# Injection-Induced Seismicity Short-Term Hazard Assessment

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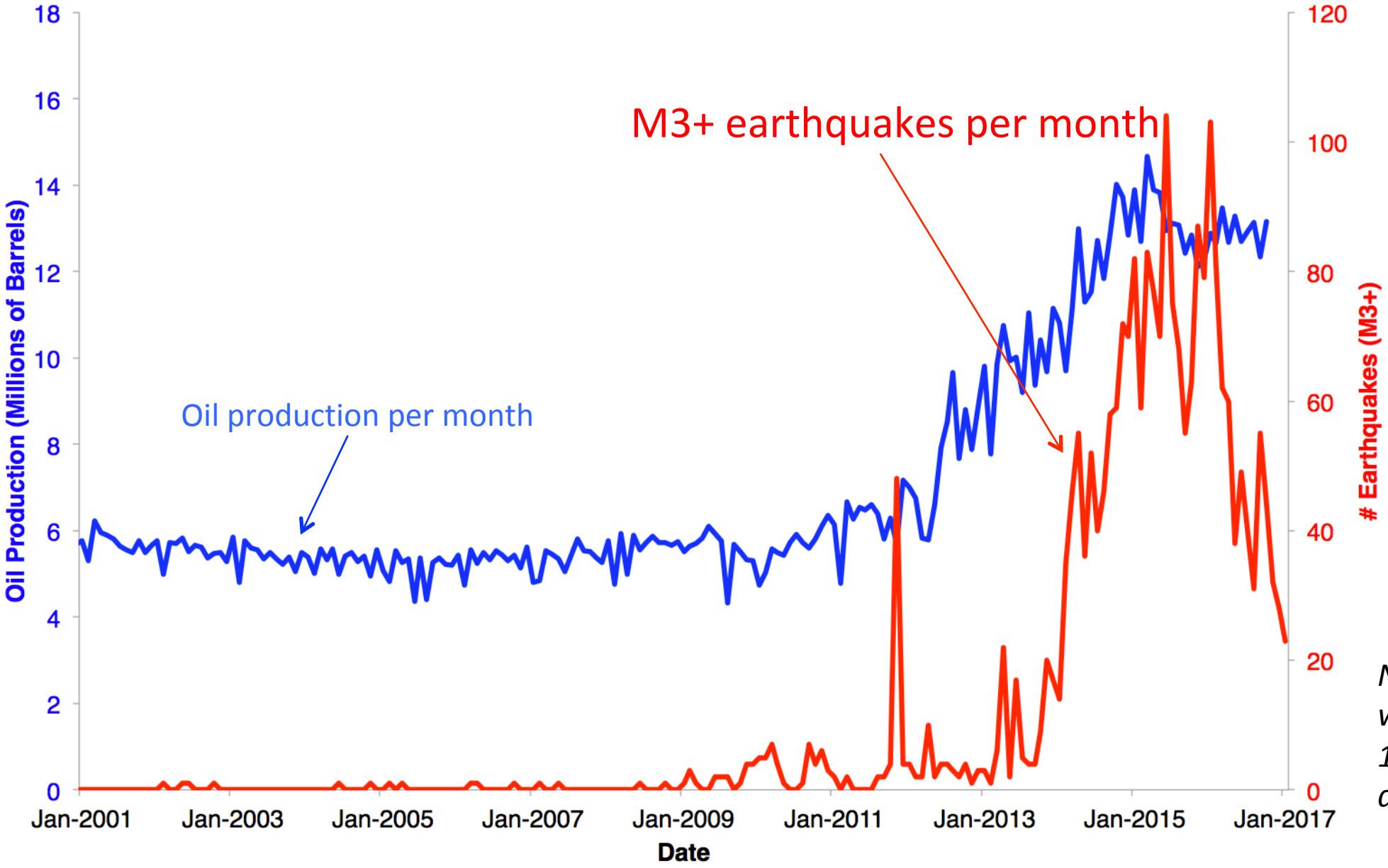
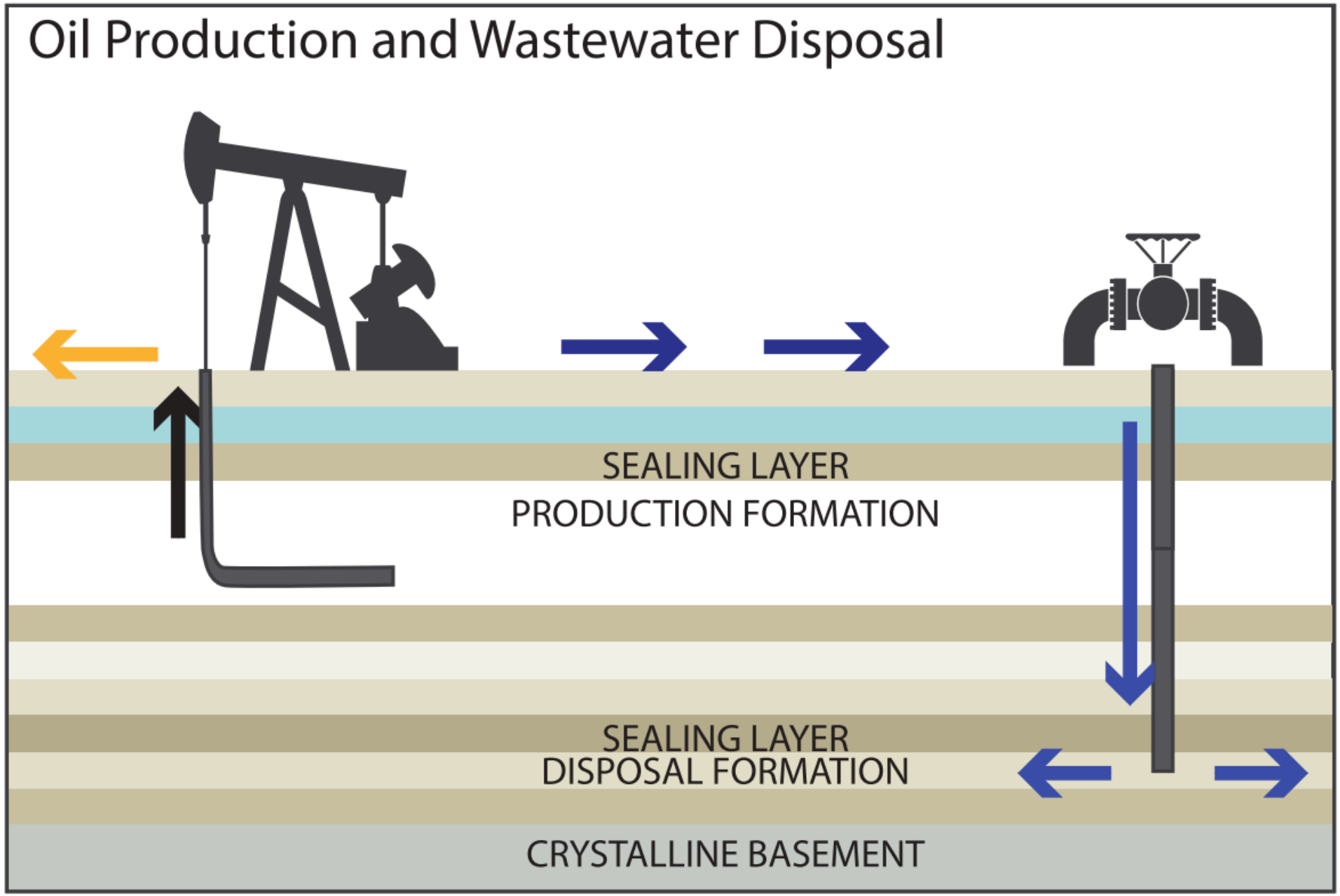
COSG Meeting
14 November 2018

