Estimating Seismic Hazard Across the United States

Art Frankel

U.S. Geological Survey

Seattle

Committee on Seismology and Geodynamics, Nov. 14, 2018

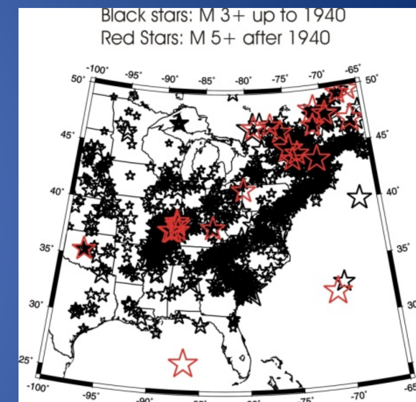
USGS
science for a changing world

Seismic hazard assessment integrates what we know about earthquake sources, faults, crustal deformation, and ground motions

Geologic mapping, fault slip rates
EQ chronologies from paleoseismology
potential fields, seismic reflection/refraction

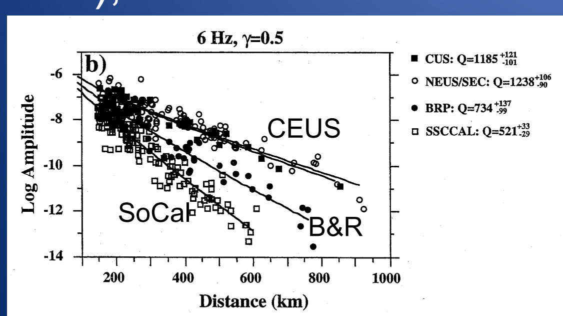
Photo from Nelson et al. (2003)

Earthquake catalogs (instrumental and historical), source parameters, ANSS



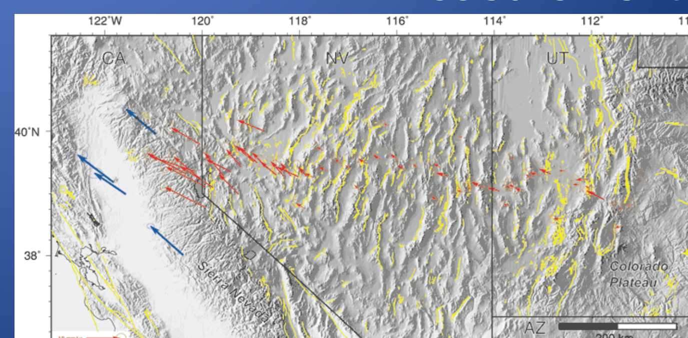
National Seismic Hazard Maps (probabilistic seismic hazard assessment)

Seismograms: weak and strong motion (ANSS, CGS)
Ground-motion models: empirical (WUS); simulated (CEUS)



From Benz, Boore, Frankel (1997)

Crustal deformation measurements (GPS)

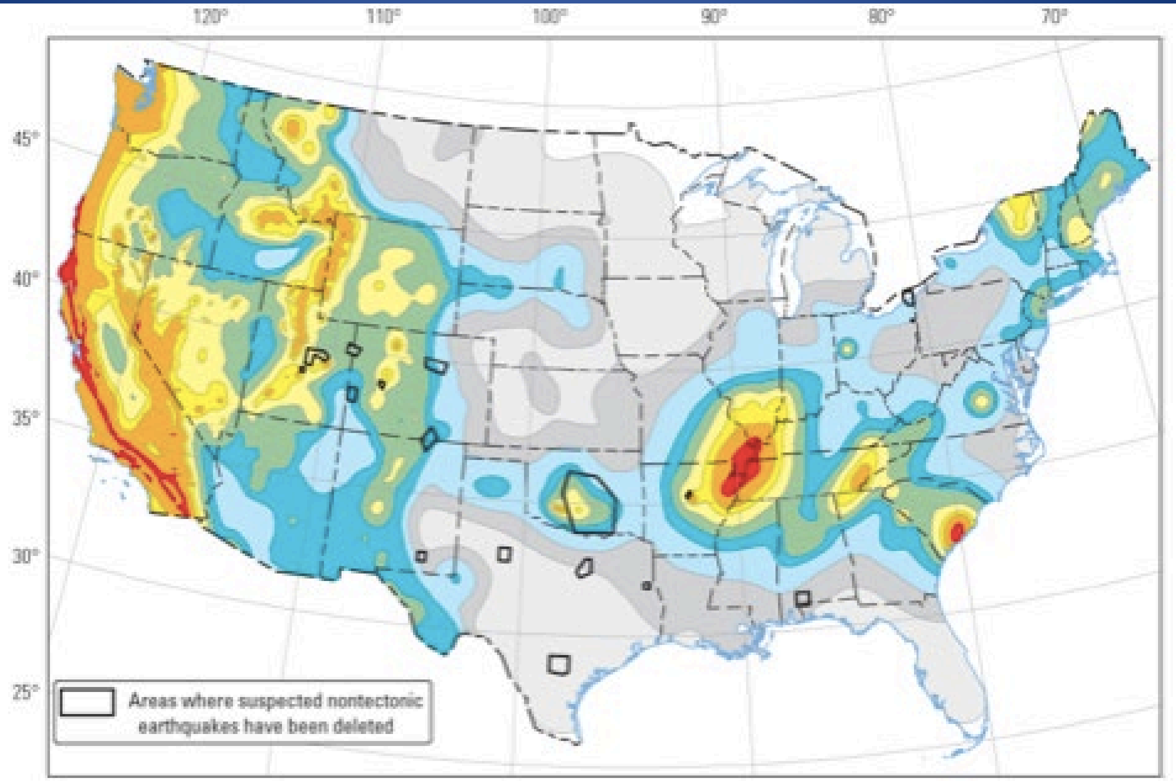


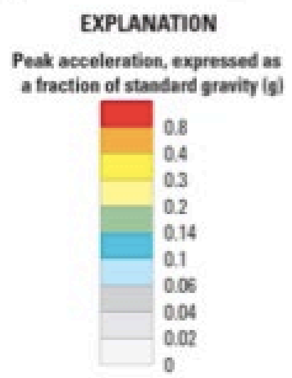
From Thatcher et al. (1997)

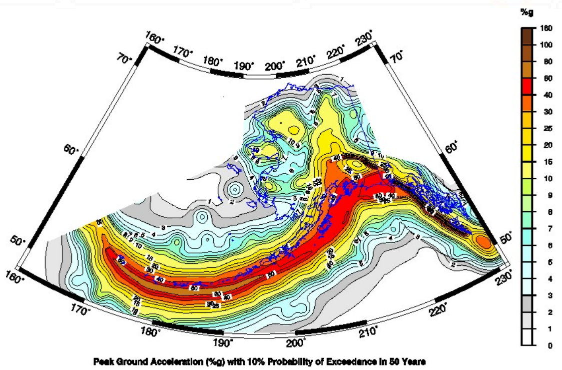
One of the 2014 National Seismic Hazard Maps (Petersen et al., 2014)
Peak ground acceleration with 2% chance of being exceeded in 50 Years
The NSHM's have been the basis of seismic provisions in building codes since 2000

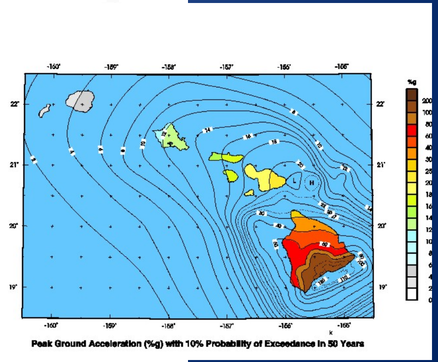
Black outlines denote areas of Induced seismicity

(see 1 year Hazard maps)









Wesson et al. 2007

Klein et al., 1998

USGS
science for a changing world

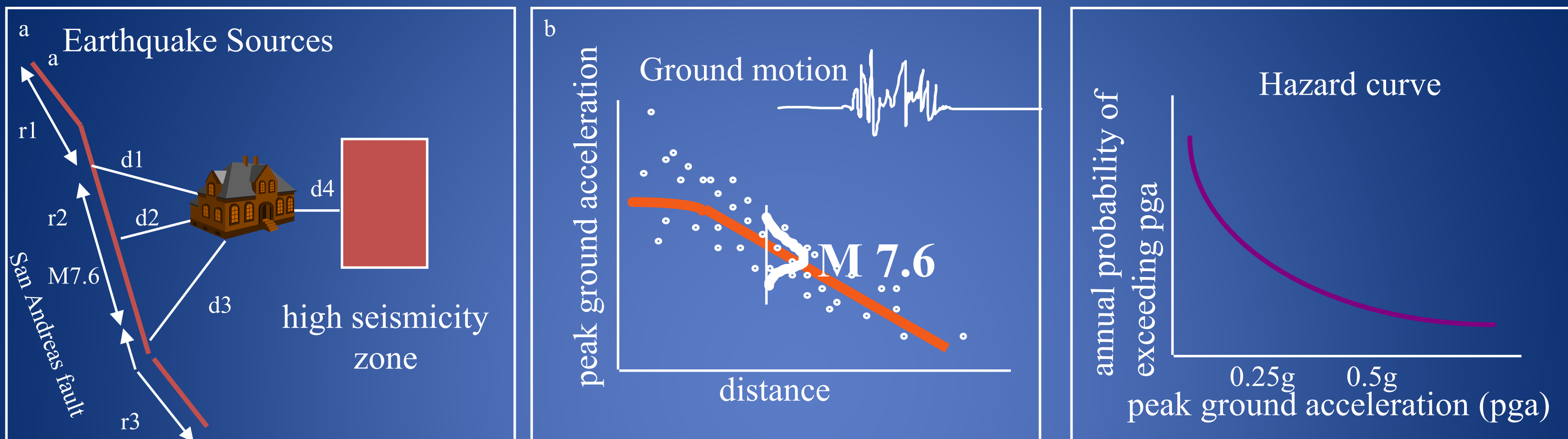
NSHM’s are usually updated about every 6 years, to incorporate new published, vetted research on earthquake sources and ground motions. Mark Petersen is Project Chief

Steering Committee chaired by John Anderson reviews the maps; Draft maps are placed on web for comments.

For each update cycle, there is a set of regional, topical, and user-needs workshops involving hundreds of scientists and engineers. There are several sub-groups that provide inputs to NSHMs (e.g., UCERF, fault slip rates, geodetic models, ground motion models)

USGS science for a changing world

Probabilistic Seismic Hazard Analysis (PSHA)



Specify recurrence rates of earthquakes for each source that can affect site of Interest

Time independent or time dependent

Ground-motion models tell you median ground motions that each potential earthquake will produce at site, and variability

Derived from strong-motion data (WUS) or models (CEUS). Can include site amp and 3D sedimentary basin effects

Hazard curve: describes probability of having ground motions ≥ a certain intensity

We use mean hazard curves from logic trees with alternative models

USGS science for a changing world

PSHA for a single rupture source

Annual probability of having ground motions larger than some specified value U =

annual probability of earthquake occurring

X

probability of having ground motions larger than U when earthquake occurs

Basic PSHA equation for multiple sources; time independent case

Annual probability of having ground motion exceeding u_0 at site i:

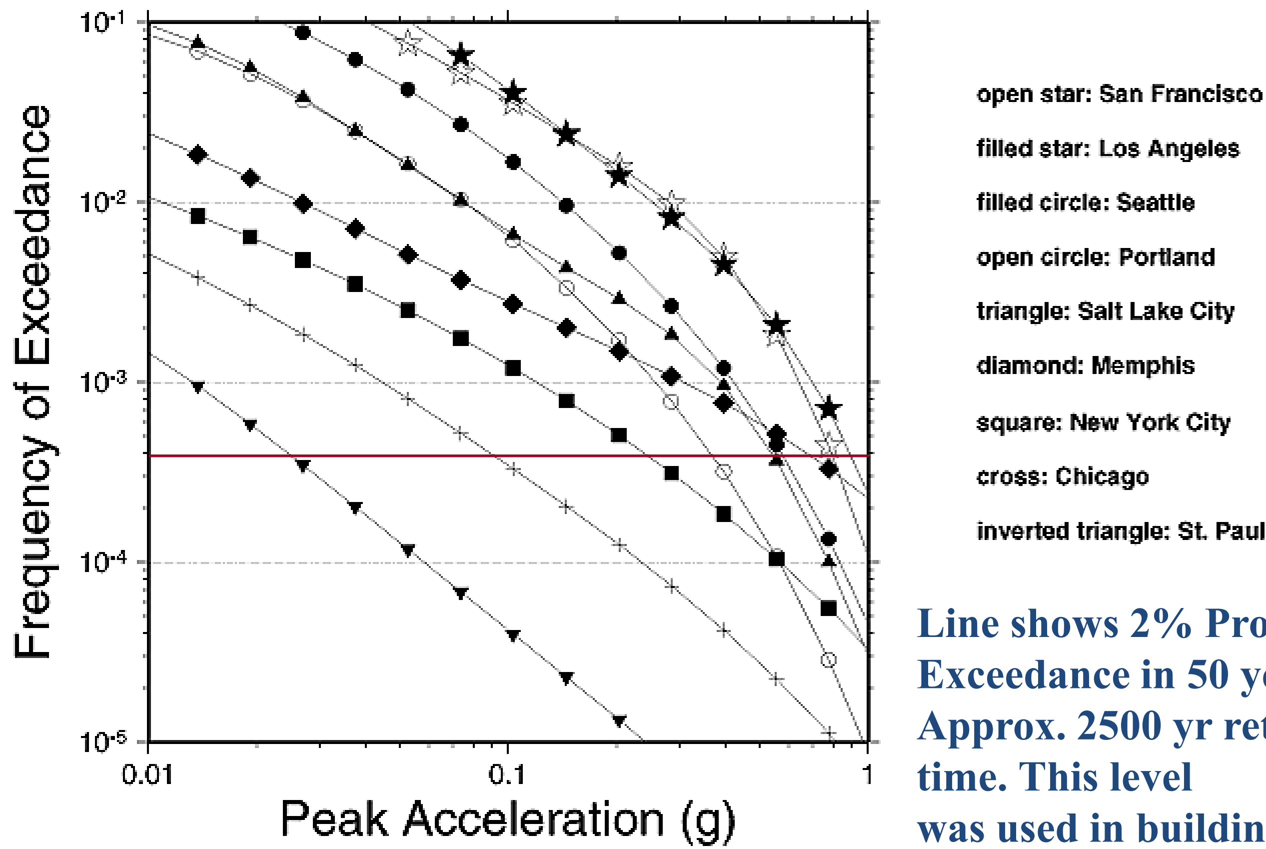
$$P(u \geq u_0) \approx \sum_{M} \sum_{\text{source}_j} \text{rate}(M, \text{source}_j) P(u \geq u_0 | \text{site}_i, \text{source}_j, M)$$

Determined from ground-motion prediction equations

If you're using Gutenberg-Richter recurrence relation, sum up to Mmax

Rate (M) = $10^{(a - bM)}$

Hazard Curves from 1996 NSHM



Line shows 2% Prob. of Exceedance in 50 year; Approx. 2500 yr return time. This level was used in building codes since 2000 until risk-targeted values adopted.

