Mapping Earthquake Hazard in the United States

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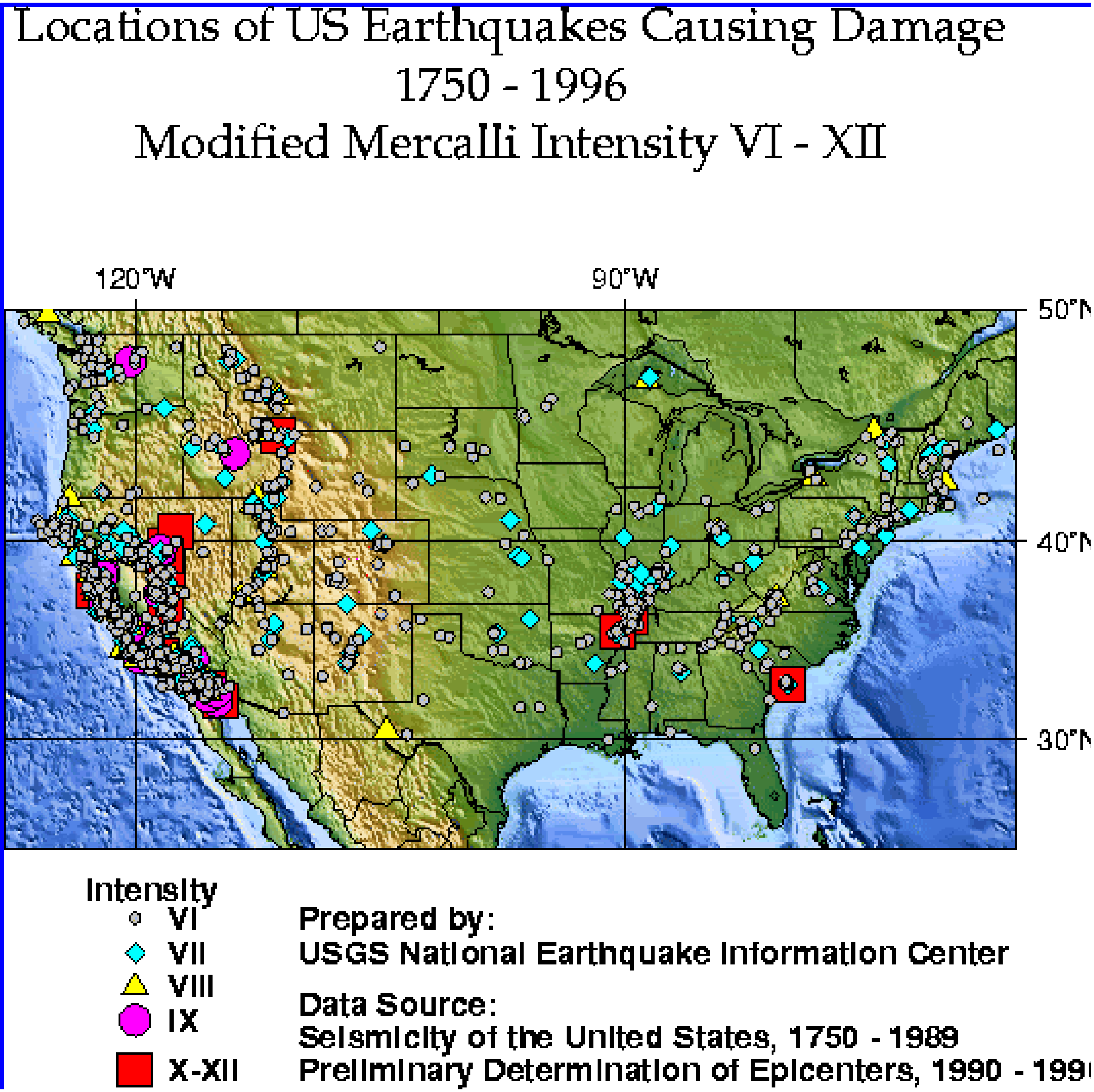
U.S. Geological Survey

A talk presented to the Geology Department, Oberlin College, Oberlin, Ohio, 9 March 2004

In both Canada and the U.S., damaging earthquakes are experienced over much of the country, making seismic hazard a national issue

- From G. Atkinson



USGS National Seismic Hazard Maps: 2002 Update

A. Frankel, M. Petersen, C. Mueller,
K. Haller, R. Wheeler, E. Leyendecker,
R. Wesson, S. Harmsen, C. Cramer,
D. Perkins, and K. Rukstales
U.S. Geological Survey
California maps produced jointly with
California Geological Survey:
T. Cao and W. Bryant

What's Ahead?

- What is "earthquake (seismic) hazard''?
- Response spectrum: the measure of ground shaking that is mapped
- Mapping the hazard
  - seismicity (with special attention to New Madrid)
    - where do earthquakes occur?
    - how often do they occur?
    - how large are they?
  - ground motion
    - specify the ground shaking as a function of earthquake size and distance from a site
  - computing the hazard values to be mapped
  - results
- Paleoseismometry: precarious rocks

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"Civilisation exists by geological consent, subject to change without prior notice."

William Durant, *historian*

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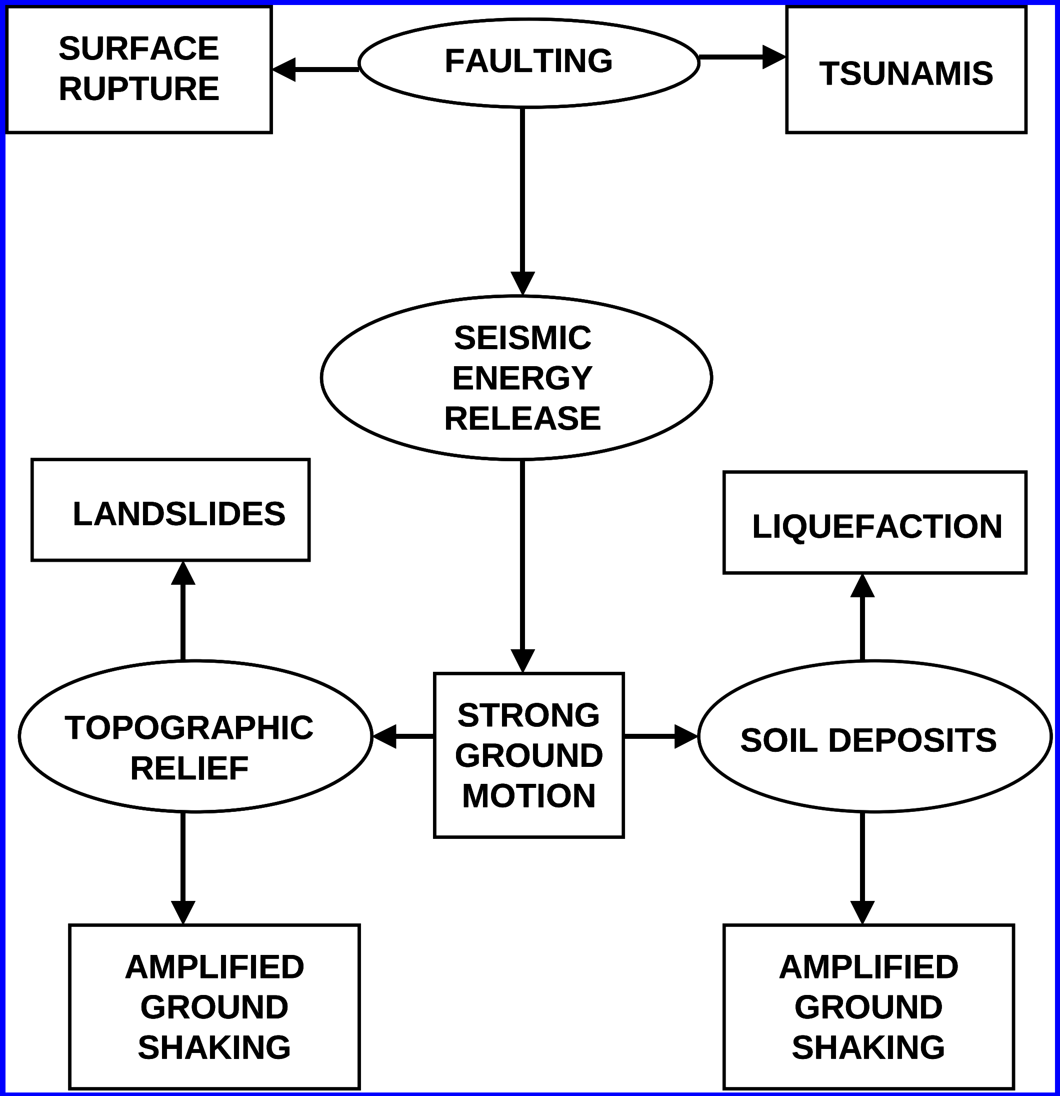
SEISMIC HAZARD -

the <u>possibility</u> of that consent being withdrawn.

SEISMIC HAZARD
is the possibility of
potentially destructive
earthquake effects
occurring at a particular
location within a specified
period.

Earthquake Effects



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HAZARD is not RISK

RISK =

HAZARD * EXPOSURE * VULNERABILITY

The hazard is controlled by Nature.

Vulnerability and Exposure are controlled by humans.

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Seismic Risk Mitigation

HAZARD * EXPOSURE * VULNERABILITY = COST

Assess

Control

Reduce

Balance

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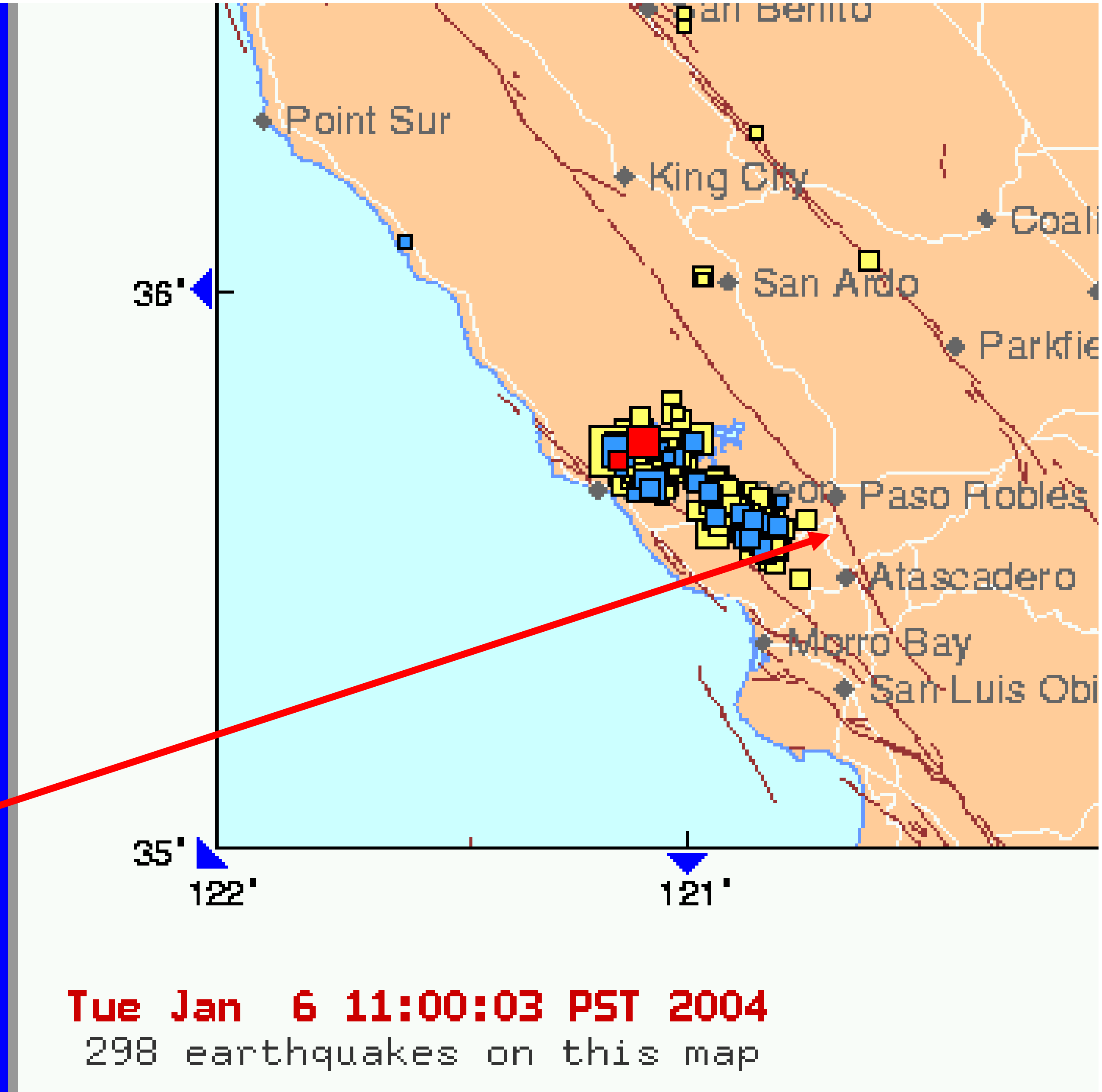
2003 San Simeon earthquake (**M** 6.5): 2 deaths in Paso Robles

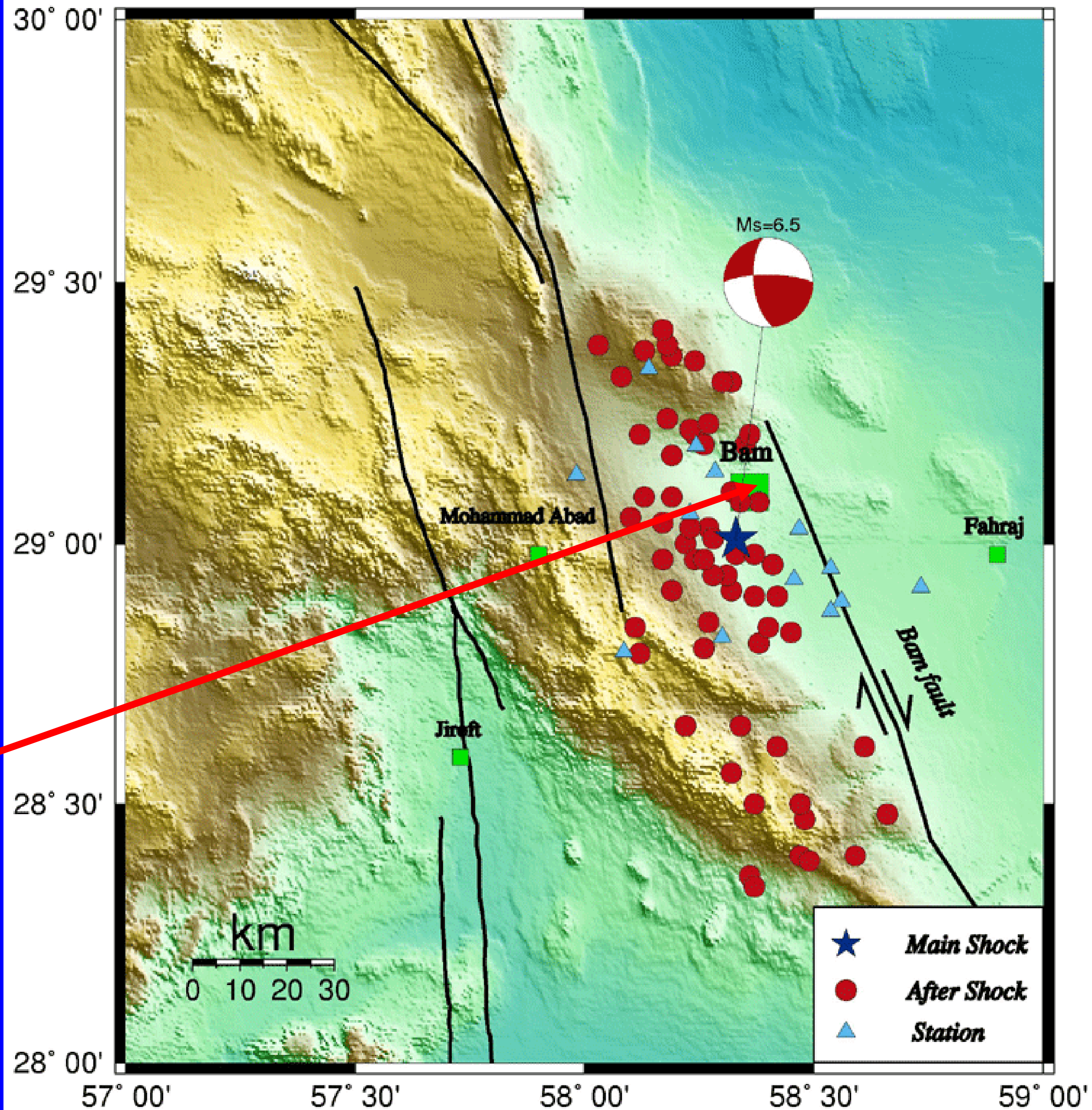


0.48g

Damage in Paso Robles, CA, due to collapse of unreinforced masonry building (2 lives lost) during the 2003 San Simeon earthquake

•Contrast damage with that in Bam, Iran (M 6.6)
•>30,000 deaths
•Why so many deaths, compared to Paso Robles?
    •Was ground motion higher than in Paso Robles? (0.98g pga in Bam; 0.48g 10 km from Paso Robles)
    •Was the construction less earthquake resistant?

0.98g



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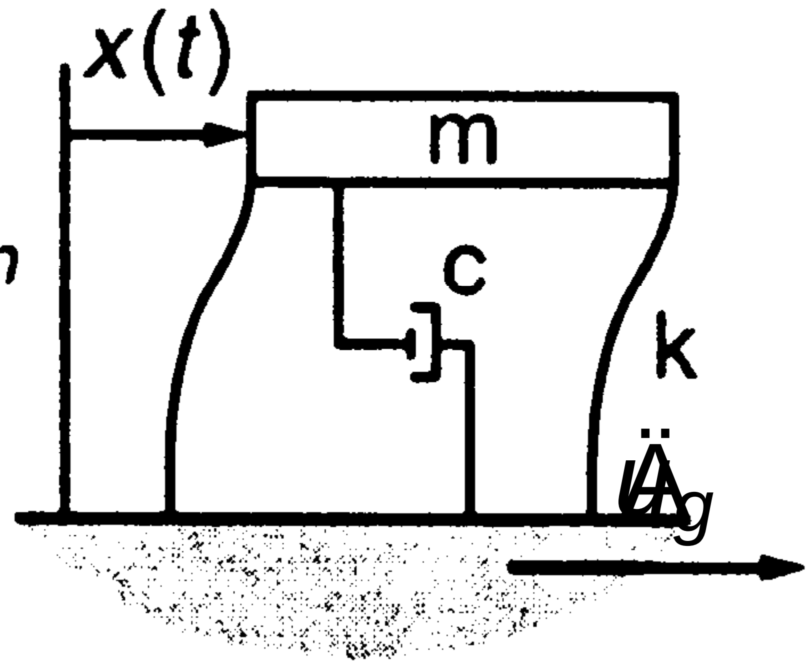
Measures of ground motion for engineering purposes

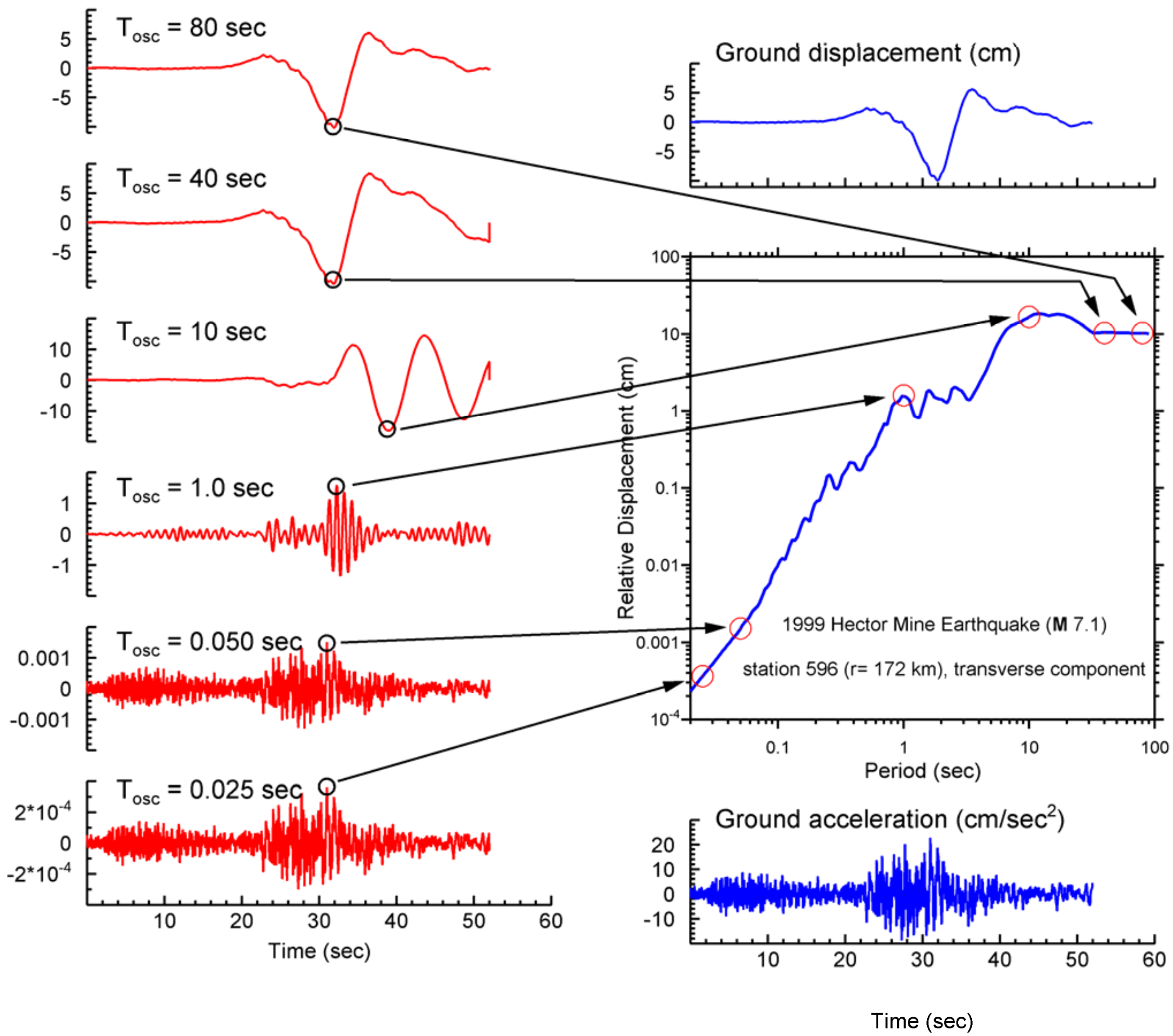
- Peak motions (acceleration, velocity, displacement)
- Elastic response spectra

Elastic response spectra

PERIOD = $2\pi/\omega_n$

DAMPING = ζ_n





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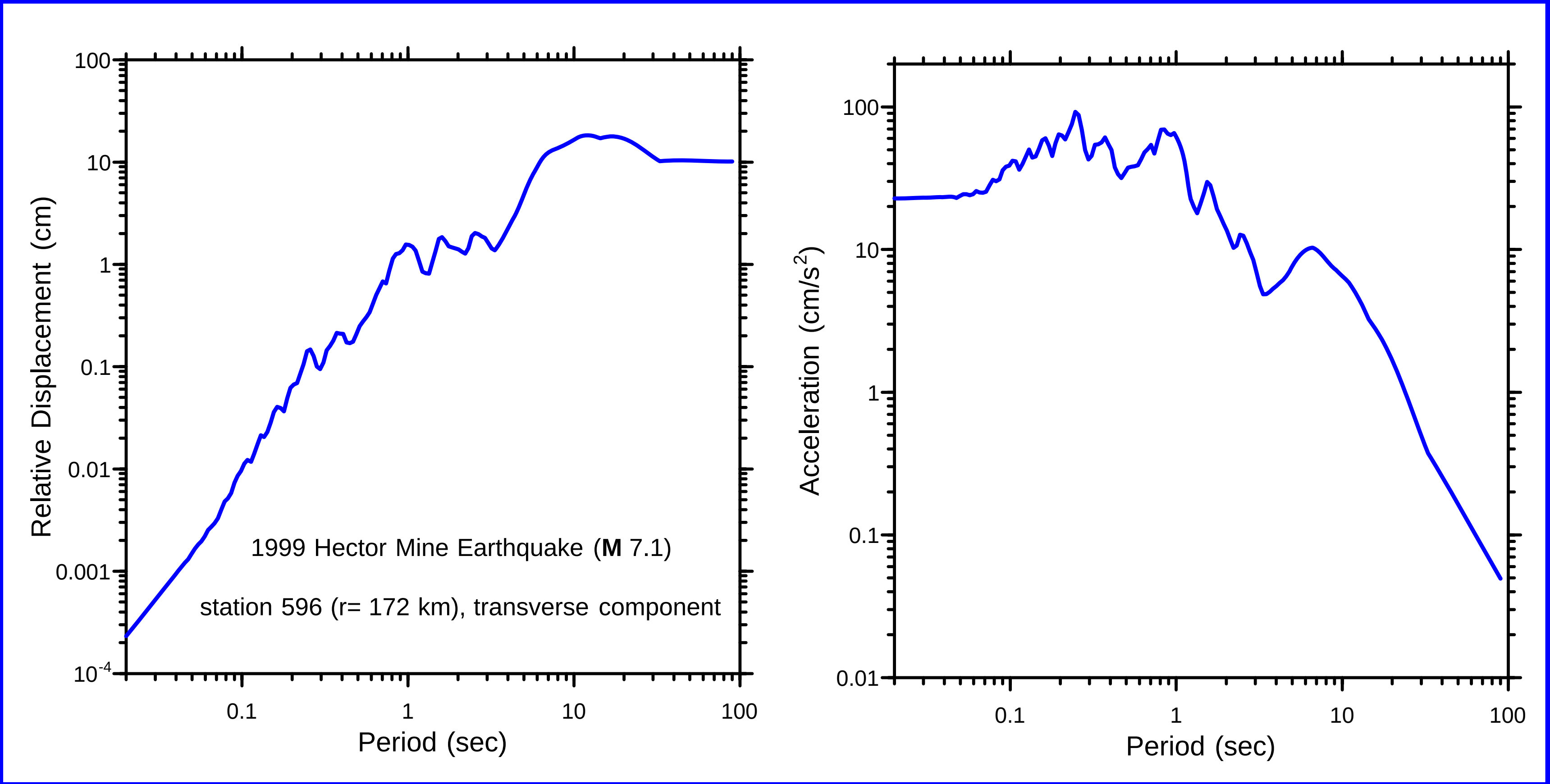
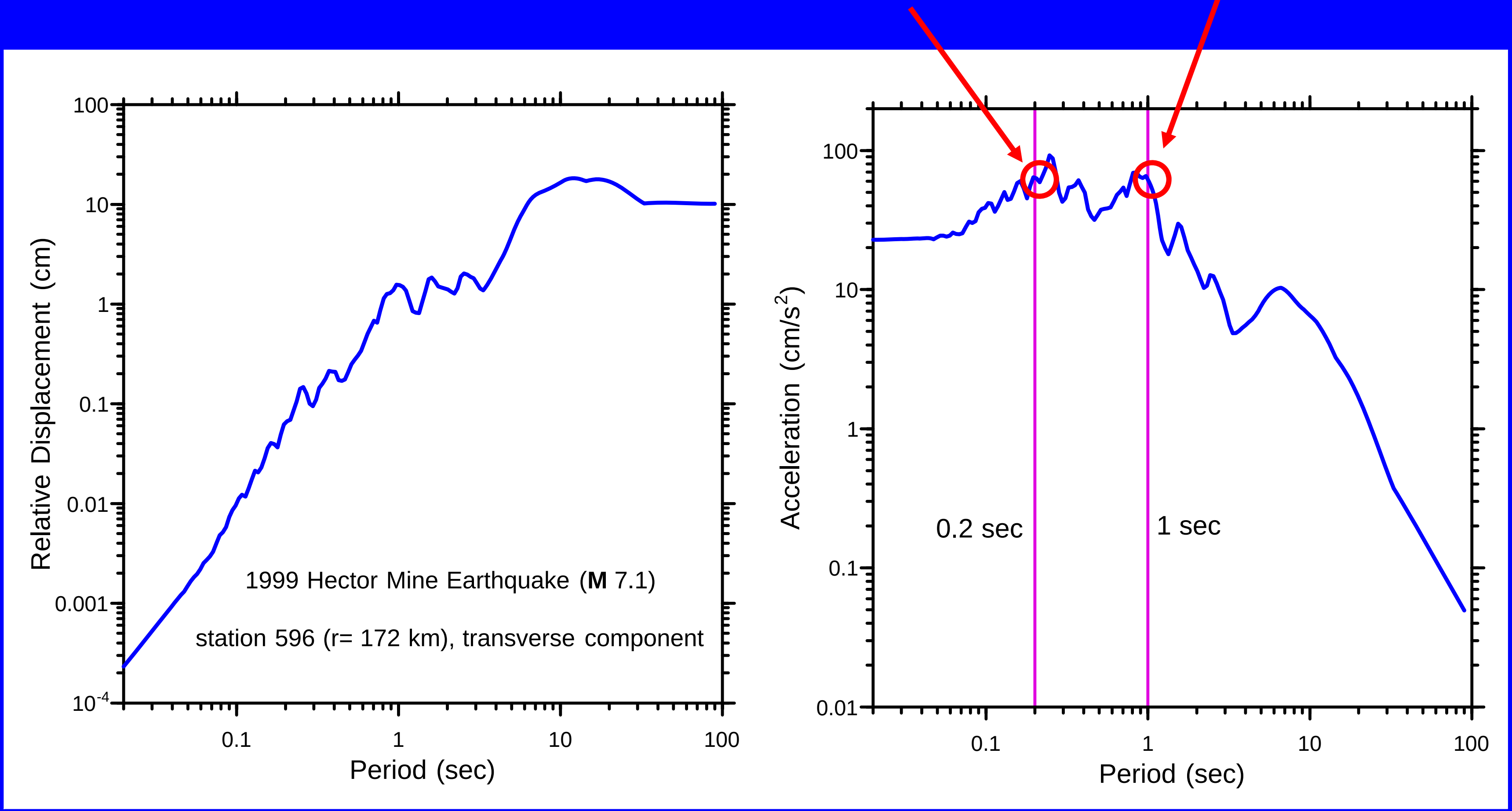
convert displacement spectrum into acceleration spectrum (multiply by $(2\pi/T)^2$)



pick off values of SA at 0.2 sec and 1 sec



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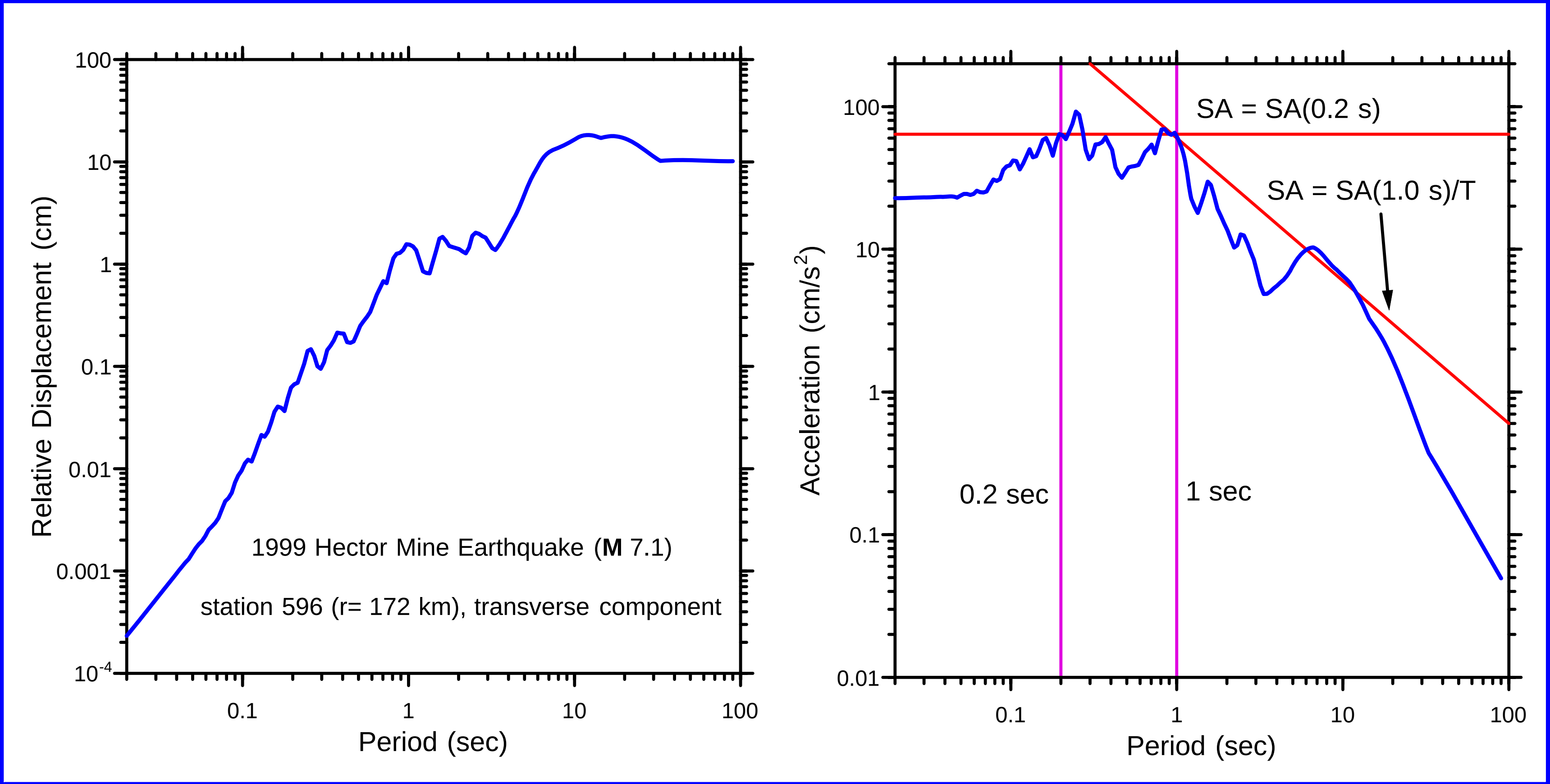
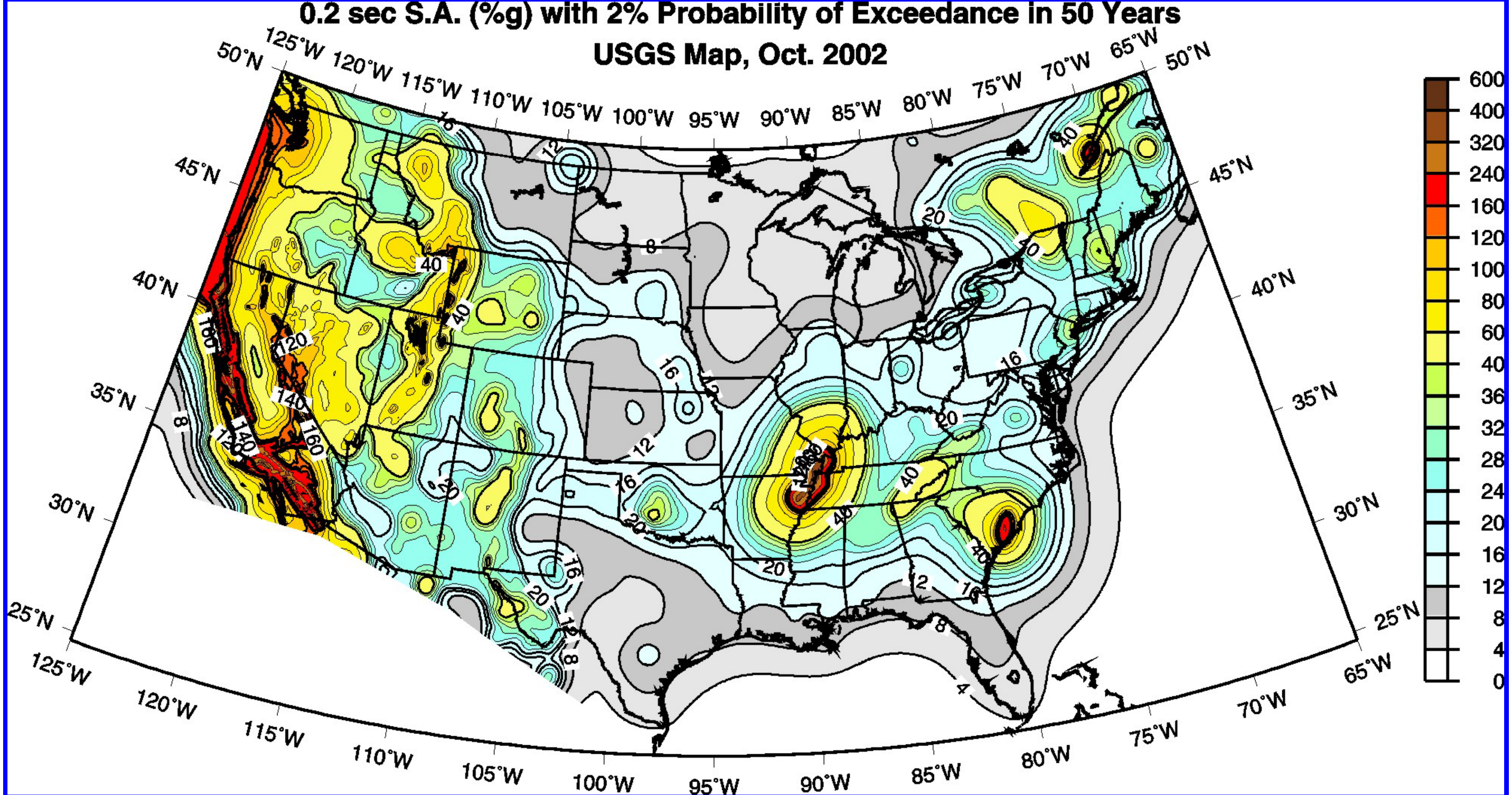
fit functions through values to form an approximate response spectrum



similarity of SA(0.2) and SA(1.0) a coincidence here!