# Tracking the Seismic Crisis in Oklahoma




*Note: Oil production was higher in the 1980s without associated seismicity*




Rubinstein and Mahani (2015)

# USGS Induced Seismicity Project Objectives:

- Understand and mitigate the hazards associated with earthquakes that are induced by human activities.
- Explore the physics of earthquake failure.

**Direct application of science to reduce hazard**

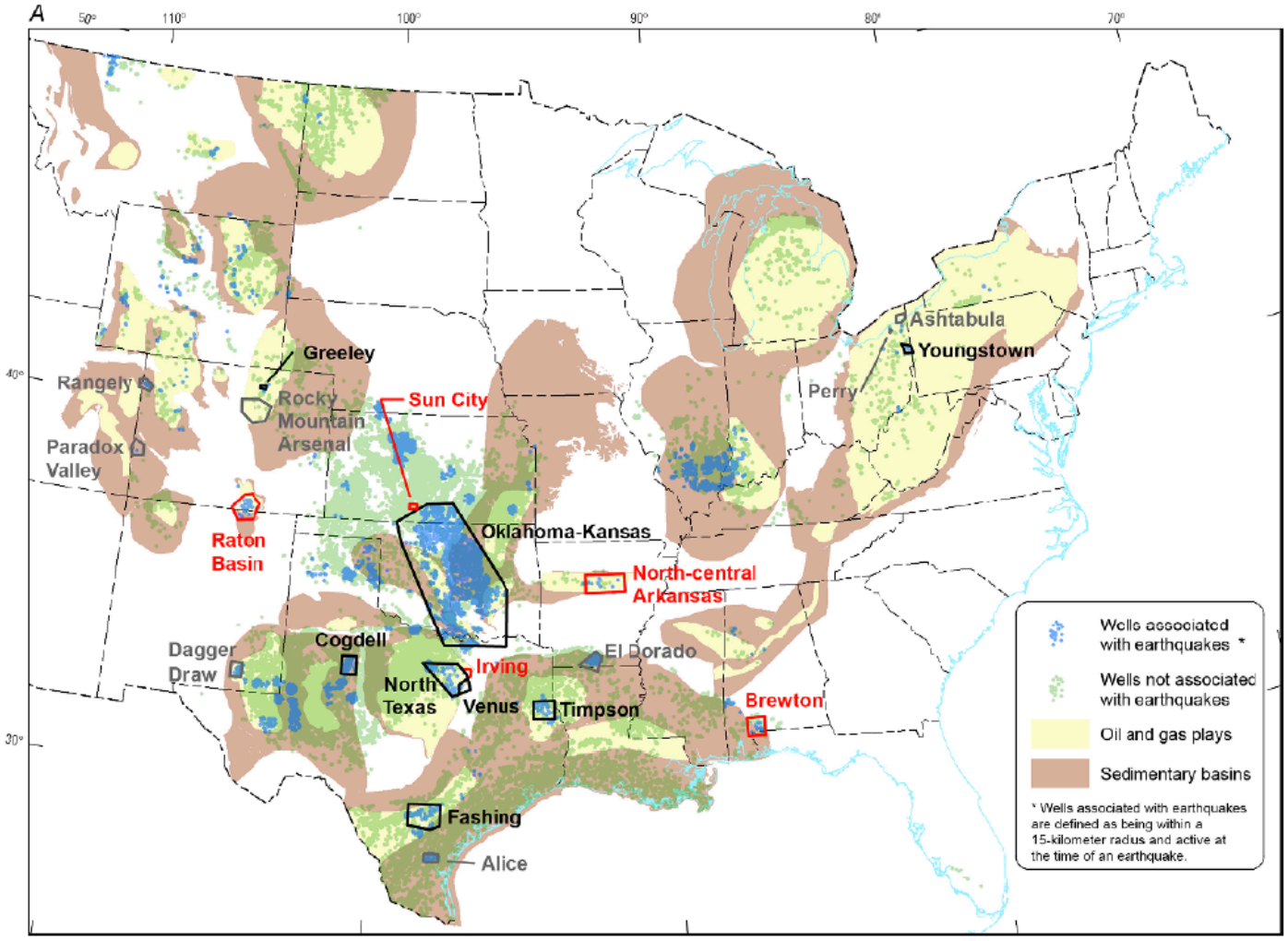
- Identification of risk factors for IS
- Inform regulations
- Short-term hazard forecasts
- Injection protocols
- Risks of sudden shut-in versus flowback

**Basic earthquake science**

- Conditions and stress changes that lead to fault slip
- What causes ruptures to start and stop
- Role of fluids in triggering slip
- Ground motion variability

