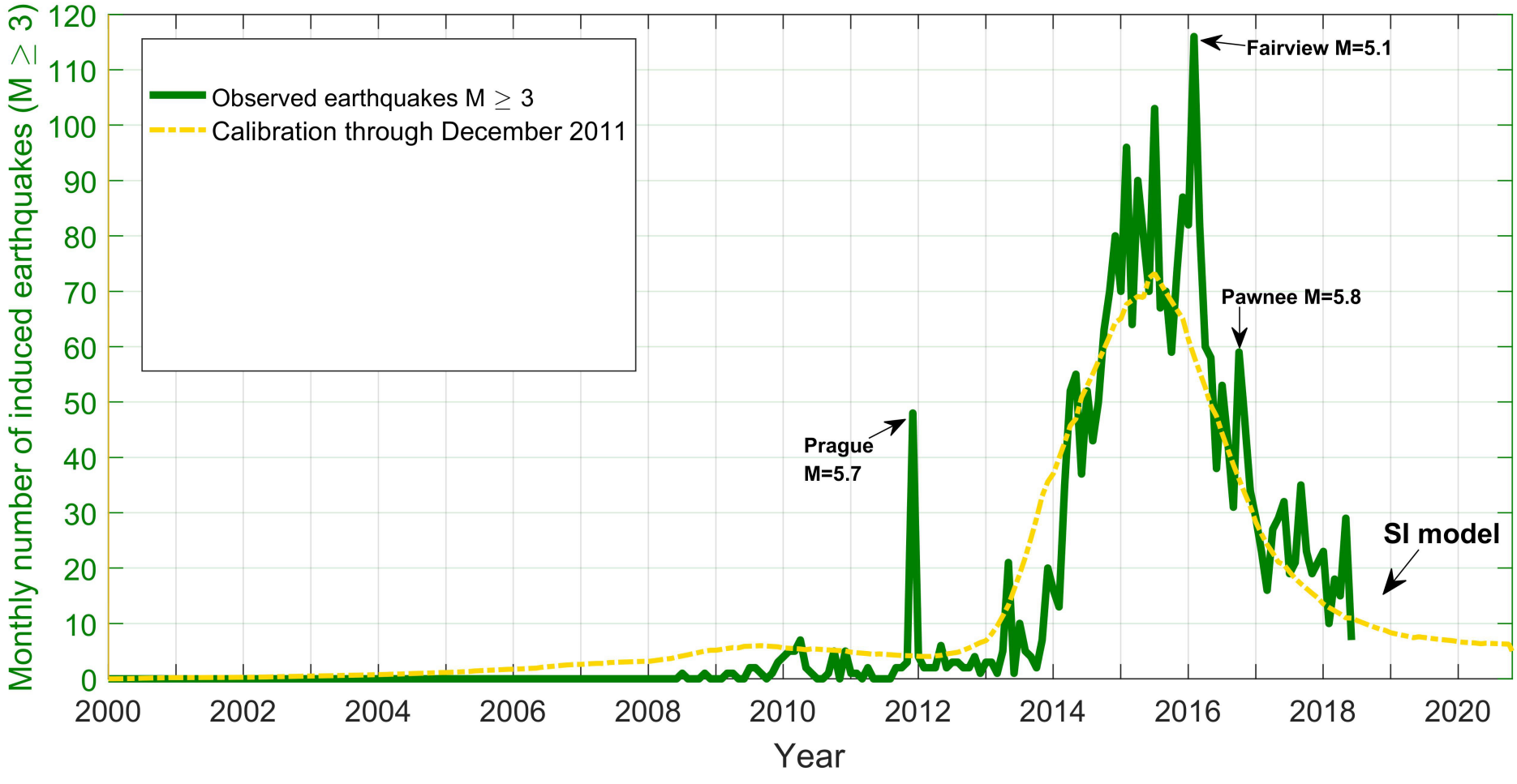


The seismogenic index embodies the seismicity response to injection, which varies spatially and must be empirically calibrated.

