Linking Oklahoma seismicity and saltwater disposal with a hydromechanical rate and state friction model

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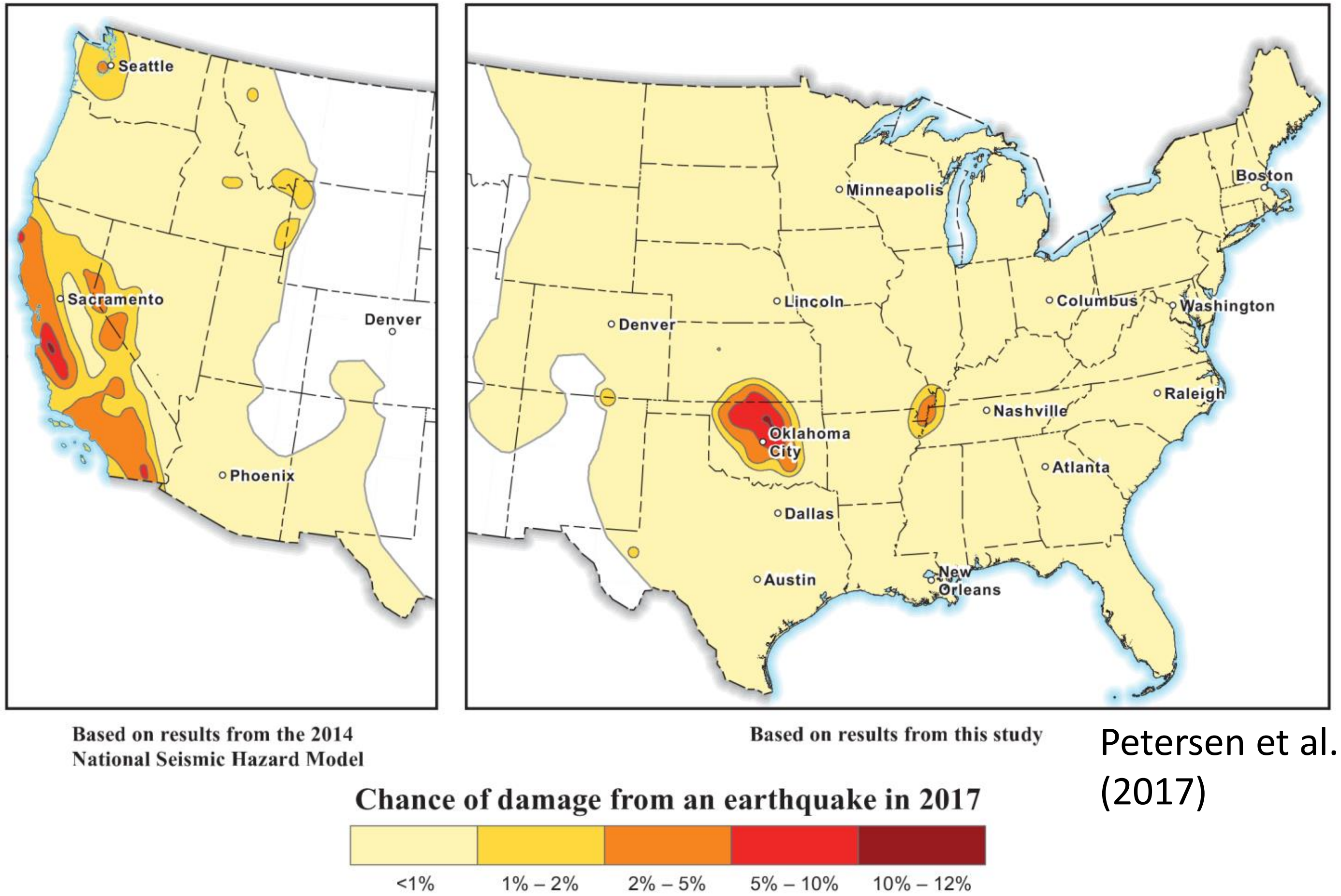
13 March, 2019

SIAM Conference on Mathematical & Computational Issues in Geosciences

Motivation

- ❑ 2016/2017/2018 USGS one-year hazard forecasts neglected saltwater disposal well operational activity

- ❑ My goal:
  - ❖ Forecast seismicity rates based upon injection data
  - ❖ Reservoir engineering approach
  - ❖ Geomechanics and earthquake physics



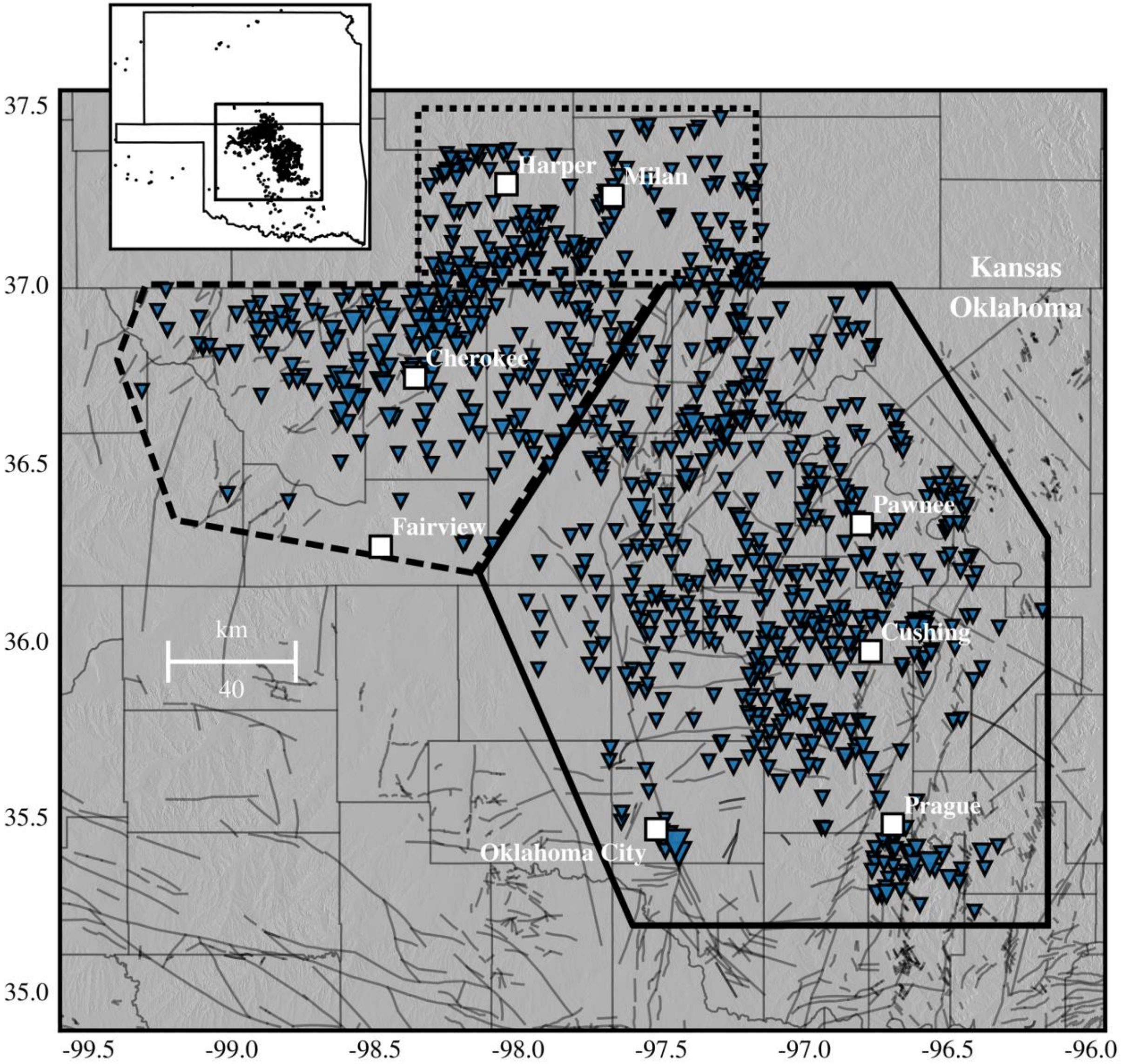
Based on results from the 2014 National Seismic Hazard Model

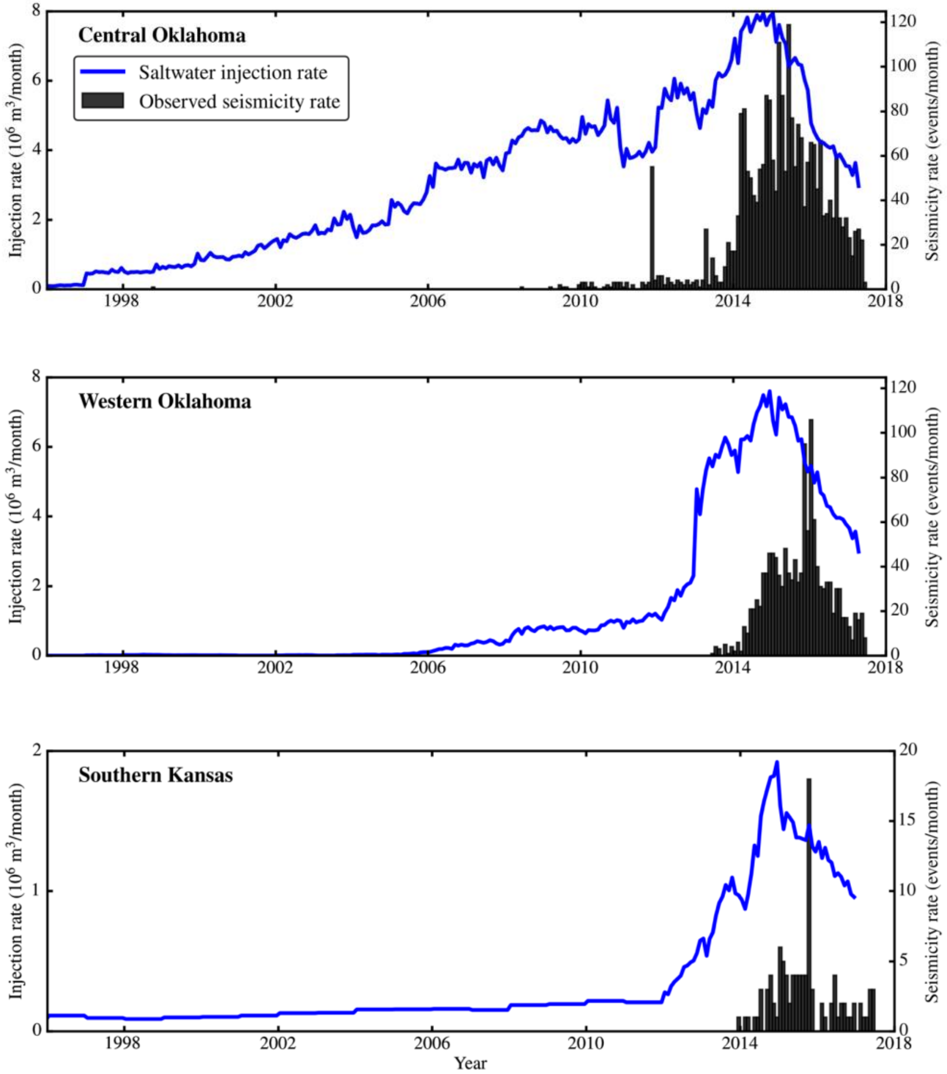
Based on results from this study

Chance of damage from an earthquake in 2017

Petersen et al. (2017)

