The Abdus Salam
International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA
International Atomic Energy Agency

2142-13

Advanced Conference on Seismic Risk Mitigation and Sustainable Development

10 - 14 May 2010

Seismic Hazard and Risk Assessment and Mitigation Policy in USA

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ICTP Advanced Conference on Seismic Risk Mitigation and Sustainable Development

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Outline

- Introduction
  - The NEHRP Provisions
  - NRC Regulatory Guide 1.208
- Probabilistic Seismic Hazard Analysis (PSHA)
- Alternative Seismic Hazard Assessments
  - Seismic Hazard Analysis (SHA)
  - Deterministic Seismic Hazard Analysis (DSHA)
  - Neo-DSHA or Scenario-Based Hazard Analysis
- Lesson from Wenchuan, China, earthquake
- Summary

Development of *Design Ground Motion (Policy)*

Science

Seismic Hazard Map
(USGS)

↓

BSSC – engineers,
seismologists, and others

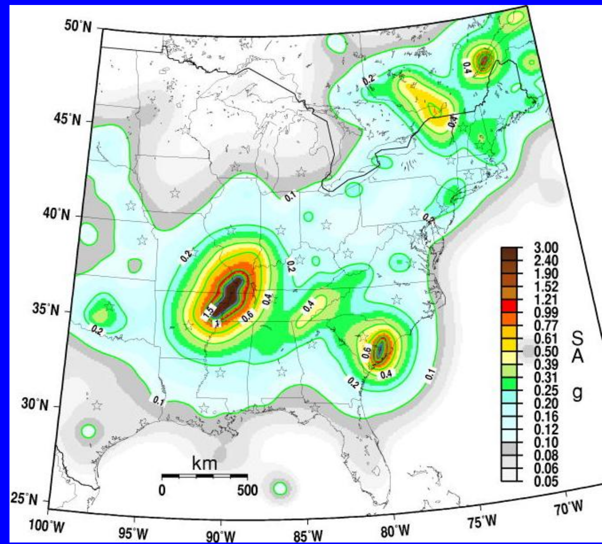
↓

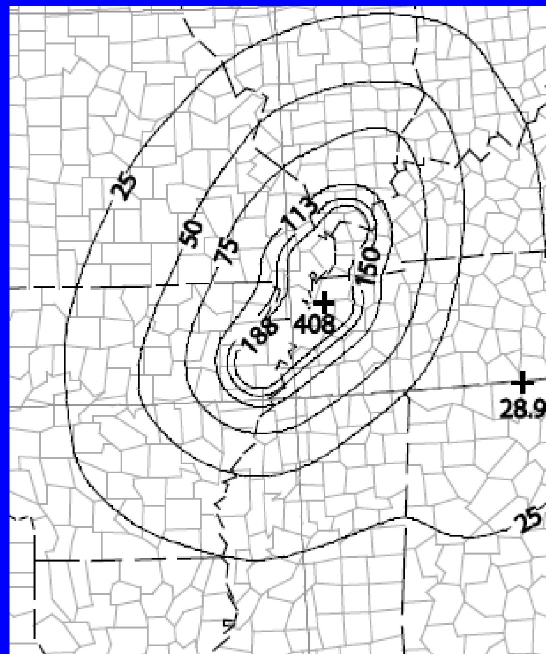
Policy

Seismic *Design Ground Motions*
(FEMA)

↓

- Federal agencies
- State Agencies
- Other organizations





2009 NEHRP Provisions (Policy)

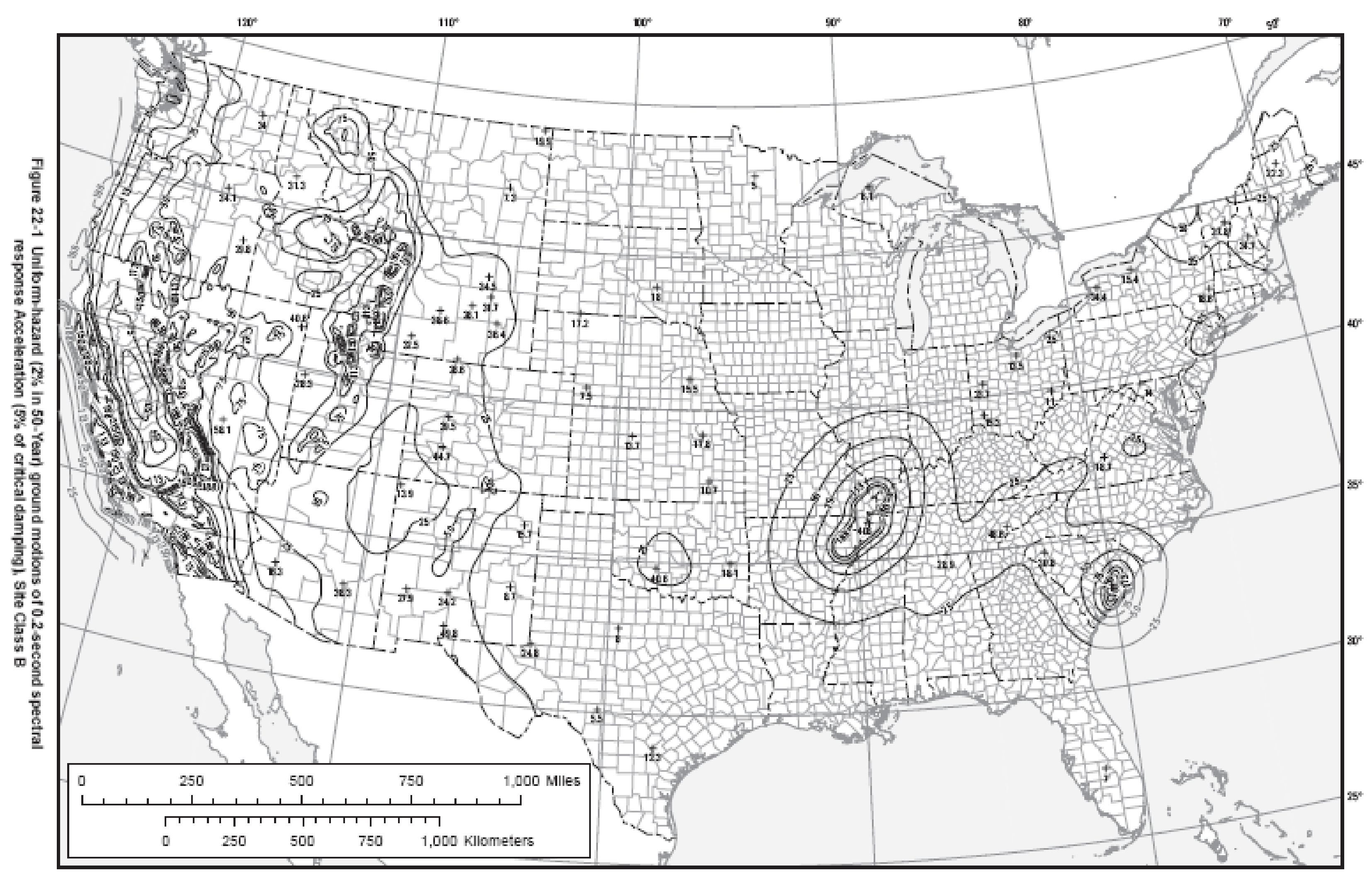
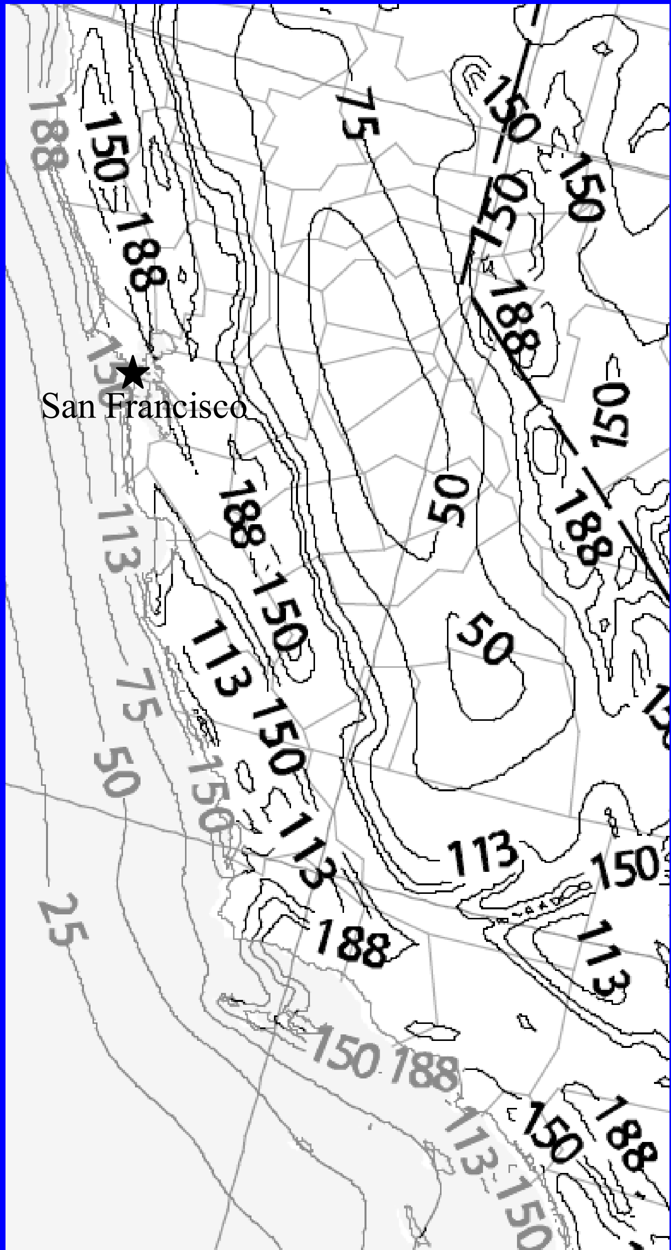
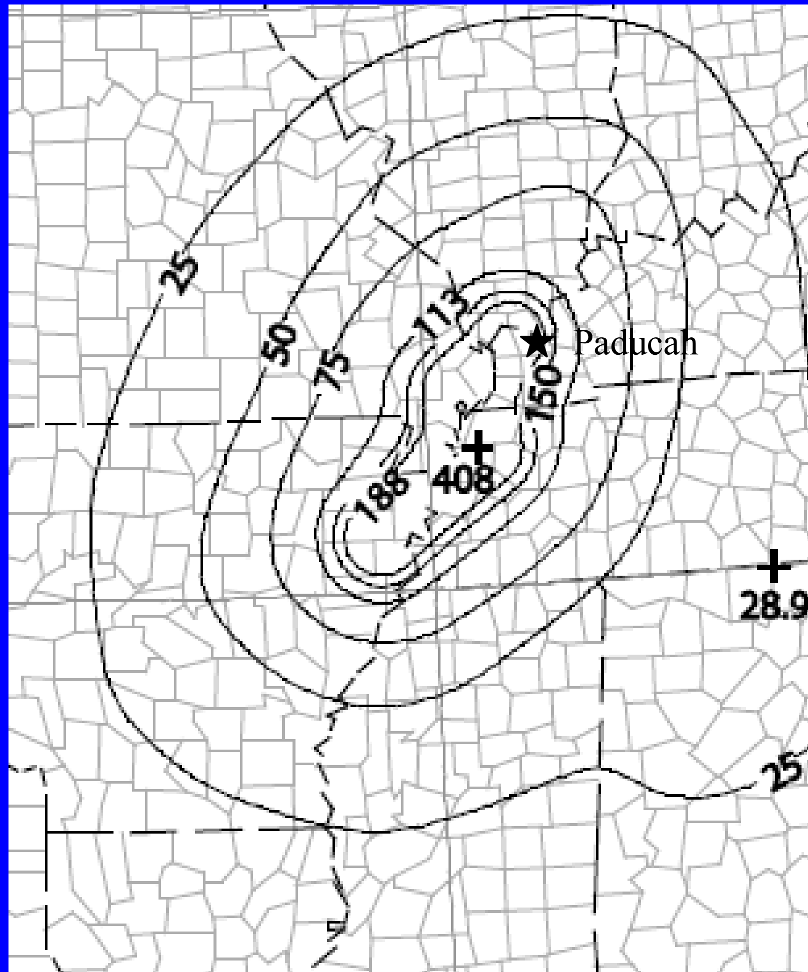


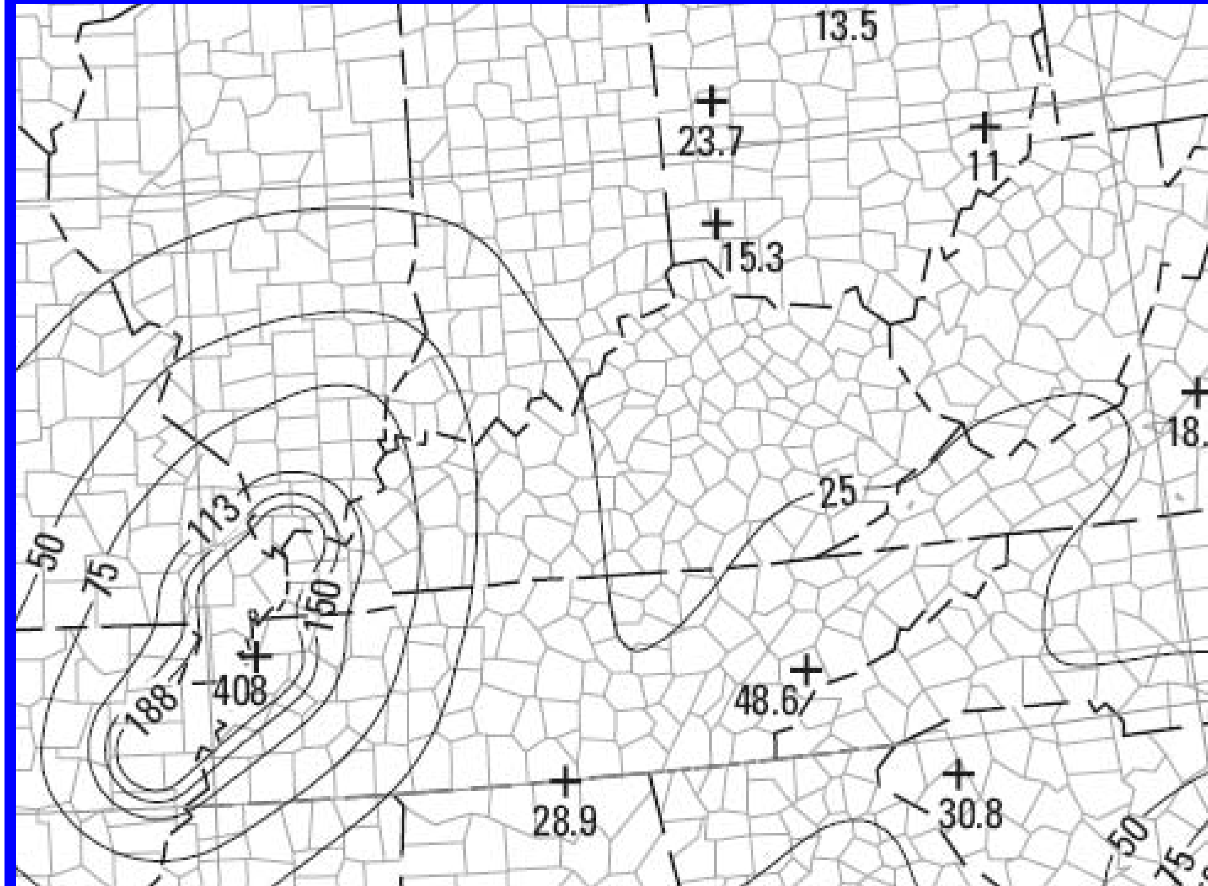
Figure 22-1 Uniform-hazard (2% in 50-Year) ground motions of 0.2-second spectral response Acceleration (5% of critical damping), Site Class B

California



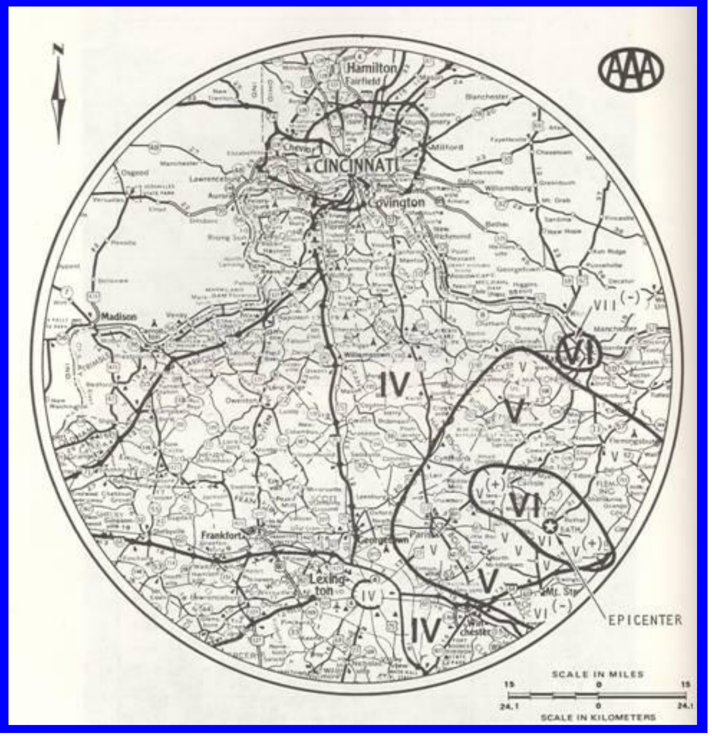
The central US



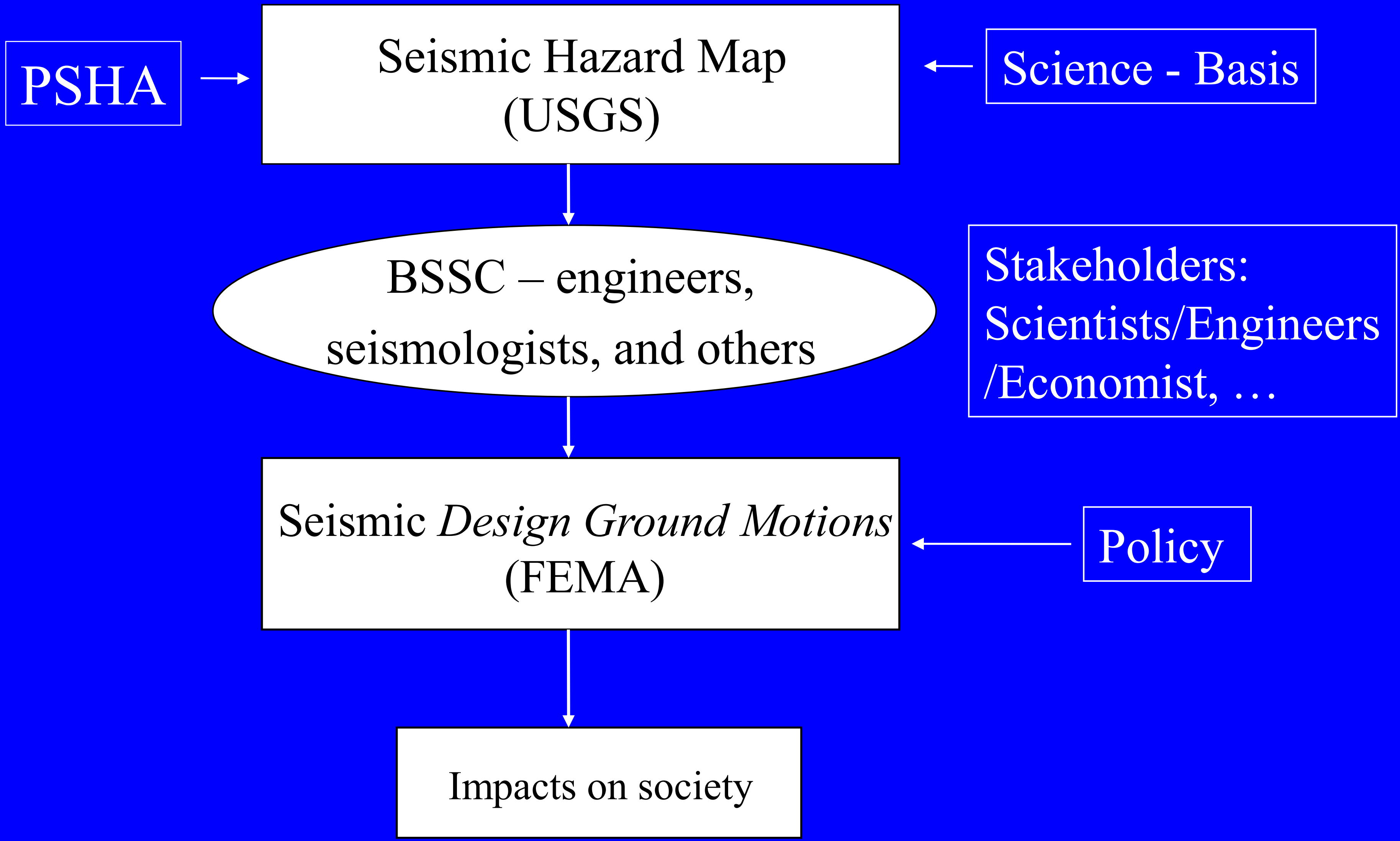


0.2-second spectral response Acceleration (5% of critical damping), Site Class B

1980 Sharpsburg Earthquake (M5.2)



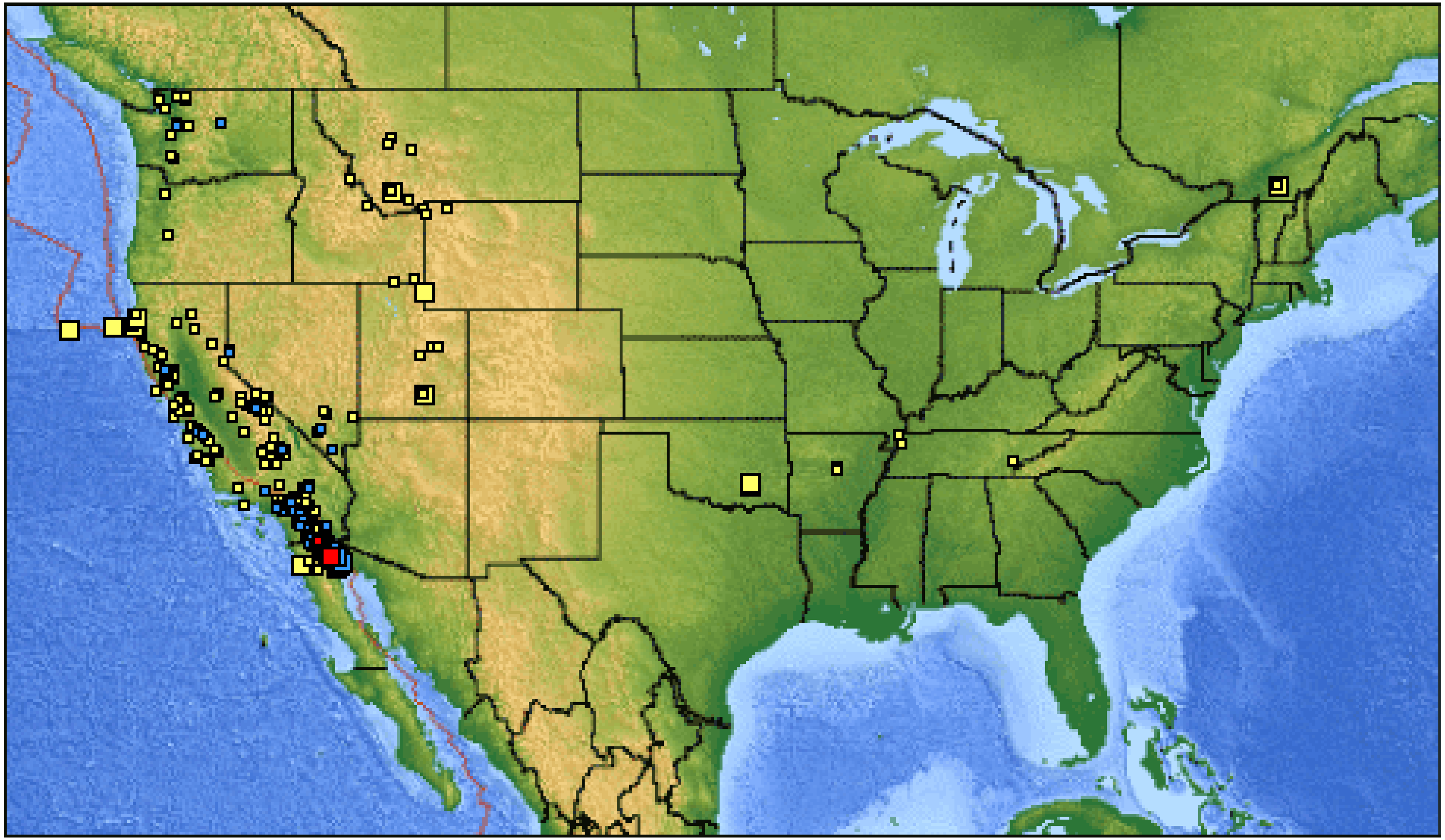
Development of *Seismic Ground Motion (policy)*



