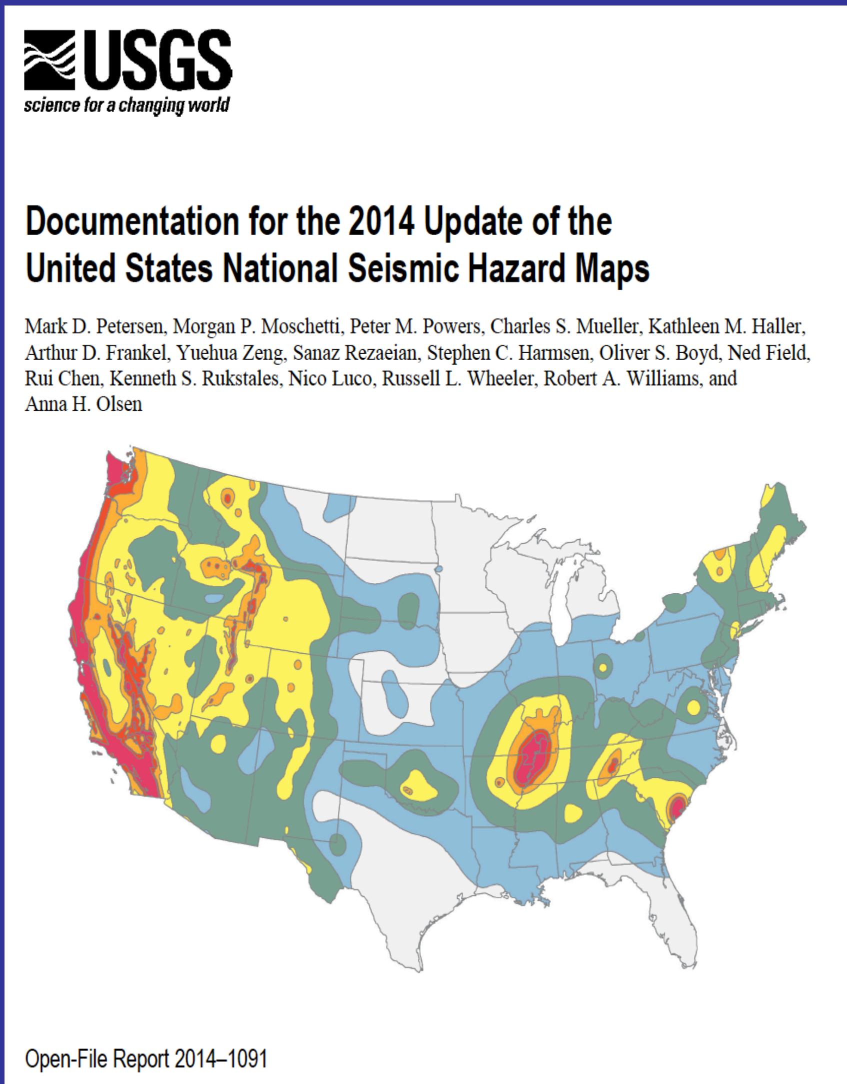
# Induced earthquakes and the USGS National Seismic Hazard Maps

Charles Mueller

U. S. Geological Survey, Golden, CO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Documentation for the 2014 Update of the United States National Seismic Hazard Maps

Mark D. Petersen, Morgan P. Moschetti, Peter M. Powers, Charles S. Mueller, Kathleen M. Haller, Arthur D. Frankel, Yuehua Zeng, Sanaz Rezaeian, Stephen C. Harmsen, Oliver S. Boyd, Ned Field, Rui Chen, Kenneth S. Rukstales, Nico Luco, Russell L. Wheeler, Robert A. Williams, and Anna H. Olsen

Open-File Report 2014–1091

**Goal**: Estimate future ground shaking for a specified risk/hazard level

**Primary Application:** Building codes – the 48-State maps are updated every six years in sync with the update cycle of the International Building Code (1996, 2002, 2008, 2014)

**Other Applications:** Insurance & financial risk, emergency planning, land-use planning, military facilities, critical facilities, setting earth science research priorities, *etc*

**USGS Charge:** Hazard assessments for the United States and US Territories

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# Seismic Hazard Models

Earthquake sources

✓ faults

✓ catalog-based sources

Recurrence

Maximum magnitude

Source forecast

+

Ground motions: estimated shaking for each source

(as a function of magnitude, distance, *etc*)

# Treatment of induced earthquakes (IE)
# in the National Seismic Hazard Maps (NSHM)
# through the 2008 update

# THE DENVER AREA EARTHQUAKES AND THE ROCKY MOUNTAIN ARSENAL DISPOSAL WELL

DAVID M. EVANS: Consulting Geologist, Denver, Colorado

ABSTRACT: During 1961, a deep well was drilled at the Rocky Mountain Arsenal northeast of Denver, Colorado, to dispose of contaminated waste water. The well is bottomed in 75 feet of highly fractured Precambrian gneiss. Pressure injection of waste water into the fractured Precambrian rock was begun in March 1962. Since the start of fluid injection, 710 Denver-area earthquakes have been recorded. The majority of these earthquakes had epicenters within a five-mile radius of the Arsenal well. The volume of fluid and pressure of fluid injection appear to be directly related to the frequency of earthquakes. Evidence also suggests that rock movement is due to the increase of fluid pressure within the fractured reservoir and that open fractures may exist at depths greater than previously considered possible.

## INTRODUCTION

Products for chemical warfare have been manufactured on a large scale under the direction of the Chemical Corps of the U. S. Army at the Rocky Mountain Arsenal since 1942. A by-product of this operation is contaminated waste water and, until 1961, this waste water was disposed of by evaporation from dirt reservoirs (Scopel, 1964).

When it was determined that Arsenal waste water was contaminating the local groundwater supply and endangering crops (Gahr, 1961; Walker, 1961), the Chemical Corps tried evaporation of the contaminated waste from water-tight reservoirs. This proved unsuccessful. The Chemical Corps and the Corps of Engineers then decided to drill an injection disposal well for the purpose of disposing of the contaminated waste water (Scopel, 1964).

The U. S. Army Corps of Engineers, Omaha District, commissioned the firm of E. A. Polumbus, Jr., and Associates, Inc., to design the well, supervise the drilling and completion, provide the necessary engineering geological services, and manage the project. Louis J. Scopel, as an associate, was the Project Geologist and was responsible for all geological aspects of the operation. Another geological associate was George R. Downs,

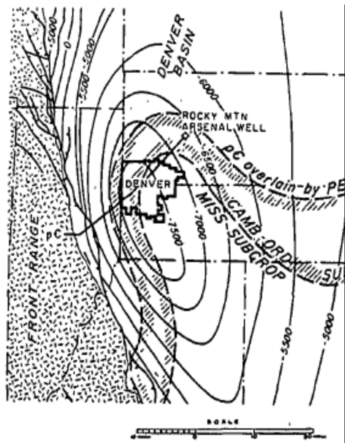
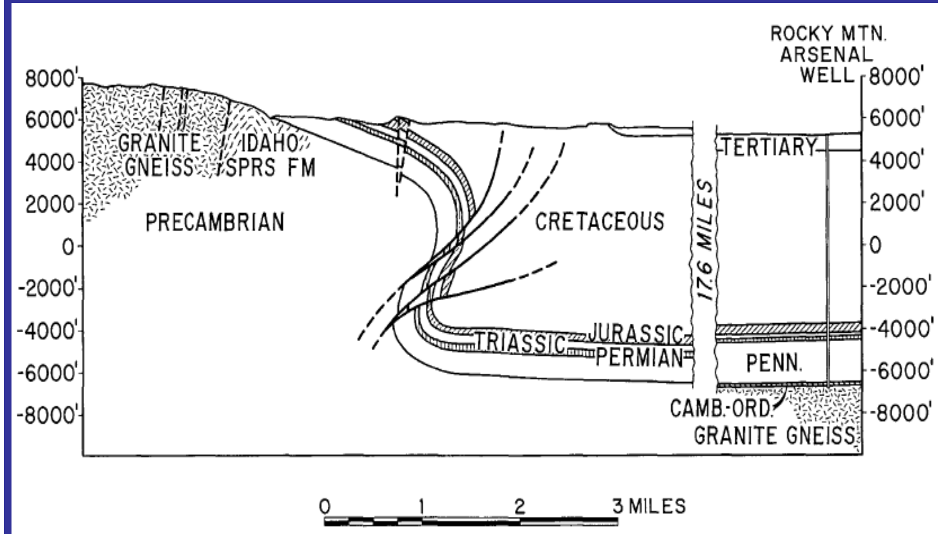
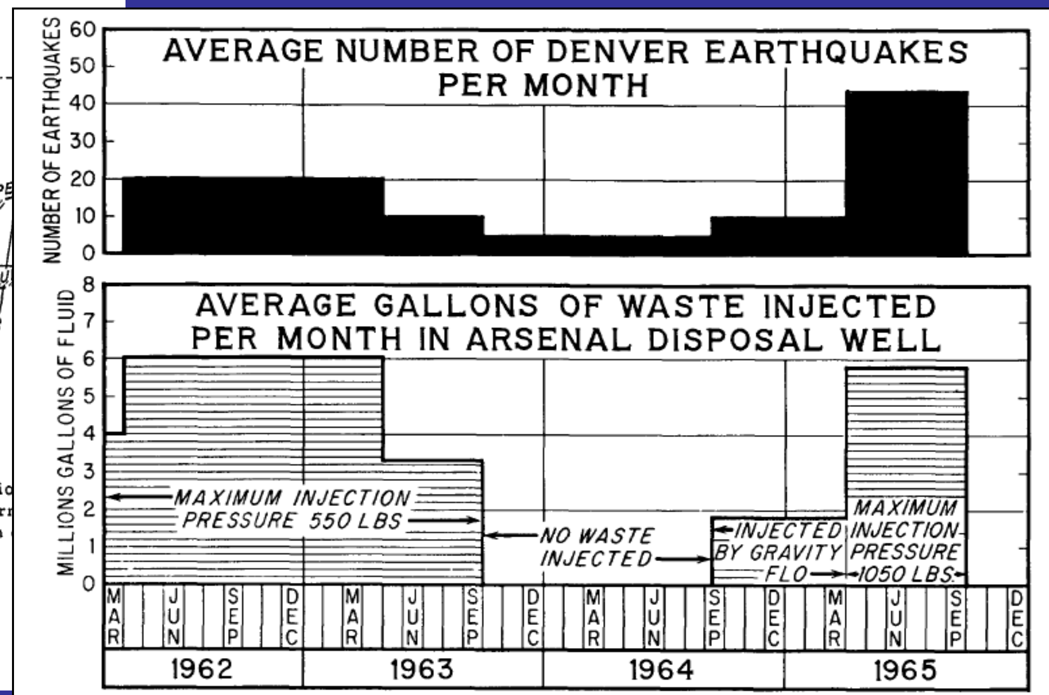



Figure 1. Structural map of a portio[n of the] Denver-Julesburg Basin (after Ander[son and] Ackman, 1963), showing the location [of the] Rocky Mountain Arsenal well.

(D.M. Evans, The Mountain Geologist, 1966)






earthquake rate (top) & injection rate (bottom)

Toward a more quantitative understanding of the RMA earthquakes...

