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

How will induced seismicity in Oklahoma respond to decreased saltwater injection rates?

Cornelius Langenbruch and Mark D. Zoback

In early 2016 regulators in Oklahoma mandated a 40% reduction of waste-water injection volumes.

SCIENCE ADVANCES | RESEARCH ARTICLE

SEISMOLOGY

How will induced seismicity in Oklahoma respond to decreased saltwater injection rates?

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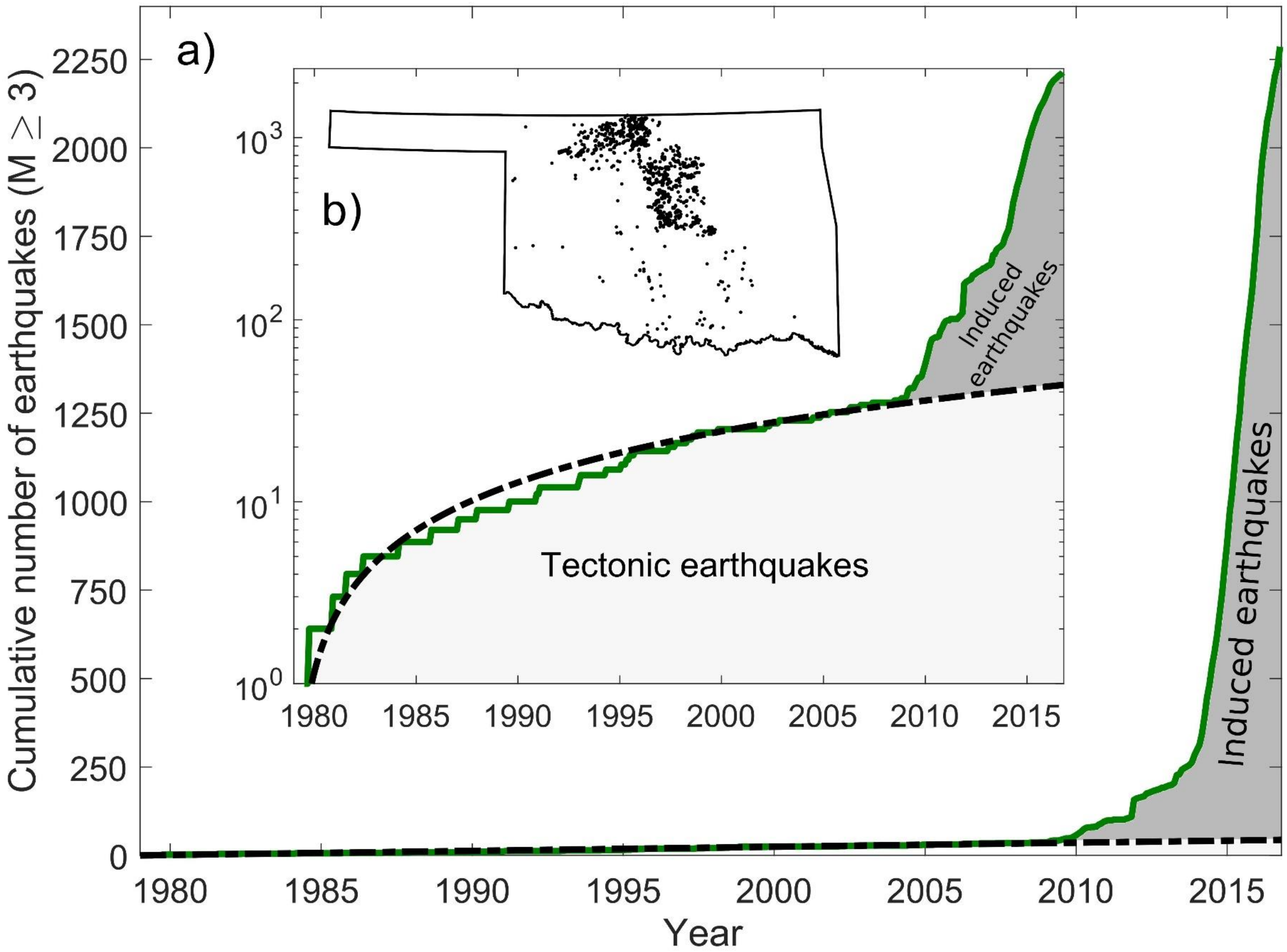
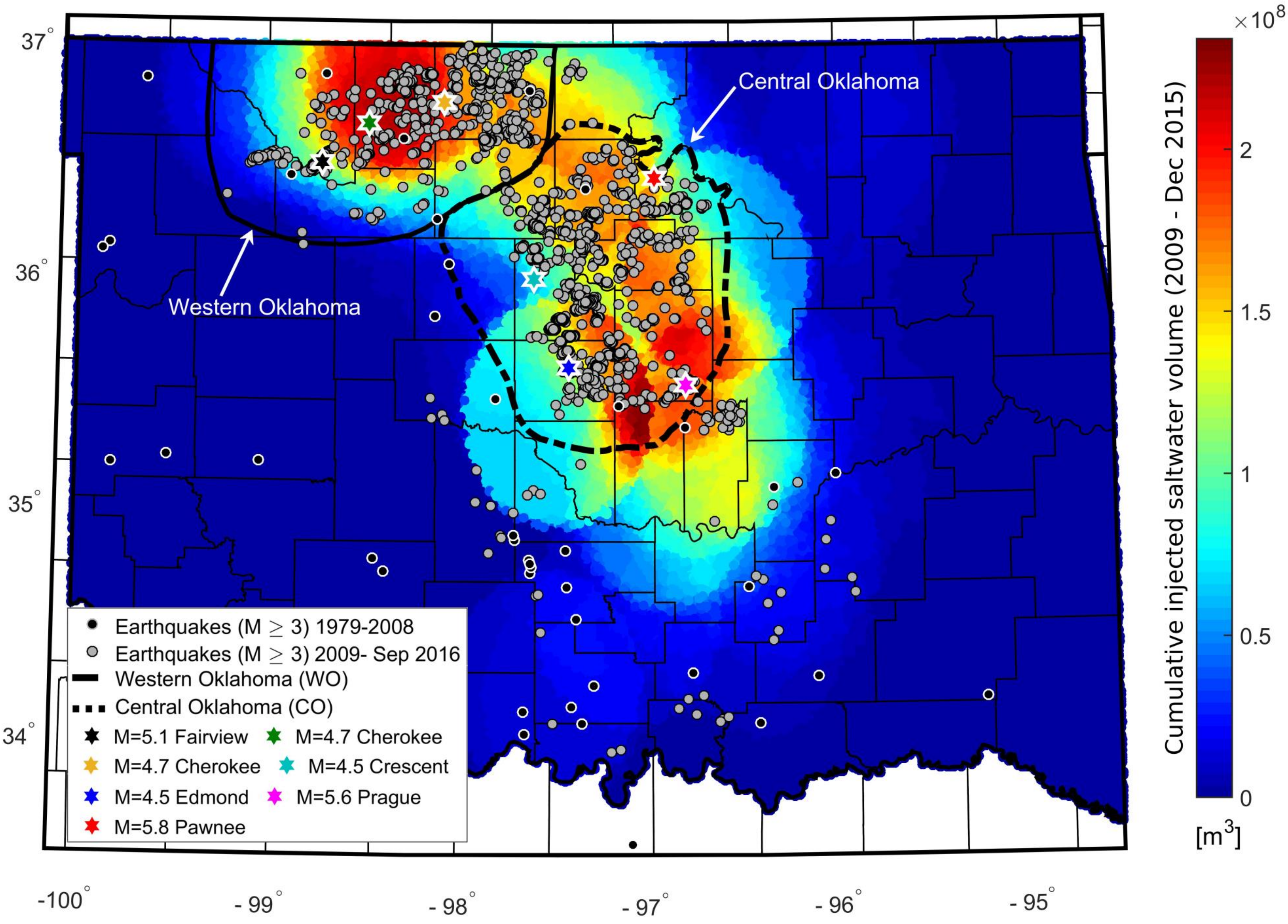
In response to the marked number of injection-induced earthquakes in north-central Oklahoma, regulators recently called for a 40% reduction in the volume of saltwater being injected in the seismically active areas. We present a calibrated statistical model that predicts that widely felt $M \geq 3$ earthquakes in the affected areas, as well as the probability of potentially damaging larger events, should significantly decrease by the end of 2016 and approach historic levels within a few years. Aftershock sequences associated with relatively large magnitude earthquakes that occurred in the Fairview, Cherokee, and Pawnee areas in north-central Oklahoma in late 2015 and 2016 will delay the rate of seismicity decrease in those areas.

