Credits: 3 + 0
PG 2019
Spring 2020 Semester

Performance-based Seismic Design of Structures

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- The material is taken solely for educational purposes. **All sources are duly acknowledged.**

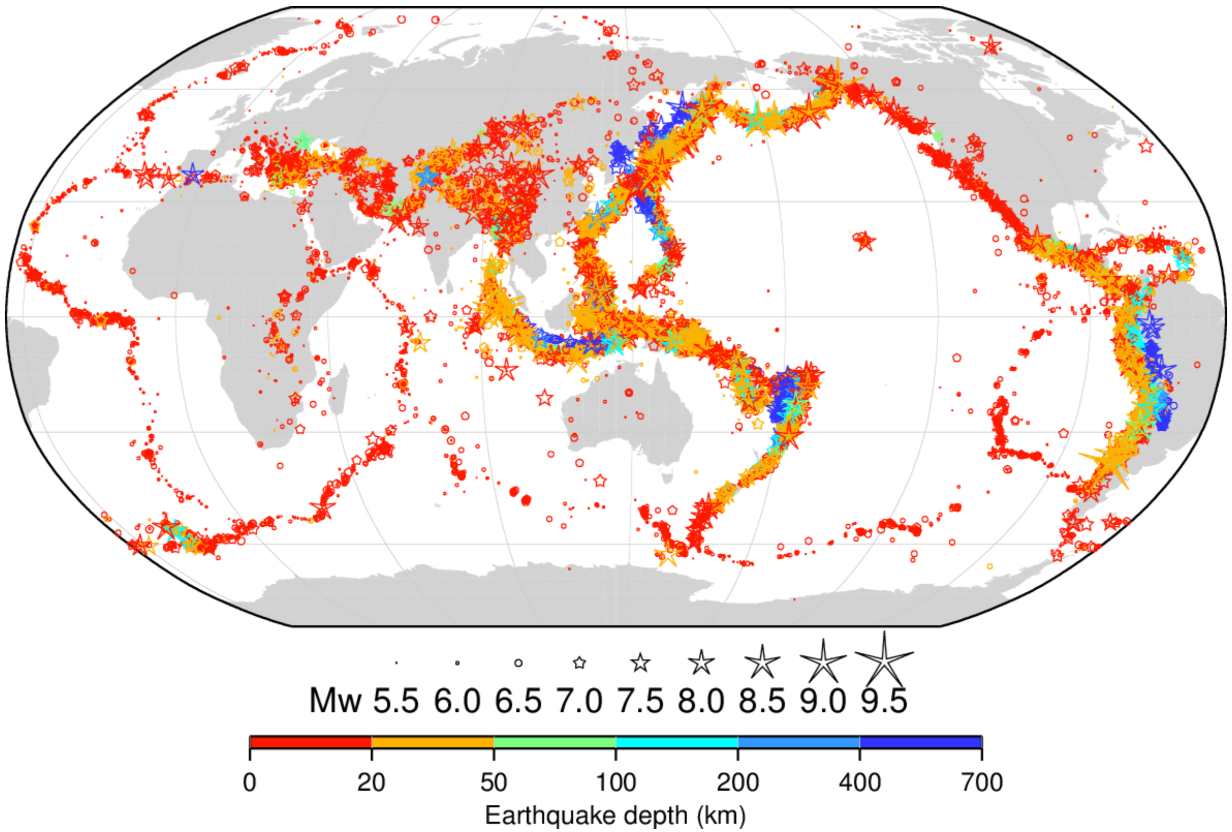
Lecture 2 (a): Introduction to Seismic Hazard Assessment

- Earthquake Hazards
- Seismic Hazard Assessment
- Probabilistic Seismic Hazard Assessment (PSHA)
  - PSHA Process
  - Magnitude-Recurrence Relationship
  - Attenuation Relationships
- Simplified PSHA
- Use of Probabilistic Ground Motions in Earthquake-resistant Design of Buildings
- Deaggregation of Seismic Hazard

Earthquake Hazards

Earthquake Hazards

- Earthquake is the most calamitous disaster
- 60% of all deaths by natural disasters are caused by Earthquakes [1]
- In 20th century, 17000 persons per year [2]



1. Shedlock and Tanner, 1999
2. Chen and Scawthorn, 2002

Figure Source: ISC

Earthquake Hazards

- Ground shaking
- Ground displacement along faults: surface rupture
- Ground failures: soil liquefaction, landslide, mud slide, differential soil settlement, etc.
- Tsunami
- Floods from dam and levee failures
- Fires resulting from earthquakes

Ground Shaking Hazard: Wenchuan Earthquake (2008), China

Magnitude = 8.0

Ground Shaking Hazard: Kashmir Earthquake (2005), Balakot, Pakistan (*Magnitude = 7.7)*

Ground Shaking Hazard: Yogyakarta Earthquake (2006), Indonesia

Magnitude = 6.2

Surface Rupture Hazard: The 1999 Chi-Chi earthquake, Taiwan

The 1999 Chi-Chi earthquake, Shih-Kang Dam

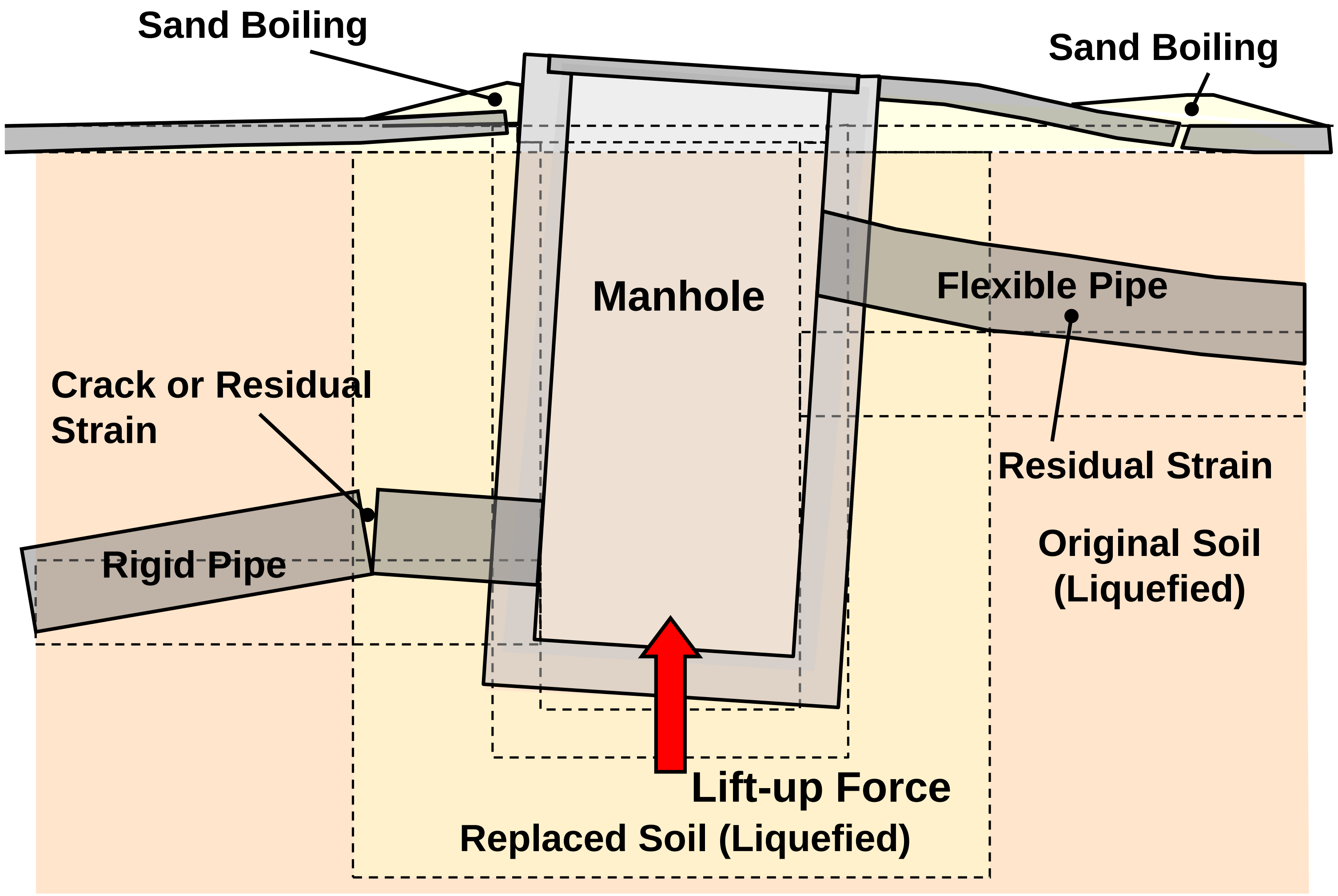
Soil Liquefaction Hazard

Loss of Bearing Capacity

A building in Dagupan, Philippines after the 1990 Luzon EQ

Overturned building in Adpazari, Turkey in the 1999 Kocaeli EQ

Damage to Sewers



Tokachi-oki EQ, Hokkaido (2003)

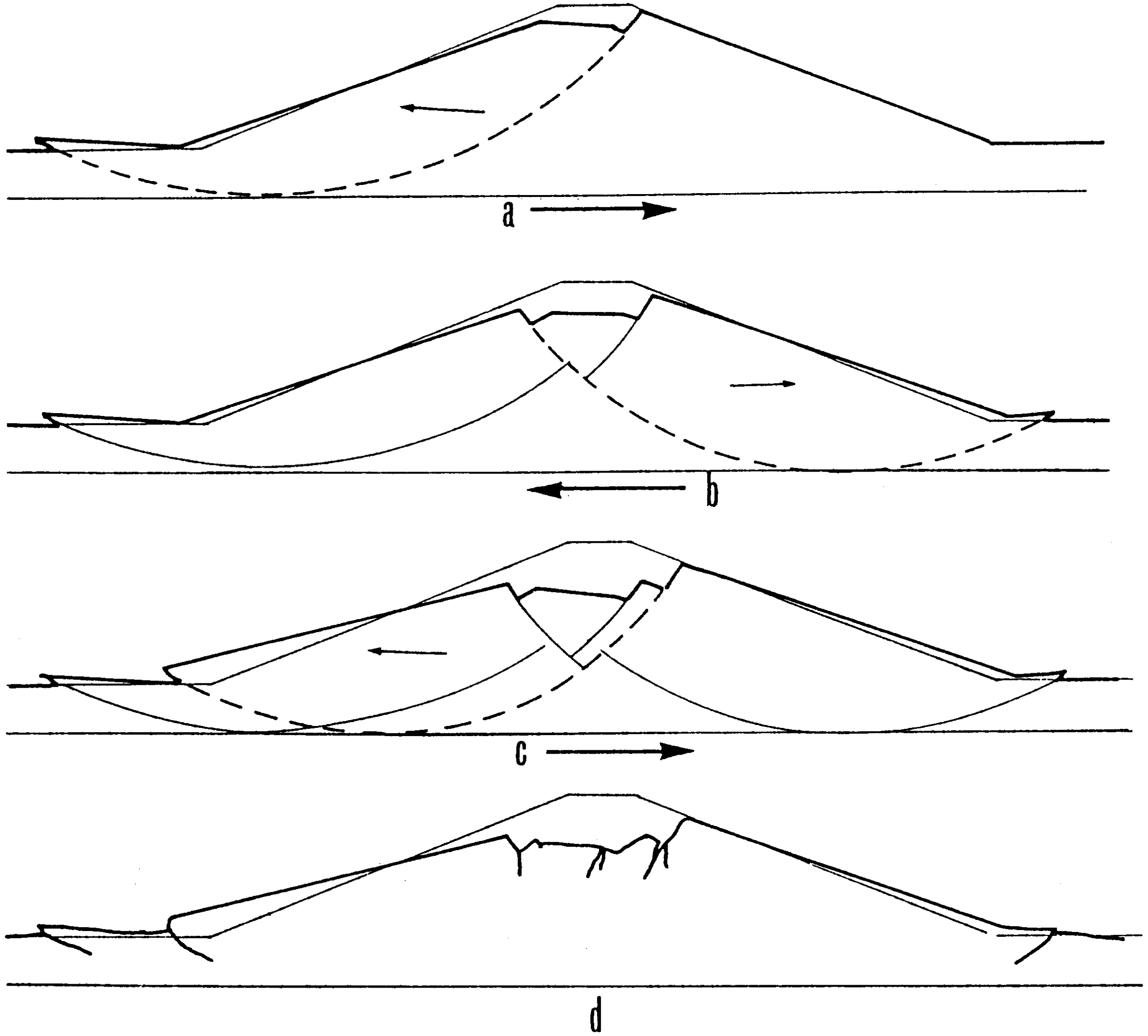
Underground Pipe Failure in Baguio, Philippines

(Luzon Earthquake, 1990)

Earthquake-induced Landslide in Wenchuan County, China

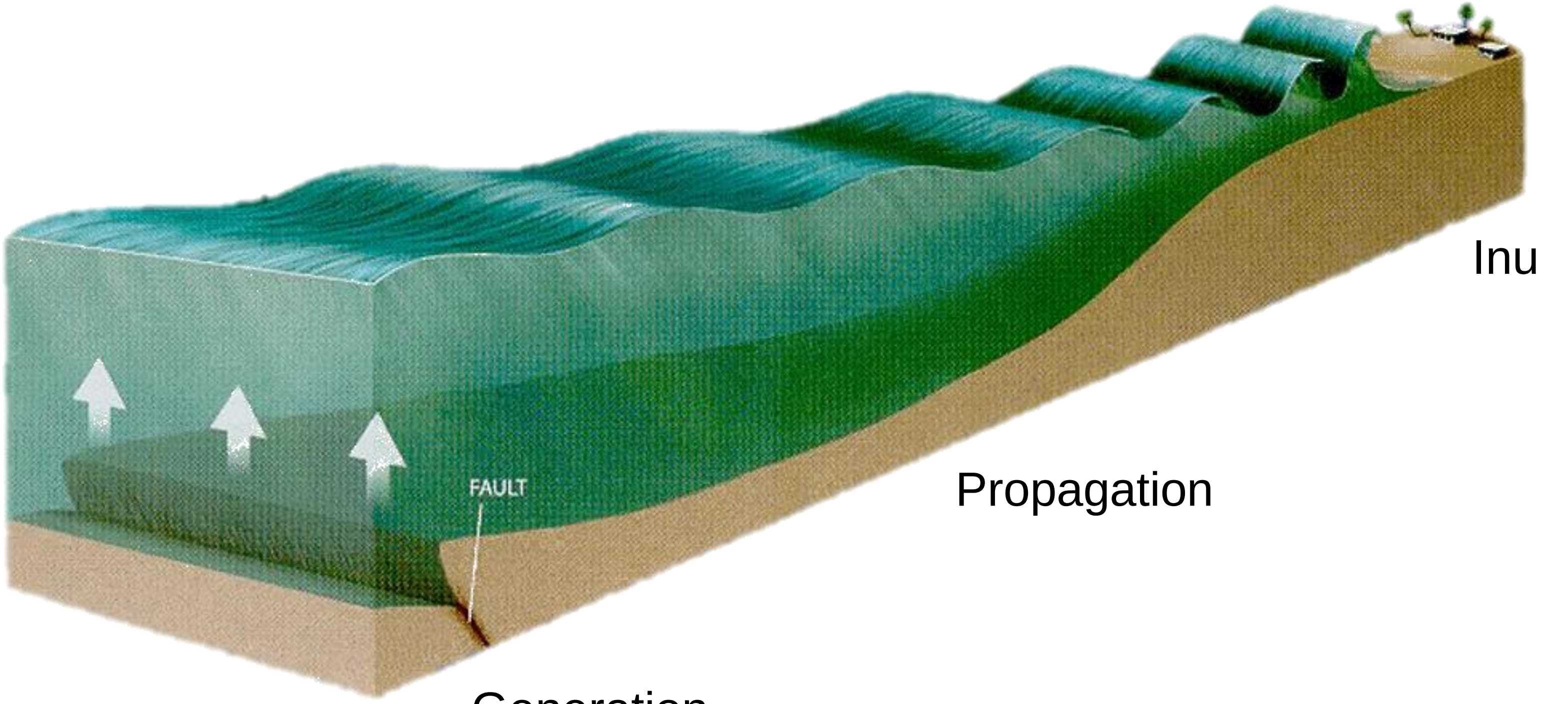
(Wenchuan Earthquake, 2008)

Dynamic Stability of Embankment



Bhuj earthquake 2001 Irrigation Dams

Tsunami generated by an Earthquake



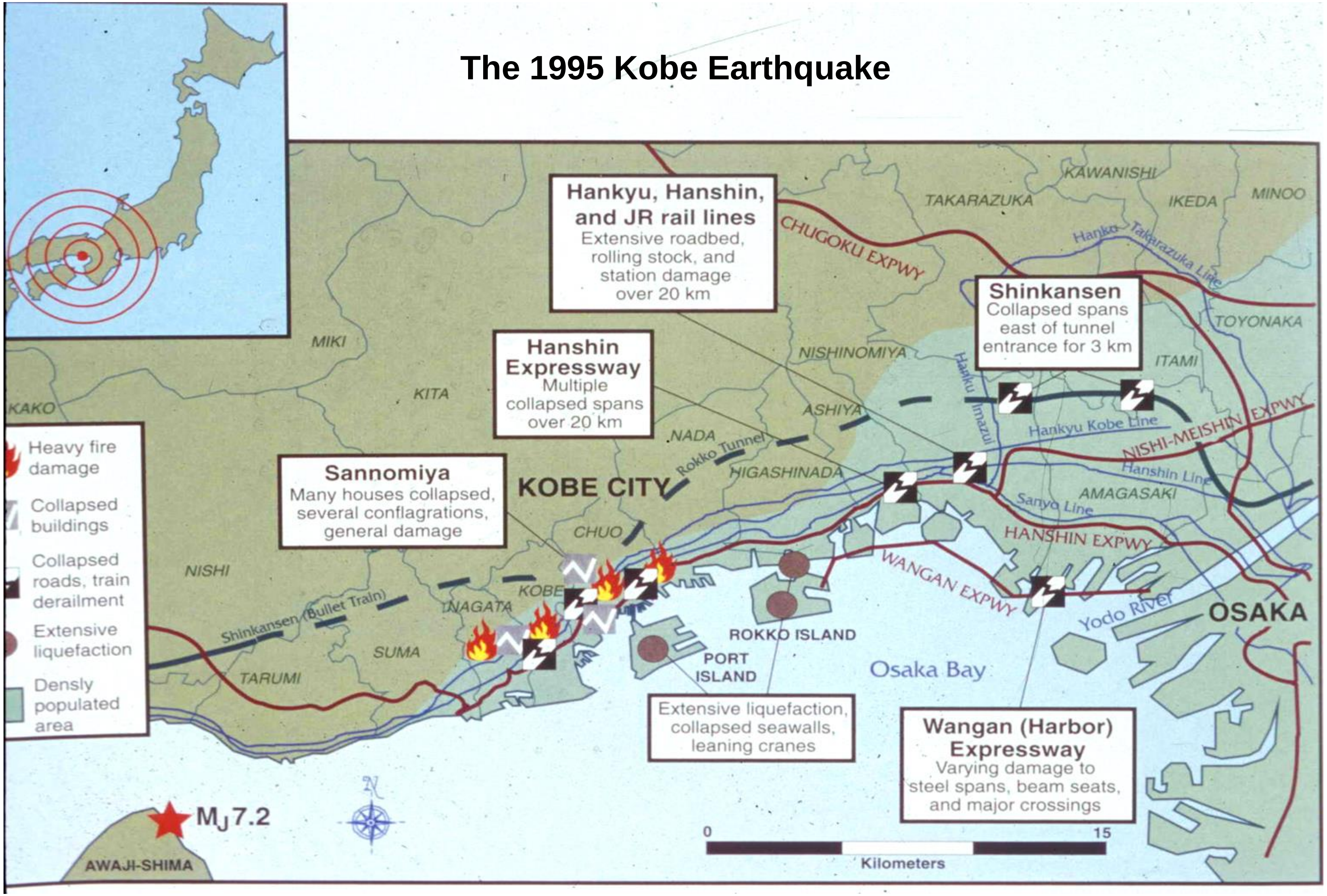
Inundation

Propagation

Generation


Khao Lak, Phang-Nga
Maximum Water Level

The 1995 Kobe Earthquake



Fires resulting from the Earthquake (Kobe EQ, 1995)

Fires resulting from the Earthquake (Kobe EQ, 1995)

Basic Questions

- Where will future earthquakes occur?
- What will be their size?
- What will be their frequency of occurrence?
- What will be the ground shaking intensity at the site produced by earthquakes of different size, focal depth, and epicentral location?
- How will the ground motion be influenced by local soil conditions and geology?
- What will be the earthquake hazards (landslide, liquefaction, etc.) produced at the site?
- How about the susceptibility of buildings and structures to damage from the ground shaking and ground failures?

Lack of Resources for Communities

Population

Natural or Man-made Phenomena

Inappropriate Built Environment

Urbanization and Un-planned development

Disaster = **H**azard . **V**ulnerability . **E**xposure

Risk

(Risk = Hazard . Vulnerability)

To reduce risk of disaster and increase safety,
we need to estimate hazard properly,
and Reduce **Vulnerability**

Seismic Hazard Assessment

Seismic Hazard Assessment

SEISMIC HAZARD × SEISMIC VULNERABILITY = SEISMIC RISK

- In principle, **Seismic Hazard Assessment (SHA)** can address any natural hazard associated with earthquakes, including ground shaking, fault rupture, landslide, liquefaction, or tsunami.

- However, most interest is in the estimation of **ground-shaking hazard**, since it causes the largest economic losses in most earthquakes.

- Moreover, of all the seismic hazards, **ground motion is the predominant cause of damage from earthquakes**; building collapses, dam failures, landslides, and liquefactions are all the direct result of ground motion.

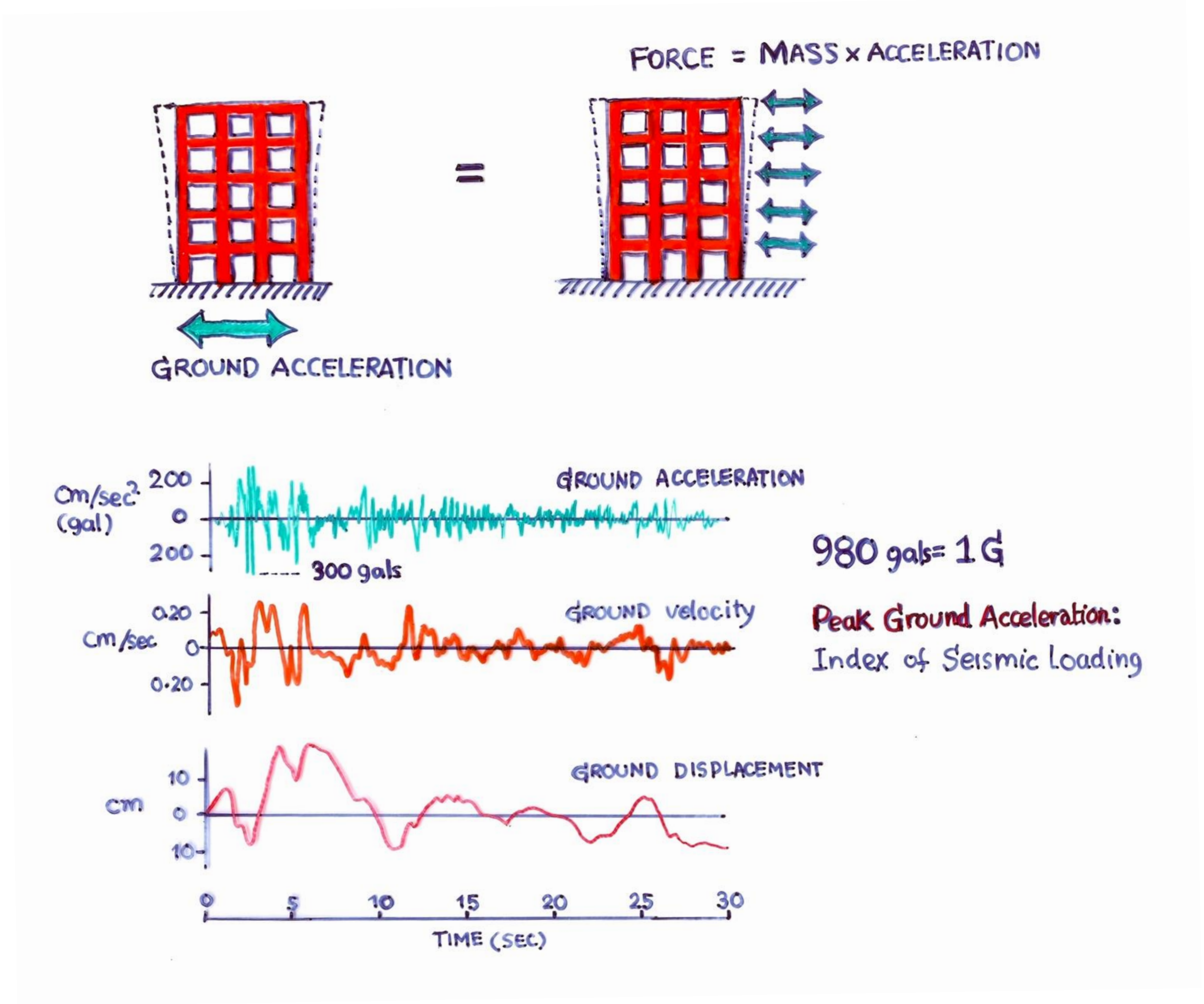
- *The Chapter, therefore, is restricted to the estimation of the* ***earthquake ground motion hazard***

Ground Motion Parameters

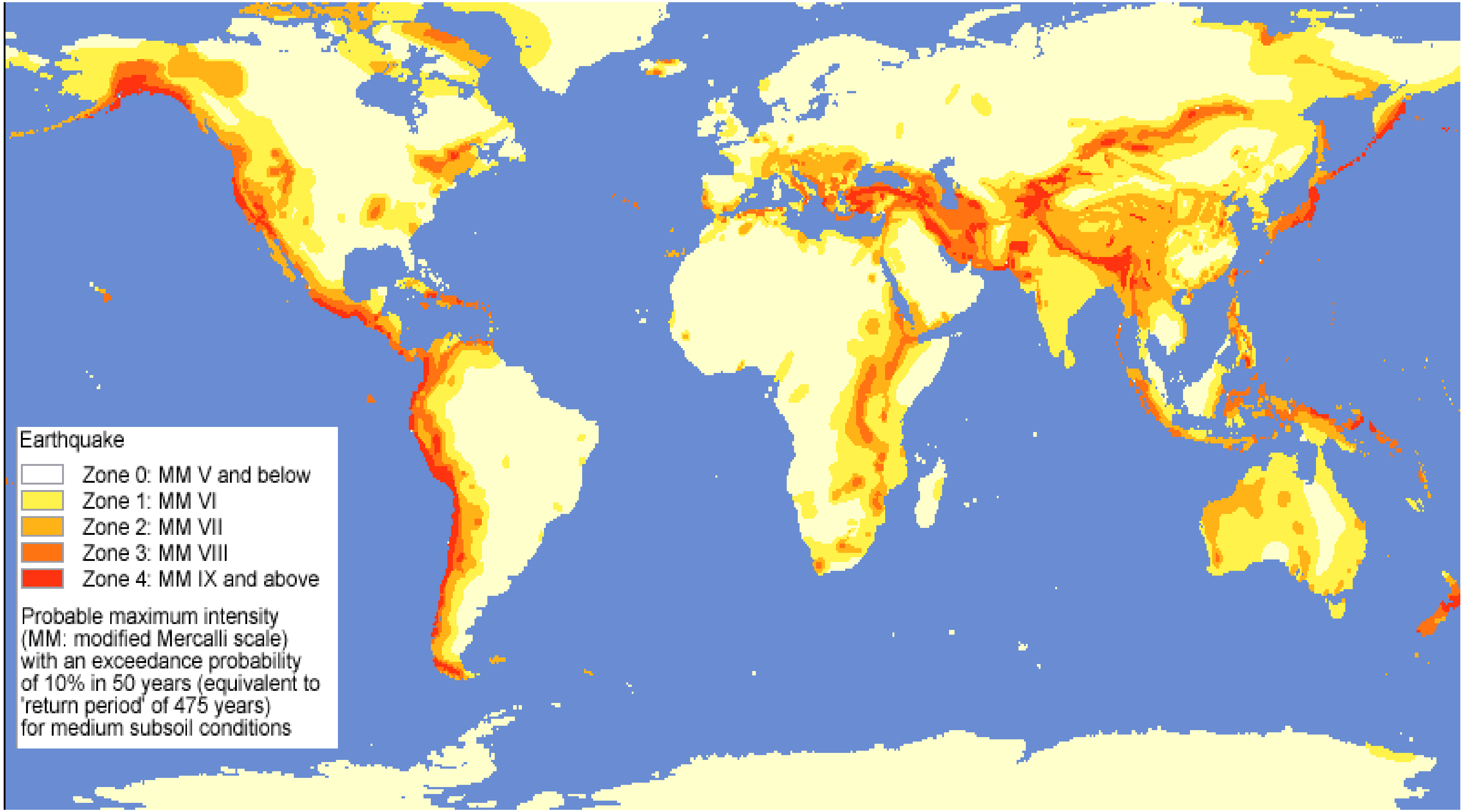
- There are many different ground motion parameters—displacement, velocity, acceleration, or MMI.

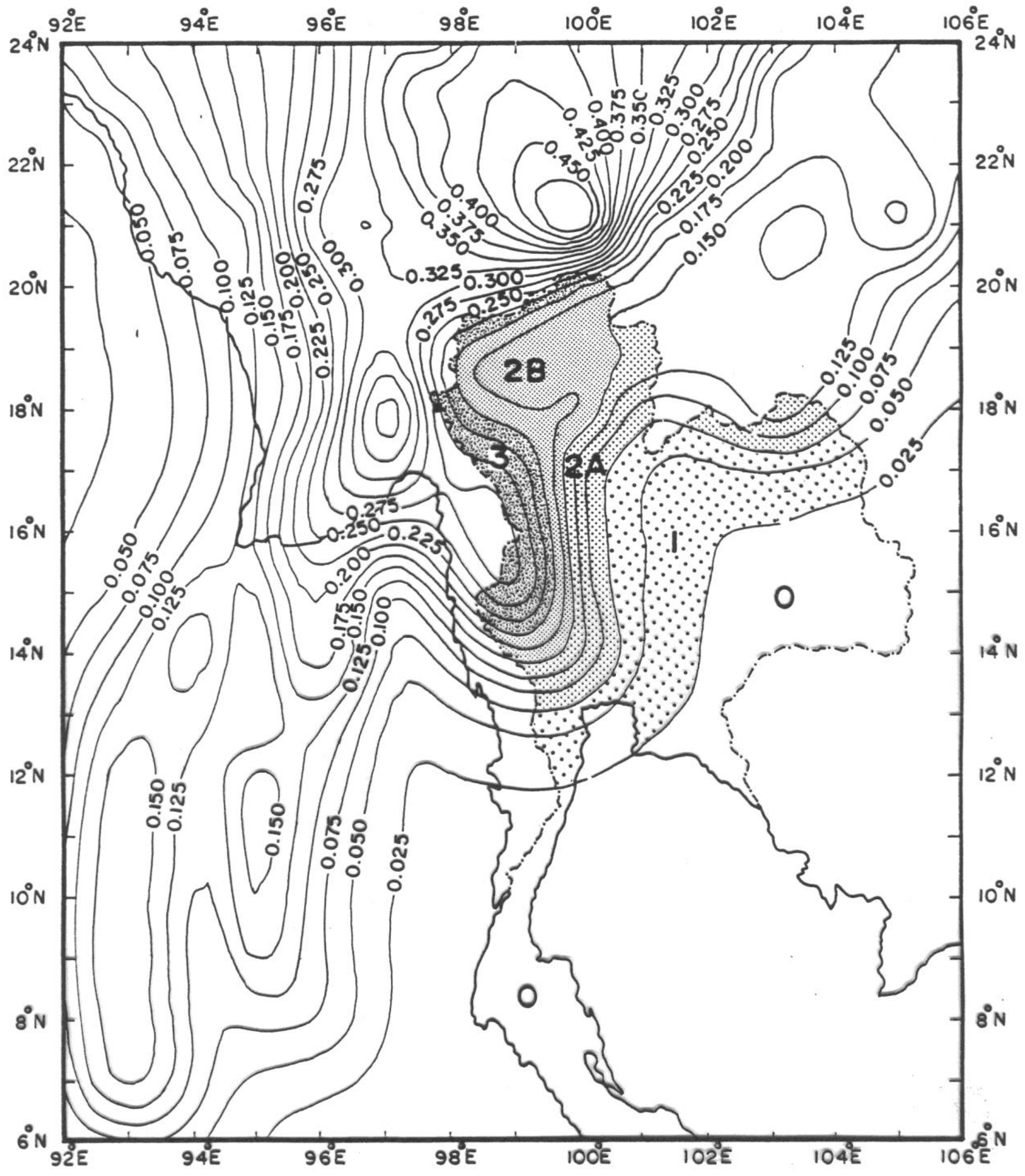
- Usually Peak **Ground Acceleration (PGA)** is considered to be the preferred ground motion parameter.

- **Seismic Hazard = Ground-shaking Hazard = the probability of occurrence of potentially destructive seismic ground shaking at a given site within a given time interval.**


FORCE = MASS x ACCELERATION
=
GROUND ACCELERATION
cm/sec²
(gal)
200
0
200
300 gals
GROUND ACCELERATION
0.20
cm/sec
0
0.20
GROUND velocity
10
cm
0
10
GROUND DISPLACEMENT
0
5
10
15
20
25
30
TIME (SEC)
980 gals= 1 G
Peak Ground Acceleration:
Index of Seismic Loading

Global Seismic Hazard Map





Seismic Hazard Map of Thailand

This map shows contours of PGA (in unit of *g*) with 10% probability of exceedance in a 50-year exposure period.