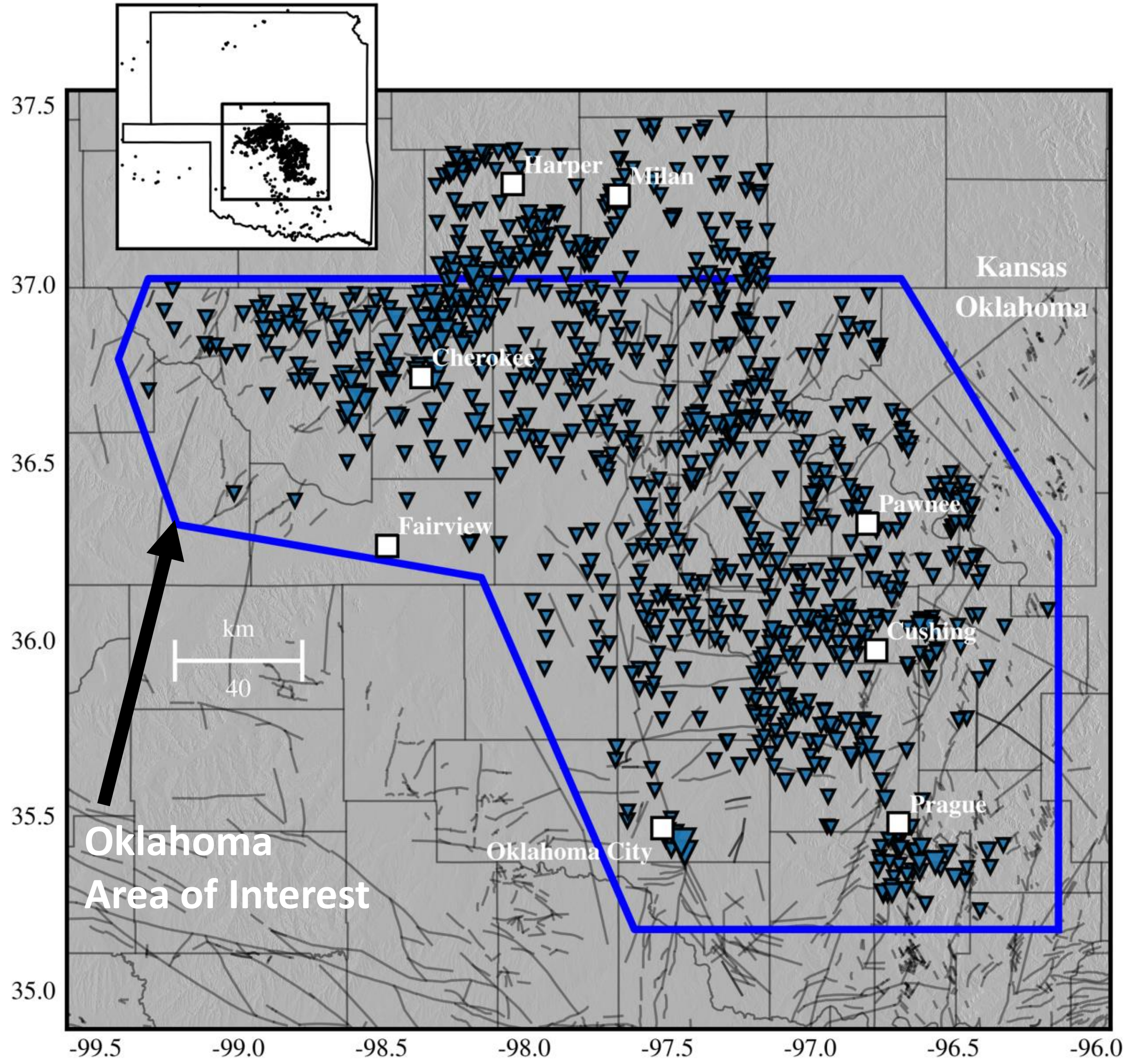
Injection-induced earthquake sequence



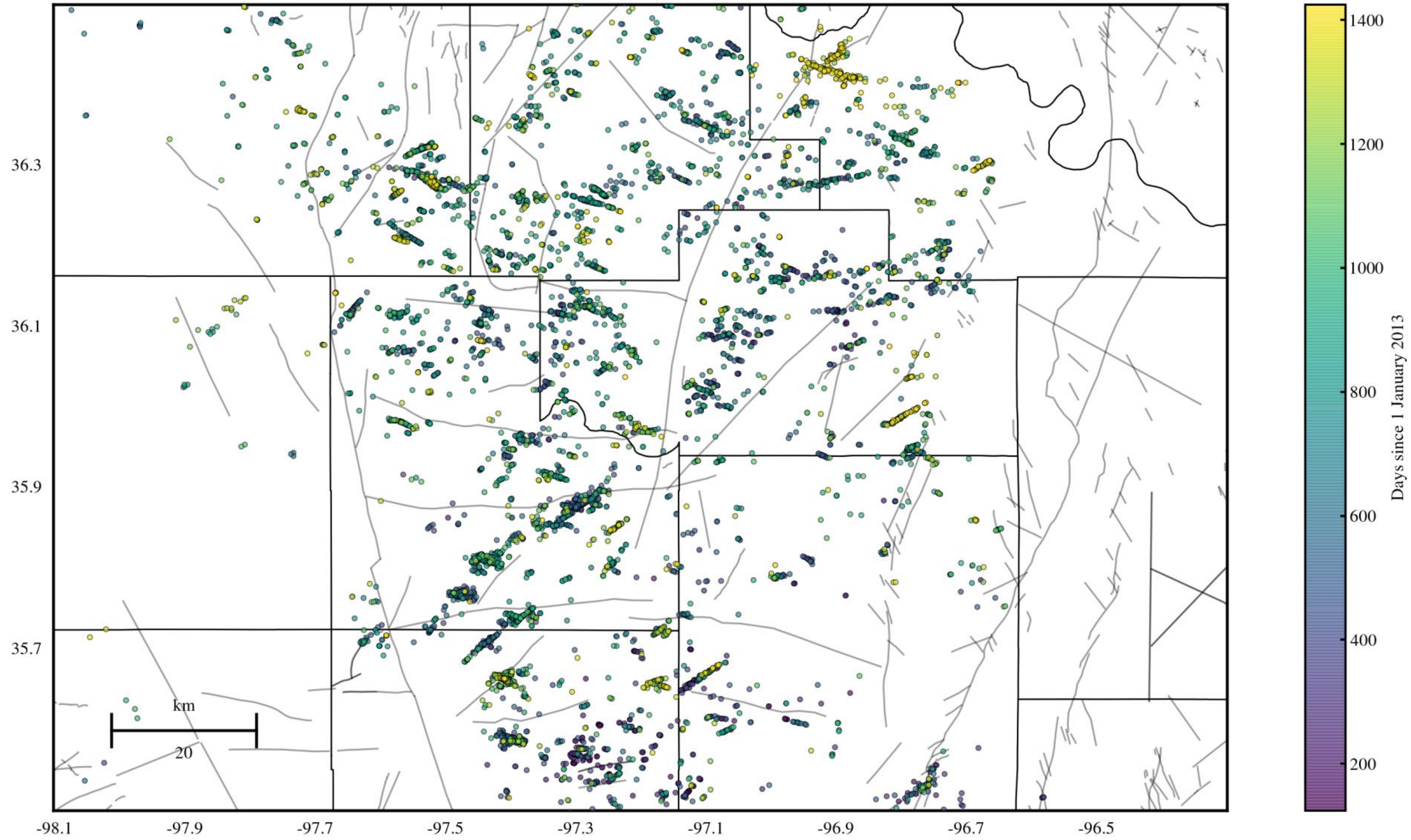


Saltwater disposal well database

- 900 injection wells
  - OCC (735), KCC (120), EPA (45)
- Only wells completed in the Arbuckle aquifer
- Active during 1995 – 2018
- Injection rate data typically at a resolution of 1 month