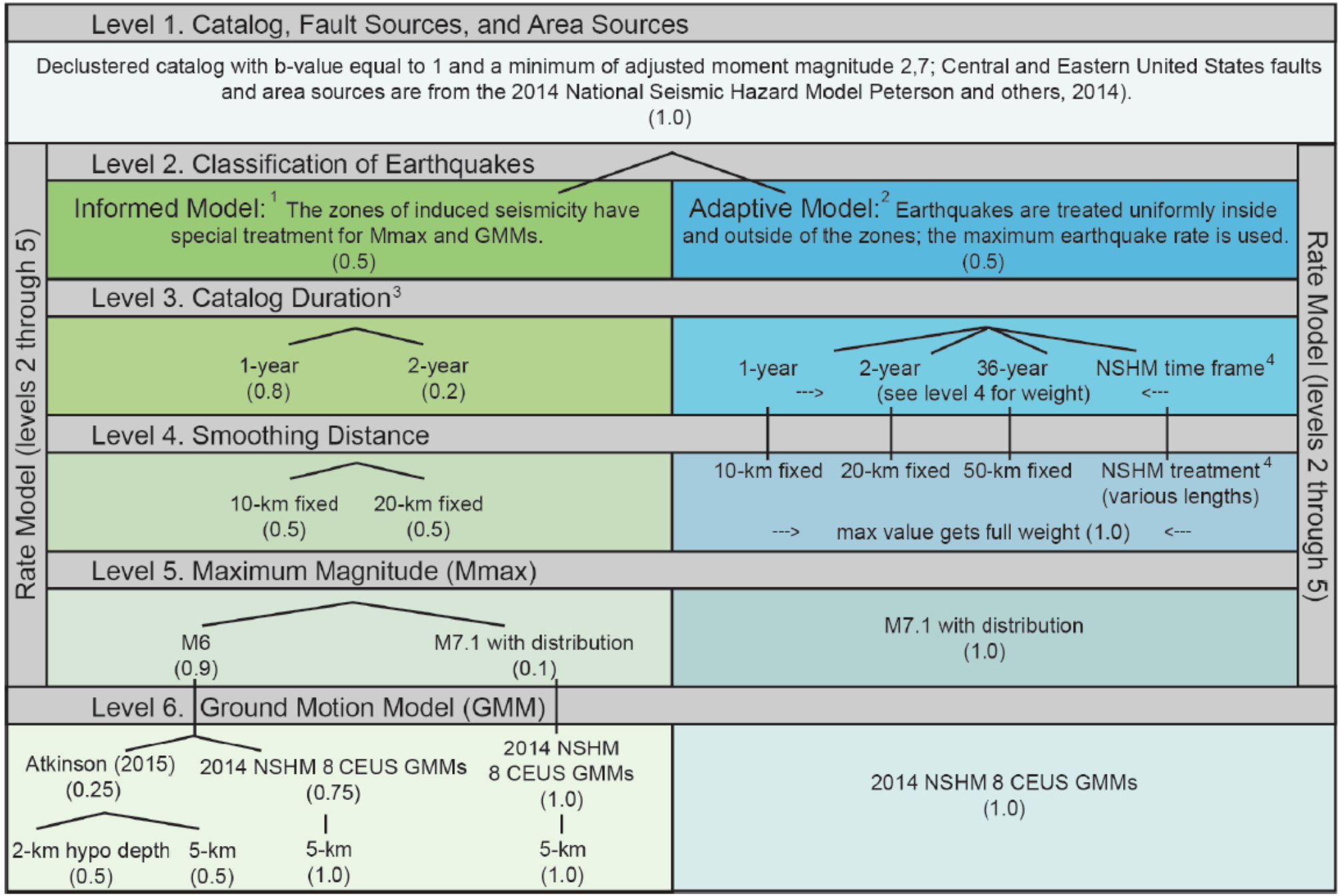
# Short-term (one-year) Hazard Forecasts

- One year forecast for Central and Eastern US (natural + induced)
- Goal: Communicate risks to local populations.
- Based on short term seismicity rates:
  - Past rates of smaller earthquakes
  - Truncated Gutenberg-Richter magnitude-frequency from $M_{min}$ to $M_{max}$
- Forecasts made for 2016, 2017, and 2018.



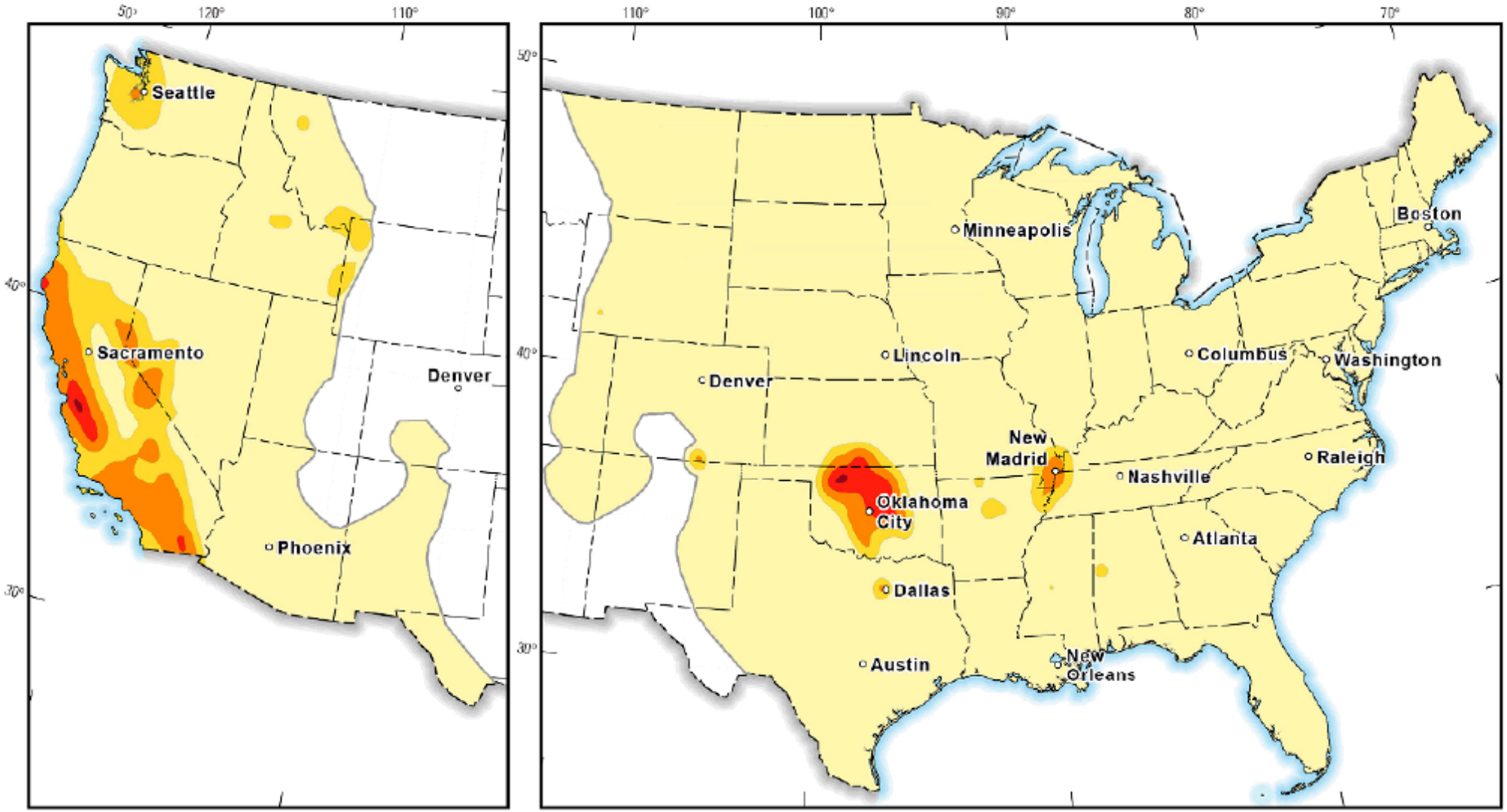

Petersen et al. (2016)