27 September 1968, Volume 161, Number 3848 **SCIENCE**

# The Denver Earthquakes

Disposal of waste fluids by injection into a deep well has triggered earthquakes near Denver, Colorado.

J. H. Healy, W. W. Rubey, D. T. Griggs, C. B. Raleigh

Scientists and public officials are seriously considering the question of whether removal of fluid from a deeply buried reservoir will reduce the likelihood of a destructive earthquake near Denver, Colorado. The question at issue in the discussions is not so absurd as it might seem. It is widely, though not unanimously, held that injection of chemical-waste fluid into the reservoir in the Denver basin triggered the earthquakes. We attempt here to present the statistical evidence for correlating the two events—fluid injection and earthquakes—and to develop a hypothesis relating the two as cause and effect.

In 1961 a deep disposal well was completed for the U.S. Army at the Rocky Mountain Arsenal, northeast of Denver, Colorado. The well was drilled through 3638 meters of nearly flat-lying sedimentary rocks in the Denver basin into Precambrian crystalline rocks; its depth at completion was 3671 meters. The disposal of waste fluids from chemical-manufacturing operations at the arsenal had been a difficult problem, for which the deep well appeared to be an ideal solution. Injection of fluids on a routine basis was begun on 8 March 1962 and continued through 30 September 1963 at an average rate of about 21 million liters per month. No fluid was injected from October 1963 to August 1964. Then for a time fluid was put into the well under gravity flow at an average rate of about 7.5 million liters per month. Gravity flow was continued until 6 April 1965, when injection under pressure was resumed, at an average rate of 17 million liters per month. On 20 February 1966 injection of fluid was stopped because of a suggested connection between the well and earthquakes in the Denver area.

Two seismograph stations were operating in the Denver area in 1962, one by the Colorado School of Mines, at Bergen Park, about 34 kilometers west of Denver, the other at Regis College in Denver. Both stations began to record earthquakes from the region northeast of Denver, starting on 24 April 1962. As the sequence continued, the U.S. Geological Survey established several additional stations, and Yung-Liang Wang, a graduate student at the Colorado School of Mines, undertook a study of all the available seismic recordings. He located many of the earthquakes (*1*) within a region about 75 kilometers long, 40 kilometers wide, and 45 kilometers deep (Fig. 1, left). It was pointed out later that most of the earthquakes located by Wang were within 8 kilometers of the disposal well.

Father Joseph V. Downey, director of the Regis College Seismological Observatory, was among the first to suggest the possibility of a relationship between the disposal well and the earthquakes. In November 1965 David Evans (*2*), a consulting geologist in Denver, showed a correlation between the volumes of fluid injected into the well and the number of earthquakes detected at Bergen Park, and publicly suggested that a direct relation did exist (Fig. 1, right).

The proximity of the earthquakes to the Denver metropolitan area created considerable public interest and concern. A number of the larger earthquakes, of Richter magnitude between 3 and 4, were felt over a wide area, and minor damage was reported near the epicenters. The sudden appearance of seismic activity close to a major city posed serious questions, and the possibility that the earthquakes were caused by operations at the Rocky Mountain Arsenal had to be evaluated as quickly as possible.

## The Preliminary Program

The U.S. Army Corps of Engineers was called upon for technical support and advice, and the U.S. Geological Survey, in cooperation with the Corps of Engineers, began a program of investigation to evaluate the Evans theory. The Colorado School of Mines played a major role in those investigations, with support from the State of Colorado, the Corps of Engineers, and the Environmental Science Services Administration.

A search of the available instrumental and historical records was one of the first investigations undertaken. Any earthquakes that had occurred before the start of fluid injection would lessen the correlation between water injection and earthquake occurrence. The seismograph station at Bergen Park began operation only a few months before the start of water injection, and no earthquakes were recorded from the Denver area during that period. The station at Regis College had been in operation since 1909, but it is located in an area of high background noise and, for most of its history, was operated at low magnification. Thus, earthquakes of small magnitude could have

Drs. Healy and Raleigh are affiliated with the U.S. Geological Survey, Menlo Park, California; Drs. Rubey and Griggs, with the Institute of Geophysics and Planetary Physics, University of California, Los Angeles.

# An Experiment in Earthquake Control at Rangely, Colorado

C. B. Raleigh, J. H. Healy, J. D. Bredehoeft

The discovery in 1966 that injection of fluid underground at high pressure was responsible for the triggering of earthquakes near Denver, Colorado, led to speculations that earthquakes might be controllable (1).

locations and focal plane solutions for the earthquakes, and most important (iv) to be confident that the active phase of the experiment would not materially increase the likelihood of a damaging earthquake. In

### The Rangely Field

The Rangely structure consists of a doubly plunging anticline in Mesozoic and Paleozoic sedimentary rocks (Table 1 and Fig. 1a). The Cretaceous Mancos shale is exposed at the surface, and is underlain at 900 m below the surface by an 800-m section of Mesozoic sandstones and siltstones. The Pennsylvanian and Permian Weber sandstone, the principal oil reservoir rock, is 350 m thick and is encountered at a depth of about 1700 m. The Paleozoic sandstones and limestones beneath the Weber rest on crystalline basement rock at a depth of about 3000 m.

There is little evidence of faulting in the Rangely area. At the western end of the field, drainage patterns are aligned along a

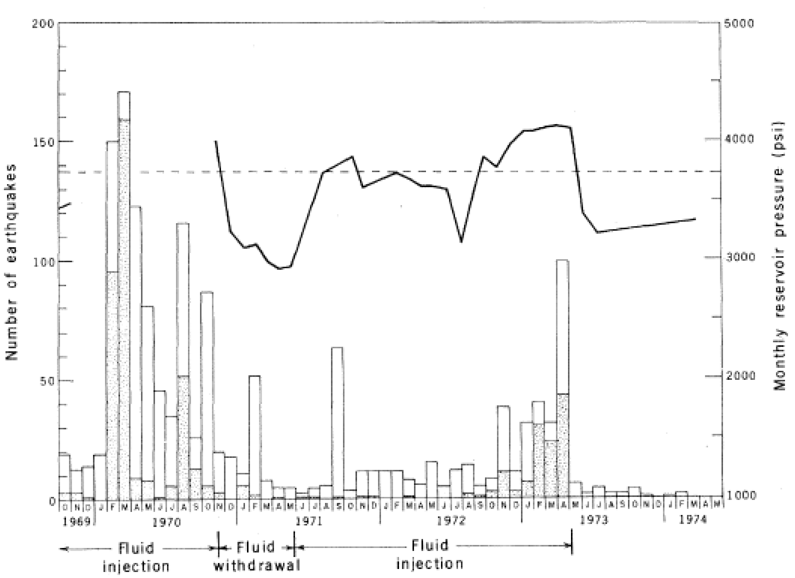



Fig. 7. Frequency of earthquakes at Rangely. Stippled bars indicate earthquakes within 1 km of experimental wells. The clear areas indicate all others. Pressure history in well Fee 69 is shown by the heavy line; predicted critical pressure is shown by the dashed line.

For an adequate field experiment it was necessary (i) to know the fluid pressure in the vicinity of the hypocenter of the earthquakes, (ii) to measure the absolute state of stress, (iii) to have precise hypocentral

used to establish the reservoir performance and make predictions of the spatial distribution of pressure with the cycles of injection and withdrawal. By measuring the stresses in situ and the frictional properties of the reservoir rock, a test of the effective stress hypothesis could be made by comparing the observations with the predicted fluid pressure for triggering of earthquakes.

detected if it were not within an oil field.

The Weber sandstone is a dense, fine-grained sandstone with an average porosity of 12 percent and an average permeability of 1 millidarcy in the oil-producing zone. Consequently, despite the large estimated reserves, the reservoir pressure and production rate declined rapidly following development of the field in 1945. In 1957, the field was divided into units to fa-

C. B. Raleigh and J. H. Healy are geophysicists at the National Center for Earthquake Research, U.S. Geological Survey, Menlo Park, California 94025. J. D. Bredehoeft is a hydrologist at the U.S. Geological Survey, Reston, Virginia 22092.



At Rangely, CO: fluid injection for secondary recovery of oil was causing earthquakes in the late 1960s...

In the light of RMA, scientists proposed an experiment to test the effective-stress hypothesis: By increasing fluid pressure can we lower the clamping stress on a fault & increase the seismicity? And inversely?

- Working with Chevron, USGS lowered & raised the fluid pressure through several cycles
- New local seismic network for precise eqk locations
- Lab tests of reservoir rock cores & in-situ rock fracture tests => fluid pressure threshold value

This was a near-ideal, controlled experiment

Conclusions:

*" An experiment in an oil field at Rangely, Colorado, has demonstrated the feasibility of earthquake control. Variations in seismicity were produced by controlled variations in fluid pressure in a seismically active zone."*

The fluid pressure threshold value determined from theory + lab tests + field tests was validated.

IE aren't considered suitable for long-term (50-year+) hazard applications like building codes, because they are transitory and may be limited in size

For NSHM updates through 2008 we identified IE in five areas (scientific consensus) and deleted them from the seismicity catalogs:

1. Rocky Mountain Arsenal, CO
2. Rangely, CO
3. Cogdell, TX (water flooding for secondary oil recovery)
4. Paradox Valley, CO (underground disposal of saline groundwater)
5. Dagger Draw NM (oil production)

(No consensus for Raton, CO eqks; left in the catalog through 2008)