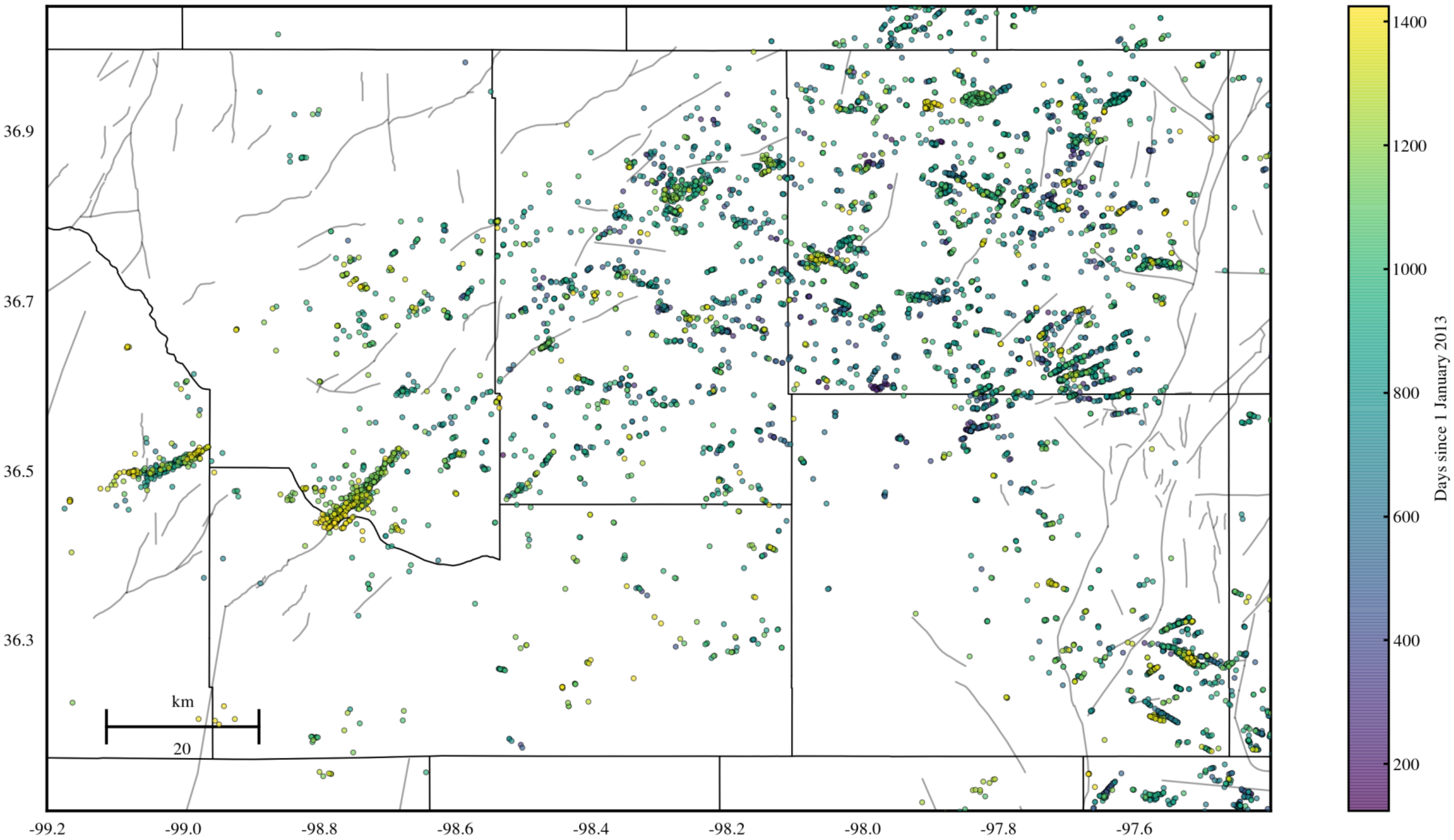


Potentially active faults are ubiquitous



Schoenball and Ellsworth (2017) in *SRL*

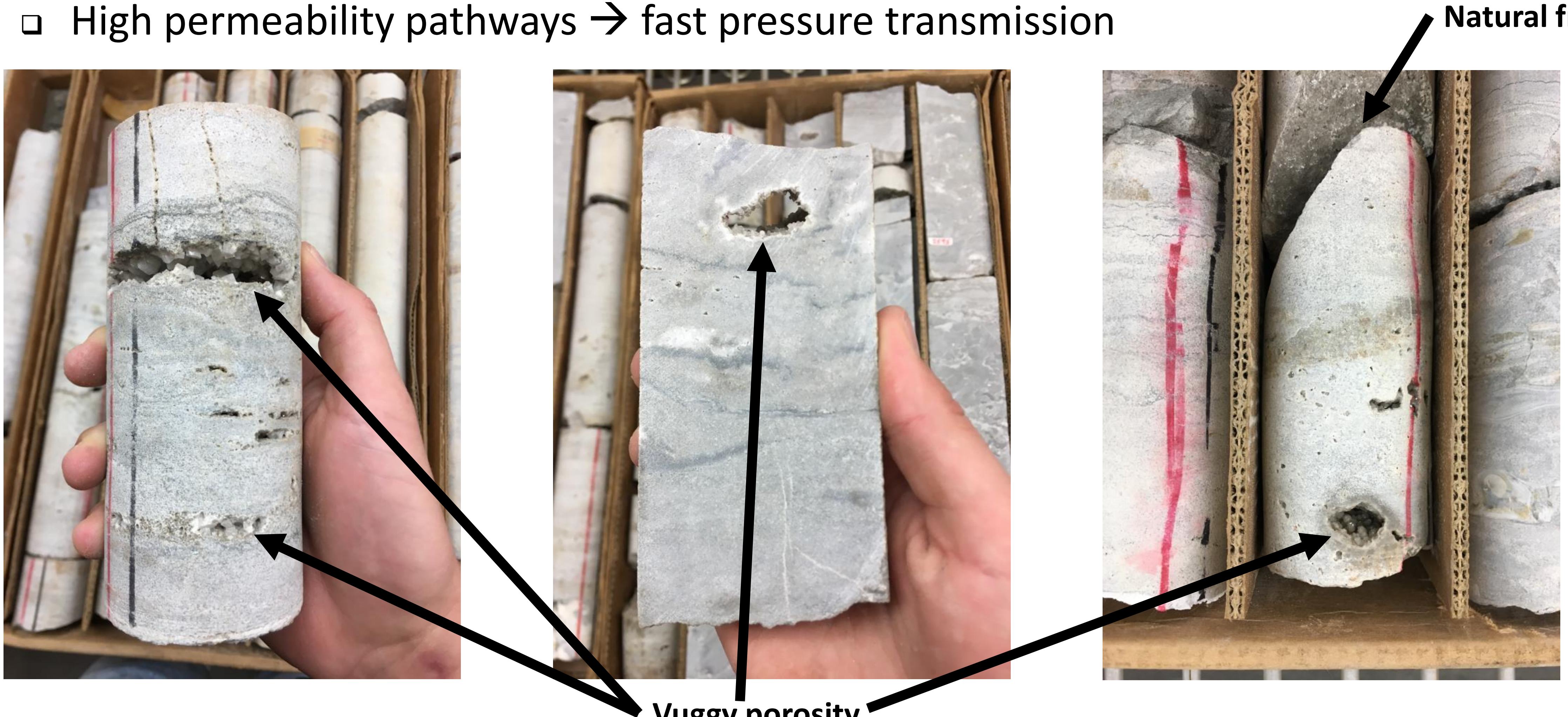
Potentially active faults are ubiquitous



Schoenball and Ellsworth (2017) in *SRL*

Pressure transients in the Arbuckle

- High permeability pathways → fast pressure transmission



Natural fracture

Vuggy porosity

SHADS core from a well near Tulsa (OGS Core Facility)

Pressure transients in basement rock

- Densely spaced vertical fractures and faults → pressure transmission to seismogenic depths occurs quickly

Quarry in basement rock that outcrops in southern Oklahoma

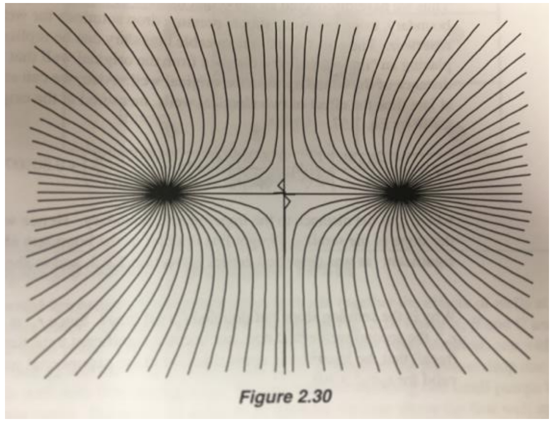
Near-vertical fracture in basement section of SHADS core

Fluid pressure model

- We developed a reservoir model to capture first-order effects
  - Pressure changes are dominated by compressibility effects
  - Conservative end-member (i.e., likely overestimates pressure changes slightly)

$$\dot{p} = \frac{\overset{\text{Injection rate}}{q}}{\underset{\text{Bulk volume}}{V}\,\underset{\text{Porosity}}{\phi}\,\underset{\text{Reservoir compressibility}}{\beta}} \longleftarrow \text{Fluid pressurization rate}$$

- Three reasons why the approximations in this model are valid
  1. Wilzetta/Nemaha faults act as no-flow boundaries
  2. Injection is distributed over a broad extent
     - ~300 km wide injection zone
  3. Dense well spacing on the order of 2 to 5 km
     - Imagine 'five-spot' pattern of injector wells



Horne (1995)

Earthquake nucleation model

- ❑ How do faults respond to Arbuckle pressurization?

- ❑ Rate and state friction
  - ❖ Dieterich (1994) in *JGR*
  - ❖ Segall and Lu (2015) in *JGR*
  - ❖ Barbour et al. (2017) in *SRL*

- ❑ Assumptions
  1. A set of potentially active faults
  2. Basement faults are in direct communication with the Arbuckle
  3. Arbuckle fluid pressure is main driver

Stressing rate on faults

$$\frac{dR}{dt} = \frac{R}{t_{c0}}\left(\frac{\dot{s}}{\dot{s}_0} - R\right)$$

Seismicity rate evolution

Tectonic “background” stressing rate

$$\dot{s} = \dot{\tau} - f\left[\dot{\sigma} - \dot{p}\right]$$

Coulomb stressing rate

$$\dot{s} \approx \dot{p} = \frac{q}{V\phi\beta}$$

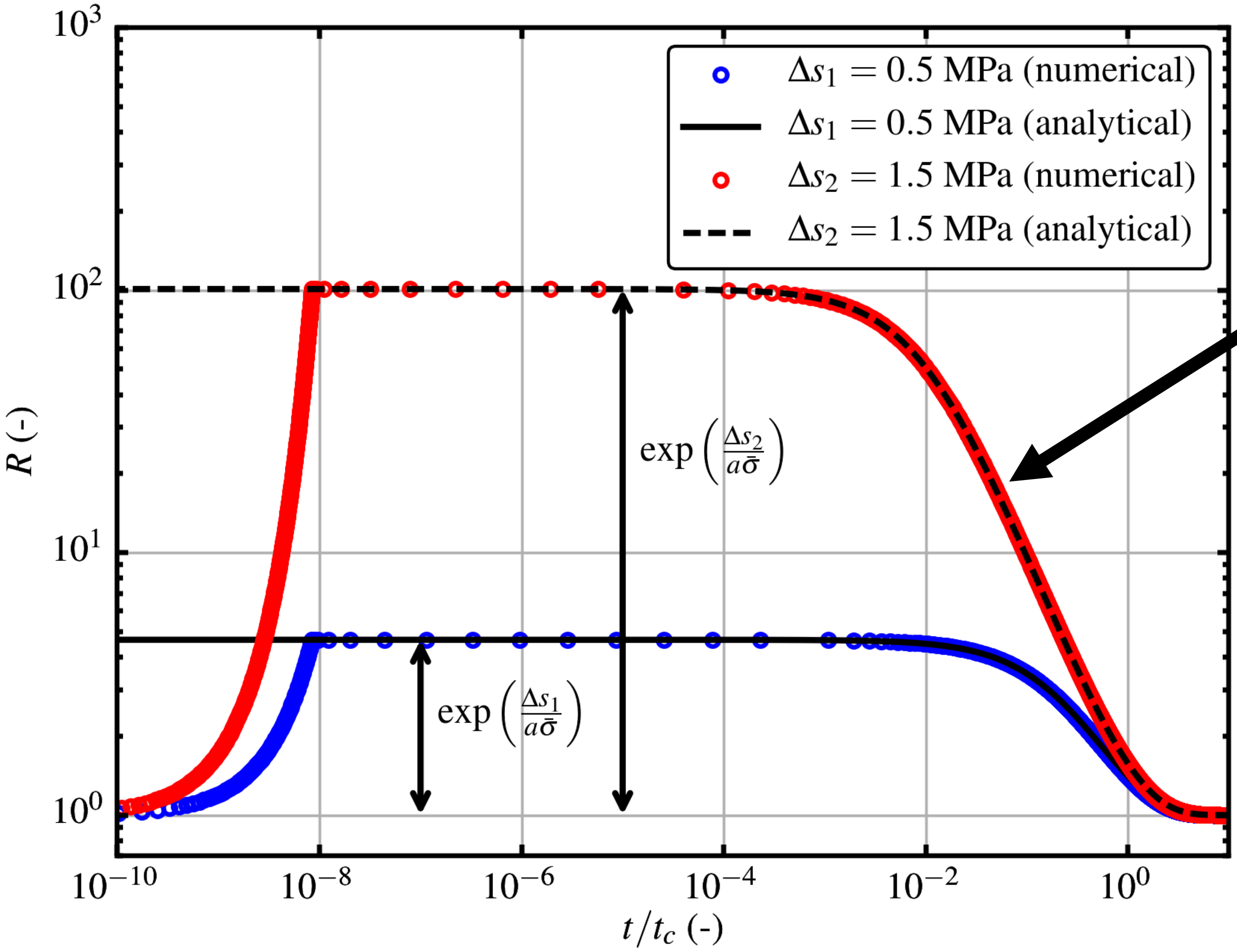
Stressing rate on faults is dominated by pressure changes

