Assessing Potential Seismic Hazards from Induced Earthquakes in the Central and Eastern United States*

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Abstract

Induced seismicity related to unconventional oil and gas production has drawn much attention in recent years in the central and eastern United States, Arkansas, Kansas, Ohio, Oklahoma, and Texas, in particular. For example, the 2011 M 5.7 Prague, Okla., earthquake resulted in more than $10 million in insured losses. However, assessing the seismic hazard from induced seismicity is not an easy task because of large inherent uncertainties in location, magnitude, and recurrence interval of earthquakes, as well as ground-motion attenuation. Thus, how to quantify and communicate the inherent uncertainty is critical for assessing seismic hazard from induced seismicity.

Seismic hazards include primary ones that are directly generated by an earthquake (fault rupture): surface rupture and ground motion (shaking); and secondary ones that could be caused by strong ground motion under certain site conditions: amplification, liquefaction, and landslides. Surface rupture occurs in the vicinity of the fault rupture, whereas ground motion can propagate far away from the fault, affecting a much larger area. Secondary hazards are concentrated at locations with certain site conditions under the influence of strong ground motion. No surface rupture has been found to be associated with induced earthquakes in the central and eastern United States. Also, amplification, liquefaction, and landslides are not major concerns because the magnitudes of induced earthquakes are less than M 6.0. Thus, ground-motion hazard is the main concern from induced earthquakes.

Probabilistic seismic hazard analysis has been used to assess ground-motion hazard from induced earthquakes. However, PSHA is scientifically invalid because it contains a mathematical error: equating the annual probability of exceedance (i.e., the probability of exceedance in 1 year and a dimensionless quantity) with a frequency or rate of exceedance (i.e., the annual frequency of exceedance and a dimensional quantity with the unit of 1/year). Thus, PSHA should not be used for ground-motion hazard assessment from induced earthquakes. We propose using a scenario-based seismic hazard analysis to assess ground-motion hazard from induced earthquakes.

Selected References

Petersen, M.D., C.S. Mueller, M.P. Moschetti, S.M. Hoover, J.L. Rubinstein, A.L. Llenos, A.J. Michael, W.L. Ellsworth, A.F. McGarr, A.A. Holland, and J.G. Anderson, 2015, Incorporating induced seismicity in the 2014 United States National Seismic Hazard Model—Results of 2014 workshop and sensitivity studies: U.S. Geological Survey Open-File Report 2015–1070, 75p. Website accessed December 14, 2016, https://pubs.usgs.gov/of/2015/1070/pdf/ofr2015-1070.pdf.

Petersen, M.D., C.S. Mueller, M.P. Moschetti, S.M. Hoover, A.L. Llenos, W.L. Ellsworth, A.J. Michael, J.L. Rubinstein, A.F. McGarr, and K.S. Rukstales, 2016, One-year seismic hazard forecast for the Central and Eastern United States from induced and natural earthquakes: U.S. Geological Survey Open-File Report 2016-1035, version 1, 58p. Website accessed December 14, 2016, https://pubs.usgs.gov/of/2016/1035/ofr20161035ver1_1.pdf.

Websites

http:///www.newson6.com/story/15972590/earthquake-damages-historic-building-at-university-in-shawnee

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http://www.usgs.gov/blogs/features/usgs_top_story/man-made-earthquakes

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Eastern Section AAPG, Lexington, Kentucky, 26-Sep-2016

Outline

- Induced Seismicity from Hydraulic Fracturing (Fracking)/Waste Water Injection in CEUS

- Induced Seismic Hazards

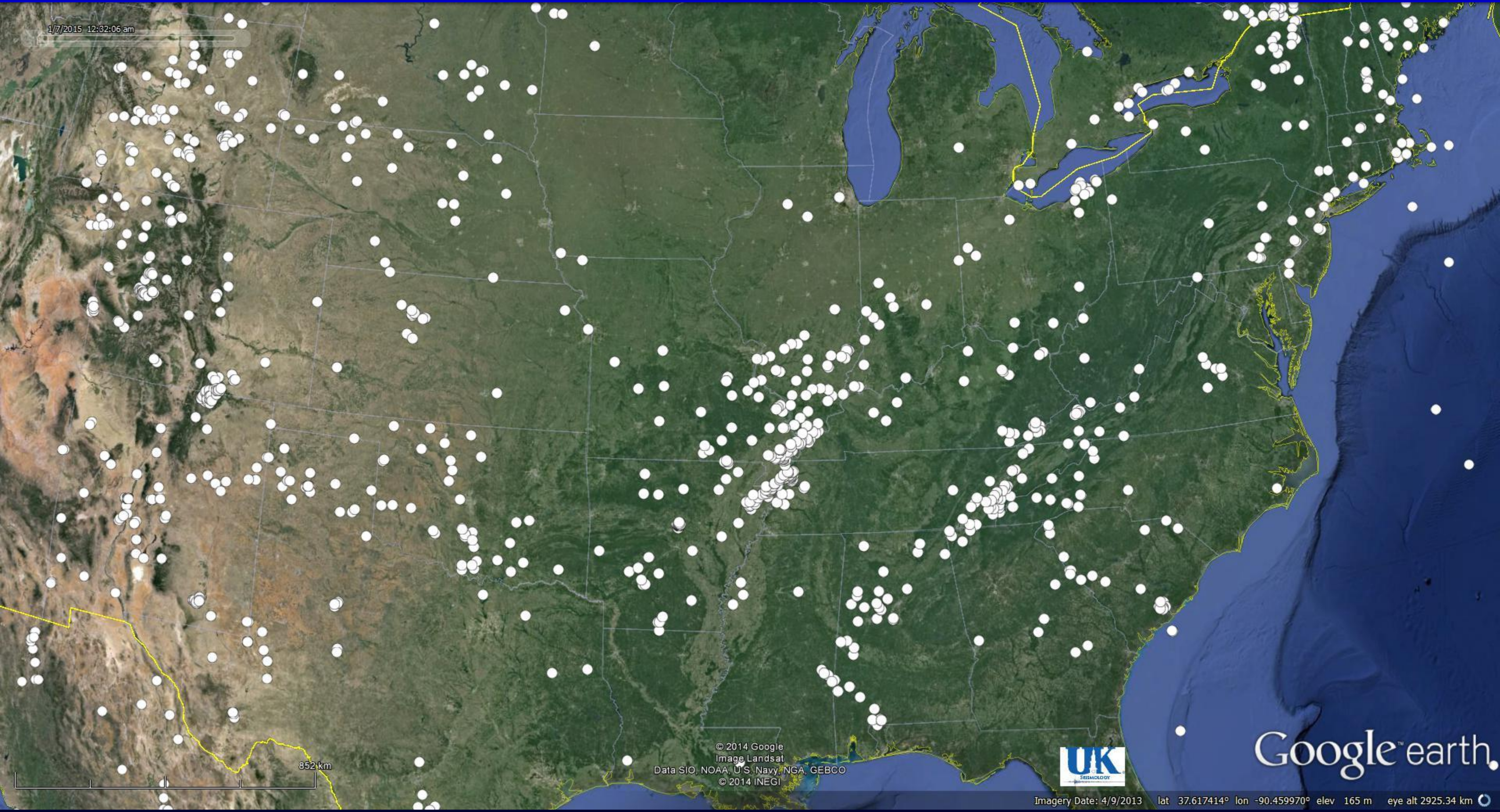
- Ground Motion Hazard Assessment
  - Probabilistic seismic hazard analysis
  - Scenario-based seismic hazard analysis