# Things changed

# between the 2008 and 2014 NSHM updates

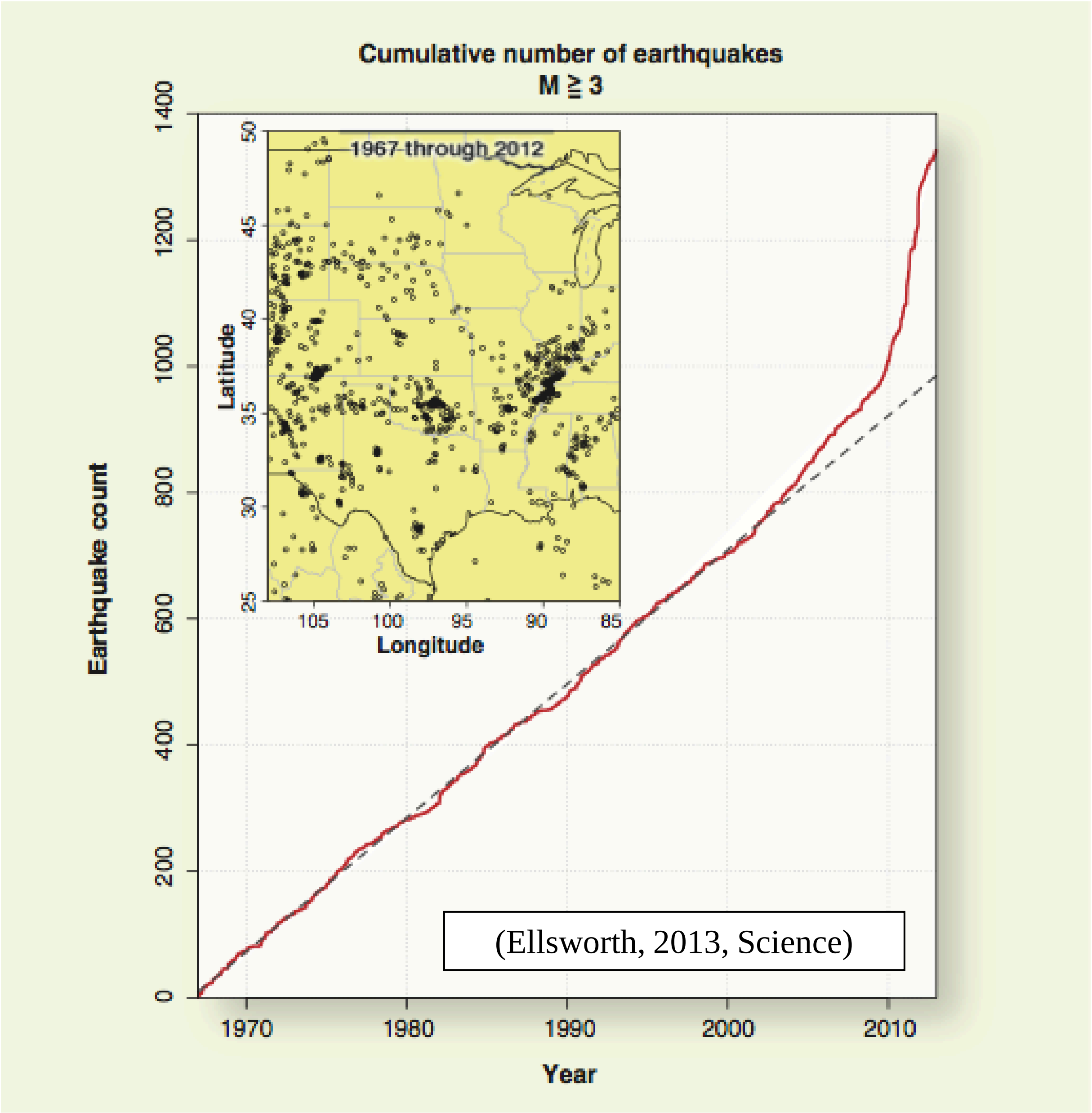
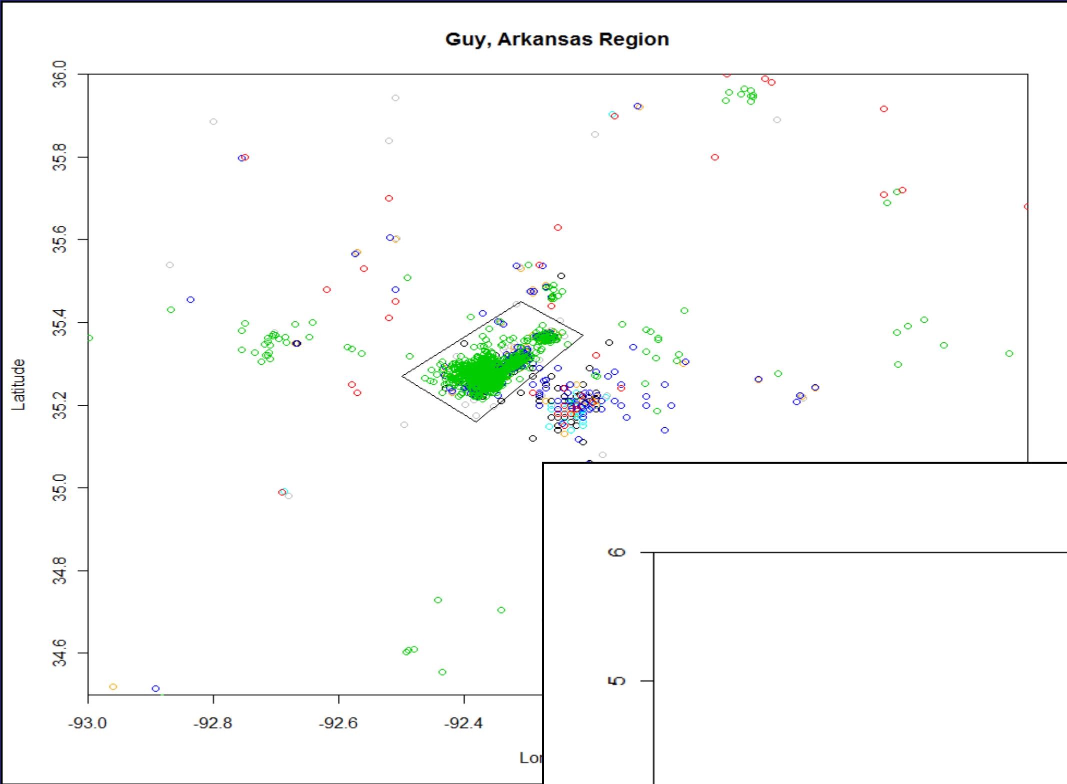
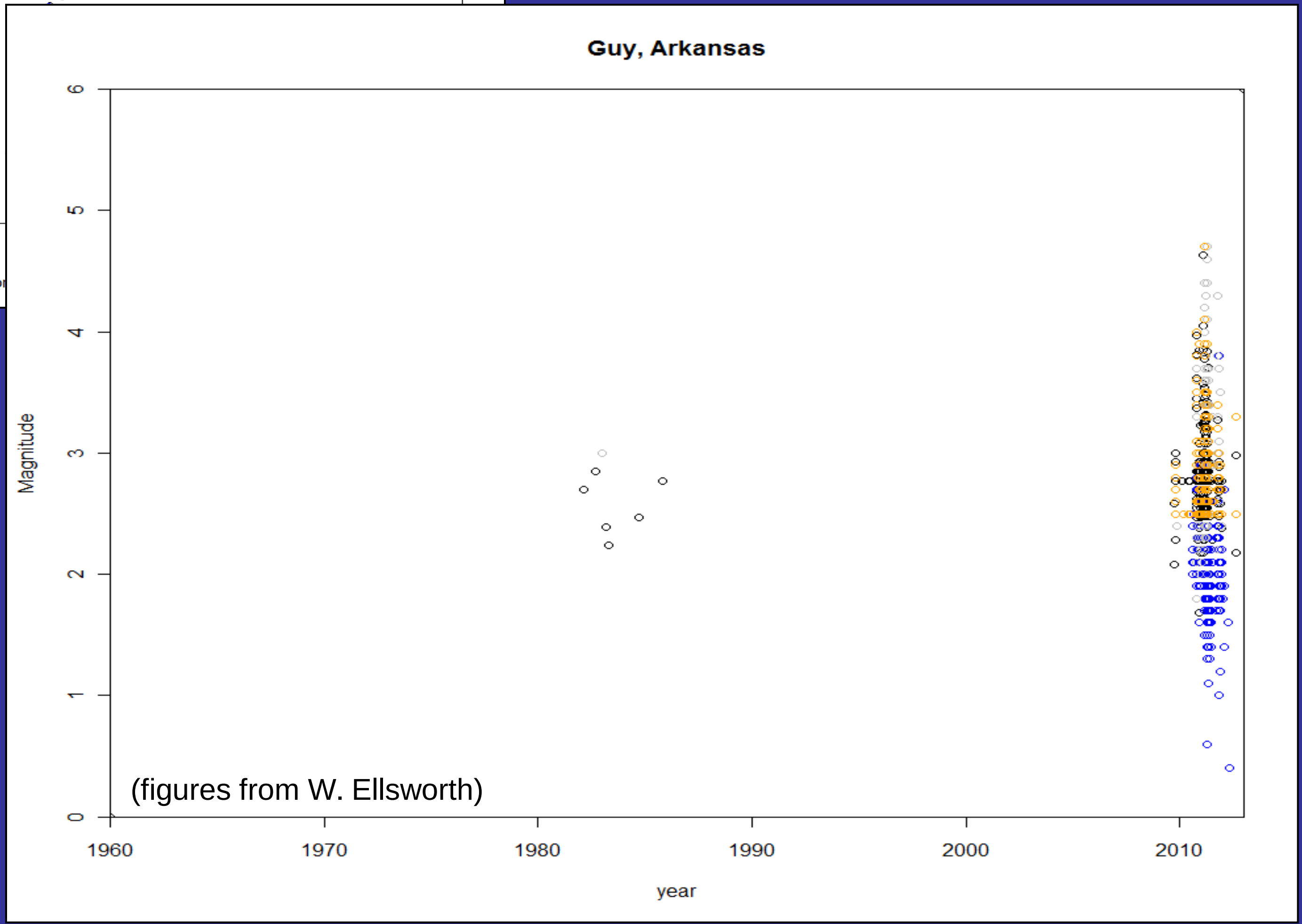



**Fig. 2. Cumulative count of earthquakes with *M* ≥ 3 in the central and eastern United States, 1967–2012.** The dashed line corresponds to the long-term rate of 21.2 earthquakes/year. (**Inset**) Distribution of epicenters in the region considered here.

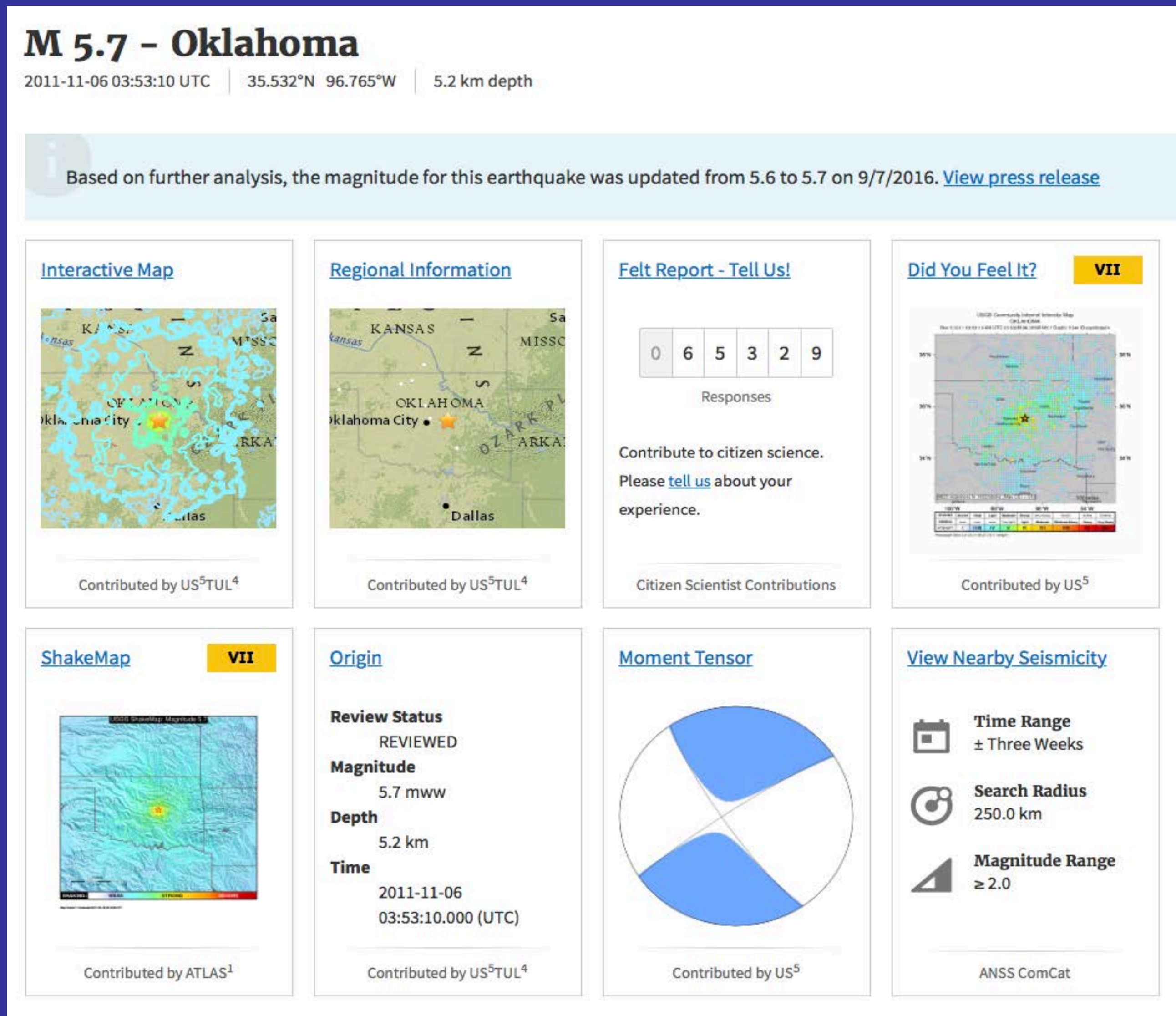
# North-central Arkansas




(figures from W. Ellsworth)

