Seismic Hazard Assessment

Part 2: Introduction to Probabilistic Seismic Hazard Analysis (PSHA)

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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.

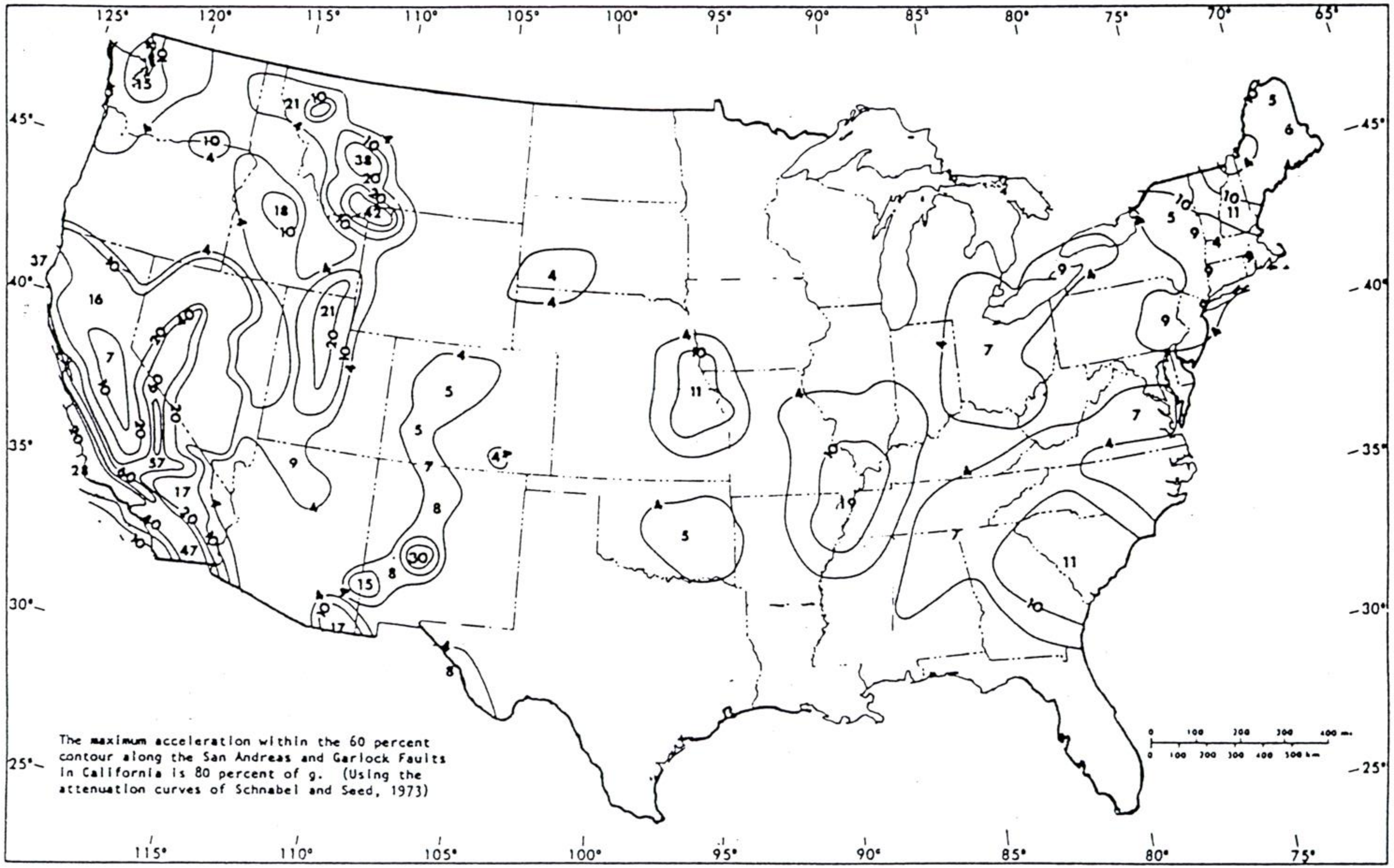


Figure 47. Probabilistic ground acceleration map of the conterminous United States, 50 year exposure time, 10 percent chance of exceedance, contours are percent of g (Algermissen and Perkins, 1976, Ref. 169).

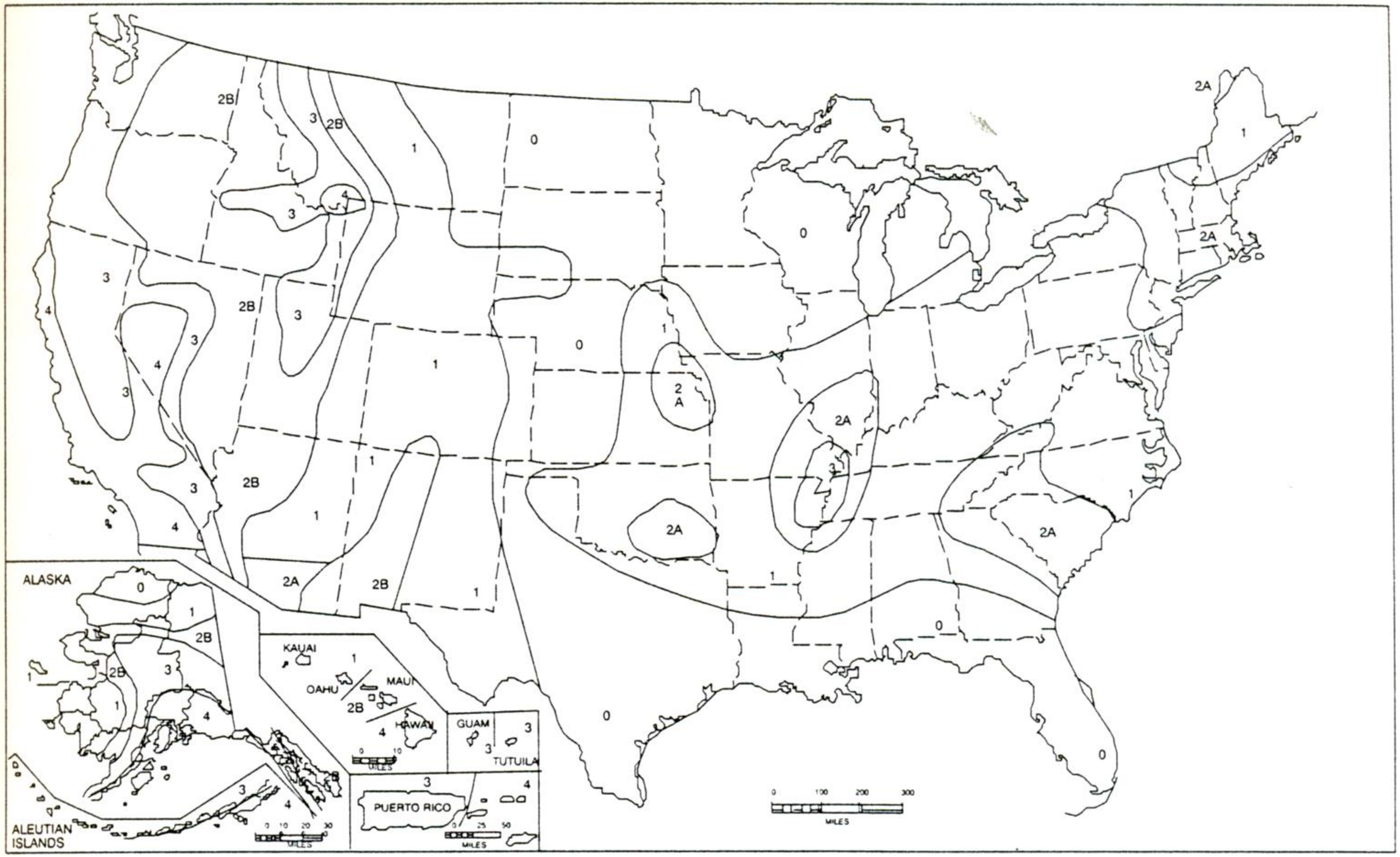
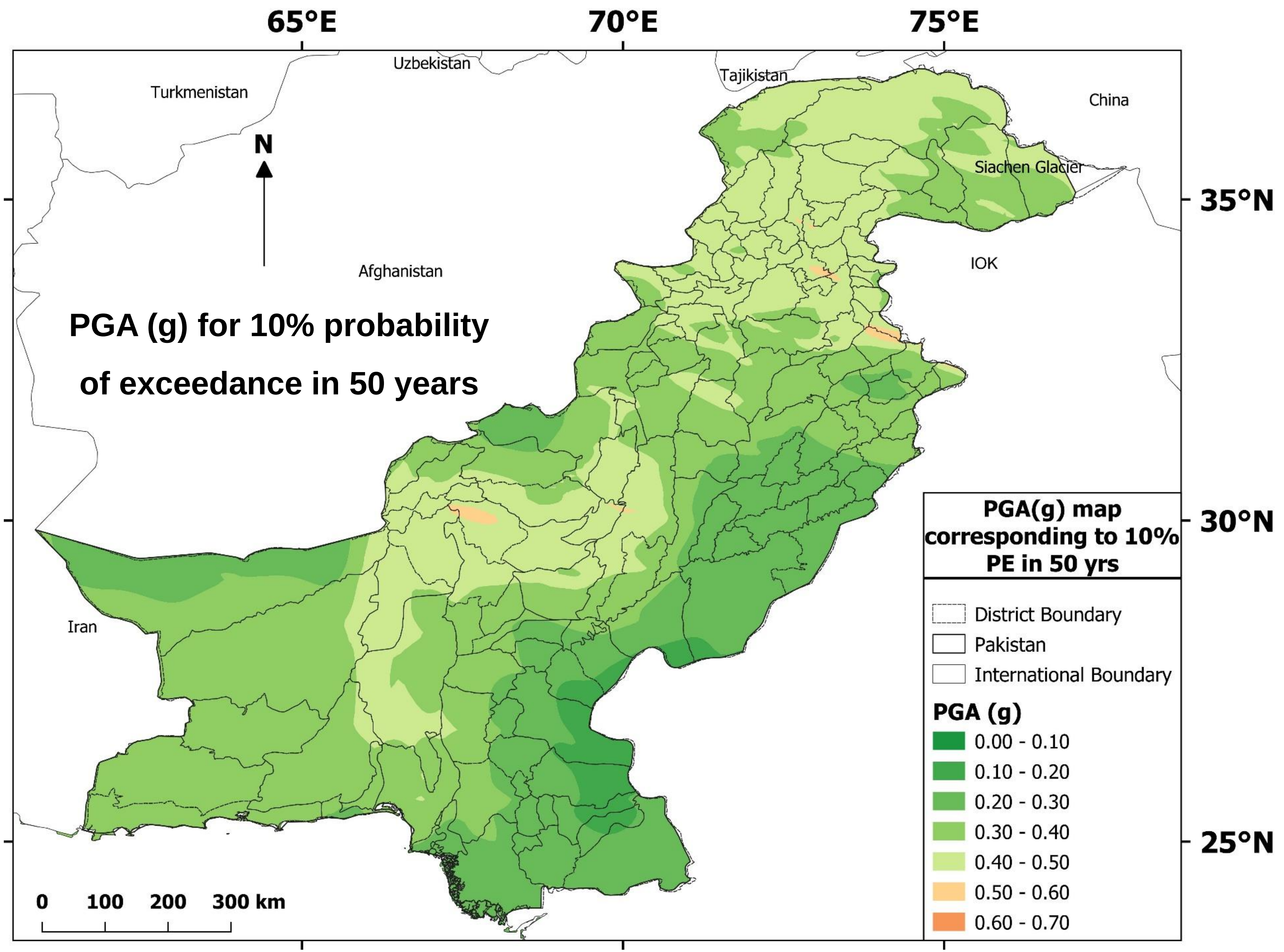
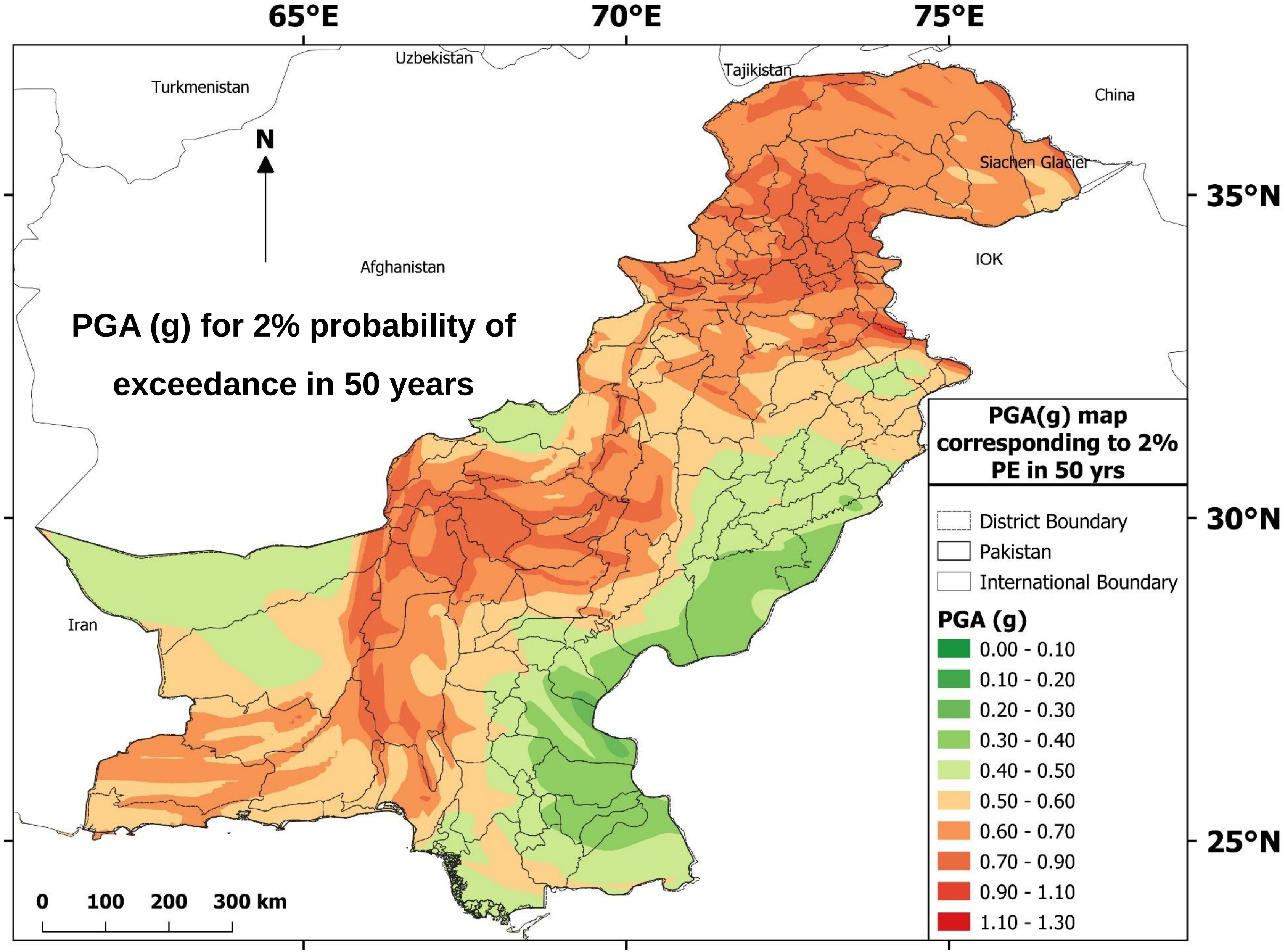


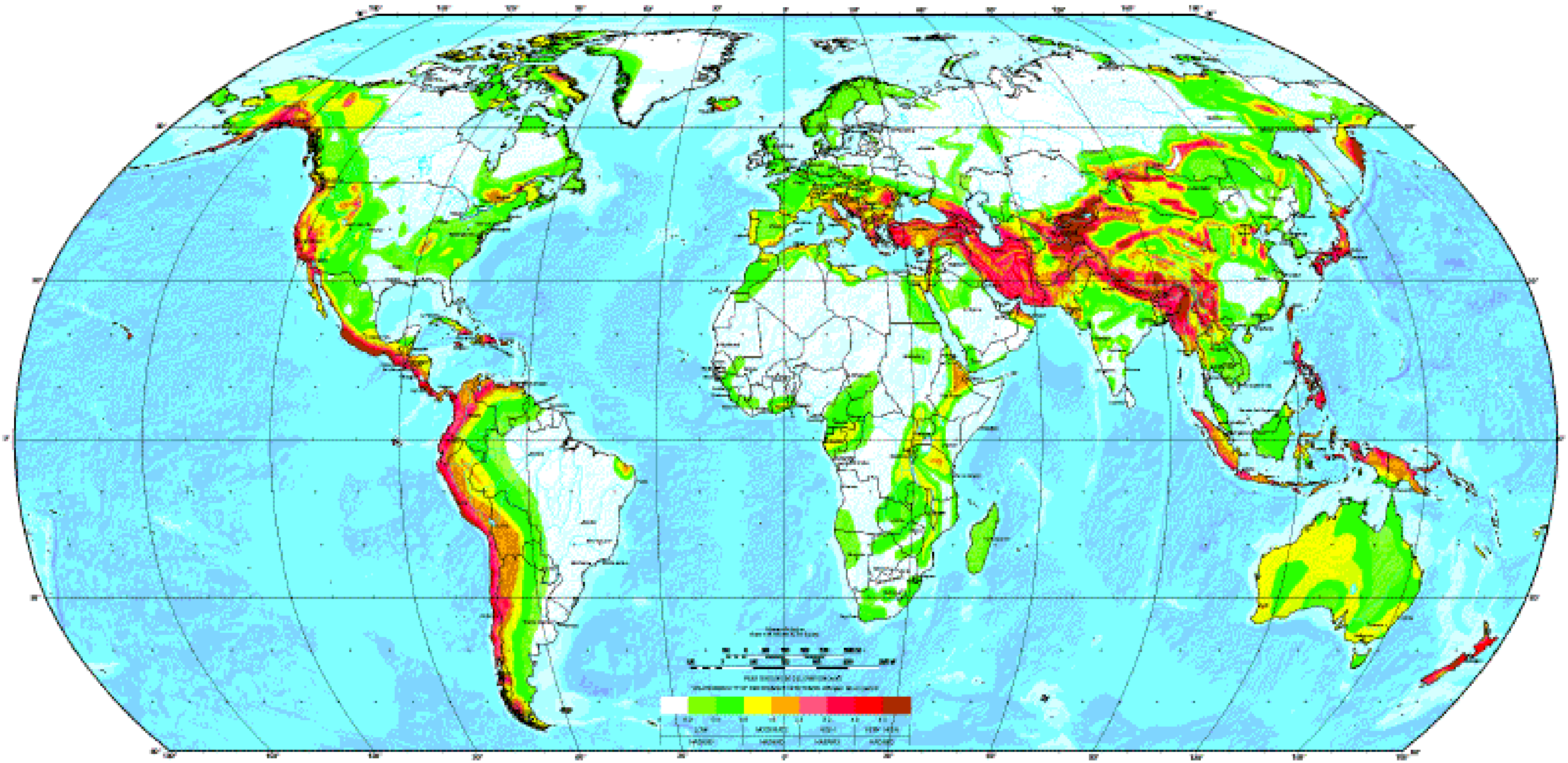
FIGURE 16-2—SEISMIC ZONE MAP OF THE UNITED STATES
For areas outside of the United States, see Appendix Chapter 16.


65°E
70°E
75°E
35°N
30°N
25°N
Uzbekistan
Turkmenistan
Tajikistan
China
Siachen Glacier
N
Afghanistan
IOK
PGA (g) for 10% probability
of exceedance in 50 years
Iran
PGA(g) map corresponding to 10% PE in 50 yrs
District Boundary
Pakistan
International Boundary
PGA (g)
0.00 - 0.10
0.10 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.50
0.50 - 0.60
0.60 - 0.70
0 100 200 300 km



65°E
70°E
75°E
35°N
30°N
25°N
Uzbekistan
Turkmenistan
Tajikistan
China
Siachen Glacier
N
Afghanistan
IOK
PGA (g) for 2% probability of exceedance in 50 years
PGA(g) map corresponding to 2% PE in 50 yrs
District Boundary
Pakistan
International Boundary
PGA (g)
0.00 - 0.10
0.10 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.50
0.50 - 0.60
0.60 - 0.70
0.70 - 0.90
0.90 - 1.10
1.10 - 1.30
Iran
0 100 200 300 km

Global Seismic Hazard Map



GLOBAL SEISMIC HAZARD ASSESSMENT PROGRAM

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

Key Assumptions in Calculating Probabilistic Ground Motions

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

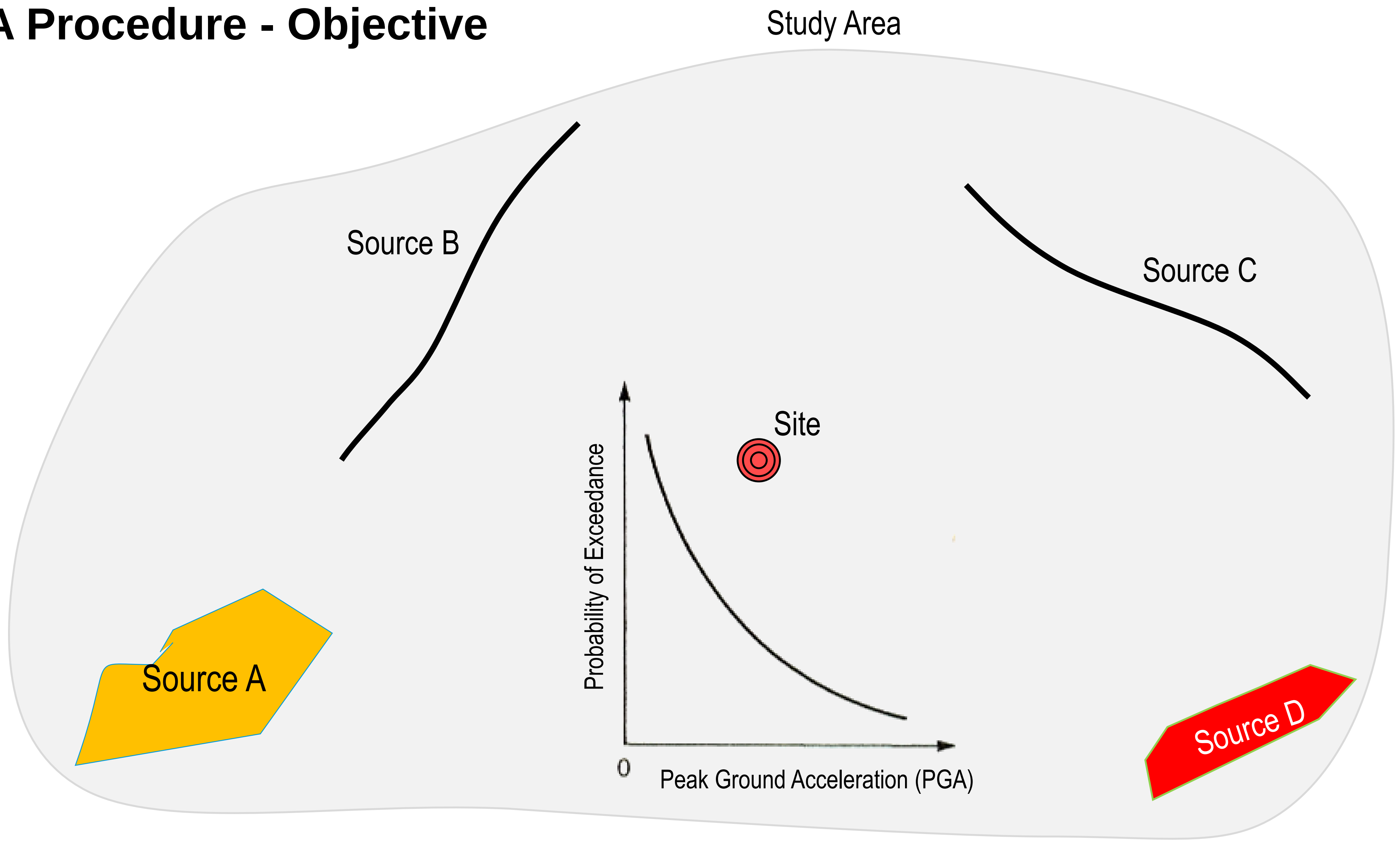
2) Within each defined seismic source zone (or active fault), **earthquakes occur randomly at any location** with an equal chance (probability).