- Summary

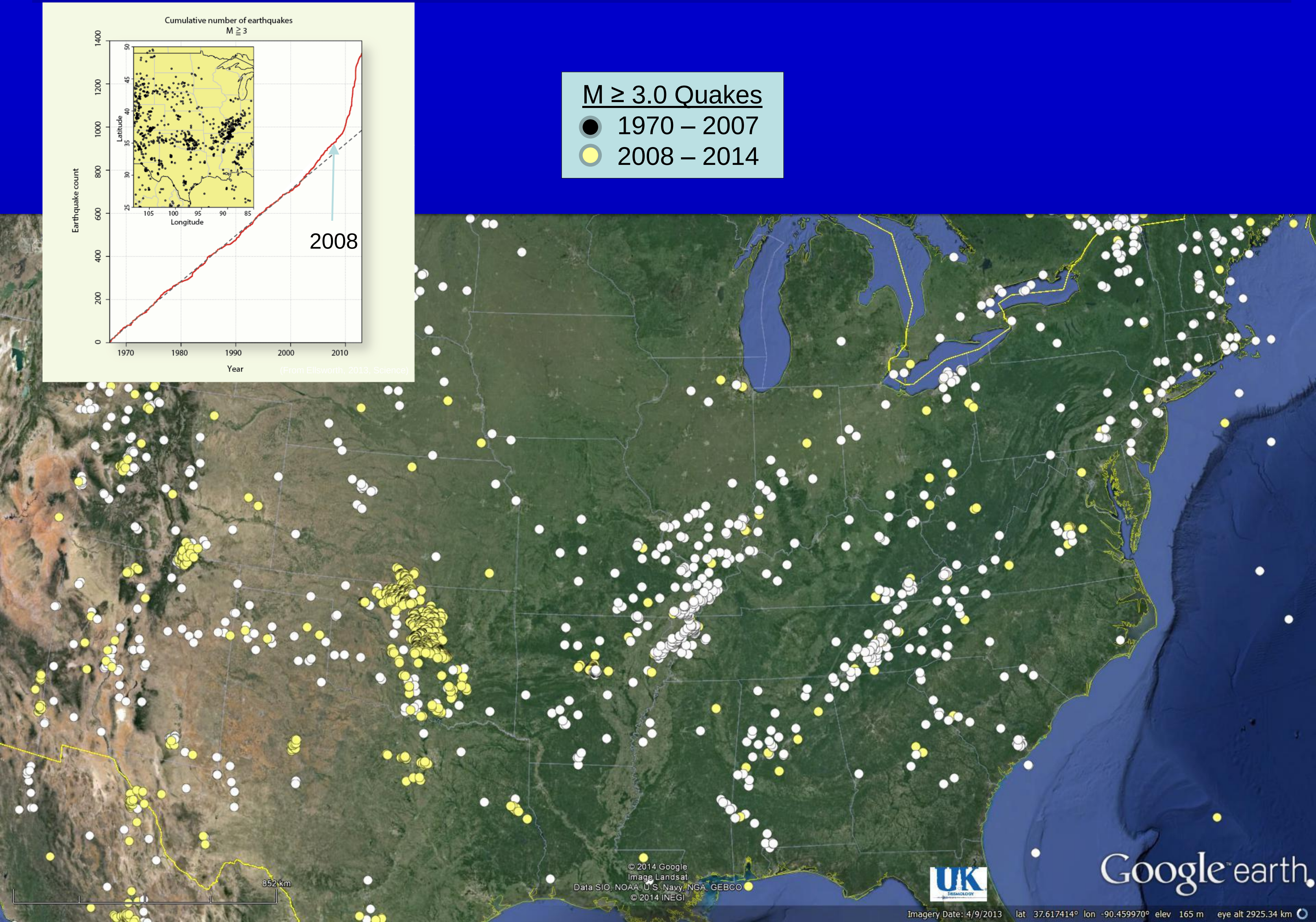
Induced-Seismicity in CEUS

M ≥ 3.0 Quakes

● 1970 – 2007



Induced-Seismicity in CEUS



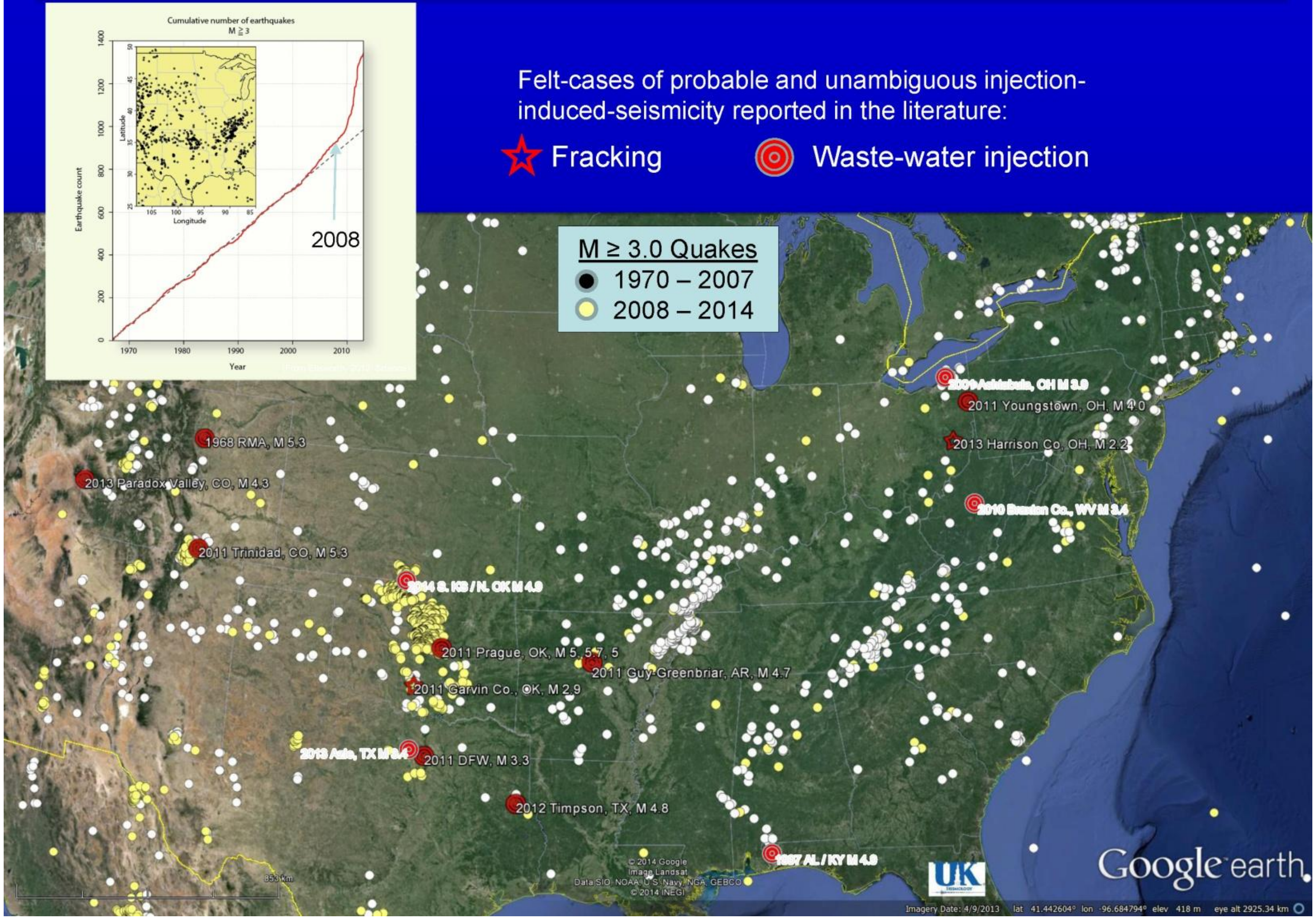
(From Ellsworth, 2013, Science)

M ≥ 3.0 Quakes
- ● 1970 – 2007
- ○ 2008 – 2014

Induced-Seismicity in CEUS

Felt-cases of probable and unambiguous injection-induced-seismicity reported in the literature:

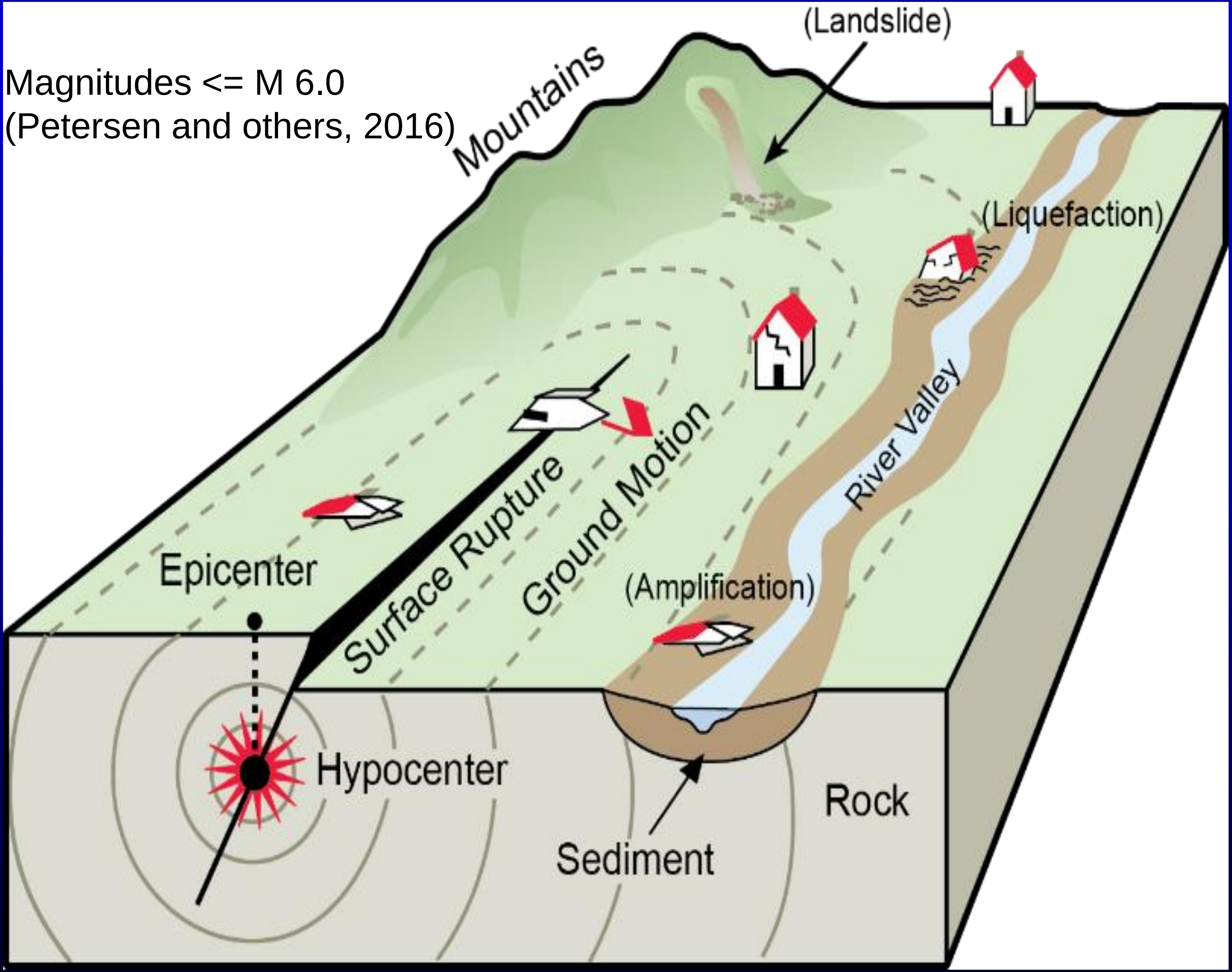
☆ Fracking ◎ Waste-water injection



Presenter's notes: 14 cases on this map – w/ focus on Central & Eastern U.S.
Rearrangement of the most-frequent induced-event type in previous slides.