# Magnitude 5.7 earthquake near Prague, OK in Nov2011



# M 5.7 - Oklahoma

2011-11-06 03:53:10 UTC | 35.532°N 96.765°W | 5.2 km depth

Based on further analysis, the magnitude for this earthquake was updated from 5.6 to 5.7 on 9/7/2016. View press release

**Interactive Map**

Contributed by US[5]TUL[4]

**Regional Information**

Contributed by US[5]TUL[4]

**Felt Report - Tell Us!**

0 6 5 3 2 9

Responses

Contribute to citizen science. Please tell us about your experience.

Citizen Scientist Contributions

**Did You Feel It?** VII

Contributed by US[5]

**ShakeMap** VII

Contributed by ATLAS[1]

**Origin**

**Review Status**
REVIEWED
**Magnitude**
5.7 mww
**Depth**
5.2 km
**Time**
2011-11-06
03:53:10.000 (UTC)

Contributed by US[5]TUL[4]

**Moment Tensor**

Contributed by US[5]

**View Nearby Seismicity**

**Time Range**
± Three Weeks

**Search Radius**
250.0 km

**Magnitude Range**
≥ 2.0

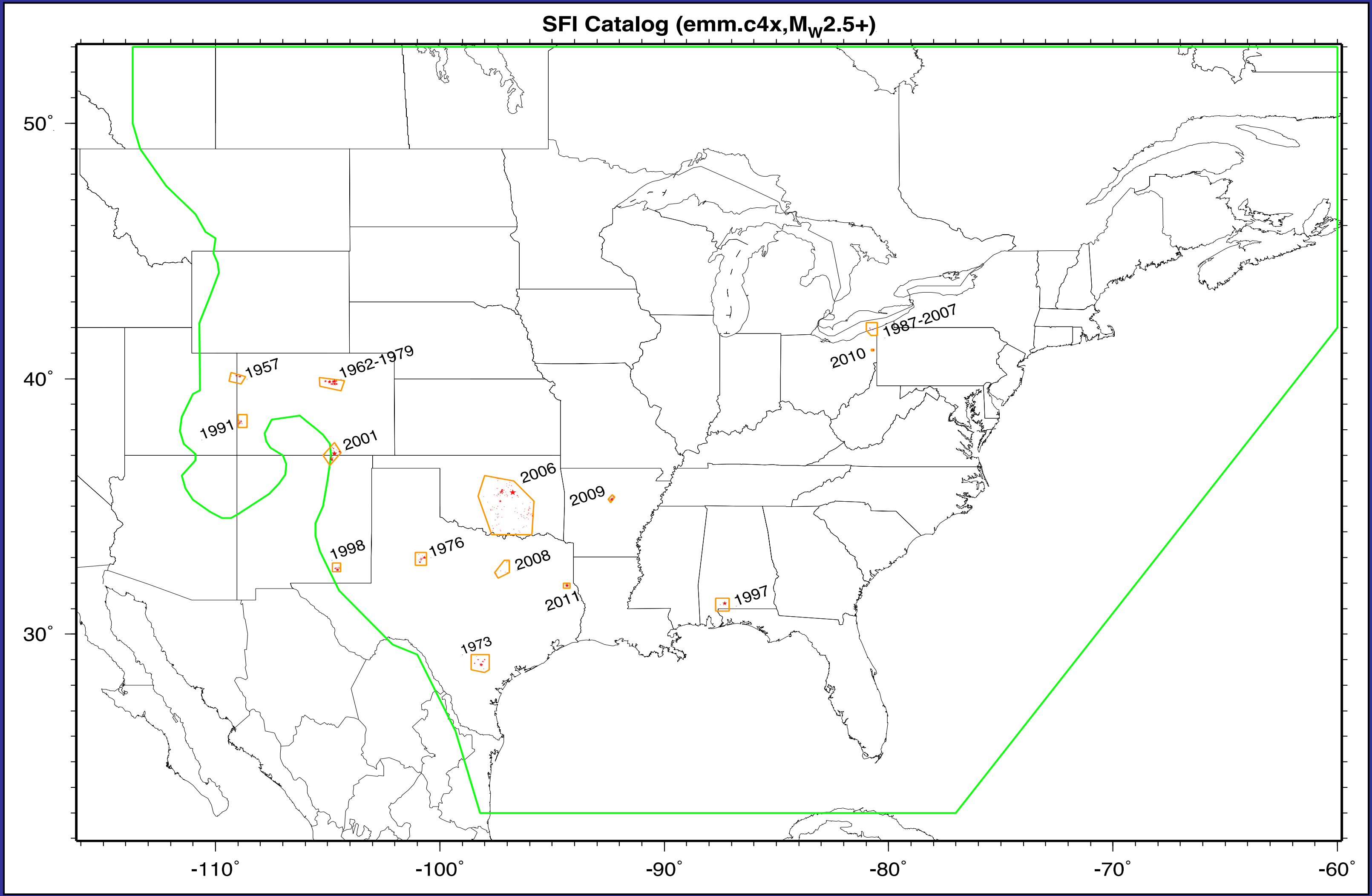
ANSS ComCat

# Modeling Challenges

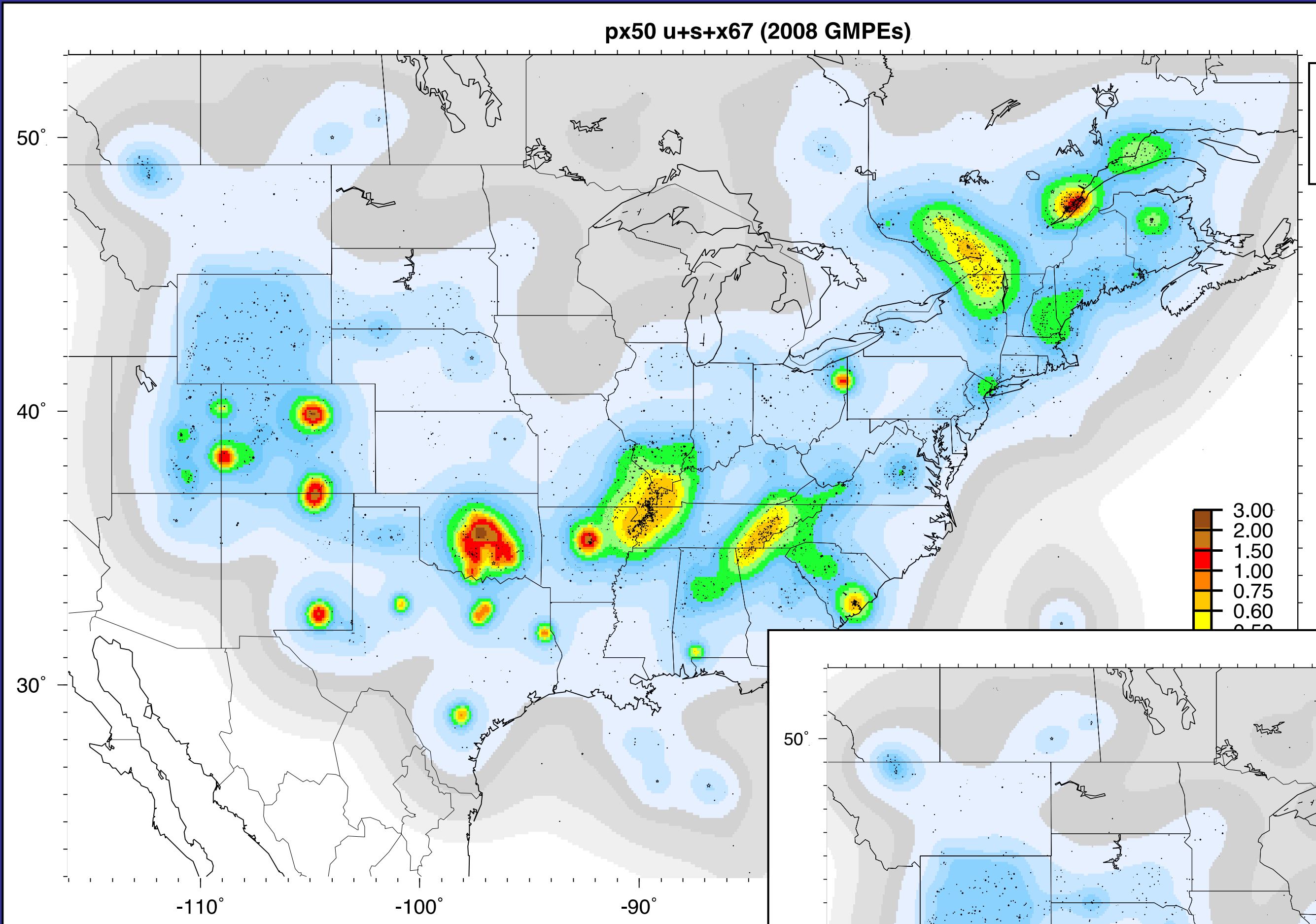
- We have always tried to remove man-made eqks from the building-code maps.
- But now the “missing” hazard from IE is significant...
- How do we adapt models & present results? Who is the audience?
- Because of their transitory nature: Should a forecast for IE hazard have a time limit? Does the past year forecast the next year? Six months? Three months?
- Are IE seismologically different than natural eqks: swarm-like?, recurrence?, maximum magnitude?, depth?, ground shaking?
- Can we get beyond simply using past seismicity? Injection data? Physics-based models?

