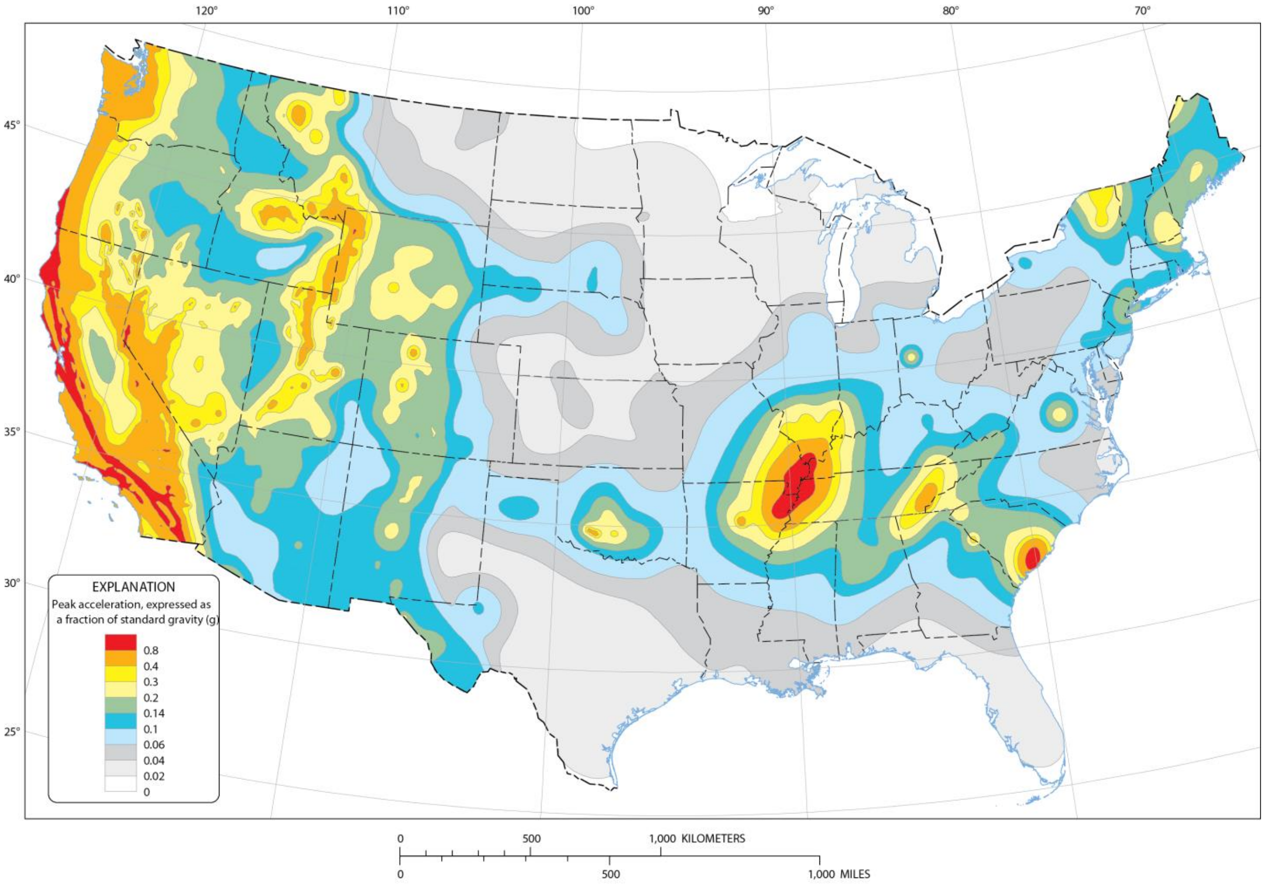
Earthquake Hazard When the Rate is Non-Stationary: The Challenge of the U. S. Midcontinent



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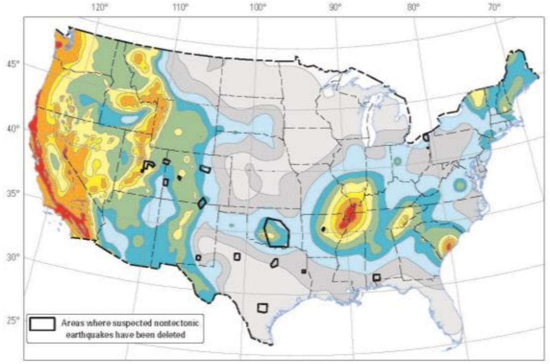


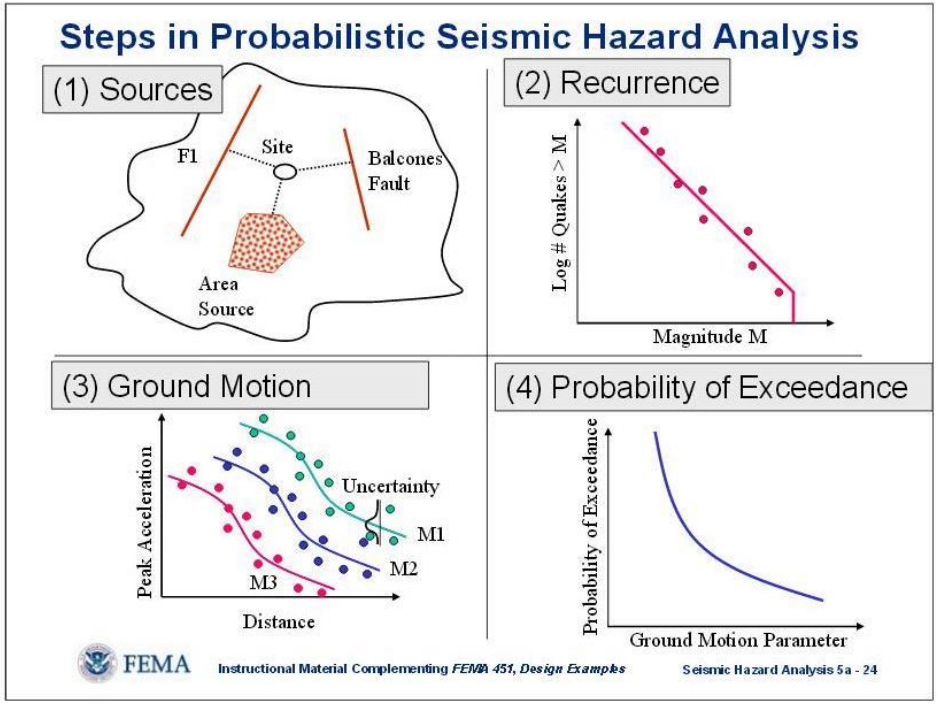
Outline

- Review of Probabilistic Seismic Hazard (briefly)
- Increasing Seismicity in the U. S. Midcontinent
- Adapting PSHA to Non-Stationary Seismicity
- Preliminary Look at Hazard and Its Sensitivity to Epistemic Uncertainty
- Outlook

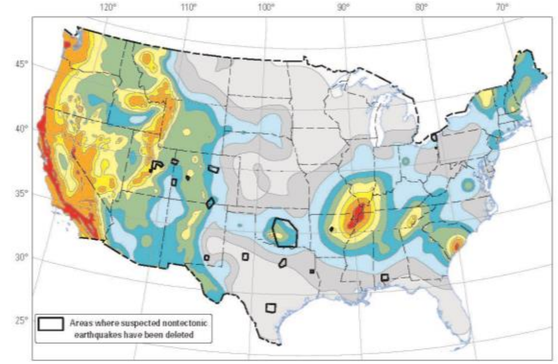
Special thanks to the USGS Induced Seismicity team, especially
Harley Benz, Elizabeth Cochran, Jim Dewey, Steve Hickman, Andrea Llenos,
Art McGarr, Andy Michael, Chuck Mueller, Mark Petersen, Justin Rubinstein
and Rob Williams

Probabilistic Seismic Hazard Analysis

1. Sources: Where will earthquakes occur in the future?
2. Recurrence: How often will they happen and how large can they get?
3. Ground Motion: How hard will they shake the ground?
4. PSHA: When answers are available for Steps 1-3: Add up all of the sources to find the probability of exceeding damaging shaking.