# Sources Within Zones of Induced Seismicity

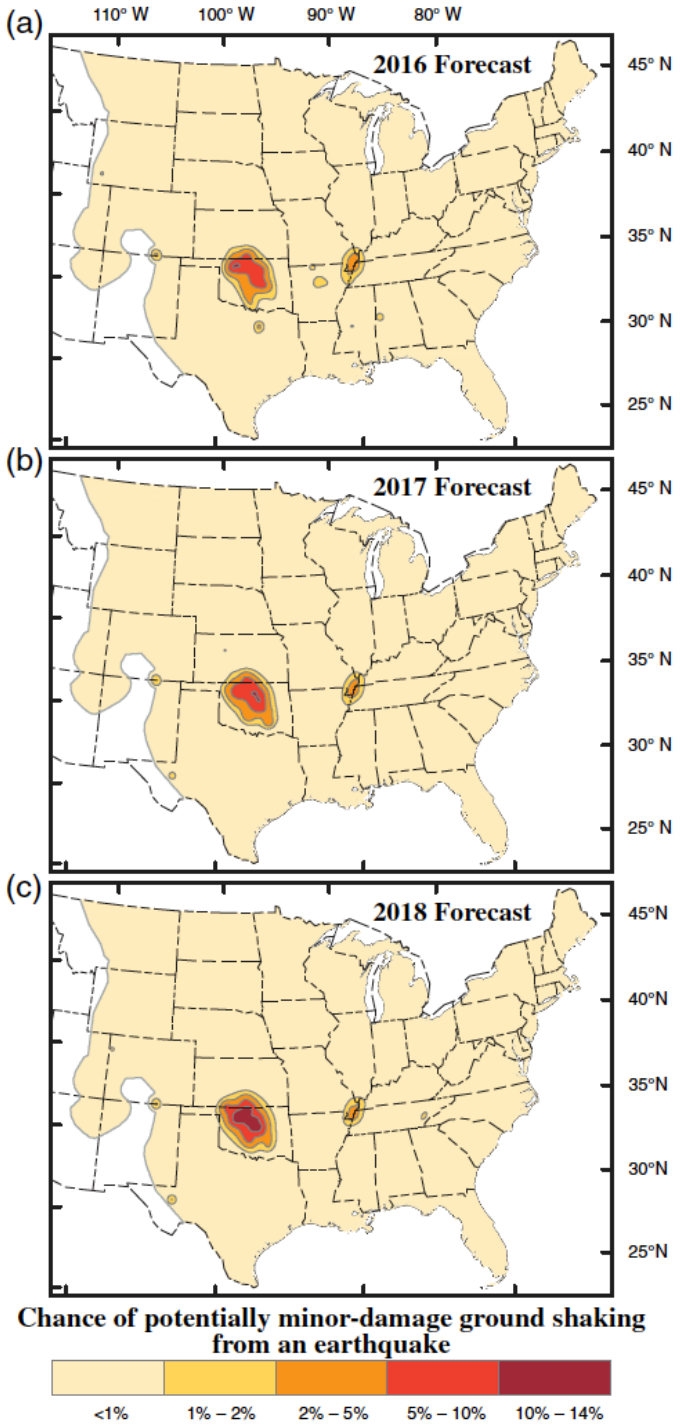



Petersen et al. (2016)

# 2016

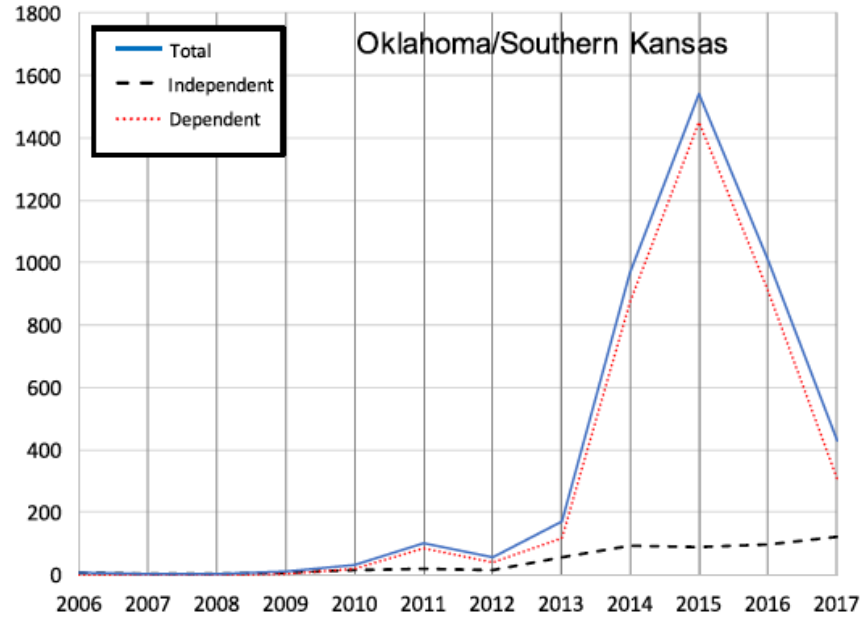



Petersen et al. (2016)




Overall success of 2016 and 2017 maps in forecasting areas with moderate earthquakes

2018 forecast shows greater potential for minor-damage ground shaking than in previous years despite declining seismicity rates
→ consequence of declustering



# Known Issues with One-Year Forecasts:

- Appropriate GR relation: What is b-value? What is $M_{max}$? What (if any) declustering is appropriate?
- Are ground motions values for induced earthquakes different than tectonic earthquakes?
- How can we use physics-based approaches that account for injection?
- Are the products effective for end-users?

