Workshop on
Seismic Hazard Assessment Issues in the island arc of
Taiwan and Japan

Earthquake Hazard Map of Taiwan

Thomas, Chin-Tung Cheng Ph.D.
鄭錦桐 博士

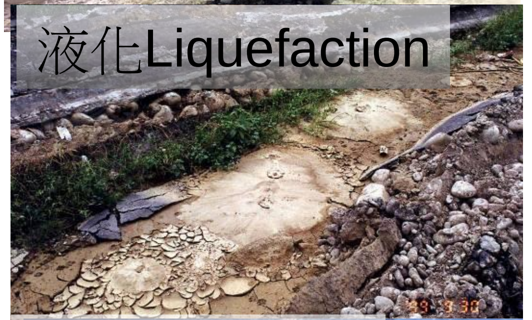
Disaster Prevention Technology Research Center **(DPTRC)**
Sinotech Engineering Consultants, INC.
Taipei, Taiwan

CONTENTS

What’s SHA?

Earthquake Hazard and Risk

- **Hazard:**
  - Potential for earthquake related natural phenomena
    - Ground motion (√) **PGA, PGV, PGD, Sa, Ia**
    - Fault rupture
    - Liquefaction
    - Landslide
    - Tsunami
  - Key questions:
    - <u>How severe</u> is the ground motion?
    - <u>How often</u> does it happen?



Earthquake Hazard and Risk

- Risk: Probability of loss to society due to hazards and vulnerability
  - GEM (Global Earthquake Model)
  - TEM (Taiwan Earthquake Model)
  - TELES (Taiwan Earthquake Loss Estimation System)

Seismic Hazard Analysis

- Quantitative estimation of ground motion at a site → Design earthquake (response spectra)
- SHA involves the following steps
  - Seismic Source Characterization: Evaluate all potential earthquake sources close to the site
    - Earthquake activity rate
    - Fault slip rate
    - Location, orientation, and style of faulting
    - Magnitudes
    - By geologists and seismologists

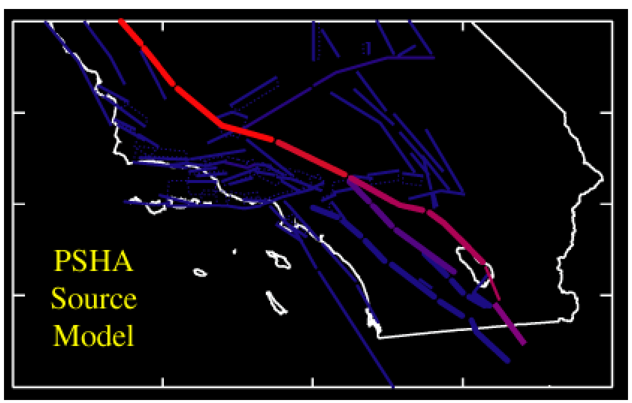
What is Seismic Hazard Analysis?

Two Components:

(1) Earthquake Forecast

logN=a-bM

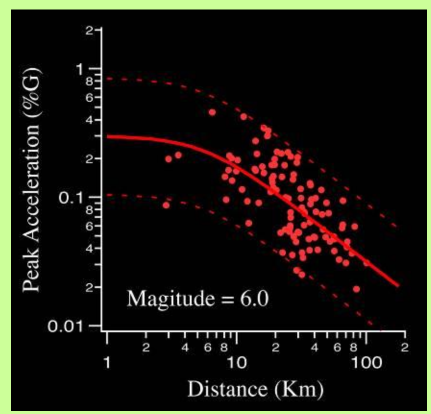
Probability in time and space of all M≥5 events



(2) Ground-Motion Estimation

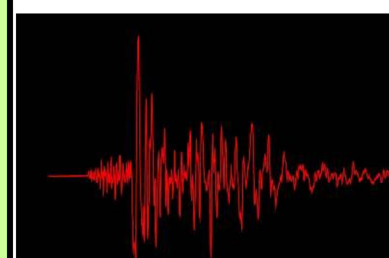
Experience

Intensity Measure (PGA, Sa) Regressions



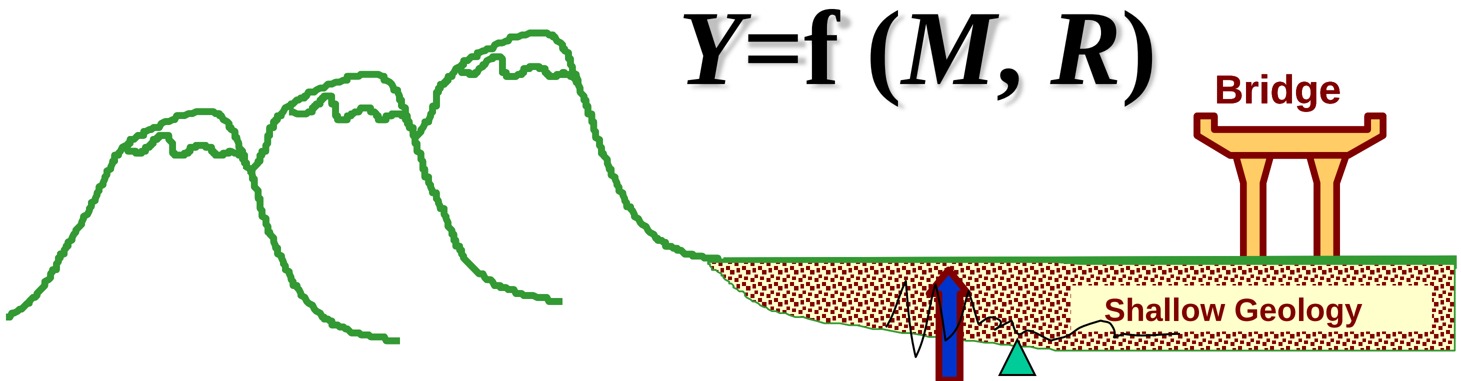
Simulation

Full waveform modeling



Variables that Influence Strong Ground Motion

$$Y = f\,(M, R)$$

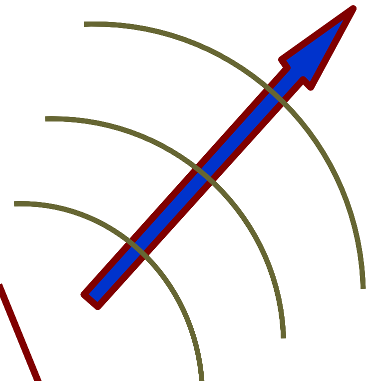


Earthquake Source

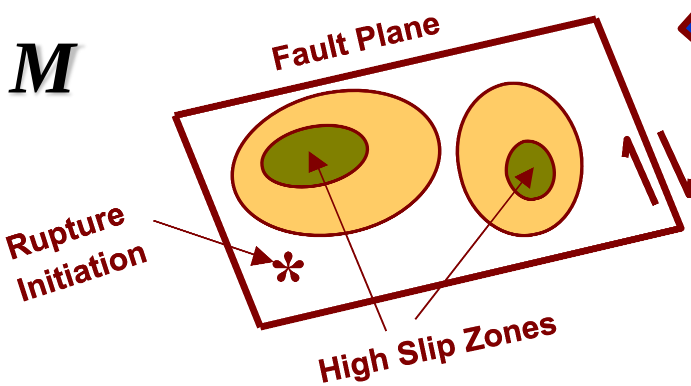
- Fault Size, Slip Distribution, Rise Time, Style-of-Faulting
- Rupture Propagation

Site Response (100 m)

- Soil Depth & Type
- Wave Velocity
- Non -Linearity



M



R

Wave Propagation

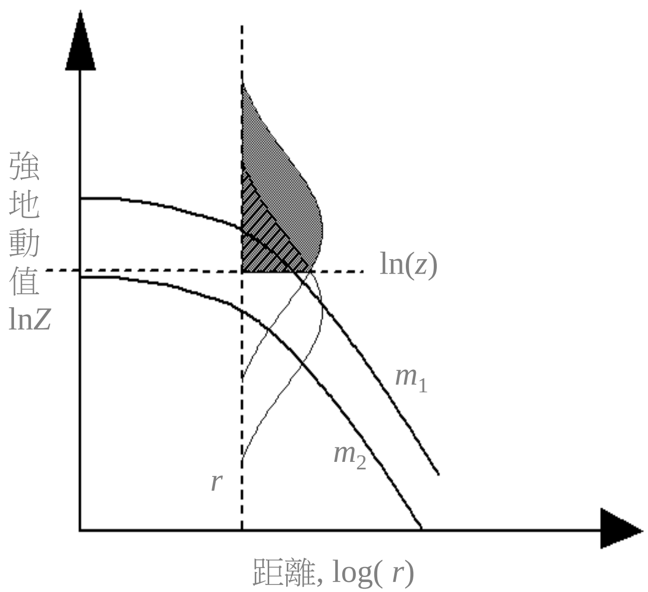
- Crustal Velocity Structure
- 3 -D Sedimentary Basin
- Small -Scale Heterogeneity (Wave Scattering)