ScienceAdvances
AAAS

Tectonic and induced earthquakes in Oklahoma

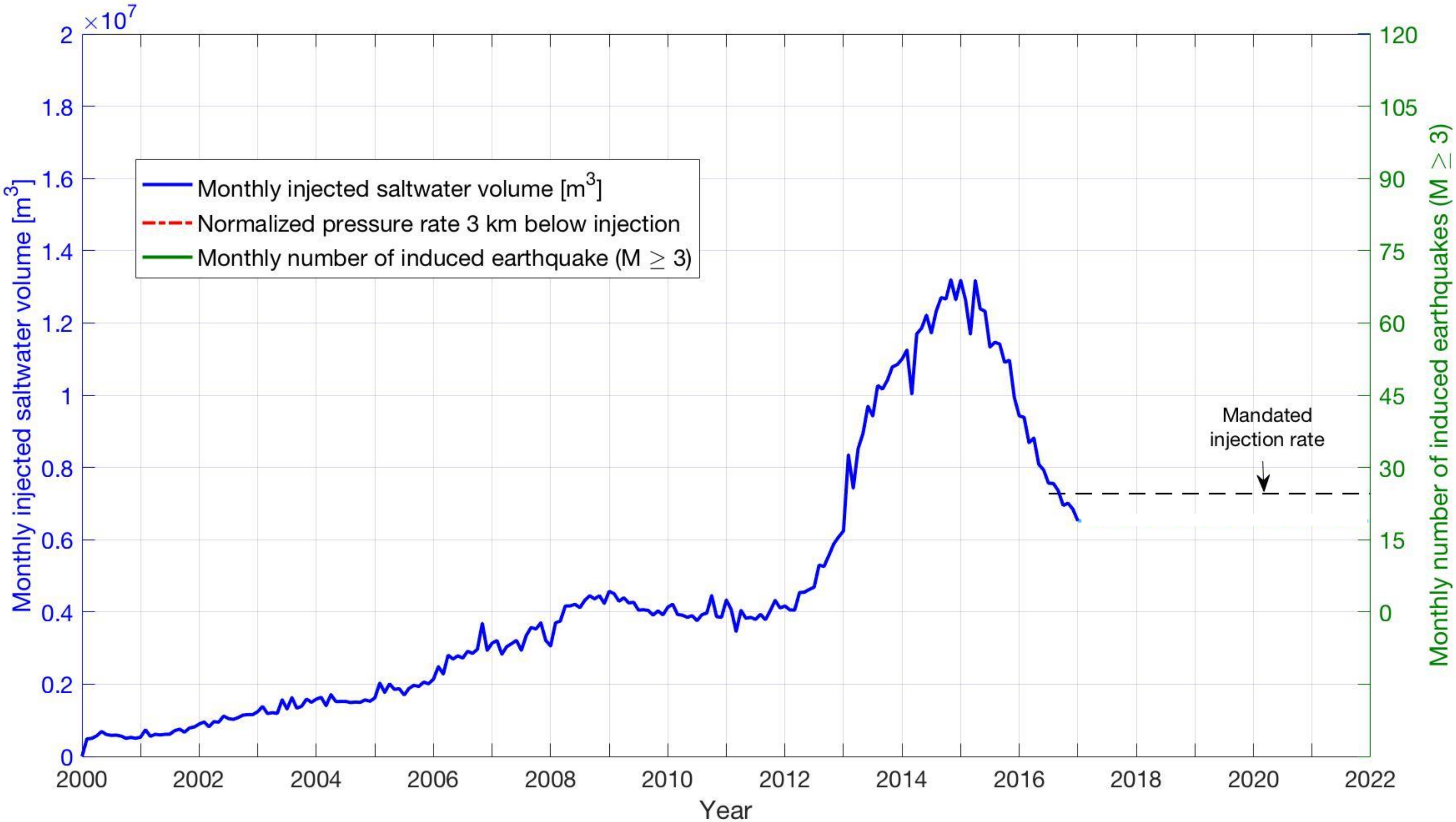


The number of earthquakes induced during the last six year corresponds to 2000 years of tectonic activity in Oklahoma.