**2019 One-Year Hazard Forecasts will not be released**

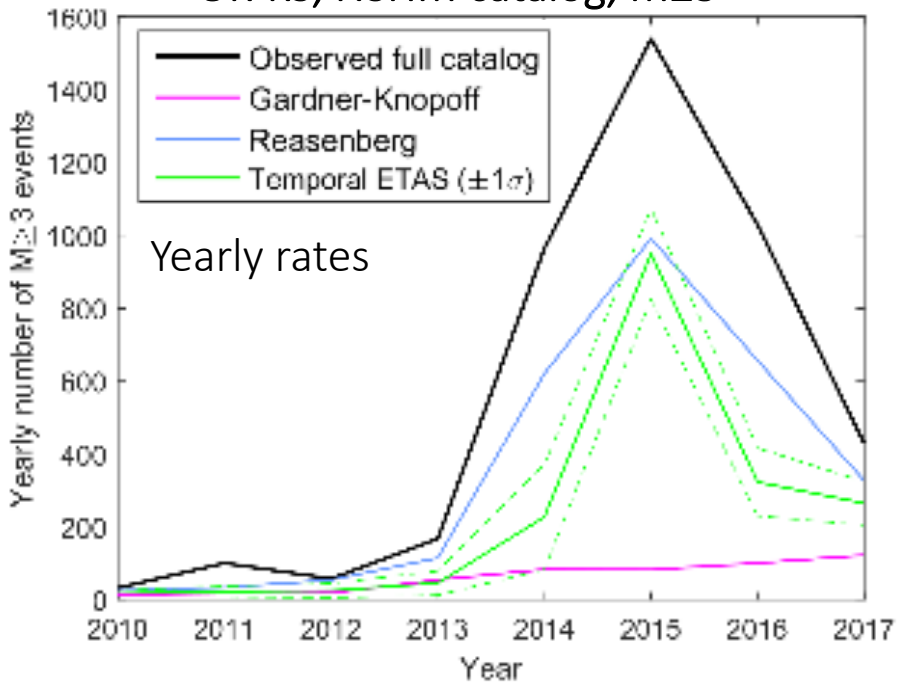
# Declustering and Hazard Estimates

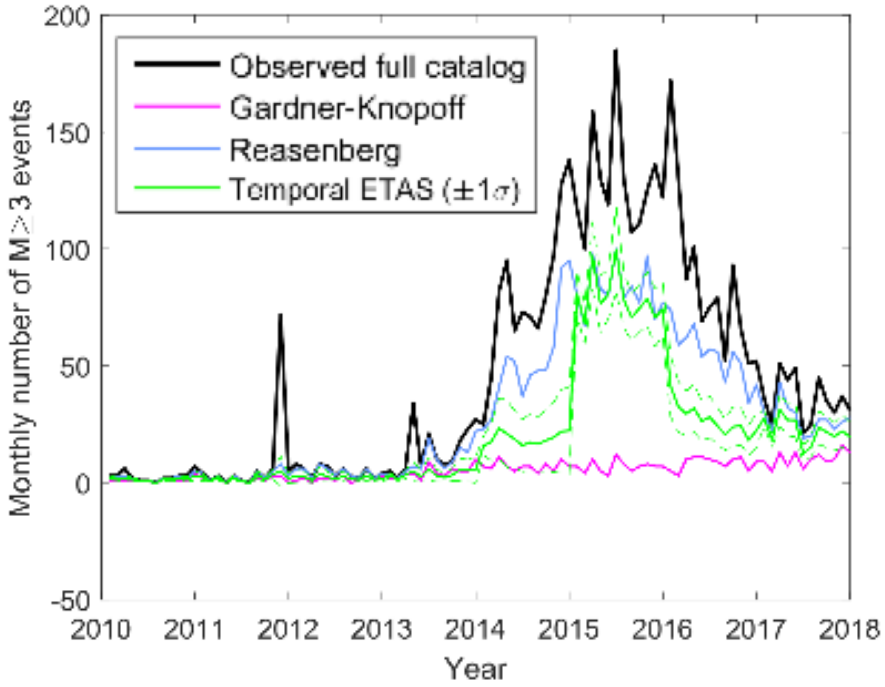
Using different declustering methods creates large disparities in the EQ rates used in hazard computations

Stochastic declustering via the ETAS model can **provide uncertainties for the declustered rate** that could improve seismic hazard assessments.

**Accounting for this formal uncertainty could lead to more accurate hazard forecasts.**

OK-KS, NSHM catalog, M≥3



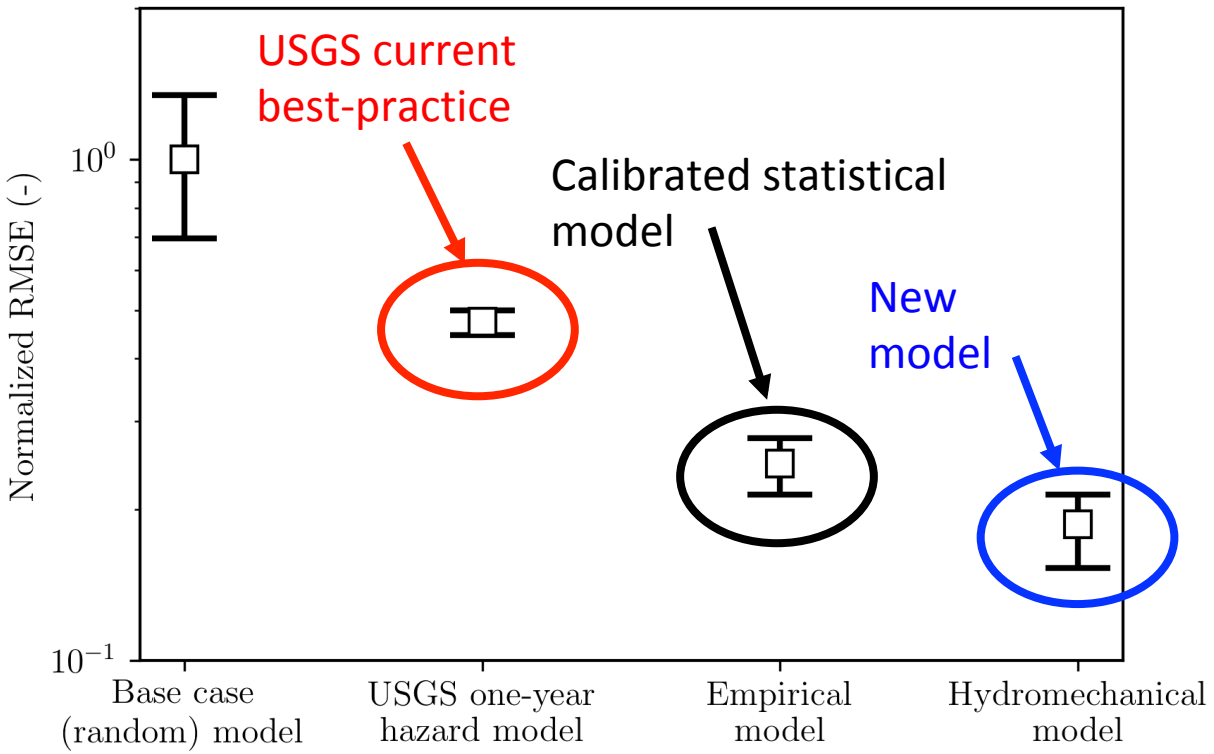

Llenos and Michael (in prep)