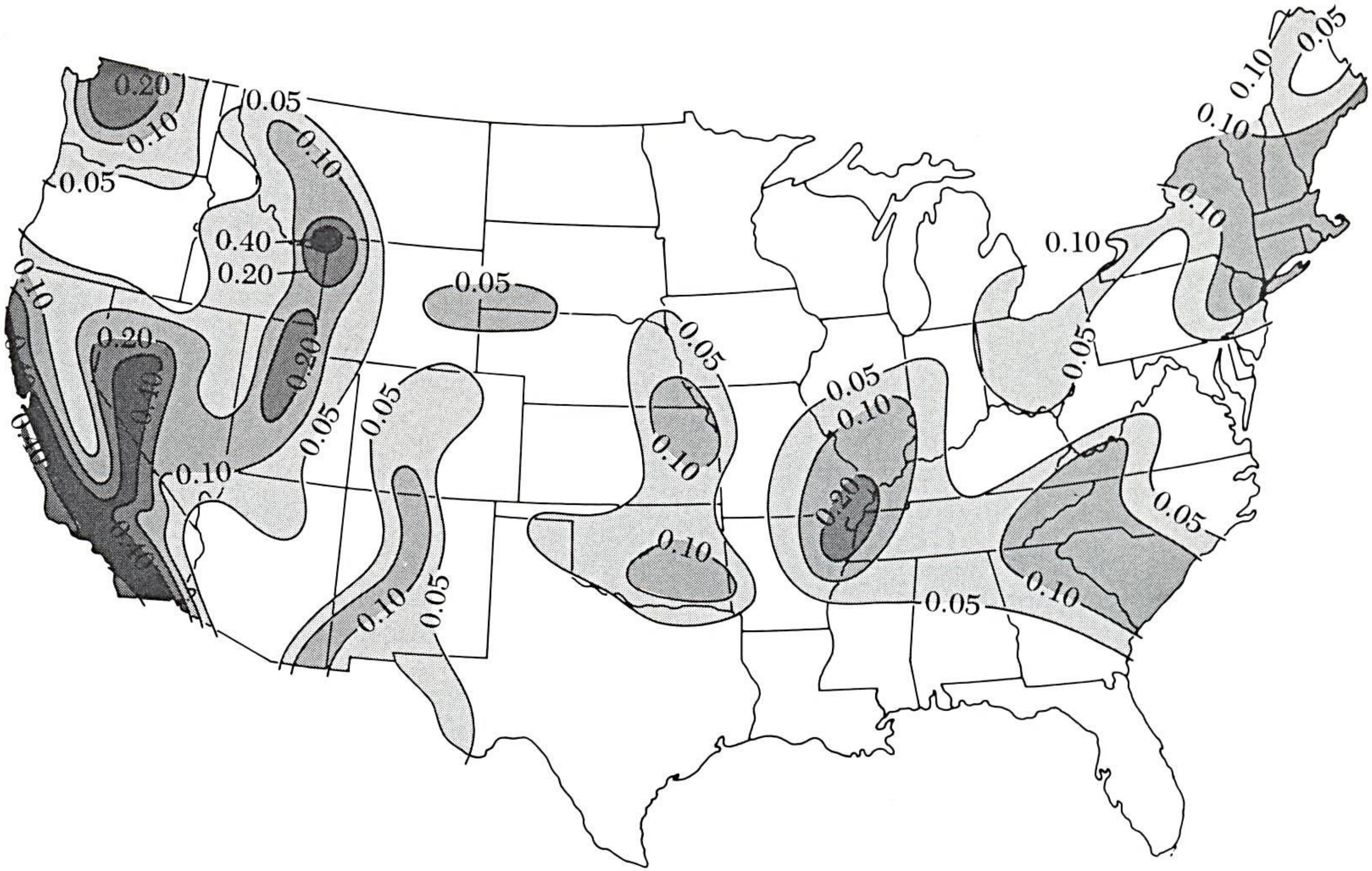


FIGURE 1

A new seismic risk map for the United States, prepared for the Applied Technology Council in 1976–77. The contours indicate effective peak, or maximum, acceleration levels (values are in decimal fractions of gravity) that might be expected (with odds of only 1 in 10) to be exceeded during a 50-year period.

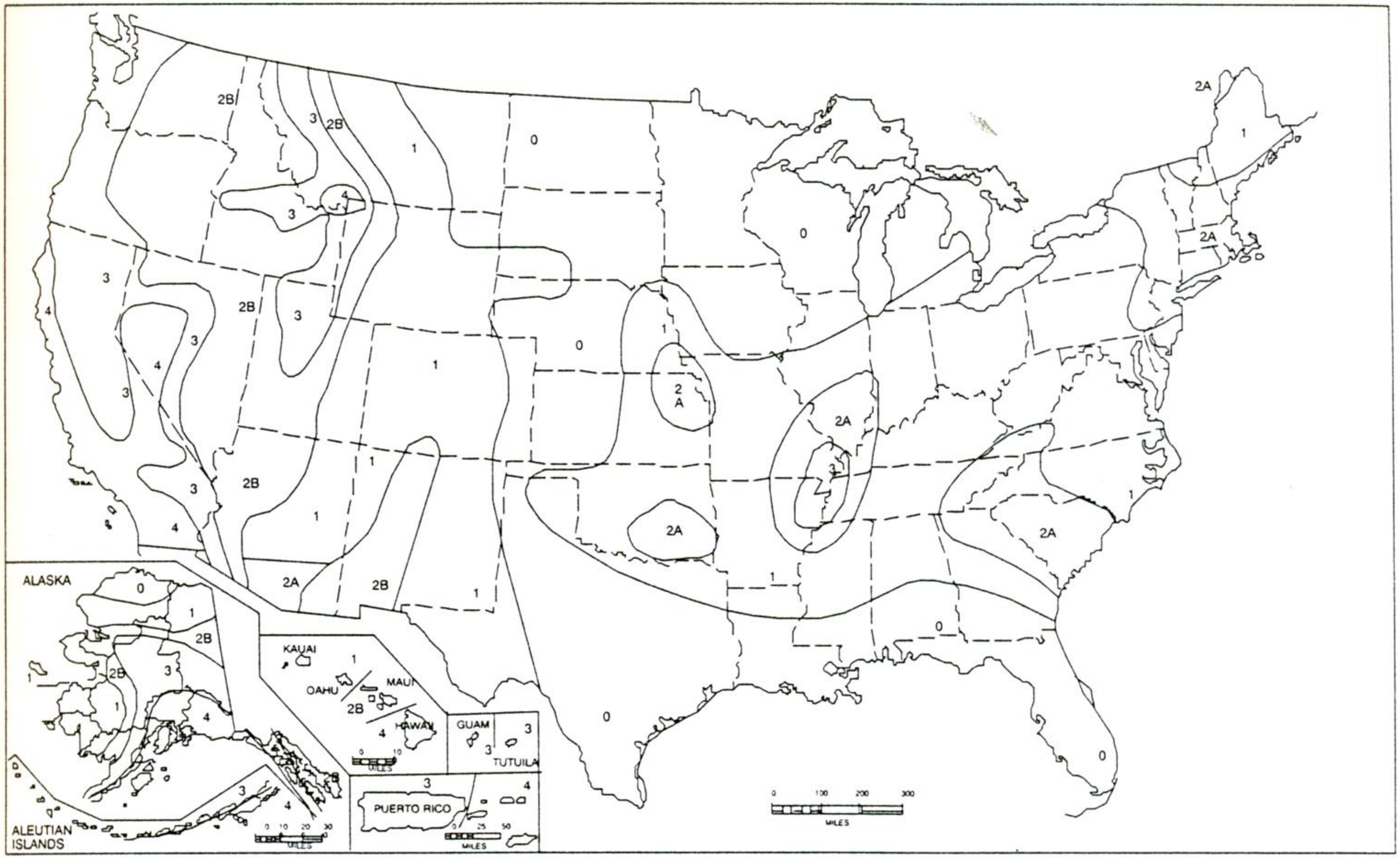
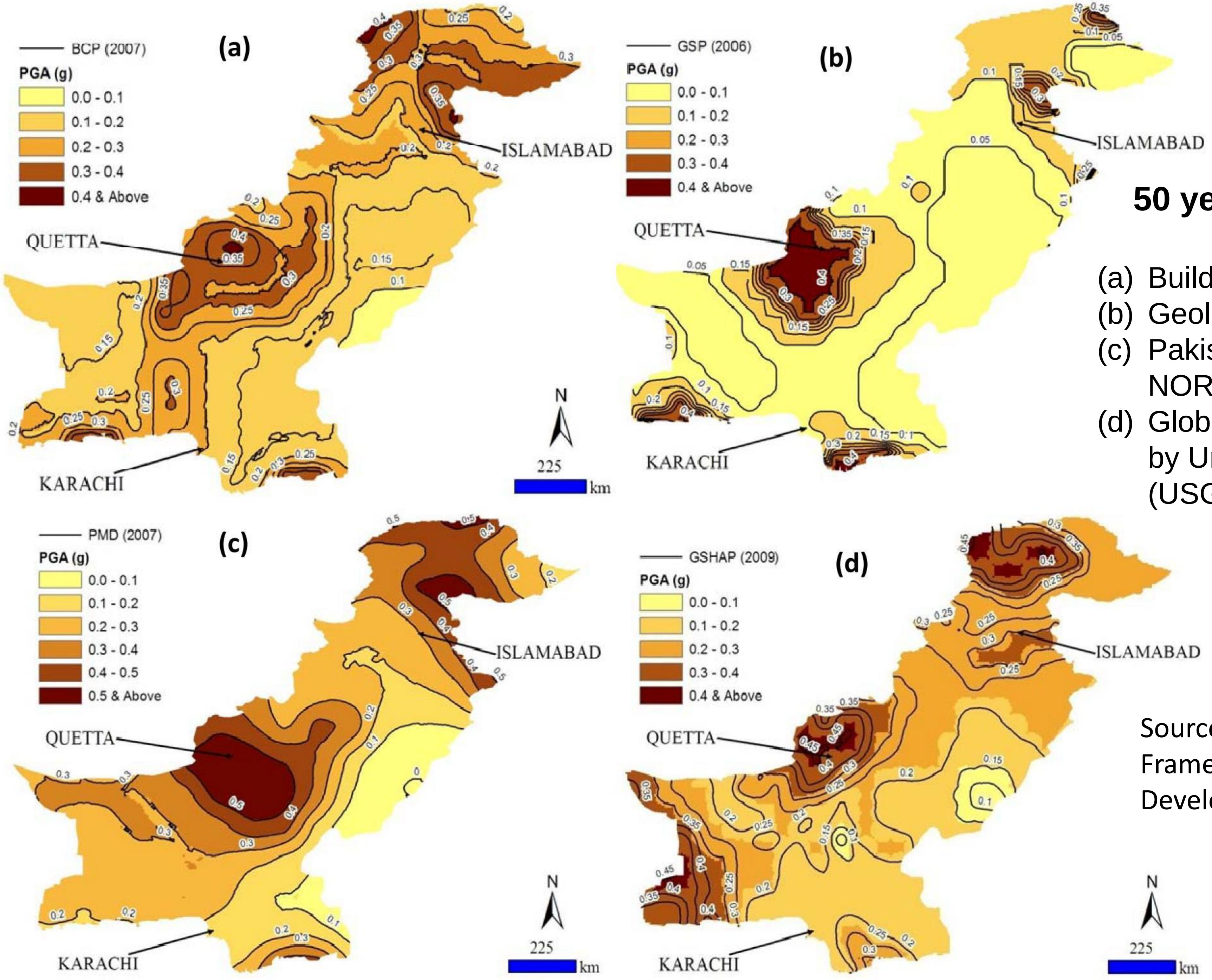


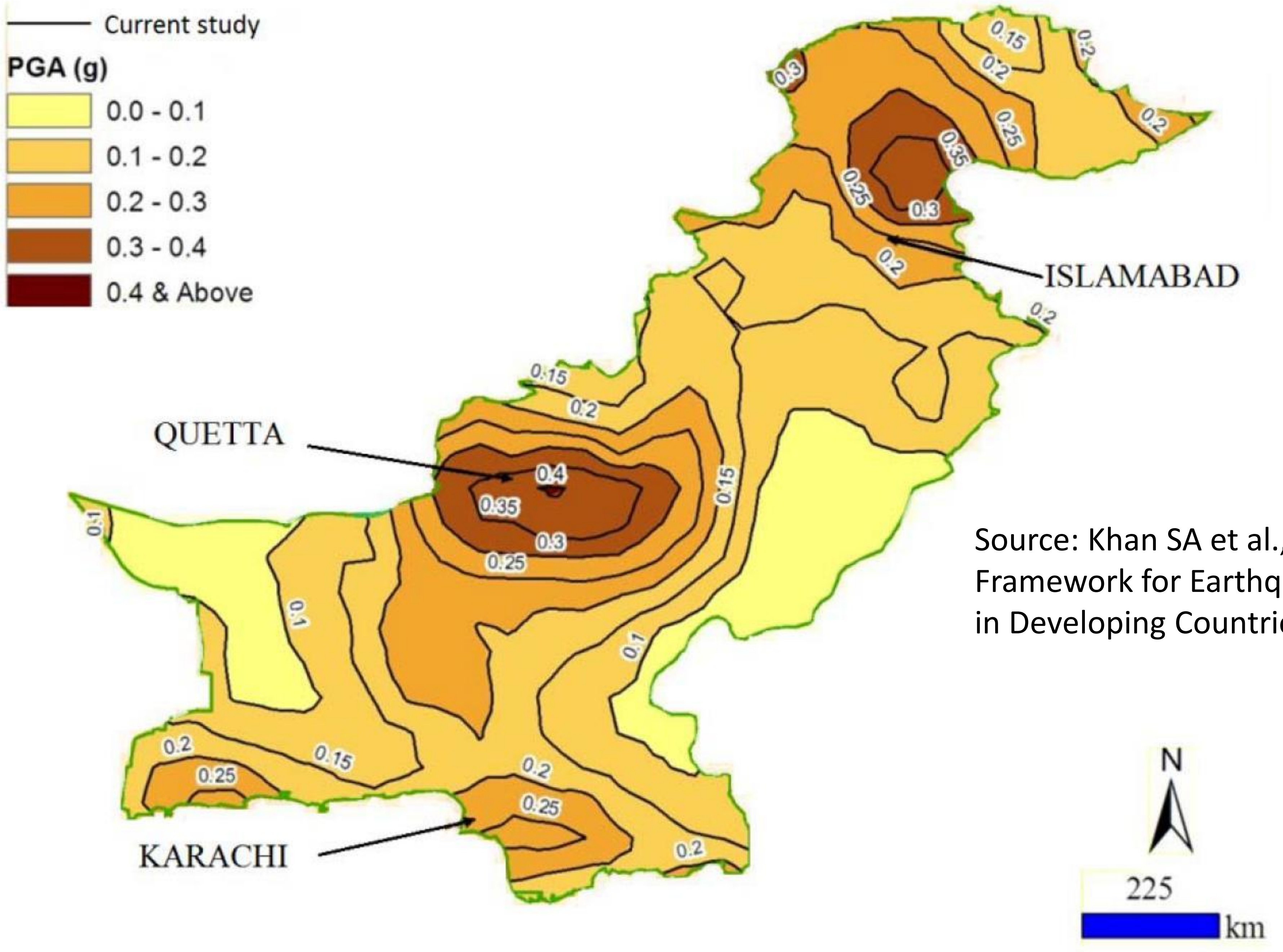
FIGURE 16-2—SEISMIC ZONE MAP OF THE UNITED STATES
For areas outside of the United States, see Appendix Chapter 16.



50 year with 10% PE seismic hazard map by

(a) Building Code of Pakistan (BCP, 2007),
(b) Geological Survey of Pakistan (GSP, 2006)
(c) Pakistan Meteorological Department (PMD-NORSAR, 2007) and
(d) Global Seismic Hazard Program (GSHAP) by United States Geological Survey (USGS, 2008)

Source: Khan SA et al., (2012). A New Framework for Earthquake Risk Assessment in Developing Countries



Source: Khan SA et al., (2012). A New Framework for Earthquake Risk Assessment in Developing Countries

Seismic Hazard Assessment

- Seismic Hazard Analysis (SHA) has been widely used by engineers, regulators, and planners to mitigate earthquake losses:

  ✓ **Specifying seismic design levels for individual structures and building codes**

  ✓ **Evaluating the seismic safety of existing facilities**

  ✓ **Planning for societal and economic emergencies (emergency preparedness)**

  ✓ **Setting priorities for the mitigation of seismic risk**

  ✓ **Insurance analysis**

Probabilistic vs. Deterministic

- **DSHA** considers the effect at a site of either a single scenario earthquake, or a relatively small number of individual earthquakes.
- Difficulties surrounded the selection of a representative earthquake on which the hazard assessment would be based.
- **PSHA** quantifies the hazard at a site from all earthquakes of all possible magnitudes, at all significant distances from the site of interest, as a probability by taking into account their frequency of occurrence.
- Deterministic earthquake scenarios, therefore, are a subset of the probabilistic methodology.

Probabilistic Seismic Hazard Assessment (PSHA)

Probabilistic Seismic Hazard Assessment (PSHA)

- Probabilities are useful in characterizing seismic hazard since earthquakes and their effects are **random phenomena**.

- **Probabilistic seismic hazard analysis(PSHA)** takes into account the seismic potential of the seismic sources, the random nature of earthquake occurrences, the random nature of the ground motion produced by these earthquakes, the damage potential of these ground motions, and the uncertainties involved at all levels of the process .

- Prior to the widespread use of PSHA for assessing earthquake hazards, **Deterministic methods (DSHA)** dominated such assessments.

Probabilistic Seismic Hazard Analysis

- The analytical approach of PSHA was first developed by **C.A. Cornell** in 1968.
- It was used by S.T. Algermissen et.al. (USGS) for developing a probabilistic seismic hazard map of US in 1976.
- The map was later on used as a basis for developing the US seismic zone map in the Uniform Building Code (US) in 1988.
- The analysis procedure is currently widely accepted and used all over the world.

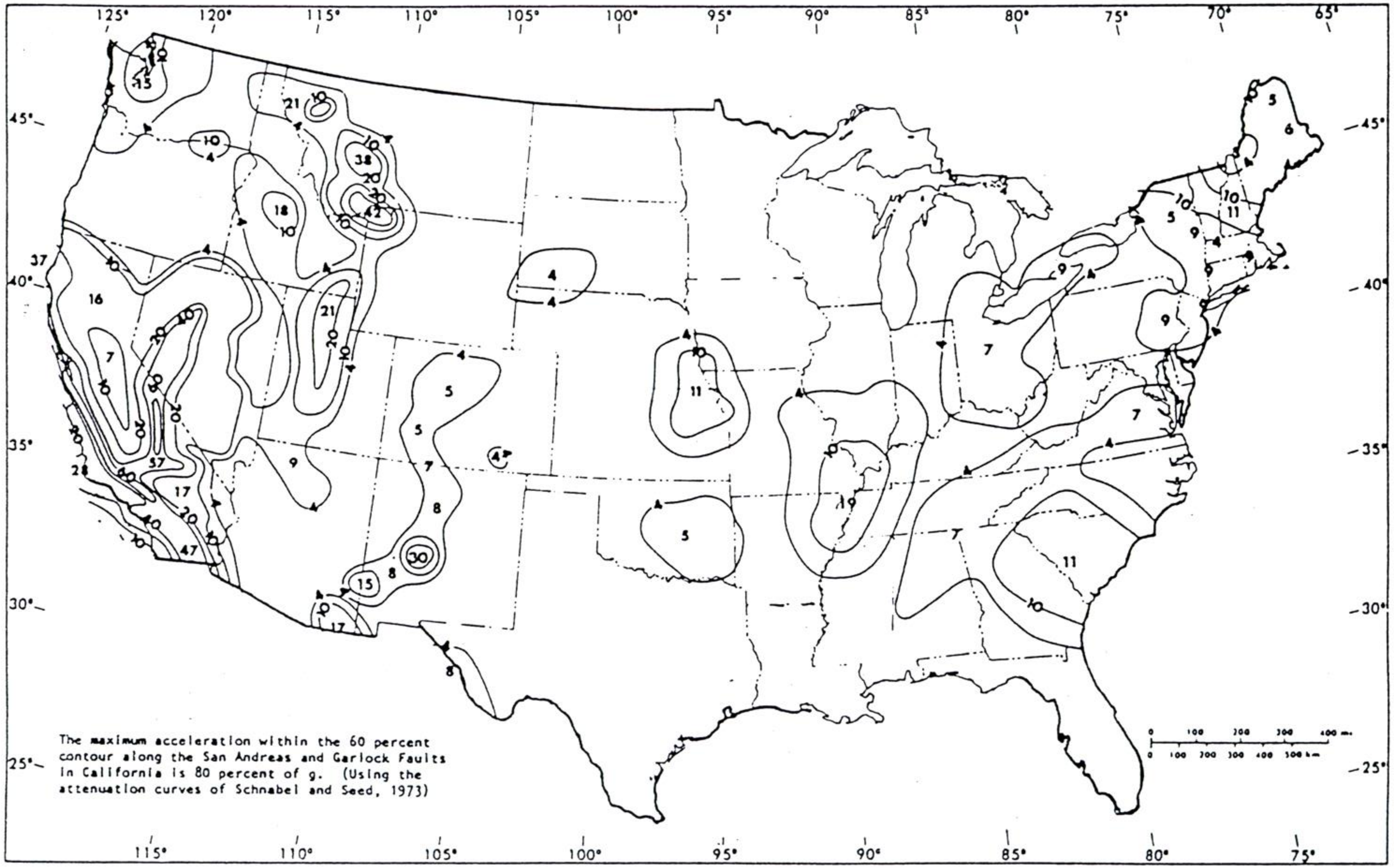


Figure 47. Probabilistic ground acceleration map of the conterminous United States, 50 year exposure time, 10 percent chance of exceedance, contours are percent of g (Algermissen and Perkins, 1976, Ref. 169).

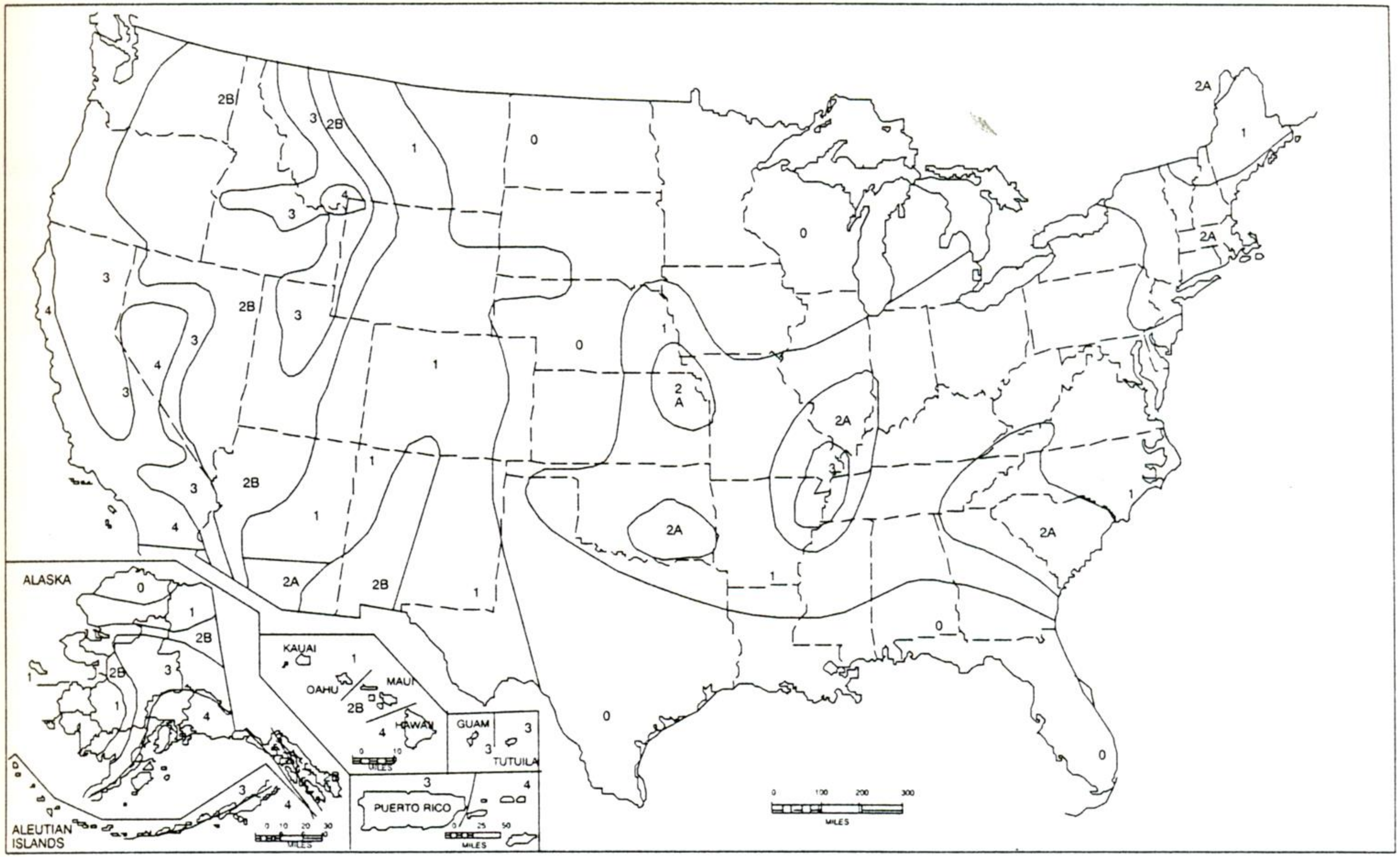


FIGURE 16-2—SEISMIC ZONE MAP OF THE UNITED STATES
For areas outside of the United States, see Appendix Chapter 16.

Key Assumptions in Calculating Probabilistic Ground Motions

1) Earthquakes occur **within the defined seismic source zones** or along the defined active faults.

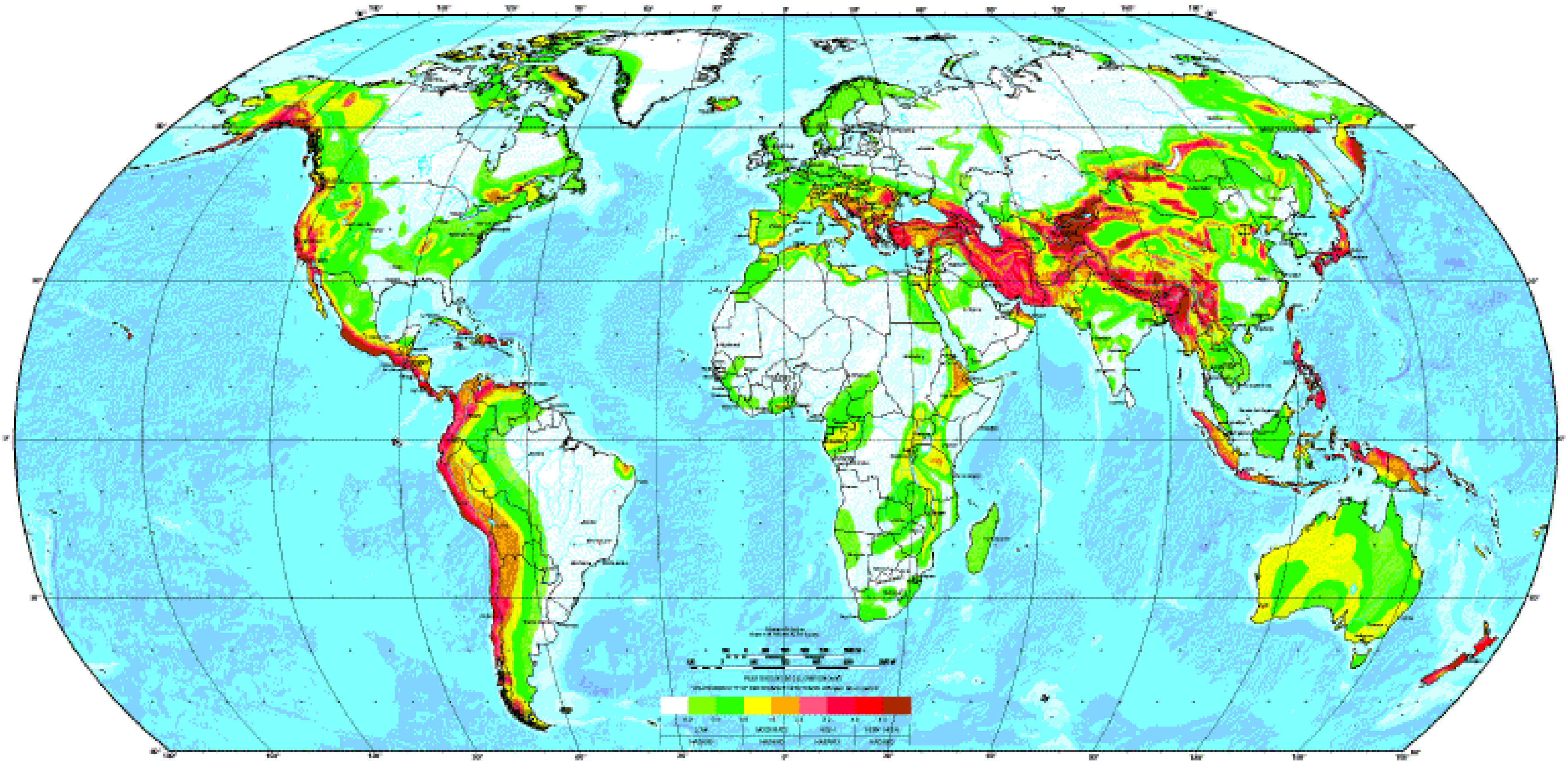
2) Within each defined seismic source zone (or active fault), **earthquakes occur randomly at any location** with an equal chance (probability).

3) Within each defined seismic source zone (or active fault), **earthquakes randomly occur in time**, in which the average rate of occurrence is defined by its magnitude-recurrence relation. This random occurrence in time is modeled as a **Possion process**.

4) The occurrence of an earthquake is **statistically independent** of the occurrence of other earthquakes.

5) In any earthquake event, the ground motion parameter (e.g. PGA, SA) at the site of interest can be estimated from the earthquake magnitude, source-to-site distance, and other earthquake parameters by using the **selected attenuation relationship**.

Global Seismic Hazard Map



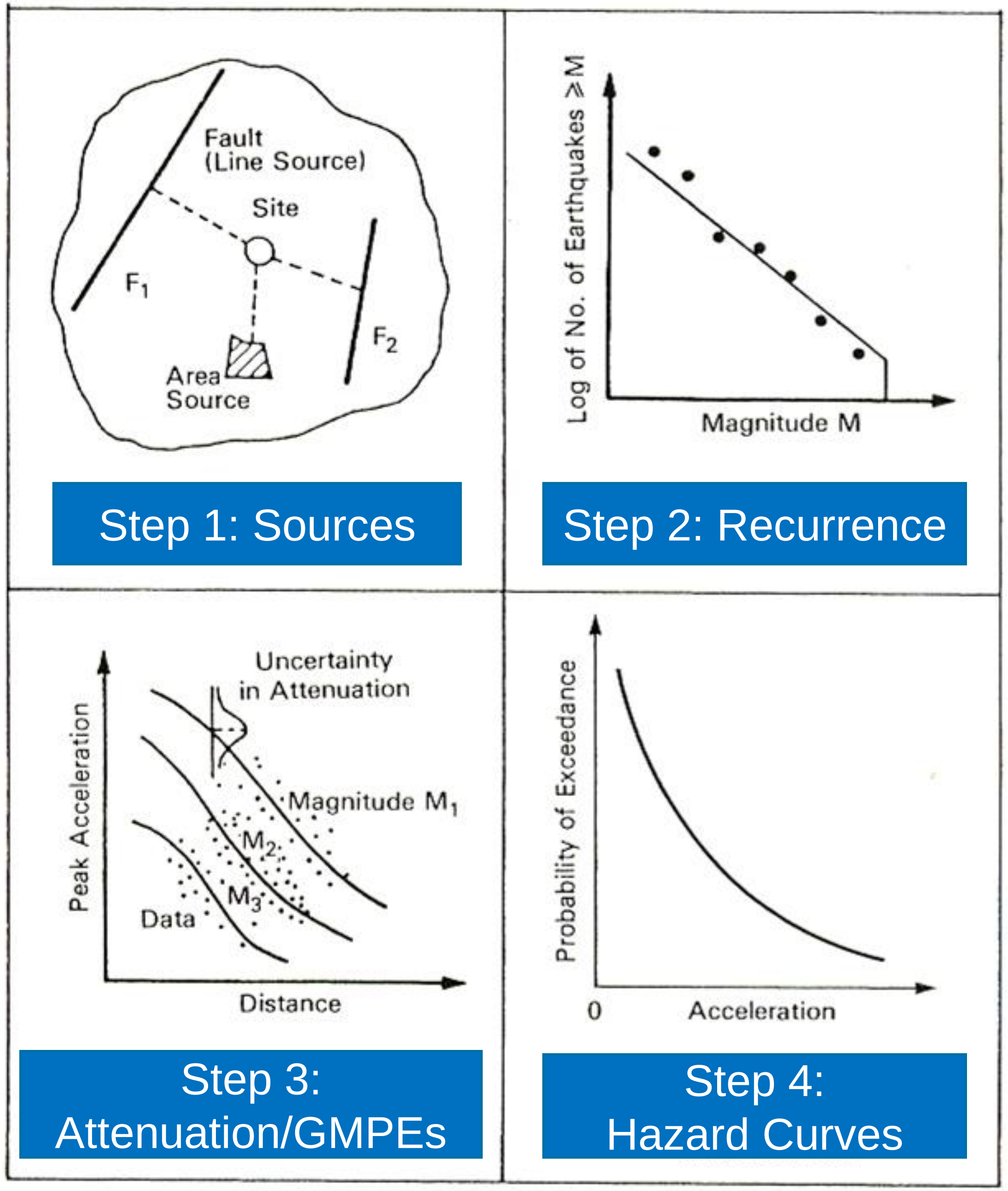
GLOBAL SEISMIC HAZARD ASSESSMENT PROGRAM

http://seismo.ethz.ch/gshap/

PSHA Procedure

- ✓ Selection of site(s)
- ✓ Identification of all critical tectonic features (e.g. active faults, seismic source zones) likely to generate significant earthquakes—**seismic sources**
- ✓ Defining the **seismicity** of these seismic sources
- ✓ Selection of **a suitable attenuation relationship**—an equation that estimates ground-motion parameters from earthquake magnitude and source-to-site distance for various site conditions
- ✓ Computation of the **ground motion parameters** at the site.

- Identification of all potential seismic sources
- Defining the seismicity of these seismic sources
- Selection of appropriate ground-motion prediction equations (GMPEs)
- Determining of Probabilities of Exceedance (Hazard Curve)



Identification of Seismic Sources

- Where **active faults** have been identified and mapped, they become the sources of future earthquakes.
- Where specific faults have not been identified or their characteristics are not well understood, it is common to define '**seismic source zone**'.
- Within the seismic source zone, earthquakes are typically modeled either as a single point of energy release (**a point source**) or as a rupture on a fault (**a finite-size source**) with a random location or orientation.
- In such cases, the challenge of the analyst is to identify source zones in which the seismicity is relatively uniform.
- Even in areas where faults are well defined, a source zone may be needed to model the random occurrence of small and moderate earthquakes ($M < 6.5$)—**background seismicity**.

Step 1: Sources

Seismic Source Zones within the U.S.