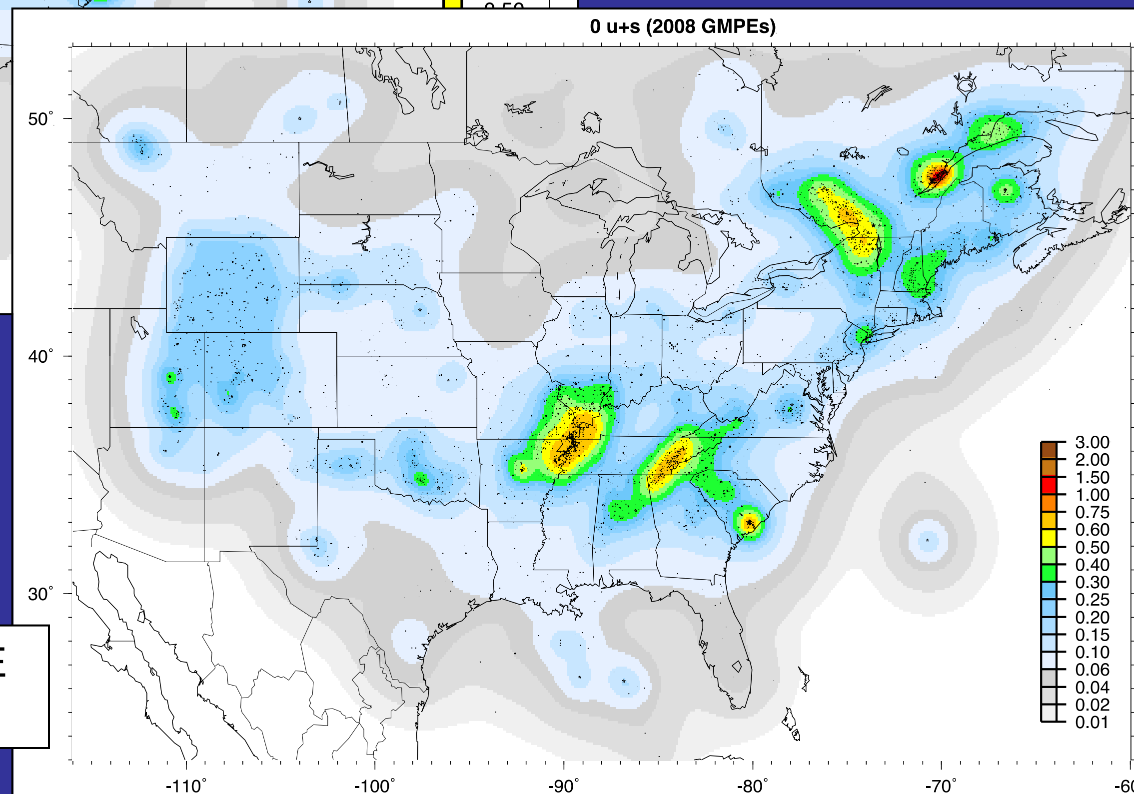
# A simple classification scheme for the 2014 NSHM update

- Consult science literature and local expertise
- Identify suspicious seismic activity in historically quiet areas
- Define time windows and areal zones to delete IE



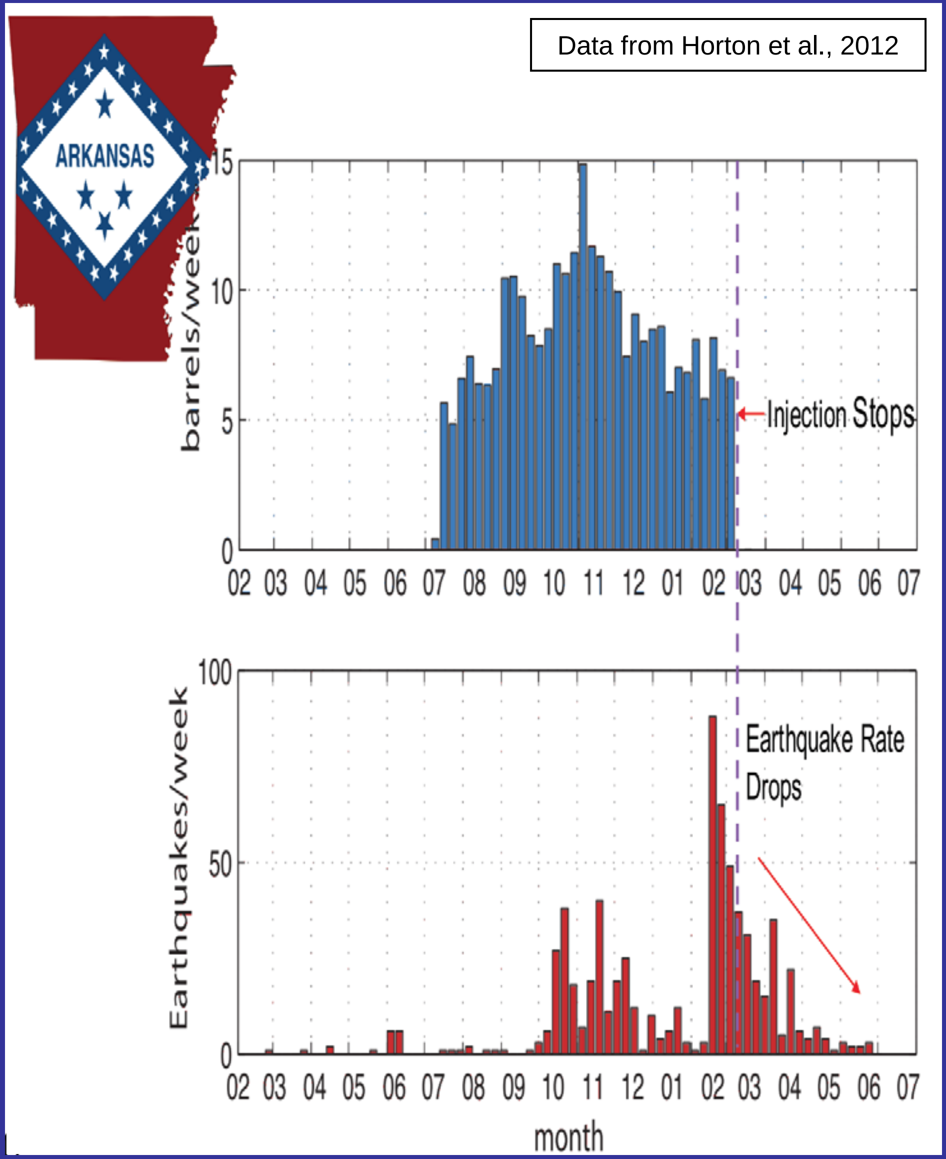
Hazard map including IE
(5-HzSA, 2%px50)

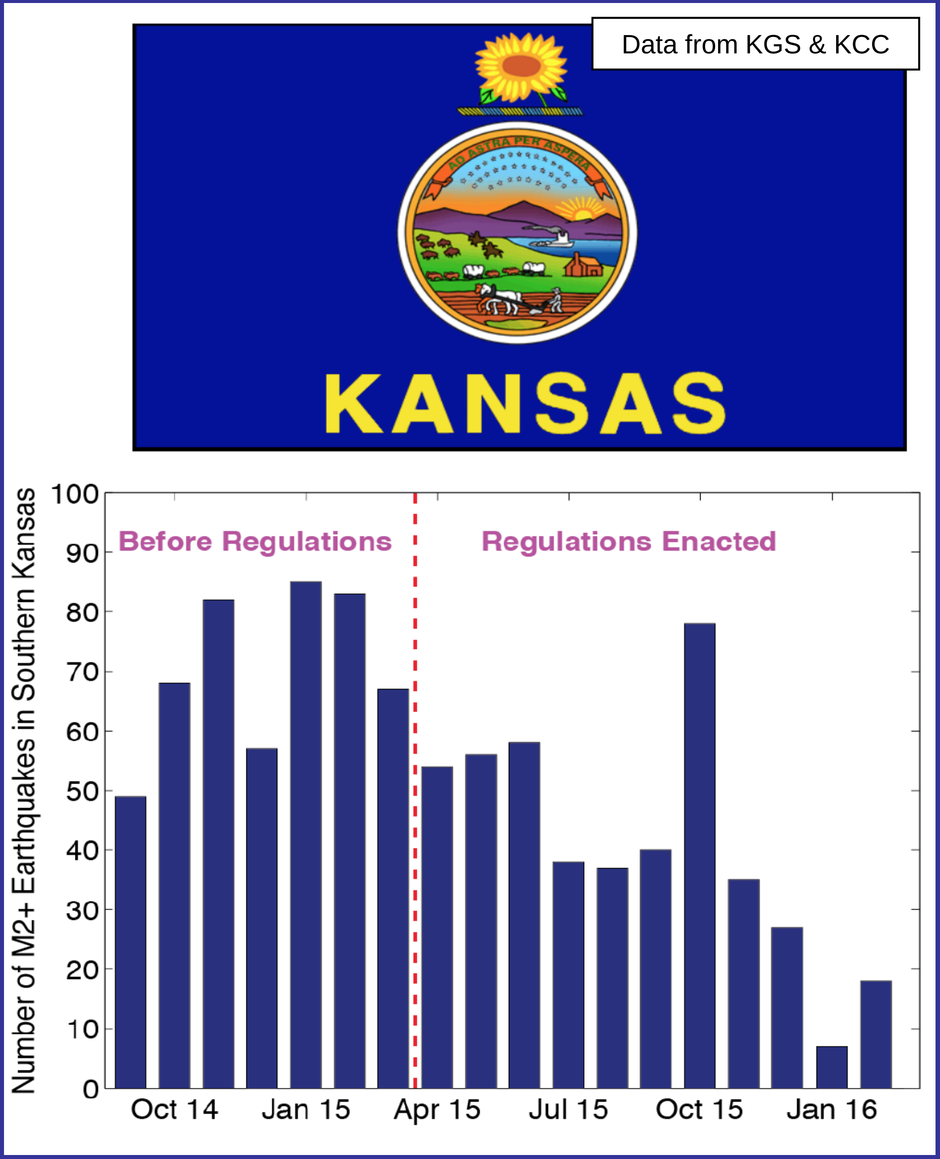



Hazard map excluding IE
(5-HzSA, 2%px50)

# Two examples of response at the state level

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## In 2016: A new USGS short-term model to forecast the hazard from IE