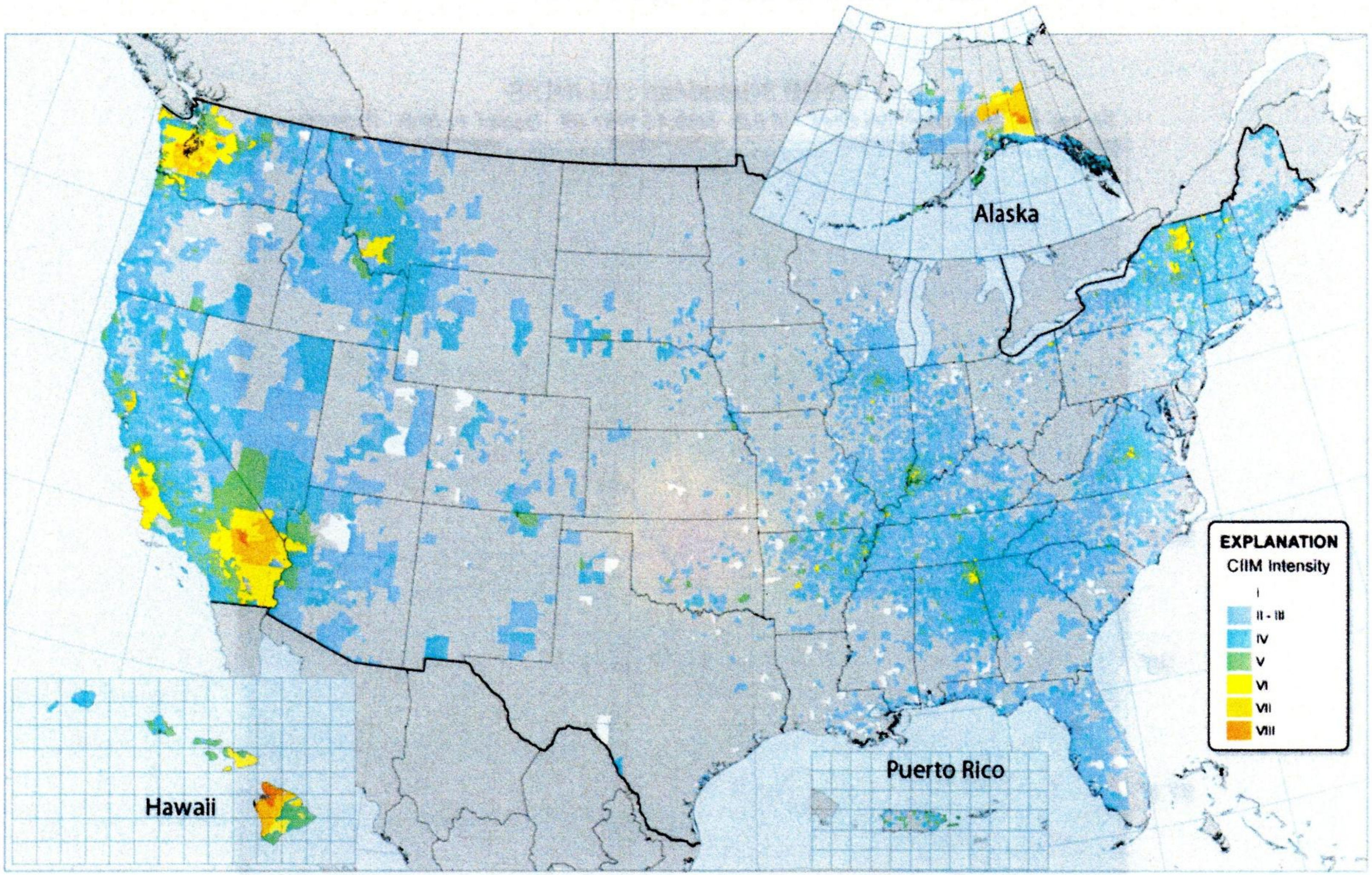
Seven-Day Earthquakes

Mon Apr 19 15:46:28 UTC 2010

1803 earthquakes on these maps



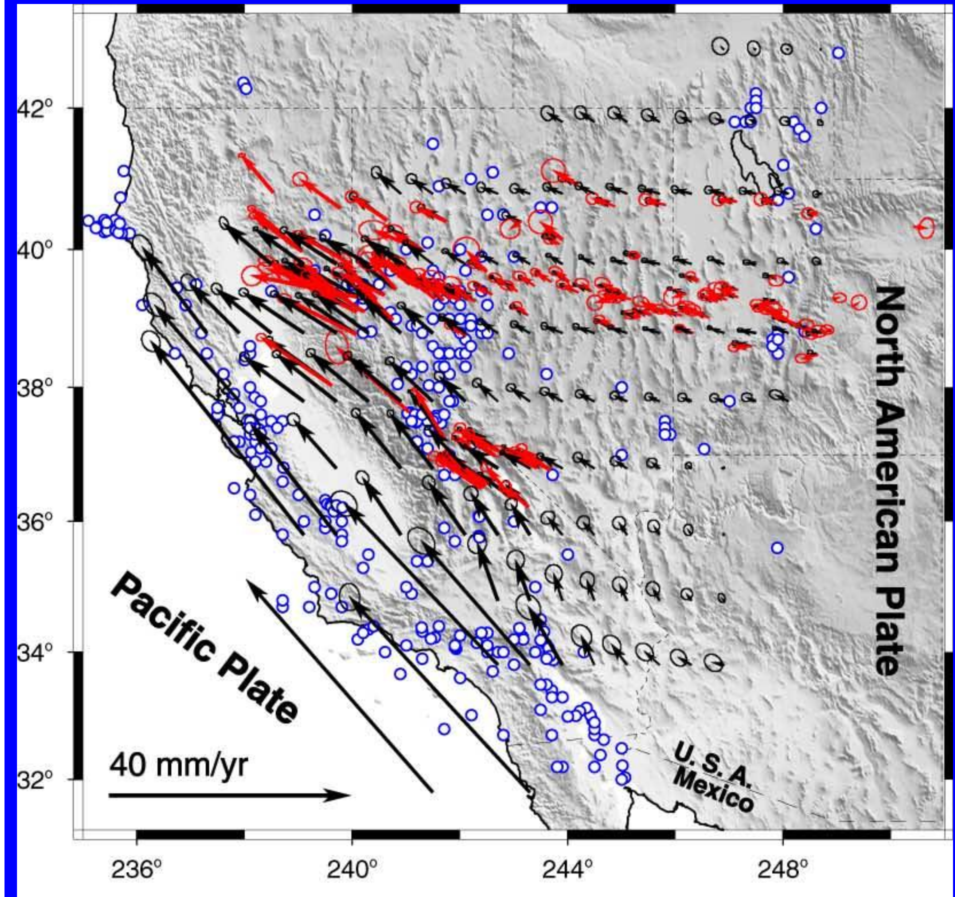
CONTERMINOUS 48 STATES



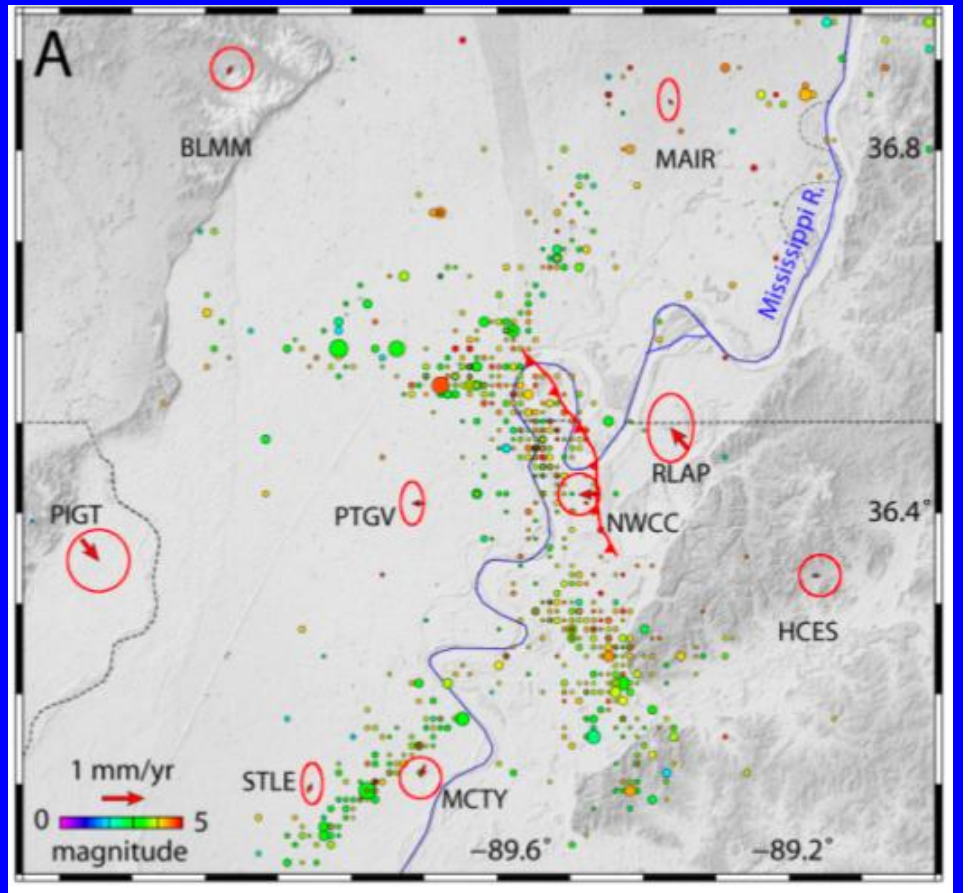
(Leith and others, 2009)

Figure 9. Composite DYFI? map of the U.S. (1988–2007) showing the maximum credible intensity reported by the public for each zip code for which there is reported felt information. To date, there are more than one million DYFI? entries for the U.S.

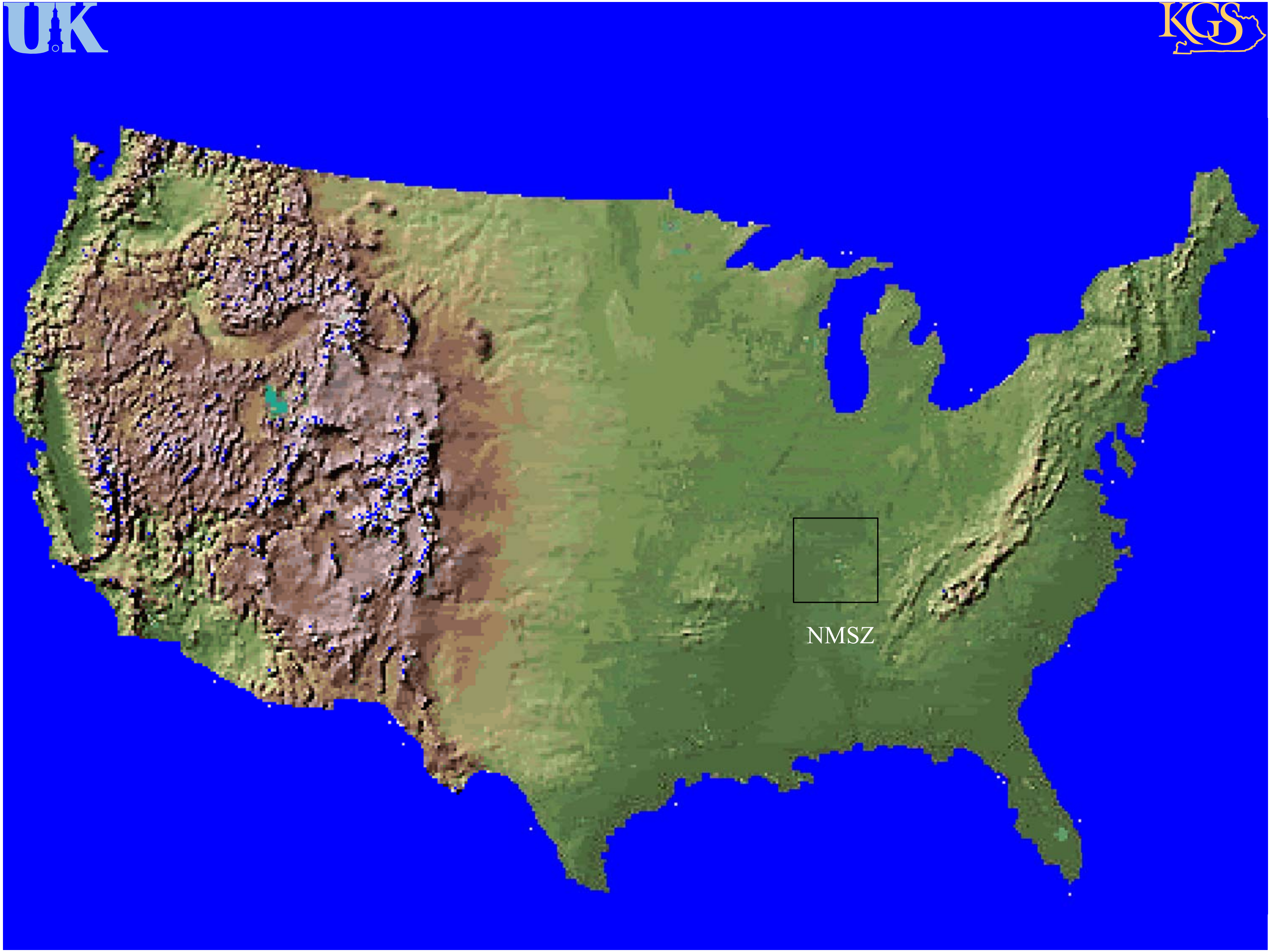
GPS results



42°
40°
38°
36°
34°
32°
236°
240°
244°
248°
North American Plate
Pacific Plate
40 mm/yr
U. S. A.
Mexico



A
BLMM
MAIR
36.8
Mississippi R.
RLAP
PIGT
PTGV
NWCC
36.4°
HCES
STLE
MCTY
1 mm/yr
0
5
magnitude
−89.6°
−89.2°


NMSZ

Deformation rate: > 30 mm/y

Deformation rate: < 3 mm/y

U.S. NUCLEAR REGULATORY COMMISSION

March 2007

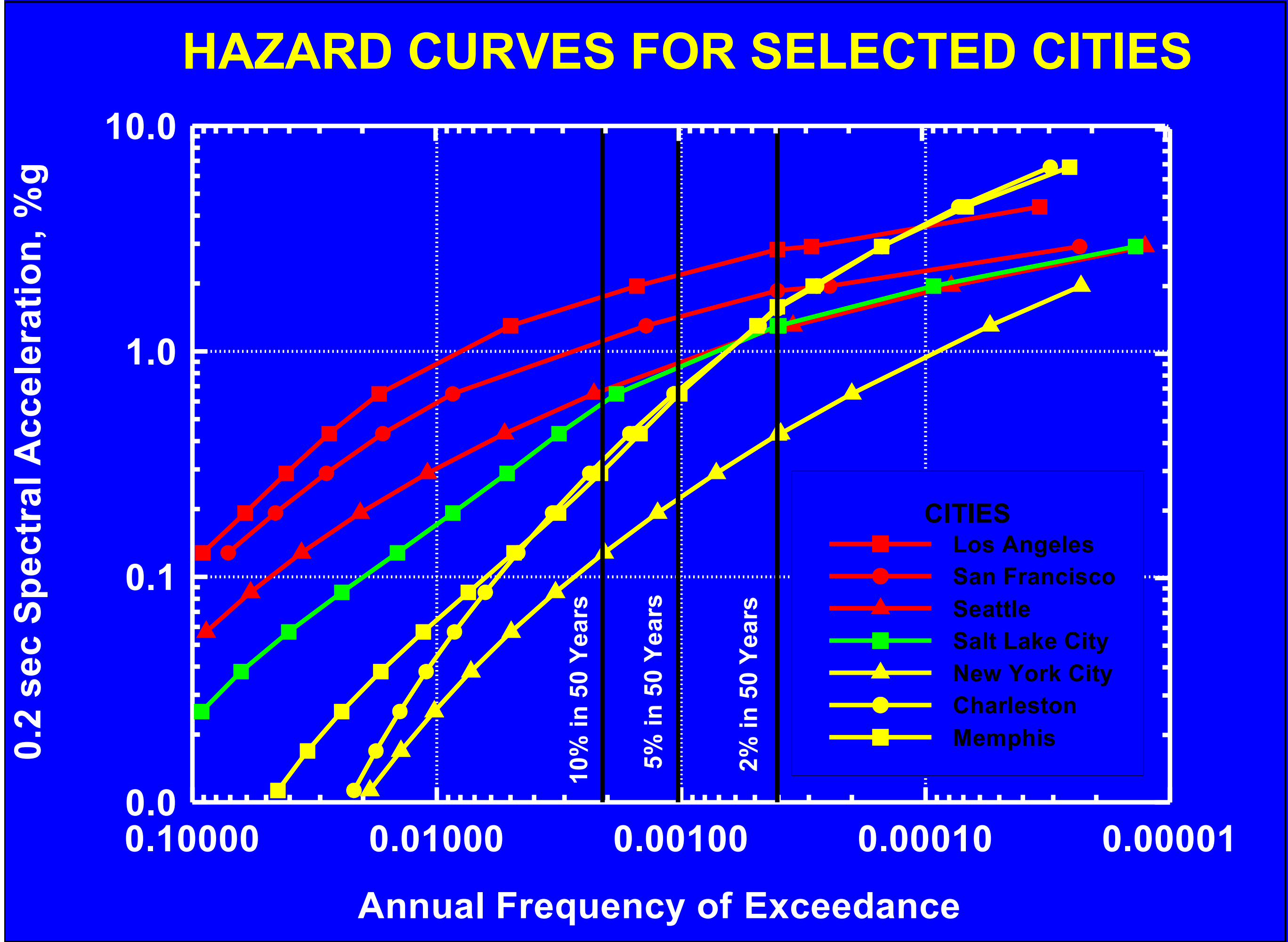
REGULATORY GUIDE

OFFICE OF NUCLEAR REGULATORY RESEARCH

REGULATORY GUIDE 1.208

The general process to determine a site-specific, performance-based GMRS includes the following:

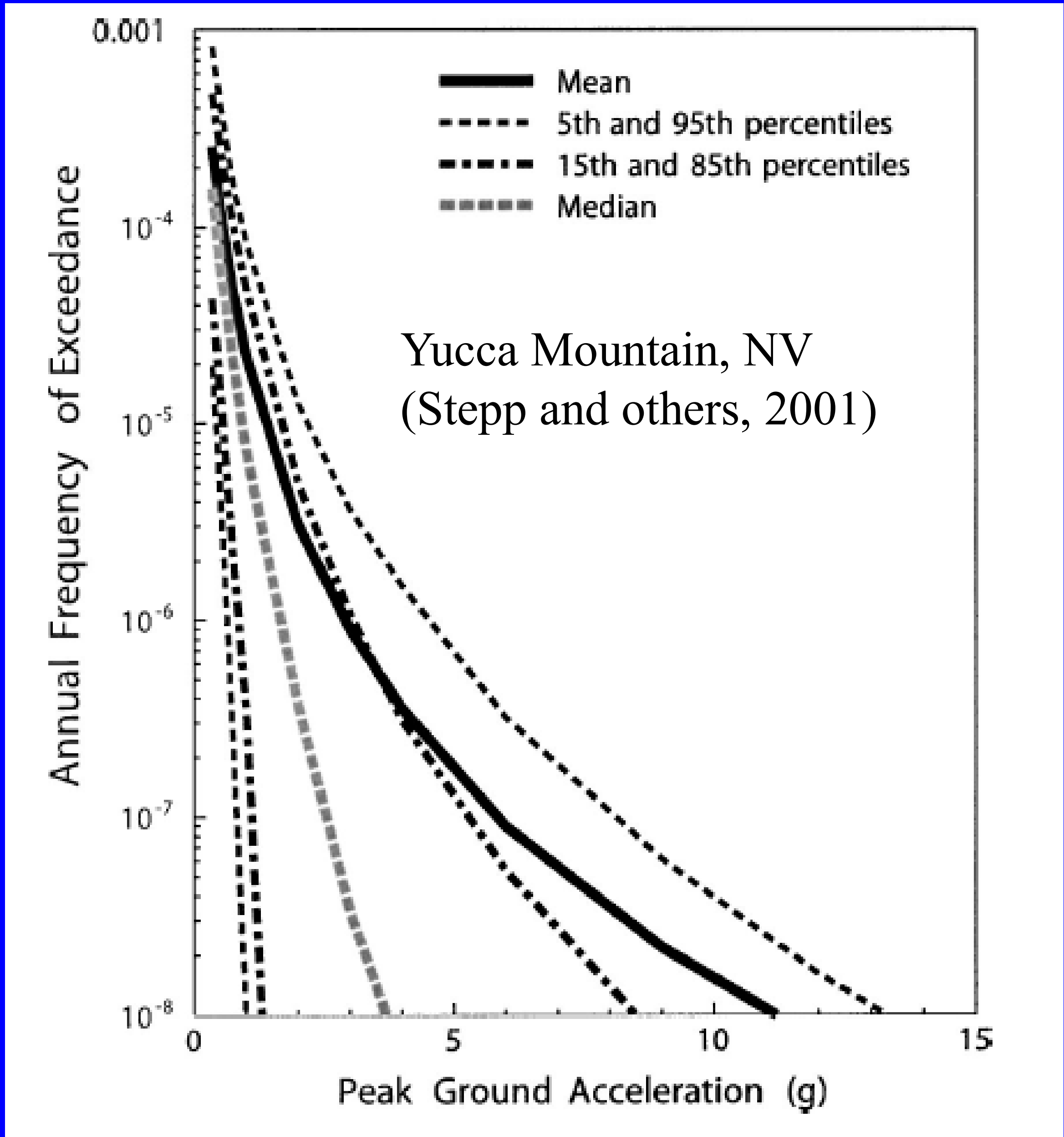
(1) site- and region-specific geological, seismological, geophysical, and geotechnical investigations
(2) a probabilistic seismic hazard analysis (PSHA)
(3) a site response analysis to incorporate the effects of local geology and topography
(4) the selection of appropriate performance goals and methodology



NRC RG: $10^{-4} – 10^{-5}$

(annual frequency of exceedance)

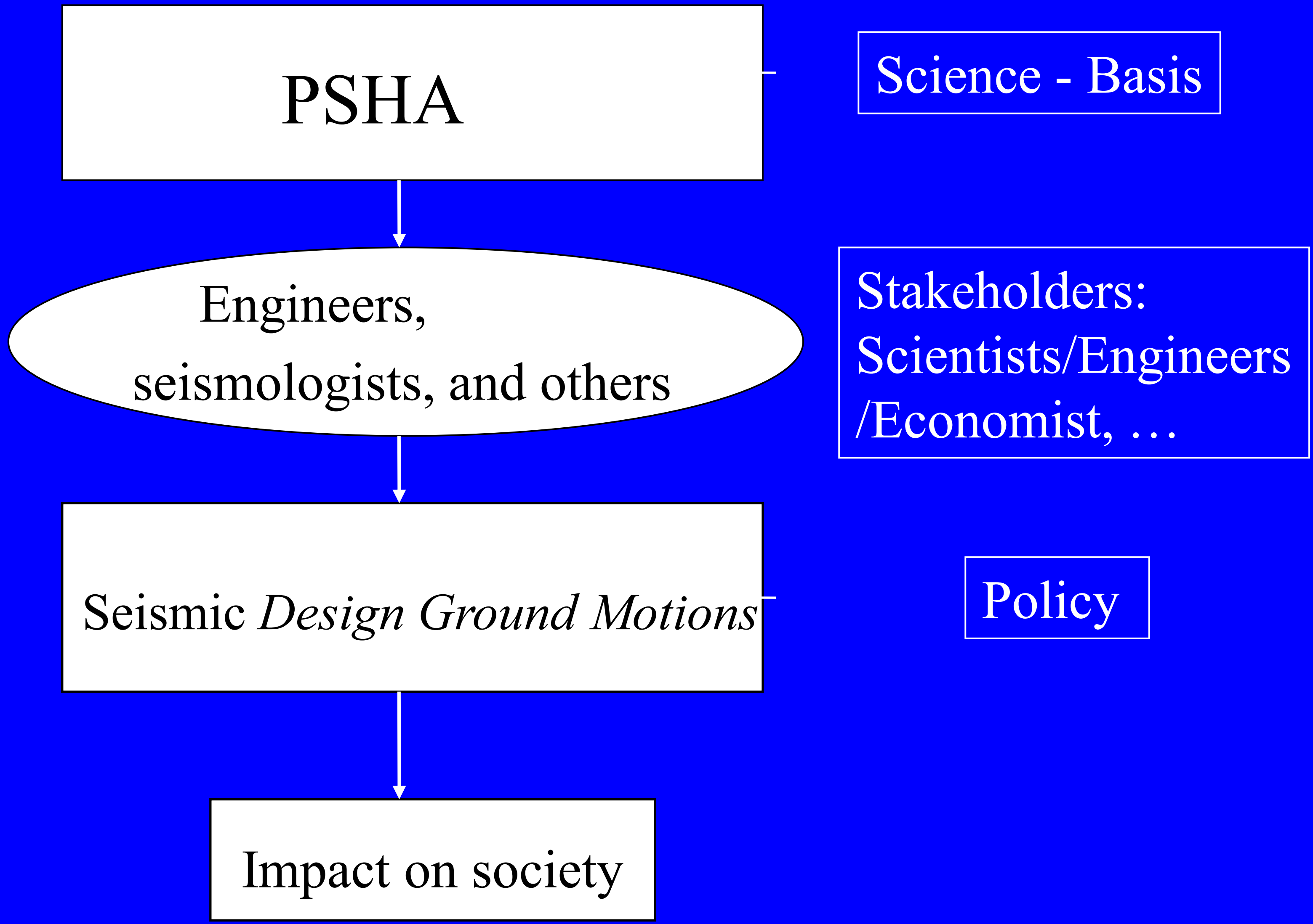
(Frankel and others, 1996)



Example:
100,000,000y RP,
11g PGA?

It was concluded in 2008 that "while many of the observations we present here are preliminary, they nevertheless suggest that the 1998 PSHA overstates <u>the true seismic hazard at Yucca Mountain</u>" (Abrahamson and Hanks, 2008)

Development of mitigation *policy in US*



Seismic Hazard versus Seismic Risk

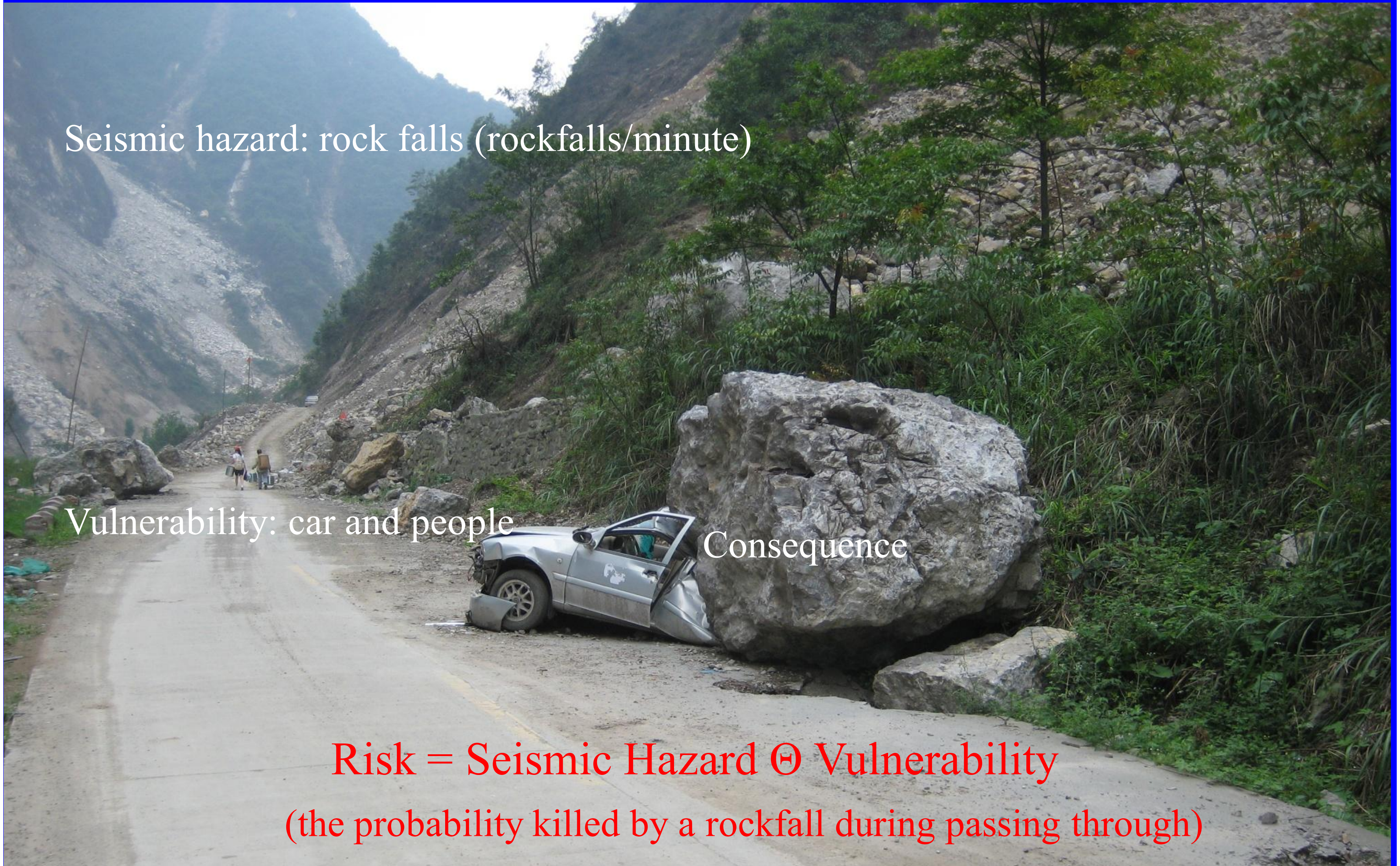
Seismic Risk= Seismic Hazard Θ Vulnerability

- Seismic Hazard
  - Quantification:
    - Physical measurement (magnitude, PGA, MMI)
    - Temporal measurement
    - Spatial measurement
- Seismic Risk
  - Quantification:
    - Probability
    - Physical/monetary measurement
    - Temporal measurement
    - Spatial measurement

References

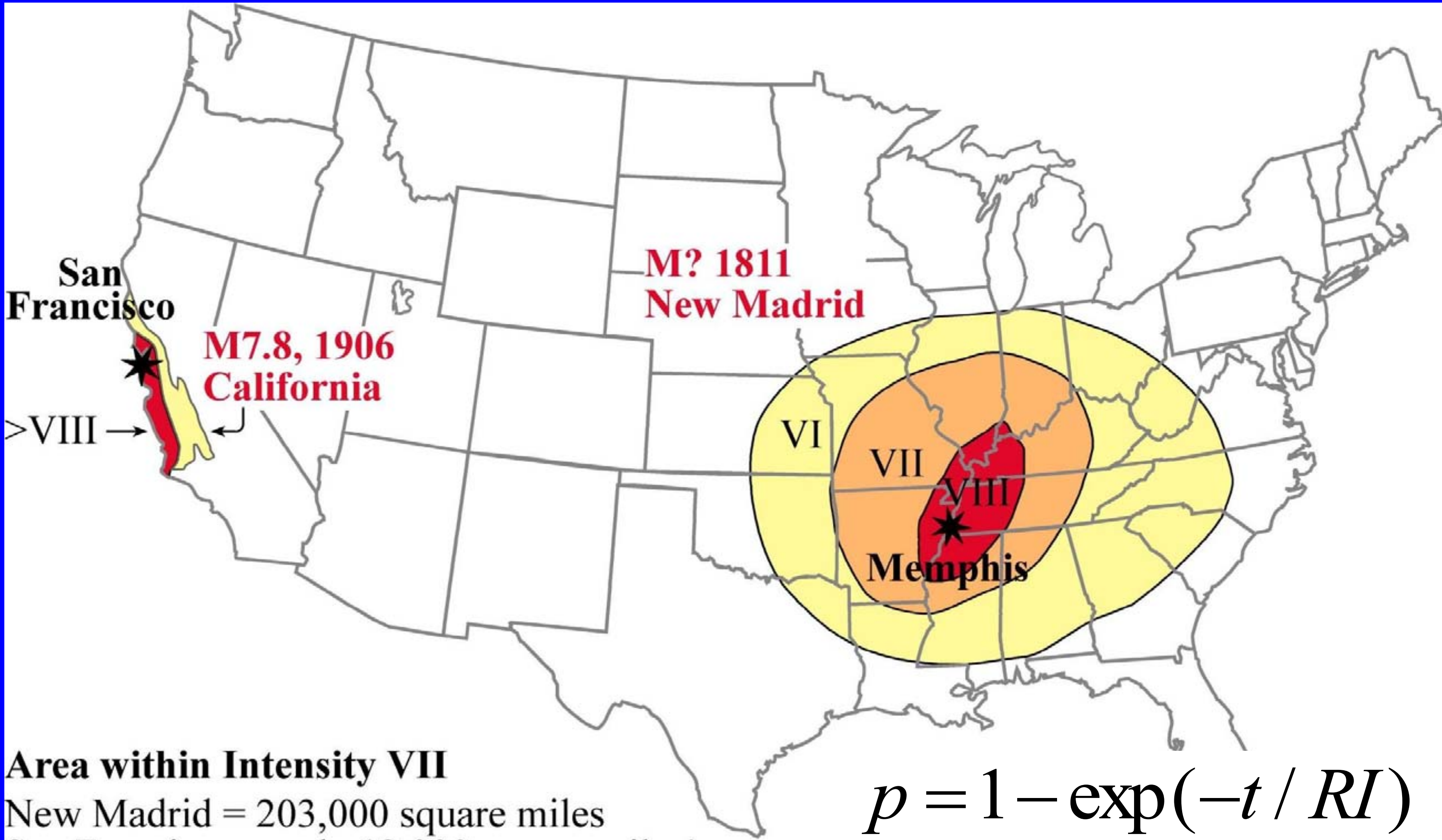
1. Wang, Z., 2009, Seismic hazard vs. seismic risk, *Seismological Research Letters*, **80**: 673–674.
2. Panza and others (in press), Introduction, Pure and Applied Geophysics, Special Volume on Advanced Seismic Hazard Assessment

Seismic Hazard vs. Seismic Risk



Hazard may or may not be mitigated, but risk can always be reduced

Seismic Hazard vs. Seismic Risk

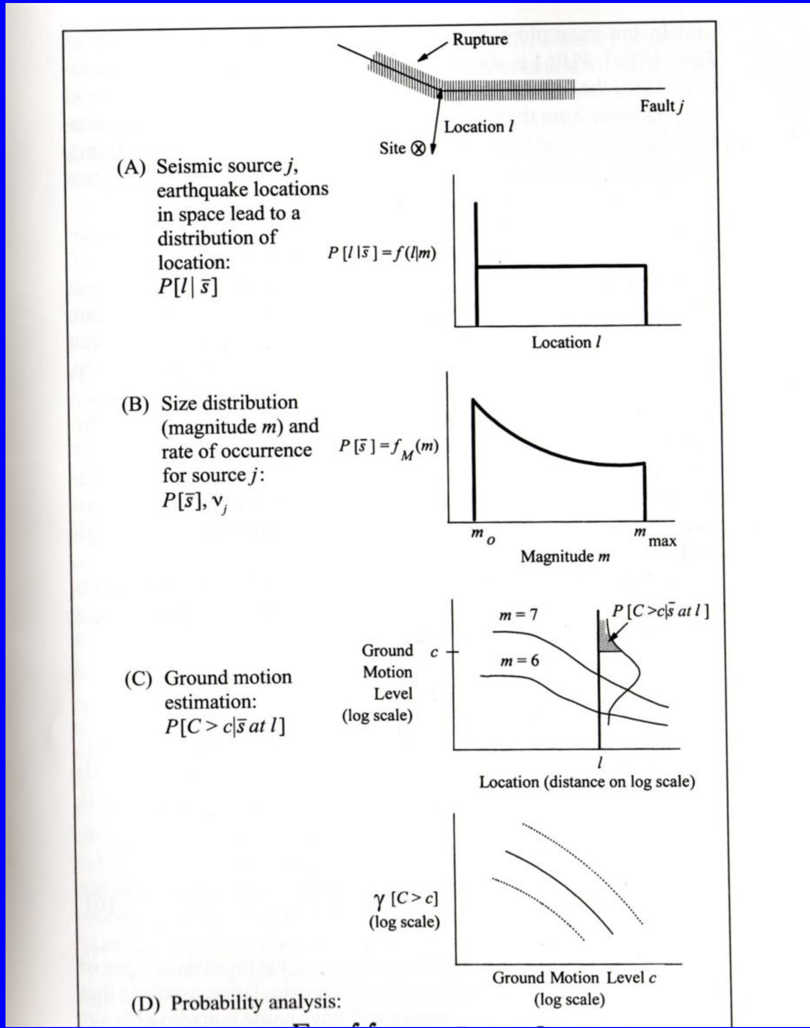


Area within Intensity VII
New Madrid = 203,000 square miles
San Francisco = only 12,000 square miles!

$$p = 1 - \exp(-t / RI)$$

San Francisco	M7.8 or MMI VIII every 100 to 200 years	22 to 39% probability of M7.8 or MMI VIII being exceeded in 50 years
Memphis	M7.7 or MMI VIII every 500 to 1,000 years	5 to 10% probability of M7.7 or MMI VIII being exceeded in 50 years

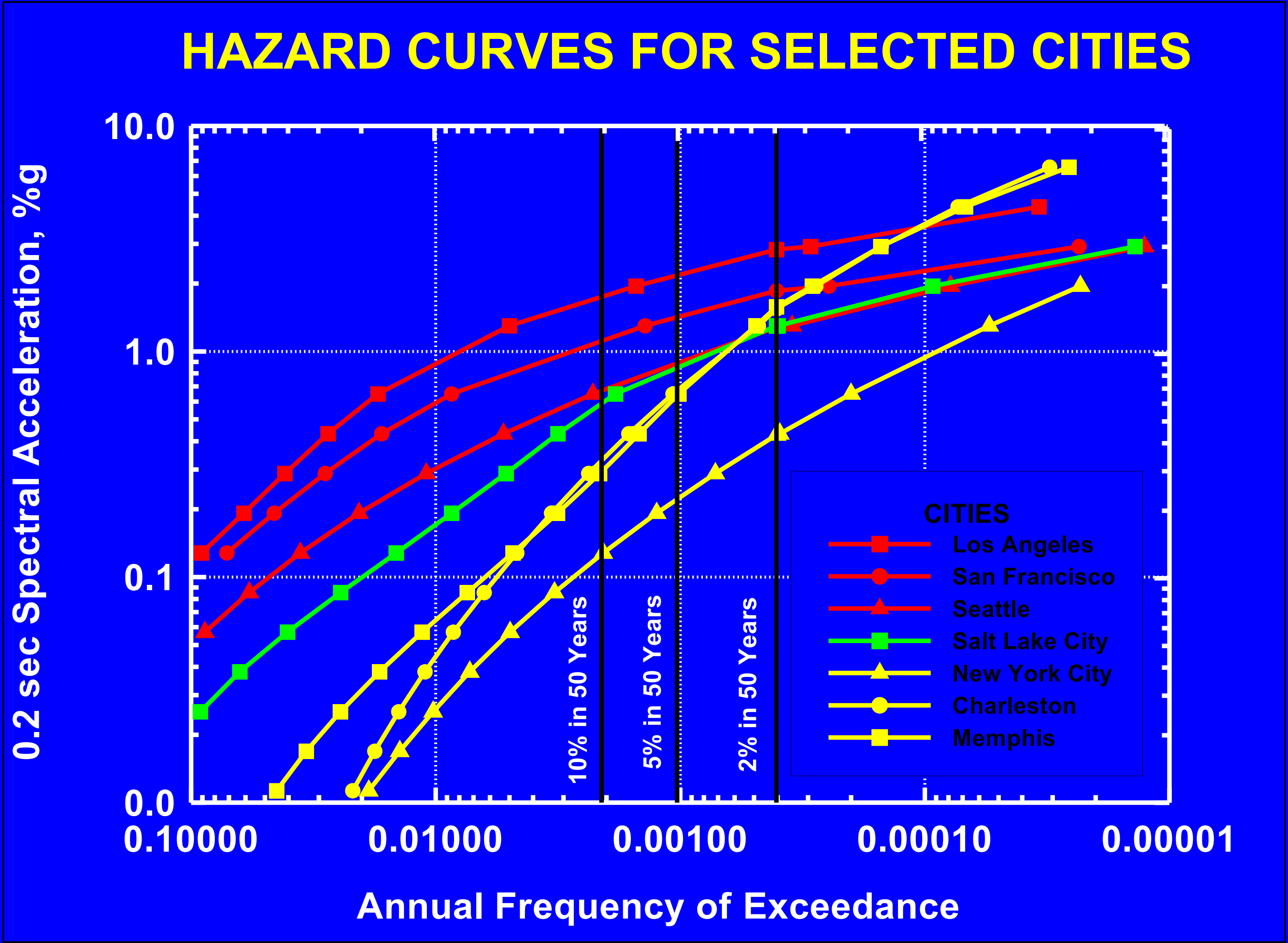
Probabilistic Seismic Hazard Analysis – PSHA



(McGuire, 2004)

$$\gamma(y) = \sum vP(Y \geq y) = \sum v \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}] d(\ln y)\} f_M(m) f_R(r) dm dr$$

Developed by Cornell in 1970 (Cornell, 1968, 1971)



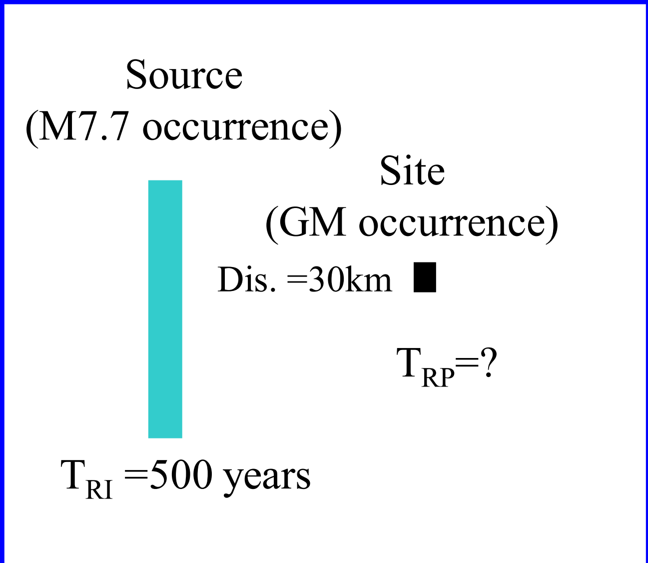
PSHA end result: a hazard curve of ground motion vs. “frequency” at a site