U.S. National Seismic Hazard Map – 2002 Edition



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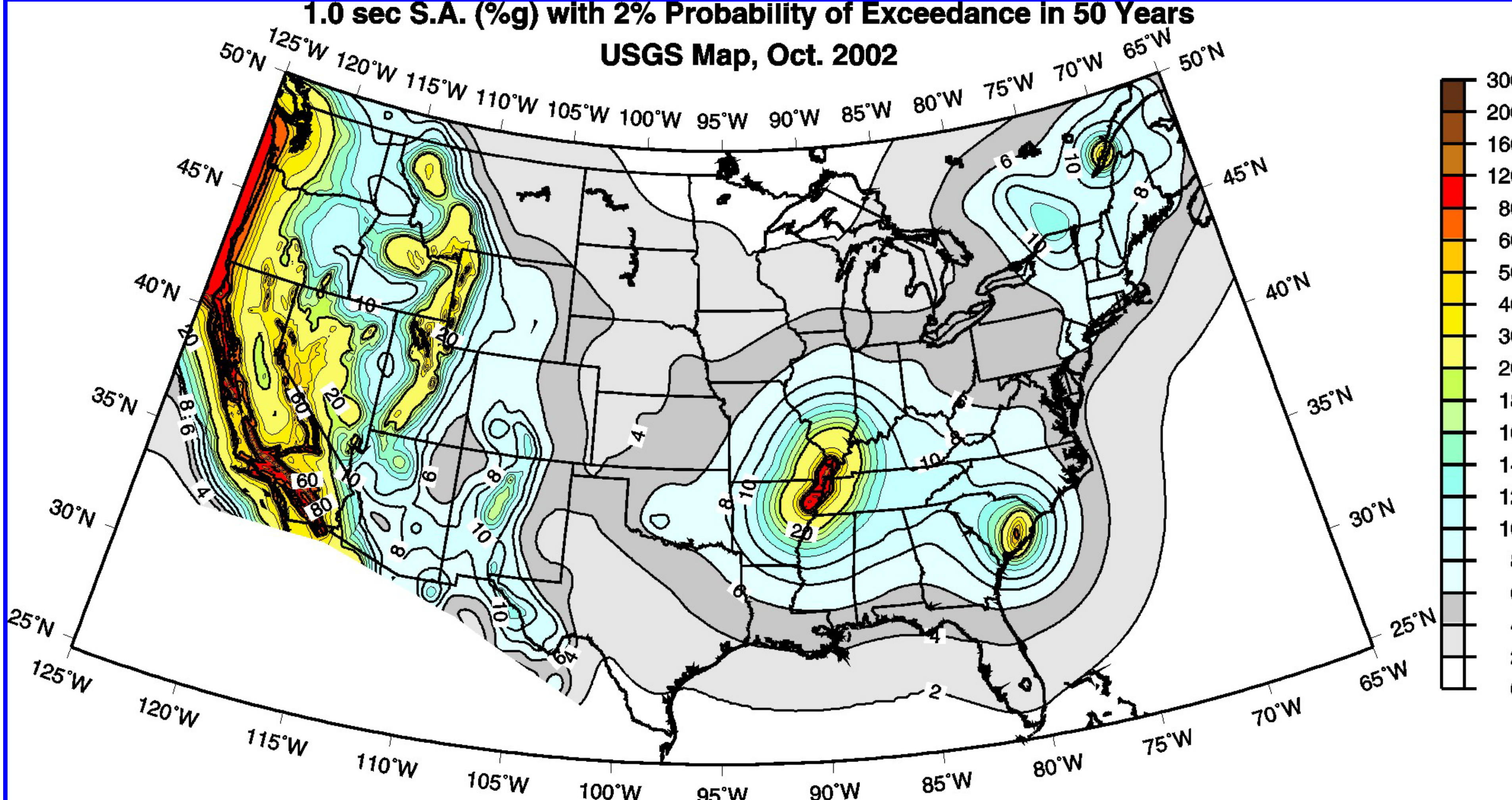
U.S. National Seismic Hazard Map – 2002 Edition



Some Major Uses of the National Seismic Hazard Maps and Associated Products

- Building codes: International Building Code, International Residential Code, ASCE national design load standard, NEHRP Provisions
- Design of highway bridges, dams, landfills
- Loss estimation (e.g., HAZUS), earthquake insurance
- Emergency management, EQ scenarios

USGS Seismic Hazard Maps (1996 and update in 2002)

- Consensus of experts: regional workshops (CEUS 1995, 2000), external review panel, open review of interim maps on Internet
- Average hazard estimate, not worst case; used alternative ground-motion prediction equations and fault locations; uncertainty estimates published in 1997, 2000, 2001

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Probabilistic Seismic Hazard Analysis (PSHA)

- **Seismicity**: for each spatial point, assign the probability of an earthquake with particular magnitude occurring each year (consider all magnitudes in a range from small to large).
- **Ground motion**: for a spatial point, compute the probability that a level of ground motion will be exceeded, considering all surrounding points as potential sources (each magnitude and distance can be thought of as a scenario).
- Combine probabilities to obtain a frequency of exceedance for each scenario.
- Add frequencies of exceedance for a particular level of ground motion (combining all scenarios). This gives the **HAZARD CURVE**

Seismicity

1. Identify the potential sources of future earthquakes
2. Estimate the maximum magnitude (M_{max}) earthquake that could occur within each source
3. Calculate the recurrence relationship that defines how frequently, on average, earthquakes of different magnitude occur within each source.

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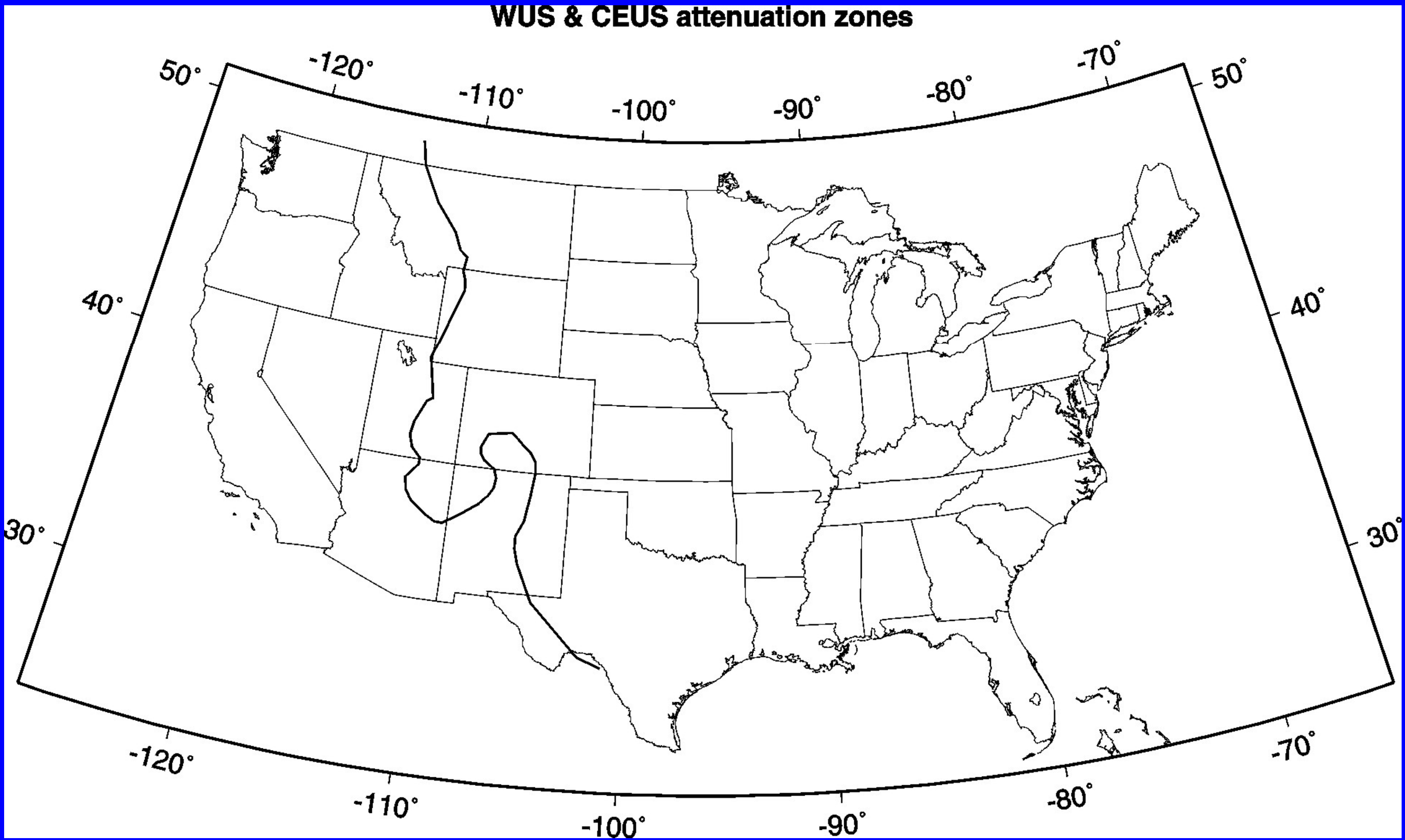
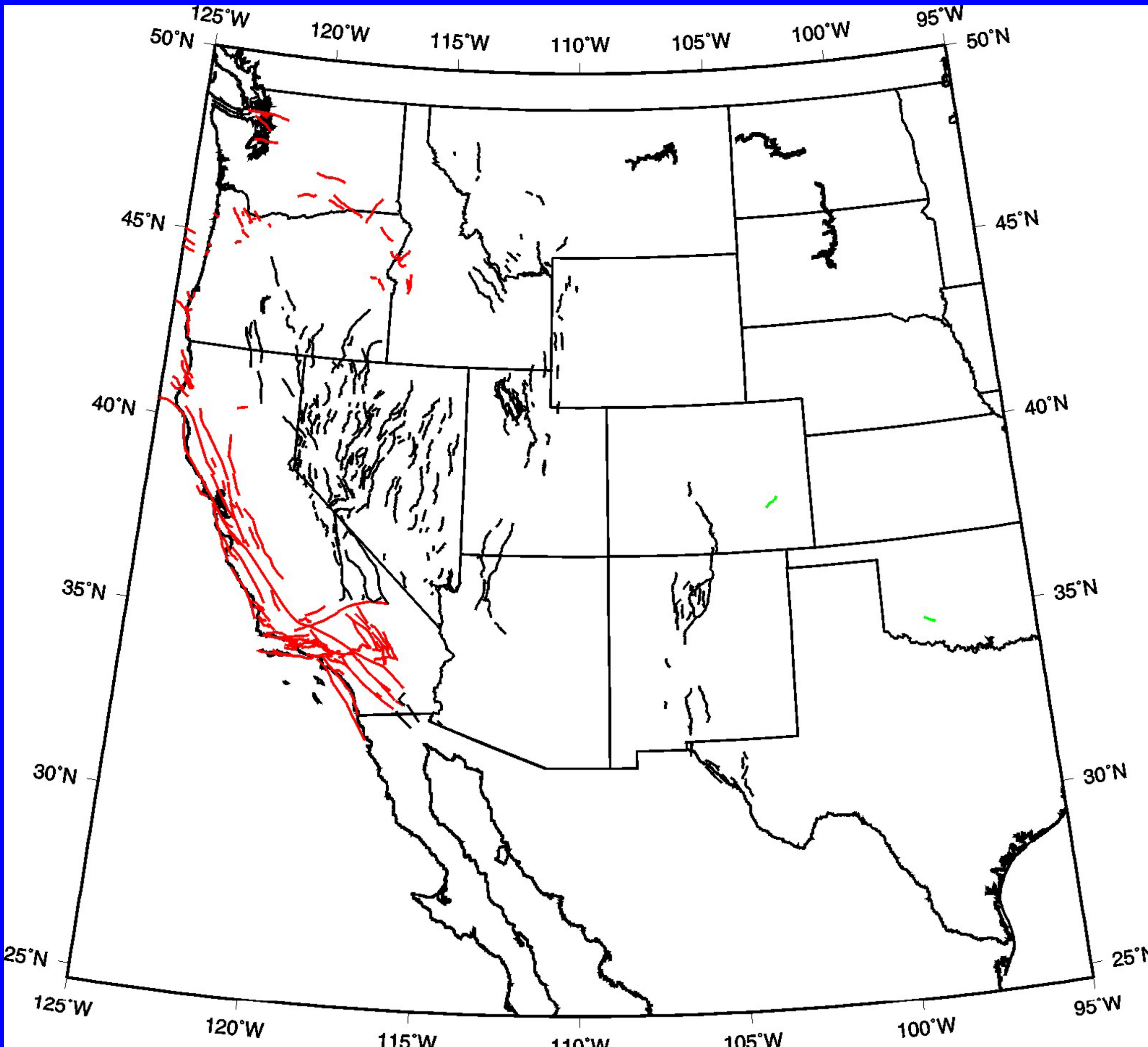
Divide the US into WUS and CEUS




125°W
120°W
115°W
110°W
105°W
100°W
95°W
50°N
45°N
40°N
35°N
30°N
25°N
50°N
45°N
40°N
35°N
30°N
25°N
125°W
120°W
115°W
110°W
105°W
100°W
95°W

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San Andreas fault– Carrizo Plain
(taken from a radio-controlled kite; see http://quake.usgs.gov/kap/carrizo)

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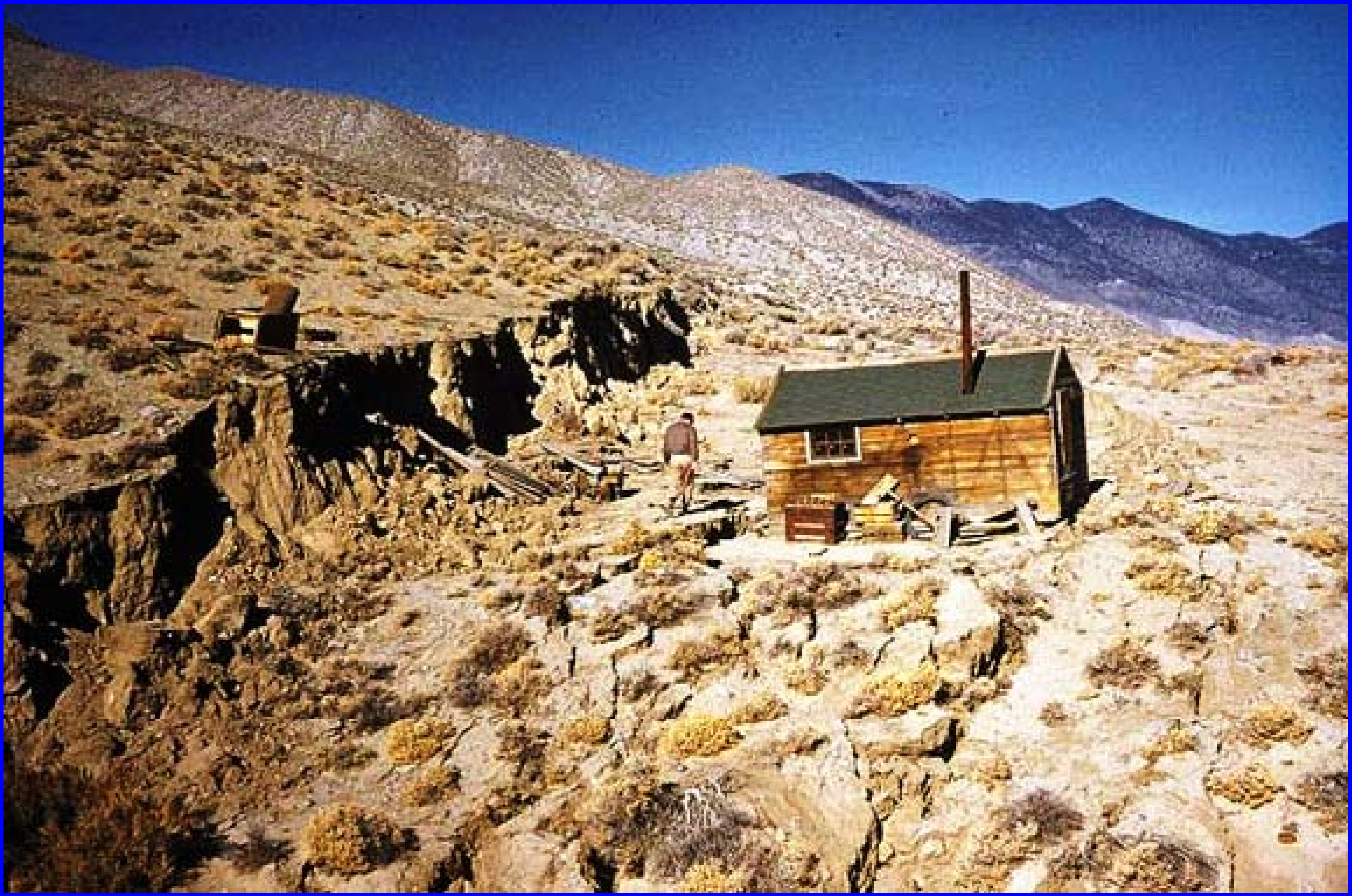
Faults (Fairview Valley, NV)



Note the flimsy cabin and stovepipe; does this say anything about the strength of ground shaking?

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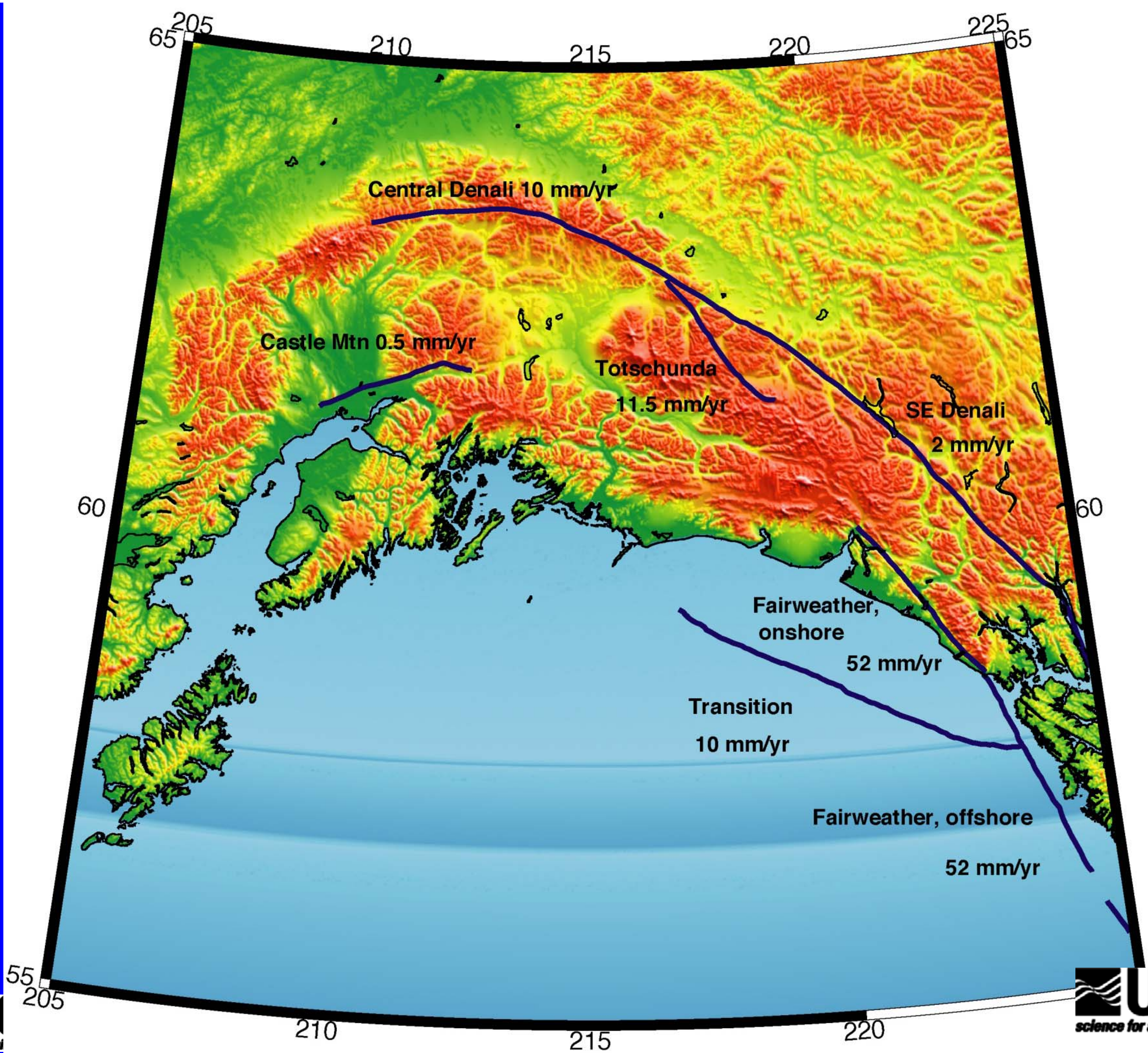
205
210
215
220
225
65
60
55
Central Denali 10 mm/yr
Castle Mtn 0.5 mm/yr
Totschunda
11.5 mm/yr
SE Denali
2 mm/yr
Fairweather,
onshore
52 mm/yr
Transition
10 mm/yr
Fairweather, offshore
52 mm/yr

Intraplate Earthquakes

- The driving forces, and stress fields, that are characterized by intraplate earthquakes are difficult to characterize and vary widely
- One example mechanism for intraplate earthquakes is stress associated with post-glacial rebound
- Stress concentrations and weak “failed” rifts another possibility

Specification of **seismicity** for the National Seismic Hazard Maps

- 1. Use spatially-smoothed historic seismicity; assumes that moderate and large earthquakes will occur near previous M3+ events
- 2. Use large background zones based on broad geologic criteria; addresses non-stationary seismicity; quantifies hazard in areas with little historic seismicity but potential for damaging earthquakes
- 3. Use specific fault sources with recurrence rates determined from geologic slip rates, trenching studies, or paleoliquefaction dates

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Direct Inputs to Hazard Maps

- Earthquake catalogs (instrumental and historic)
- Fault data (geologic slip rates, dates of past events from trenching, fault geometry, etc.)
- Effects of prehistoric earthquakes: paleoliquefaction (New Madrid, Charleston, Wabash Valley), subsidence and uplift (Cascadia, Seattle flt)
- Geodetic data (NV-CA, Puget Lowland)

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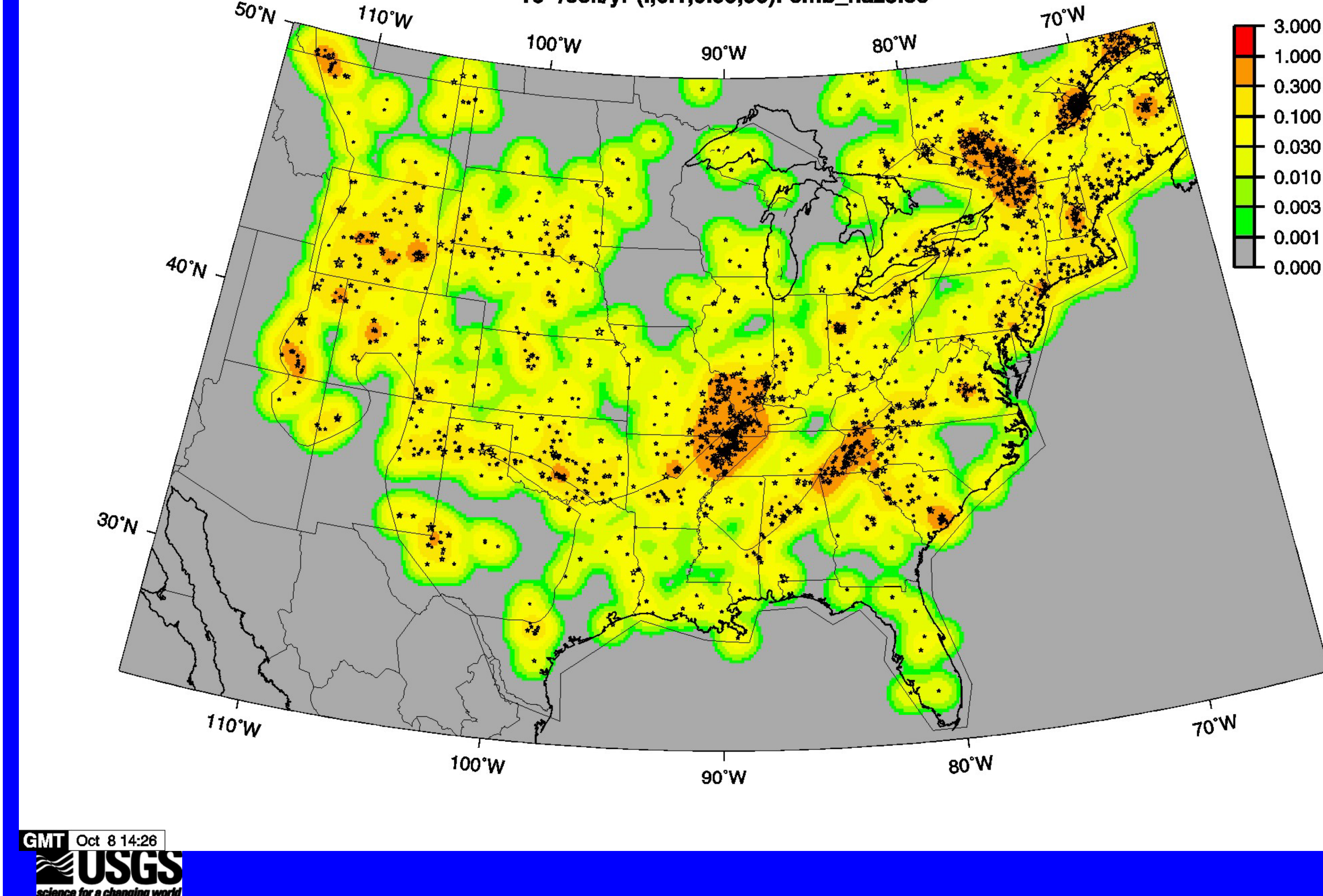
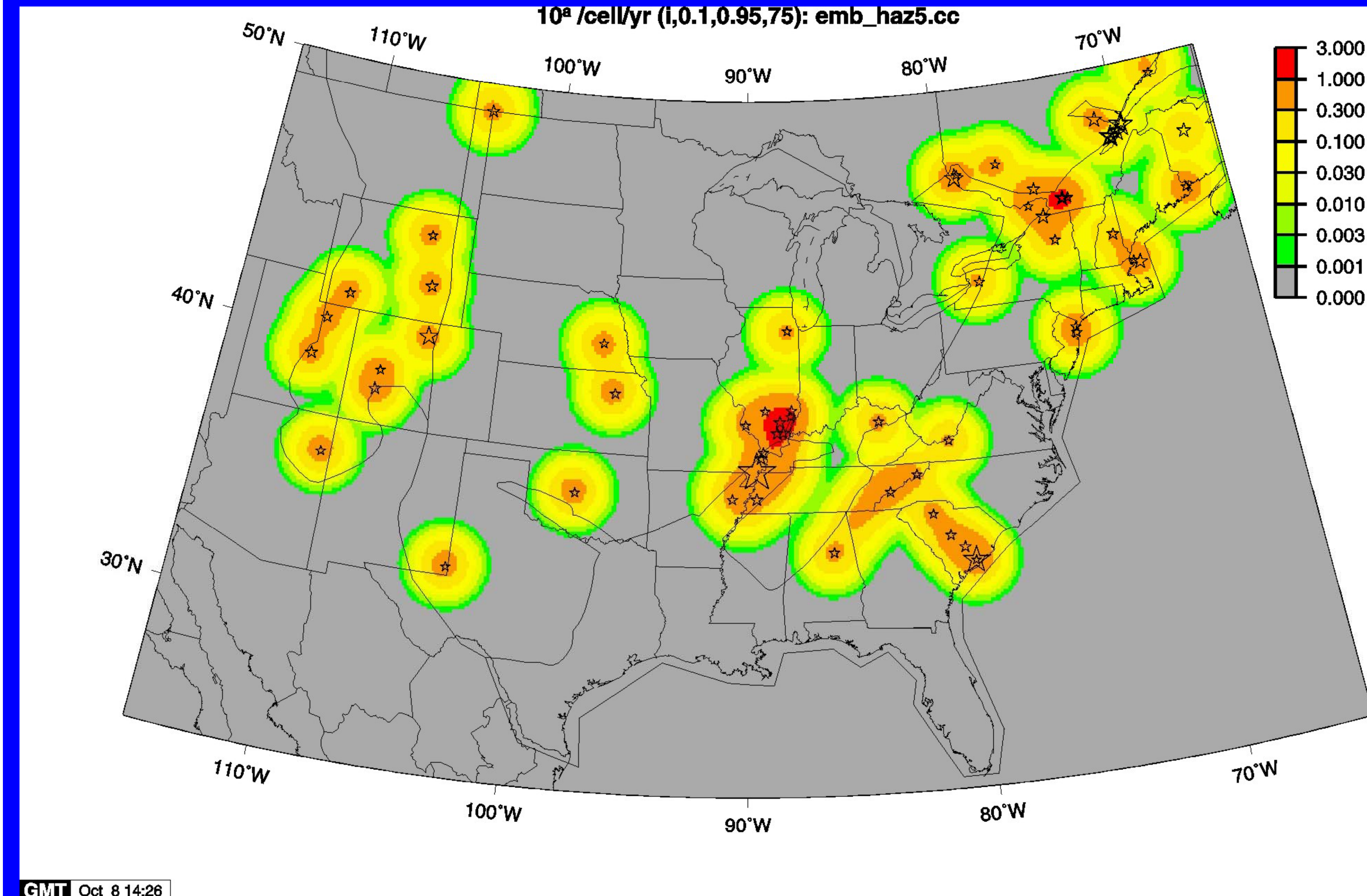
10ª /cell/yr (i,0.1,0.95,50): emb_haz3.cc