Induced Seismic Hazards

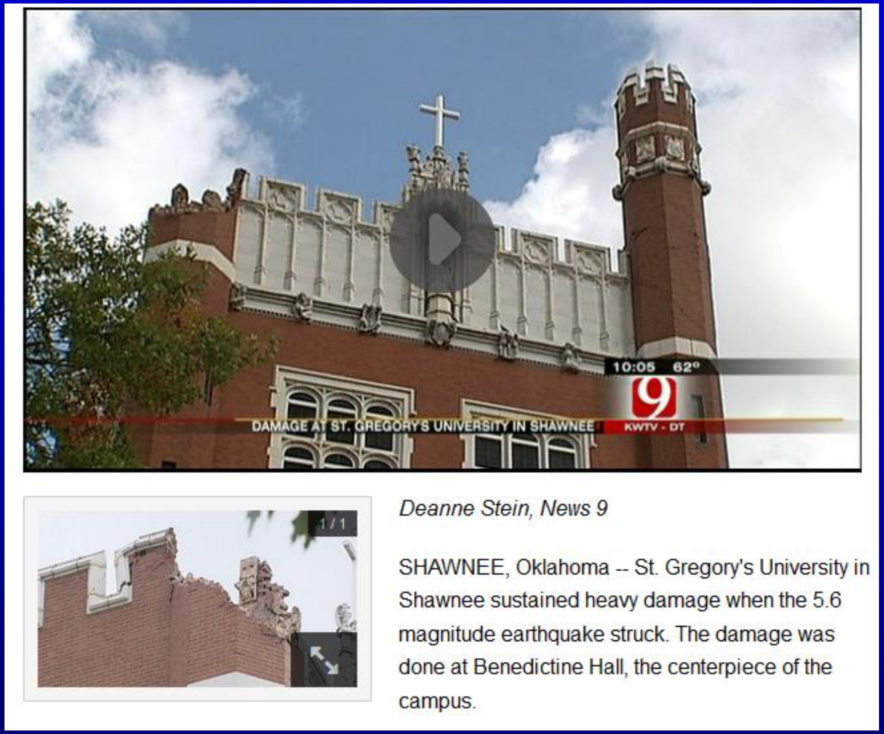
Magnitudes <= M 6.0
(Petersen and others, 2016)



Ground-motion hazard is the main concern from induced earthquakes

Induced Ground Motion Hazards

2011 Prague, Oklahoma, earthquake (M 5.7)



Deanne Stein, News 9

SHAWNEE, Oklahoma -- St. Gregory's University in Shawnee sustained heavy damage when the 5.6 magnitude earthquake struck. The damage was done at Benedictine Hall, the centerpiece of the campus.

http://www.newson6.com/story/15972590/earthquake-damages-historic-building-at-university-in-shawnee

http://www.usgs.gov/blogs/features/usgs_top_story/man-made-earthquakes/

Induced Ground Motion Hazards

2016 Pawnee, Oklahoma, earthquake (M 5.8)

Ground Motion Hazard Assessment

- Probabilistic Seismic Hazard Analysis (PSHA)
  - Emphasizing the statistical properties of ground motion
  - Expressing in terms of probability of ground motion occurrence
  - USGS

- Scenario-based (Deterministic) Seismic Hazard Analysis (SSHA)
  - Emphasizing the physical properties of ground motion
  - Expressing in terms of ground motion with a specific level of uncertainty (i.e., mean or median)
  - KGS

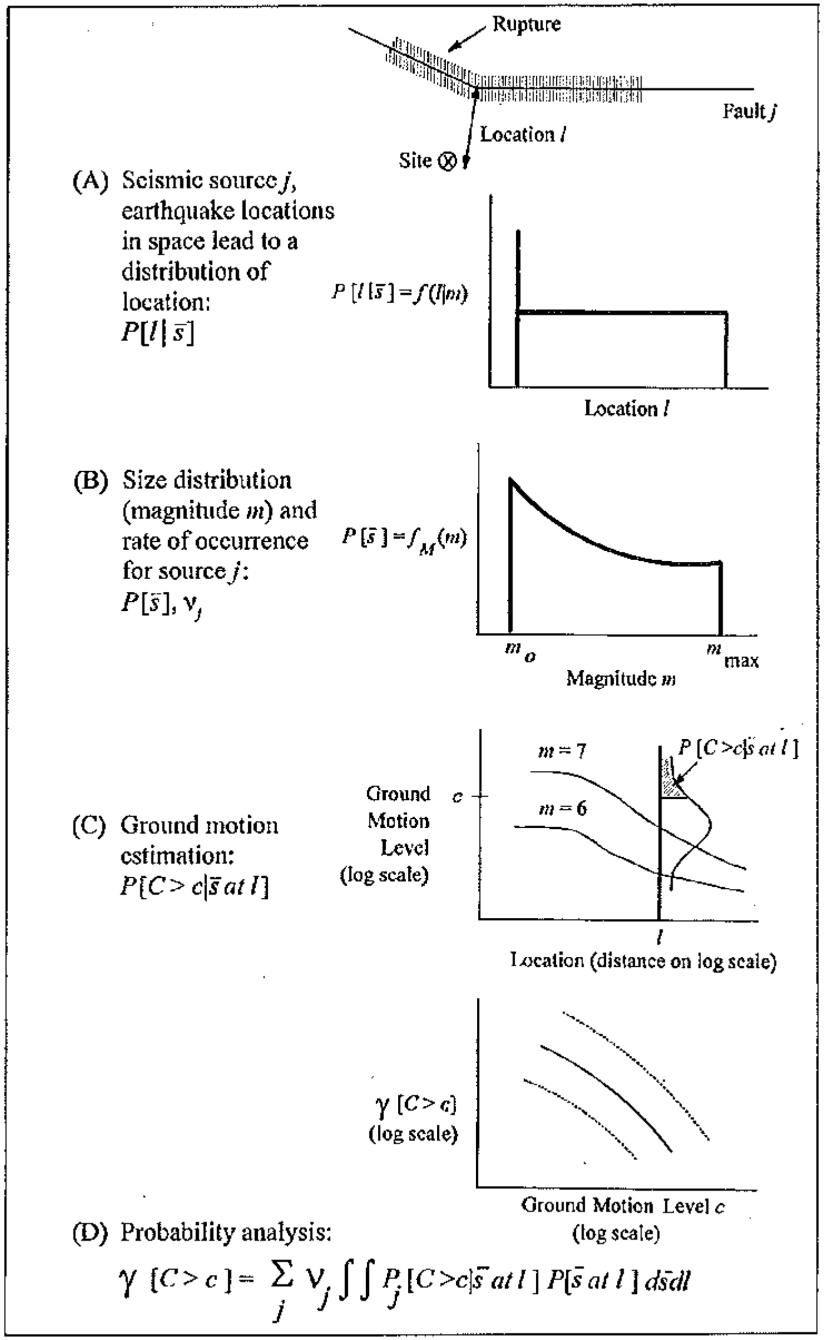


Figure 2. The steps in performing a PSHA.

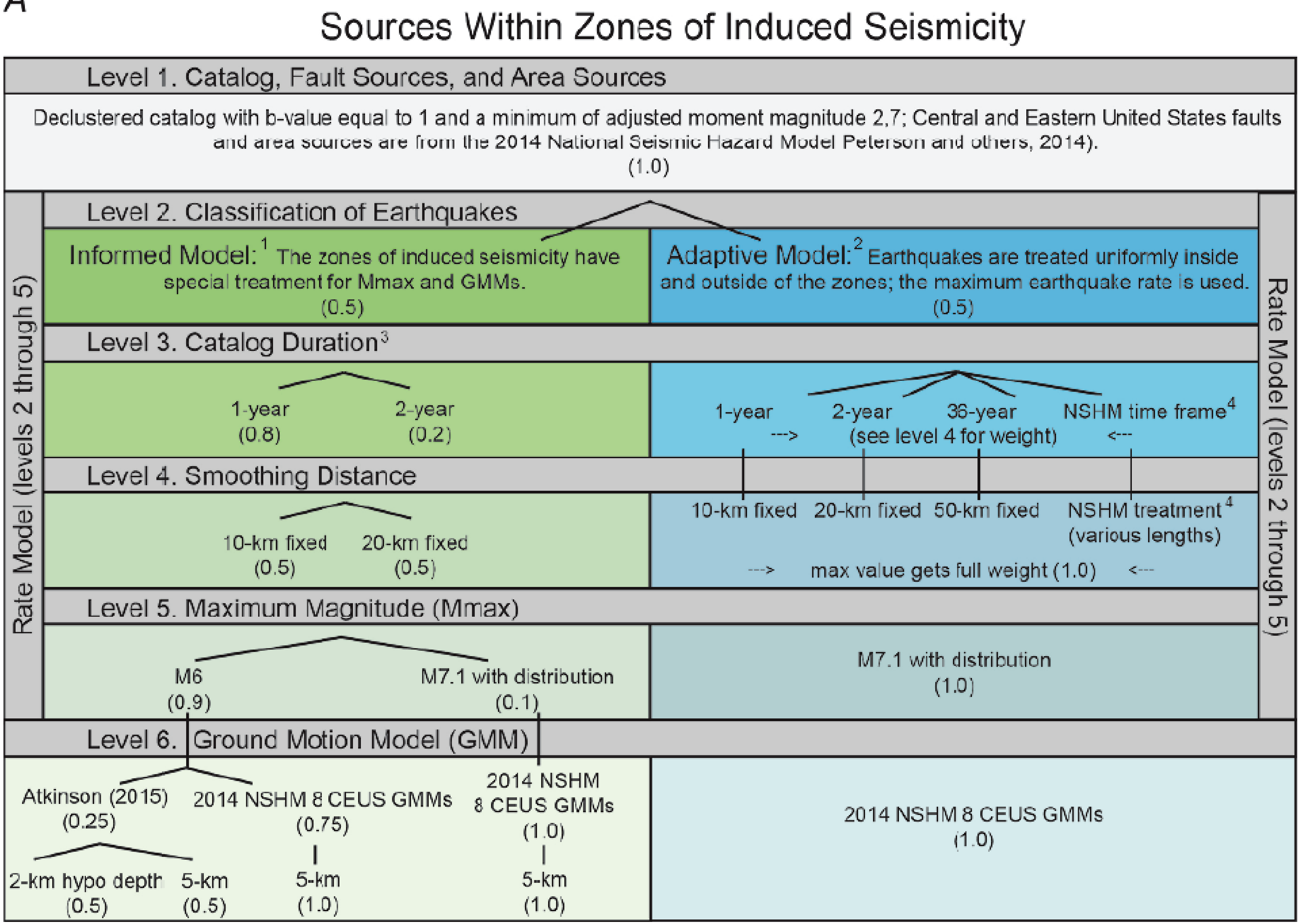
PSHA

- Uncertainty in space (probability model)

- Uncertainty in earthquake size (probability model)

- Uncertainty in ground motion (probability model)

- **Probability** that ground motion exceeds a given level in one year



Sources Within Zones of Induced Seismicity

Level 1. Catalog, Fault Sources, and Area Sources

Declustered catalog with b-value equal to 1 and a minimum of adjusted moment magnitude 2.7; Central and Eastern United States faults and area sources are from the 2014 National Seismic Hazard Model Peterson and others, 2014).
(1.0)

Rate Model (levels 2 through 5)

Level 2. Classification of Earthquakes

Informed Model:[1] The zones of induced seismicity have special treatment for Mmax and GMMs.
(0.5)