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**.

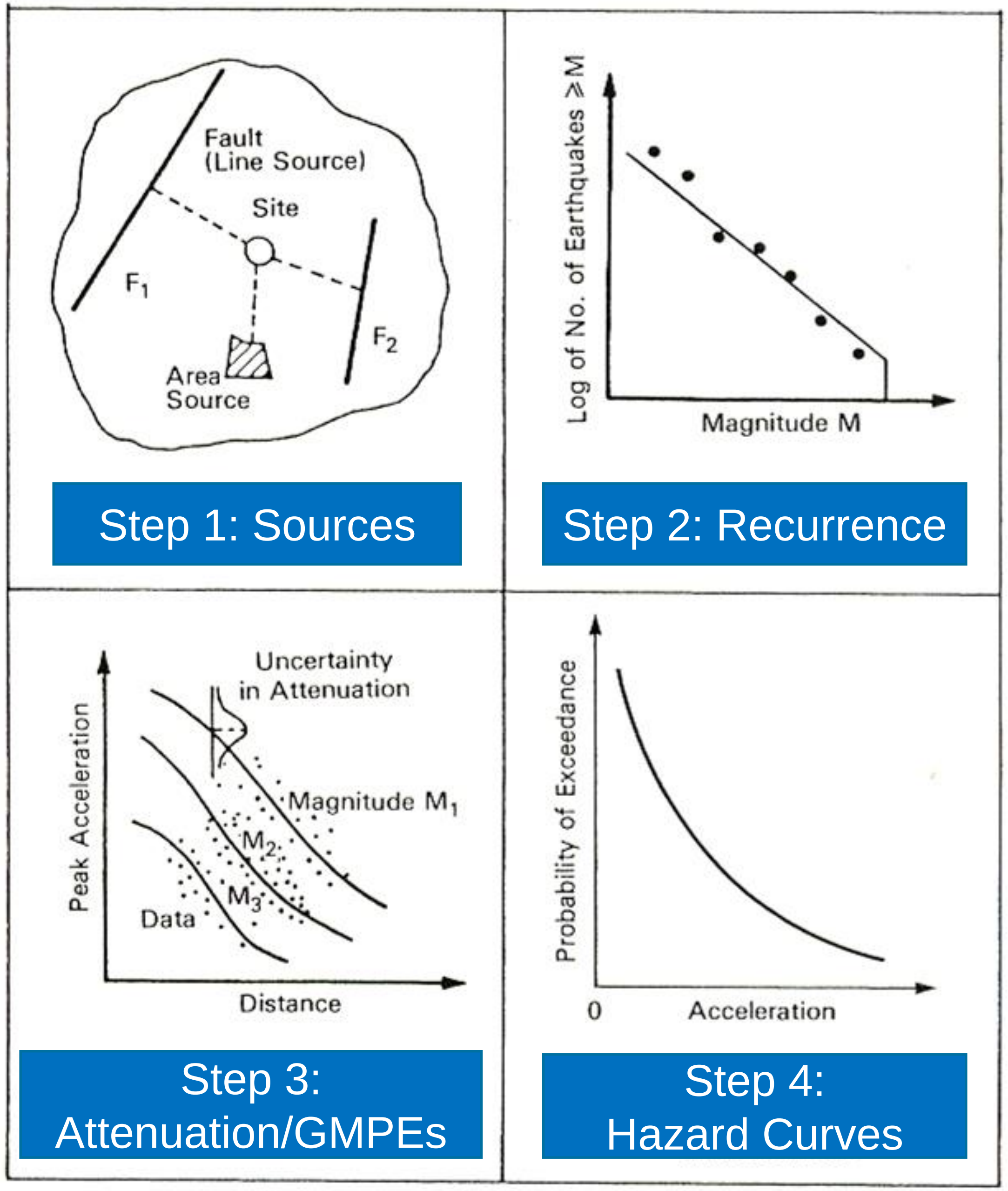
PSHA Procedure - Objective



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)



Step 1: Identification of all Seismic Sources

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.

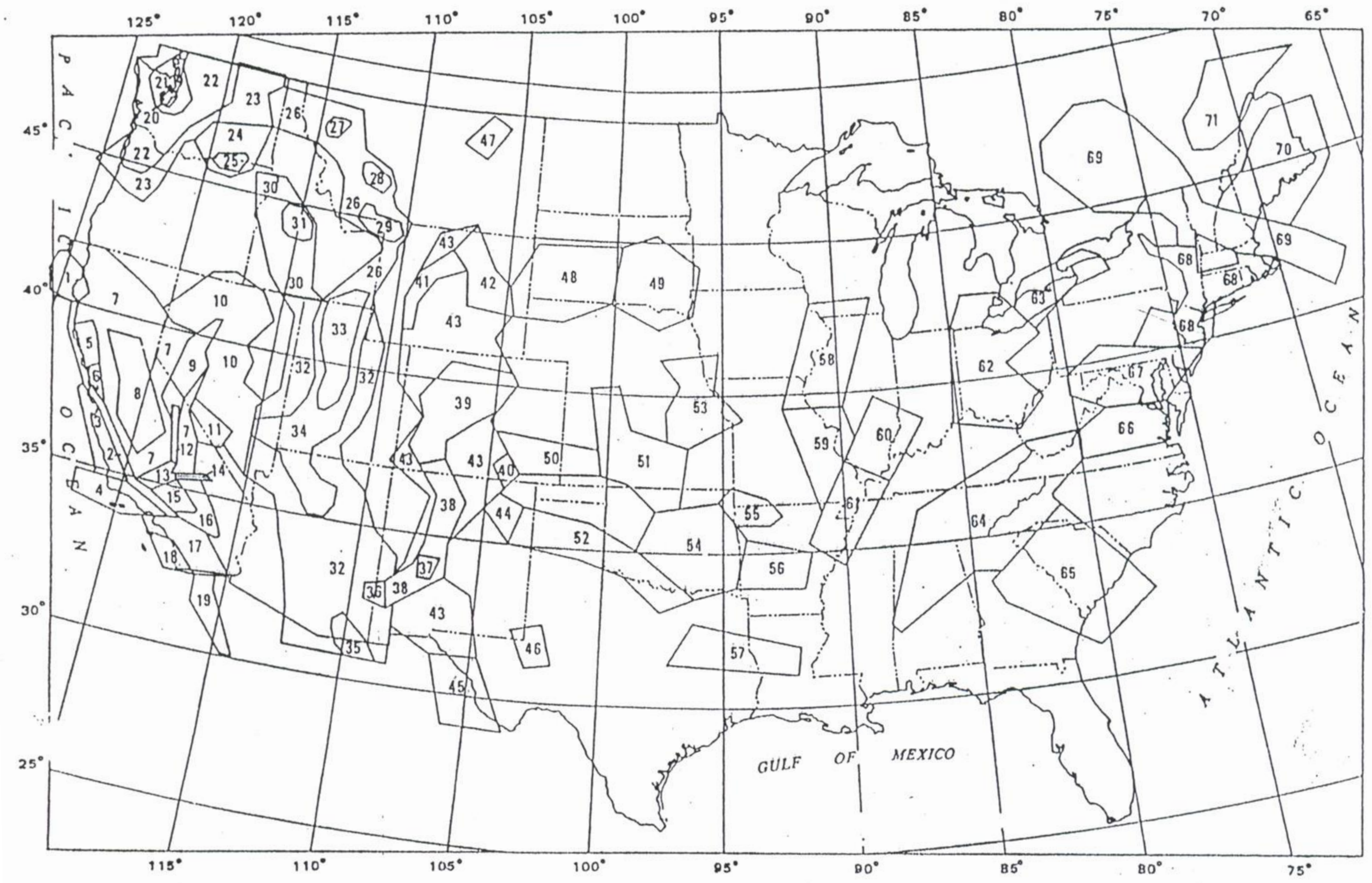
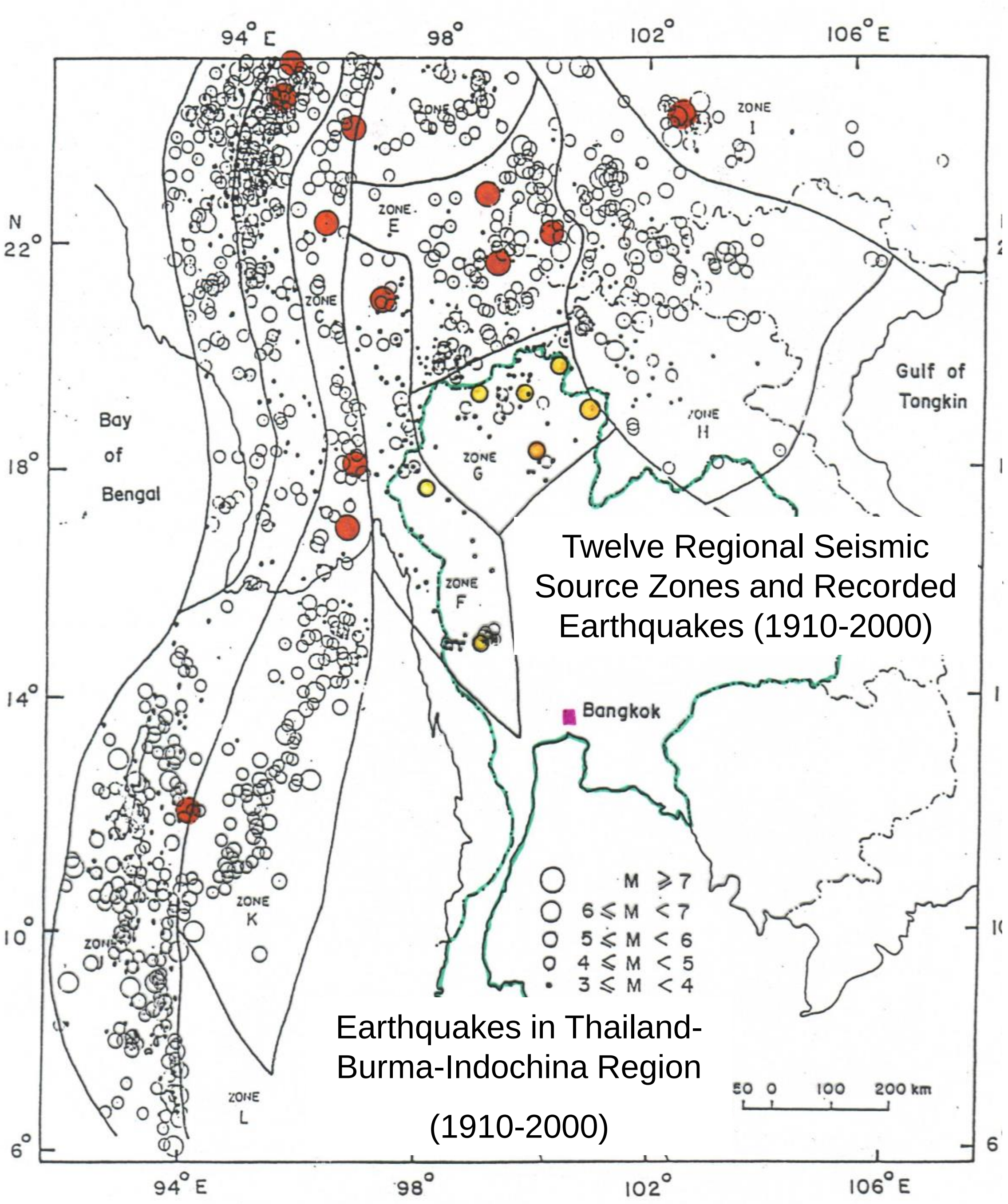


FIGURE 4.—Seismic source zones within the conterminous United States (from Algermissen and Perkins, 1976). Zone numbers correspond to those in table 4.

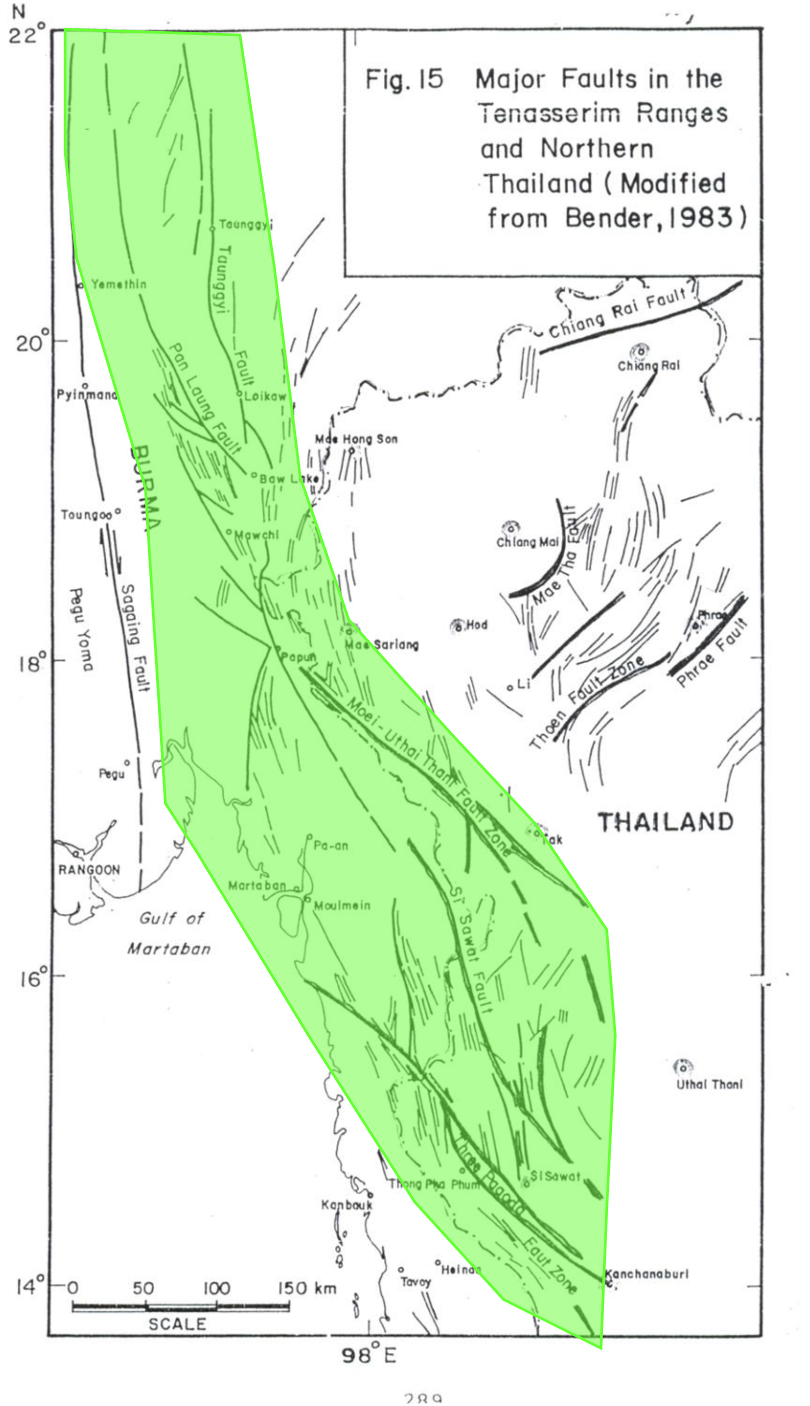
Step 1: Sources



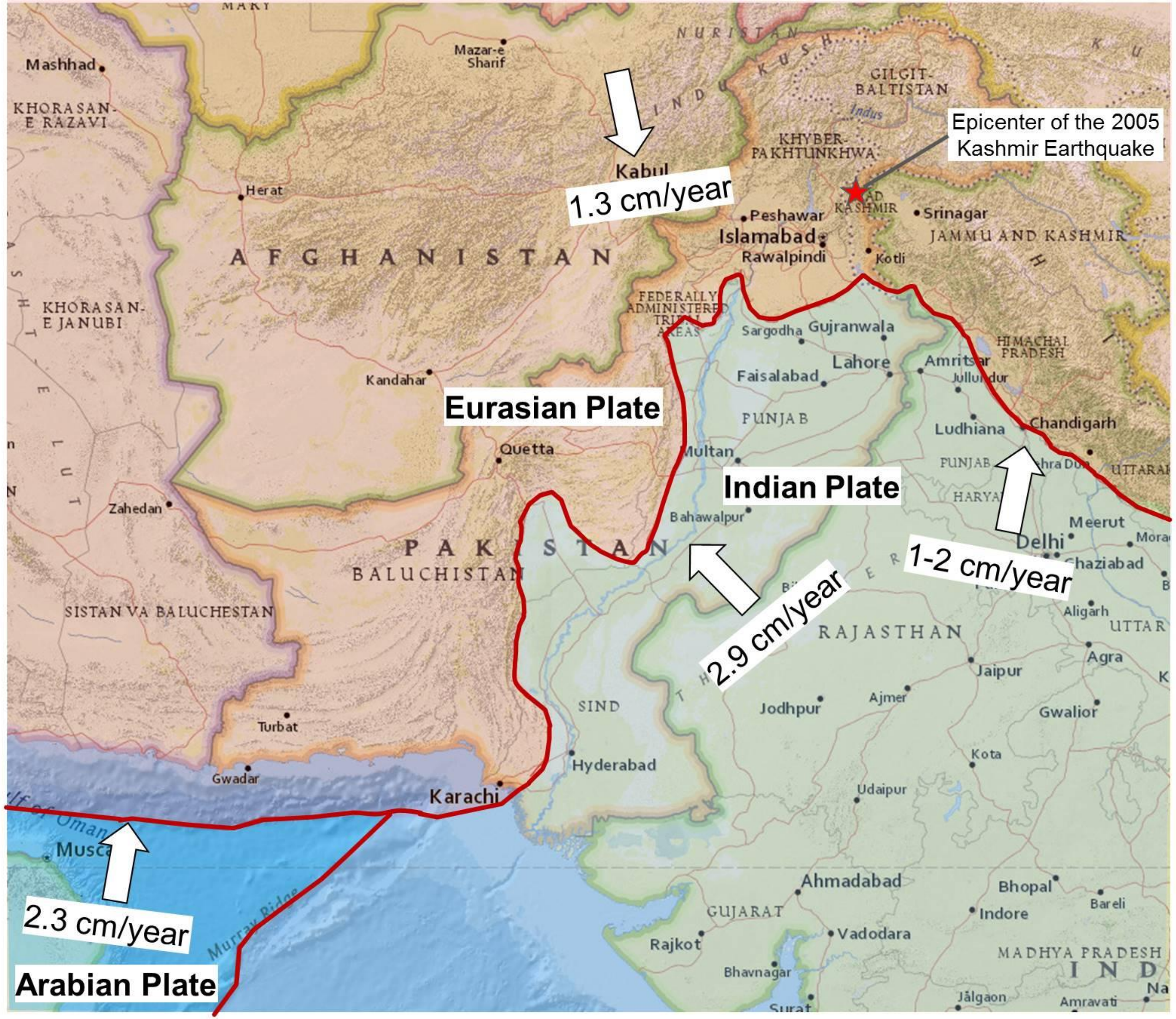
Twelve Regional Seismic Source Zones and Recorded Earthquakes (1910-2000)

Earthquakes in Thailand-Burma-Indochina Region

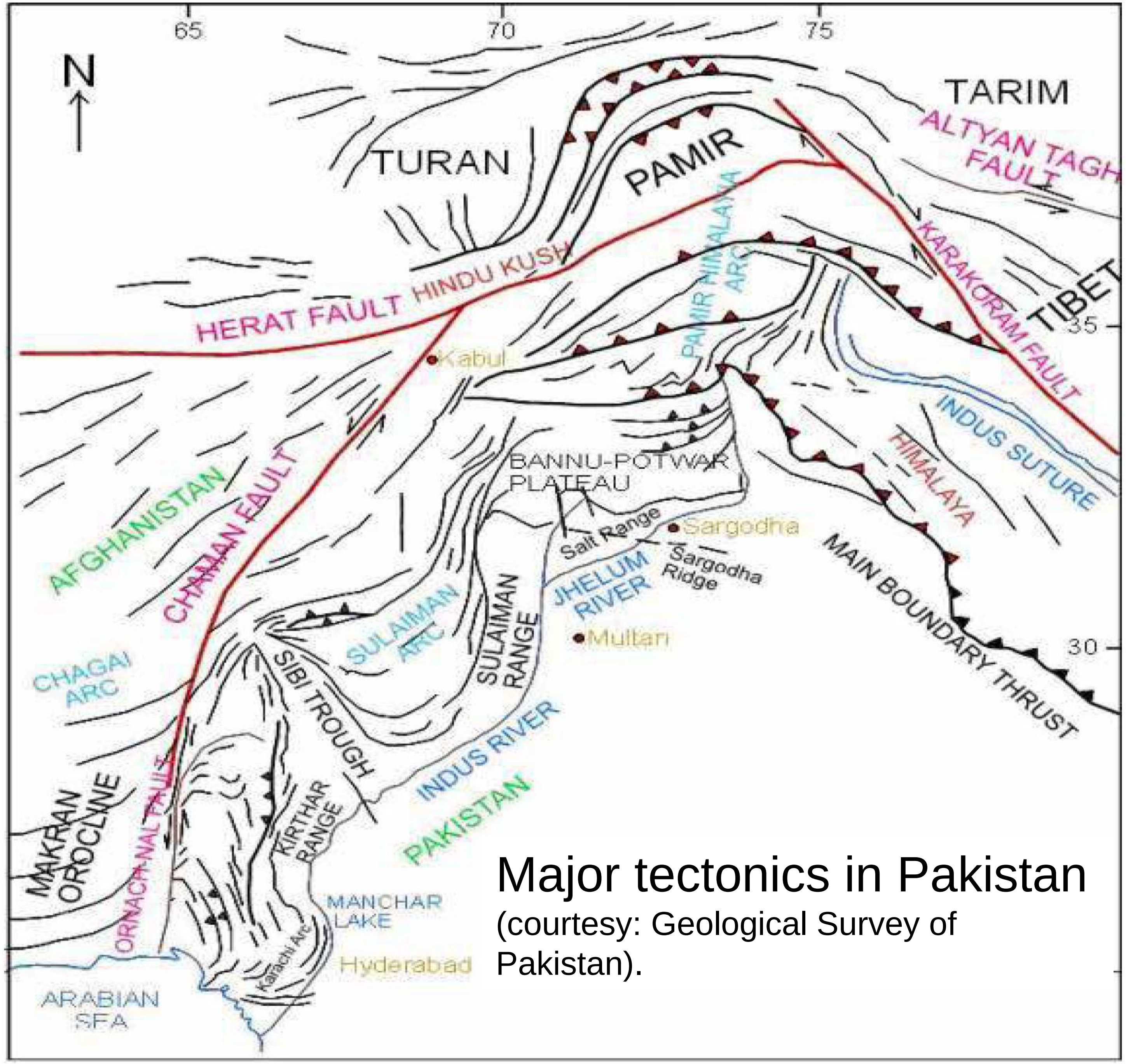
(1910-2000)