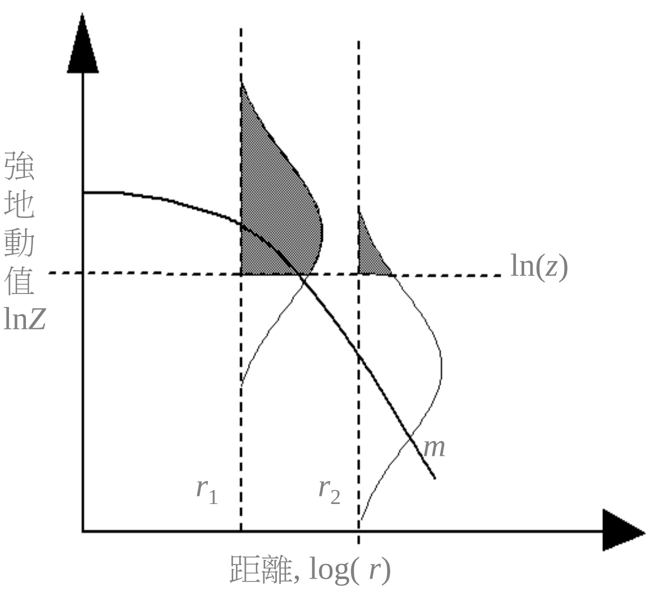
Uncertainties in SHA

- Uncertainties considered in SHA
  - A fault is active or not (include or exclude from further consideration)
  - Possible magnitudes
    - Rupture the entire fault or part of the fault
  - Likelihood of occurrence of a given magnitude earthquake during the life span of structure -- How often does the earthquake occur? (earthquake recurrence rate)
  - Distance to the earthquake source (location of source)
    - Areal source (random location)
    - Rupture location along the fault

Uncertainties in SHA

- Uncertainties encountered when conducting SHA (cont)
  - Variability of ground motion





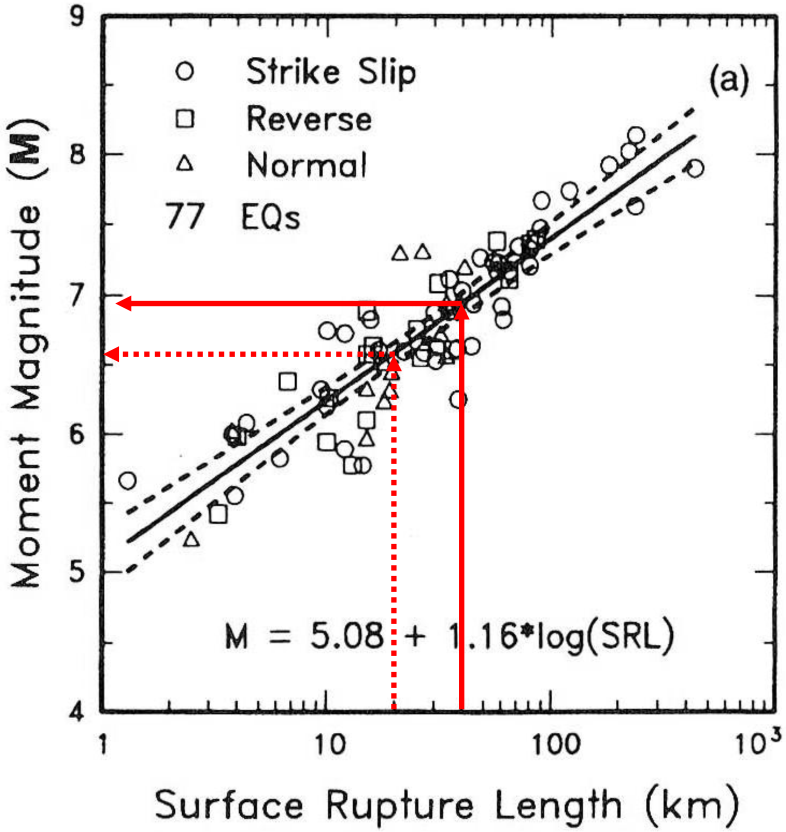
Two Approaches to SHA

- Deterministic (DSHA) & Probabilistic (PSHA)
- Use the same source characterization and attenuation relation
- Differ in the way uncertainties are handled
  - Deterministic: Pick a conservative value
  - Probabilistic: Explicitly treat all the possible scenarios and pick the design motion based on acceptable hazard

Deterministic Seismic Hazard Analysis (DSHA)

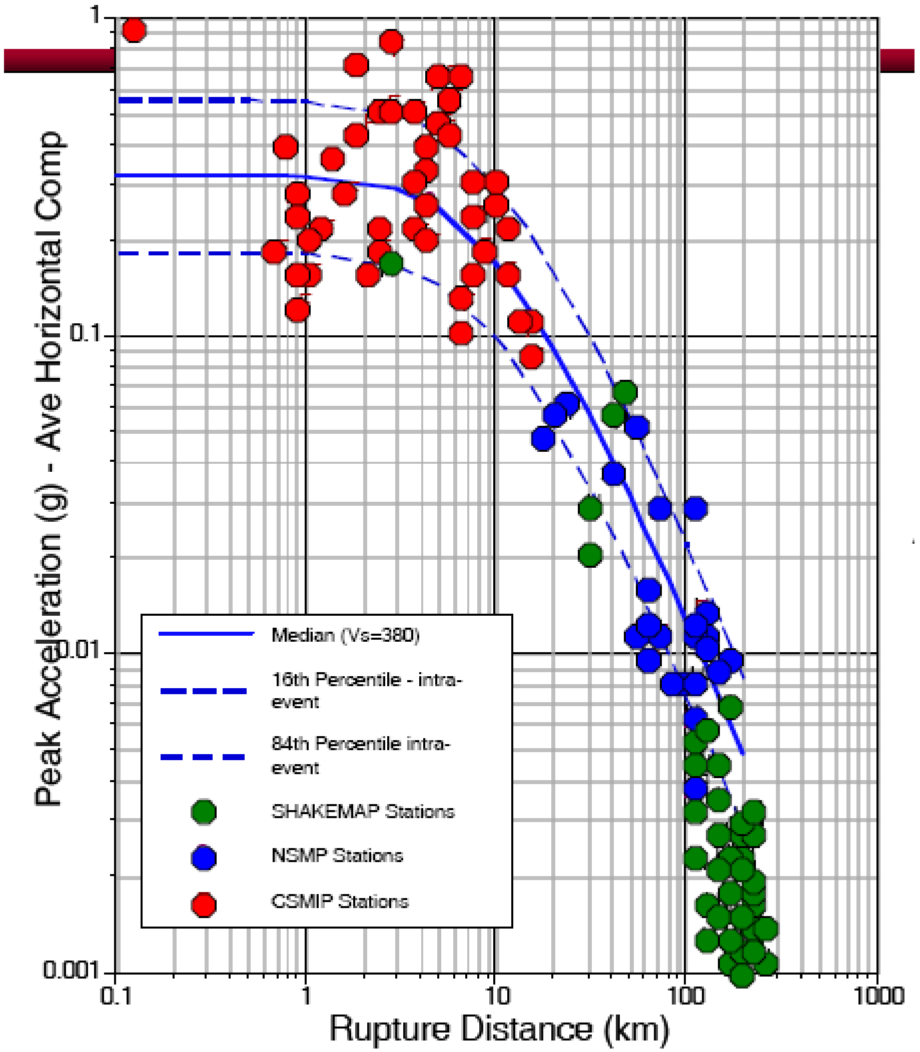
- Make a conservative selection of Source
  - Active fault (Late Pleistocene)
    - Taiwan: 100,000 yrs (Taiwan, CGS's active fault map)
    - Japan: 100, 000yrs
    - Caltrans: 70,000 yrs
    - Cal. state fault map: 11,000 yrs
    - COE: 35,000 yrs
    - USBR: 100,000 yrs
  - magnitude and distance
    - Rupture the entire mapped fault length
    - Rupture ½ the mapped fault length

Wells and Coppersmith (1994)



Deterministic Seismic Hazard Analysis (DSHA)

- ❑ Selection of GMPEs
  - ● Mag., Dis.
- ❑ Variation of GMPEs, conservative?
  - ● 84% (medium + 1 σ)
  - ● 50% (medium)



Deterministic Seismic Hazard Analysis (DSHA)

- Who makes the decision? How?
  - Consultants: precedence and expert's opinion
  - Owners
  - Regulatory agency
  - Safety/performance and cost
    - MCE, DBE, OBE
- The level of conservatism is not quantified
  - Don't know if design motion is reasonable

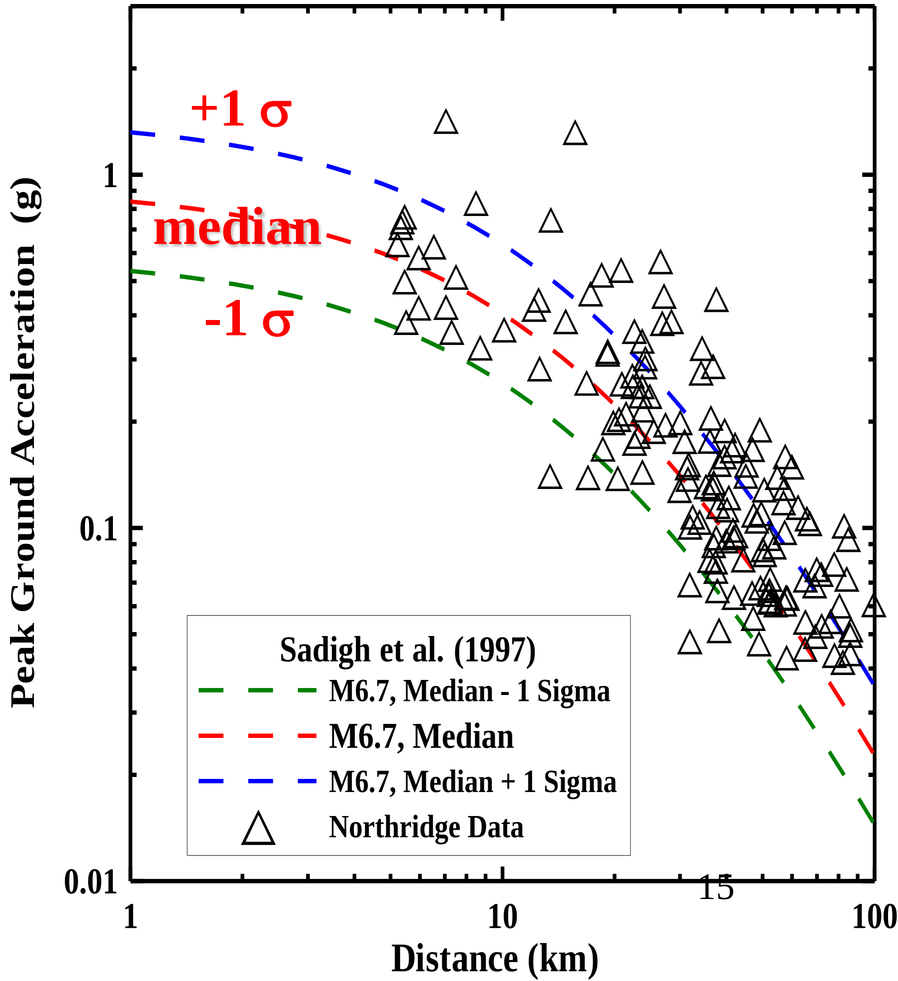
Why PSHA?