Adaptive Model:[2] Earthquakes are treated uniformly inside and outside of the zones; the maximum earthquake rate is used.
(0.5)

Level 3. Catalog Duration[3]

1-year (0.8)
2-year (0.2)

1-year
2-year
36-year
NSHM time frame[4]
---> (see level 4 for weight) <---

Level 4. Smoothing Distance

10-km fixed (0.5)
20-km fixed (0.5)

10-km fixed
20-km fixed
50-km fixed
NSHM treatment[4] (various lengths)
---> max value gets full weight (1.0) <---

Level 5. Maximum Magnitude (Mmax)

M6 (0.9)
M7.1 with distribution (0.1)

M7.1 with distribution (1.0)

Level 6. Ground Motion Model (GMM)

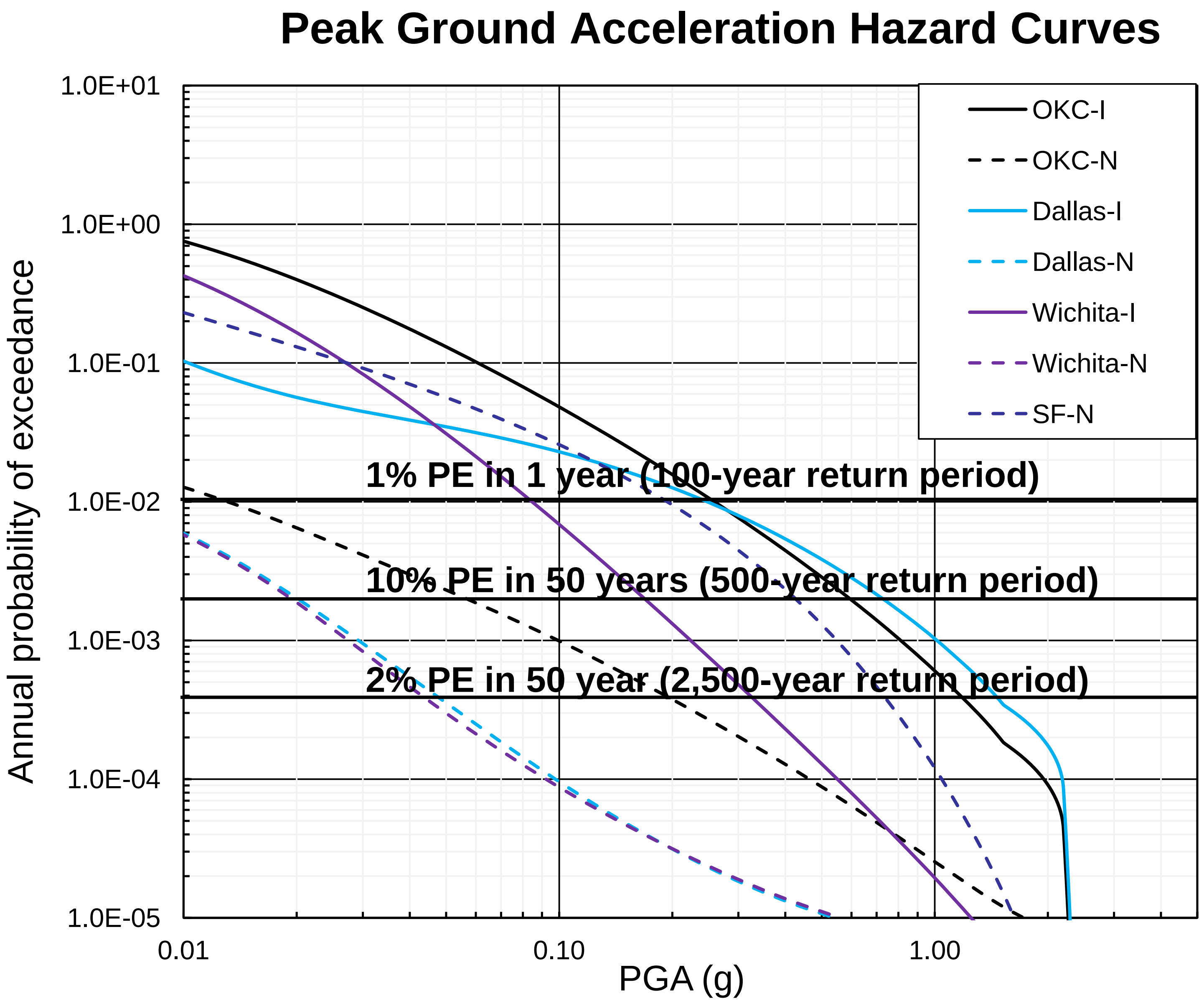
Atkinson (2015) (0.25)
- 2-km hypo depth (0.5)
- 5-km (0.5)

2014 NSHM 8 CEUS GMMs (0.75)
- 5-km (1.0)

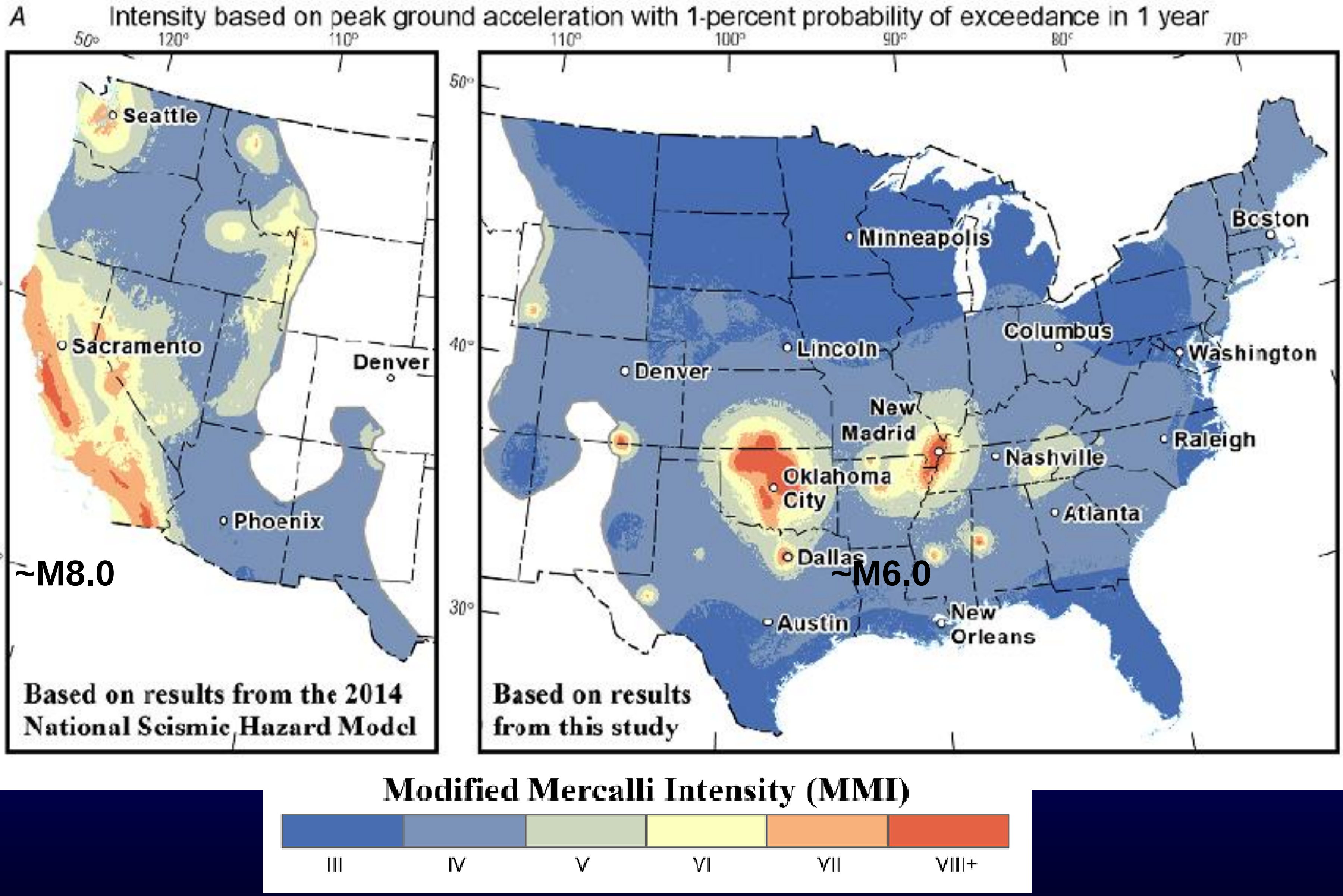
2014 NSHM 8 CEUS GMMs (1.0)
- 5-km (1.0)

2014 NSHM 8 CEUS GMMs (1.0)

(USGS, 2016)