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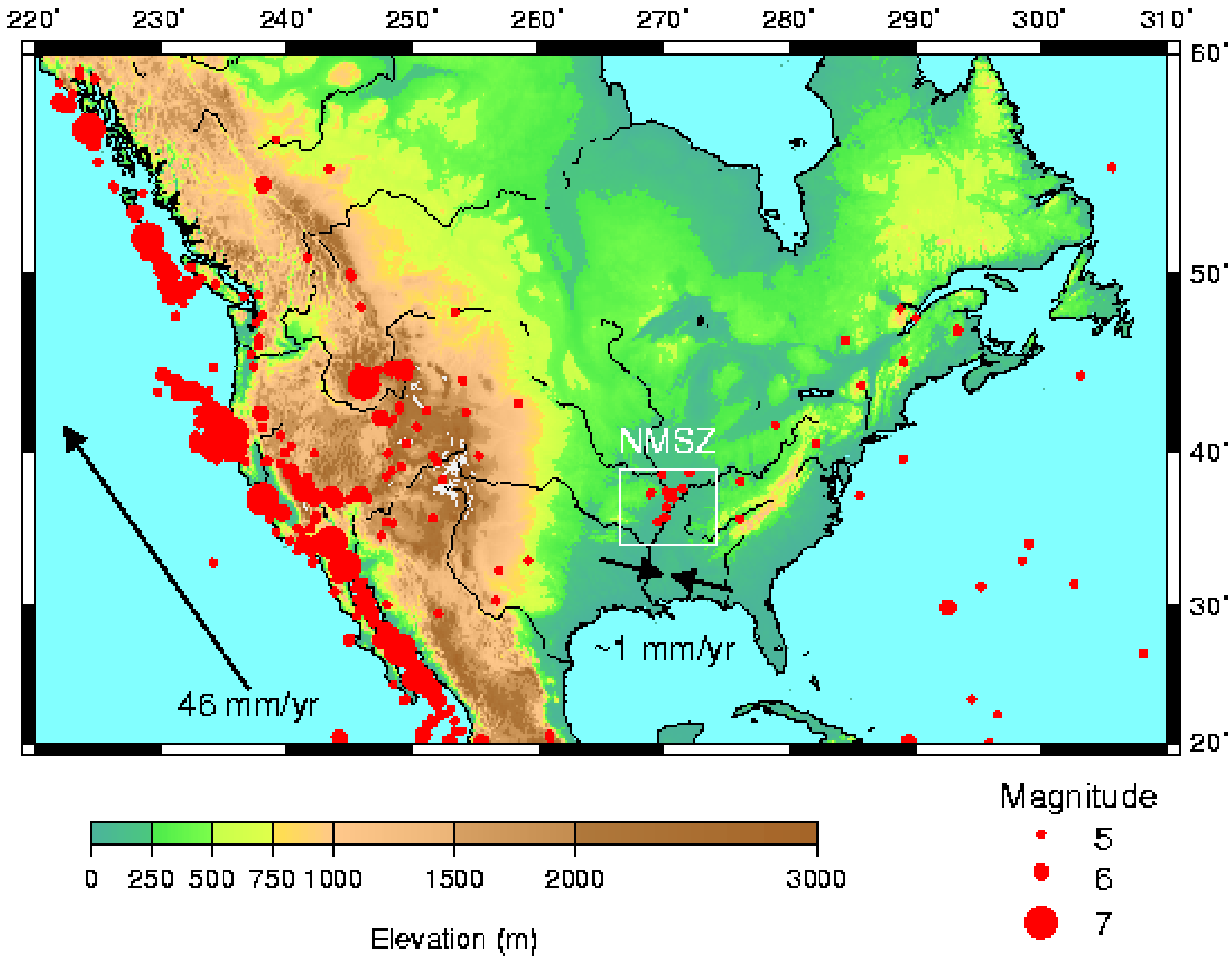
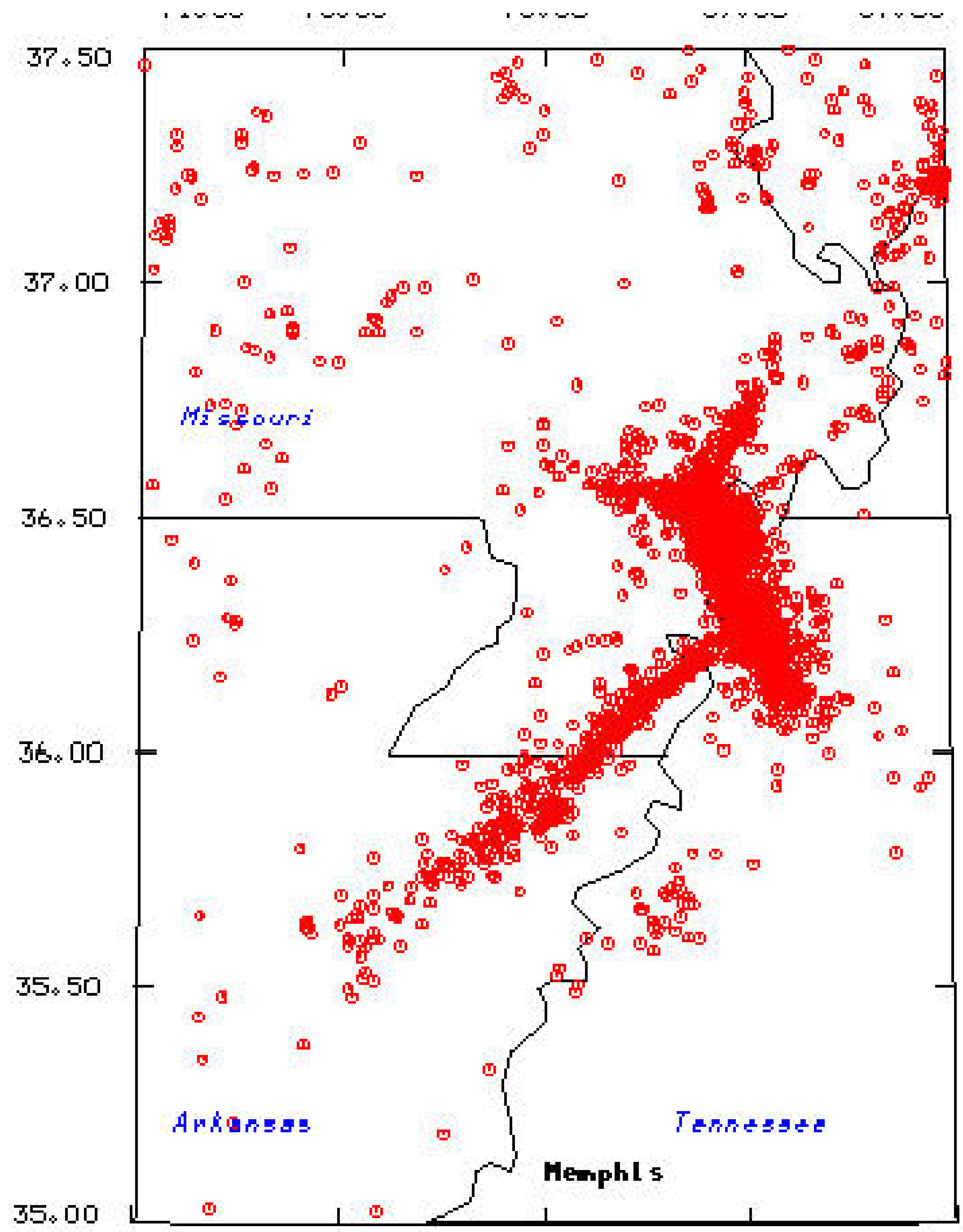
North American Seismicity



Stein

Note linear pattern of New Madrid seismicity – but no surface faulting found



New Madrid seismicity believed related to buried rift faults (under several km of overlying sediments)

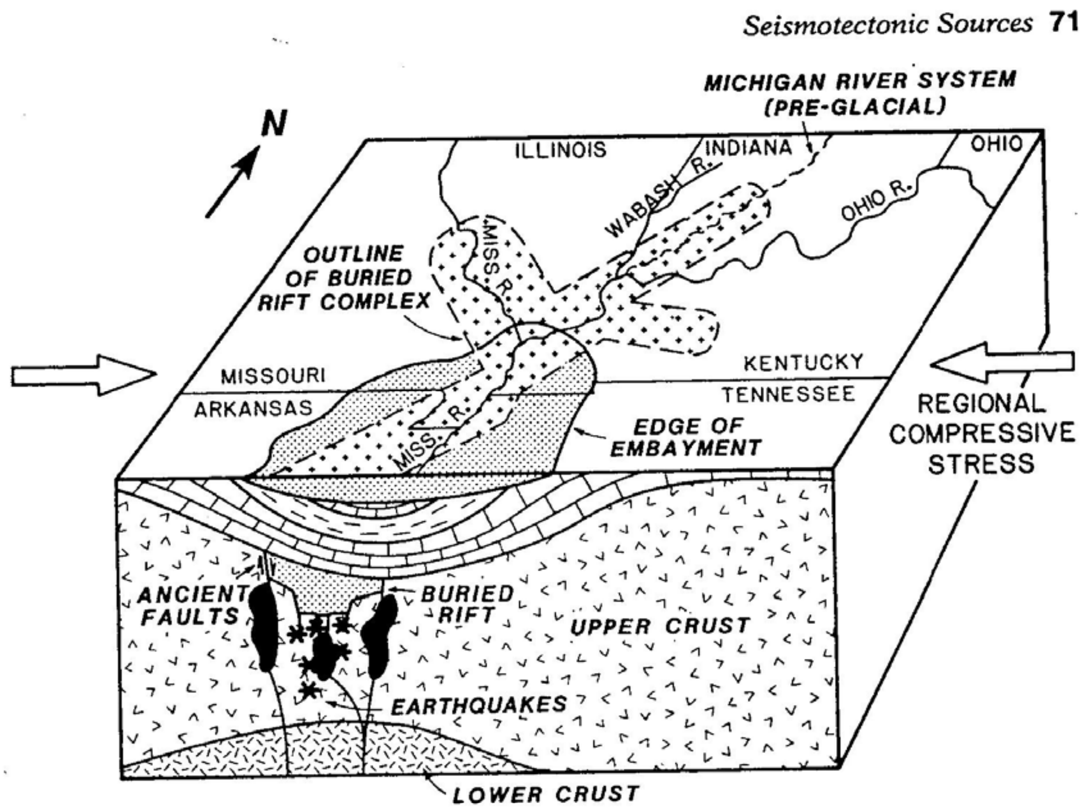
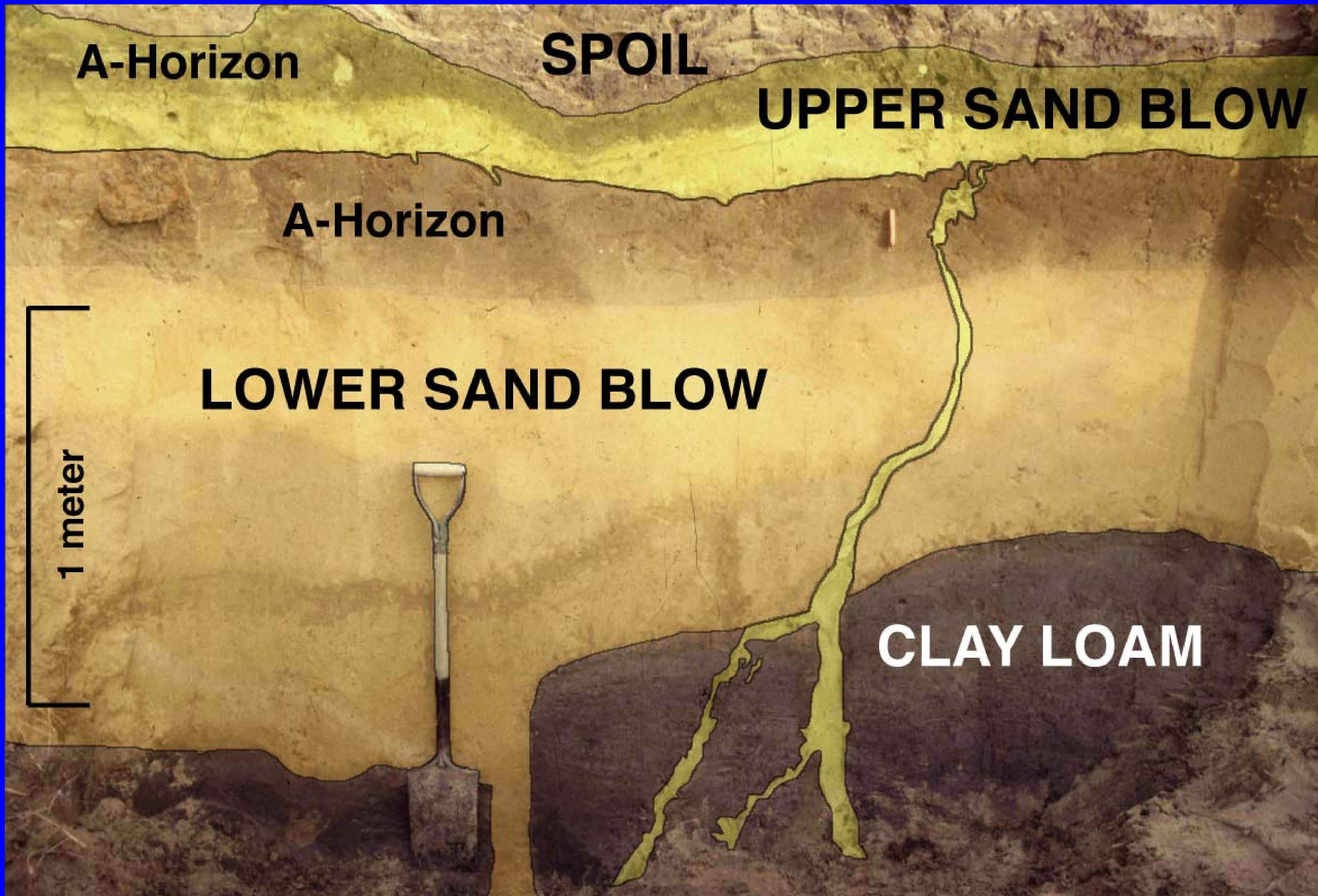


FIGURE 4.8 Block diagram illustrating the present configuration of the New Madrid Rift Complex. Dark areas indicate intrusions near the edge of the buried rift. An uplifted and possibly anomalously dense lower crust is suggested as the cause of the positive gravity anomaly associated with the upper Mississippi Valley (after Braile and others 1986).



A-Horizon
SPOIL
UPPER SAND BLOW
A-Horizon
LOWER SAND BLOW
1 meter
CLAY LOAM

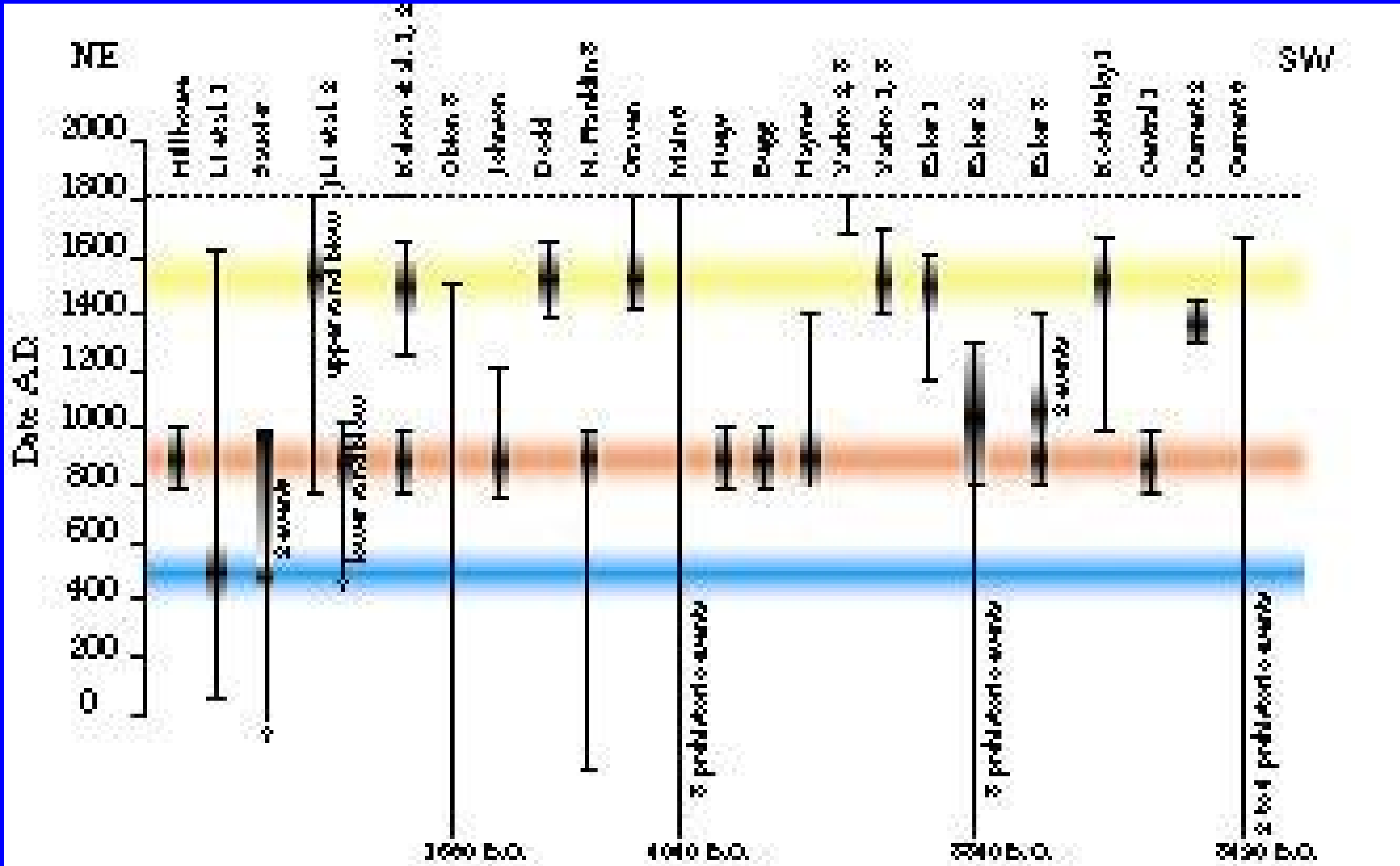


Figure 3

The Smoking Guns for New Madrid Earthquakes

- 1811-12: three largest earthquakes felt as far away as New England, producing intensity 9-10 in Memphis, very large liquefaction area
- between 1300 and 1600 A.D.: sequence of three large earthquakes with similar liquefaction area as 1811-12 (Tuttle and Schweig)
- between 800 and 1000 A.D.: sequence of three large earthquakes with similar liquefaction area as 1811-12 (Tuttle and Schweig)
- also: M6.6 earthquake in 1895 in Charleston, MO; M6 in 1843 in Marked Tree, AR; history of M5.1 and smaller events since 1900

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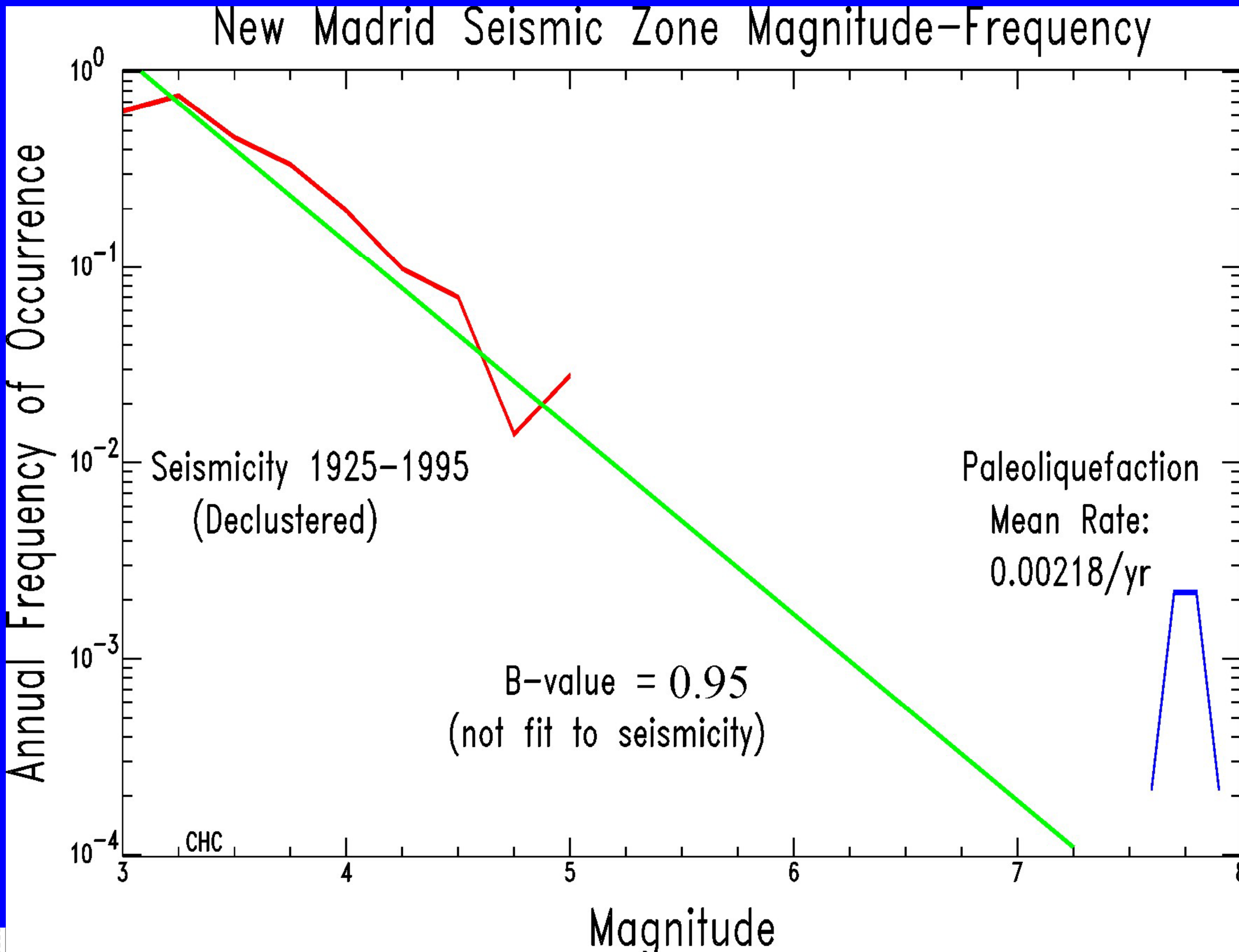
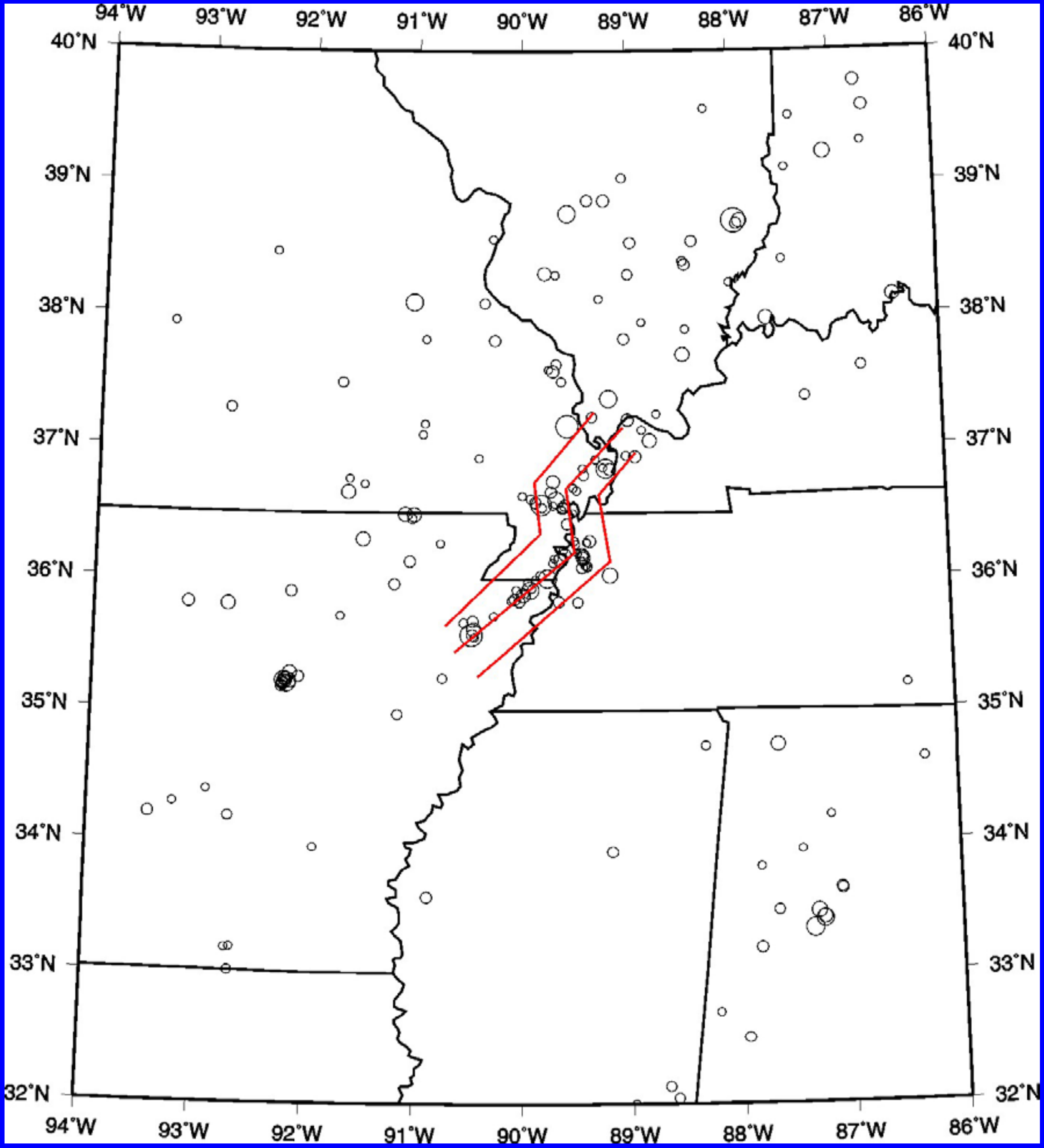


New Madrid Seismic Zone Magnitude-Frequency
Annual Frequency of Occurrence
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Seismicity 1925-1995
(Declustered)
Paleoliquefaction
Mean Rate:
0.00218/yr
B-value = 0.95
(not fit to seismicity)
CHC
3
4
5
6
7
8
Magnitude



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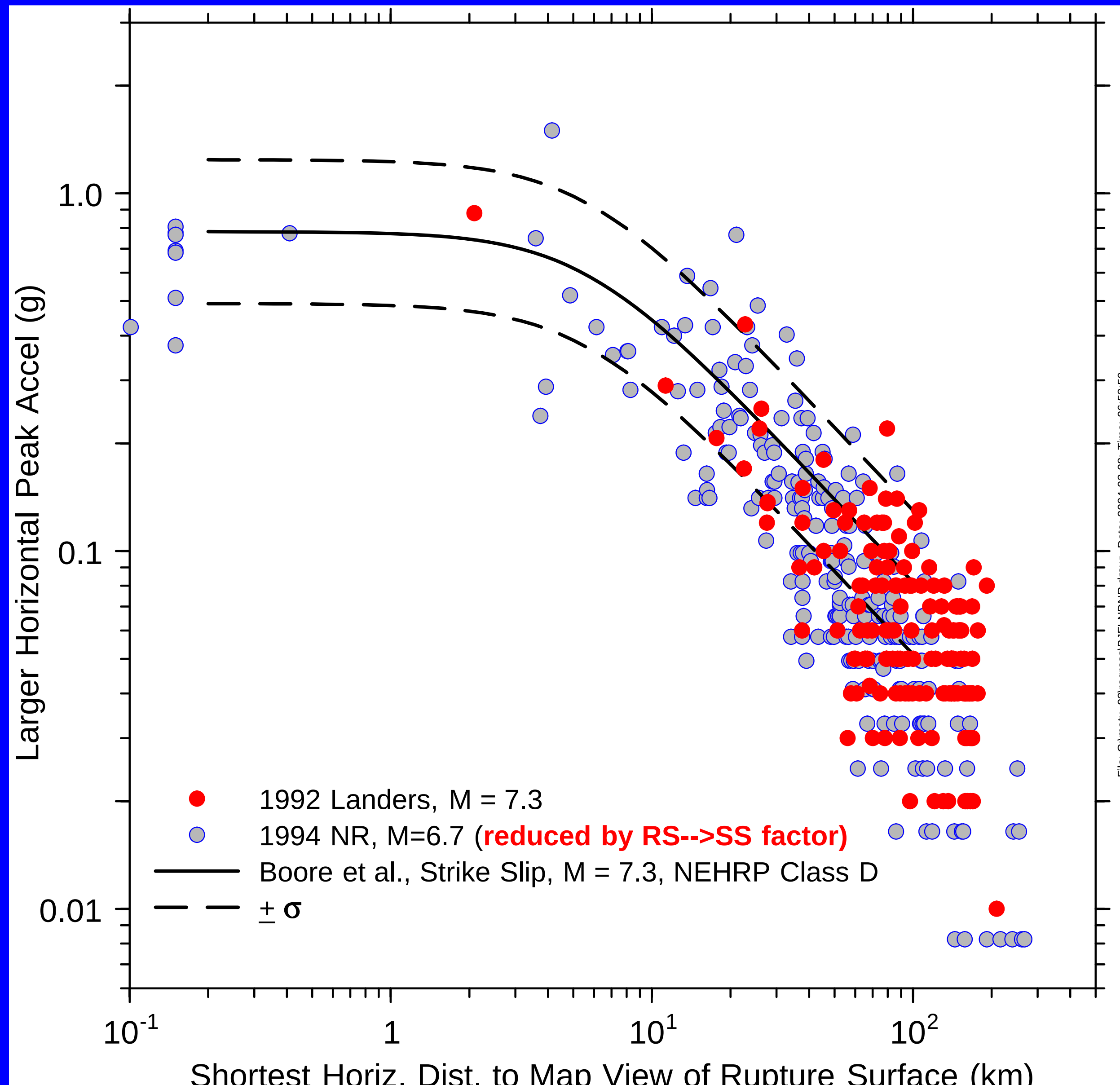
Ground-Motion Prediction Equations

Gives mean and standard deviation of response-spectrum ordinate (at a particular frequency) as a function of magnitude distance, site conditions, and perhaps other variables.



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Deriving the Equations

- Regression analysis of observed data if have adequate observations (rare for most of the world).
- Regression analysis of simulated data for regions with inadequate data (making use of motions from smaller events if available to constrain distance dependence of motions).
- Hybrid methods, capturing complex source effects from observed data and modifying for regional differences.

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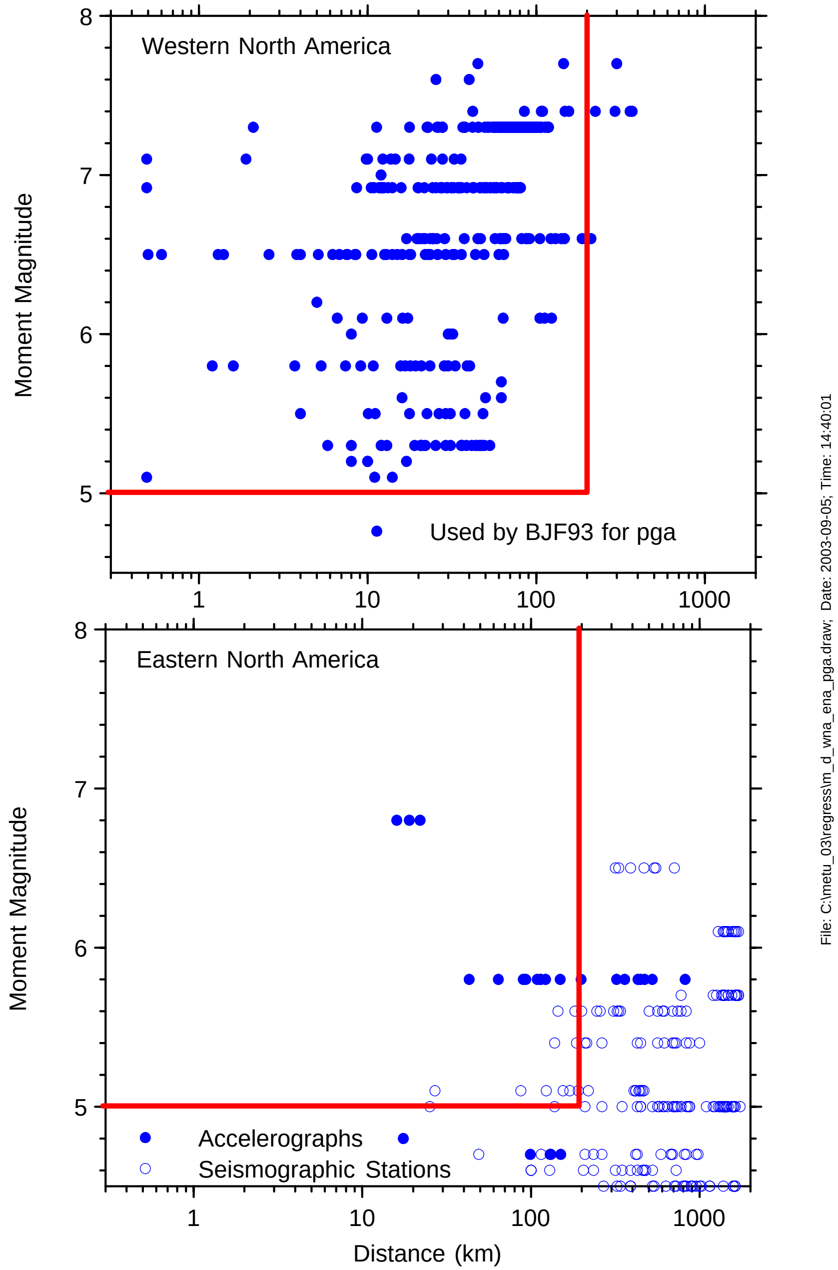
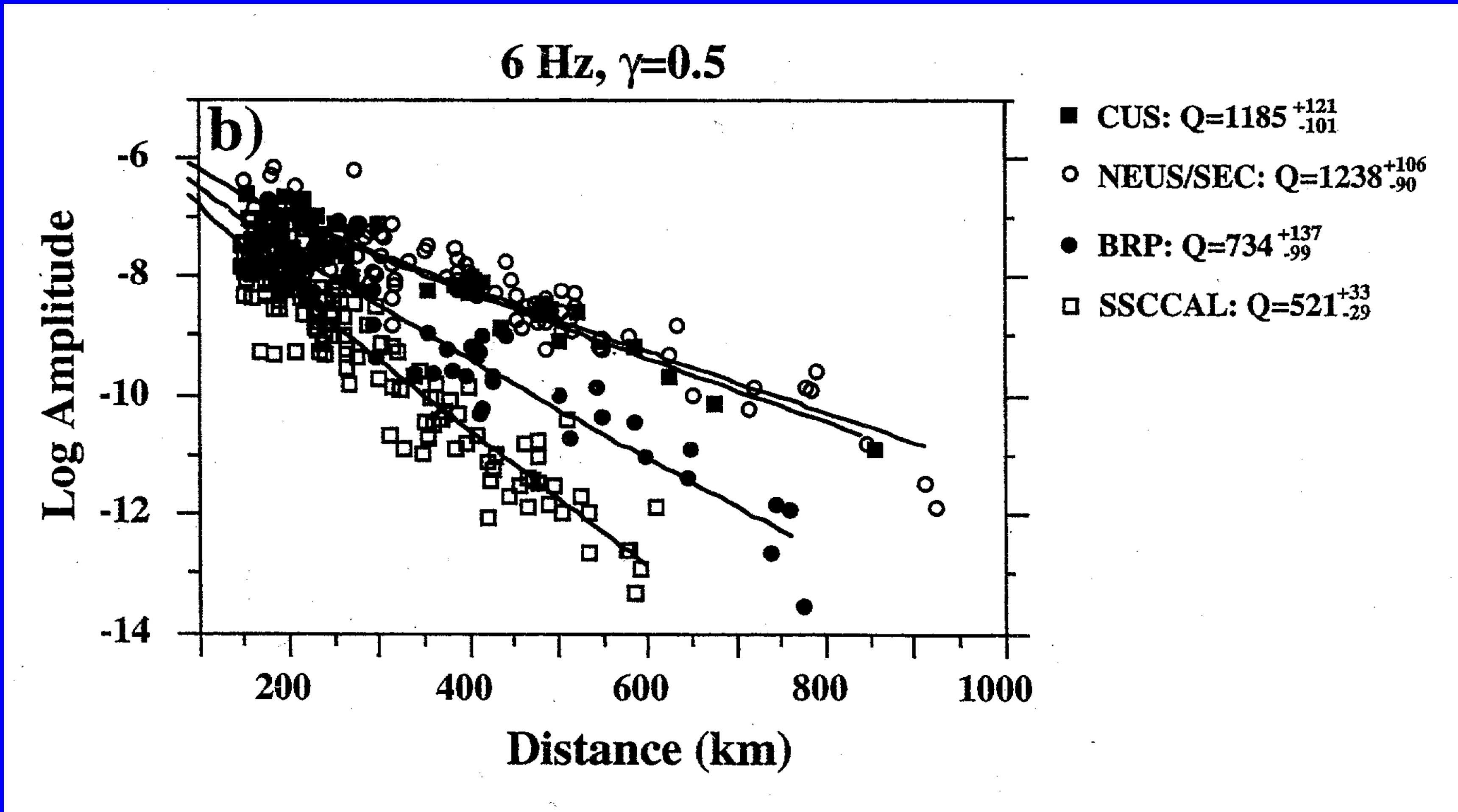