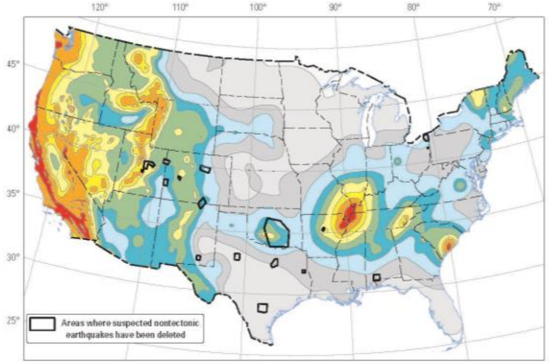


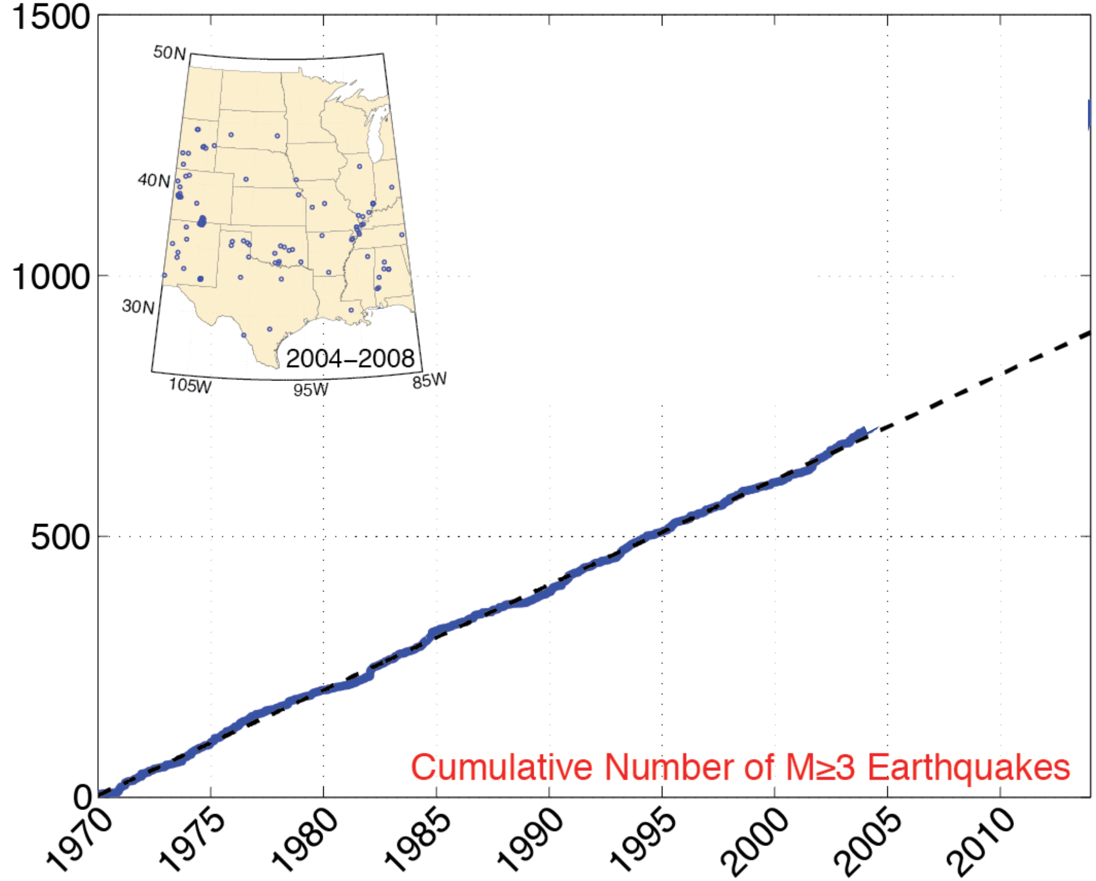
2014 National Seismic Hazard Map



- Probabilistic estimate of earthquake shaking
  - e.g., 2% probability of exceedance in 50 years
- Underlies seismic design provisions of the build codes
  - Assumes time-independent rate of earthquake occurrence
- Developed from geology, geodesy, seismology in the western U.S.
- Based primarily on rate of small-magnitude earthquakes in the central and eastern U.S. where there are few active faults and deformation rates are near zero
- Areas with increased earthquake activity acknowledged but ignored in preparing the map

2008 Hazard Map used earthquake catalog data through 2006

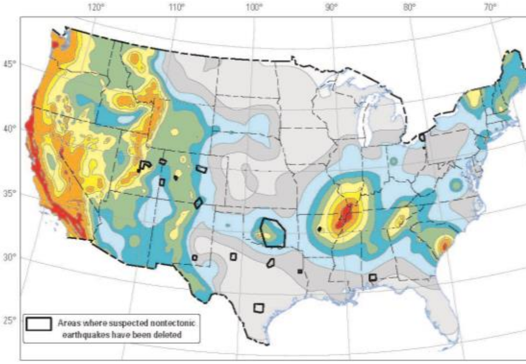




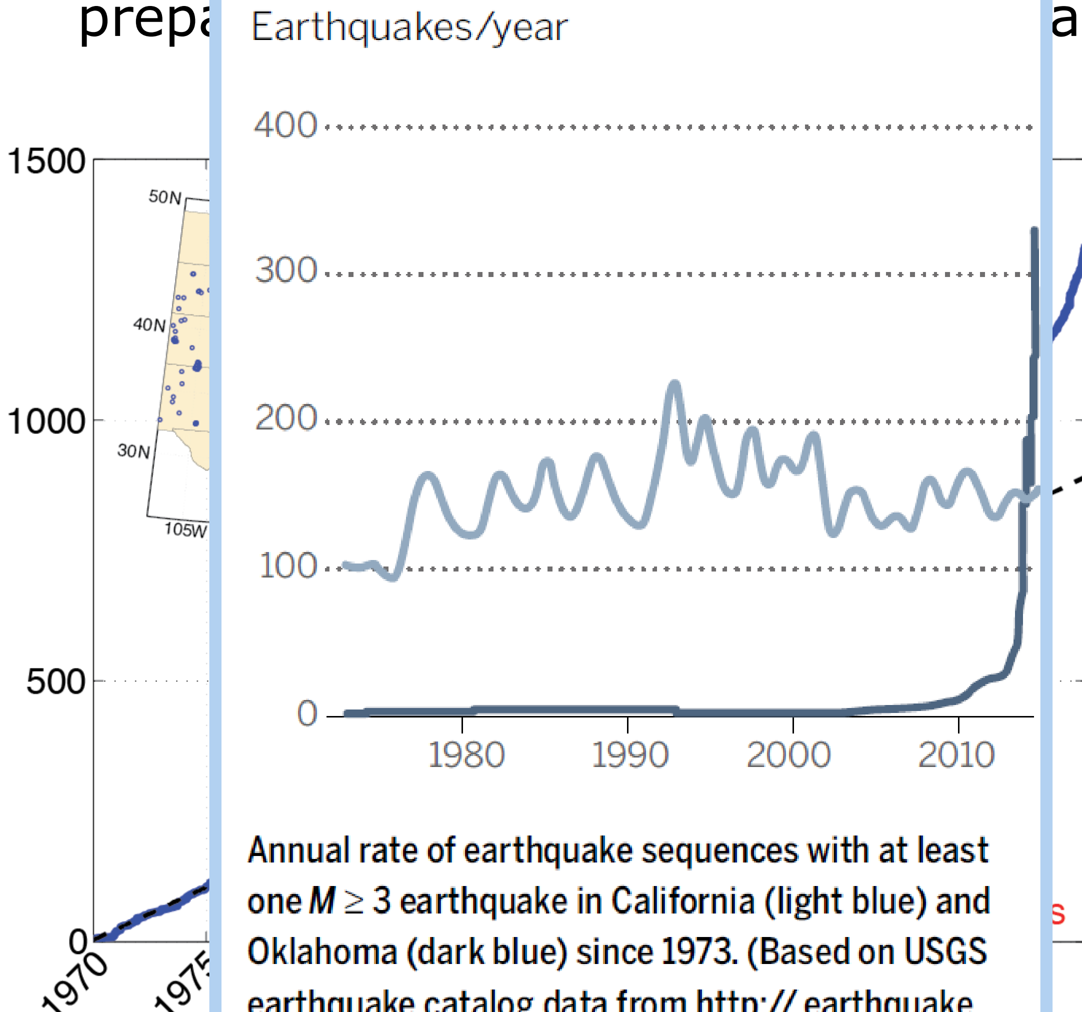
Earthquake rate modeled by a time-independent Poisson Process.

Selected areas of known or suspected induced seismicity removed from map.

Increasing earthquake activity in the U. … n prep… ate



Seismic surge in Oklahoma



Annual rate of earthquake sequences with at least one $M \geq 3$ earthquake in California (light blue) and Oklahoma (dark blue) since 1973. (Based on USGS earthquake catalog data from http://.earthquake.usgs.gov.)

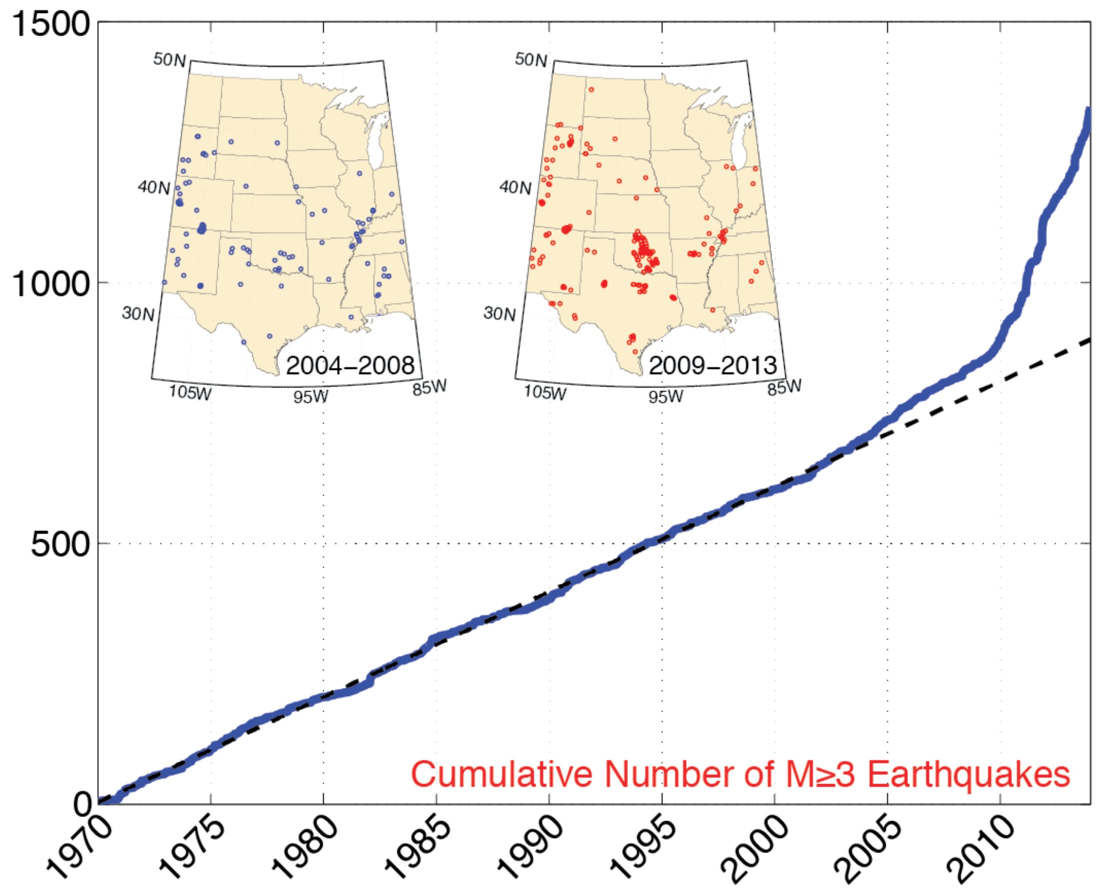
Higher rate of earthquakes implies higher hazard.