Step 1: Sources



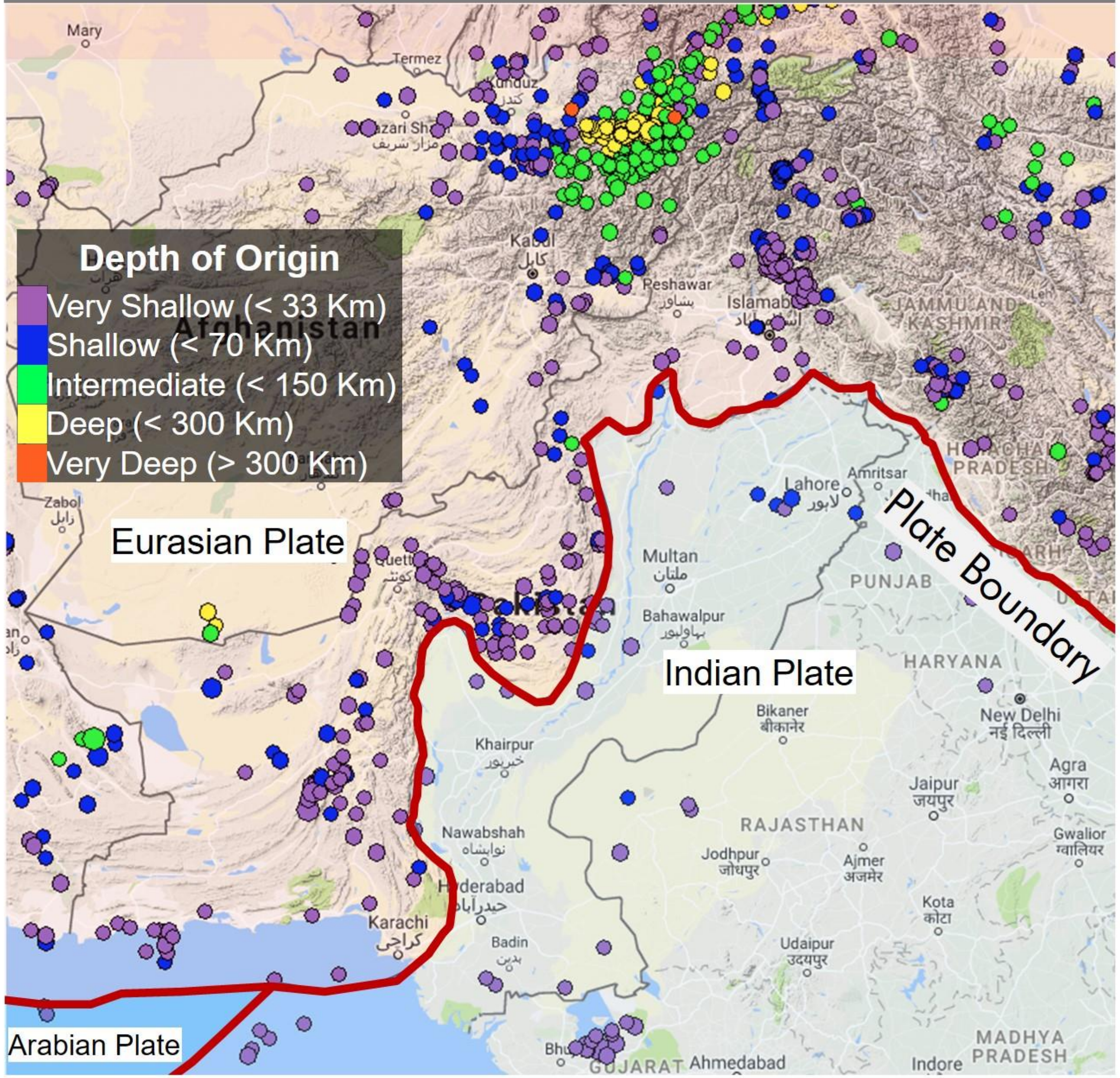
Step 1: Sources



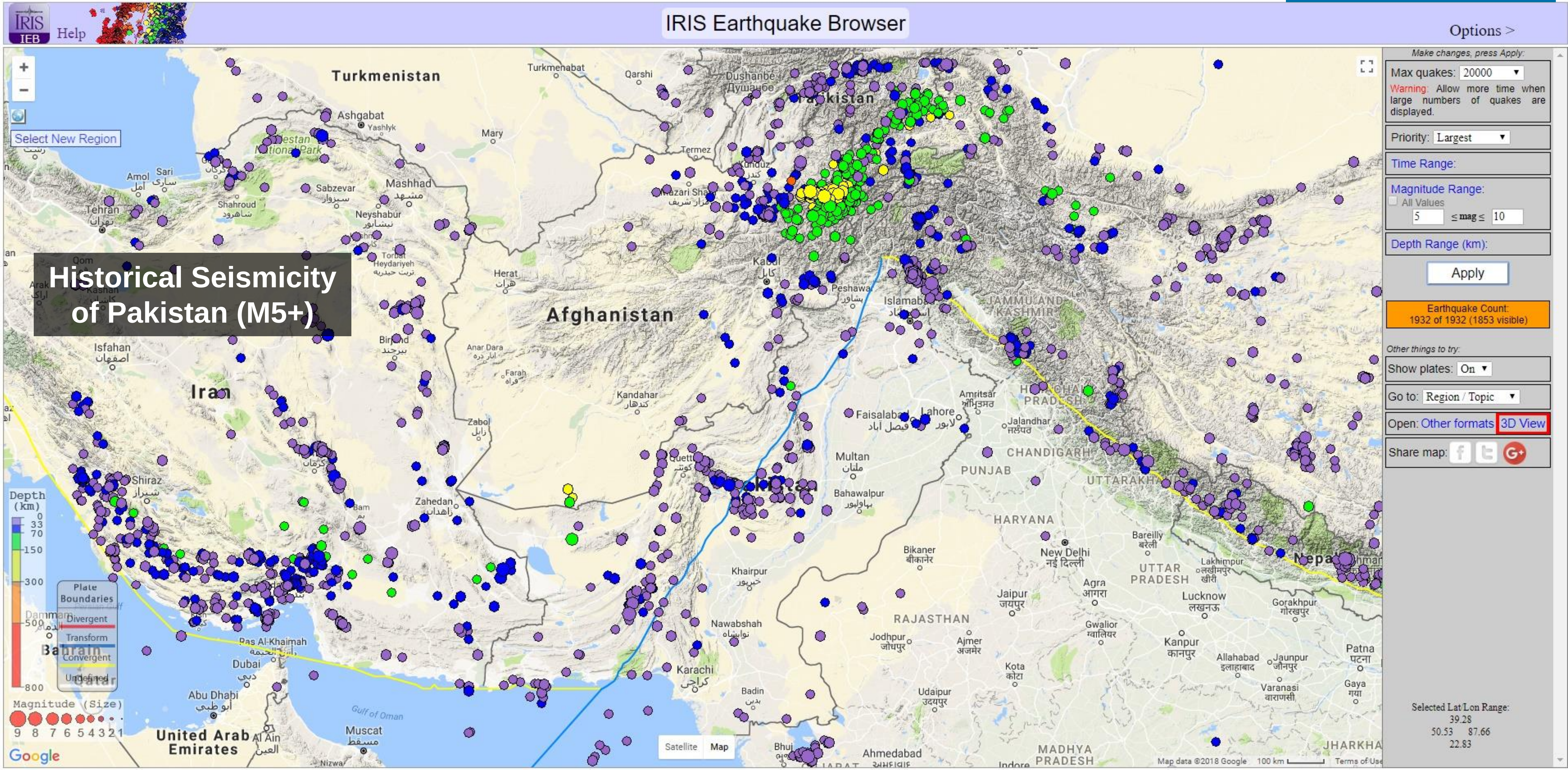
Major tectonics in Pakistan (courtesy: Geological Survey of Pakistan).

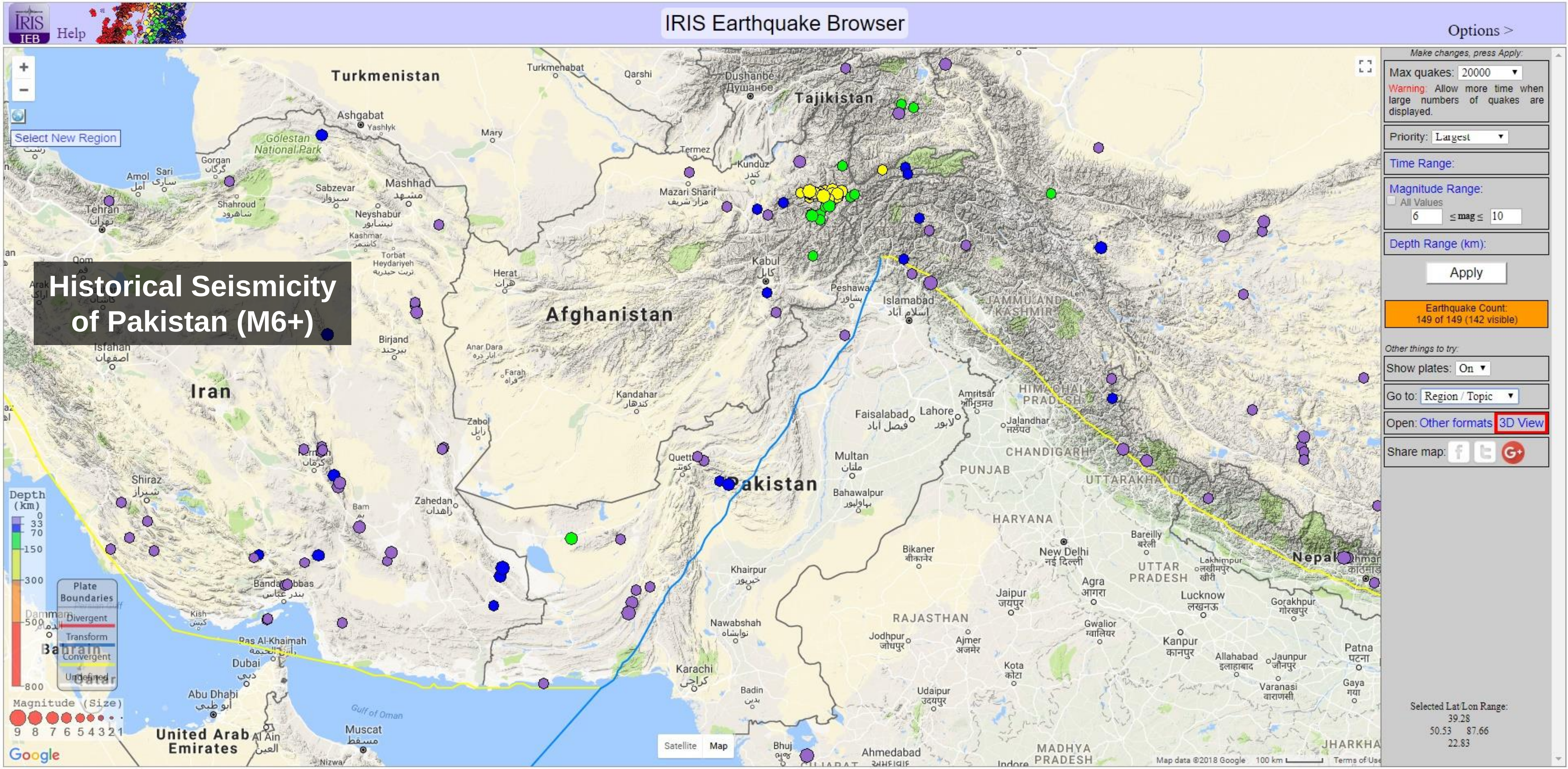
Step 1: Sources

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

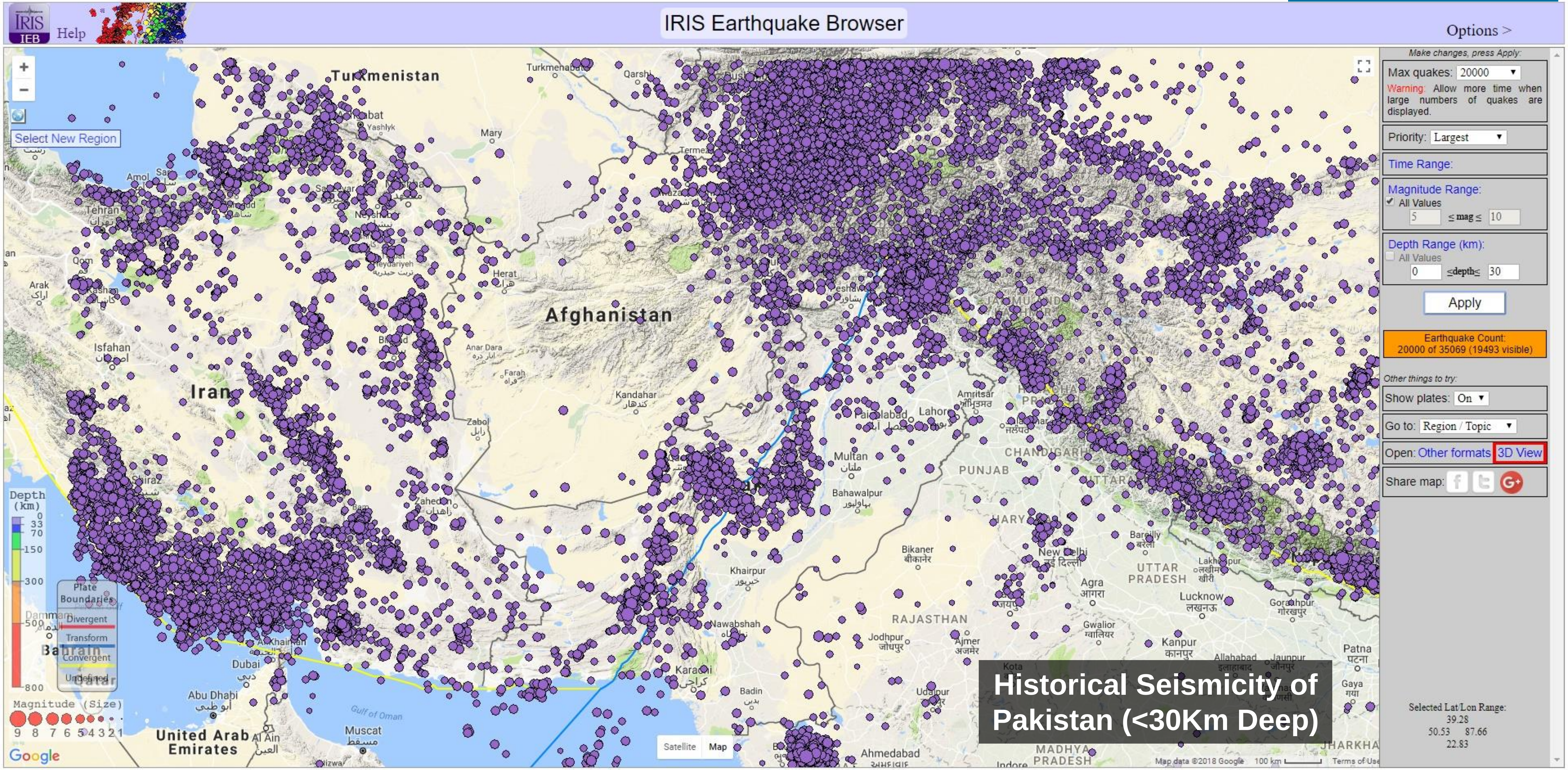


Step 1: Sources

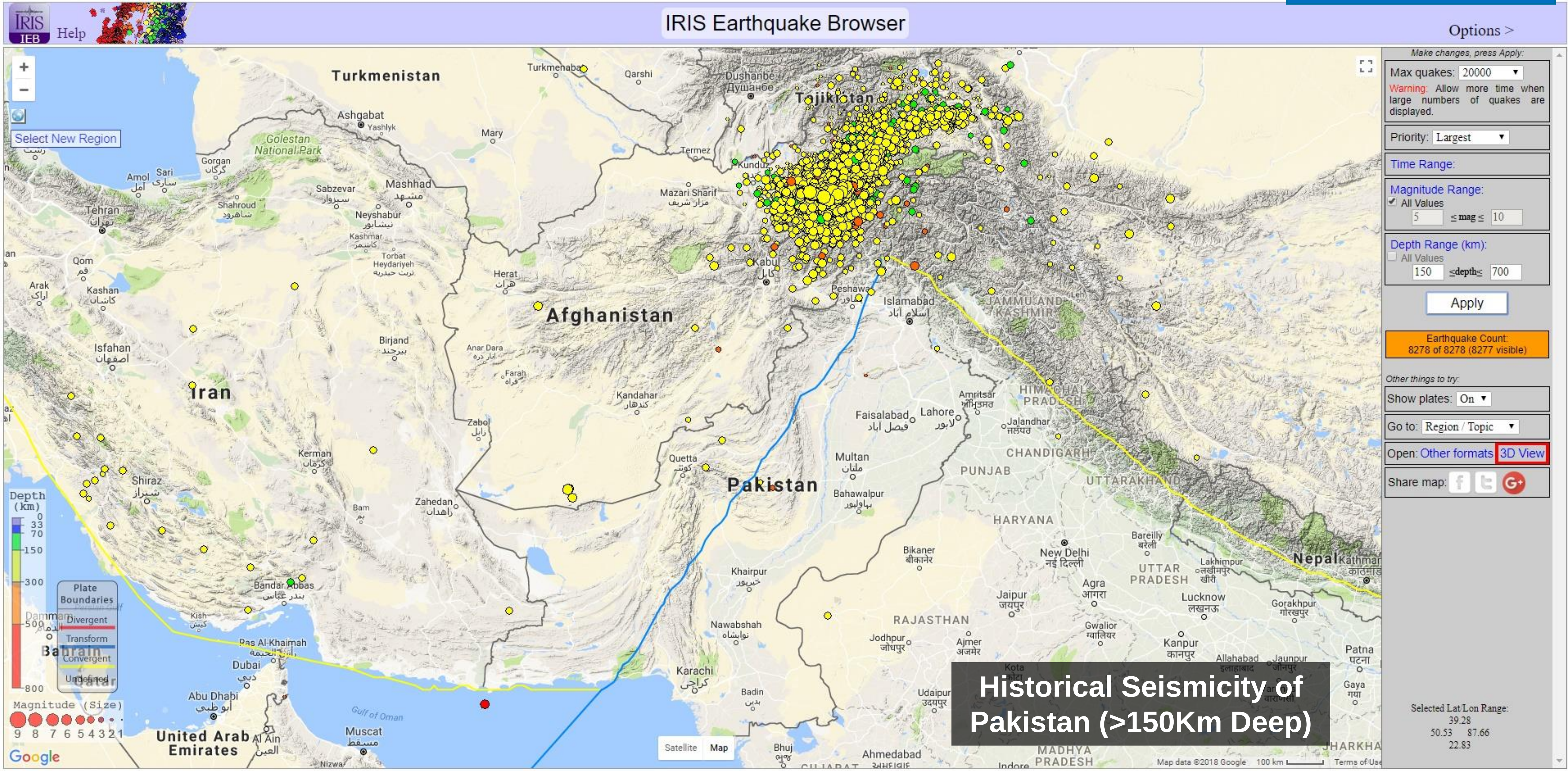



IRIS Earthquake Browser
Help
Options >
Historical Seismicity of Pakistan (M6+)
Select New Region
Turkmenistan
Tajikistan
Afghanistan
Iran
Pakistan
Nepal
Depth (km)
0
33
70
150
300
500
800
Magnitude (Size)
9 8 7 6 5 4 3 2 1
Plate Boundaries
Divergent
Transform
Convergent
Undefined
Satellite
Map
Make changes, press Apply:
Max quakes: 20000
Warning: Allow more time when large numbers of quakes are displayed.
Priority: Largest
Time Range:
Magnitude Range:
All Values
6 ≤ mag ≤ 10
Depth Range (km):
Apply
Earthquake Count:
149 of 149 (142 visible)
Other things to try:
Show plates: On
Go to: Region / Topic
Open: Other formats 3D View
Share map:
Selected Lat/Lon Range:
39.28
50.53 87.66
22.83
Map data ©2018 Google
100 km
Terms of Use