A new formulation of the Seismogenic Index model predicts the earthquake rate when informed by the injection data



A new formulation of the Seismogenic Index model predicts the earthquake rate when informed by the injection data



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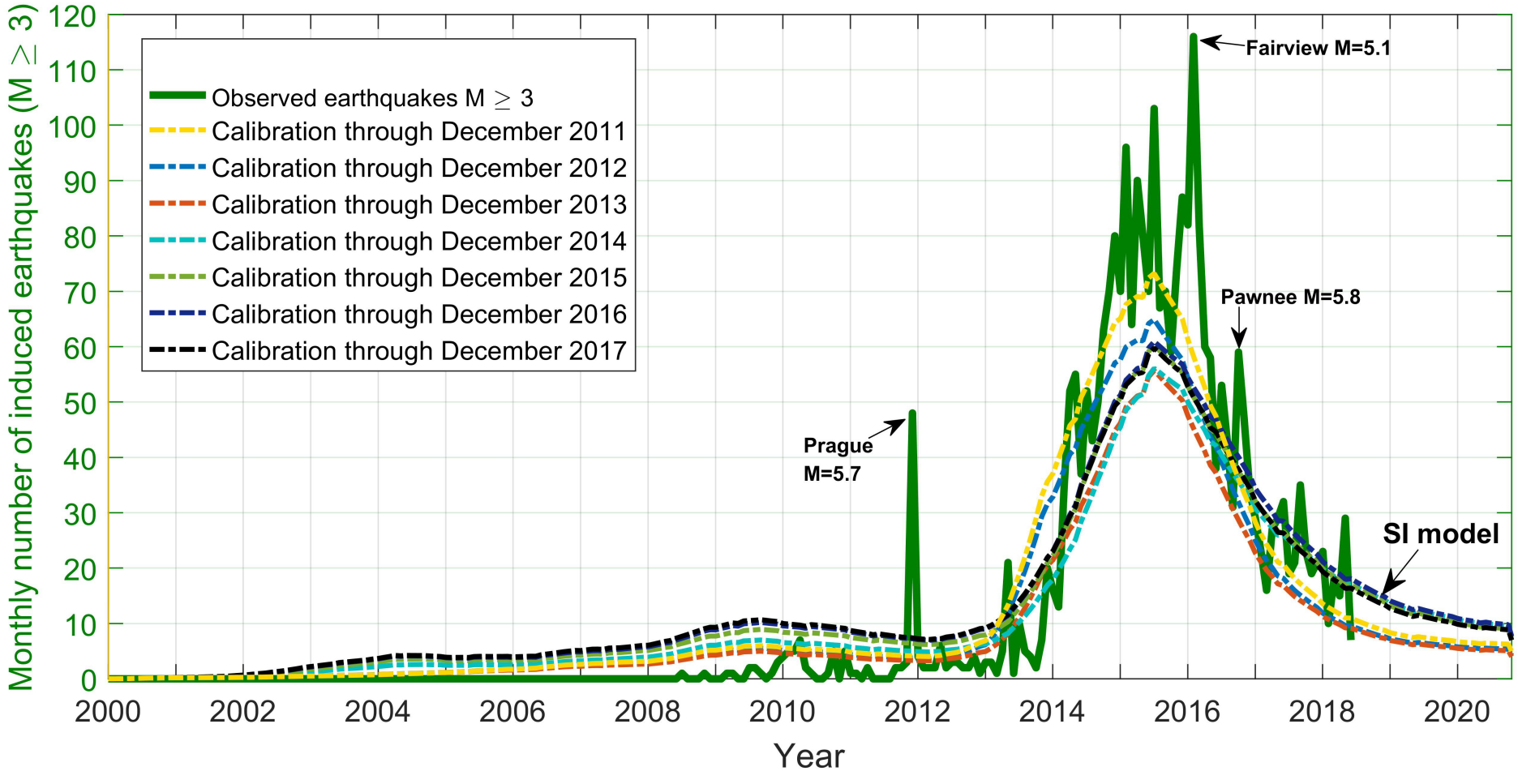
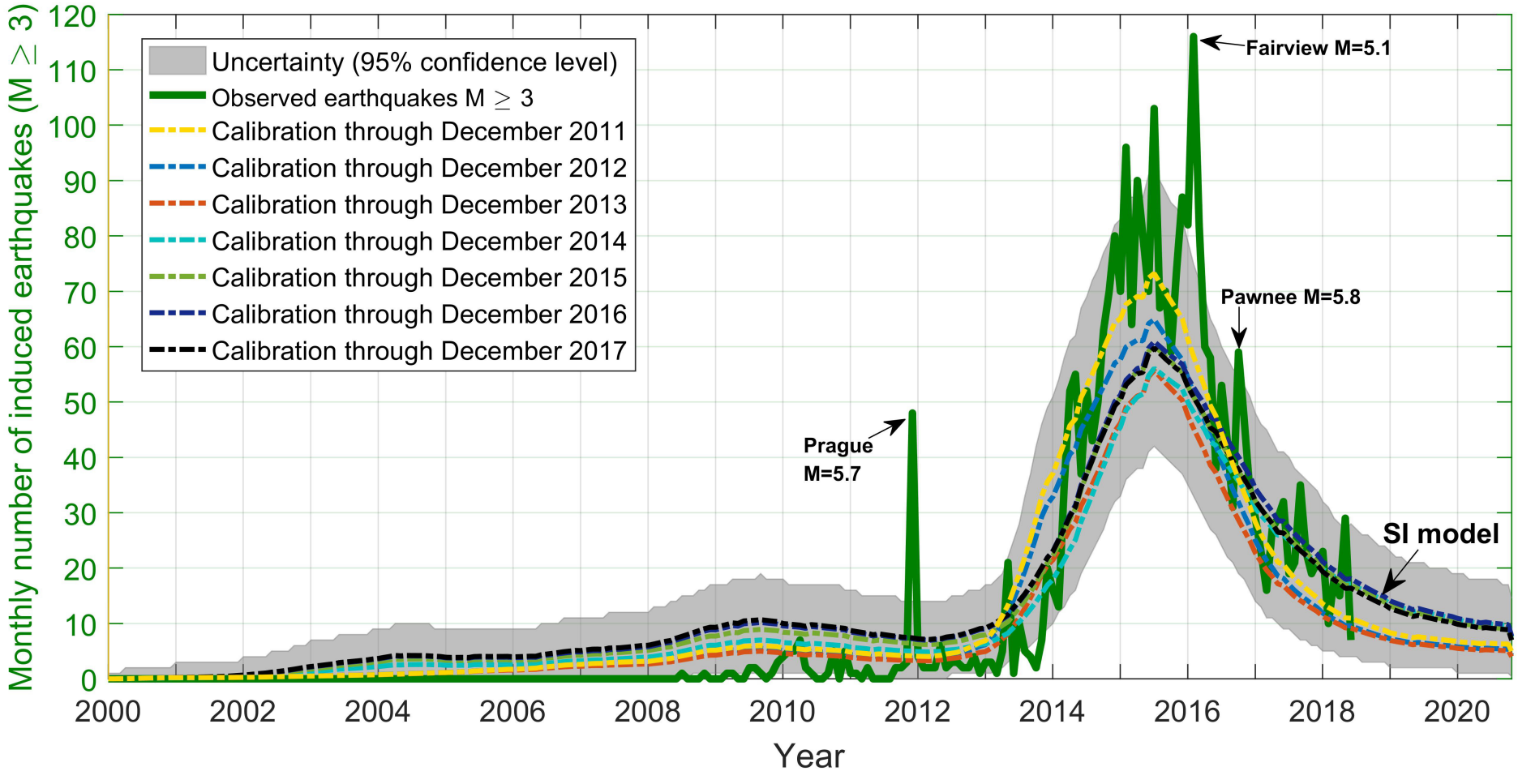
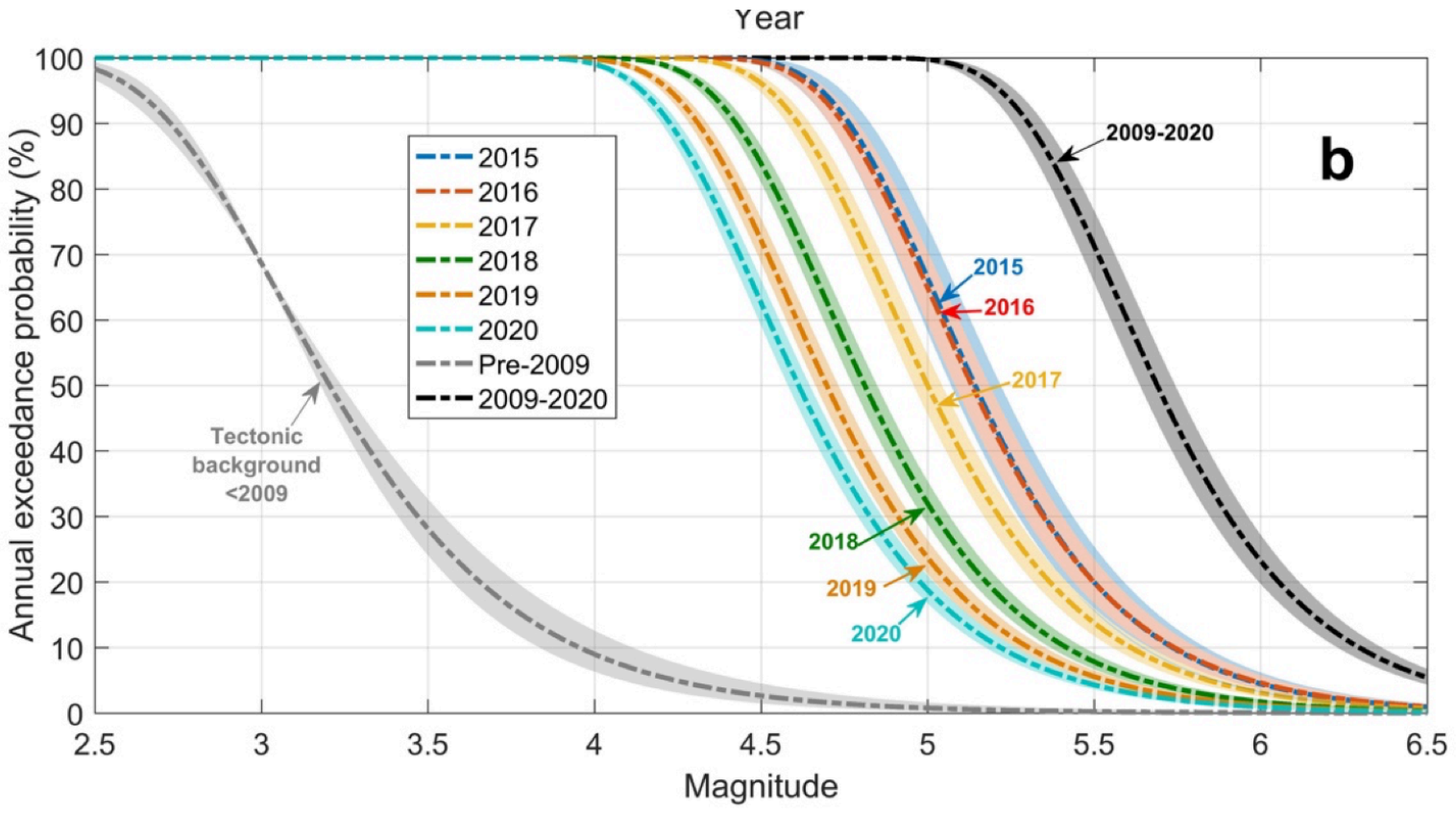