Observed data adequate for regression except close to large ‘quakes

Observed data not adequate for regression, use simulated data

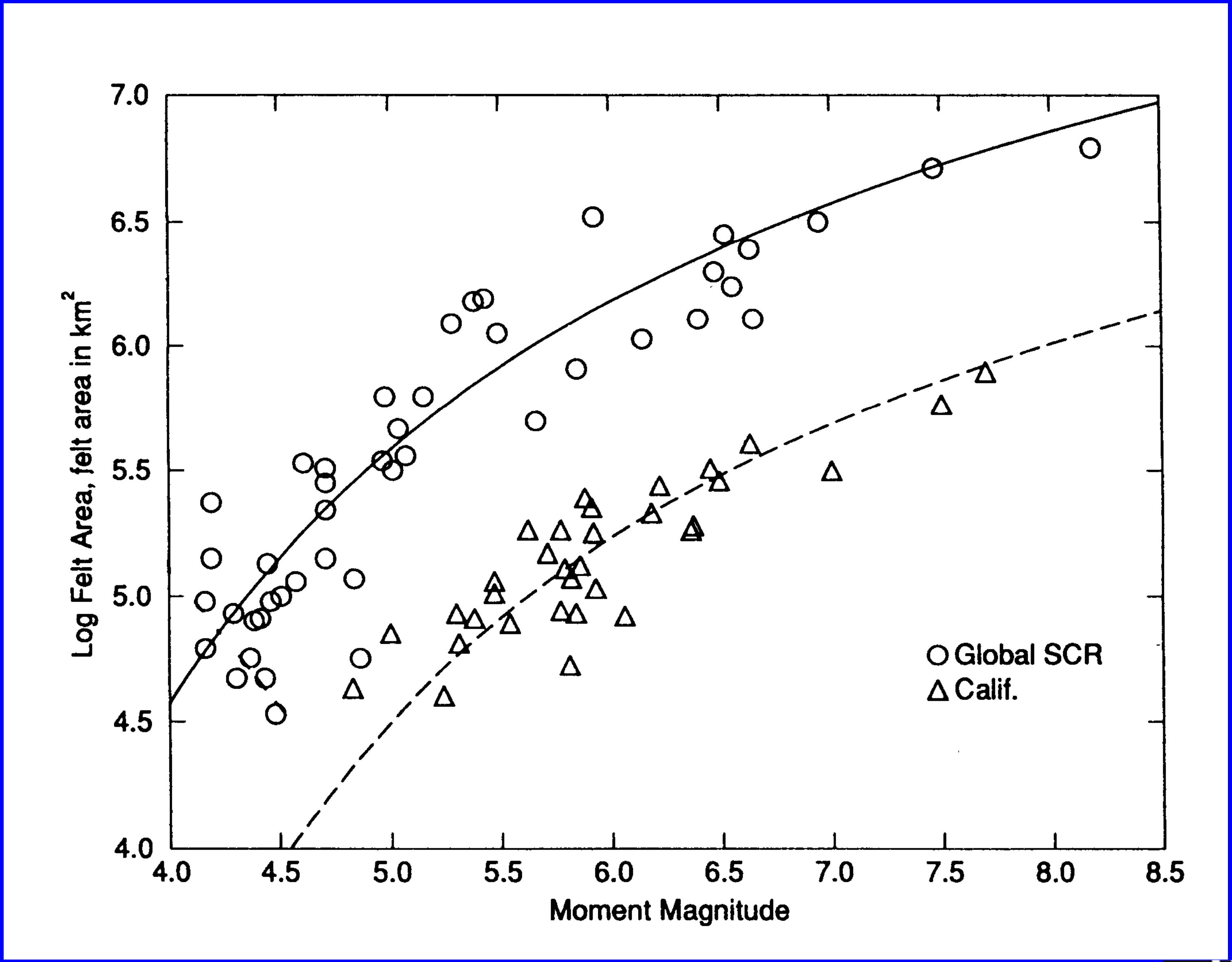
Higher ground motions for given Magnitude, Distance for CEUS Earthquakes Compared with WUS

- Higher Q in crust: less attenuation with distance
- Higher earthquake stress drop: more high-frequency ground motion for specified moment magnitude
- Determined from instrumental analysis of small and moderate events in CEUS and isoseismals of large historic events

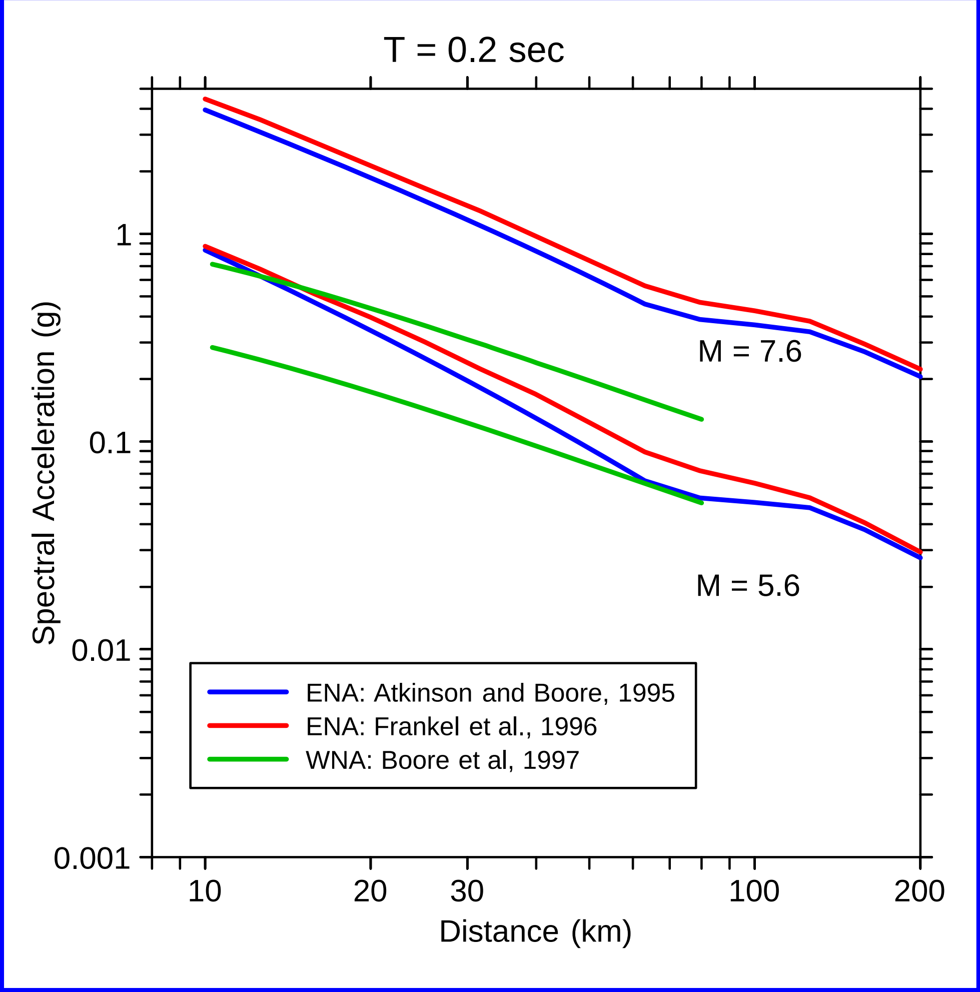


Distance-decay of regional shear waves determined by Benz, Frankel, and Boore (1997)

Fits using magnitude-independent stress drop, omega –2 model



From Frankel (1994)

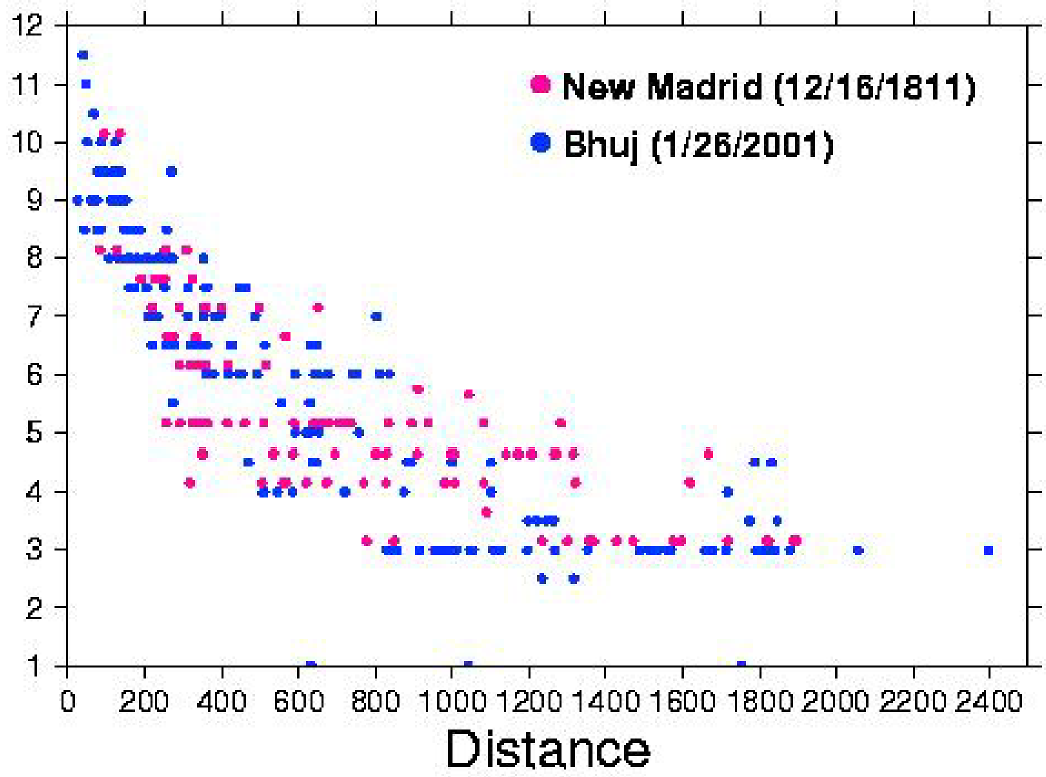


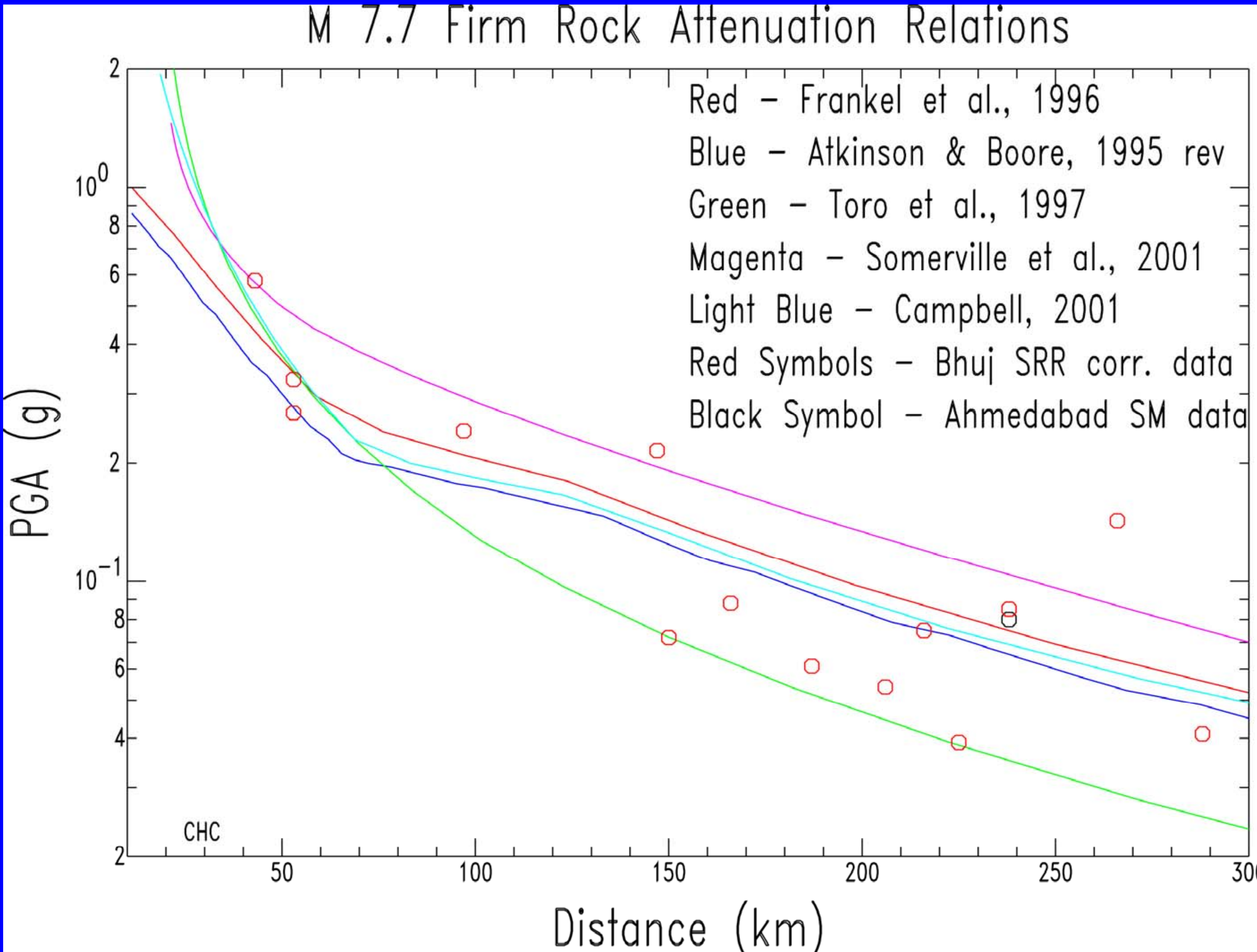
T = 0.2 sec
Spectral Acceleration (g)
1
0.1
0.01
0.001
10
20
30
100
200
Distance (km)
M = 7.6
M = 5.6
ENA: Atkinson and Boore, 1995
ENA: Frankel et al., 1996
WNA: Boore et al, 1997

How do we estimate ground motions for large earthquakes near New Madrid?

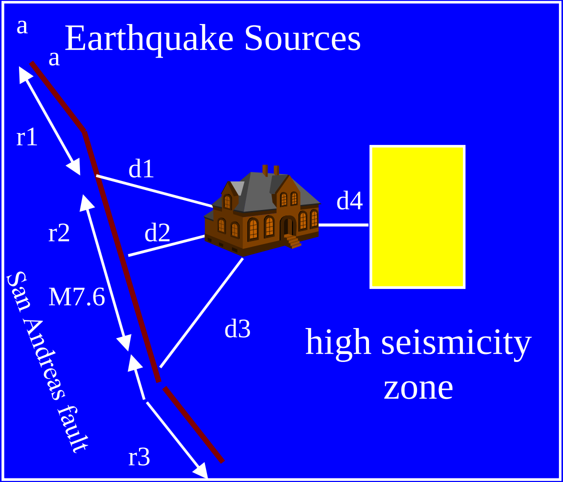
- use estimated magnitude to calculate ground motions from various ground-motion prediction equations: stochastic models using source parameters and derived for small earthquakes; constant stress drop with magnitude model validated with felt area vs. magnitude data; in 2002 added two corner frequency model, hybrid extended-source model, and semi-empirical model
- Atkinson and Boore (1998) compared predictions with regional ENAM data
- check with recorded ground motions of Bhuj, India earthquake

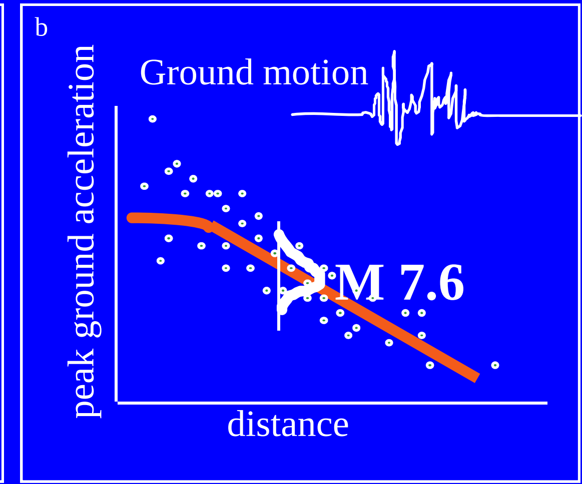
Intensity Distribution

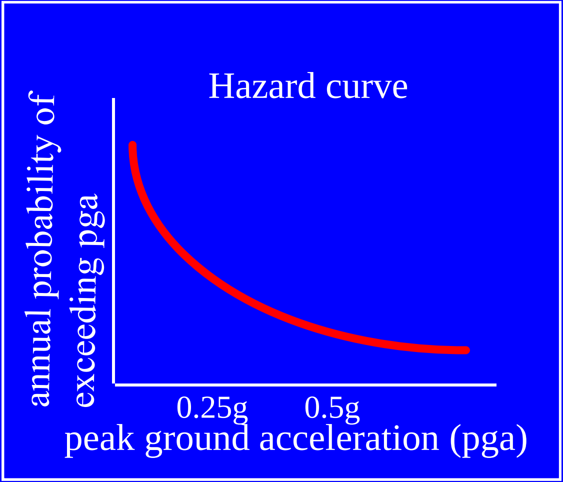



M 7.7 Firm Rock Attenuation Relations
Red – Frankel et al., 1996
Blue – Atkinson & Boore, 1995 rev
Green – Toro et al., 1997
Magenta – Somerville et al., 2001
Light Blue – Campbell, 2001
Red Symbols – Bhuj SRR corr. data
Black Symbol – Ahmedabad SM data
PGA (g)
Distance (km)
CHC
10^0
10^{-1}
2
8
6
4
50
100
150
200
250
300

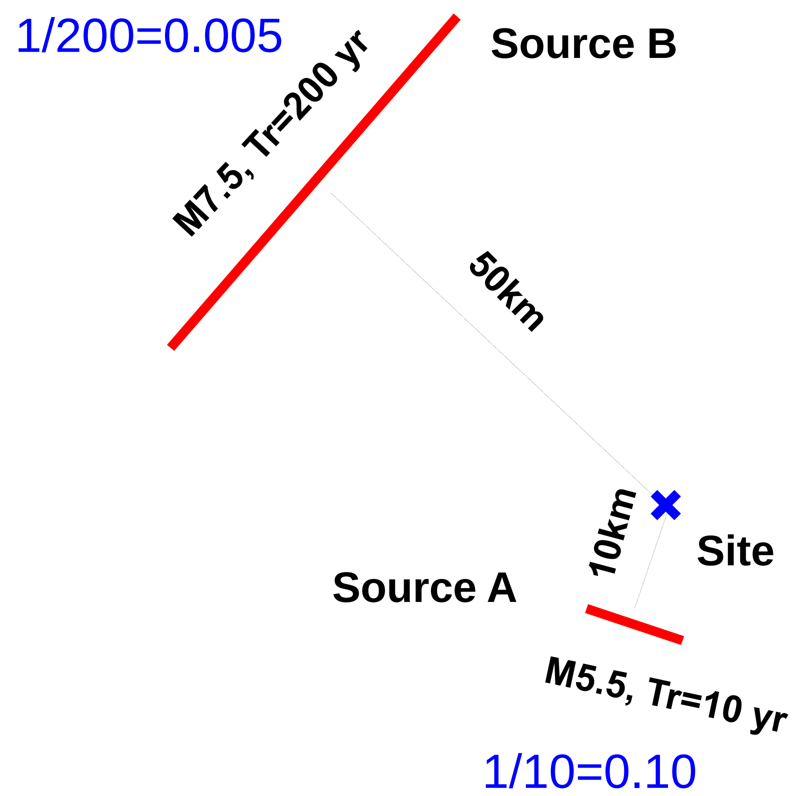
Hazard Methodology Example



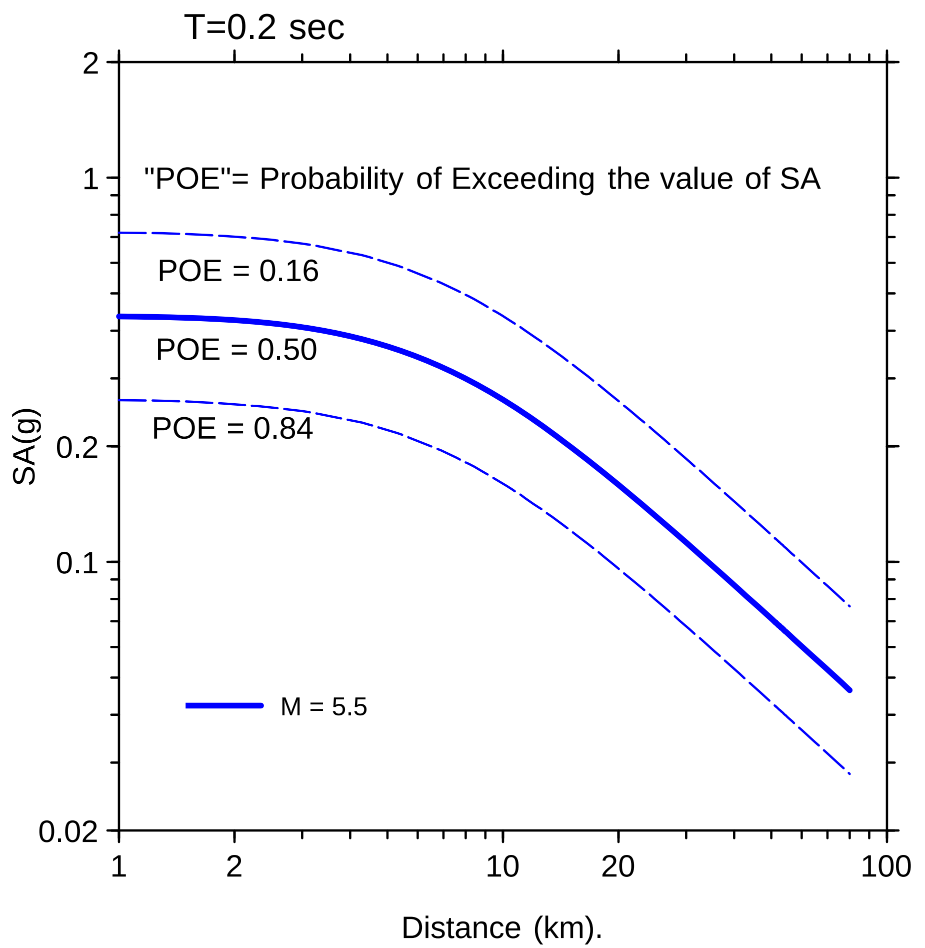




Annual probability that earthquake occurs:



After Wang et al., 2003



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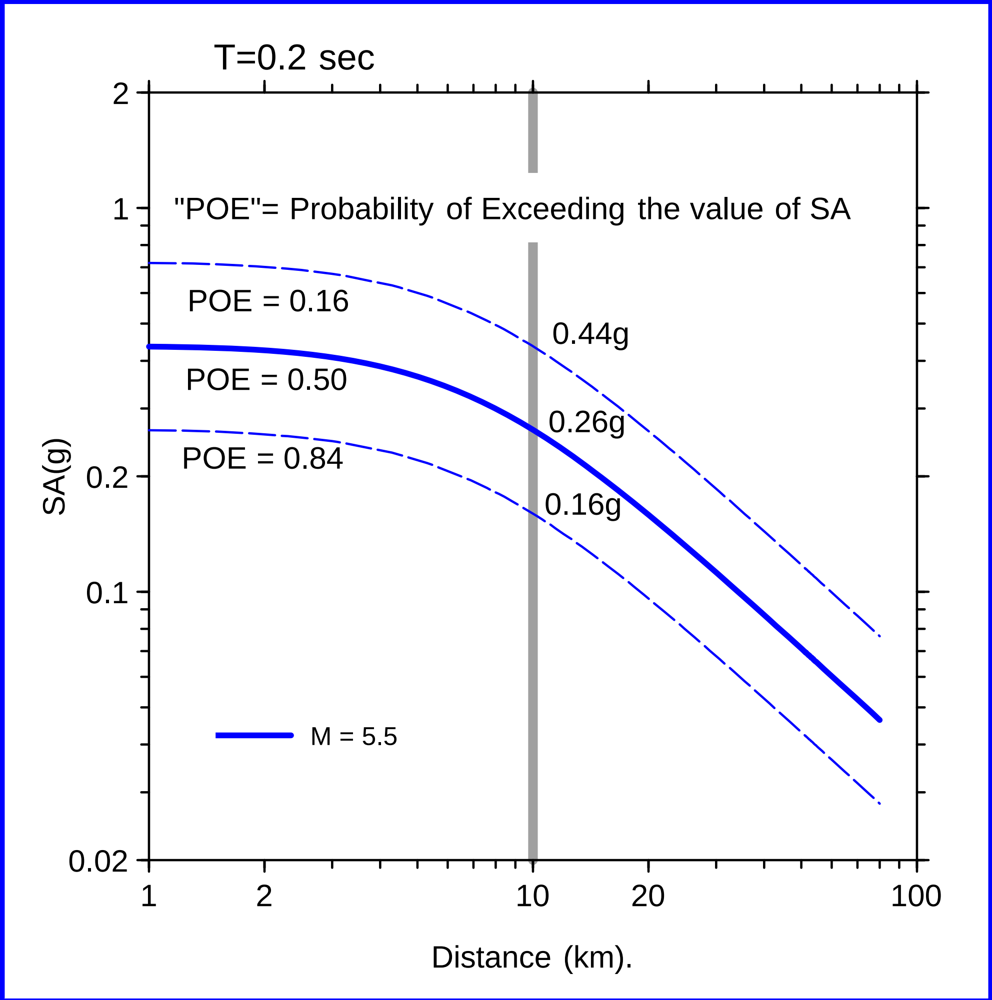
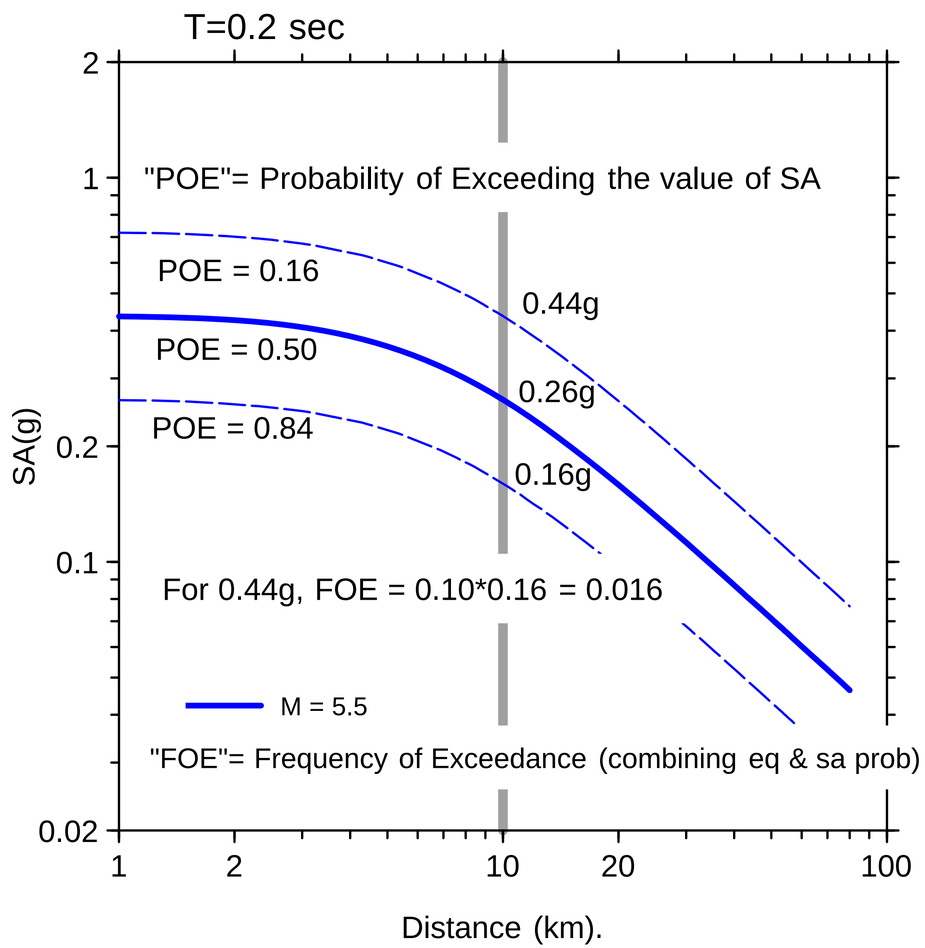


T=0.2 sec
"POE"= Probability of Exceeding the value of SA
POE = 0.16
POE = 0.50
POE = 0.84
0.44g
0.26g
0.16g
M = 5.5
SA(g)
2
1
0.2
0.1
0.02
1
2
10
20
100
Distance (km).