Step 1: Sources

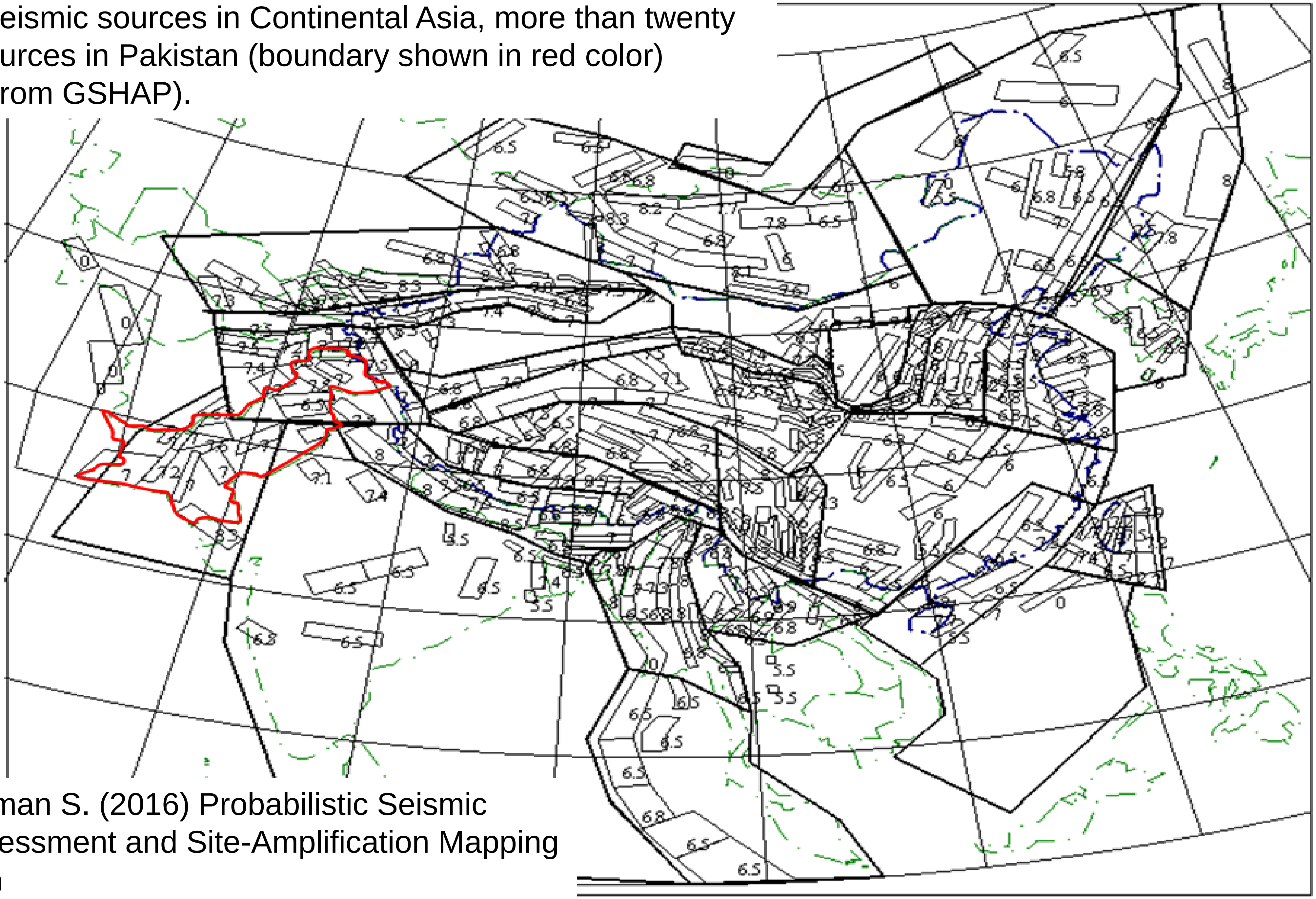


Step 1: Sources



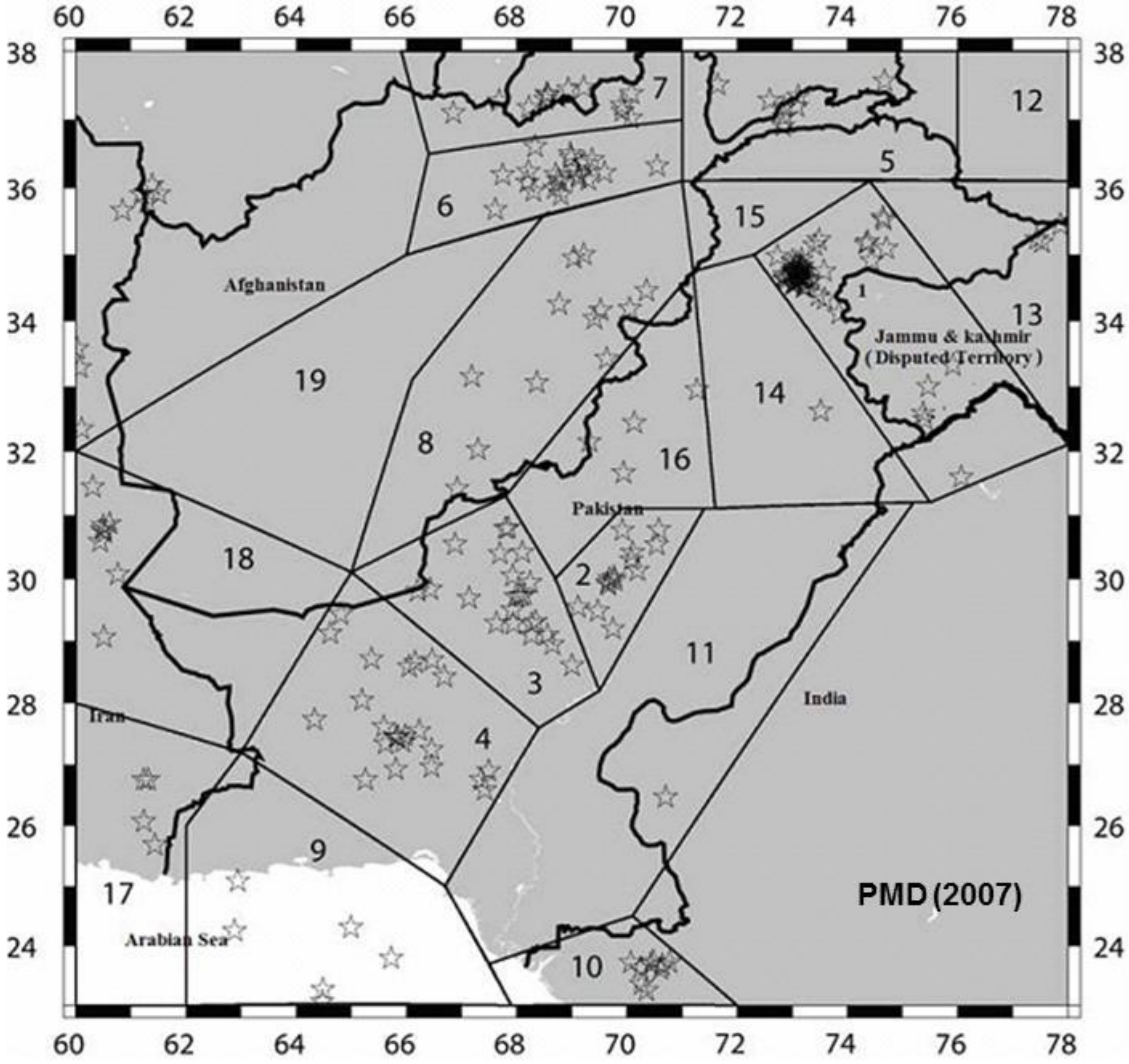
Historical Seismicity of Pakistan (>150Km Deep)

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

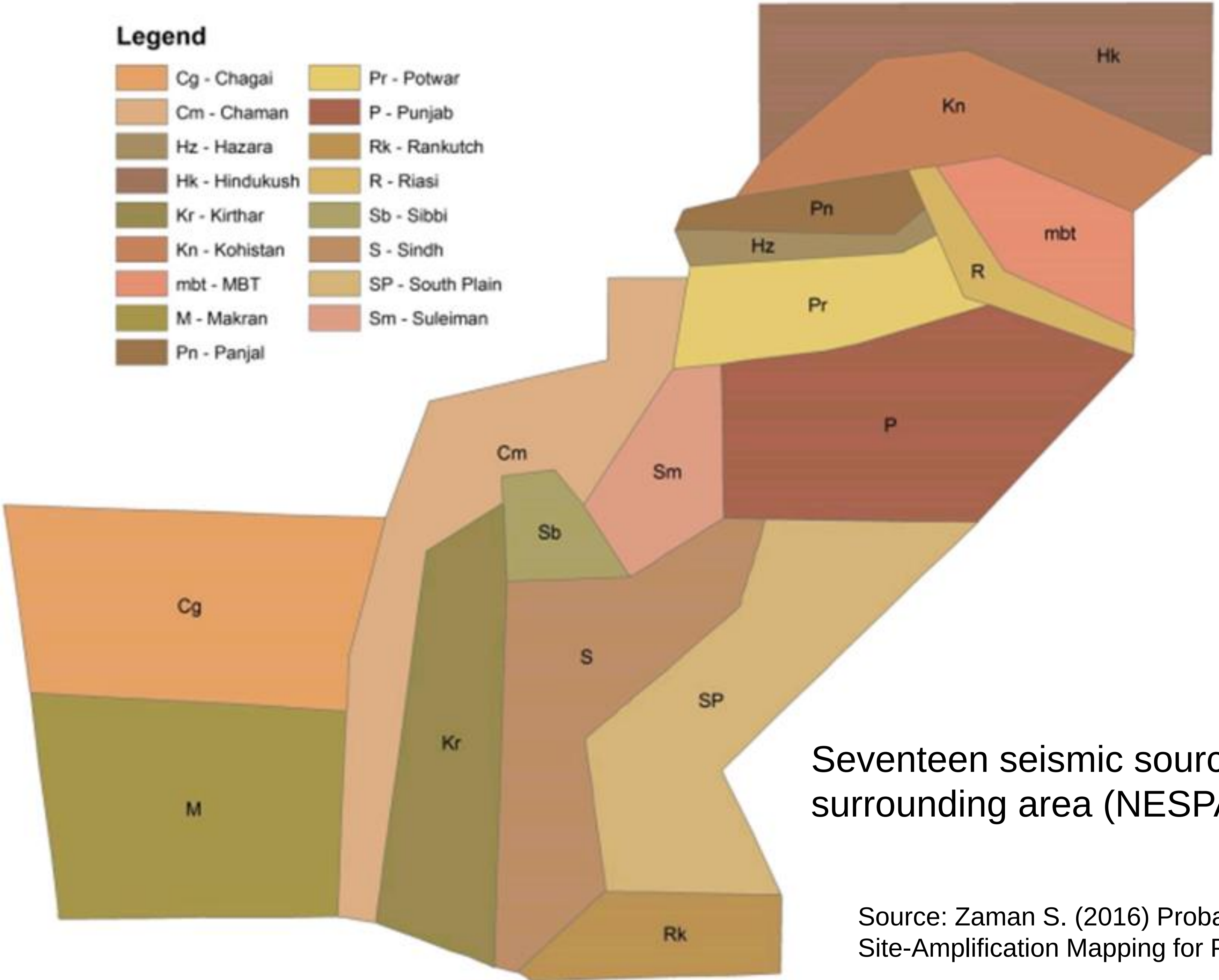


Source: Zaman S. (2016) Probabilistic Seismic Hazard Assessment and Site-Amplification Mapping for Pakistan

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

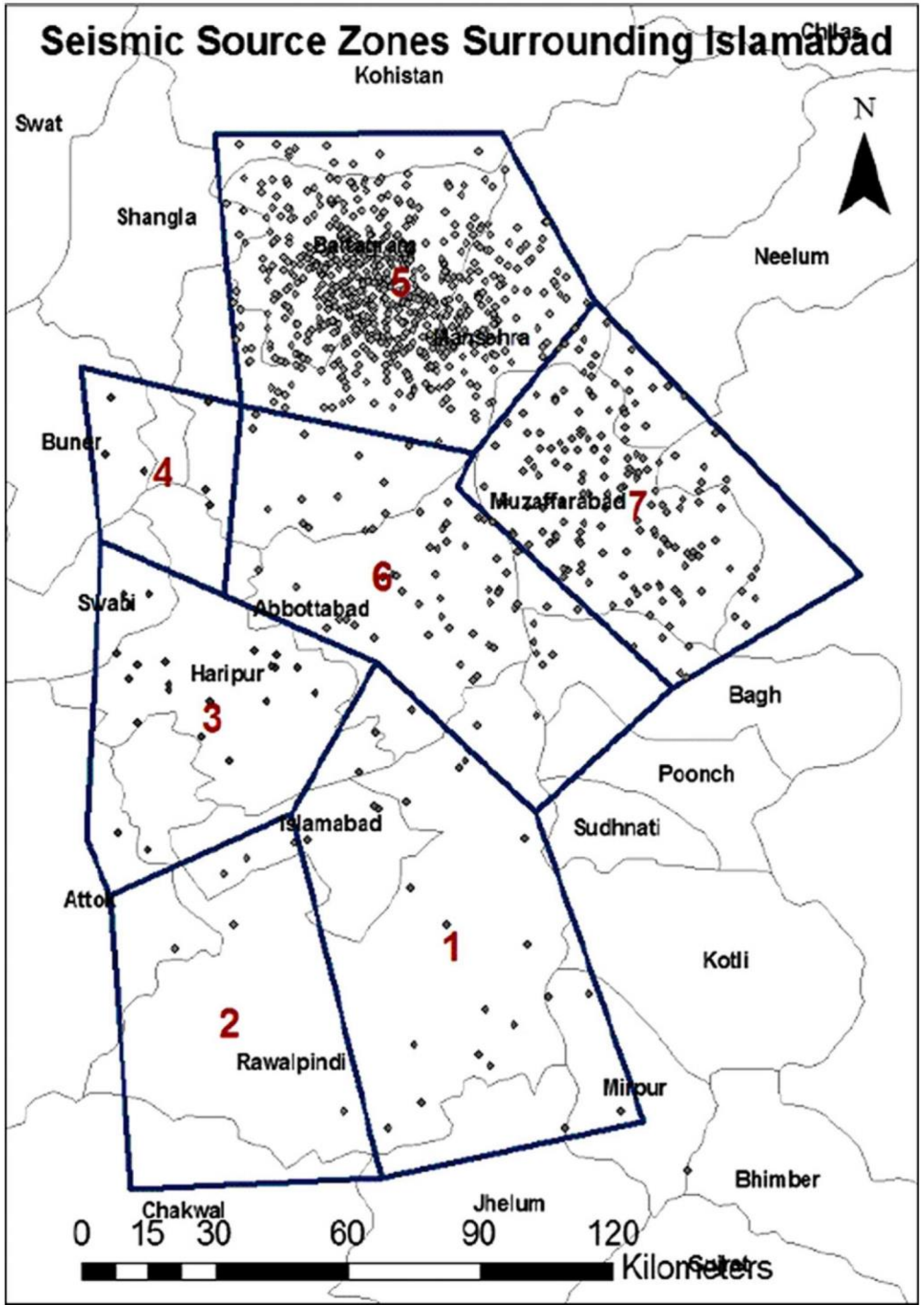


Source: PMD and NORSAR (2007) Seismic Hazard Analysis and Zonation for Pakistan, Azad Jammu and Kashmir



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

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

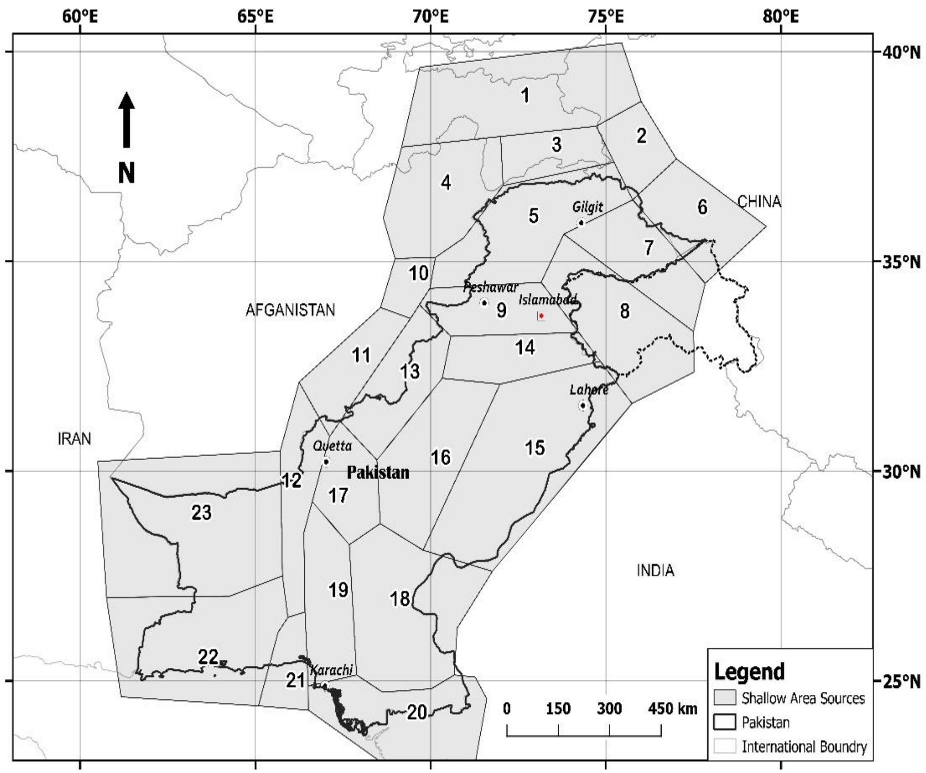


Source: Bhatti et al., (2011) Probabilistic seismic hazard analysis of Islamabad, Pakistan

Step 1: Sources

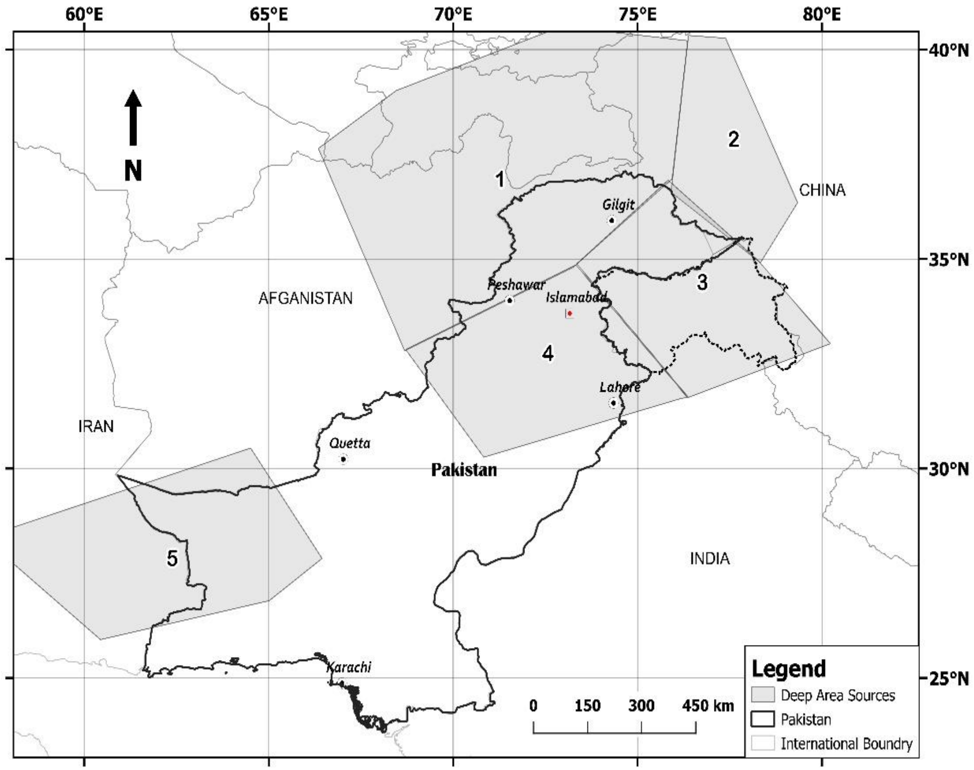
Area Sources of Pakistan

Shallow Area Sources (23)



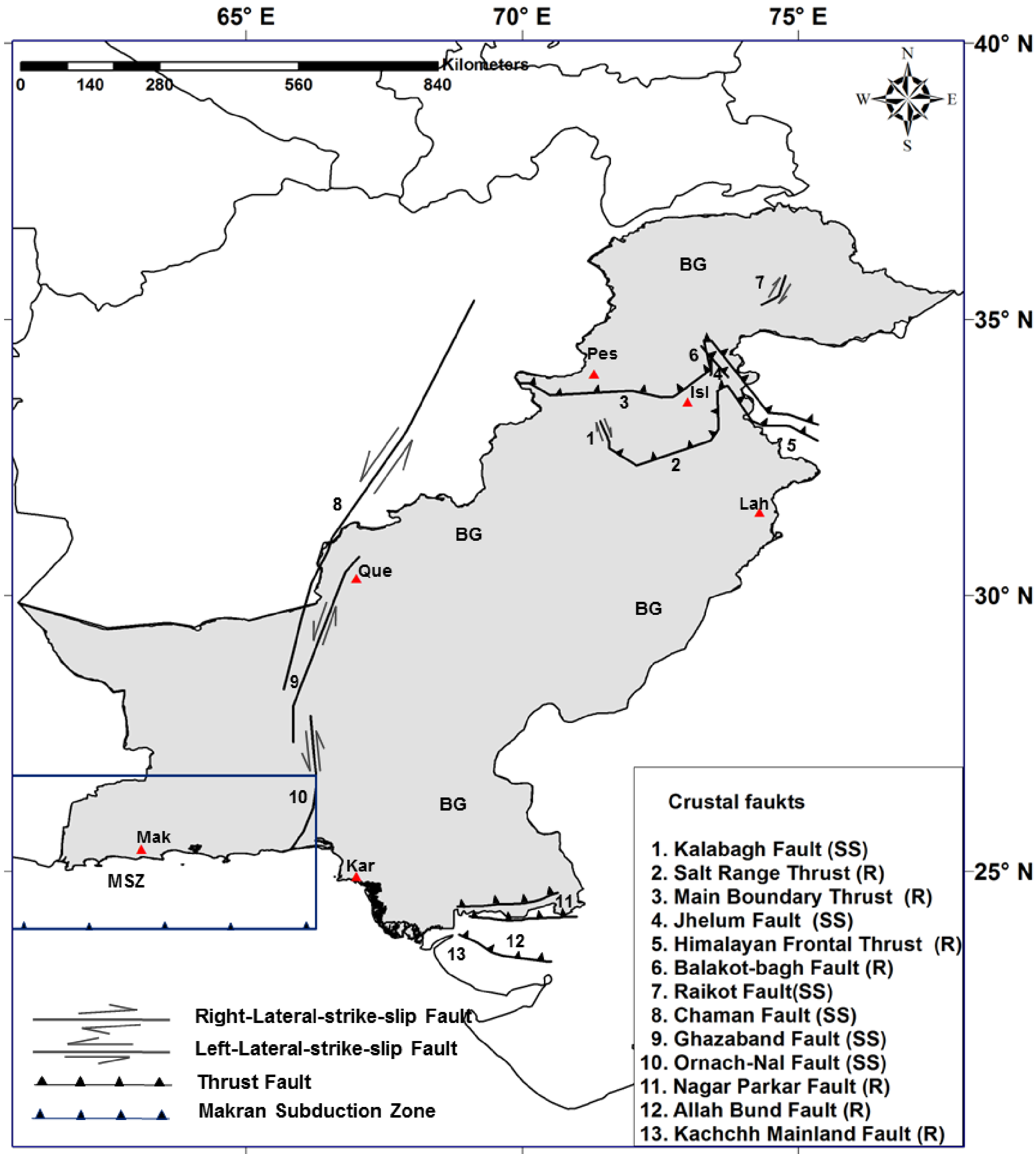
4823 Earthquake Events

Deep Area Sources (5)