2% chance of exceenace in 50 years is 1/2500 chance per year

Engineering groups decide on acceptable level of risk for building codes

Basic components to U.S. NSHMs

- Use spatially-smoothed instrumental and historic seismicity M ≥ 3.0 in CEUS; M ≥ 4.0 in most of WUS; assumes future large earthquakes will occur near past earthquakes
- Use large uniform background zones to quantify hazard in areas with low rates of recorded seismicity and/or incomplete inventory of faults; supplement with regional deformation from GPS data
- Use specific fault sources with recurrence rates determined from paleoseismic studies and/or geologic slip rates and/or GPS data

Types of uncertainty in PSHA

- Aleatory: inherent randomness of earthquake sources and ground motions; treated as a probability distribution within PSHA equation
- Epistemic: uncertainty due to lack of knowledge; not knowing if you have accurate models of earthquake recurrence rates and ground motions; treated with logic trees with multiple models, producing multiple hazard curves; we seek to reduce epistemic uncertainty through data collection, testing, and improvement of models

2014 USGS NSHMs also included logic tree branches from "Central and Eastern United States Seismic Source Characterization for Nuclear Facilities" (U.S. Dept of Energy, Electric Power Research Institute, and U.S. Nuclear Regulatory Commission, 2012)

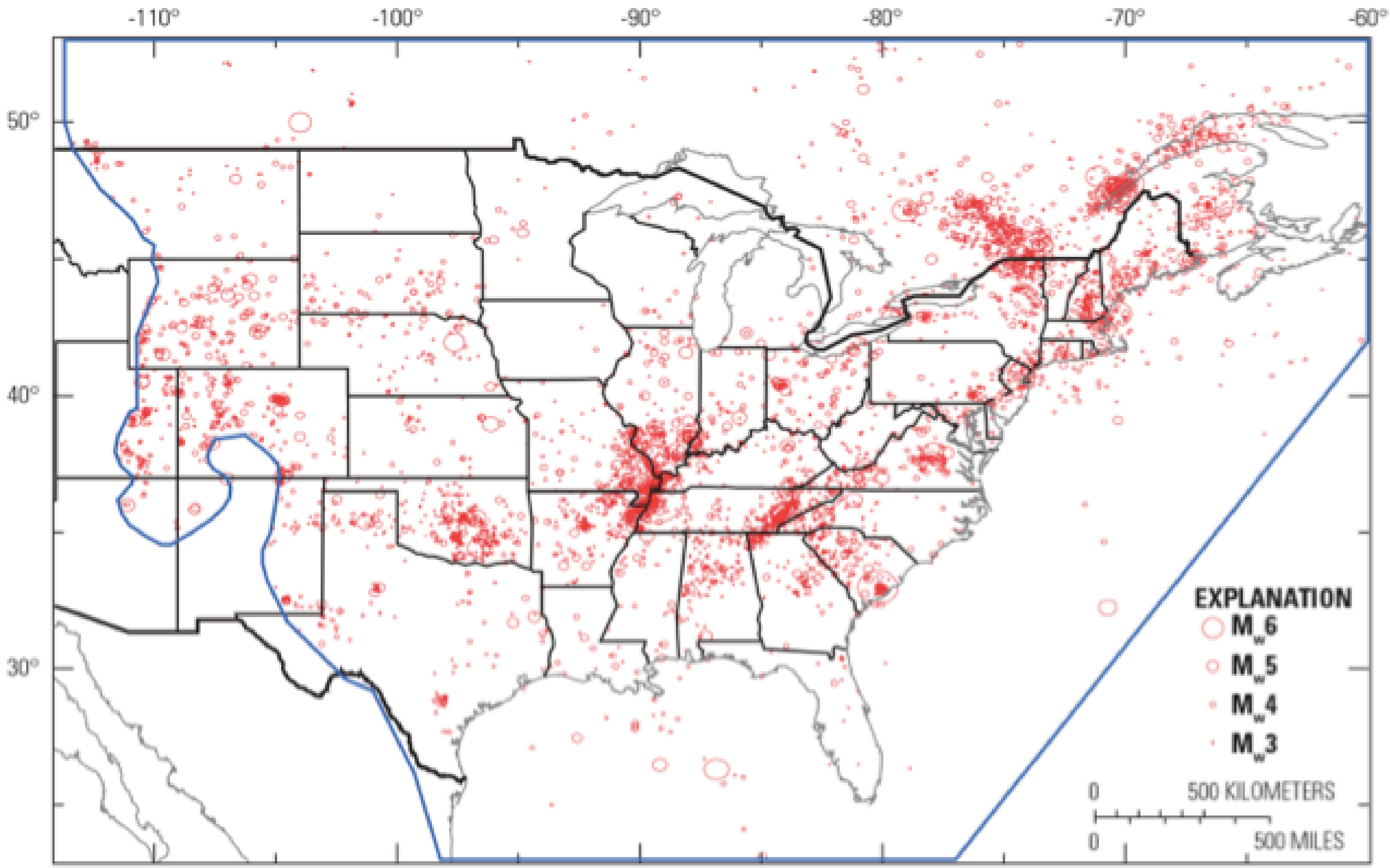
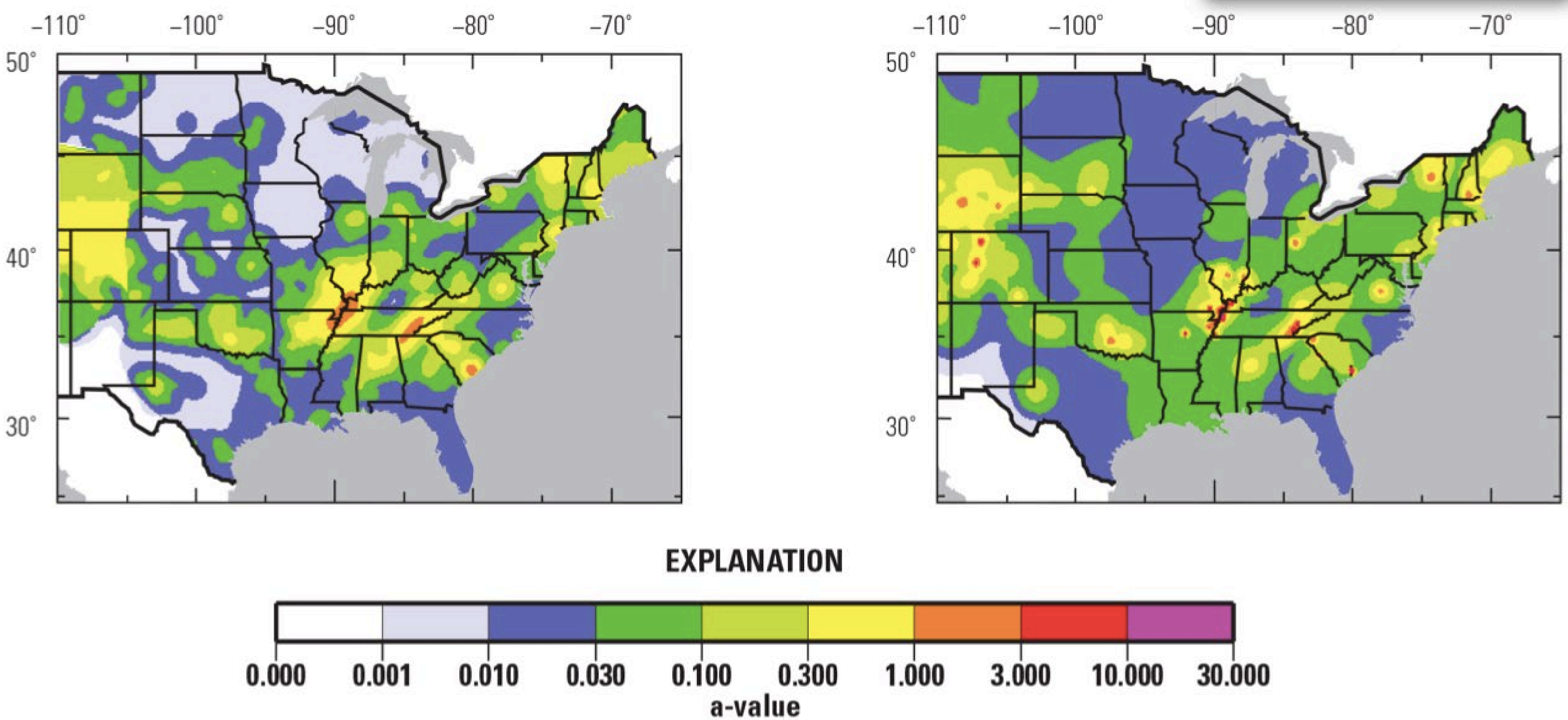


Figure 14. Declustered catalog for the Central and Eastern United States including $M_w2.5$ and greater earthquakes occurring since 1700, including potentially induced earthquakes.

Seismicity rate grids based on instrumental and historical seismicity, M ≥3.0
left: constant smoothing width; right: adaptive smoothing



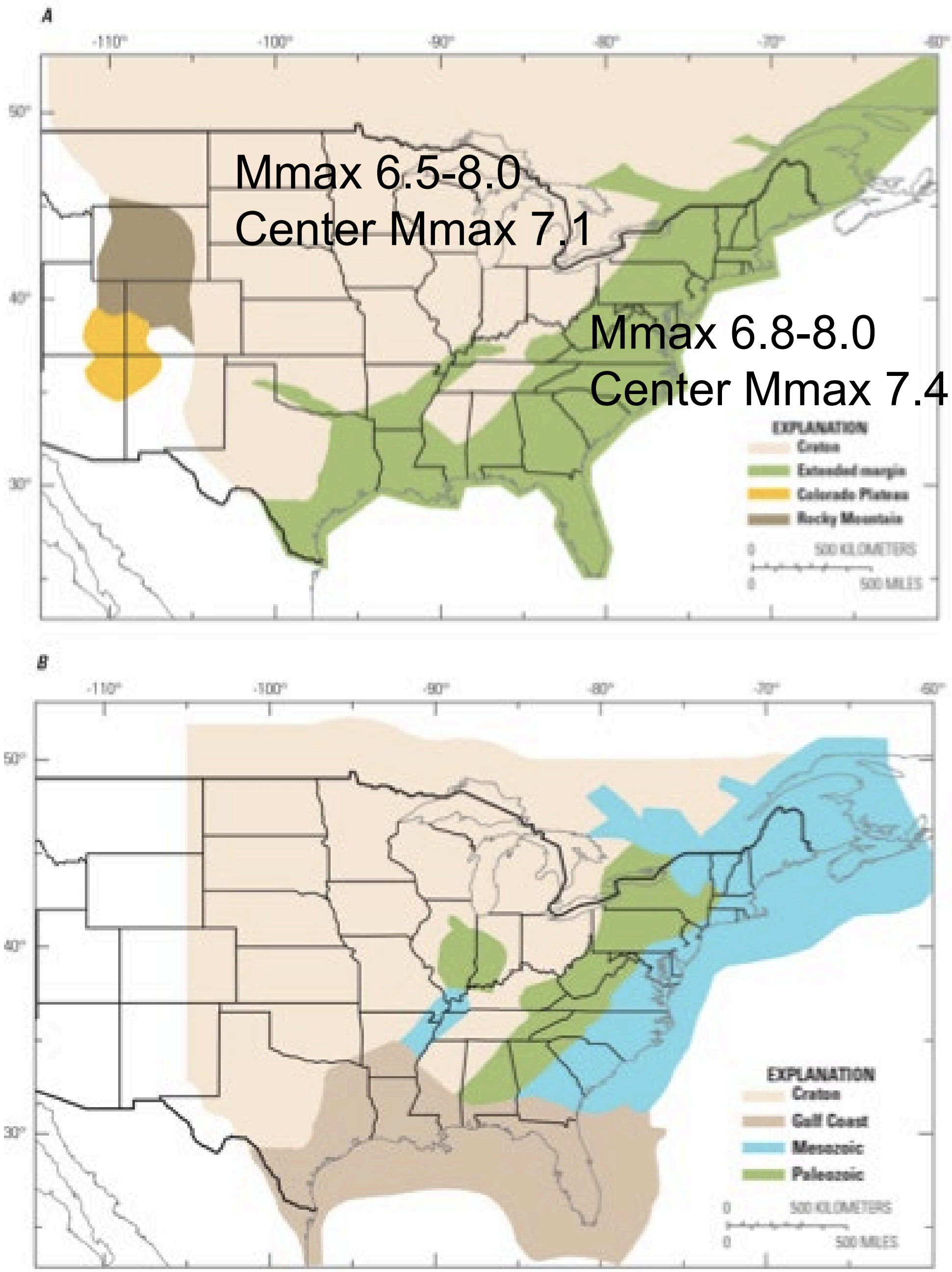


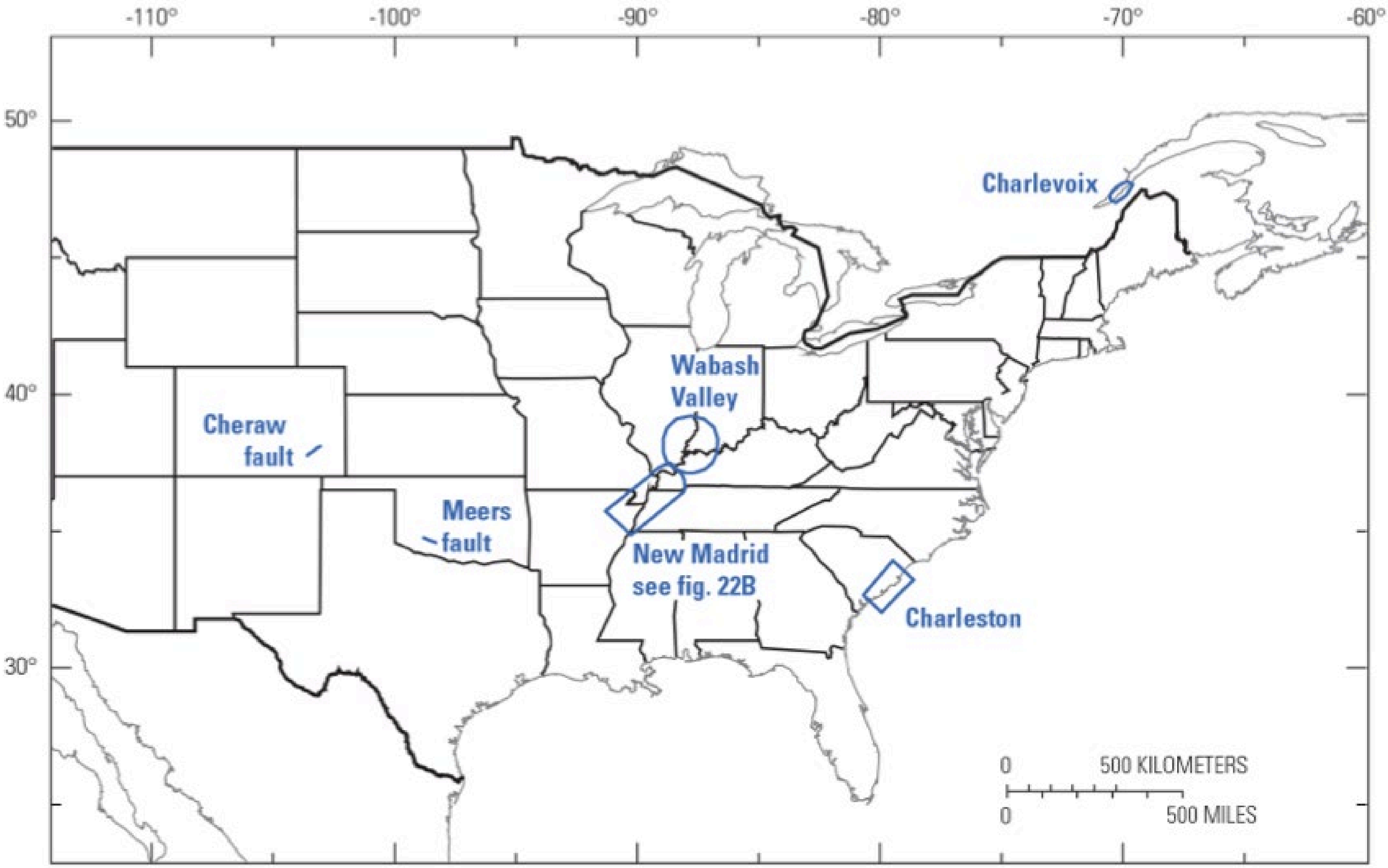
Figure 16. Alternative seismotectonic zonation models used to assign floor *a*-values and Mmax. Map of zonation model based on *A*, 2008 NSHMP model and *B*, generalized CEUS–SSCn (2012) models.

These are uniform rate background source zones that get partial weight in hazard maps. This produces a floor of hazard; meant to account for Incomplete paleoseismic studies; temporal clustering of seismicity, etc

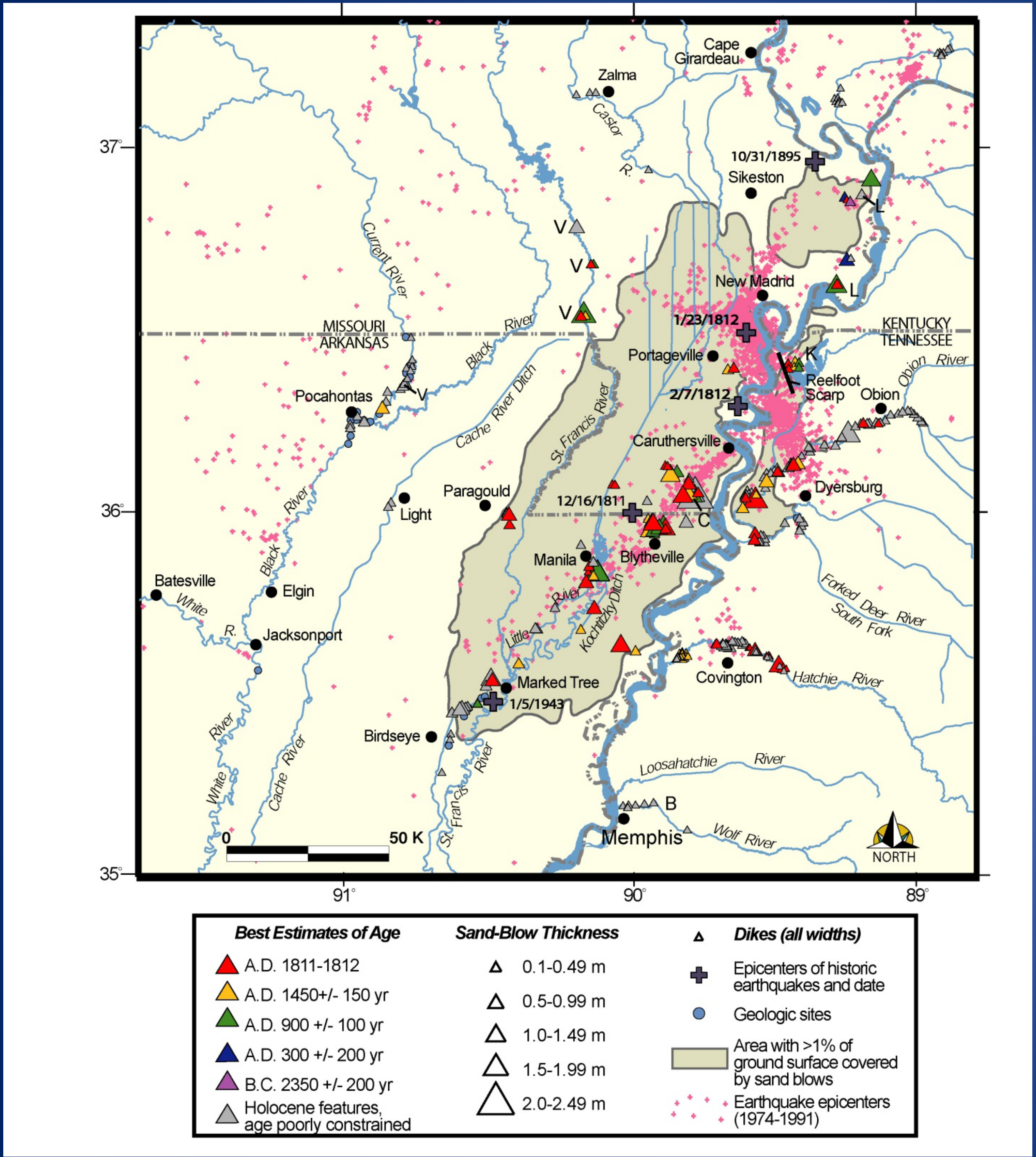
These zones also assign Range of Mmax values based on age of rifting and global compilation of magnitudes of earthquakes in Stable continental regions