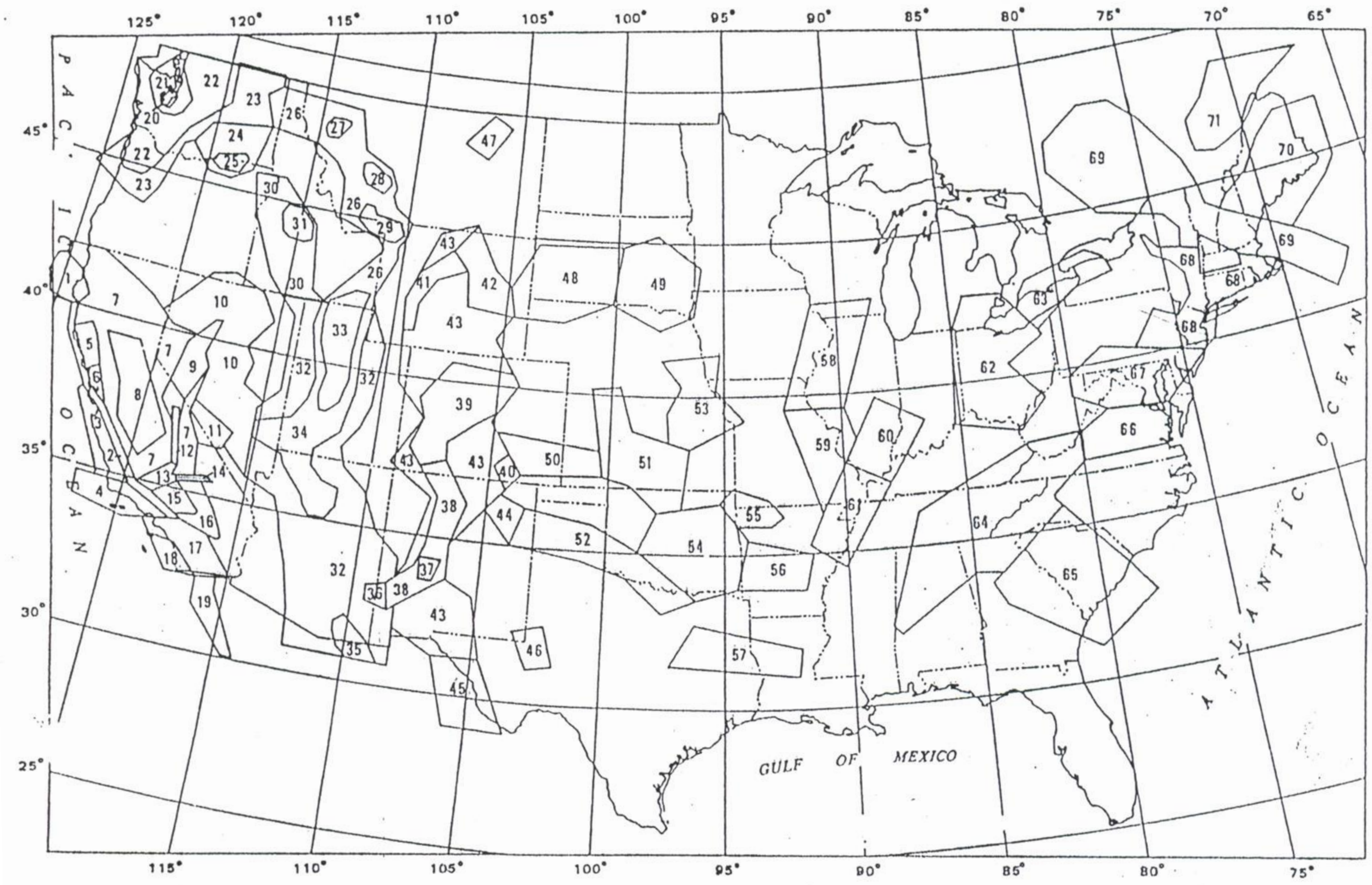
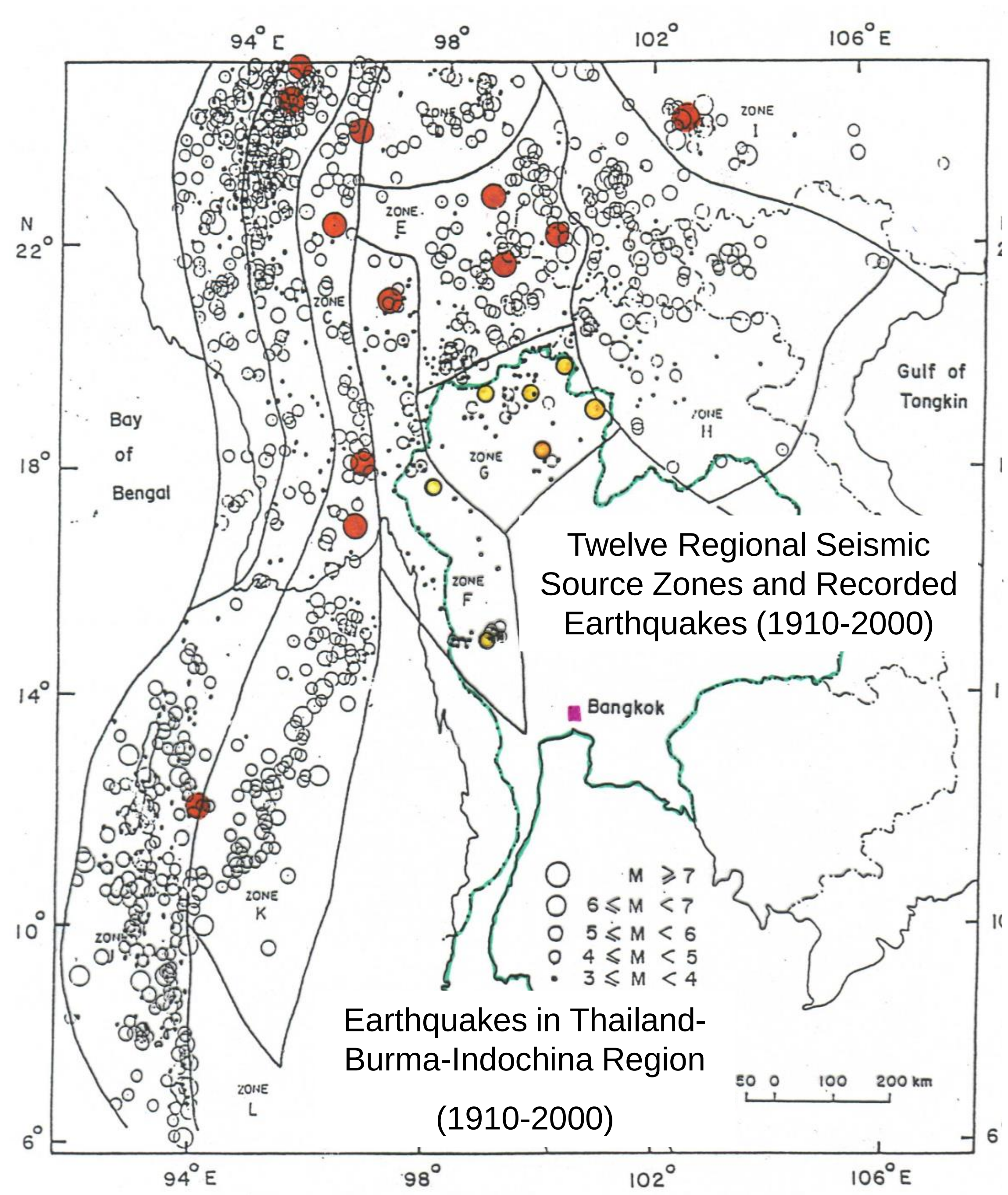


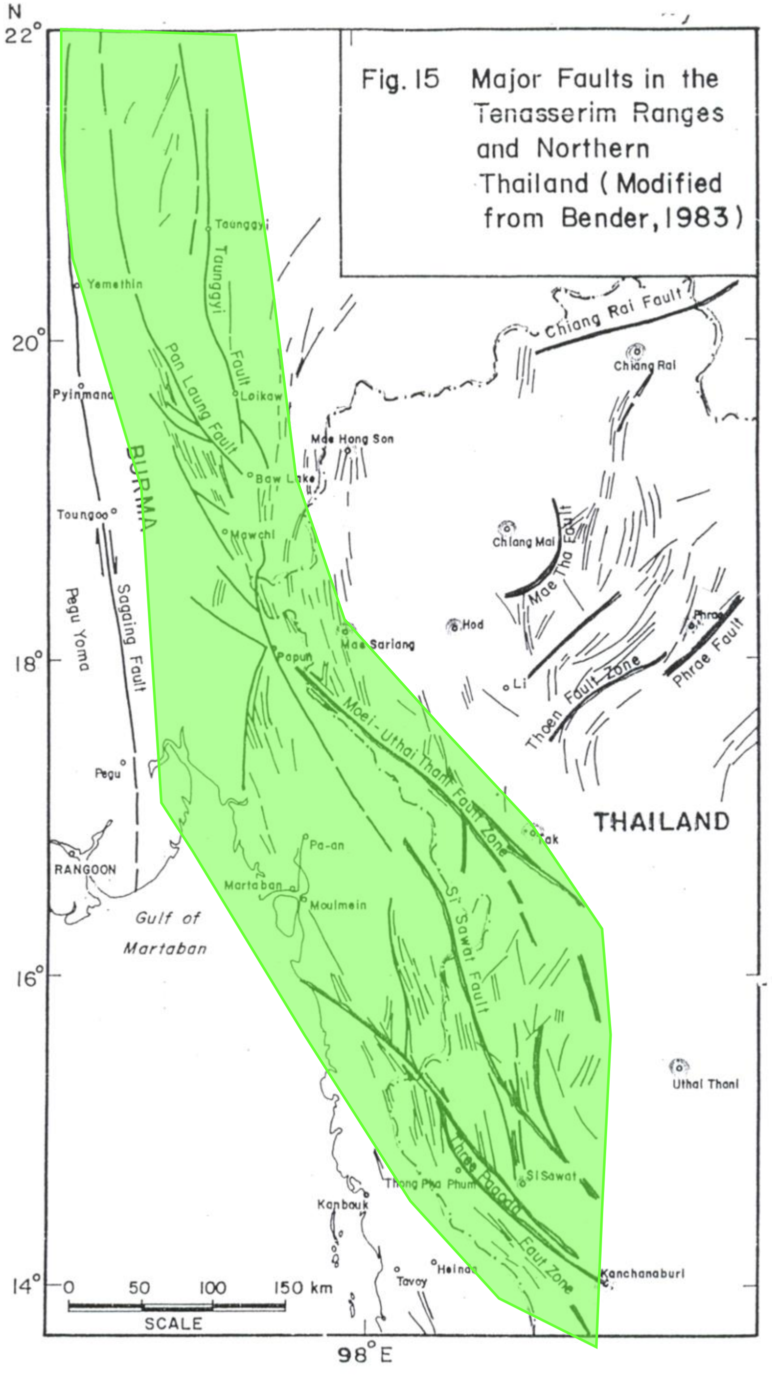
FIGURE 4.—Seismic source zones within the conterminous United States (from Algermissen and Perkins, 1976). Zone numbers correspond to those in table 4.



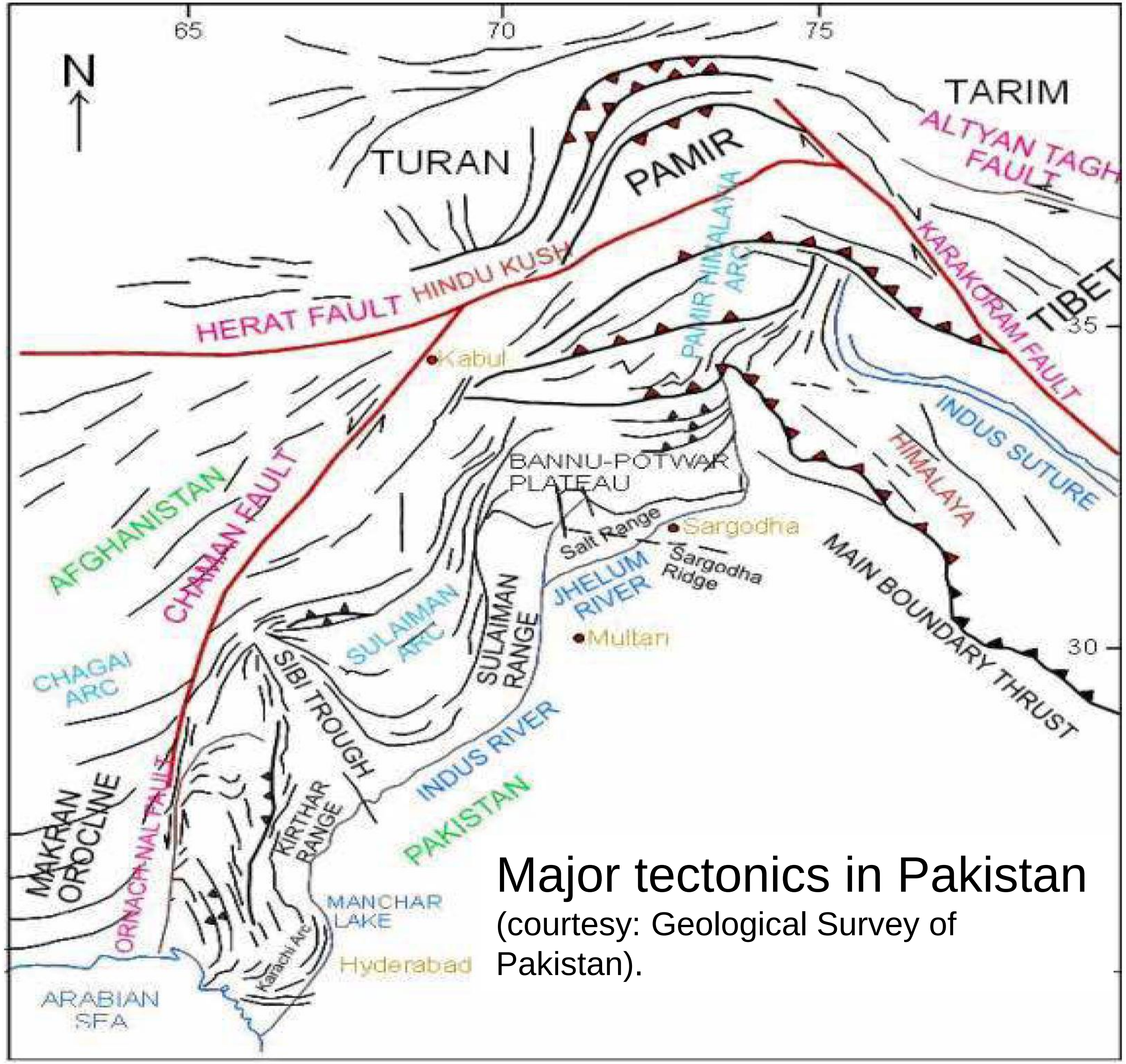
Twelve Regional Seismic Source Zones and Recorded Earthquakes (1910-2000)

Earthquakes in Thailand-Burma-Indochina Region

(1910-2000)

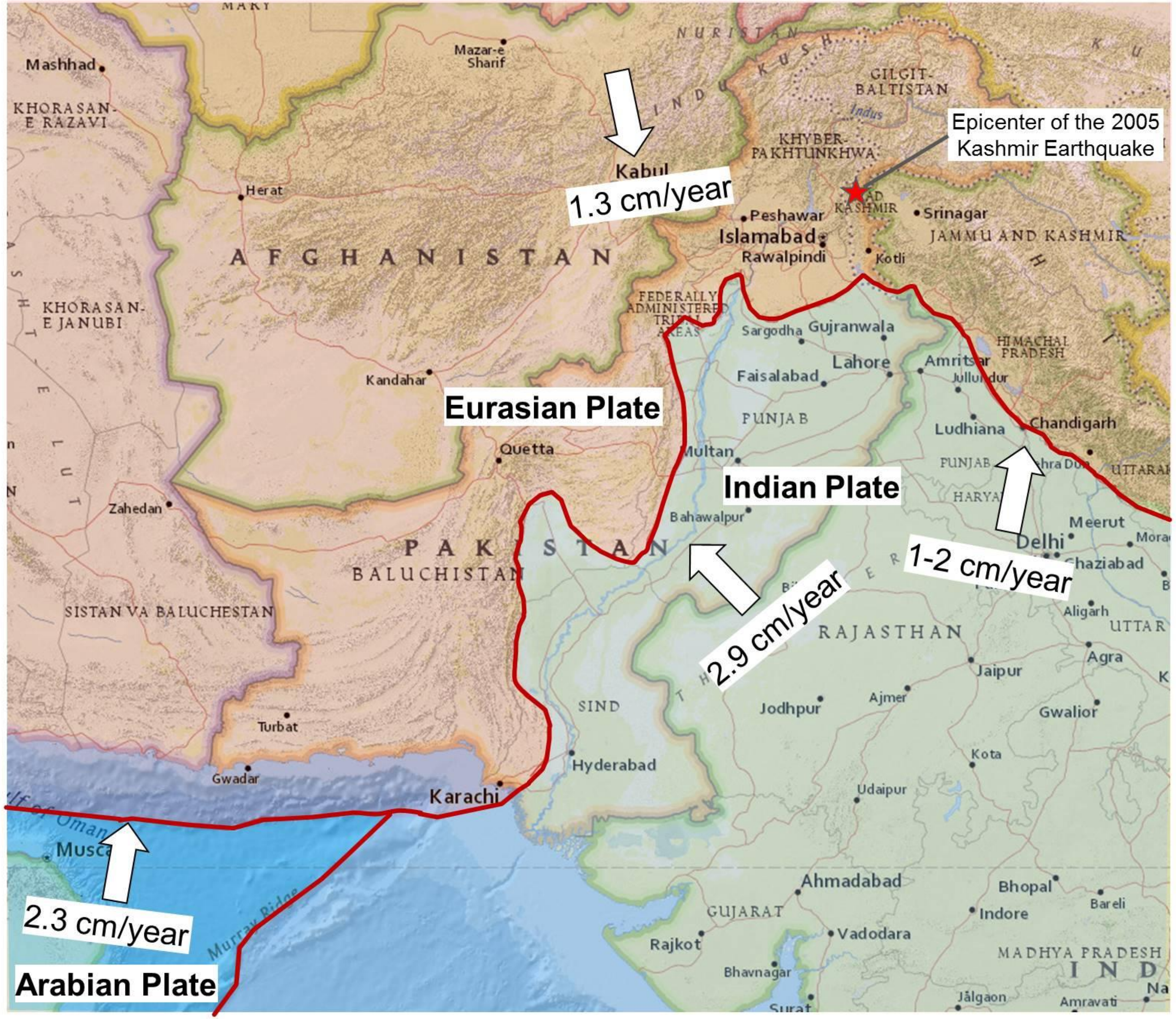


Step 1: Sources



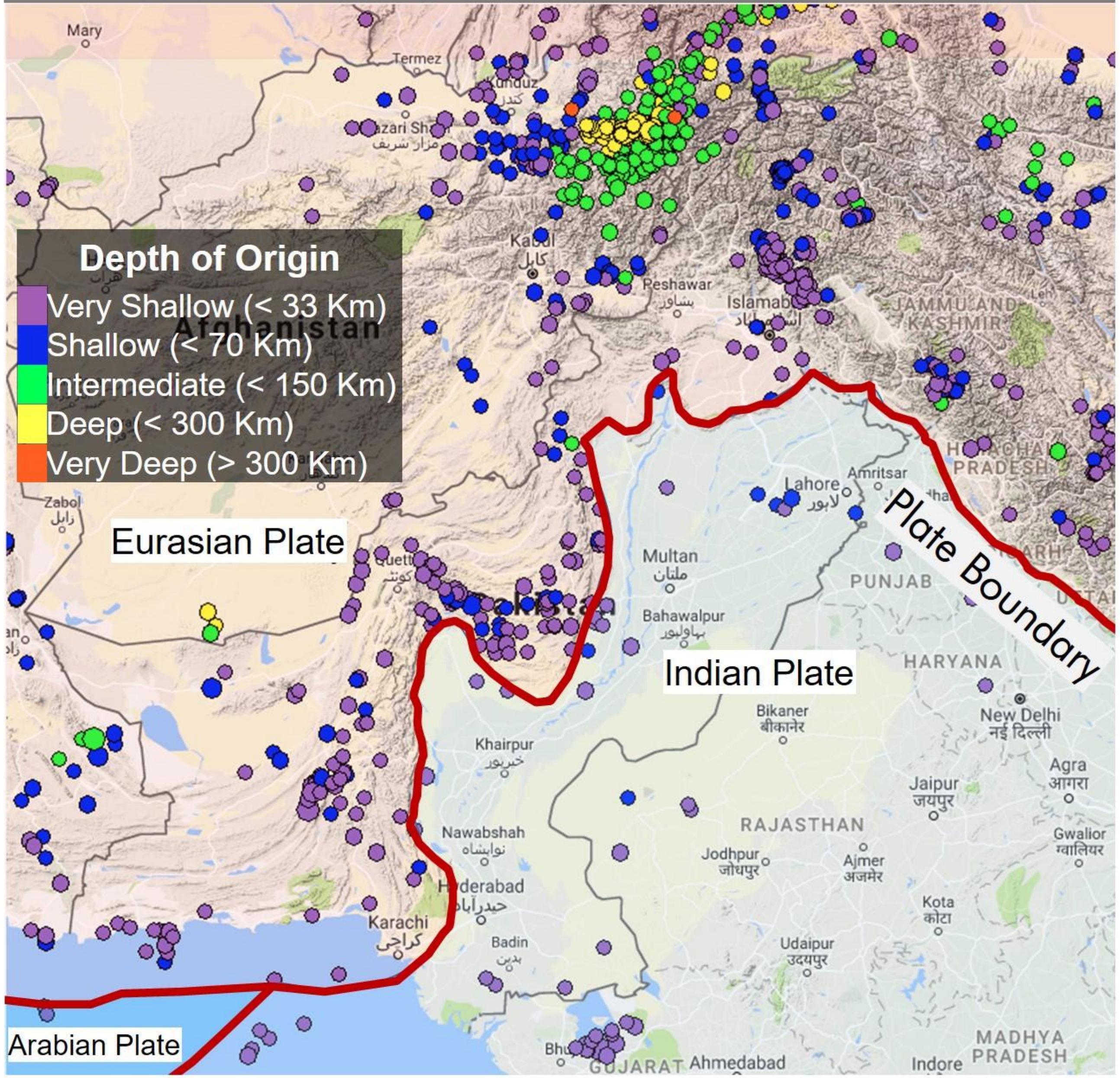
Major tectonics in Pakistan (courtesy: Geological Survey of Pakistan).

Step 1: Sources

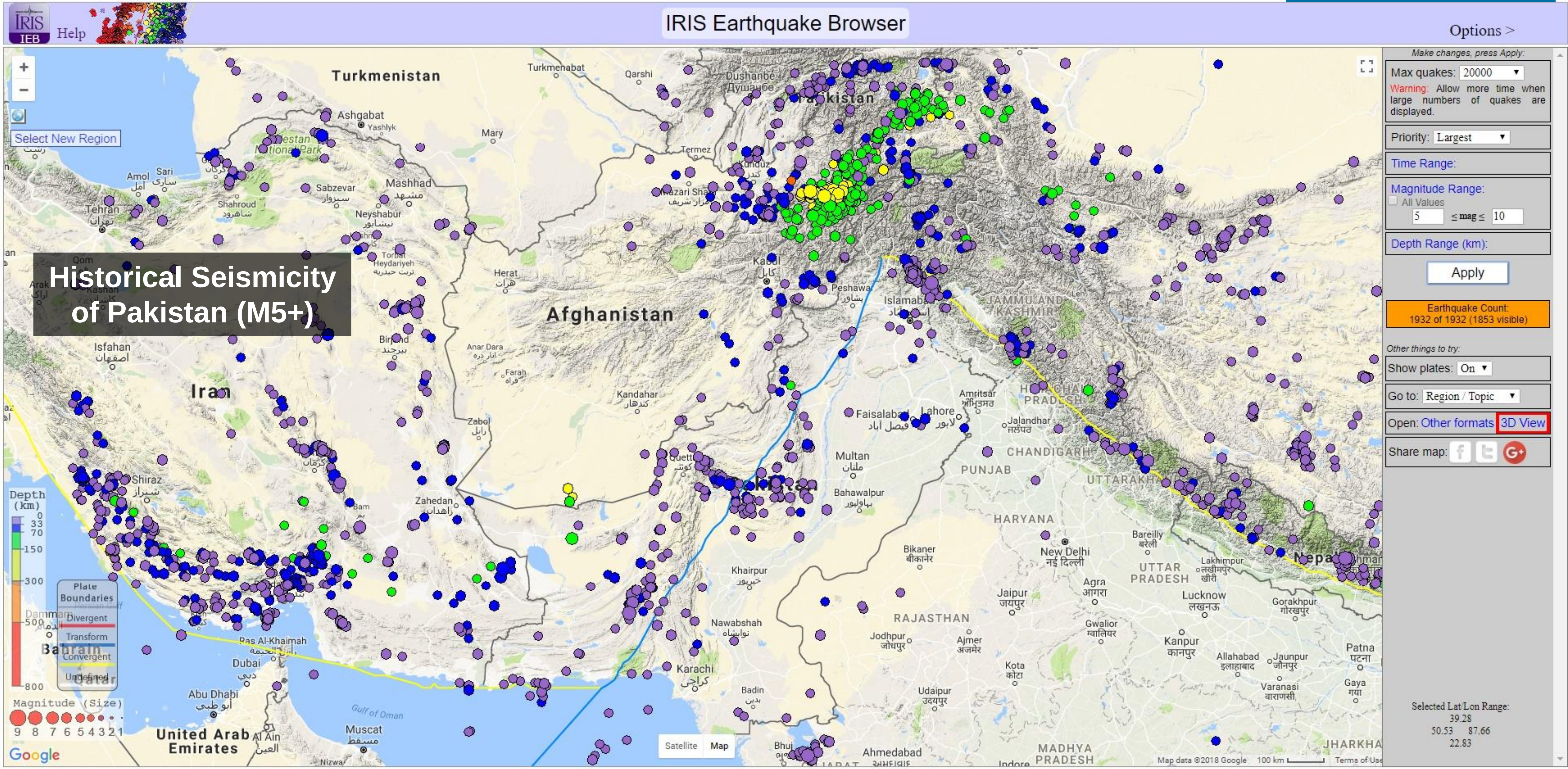


Location of Earthquakes (with Magnitude greater than 5) in Pakistan (1900 – 2017)

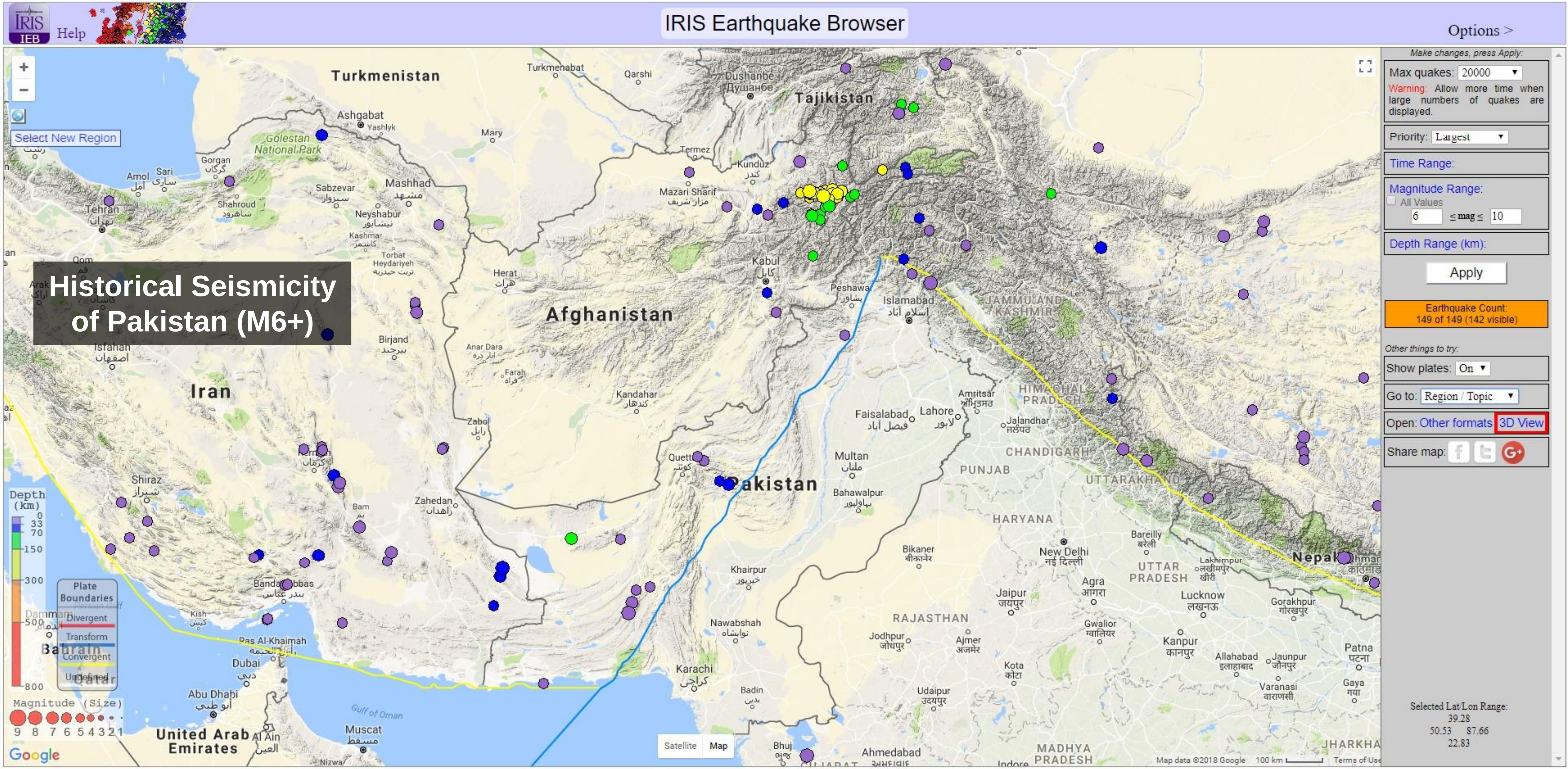
Step 1: Sources



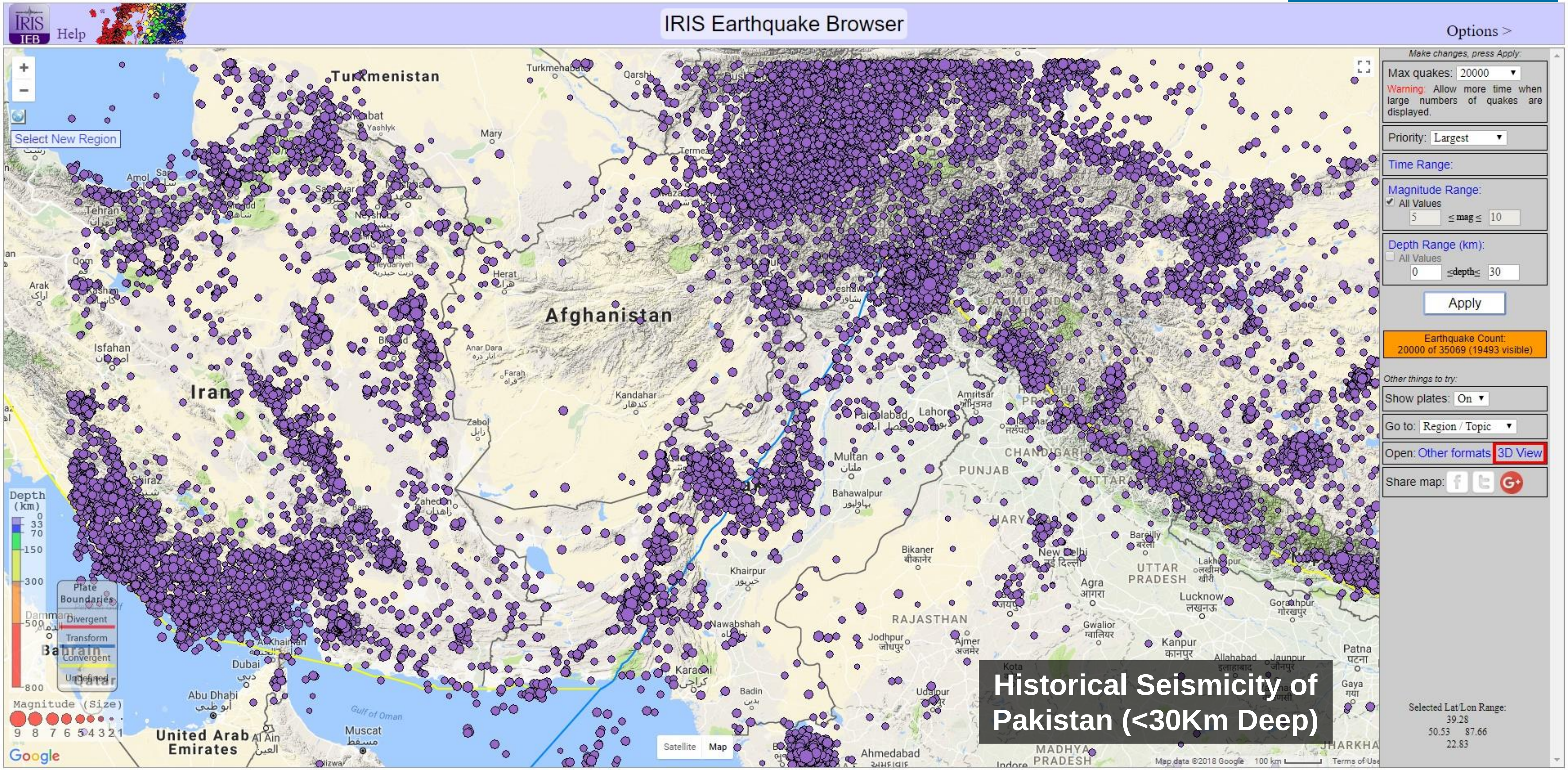
Step 1: Sources



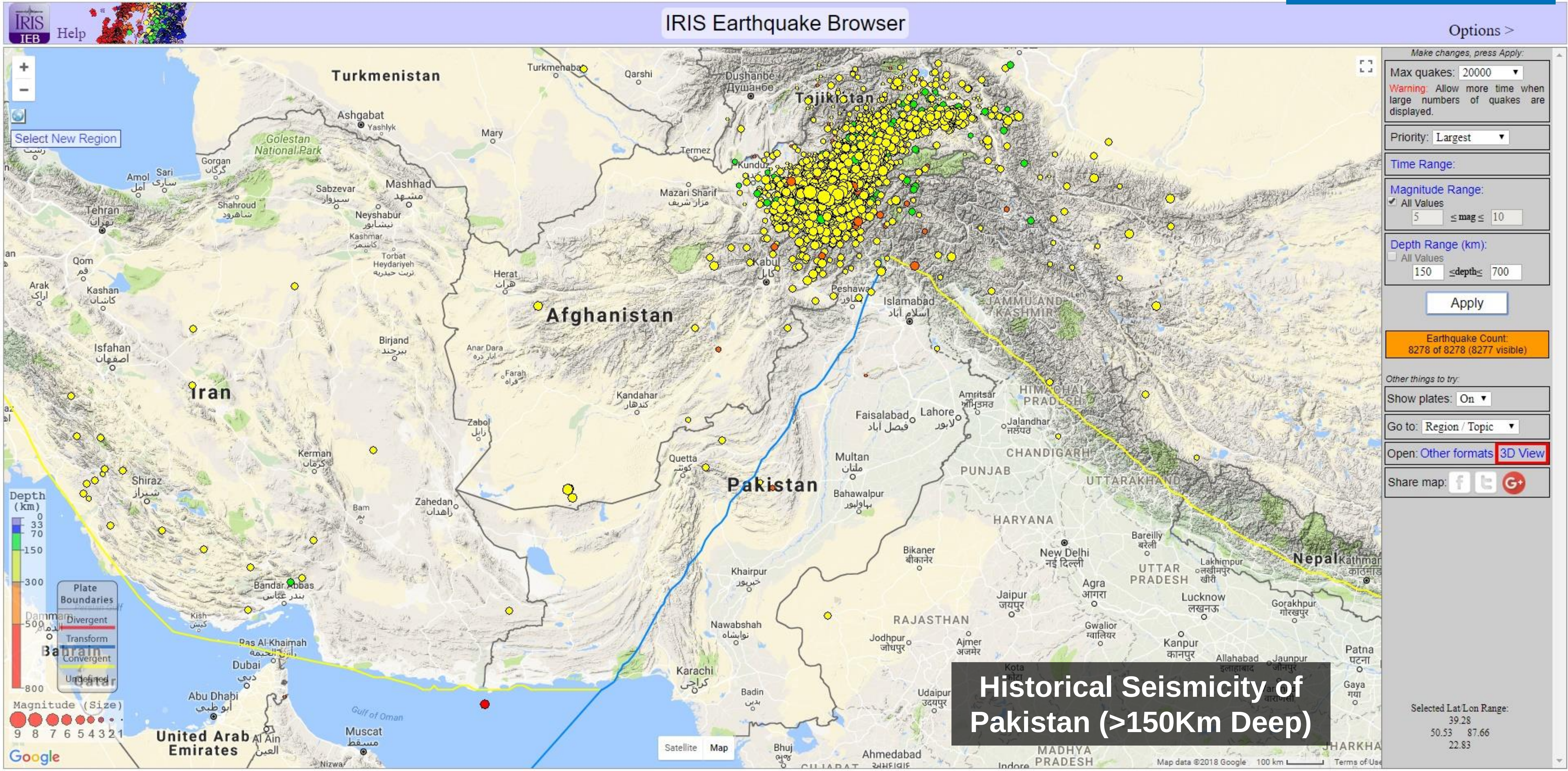
Historical Seismicity of Pakistan (M6+)