1457 Earthquake Events

Source: Rahman et al. (2020)



Fault Sources of Pakistan

Earthquake sources of the study area:

a) Background seismicity zone (BG)

b) Crustal faults (1-13) SS: Strike-Slip fault, R: Reverse fault), and

c) Makran subduction zone (MSZ)

Red Triangle shows major cities of Pakistan that is Peshawar (Pes), Islamabad (Isl), Lahore (Lah), Quetta (Que), Karachi (Kar), and Makran (Mak)

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

Step 2: Quantifying the Seismicity Rate of Sources (The Development of Magnitude-Recurrence Relationships for All Sources)

Defining the Seismicity of Seismic Sources

- One commonly used parameter for defining the seismicity:

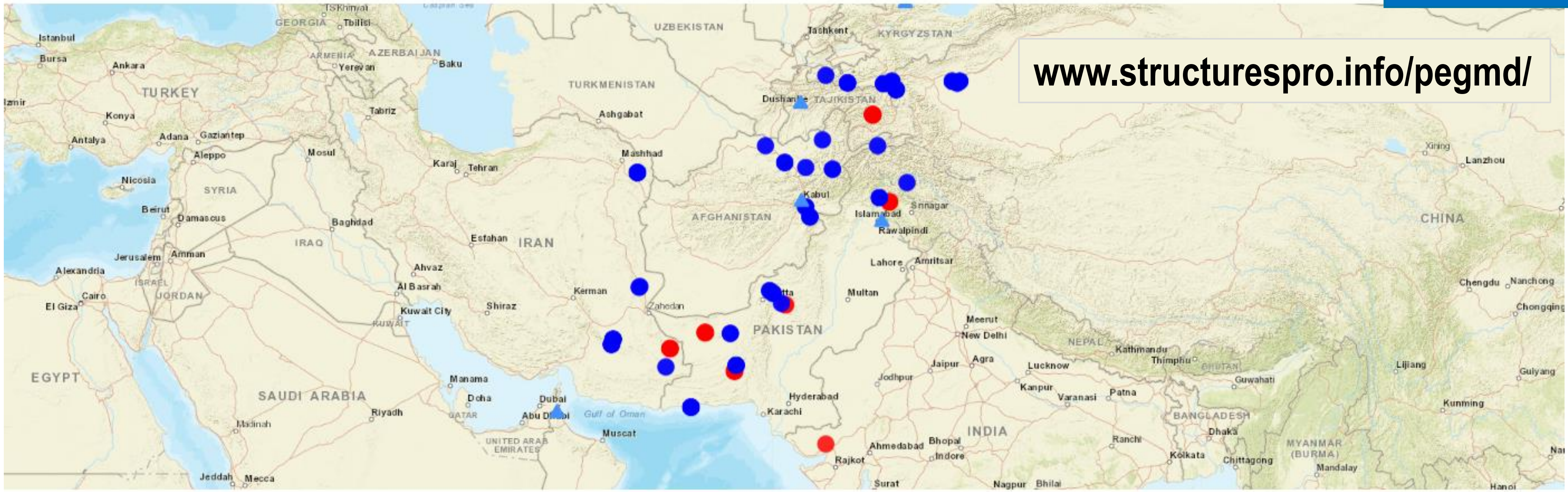
  The rate of occurrence of earthquakes larger than some lower-bound magnitude $m_o = \nu$

- m_o is defined as the smallest earthquake expected to produce damage.
- Typically $m_o = 4.0$
- In traditional applications of PSHA, ν 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.

Step 2: Recurrence

www.structurespro.info/pegmd/

Magnitude 4 - 5 : Magnitude 5 - 6 : Magnitude 6 - 7 : Magnitude ≥ 7.0 : Station



Minimum Magnitude: Maximum Magnitude:

Date & Time (UTC)	Magnitude	Latitide	Longitude	Depth (km)	Region	View
1990-03-05 20:47:06	6.2	36.8989	73.0236	59.7	NORTHWESTERN KASHMIR	Open
1994-02-23 08:02:04	6.0	30.8064	60.5695	6	NORTHERN AND CENTRAL IRAN	Open
1994-02-24 00:11:12	6.2	30.768	60.5174	13.4	NORTHERN AND CENTRAL IRAN	Open
1994-05-01 12:00:36	6.1	36.9268	67.1569	18.5	HINDU KUSH REGION, AFGHANISTAN	Open
1997-02-27 21:08:02	7	29.9614	68.2024	33.6	PAKISTAN	Open
1997-02-27 21:30:37	6.0	30.0377	67.9747	43.4	PAKISTAN	Open
1997-04-11 05:34:43	6.0	39.5557	76.9477	20	SOUTHERN XINJIANG, CHINA	Open
1998-05-30 06:22:28	6.6	37.1533	70.1183	30.4	AFGHANISTAN-TAJIKISTAN BORD REG.	Open
1998-08-27 09:03:36	6.4	39.5762	77.3403	33	SOUTHERN XINJIANG, CHINA	Open

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

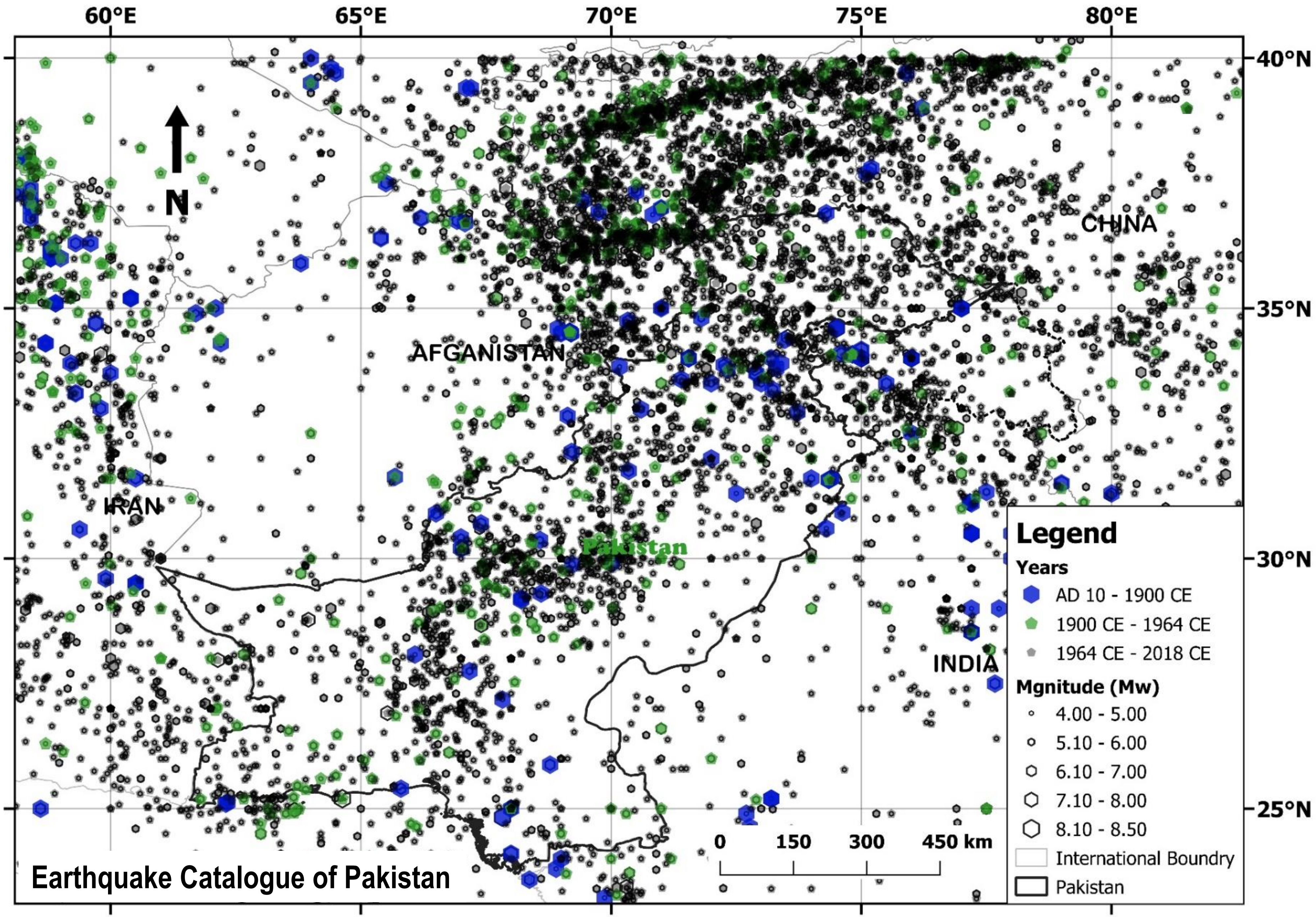

Investigation of Active Faults: Fault Trenching in Taiwan

Geological Record found in a Fault Trench in Taiwan

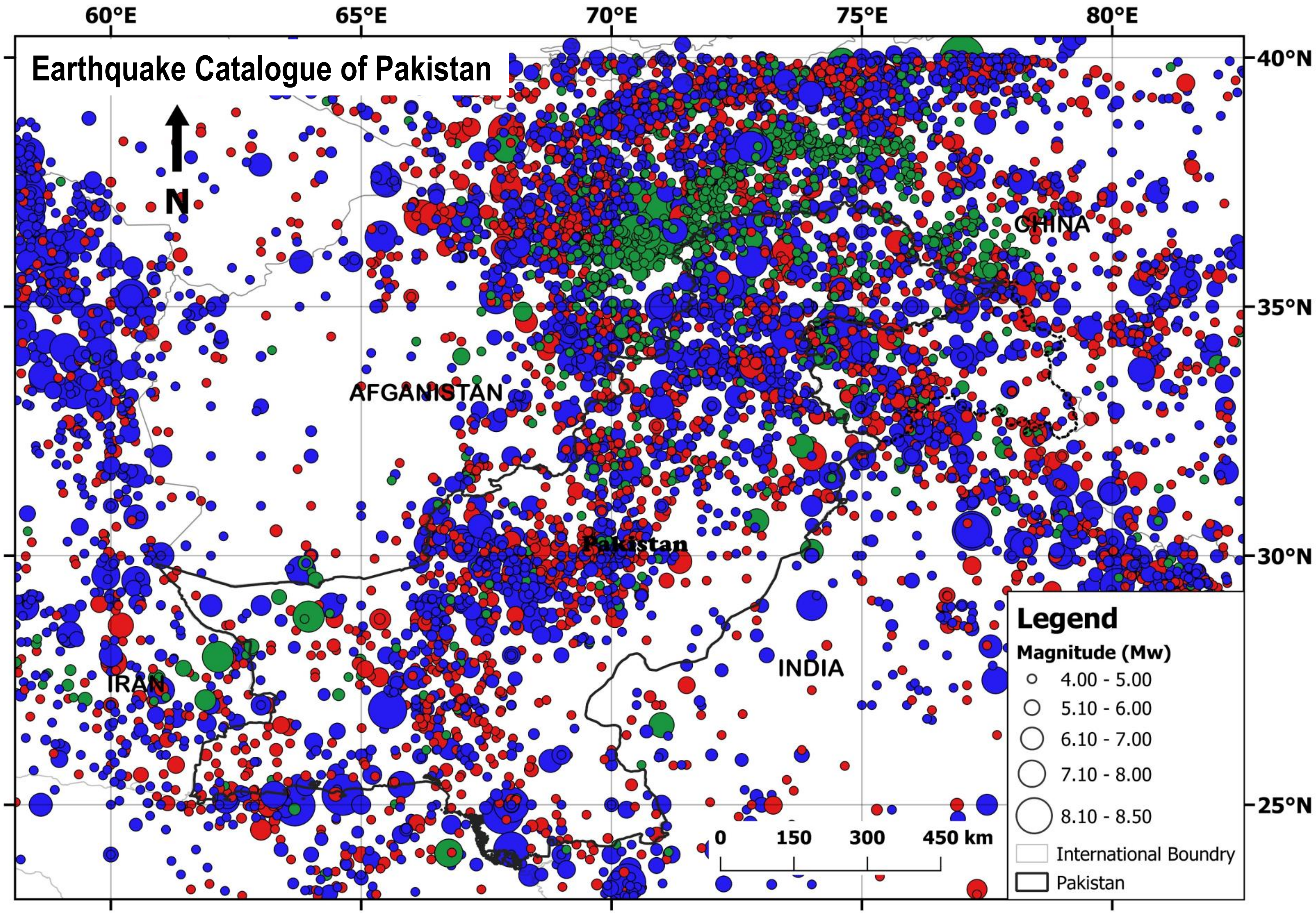
Step 2: Recurrence

Fault Trenching in Kanchanaburi, Thailand

Step 2: Recurrence



60°E
65°E
70°E
75°E
80°E
40°N
35°N
30°N
25°N
N
CHINA
AFGANISTAN
IRAN
Pakistan
INDIA
Legend
Years
AD 10 - 1900 CE
1900 CE - 1964 CE
1964 CE - 2018 CE
Mgnitude (Mw)
4.00 - 5.00
5.10 - 6.00
6.10 - 7.00
7.10 - 8.00
8.10 - 8.50
International Boundry
Pakistan
0 150 300 450 km
Earthquake Catalogue of Pakistan



Blue 0 – 25 km **Red** 25 – 50 km **Green** 50 – 250 km

Magnitude-Recurrence Relationship

T = say 100 years

m	N(m) in T years	Annual N(m) = N(m)/T	Cumulative Annual N(m)
8.0	1	0.01	0.01
7.0	7	0.07	0.08
6.0	80	0.8	0.88
5.0	1000	10	10.88
4.0	6000	60	70.88

Annual N(m) = Annual Occurrence Rate

Cumulative Annual N(m) = Cumulative Annual Frequency = Annual Frequency of Exceedance = Annual Rate of Exceedance

e.g. the rate of occurrence of an earthquake with M > 6 in one year = 0.88

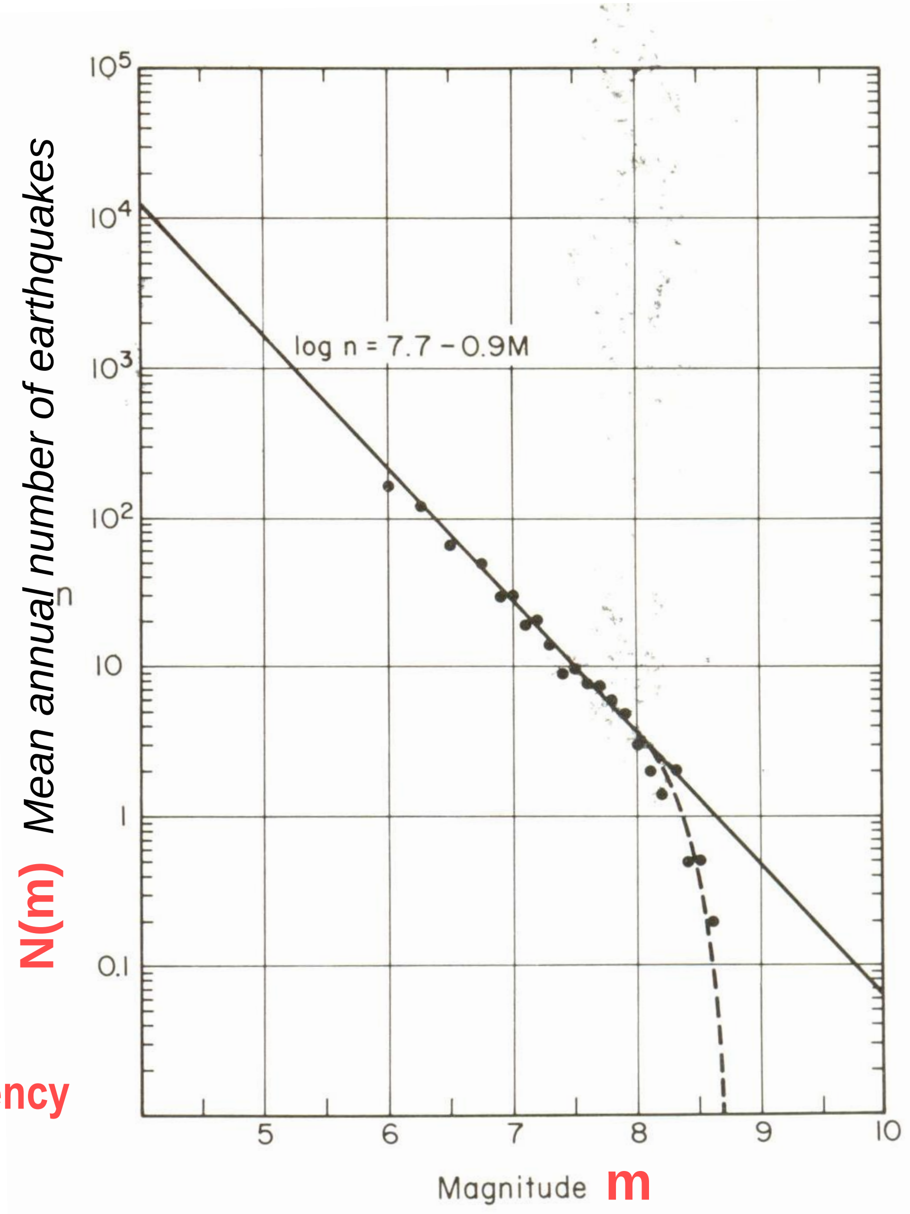


Fig. 5.5. Mean annual frequency distribution of world earthquakes, 1904–1946; ndM is the mean annual number of shocks having magnitudes lying between M and $M + dM$.

The probability of having an earthquake with M = 6 in next 1 year = 80%

The probability of having an earthquake with M > 6 in next 1 year = 88%
= ***Probability of Exceedance***

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 $\pm$ 0.3.

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

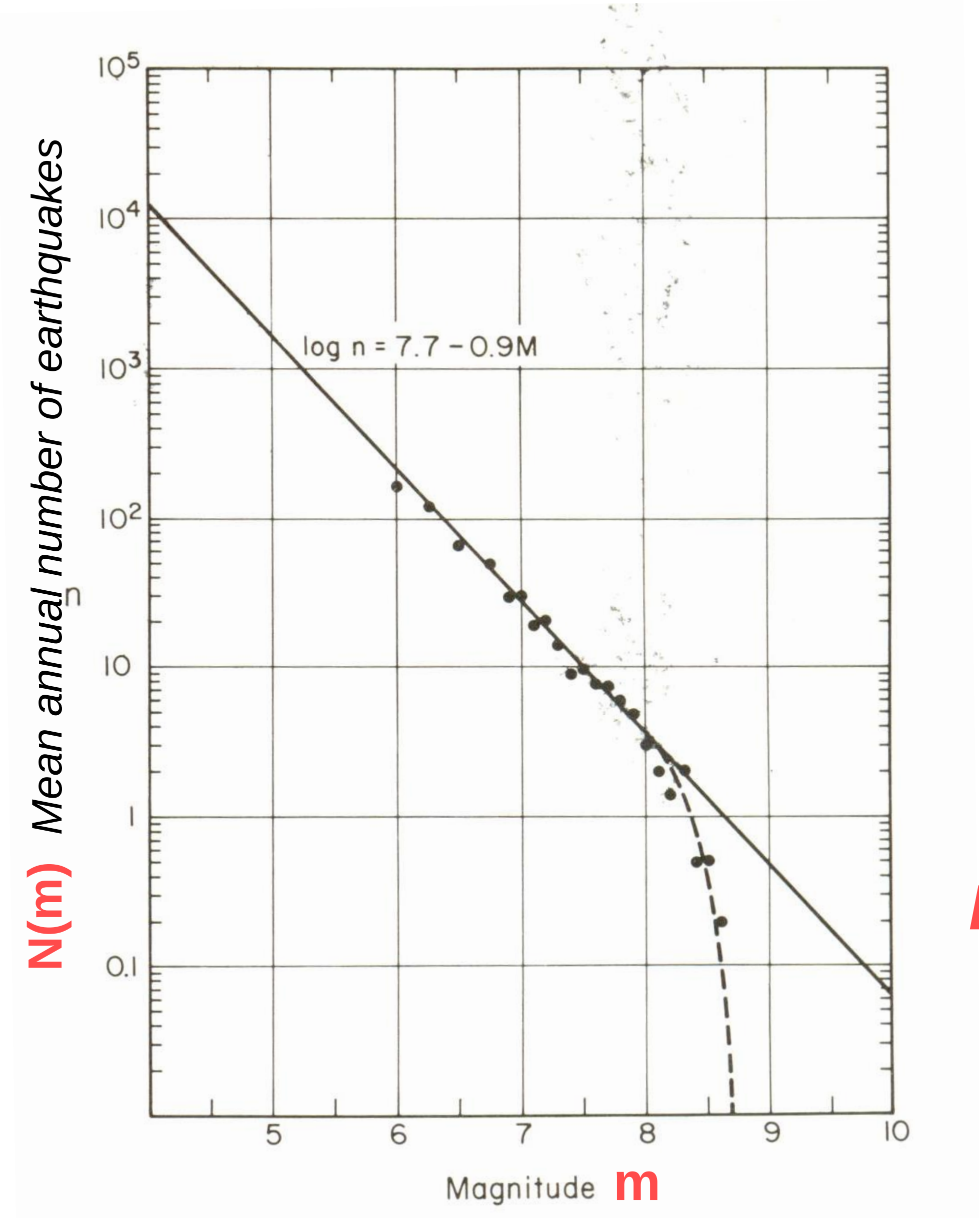


Fig. 5.5. Mean annual frequency distribution of world earthquakes, 1904–1946; *ndM* is the mean annual number of shocks having magnitudes lying between *M* and *M* + *dM*.