USGS
science for a changing world

Source areas in CENA with paleoseismic evidence of M7 earthquakes in Holocene; recurrence times determined from paleoseismic data (except Charlevoix)

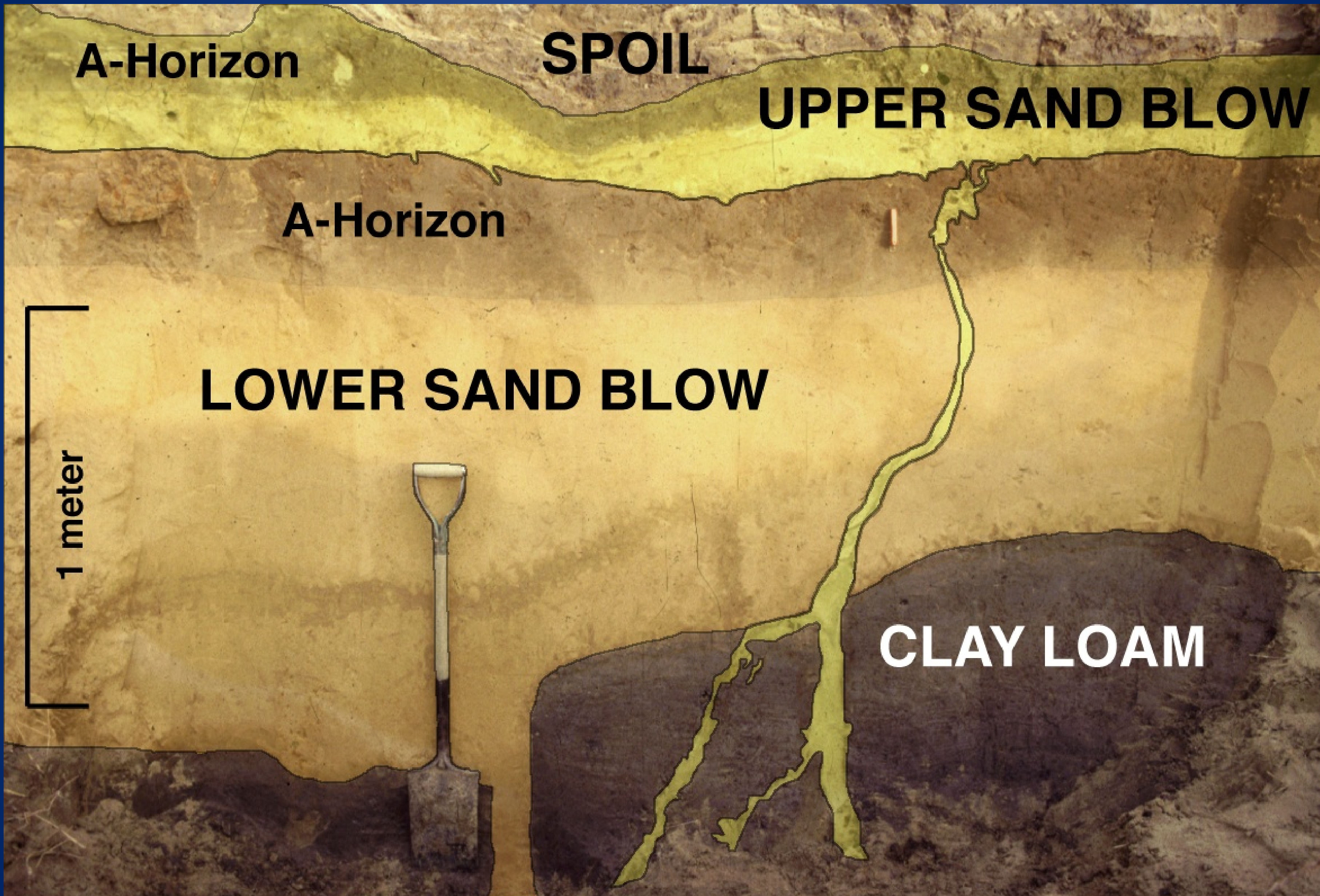


USGS science for a changing world



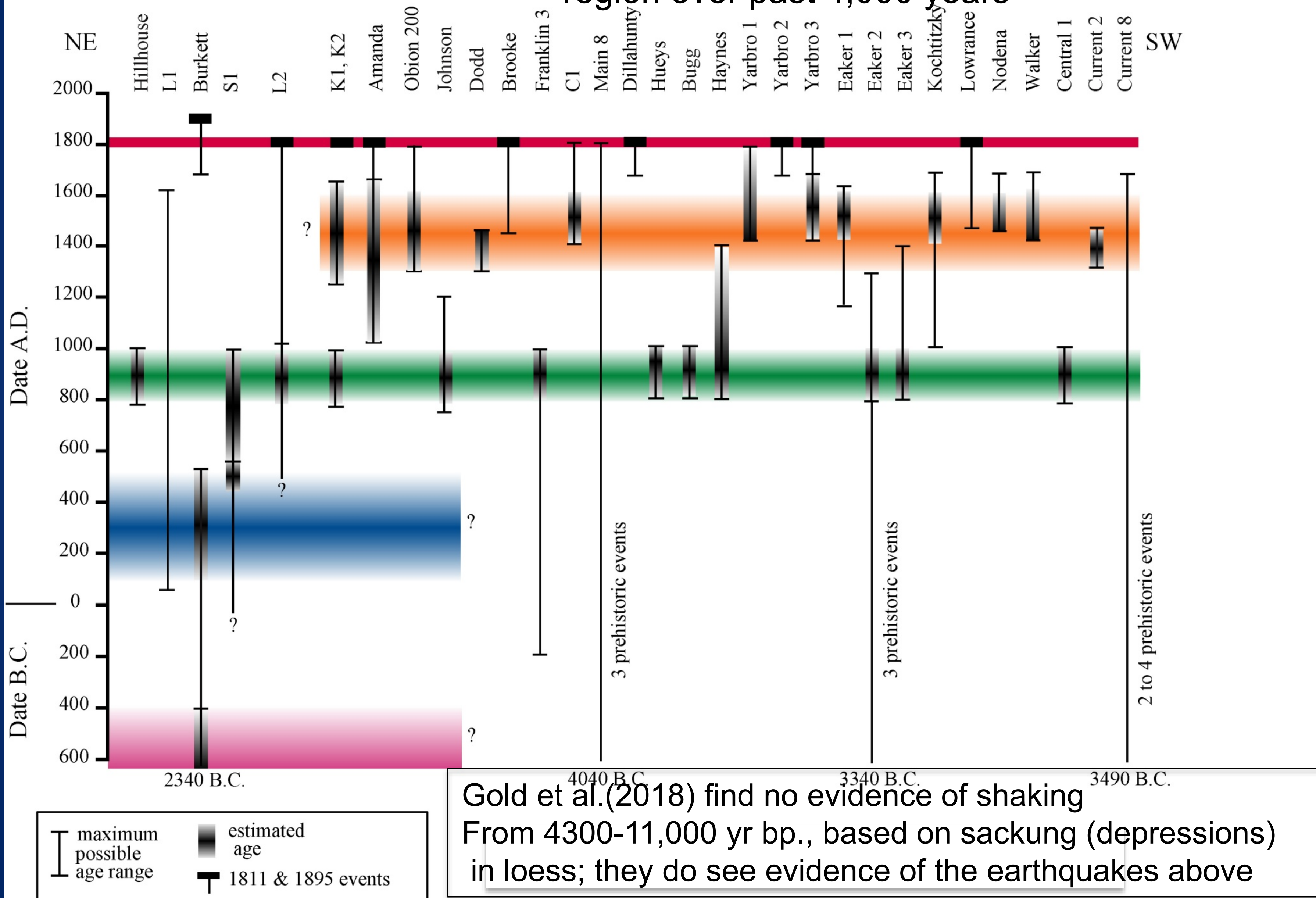
Paleoliquefaction Sites in New Madrid region From Tuttle et al. (2002)

Estimates of magnitudes of 1811-12 quakes range from 6.8-8.0 based on observed intensities

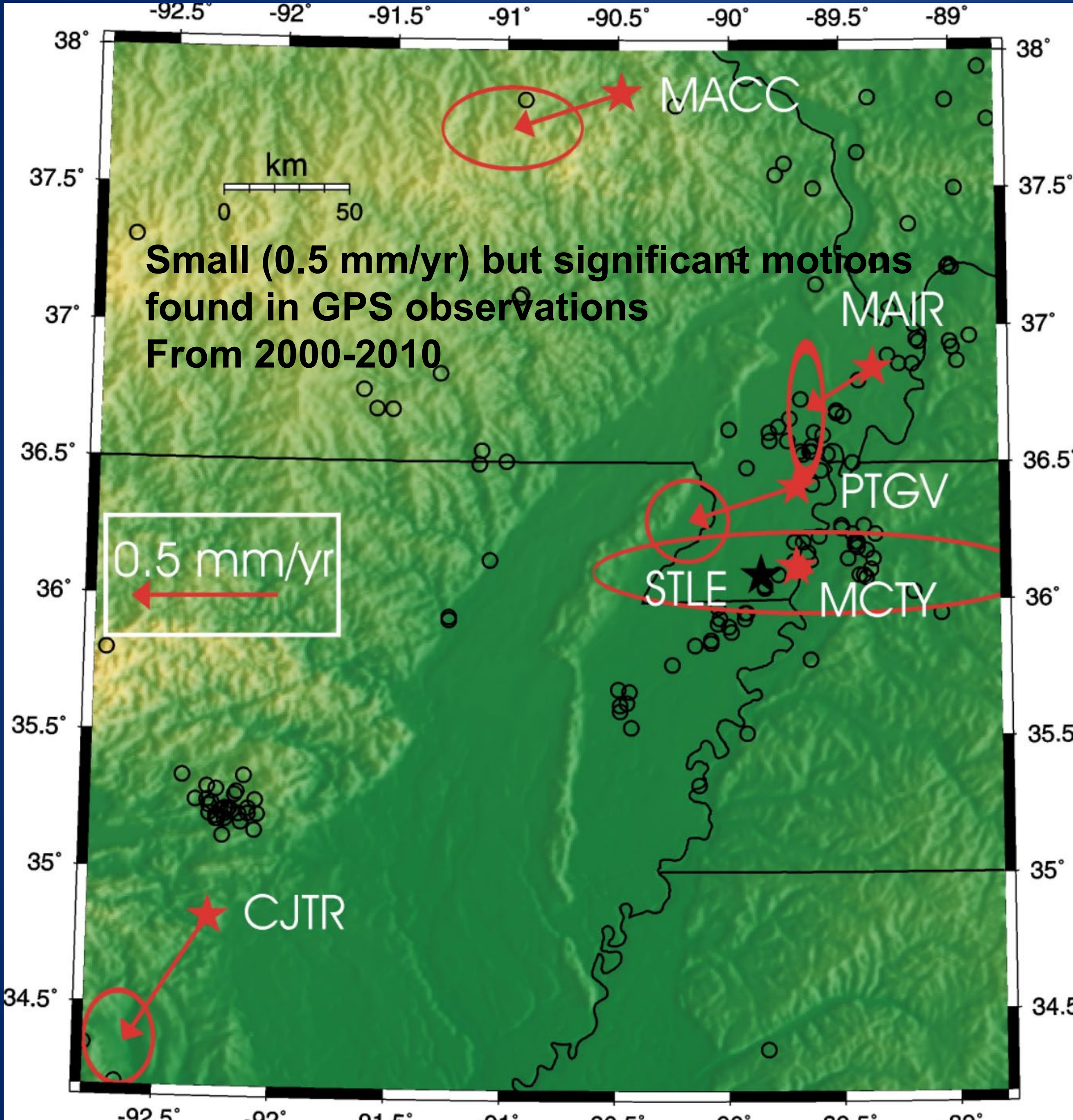


Slide provided by E.S. Schweig

From Tuttle et al. (2002) Strong shaking from earthquakes in New Madrid region over past 4,000 years



Gold et al.(2018) find no evidence of shaking
From 4300-11,000 yr bp., based on sackung (depressions)
in loess; they do see evidence of the earthquakes above



Motion
With respect
To STLE, derived
By differencing GPS
Position time series

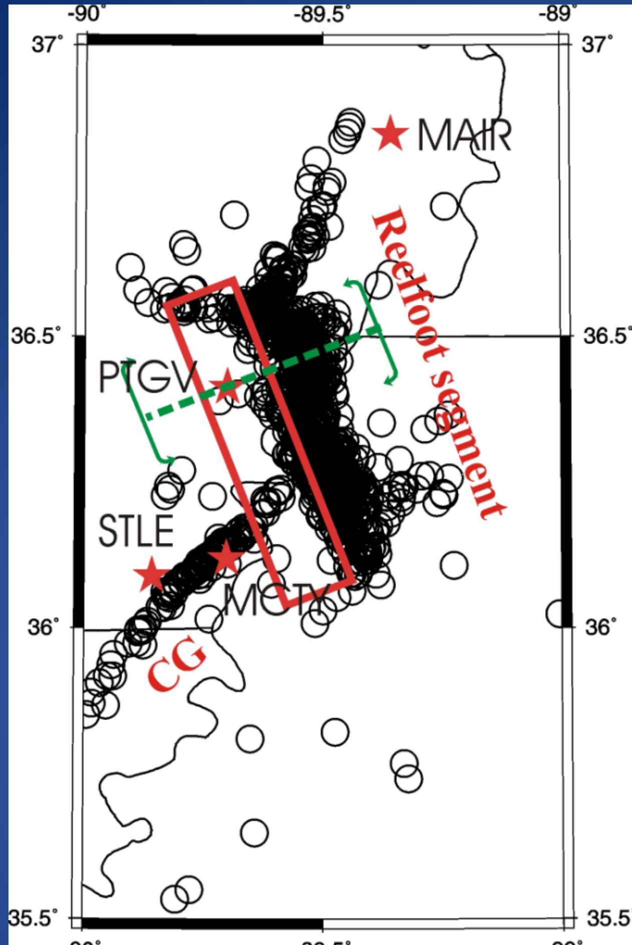
95%
Confidence
Bounds after
estimation of
flicker noise and
random walk

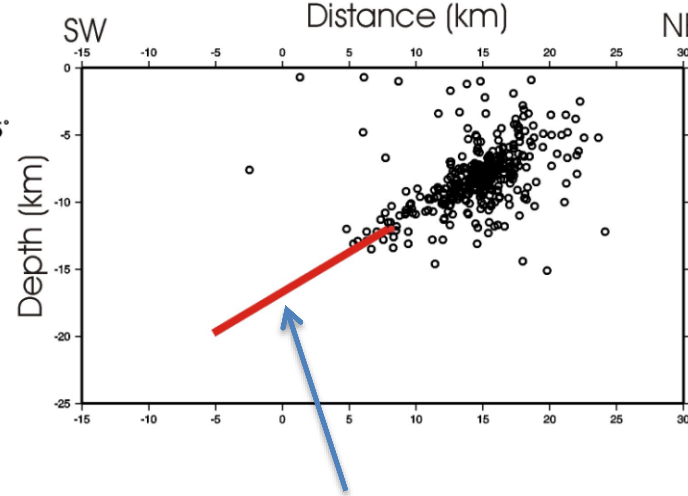
2000-2010

(Frankel et al., 2012)

Significant
GPS deformatiom
Also found by
Boyd et al.(2015)

USGS
science for a changing world



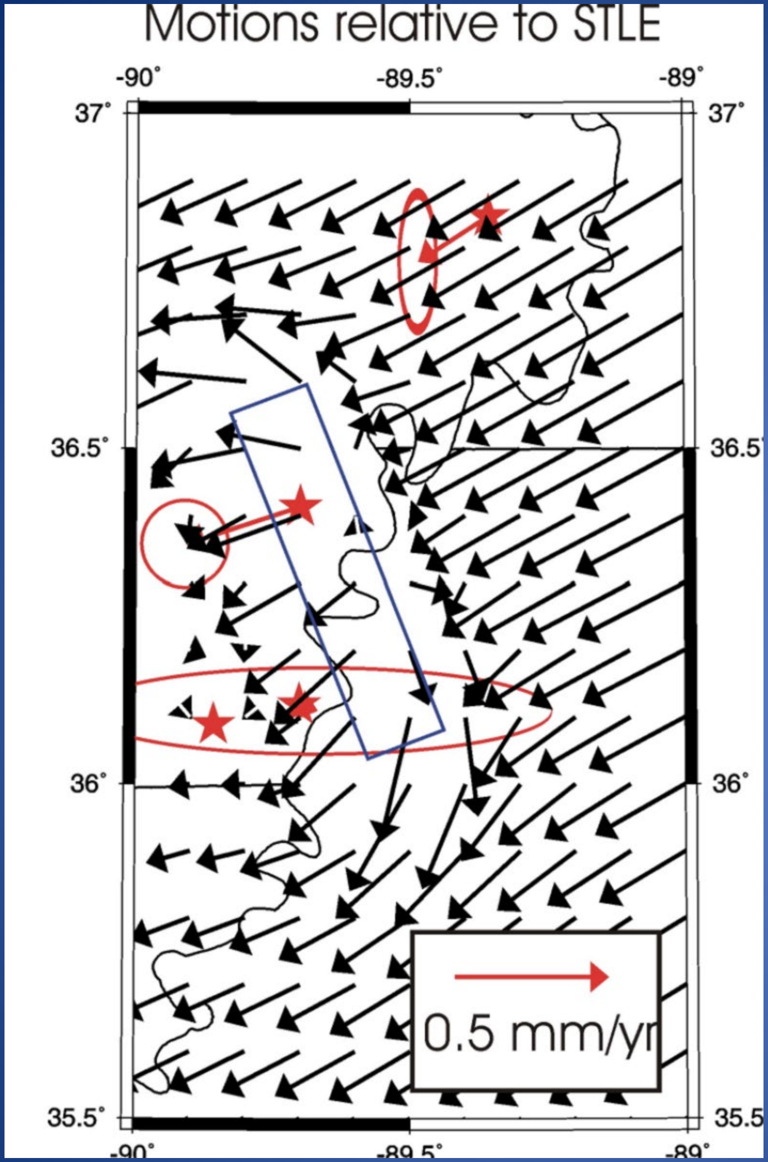


4 mm/yr deep slip
produces about 0.5 mm/yr
horizontal deformation
at surface

Model uses 4 mm/yr of creep on deep portion of Reelfoot Fault;
accumulates 2 meters of slip (M7.3) in 500 years on shallow portion of fault;
consistent with paleoseismic observations.