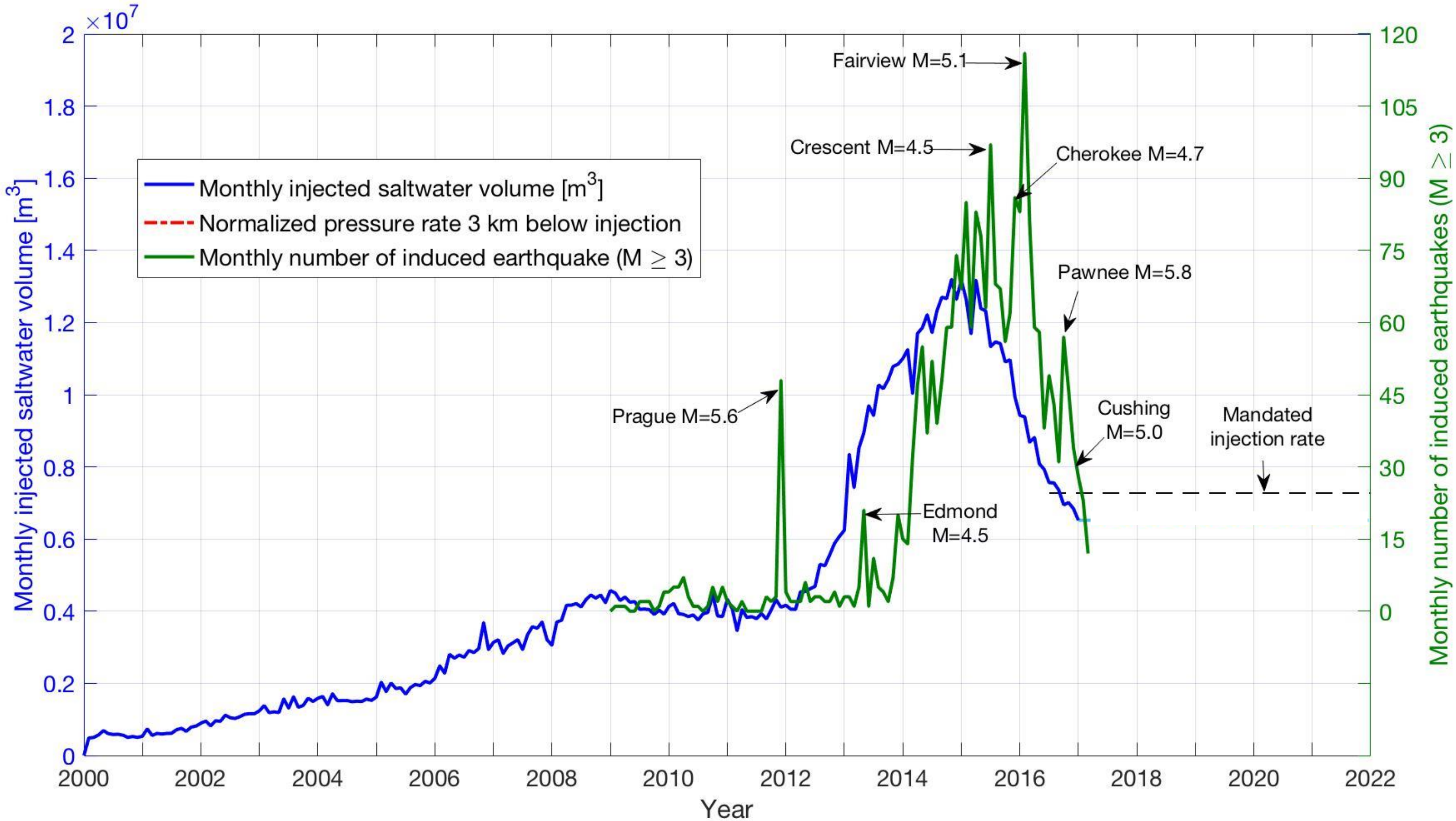


Central Oklahoma
Western Oklahoma
Earthquakes (M ≥ 3) 1979-2008
Earthquakes (M ≥ 3) 2009- Sep 2016
Western Oklahoma (WO)
Central Oklahoma (CO)
M=5.1 Fairview
M=4.7 Cherokee
M=4.7 Cherokee
M=4.5 Crescent
M=4.5 Edmond
M=5.6 Prague
M=5.8 Pawnee
37°
36°
35°
34°
-100°
- 99°
- 98°
- 97°
- 96°
- 95°
Cumulative injected saltwater volume (2009 - Dec 2015)
×10^8
2
1.5
1
0.5
0
[m^3]

Saltwater injection and earthquakes (M≥3) in CO and WO



Saltwater injection and earthquakes (M≥3) in CO and WO



The Seismogenic Index

[Shapiro, Dinske, Langenbruch and Wenzel, (2010), TLE]

Pore pressure diffusion:
Event number is proportional to fluid volume

$$N(t) = \frac{\zeta}{C_{max} S} V_I(t)$$

Fractal scaling of fault sizes:
Gutenberg-Richter type probability law

$$log_{10}\left[W_{ev \geq M}\right] = a_p - bM$$

Gutenberg-Richter law for fluid injection-induced seismicity

$$log_{10}\left[N_{\geq M}(t)\right] = \underbrace{log_{10}\left[V_I(t)\right] + \Sigma}_{\text{a-value of the classical GR relation}} - bM$$

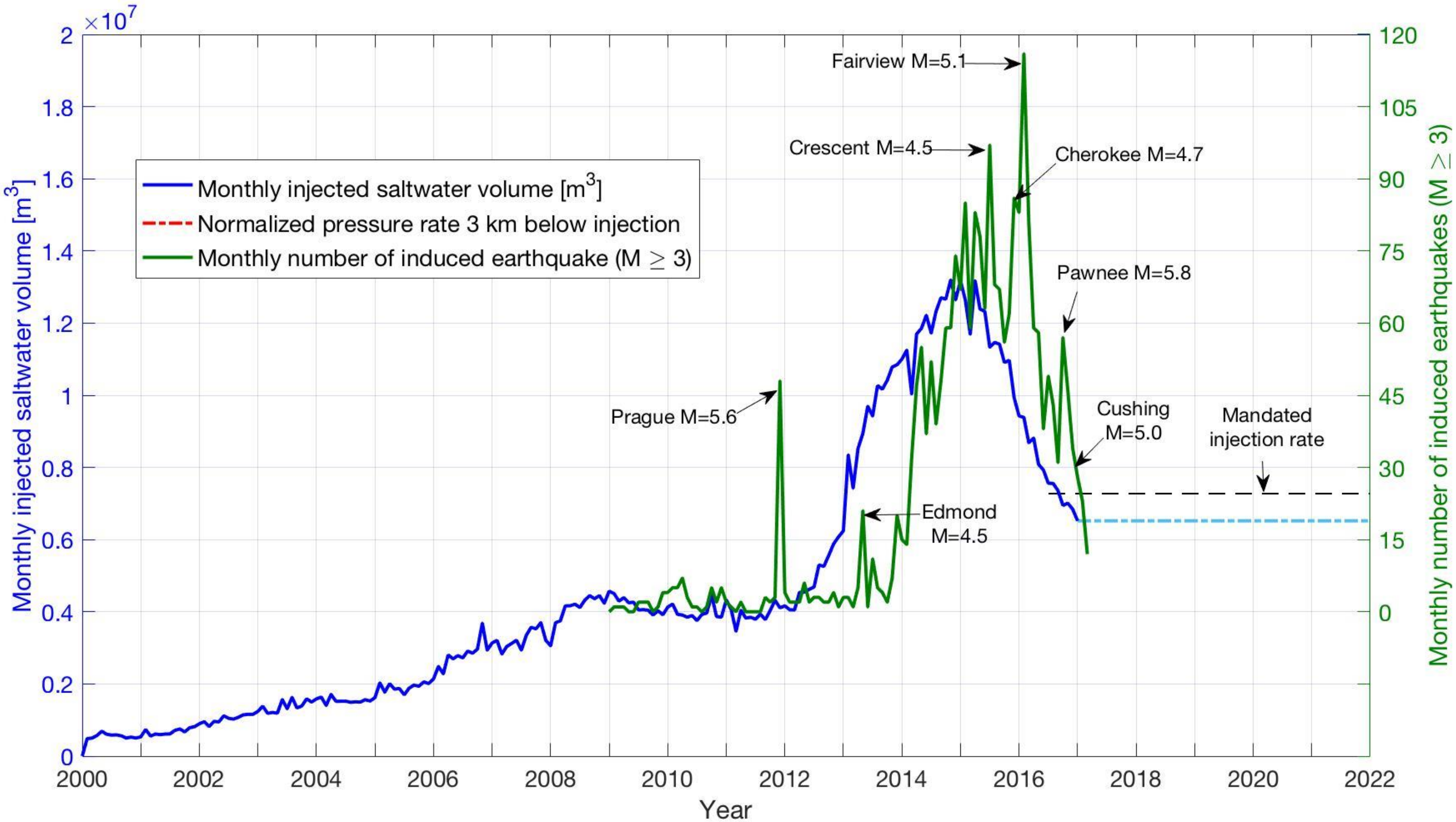
$$\Sigma = log_{10}\left[\frac{\zeta}{C_{max} S}\right] + a_p = log_{10}\left[N_{\geq M}(t)\right] - log_{10}\left[V_I(t)\right] + bM$$

The Seismogenic Index combines unknown site-specific seismo-tectonic constants at an injection location.

However, it can be computed from observations.