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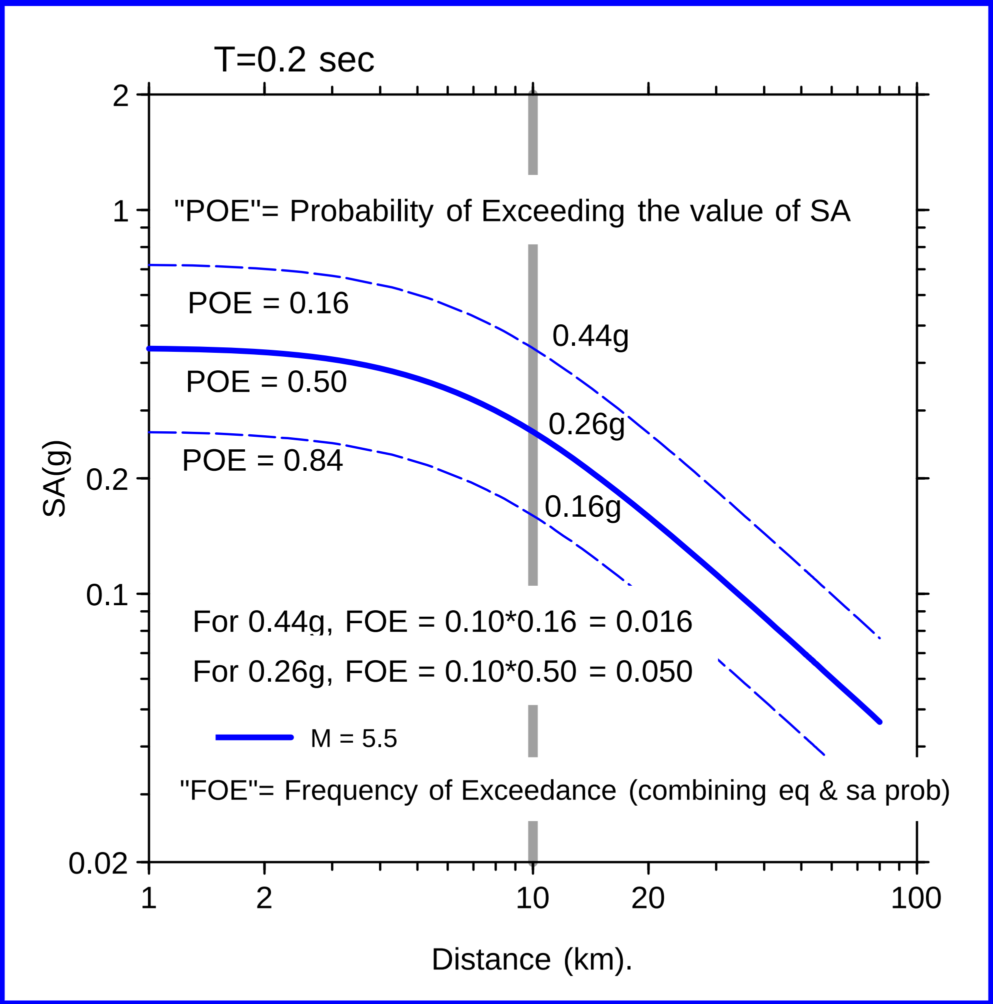
"POE"= Probability of Exceeding the value of SA
POE = 0.16
POE = 0.50
POE = 0.84
0.44g
0.26g
0.16g
For 0.44g, FOE = 0.10*0.16 = 0.016
M = 5.5
"FOE"= Frequency of Exceedance (combining eq & sa prob)
SA(g)
2
1
0.2
0.1
0.02
1
2
10
20
100
Distance (km).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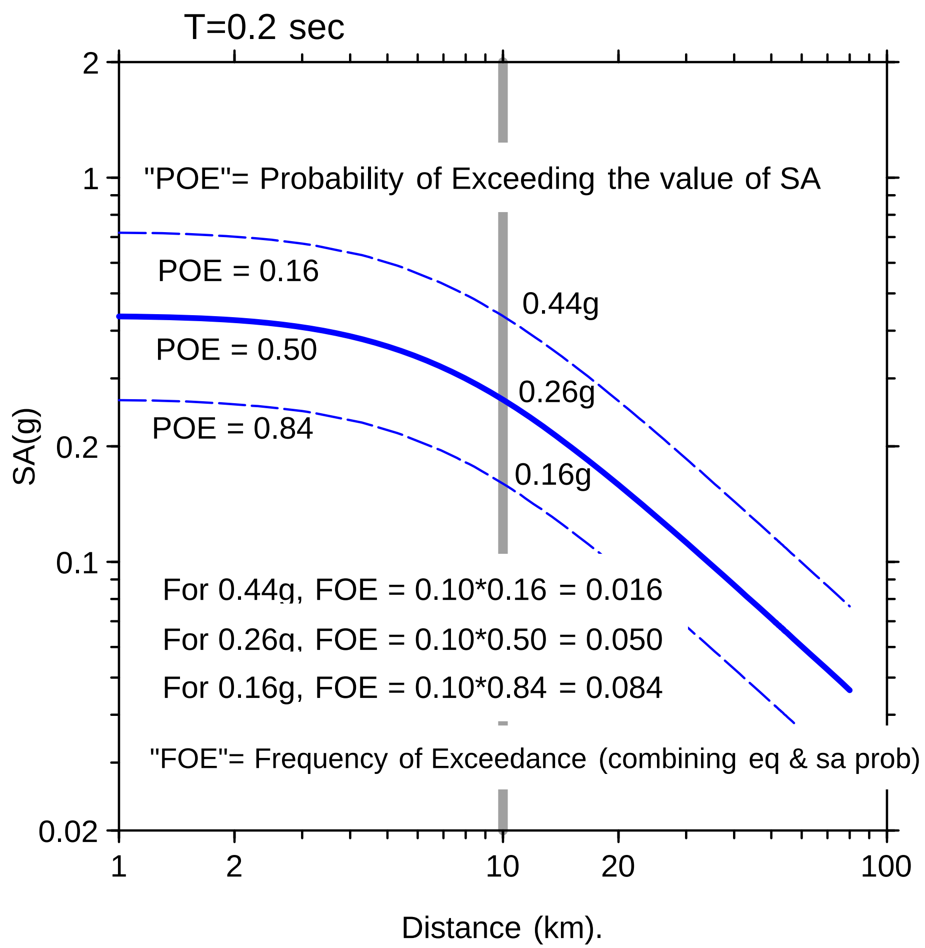
POE = 0.50
POE = 0.84
0.44g
0.26g
0.16g
For 0.44g, FOE = 0.10*0.16 = 0.016
For 0.26g, FOE = 0.10*0.50 = 0.050
M = 5.5
"FOE"= Frequency of Exceedance (combining eq & sa prob)
SA(g)
2
1
0.2
0.1
0.02
1
2
10
20
100
Distance (km).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POE = 0.50
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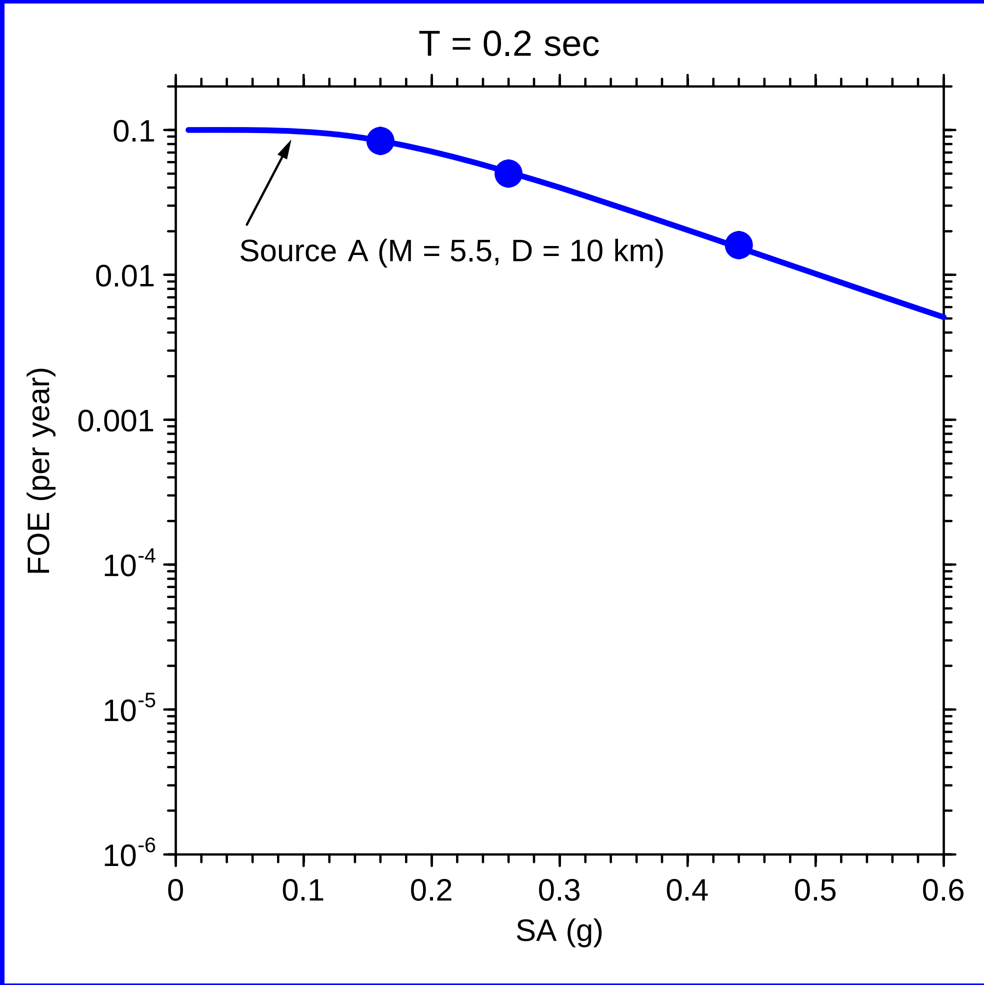
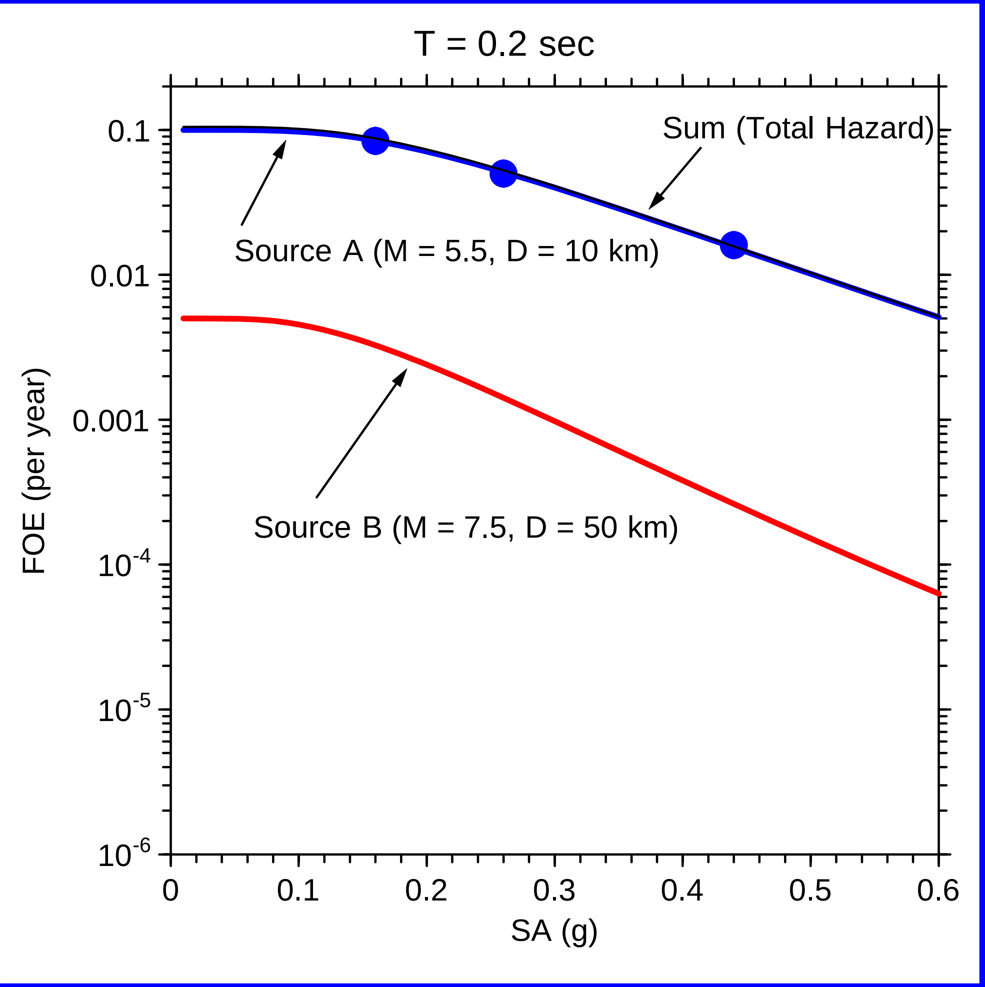
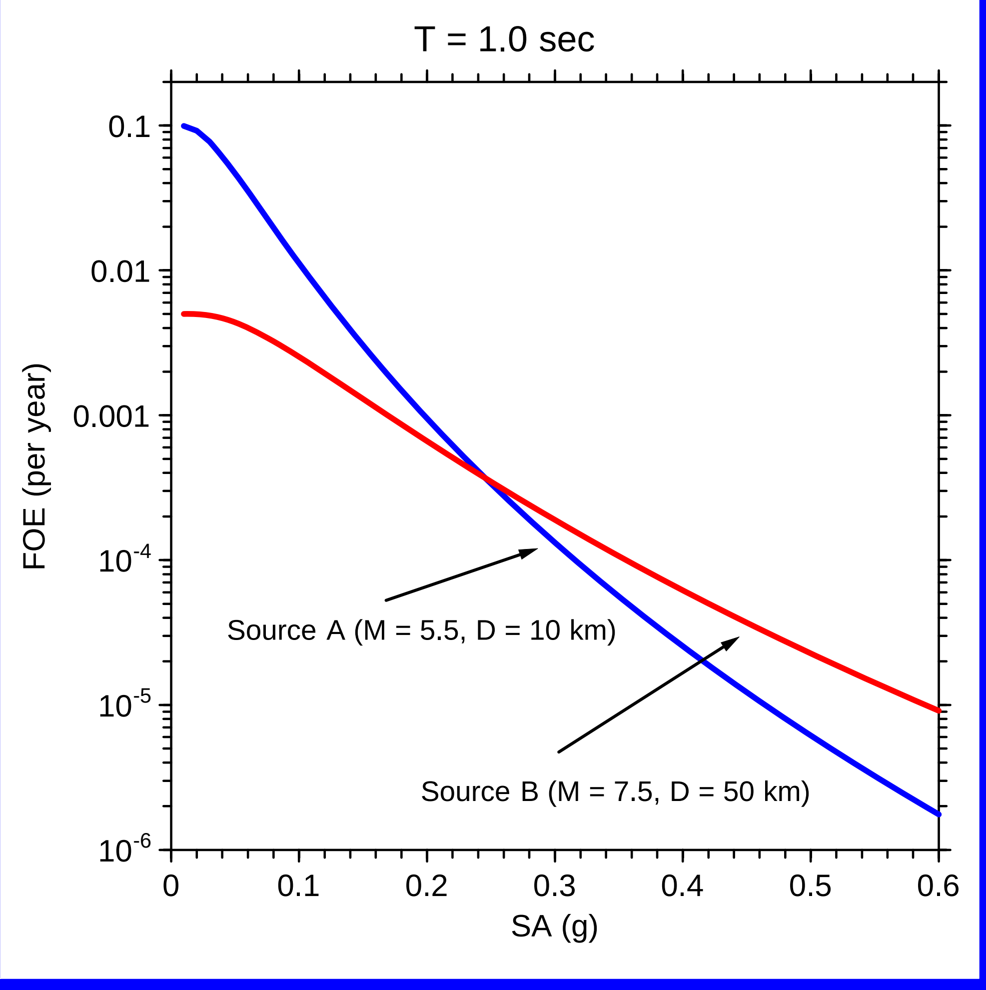
0.44g
0.26g
0.16g
For 0.44g, FOE = 0.10*0.16 = 0.016
For 0.26g, FOE = 0.10*0.50 = 0.050
For 0.16g, FOE = 0.10*0.84 = 0.084
"FOE"= Frequency of Exceedance (combining eq & sa prob)
SA(g)
2
1
0.2
0.1
0.02
1
2
10
20
100
Distance (km).

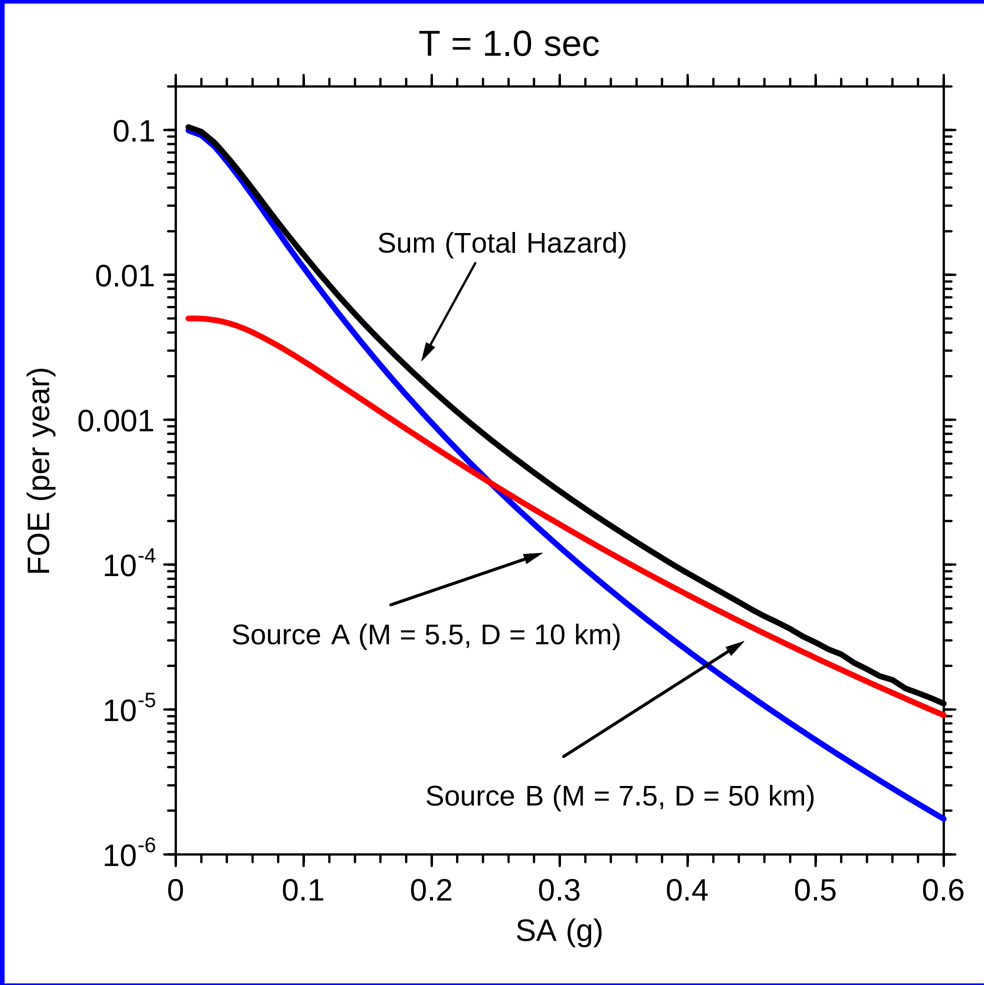


T = 0.2 sec
Source A (M = 5.5, D = 10 km)
FOE (per year)
0.1
0.01
0.001
10-4
10-5
10-6
0
0.1
0.2
0.3
0.4
0.5
0.6
SA (g)

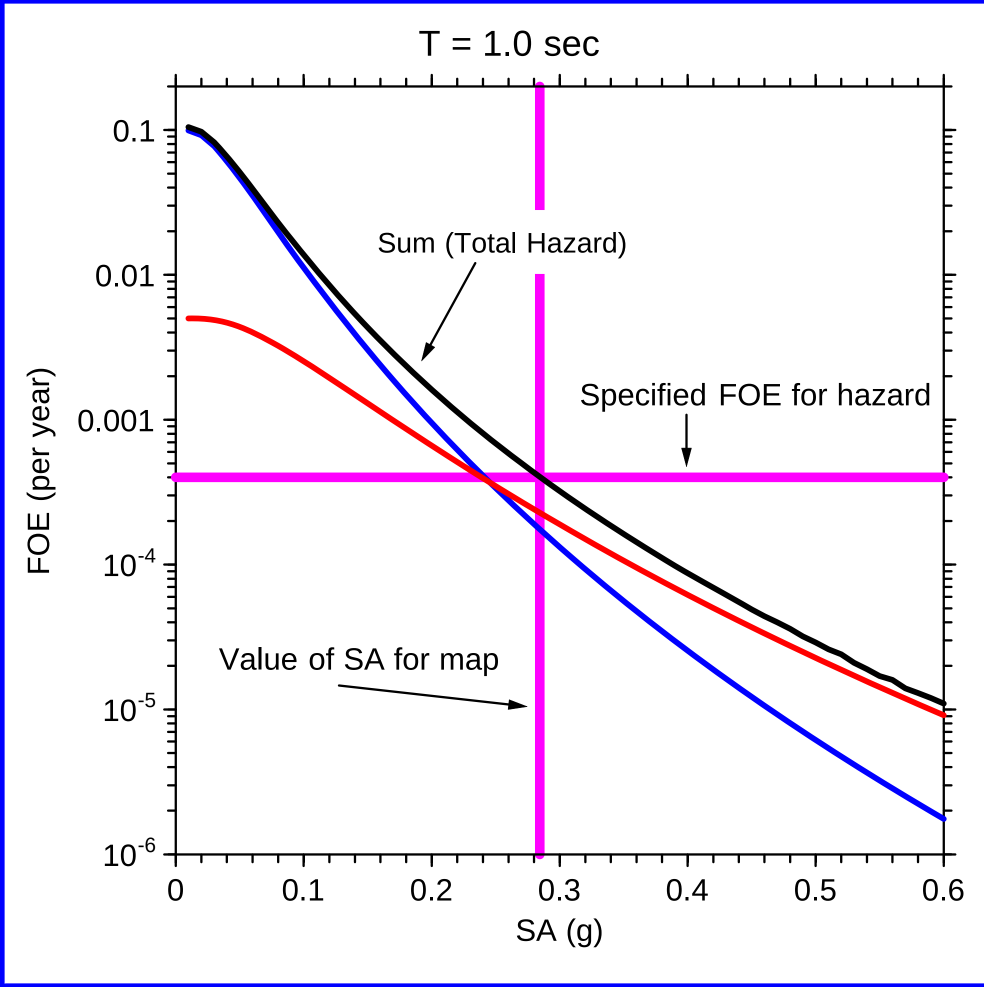

T = 0.2 sec
Sum (Total Hazard)
Source A (M = 5.5, D = 10 km)
Source B (M = 7.5, D = 50 km)
FOE (per year)
0.1
0.01
0.001
10-4
10-5
10-6
0
0.1
0.2
0.3
0.4
0.5
0.6
SA (g)



T = 1.0 sec
FOE (per year)
0.1
0.01
0.001
10-4
10-5
10-6
Source A (M = 5.5, D = 10 km)
Source B (M = 7.5, D = 50 km)
0
0.1
0.2
0.3
0.4
0.5
0.6
SA (g)



T = 1.0 sec
Sum (Total Hazard)
Source A (M = 5.5, D = 10 km)
Source B (M = 7.5, D = 50 km)
FOE (per year)
0.1
0.01
0.001
10-4
10-5
10-6
0
0.1
0.2
0.3
0.4
0.5
0.6
SA (g)



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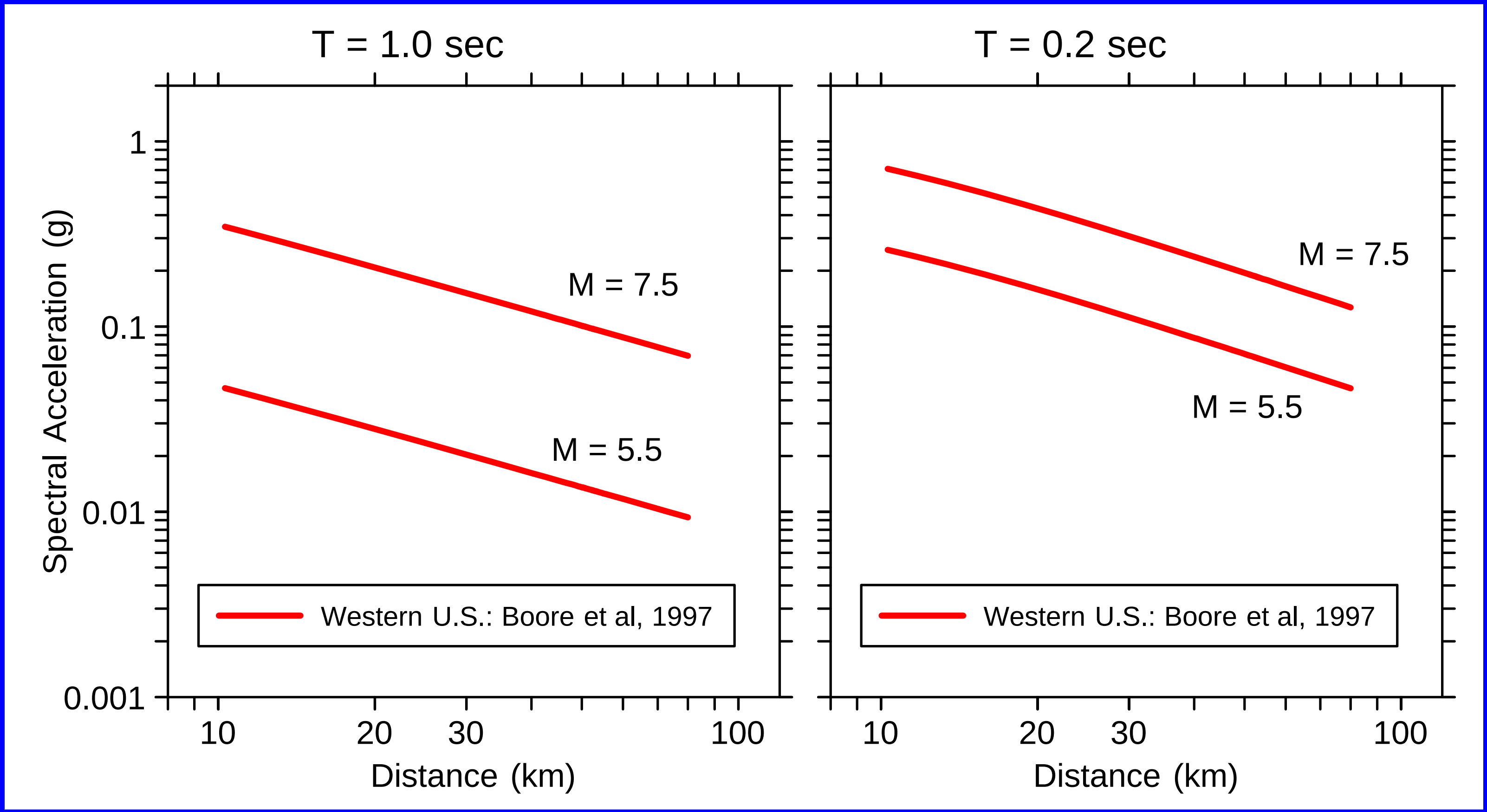
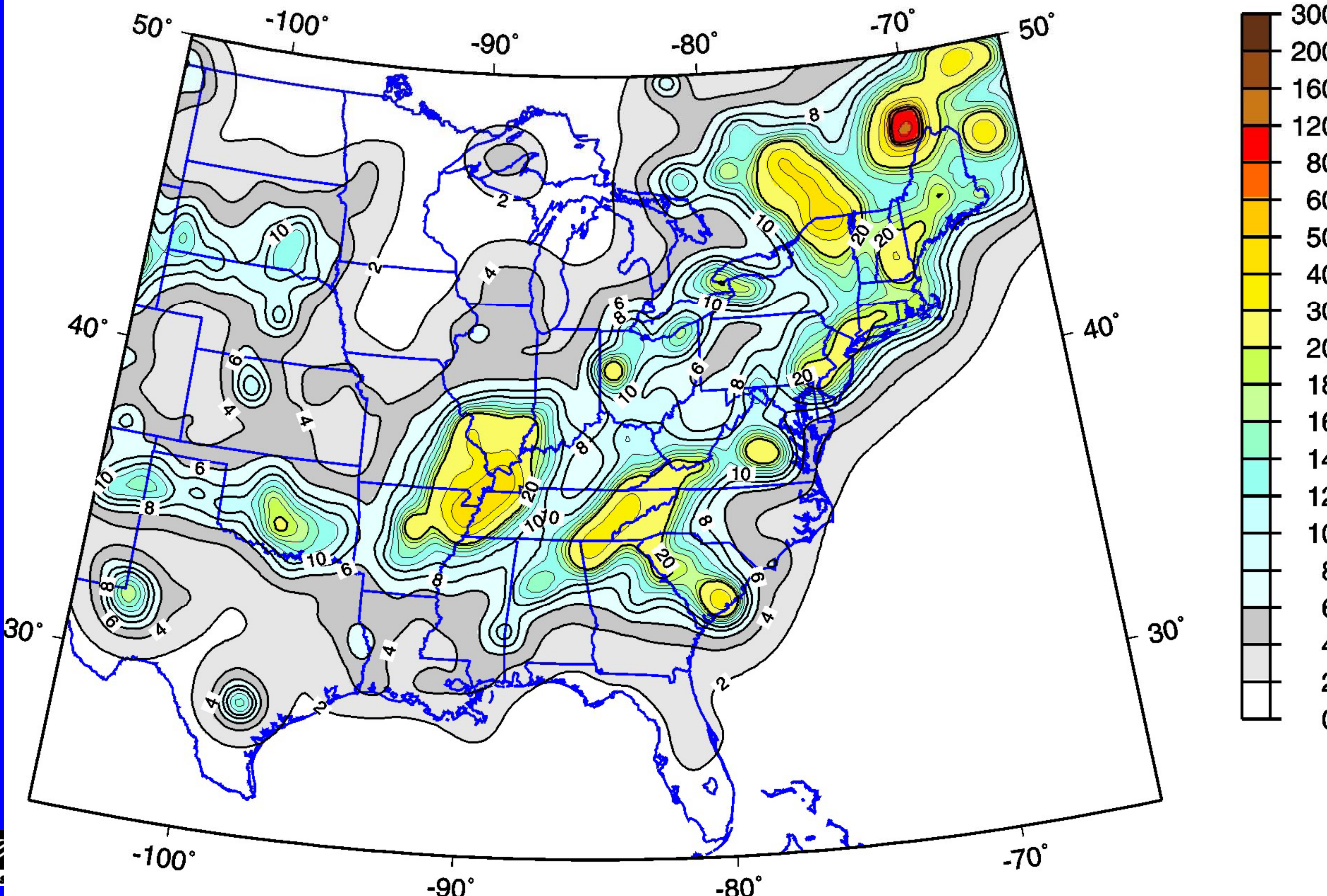
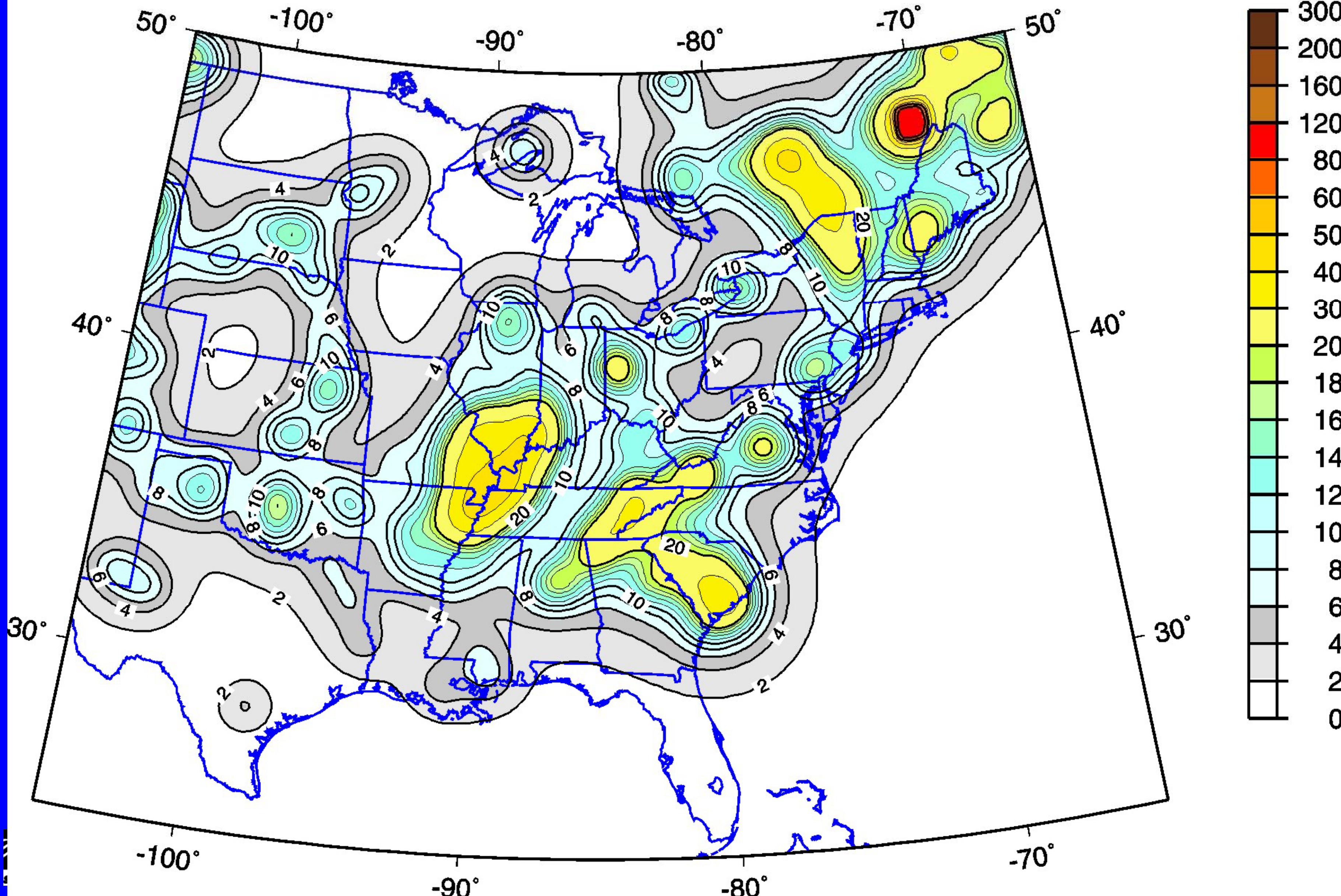
Why the different sensitivity of T=1 s and T=0.2 s hazard to magnitude? Ground motion.