Low rate of surface deformation
in intraplate areas does not necessarily mean low hazard

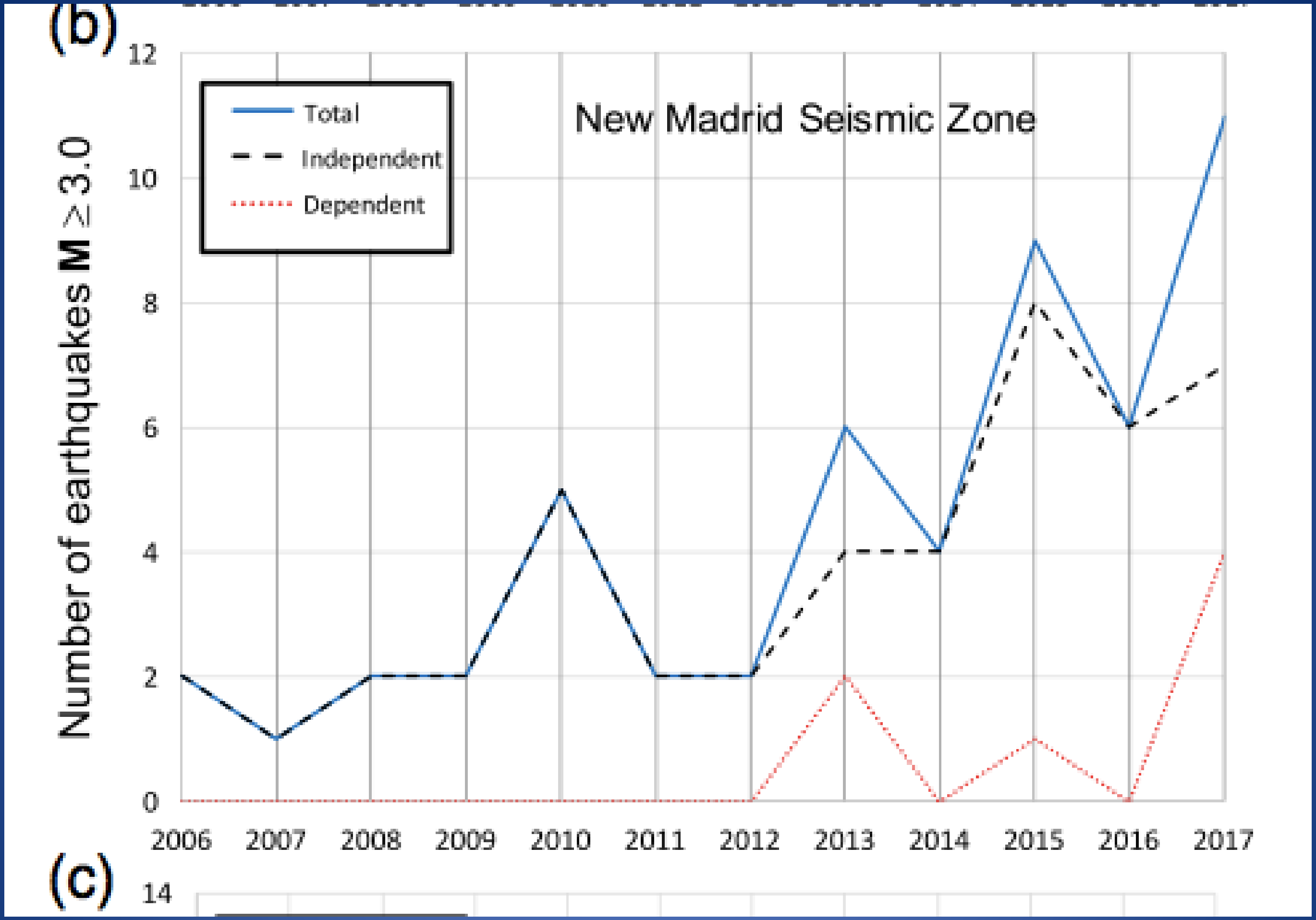
USGS
science for a changing world



Red arrows are observed motions from GPS 2000-2010
Black arrows are predicted for 4 mm/yr deep slip on Reelfoot fault

Model of 4 mm/yr deep slip on Reelfoot fault reproduces observed motion from GPS
Frankel et al., 2012

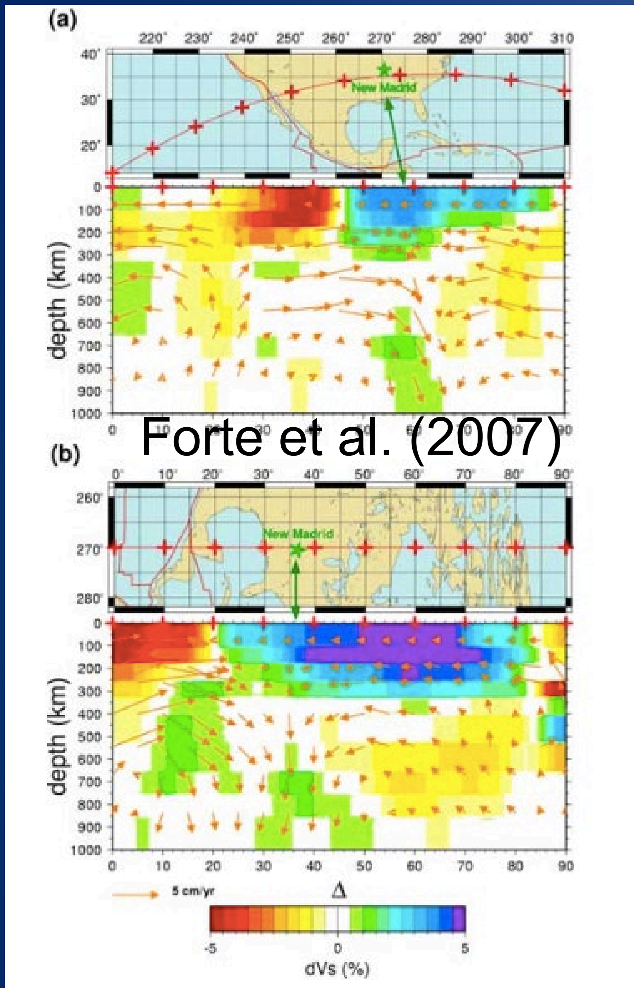
Seismicity rate in New Madrid region is increasing



Note that the 2014 NSHMs give a 10% weight to possibility that we are no longer in a temporal cluster of large earthquakes

Figure from Petersen et al. (2018)

Is the New Madrid seismic zone special?



Predicted flow velocities from Vs anomalies from tomography results of Simmons et al., 2006; Subducted Farallon plate beneath NM?

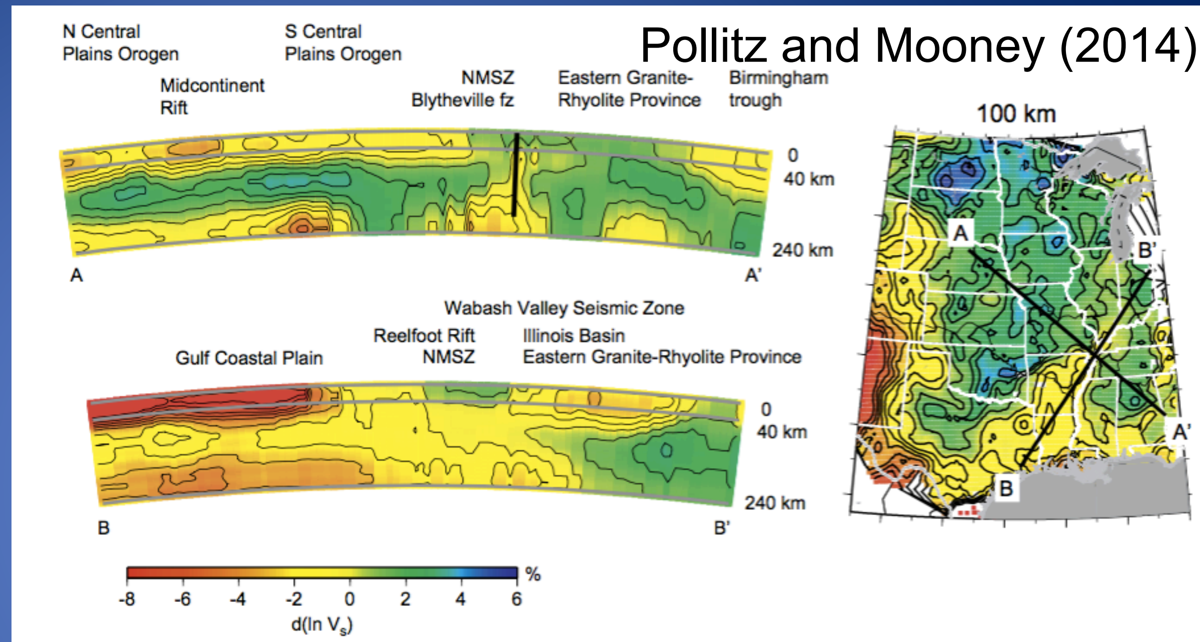


Fig. 8. Perturbation in v_s along two vertical cross-sections passing through the NMSZ (locations in inset). Geologic domains follow Van Schmus et al. (1996).

Perturbation in Vs, using surface-wave imaging from Earthscope Transportable Array. Shows mantle LVZ beneath Reelfoot Rift

Logic tree used in 2014 NSHM for Charleston source

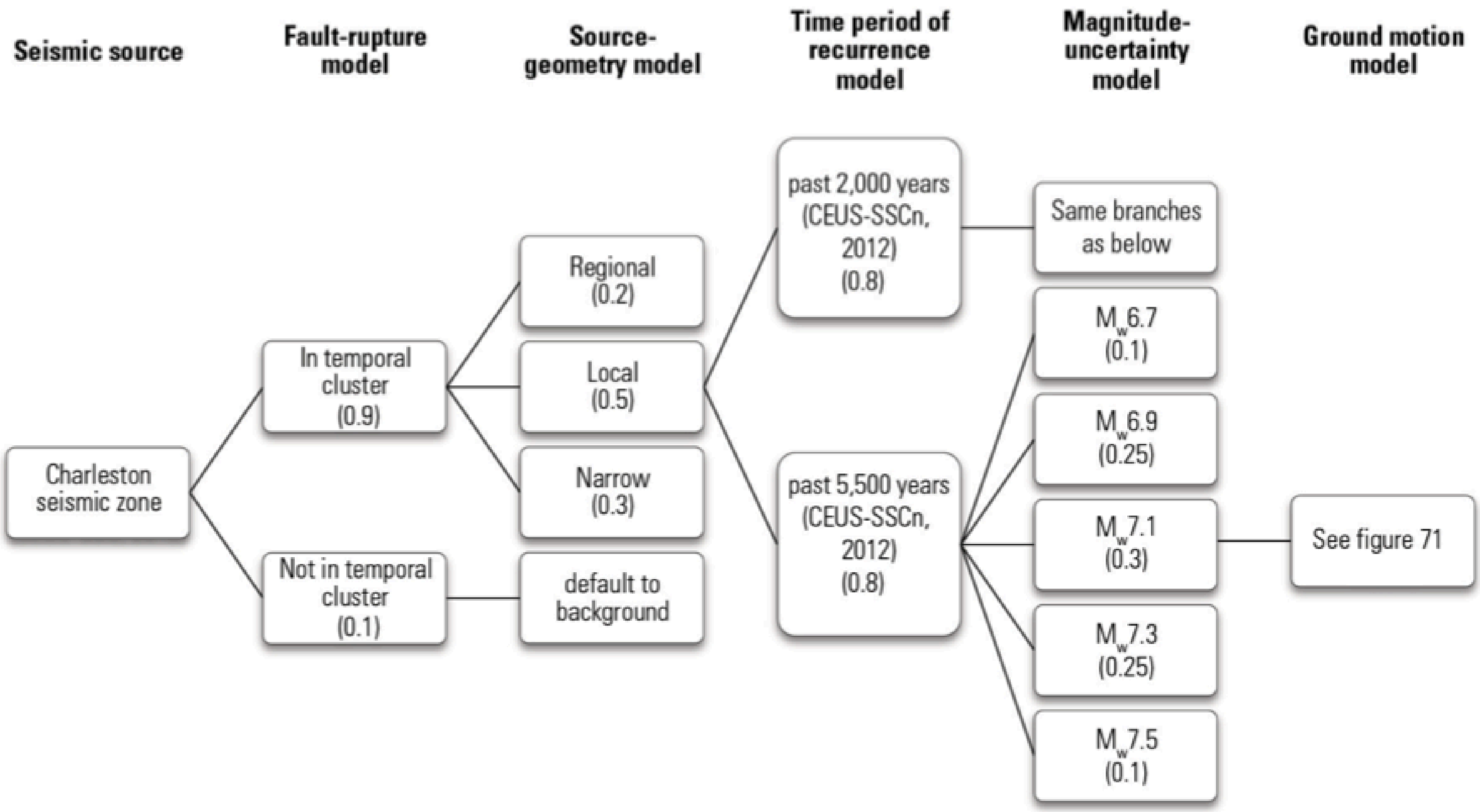
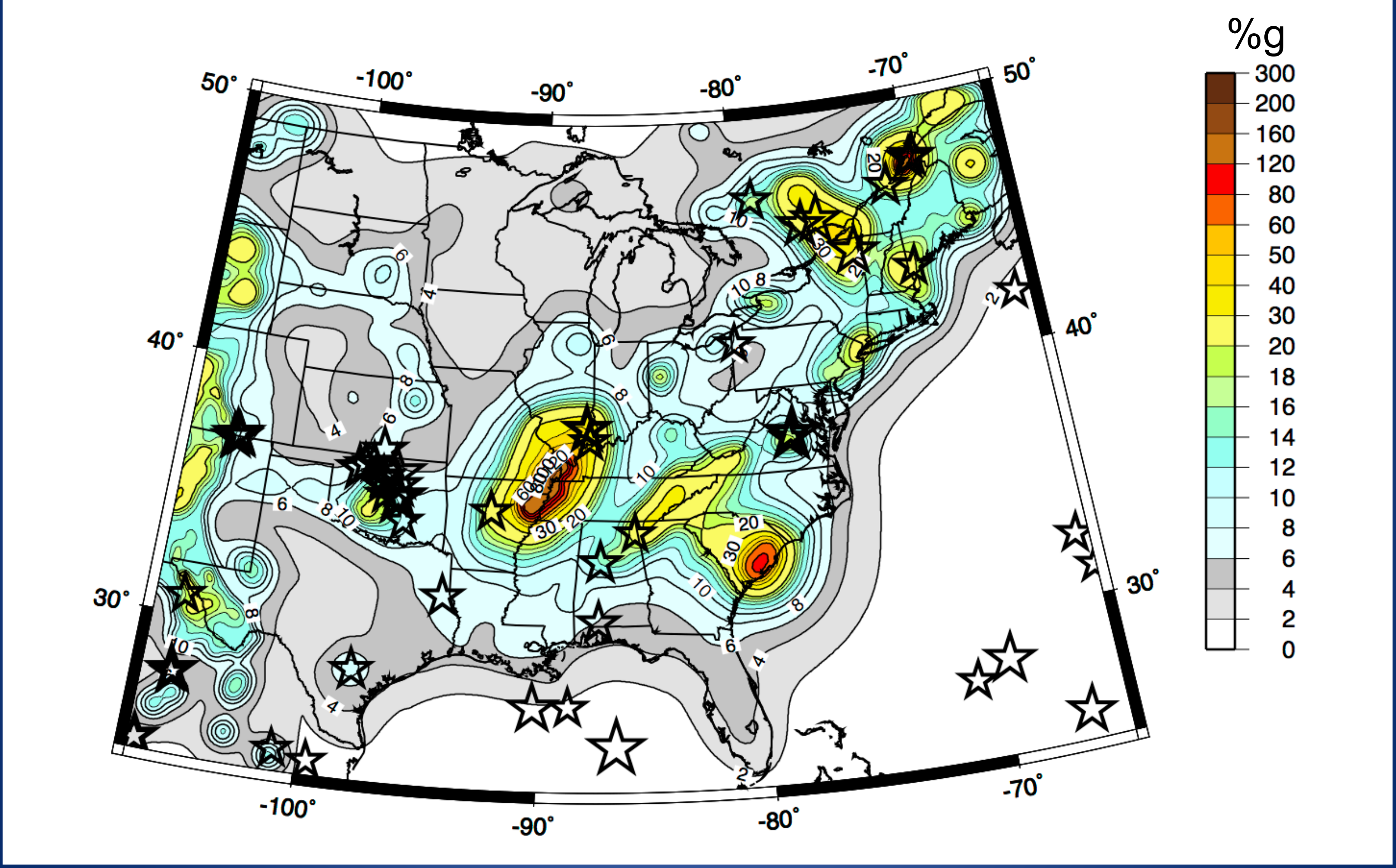