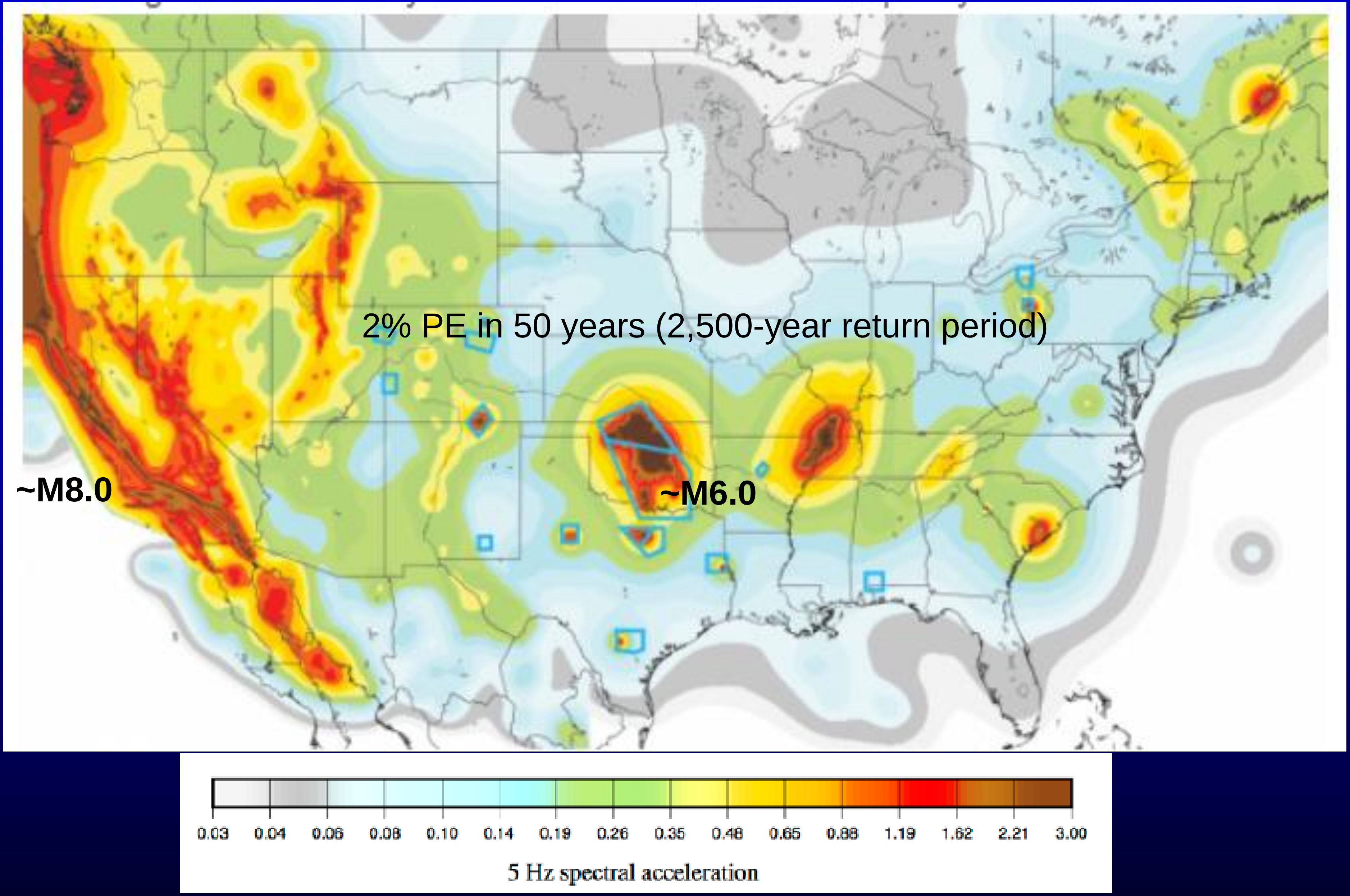
(USGS, 2014 and 2016)



~M8.0

~M6.0

(USGS, 2016)

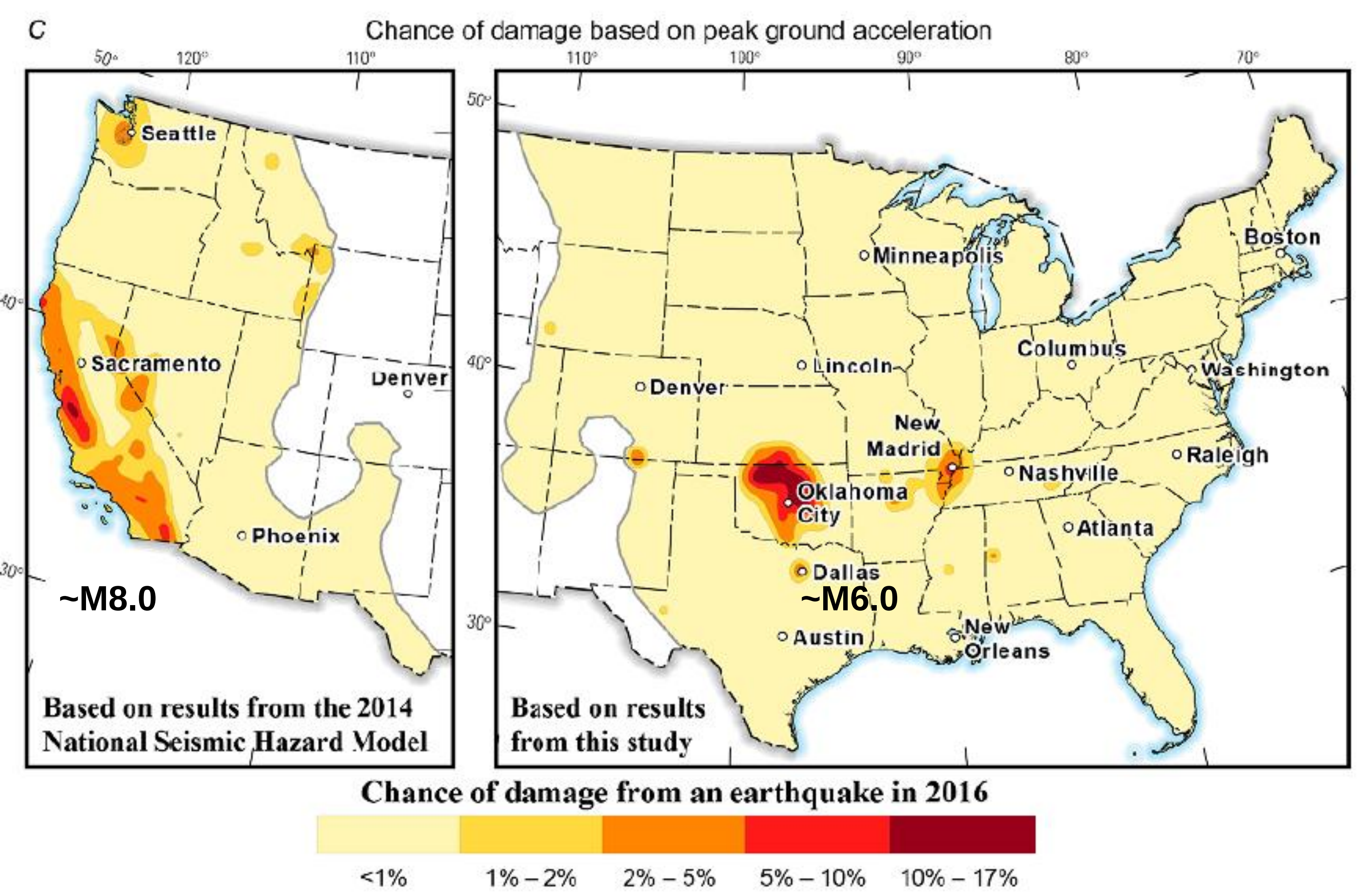


2% PE in 50 years (2,500-year return period)

~M8.0

~M6.0

(USGS, 2016)



Based on results from the 2014 National Seismic Hazard Model

Based on results from this study

~M8.0

~M6.0

(USGS, 2016)

Problems with PSHA

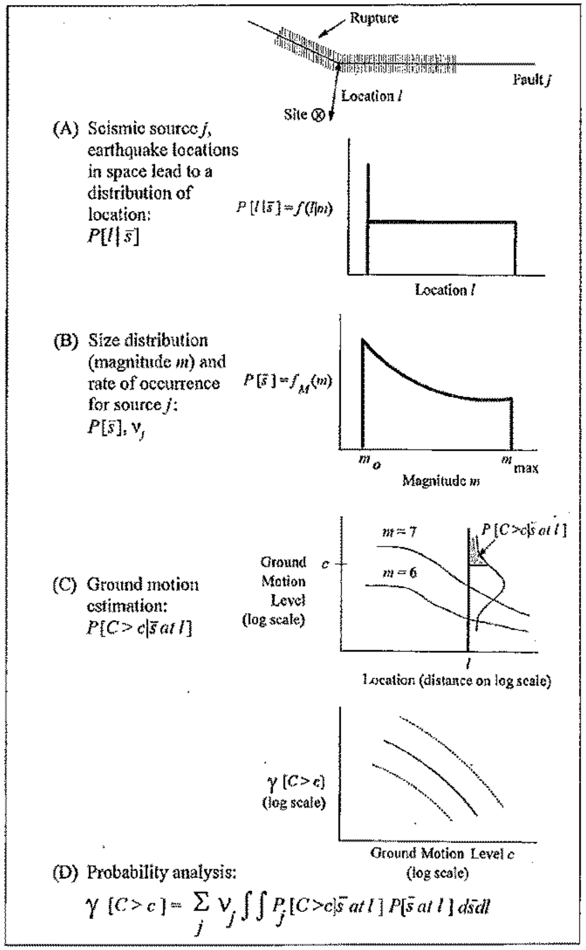


Figure 2. The steps in performing a PSHA.

The probability models are:

(1) "highly variable spatially and temporally;

(2) dependent on human economic or societal decisions regarding when to initiate or terminate wastewater disposal and how much fluid (volume) would be injected or extracted;

(3) dependent on the length and depth extent of the causative faults, which are generally unknown"

"The final model (result - probability) has high uncertainty, and engineers, regulators, and industry should use these assessments cautiously to make informed decisions on mitigating the potential effects of induced and natural earthquakes" (Petersen and others, 2016). – uncertainty of uncertainty