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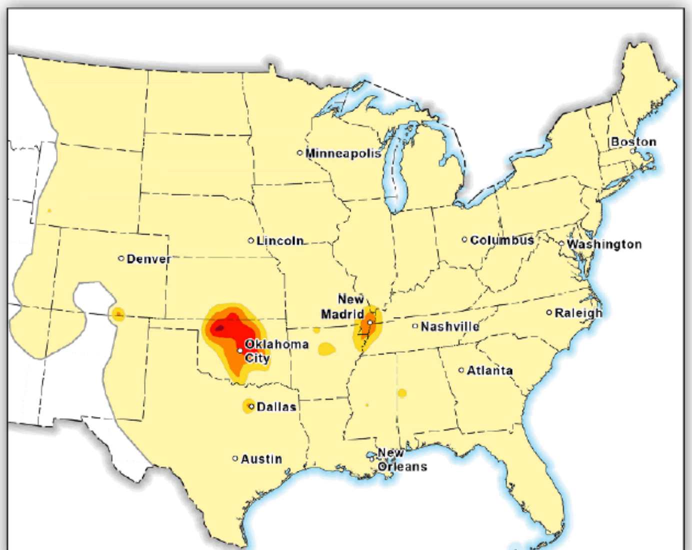
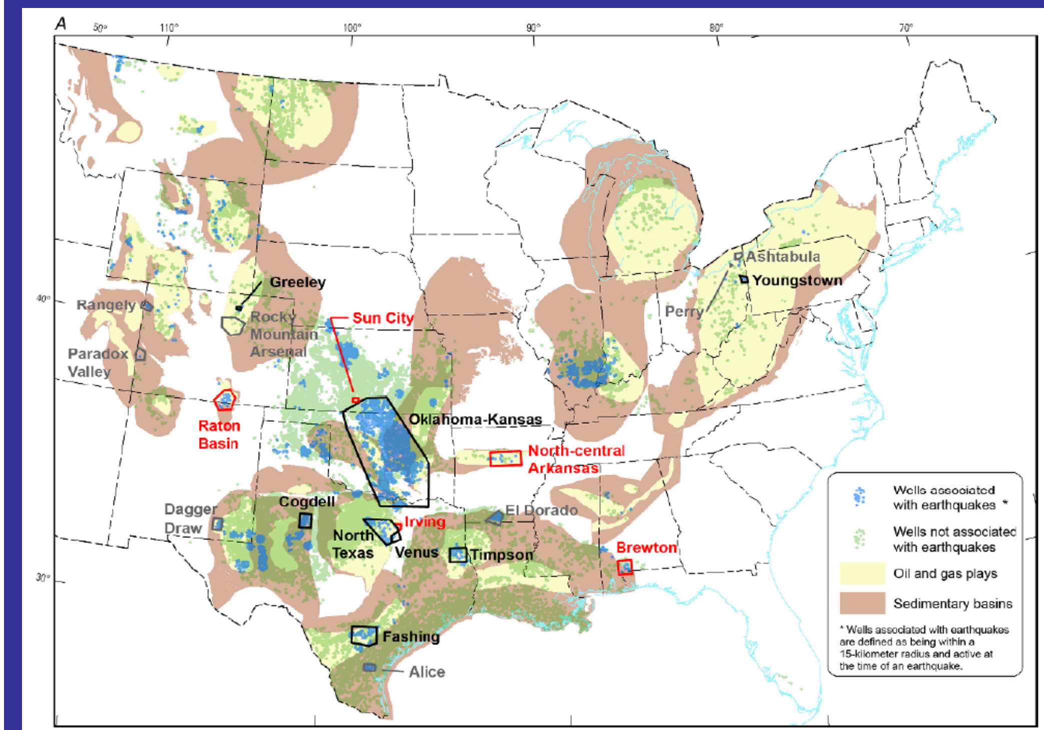
# 2016 One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes

By Mark D. Petersen, Charles S. Mueller, Morgan P. Moschetti, Susan M. Hoover, Andrea L. Llenos, William L. Ellsworth, Andrew J. Michael, Justin L. Rubinstein, Arthur F. McGarr, and Kenneth S. Rukstales




Open-File Report 2016–1035

- Emphasize recent earthquakes – the previous year gets the most weight
- Don’t incorporate injection data directly




(Figure from OFR 2016-1035, including information from USDOE, 2015, and Weingarten and others, 2015)

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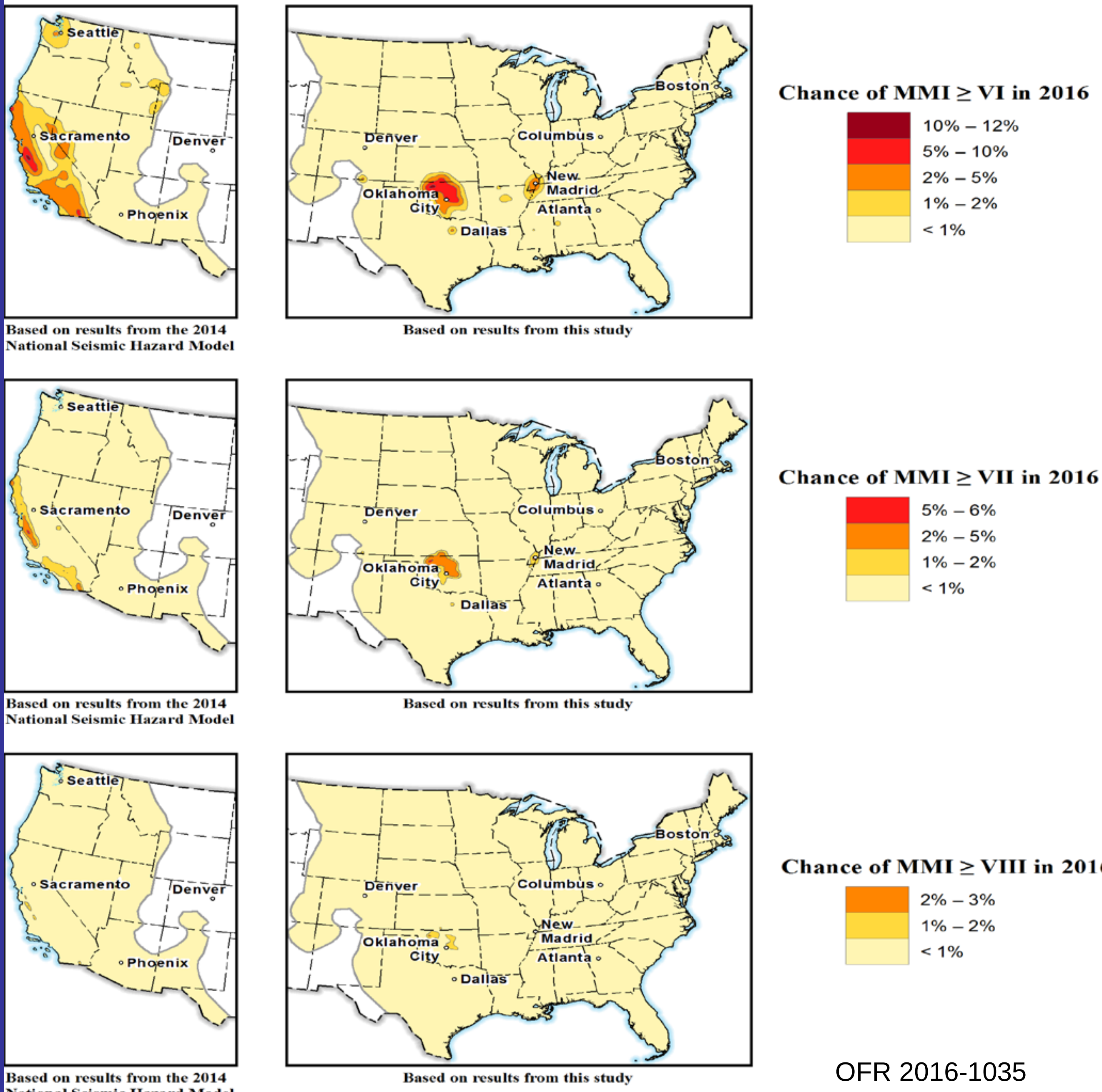
One-year probability for MMI VI, VII, VIII

Based on the average of horizontal spectral response acceleration for 1.0-second period and peak ground acceleration




OFR 2016-1035

# Current science

## Can we improve forecasts and mitigation by moving beyond seismicity-based models?

- Operational data?
  - Role of injection volume? Rate? Pressure? Depth?
- Field & lab data?
  - In-situ pore pressure? Porosity & permeability?
- Dangerous faults?
- Physics-based models for eqk occurrence/triggering?
  - Rock physics & fluid physics?
  - Earthquake physics? Critical thresholds? Mmax?
  - Stress: Increased by injection? Rearranged by earthquakes?
  - Time delays: injection => earthquake? earthquake1 => earthquake2?
- Why are some injection sites aseismic?
  - Role of geology?