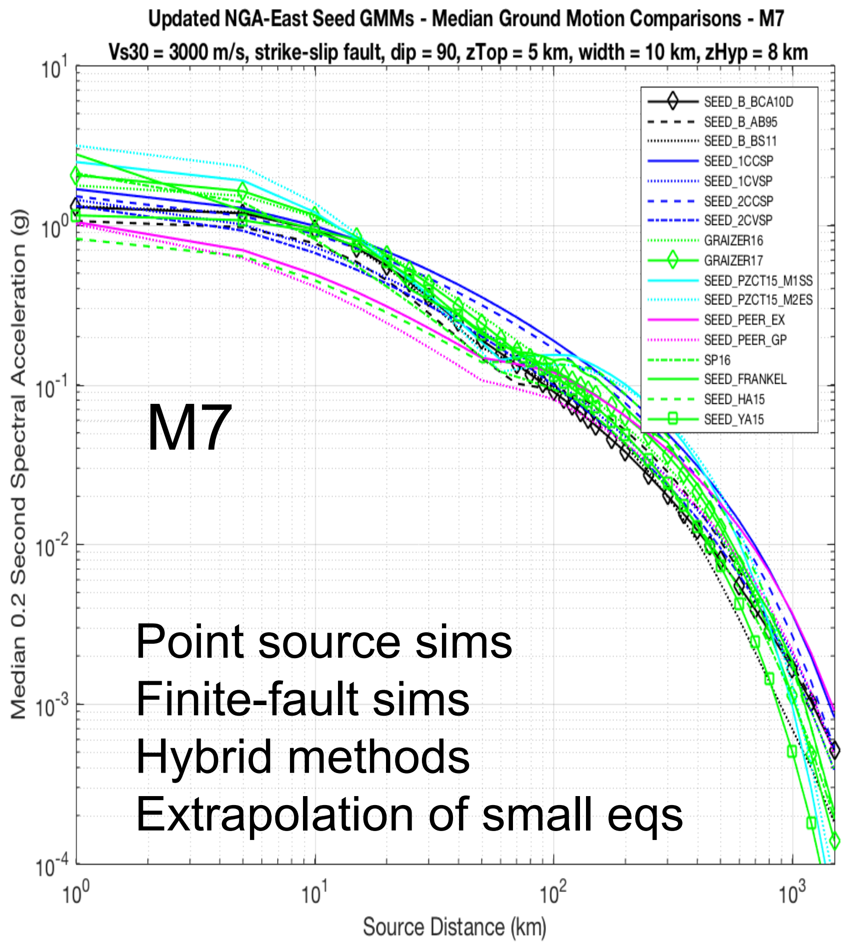
Figure 30. Logic tree for the Charleston source. Value given in "Earthquake-recurrence model" branch is number of earthquakes per year (eq/yr). Assigned branch weight shown in parentheses.

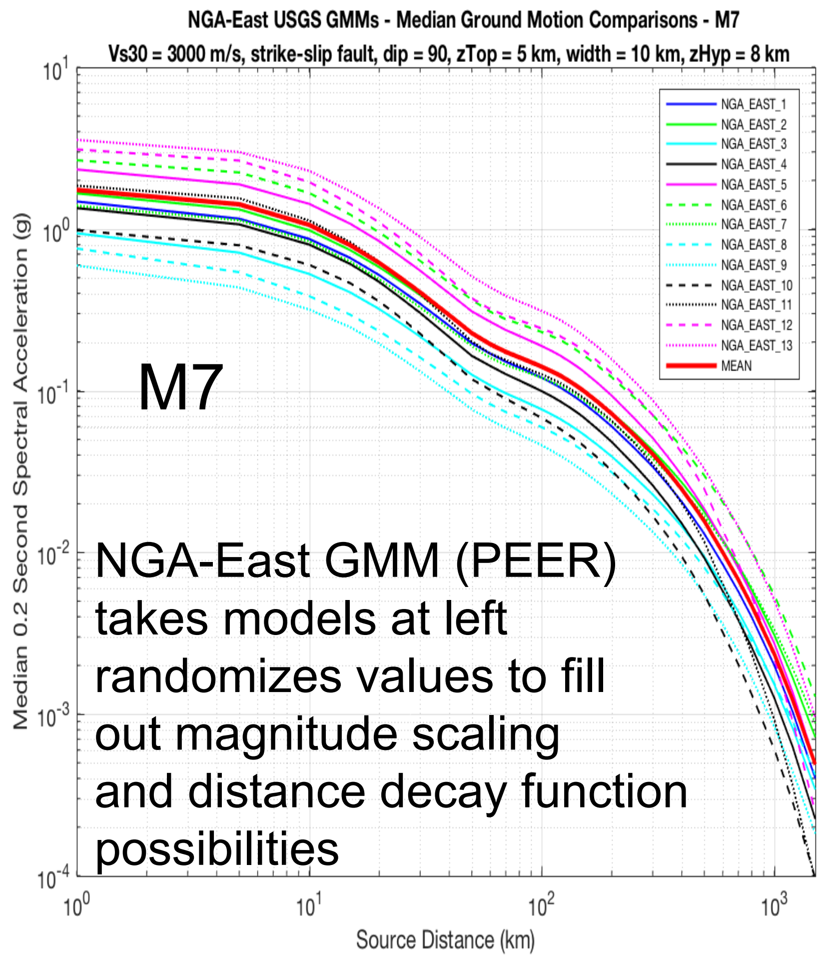
Petersen et al. (2014)

1996 NSHM (PGA with 2% chance of exceedance in 50 years) with Mb ≥ 4. 5 earthquakes 1997- present



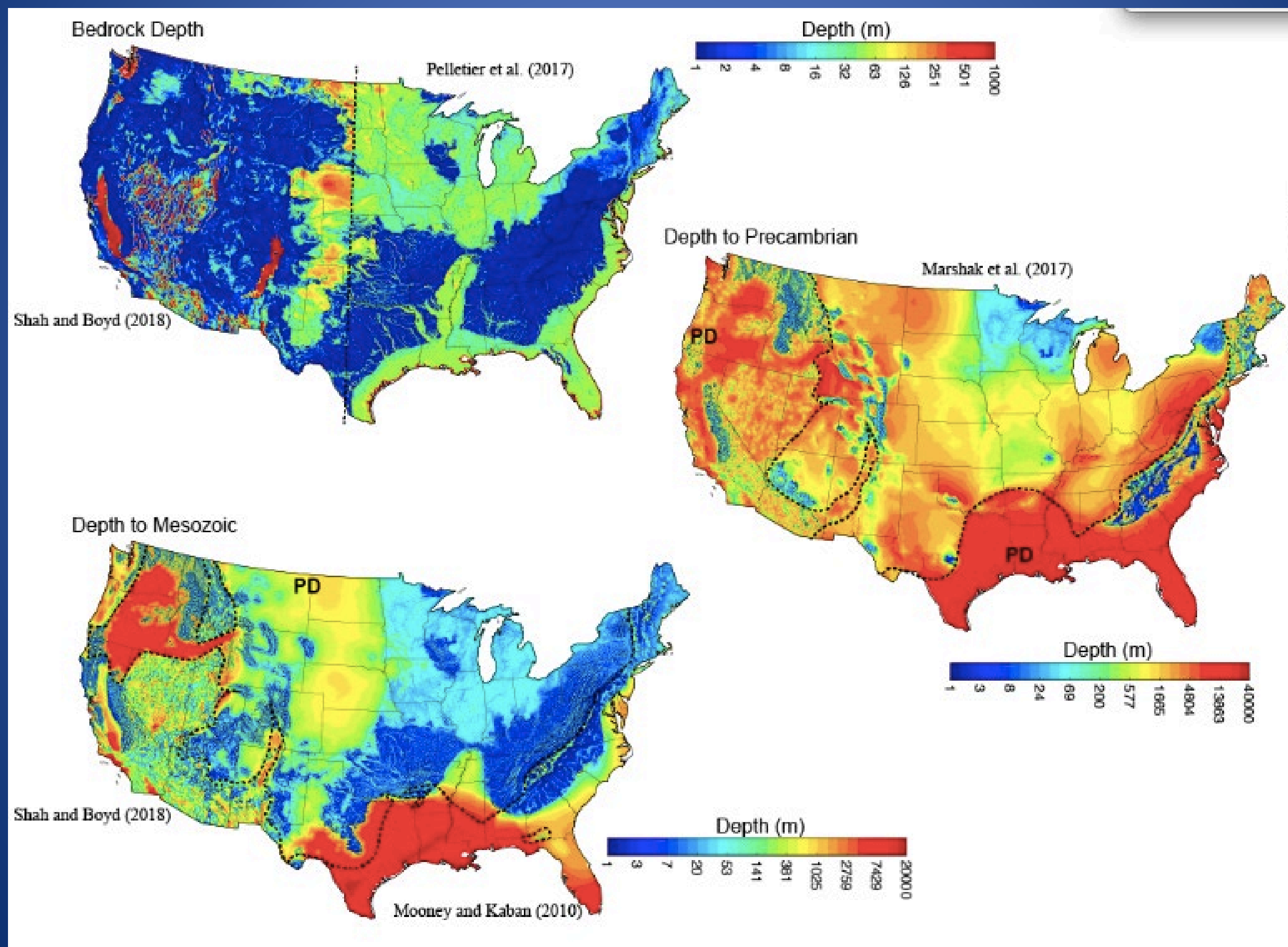
How to best estimate epistemic uncertainties for CEUS GMMs? Use physical approach or statistical approach (Sammons mapping)





Stress drops for CENA earthquakes higher than WUS; higher Q; thin soil over hard rock
Larger high-frequency motions for CENA than WUS earthquakes for same moment mag.

Towards a national crustal model for use in characterizing shallow propagation effects in GMMs for NSHMs. Boyd and Shaw (2018)



Some priorities for improving CEUS ground-motion models

- Estimate epistemic uncertainties by varying parameters in physical models of rupture and propagation; use observations of M3-5 earthquakes to assess variability of stress drop, Q, etc.
- Identify regional variations in scattering and anelastic Q and earthquake stress drops within CEUS; relate to heterogenous crustal and upper mantle structure derived from seismic tomography, reflection/refraction studies, receiver functions, etc.
- Quantify amplification, Q, and nonlinearity of thick sediments in Mississippi Embayment , Gulf coast,and Atlantic coastal plain
- Conduct large scale 3D simulations of seismic wave propagation in crustal/upper mantle velocity model (e.g., Ramirez-Guzman et al. 2015 for New Madrid earthquakes)

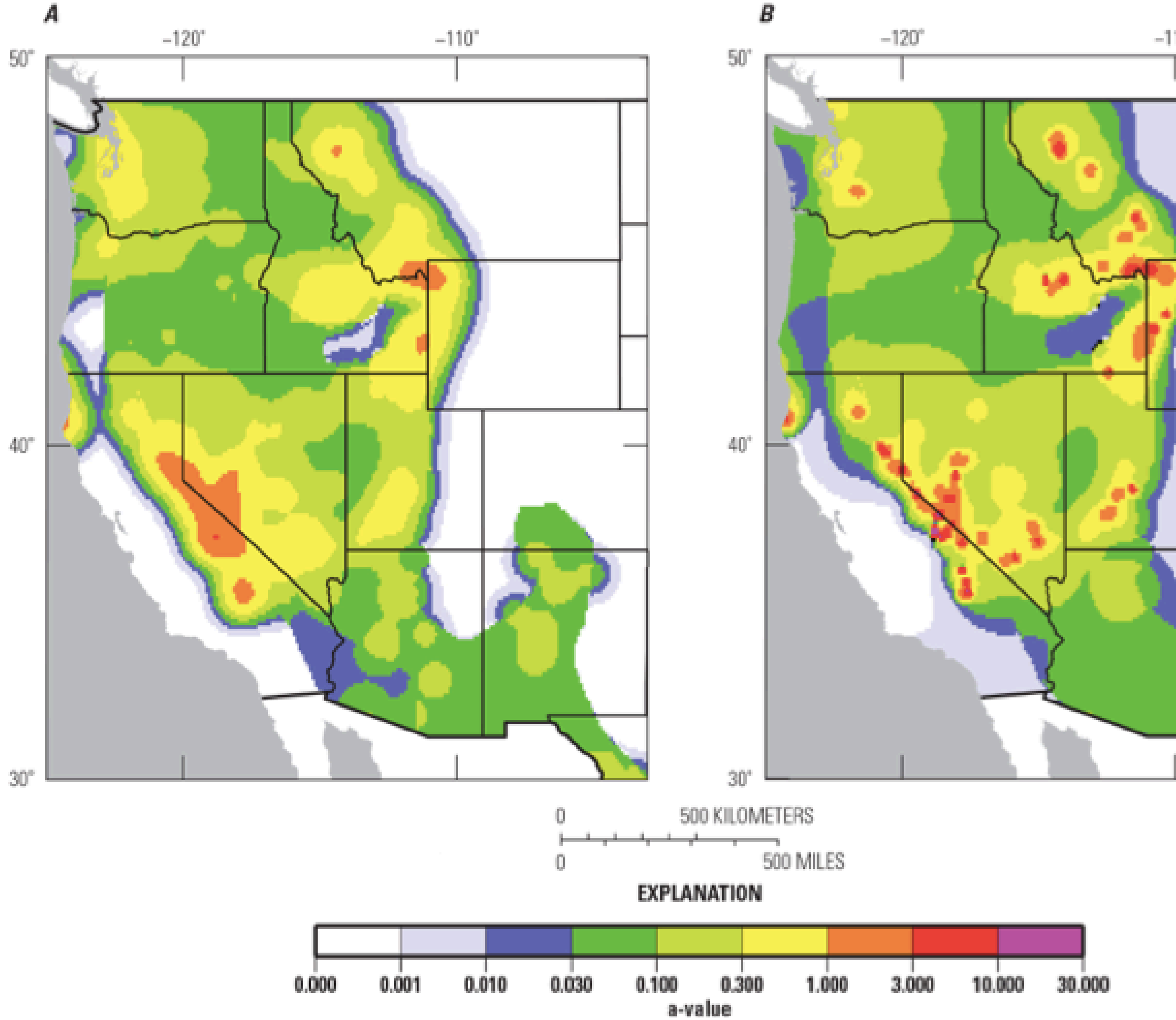


Figure 36. Maps showing incremental seismicity-rate grids from alternative smoothing methods for 5-hertz spectral acceleration. Costal California and Central and Eastern United States seismicity is not included in the grids. *A*, Map of fixed-correlation-length smoothing method and *B*, adaptive-correlation-length smoothing method.