PSHA

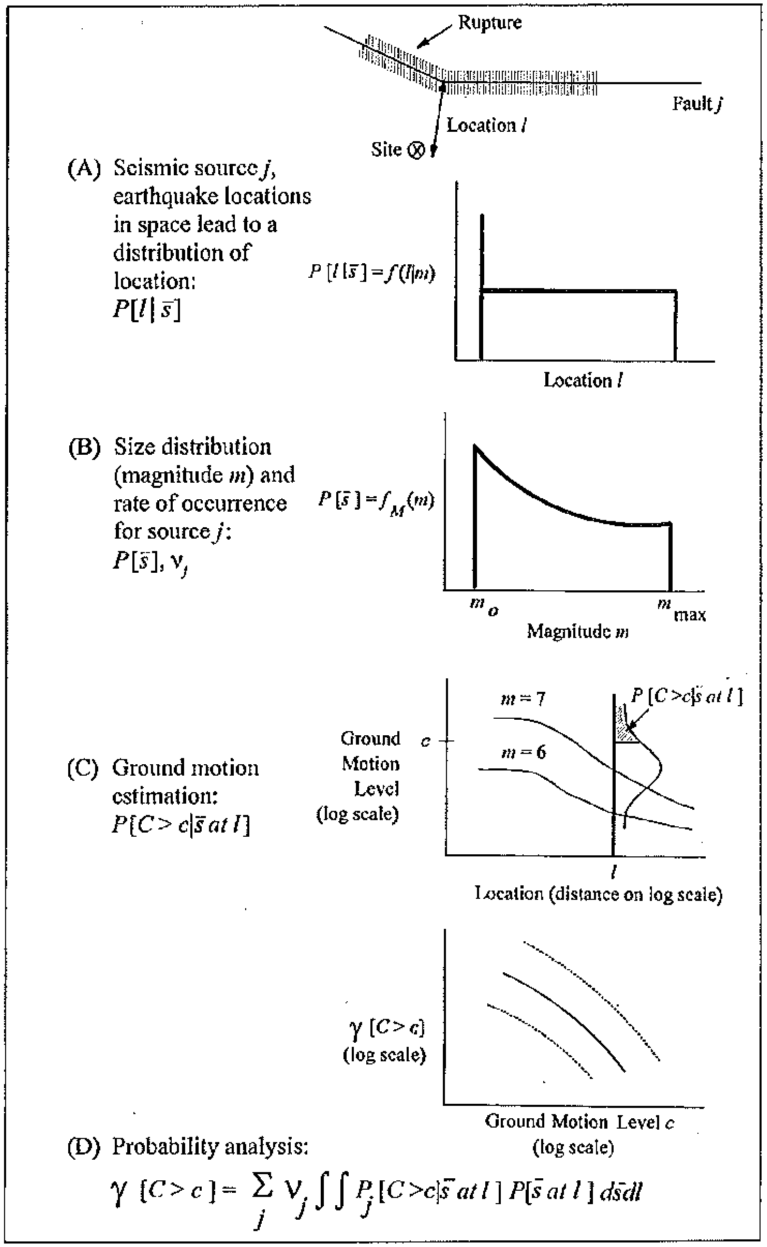


Figure 2. The steps in performing a PSHA.

DSHA (*SSHA*)

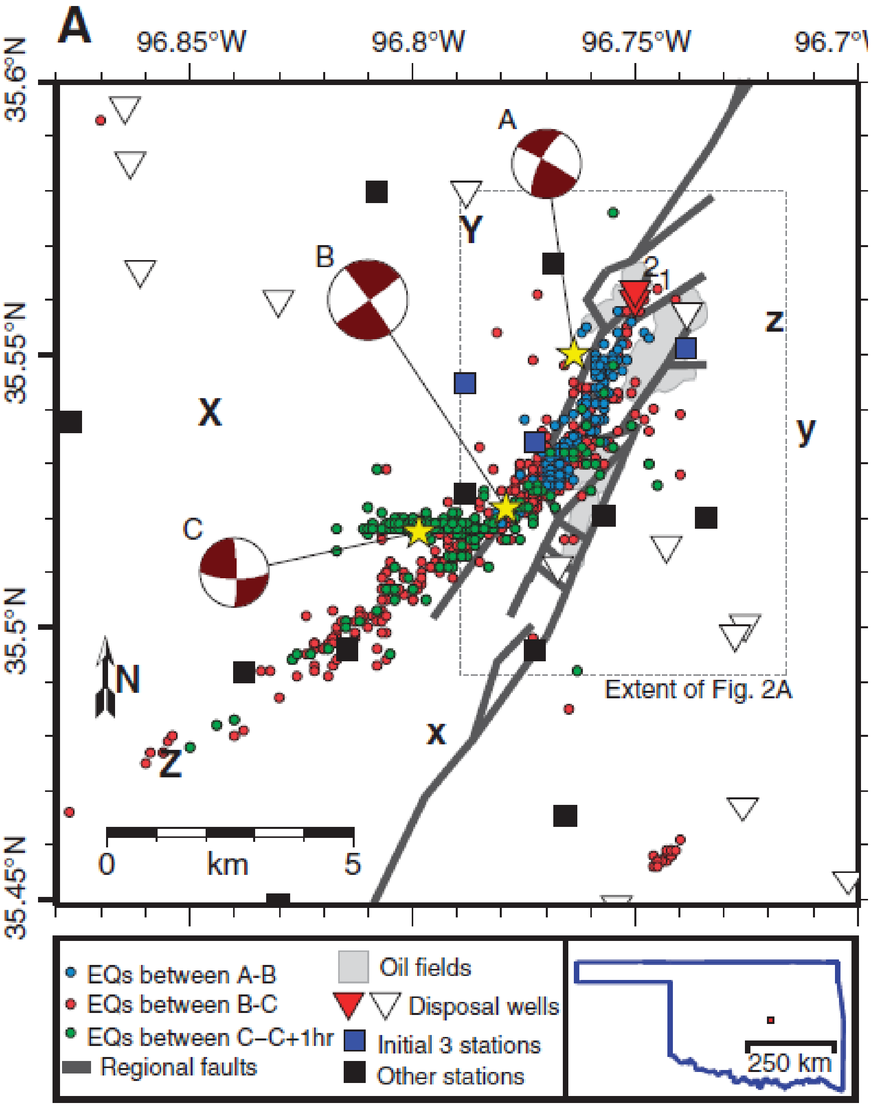
- Shortest distance (not probability model)

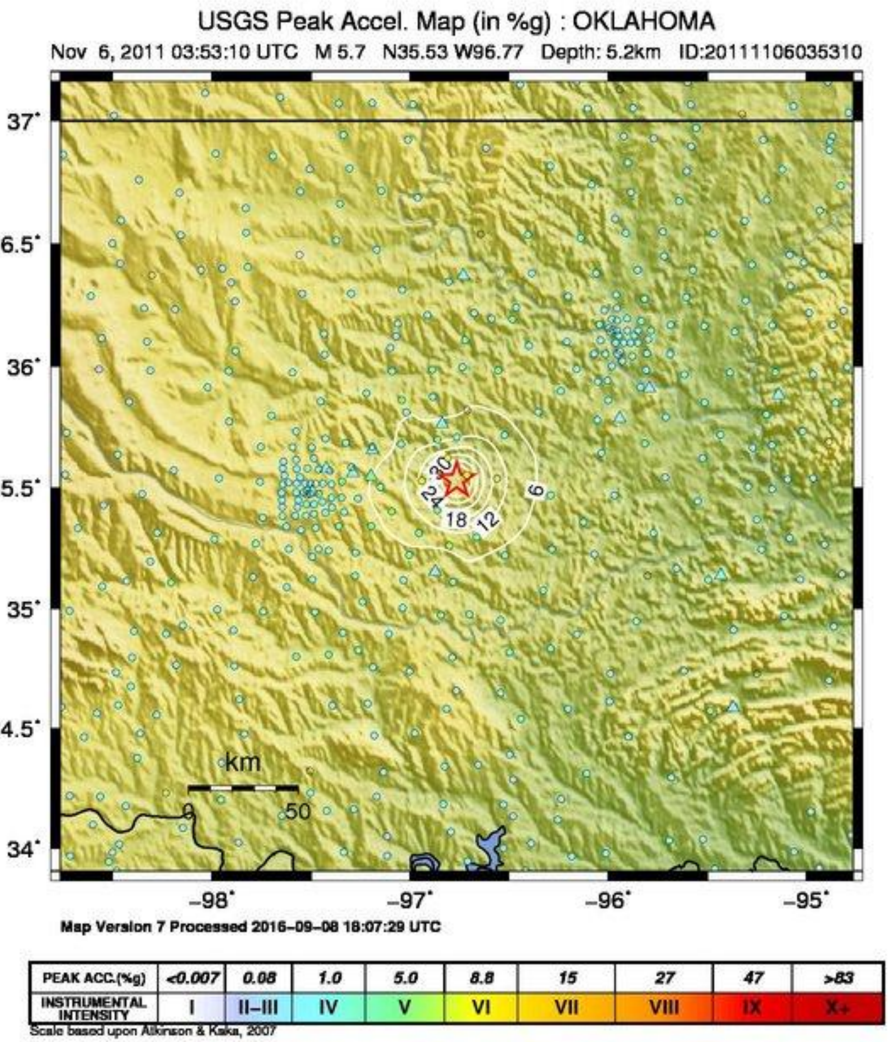
- Maximum (or mean) earthquake size

- Mean or median ground motion (***ground motion simulation***)

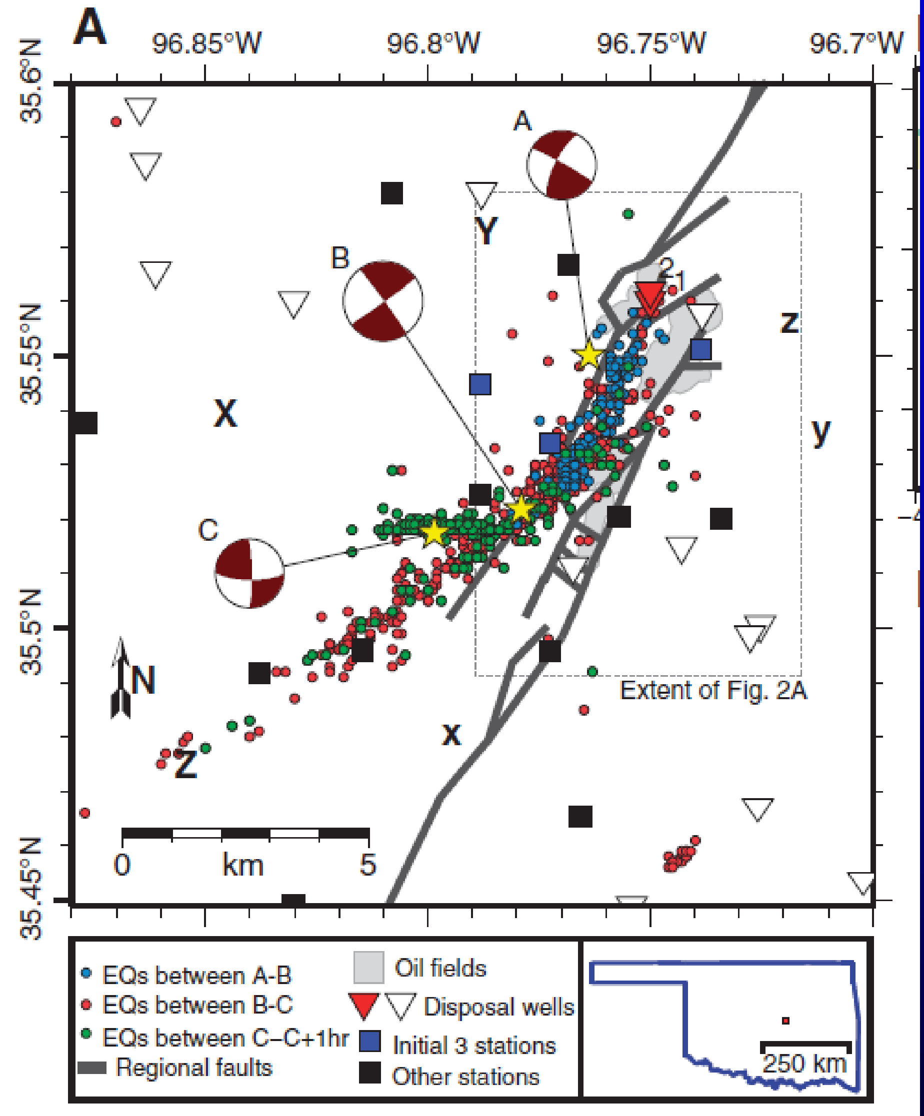
- **Ground motion associated with a specific earthquake and a level of uncertainty (mean or median)**