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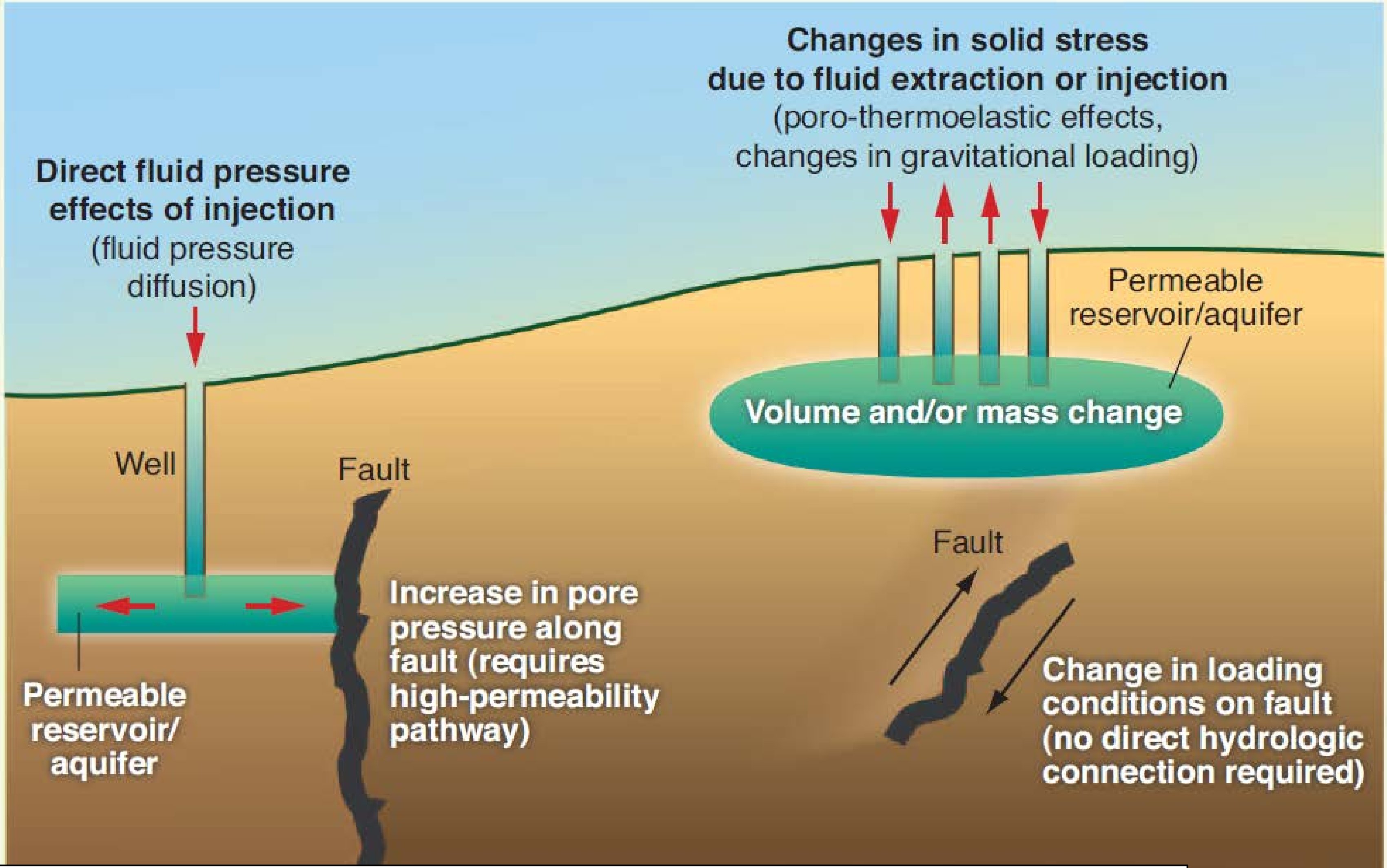
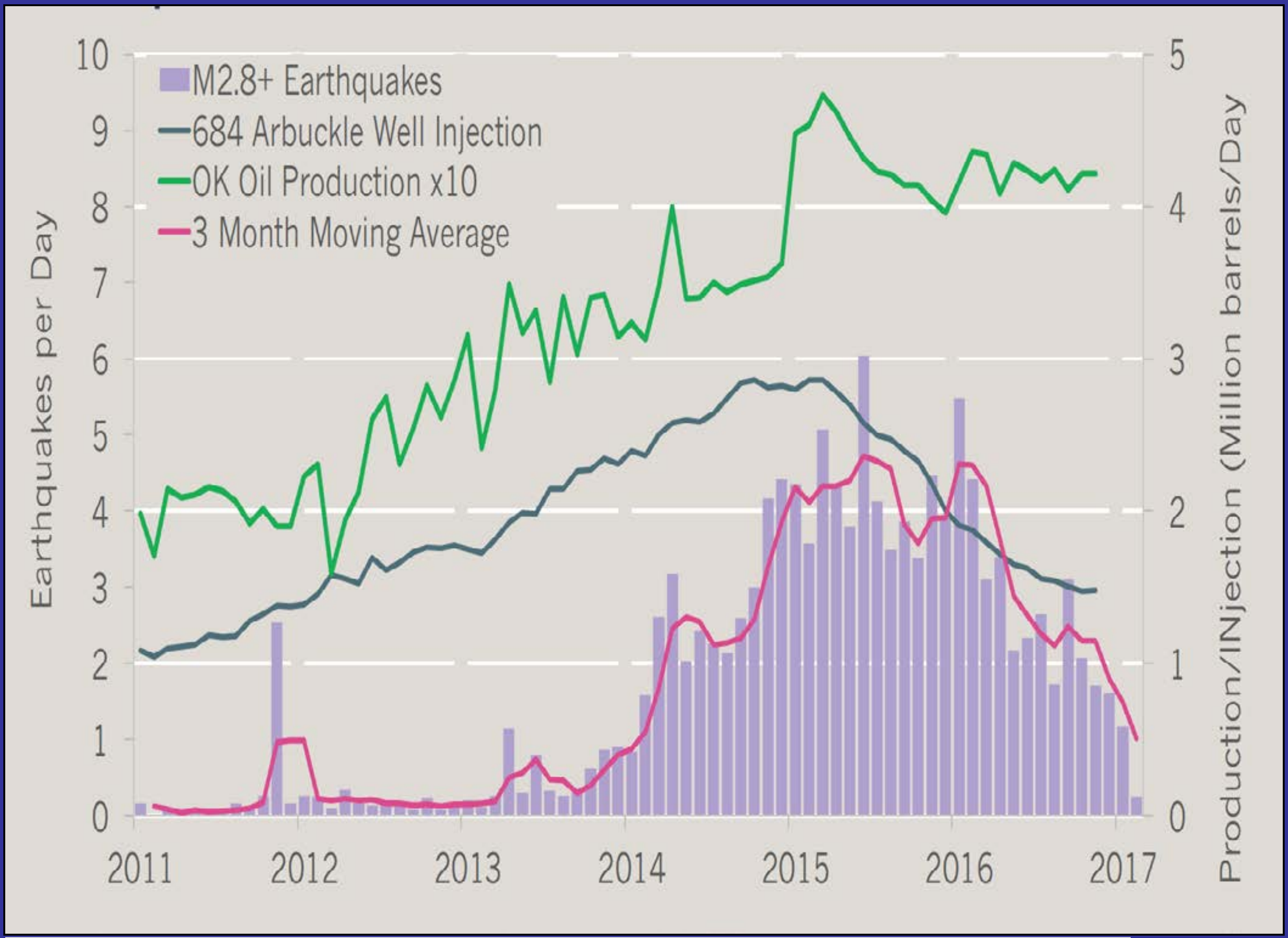
# How human activity can induce earthquakes




From W. L. Ellsworth, 2013, Injection-Induced Earthquakes, *Science* 341, 1225942 (2013). DOI: 10.1126/science.1225942

# Effect of regulations & oil prices in Oklahoma




*Data from J. Walter, J. Boak, K. Murray OGS and OCC; slide adapted from M. Petersen*

2014: OCC implemented wastewater injection reductions, case by case

2015: OCC acted to reduce wastewater injection by 40% in central OK

2016: mandatory reductions after M5.8

Reduction in earthquake rate follows reduction in wastewater injection by about 6-12 months

Recent progress...

Norbeck & Horne (JGR, 2016) studied the 2011 M5.6 Prague, Oklahoma earthquake sequence

## Key observation: one-day delay between M4.8 foreshock and M5.7 mainshock

Assume: stress change from the foreshock triggered the mainshock

Then: the delay implies some kind of hydro-mechanical process with damping

Can: the delay be used, along with a numerical fault model, to estimate properties like fluid transmissivity in the fault zone, fault compliance, and earthquake rate-and-state properties?

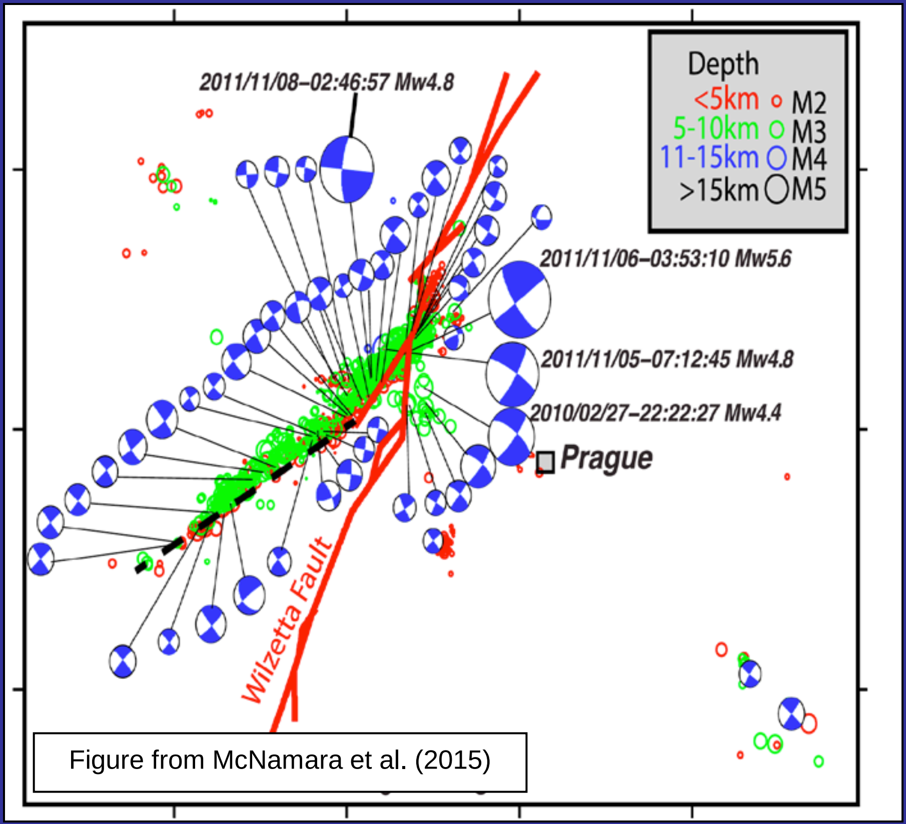
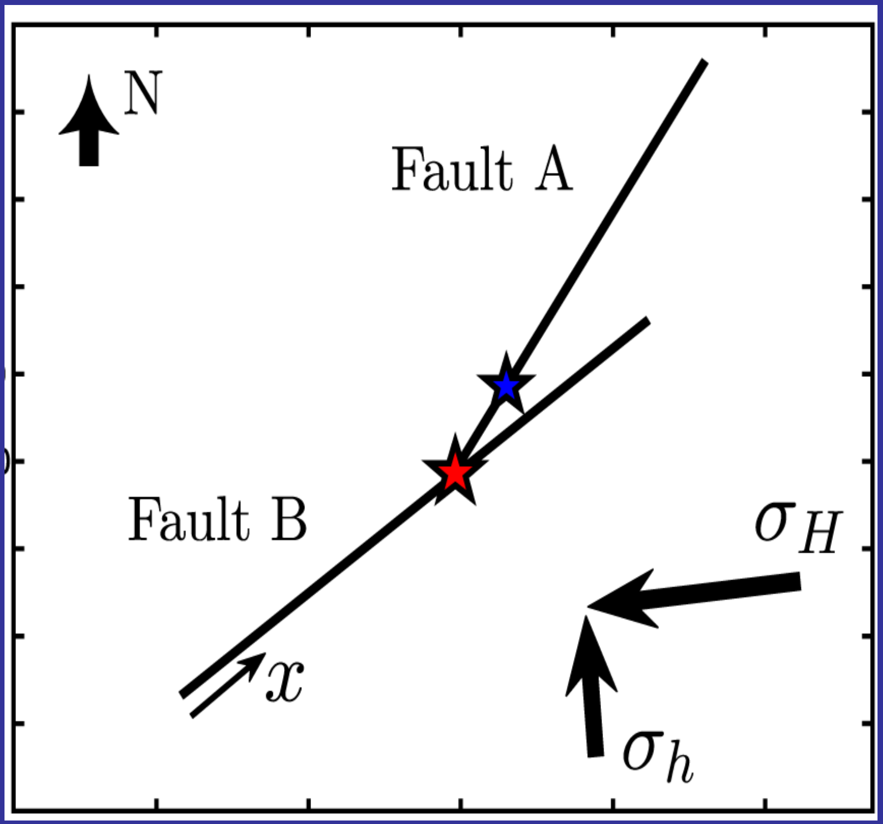



Figure from McNamara et al. (2015)




Slide adapted from J. Norbeck

# Conclusions from the Norbeck & Horne analysis

- The study was informed by previous geomechanical and seismological studies
- Key observation was the one-day delayed triggering
- Their numerical experiments suggest that hydro-mechanical effects can plausibly explain the delayed triggering behavior
- However, they are unable to define a unique set of fault properties or physical processes as “the answer”
- Best results were obtained assuming fairly high fault zone compliance and fairly low fluid transmissivity in the fault zone