Step 1: Sources

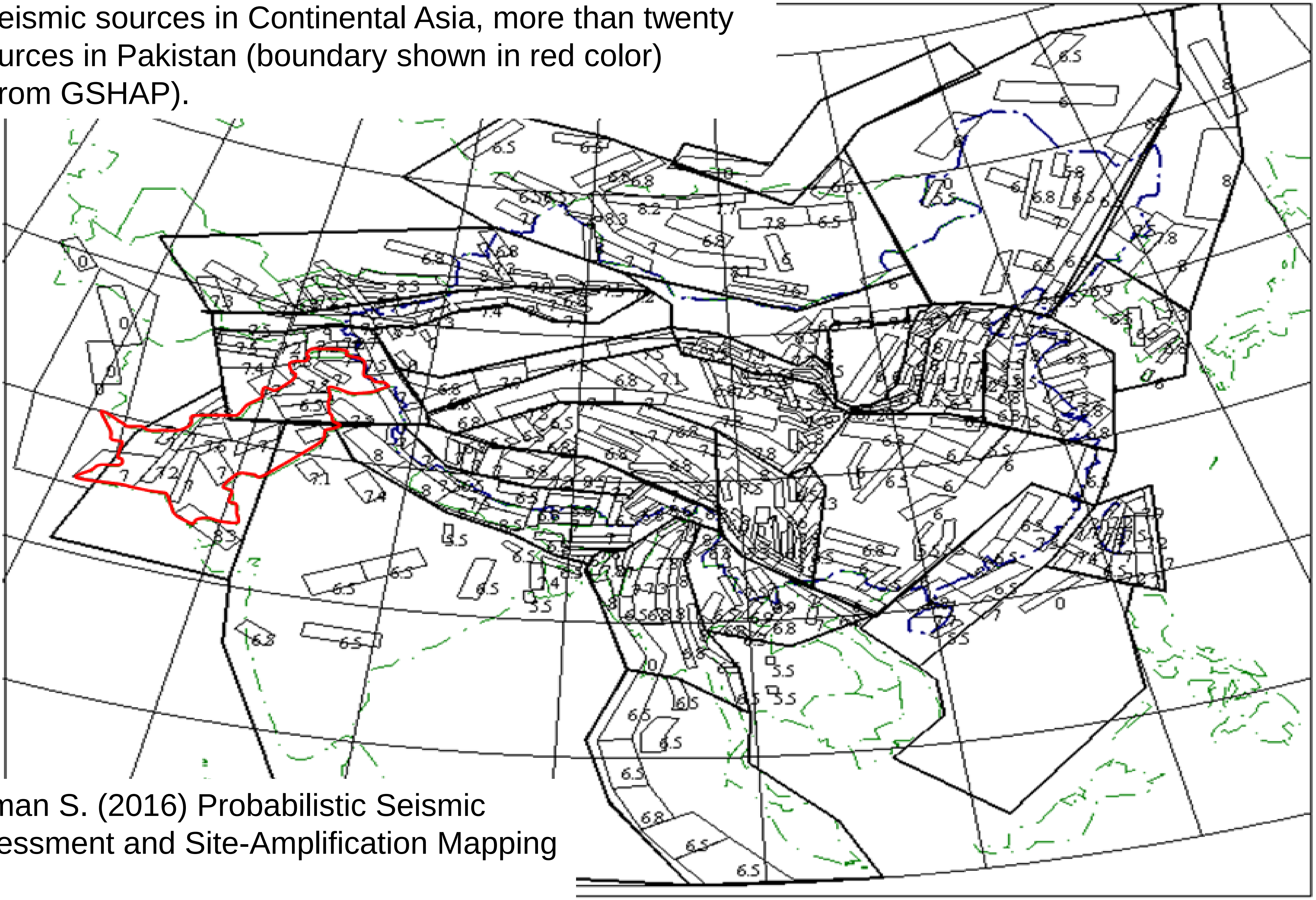


Step 1: Sources

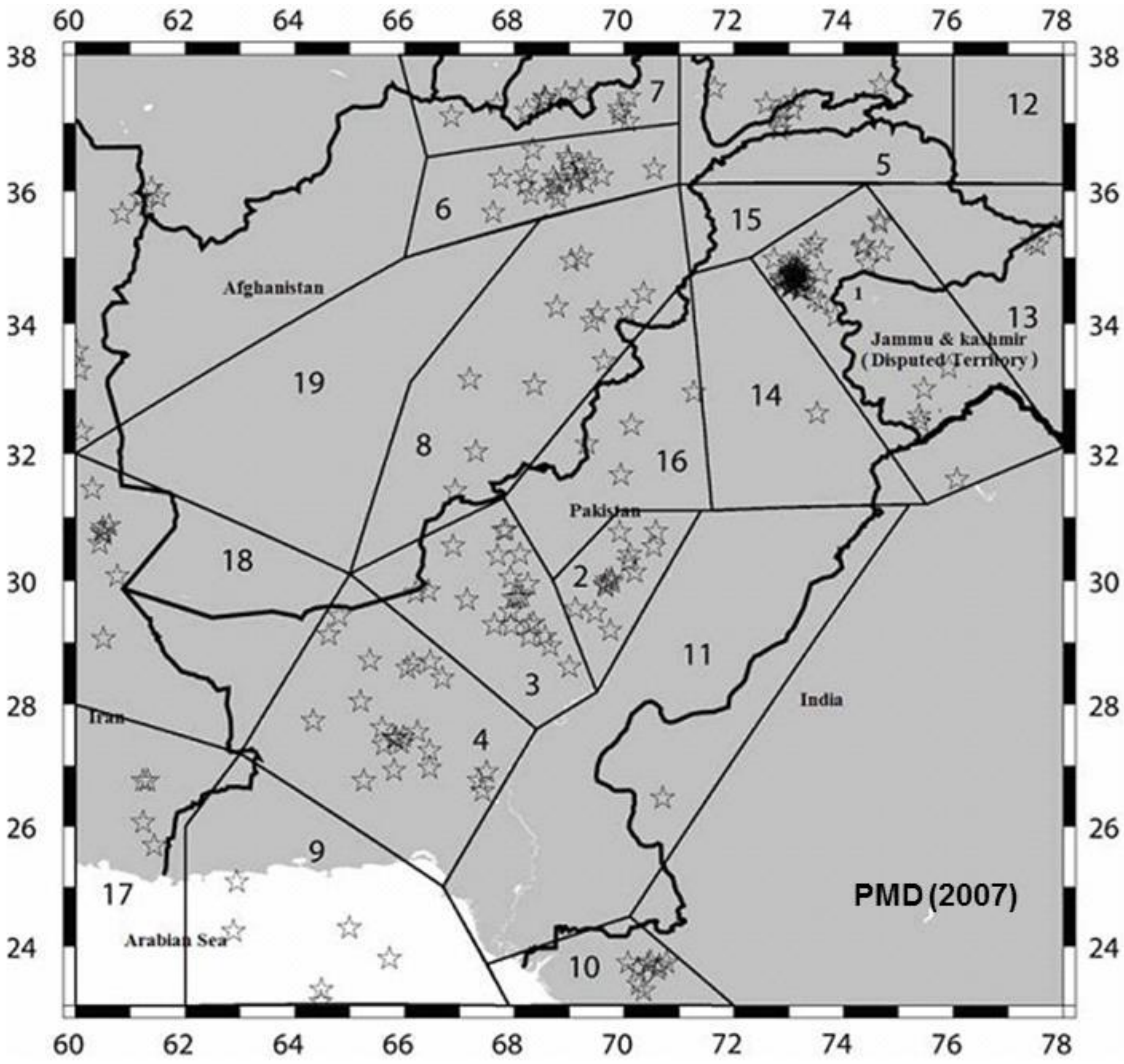


Historical Seismicity of Pakistan (>150Km Deep)

Potential seismic sources in Continental Asia, more than twenty seismic sources in Pakistan (boundary shown in red color) (modified from GSHAP).

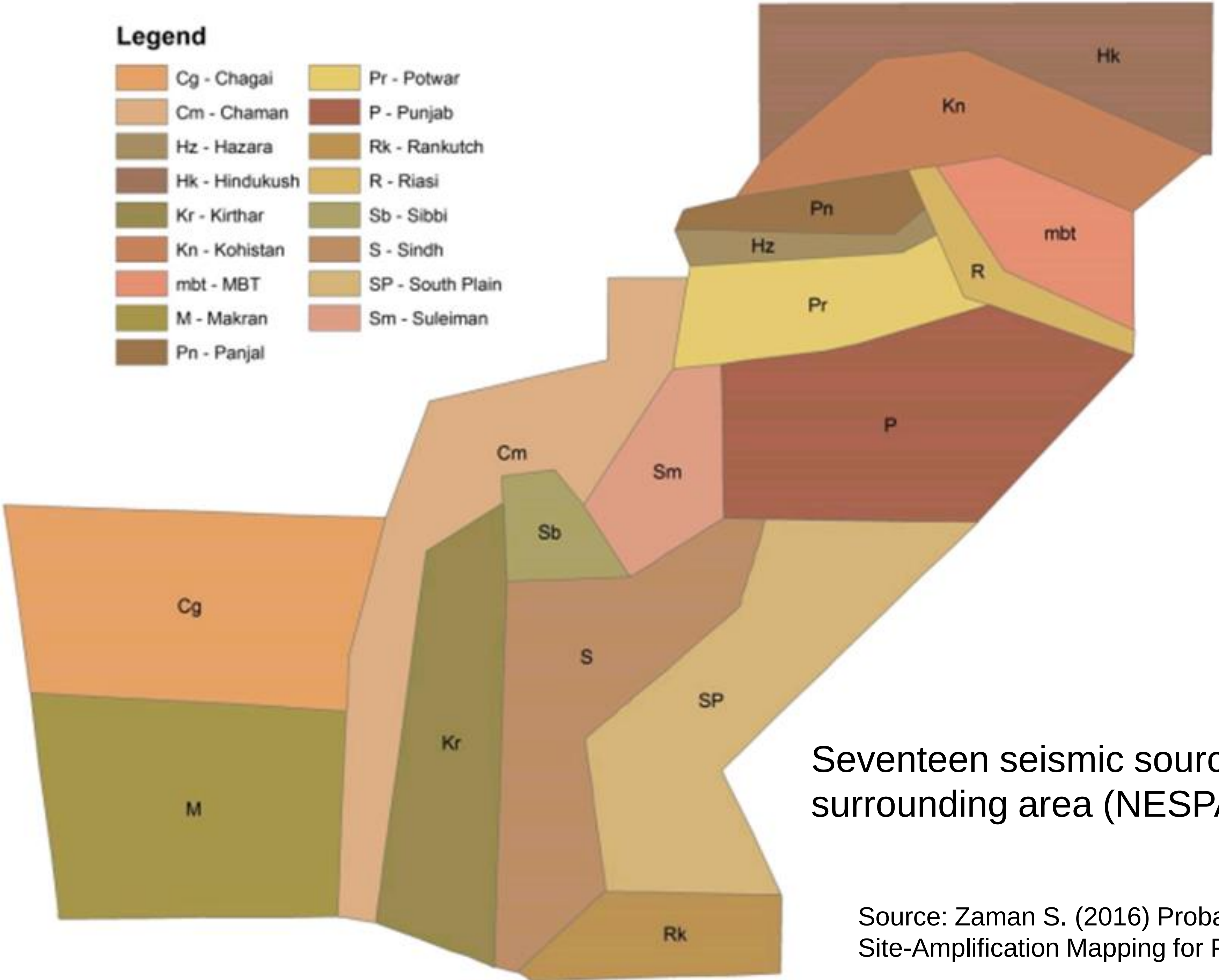


Source: Zaman S. (2016) Probabilistic Seismic Hazard Assessment and Site-Amplification Mapping for Pakistan



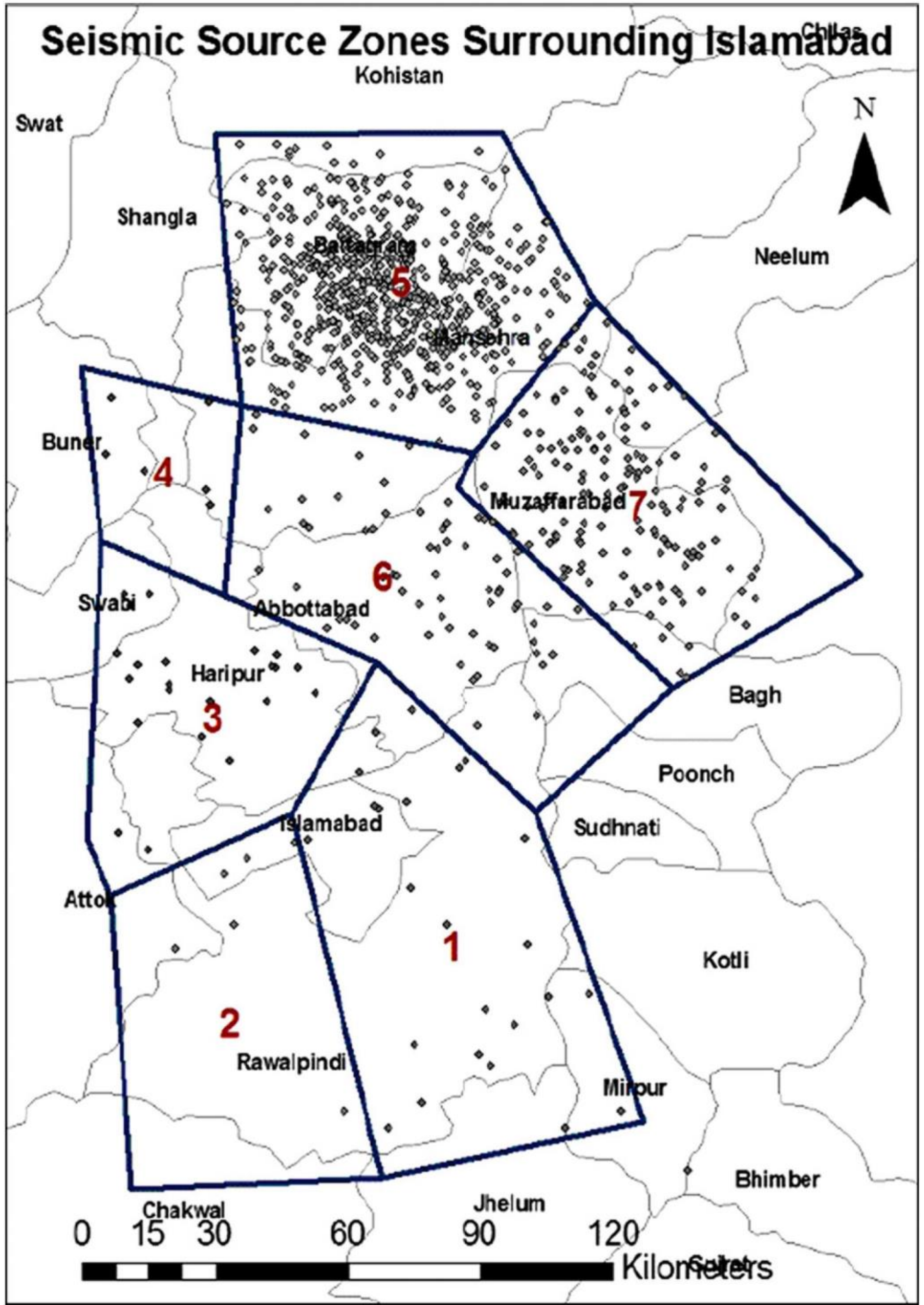
Nineteen seismic sources in Pakistan and surrounding area (PMD-NORSAR 2007)

Source: PMD and NORSAR (2007) Seismic Hazard Analysis and Zonation for Pakistan, Azad Jammu and Kashmir



Seventeen seismic sources in Pakistan and surrounding area (NESPAK 2007)

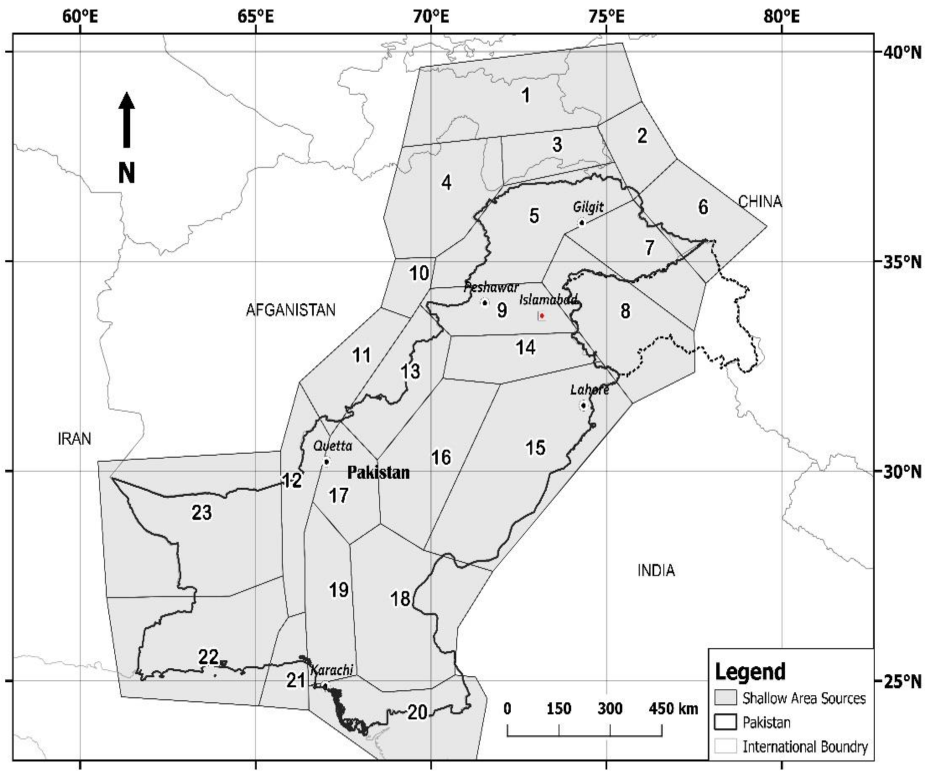
Source: Zaman S. (2016) Probabilistic Seismic Hazard Assessment and Site-Amplification Mapping for Pakistan



Source: Bhatti et al., (2011) Probabilistic seismic hazard analysis of Islamabad, Pakistan

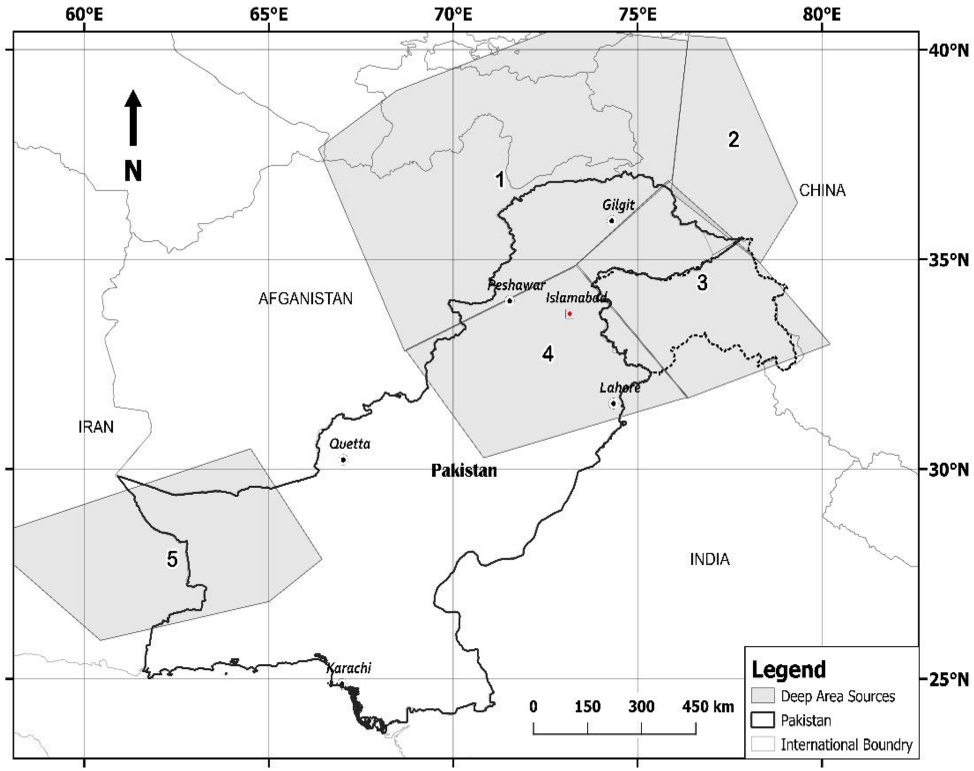
Area Sources of Pakistan

Shallow Area Sources (23)



4823 Earthquake Events

Deep Area Sources (5)



1457 Earthquake Events

Defining the Seismicity of Seismic Sources

- One commonly used parameter for defining the seismicity:

  The rate of occurrence of earthquakes larger than some lower-bound magnitude $m_o = \nu$

- m_o is defined as the smallest earthquake expected to produce damage.
- Typically $m_o = 4.0$
- In traditional applications of PSHA, n is simply estimated from the **historical rate of occurrence of earthquakes exceeding m_o**
- The estimate requires **historical and instrumental records of earthquakes**
- Another relatively new technique—**paleoseismic investigation**—has been successful in providing information on prehistoric fault movements and seismicity of active faults.

Instrumental earthquake data of Myanmar, Thailand and Indonesia

SOURCE	YEAR	MO	DA	HR	MN	SEC	LAT	LONG	DEPTH (KM)	MAGNITUDES BODY	SUR	OTHER	LOCAL	INT MAX	S.D.	OBS.
* 1 GS	1978	12	21	22	36	13.2	023.173N	096.196E	033	4.4 MB					0.5 s	008
* 2 ISC	1978	12	21	22	36	16	022.9 N	095.8 E	032	4.2 MB						
BKK	1978	12	25	08	58	24.22	017.24 N	096.45 E	010				4.2 L		0.56s	003
GS	1978	12	29	08	53	21.7	023.559N	092.970E	033	4.8 MB	4.0S				1.4 s	038
* 1 GS	1978	12	30	23	33	21.9	024.458N	093.918E	033	4.6 MB					1.0 s	008
* 2 ISC	1978	12	30	23	33	23.1	024.81 N	094.17 E	033	4.5 MB						015
* 3 NAO	1978	12	30	23	33	14	023.0 N	094.0 E		4.1 MB						
* 4 HFS	1978	12	30	23	33	21	025.0 N	094.0 E		5.0 MB						
* 1 GS	1979	01	01	18	51	10.8	020.898N	093.752E	062	5.3 MB					0.9 s	166
* 2 ISC	1979	01	01	18	51	10.9	020.89 N	093.69 E	061	5.3 MB	4.7S					236
* 3 MOS	1979	01	01	18	51	5.6	020.62 N	093.76 E	033	5.5 MB	4.6S					
* 4 PEK	1979	01	01	18	51	13	020.8 N	093.8 E	050		5.0S					
ISC	1979	01	09	02	39	56	024.96 N	092.5 E	064	4.3 MB						012
BKK	1979	01	09	17	45	50.1	019.02 N	097.29 E	010				3.5 L		0.40s	003
* 1 GS	1979	01	09	23	28	44.3	020.914N	101.770E	033	4.8 MB					1.0 s	020
* 2 ISC	1979	01	09	23	28	44.5	020.97 N	101.77 E	033	4.7 MB						030
* 1 GS	1979	01	09	23	33	44.6	020.966N	102.017E	033	4.9 MB	4.7S				1.4 s	040
* 2 ISC	1979	01	09	23	33	44.8	021.05 N	102.03 E	033	4.8 MB	4.7S					056
* 3 MOS	1979	01	09	23	33	40.0	021.01 N	102.05 E	001	4.9 MB	4.8S					
* 1 BKK	1979	01	13	06	41	20.8	021.08 N	102.90 E	018				4.5 L		1.71s	003
* 2 ISC	1979	01	13	06	41	28.5	021.34 N	102.39 E	000							005
* 3 PEK	1979	01	13	06	41	26	021.2 N	103.0 E			4.4S					
BKK	1979	01	14	12	38	47.6	022.48 N	100.68 E	009				4.4 L		0.85s	003
BKK	1979	01	18	01	40	28.3	014.36 N	096.56 E	010				3.7 L		1.59s	003
* 1 GS	1979	01	20	17	06	50.5	015.847N	096.262E	033	4.1 MB					0.9 s	008
* 2 ISC	1979	01	20	17	06	48.8	016.1 N	096.08 E	033	4.1 MB						011
BKK	1979	01	20	21	40	31.2	020.79 N	102.05 E	016				3.8 L		1.18s	003
BKK	1979	01	20	21	52	44.9	020.80 N	101.91 E	007				3.6 L		0.31s	003
BKK	1979	01	21	17	19	54.2	018.05 N	096.25 E	008				4.1 L		0.87s	003

Investigation of Active Faults: Fault Trenching in Taiwan

Geological Record found in a Fault Trench in Taiwan

Step 2: Recurrence

Fault Trenching in Kanchanaburi, Thailand

Step 2: Recurrence

Magnitude-Recurrence Relationship

- The most commonly used equation (model) to describe the occurrence of earthquakes is the well-known Gutenberg-Richter relationship:

$$Log_{10} N(m) = a - b.m$$

where

N(m) is the average number per year of earthquakes having magnitudes greater than **m**.

a and ***b*** are constants; they are conventionally obtained from an appropriate statistical analysis of historical earthquakes.

10^a is the average number per year of earthquakes above magnitude zero.

b describes the relative rate of occurrence of different magnitudes. ***b*** is typically 1.0 ± 0.3.

- **The form of this relationship has been verified from observations of seismicity throughout the world.**

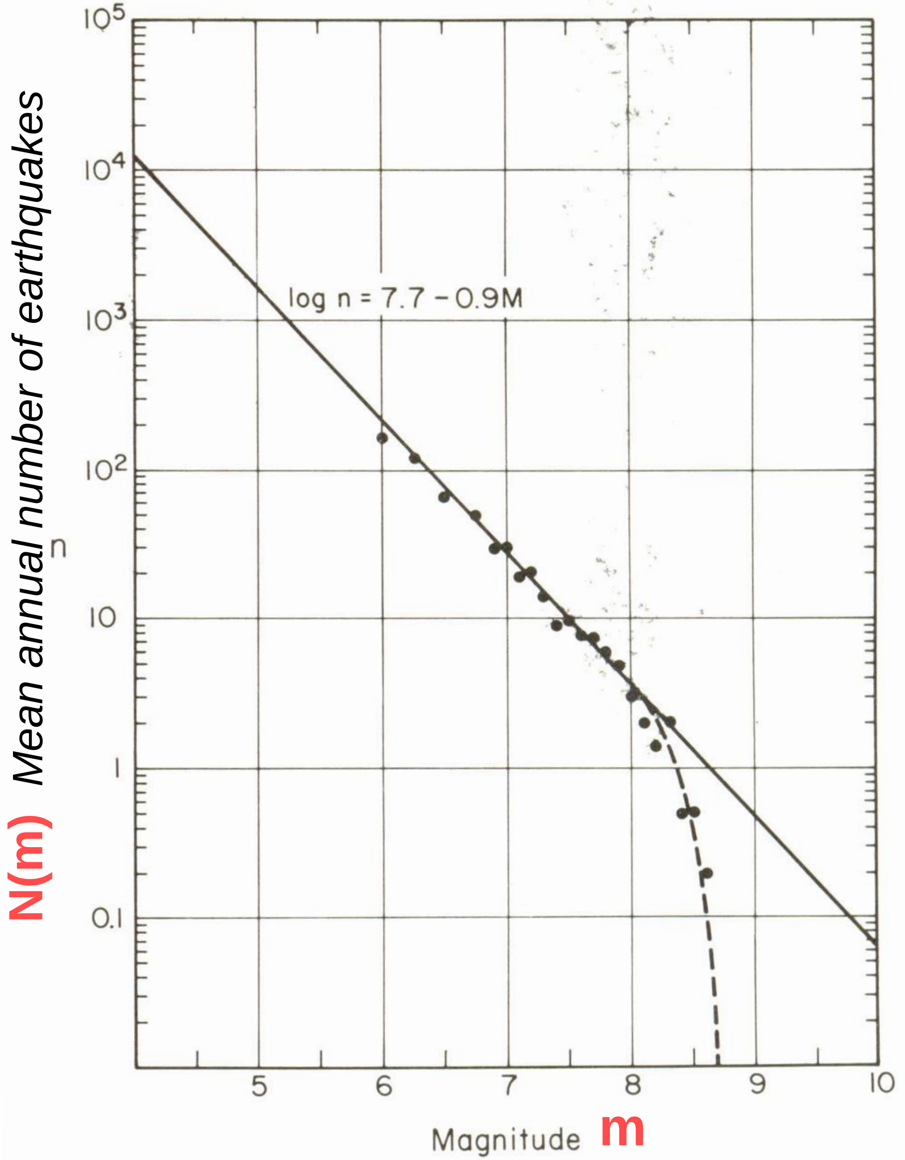
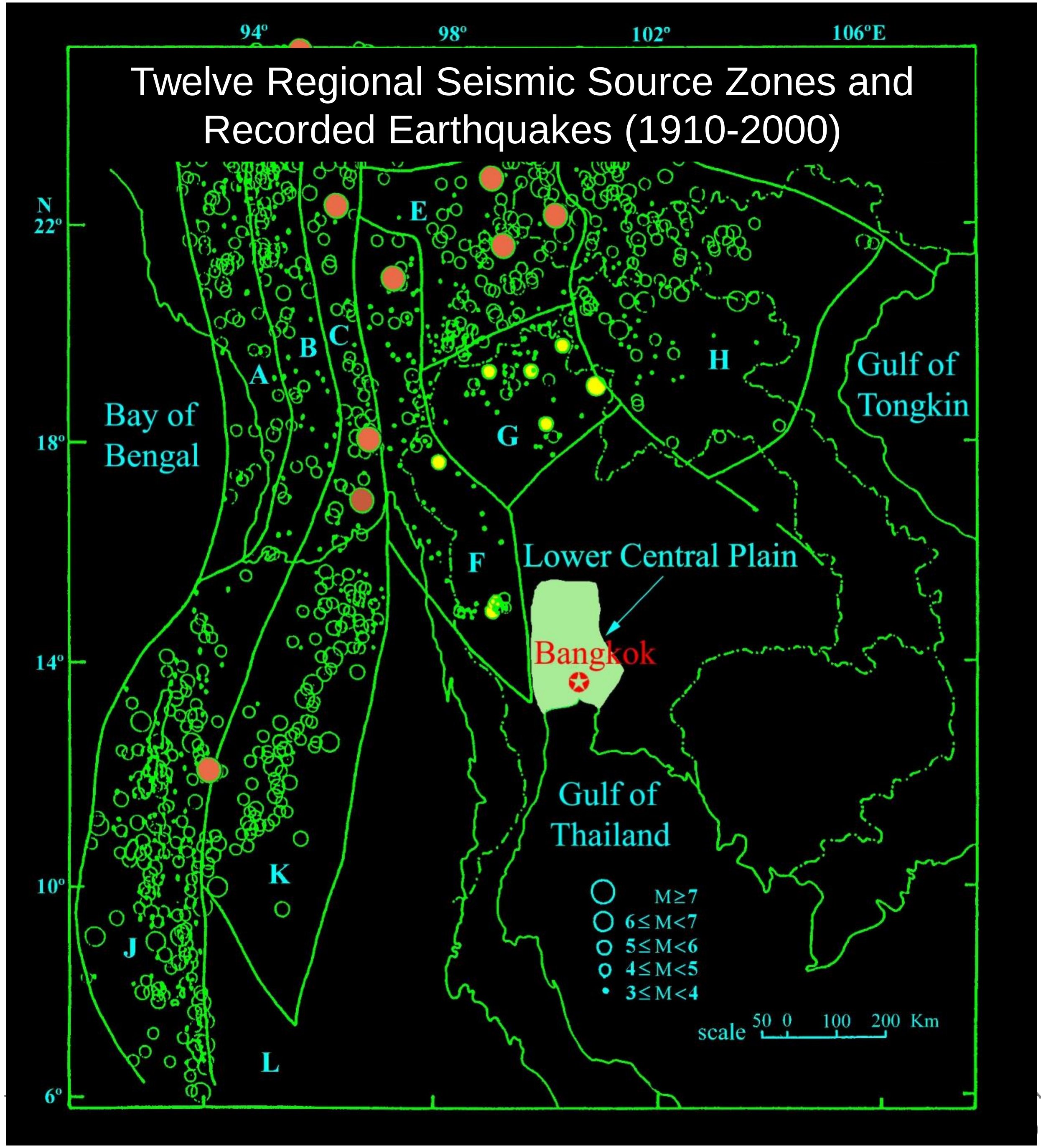


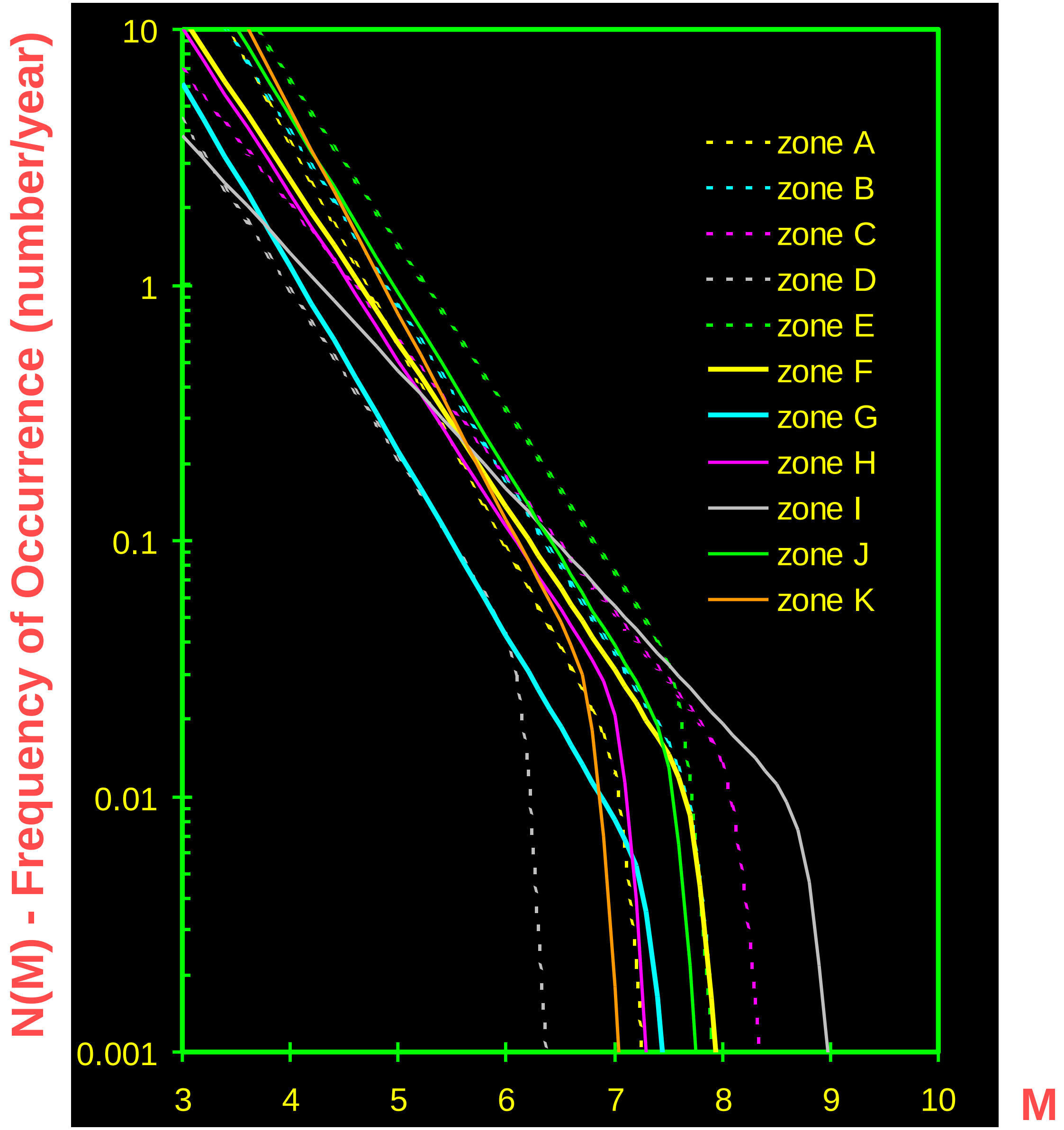
Fig. 5.5. Mean annual frequency distribution of world earthquakes, 1904–1946; ndM is the mean annual number of shocks having magnitudes lying between M and $M + dM$.

m	N(m)
8.0	2
7.0	20
6.0	100
5.0	3,000
4.0	15,000

The Gutenberg-Richter (exponential) model



Magnitude-Recurrence Relationships



Fault Sources

- For some faults, the occurrence rate of large earthquakes deviates from that predicted by Gutenberg-Richter relationship.