The "Worst-case" Ground Motion

- PGA of 2 standard deviations (σ) above median can and do occur
- But not very often

Magnitude **M** 7
at distance ***R*** = 5 km

Number of σ above median	PGA (g)	Probability (How often?)
0 σ	0.52	50%
1 σ	0.79	16%
2 σ	1.18	2.6%



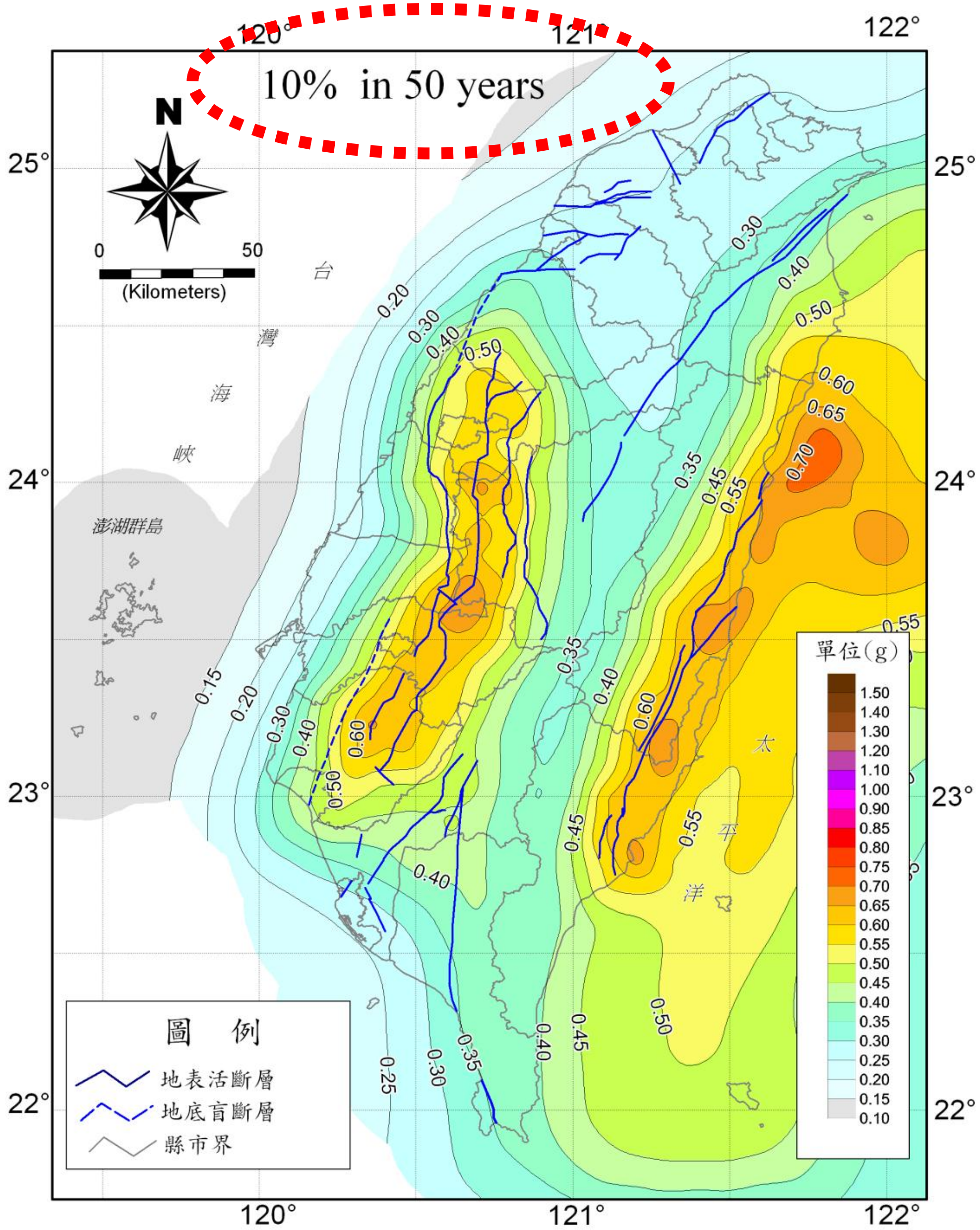
Motivation To Conduct a PSHA

- Need to back-off from the worst-case motion and select a **'reasonable'** design motion

- Selection should be based on the joint consideration of **'rate of occurrence'** **and** **performance goal**
  - More safety
  - More economical

- PSHA is a methodology that provides information needed for **such rational selection**

What is Probability Seismic Hazard Map?



Source

+

Attenuation (path)

+

Site

=

Hazard

PSHA METHODOLOGY

The probability (P) of exceeding ground motion amplitude (Z) in a given period of time (T) is related to annual frequency of exceedance *v*(z) by the equation:

$$P(Z > z|T) = 1.0 - e^{-v(z)\cdot T} \leq v(z)\cdot T$$

Poisson Process

T=50yr, P=10% → *v*(z)=1/475 → return period 475yr

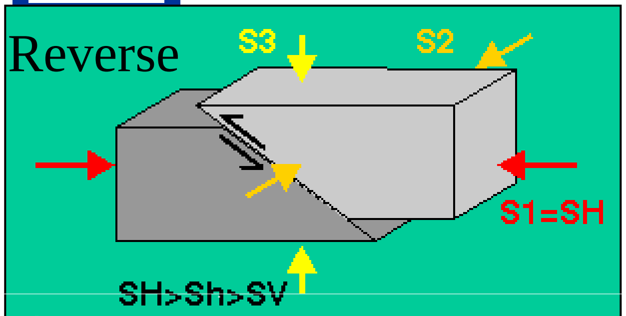
T=50yr, P= 2% → *v*(z)=1/2475 → return period 2475yr

$$v(z) = \sum_{n=1}^{N} \sum_{m_i=m_0}^{m_i=m_u} \lambda_n(m_i) \cdot \left[\sum_{r_j=0}^{r_j=r_{max}} P_n(R = r_j|m_i) \cdot P(Z > z|m_i, r_j) \right]$$

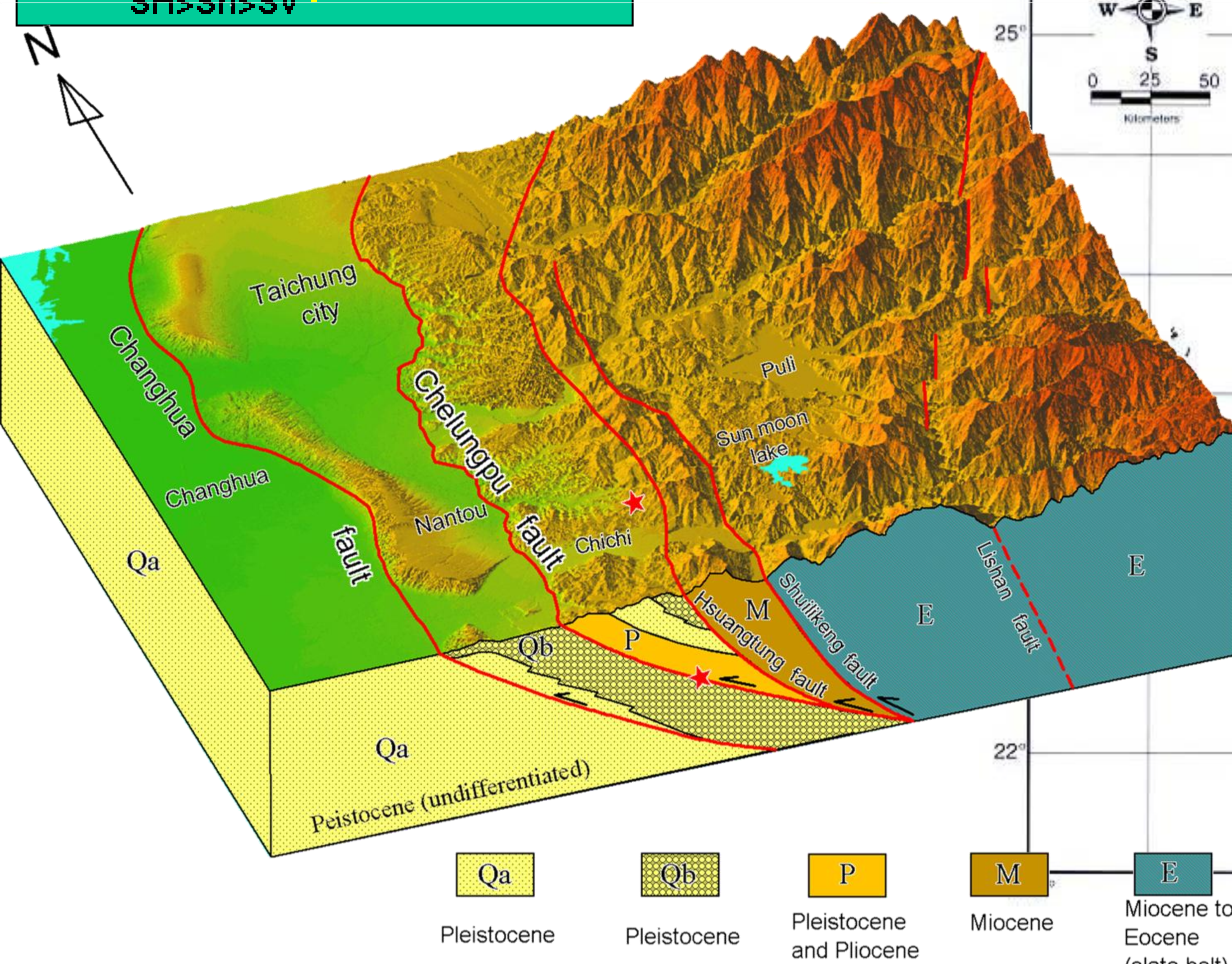
- There are N sources n=1~N
- $\lambda_n(m_i)$ is the annual frequency of n^{th} source in magnitude bin m_i
- m_i from lower bound magnitude m_0 to upper bound magnitude m_u
- $P_n(R=r_j|m_i)$ is the probability density function of n^{th} source within r_j while magnitude m_i
- $P_n(Z>z|m_i, r_j)$ is the probability of ground motion Z exceed z at m_i *and* r_j.