Probabilistic Seismic Hazard Analysis – PSHA

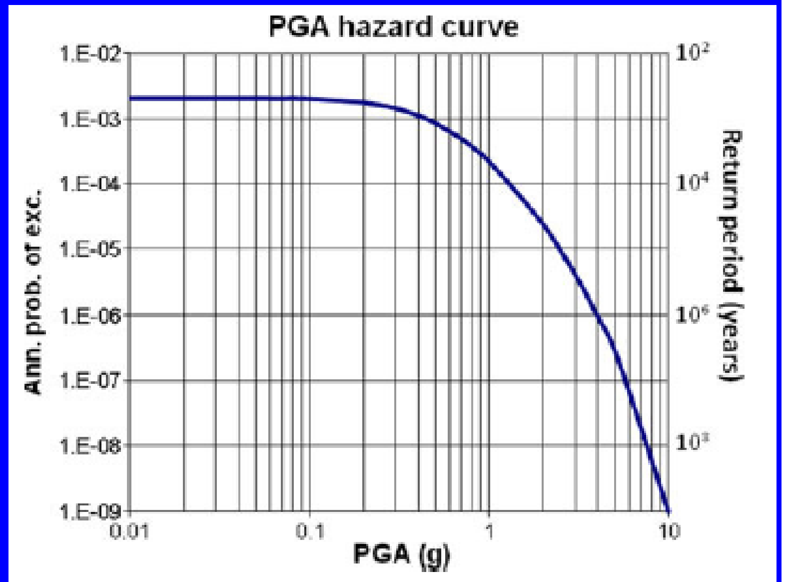
Sensitivity Test

PSHA

Input → A single EQ → "Model" → Infinite GM ← Output



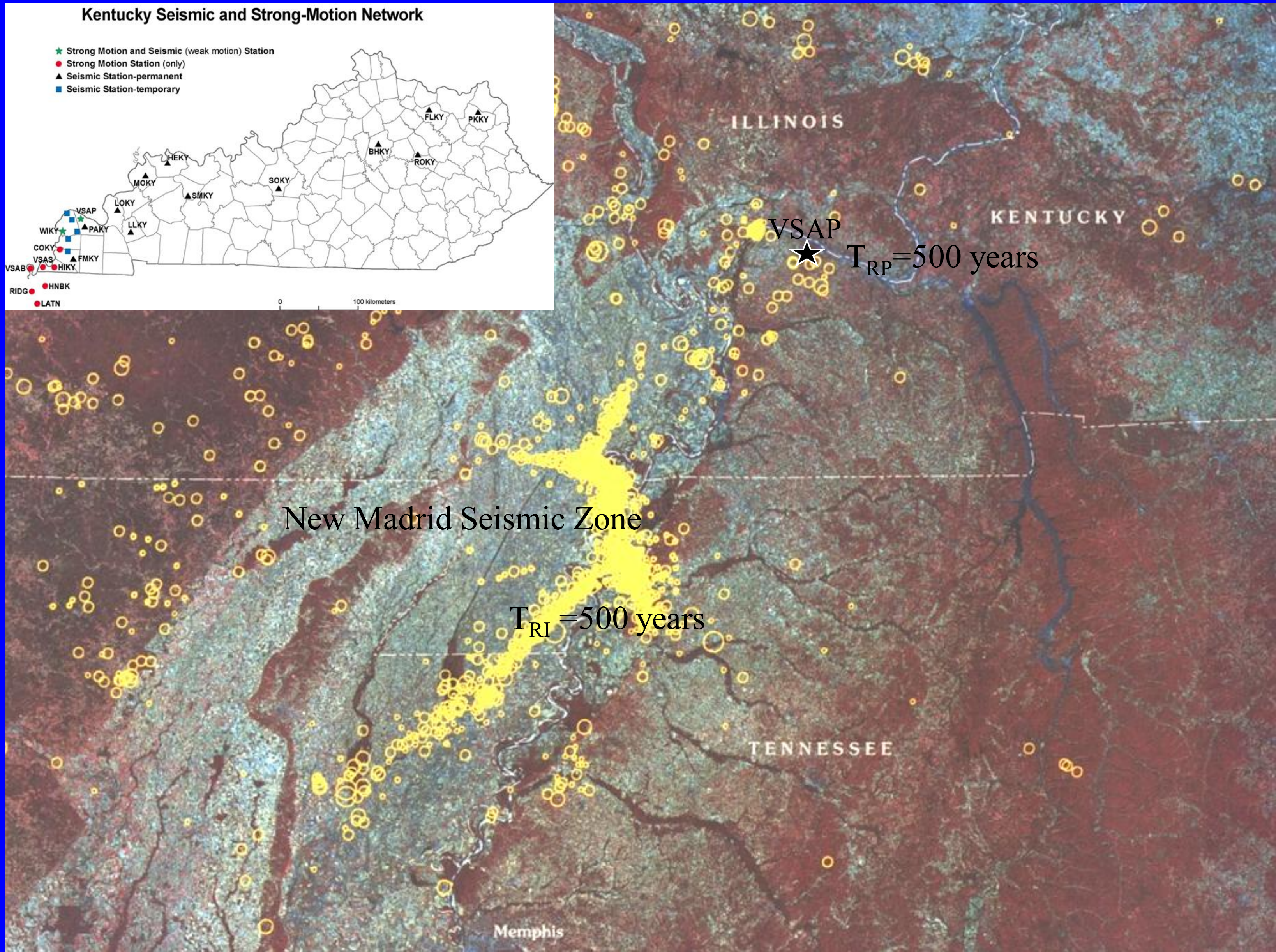
(Cornell, personal communication, 2004)



T_{RP}: 500y to infinity?

The return period: "the mean (average) time between occurrences of a seismic hazard, for example, a certain ground motion at a site" (McGuire, 2004, p.8).

Probabilistic Seismic Hazard Analysis – PSHA



Probabilistic Seismic Hazard Analysis – PSHA

What is PSHA?

$$\gamma(y) = \sum vP(Y \geq y) = \sum v \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}] d(\ln y)\} f_M(m) f_R(r) dm dr$$

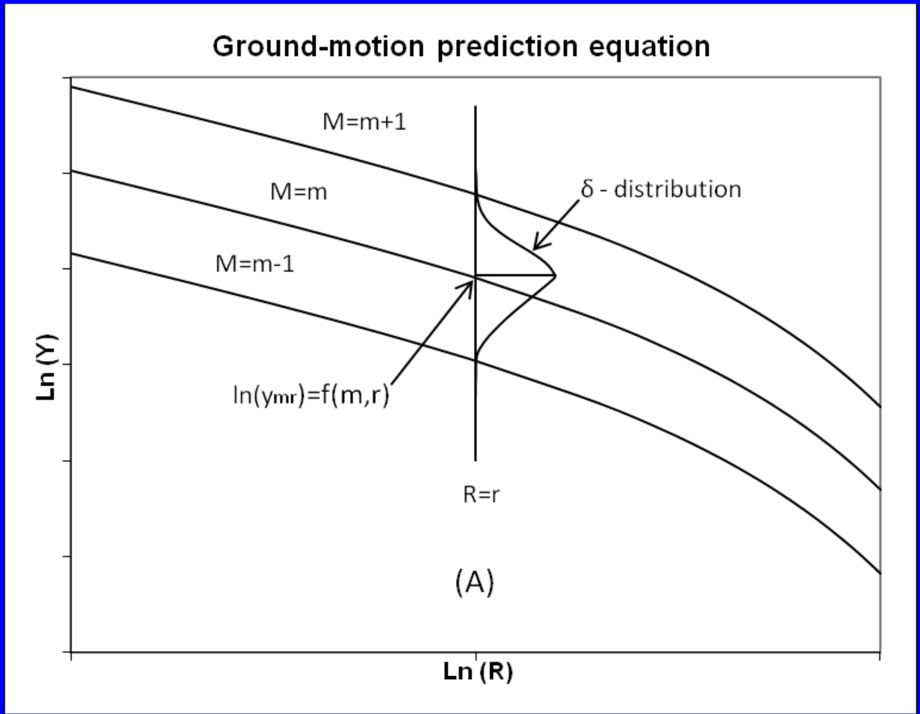
$\gamma(y)$: the annual probability of ground motion y being exceeded

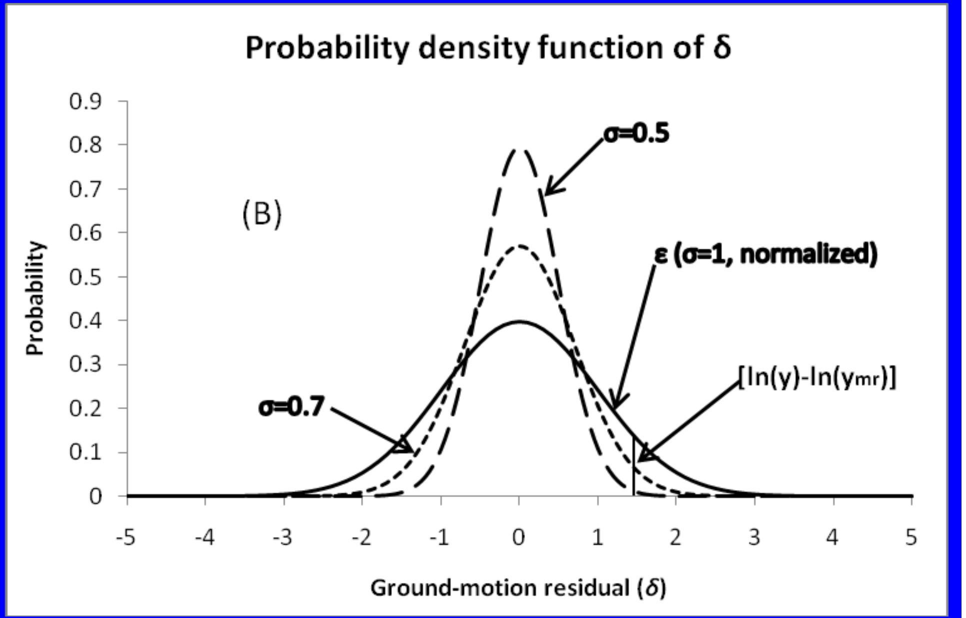
It was developed from mathematical statistics (Benjamin and Cornell, 1970; Mendenhall and others, 1986) under four fundamental assumptions (Cornell 1968, 1971):

(a) Constant-in-time average occurrence rate of earthquakes
(b) Equal likelihood of earthquake occurrence along a line or over an areal source (single point)
(c) Variability of ground motion at a site is independent
(d) Poisson (or "memory-less") behavior of earthquake occurrences.

Probabilistic Seismic Hazard Analysis – PSHA

GMPE: $$\ln(Y) = f(M,R) + \delta = f(M,R) + \varepsilon\sigma$$





1. δ distribution depends on *σ,* but not on *ε*

2. ε is a standardized normal distribution with a zero mean and standard deviation of 1

Probabilistic Seismic Hazard Analysis – PSHA

GMPE: $\ln(Y) = f(M,R) + \delta = f(M,R) + \varepsilon\sigma$

According to ***mathematical statistics*** (Benjamin and Cornell, 1970; Mendenhall and others, 1986), if and only if *M*, *R*, and *δ* are independent random variables, then the exceedance probability $P[Y \geq y]$ for seismic source *j* is

$$P_j[Y \geq y] = \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_j} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_j^2}] d(\ln y)\} f_{M,j}(m) f_{R,j}(r) dm dr$$

Probabilistic Seismic Hazard Analysis – PSHA

Assumption (a): Constant-in-time average occurrence rate of earthquakes. For G-R relationship

$$\lambda = \frac{1}{\tau} = e^{\alpha - \beta M} \qquad m_0 \le M \le m_{\max}$$

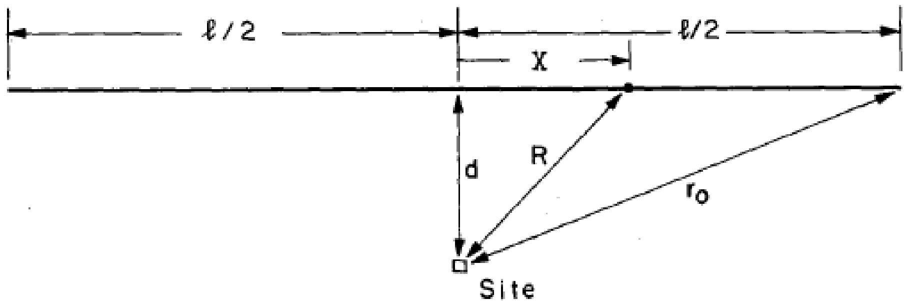
M is independent

PDF for *M*

$$f_M(m) = \frac{\beta e^{-\beta(m-m_0)}}{1-e^{-\beta(m_{\max}-m_0)}} \qquad m_0 \le m \le m_{\max} \; .$$

Probabilistic Seismic Hazard Analysis – PSHA

Assumption (b): Equal likelihood of earthquake occurrence along a line or over an areal source (single point)



b) ABD Plane
Fig. 1. Line source.

PDF for *R*

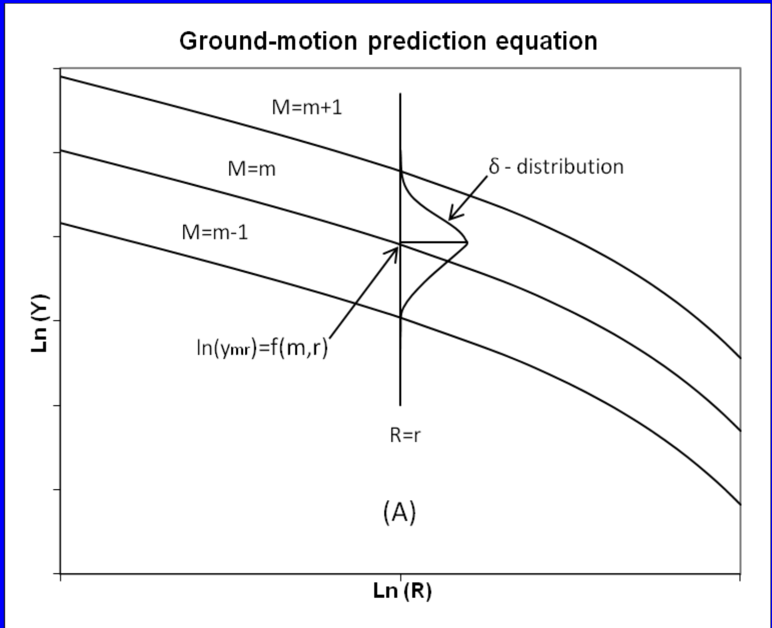
$$f_R(r) = \frac{dF_R(r)}{dr} = \frac{d}{dr}\left(\frac{2\sqrt{r^2 - d^2}}{l}\right)$$

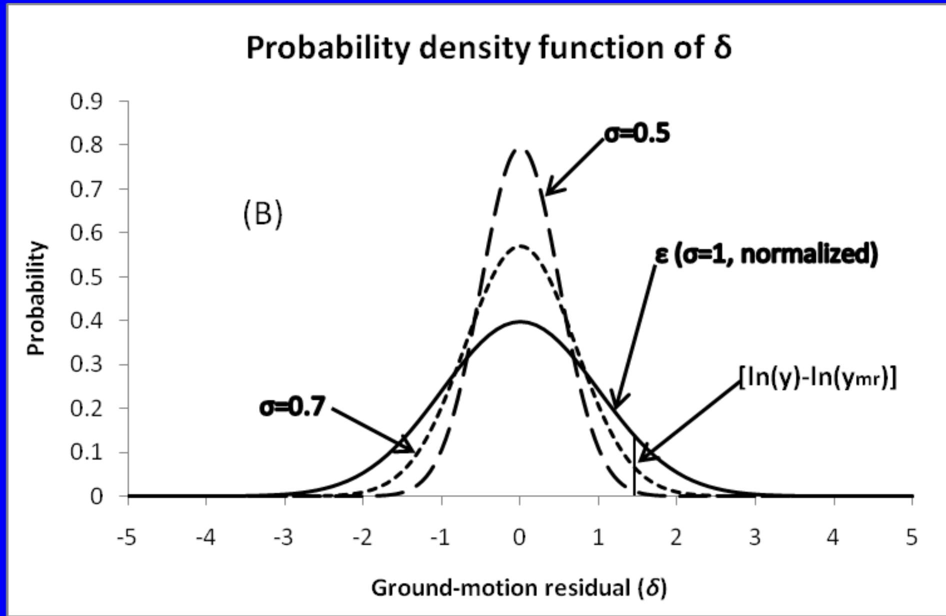
$$= \frac{2r}{l\sqrt{r^2 - d^2}} \qquad d \leq r \leq r_0 .$$

R is independent

(Cornell, 1968)

Probabilistic Seismic Hazard Analysis – PSHA





$$\ln(Y) = f(M,R) + \delta = \ln(Y_{MR}) + \varepsilon\sigma$$

PDF for δ

$$f_\Delta(\delta) = \frac{1}{\sqrt{2\pi}\sigma}\exp[-\frac{(\delta - \ln y_{mr})^2}{2\sigma^2}]$$

PDF for ε

$$f(\varepsilon) = \frac{1}{\sqrt{2\pi}\,1}\exp[-\frac{(\varepsilon - \ln y_{mr})^2}{2\cdot 1^2}]$$

Assumption (c): Variability of ground motion at a site is independent

Probabilistic Seismic Hazard Analysis – PSHA

Assumption (d) Poisson (or "memory-less") behavior of earthquake occurrences

fault. Next we must consider the question of the random number of occurrences in any time period. For illustration, it is assumed that the occurrences of these major events follow a Poisson arrival process (Parzen, 1962; Cornell, 1964) with average occurrence rate (along the entire fault) of ν per year. Then, $\tilde{N}$, the number of events of interest along the fault in a time interval of length t years is known to be Poisson distributed

$$p_{\tilde{N}}(n) = P[\tilde{N} = n] = \frac{e^{-\nu t}(\nu t)^n}{n!} \qquad n = 0, 1, 2, \cdots . \qquad (18)$$

It is easily established that, if certain events are Poisson arrivals with average arrival rate ν and if each of these events is independently, with probability p, a "special event," then these special events are Poisson arrivals with average rate $p\nu$. (This is said to be a Poisson process with ("random selection.") In our case the special events are those which cause an intensity at the site in excess of some value i. The probability, p_i, that any event of interest ($M \geqq m_0$) will be a special event is given by equation 12.

$$p_i = P[I \geqq i] = \frac{1}{l} CG \exp\left[\frac{-\beta}{c_2} i\right].$$

Thus the number of times N that the intensity at the site will exceed i in an interval of length t is

$$p_N(n) = P[N = n] = \frac{e^{-p_i \nu t}(p_i \nu t)^n}{n!} \qquad n = 0, 1, 2, \cdots . \qquad (20)$$

(page 1590 of Cornell, 1968)

$$\nu_j = e^{\alpha_j - \beta_j m_0}$$

$$I = c_1 + c_2 M - c_3 \ln R$$

$$\ln(Y) = f(M,R) + \delta = f(M,R) + \varepsilon\sigma$$

$$P_j[Y \geq y] = \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_j} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_j^2}] d(\ln y)\} f_{M,j}(m) f_{R,j}(r)\, dm\, dr$$

Probabilistic Seismic Hazard Analysis – PSHA

Pre-condition (1), t ≡ 1 (year)

Of particular interest is the probability distribution of $I_{\max}^{(t)}$ the maximum intensity over an interval of time t (often one year). Observe that

$$P[I_{\max}^{(t)} \leqq i] = P[\text{exactly zero special events in excess of } i \text{ occur in the time interval 0 to } t]$$

which from equation (20) is

$$P[I_{\max}^{(t)} \leqq i] = P[N = 0] = e^{-p_i \nu t}. \quad (21)$$

If we let $I_{\max}$ equal $I_{\max}^{(1)}$, the *annual* maximum intensity, $t = 1$, and

$$F_{I_{\max}^{(i)}} = e^{-p_i \nu} = \exp\left[-\nu C G \exp\left(-\frac{\beta}{c_2} i\right)\right] \qquad i \geqq i' \quad (22)$$

Pre-condition (2) Small annual prob. of exc. ≤ 0.05

$$e^x = 1 + x + \frac{x^2}{2!} + \ldots + \frac{x^n}{n!} + \ldots$$

If the annual probabilities of exceedance are small enough (say ≦0.05), the distribution of $I_{\max}$ can be approximated by

$$1 - F_{I_{\max}^{(i)}} = 1 - e^{-p_i \nu} \cong 1 - (1 - p_i \nu)$$

$$\cong p_i \nu$$

$$\cong \nu C G \exp\left(-\frac{\beta}{c_2} i\right) \qquad i \geqq i'. \quad (23)$$

(page 1590-91 of Cornell, 1968)

Probabilistic Seismic Hazard Analysis – PSHA

The annual probability of exceedance – probability of exceedance in ONE year

$$1 - F_{I_{\max}^{(i)}} = 1 - e^{-p_i \nu} \cong 1 - (1 - p_i \nu)$$
$$\cong p_i \nu$$

Pre-condition (1): t ≡ 1 (year)
Pre-condition (2): ≤ 0.05

The return period

The average return period, T_i, of an intensity equal to or greater than i is defined as the reciprocal of $1 - F_{I_{\max}^{(i)}}$ or

Basic Equation of PSHA (total annual probability of exceedance)

$$\gamma(y) = \sum \nu \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}] d(\ln y)\} f_M(m) f_R(r) dm dr$$

Probabilistic Seismic Hazard Analysis – PSHA

Assumption (a): Constant-in-time average occurrence rate of earthquakes

Assumption (b): Single point source

Assumption (c): Variability of ground motion at a site is independent

Assumption (d): Poisson (or "memory-less") model

1) Pre-condition (1) t ≡ 1 (year)

2) Pre-condition (2) small annual prob. of exc. ≤ 0.05

$$\gamma(y) = \sum v \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}] d(\ln y)\} f_M(m) f_R(r) dm dr$$

1. If any of the assumptions is not valid, PSHA calculation is NOT valid.
2. If any of the pre-conditions is violated, PSHA calculation is NOT valid.
3. The annual probability of exceedance is a PROBABILITY of exceedance in ONE year and dimensionless.