- For these faults, a **characteristic earthquake model** is thought to represent more accurately the seismicity of the fault.

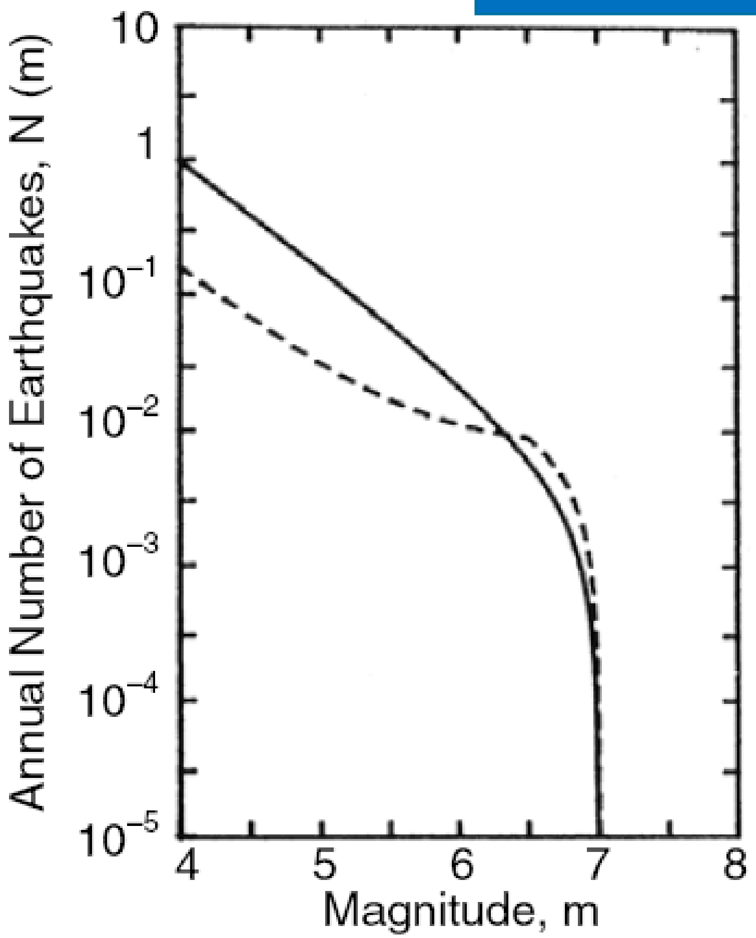
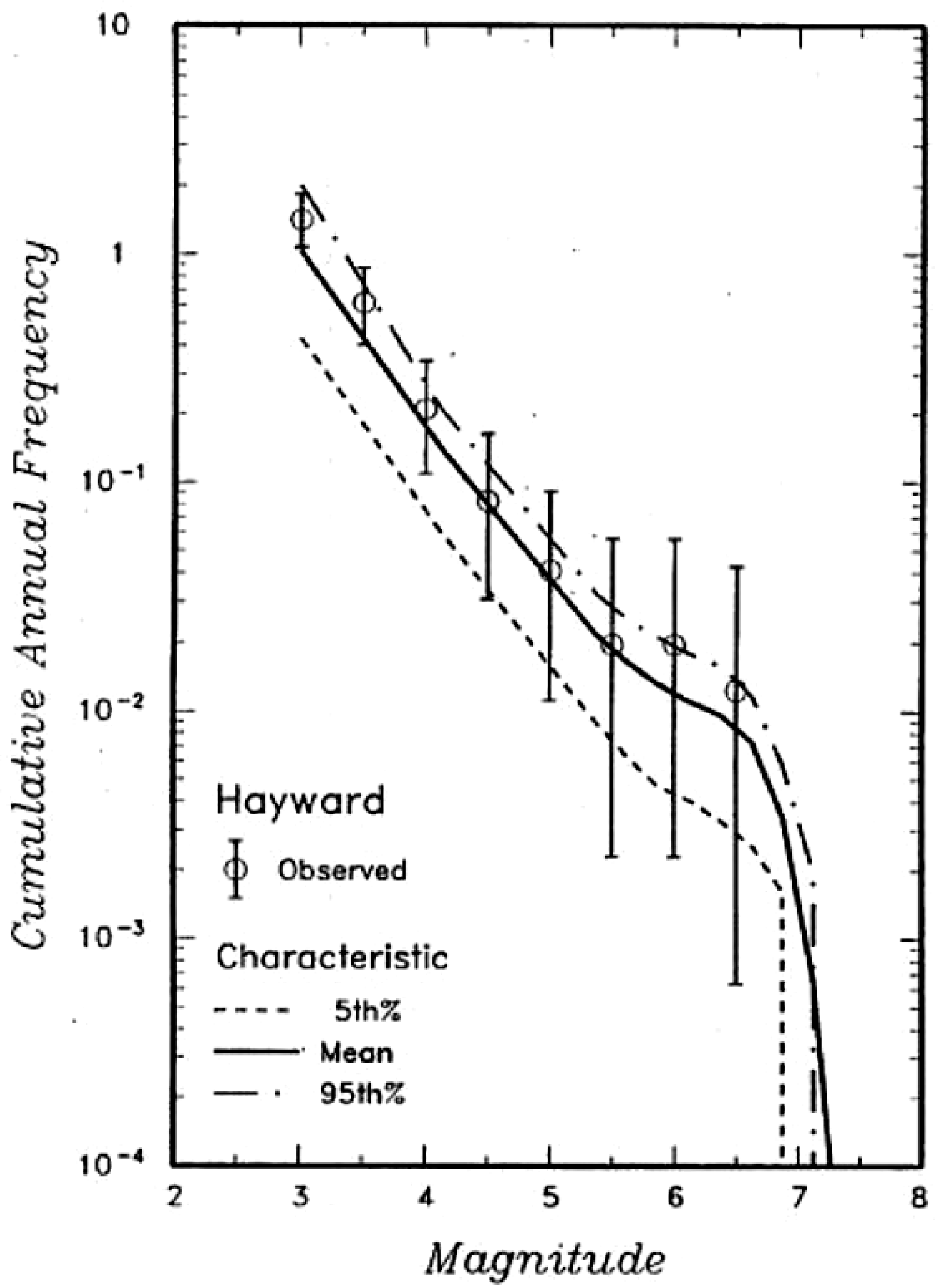
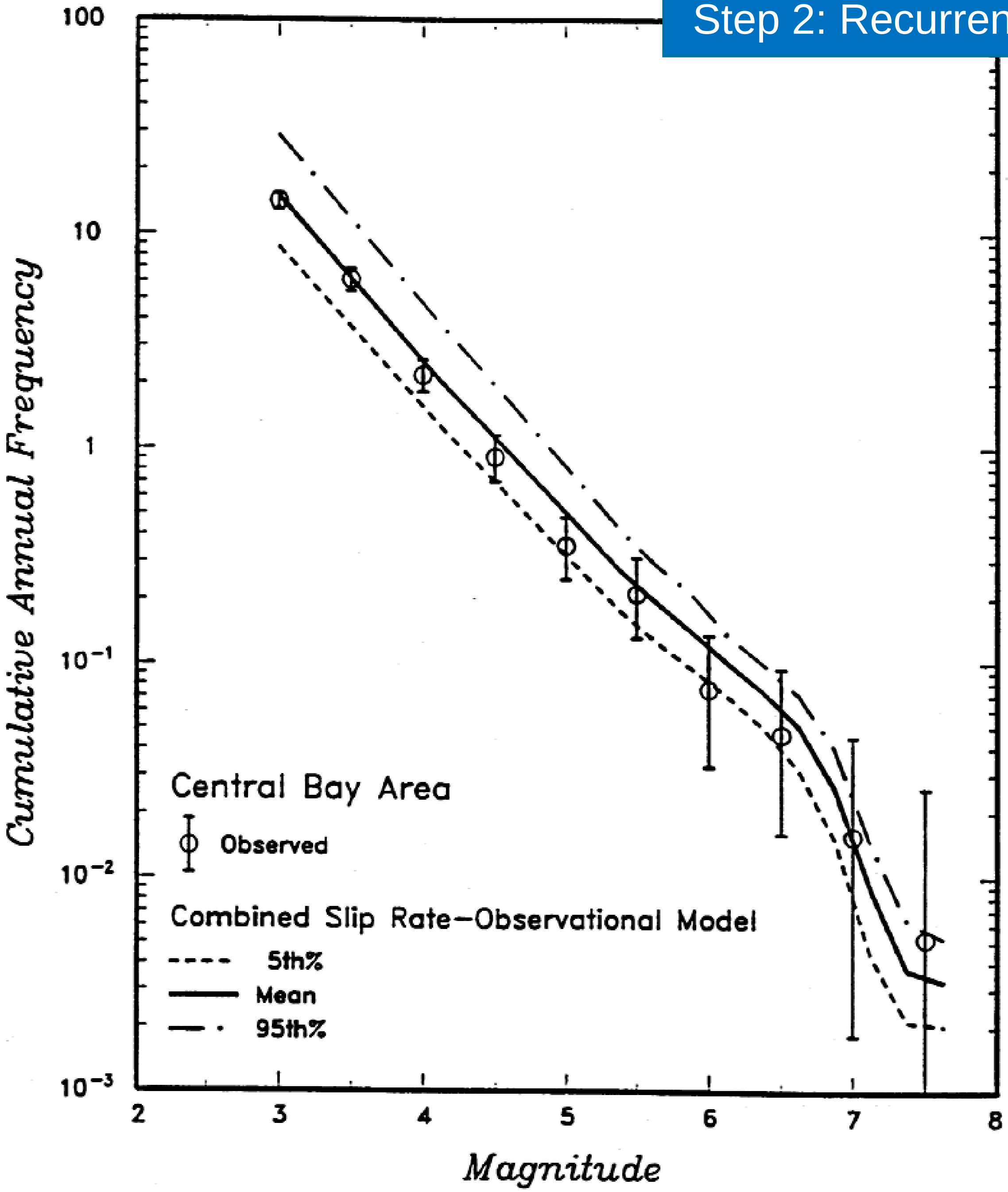


FIGURE 8.7 Comparison of the exponential (solid line) and characteristic recurrence (dashed line) frequency curves. (From Youngs, R.R. and Coppersmith, K.J., *Bull. Seismol. Soc. Am.*, 75, 939–964, 1985.)

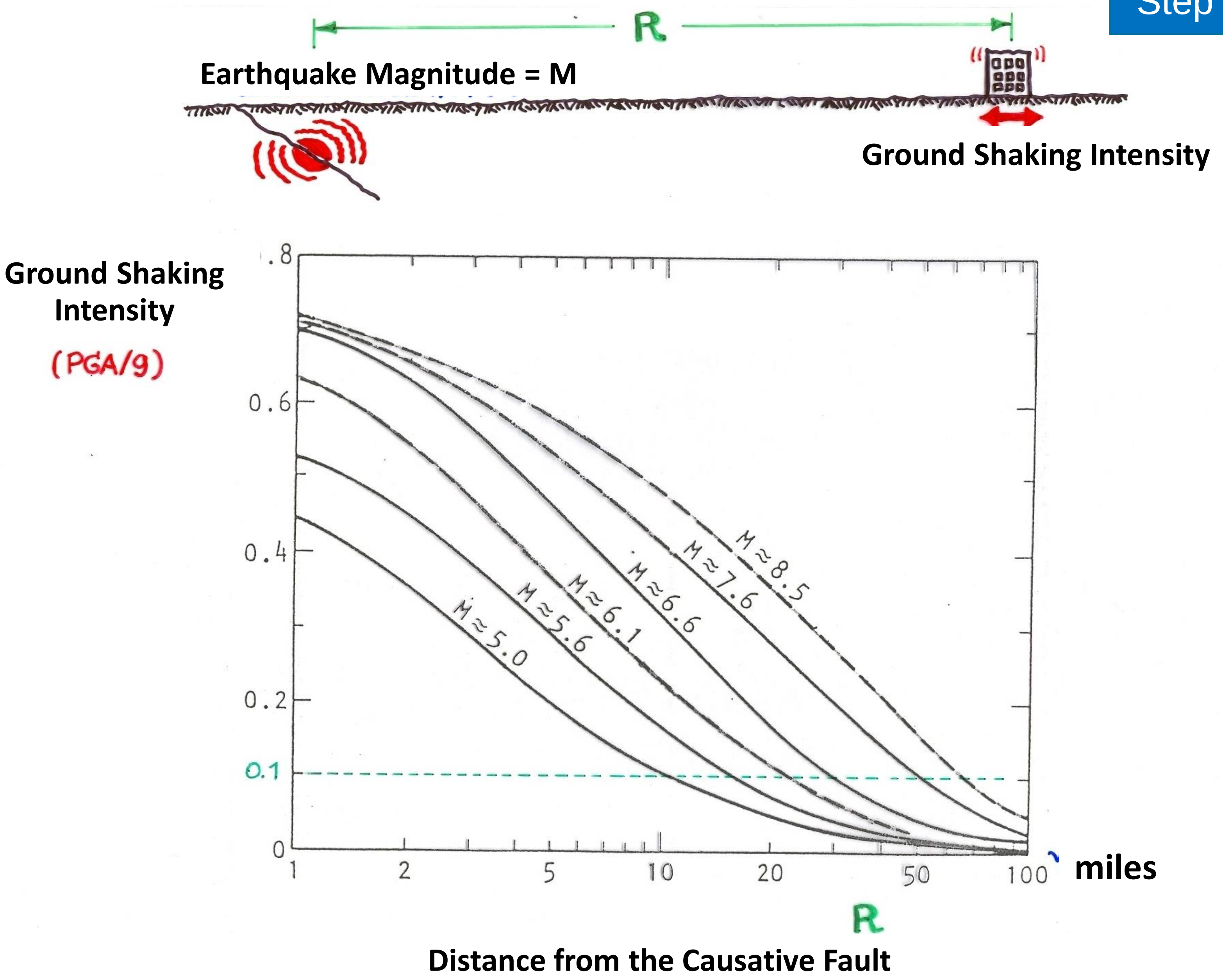
Step 2: Recurrence





Attenuation Relationships

- The ground motion **attenuation relationships** provide the means of estimating a strong-ground-motion parameter of interest from parameters of the earthquake, such as magnitude, source-to-site distance, fault mechanism, local site conditions, etc.
- A wide variety of **empirical ground motion attenuation relationships** is available for application in PSHA.
- The choice of an appropriate relationship is governed by the regional tectonic setting of site of interest, whether it is located within a **stable continental region**, or an **active tectonic region**, or whether the site is in proximity to a **subduction zone** tectonic environment.


R
Earthquake Magnitude = M
Ground Shaking Intensity
Ground Shaking Intensity
(PGA/g)
.8
0.6
0.4
0.2
0.1
0
1
2
5
10
20
50
100
miles
R
M ≈ 8.5
M ≈ 7.6
M ≈ 6.6
M ≈ 6.1
M ≈ 5.6
M ≈ 5.0
Distance from the Causative Fault

Tectonic Regions

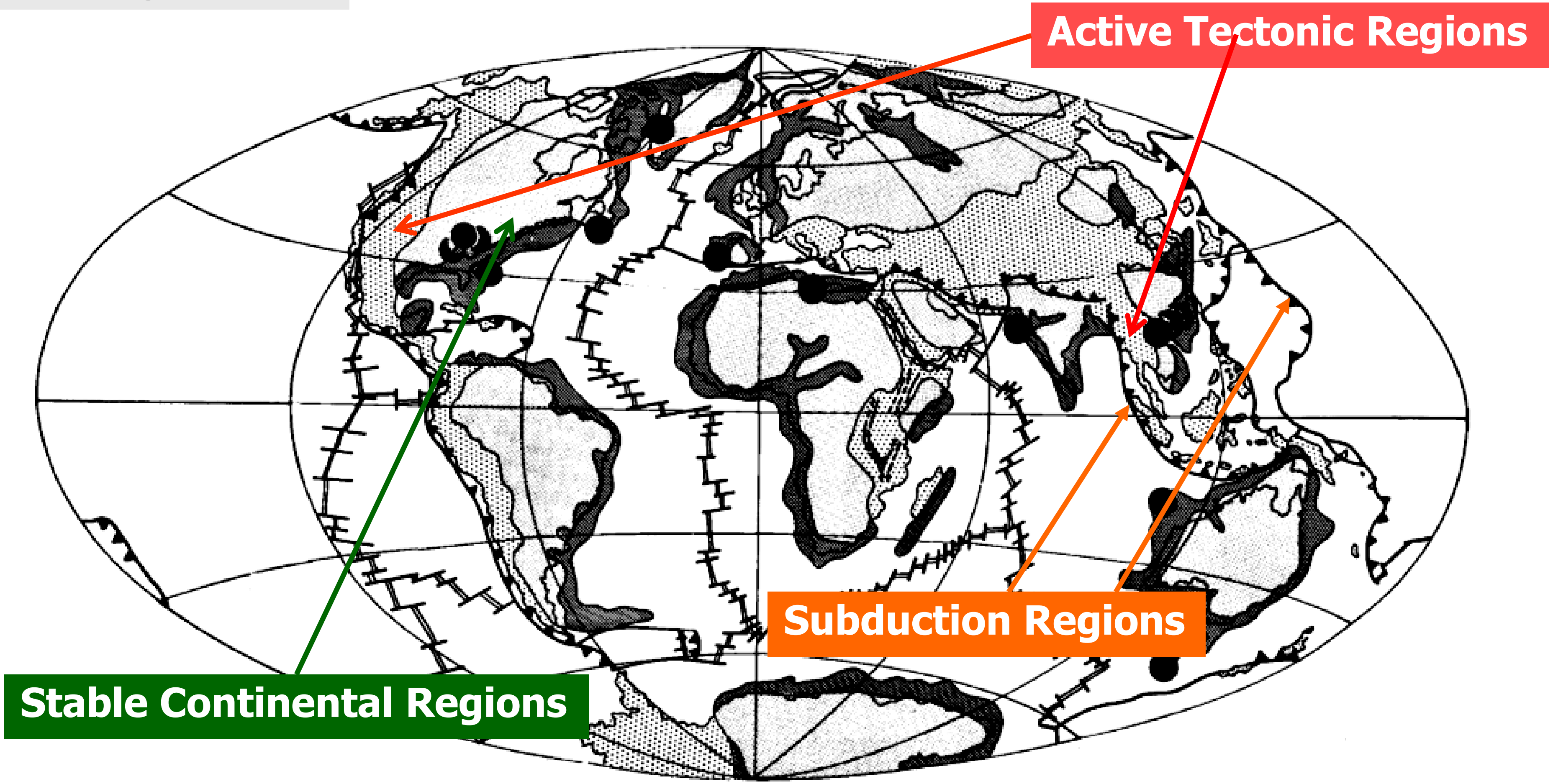


FIGURE 5.6 Geographic distribution of active and stable continental tectonic regions worldwide. (From Johnston, A.C. 1994. "Seismotectonic Interpretations and Conclusions from the Stable Continental Region Seismicity Database," in *The Earthquake of Stable Continental Regions, Vol. 1, Assessment of Large Earthquake Potential*, Electric Power Research Institute, Palo Alto, CA, pp. 1–103. With permission.)

TABLE 5.3 List of Selected Attenuation Relations

Region	Tectonic Environment	Attenuation Relation
Western North America	Shallow active crust	Abrahamson and Silva [1997]
		Boore et al. [1997]
		Campbell and Bozorgnia [in press]
		Sadigh et al. [1993, 1997]
Eastern North America	Shallow stable crust	Atkinson and Boore [1995, 1997]
		Toro et al. [1997]
		Campbell [in press]
Europe	Shallow active crust	Ambraseys et al. [1996]
	Shallow stable crust	Dahle et al. [1990]
Japan	All types undivided	Molas and Yamazaki [1995, 1996]
Worldwide	Shallow extended crust	Spudich et al. [1999]
	Subduction interface	Youngs et al. [1997]
	Subduction intraslab	Youngs et al. [1997]
	Subduction undivided	Crouse [1991a, 1991b]

Attenuation Relationships

Ground motion attenuation is often represented by the form:

$$Log_{10}Y = c_1 + c_2.M + c_3.Log_{10} R + c_4.R + c_5.F + c_6.S + \varepsilon$$

where

Y is the ground motion parameter of interest (i.e. PGA, PGV, SA, SD)

M is earthquake magnitude

R is source-to-site distance

F is the faulting mechanism of the earthquake

S is a description of the local site conditions

ε is a random error term with a mean of zero and a standard deviation of s (a Gaussian probability distribution); this term describes the variability in ground motion.

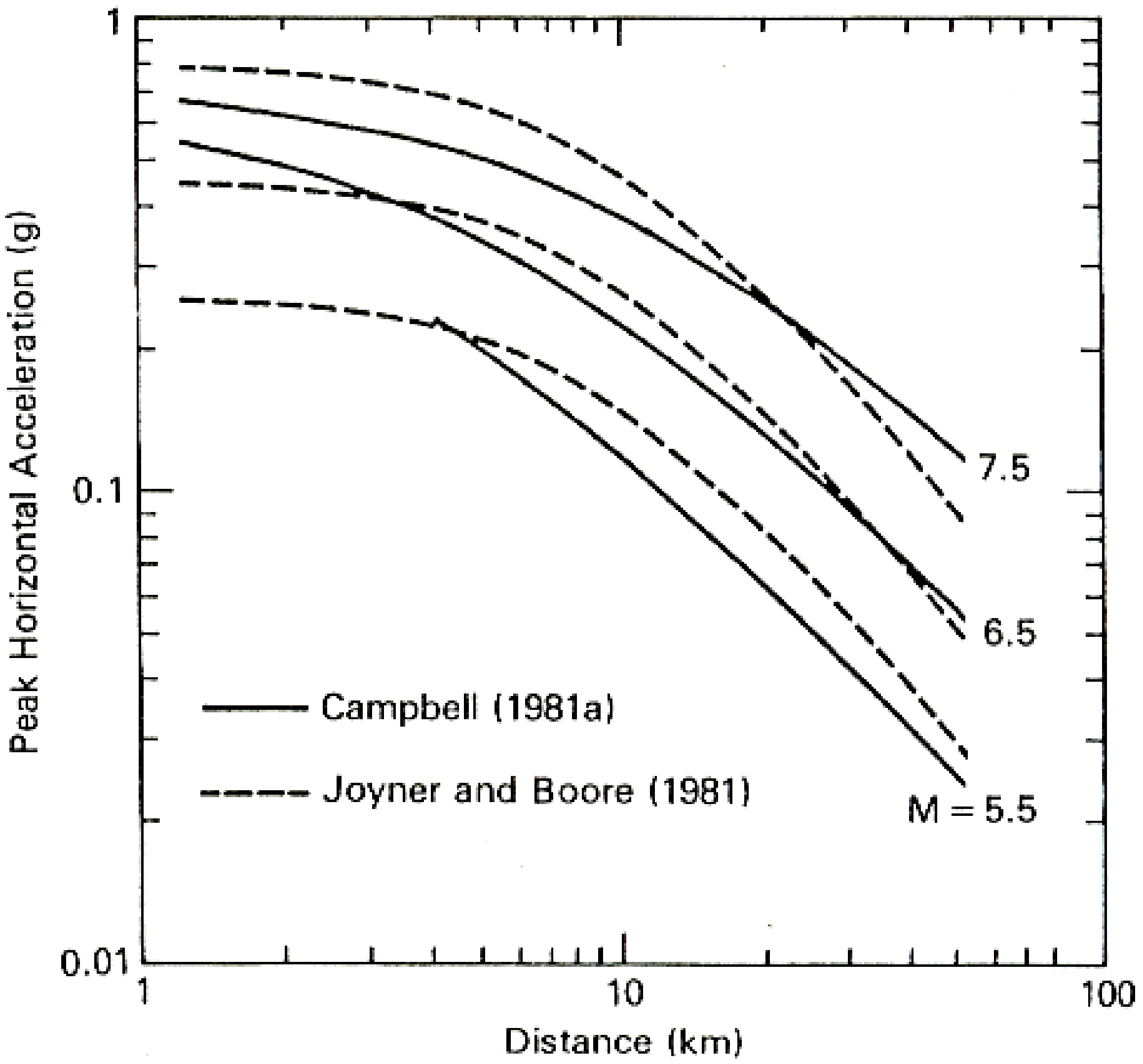
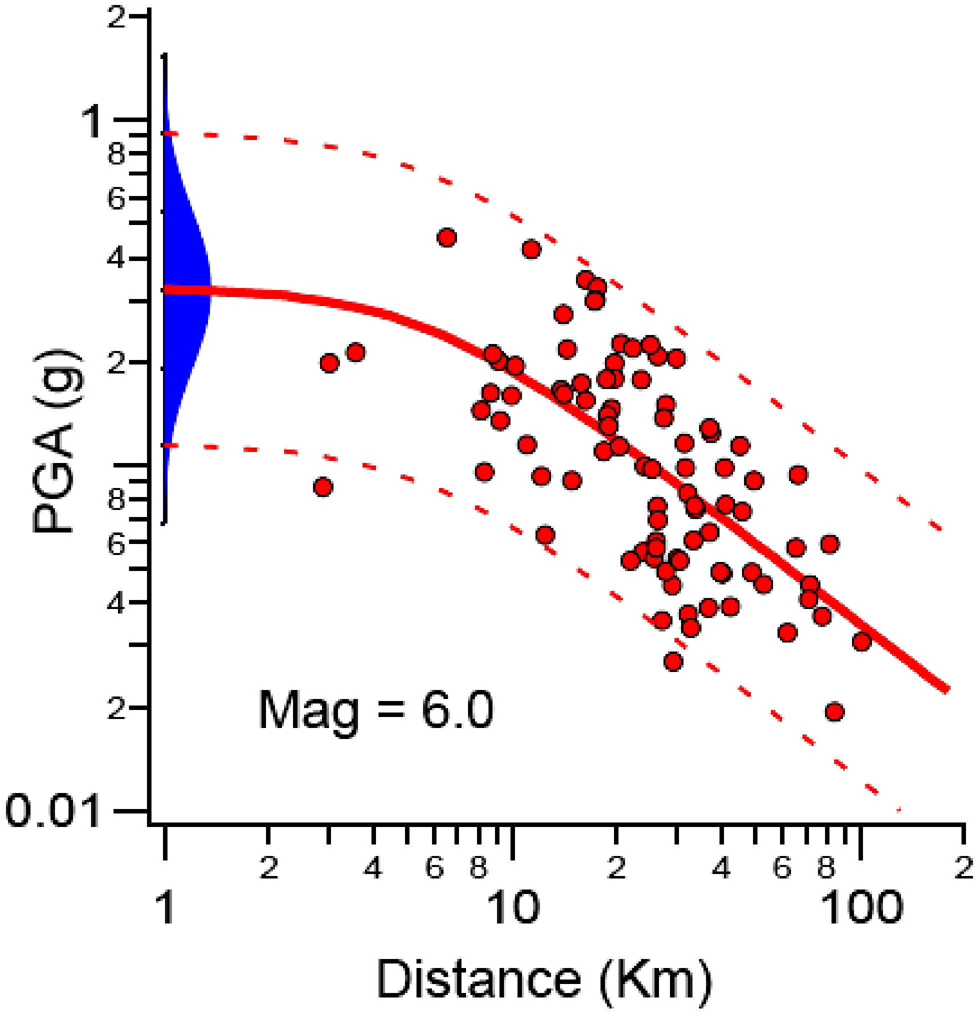


FIGURE 7.4 Median (50th percentile) estimates for peak horizontal acceleration from Campbell (1981a) and Joyner and Boore (1981). Joyner and Boore (1981) estimates of the maximum horizontal component have been reduced by 12% so that they may be compared with the (Campbell 1981a) estimates of the mean horizontal component (after Campbell 1981a).

Random Error of Attenuation Model



Source-to-Site Distance

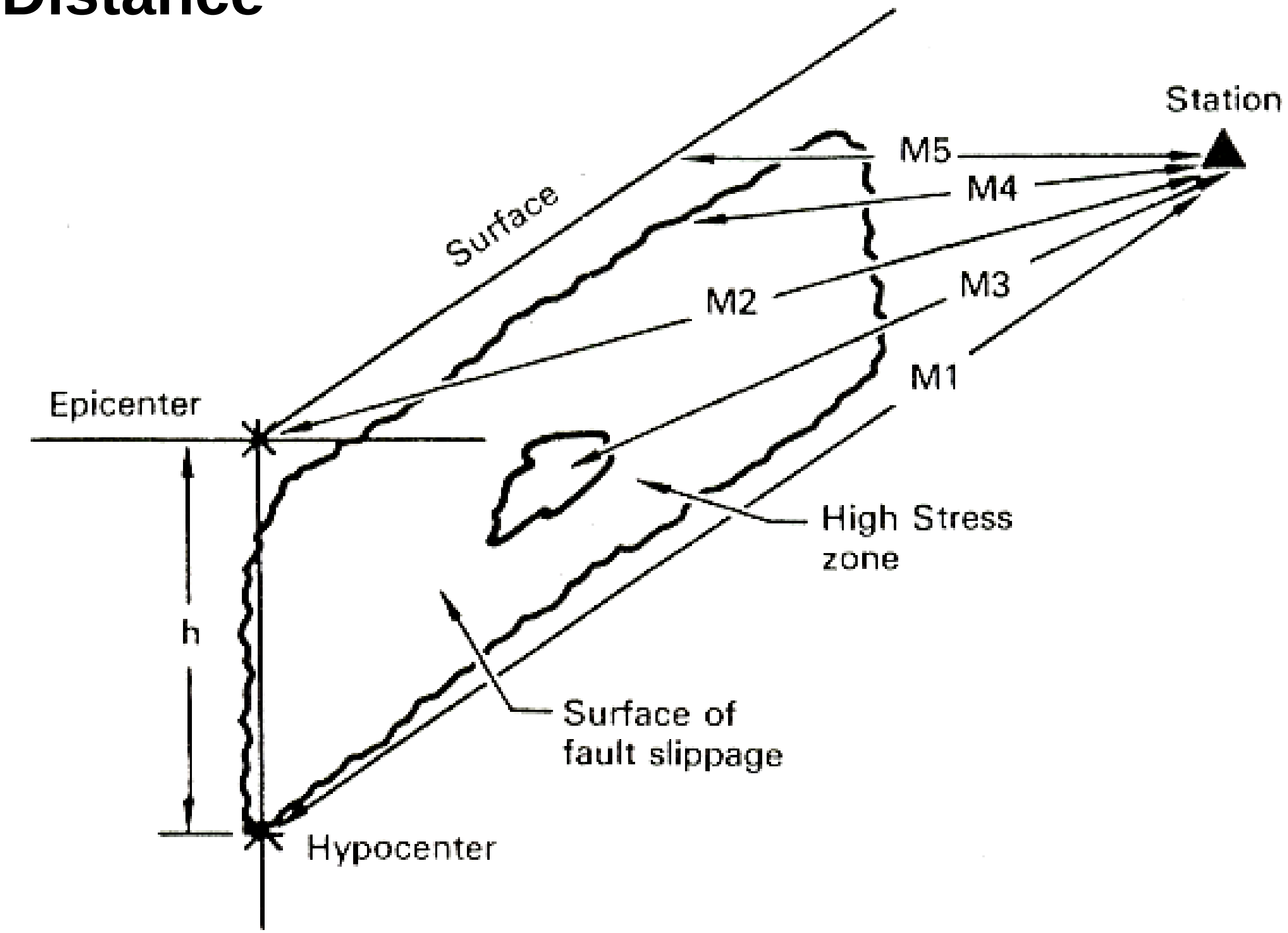


FIGURE 7.3 Schematic illustration of methods of distance measurement used in the determination of the distance value to be associated with a ground motion observation. M1 is the hypocentral distance (focal depth is h), M2 is the epicentral distance. M3 is the distance to the center of high-energy release (or high localized stress drop), M4 is the closest distance to the slipped fault, in this case, the fault rupture does not extend to the surface, and M5 is the closest distance to the surface projection of the fault rupture (after Shakal and Bernreuter 1981).