Lesson Learned form Chi-Chi Earthquake

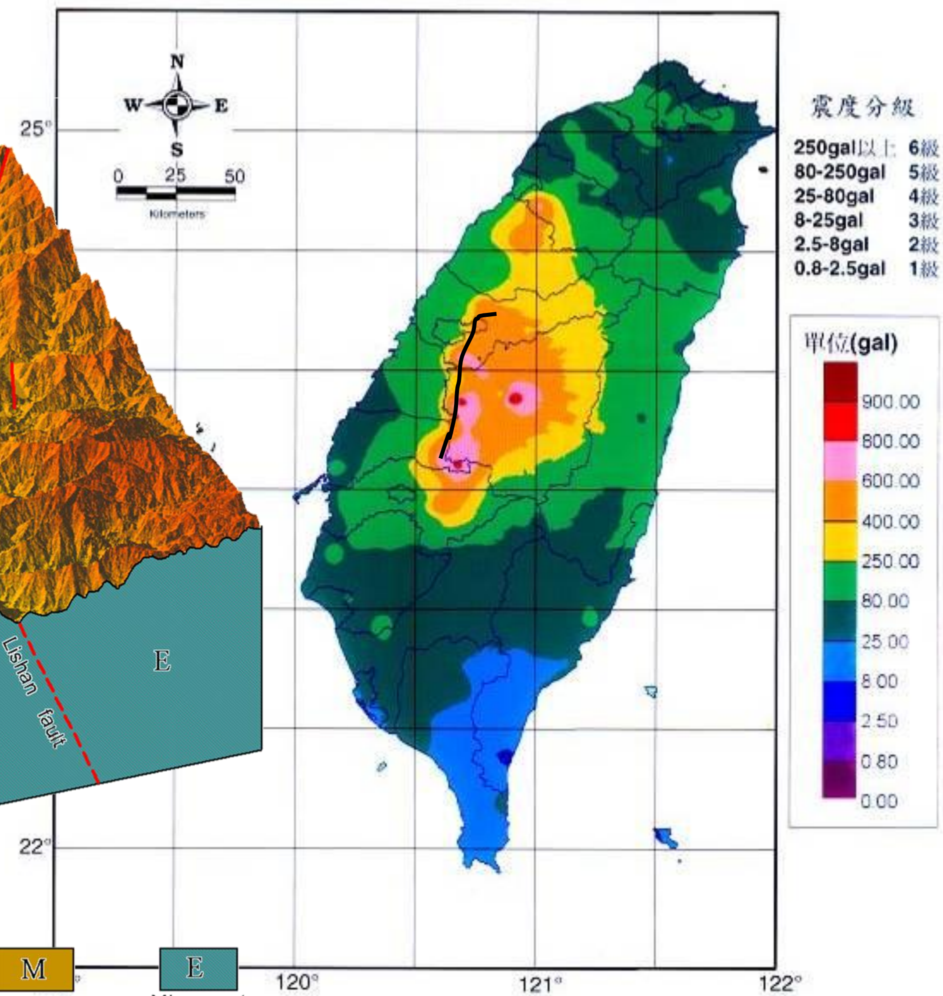
Hangingwall Effect



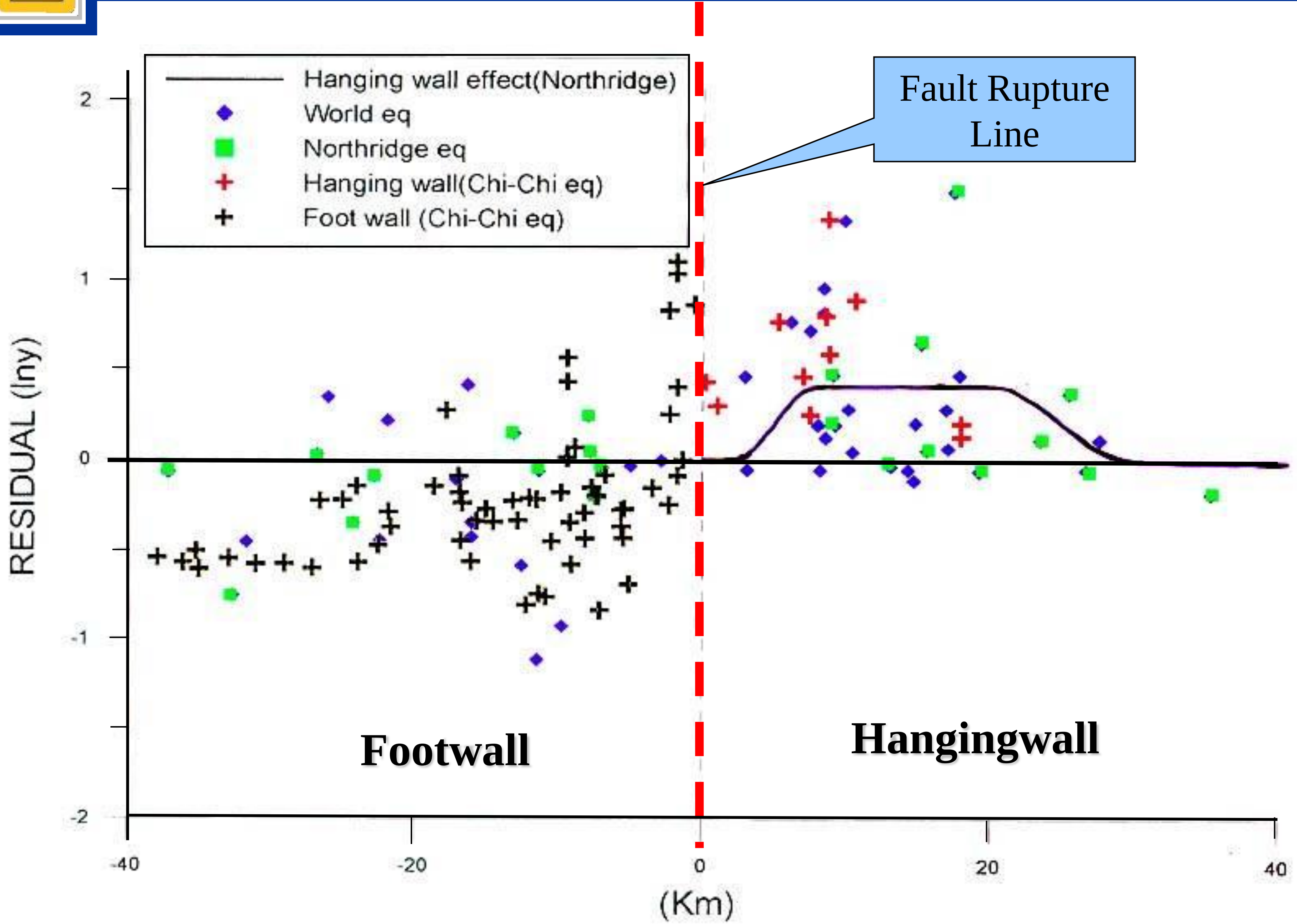
Strong Ground motion is higher in HW



Intensity map of Chi-Chi Eqk.