# Physics-Based Forecasting

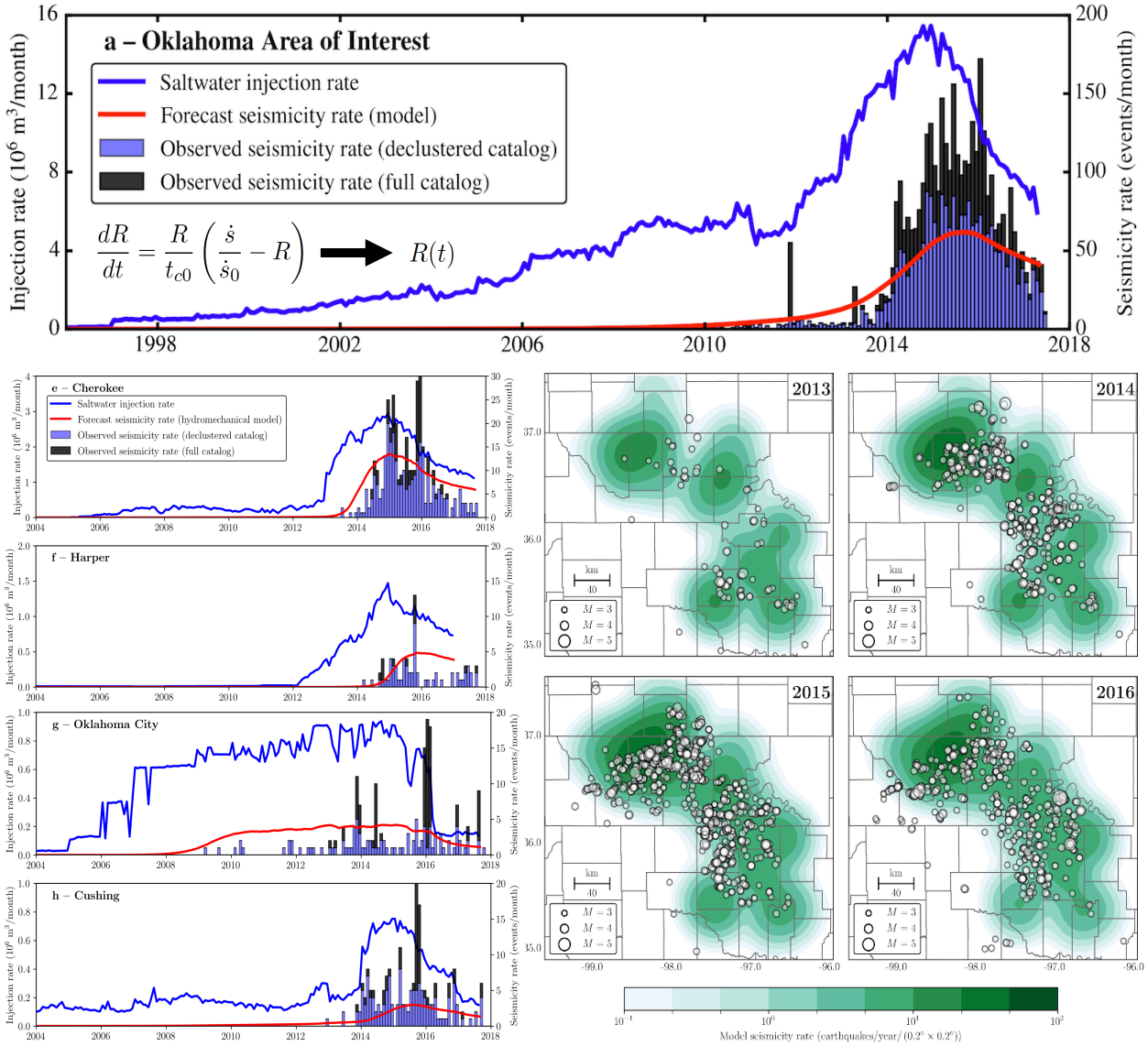
Method:

1. Calculate pressurization rate to represent ‘average’ pressure
2. Use rate-and-state friction to determine seismicity rate transients