Faulting Mechanism

TABLE 5.5 Faulting Mechanism Categories and Related Rake Angles for Selected Attenuation Relations

Attenuation Relation	Category	F	Rake Angle (λ)
Abrahamson and Silva [1997]	Strike slip	0	0–30°, 150–210°, 330–360°
	Normal	0	210–330°
	Reverse-oblique	0.5	30–60°, 120–150°
	Reverse	1.0	60° to 120°
Boore et al. [1997]	Strike slip	—	0–30°, 150–210°, 330–360°
	Normal	—	210–330°
	Unknown	—	Unknown or random
	Reverse	—	30–150°
Campbell and Bozorgnia [in press]	Strike slip	0	0–22.5°, 177.5–202.5°, 337.5–360°
	Normal	0	202.5–337.5°
	Reverse (F_{RV} =1)	1.0	22.5–157.5° ($\delta > 45°$)
	Thrust (F_{TH} =1)	1.0	22.5–157.5° ($\delta \leq 45°$)
Sadigh et al. [1993, 1997]	Strike slip	0	0–45°, 135–225°, 315–360°
	Normal	0	225–315°
	Reverse	1.0	45–135°
Spudich et al. [1999]	Strike slip	—	0–45°, 135–225°, 315–360°
	Normal	—	225–315°

Note: Unless otherwise indicated, an unknown or random faulting mechanism is given by $F = 0.5$, $F_{RV} = 0.25$, and $F_{TH} = 0.25$.

Local Site Conditions

TABLE 5.2 Definition of Building-Code Site Classes

Site Class	Soil Profile Name	30-m Velocity, V_{S30} (m/sec) Range	Average
A	Hard rock	>1,500	1890
B	Rock	760–1500	1130
BC	BC boundary	555–1000	760
C	Very dense soil and soft rock	360–760	560
CD	CD boundary	270–555	360
D	Stiff soil	180–360	270
DE	DE boundary	90–270	180
E	Soft soil	<180	150

Source: Adapted from Wills, C.J. et al. 2000. "A Site-Conditions Map for California Based on Geology and Shear-Wave Velocity," *Bull. Seismol. Soc. Am.*, 90, S187–S208. With permission.

Attenuation Relationships

$$Log_{10}Y = c_1 + c_2.M + c_3.Log_{10}R + c_4.R + c_5.F + c_6.S + \varepsilon$$

Coefficients c_1, c_2, c_3, c_4, c_5, and c_6 are normally determined by fitting the equation to actual ground motion data (applying statistical regression analyses).

The term $c_3.Log_{10}R$ represents the geometric attenuation of the seismic wave front as it propagates away from the earthquake source.

The term $c_4.R$ represents the anelastic attenuation that results from the material damping and scattering as the seismic waves propagate through the crust.

Ground motion database used for developing an attenuation relationship

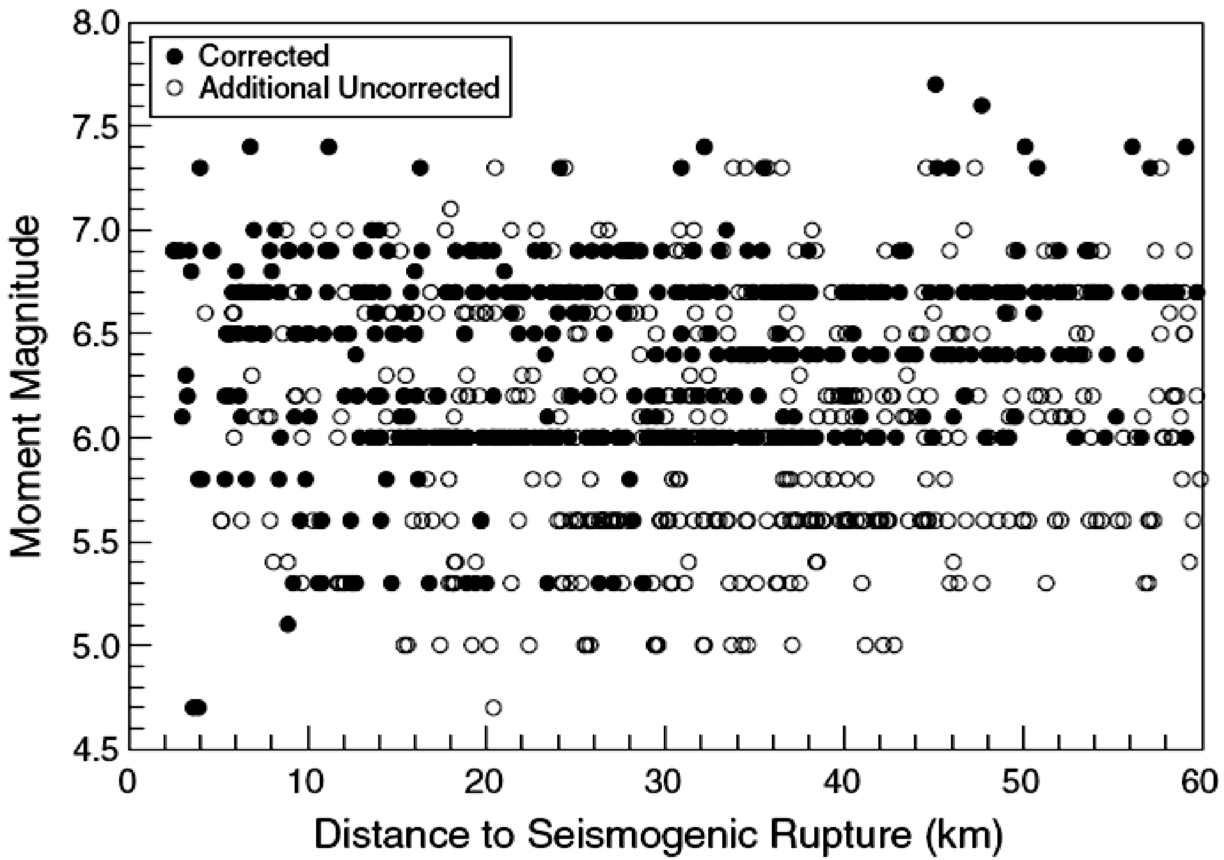


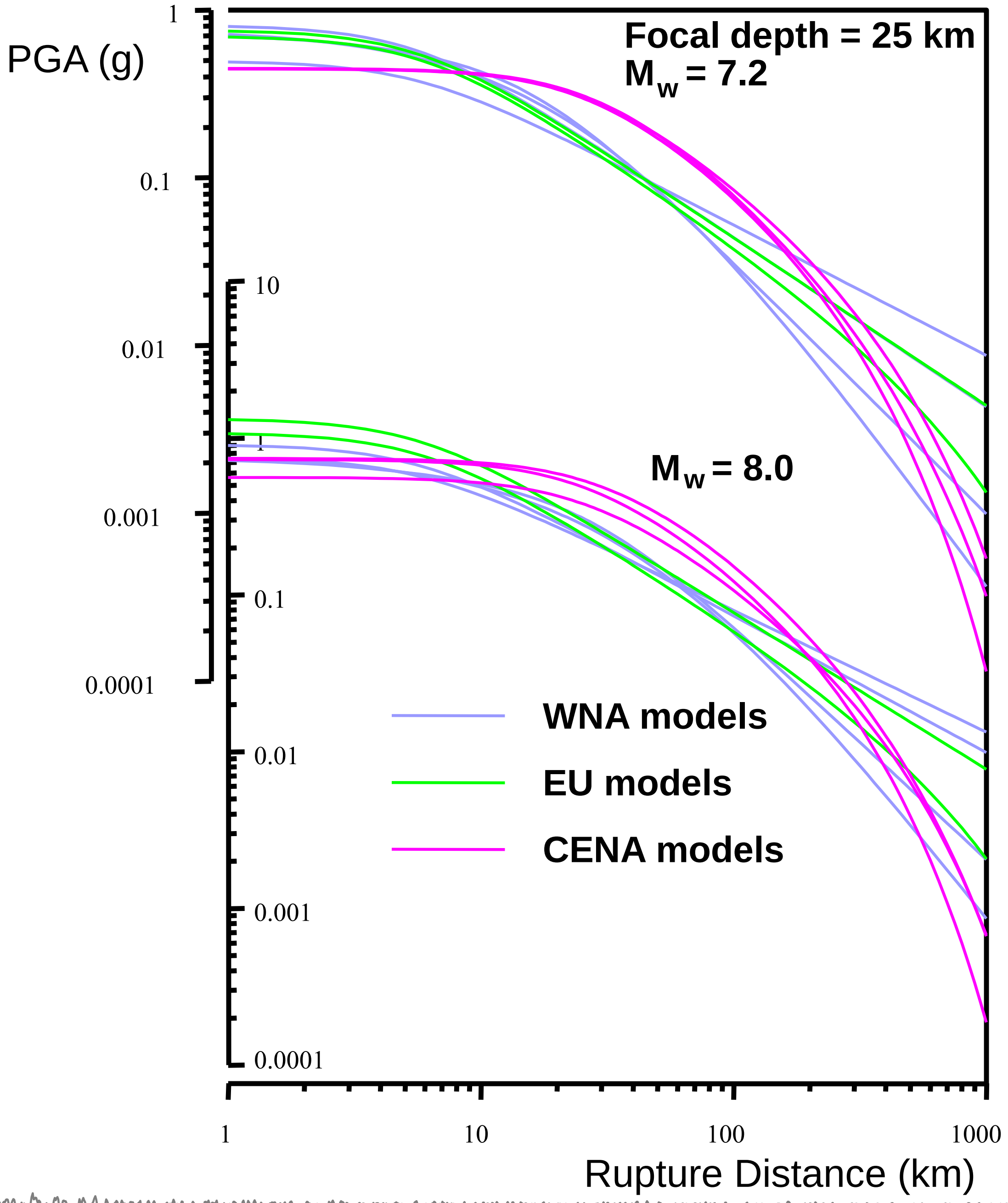
FIGURE 5.1 Example PGA attenuation relation (top) and its associated database (bottom). Uncorrected recordings are analog or digital acceleration time histories that have not been processed and, therefore, can provide only estimates of PGA. Corrected recordings are acceleration times histories that have been processed to derive velocity and displacement time histories, response spectra, and Fourier amplitude spectra. (From Campbell, K.W. and Bozorgnia, Y. 1999. "Vertical Ground Motion: Characteristics, Relationship with Horizontal Component, and Building-Code Implications," in *Proc. SMIP99 Seminar on Utilization of Strong-Motion Data*, M. Huang, Ed., Sept. 15, San Francisco, pp. 23–49. California Strong Motion Instrumentation Program, Sacramento. With permission.)

Coefficients of an attenuation relationship

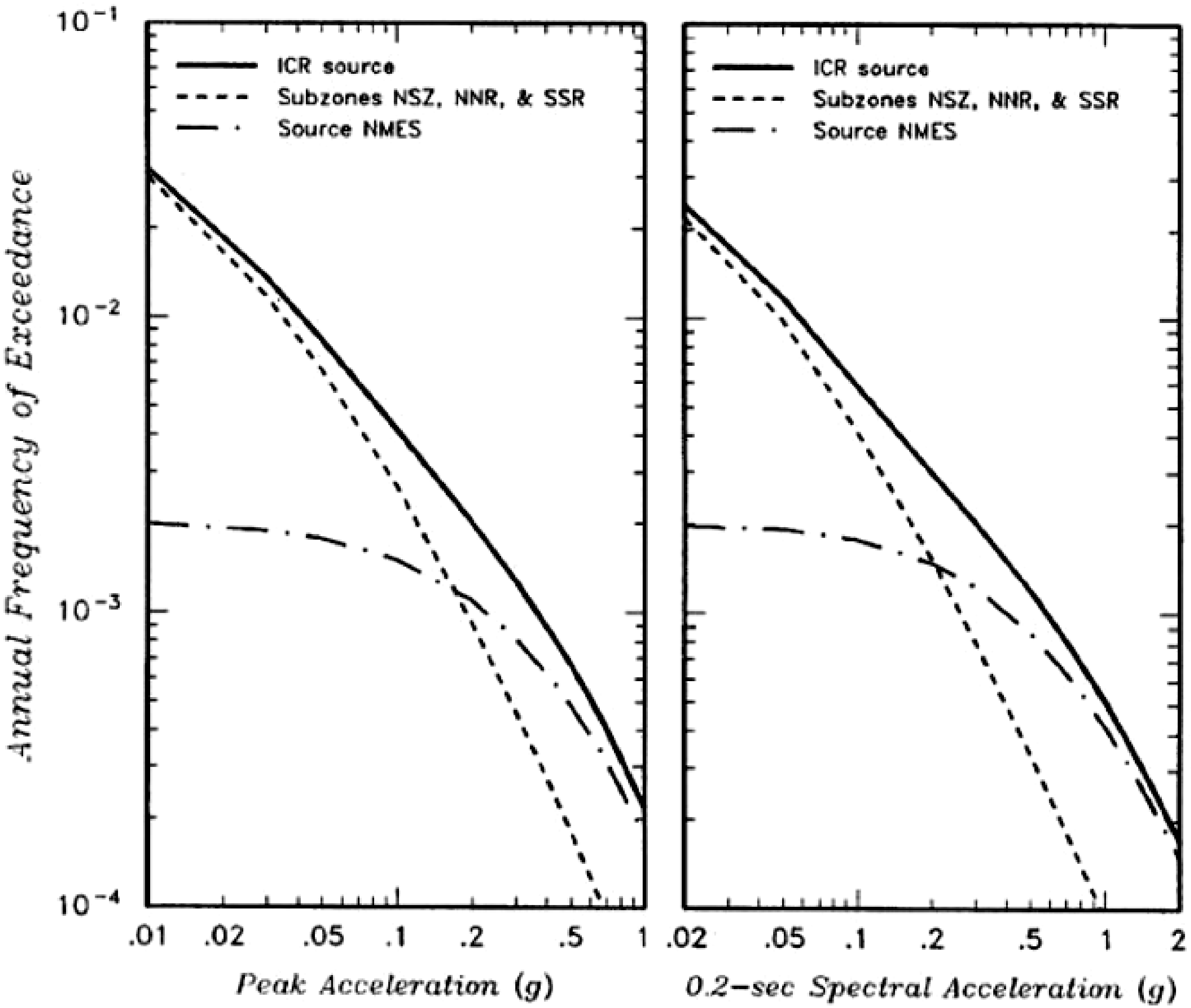
TABLE 5.11 Coefficients for Sadigh et al. Rock Attenuation Relation: Horizontal Component

T_n (s)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}
						$M_W \leq 6.5$								
PGA	0.182	–0.624	1.0	0	–2.100	0	3.6564	0.250	0	1.39	0.14	0.38	0	7.21
0.05	0.182	–0.090	1.0	0.006	–2.128	–0.082	3.6564	0.250	0	1.39	0.14	0.38	0	7.21
0.07	0.182	0.110	1.0	0.006	–2.128	–0.082	3.6564	0.250	0	1.40	0.14	0.39	0	7.21
0.09	0.182	0.212	1.0	0.006	–2.140	–0.052	3.6564	0.250	0	1.40	0.14	0.39	0	7.21
0.10	0.182	0.275	1.0	0.006	–2.148	–0.041	3.6564	0.250	0	1.41	0.14	0.40	0	7.21
0.12	0.182	0.348	1.0	0.005	–2.162	–0.014	3.6564	0.250	0	1.41	0.14	0.40	0	7.21
0.14	0.182	0.307	1.0	0.004	–2.144	0	3.6564	0.250	0	1.42	0.14	0.41	0	7.21
0.15	0.182	0.285	1.0	0.002	–2.130	0	3.6564	0.250	0	1.42	0.14	0.41	0	7.21
0.17	0.182	0.239	1.0	0	–2.110	0	3.6564	0.250	0	1.42	0.14	0.41	0	7.21
0.20	0.182	0.153	1.0	–0.004	–2.080	0	3.6564	0.250	0	1.43	0.14	0.42	0	7.21
0.24	0.182	0.060	1.0	–0.011	–2.053	0	3.6564	0.250	0	1.44	0.14	0.43	0	7.21
0.30	0.182	–0.057	1.0	–0.017	–2.028	0	3.6564	0.250	0	1.45	0.14	0.44	0	7.21
0.40	0.182	–0.298	1.0	–0.028	–1.990	0	3.6564	0.250	0	1.48	0.14	0.47	0	7.21
0.50	0.182	–0.588	1.0	–0.040	–1.945	0	3.6564	0.250	0	1.50	0.14	0.49	0	7.21
0.75	0.182	–1.208	1.0	–0.050	–1.865	0	3.6564	0.250	0	1.52	0.14	0.51	0	7.21
1.0	0.182	–1.705	1.0	–0.055	–1.800	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
1.5	0.182	–2.407	1.0	–0.065	–1.725	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
2.0	0.182	–2.945	1.0	–0.070	–1.670	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
3.0	0.182	–3.700	1.0	–0.080	–1.610	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
4.0	0.182	–4.230	1.0	–0.100	–1.570	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
5.0	0.182	–4.714	1.0	–0.100	–1.540	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
7.5	0.182	–5.530	1.0	–0.110	–1.510	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21

Attenuation Relationships



Probability of Exceedance

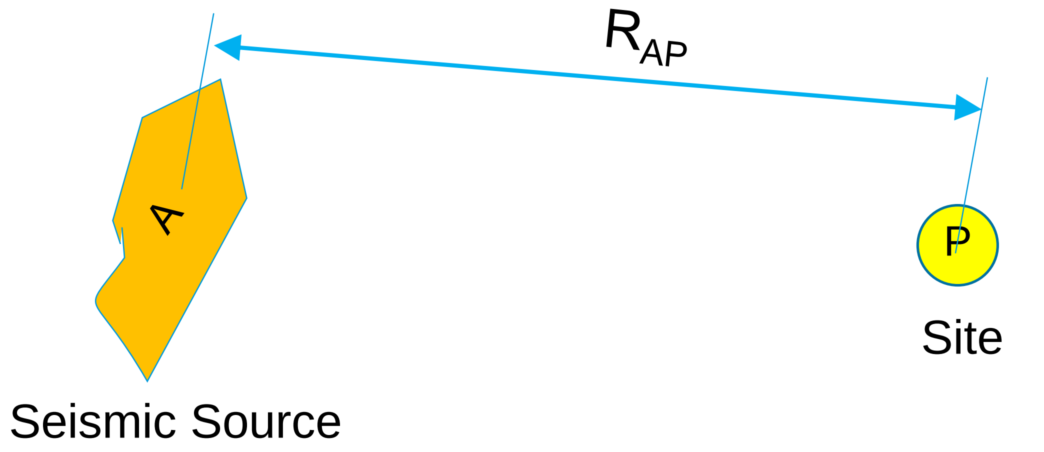


Simplified PSHA – An Example

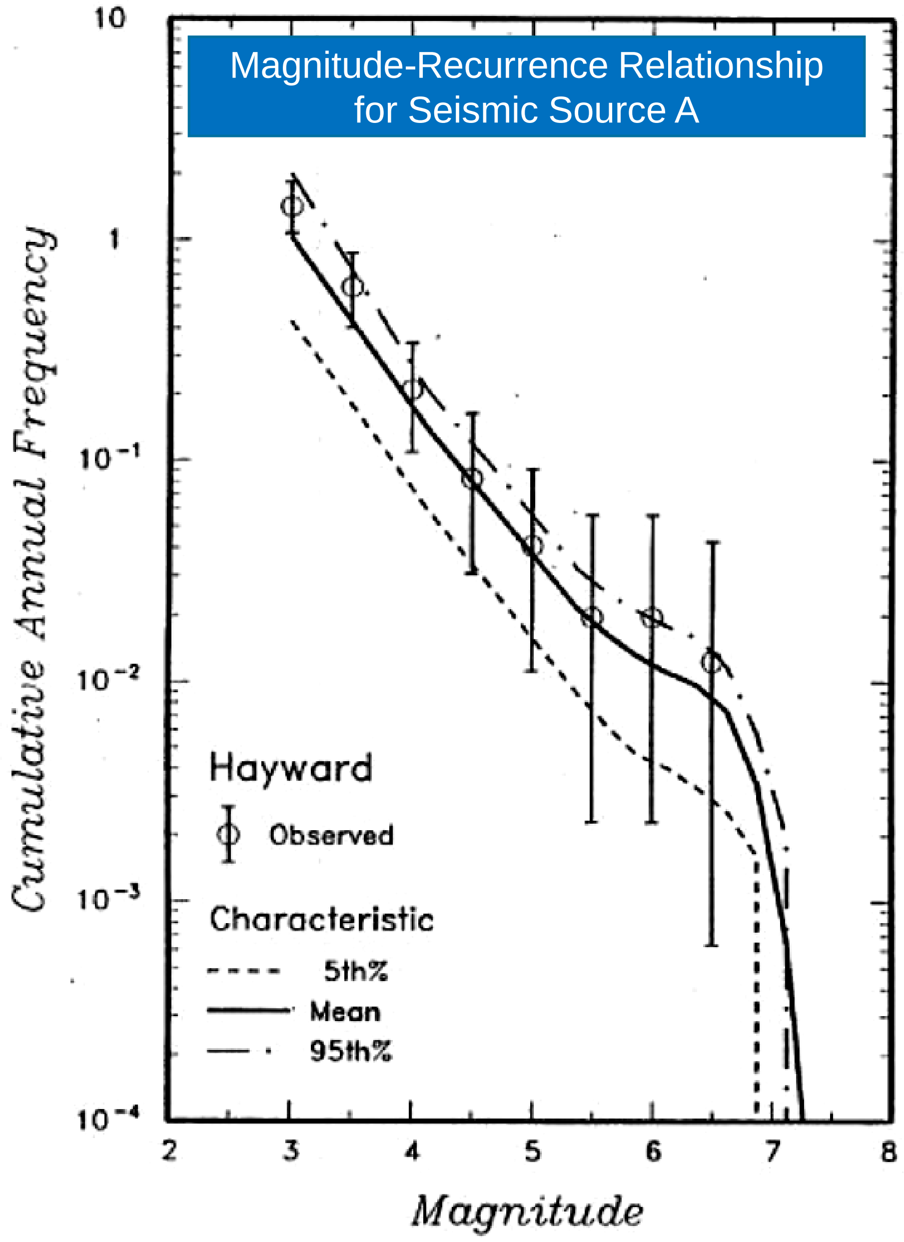
Simplified PSHA – An Example

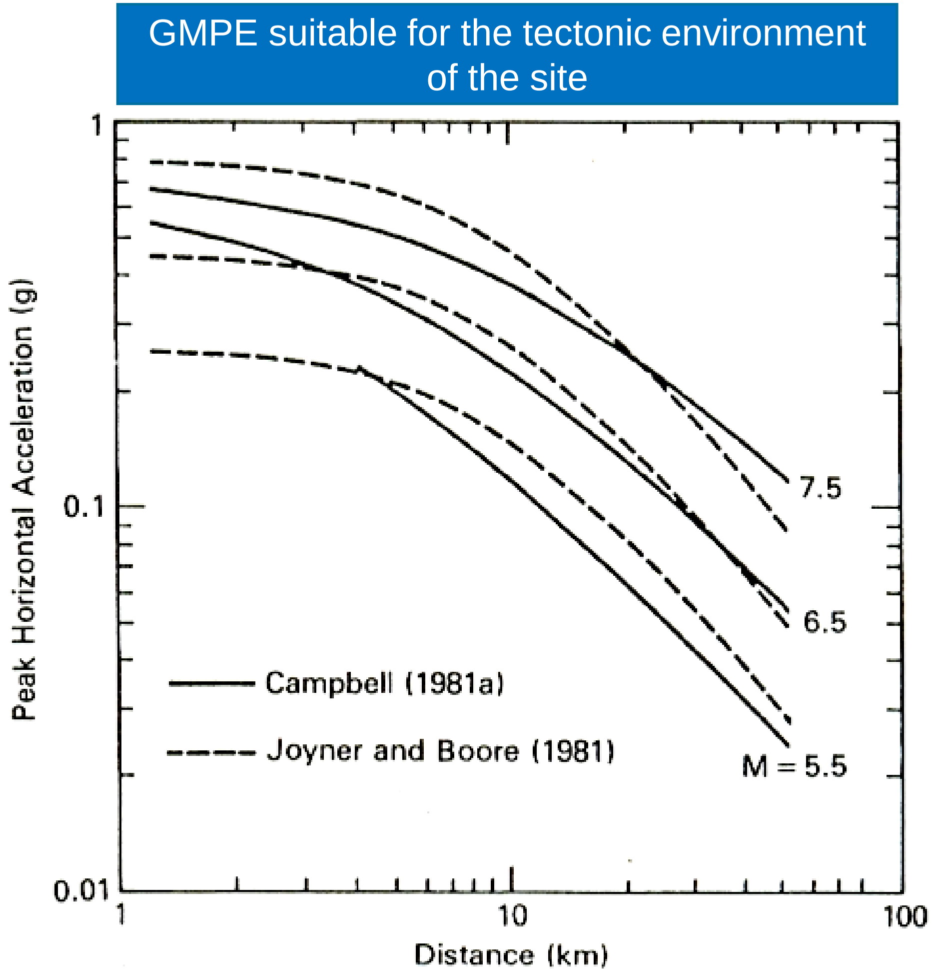
To demonstrate on how probabilistic ground motion is estimated, a simplified calculation of probabilistic ground motion is presented as follows:

Let's consider a simple case where only one seismic source (A) is located near the site of interest (P).



The source-to-site distance = R_{AP} = 30 km.

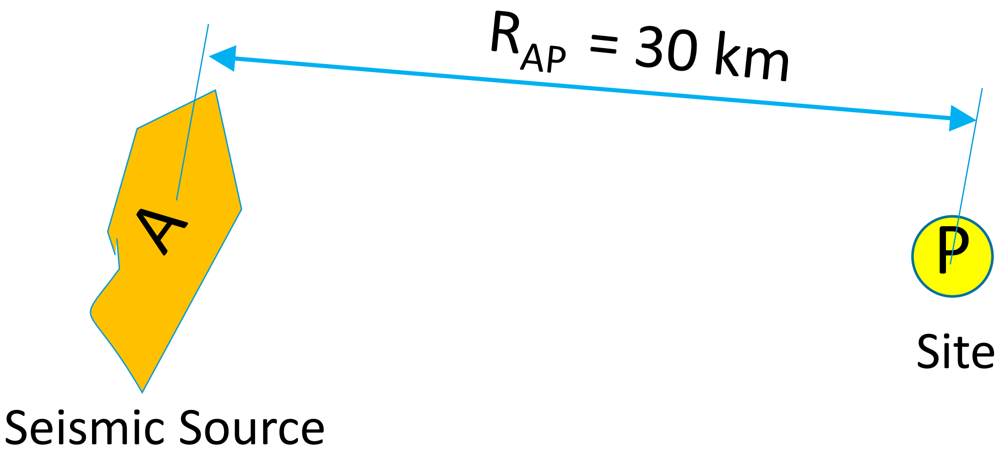

Magnitude-Recurrence Relationship
for Seismic Source A
Cumulative Annual Frequency
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
2
3
4
5
6
7
8
Magnitude
Hayward
Observed
Characteristic
5th%
Mean
95th%

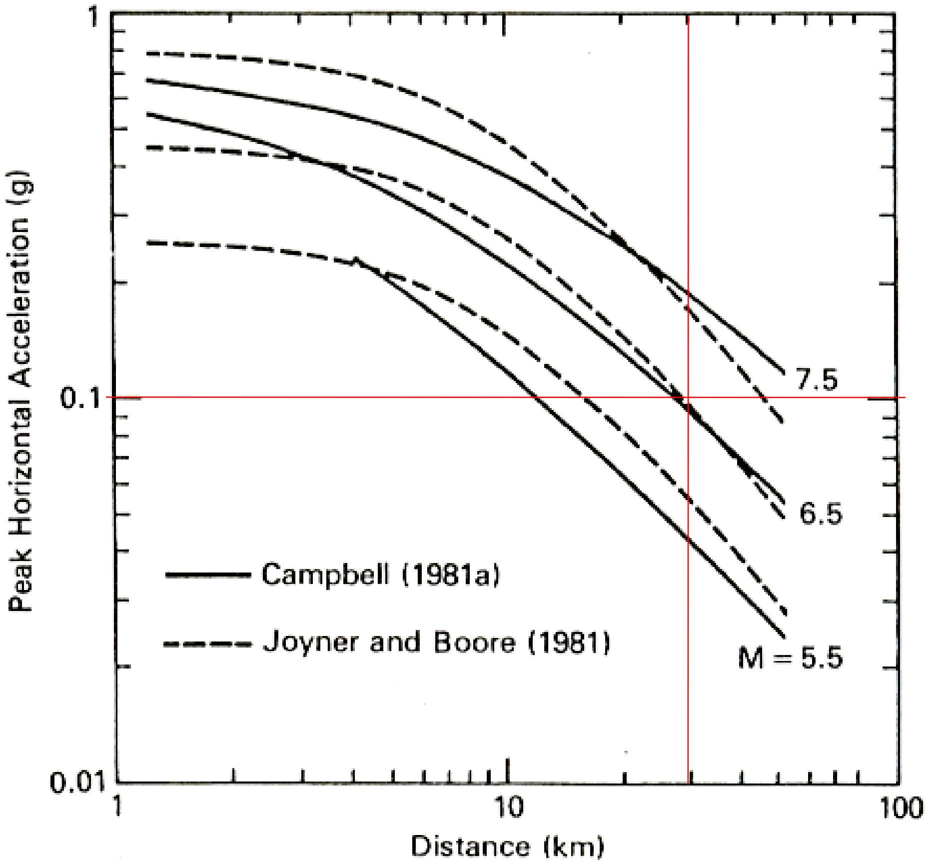

GMPE suitable for the tectonic environment
of the site
Peak Horizontal Acceleration (g)
1
0.1
0.01
1
10
100
Distance (km)
Campbell (1981a)
Joyner and Boore (1981)
7.5
6.5
M = 5.5

Simplified PSHA

Let's set the PGA level of interest at the site to, say, 0.10 g.

According to the selected attenuation relationship, earthquakes with magnitude greater than 6.6 will produce PGA at the site equal to or greater than 0.10 g.



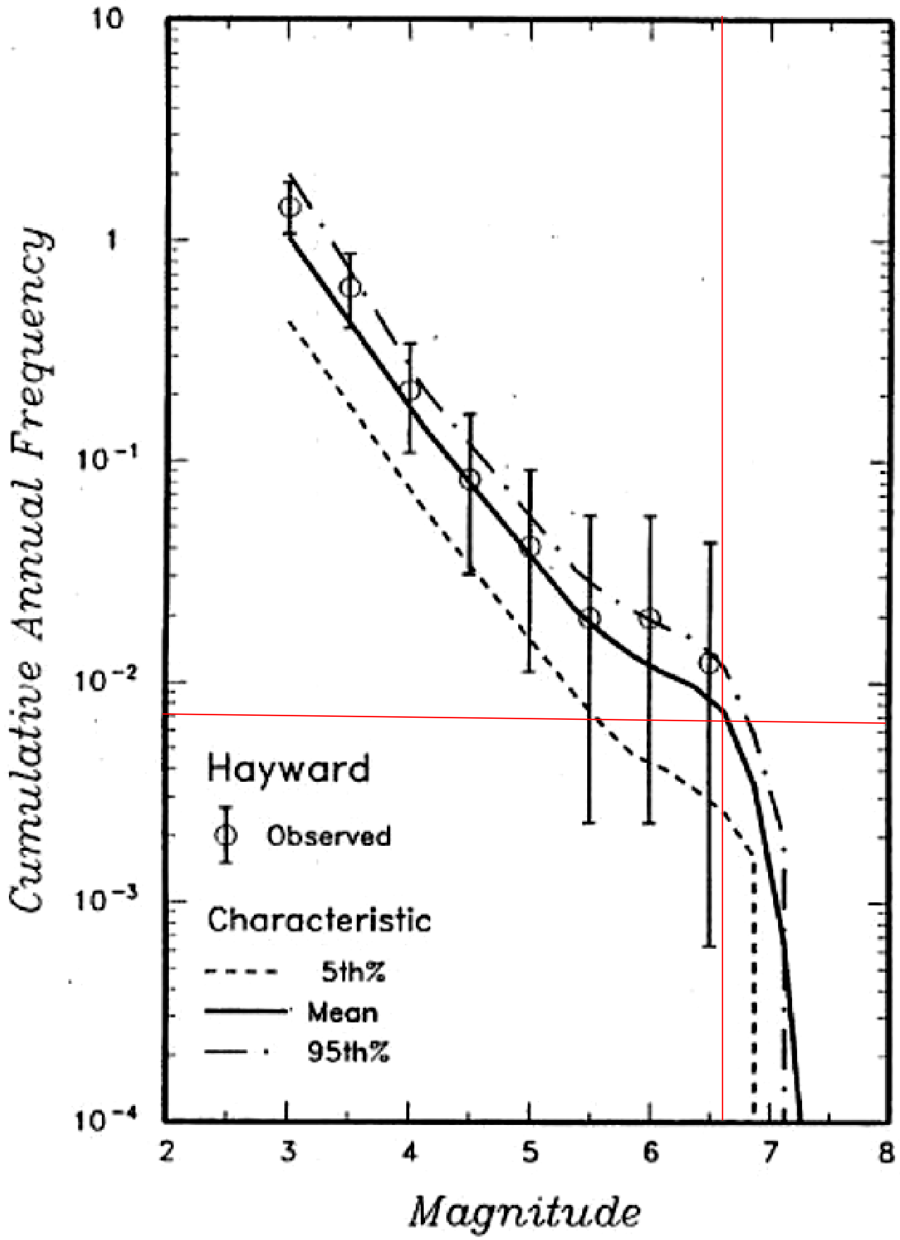


Simplified PSHA

According to the magnitude-recurrence relationship of the source zone A, the annual occurrence rate of earthquakes with M > 6.6 = $N_{(M=6.6)}$ = 0.007 event per year

Hence, the annual occurrence rate of having PGA at the site exceeding 0.10 g = 0.007 (event per year) = annual exceedance rate.

In the other words, the return period for PGA > 0.10 g = 1/0.007 = 143 years.