$$t_c = a\sigma/\dot{s}$$

Characteristic timescale for seismicity rate transients

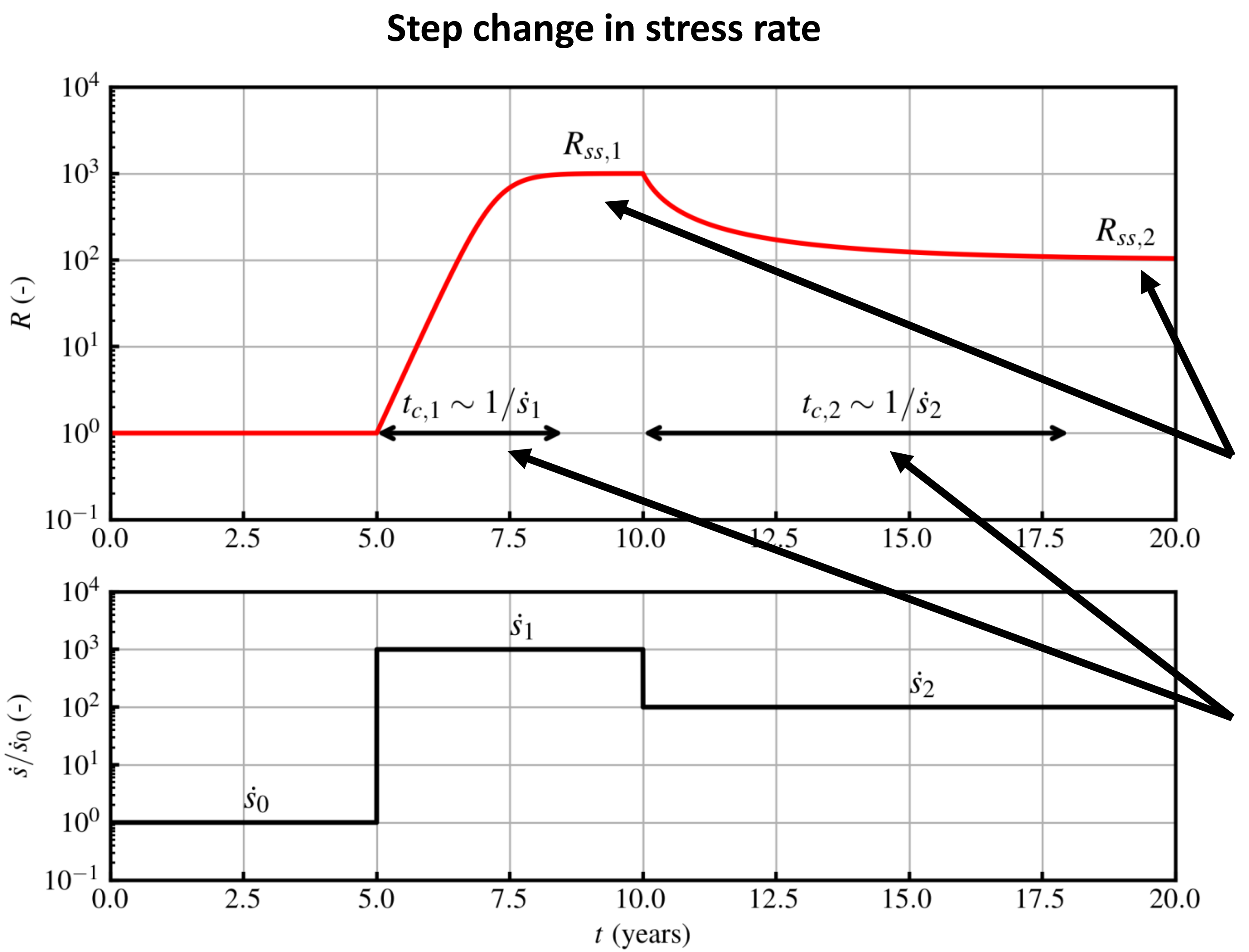
Nucleation model: response to stress changes

Step change in Coulomb stress



t^{-1} Omori-like decay

Nucleation model: response to stress changes



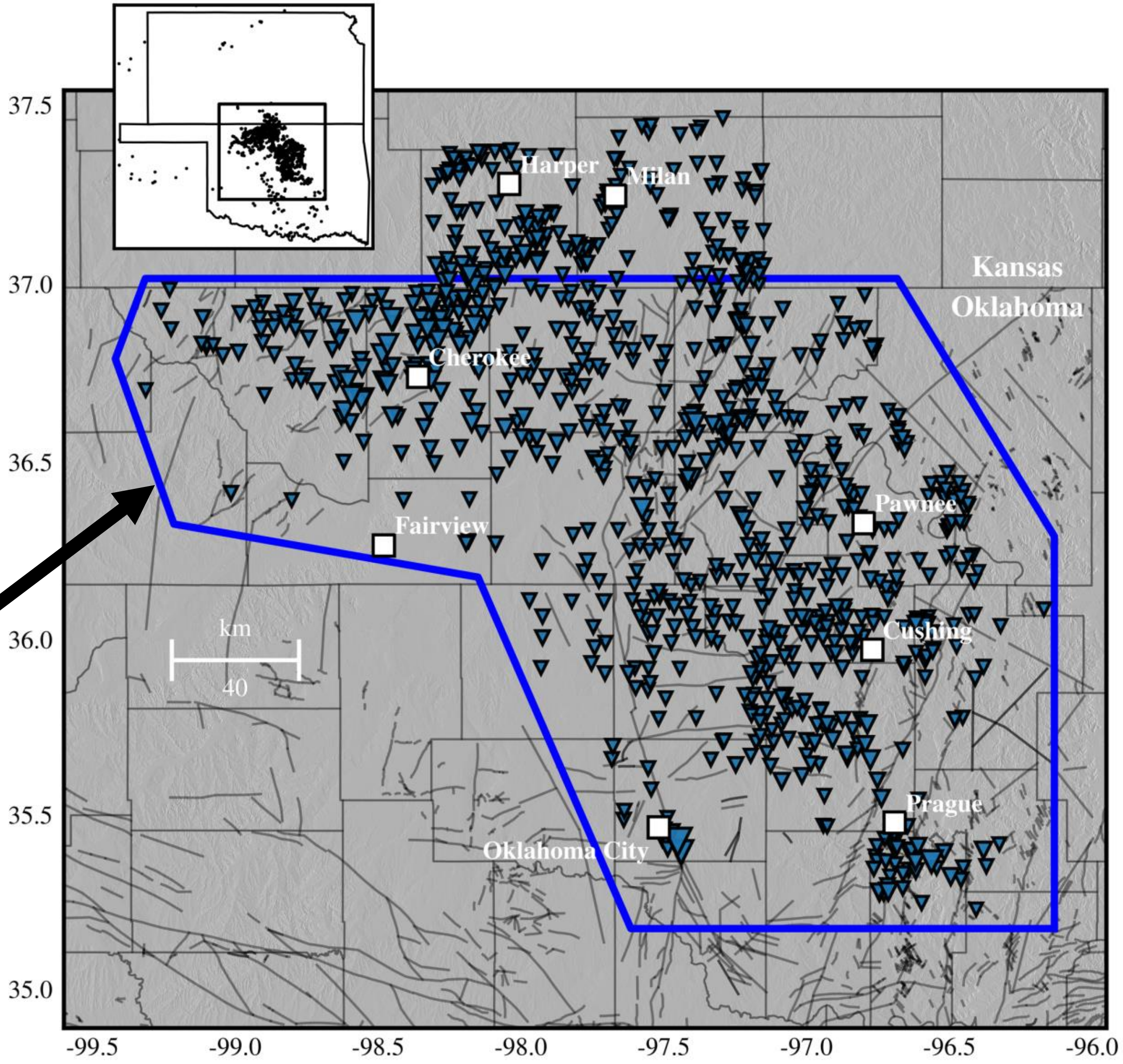
Step change in stress rate

System seeks a “steady-state” seismicity rate proportional to stressing rate

Seismicity rate changes occur more quickly at higher stressing rates

Statewide seismicity forecast

1. Combine injection rates for all wells in area to be analyzed
2. Estimate reservoir volume (area x thickness) and porosity
3. Calculated pressurization rate
    - ❖ Represents ‘average’ pressure

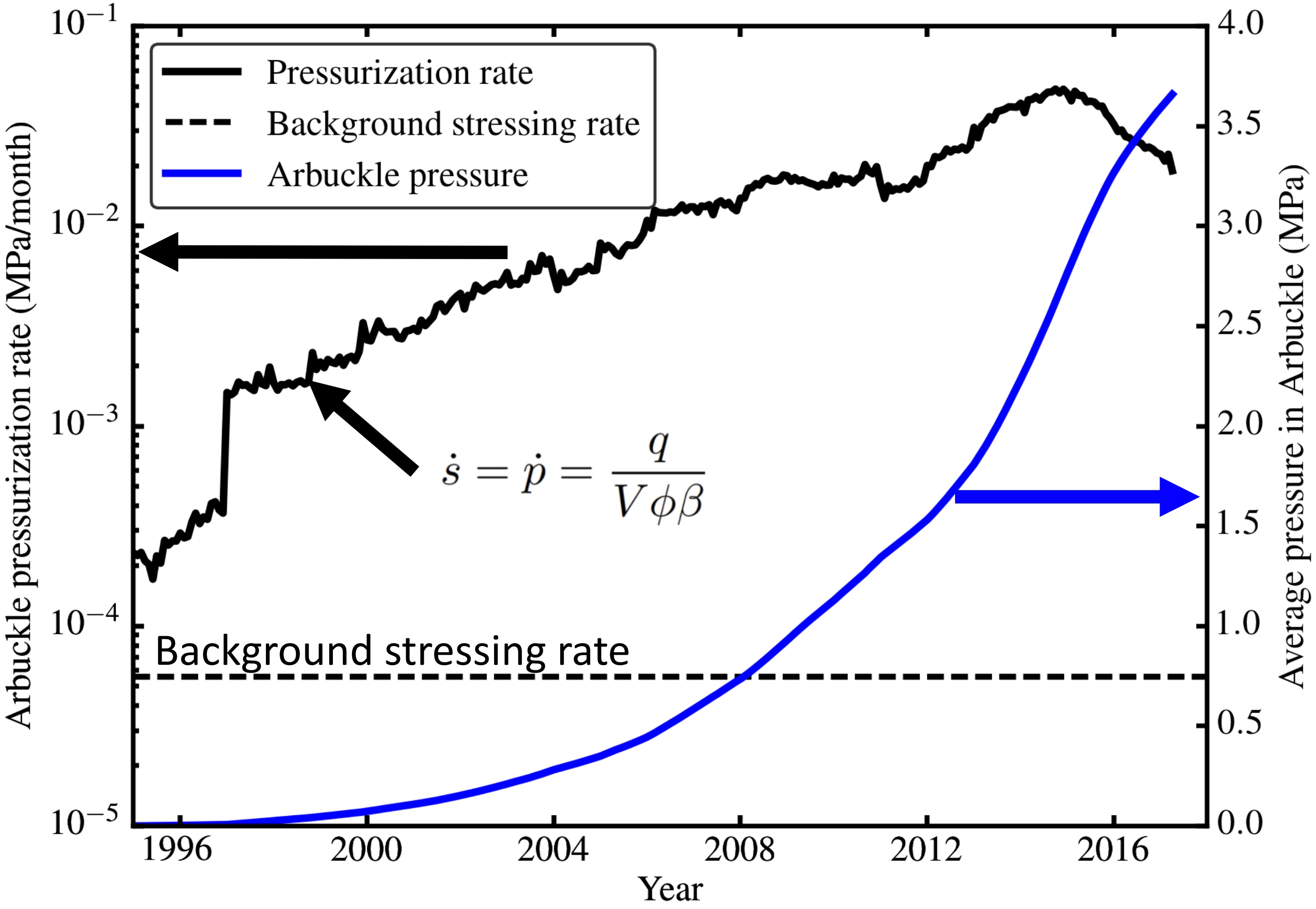


Oklahoma “Area of Interest”