**Accuracy of Forecasts:**




## Hazard Forecast Based on Injection Rates



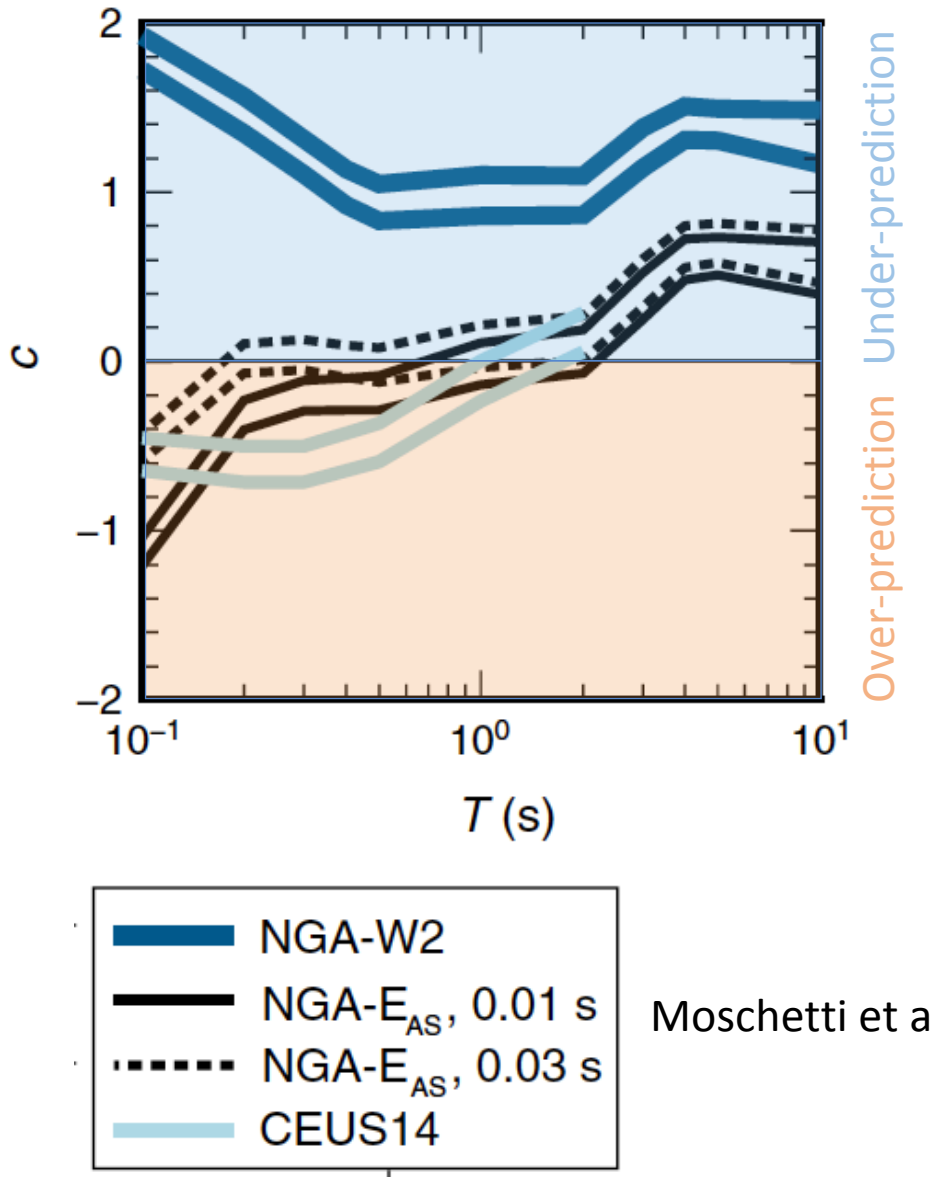

Norbeck and Rubinstein (2018)

# Ground Motion Prediction Equations for Injection-Induced Events

Ground motions from induced events are not well modeled by current tectonic GMPEs.

CEUS GMPEs over-predict ground motion at short periods (T ~ 0.1 s) and under-predict observations at longer periods (T > 3 s)

Short period between-event terms consistent with with increasing stress parameter/stress drop for earthquakes up to M5 (also observed in stress drop studies).




Moschetti et al. (2018)

# Use of One-Year Forecasts

Release of each one-year forecast is widely covered by media



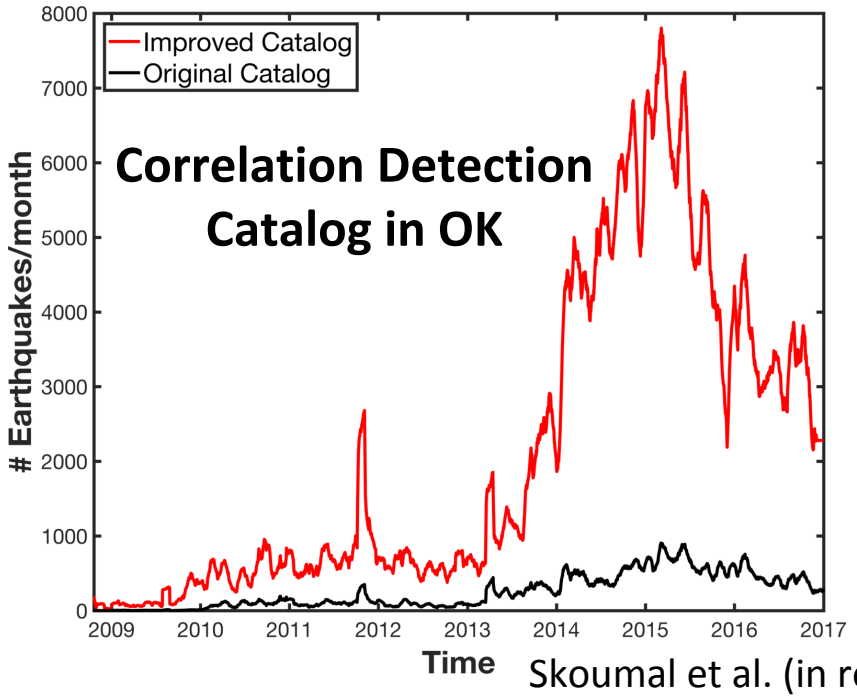
… but, examples of specific use cases where maps changed behavior or outcomes is lacking.

How do we assess the impact of one-year forecasts?

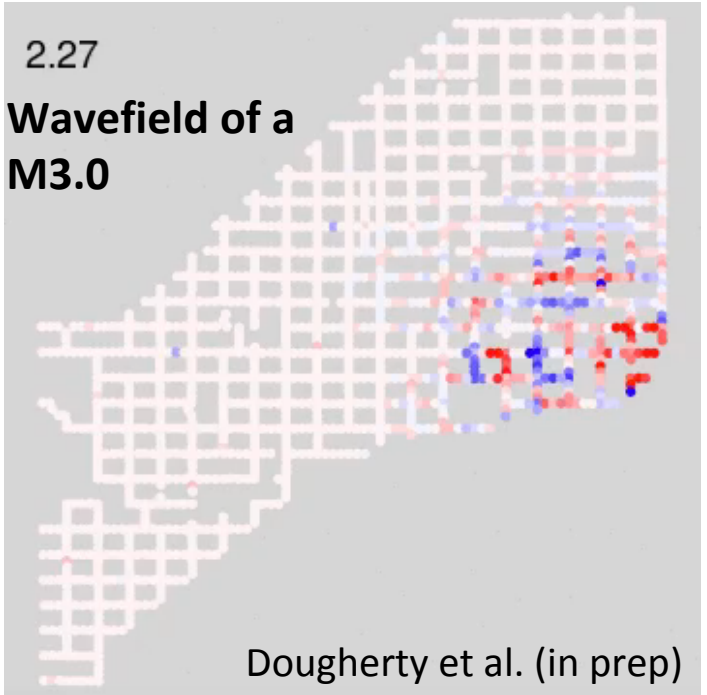
- Do we need to improve usability?
- Are different product(s) needed?