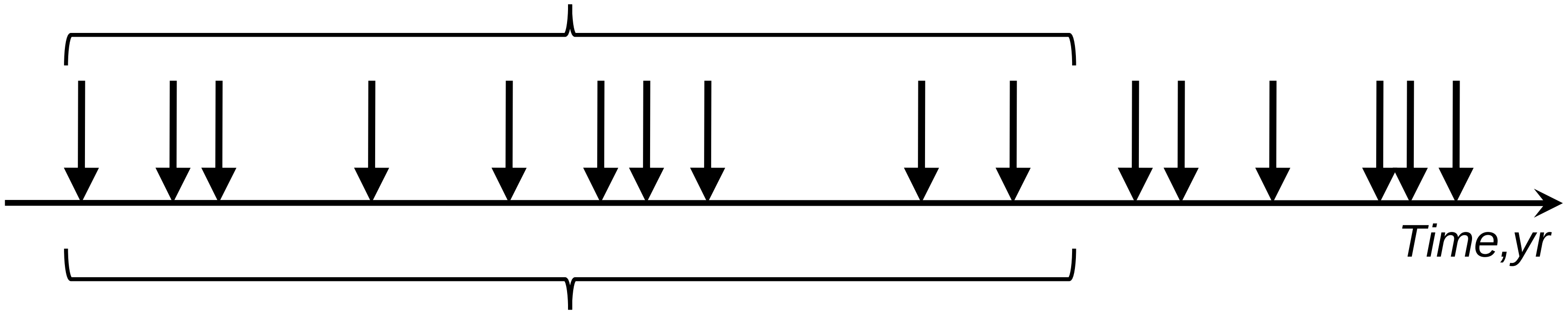


Random Occurrence of Earthquakes in Time:

Poisson Process

Annual exceedance rate = total number of events/time period = 0.007

Annual Frequency of Exceedance



Return Period = time period/total number of events = 143 yr

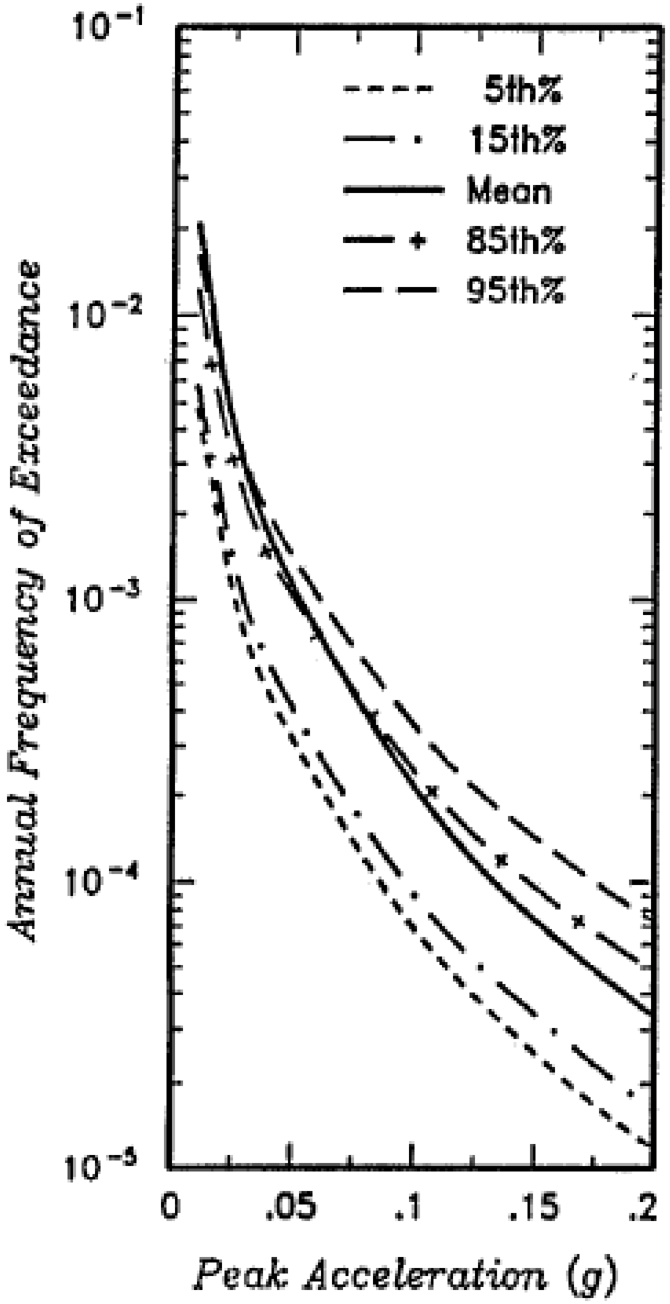

= *Earthquake Event with PGA > 0.10 g at the site*

Given a time period of 10 years,
the chance of having such event in this time period
= *0.007 x 10 = 0.07 = 7 %, or*
= *10/147 = 0.07 = 7 %*

7% PE in 10 Years → **PGA = 0.1 g**

Simplified PSHA

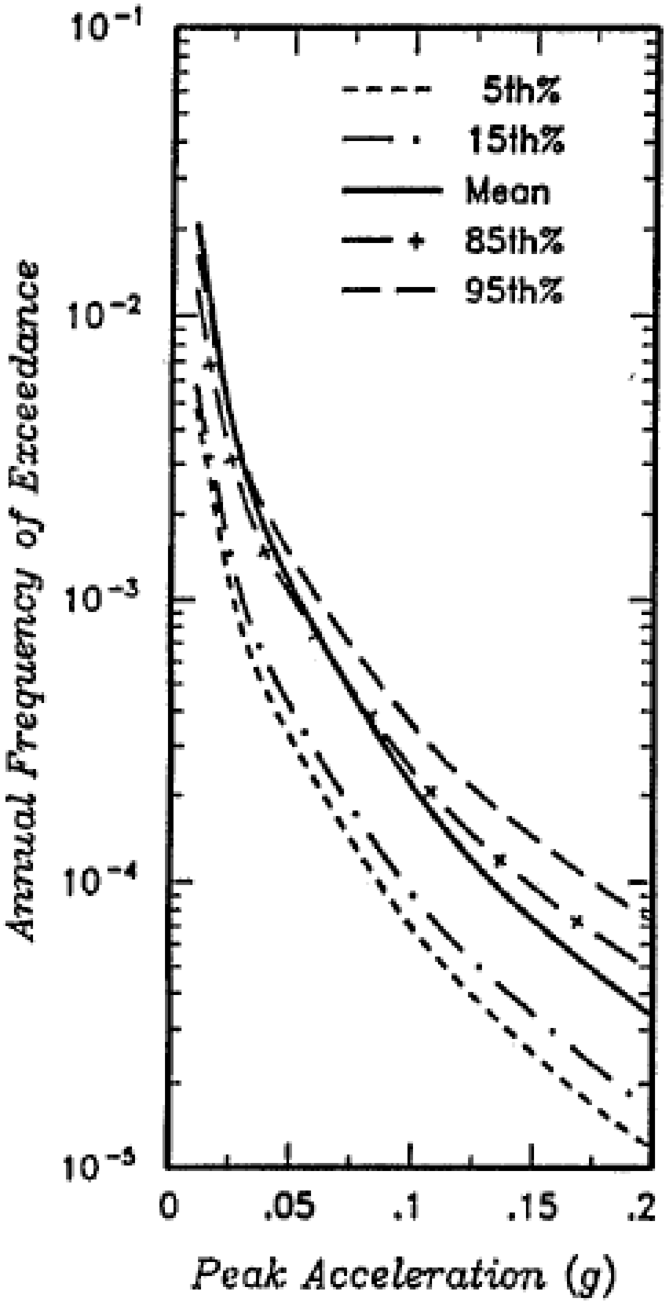
- Repeat the calculation process for many other PGA levels (0.01g, 0.05g, 0.20g, etc.).
- Draw the relationship between PGA and the corresponding annual exceedance rate.



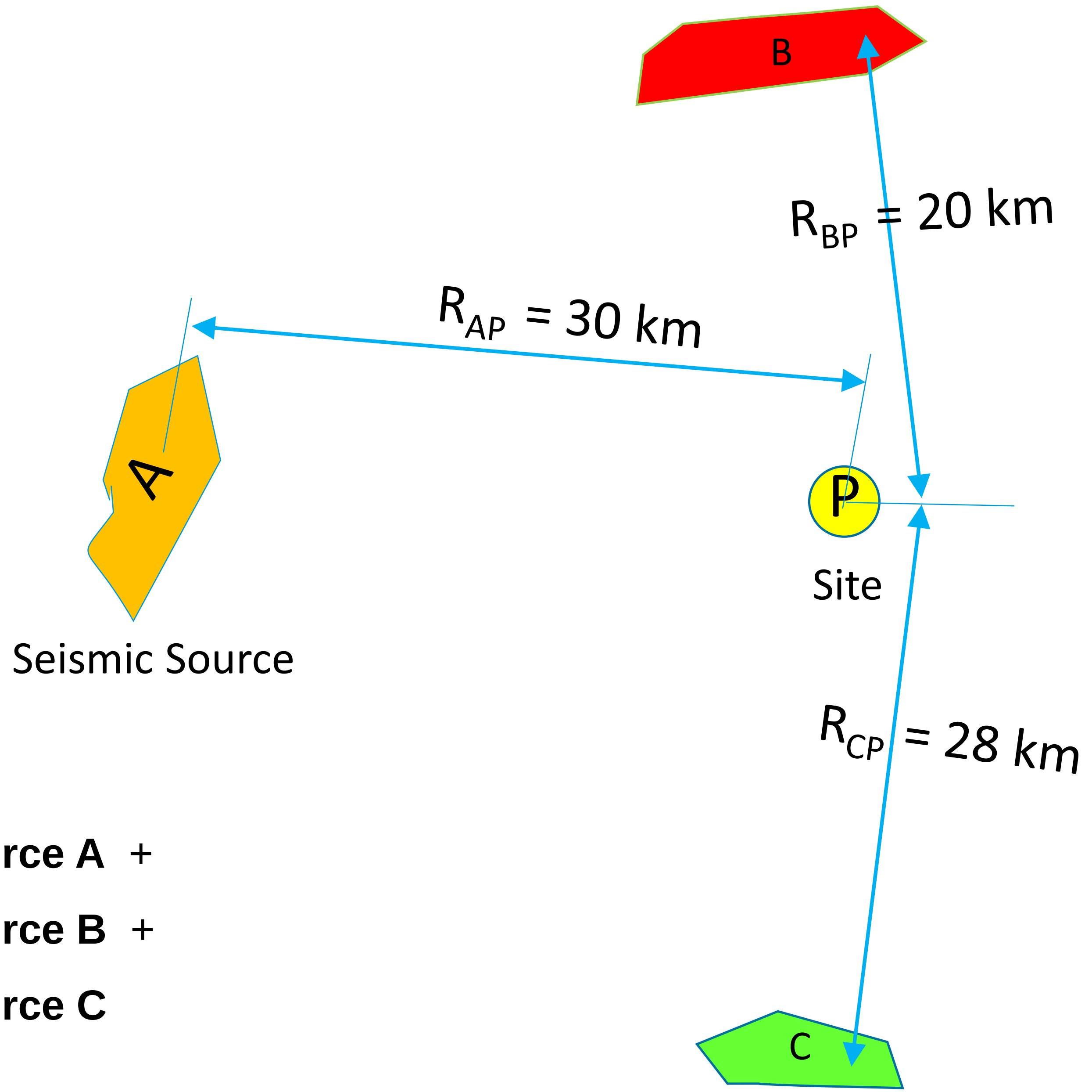
Simplified PSHA

How to read the hazard curve?

- Determine the PGA level with annual exceedance rate of 0.002.
- This PGA level is equal to, say, 0.22 g.
- The exceedance rate in one year = 0.002. The exceedance rate in a 50-yr period = 0.002x50 = 0.10.
- The chance of exceeding PGA of 0.22g in a 50-yr period = 10%.
- Hence, the PGA level with 10% chance of being exceeded in a 50-yr period is 0.22g.



Multiple Sources



Annual exceedance rate at the site P =

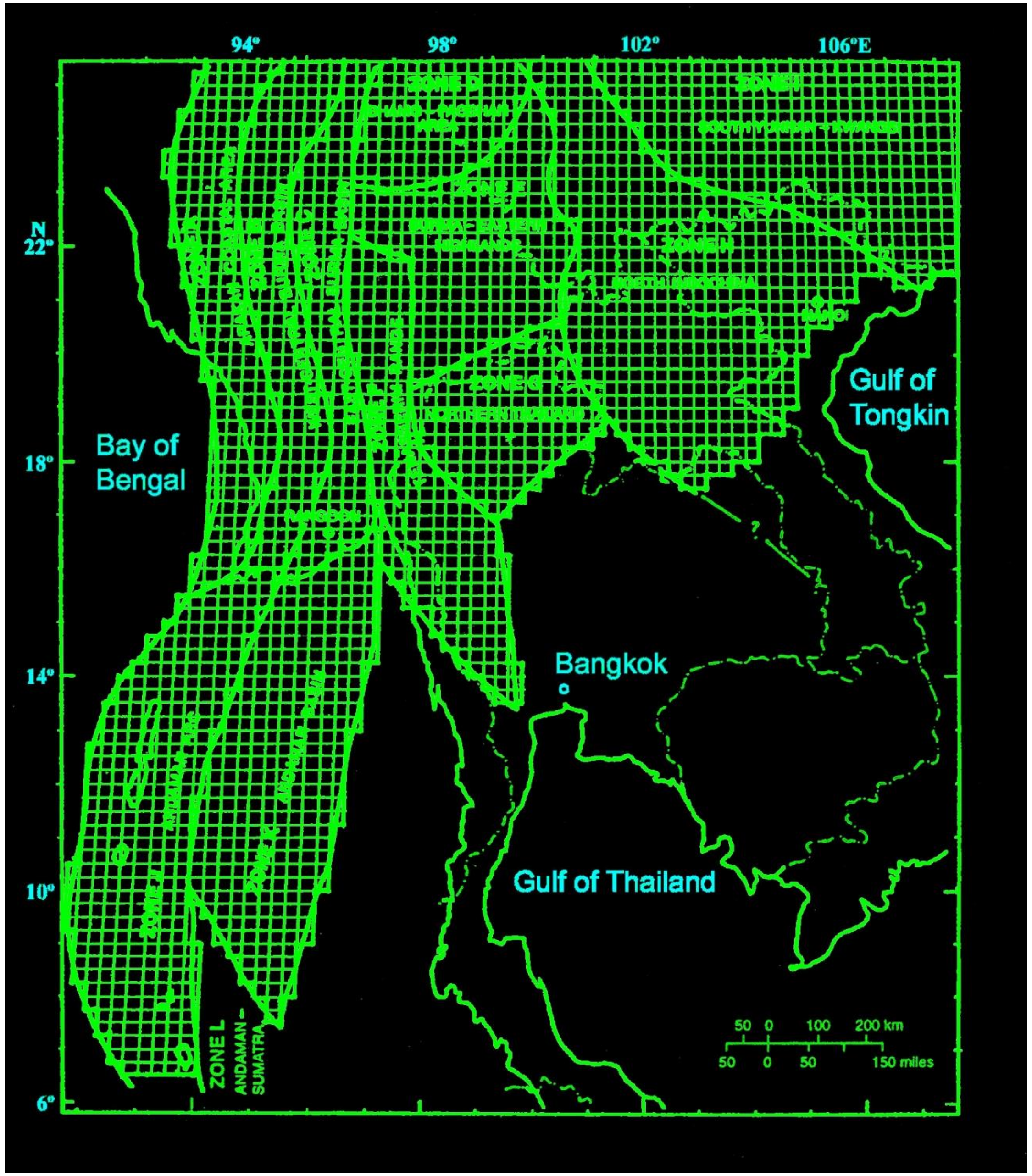
Annual exceedance rate caused by EQs in **source A** +

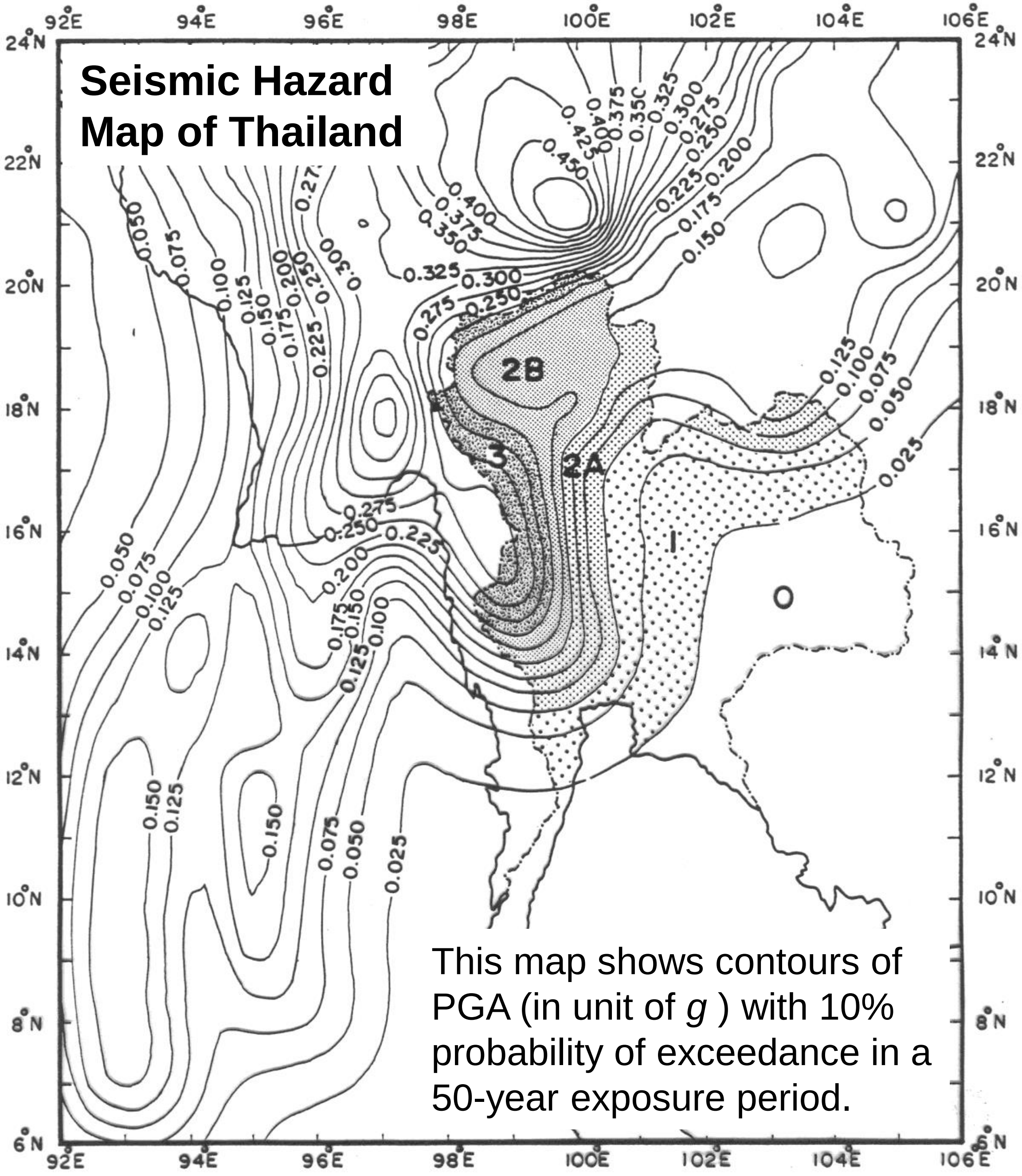
Annual exceedance rate caused by EQs in **source B** +

Annual exceedance rate caused by EQs in **source C**

Use of Probabilistic Ground Motions in Earthquake-resistant Design of Buildings

Probabilistic Seismic Hazard Analysis





Seismic Hazard Map of Thailand

This map shows contours of PGA (in unit of *g*) with 10% probability of exceedance in a 50-year exposure period.

Use of Probabilistic Ground Motions in Earthquake-resistant Design of Buildings

- The expected performance of buildings in modern earthquake-resistant design codes are:

1) Resist **a minor level of earthquake** ground shaking (SE) without damage

   SE = Serviceability earthquake—50% probability of exceedance in 30 years (43-year return period)

2) Resist **the design level of eart**hquake ground shaking (DBE) with damage (which may or may not be economically repaired) but without causing extensive loss of life.

   DBE = Design basis earthquake—10% probability of exceedance in 50 years (472-year return period)

3) Resist **the strongest earthquake** shaking expected at the site (MCE) without collapse, but potentially with extreme damage.

   MCE = Maximum considered earthquake—2% probability of exceedance in 50 years (2475-year return period)

Seismic Design Criteria of Major Dam Projects

- According to ICOLD (International Commission of Large Dams) Bulletin 72 (1989), large dams have to be able to withstand the effects of **the Maximum Credible Earthquake Shaking Level (MCE)**.

- This MCE is the strongest earthquake shaking level that could occur in the region of a dam, and is considered to have **a return period of several thousand years (typically 10,000 years in regions of low to moderate seismicity)**.

MCE = Maximum considered earthquake—0.5% probability of exceedance in 50 years (about 10,000-year return period)

Probabilistic Ground Motion Parameters: PGA, PGV, SA

- Traditionally **Peak Ground Acceleration (PGA)** has been used to quantify ground motion in PSHA. PGA is a good index to hazard for low-rise buildings, up to about 7 stories.
- **PGV, peak ground velocity,** is a good index to hazard to taller buildings. However, it is not clear how to relate velocity to force in order to design a taller building.
- Today the preferred parameter is **Response Spectral Acceleration (SA)**.
- While **PGA (peak acceleration)** is what is experienced by a particle on the ground, **SA** is approximately what is experienced by a building, as modeled by a particle mass on a massless vertical rod having the same natural period of vibration as the building.
- **SA = The maximum acceleration experienced by a damped, single-degree-of-freedom oscillator (a crude representation of building response).**
- **Max. Earthquake Force in the Building = Building Mass x SA**

Response Spectrum Parameters: SA, SD, SV

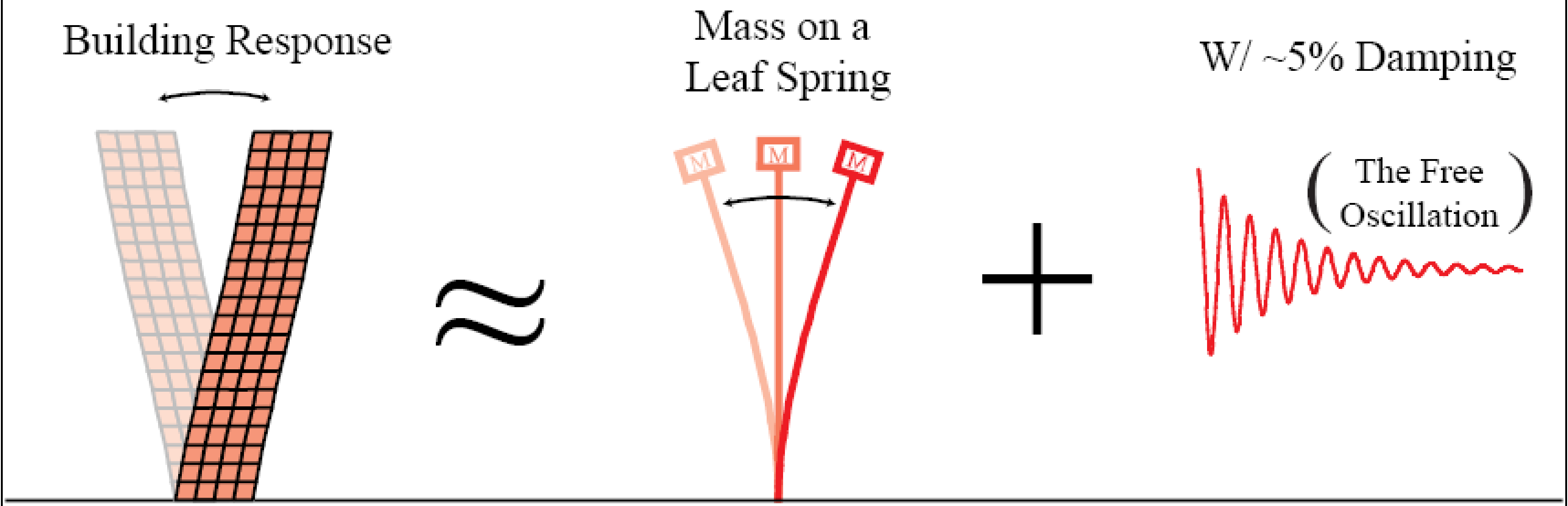


Figure 1. The response-spectrum value is the peak motion (displacement, velocity, or acceleration) of a damped single-degree of freedom harmonic oscillator (with a particular damping and resonant period) subjected to a prescribed ground motion.

If we look at the displacement response, we can identify the maximum displacement. If we take the derivative (rate of change) of the displacement response with respect to time, we can get the velocity response. The maximum velocity can likewise be determined. Similarly for response acceleration (rate of change of velocity) also called response spectral acceleration (SA).

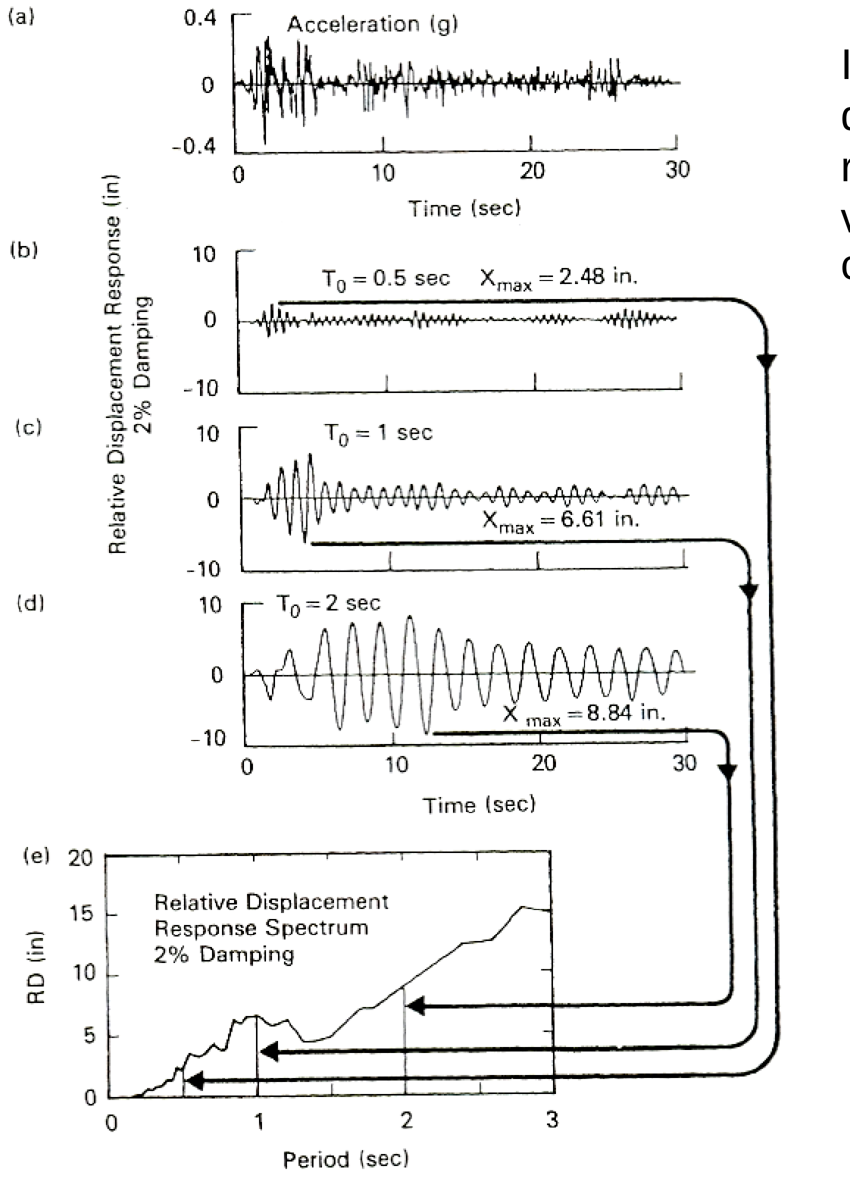
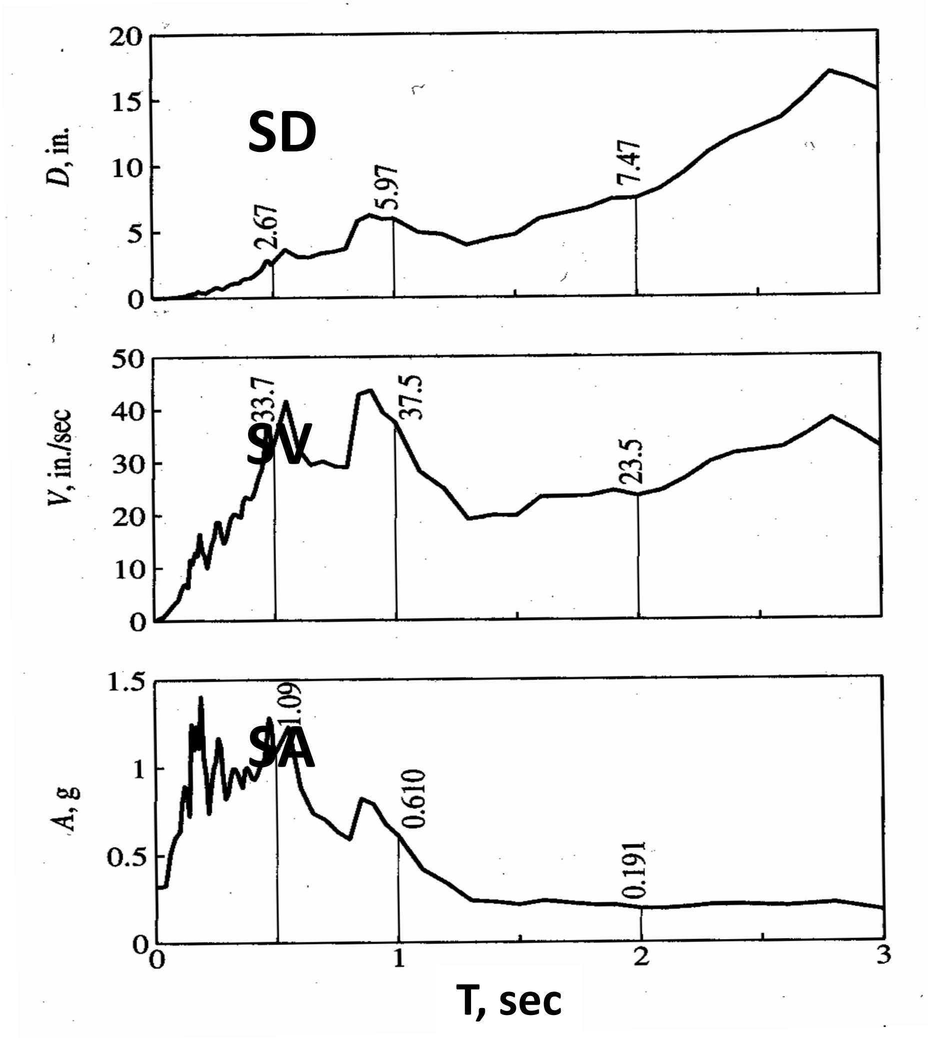
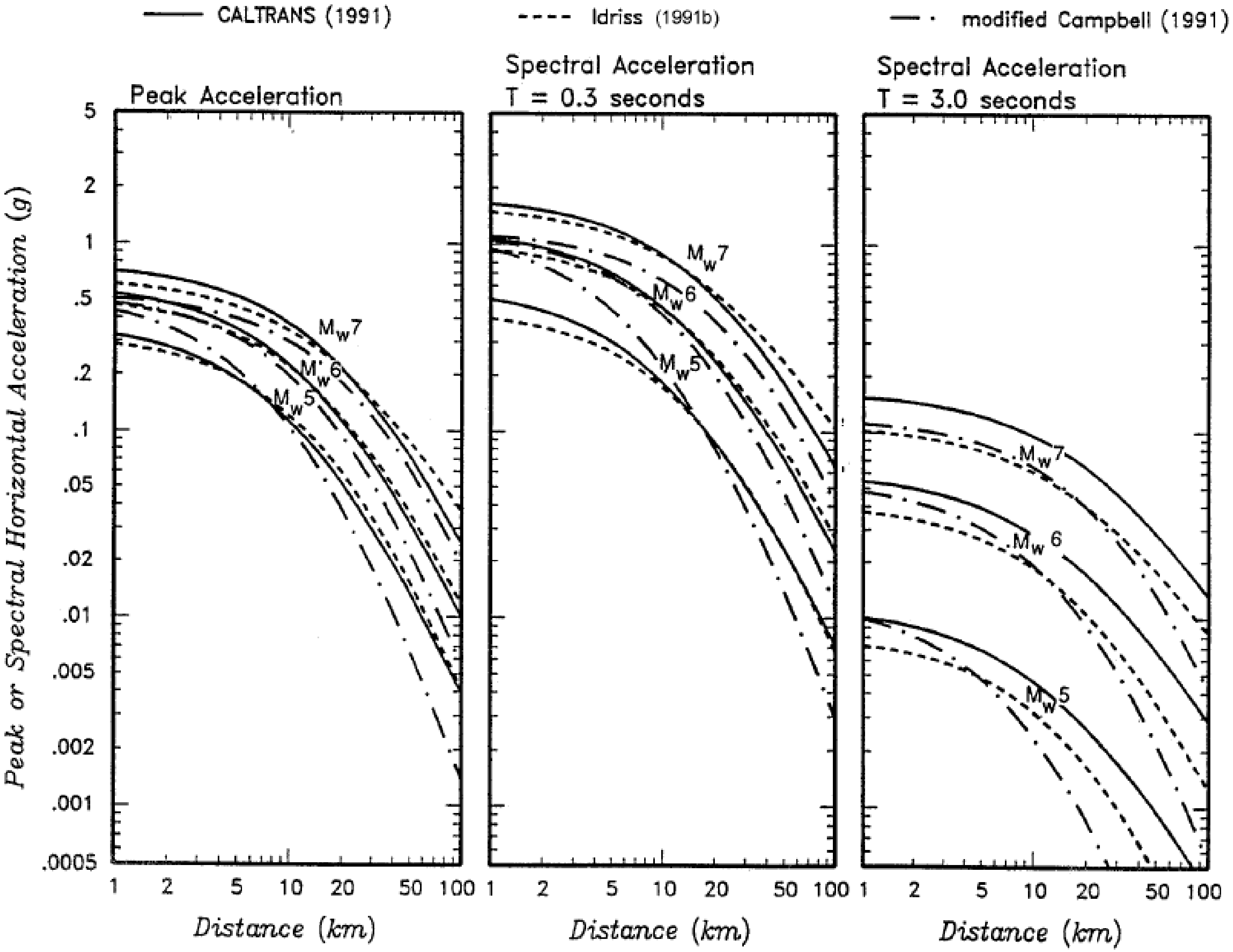


FIGURE 6.3 Construction of a response spectrum. (a) earthquake acceleration time history (El Centro, California 1940) used as input, (b) relative displacement response of a 2% damped oscillator with a natural period of 0.5 seconds, (c) relative displacement response of a 2% damped oscillator with a natural period of 1.0 seconds, (d) relative displacement response of a 2% damped oscillator with a natural period of 2.0 seconds and (e) maxima of b, c and d become points on the 2% damped relative displacement response spectrum (after Chopra 1981).