QT faults with recurrence rates from paleoseismology and/or geologic slip rates

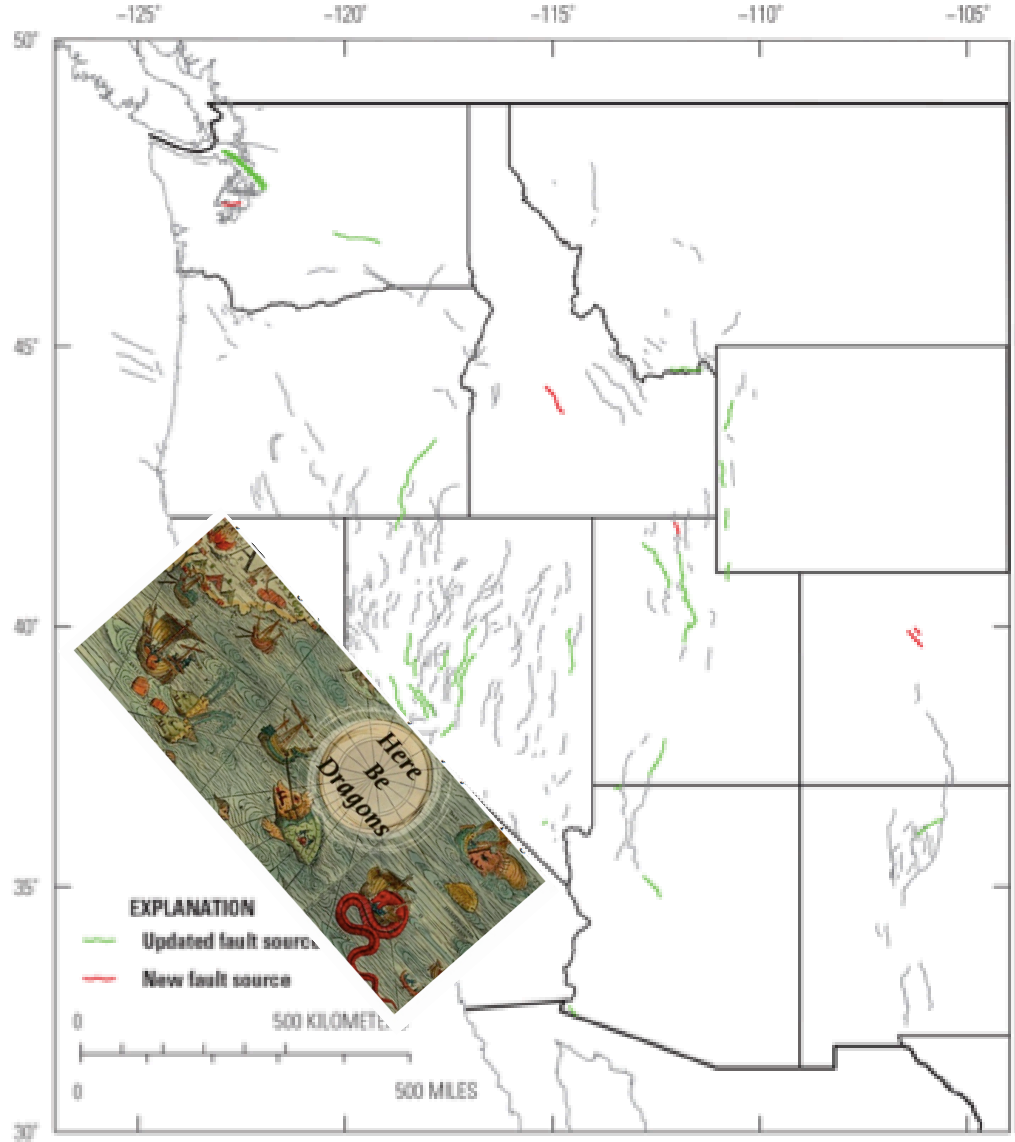
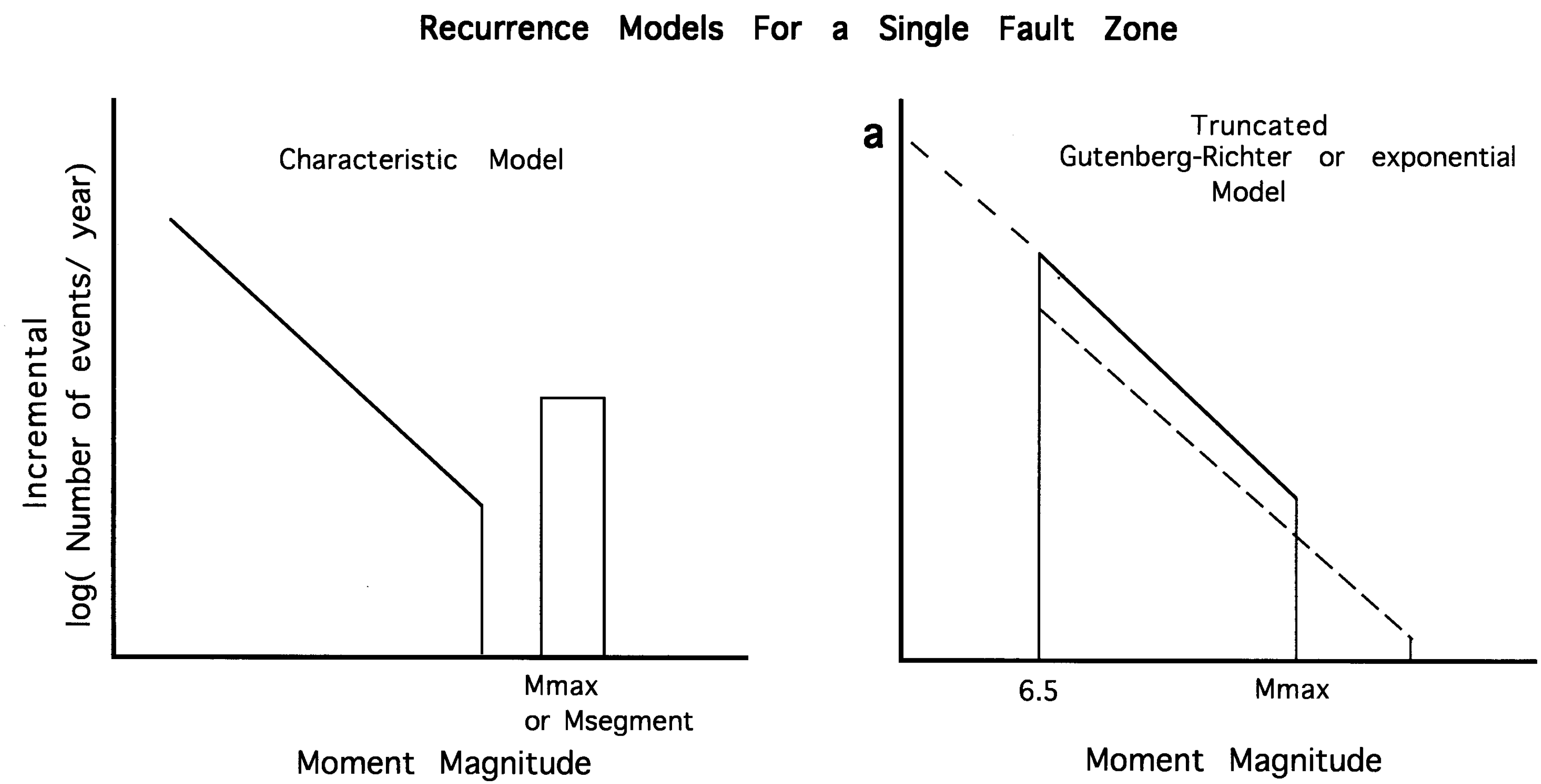


Figure 48. Map of crustal fault sources in the Intermountain West and Pacific Northwest. Fault sources in California are not shown.

Two models of earthquake recurrence on a single fault; NSHMs use these models to go from slip rate to earthquake recurrence rates for non CA faults



characteristic model was developed from observations of low rates of M < 6 earthquakes on long faults that produce M7 quakes in paleoseismic record (Schwartz and Coppersmith, 1984)

Faults used in UCERF 3 (Field et al., 2013). Inverted fault slip rates, recurrence time data to get rates of about 250,000 rupture scenarios, using region GR with b=1 as constraint

Challenge: how to characterize multi-segment, multi-fault ruptures in a physically-realistic manner

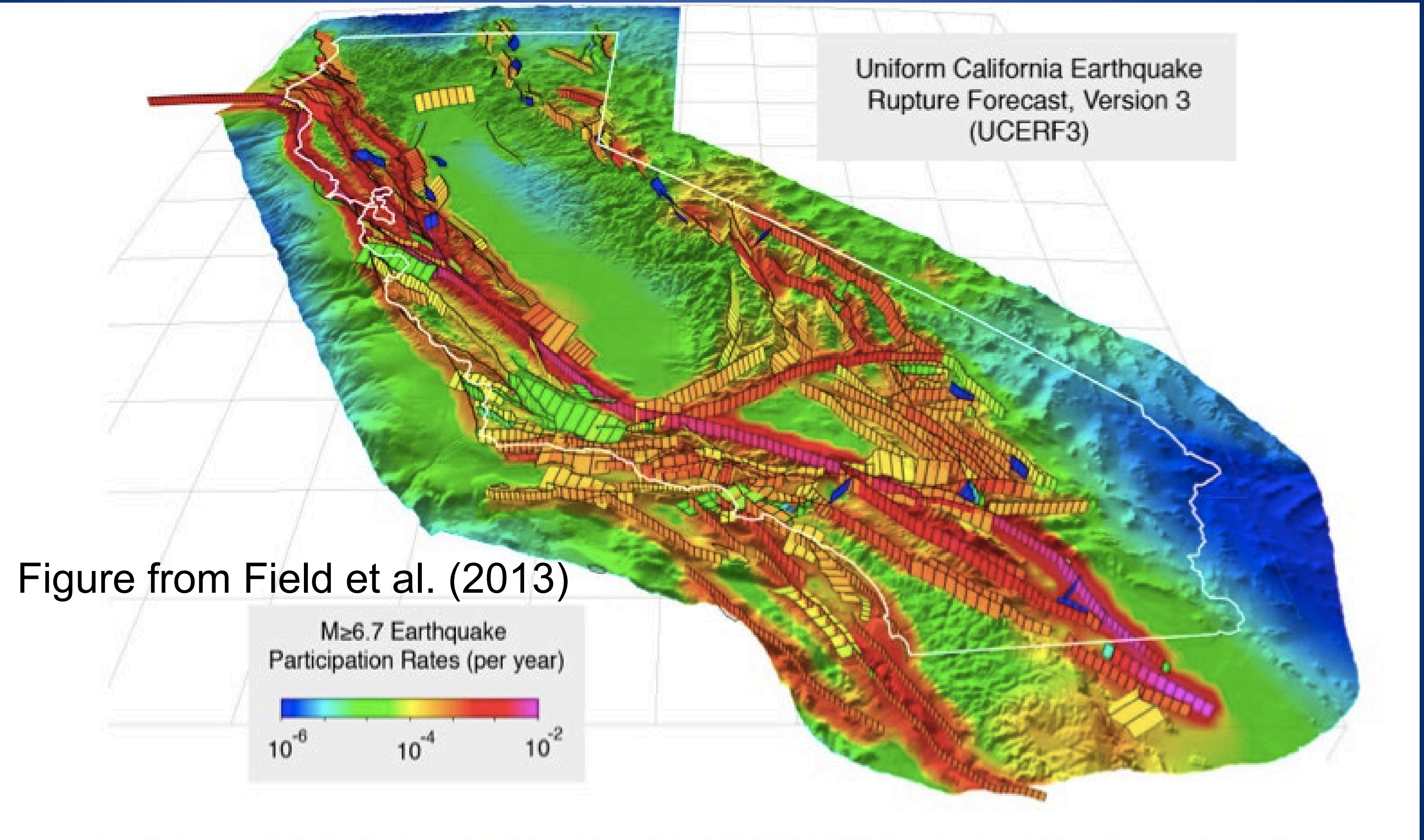


Figure 66. Map of earthquake participation rate for the Uniform California Earthquake Rupture Forecast, ver. 3.3 (UCERF3) model. For the purpose of this illustration, faults are projected above the earth's surface.

Uniform California Earthquake Rupture Forecast 3

GPS data used to constrain fault slip rates in NSHM, along with geologic data
2014 maps used 2 different inversion results (Zheng and Shen 2013; Bird, 2013)

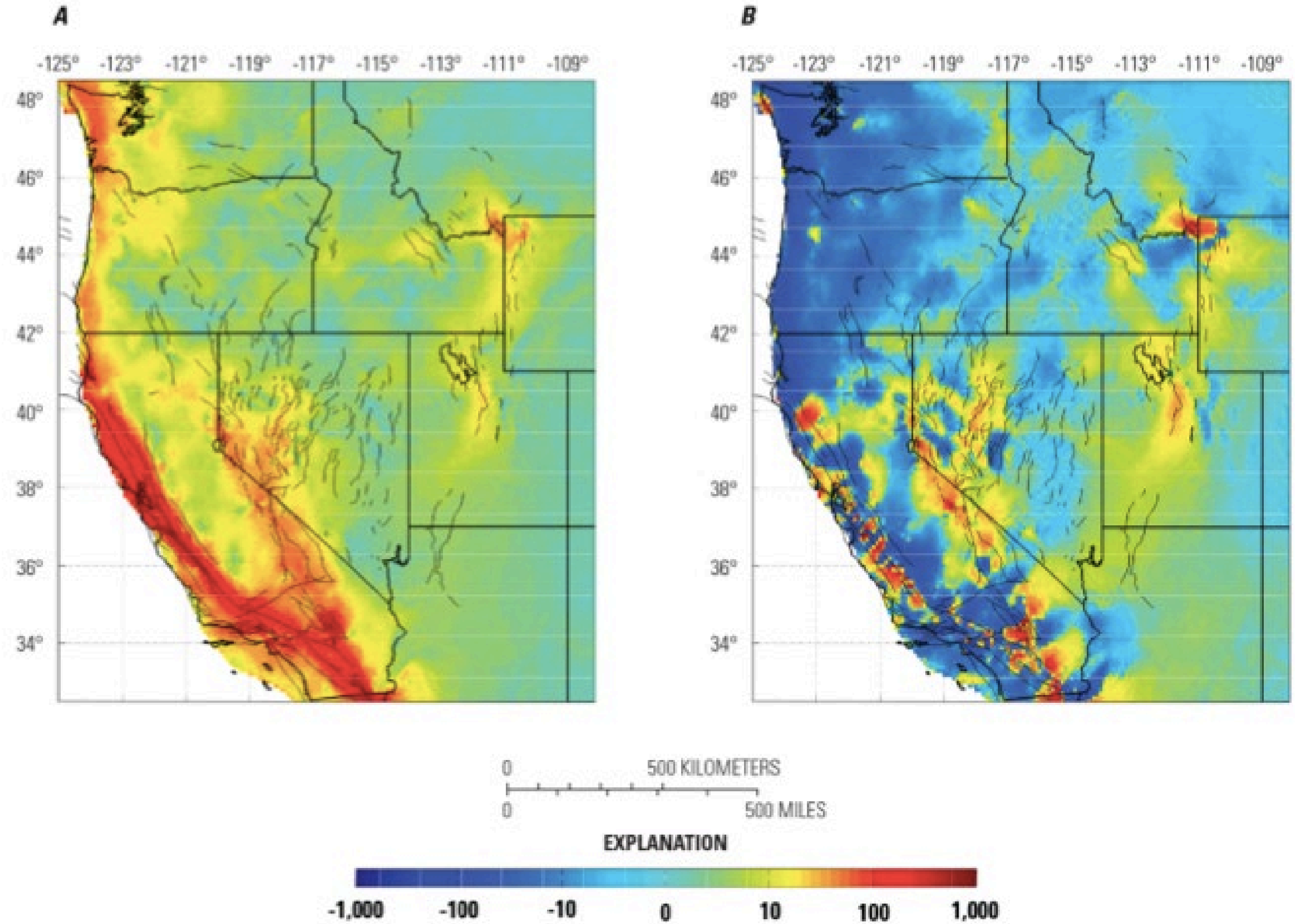
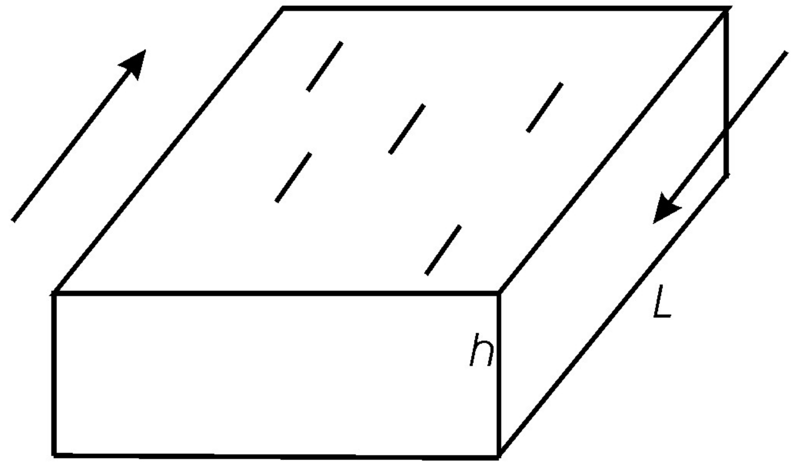


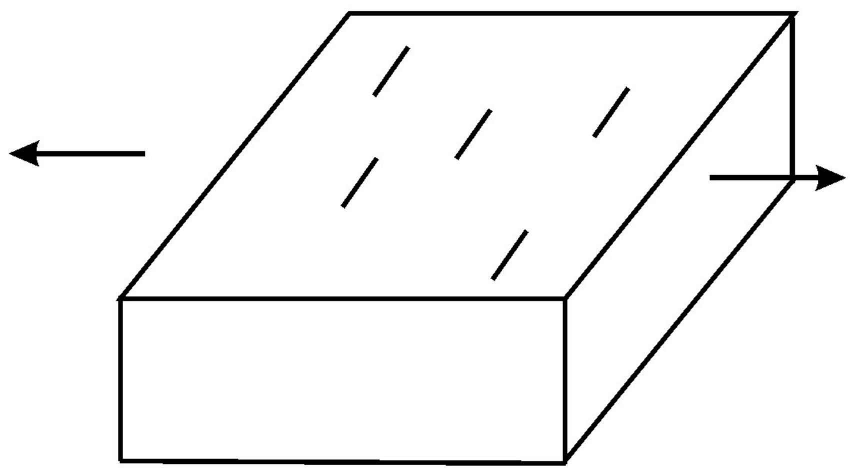
Figure 50. Strain-rate maps of the Western United States calculated using the global positioning system (GPS) dataset collected for the combined-inversion models showing *A*, maximum shear and *B*, dilatational strain. Fault sources are shown (black lines).