Combined total of 780 disposal wells

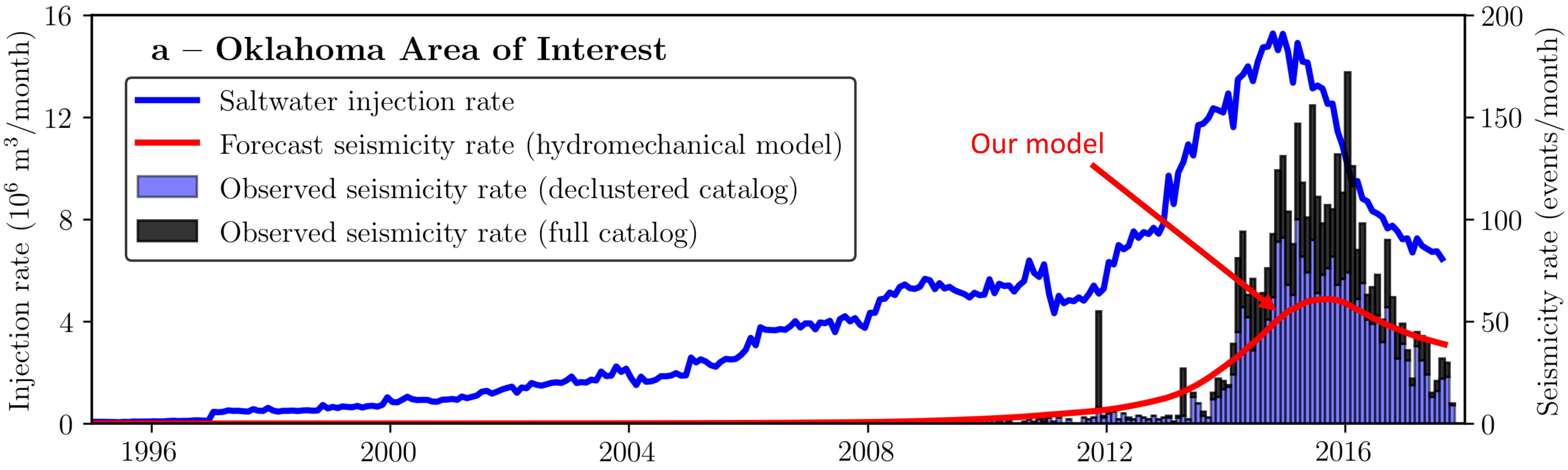
Stressing rate and pressure change

1. Combine injection rates for all wells in area to be analyzed
2. Estimate reservoir volume (area x thickness) and porosity
3. Calculated pressurization rate
   - ❖ Represents 'average' pressure



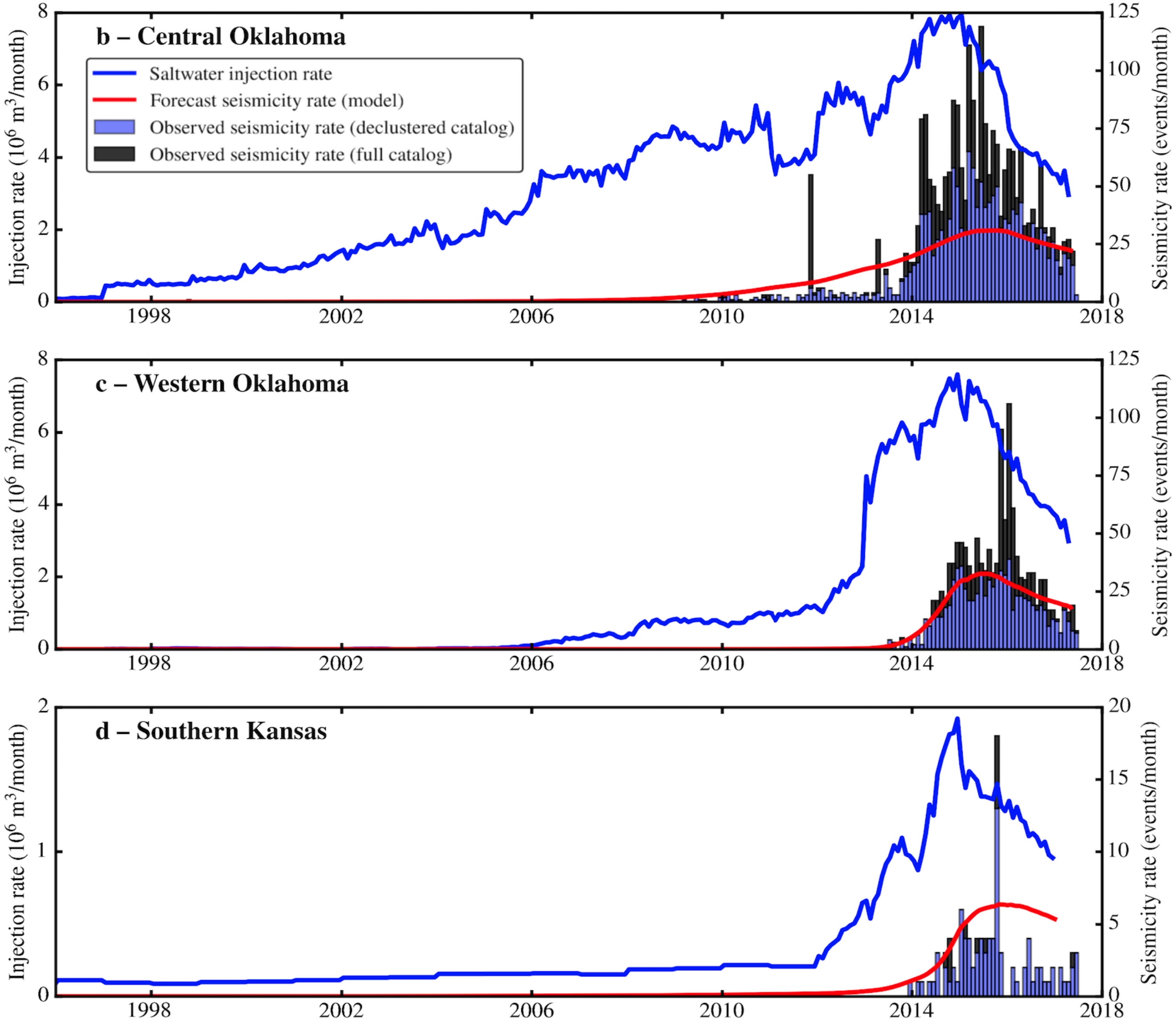
Statewide seismicity forecast

$$\frac{dR}{dt} = \frac{R}{t_{c0}}\left(\frac{\dot{s}}{\dot{s}_0} - R\right) \longrightarrow R(t)$$

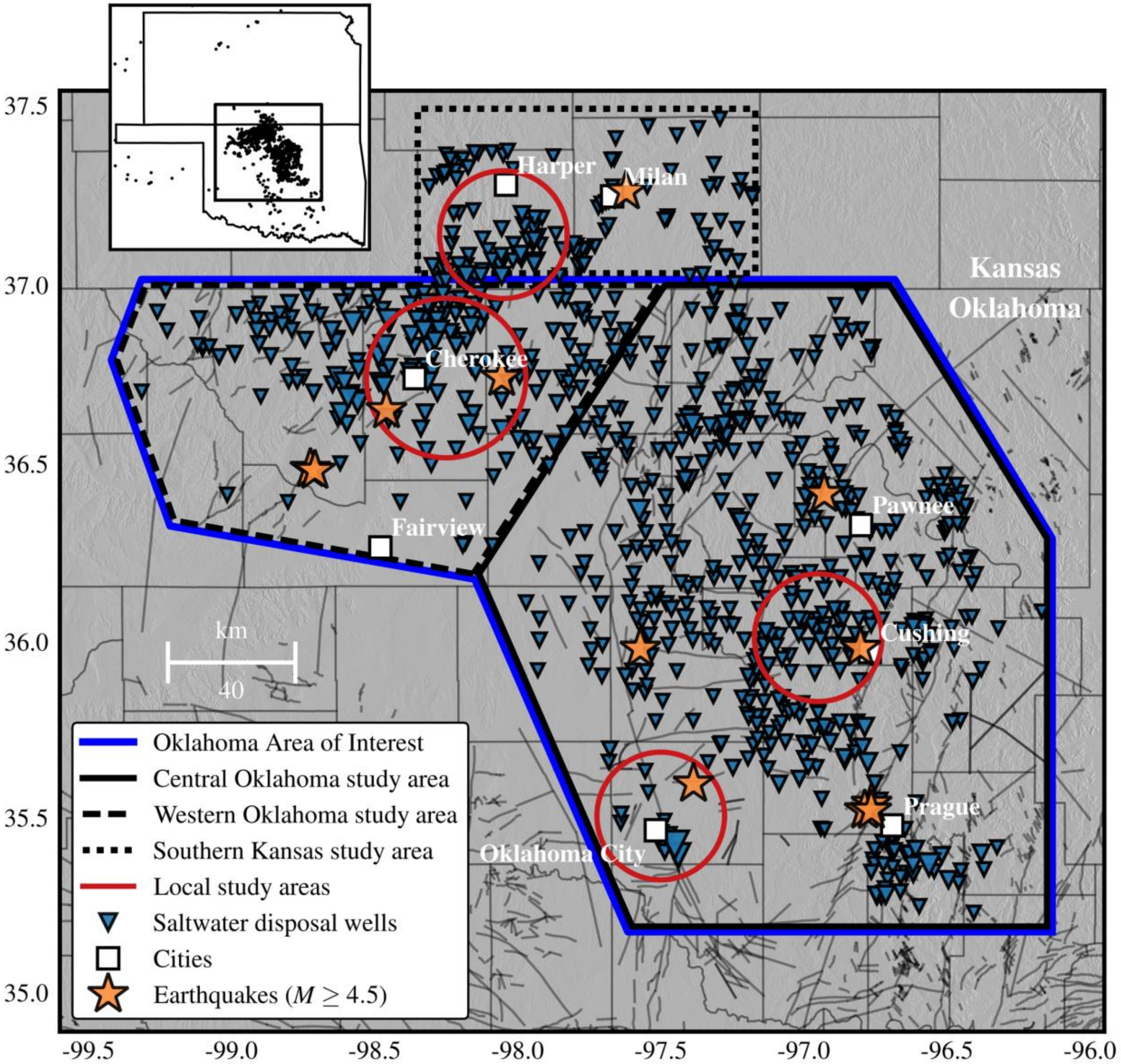


- Our model captures the onset, peak, and falling rates of seismicity
- No ‘calibration’ against earthquake data required
- Based on known Arbuckle reservoir properties and injection data