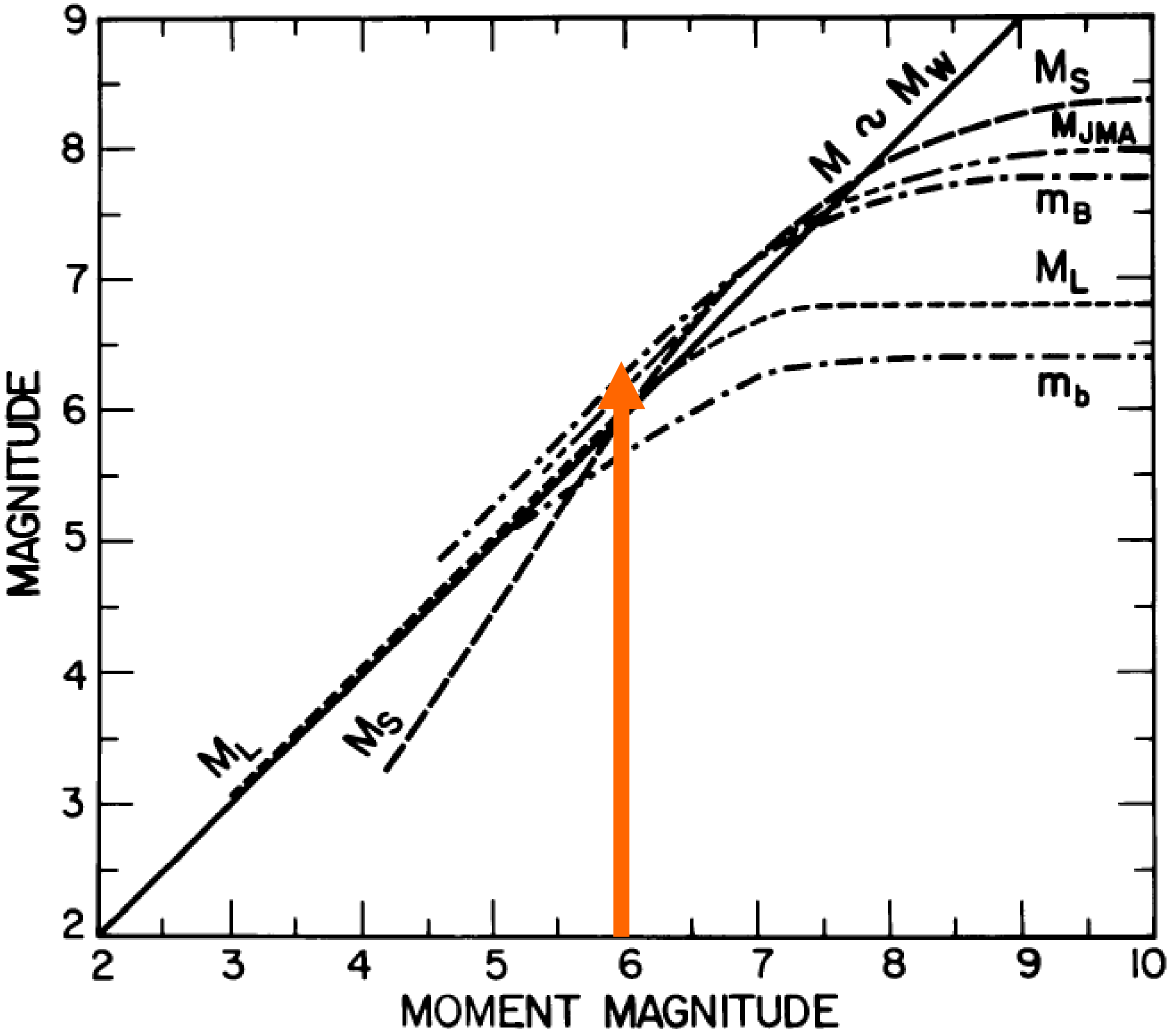


Hangingwall Effect



Magnitude of Earthquake

- M_L
- M_S
- M_w √



Magnitude of Chi-Chi Eqk.

- **M_L 7.3(CWB)**
- **Mw7.6 or 7.7 (CMT, USGS)**

Scaling With Distance: Distance Metric

- Hypocentral distance – outdated (X)
- Closest distance to the fault (√)
- Closest distance to the surface projection of fault – Joyner-Boore Distance (√)

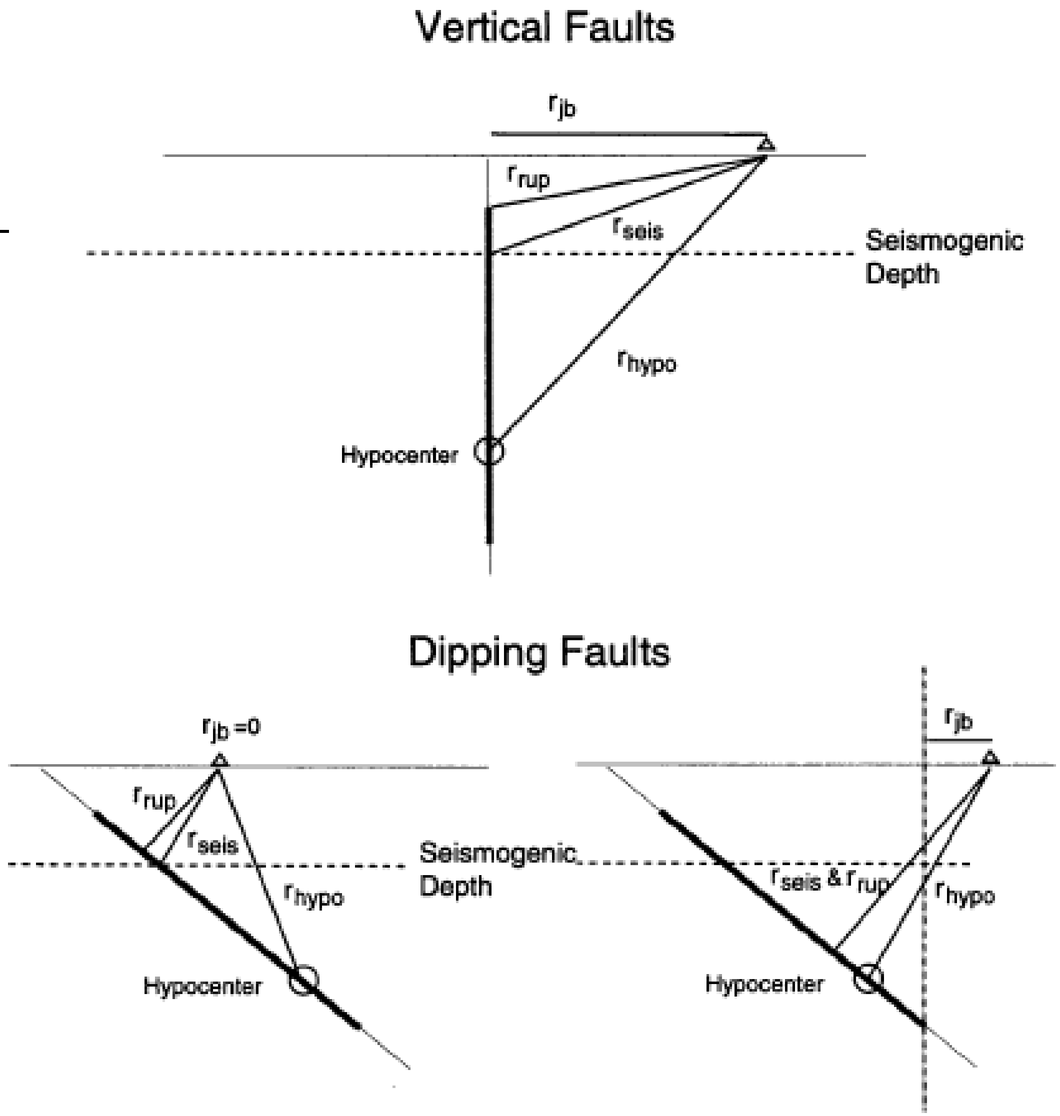


Figure 3. Comparison of distance measures. Source: Abrahamson and Shedlock [1997].

Previous PSHA Model in Taiwan

(Tsai et al., 1986)