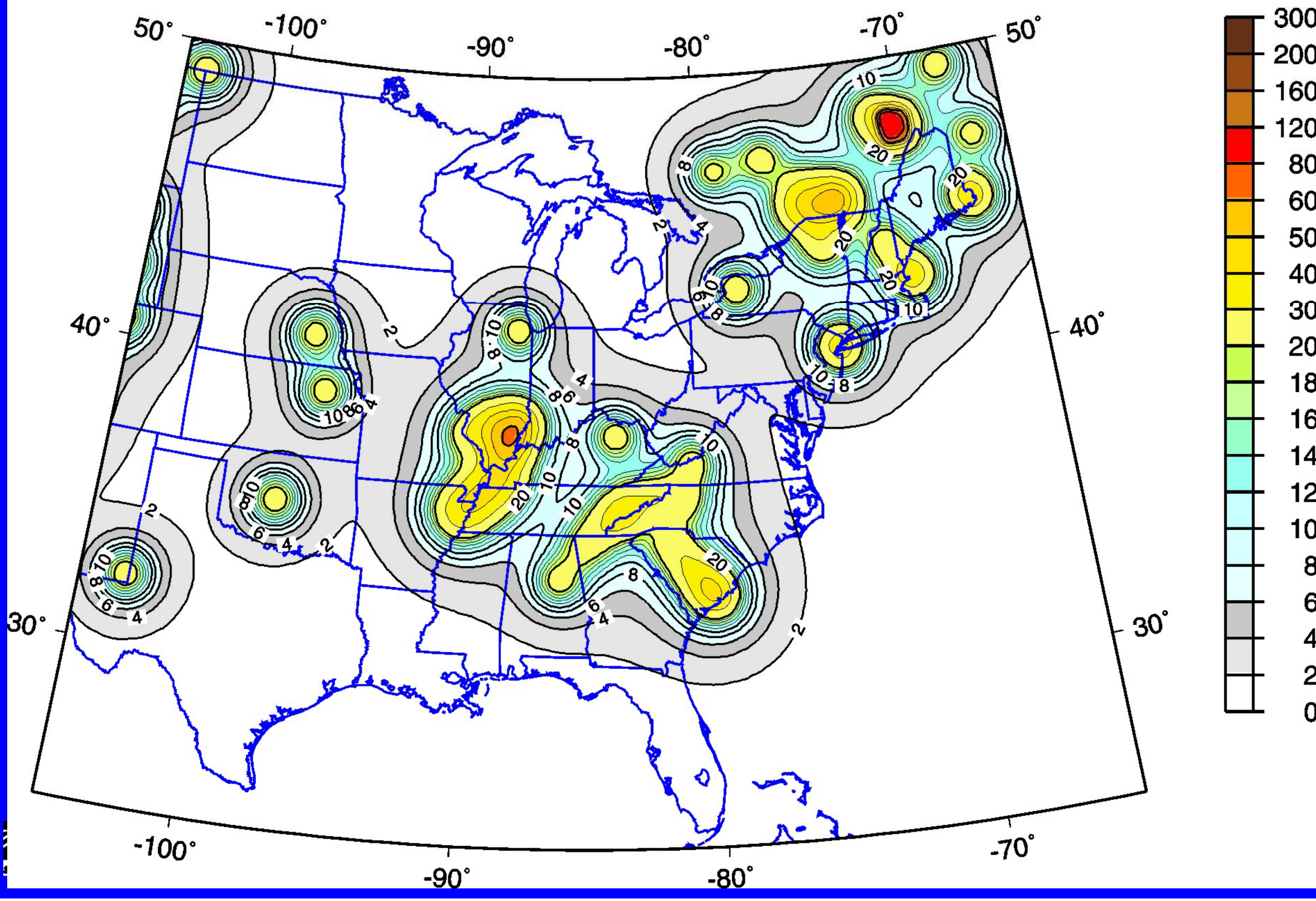
Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years from M3+ since 1924



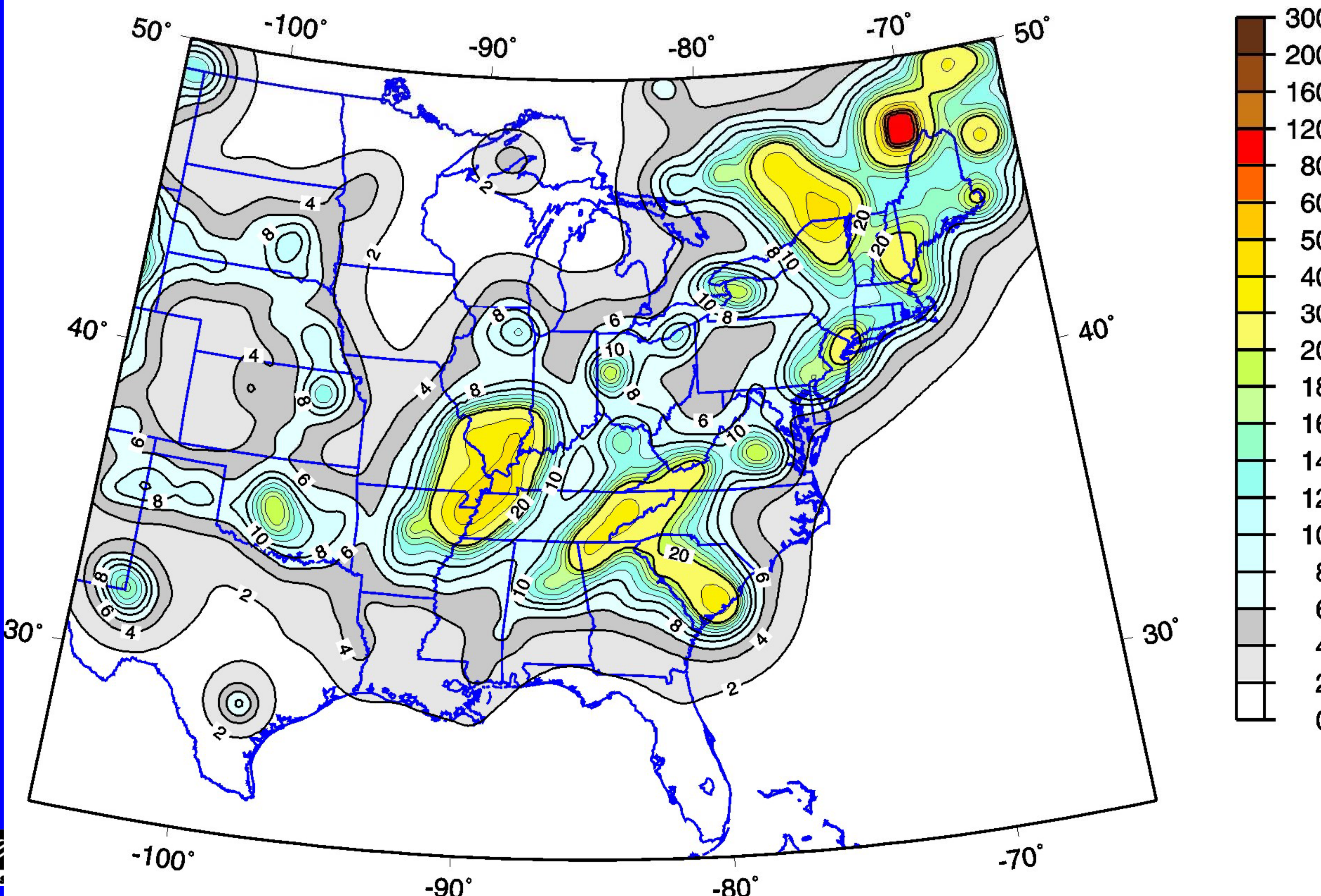
Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years from M4+ since 1860



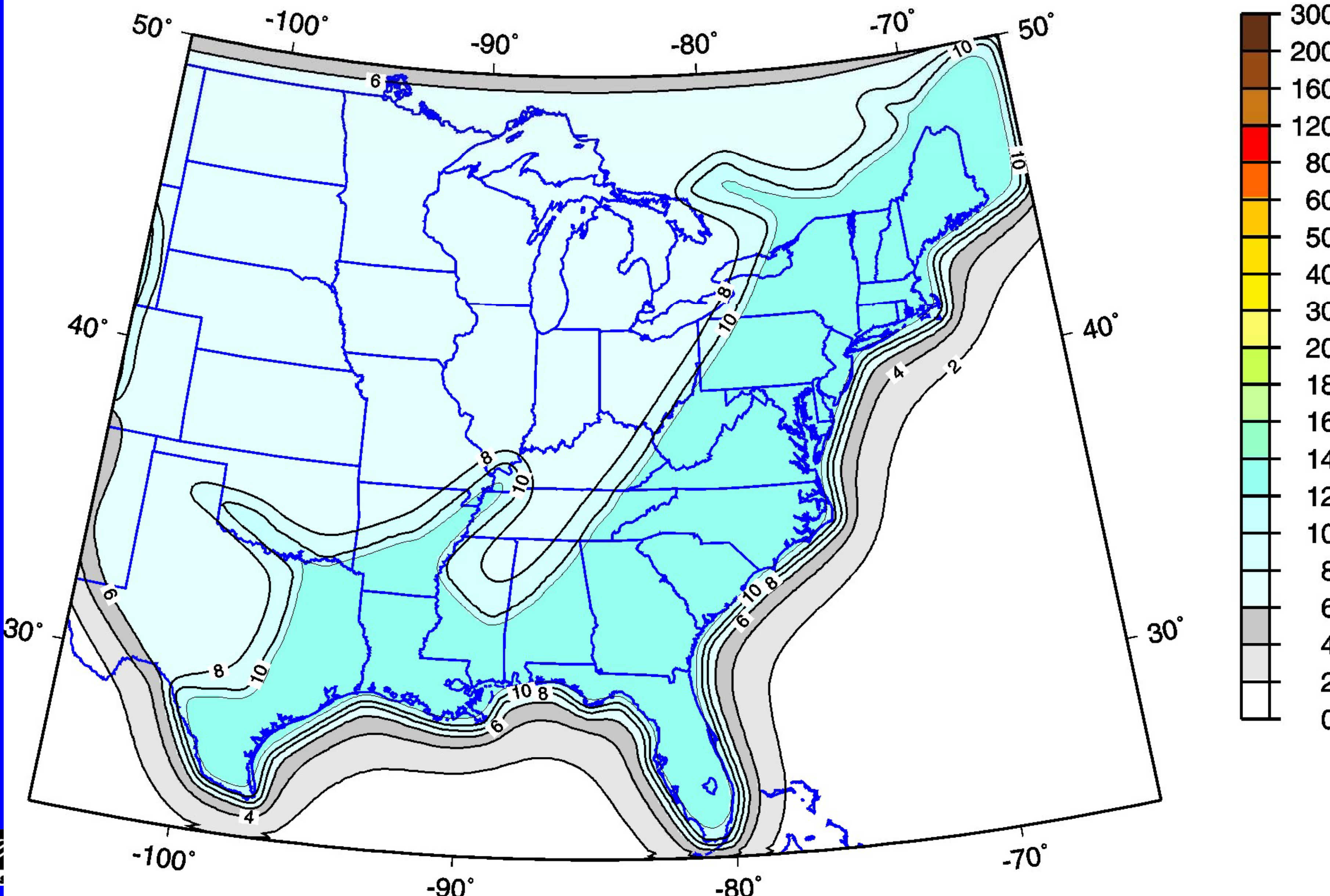
Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
from M5+ since 1700



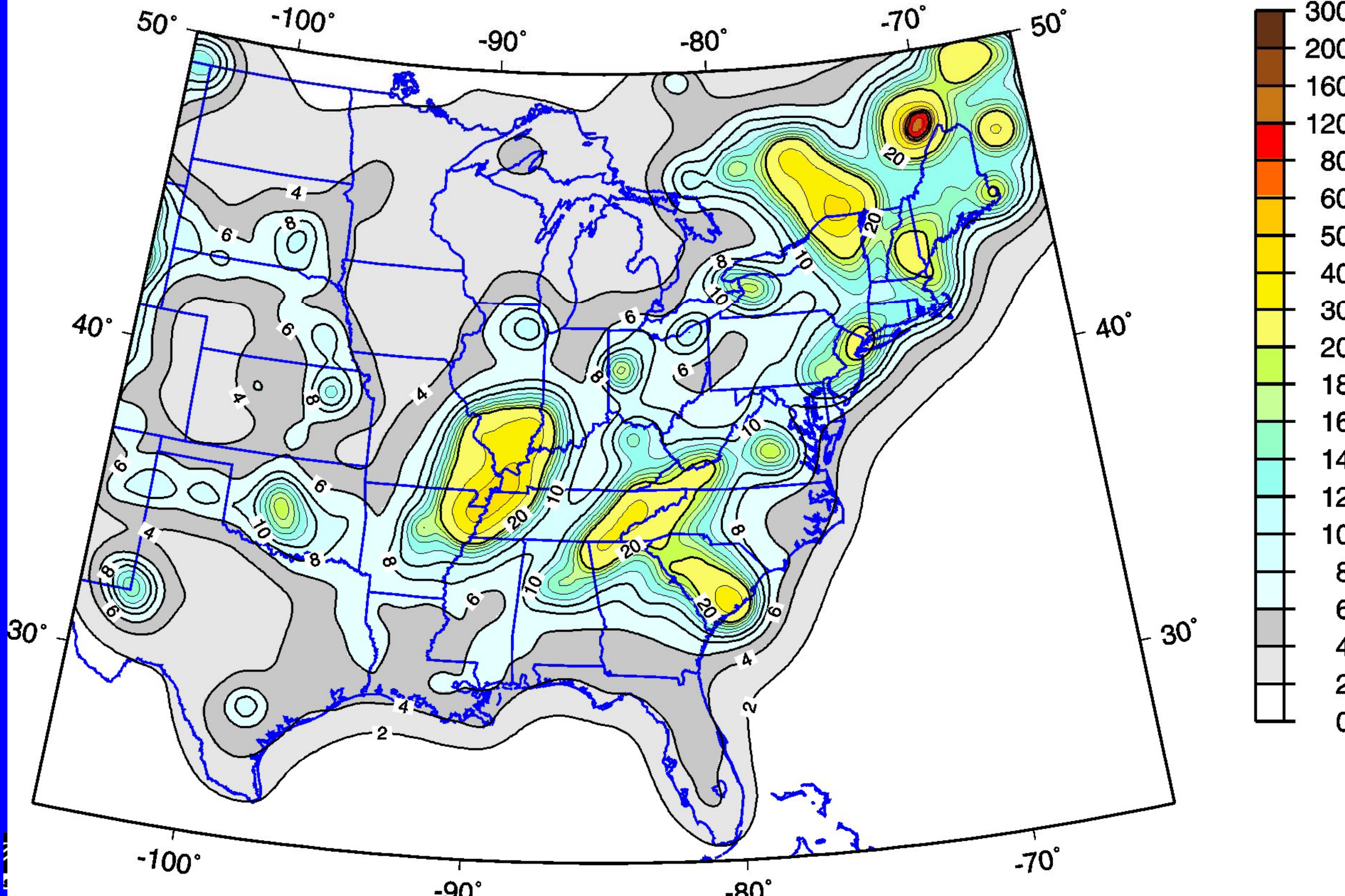
Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years from models 1-3, no background zones



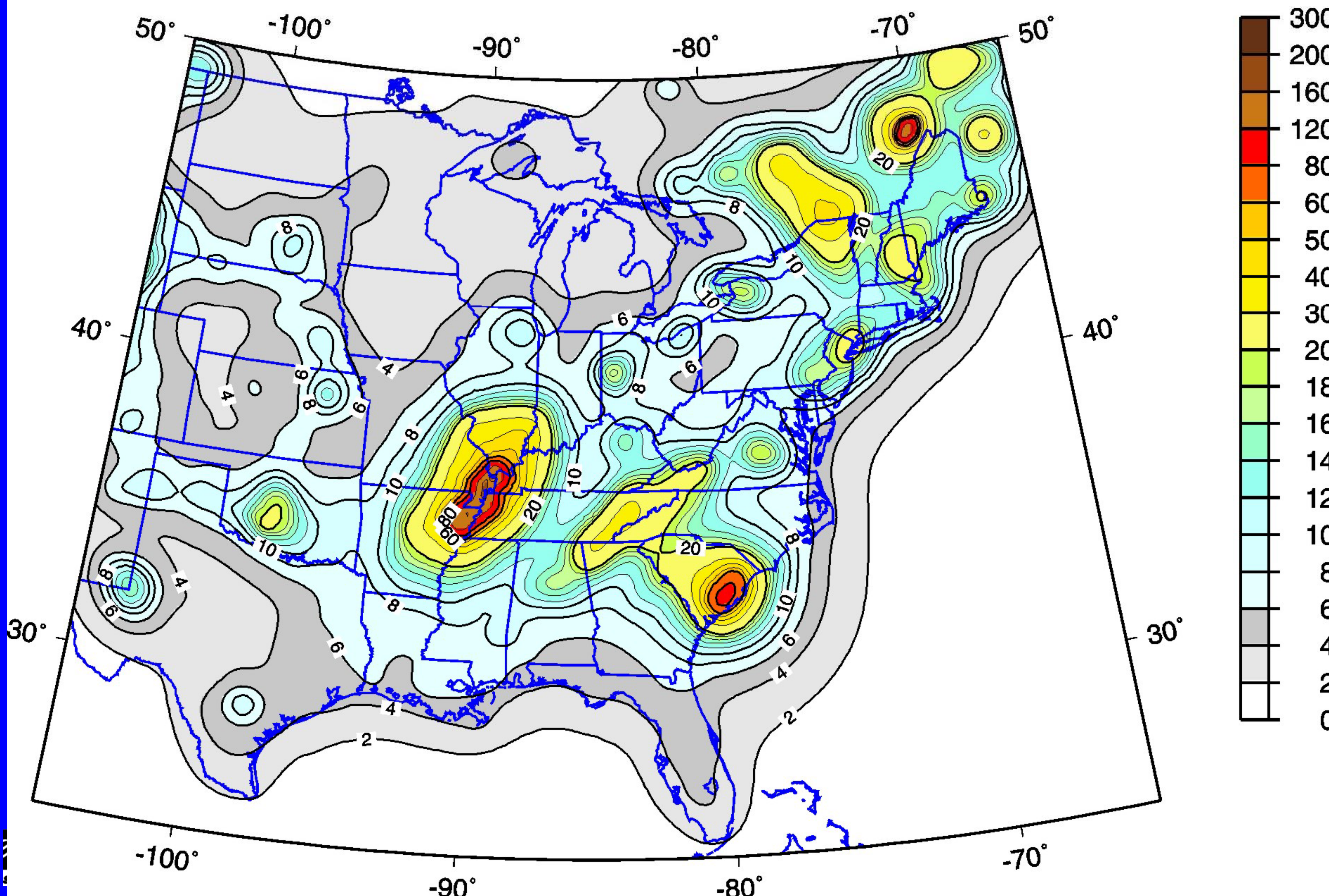
Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years from background zones



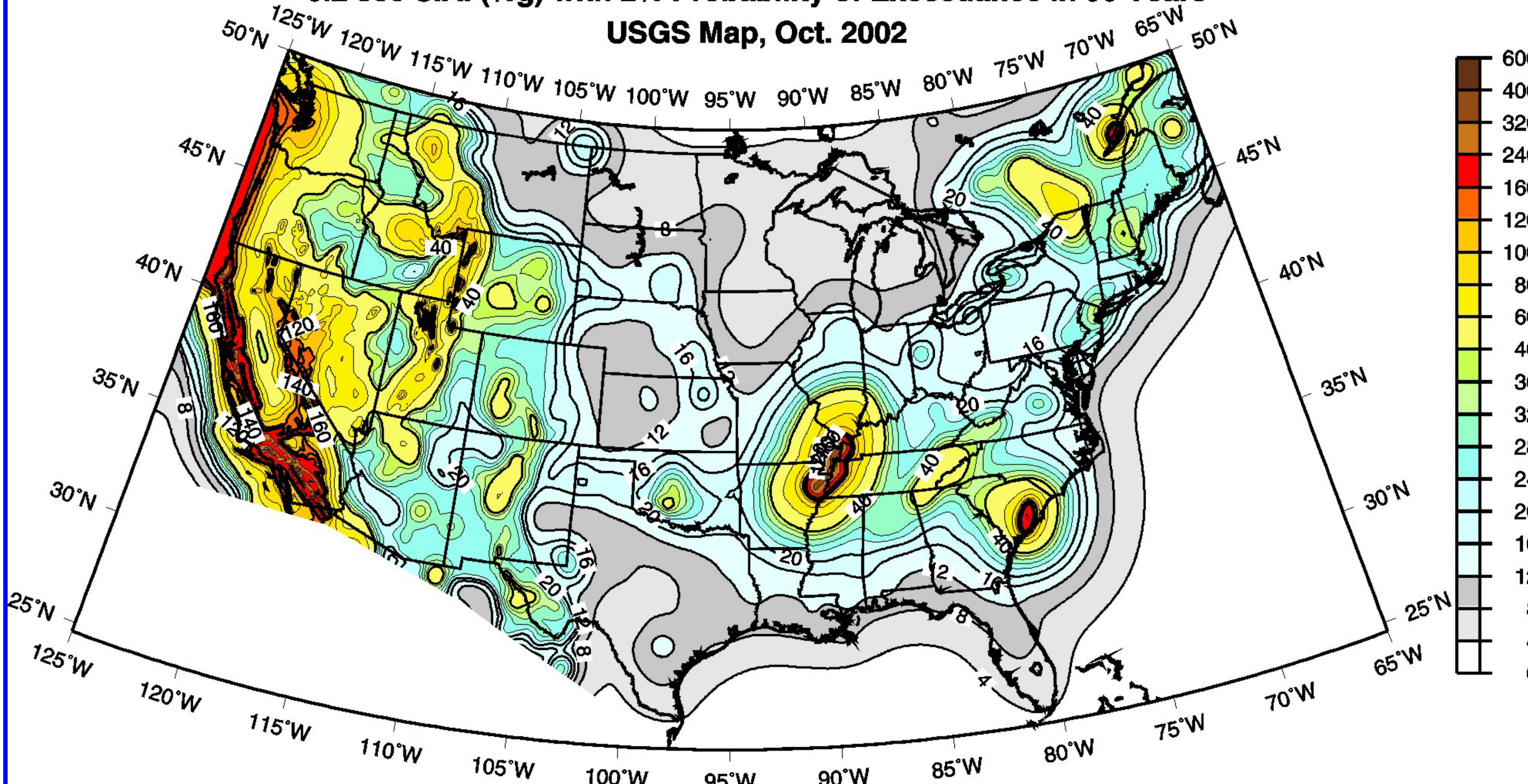
Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
from models 1-4



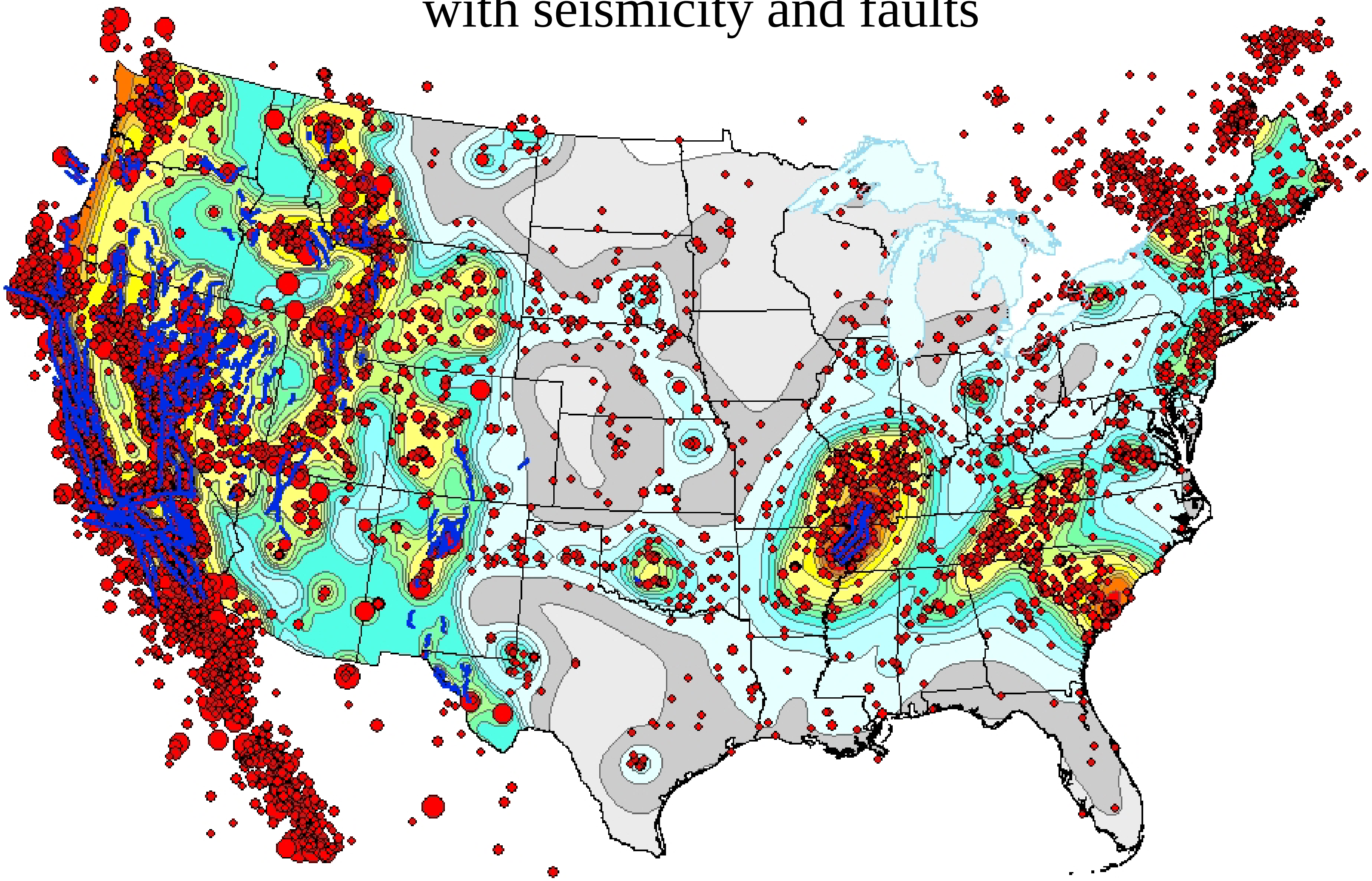
Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
all sources

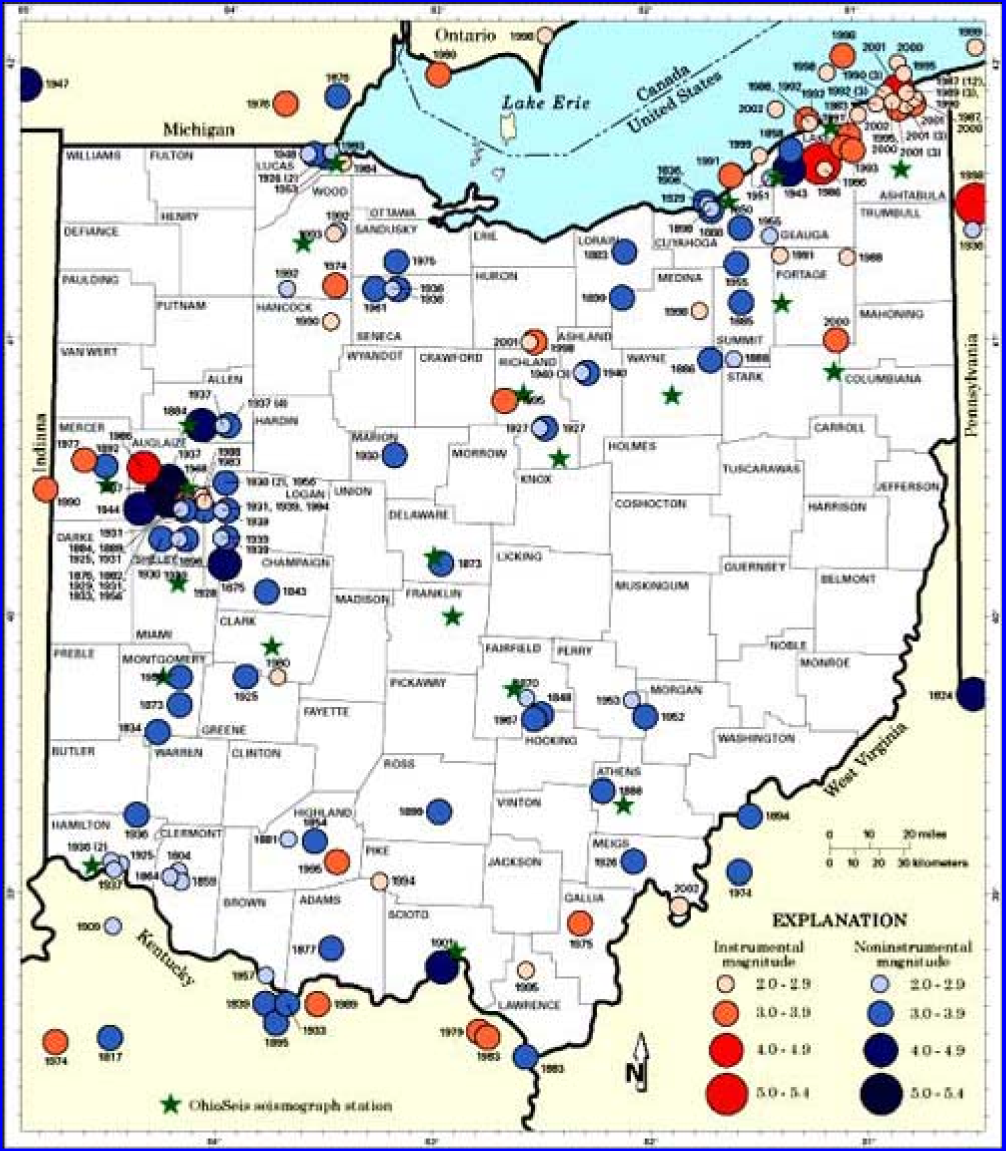


0.2 sec S.A. (%g) with 2% Probability of Exceedance in 50 Years
USGS Map, Oct. 2002



1996 map (PGA with 2% PE in 50 yr)
with seismicity and faults





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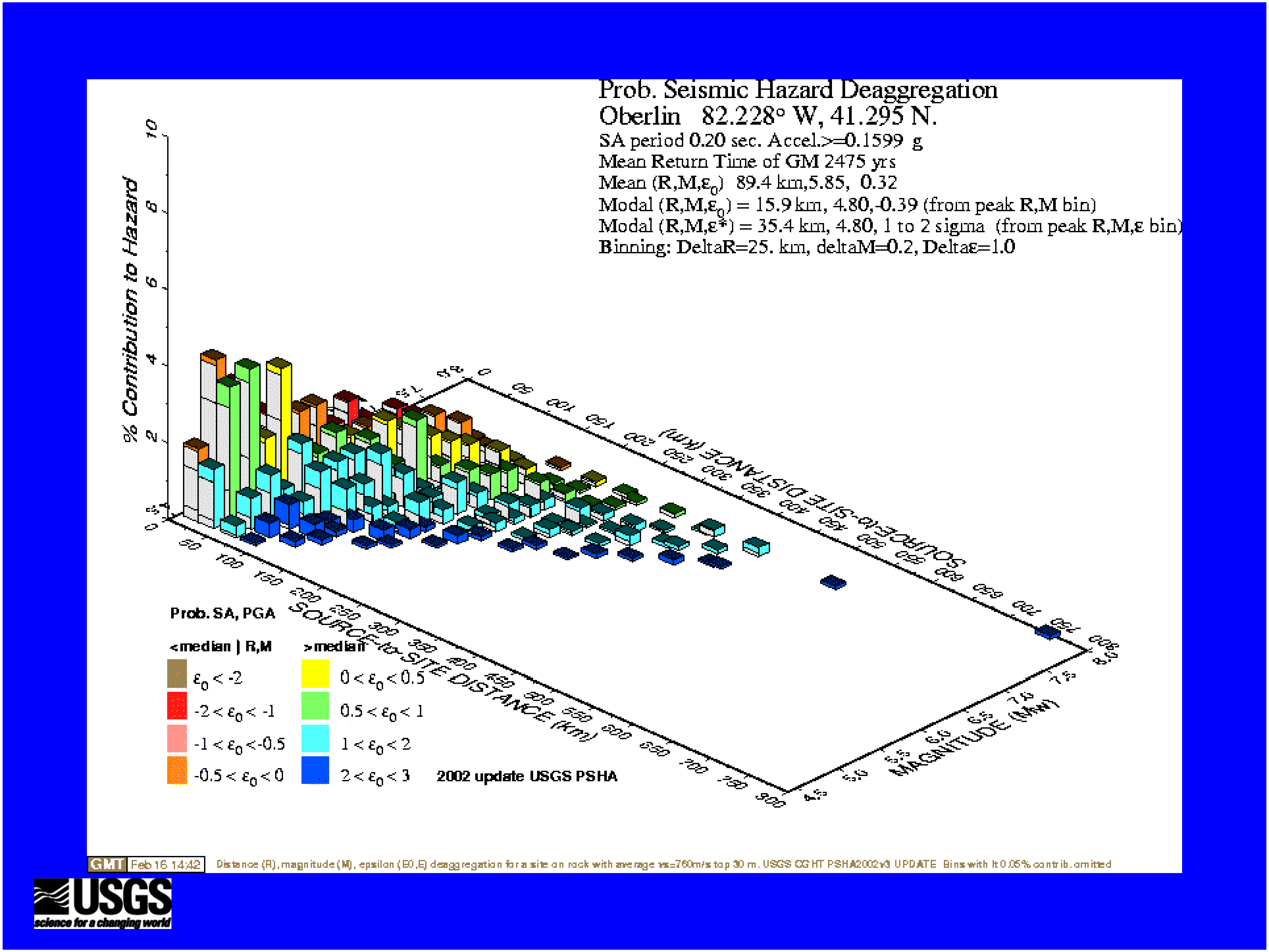
http://www.ohiodnr.com/OhioSeis/



Prob. Seismic Hazard Deaggregation
Oberlin 82.228° W, 41.295 N.
SA period 0.20 sec. Accel.>=0.1599 g
Mean Return Time of GM 2475 yrs
Mean (R,M,ε0) 89.4 km,5.85, 0.32
Modal (R,M,ε0) = 15.9 km, 4.80,-0.39 (from peak R,M bin)
Modal (R,M,ε*) = 35.4 km, 4.80, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR=25. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
SOURCE-to-SITE DISTANCE (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median | R,M
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 < -0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
2002 update USGS PSHA
GMT Feb 16 14:42
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs=760m/s top 30 m. USGS CGHT PSHA2002v3 UPDATE Bins with lt 0.05% contrib. omitted
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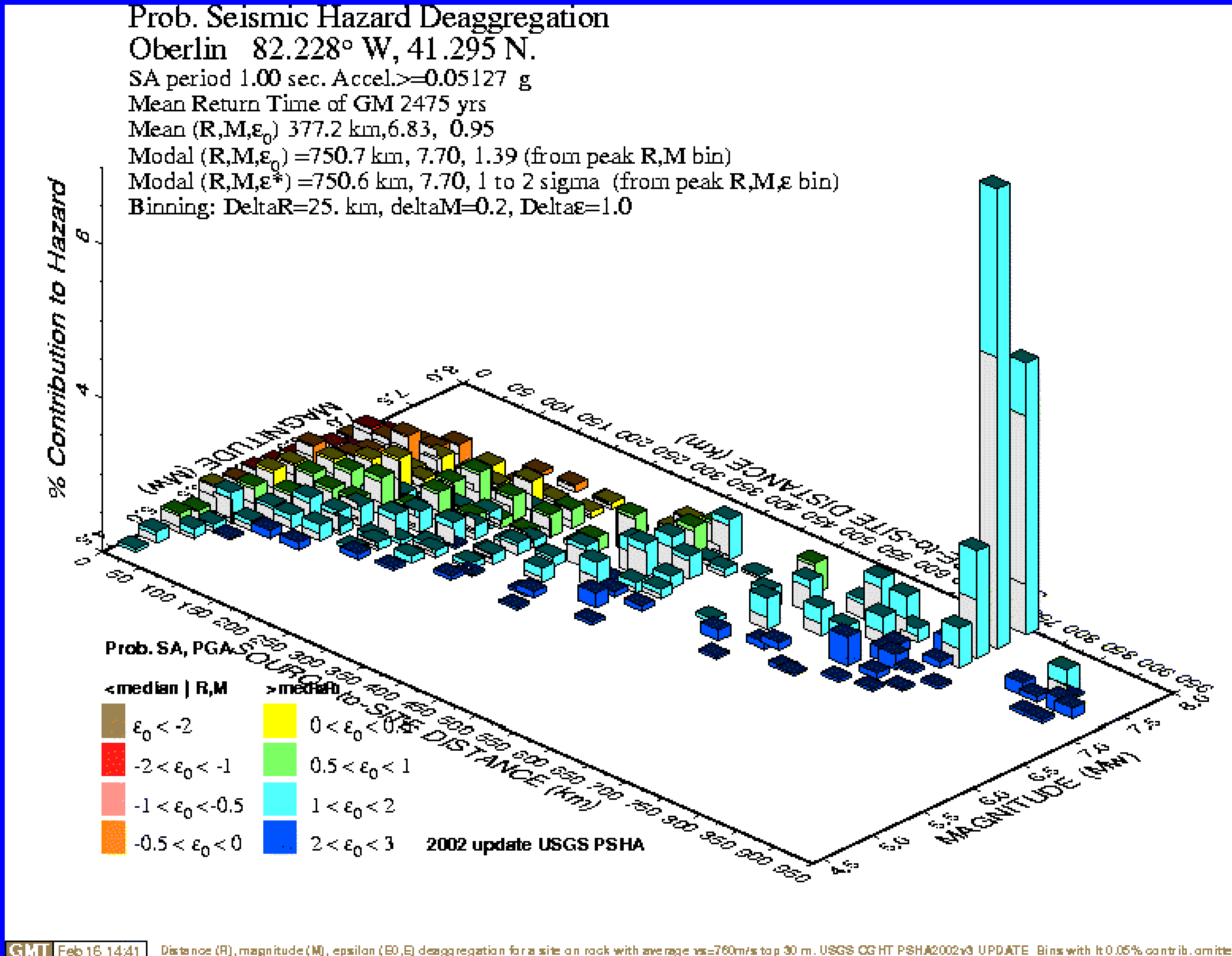