Probabilistic Seismic Hazard Analysis – PSHA

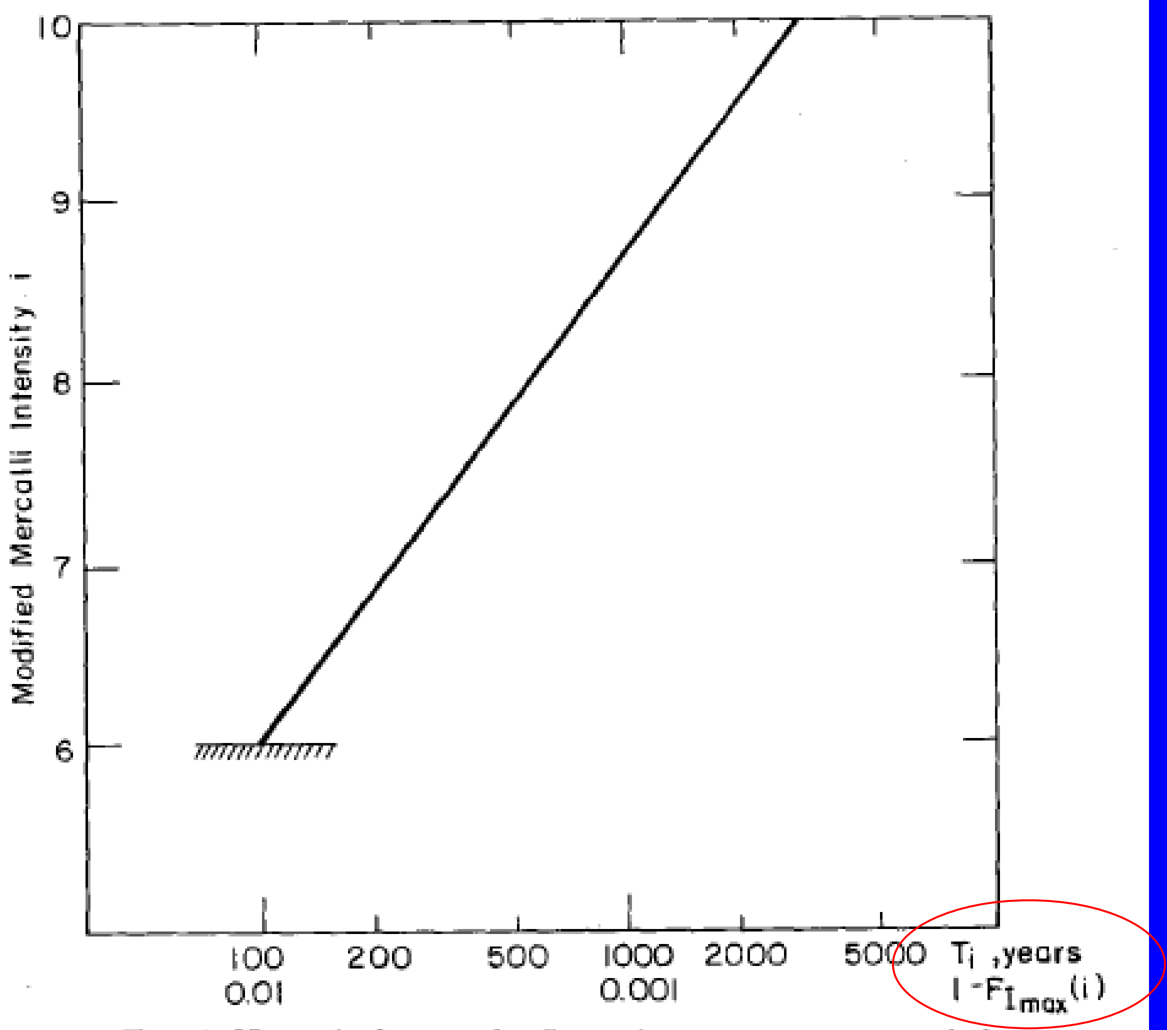
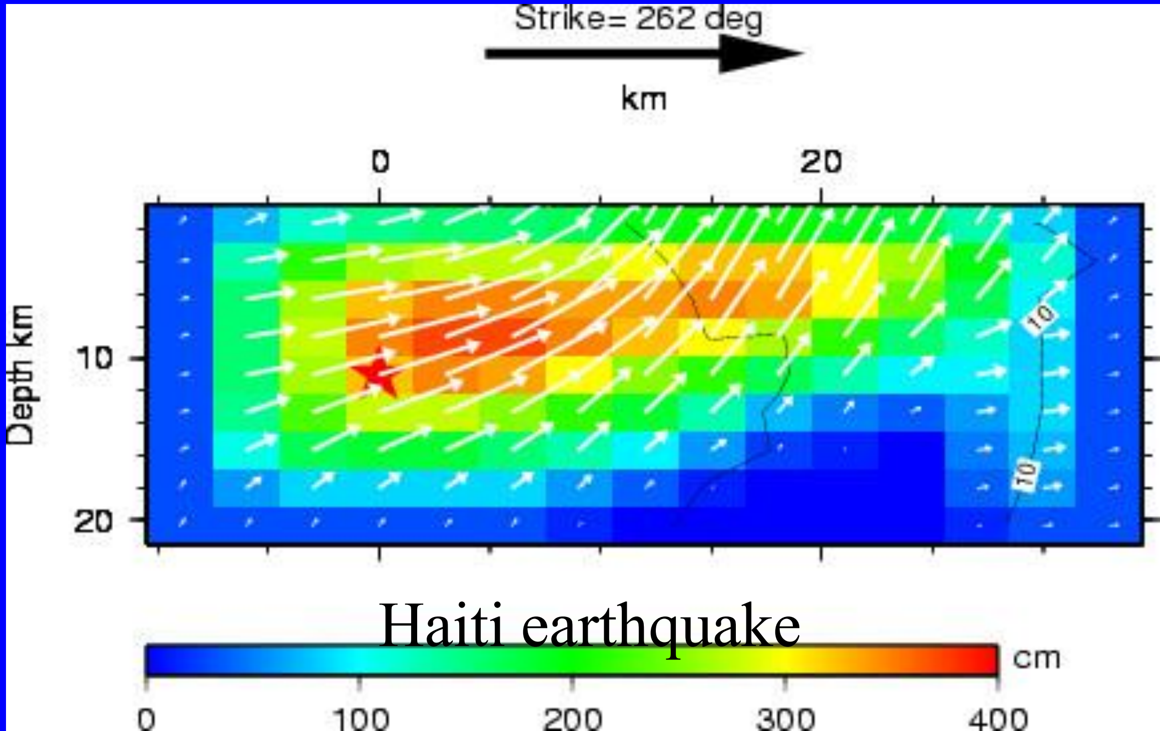


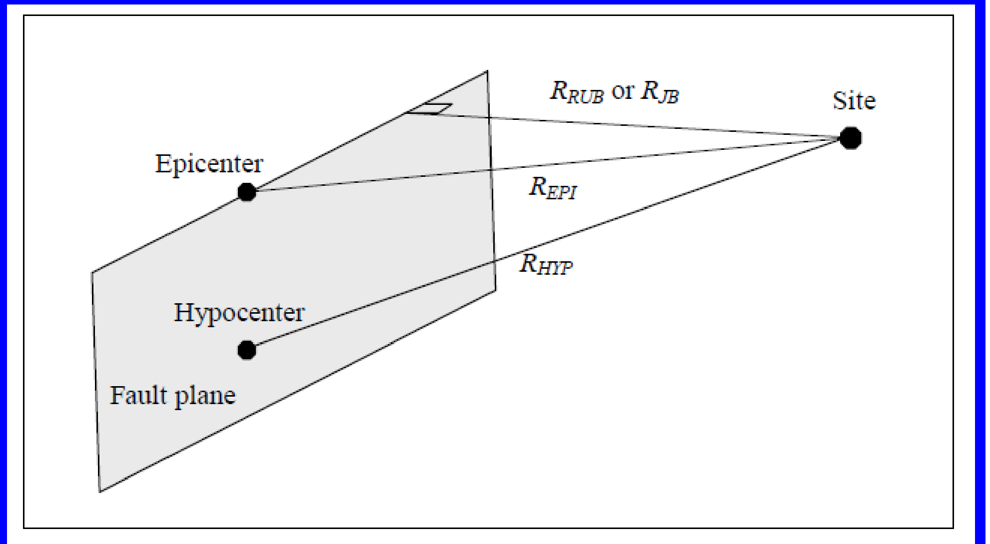
FIG. 4. Numerical example: Intensity versus return period.

The average return period, T_i , of an intensity equal to or greater than i is defined as the reciprocal of $1 - F_{I_{\max}^{(i)}}$ or

Source model: finite fault, not point source

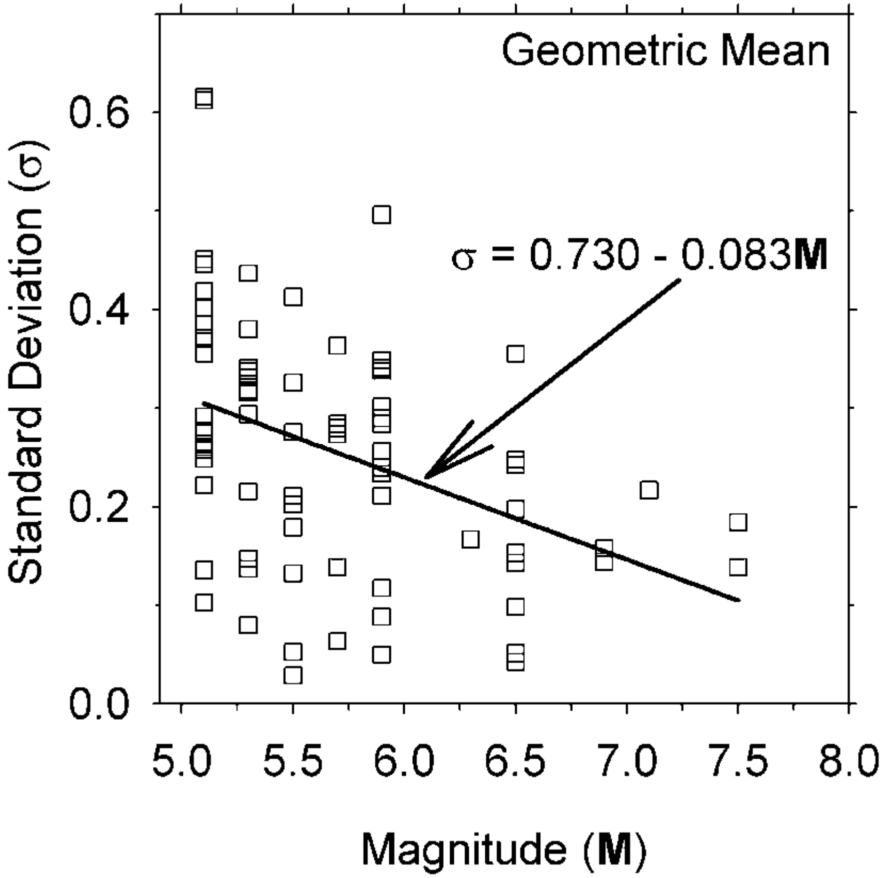


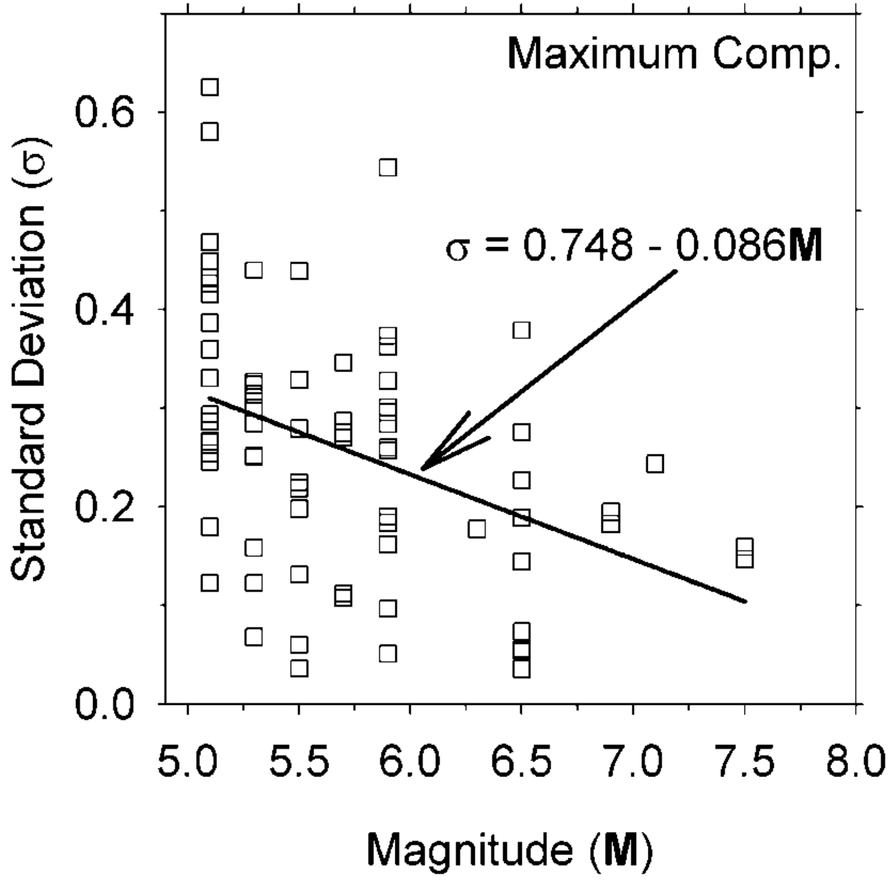
Haiti earthquake



Probabilistic Seismic Hazard Analysis – PSHA

δ (σ) is not independent





Probabilistic Seismic Hazard Analysis – PSHA

Assumption (a): Constant-in-time average occurrence rate of earthquakes ?

Assumption (b): Single point source – Not valid

Assumption (c): Variability of ground motion at a site is independent - No

Assumption (d): Poisson (or "memory-less") model - ?

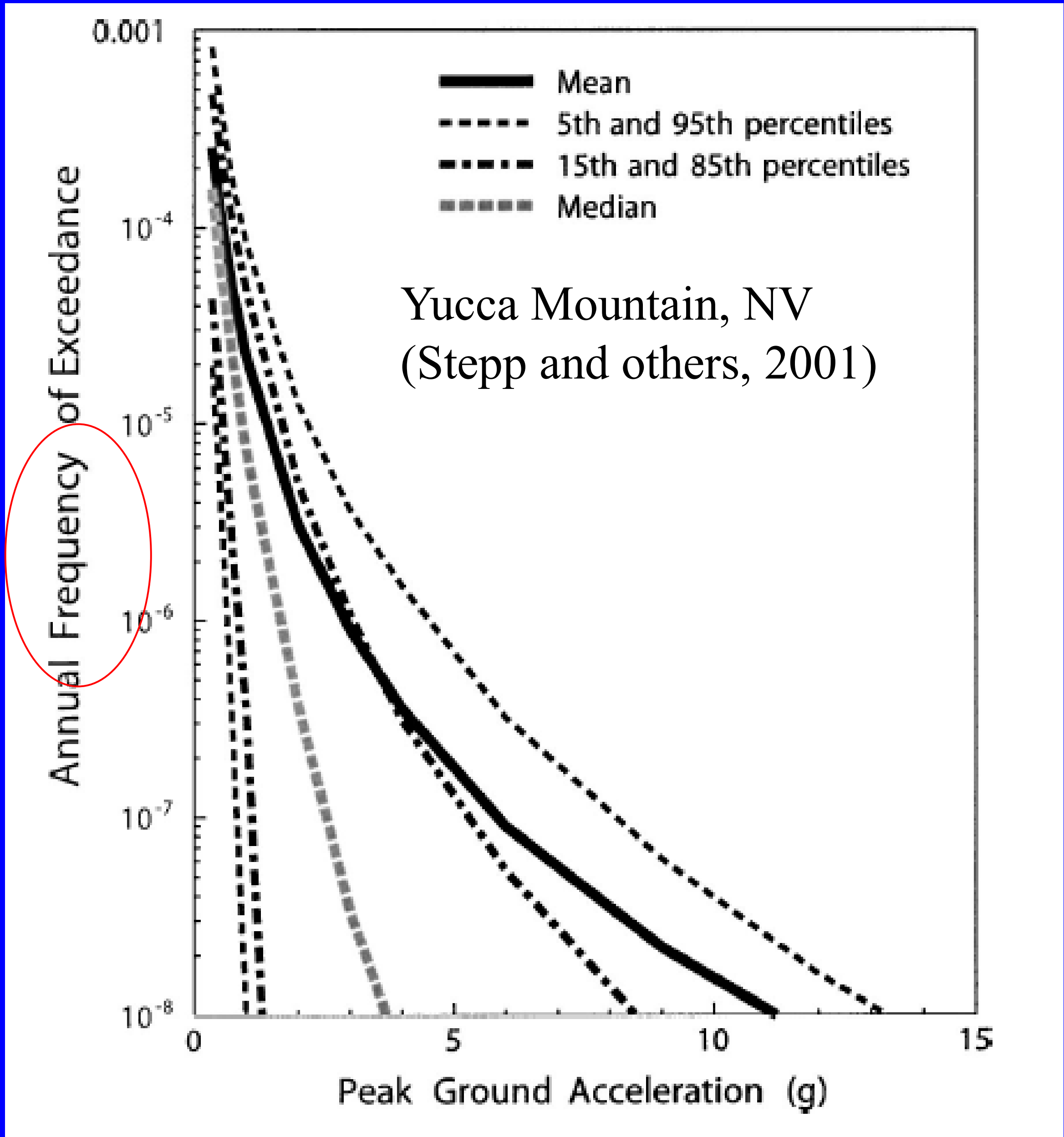
1) Pre-condition (1) t ≡ 1 (year)

2) Pre-condition (2) small annual prob. of exc. ≤ 0.05

$$\gamma(y) = \sum v \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}] d(\ln y)\} f_M(m) f_R(r) dm dr$$

1. PSHA (model) is NOT valid.
2. The annual probability of exceedance is a PROBABILITY of exceedance in ONE year and dimensionless - Not “frequency”.

Probabilistic Seismic Hazard Analysis – PSHA



PSHA could "create" 11g PG with a return period of 100,000,000 years.

Probabilistic Seismic Hazard Analysis – PSHA

Assumption (d) Poisson (or "memory-less") behavior of earthquake occurrences

$$1 - F_{I_{\max}^{(i)}} = 1 - e^{-p_i \nu} \cong 1 - (1 - p_i \nu) \cong p_i \nu$$

Pre-condition (1): t ≡ 1 (time unit)
Pre-condition (2): ≤ 0.05

<u>Example: tossing a coin</u>

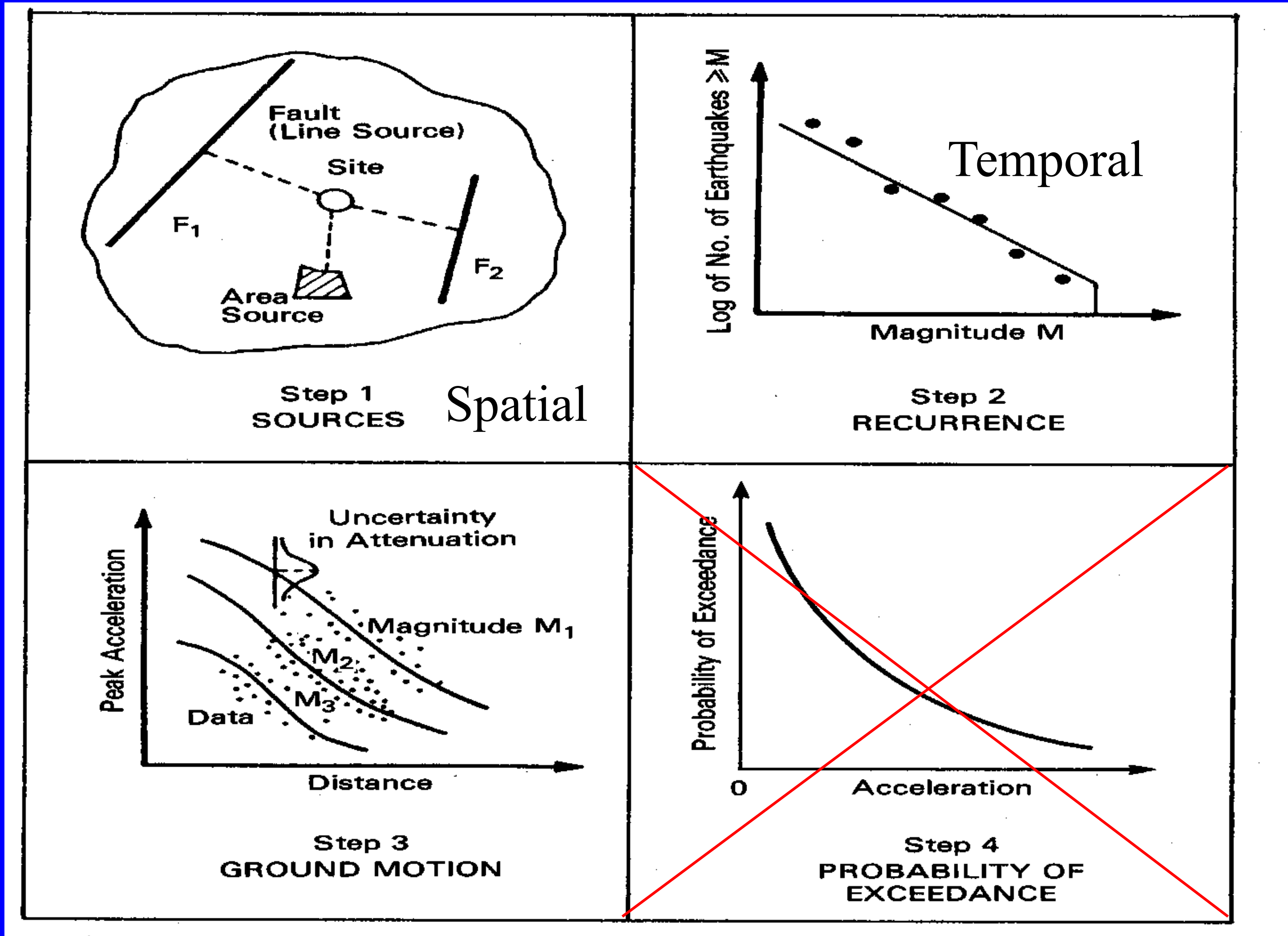
p_h=0.5

p_t=0.5

ν = 10 (tosses/min.)