From Kostrov (1974), Anderson (1979)



For shear on vertical faults

$$\dot{M}_0 = \mu h L \dot{u}$$

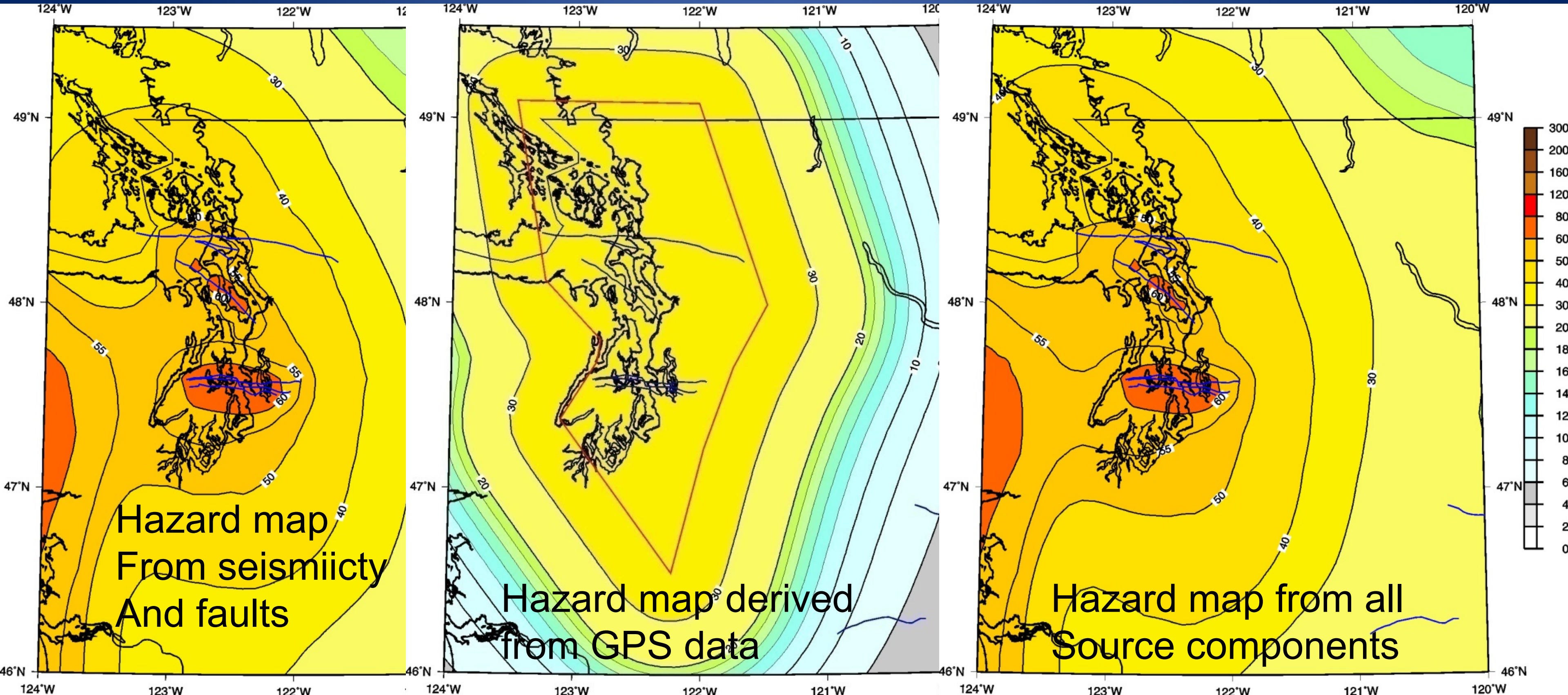


For extension on 45 deg. dipping faults

$$\dot{M}_0 \cong 2\mu h L \dot{u}$$

USGS
science for a changing world

Puget Sound: Effect of including areal source zone accommodating 3 mm/yr N-S convergence measured by GPS (2002 maps)

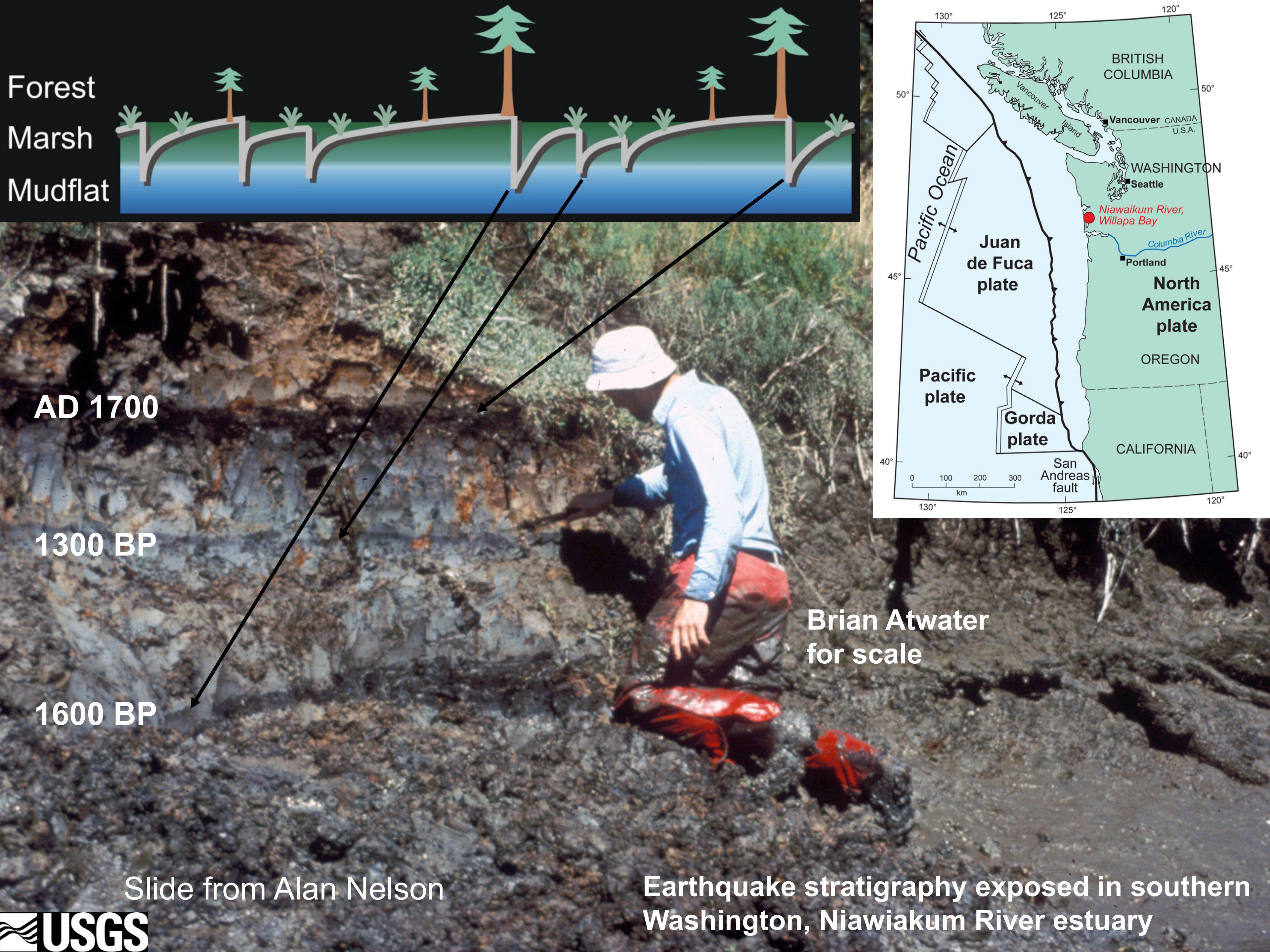


PGA (%g) with 2% P.E. in 50 Years

How many unknown faults are in the hazard maps?

Frankel et al., 2002

USGS
science for a changing world


Forest
Marsh
Mudflat
AD 1700
1300 BP
1600 BP
BRITISH COLUMBIA
Vancouver
CANADA
U.S.A.
Vancouver Island
WASHINGTON
Seattle
Niawaikum River, Willapa Bay
Columbia River
Portland
Pacific Ocean
Juan de Fuca plate
North America plate
OREGON
Pacific plate
Gorda plate
CALIFORNIA
San Andreas fault
0 100 200 300 km
130°
125°
120°
50°
45°
40°
Brian Atwater for scale
Slide from Alan Nelson
USGS
Earthquake stratigraphy exposed in southern Washington, Niawiakum River estuary

Interpretation of rupture history of M8-9 earthquakes from 10,000 year record of turbidites (submarine deposits of turbulent flows of sand, silt, mud, and water)

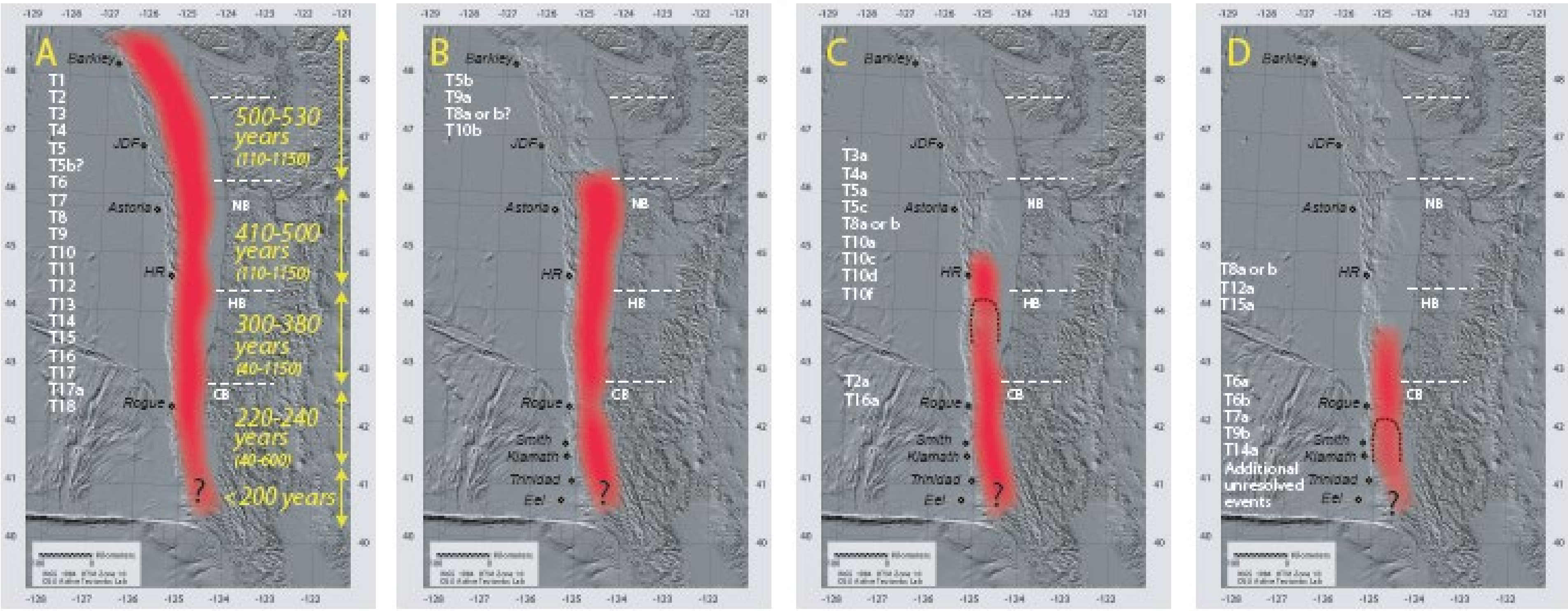
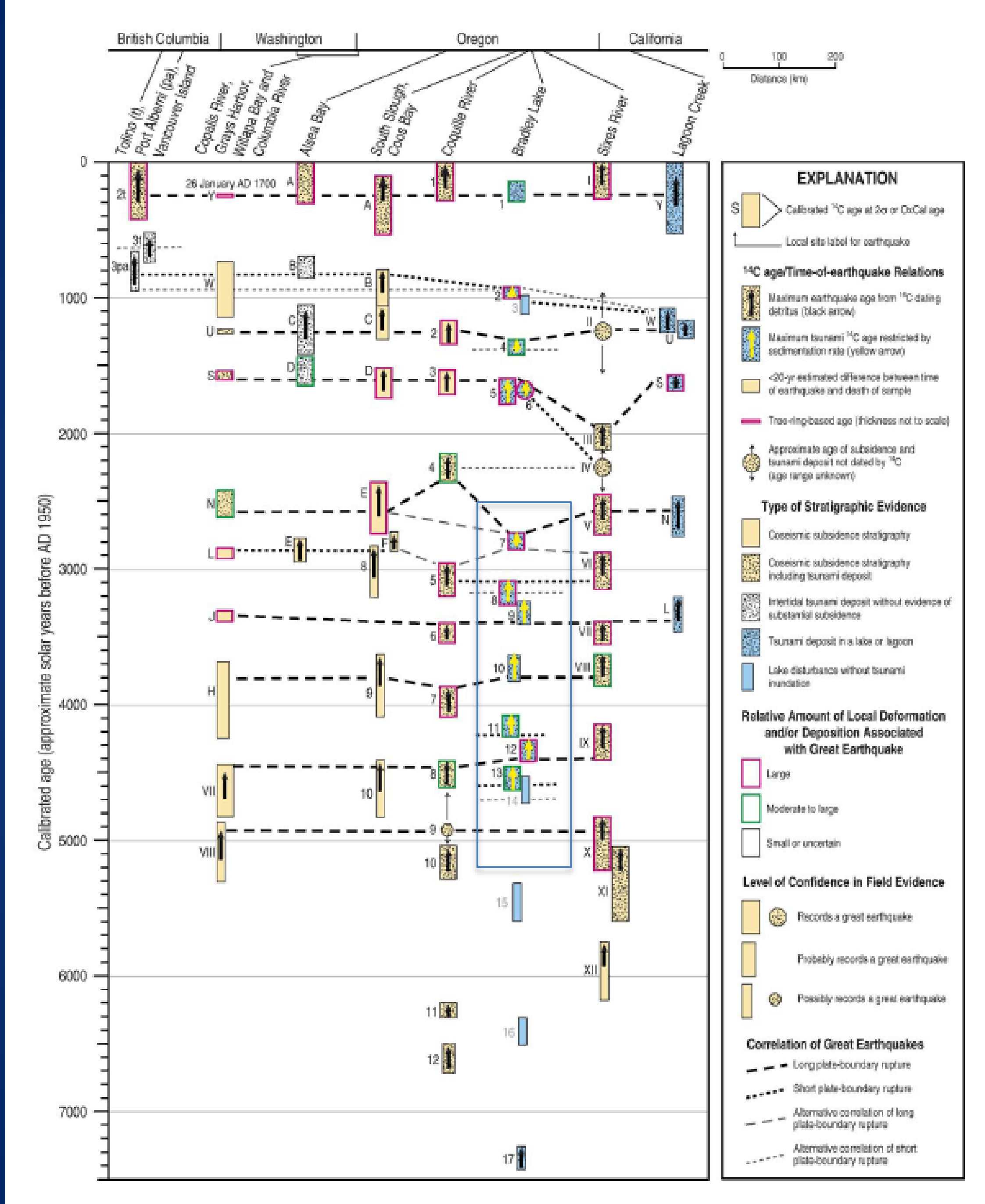


Figure from Goldfinger et al. (USGS Professional Paper 1661-F, 2012); We give partial weight for this model.

Some of these inferred M8 earthquakes may be seen in onshore paleoseismic dats some are not. Are all turbidites caused by M8-9 Cascadia interface earthquakes?

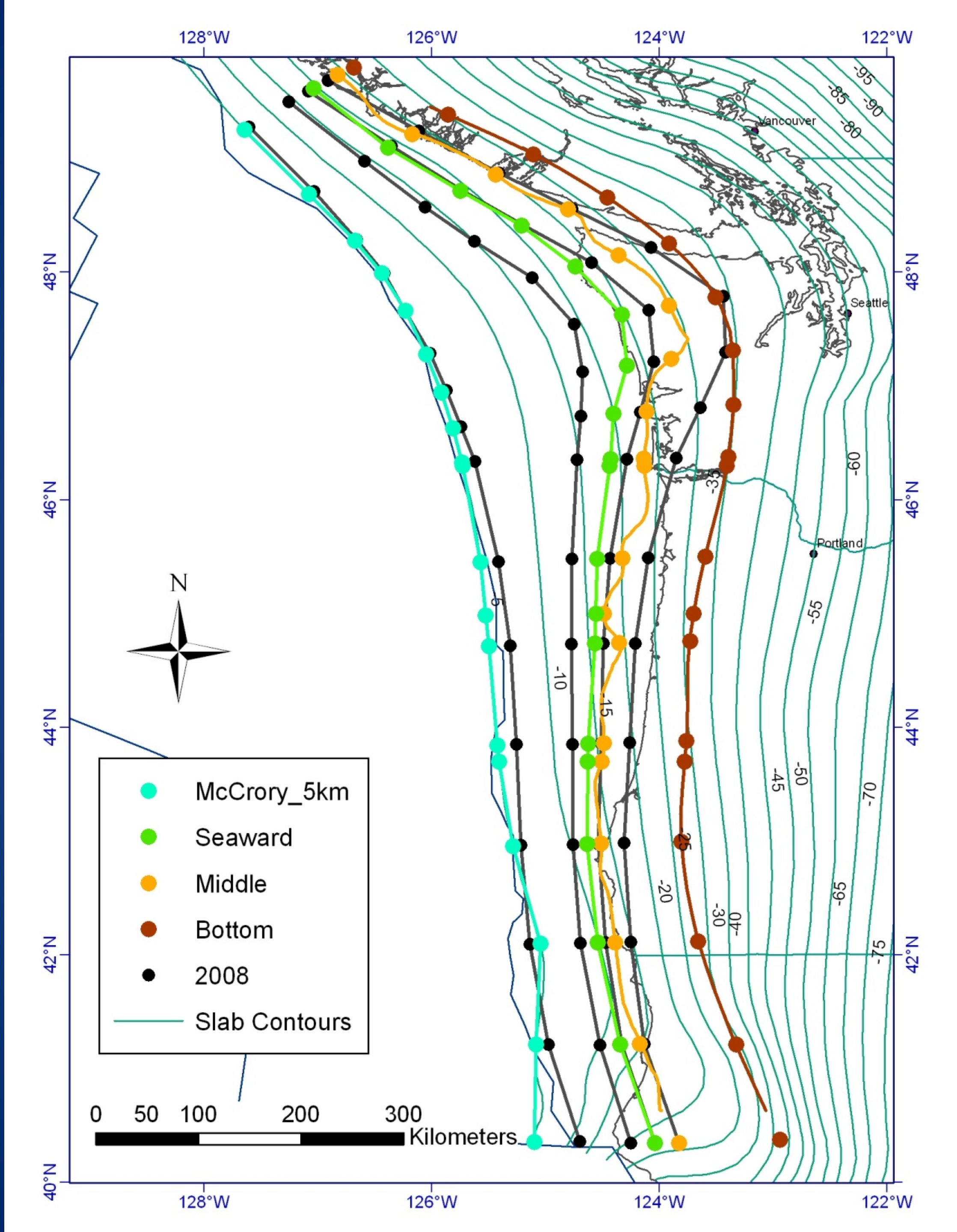


Compilation of on land paleoseismic data

From Nelson et al. (2006)

Evidence for M8 earthquakes That rupture southern portion of CSZ in intervals between M9 earthquakes

USGS
science for a changing world



Models for
eastern, down-dip edge of
CSZ M8-9 rupture zones

Red: top of tremor zone
(0.3 wt)

Orange: 25% coupling
(1 cm/yr) from inversion of
GPS data (0.5 wt)

Green: midpoint of
locked zone from
thermal modeling
and 25% coupling
From GPS (0.2 wt)