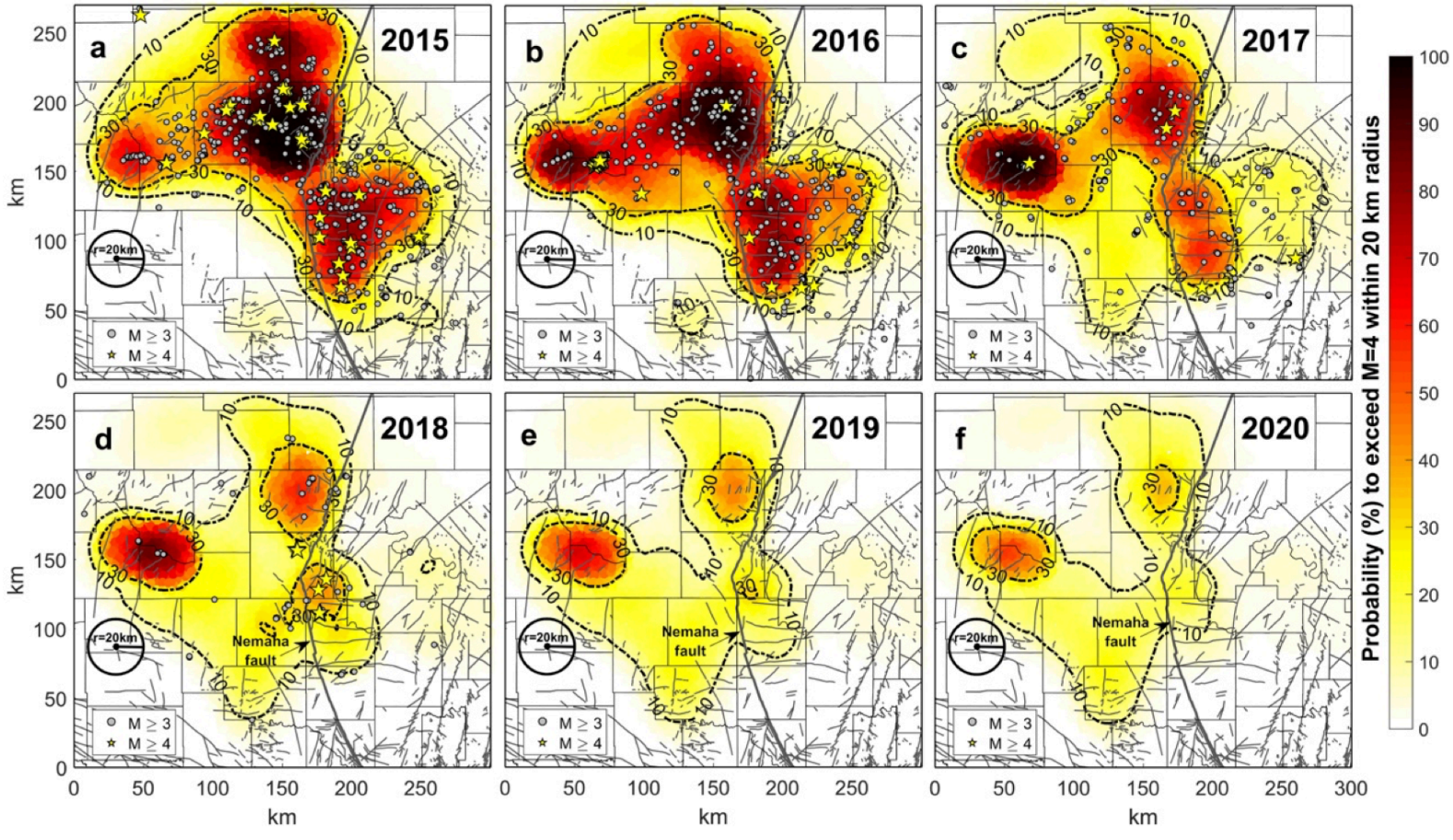
A new formulation of the Seismogenic Index model predicts the earthquake rate when informed by the injection data