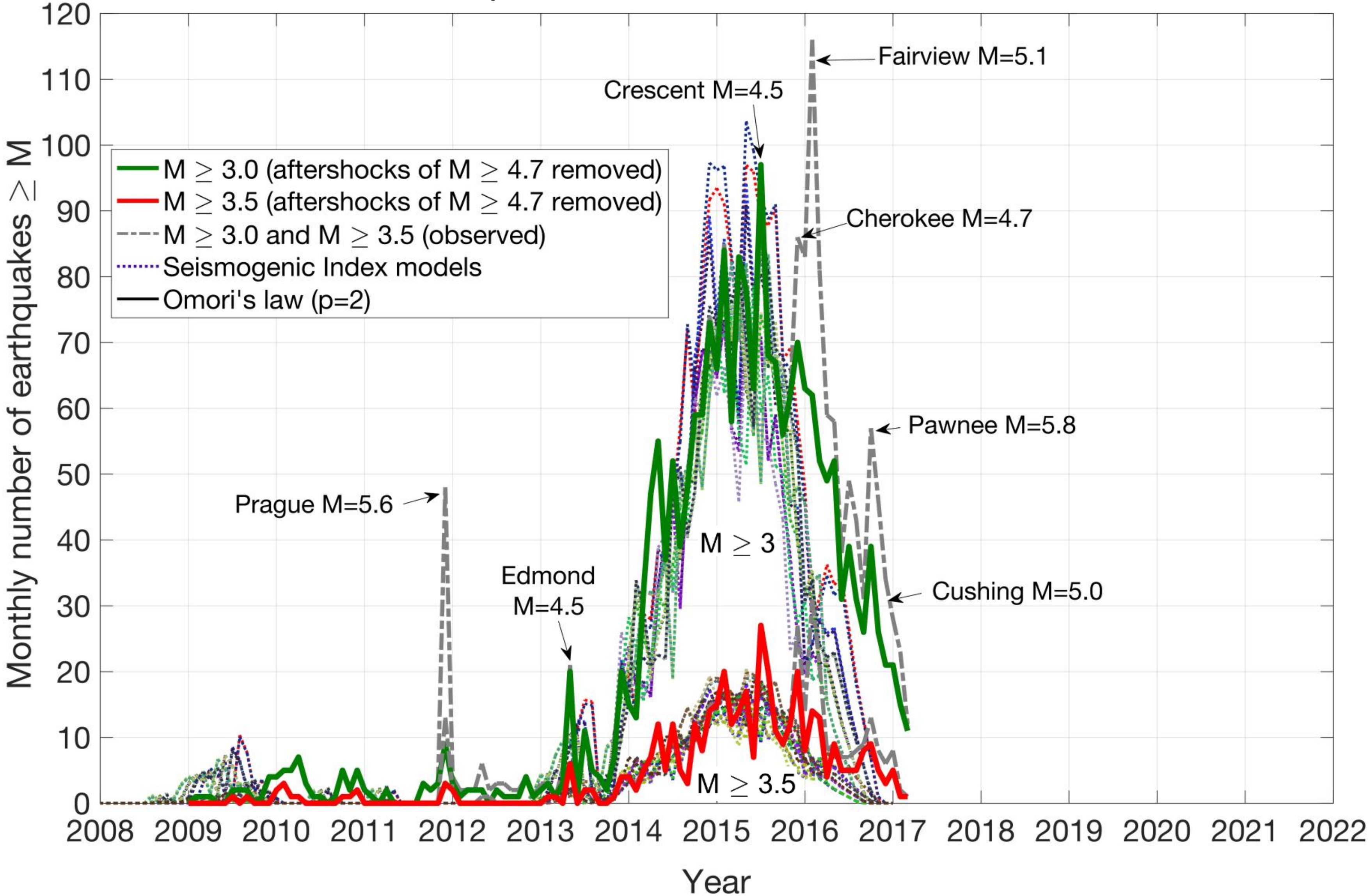
Saltwater injection and earthquakes (M≥3) in CO and WO

$$log_{10}\left[N_{\geq M}(t)\right] = log_{10}\left[V_I(t)\right] + \Sigma - bM$$



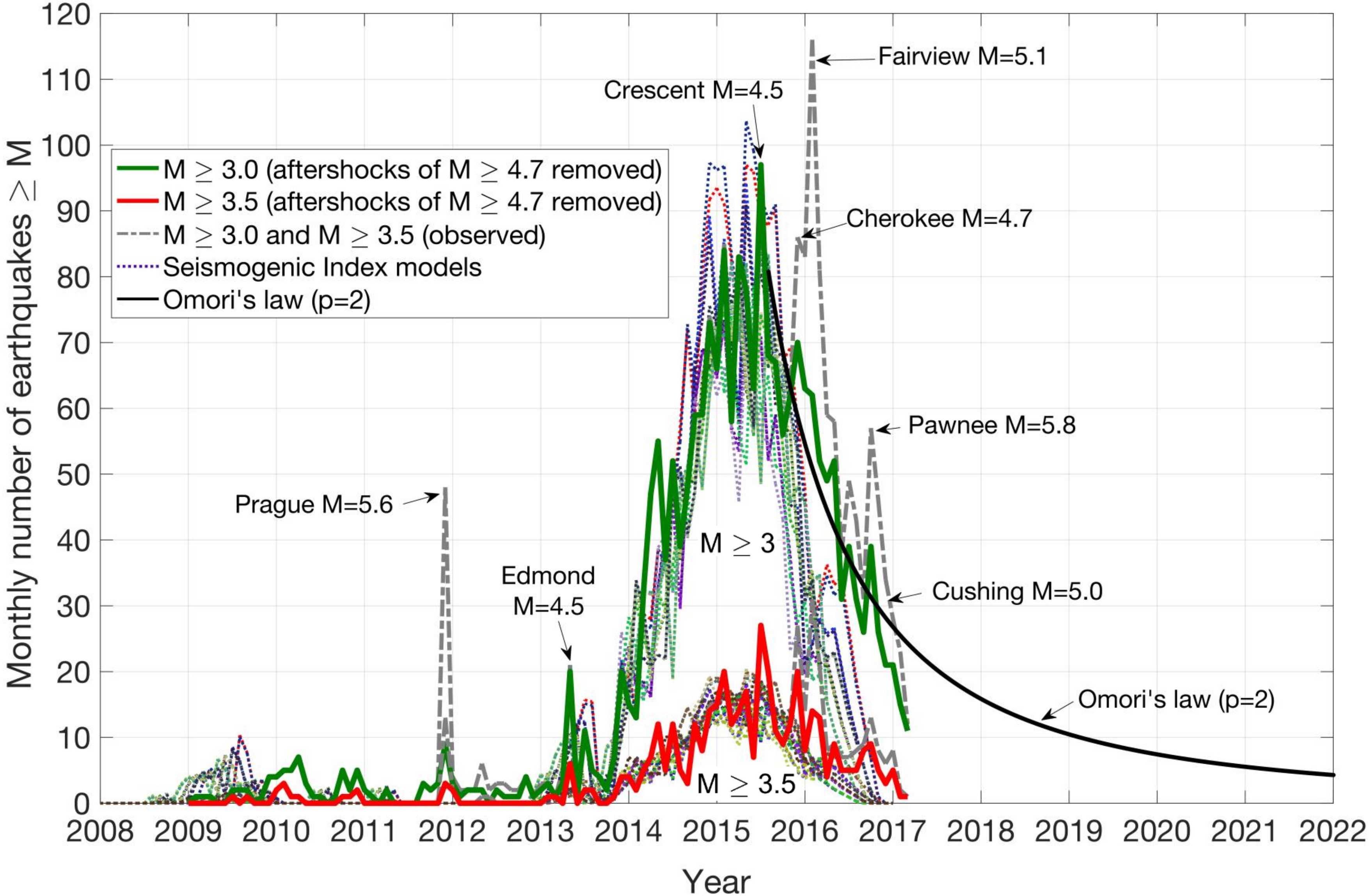
We introduce a seismicity triggering threshold and a time shift in the SI model.