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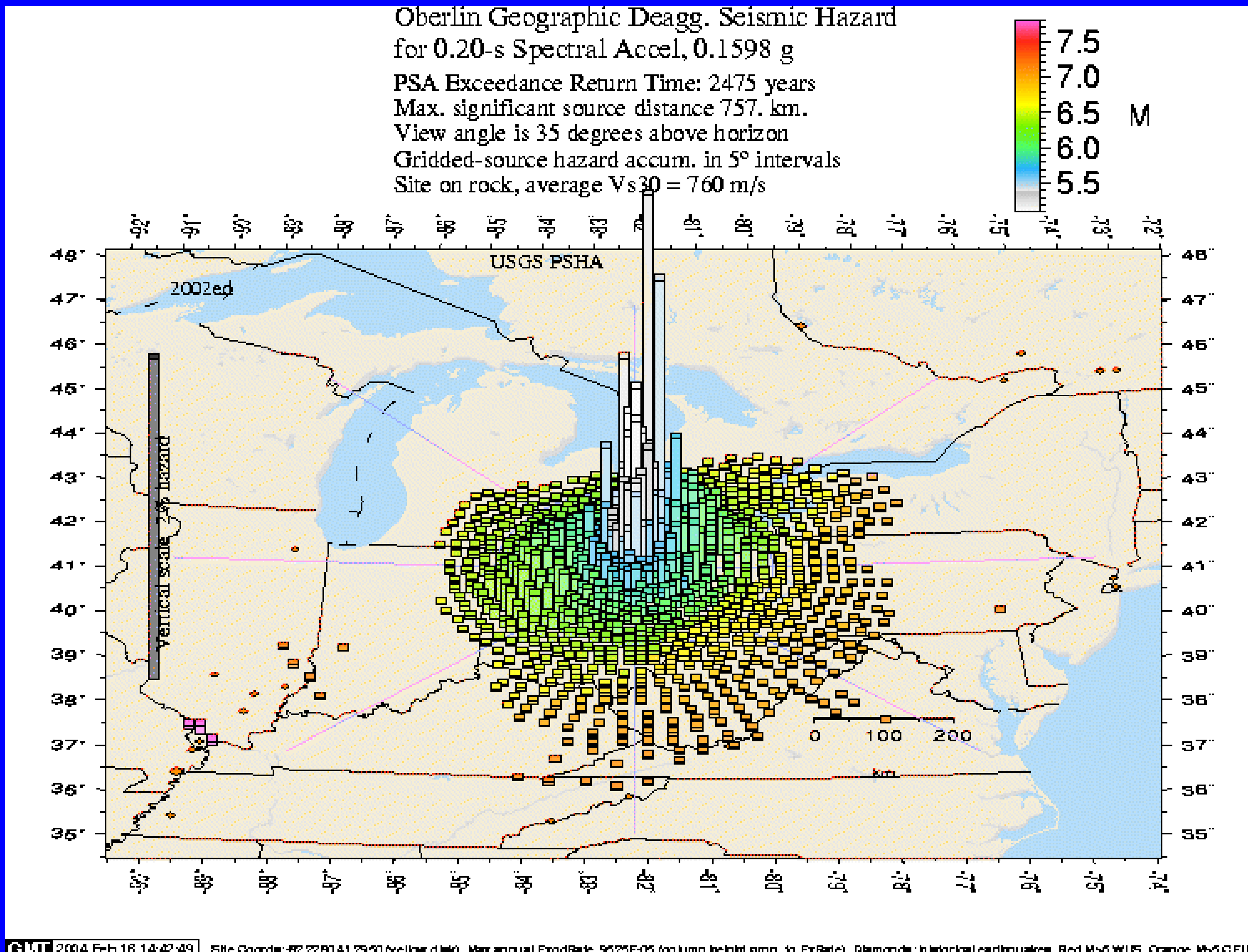
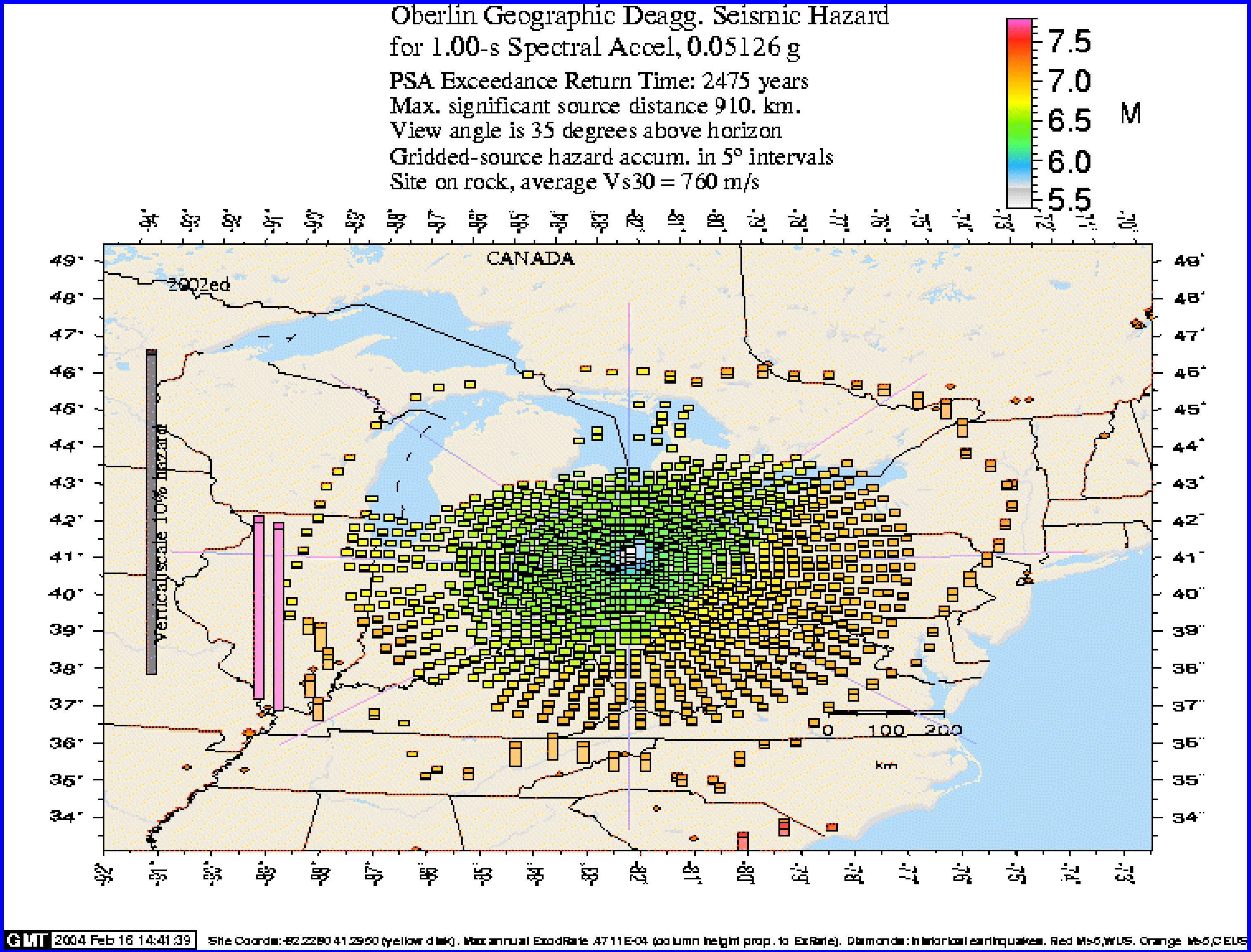


Oberlin Geographic Deagg. Seismic Hazard
for 0.20-s Spectral Accel, 0.1598 g
PSA Exceedance Return Time: 2475 years
Max. significant source distance 757. km.
View angle is 35 degrees above horizon
Gridded-source hazard accum. in 5° intervals
Site on rock, average Vs30 = 760 m/s
7.5
7.0
6.5
6.0
5.5
M
USGS PSHA
2002ed
Vertical scale 2% hazard
0 100 200
km
48°
47°
46°
45°
44°
43°
42°
41°
40°
39°
38°
37°
36°
35°
GMT 2004 Feb 16 14:42:49
Site Coords: -82.2280 41.2950 (yellow disk). Max annual ExcdRate .5625E-05 (column height prop. to ExRate). Diamonds: historical earthquakes. Red M>6,WUS. Orange M>5,CEUS



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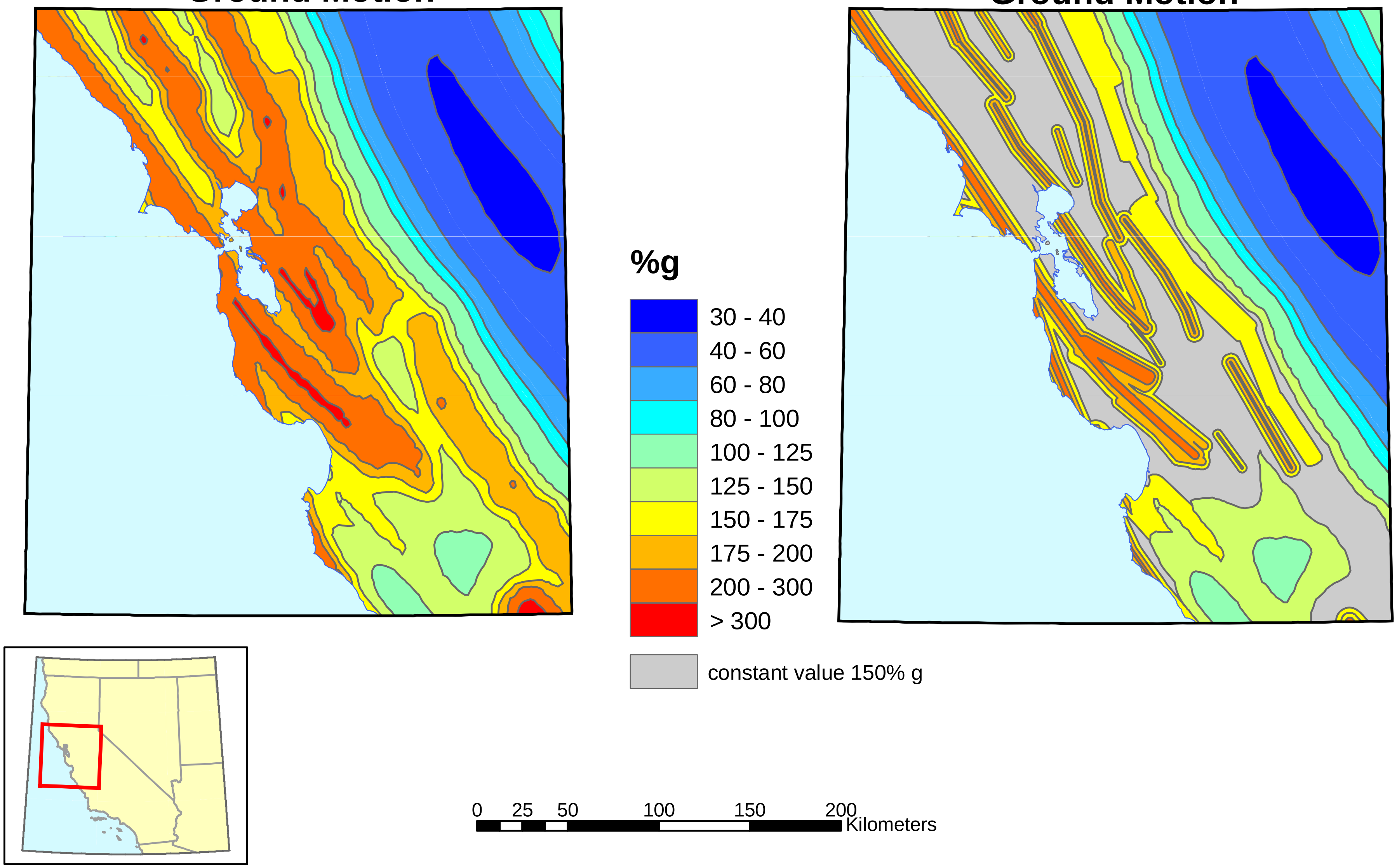
Spectral response acceleration for 0.2 sec spectral ordinate

2% probability of exceedance in 50 years Ground Motion

Maximum Considered Earthquake Ground Motion



Precarious Rocks

Jim Brune, U. Nevada Reno

Near Antelope Valley fault, Walker, California (Brune, 2000)

Brune, 2000

Near Antelope Valley fault, Walker, California (Brune, 2000)

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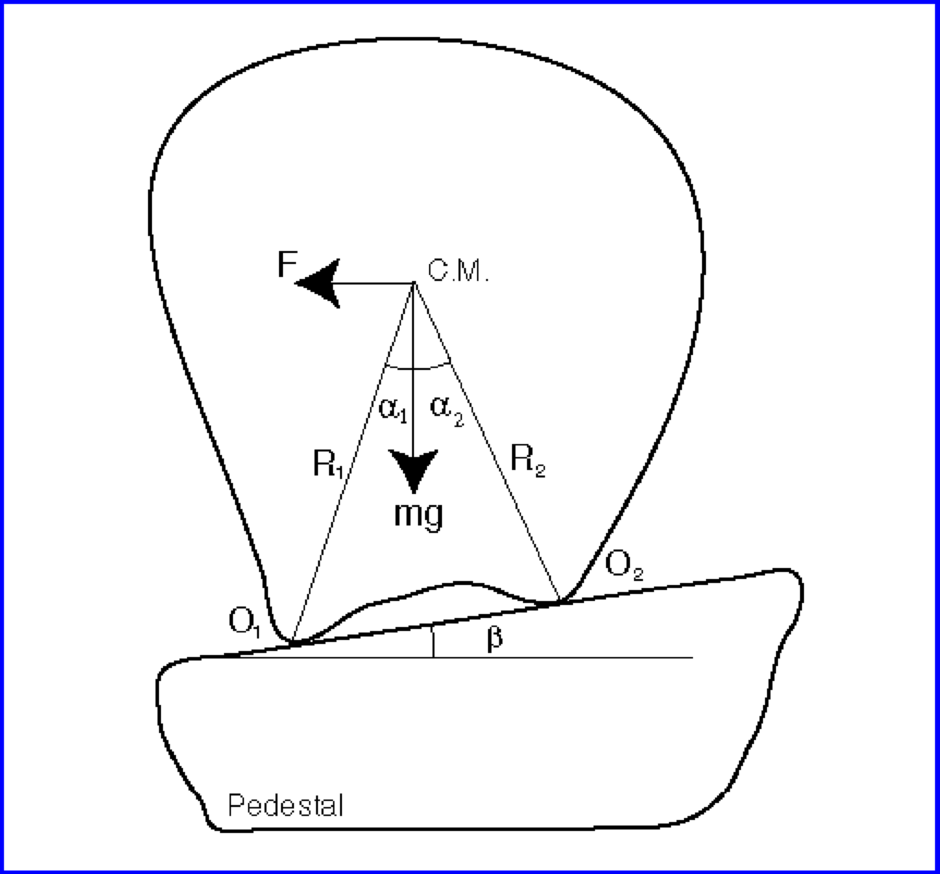
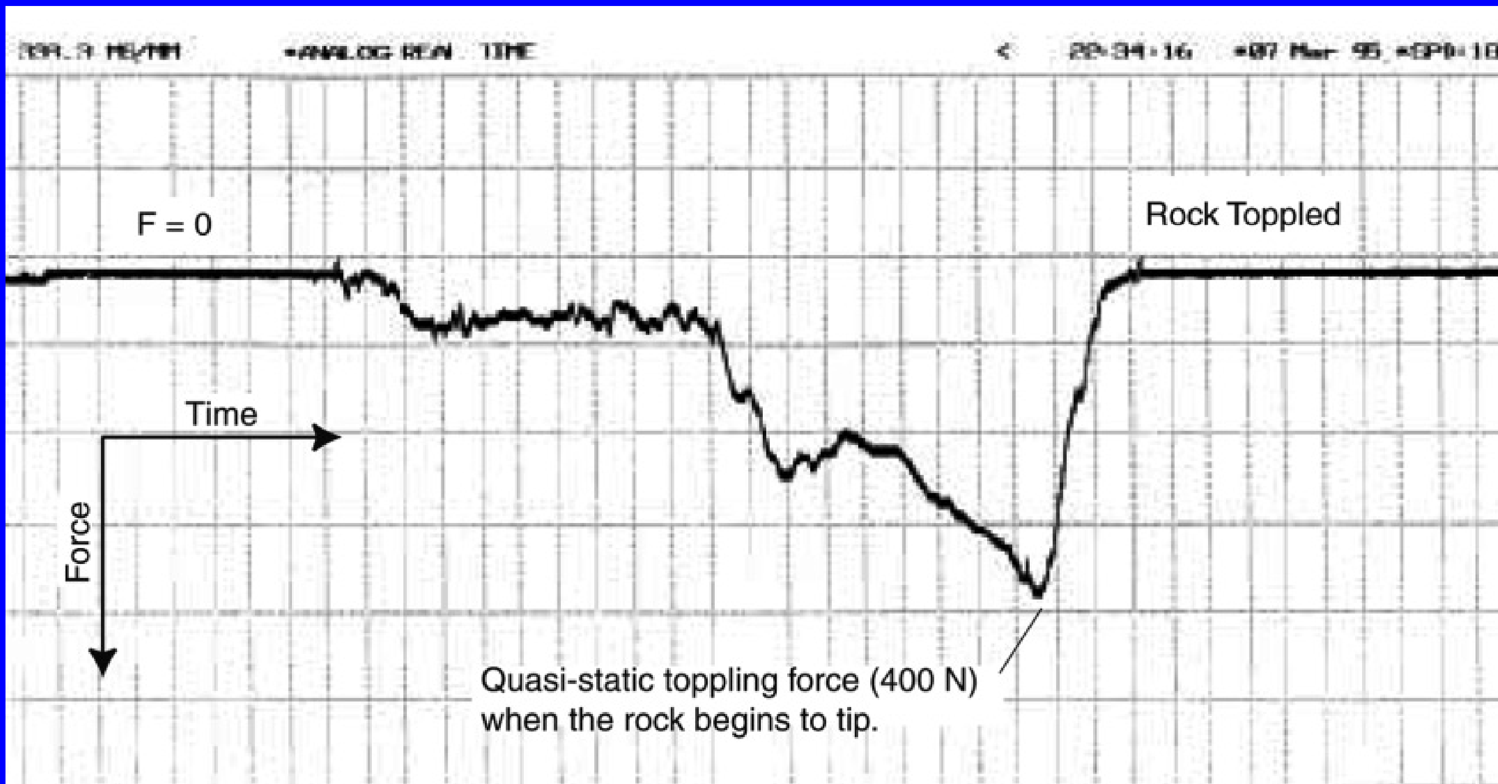


Quasi-static toppling force: $F = mg \tan \alpha$

Anooshehpoor et al., 2004

Anooshehpoor et al., 2004

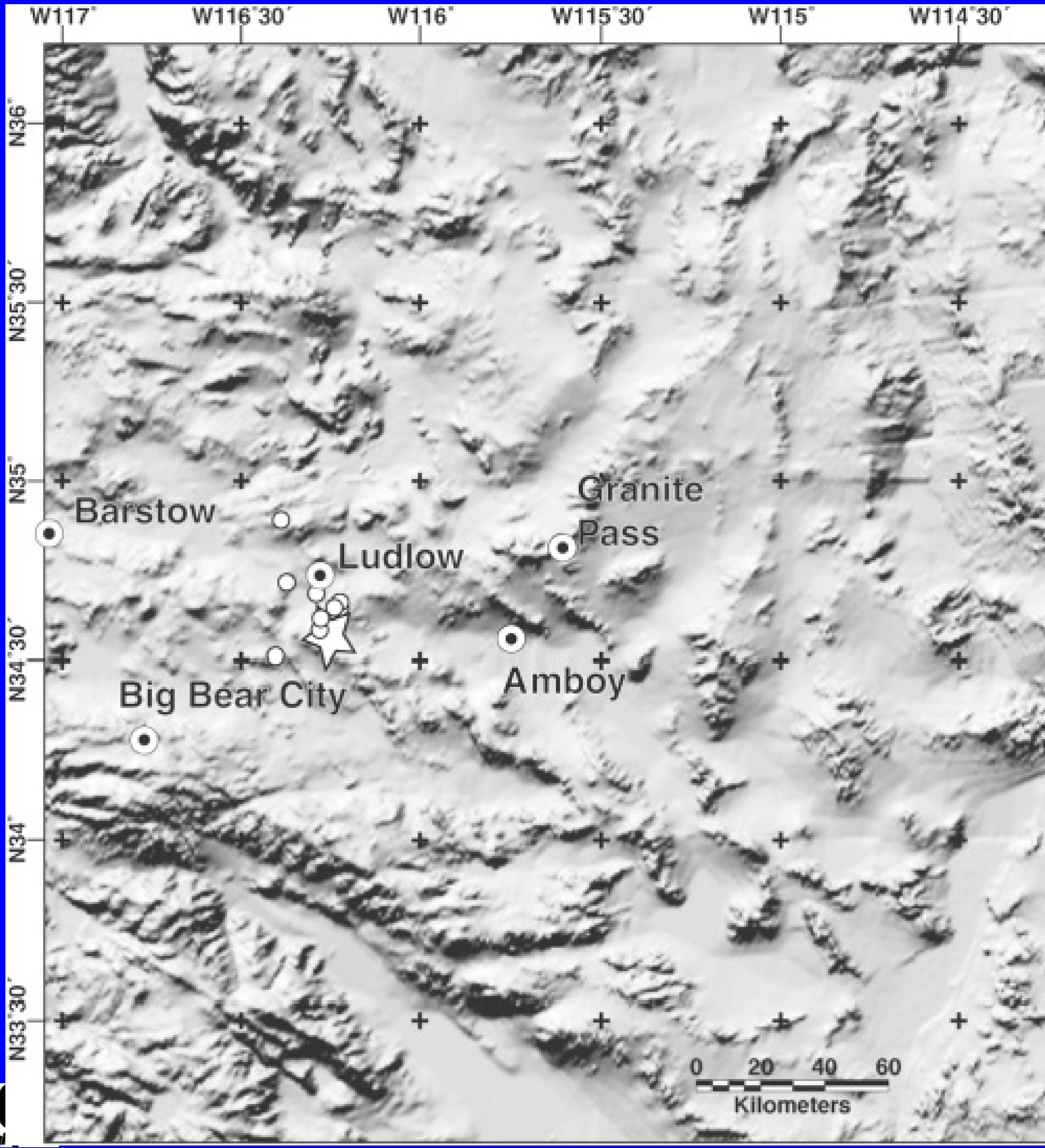
Anooshehpoor et al., 2004



Anooshehpoor et al., 2004

Anooshehpoor et al., 2004

Anooshehpoor et al., 2004



Anooshehpoor et al., 2004

Anooshehpoor et al., 2004

Anooshehpoor et al., 2004

Preliminary Conclusions from Study of Precarious Rocks

- Strong asymmetry in ground shaking from reverse faults (low on footwall side, high on hanging wall side)
- Ground motions for normal faults smaller than predicted by standard equations
- Ground motions near San Andreas fault in S. California smaller than shown by hazard maps (!)

SUMMARY

- Defined hazard
- Described response spectra
- Basis for hazard maps: seismicity
- Basis for hazard maps: ground motion
- Mapping hazard
- Results
- Paleoseismometry: precarious rocks

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Stacy and Dave studying geology in the Dolomites, Italy, in January during Winter term

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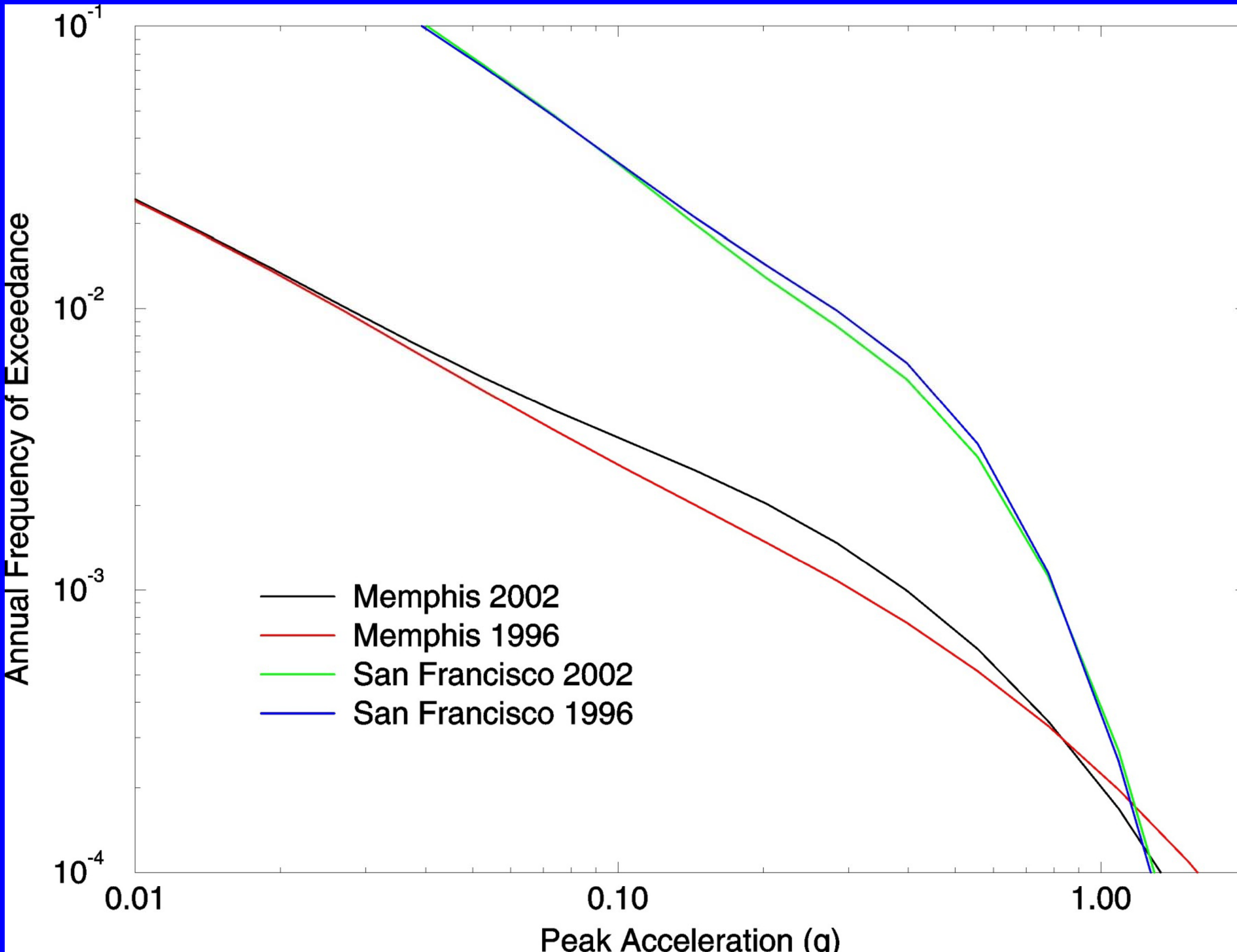
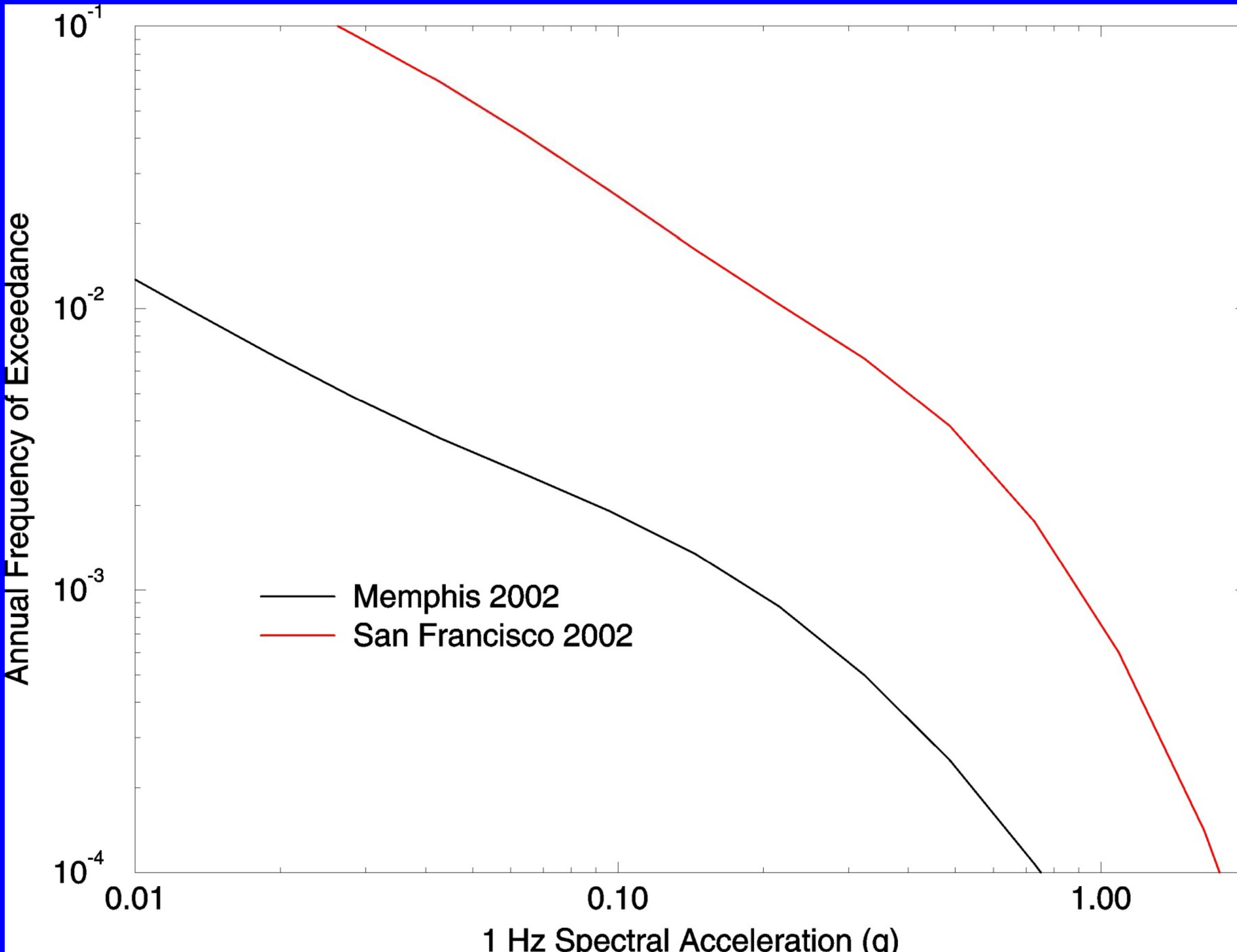
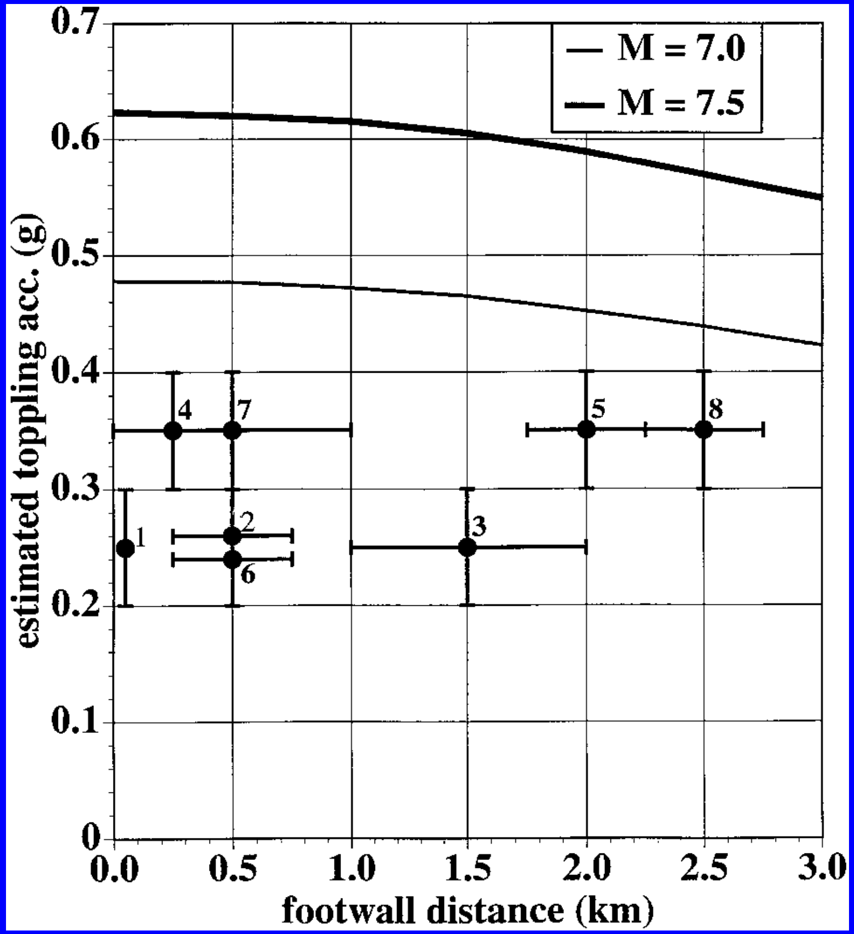
?