The hazard is declining from the peak in 2015-2016 but is still far from the tectonic background



Prospective physics-based earthquake rupture forecast



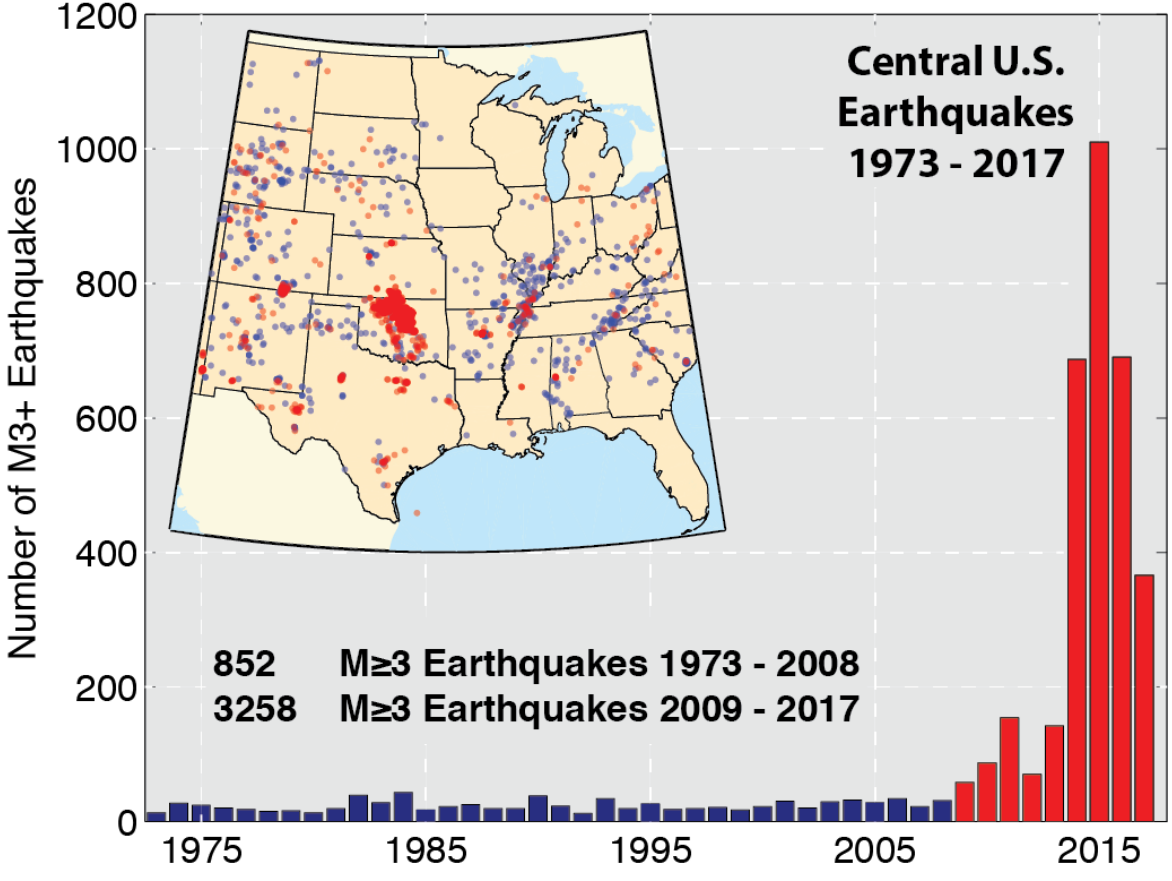
Key points: Future earthquake hazard in Oklahoma

- The short-term hazard from induced earthquakes in Oklahoma is declining due to reduced wastewater disposal into the Arbuckle Formation.

- A physics-base hazard model informed by the injection data correctly predicts the rate of decline of seismicity.

- The hazard is still high compared to the natural tectonic hazard and is predicted to remain so for years.

Questions?


Central U.S.
Earthquakes
1973 - 2017
852 M≥3 Earthquakes 1973 - 2008
3258 M≥3 Earthquakes 2009 - 2017
Number of M3+ Earthquakes
0
200
400
600
800
1000
1200
1975
1985
1995
2005
2015