Model prediction and observation



$$log_{10}\left[N_{\geq M}(t)\right] = log_{10}\left[V_I(t)\right] + \Sigma - bM$$

Omori's law describes the decay of aftershocks after large tectonic earthquakes …

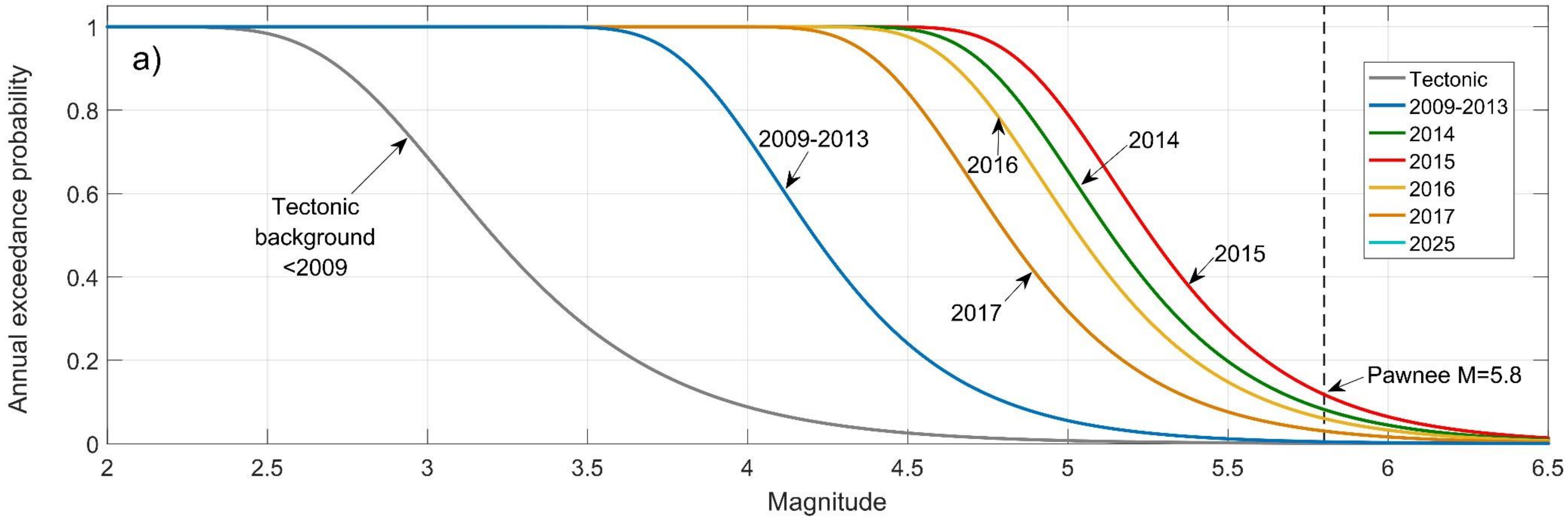


… and the decay of seismicity following injection:

$$R(t) = \frac{R_0}{\left(\frac{t}{t_0}\right)^p}, \quad t \geq t_0$$

(Langenbruch and Shapiro, 2010, Geophysics)

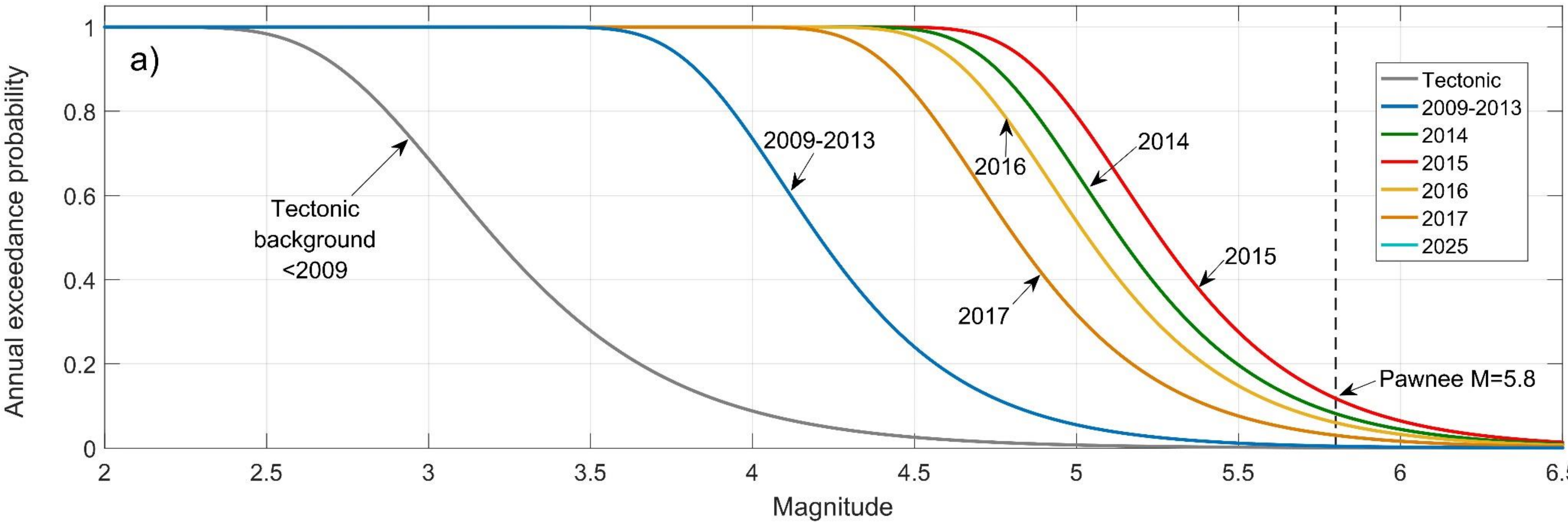
Occurrence probability of potentially-damaging earthquakes

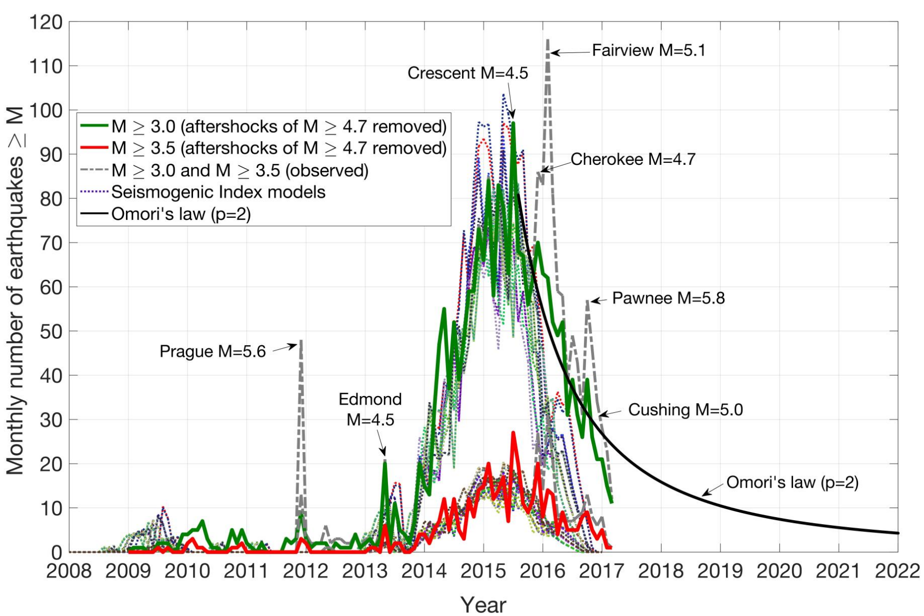


Langenbruch and Zoback, 2016

Homogeneous Poisson process in the volume domain	Probability to exceed magnitude M
(Langenbruch et al. 2011, GRL)	$$1 - P(0, M, V_I) = 1 - exp\left(-V_I\ 10^{\Sigma - bM}\right)$$

Occurrence probability of potentially-damaging earthquakes





Langenbruch and Zoback, 2016

The probability to exceed M=5 in 2017 is 37%.

Conclusions I

In response to decreased saltwater injection rates earthquake rates in Oklahoma significantly decreased by the end of 2016.

The probability of damaging earthquakes is decreasing but occurrence of M>5 cannot be discounted in 2017 (37%).