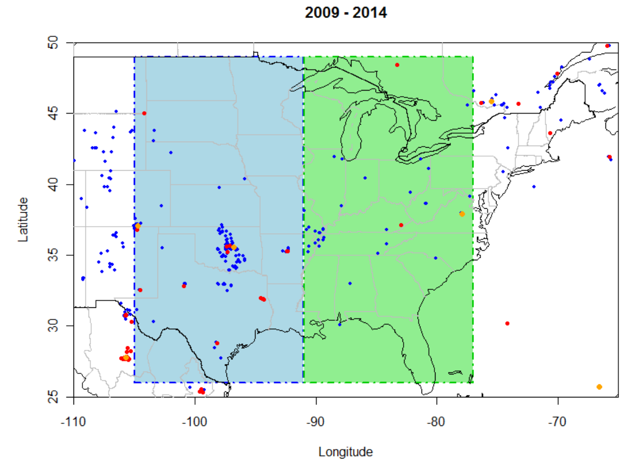
But how much higher?

How long will the higher hazard last?

What types of hazard models do users want?

Examine evolution of seismicity in the central and eastern U. S. using National Seismic Hazard Map catalog

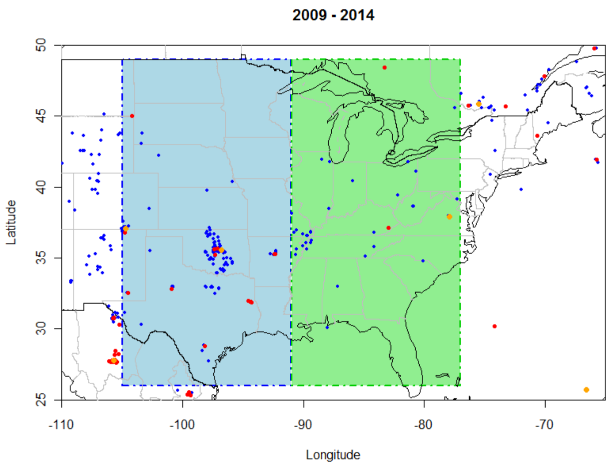




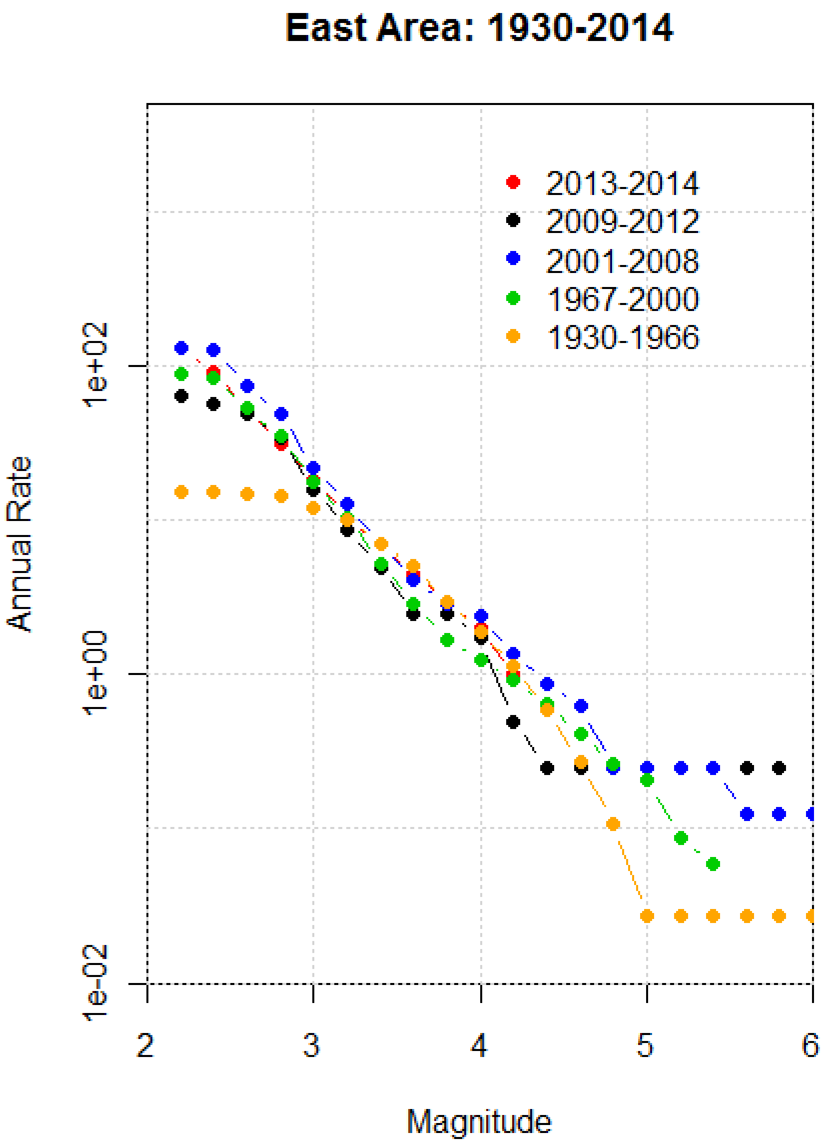
Divide region into an east and west areas

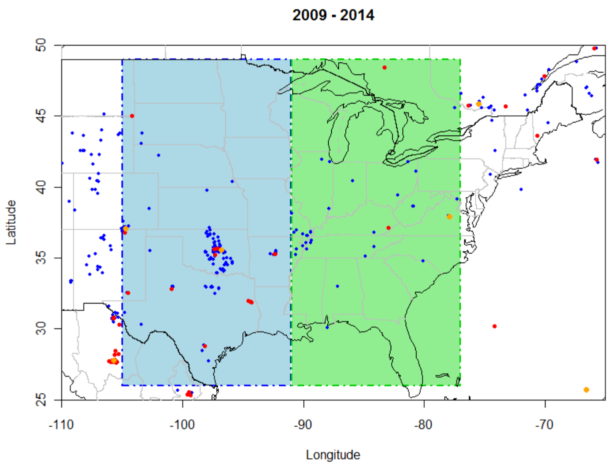
East area contains source region of 1811-1812 New Madrid earthquakes and 1886 Charleston earthquake

West area includes many areas of known and suspected induced seismicity

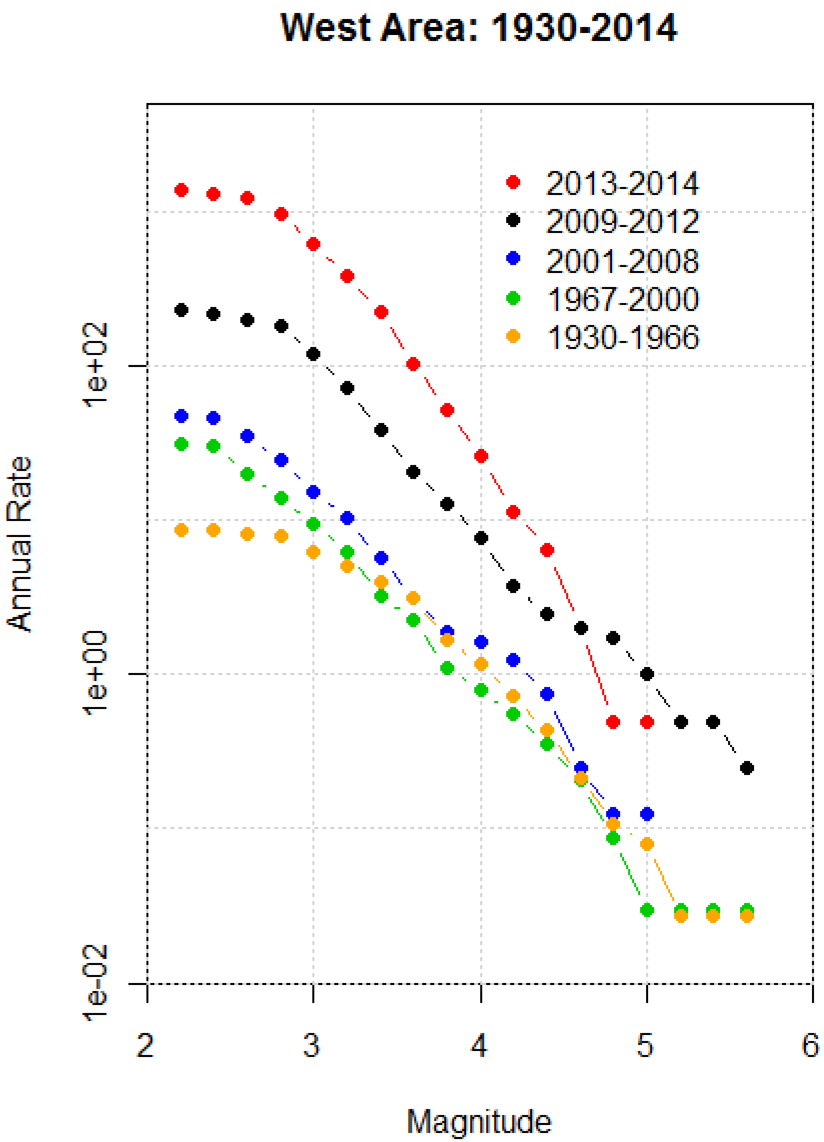


Magnitude-frequency analysis in the east area indicates no significant variation in earthquake rate from 1930 through 2014 for M≥ 3.5