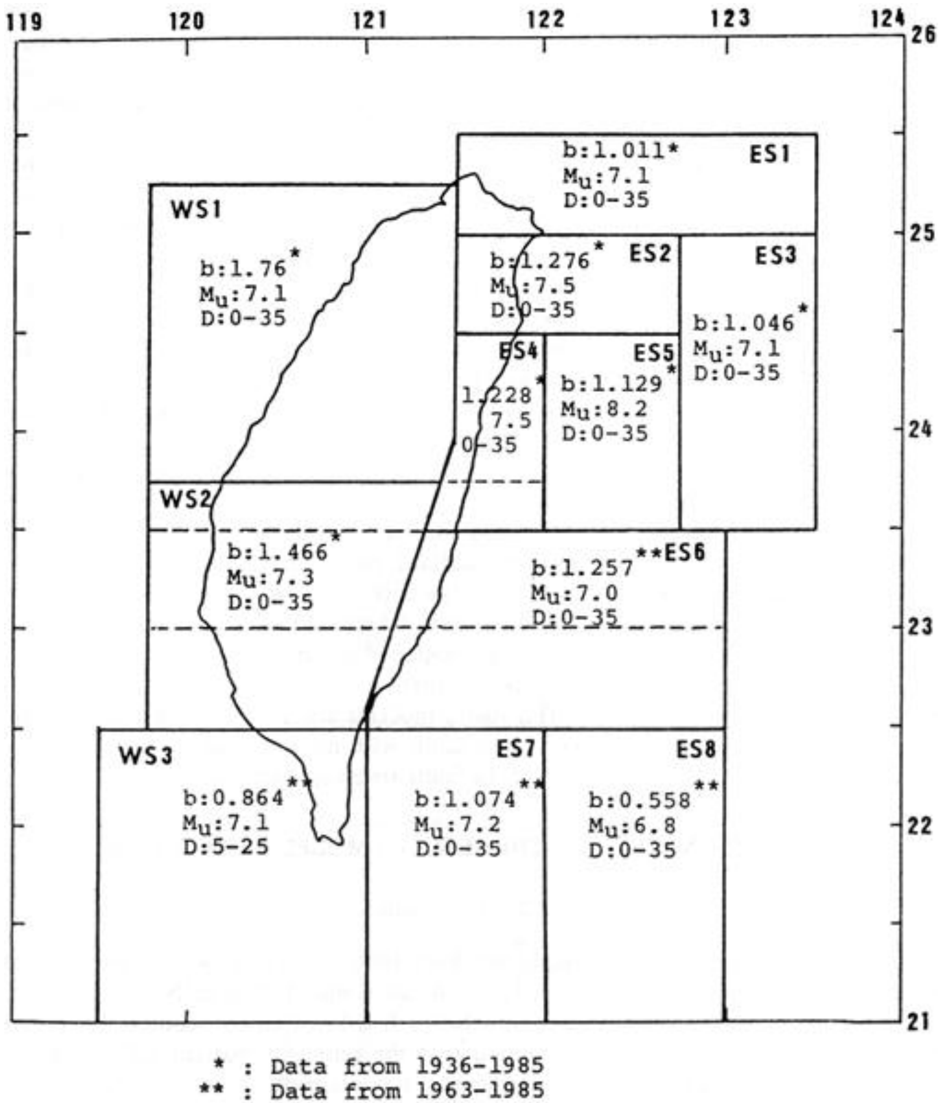
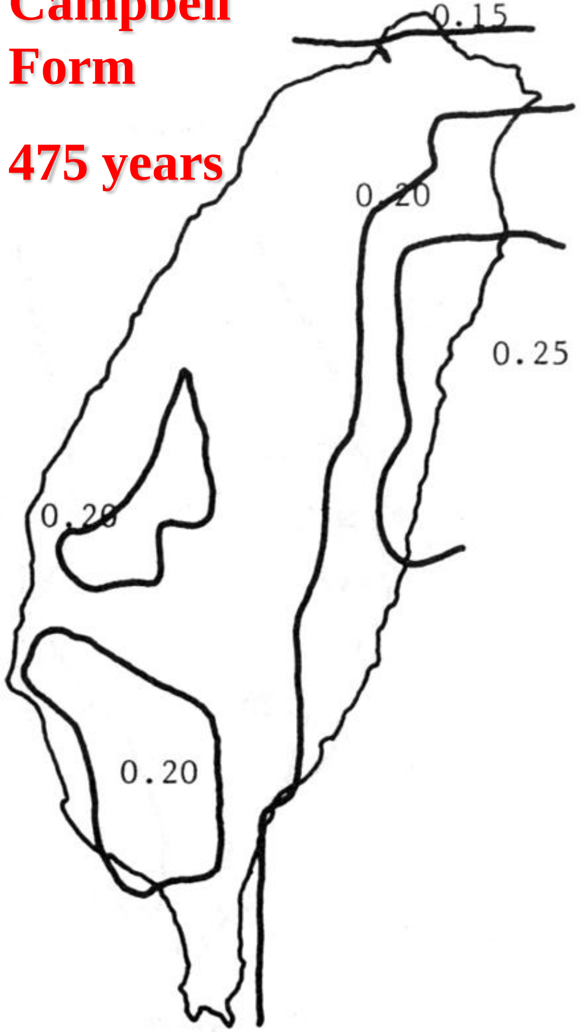


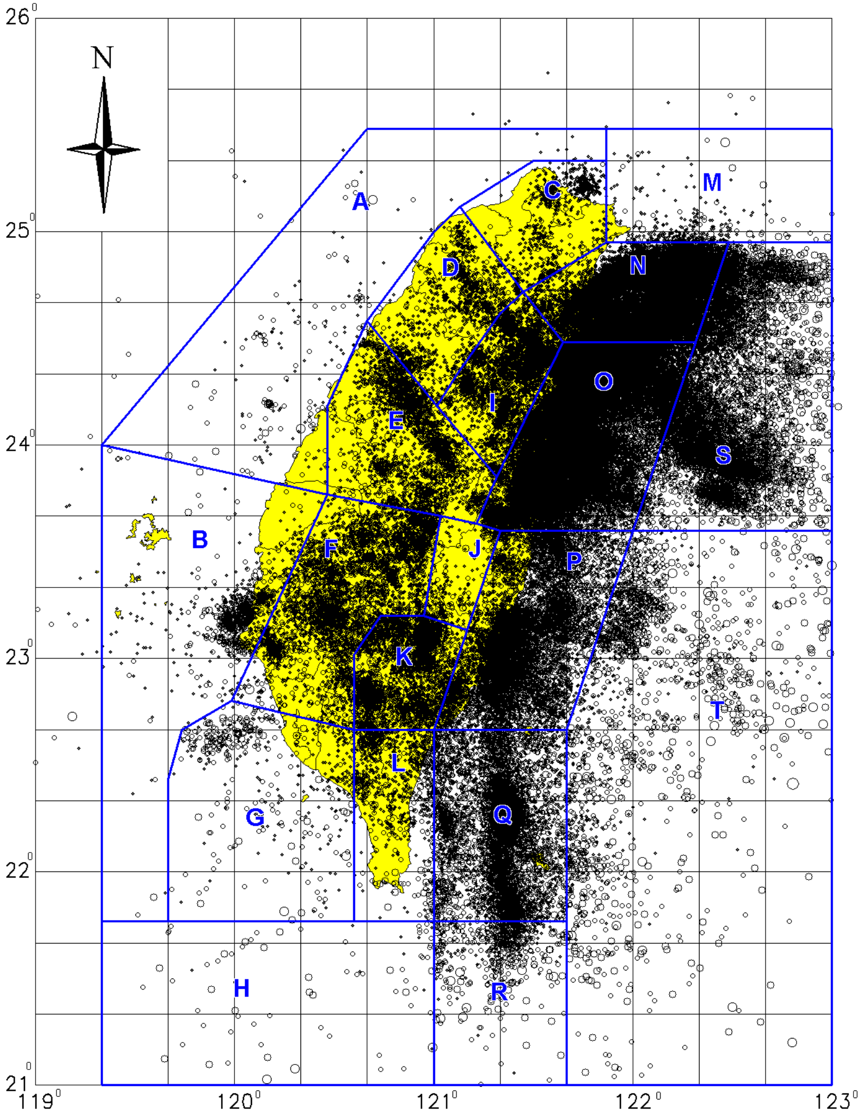
Fig. 7a. Seismogenic zoning of Taiwan (shallow zone).