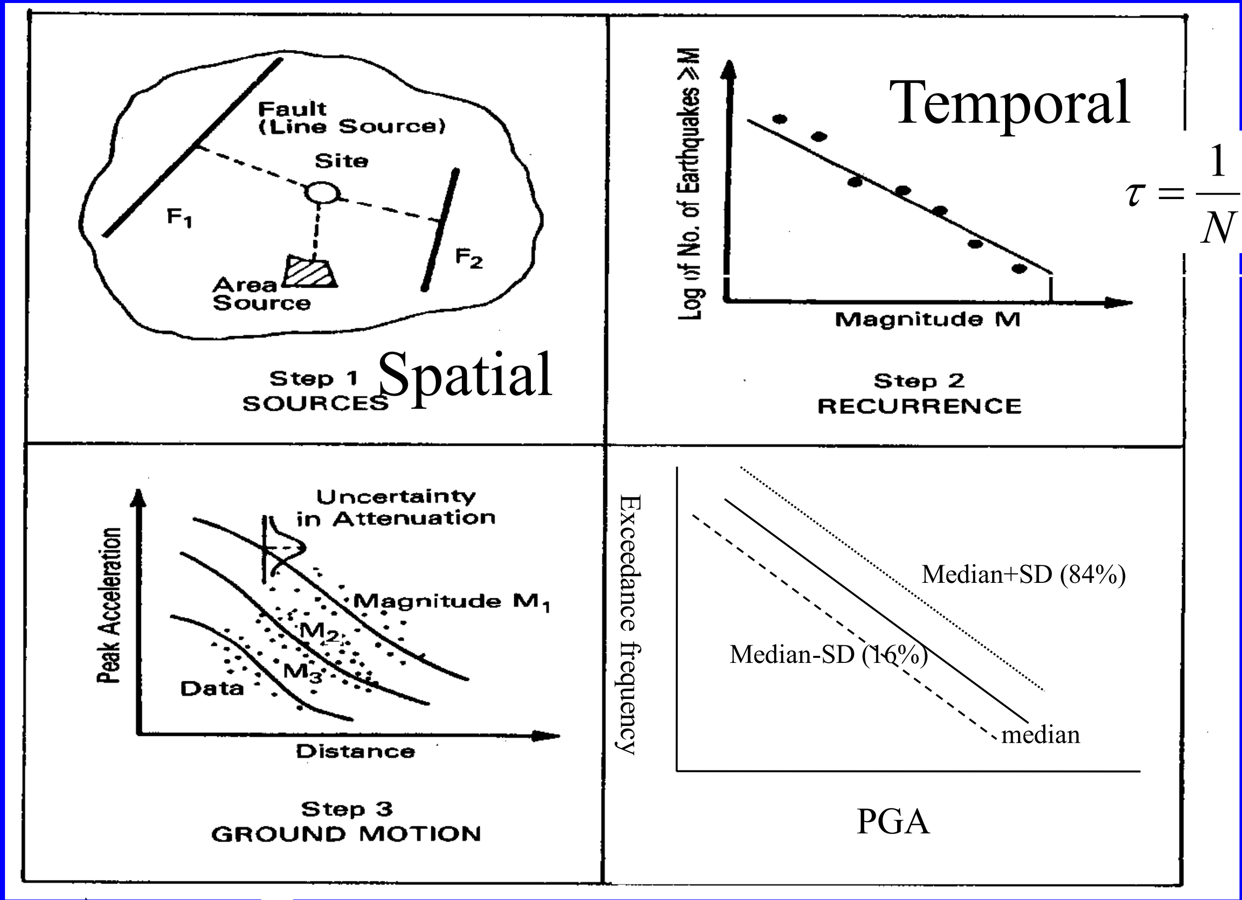
The probability of having at least one head in 1 minute 5.0

Alternative Seismic Hazard Assessment



(Reiter, 1990)

1. Seismic Hazard Assessment - Theoretical



$$\tau = \frac{1}{N} = e^{-2.303a + 2.303bM}$$

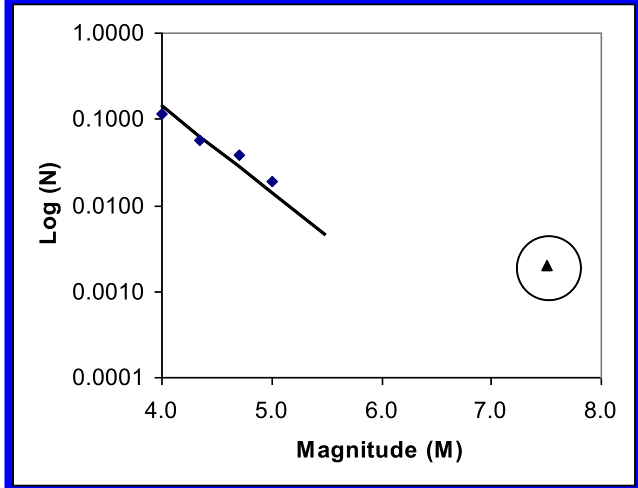
$$\ln(Y) = f(M, R) + \varepsilon\sigma$$

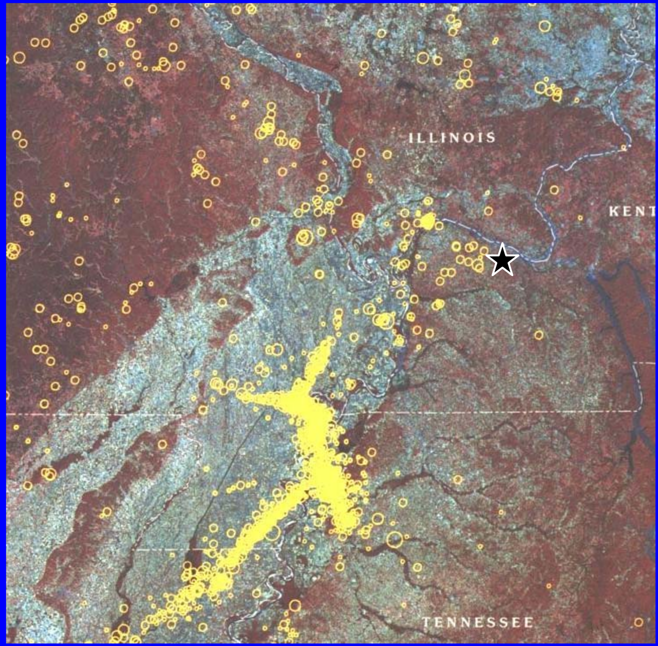
$$M = g(R, \ln Y, \varepsilon\sigma)$$

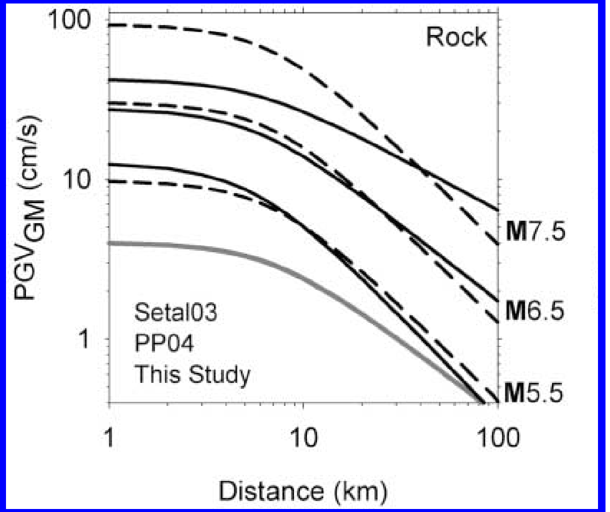
$$\tau = \frac{1}{N} = e^{-2.303a + 2.303bg(R, \ln Y, \varepsilon\sigma)}$$

(Wang, 2006, 2007)

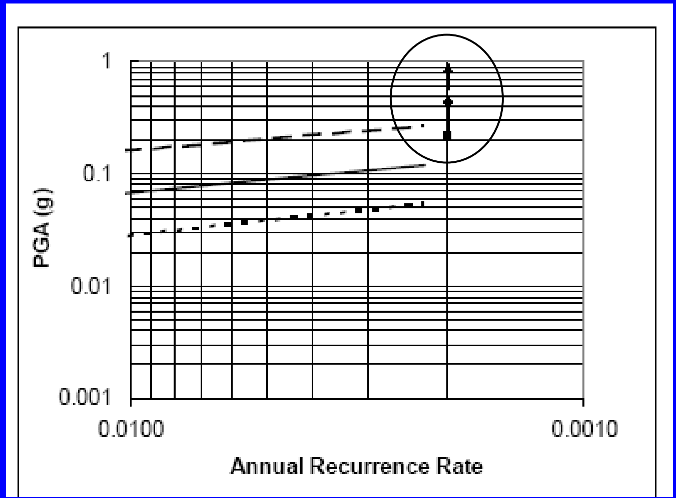
SHA to DSHA





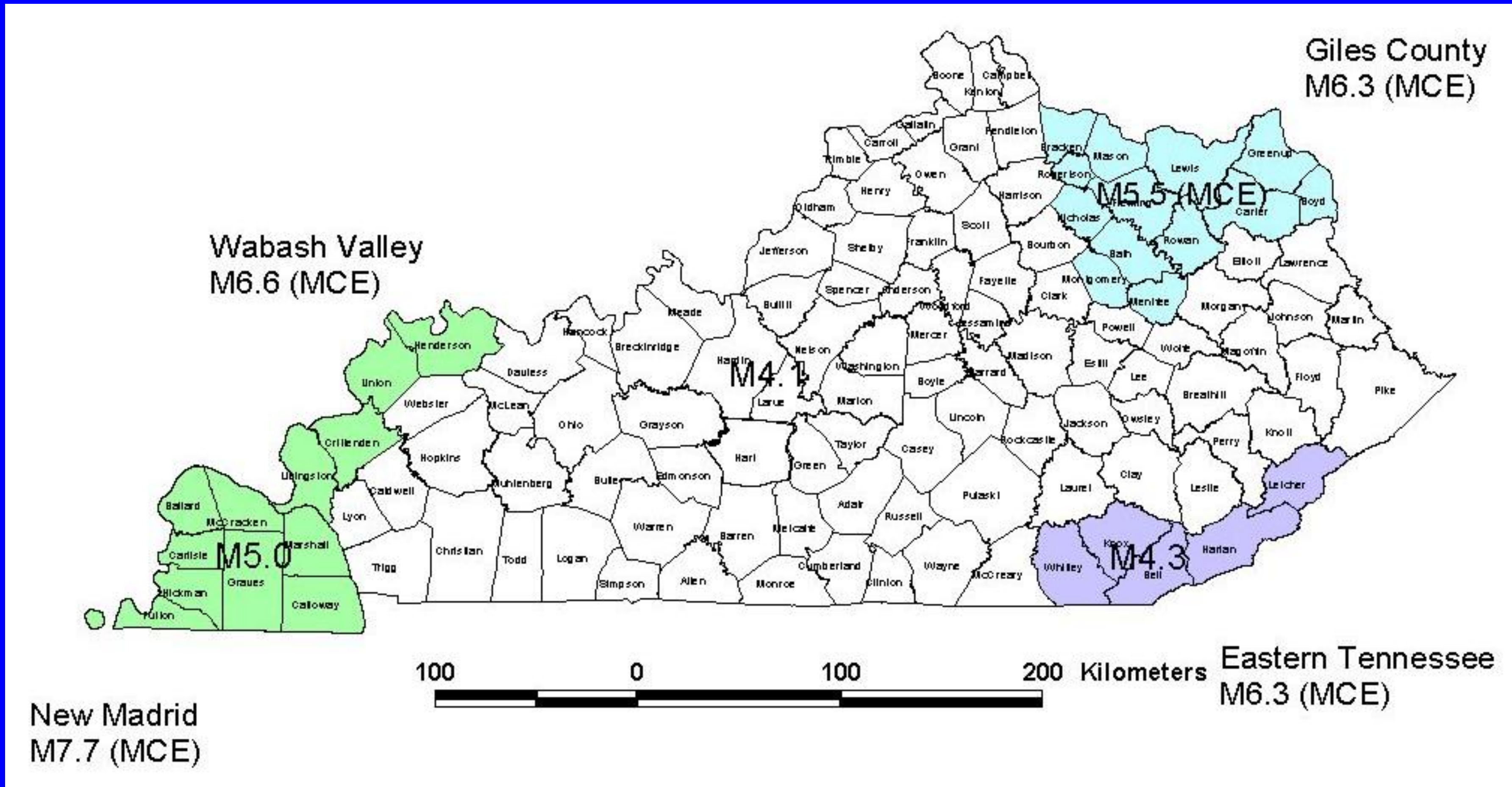


Characteristic earthquake:
M7.5/RI=500y

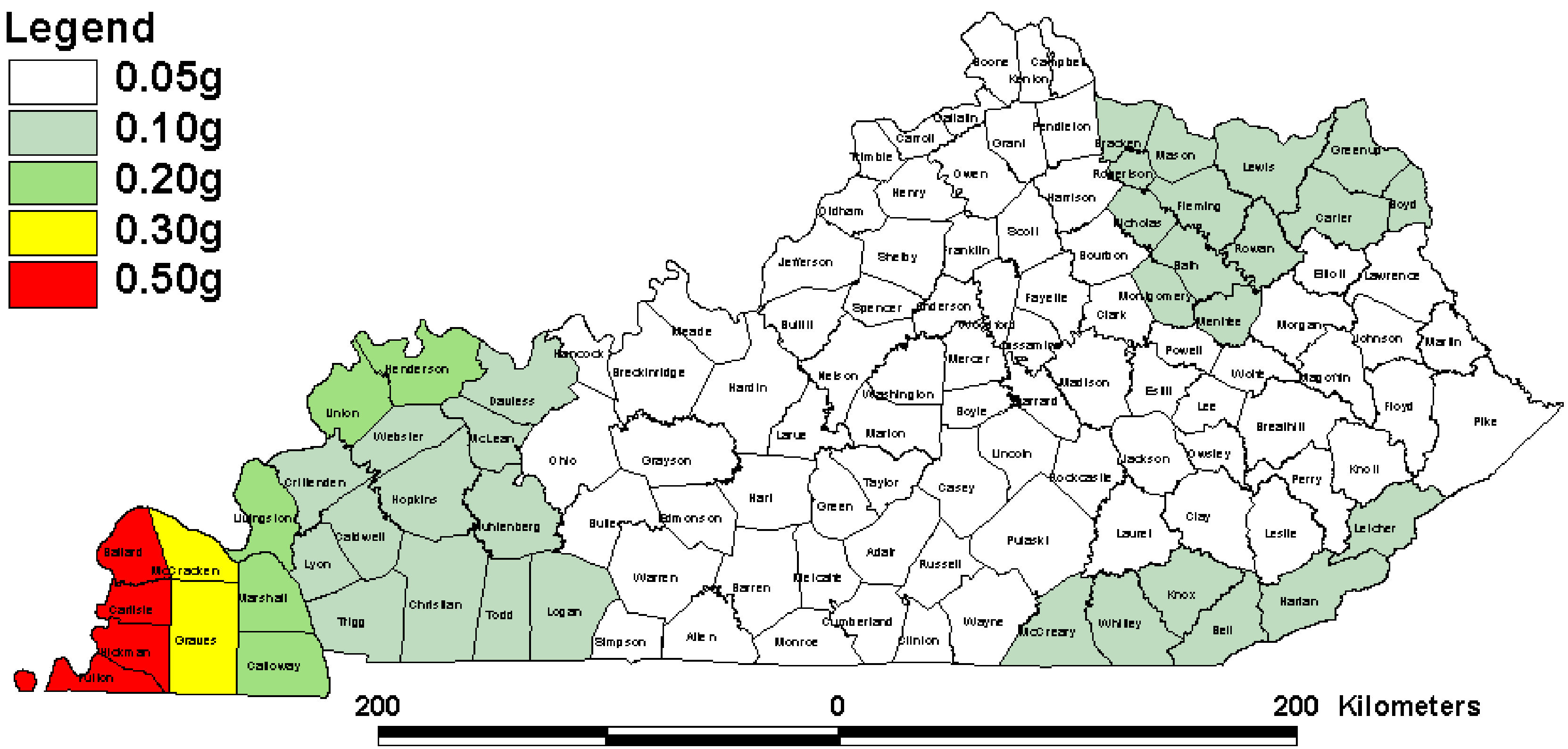


<u>For one characteristic Earthquake:</u>
<u>SHA becomes DSHA</u>

Ground motion at 30km:
0.44g PGA (median)
0.22g PGA (median–SD)
0.88g PGA (median+SD)
/RP≡500y



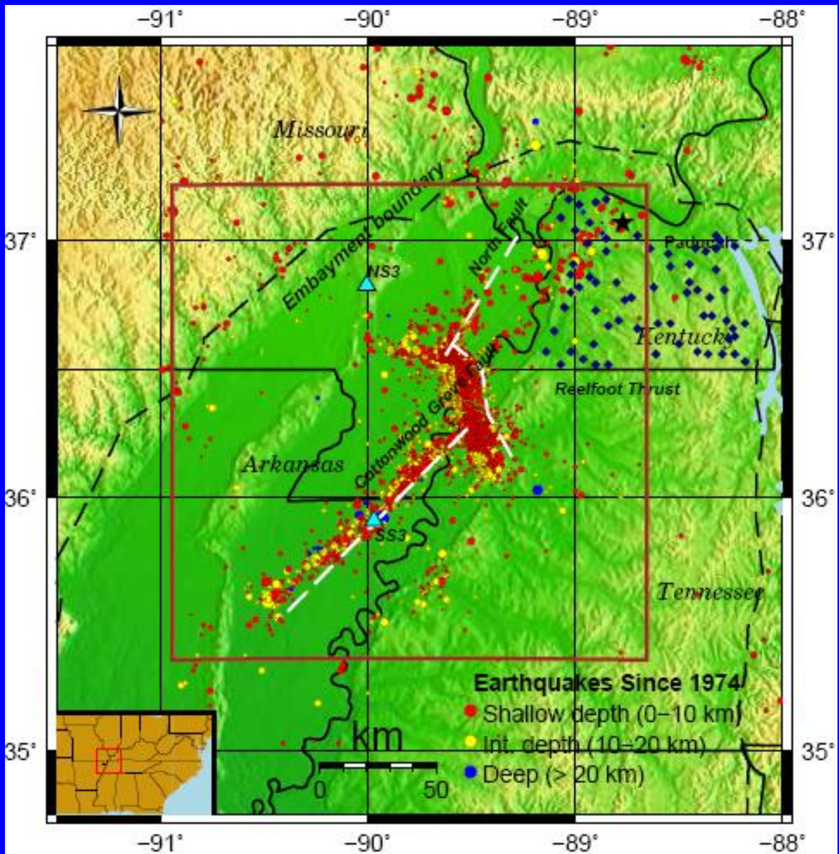
Maximum Credible Earthquake

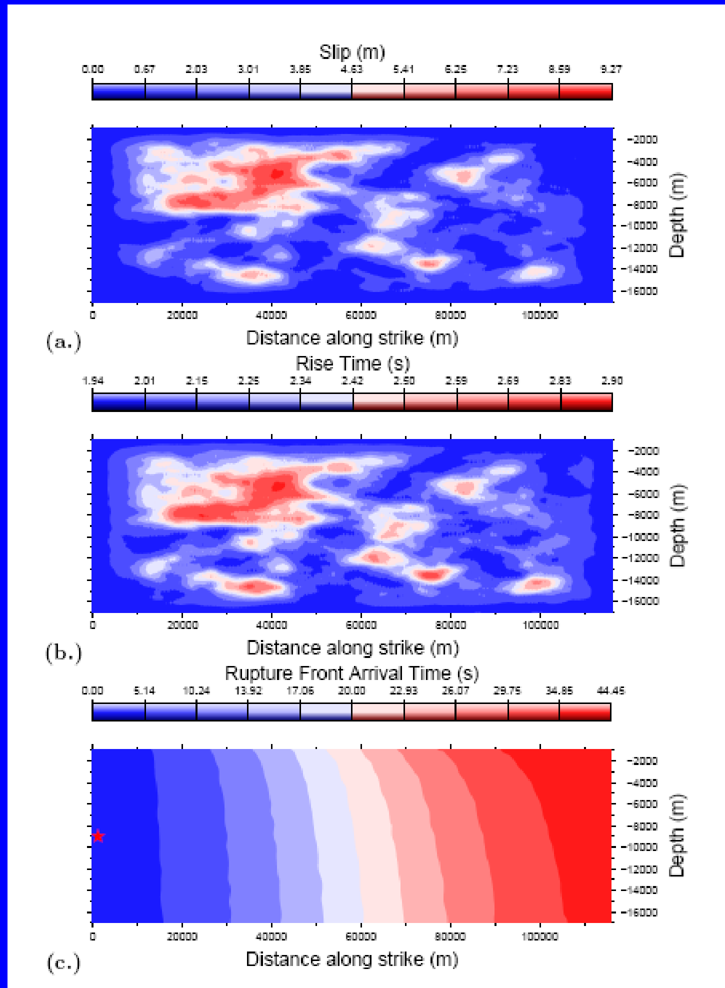


PGA for Maximum Credible Earthquake

SHA to DSHA to Neo-DSHA

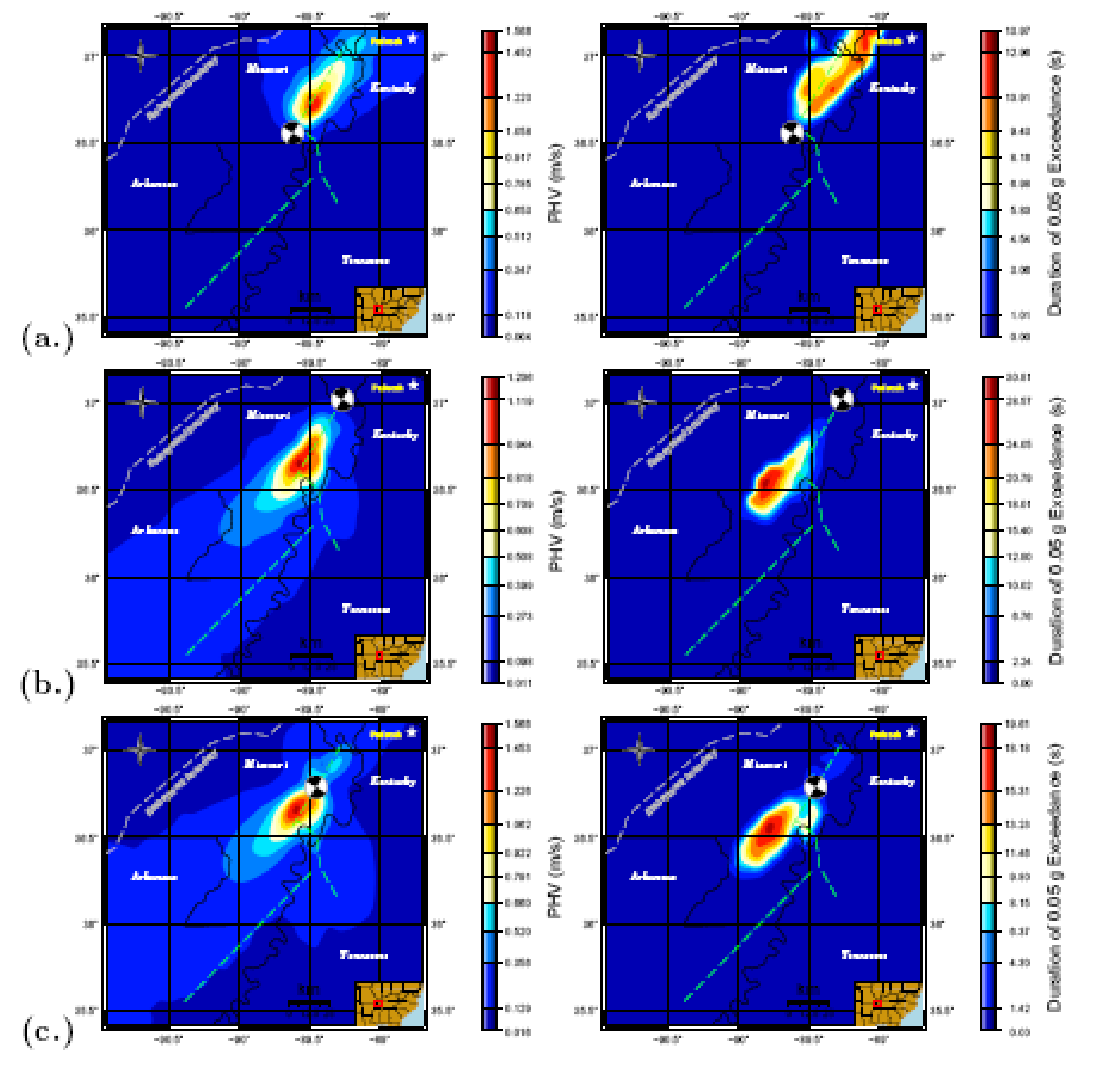
Neo-DSHA (Panza and others, 2001)