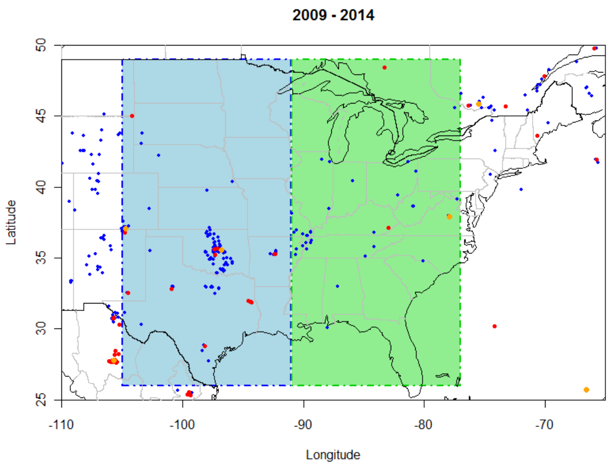


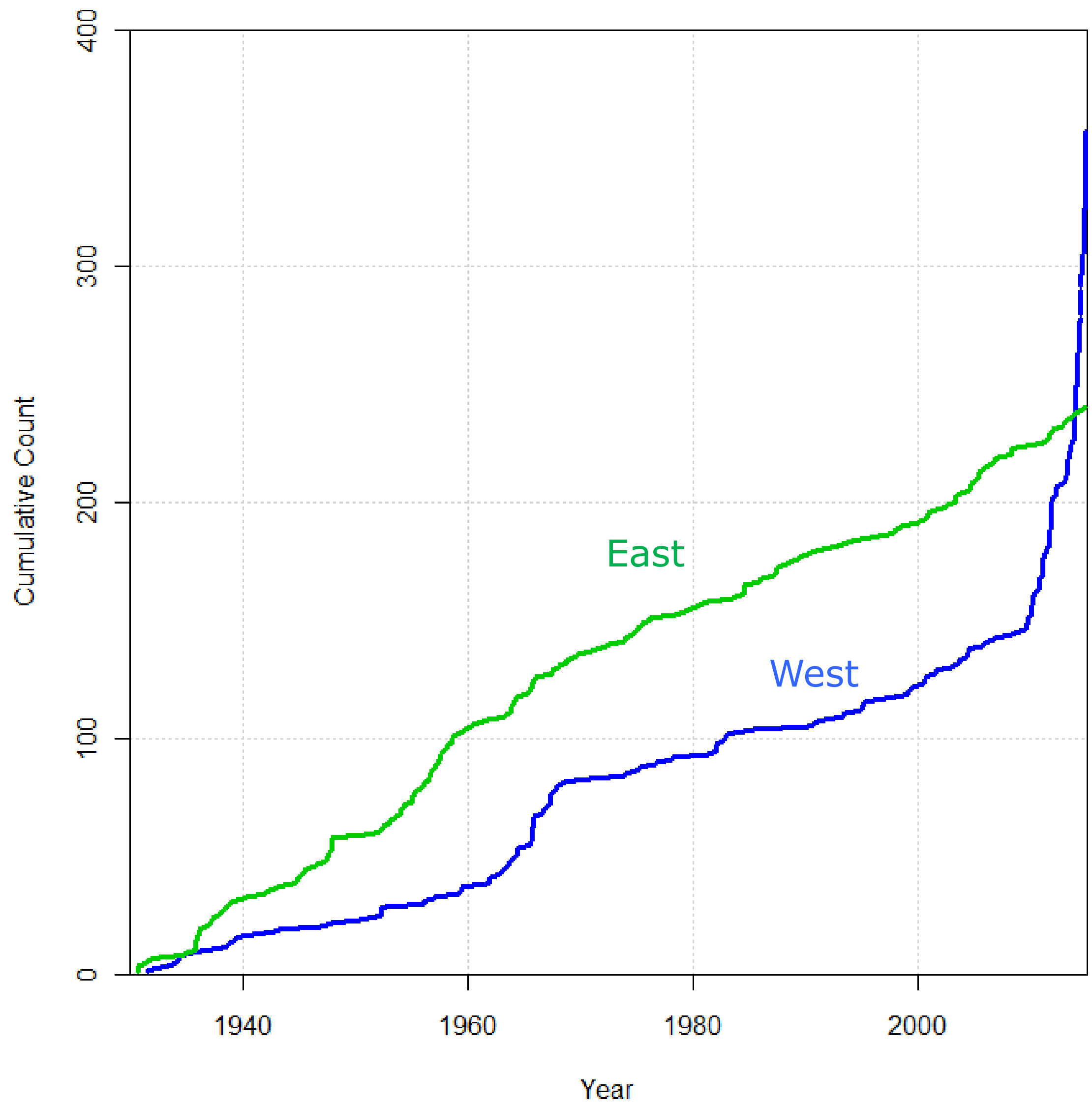


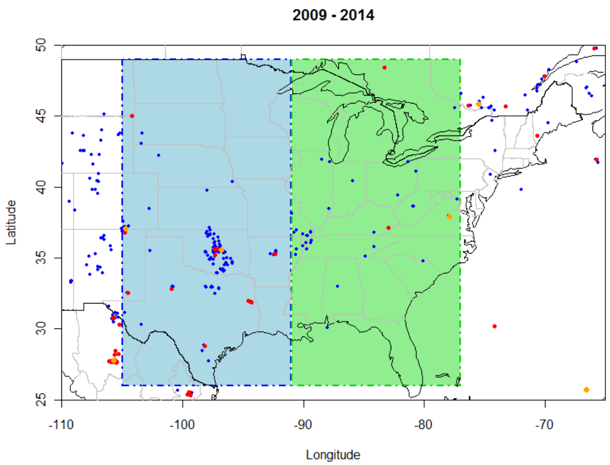
Magnitude-frequency analysis in the west area shows increasing seismicity after 2008 for M≥ 3.5