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Physics-based seismic hazard forecast for induced seismicity in Oklahoma

Cornelius Langenbruch, Matthew B. Weingarten and Mark D. Zoback

Motivation

Seismicity rates should be proportional to the stressing rate …

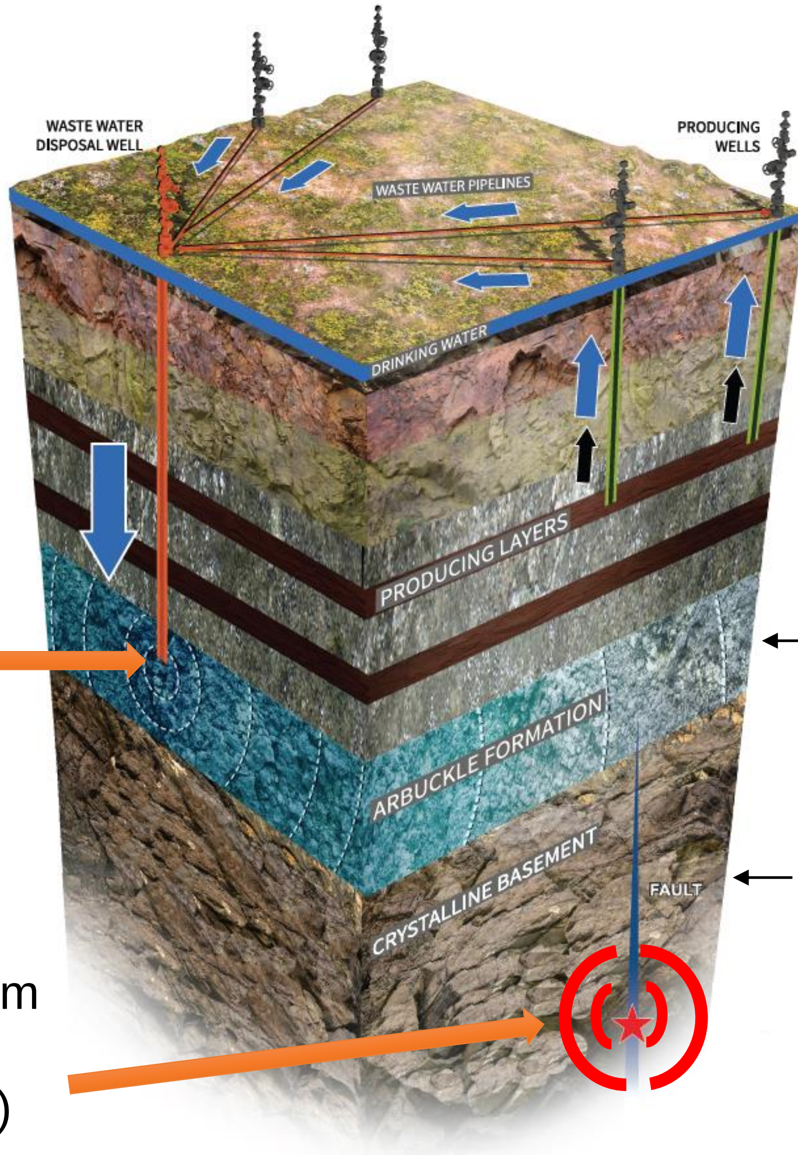
[Dieterich, 1994 ; Toda et al. 2002, Hakimhashemi et al., 2014; Segall & Lu, 2015]

… earthquake rates in Oklahoma should be controlled by pressurization rates at pre-existing faults in the basement.

We combine the SI with Matt Weingarten's hydrologic model!

Drawback: We need information about the permeability!

Saltwater Injection at 1.6 – 2.5 km (Arbuckle group)