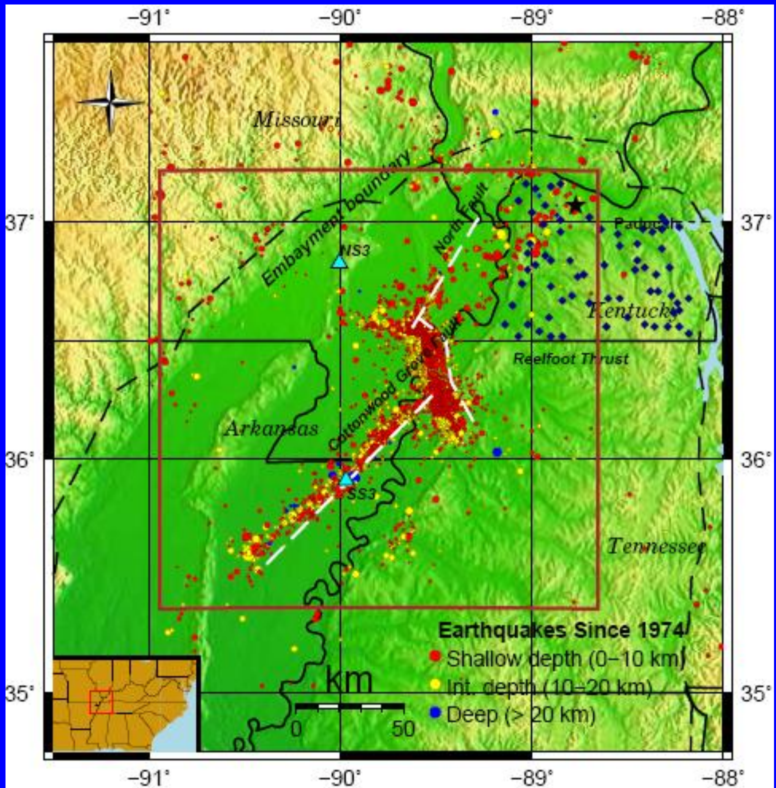
(Macpherson and others, 2009)

SHA to DSHA to Neo-DSHA

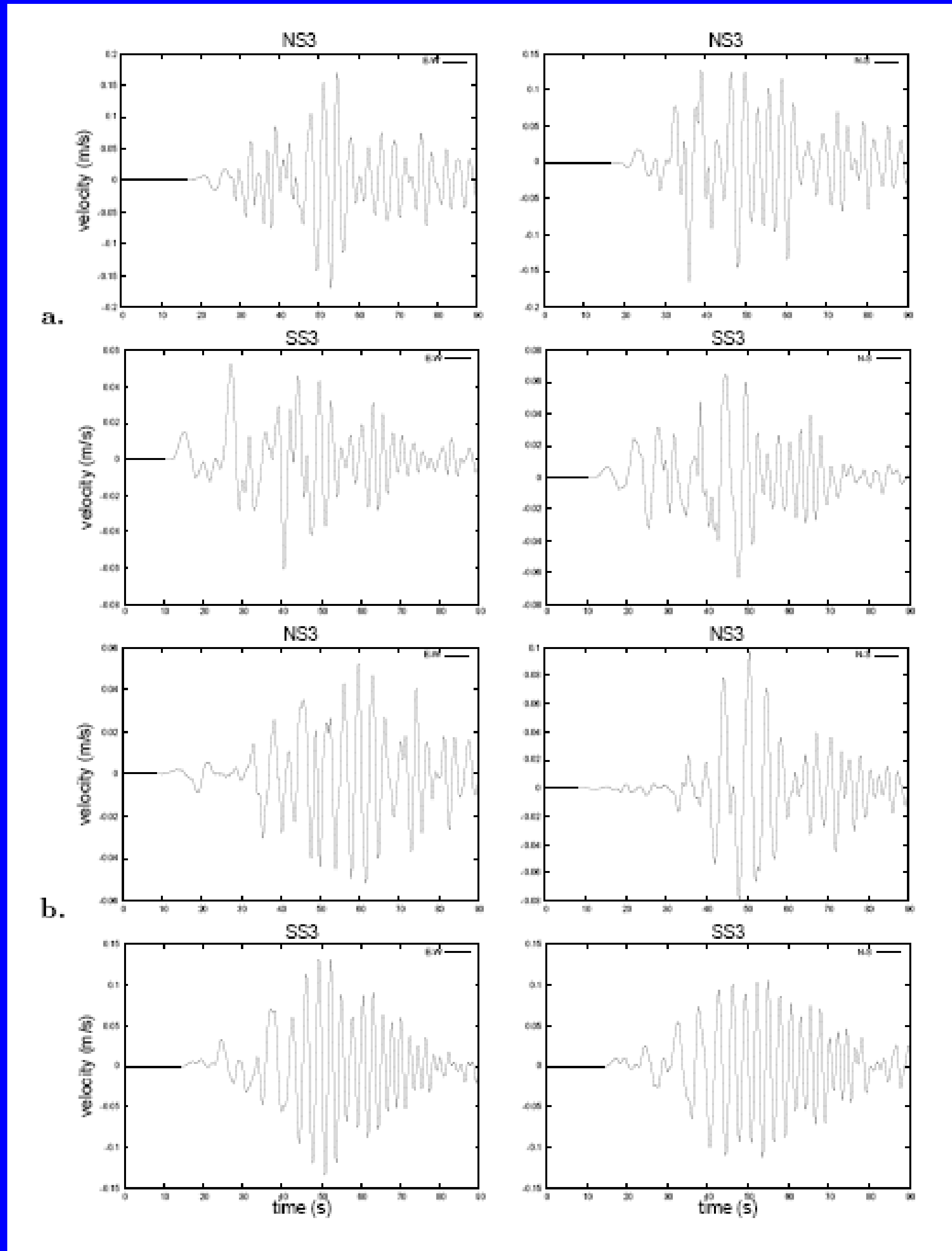


Limitation:
<0.5 Hz

SHA to DSHA to Neo-DSHA



Reelfoot (central) fault rupture



2. Seismic Hazard Assessment - Empirical

Seismic hazard curve: *A* vs. τ at a site

Step 1

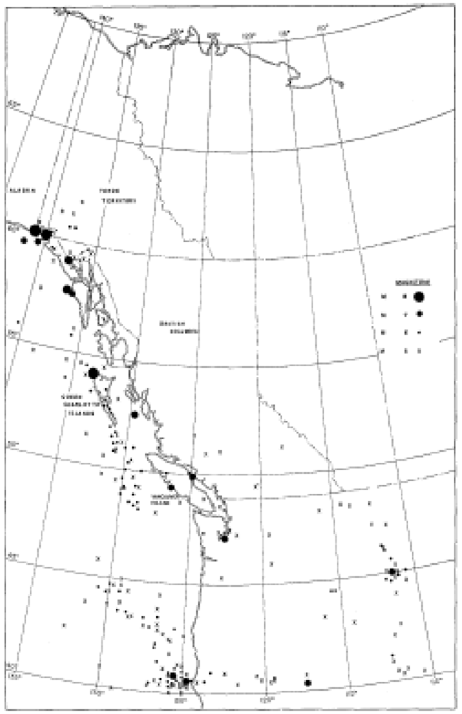
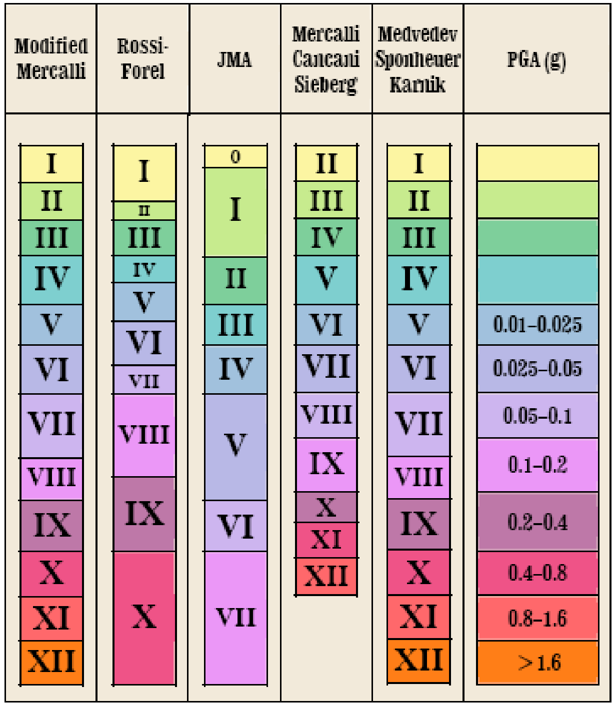


Fig. 1. Earthquake epicentres in western Canada.

(Historical records)

Step 2



Intensity table (Panza)

Step 3

Year	A (PGA,g)	Rank (m)	P
1895	0.001	96	0.888889
1896	0.01	84	0.777778
1897	0.1	29	0.268519

(ground motion at a site)

(Milne and Davenport, 1969)

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Step 3

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(ground motion at a site)

$$P = \frac{m}{N+1}$$

(N is total number of years of records)

$$\tau = \frac{1}{P} = \frac{N+1}{m}$$

Step 4

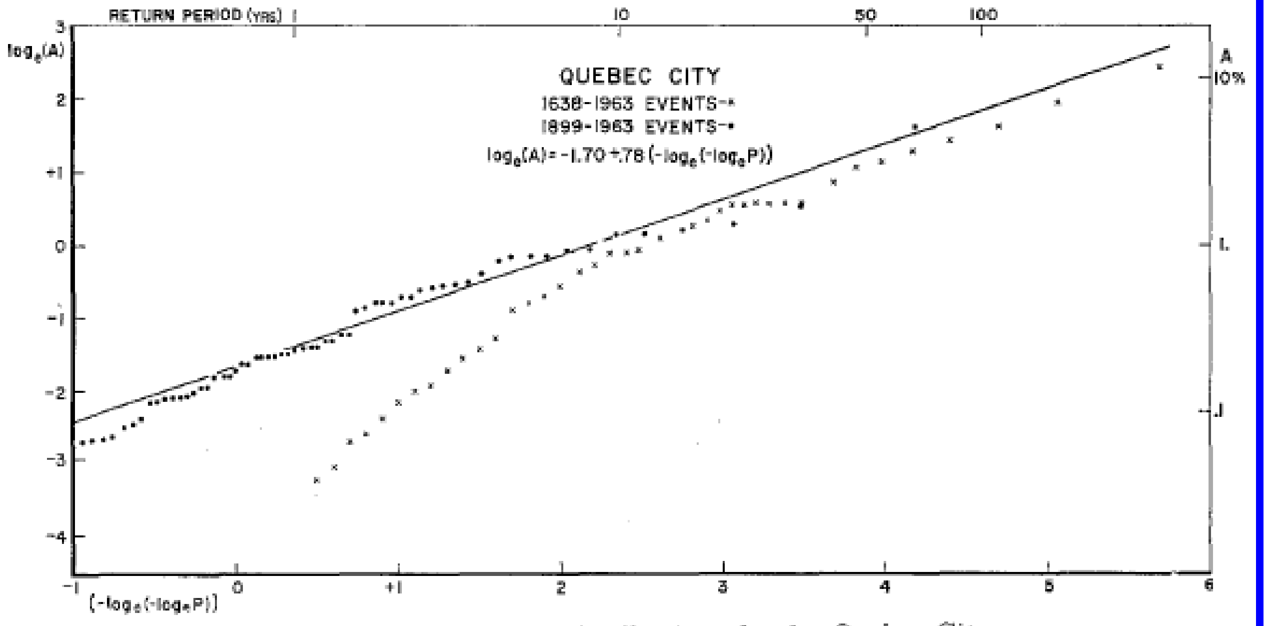
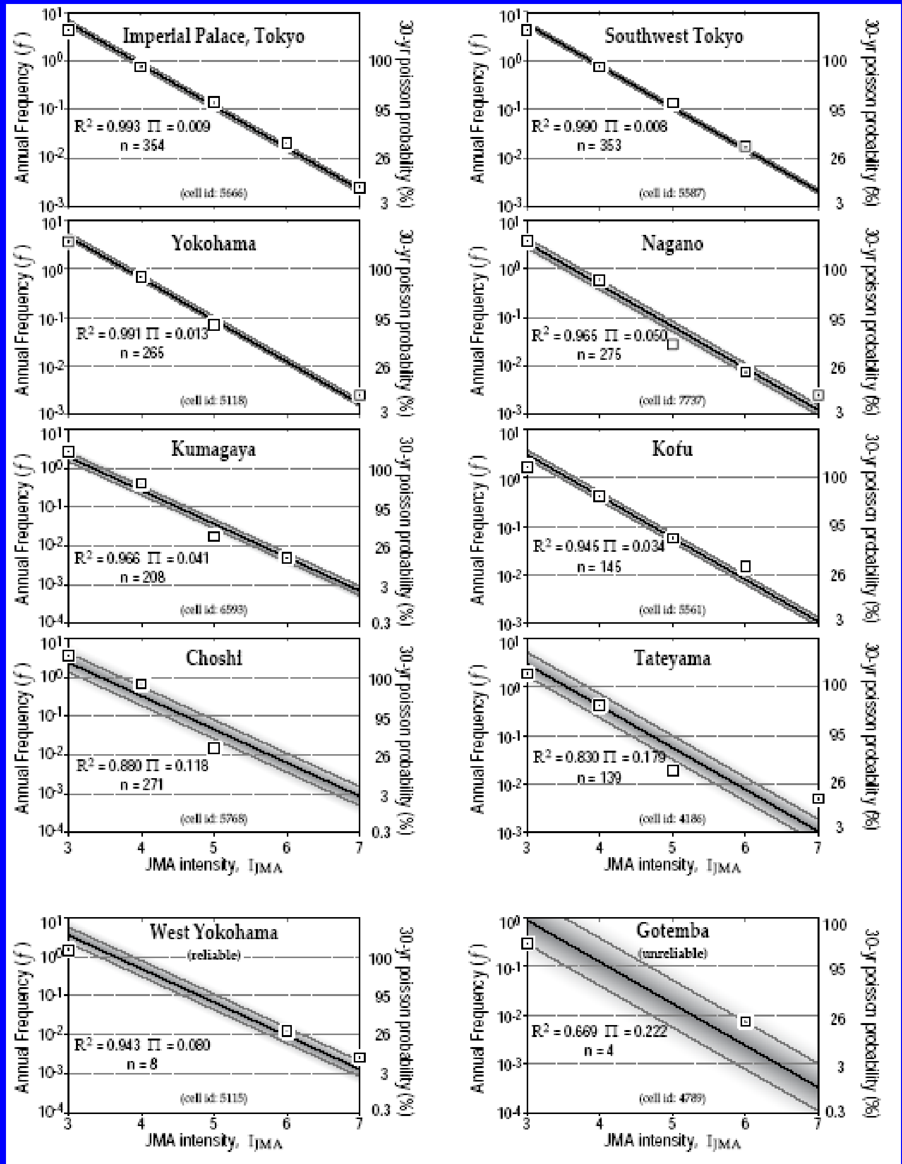


FIG. 13. Extreme value distribution plot for Quebec City.

Seismic hazard curves

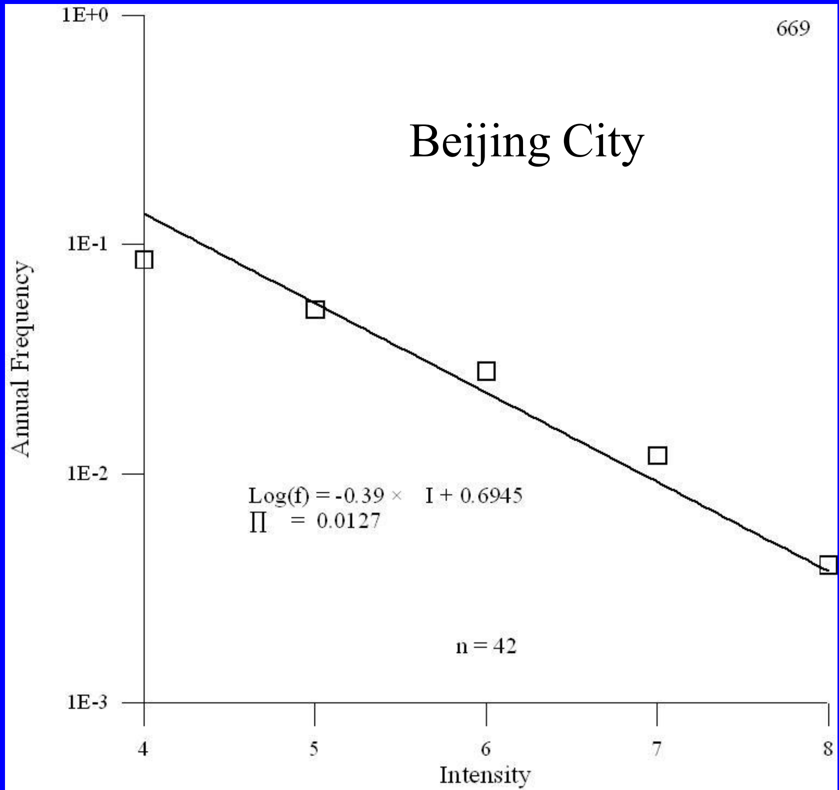
2. Seismic Hazard Assessment - Empirical

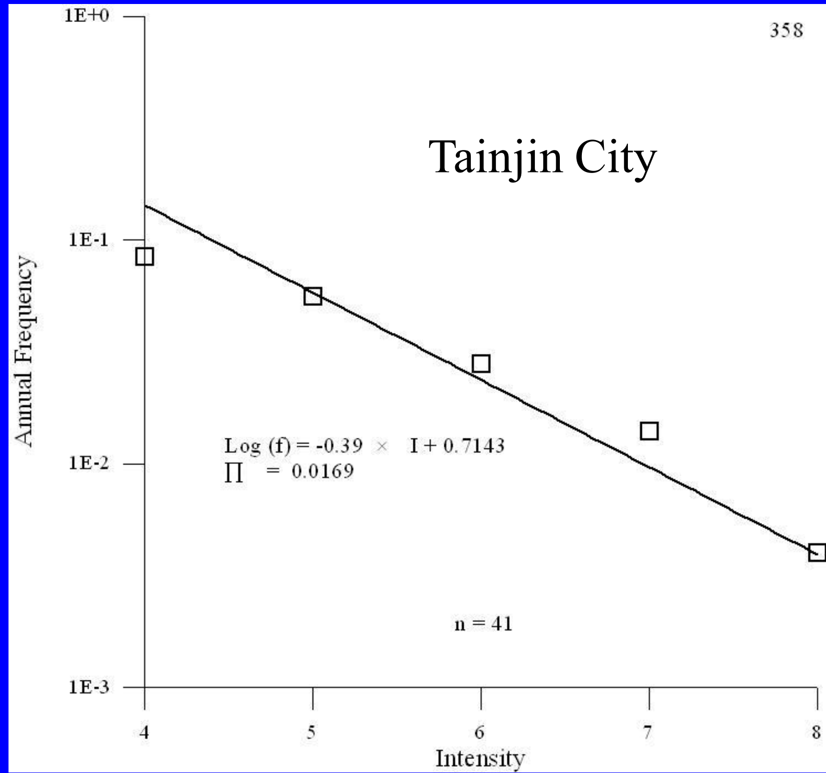


Tokyo, Japan
(400-year data)

(Bozkurt and others, 2007)