10^-1
10^-2
10^-3
10^-4
Annual Frequency of Exceedance
0.01
0.10
1.00
Peak Acceleration (g)
Memphis 2002
Memphis 1996
San Francisco 2002
San Francisco 1996



10^{-1}
10^{-2}
10^{-3}
10^{-4}
Annual Frequency of Exceedance
Memphis 2002
San Francisco 2002
0.01
0.10
1.00
1 Hz Spectral Acceleration (g)



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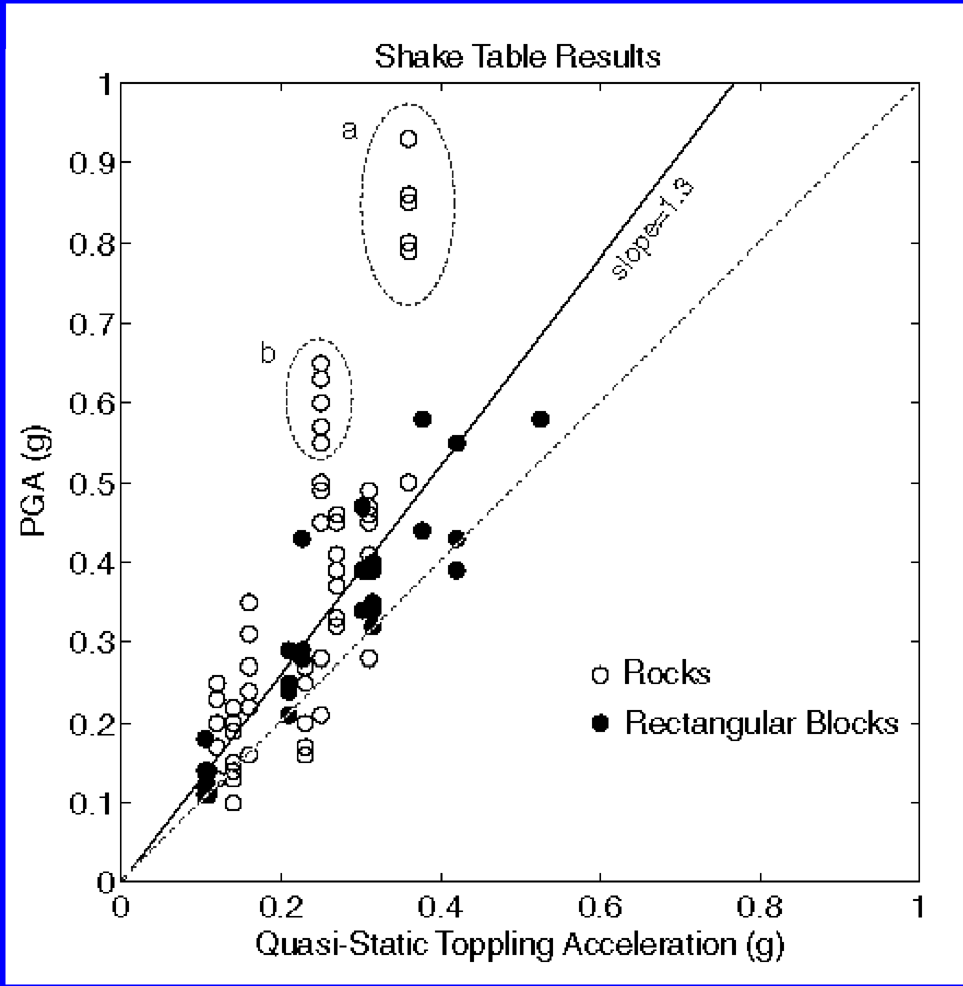
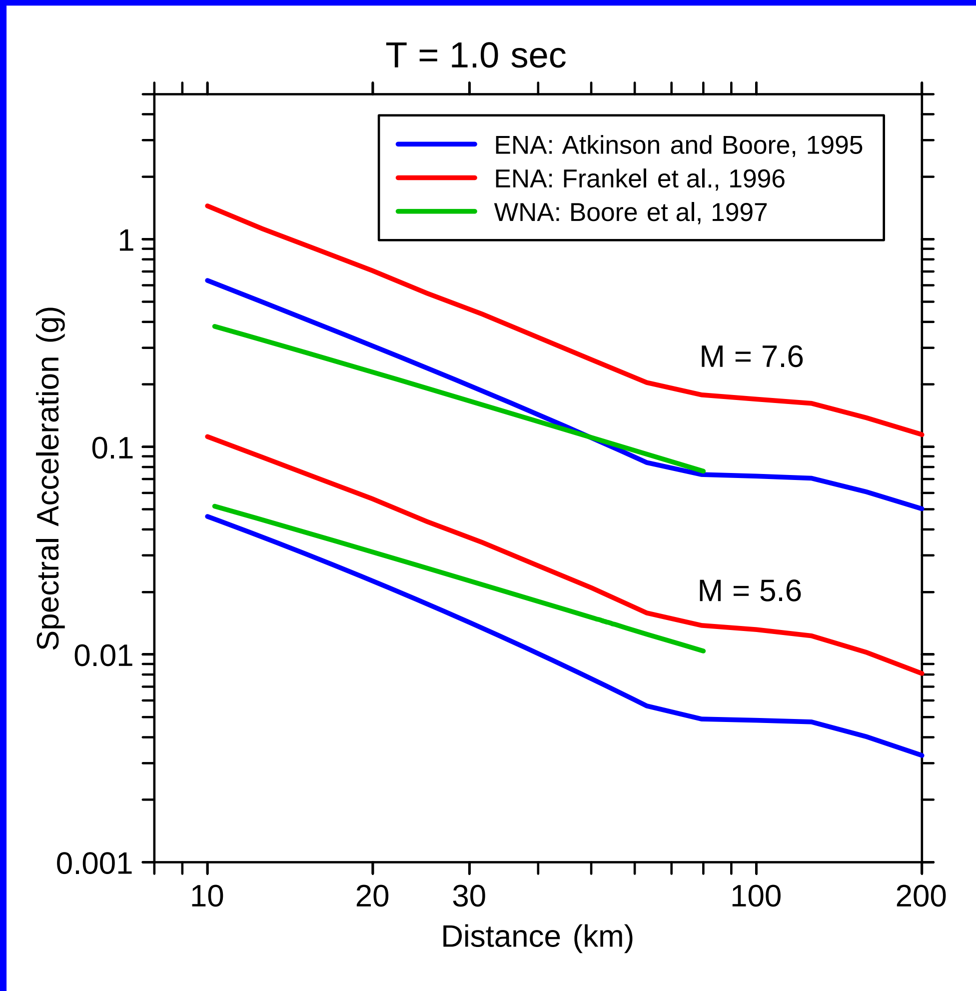
Brune, 2000



Anooshehpoor et al., 2004


T = 1.0 sec
ENA: Atkinson and Boore, 1995
ENA: Frankel et al., 1996
WNA: Boore et al, 1997
M = 7.6
M = 5.6
Spectral Acceleration (g)
1
0.1
0.01
0.001
10
20
30
100
200
Distance (km)

Conclusions

- USGS hazard maps are based on consensus of experts; represent average hazard estimates from alternative models; best maps for policy and design decisions
- USGS hazard maps are derived from observations of past earthquakes in NM (1811-12, about 1500 and 900 A.D.), historical seismicity, geology, and models of ground motions for the region that have been validated with observed ground motions and intensities
- Design maps need to have consistent rules for entire U.S.

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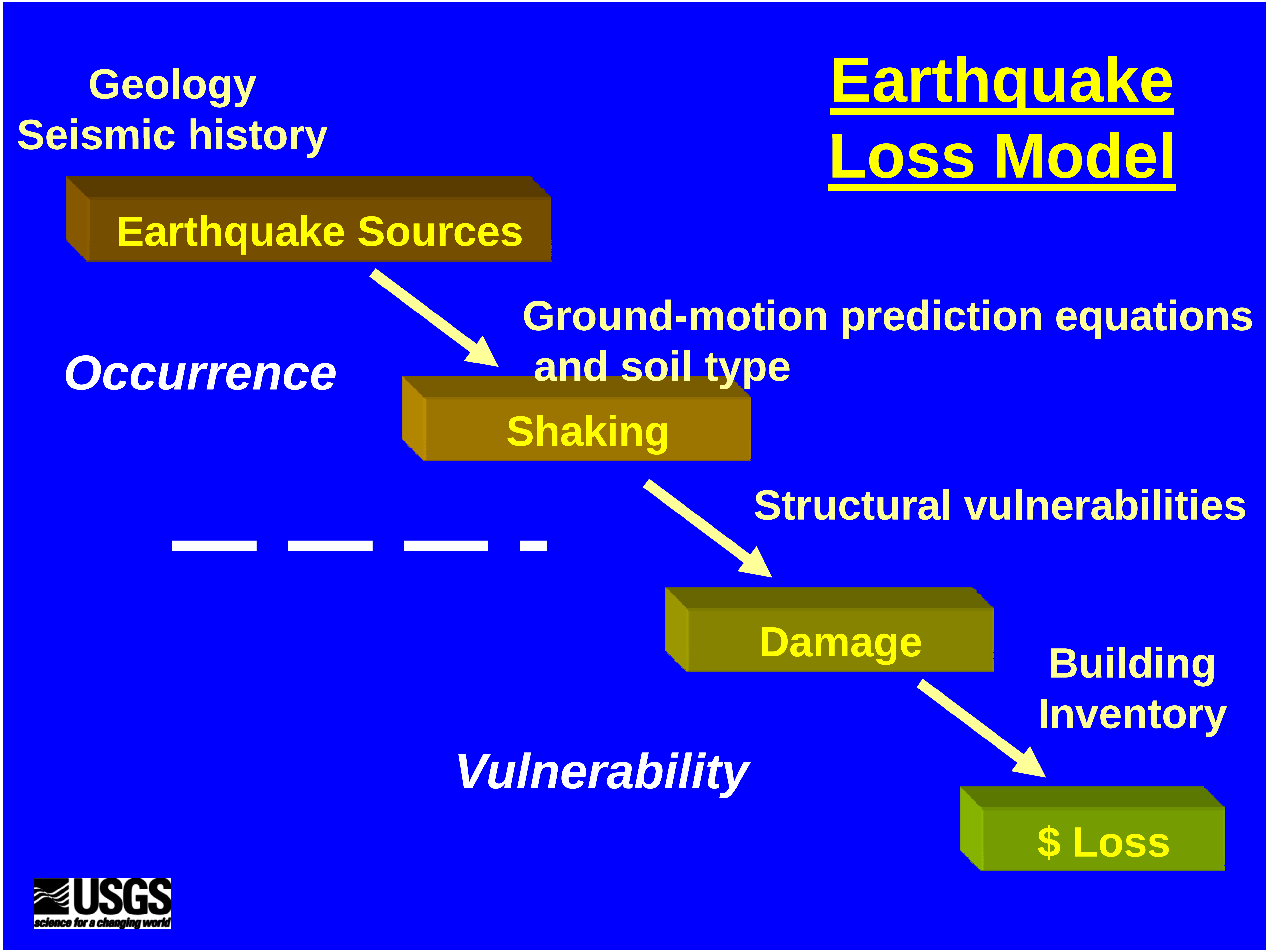
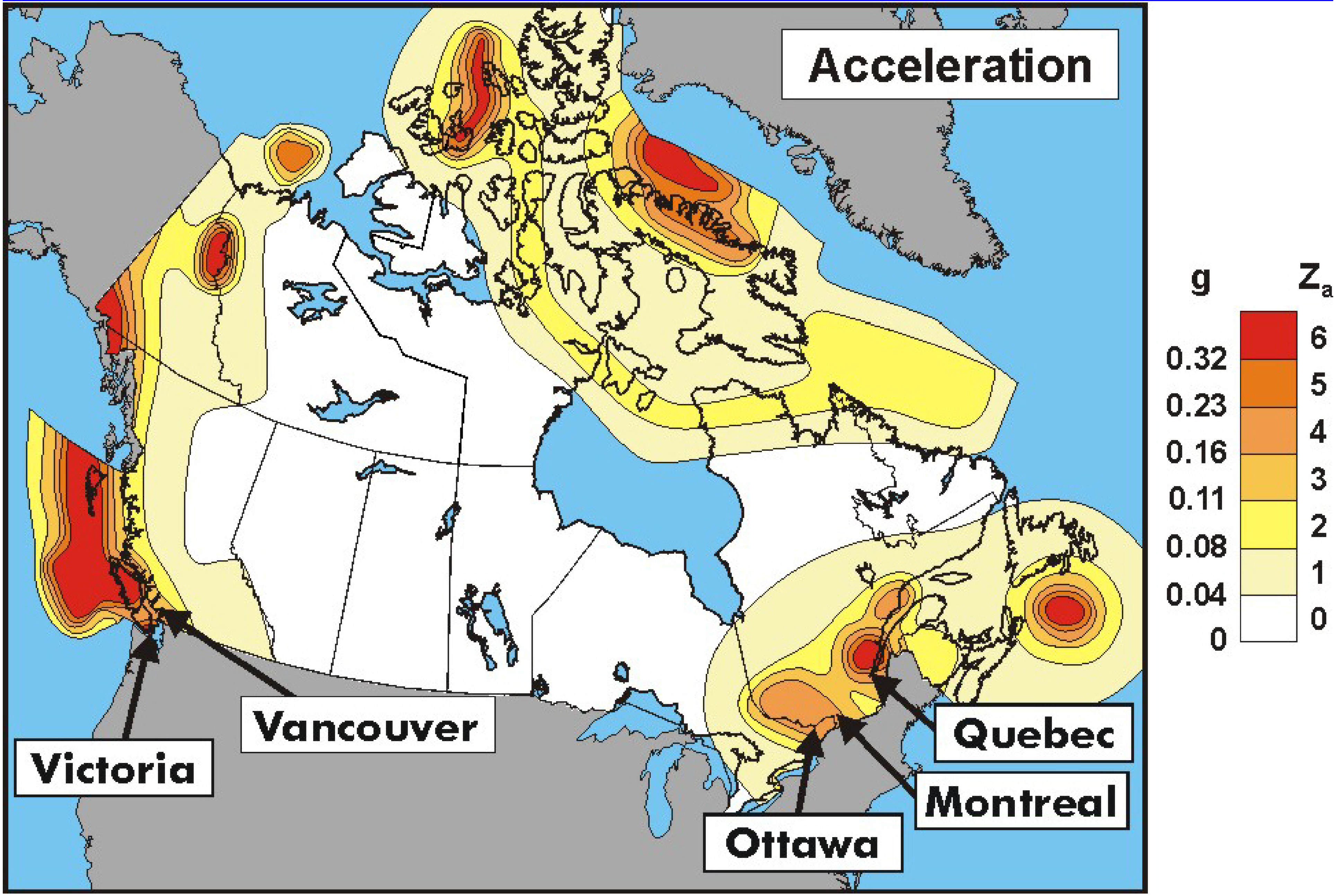
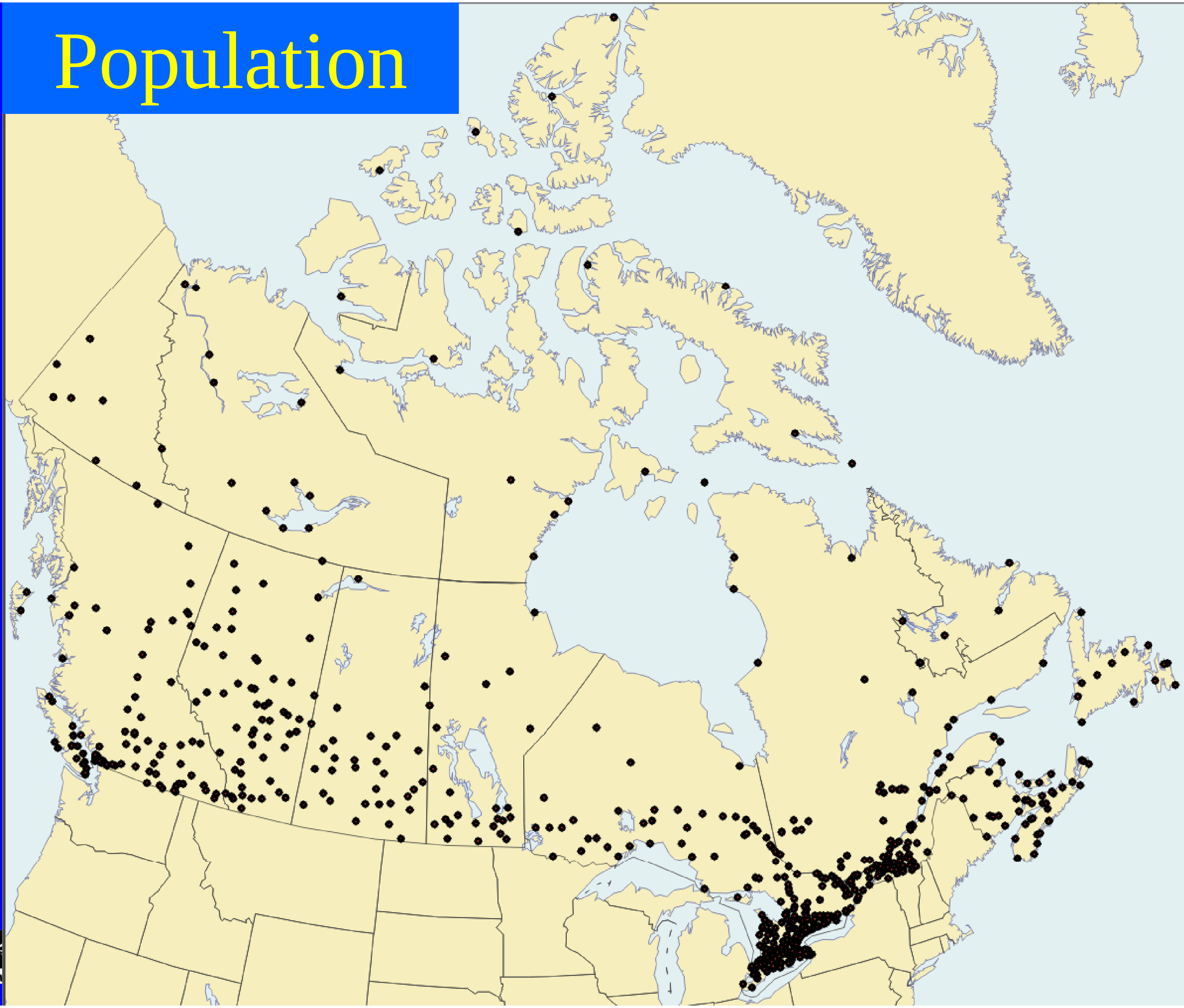

Earthquake
Loss Model
Geology
Seismic history
Earthquake Sources
Occurrence
Ground-motion prediction equations
and soil type
Shaking
Structural vulnerabilities
Damage
Building
Inventory
Vulnerability
$ Loss
USGS
science for a changing world

Hazard

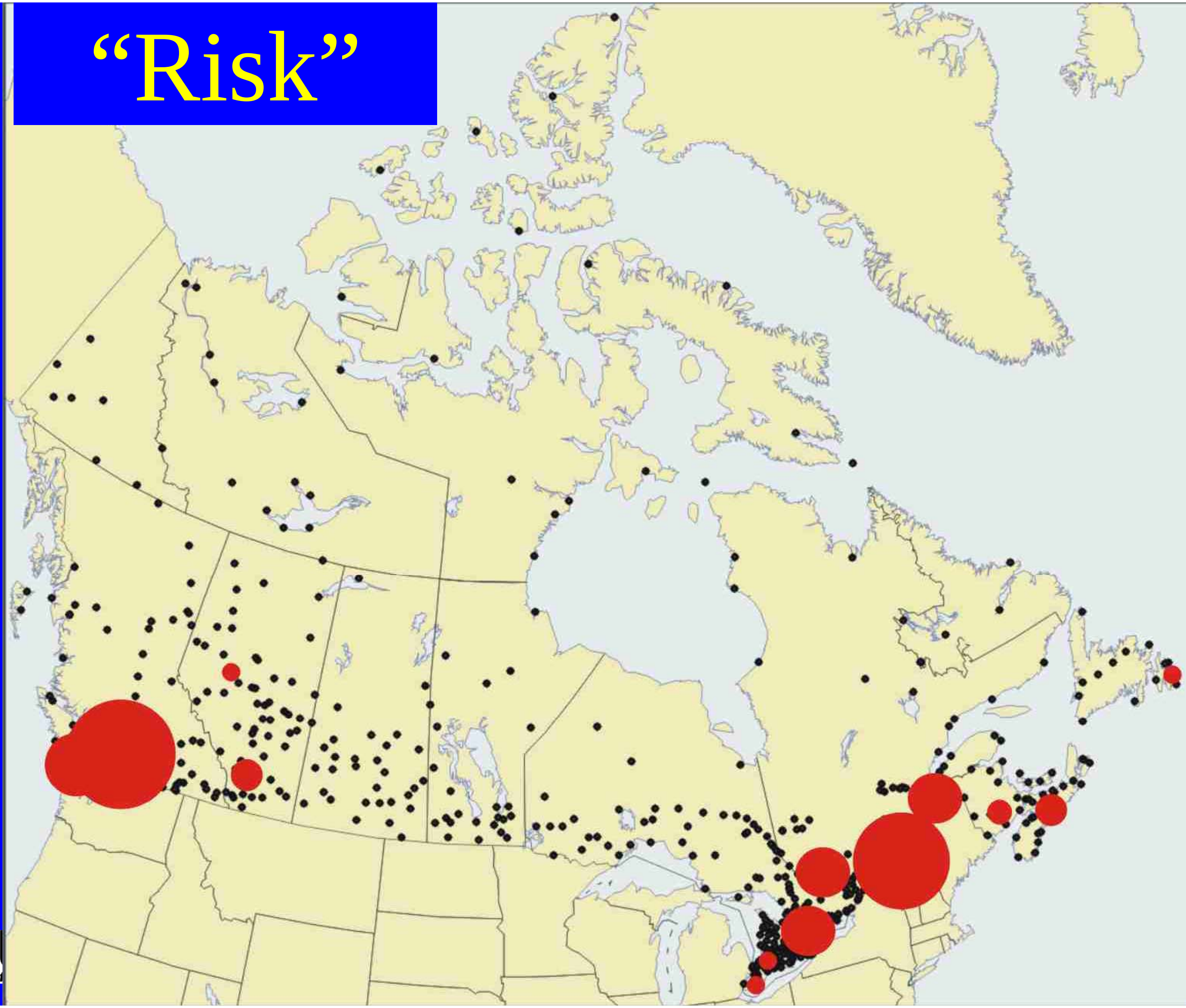


Acceleration
g
Z_a
0.32
0.23
0.16
0.11
0.08
0.04
0
6
5
4
3
2
1
0
Victoria
Vancouver
Quebec
Montreal
Ottawa

Population



“Risk”



Seismic Hazard

shaking irrespective of consequence

Seismic Risk

Hazard * Exposure * Vulnerability

	hazard	* exposure	* vulnerability	= risk
Baffin Island	high	low		low
Vancouver	high	high		high
Toronto	low	high		moderate

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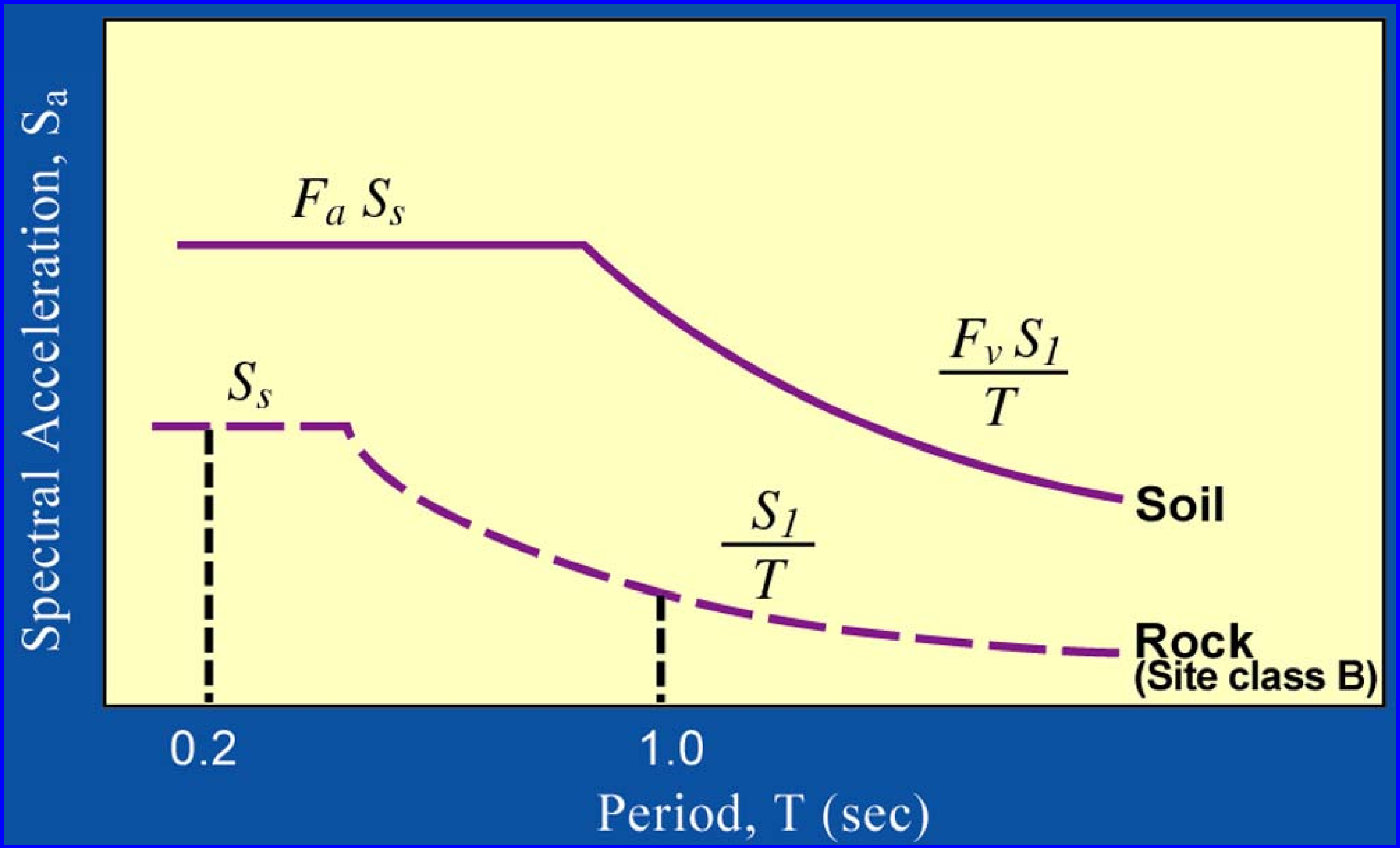
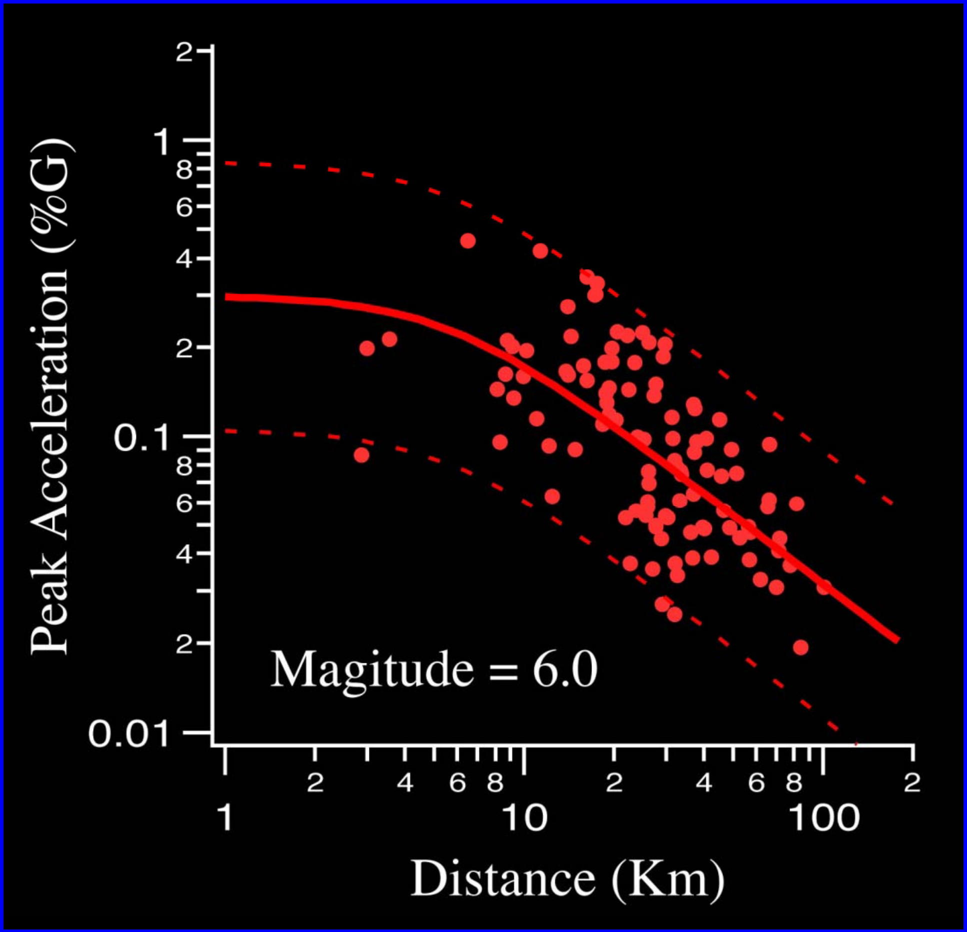
TWO-FACTOR APPROACH TO CONSTRUCTING GROUND MOTION RESPONSE SPECTRA

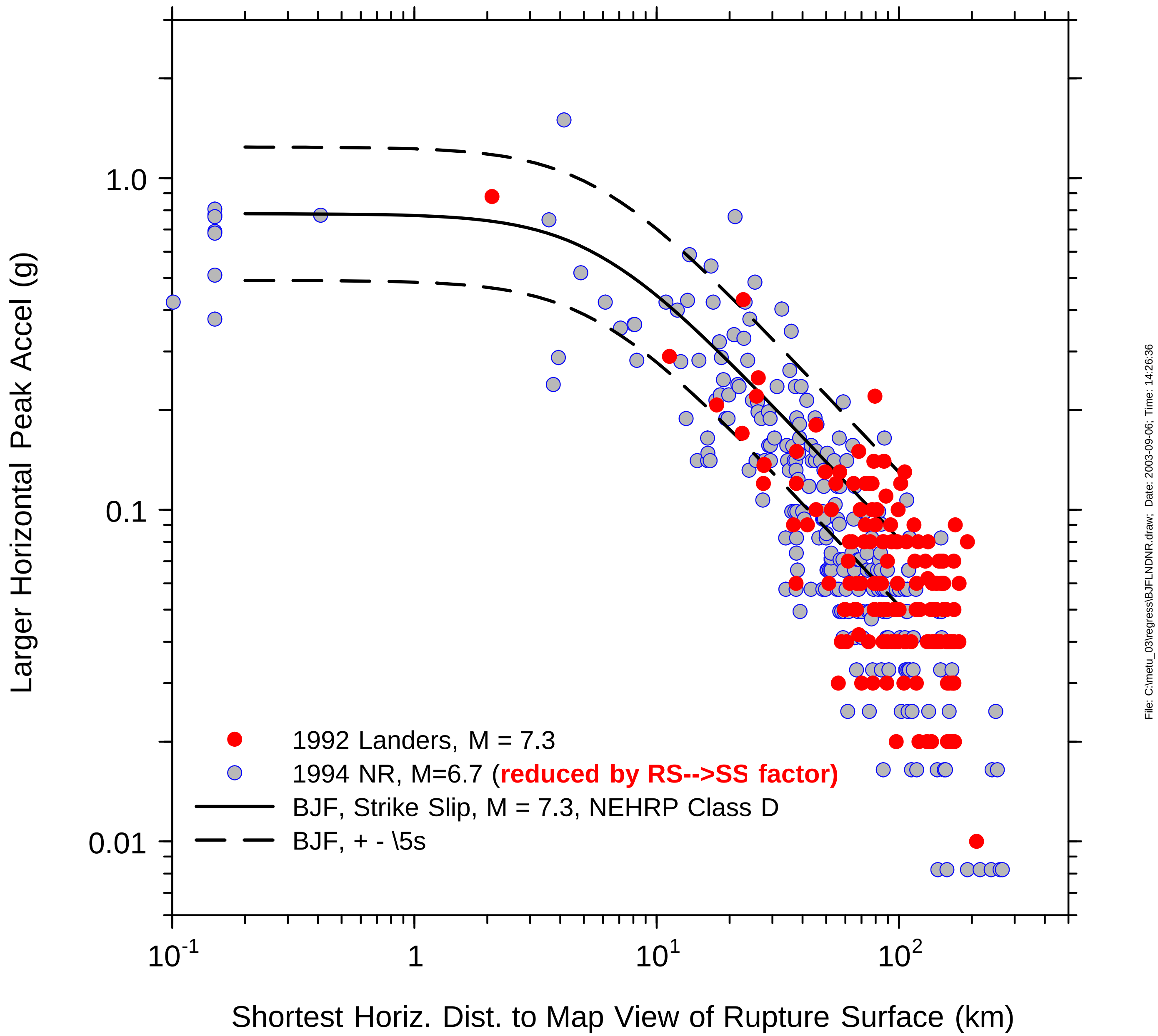


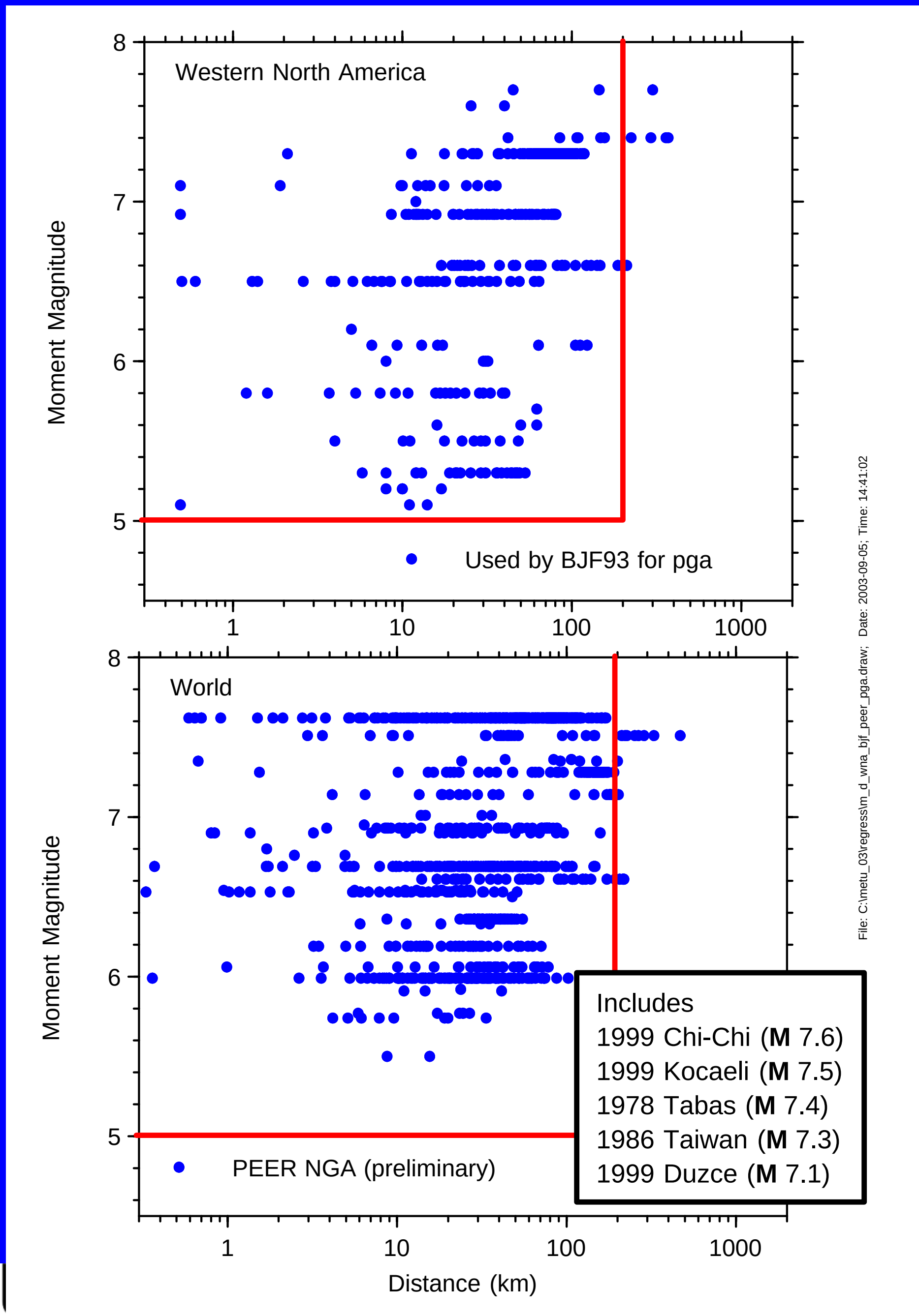
Ground-Motion Prediction Equations

Gives mean and standard deviation of response-spectrum ordinate (at a particular frequency) as a function of magnitude distance, site conditions, and perhaps other variables.



(E. Field)


Larger Horizontal Peak Accel (g)
1.0
0.1
0.01
10^-1
1
10^1
10^2
Shortest Horiz. Dist. to Map View of Rupture Surface (km)
1992 Landers, M = 7.3
1994 NR, M=6.7 (reduced by RS-->SS factor)
BJF, Strike Slip, M = 7.3, NEHRP Class D
BJF, + - \5s
File: C:\metu_03\regress\BJFLNDNR.draw; Date: 2003-09-06; Time: 14:26:36



Observed data adequate for regression except close to large ‘quakes

New recordings help fill in lack of data close to large ‘quakes (but can data be used?)

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