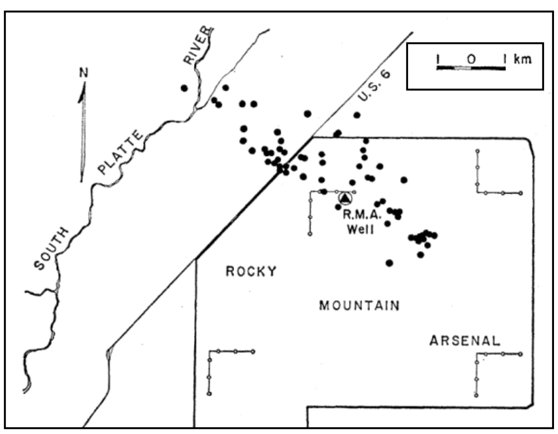


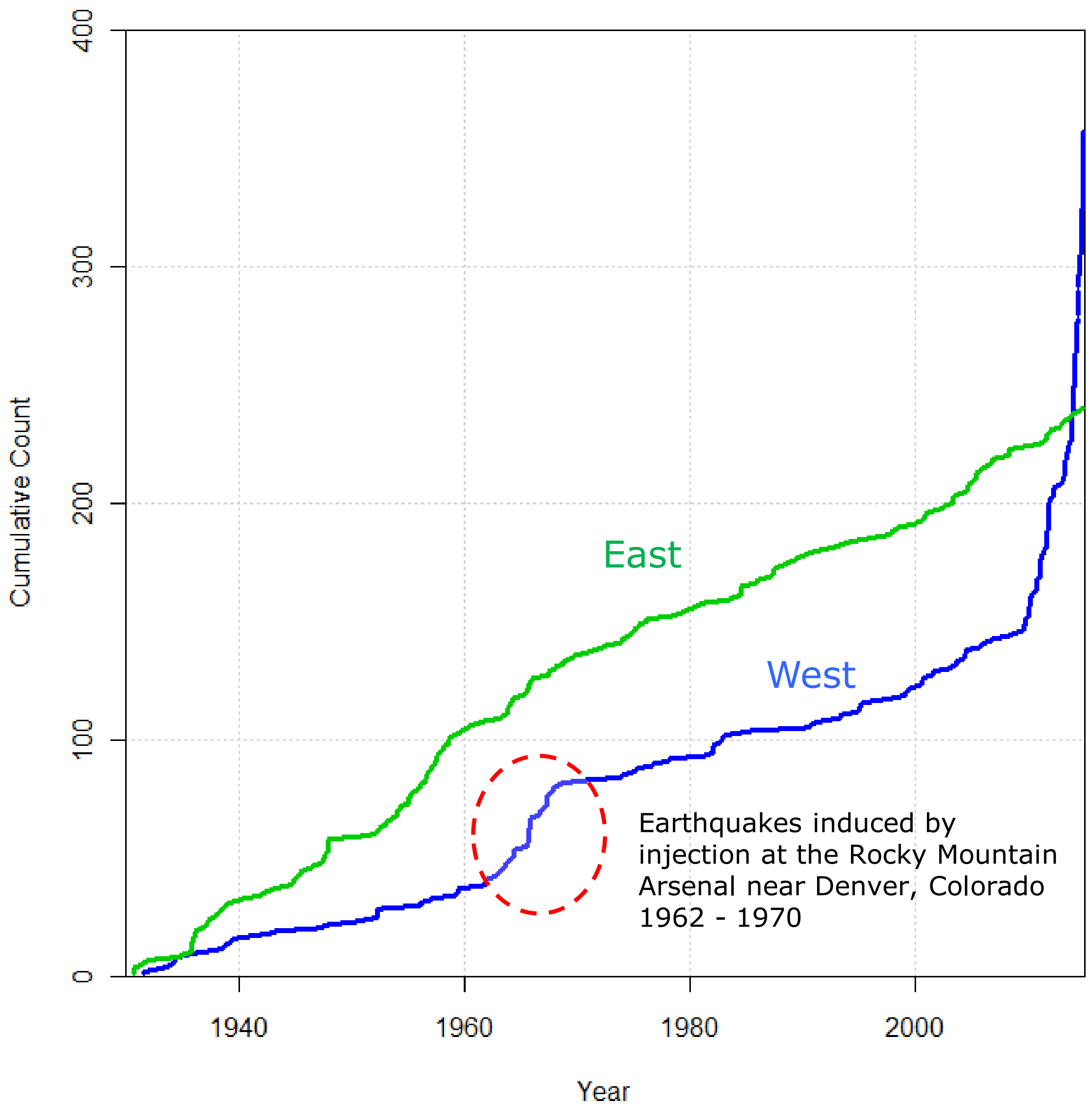
Cumulative Earthquake Count M ≥ 3.5






2009 - 2014
Latitude
Longitude
-110
-100
-90
-80
-70
25
30
35
40
45
50


N
SOUTH
PLATTE
RIVER
U.S. 6
1 0 1 km
R.M.A. Well
ROCKY
MOUNTAIN
ARSENAL


Cumulative Count
Year
East
West
Earthquakes induced by injection at the Rocky Mountain Arsenal near Denver, Colorado 1962 - 1970
0
100
200
300
400
1940
1960
1980
2000

National Seismic Hazard Workshop on Induced Seismicity

Co-hosted by: Oklahoma Geological Survey and USGS
November 17th - 19th, 2014
Reed Center, Midwest City, Oklahoma

Incorporating Induced Seismicity in the 2014 United States National Seismic Hazard Models: Results of 2014 Workshop and Sensitivity Studies

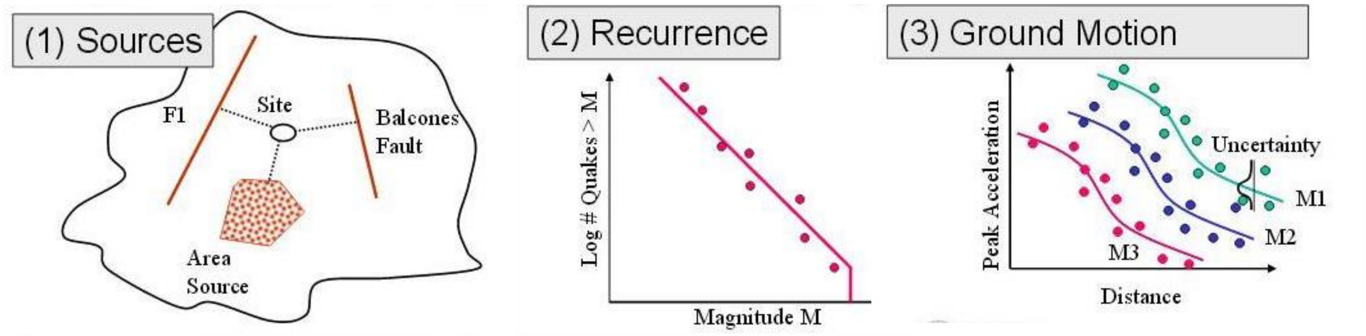
Mark D. Petersen, Charles S. Mueller, Morgan P. Moschetti, Susan M. Hoover, Justin L. Rubinstein, Andrea L. Llenos, William L. Ellsworth, Austin A. Holland, Art McGarr and John G. Anderson

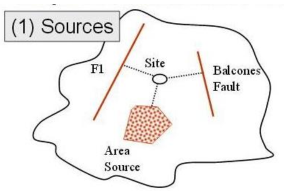
Open-File Report 2014–XXXX

Provisional Logic Tree Elements for 1-Year Hazard Map

Evaluate five classes of input models:

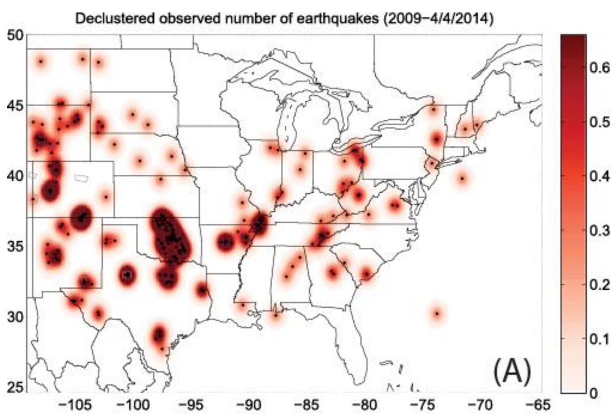
(1) earthquake catalog
(2) earthquake rates
(3) earthquake locations
(4) earthquake maximum magnitude
(5) earthquake ground motions.

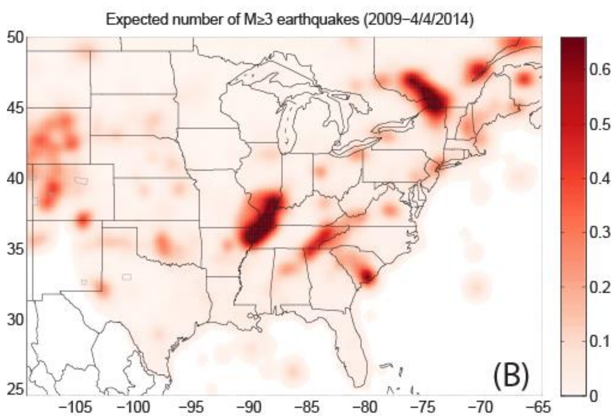


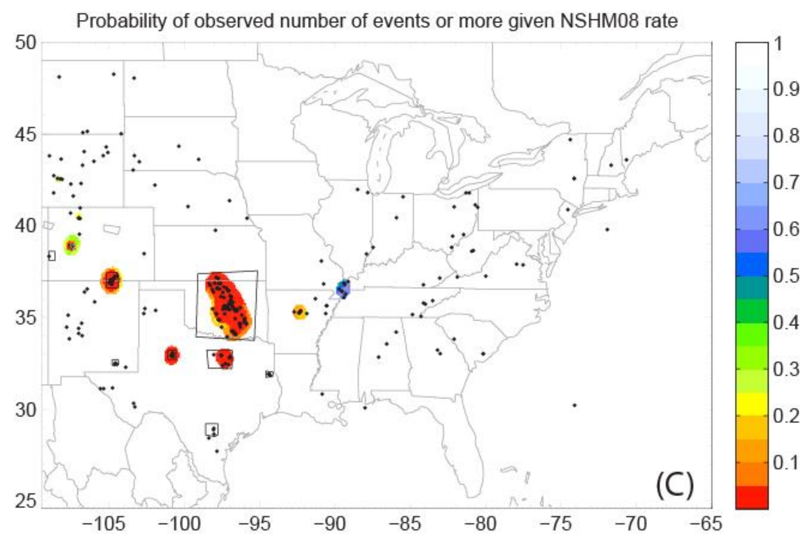


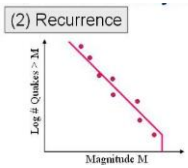
Step 1. How do we identify regions with changing activity?

Apply statistical tests to determine where seismic activity rates have changed, relative to the pre-2009 baseline. This permits us to forecast “last year’s” earthquakes.









Step 2. How do we account for changing earthquake rates?