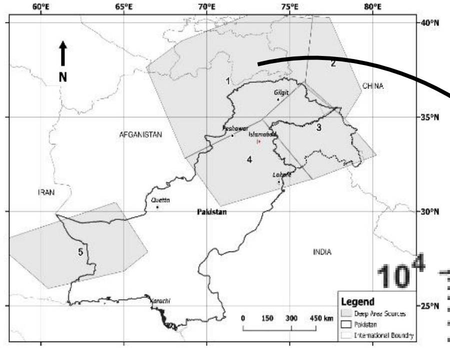
m	N(m)
8.0	2
7.0	20
6.0	100
5.0	3,000
4.0	15,000

The Gutenberg-Richter (exponential) model

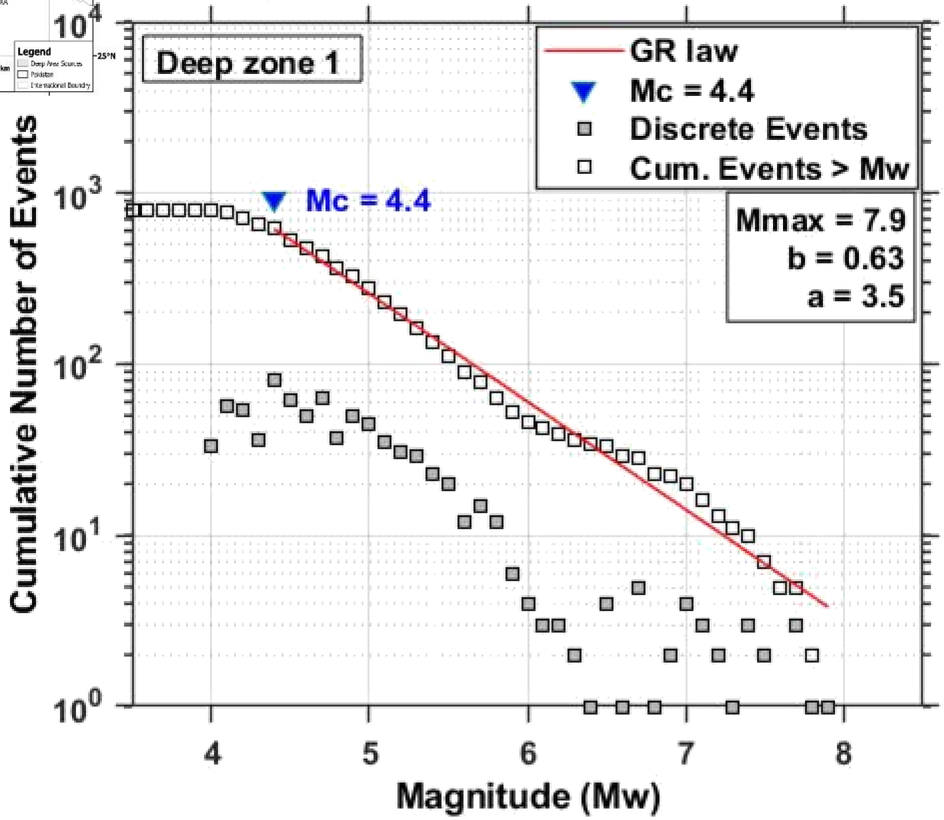
$$Log_{10} N(m) = a - b.m$$

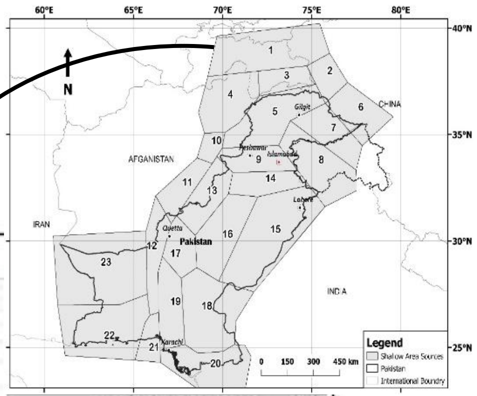
Recurrence Models and Seismicity Parameters

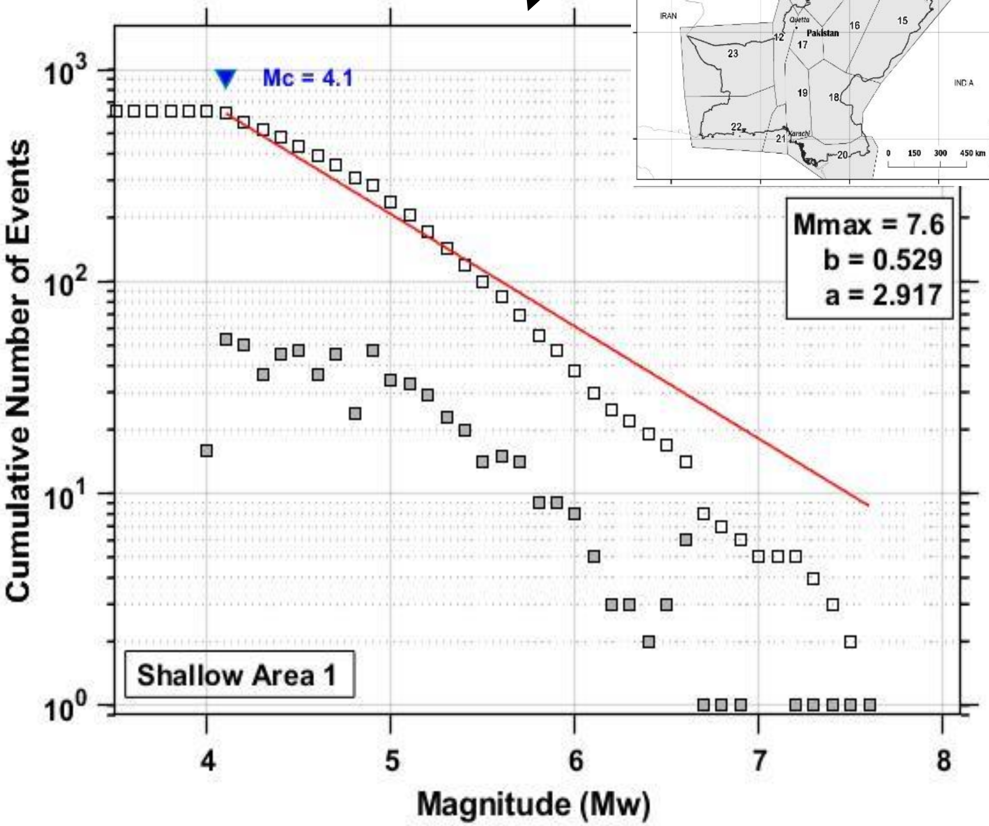
The Seismicity Parameters (Recurrence Rates) are calculated by Gutenberg-Richter Law (1974)

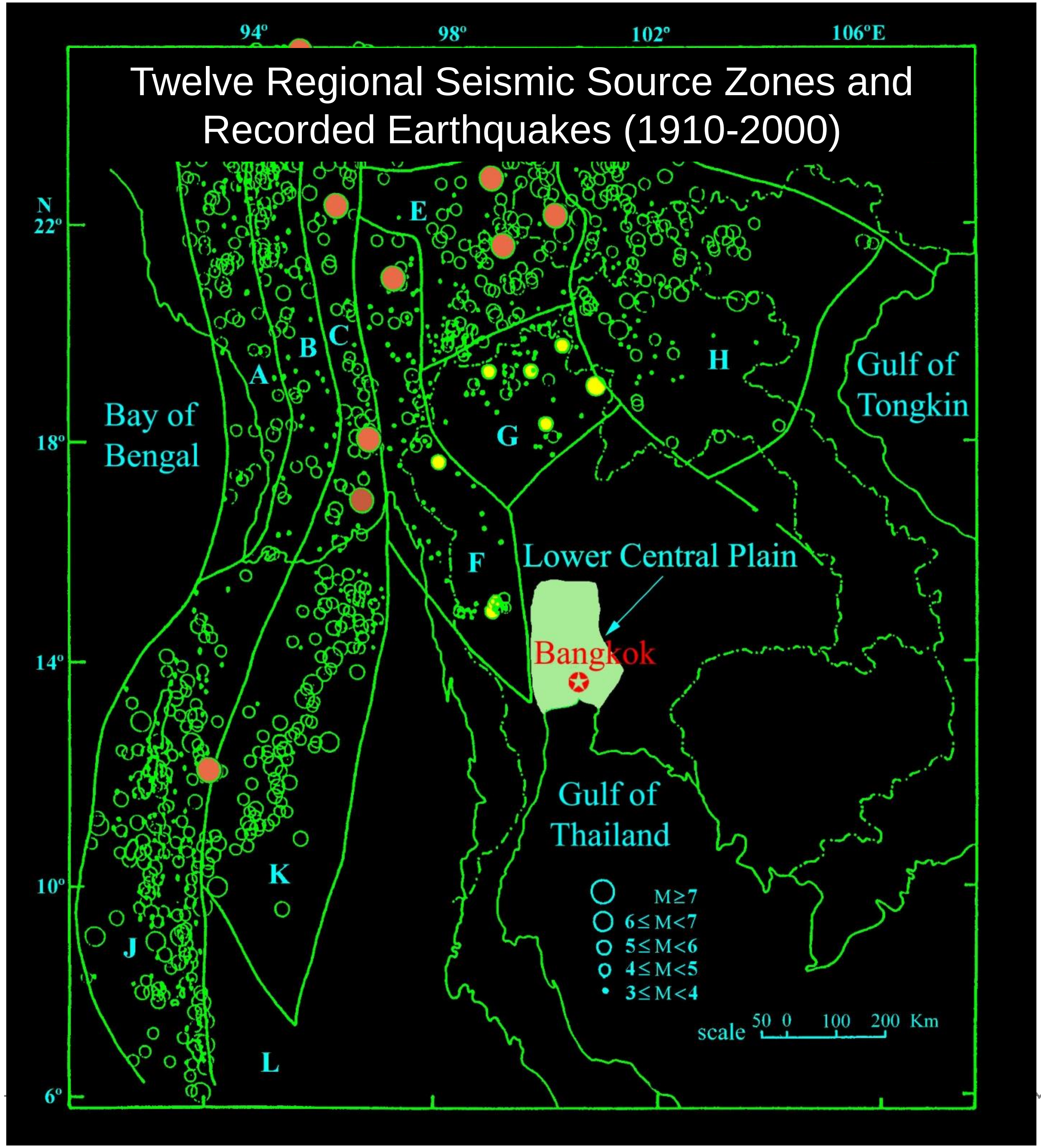


$$Log\ \lambda_M = a - b * M$$

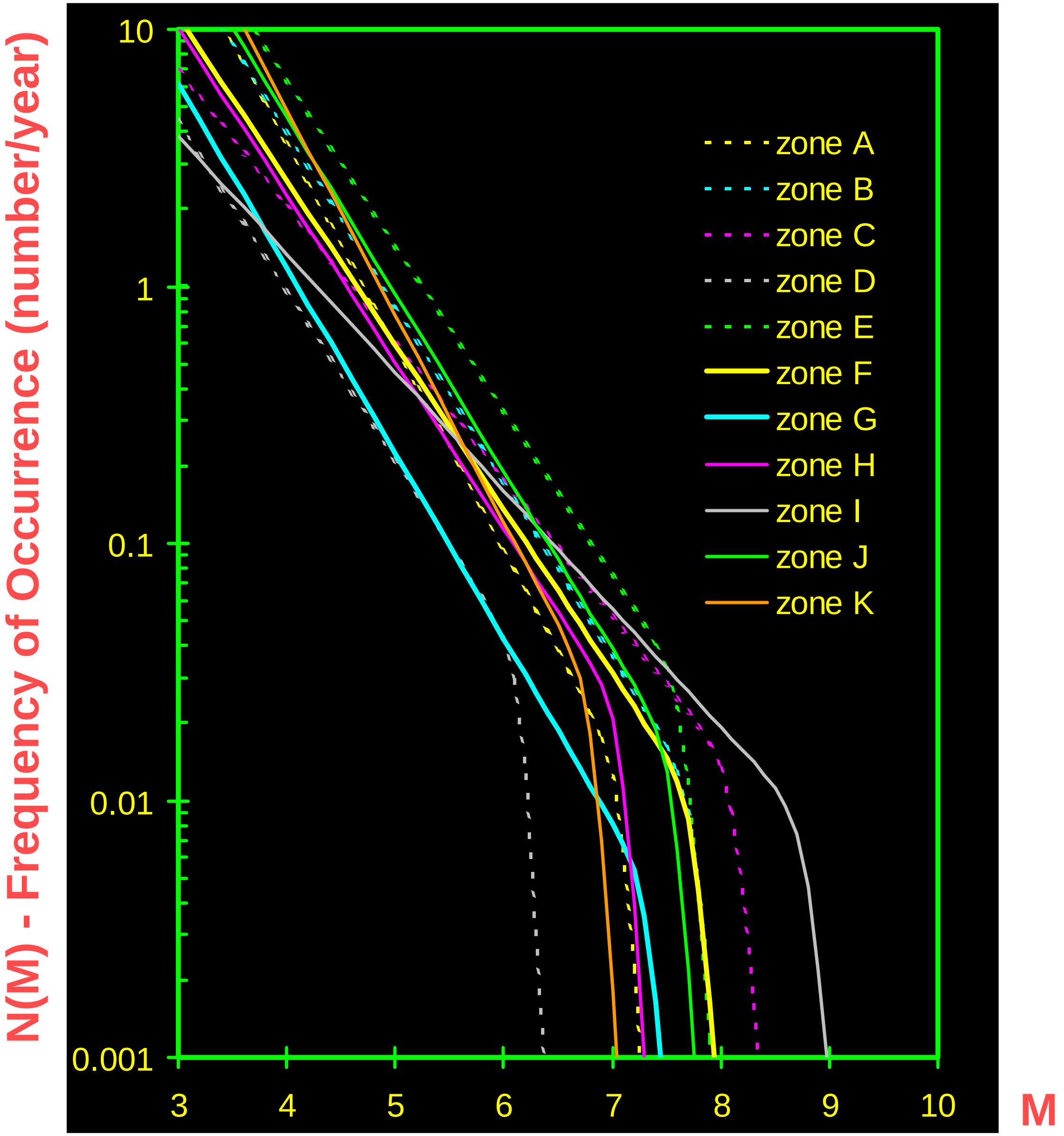








Magnitude-Recurrence Relationships



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.

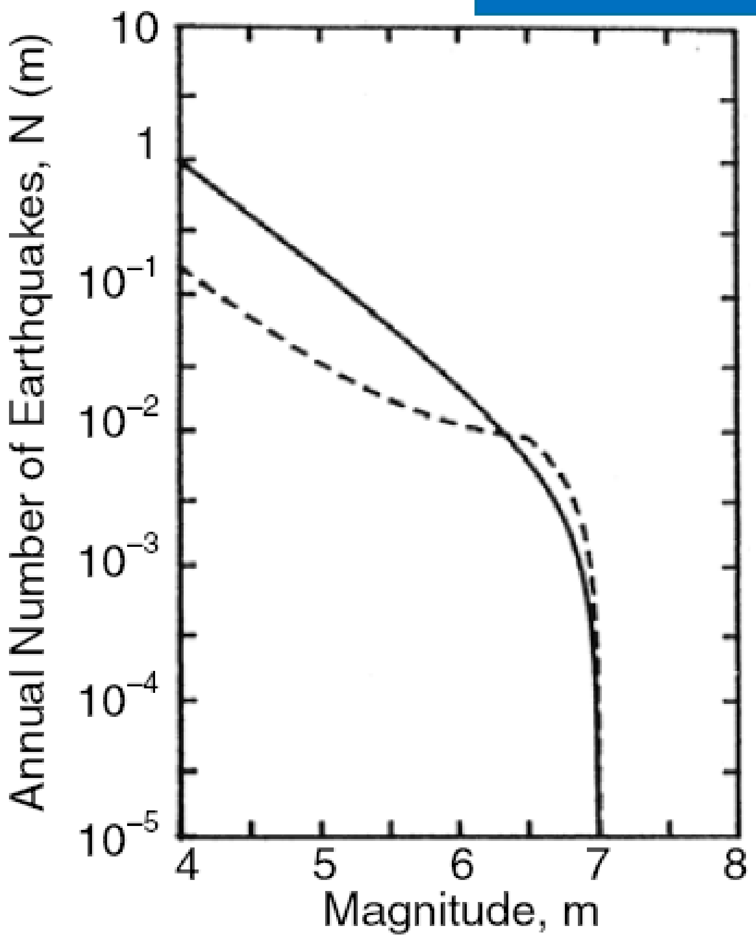
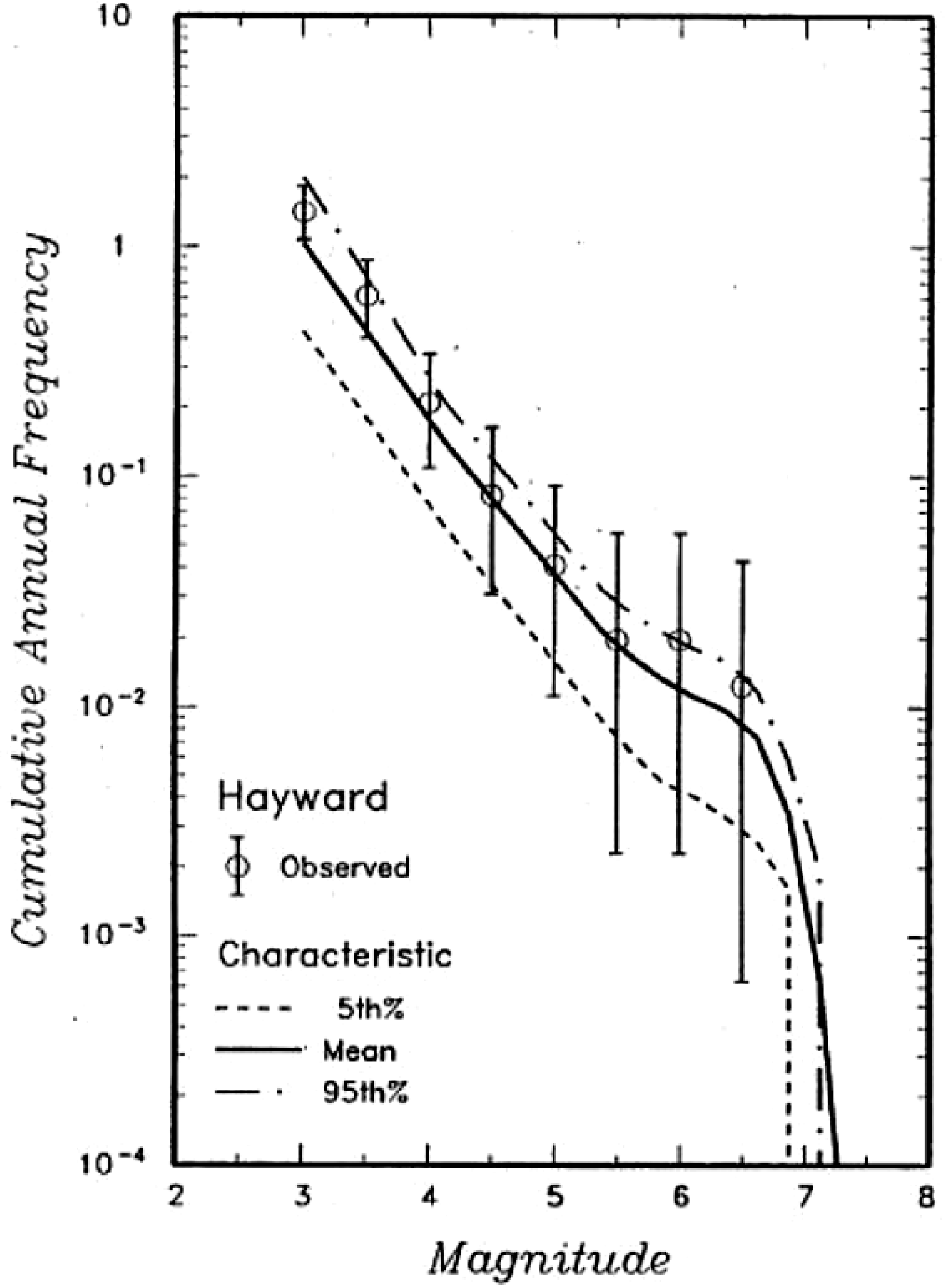
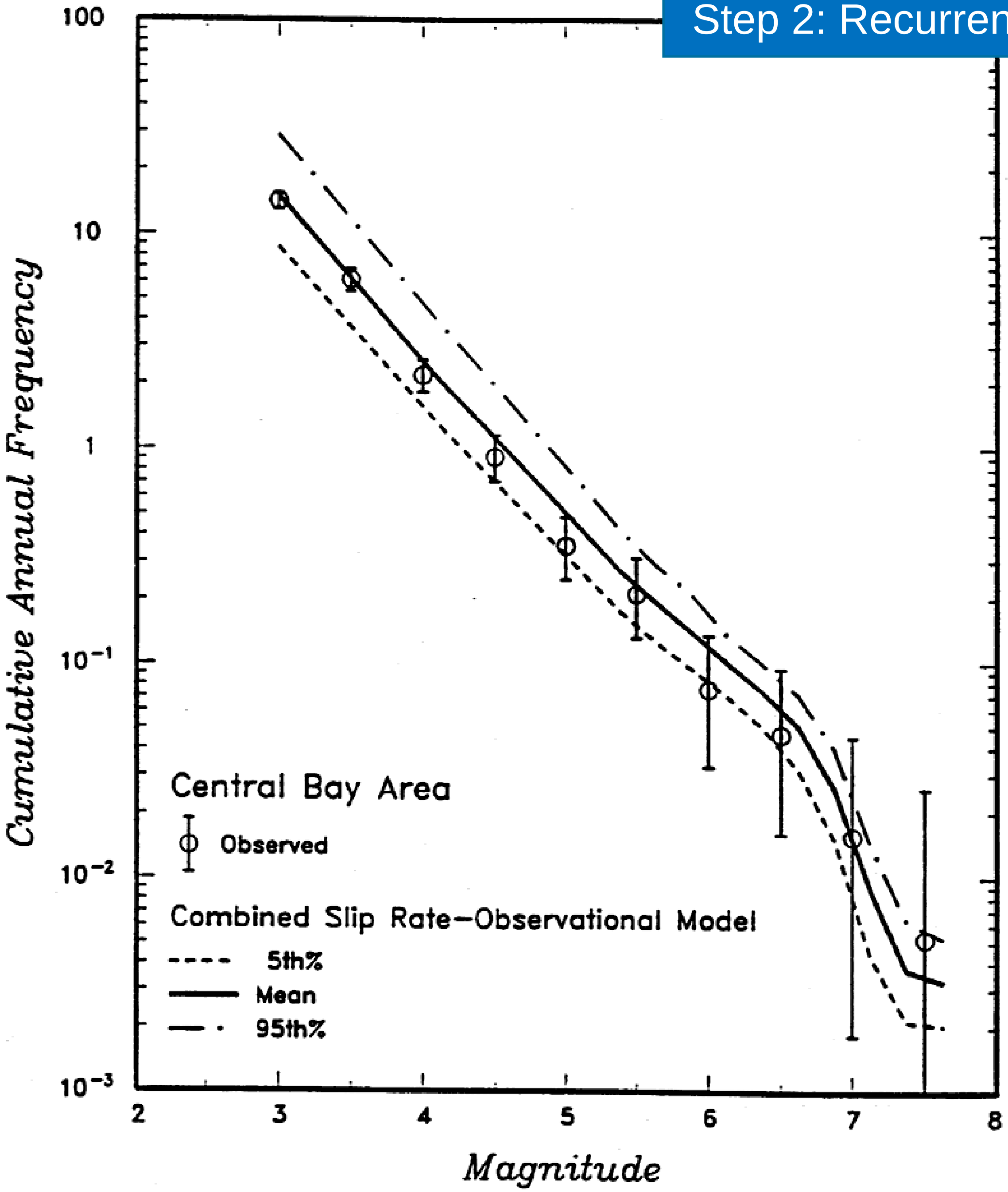


FIGURE 8.7 Comparison of the exponential (solid line) and characteristic recurrence (dashed line) frequency curves. (From Youngs, R.R. and Coppersmith, K.J., *Bull. Seismol. Soc. Am.*, 75, 939–964, 1985.)