Black lines are
previous models
from thermal modeling

Slide from
Rui Chen, CGS

Time-Dependent Hazard

- Elapsed time since last large earthquake that ruptured that fault segment; How to do this in a multi-segment, multi-fault system. How to include heterogeneous co-seismic slip on faults.
- Aftershocks
- Triggered events; fault interaction
- Temporal and spatial clustering of seismicity; possible supercycles over hundreds of years
- Induced seismicity

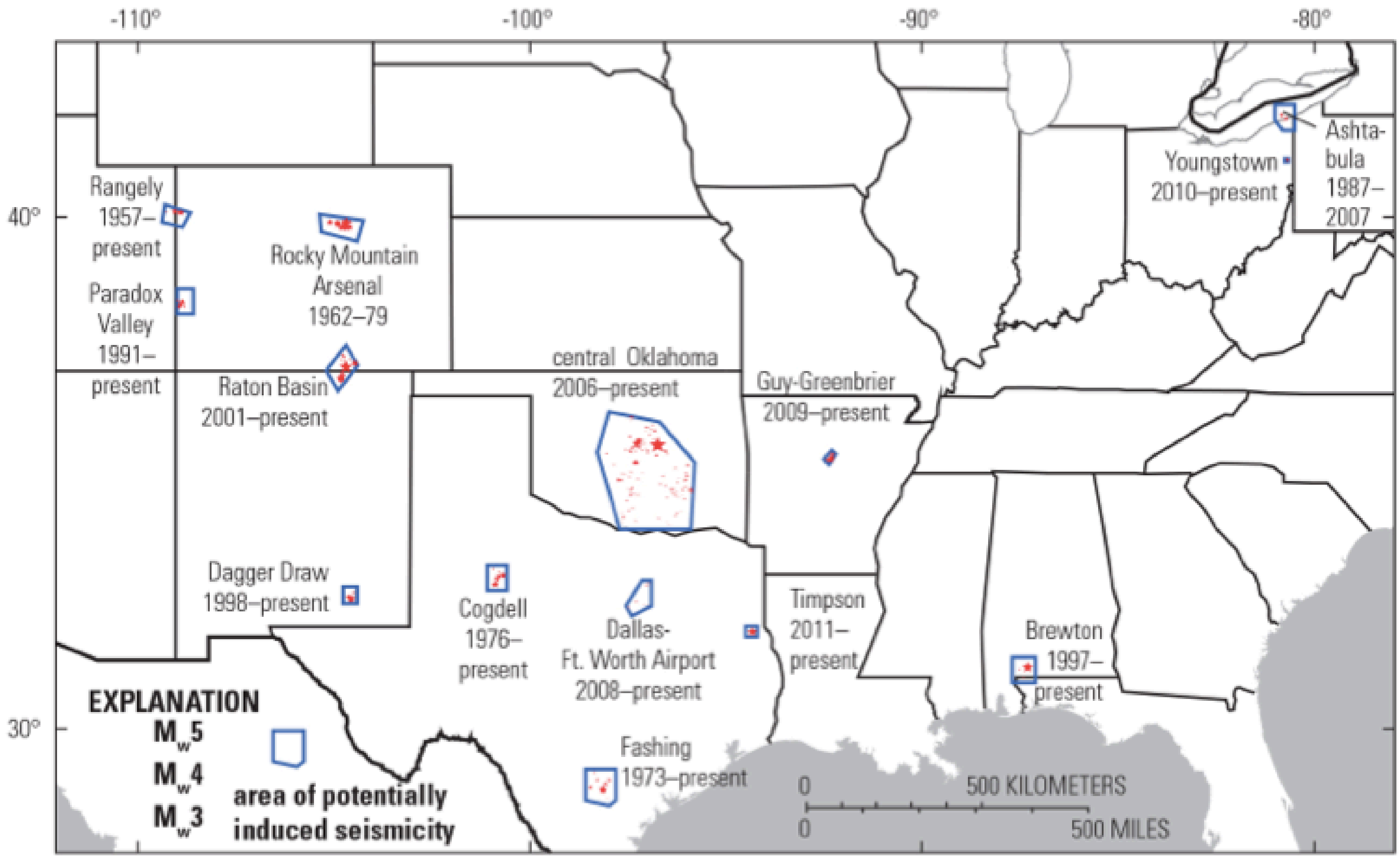
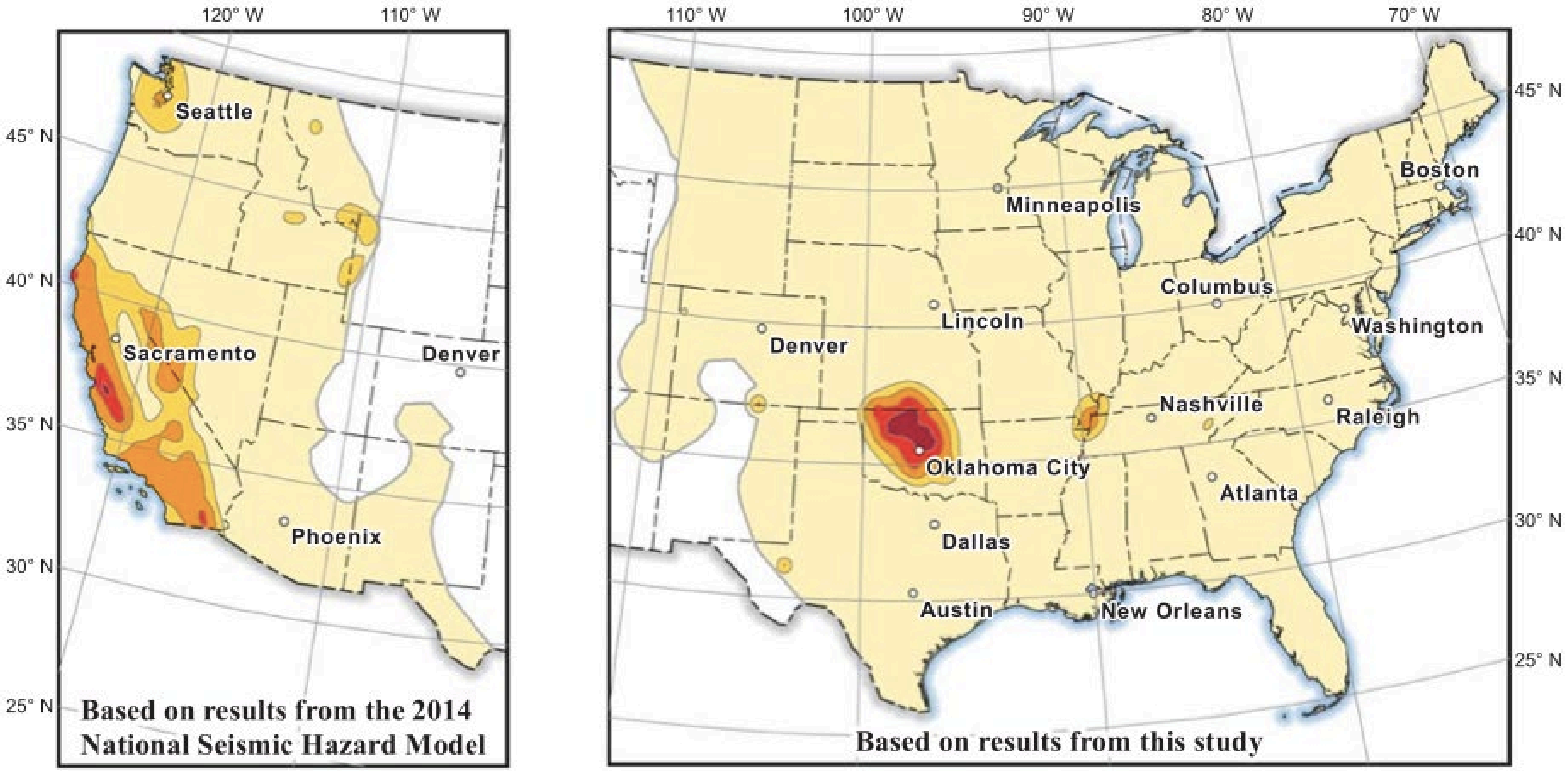


Figure 15. Map showing areas of potentially induced seismicity in the Central and Eastern United States.

Petersen et al., (2018)

USGS
science for a changing world

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



Chance of potentially minor-damage* ground shaking in 2018

<1% | 1% – 2% | 2% – 5% | 5% – 10% | 10% – 14%

* equivalent to modified Mercalli intensity VI, which is defined as: "Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight."

Petersen et al., (2018); Elizabeth Cochran (co-author on paper) will talk about the 1 year hazard maps in detail later today

Some challenges in seismic hazard assessment in areas of high uncertainty (CEUS, Pacific Northwest, Intermountain West)

- Incomplete inventory of faults and their slip rates: LIDAR can help find the faults; characterizing blind thrusts; need more systematic search for paleoliquefaction in CEUS; more use of GPS to get regional deformation in PacNW and IMW; improvement of deformation models and understanding of overall dynamics of crust and upper mantle in PacNW and IMW
- Physical understanding of intraplate seismicity and dynamics of plate interiors; role of heterogeneous crust and mantle in dynamics

Scientific research and information

Earthquake source studies

Wave propagation (linear and nonlinear) through a complex crust and upper mantle

Fault interaction, triggering, Episodic Tremor and Slip

Earthquake monitoring, Ground-motion studies

Crustal deformation studies

Paleoseismology, LIDAR, geologic mapping

Induced seismicity studies

Potential field mapping

Seismic reflection, refraction, surface wave, tomography, geotechnical, borehole studies

Products

National and regional seismic hazard maps
Urban seismic hazard maps
Site-specific PSHA

Scenario ground motion maps

Shakemaps

Loss estimation (e.g. PAGER)

Operational Earthquake Forecasting

Synthetic seismograms

Liquefaction, landslide, and surface rupture hazard maps

Applications

Seismic provisions in building and bridge codes

Seismic design for critical facilities

Seismic retrofit

Emergency preparedness and management

Early warning

Land-use planning

Earthquake insurance

Frequency-magnitude plot for M8-9 earthquakes on Cascadia megathrust, based on paleoseismology doesn't look like b=1

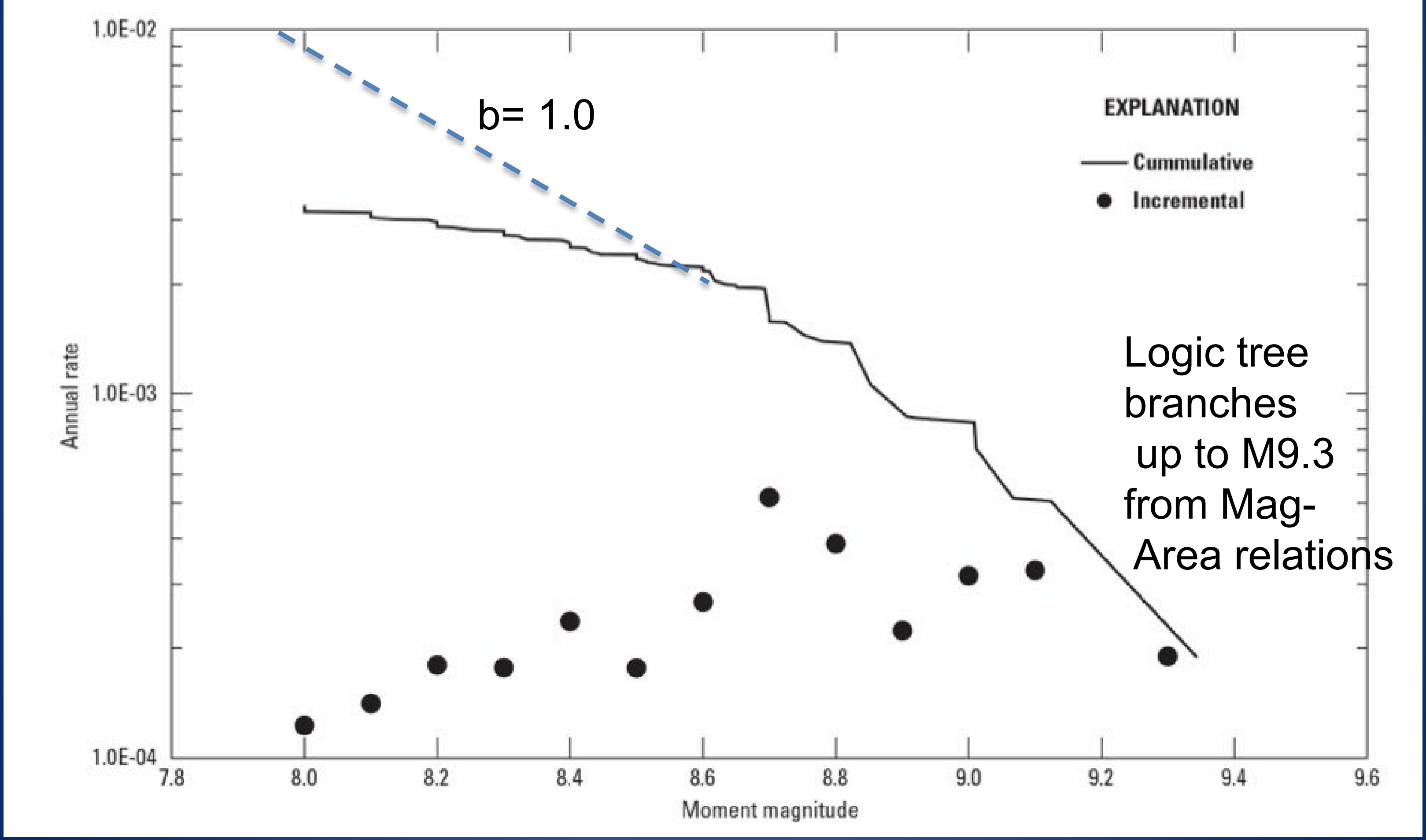
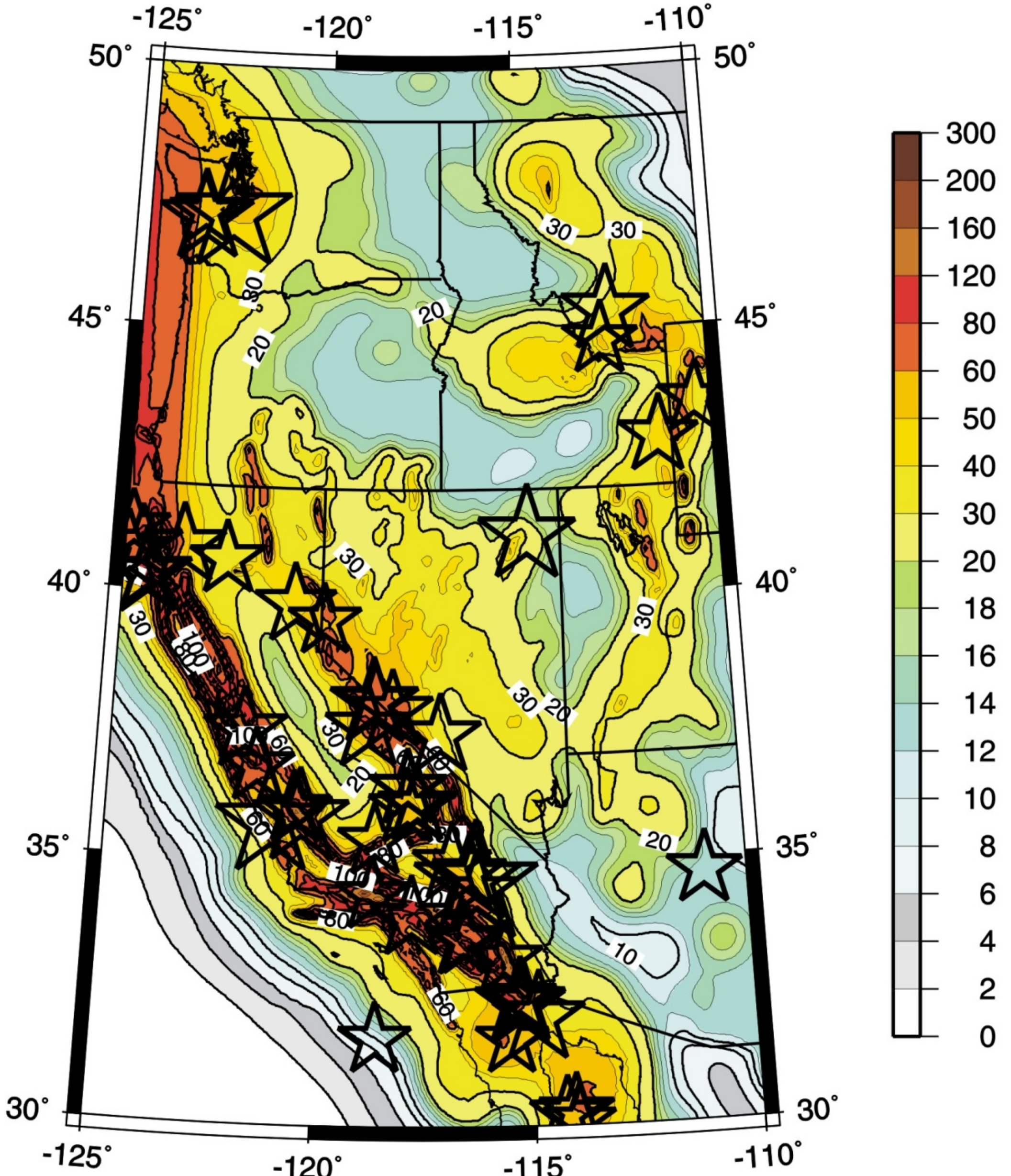


Figure by Chen, Frankel, and Petersen

1996 hazard map (2% PE in 50 years; PGA in %g) with M >= 5.0

1997-2012



USGS
science for a changing world