Earthquake rate changes in northern Oklahoma

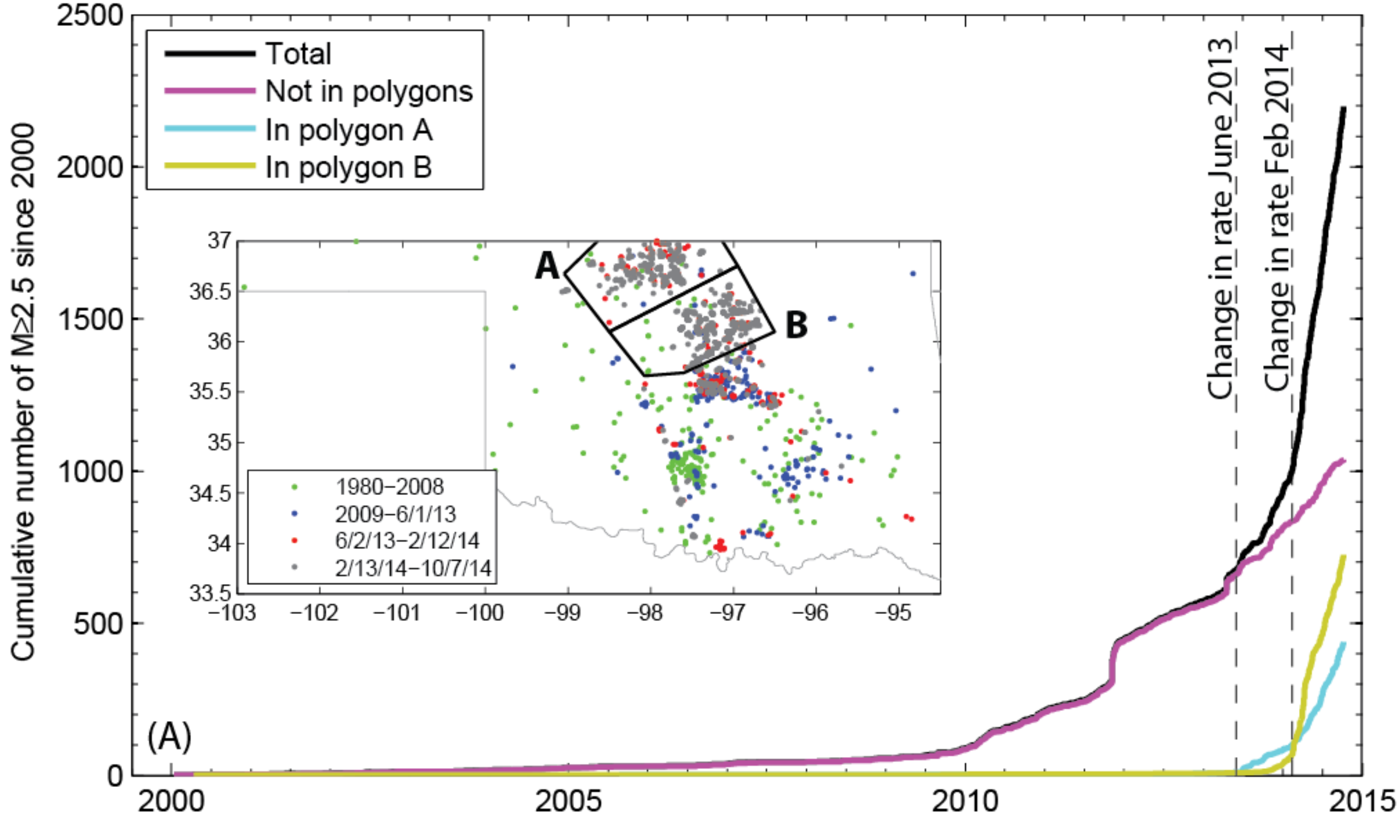
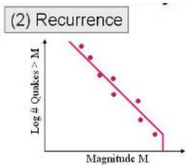
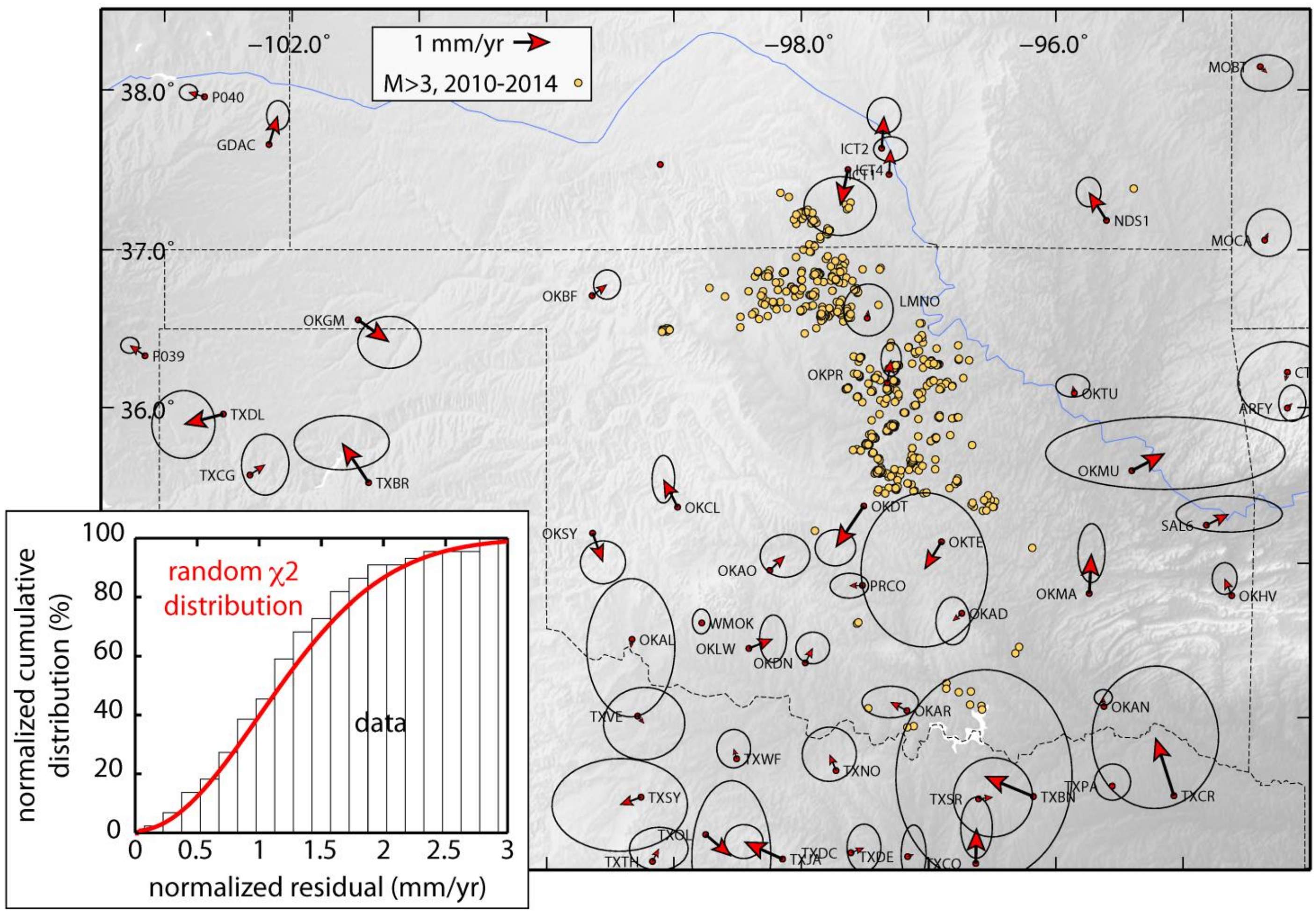


Figure from Llenos et al., Fall 2014 AGU

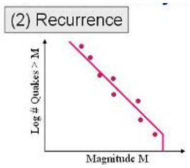


Step 2. How do we account for changing earthquake rates?

Horizontal Deformation Rate 2002 - 2014



Courtesy of Eric Calais, ENS, Paris

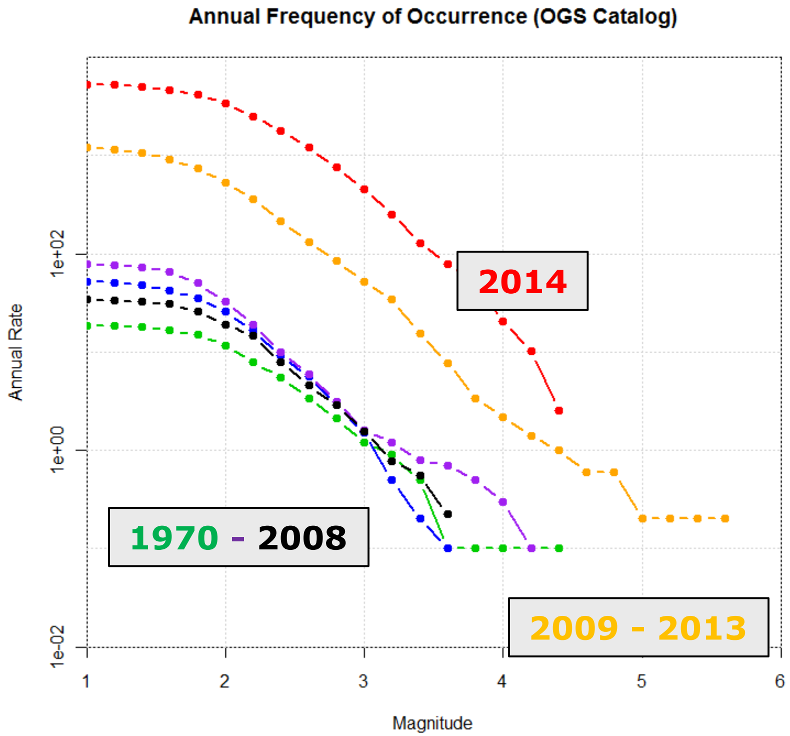


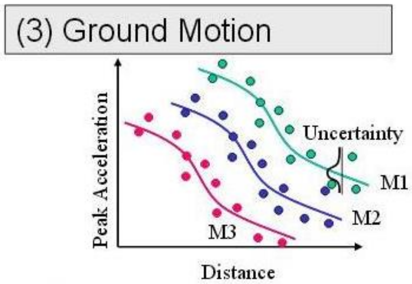
Step 2. How do we account for changing earthquake rates?

Hazard obviously depends on the a-value in the G-R relation.

What about b and Mmax?

- Hazard is not very sensitive to the choice of Mmax.
- Hazard is quite sensitive to the b=value



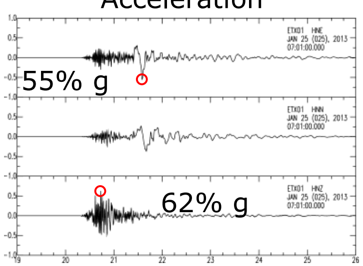


Step 3. What ground motion prediction equations are appropriate?