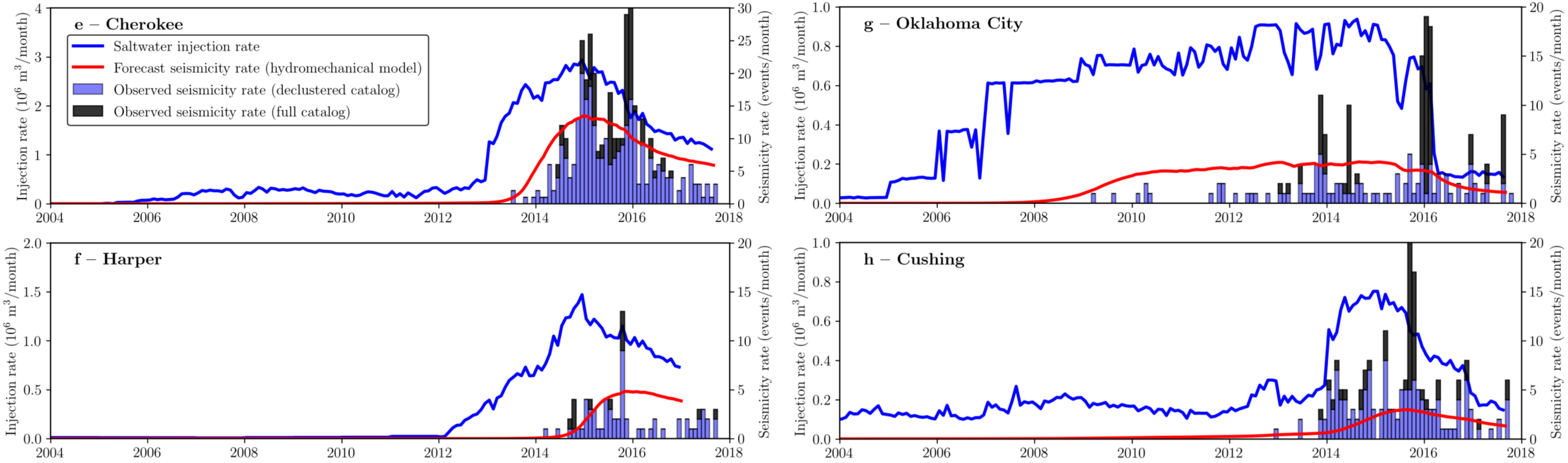
Regional-scale seismicity forecasts



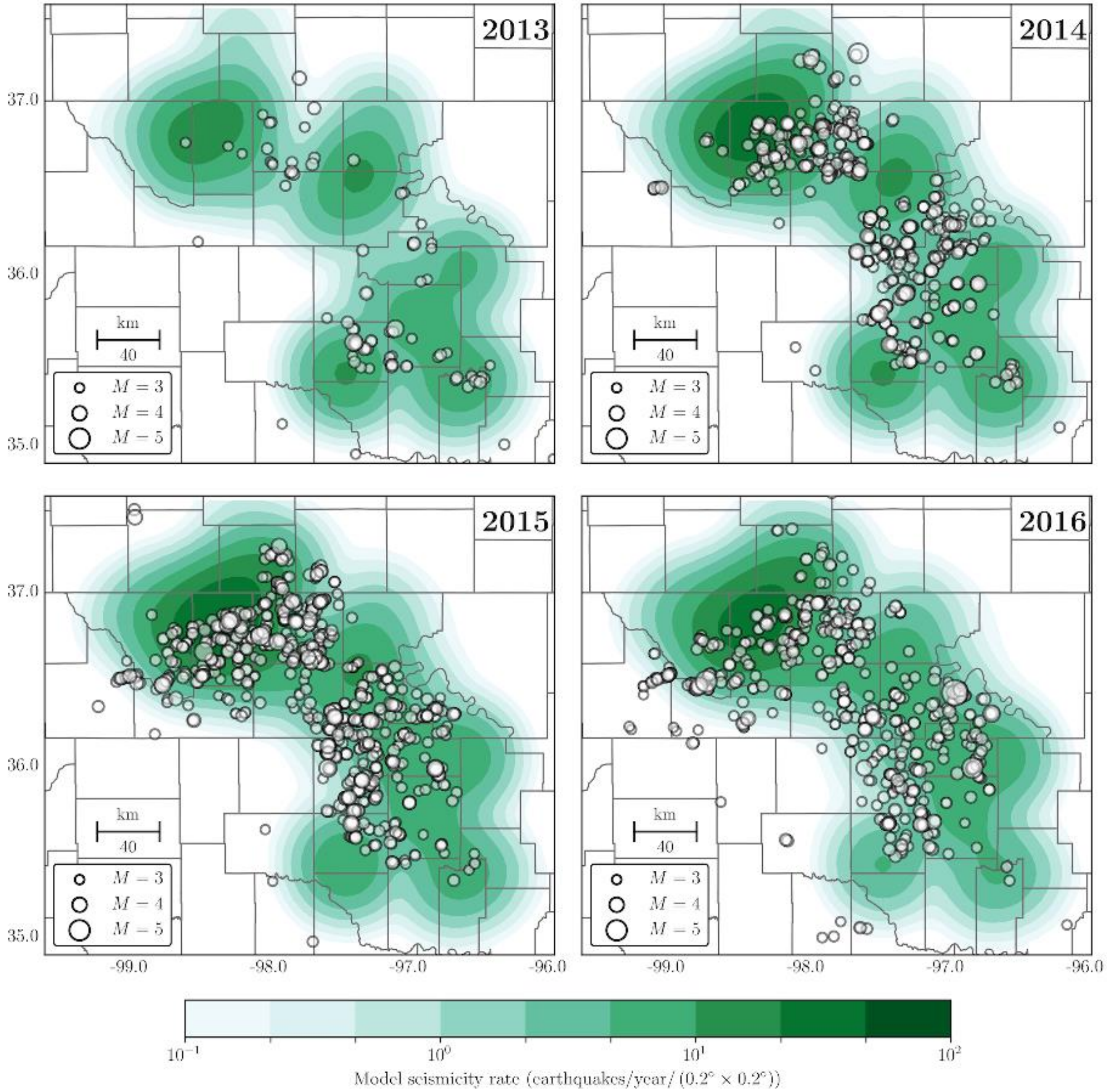
Local-scale seismicity forecasts



Local-scale seismicity forecasts

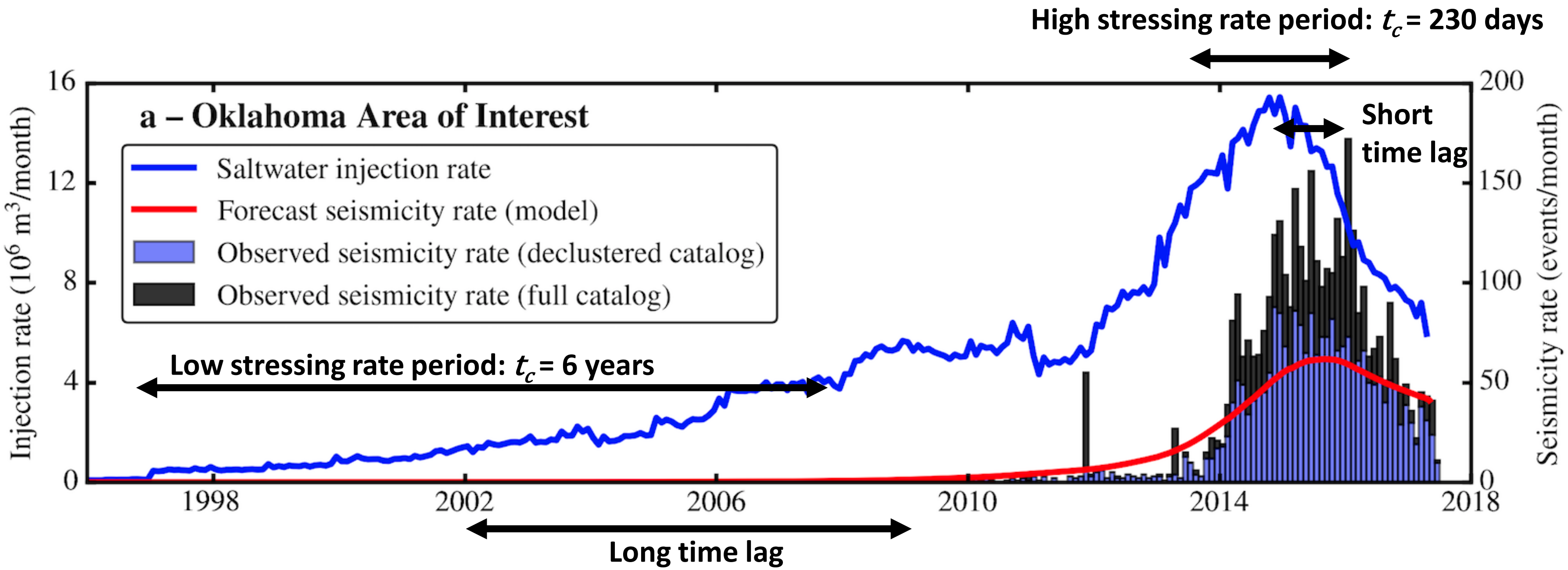


Seismicity forecasts for hazard analysis



Implications for managing hazard

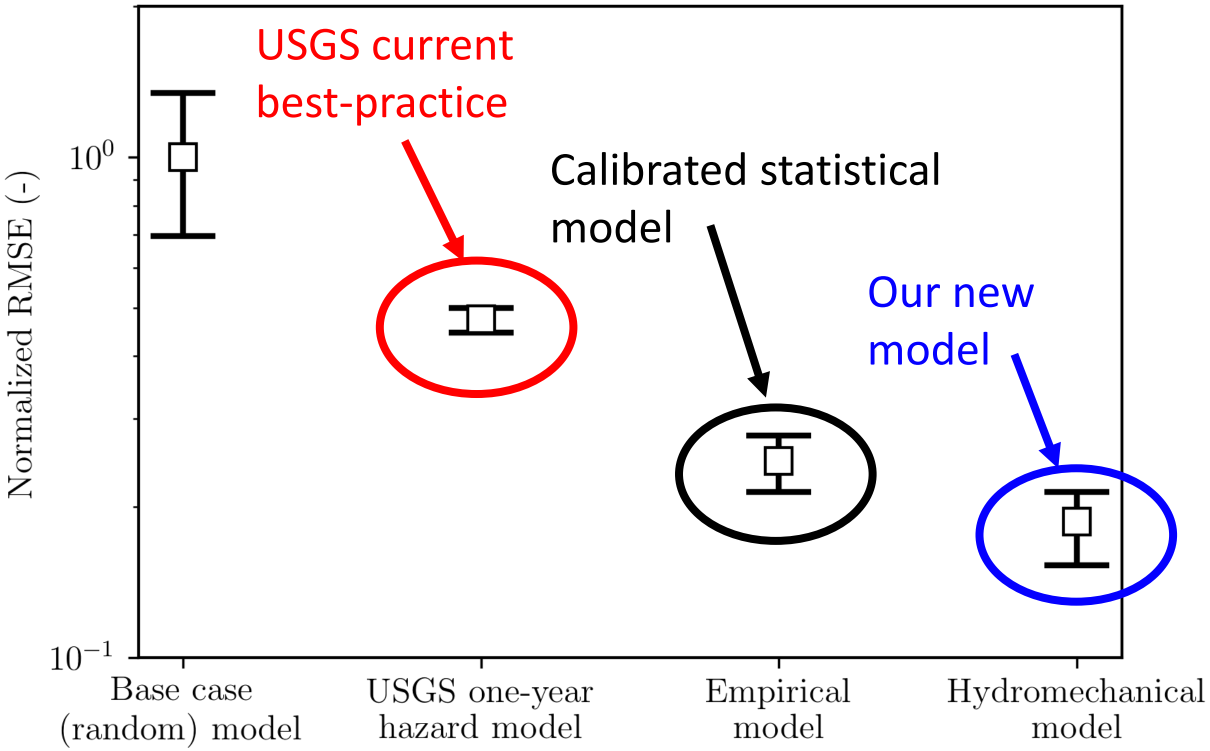
- ❑ Seismicity rate is governed by stressing rate: $\dot{s} = \dot{p} = \frac{q}{V\phi\beta}$
- ❑ System tends toward a 'steady-state' seismicity rate if injection is constant
  - ❖ Injection can be carried out such that the seismicity rate remains below tolerable threshold
- ❑ Time lag scales inversely with stressing rate: $t_c = a\sigma/\dot{s}$