# On-going Research on Seismicity Related to Oil and Gas Production

- Improved detection and characterization of earthquakes in CEUS:
  - Matched-filter catalog for OK and KS and fault identification (Skoumal et al., in review)
  - Low-stress drops of induced events (Boyd et al., 2017; Sumy et al., 2017; Trugman et al., 2017)
  - Different evolutionary characteristics of sequences near wells (Cochran et al., 2018)
  - Large-N array deployment to map spatio-temporal evolution of seismicity (Dougherty et al., in prep)
  - Stress orientations and magnitudes in areas of injection (Cochran et al., in prep)



Skoumal et al. (in review)

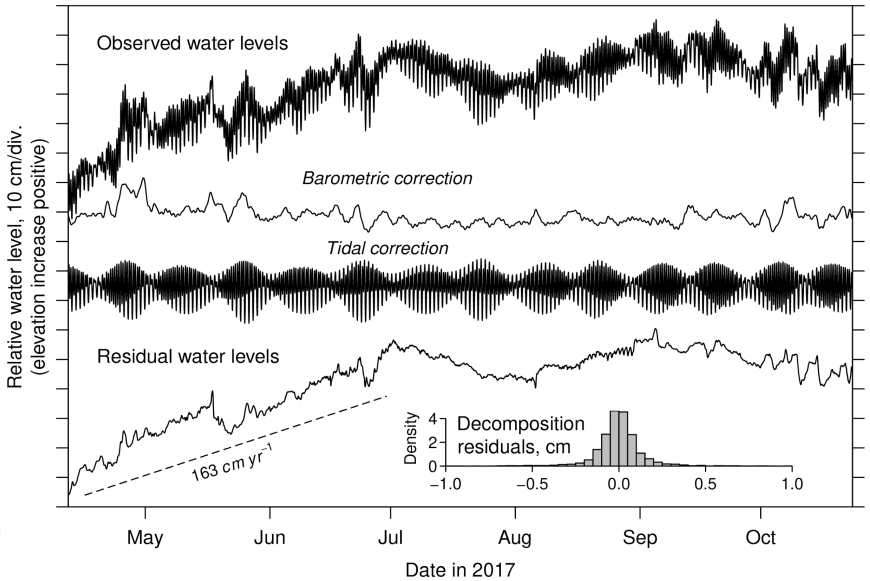


Dougherty et al. (in prep)

# On-going Research on Seismicity Related to Oil and Gas Production

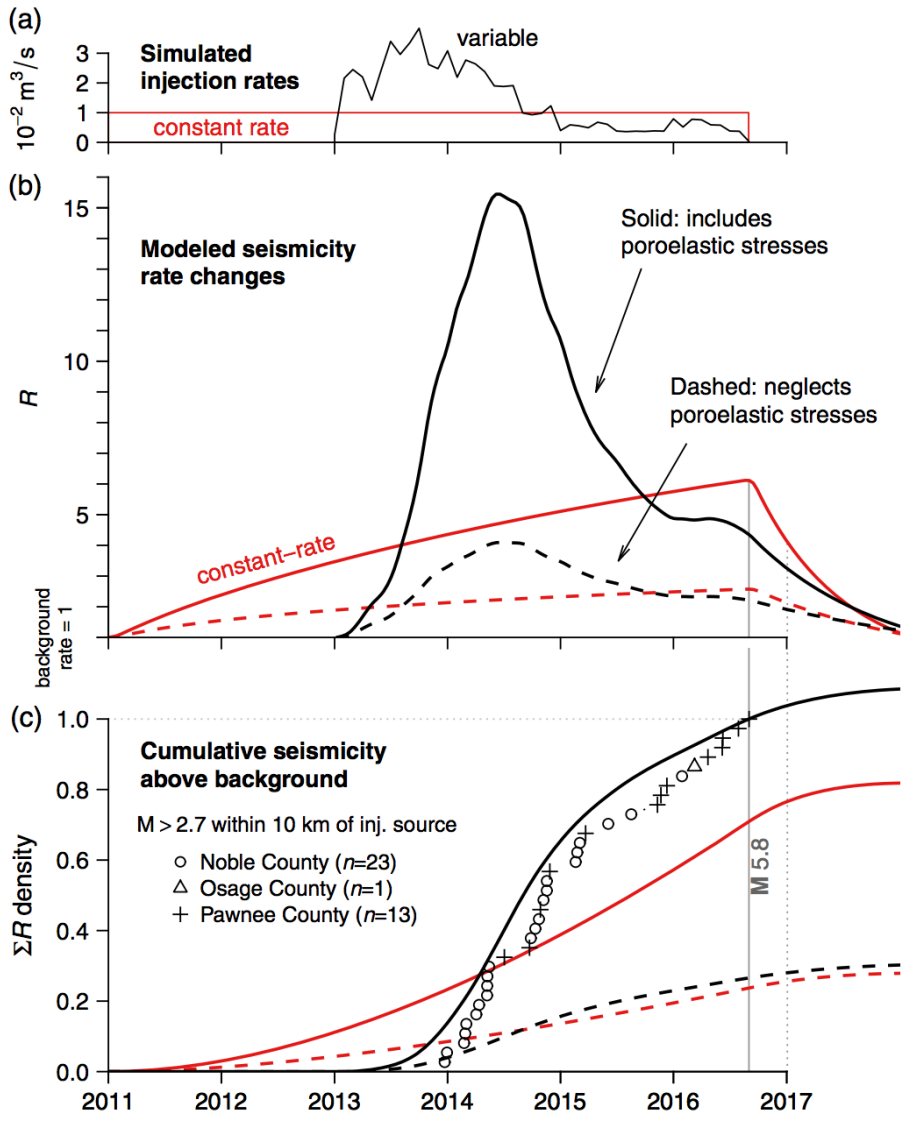
- Pore-pressure monitoring
  - Arbuckle pressure monitoring well in Osage County, OK
  - Continued pressure increase
- Improved modeling
  - Coupled fluid flow and poroelastic stress
  - Anisotropic permeability to account for preferred fracture orientation

**Osage County Well Pressure Observations**




Wang, et al. (2018);
Barbour, et al. (in review)

## Influence of poroelastic stresses on 2016 M5.8 Pawnee




Barbour et al. (2017)

## Science and hazard of induced seismicity from other causes:

- Hydraulic fracturing
  - 90%+ of earthquakes in some Oklahoma Counties due to hydraulic fracturing
- Geothermal/Enhanced Geothermal
  - Deformation and seismicity near Coso, Salton Sea, and other geothermal fields
  - DOE Frontier Observatory for Research in Geothermal Energy (FORGE)
- $CO_2$ sequestration
  - Seismicity at Decatur injection site
- Other: reservoir induced events, etc.

**Can we better communication of research/hazard findings?**

**How can we better understand and meet user needs?**

Potential users and stakeholders:

- *Federal and state government regulatory agencies (EPA, Oklahoma Corporation Commission, Texas Railroad Commission, etc.)*
- *Industry and federal agencies – inform best-practices/protocols for reducing risk of seismic events*
- *Insurance –response to short-term variability in seismic hazard*
- *Public and other sectors – understand hazard exposure*