The 2011 M_w 5.7 Oklahoma earthquake





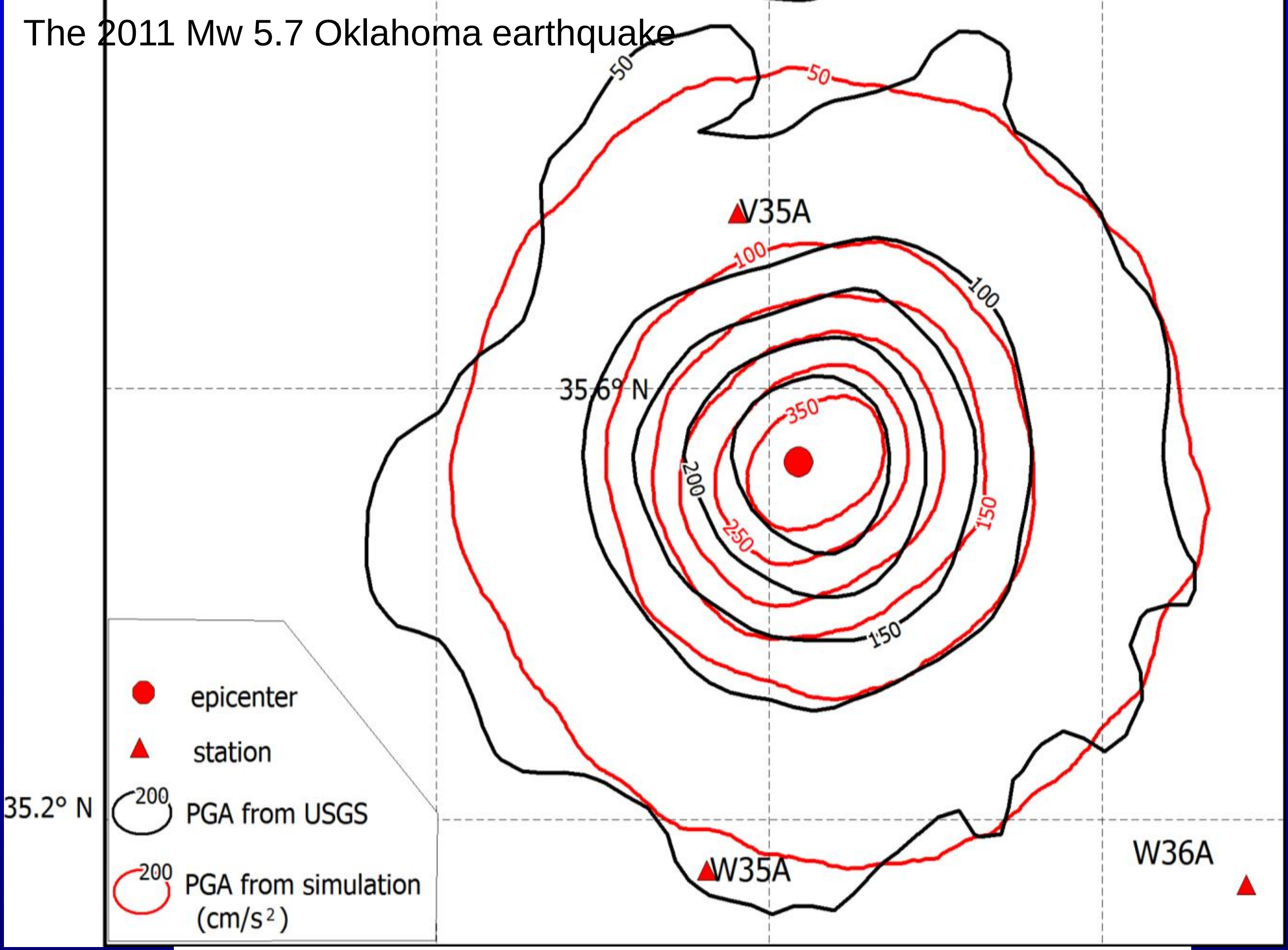
The 2011 M_w 5.7 Oklahoma earthquake

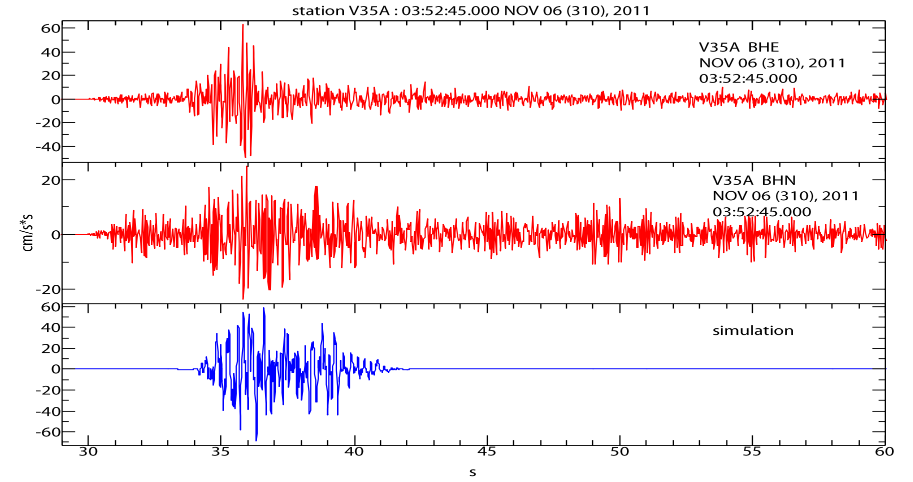


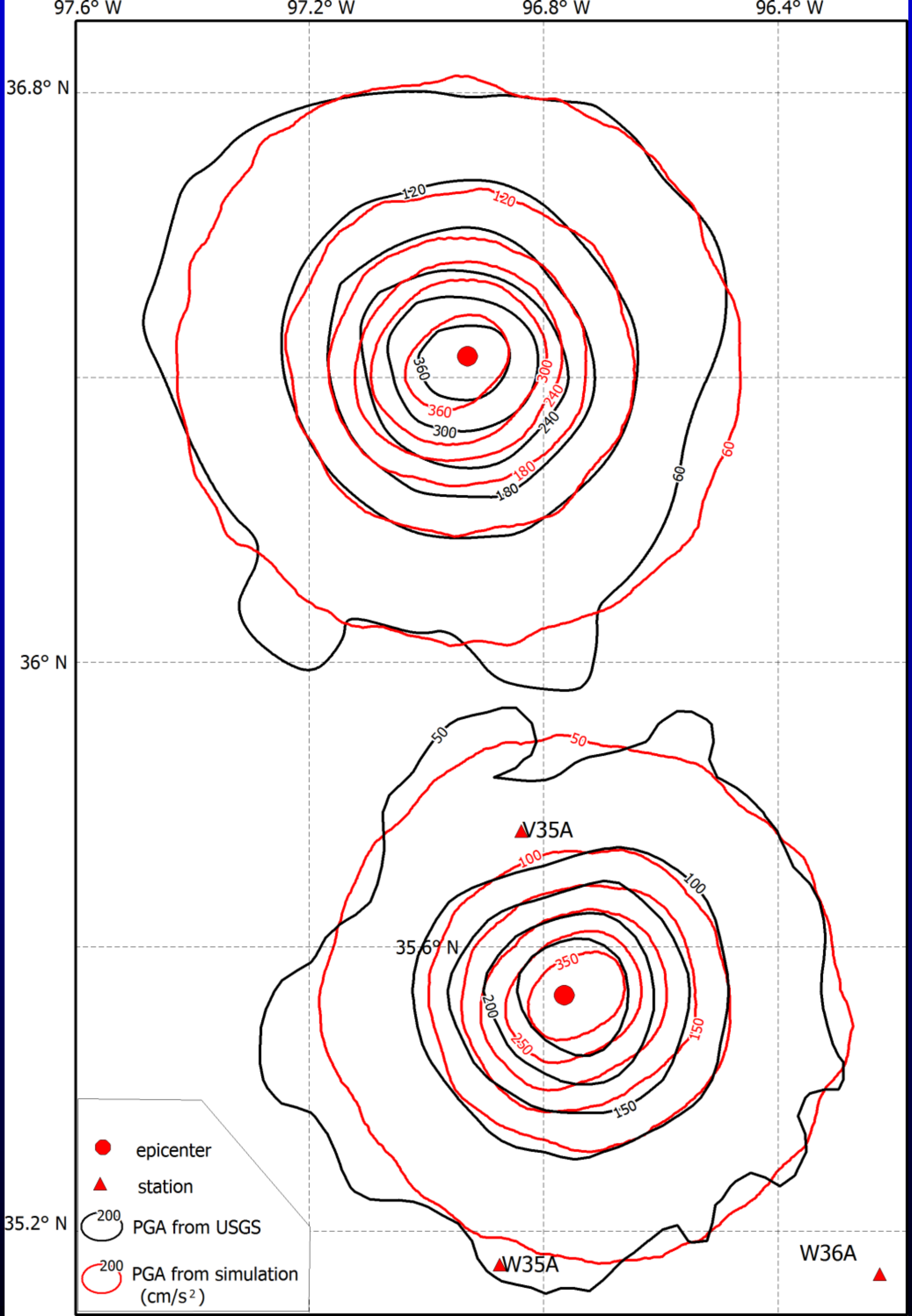
Parameter	11/6/2011 Prague, OK
Moment magnitude (Mw)	5.7
Fault orientation (strike)	60°
Fault orientation (dip)	85°
Fault depth to upper edge (H)	1 km
Fault dimension	10km(L)*7km(W)
Subfault length and width	1km
Style of fault and rake	strike-slip
Input hypo at subfault	epicenter
Fast Fourier transform	Dynamic allocation of points
Sample interval	0.02 s
Shear-wave velocity	3.8 km/s
Density	2,700 kg/m^3
Rupture velocity	0.8*shear-wave velocity
K	0.005(Atkinson and Boore,2014)
Q(f)	525f$^{0.45}$(Atkinson and Boore,2014)
Stress drop	16bars
Geometric attenuation	If R < 30, R_{-1} ; or $R_{-0.5}$
Distance-dependent duration	To + 0.1 R (s)
Site amplification function	Not applied
Slip model	Random & Gaussian distribution
Dynamic flag and pulsing (%)	1 and 50
Damping	5% critical damping