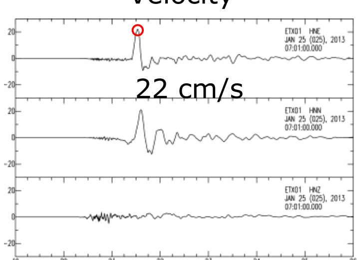
Many induced earthquakes occur at shallow depth, commonly near the top of the crystalline basement. Consequently, ground motion prediction equations (GMPEs) need to model earthquake focal depth.

Observed ground motions in Eastern U.S. induced earthquakes compare well with Western U.S. GMPEs (G. M. Atkinson, BSSA, submitted). These Western relations may be an appropriate starting point for PSHA.

Acceleration

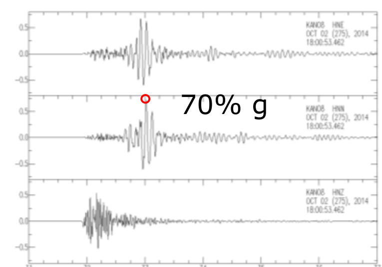


Velocity

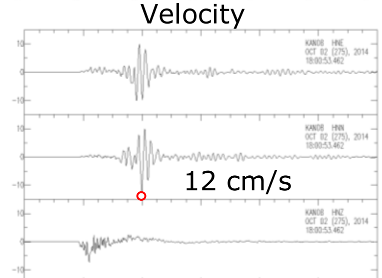


M_w 4.1 January 25,2013
Timpson, Texas Earthquake

Acceleration

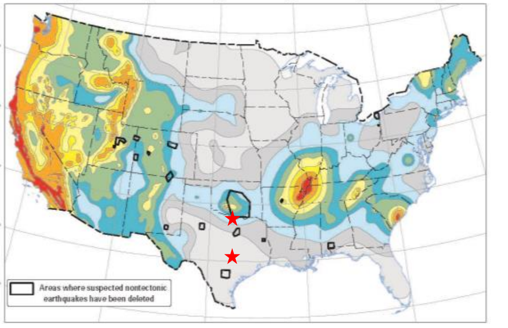


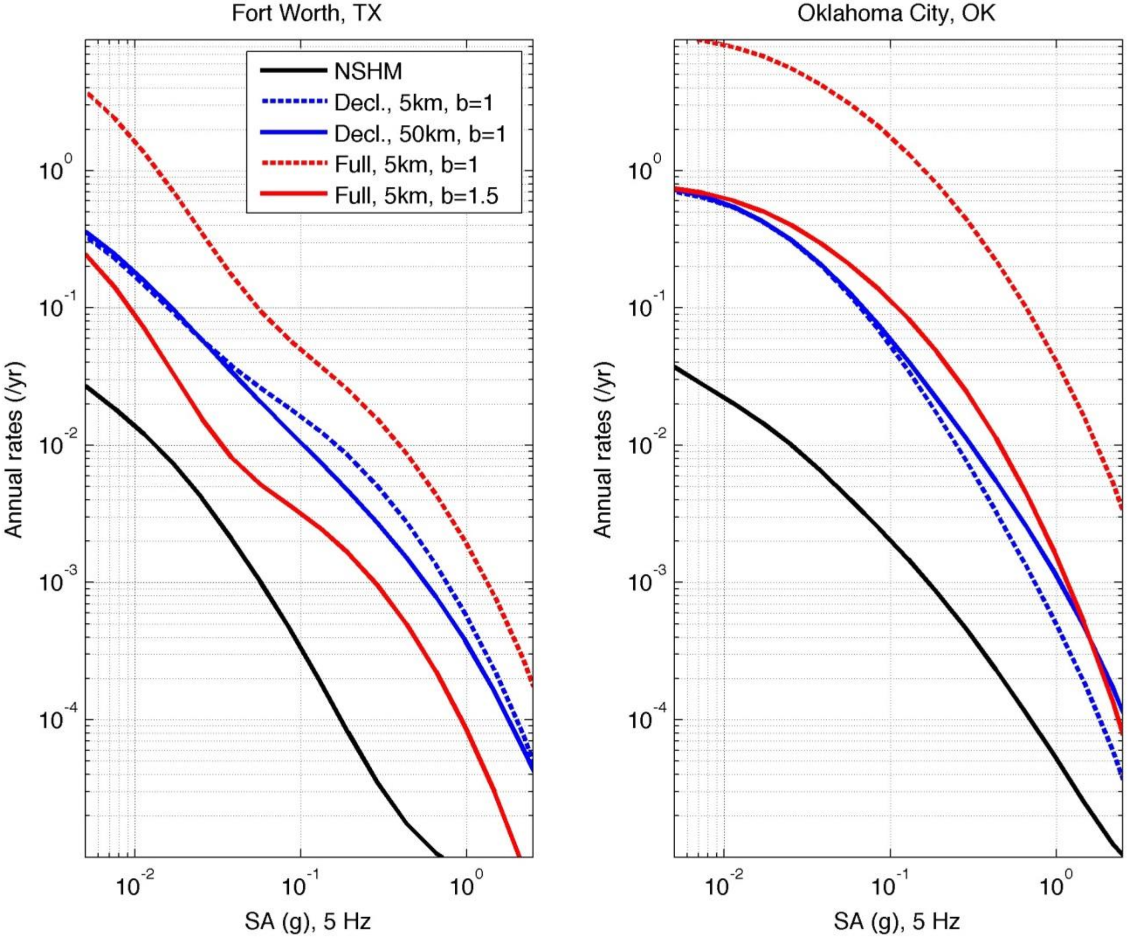
Velocity



M_w 4.3 October 2, 2014
Anthony, Kansas Earthquake

Example Hazard Curves



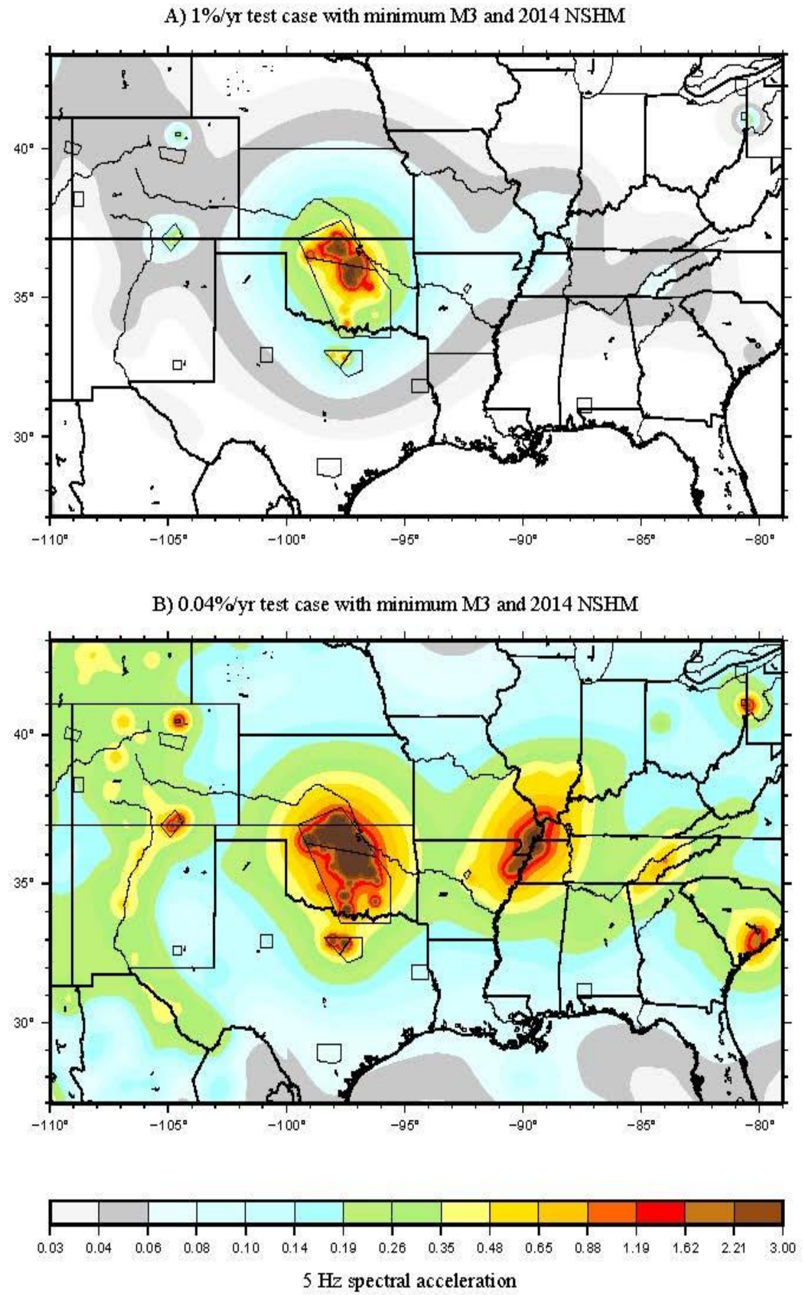


Content is preliminary and should not be considered a final USGS product.