Step 2: Recurrence

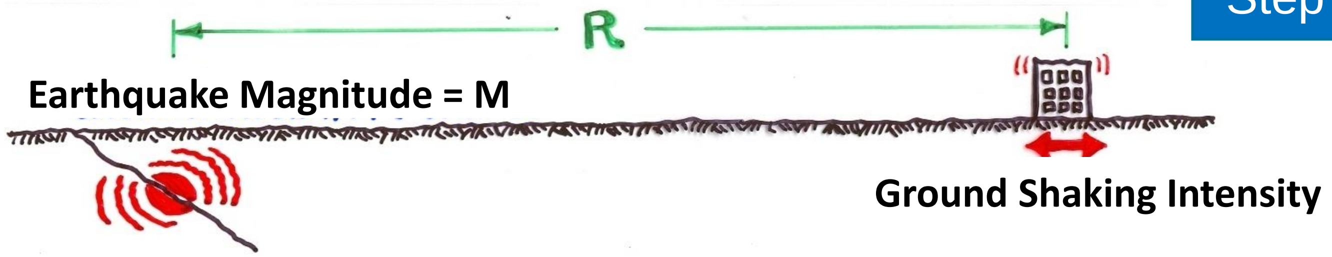


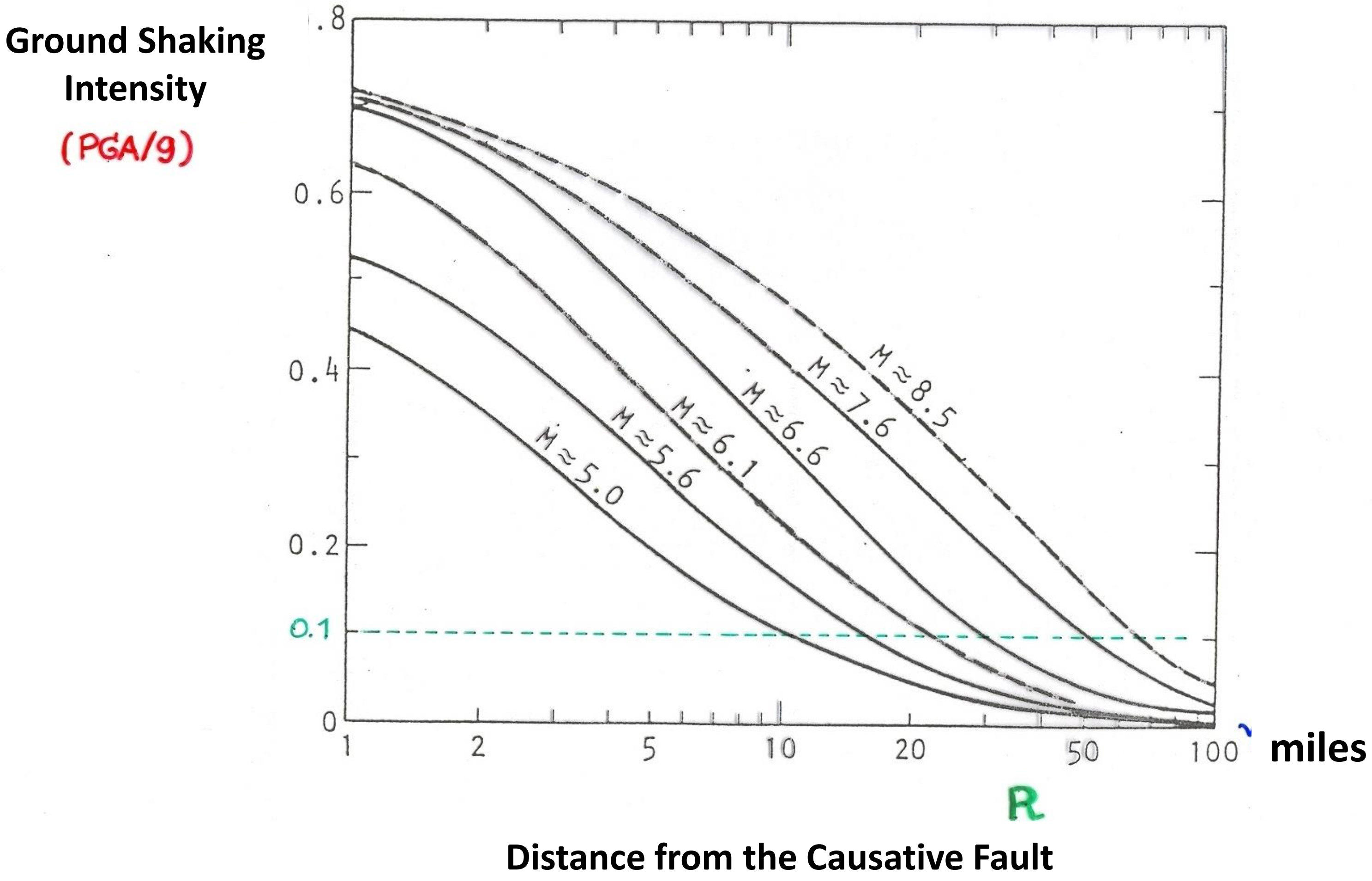


Step 3: The Selection of Attenuation Models (or Ground Motion Prediction Equations, GMPEs)

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
M ≈ 8.5
M ≈ 7.6
M ≈ 6.6
M ≈ 6.1
M ≈ 5.6
M ≈ 5.0
R
Distance from the Causative Fault

Tectonic Regions

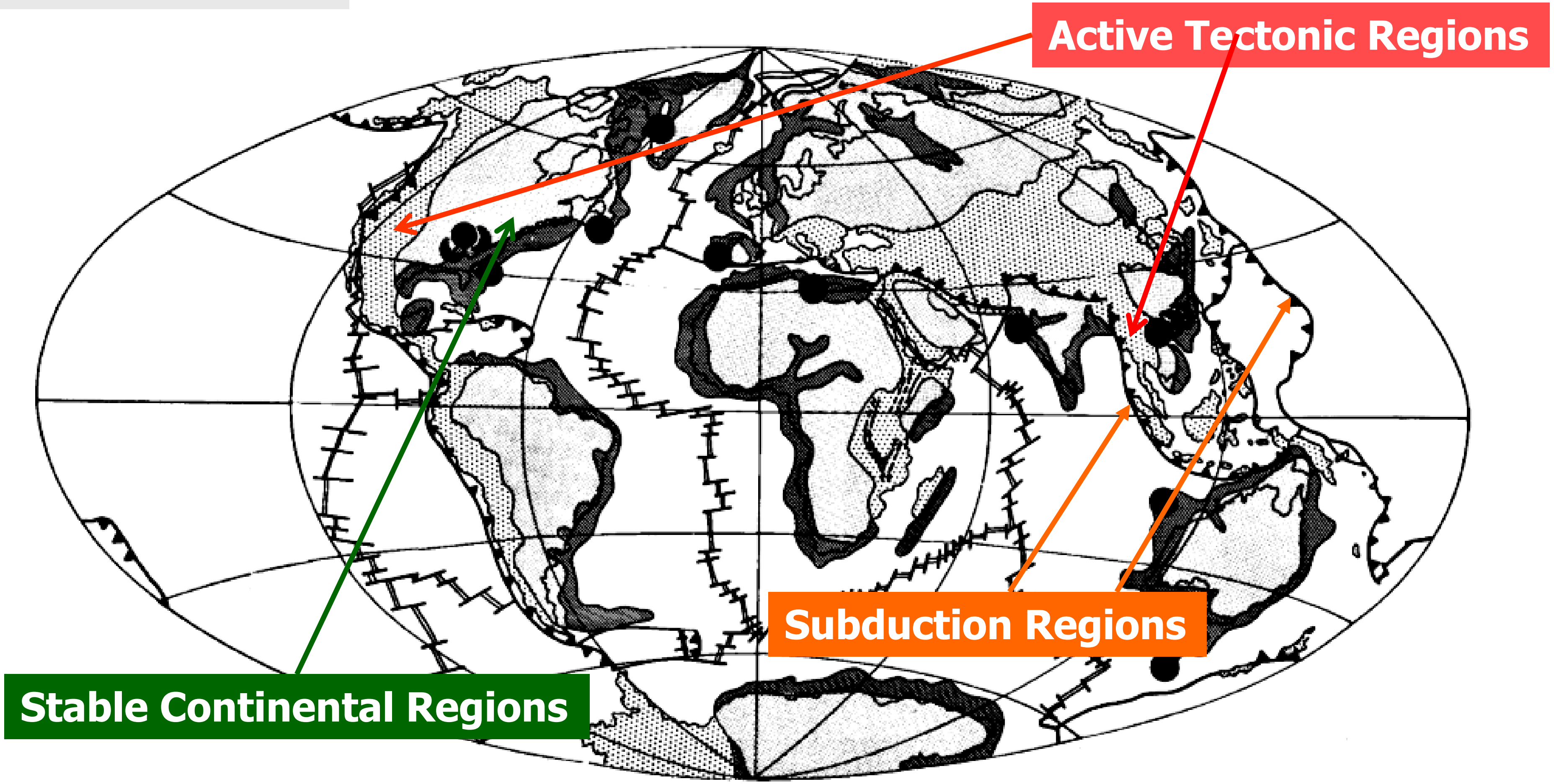


FIGURE 5.6 Geographic distribution of active and stable continental tectonic regions worldwide. (From Johnston, A.C. 1994. "Seismotectonic Interpretations and Conclusions from the Stable Continental Region Seismicity Database," in *The Earthquake of Stable Continental Regions, Vol. 1, Assessment of Large 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.

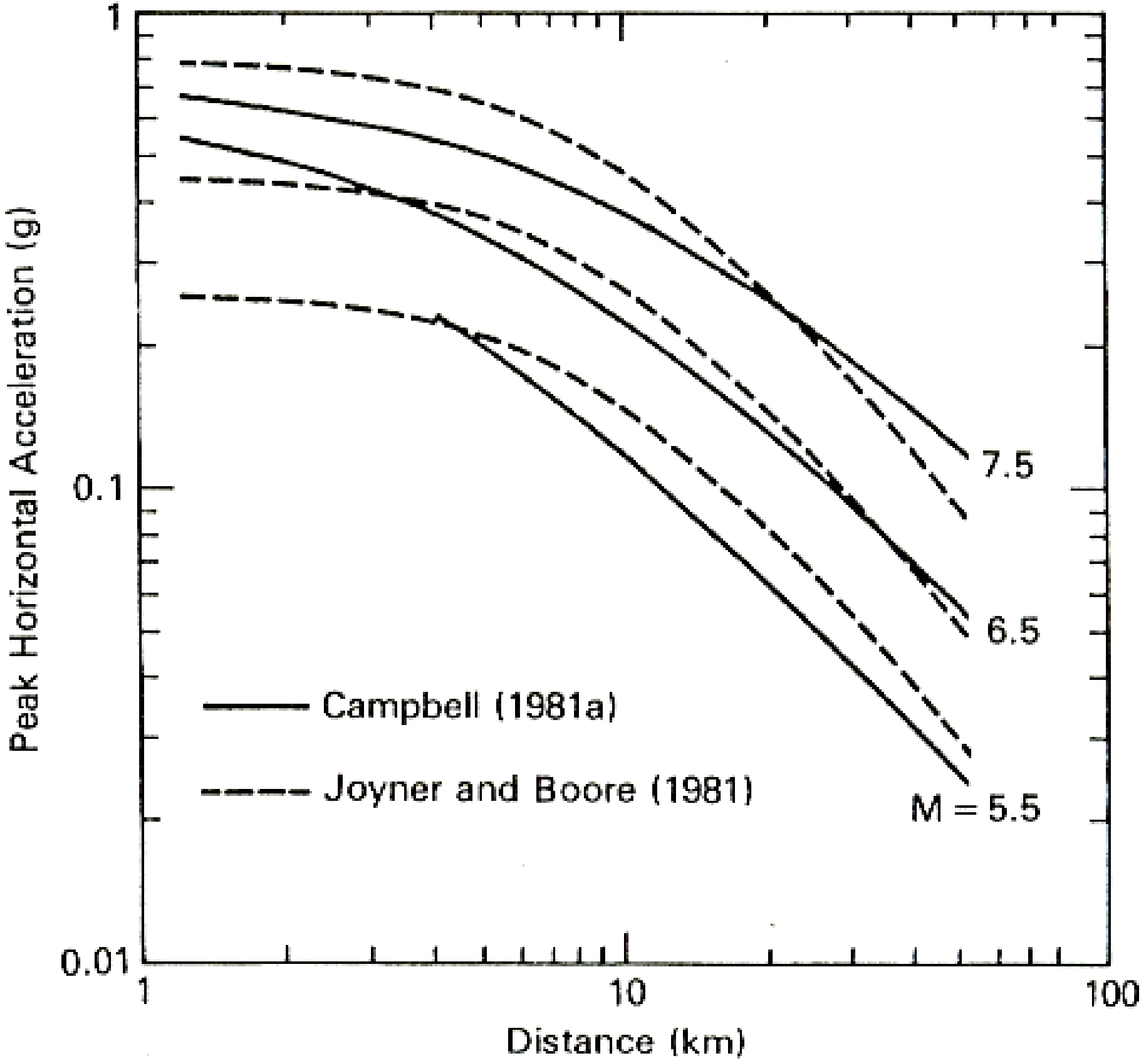
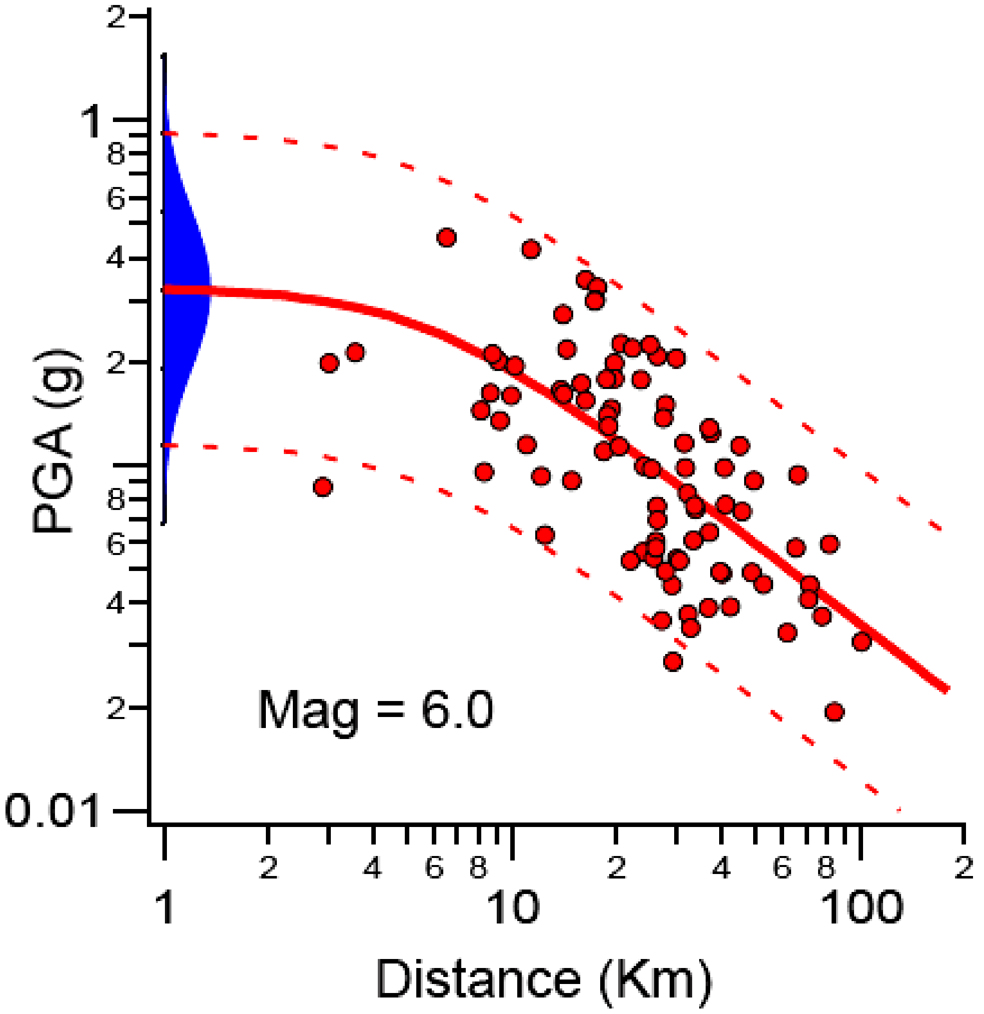


FIGURE 7.4 Median (50th percentile) estimates for peak horizontal acceleration from Campbell (1981a) and Joyner and Boore (1981). Joyner and Boore (1981) estimates of the maximum horizontal component have been reduced by 12% so that they may be compared with the (Campbell 1981a) estimates of the mean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

Random Error of Attenuation Model



Source-to-Site Distance

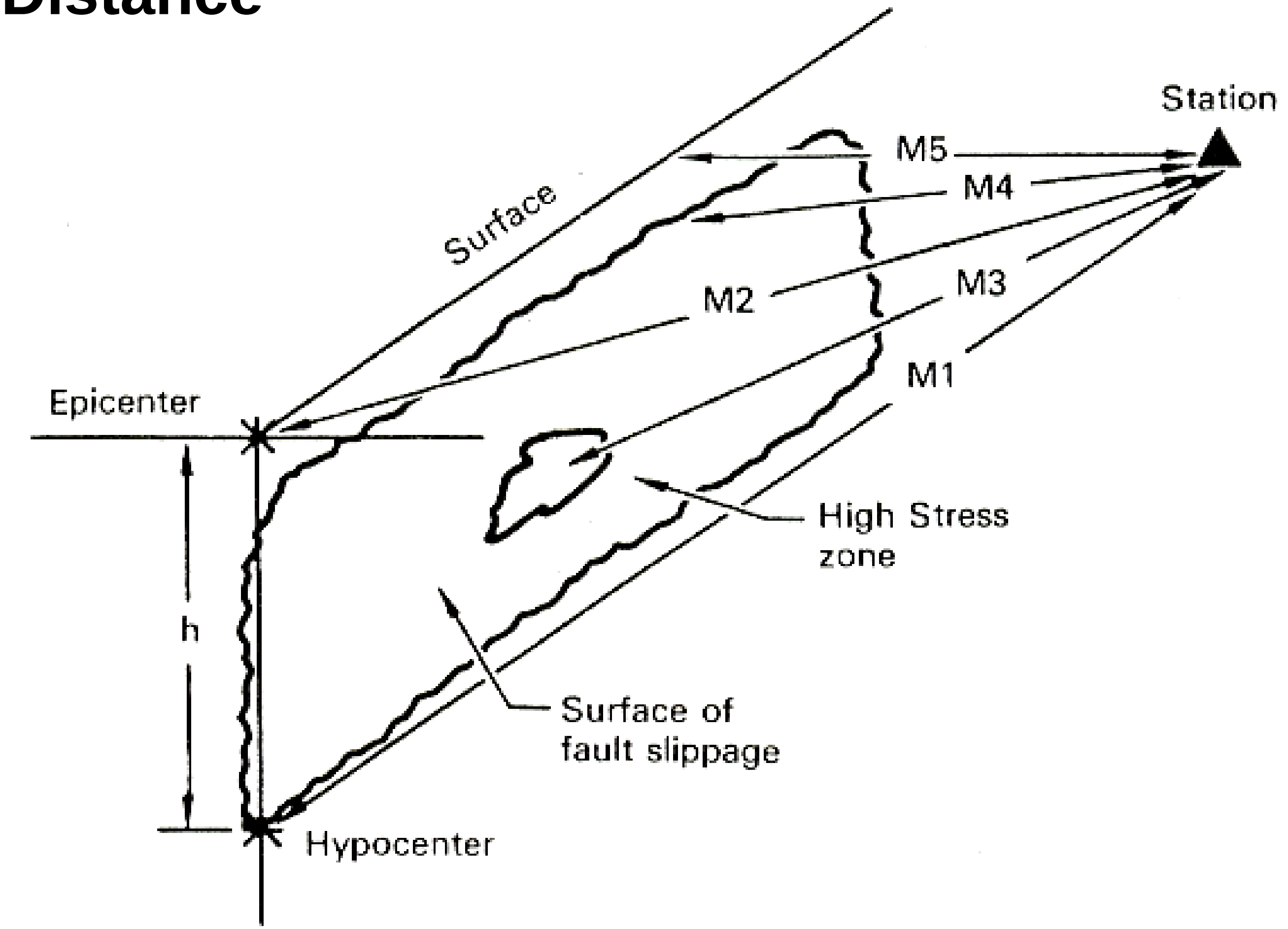


FIGURE 7.3 Schematic illustration of methods of distance measurement used in the determination of the distance value to be associated with a ground motion observation. M1 is the hypocentral distance (focal depth is h), M2 is the epicentral distance. M3 is the distance to the center of high-energy release (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).