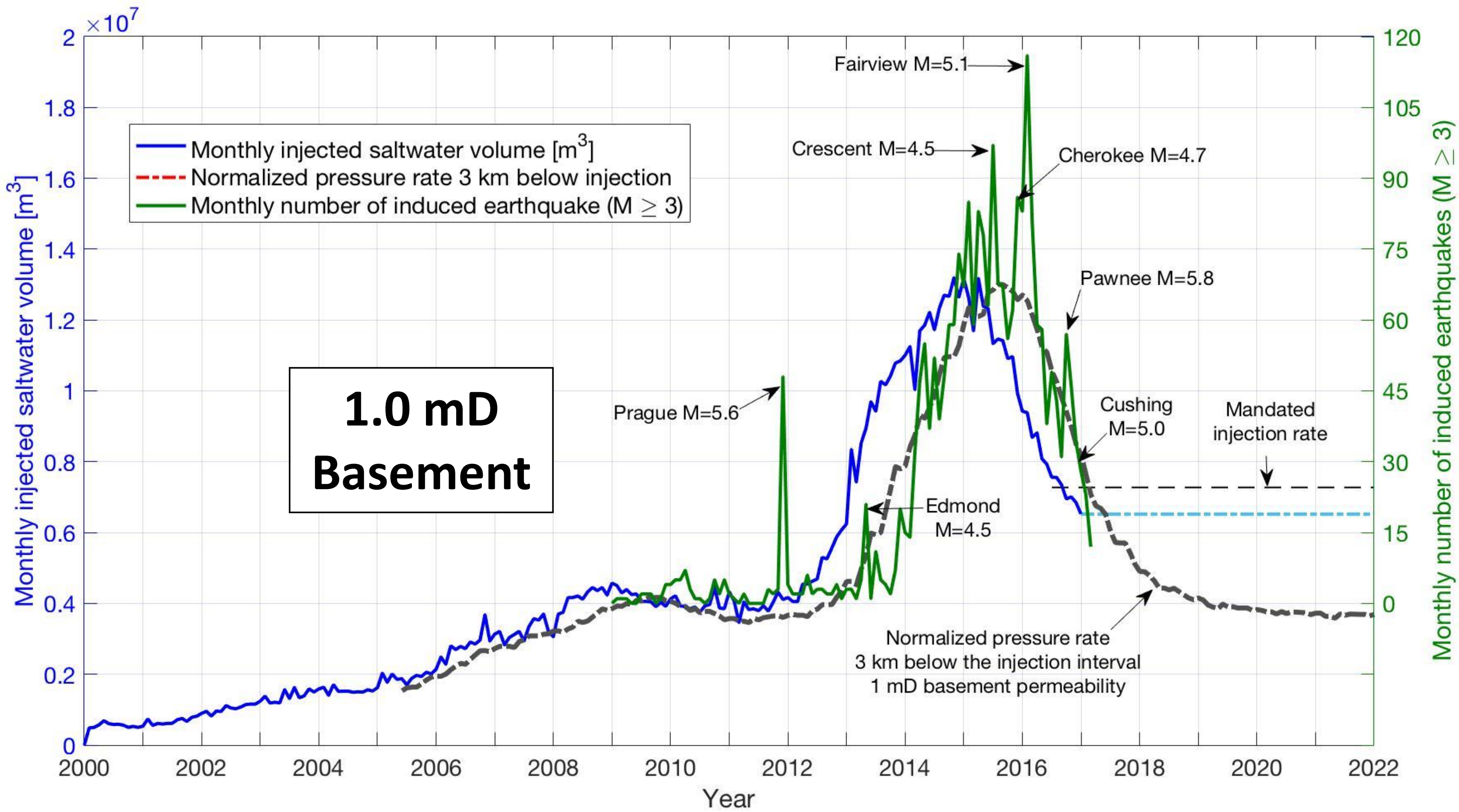


Arbuckle: 1Darcy

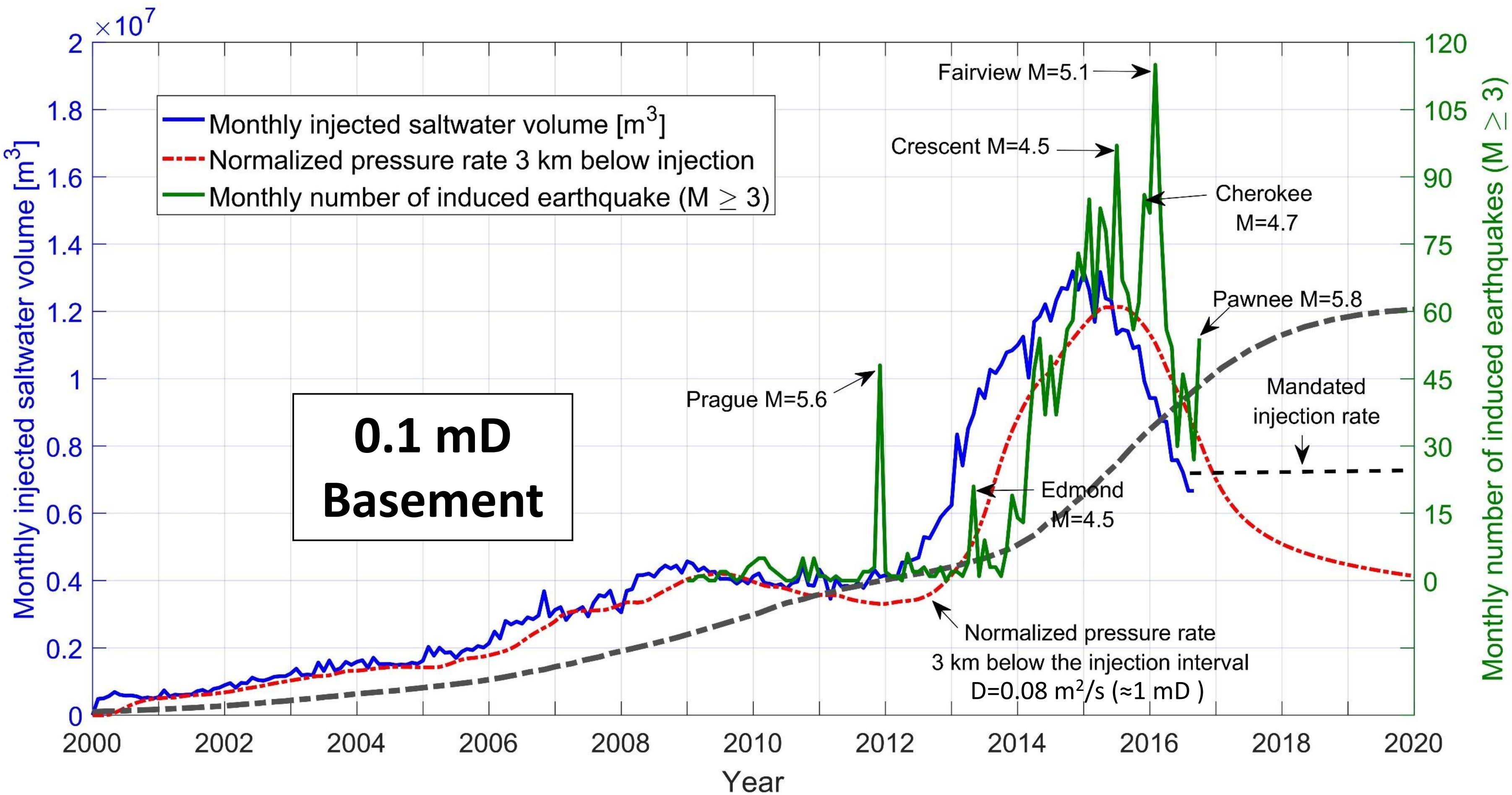
Basement: 1mDarcy

Seismicity about 3 km below injection (granitic basement)

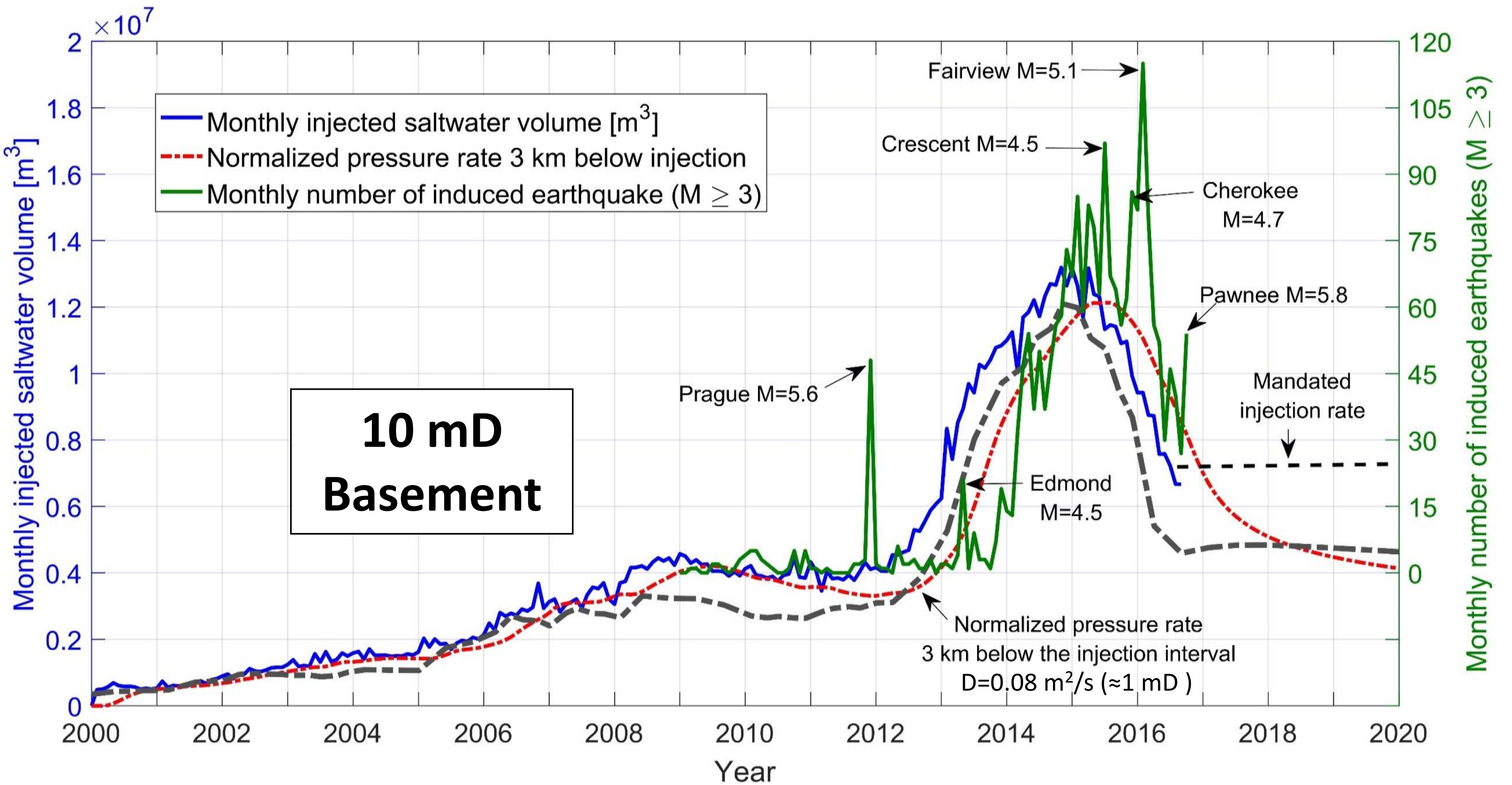
Calibration of the large scale basement permeability