Thank you

Forecast accuracy

- ❑ Quantified accuracy with a likelihood testing approach and with RMSE analysis
  1. Simple base-case model
     - Seismicity rate drawn randomly from set of observed rates
  2. USGS one-year hazard model
     - Use last year's seismicity rate to predict upcoming year
  3. Calibrated statistical model
     - Seismicity rate based on injection data (with time lag and injection threshold)
     - Langenbruch and Zoback (2016)
  4. Hydromechanical model

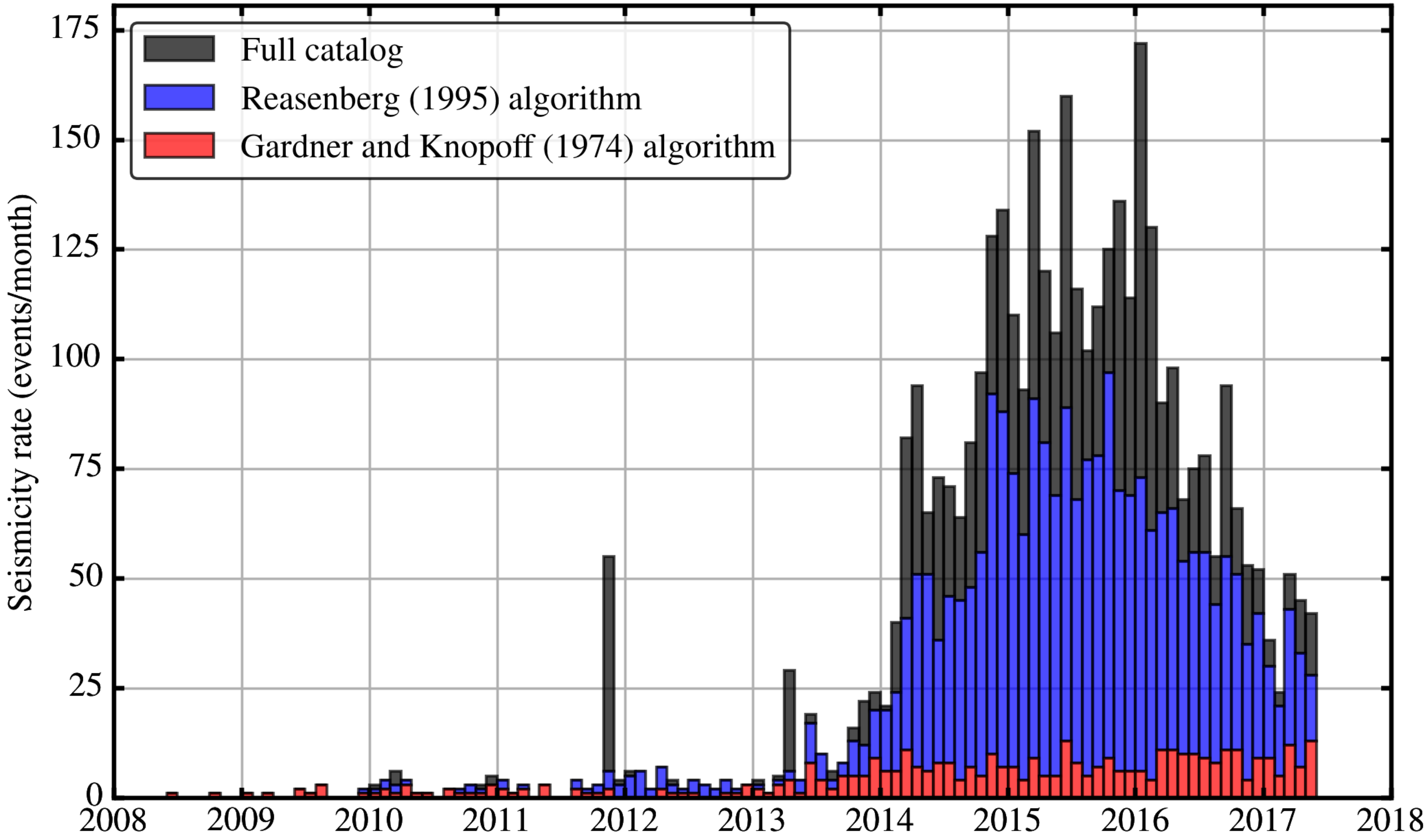


Earthquake catalog

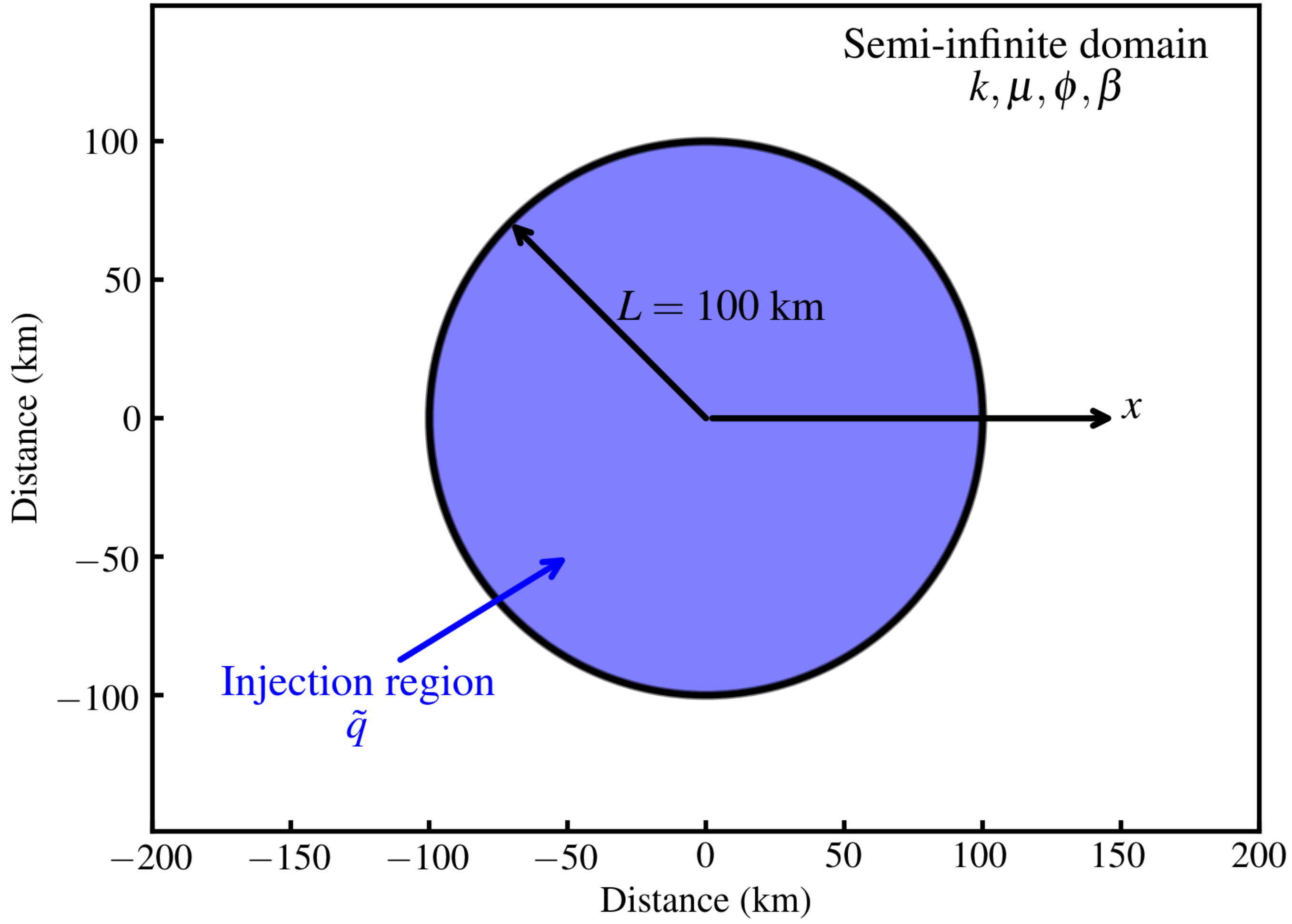
- ComCat earthquake catalog

- Reported magnitudes (local, body wave, surface wave, duration) were converted to a consistent set of moment magnitudes
  - CEUS-SSC conversions
  - $M \geq 3.0$

- We compared our model results against a declustered earthquake catalog
  - Reasenberg (1995) method