1-Year Hazard Model For 2015 for 5 Hz spectral acceleration

Assuming:

- Earthquake rate from 2014
- Non-declustered catalog
- b-value of 1.0
- 5 Km smoothing kernel
- Eight ground motion models
- Mmax of 7



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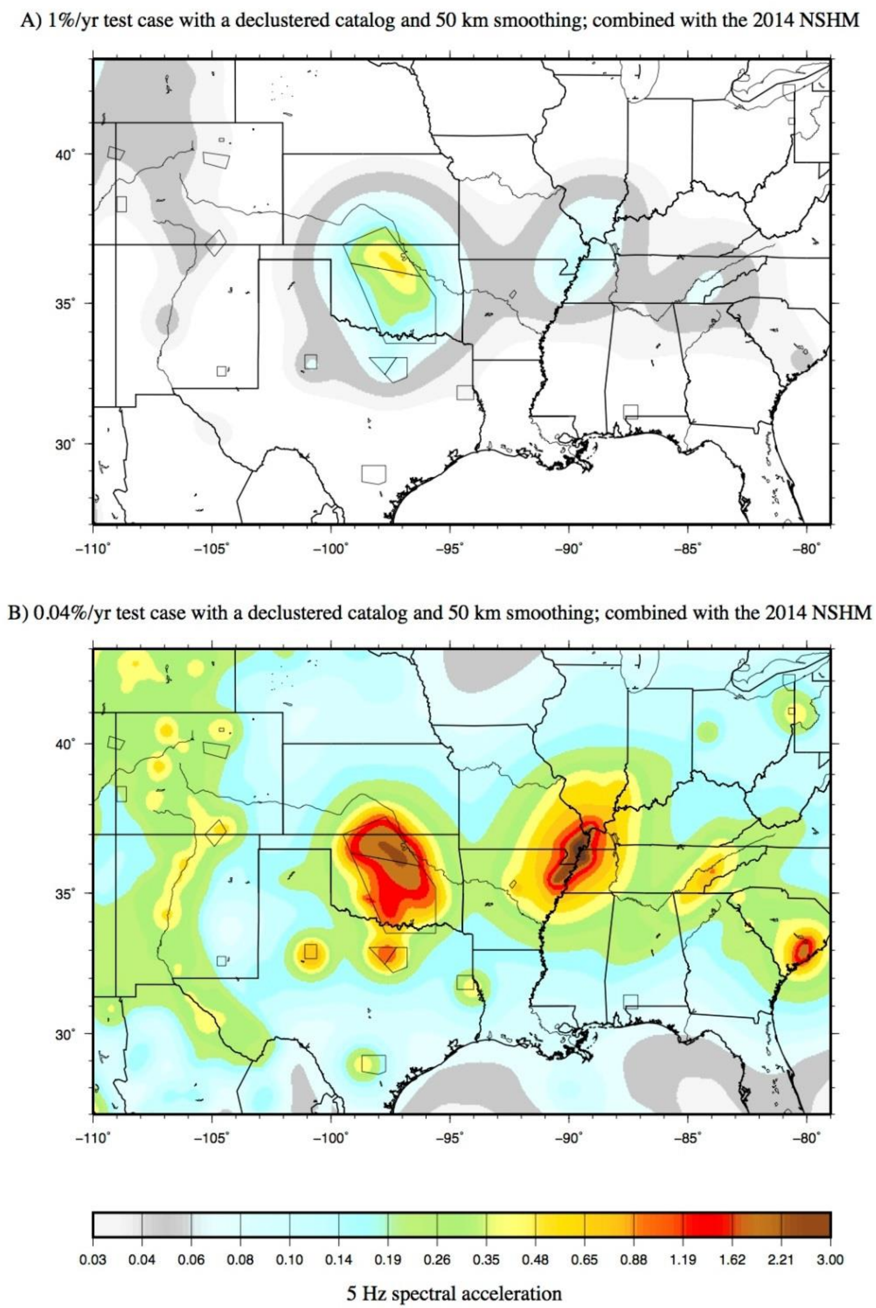
1-Year Hazard Model For 2015 for 5 Hz spectral acceleration

Assuming:

- Earthquake rate from 2014
- Declustered catalog
- b-value of 1.5
- 50 Km smoothing kernel
- Eight ground motion models
- Mmax of 7



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1-Year Hazard Model For 2015 for 5 Hz spectral acceleration

Assuming:

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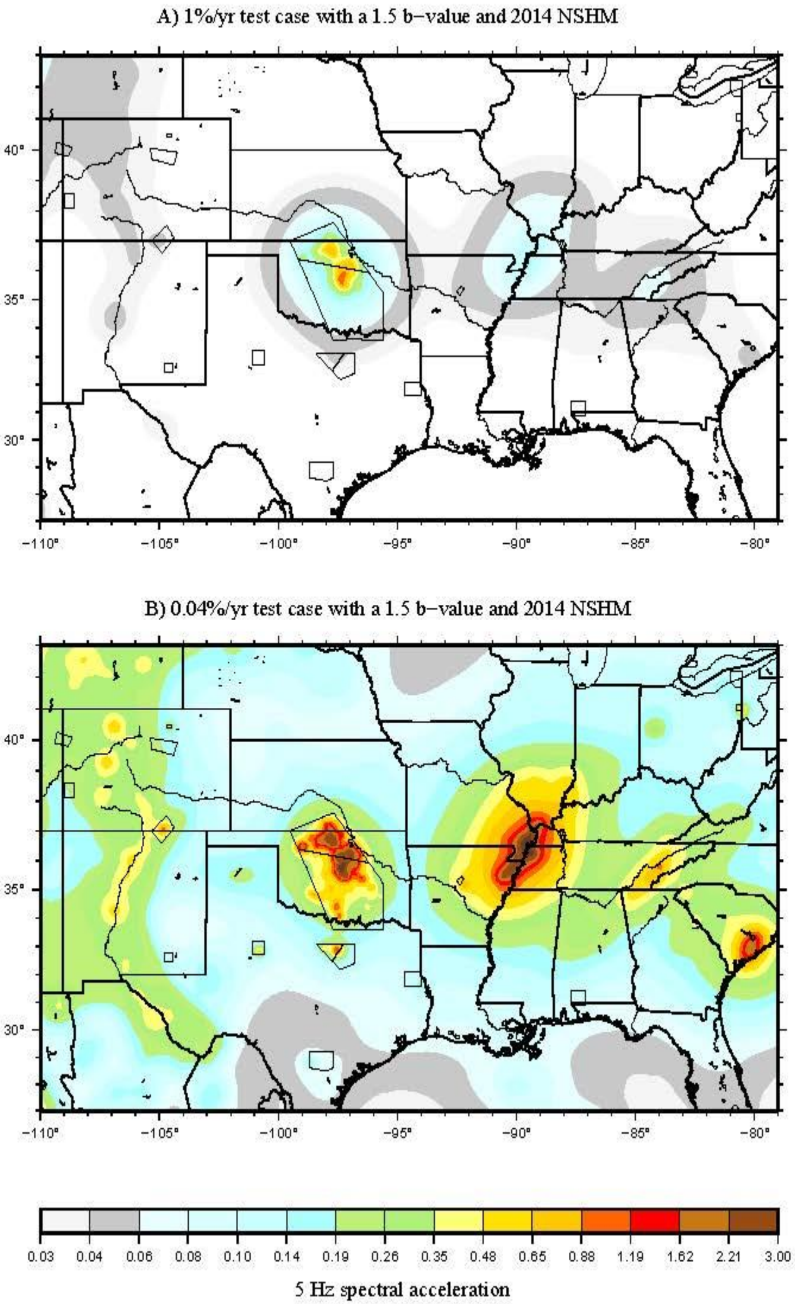
- Declustered catalog
- b-value of 1.5
- 5 Km smoothing kernel
- Eight ground motion models
- Mmax of 7



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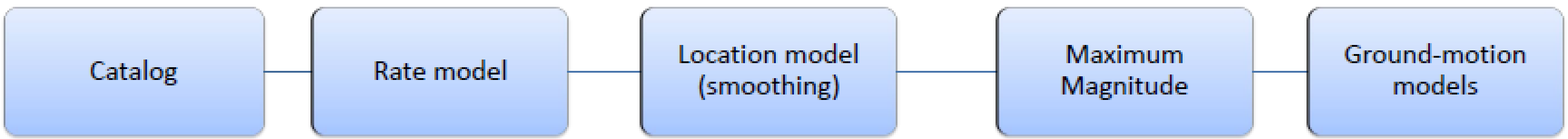
Outlook

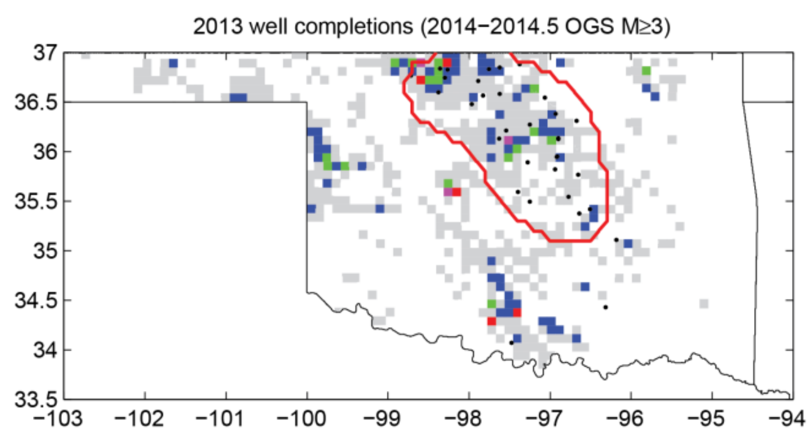
Probabilistic Seismic Hazard Analysis provides an appropriate framework for short-term forecasts of the increased hazard due to temporally changing earthquake rates.

Hazard is sensitive to epistemic uncertainty in all elements of the logic tree



and can be reduced through targeted research.

Keys to further progress include improved modeling of the physical system including the state of stress, hydrogeology, potentially active faults, and more information on oil field activities and wastewater injection, and better detection and characterization of both natural and induced earthquakes.



Thank You