Calibration of the large scale permeability

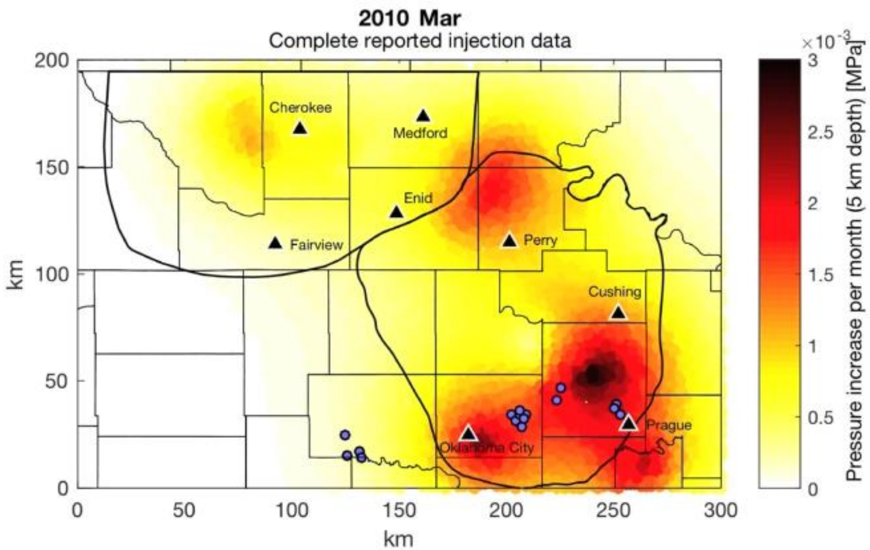


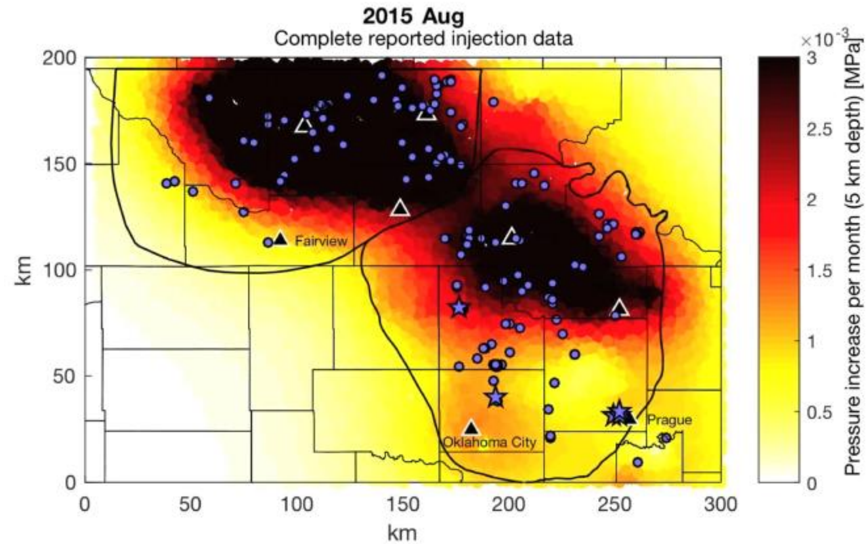
Calibration of the large scale permeability



Pressure modelling results:

Pressure rate at 5 km depth





Combining the Seismogenic Index with a hydrologic model allows to incorporate injection rates into a seismic hazard map for Oklahoma.

$$log_{10}[R_{\geq M}(t)] = log_{10}[\frac{\partial}{\partial t}P(t)] + \Sigma - bM$$

Conclusions II

Combining the Seismogenic Index with a hydrologic model allows to incorporate injection rates into a seismic hazard map for Oklahoma.

In response to the reduction of injection rates the seismic hazard in 2017 will be significantly lower than in 2016 …

(… the occurrence of damaging earthquakes cannot be discounted in 2017)

Concluding Remark

Practical implications of a critical injection/pressure rate threshold *in Oklahoma*:

Injection into the Arbuckle group is not problematic in general!

The seismic hazard is not controlled by the total volume of injected waste-water but by the injection rates per area.

Spreading out injection over a larger area should allow to inject higher total volumes without inducing damaging earthquakes.

Acknowledgements

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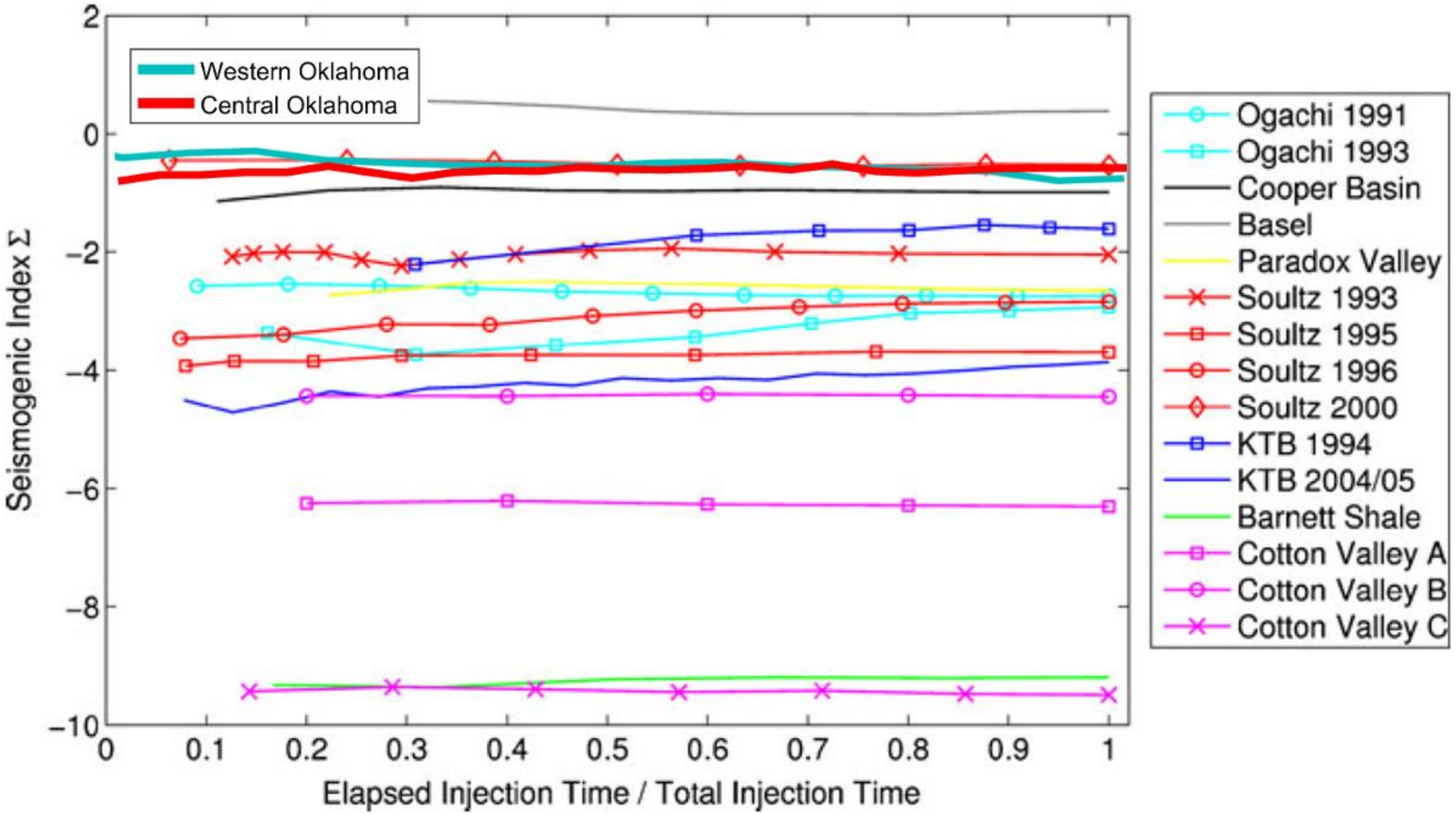
School of Earth, Energy & Environmental Sciences

Oklahoma Corporation Commission

USGS
science for a changing world

The Seismogenic Index



Modified from Dinske and Shapiro (2013)

The Seismogenic Index is constant over time.