Campbell Form

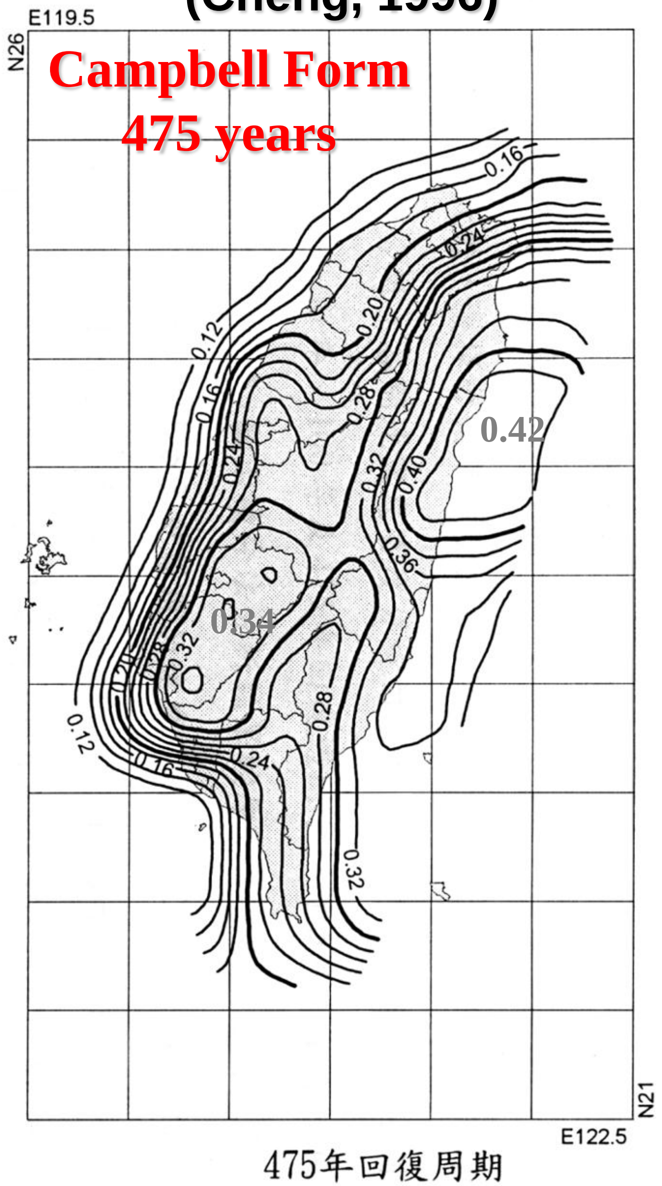
475 years



Previous SHA Model in Taiwan

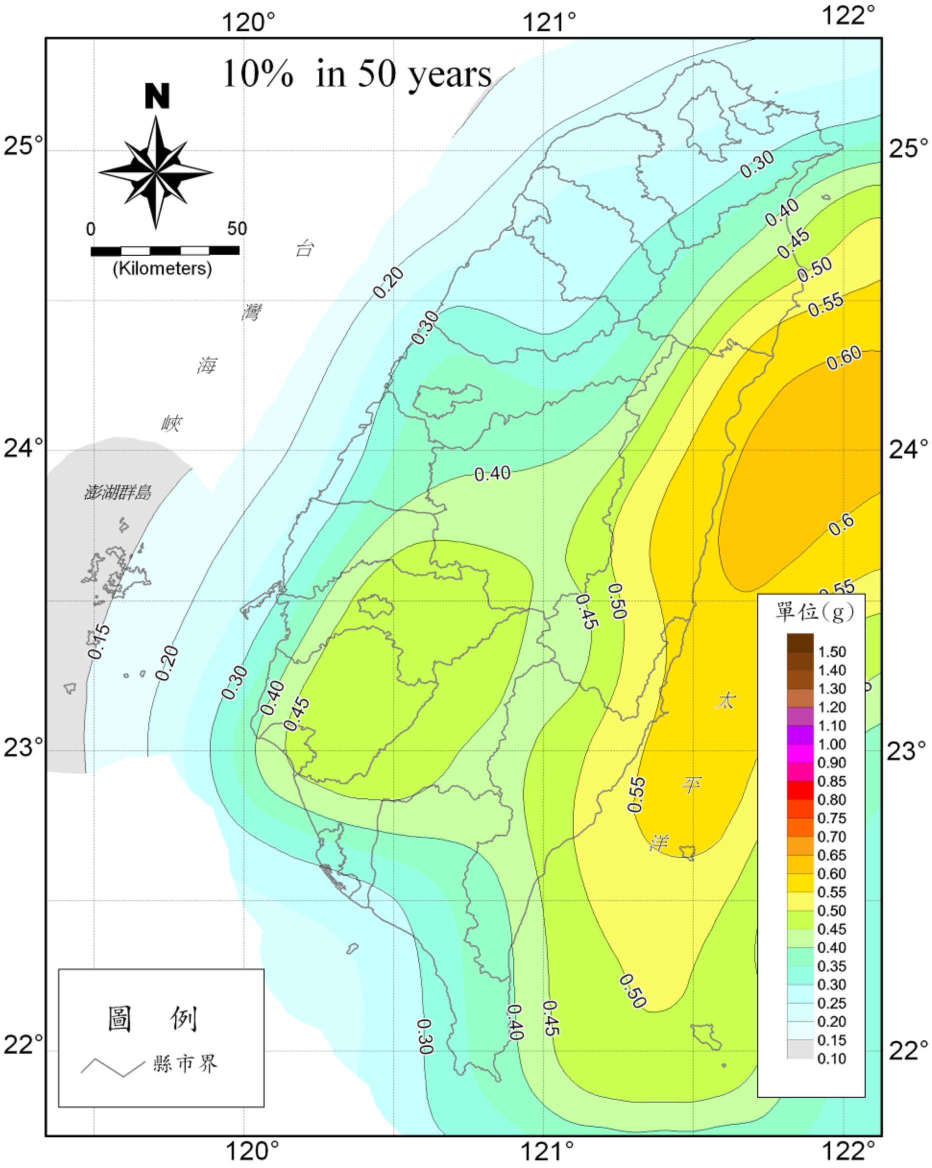


(Cheng, 1996)

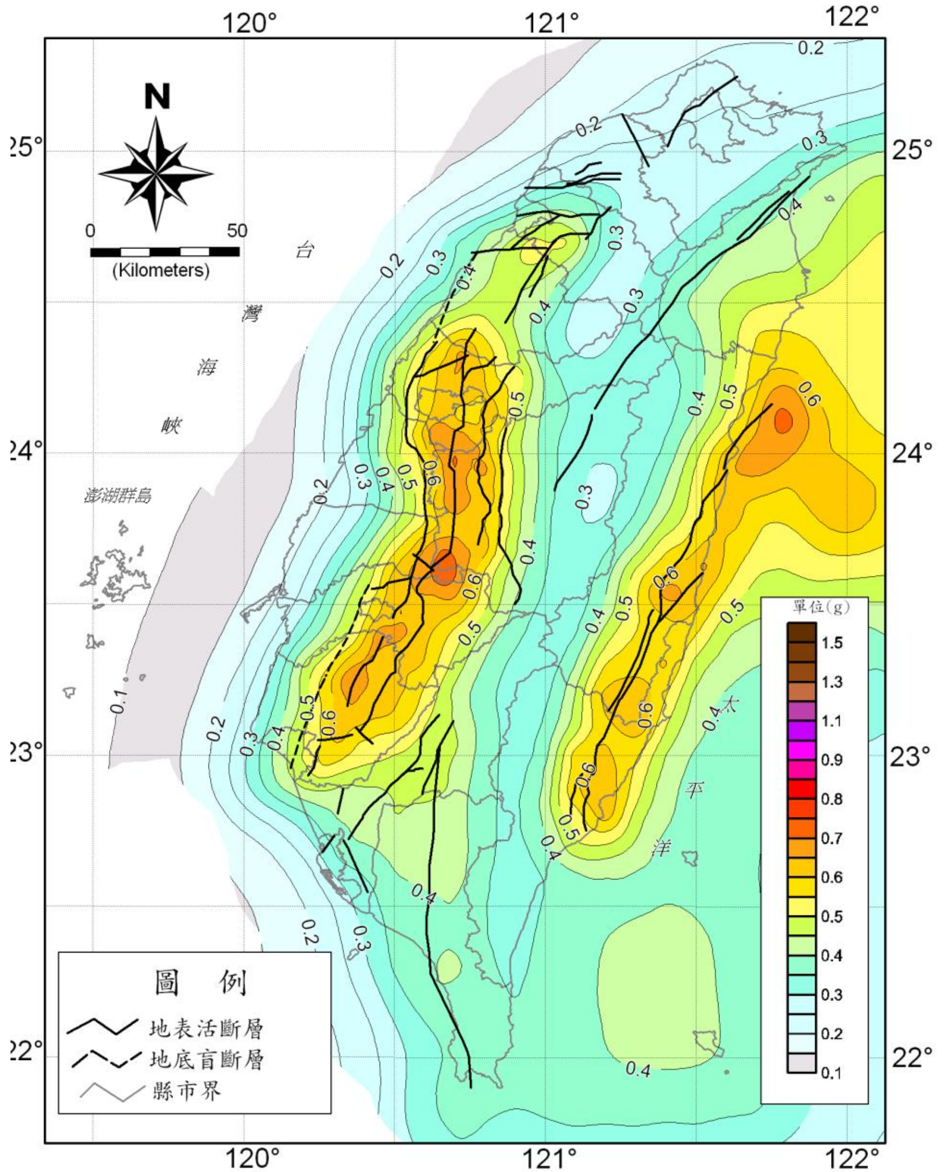


PSHA After Chi-Chi earthquake (rock site)