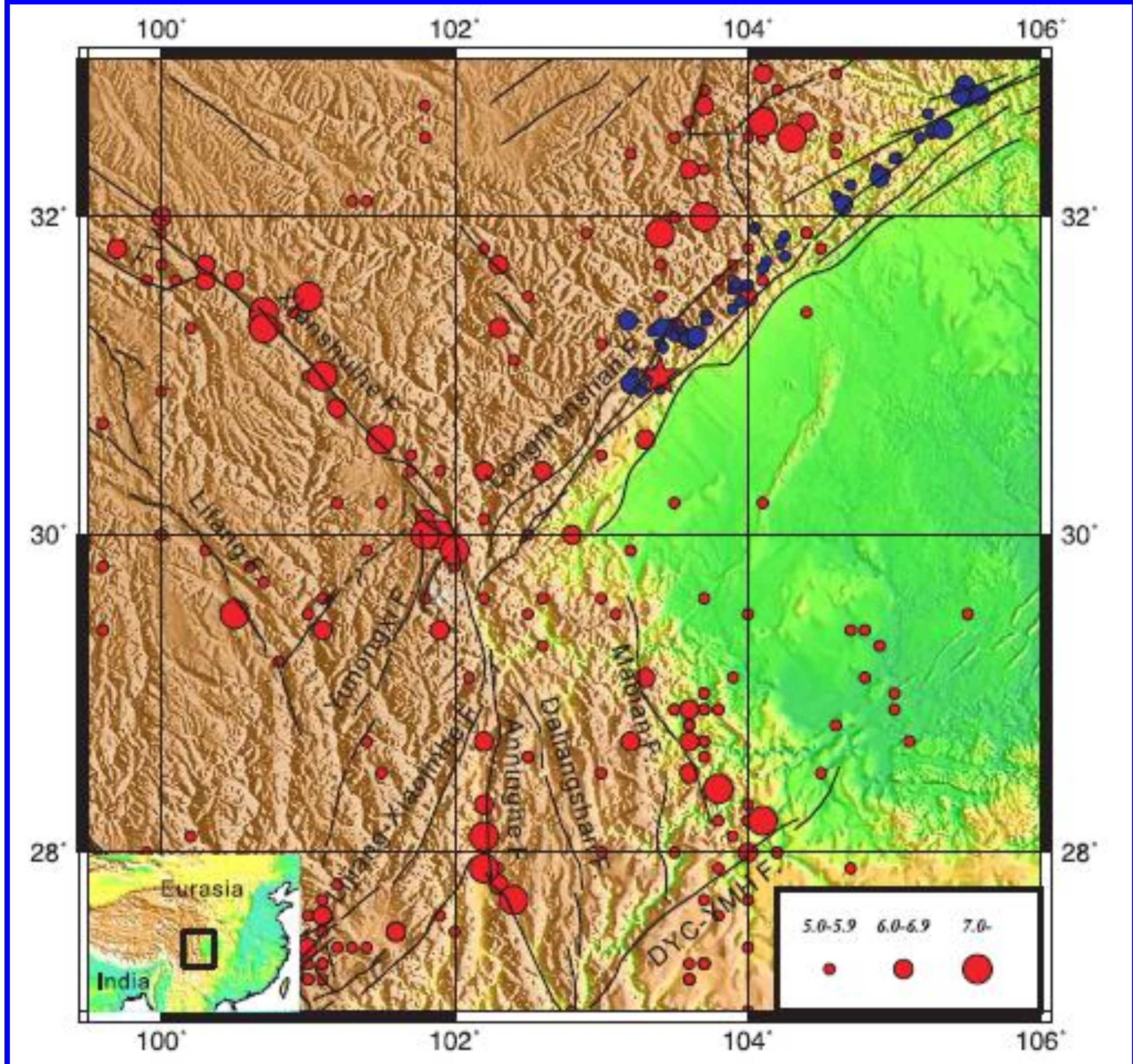
2. Seismic Hazard Assessment - Empirical





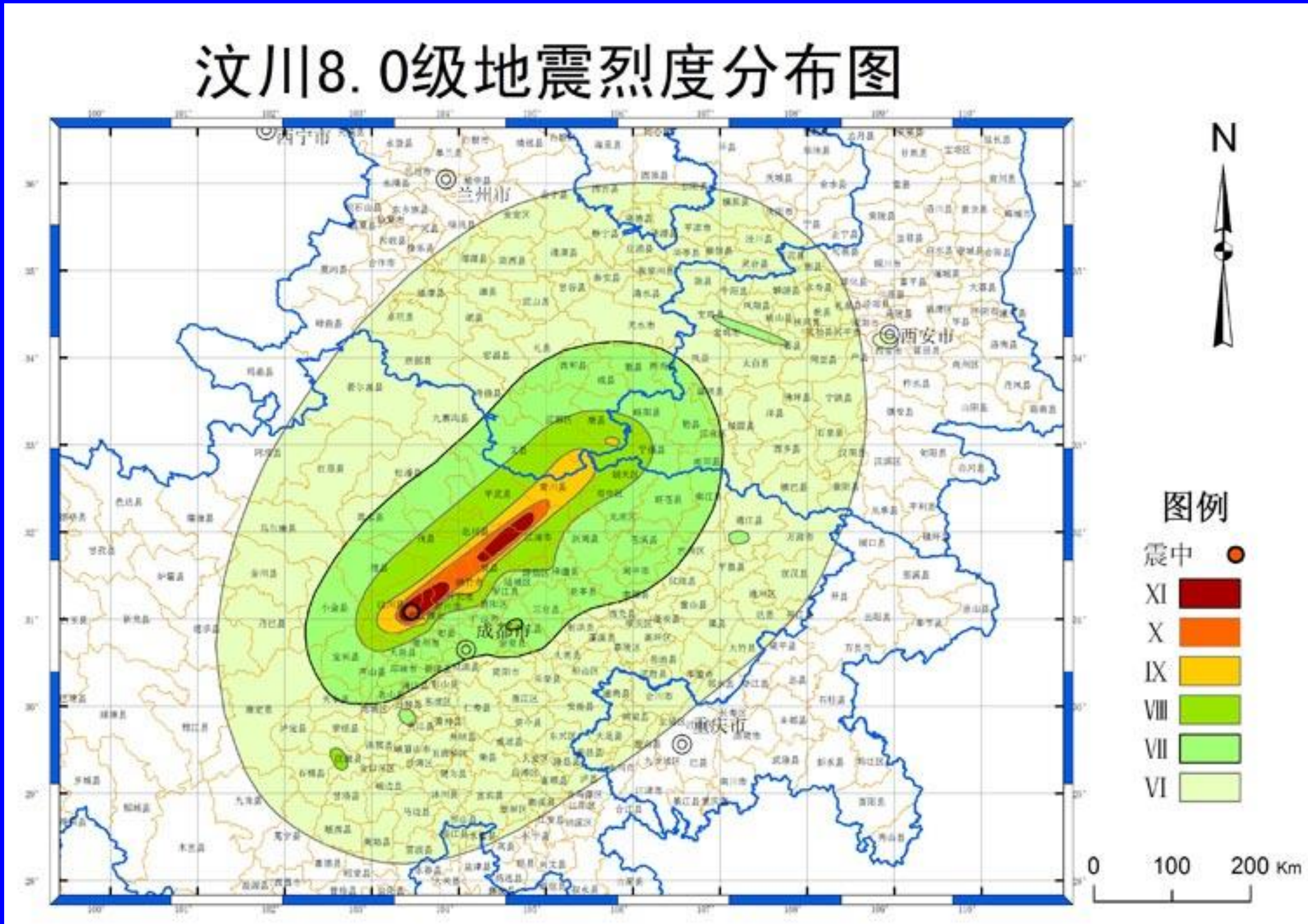
Beijing area, China (500 years data)
(Xie and others, in press)

Lesson from Wenchuan Earthquake

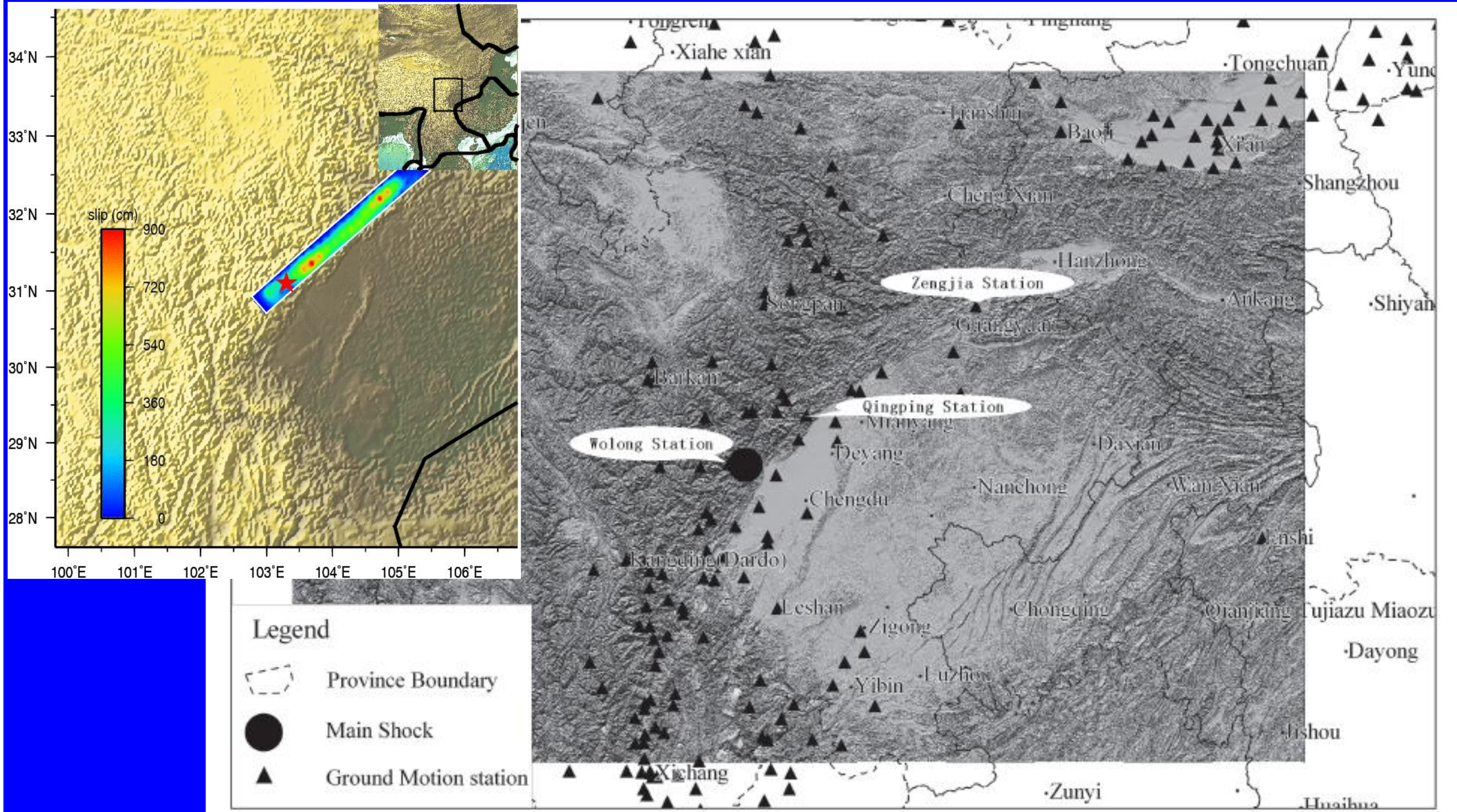


Magnitude: 8.0 (7.9 USGS)
Fault Rupture: ~300 km x 30 km
Surface Displacement: 5m (v), 4.8m (h)
Largest Recorded PGA: 0.65g
Death: ~70,000
Missing: ~20,000
Injured: ~380,000
Economic loss: >US$120B

Lesson from Wenchuan Earthquake



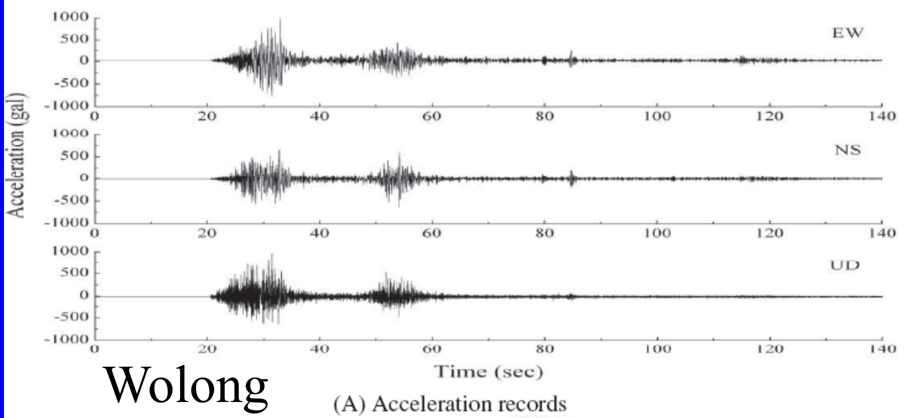
Lesson from Wenchuan Earthquake



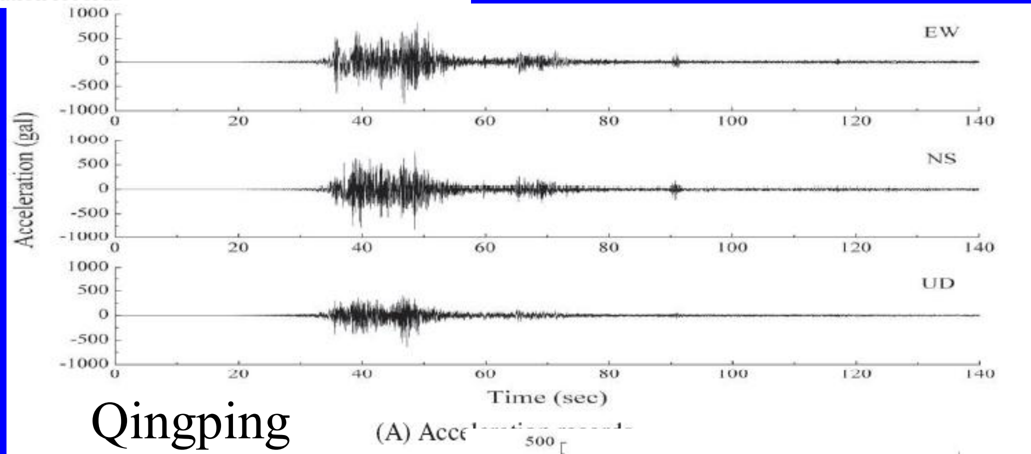
▲ **Figure 4.** Locations of strong-motion observation stations in the vicinity of the epicenter of the Wenchuan, China, earthquake of 12 May 2008 that recorded the mainshock. Locations of the three stations from which records are presented herein are indicated.

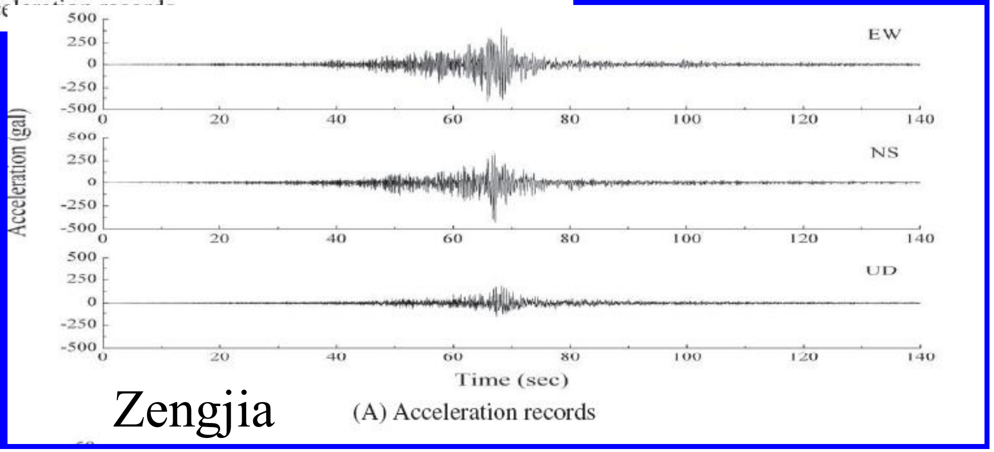
(Li and others, 2008)

Lesson from Wenchuan Earthquake

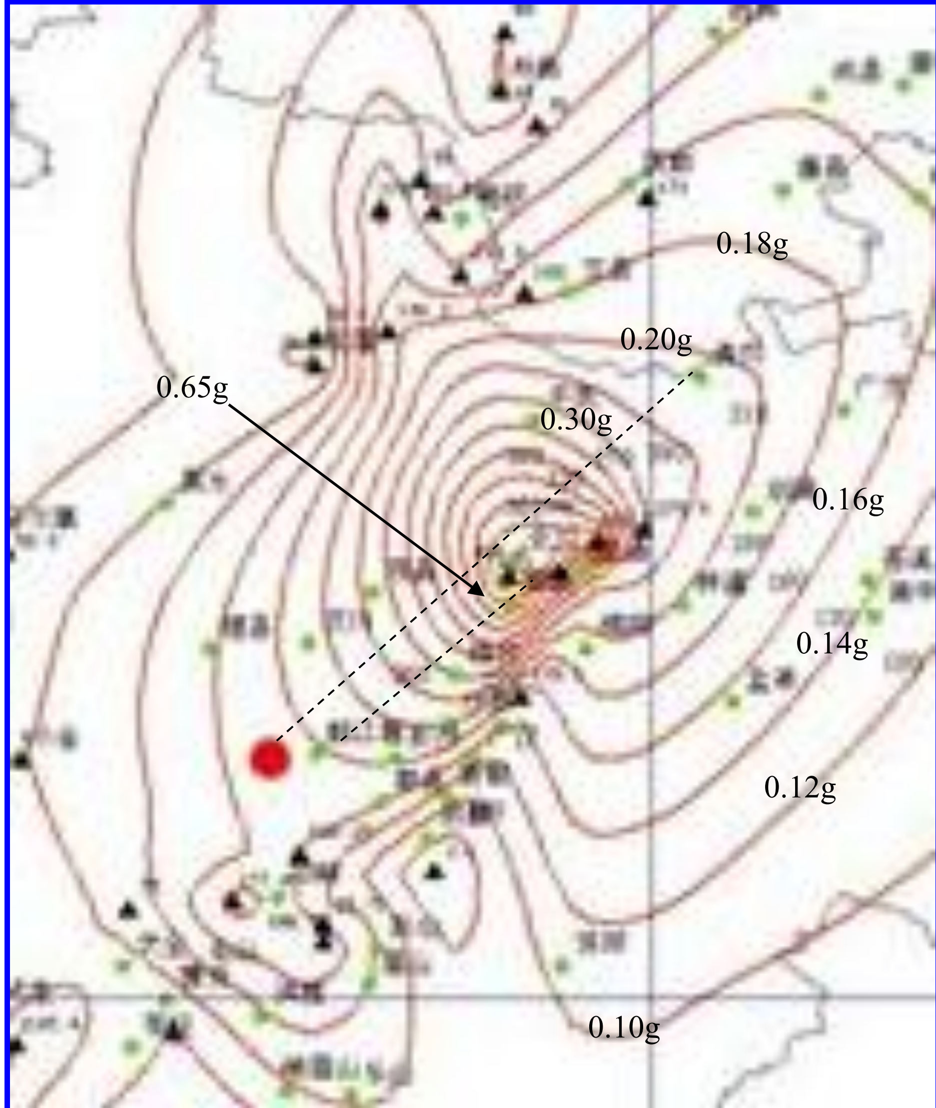


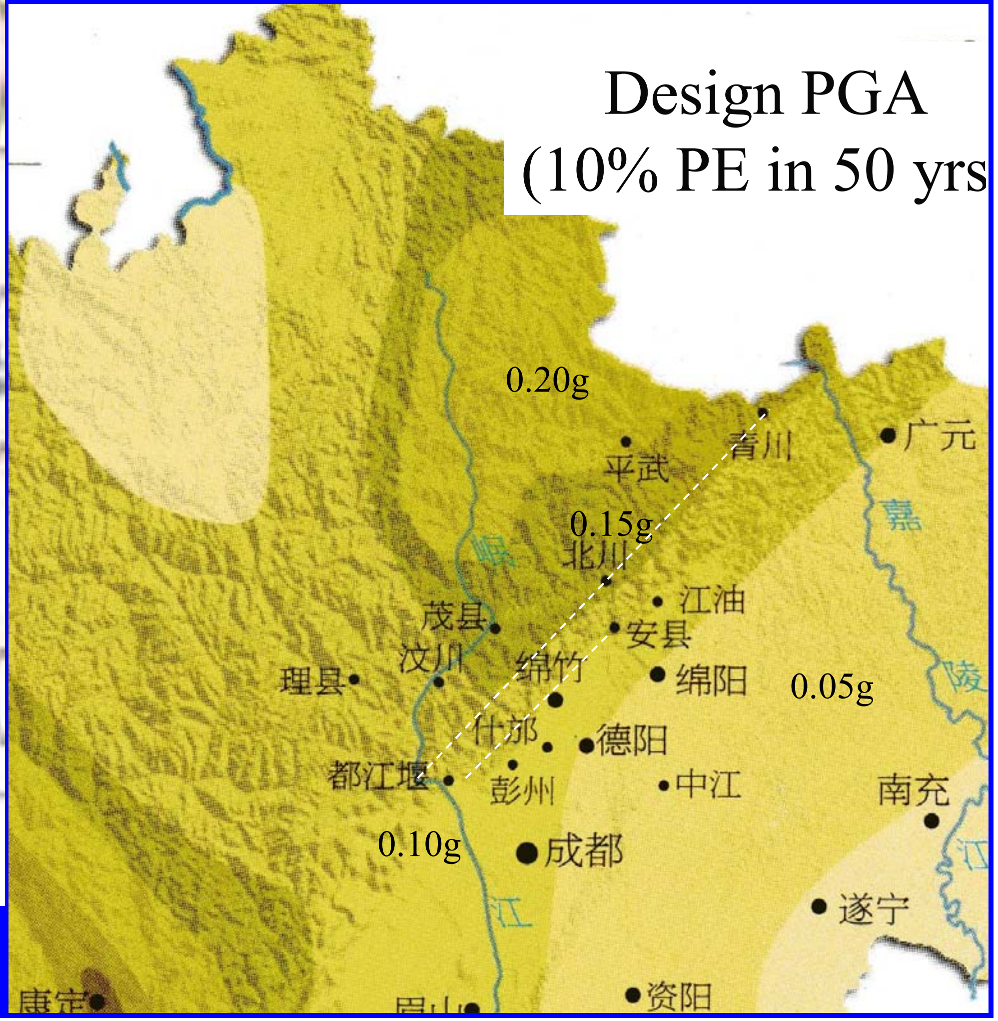
Rupture and asperity effects





Lesson from Wenchuan Earthquake





Summary

- Probabilistic seismic hazard analysis: PSHA (model) is flaw
  - Is not based on earthquake science
    - Invalid physical models
      - point source
      - Poisson distribution
    - Invalid mathematics
    - Mis-interpretation of annual probability of exceedance or return period
  - Become a pure numerical "creation"

Summary

- Alternative seismic hazard assessment
  - The goal of any seismic hazard assessment is to quantify
    - Physical measurement (ground motion)
    - Temporal measurement (when/how often)
    - Spatial measurement (where)
  - Approaches
    - Theoretical
      - SHA
      - DSHA
      - Neo-DSHA
    - Empirical

Summary

- Seismic hazard and risk are different concepts, and play different roles in policy making
- Earth-scientists, seismologists in particular, must
  - provide seismic hazard information that is consistent with modern sciences
  - also communicate the information in an understandable way
  - work with engineers and others to assess seismic risk

Thank you very much!