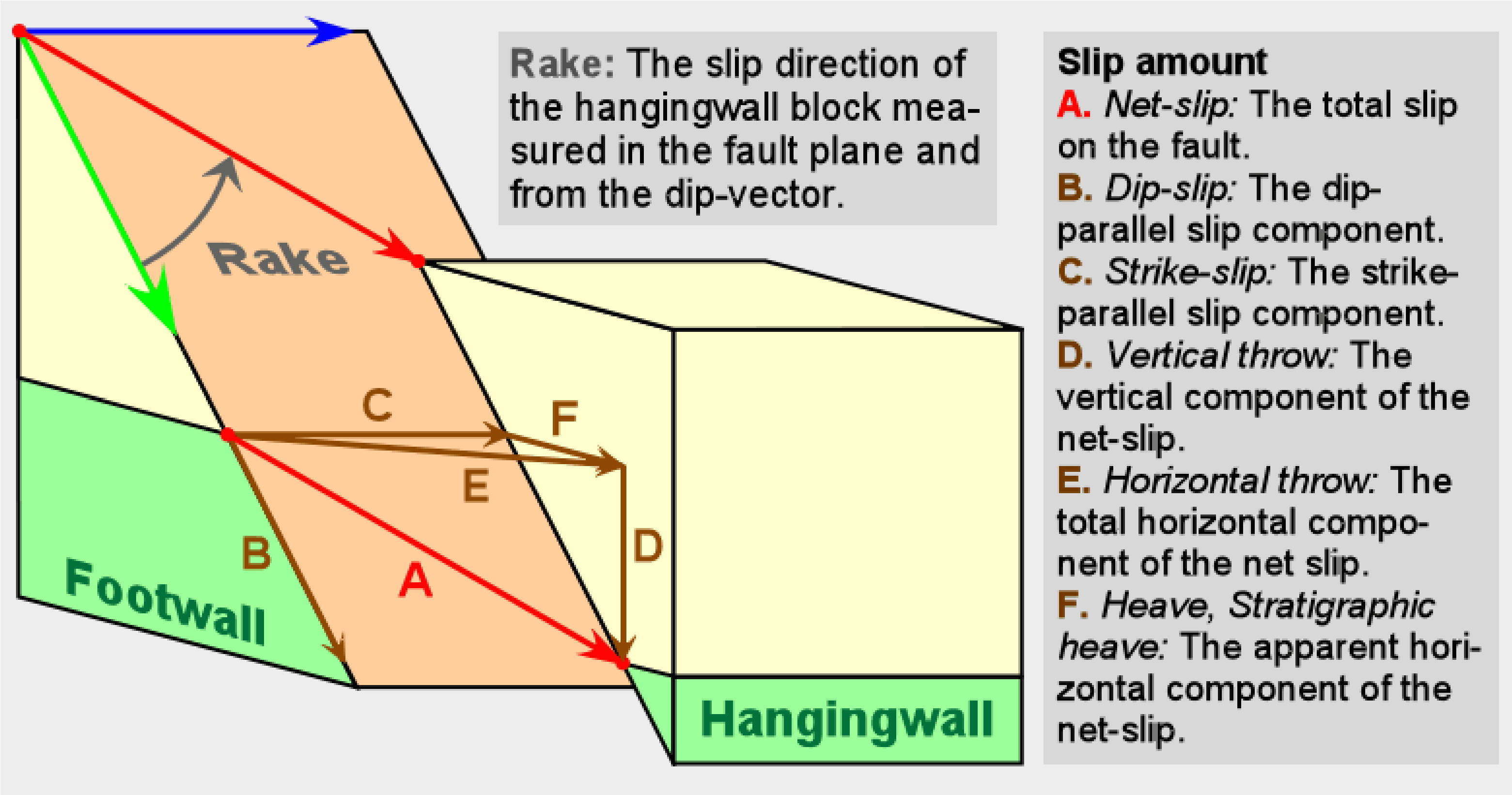
Faulting Mechanism

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 $F_{TH} = 0.25$.

Slip Terminology



Source: https://www.naturalfractures.com/

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

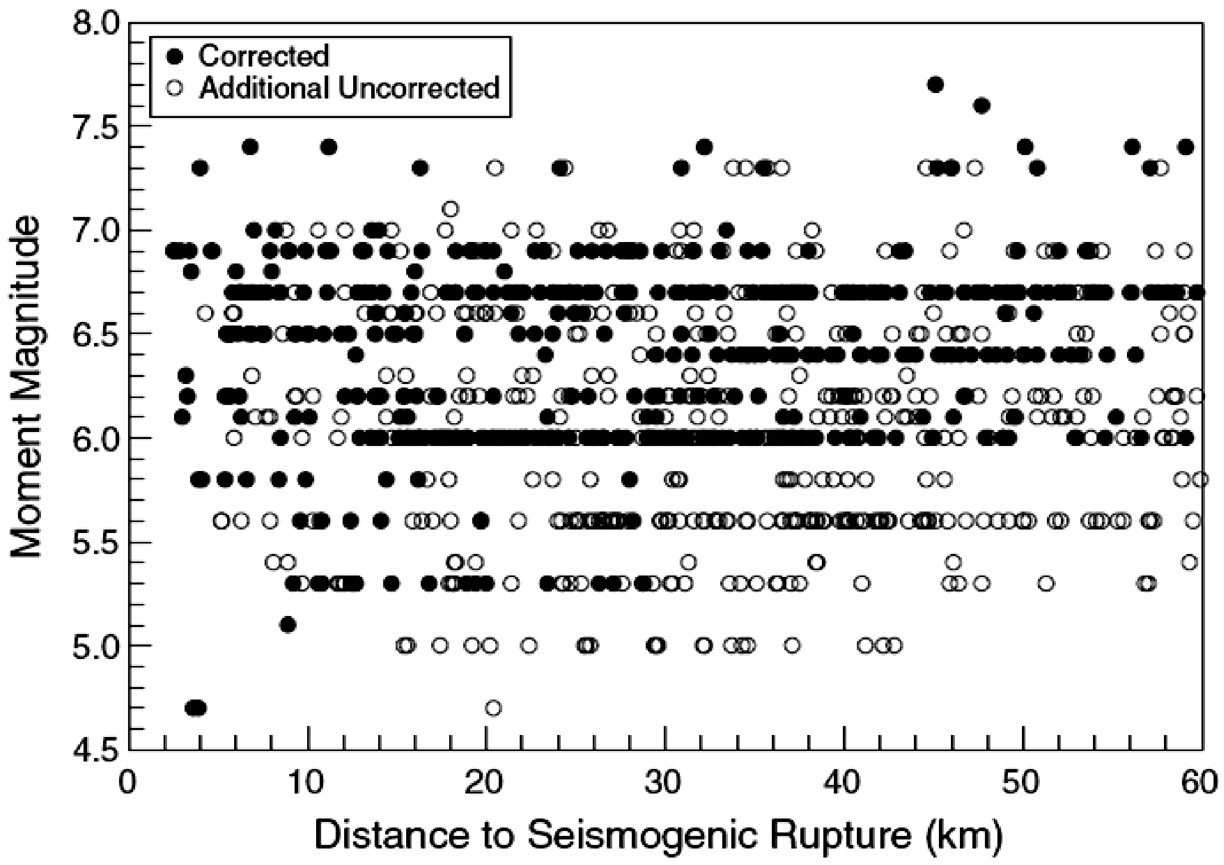


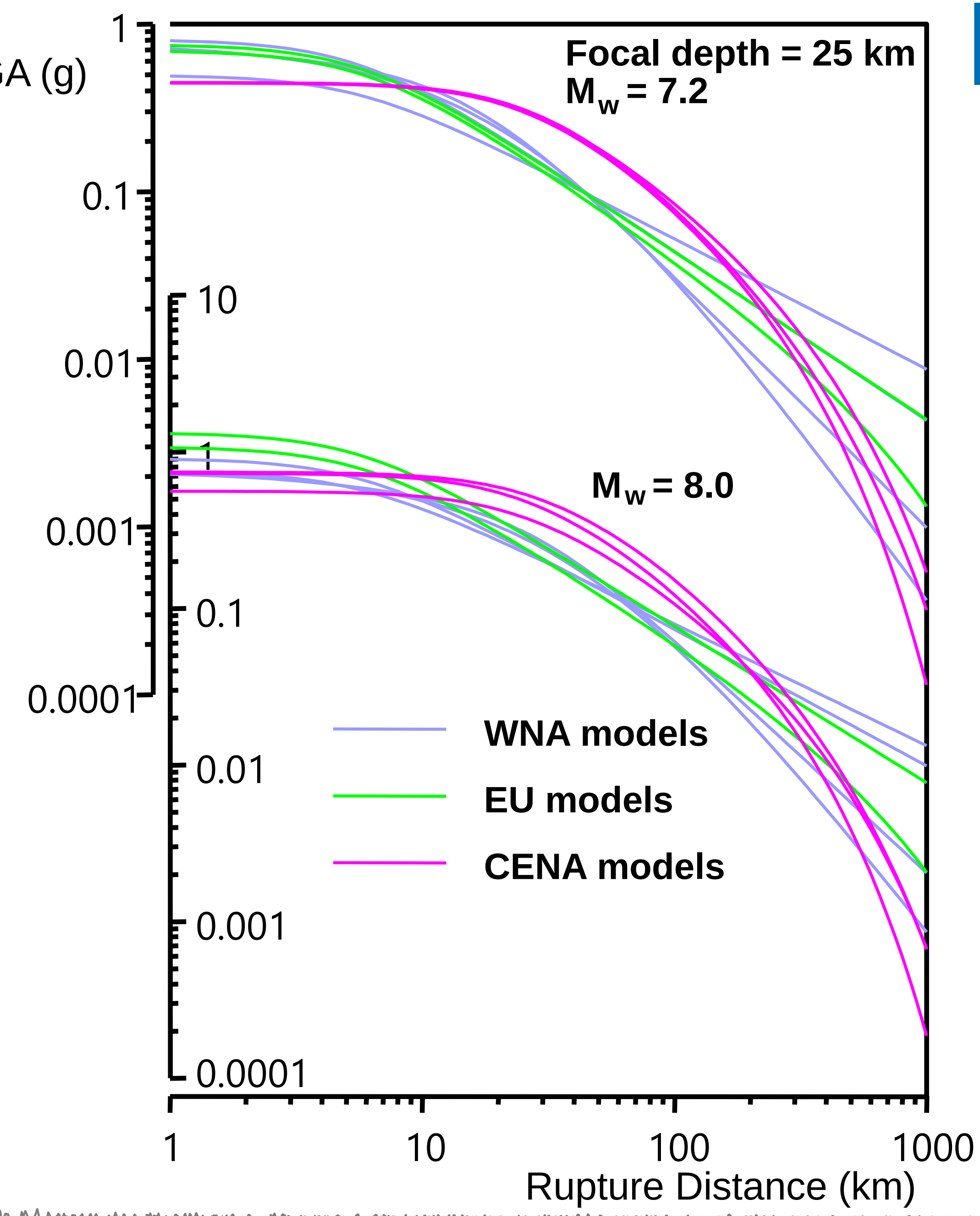
FIGURE 5.1 Example PGA attenuation relation (top) and its associated database (bottom). Uncorrected recordings are analog or digital acceleration time histories that have not been processed and, therefore, can provide only estimates of PGA. Corrected recordings are acceleration times histories that have 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}
						$M_w \le 6.5$								
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



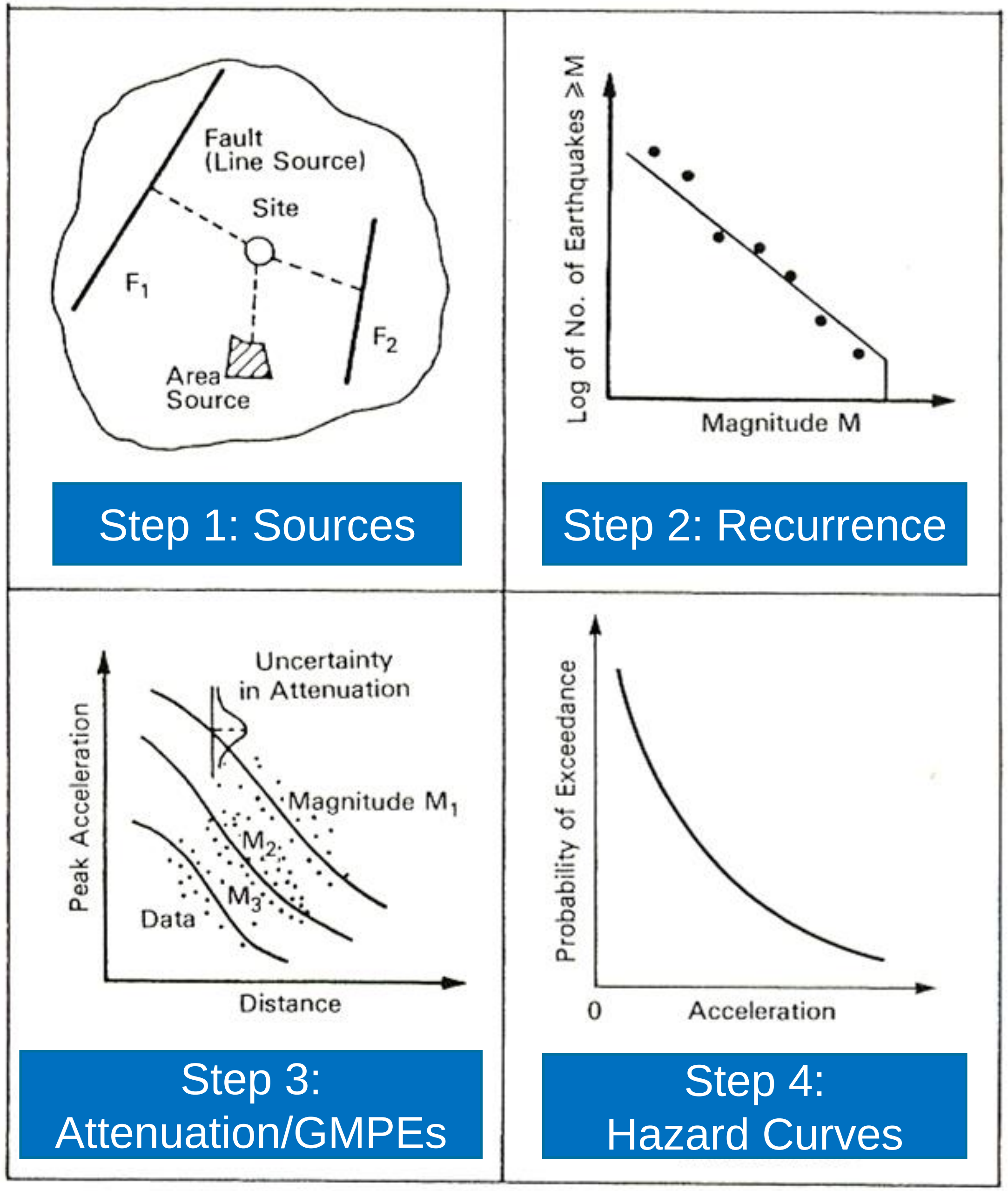
Step 4: The Development of Hazard Curves for the Sites

- Identification of all potential seismic sources

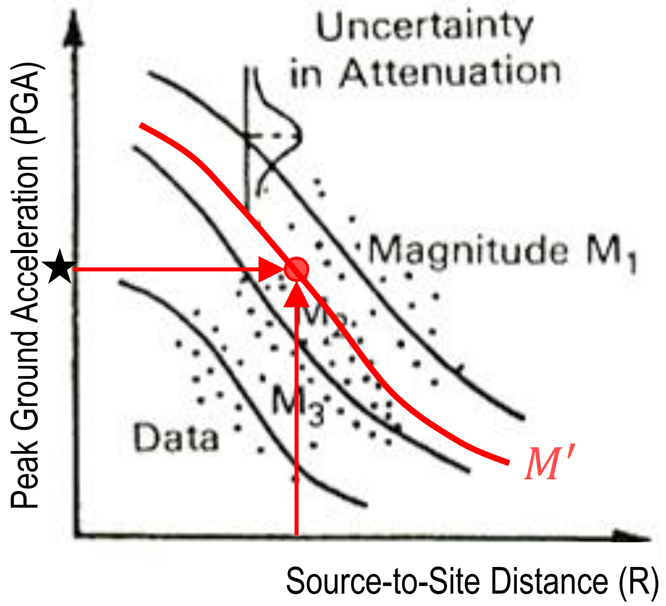
- Defining the seismicity of these seismic sources

- Selection of appropriate ground-motion prediction equations (GMPEs)

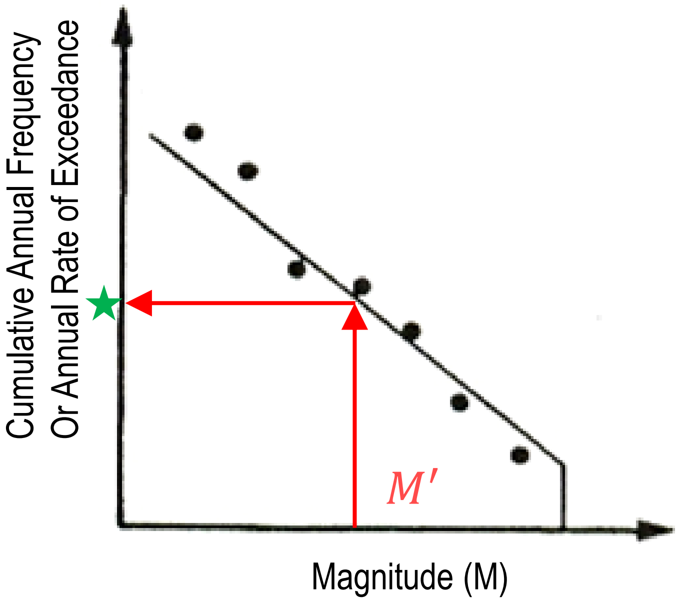
- Determining of Probabilities of Exceedance (Hazard Curve)

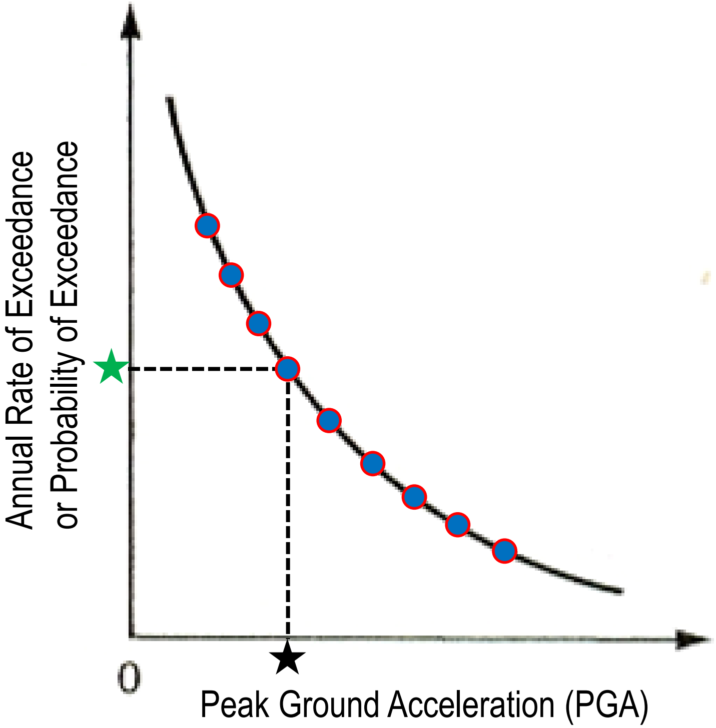


Attenuation/GMPEs



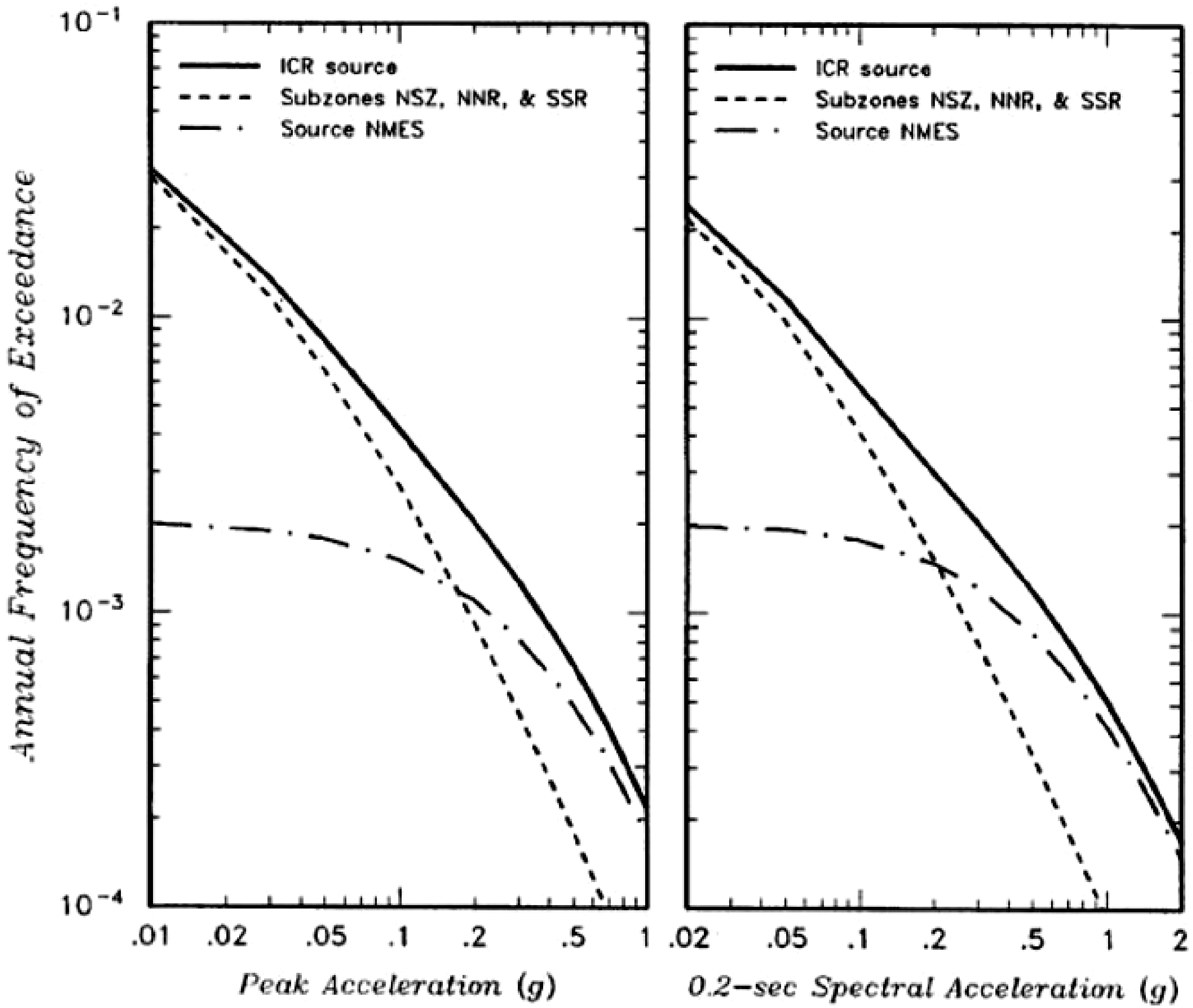
Recurrence





Hazard Curve

Hazard Curves



Thank you for your attention