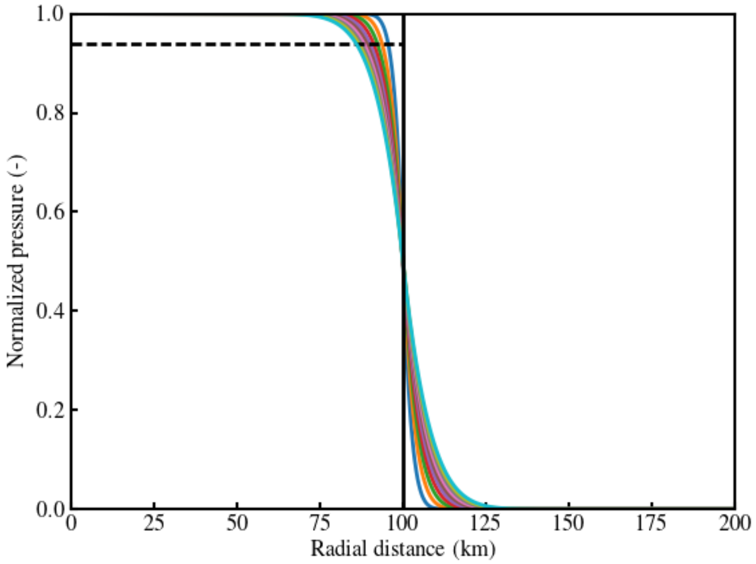


Validation of closed-system assumption

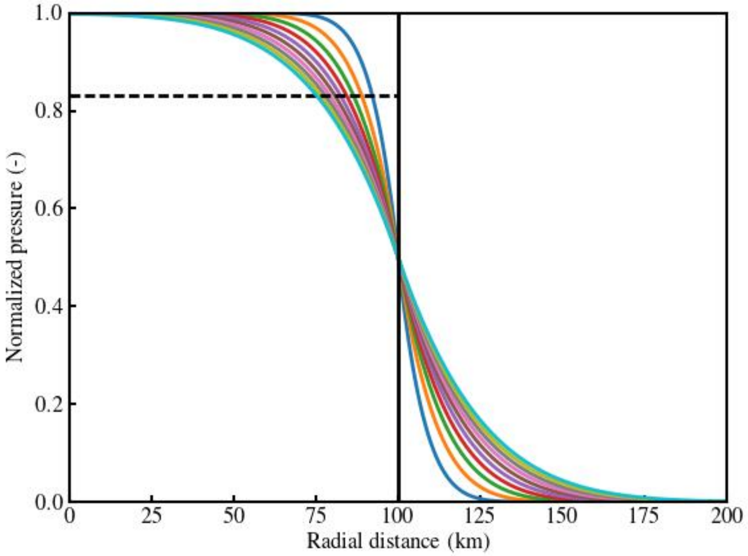


Validation of closed-system assumption

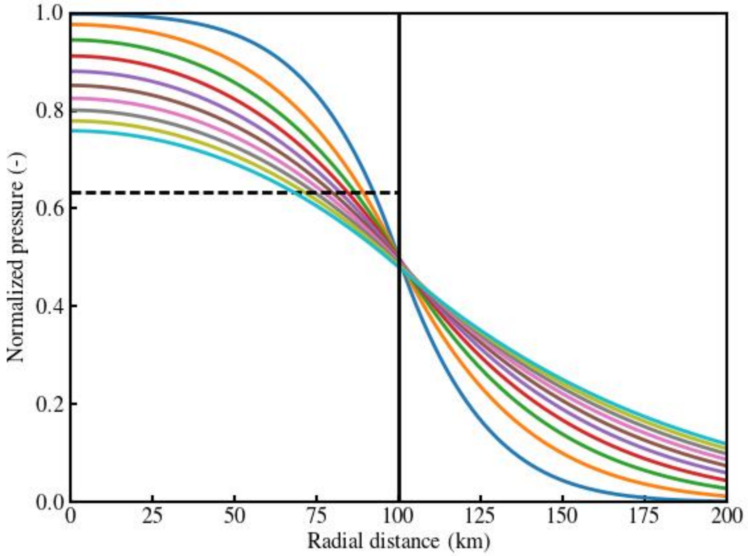
k = 10 md



k = 100 md

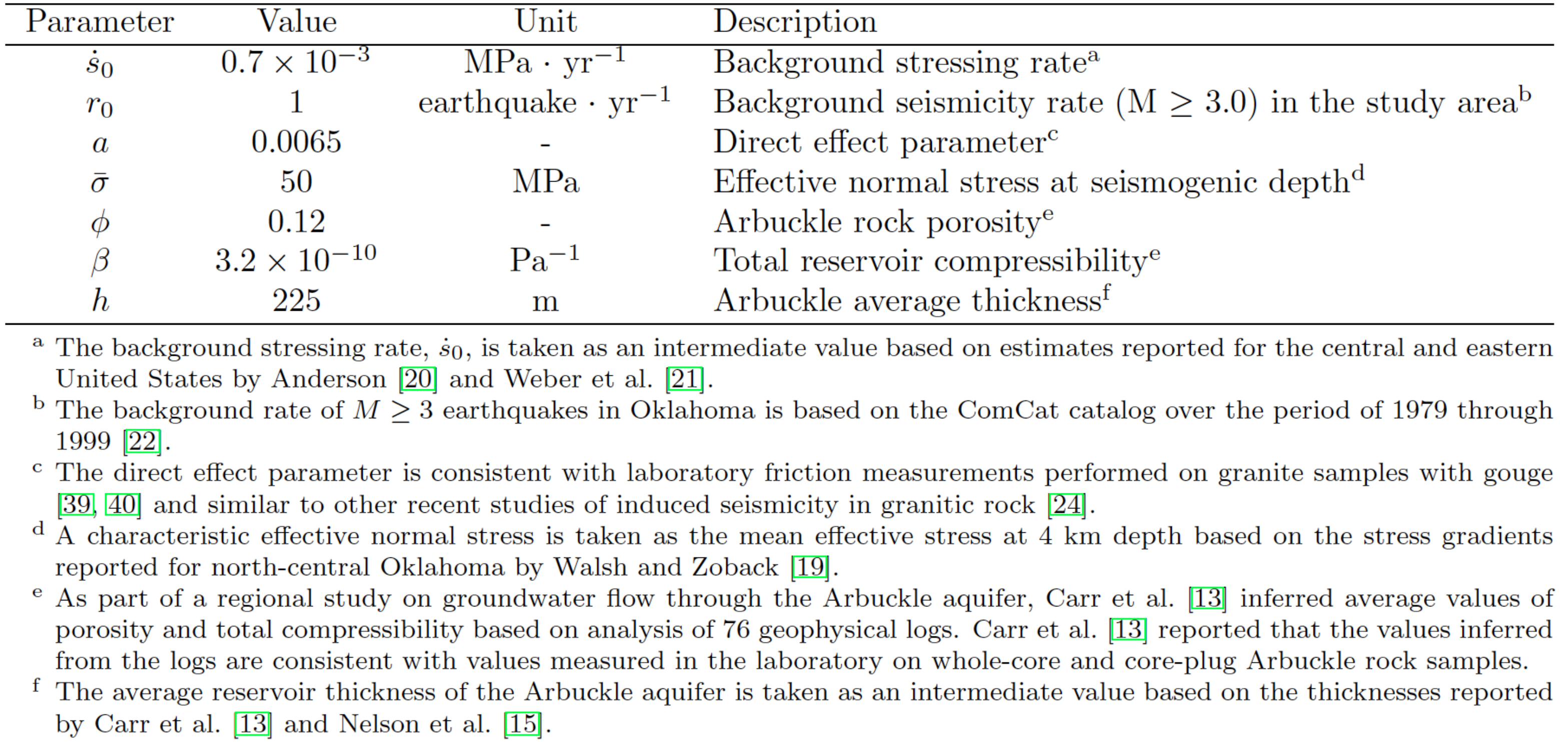


k = 1000 md



Model parameters

- Only a few physical parameters
  - Each can be measured/inferred in the field or lab
- We currently have good estimates
  - Largest uncertainty is in the background stressing rate



Parameter	Value	Unit	Description
$\dot{s}_0$	0.7×10^{-3}	$\mathrm{MPa} \cdot \mathrm{yr}^{-1}$	Background stressing rate[a]
r_0	1	$\mathrm{earthquake} \cdot \mathrm{yr}^{-1}$	Background seismicity rate ($M \geq 3.0$) in the study area[b]
a	0.0065	-	Direct effect parameter[c]
$\bar{\sigma}$	50	MPa	Effective normal stress at seismogenic depth[d]
ϕ	0.12	-	Arbuckle rock porosity[e]
β	3.2×10^{-10}	Pa^{-1}	Total reservoir compressibility[e]
h	225	m	Arbuckle average thickness[f]

[a] The background stressing rate, $\dot{s}_0$, is taken as an intermediate value based on estimates reported for the central and eastern United States by Anderson [20] and Weber et al. [21].

[b] The background rate of $M \geq 3$ earthquakes in Oklahoma is based on the ComCat catalog over the period of 1979 through 1999 [22].

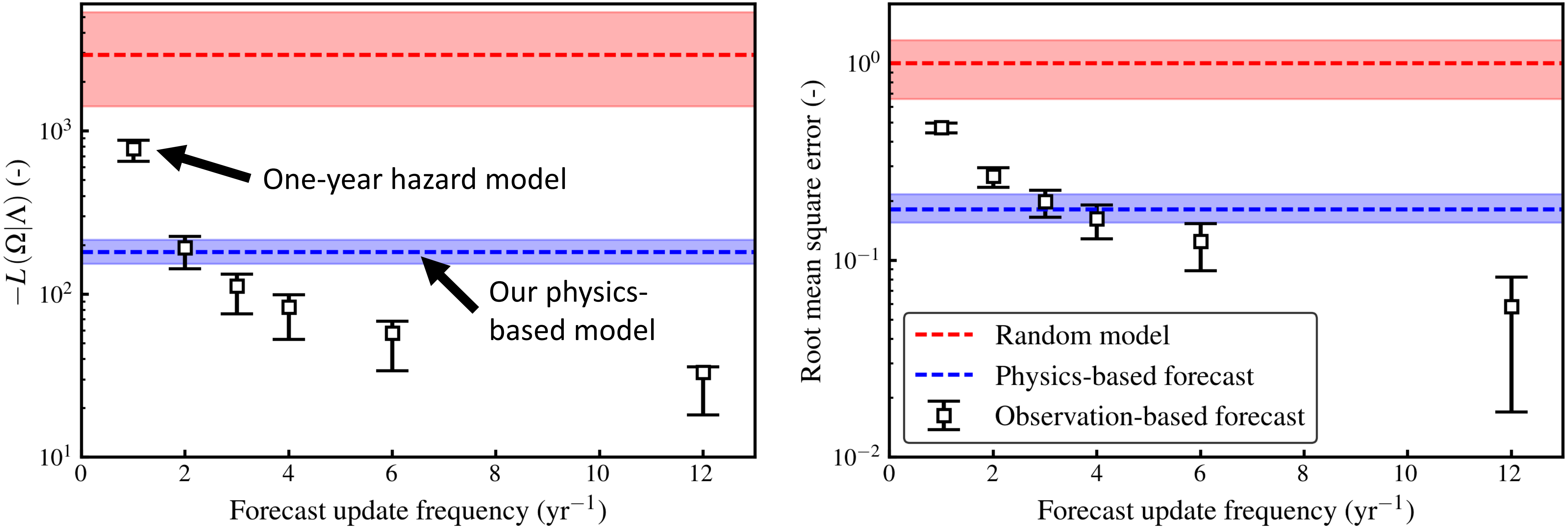
[c] The direct effect parameter is consistent with laboratory friction measurements performed on granite samples with gouge [39, 40] and similar to other recent studies of induced seismicity in granitic rock [24].

[d] A characteristic effective normal stress is taken as the mean effective stress at 4 km depth based on the stress gradients reported for north-central Oklahoma by Walsh and Zoback [19].

[e] As part of a regional study on groundwater flow through the Arbuckle aquifer, Carr et al. [13] inferred average values of porosity and total compressibility based on analysis of 76 geophysical logs. Carr et al. [13] reported that the values inferred from the logs are consistent with values measured in the laboratory on whole-core and core-plug Arbuckle rock samples.

[f] The average reservoir thickness of the Arbuckle aquifer is taken as an intermediate value based on the thicknesses reported by Carr et al. [13] and Nelson et al. [15].

Forecast accuracy



One-year hazard model

Our physics-based model