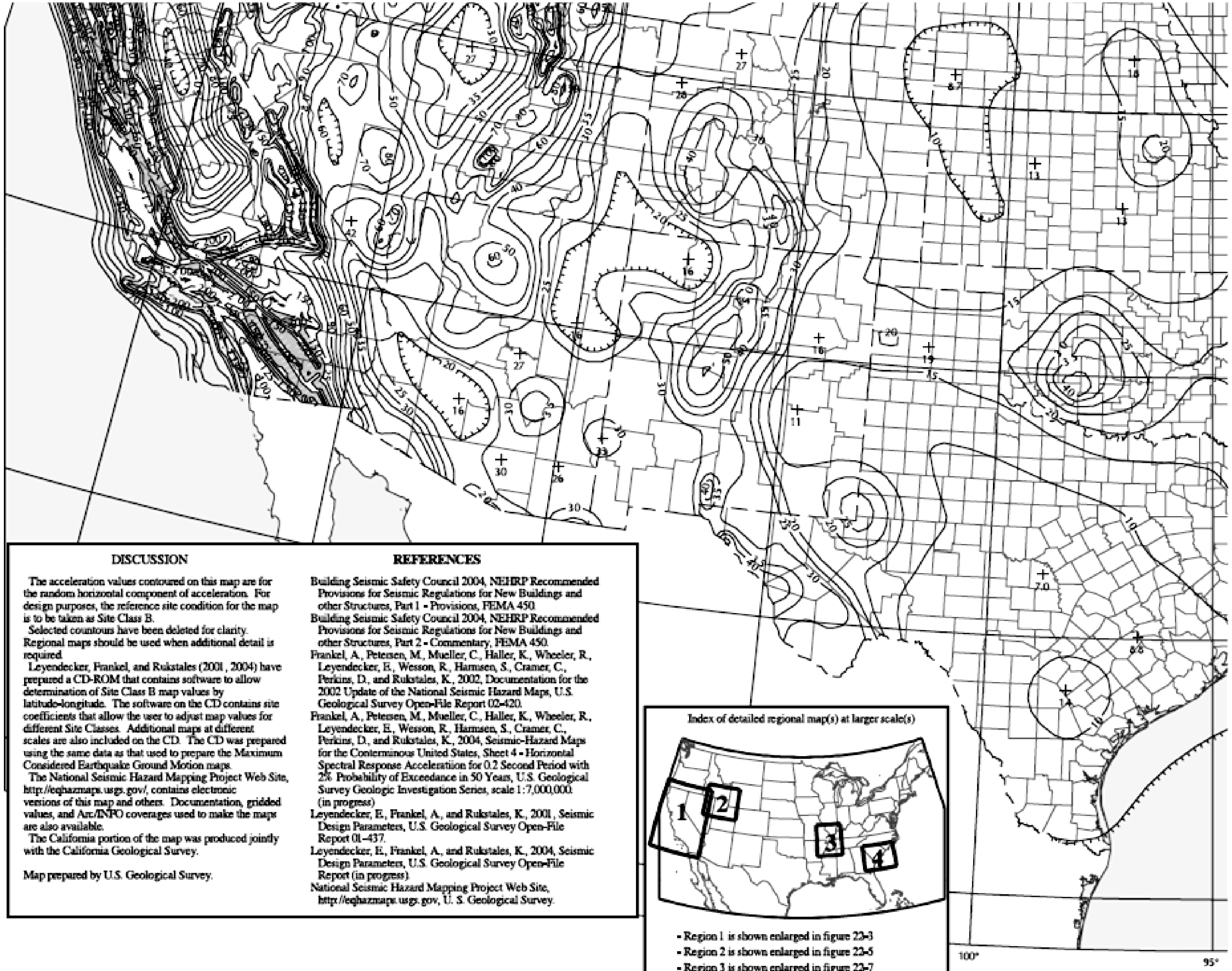
Attenuation Model for SA



Coefficients of an attenuation relationship

TABLE 5.11 Coefficients for Sadigh et al. Rock Attenuation Relation: Horizontal Component

T_n (s)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}
						$M_W \leq 6.5$								
PGA	0.182	–0.624	1.0	0	–2.100	0	3.6564	0.250	0	1.39	0.14	0.38	0	7.21
0.05	0.182	–0.090	1.0	0.006	–2.128	–0.082	3.6564	0.250	0	1.39	0.14	0.38	0	7.21
0.07	0.182	0.110	1.0	0.006	–2.128	–0.082	3.6564	0.250	0	1.40	0.14	0.39	0	7.21
0.09	0.182	0.212	1.0	0.006	–2.140	–0.052	3.6564	0.250	0	1.40	0.14	0.39	0	7.21
0.10	0.182	0.275	1.0	0.006	–2.148	–0.041	3.6564	0.250	0	1.41	0.14	0.40	0	7.21
0.12	0.182	0.348	1.0	0.005	–2.162	–0.014	3.6564	0.250	0	1.41	0.14	0.40	0	7.21
0.14	0.182	0.307	1.0	0.004	–2.144	0	3.6564	0.250	0	1.42	0.14	0.41	0	7.21
0.15	0.182	0.285	1.0	0.002	–2.130	0	3.6564	0.250	0	1.42	0.14	0.41	0	7.21
0.17	0.182	0.239	1.0	0	–2.110	0	3.6564	0.250	0	1.42	0.14	0.41	0	7.21
0.20	0.182	0.153	1.0	–0.004	–2.080	0	3.6564	0.250	0	1.43	0.14	0.42	0	7.21
0.24	0.182	0.060	1.0	–0.011	–2.053	0	3.6564	0.250	0	1.44	0.14	0.43	0	7.21
0.30	0.182	–0.057	1.0	–0.017	–2.028	0	3.6564	0.250	0	1.45	0.14	0.44	0	7.21
0.40	0.182	–0.298	1.0	–0.028	–1.990	0	3.6564	0.250	0	1.48	0.14	0.47	0	7.21
0.50	0.182	–0.588	1.0	–0.040	–1.945	0	3.6564	0.250	0	1.50	0.14	0.49	0	7.21
0.75	0.182	–1.208	1.0	–0.050	–1.865	0	3.6564	0.250	0	1.52	0.14	0.51	0	7.21
1.0	0.182	–1.705	1.0	–0.055	–1.800	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
1.5	0.182	–2.407	1.0	–0.065	–1.725	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
2.0	0.182	–2.945	1.0	–0.070	–1.670	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
3.0	0.182	–3.700	1.0	–0.080	–1.610	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
4.0	0.182	–4.230	1.0	–0.100	–1.570	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
5.0	0.182	–4.714	1.0	–0.100	–1.540	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
7.5	0.182	–5.530	1.0	–0.110	–1.510	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21



DISCUSSION

The acceleration values contoured on this map are for the random horizontal component of acceleration. For design purposes, the reference site condition for the map is to be taken as Site Class B.

Selected countours have been deleted for clarity. Regional maps should be used when additional detail is required.

Leyendecker, Frankel, and Rukstales (2001 , 2004) have prepared a CD-ROM that contains software to allow determination of Site Class B map values by latitude-longitude. The software on the CD contains site coefficients that allow the user to adjust map values for different Site Classes. Additional maps at different scales are also included on the CD. The CD was prepared using the same data as that used to prepare the Maximum Considered Earthquake Ground Motion maps.

The National Seismic Hazard Mapping Project Web Site, http://eqhazmaps.usgs.gov/, contains electronic versions of this map and others. Documentation, gridded values, and Arc/INFO coverages used to make the maps are also available.

The California portion of the map was produced jointly with the California Geological Survey.

Map prepared by U.S. Geological Survey.

REFERENCES

Building Seismic Safety Council 2004, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures, Part 1 - Provisions, FEMA 450.

Building Seismic Safety Council 2004, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures, Part 2 - Commentary, FEMA 450.

Frankel, A., Petersen, M., Mueller, C., Haller, K., Wheeler, R., Leyendecker, E., Wesson, R., Harmsen, S., Cramer, C., Perkins, D., and Rukstales, K., 2002, Documentation for the 2002 Update of the National Seismic Hazard Maps, U.S. Geological Survey Open-File Report 02-420.

Frankel, A., Petersen, M., Mueller, C., Haller, K., Wheeler, R., Leyendecker, E., Wesson, R., Harmsen, S., Cramer, C., Perkins, D., and Rukstales, K., 2004, Seismic-Hazard Maps for the Conterminous United States, Sheet 4 - Horizontal Spectral Response Accelerattion for 0.2 Second Period with 2% Probability of Exceedance in 50 Years, U.S. Geological Survey Geologic Investigation Series, scale 1:7,000,000. (in progress)

Leyendecker, E., Frankel, A., and Rukstales, K., 2001 , Seismic Design Parameters, U.S. Geological Survey Open-File Report 01-437.

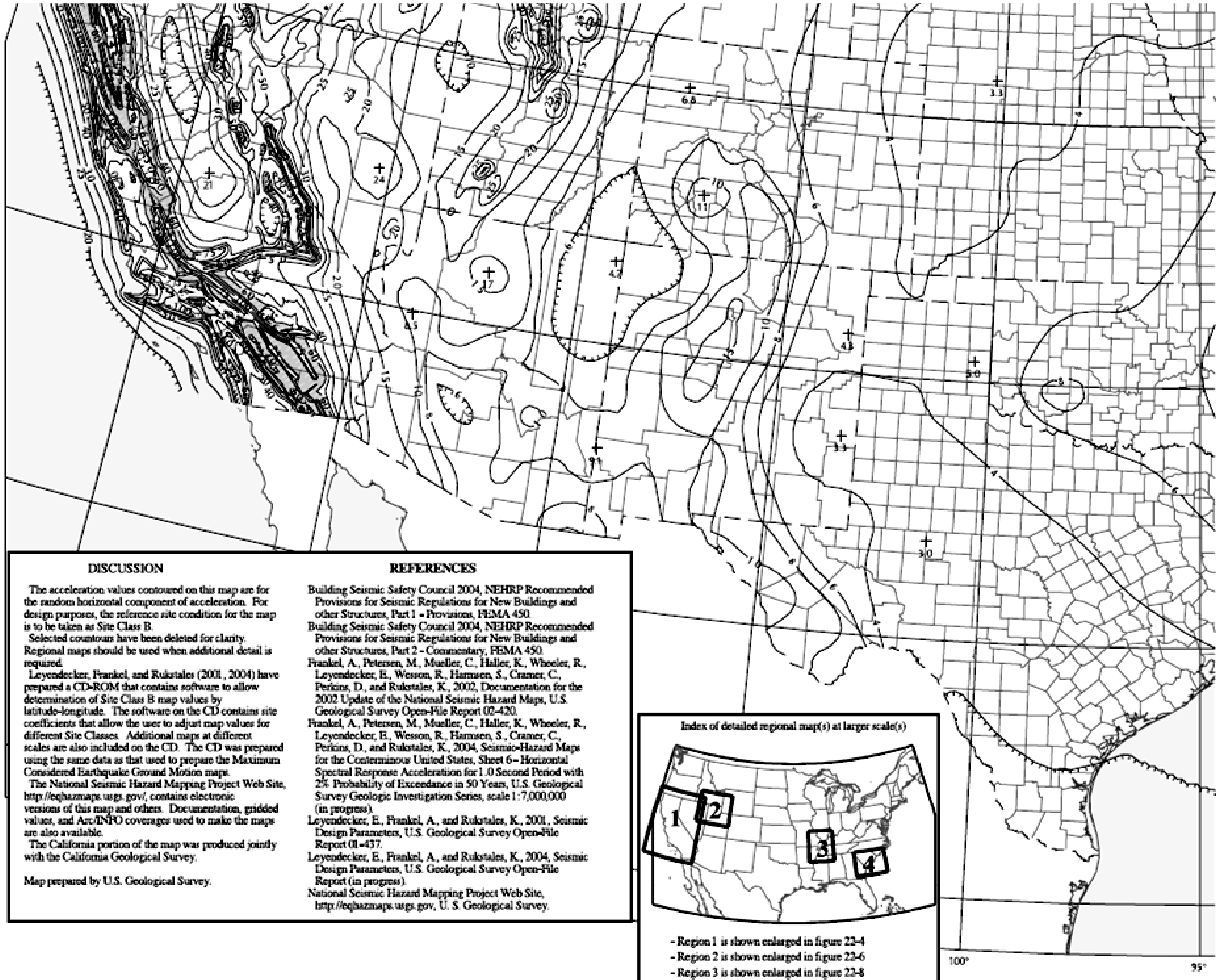
Leyendecker, E., Frankel, A., and Rukstales, K., 2004, Seismic Design Parameters, U.S. Geological Survey Open-File Report (in progress).

National Seismic Hazard Mapping Project Web Site, http://eqhazmaps.usgs.gov, U. S. Geological Survey.

Index of detailed regional map(s) at larger scale(s)

- Region 1 is shown enlarged in figure 22-3
- Region 2 is shown enlarged in figure 22-5
- Region 3 is shown enlarged in figure 22-7
- Region 4 is shown enlarged in figure 22-9

FIGURE 22-1 MAXIMUM CONSIDERED EARTHQUAKE GROUND MOTION FOR THE CONTERMINOUS UNITED STATES OF 0.2 SEC SPECTRAL RESPONSE ACCELERATION (5% OF CRITICAL DAMPING), SITE CLASS B



DISCUSSION

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Frankel, A., Petersen, M., Mueller, C., Haller, K., Wheeler, R., Leyendecker, E., Wesson, R., Harmsen, S., Cramer, C., Perkins, D., and Rukstales, K., 2002, Documentation for the 2002 Update of the National Seismic Hazard Maps, U.S. Geological Survey Open-File Report 02-420.

Frankel, A., Petersen, M., Mueller, C., Haller, K., Wheeler, R., Leyendecker, E., Wesson, R., Harmsen, S., Cramer, C., Perkins, D., and Rukstales, K., 2004, Seismic-Hazard Maps for the Conterminous United States, Sheet 6 – Horizontal Spectral Response Acceleration for 1.0 Second Period with 2% Probability of Exceedance in 50 Years, U.S. Geological Survey Geologic Investigation Series, scale 1:7,000,000 (in progress).

Leyendecker, E., Frankel, A., and Rukstales, K., 2001, Seismic Design Parameters, U.S. Geological Survey Open-File Report 01-437.

Leyendecker, E., Frankel, A., and Rukstales, K., 2004, Seismic Design Parameters, U.S. Geological Survey Open-File Report (in progress).

National Seismic Hazard Mapping Project Web Site, http://eqhazmaps.usgs.gov, U. S. Geological Survey.

Index of detailed regional map(s) at larger scale(s)

- Region 1 is shown enlarged in figure 22-4
- Region 2 is shown enlarged in figure 22-6
- Region 3 is shown enlarged in figure 22-8
- Region 4 is shown enlarged in figure 22-9

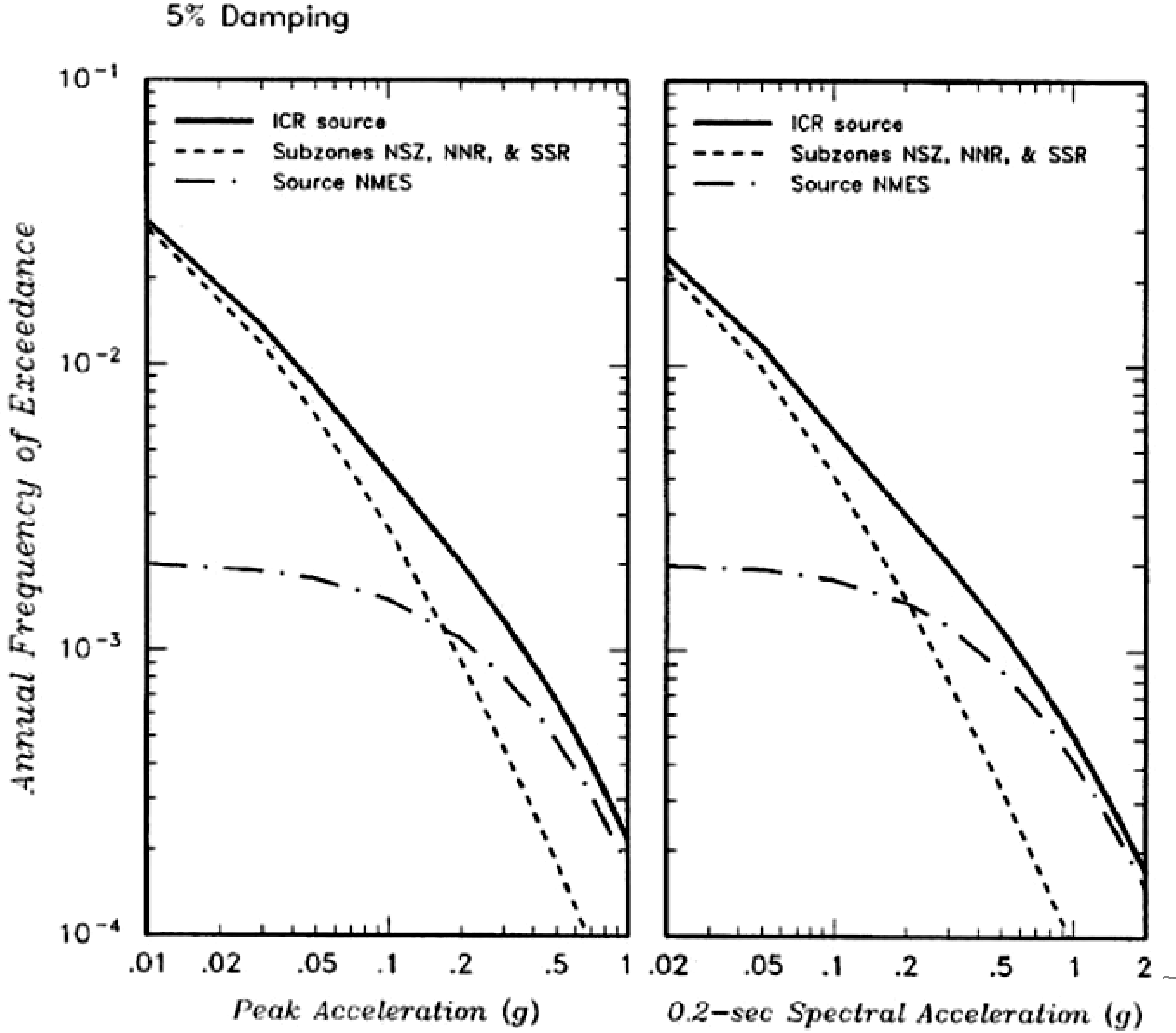
FIGURE 22-2 MAXIMUM CONSIDERED EARTHQUAKE GROUND MOTION FOR THE CONTERMINOUS UNITED STATES OF 1.0 SEC SPECTRAL RESPONSE ACCELERATION (5% OF CRITICAL DAMPING), SITE CLASS B

Deaggregation of Seismic Hazard

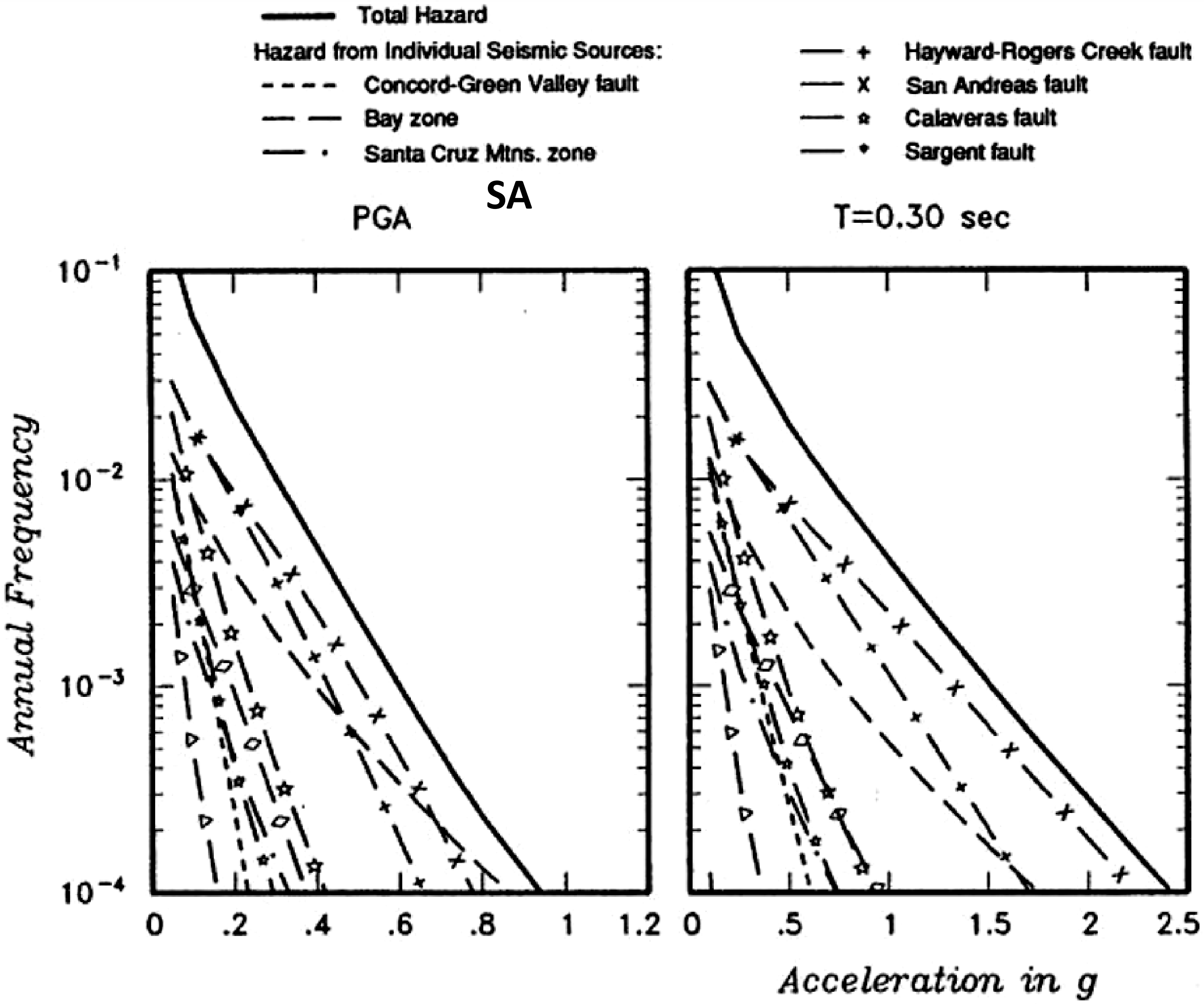
Deaggregation of Seismic Hazard

- The hazard curve gives the **combined effect** of all the seismic sources, magnitudes and distances on the probability of exceeding a given ground motion level.
- Since all of the sources, magnitudes, and distances are mixed together, it is difficult to get an intuitive understanding of what is controlling the hazard from the hazard curve by itself.
- To provide insight into what events are the most important for the hazard at a given ground motion level, **the hazard curve is broken down into its contributions from different earthquake scenarios**.
- This process is called ‘**Deaggregation of Hazard**’.

Example of Contributions of Various Seismic Sources to the Total Seismic Hazard at the Site

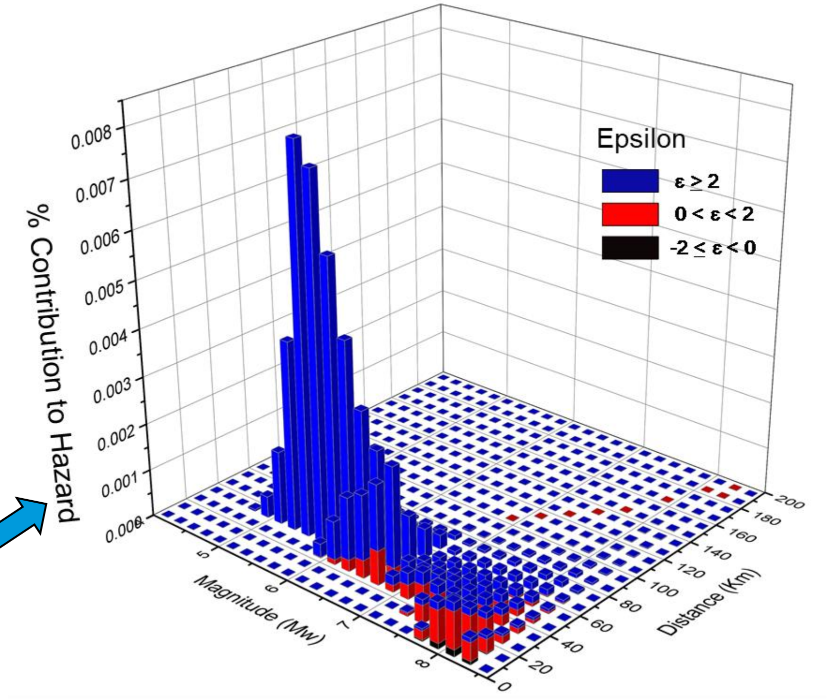


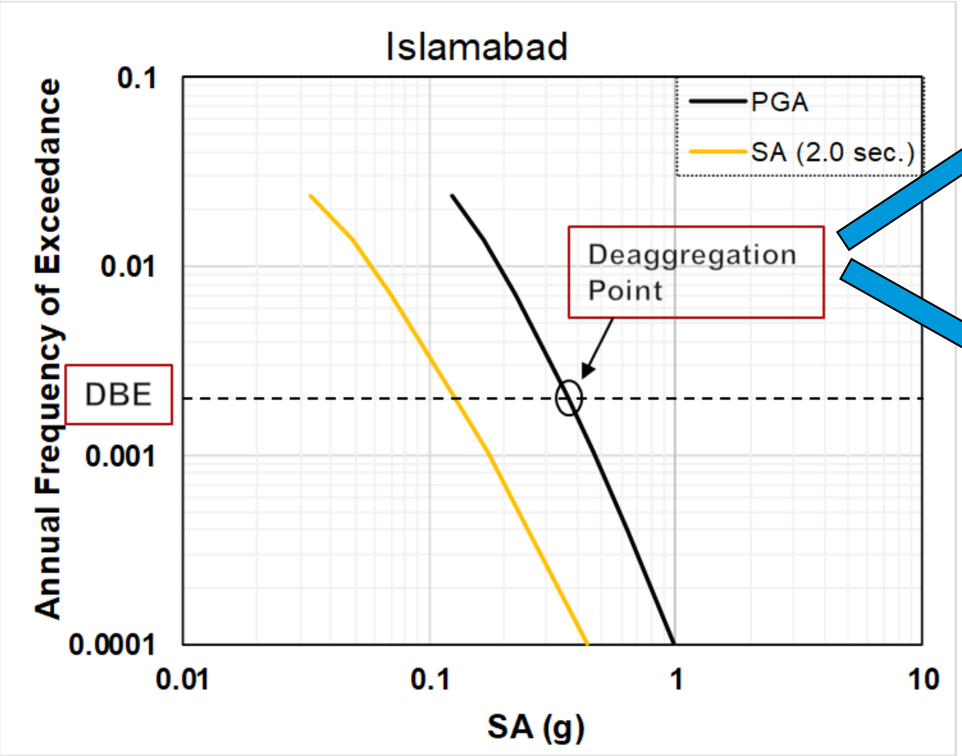
Example of Contributions of Various Seismic Sources to the Total Seismic Hazard at the Site



Probabilistic Seismic Hazard Deaggregation

- Hazard Deaggregation
- 3D Graph
- Modal Values



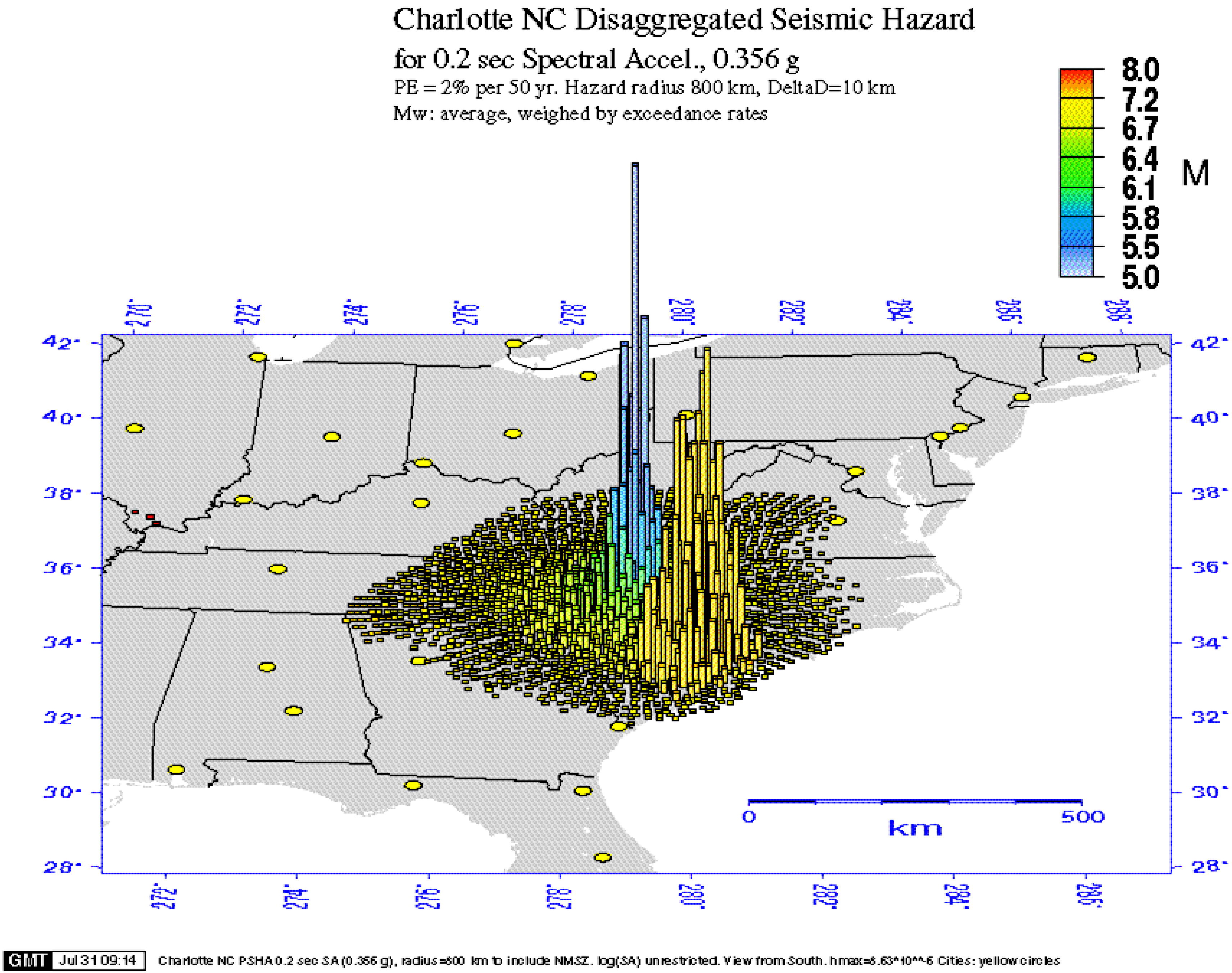


70% Source 1 (M-R Pair)

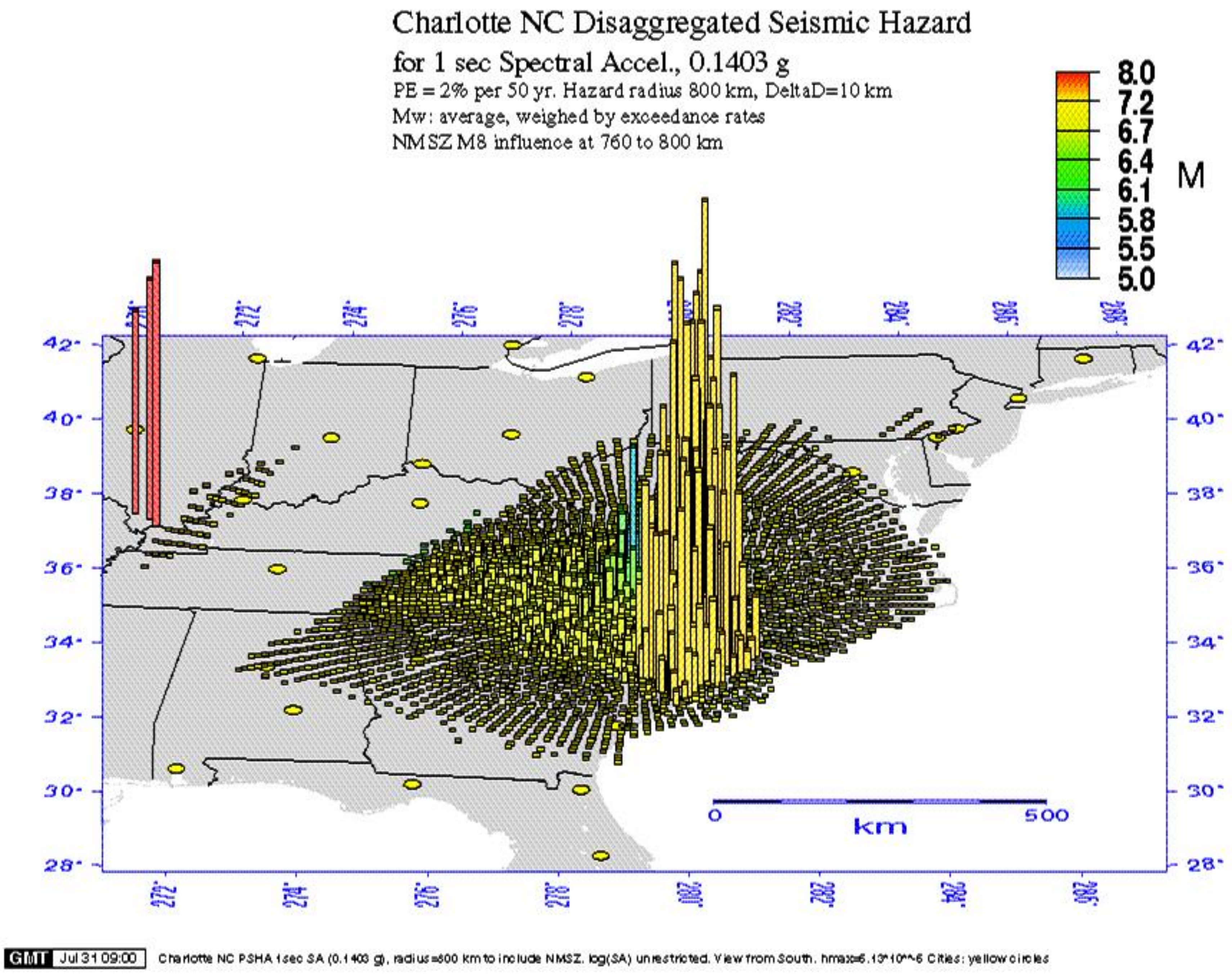
20% Source 2 (M-R Pair)

10% Source 3 (M-R Pair)

M: Magnitude
R Distance



Charlotte NC Disaggregated Seismic Hazard
for 0.2 sec Spectral Accel., 0.356 g
PE = 2% per 50 yr. Hazard radius 800 km, DeltaD=10 km
Mw: average, weighed by exceedance rates
8.0
7.2
6.7
6.4
6.1
5.8
5.5
5.0
M
0
km
500
GMT Jul 31 09:14
Charlotte NC PSHA 0.2 sec SA (0.356 g), radius=800 km to include NMSZ. log(SA) unrestricted. View from South. hmax=8.63*10**-6 Cities: yellow circles


Charlotte NC Disaggregated Seismic Hazard
for 1 sec Spectral Accel., 0.1403 g
PE = 2% per 50 yr. Hazard radius 800 km, DeltaD=10 km
Mw: average, weighed by exceedance rates
NMSZ M8 influence at 760 to 800 km
8.0
7.2
6.7
6.4
6.1
5.8
5.5
5.0
M
42°
40°
38°
36°
34°
32°
30°
28°
0
km
500
GMT Jul 31 09:00
Charlotte NC PSHA 1sec SA (0.1403 g), radius=800 km to include NMSZ. log(SA) unrestricted. View from South. hmax=6.13*10^^-6 Cities: yellow circles

Thank you for your attention