Slide adapted from J. Norbeck

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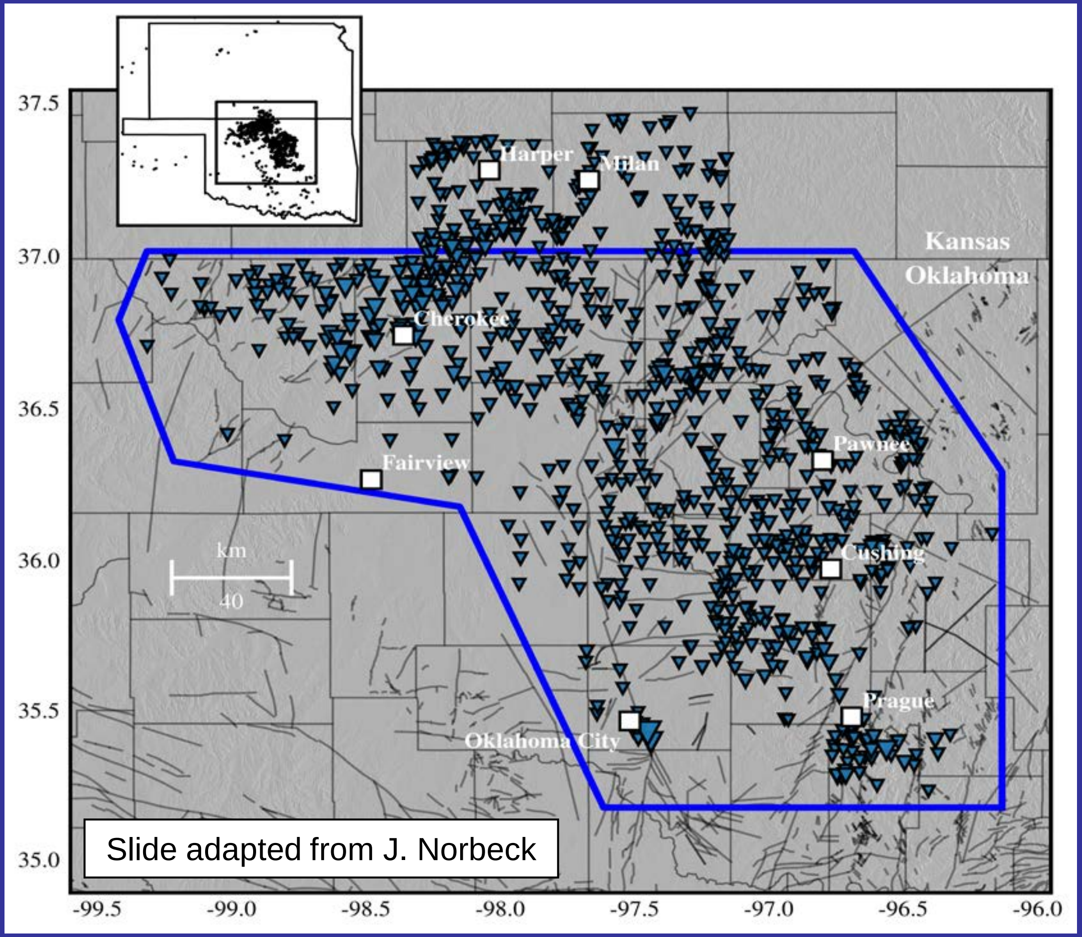
Norbeck & Rubinstein are working on

a new physics-based model for induced earthquakes

## Saltwater disposal well database

- 958 injection wells; 1995–present
- Completed in the Arbuckle aquifer; Arbuckle overlies basement rock
- Injection rate data typically at 1-month resolution
- No pressure data for most wells



# A simple fluid pressure model to capture first-order effects

- Reliable injection-rate data is available; but not pressure data
- Model: fluid pressurization rate is proportional to injection rate
- Also need a few reservoir parameters that can be measured or estimated from field or lab data

| Parameter | Value | Unit | Description |
|---|---|---|---|
| $\dot{s}_0$ | $0.7 \times 10^{-3}$ | $\mathrm{MPa} \cdot \mathrm{yr}^{-1}$ | Background stressing rate[a] |
| $r_0$ | 1 | $\mathrm{earthquake} \cdot \mathrm{yr}^{-1}$ | Background seismicity rate ($\mathrm{M} \geq 3.0$) in the study area[b] |
| $a$ | 0.0065 | - | Direct effect parameter[c] |
| $\bar{\sigma}$ | 50 | MPa | Effective normal stress at seismogenic depth[d] |
| $\phi$ | 0.12 | - | Arbuckle rock porosity[e] |
| $\beta$ | $3.2 \times 10^{-10}$ | $\mathrm{Pa}^{-1}$ | 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].

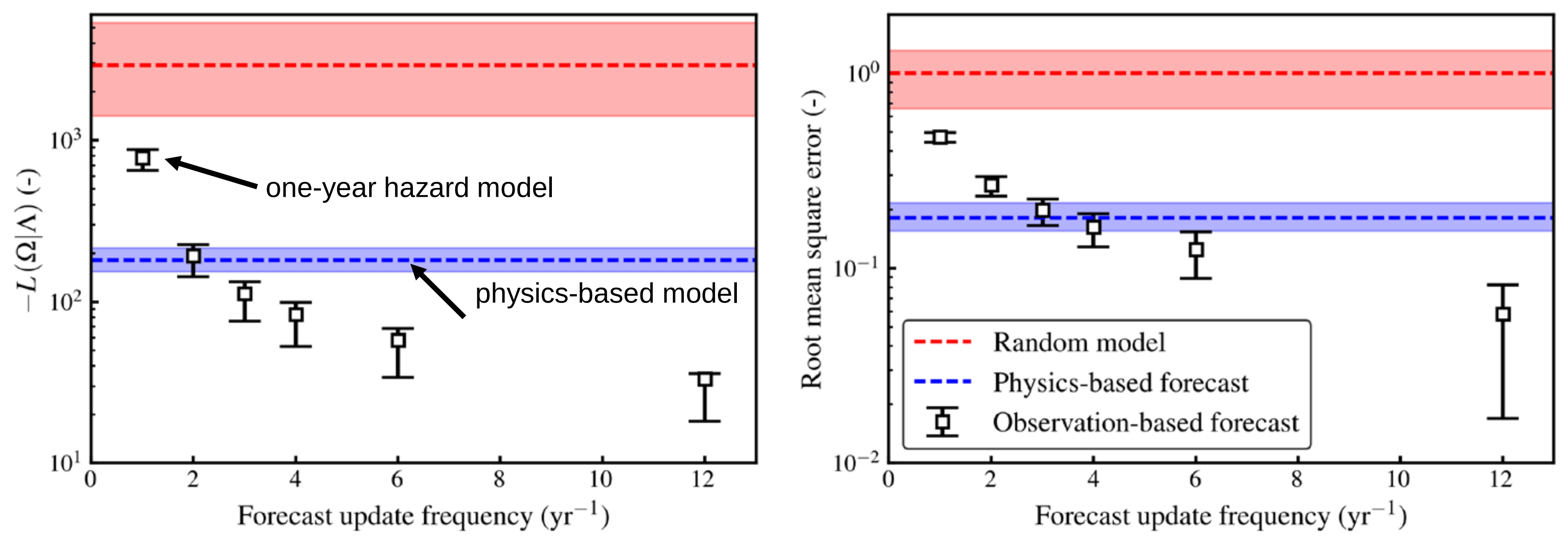
[d] A characteristic effective normal stress is taken as the mean effective stress at 4 km depth based on the stress gradients reported for north-central Oklahoma by Walsh and Zoback [19].

[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].

Slide adapted from J. Norbeck

# Forecast accuracy




Slide from J. Norbeck

# Conclusions & Implications from Norbeck & Rubinstein analysis

- Model is informed by injection rates and locations of disposal wells
- Seismicity rate is governed by stressing rate
- Model does a good job of estimating the seismicity rate
- The system tends toward a steady-state seismicity rate; can injection be carried out such that the seismicity rate remains below some tolerable threshold?

Slide adapted from J. Norbeck

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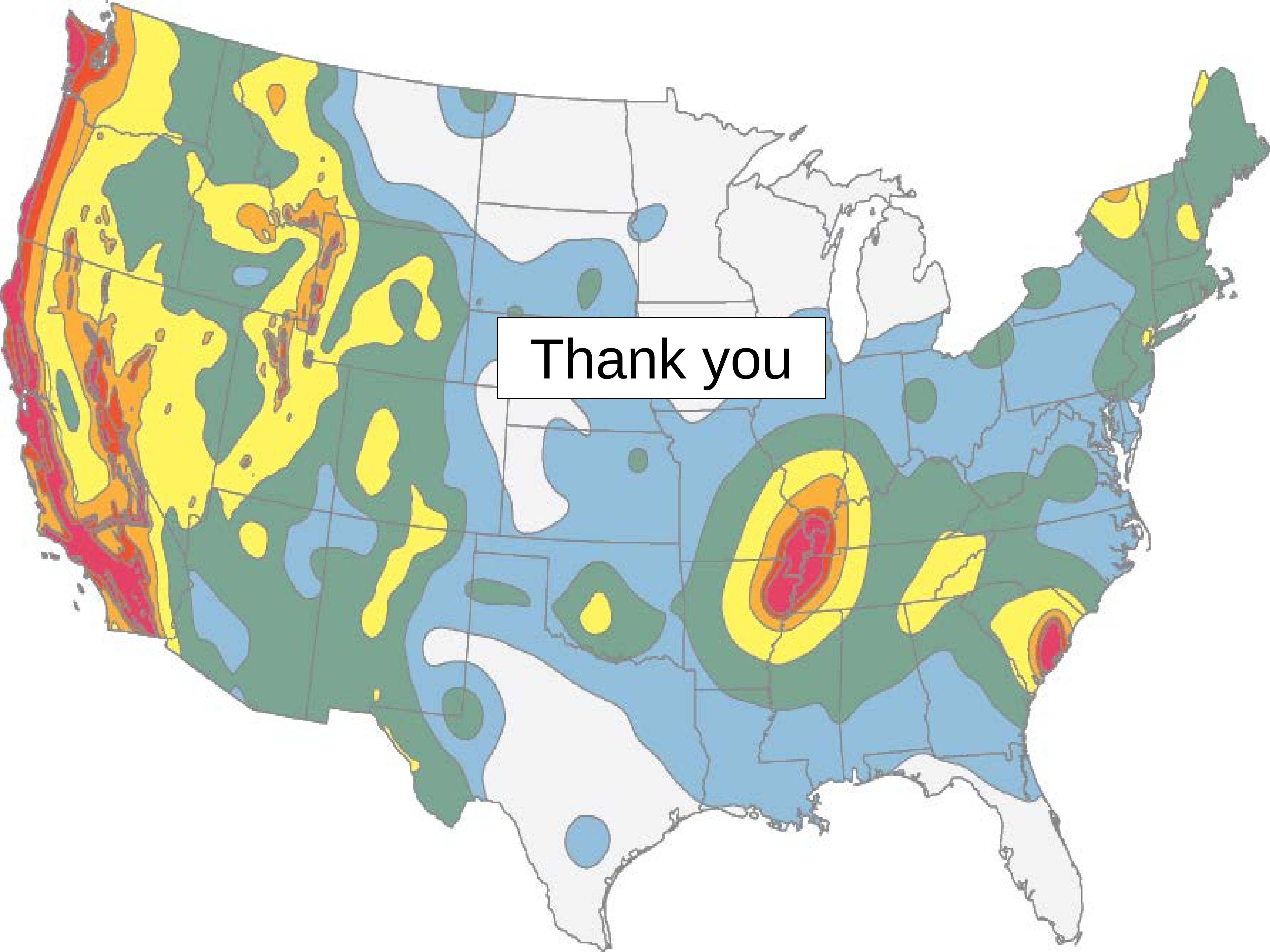
Thank you