Stochastic Finite-Fault Simulation

The 2011 Mw 5.7 Oklahoma earthquake

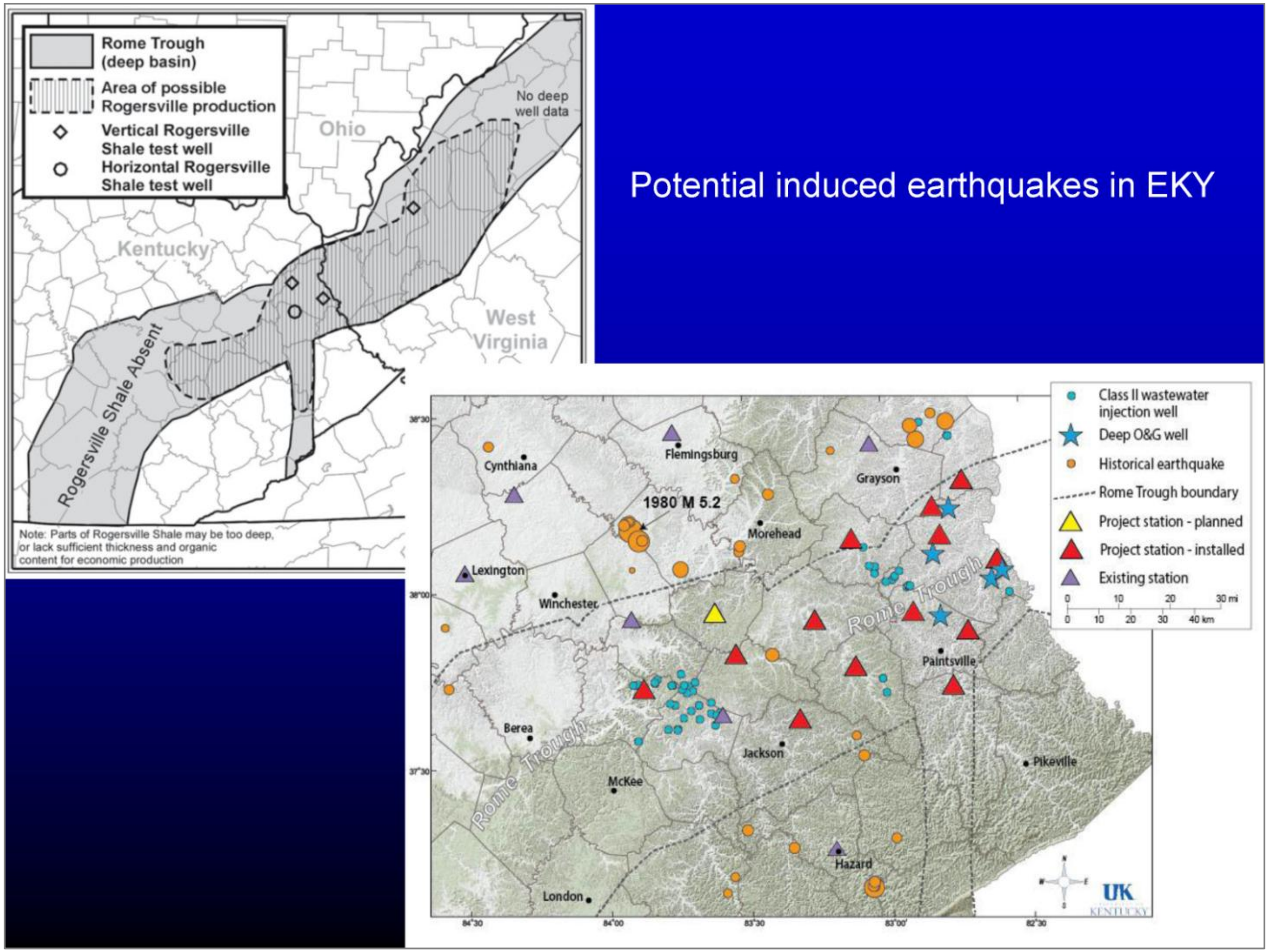






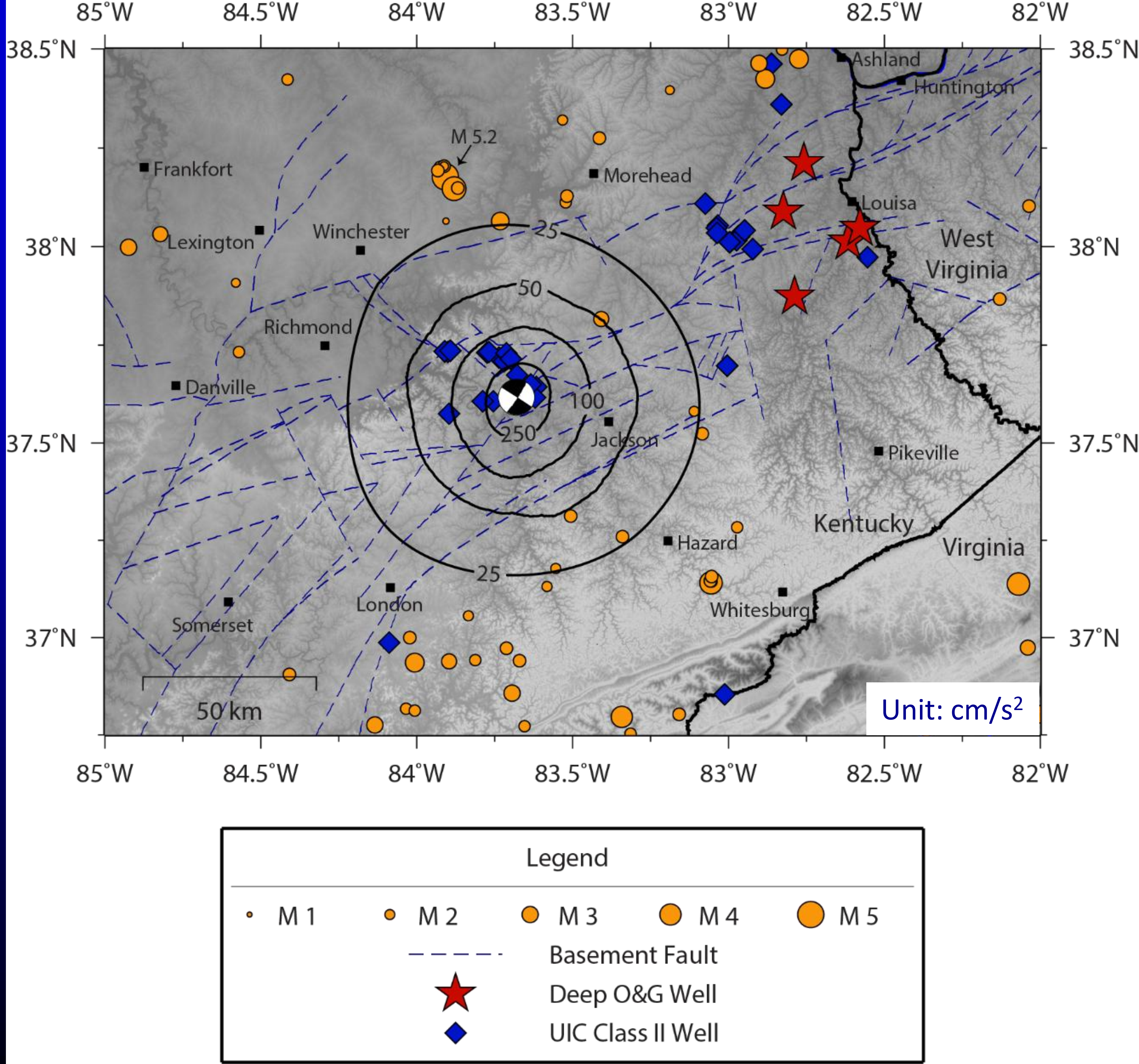
The 2016 Mw 5.8 Oklahoma earthquake

The 2011 Mw 5.7 Oklahoma earthquake



Potential induced earthquakes in EKY

Presenter's notes: It is important to perform a high-resolution study of microseismicity in eastern Kentucky because of the interest in developing deep shale-gas plays and because the effects of disposal of wastewater in deep injection wells in the heavily faulted Rome Trough of Kentucky are largely unknown. In addition, this part of eastern Kentucky is known to have moderate natural earthquakes, such as the 1980 magnitude-5.2 Sharpsburg earthquake.


85°W
84.5°W
84°W
83.5°W
83°W
82.5°W
82°W
38.5°N
38°N
37.5°N
37°N
Ashland
Huntington
Frankfort
M 5.2
Morehead
Louisa
Lexington
Winchester
West Virginia
Richmond
Danville
Jackson
Pikeville
Kentucky
Hazard
Virginia
London
Whitesburg
Somerset
25
50
100
250
50 km
Legend
M 1
M 2
M 3
M 4
M 5
Basement Fault
Deep O&G Well
UIC Class II Well

Unit: cm/s^2

Summary

- Ground motion hazards from induced earthquakes are of safety concern in the central and eastern US

- Assessing ground motion hazards is difficult because of the lack of understanding on the sources, ground motions, as well as human influence.

- PSHA is not appropriate for assessing ground motion hazards from induced earthquakes
  - Uncertainty of uncertainty
  - Difficult to understand and use

- SSHA is viable approach for assessing ground motion hazards from induced earthquakes
  - Ground motion with a level of uncertainty
  - Easy to understand and use

Thanks

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