Without Faults

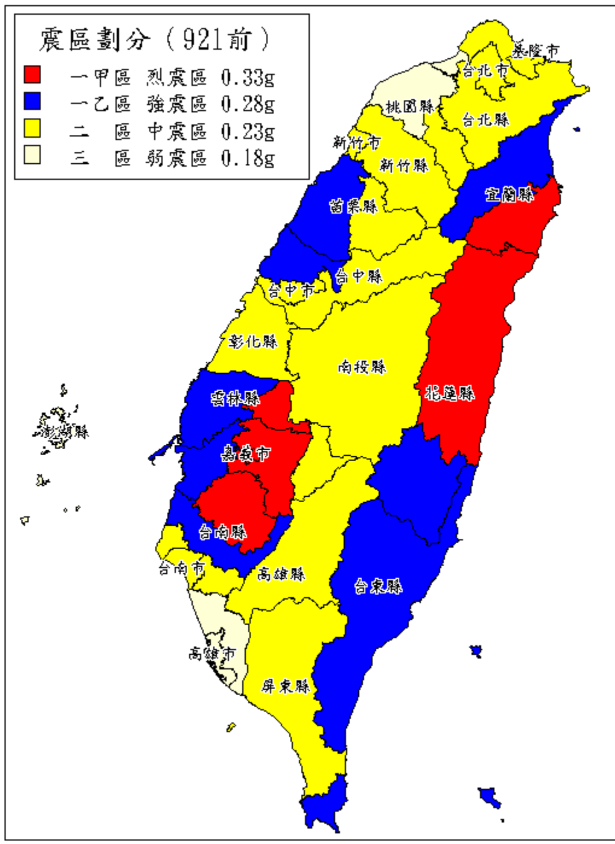


Consideration of Fault Activity

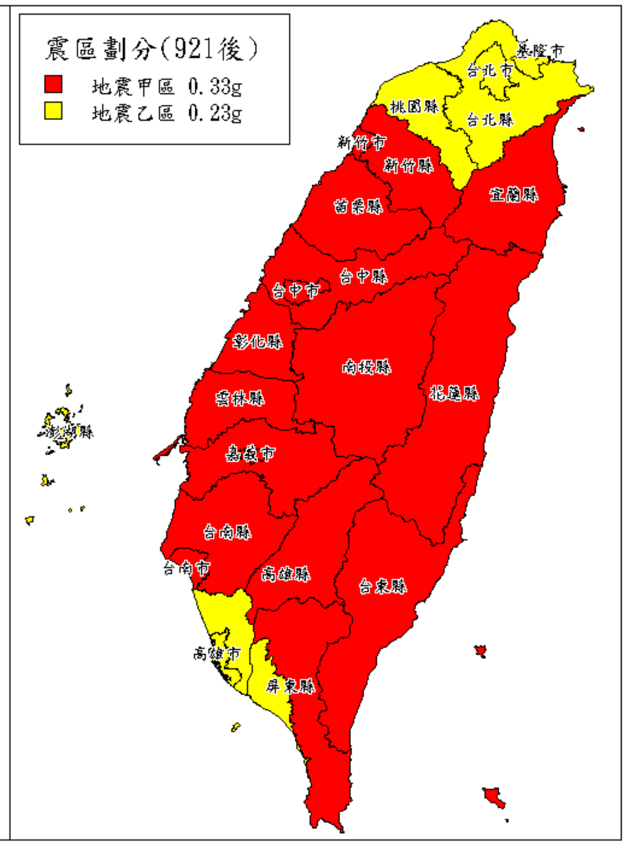


Taiwan Building Code Revising Progress

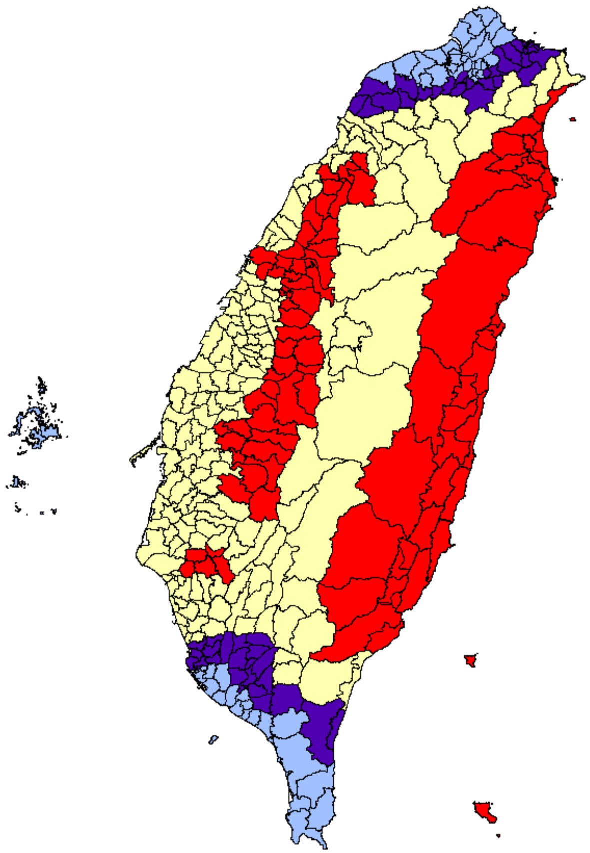
1997
(before Chi-Chi Eqk)



2000
(after Chi-Chi Eqk)

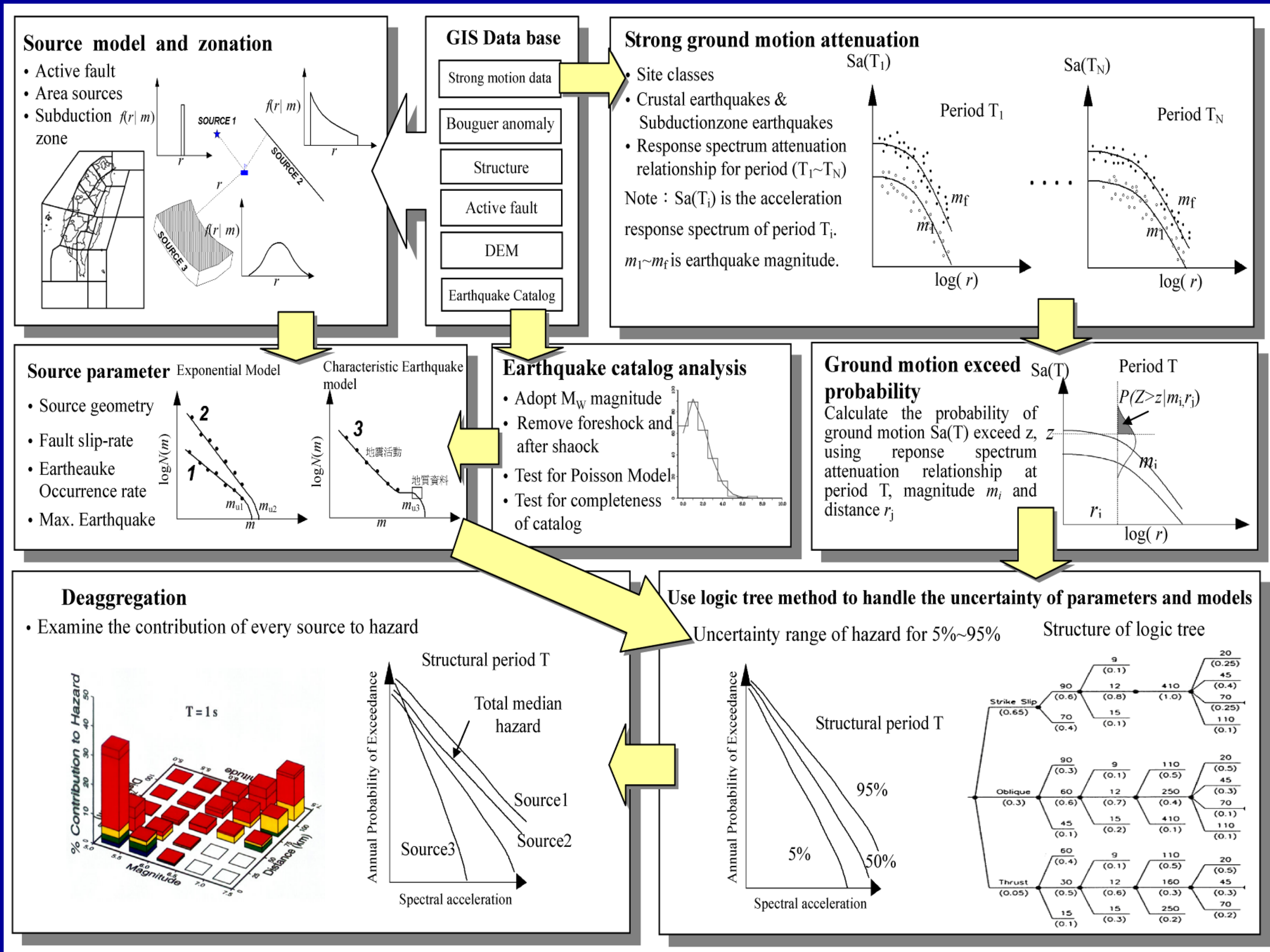


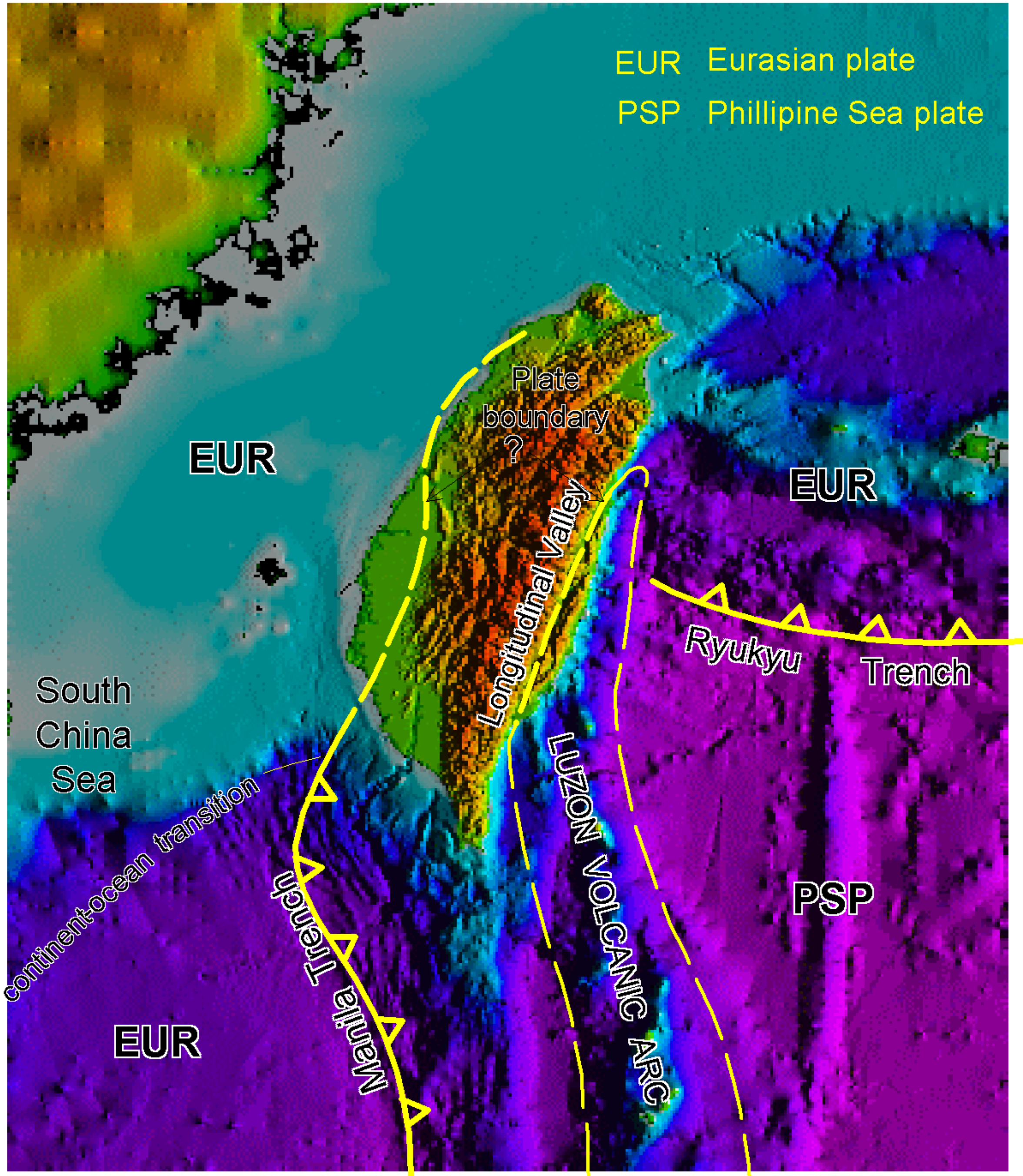
Updated in 2006



Taiwan PSHA Model

Flow Chart for **Probabilistic Seismic Hazard Analysis (PSHA)**





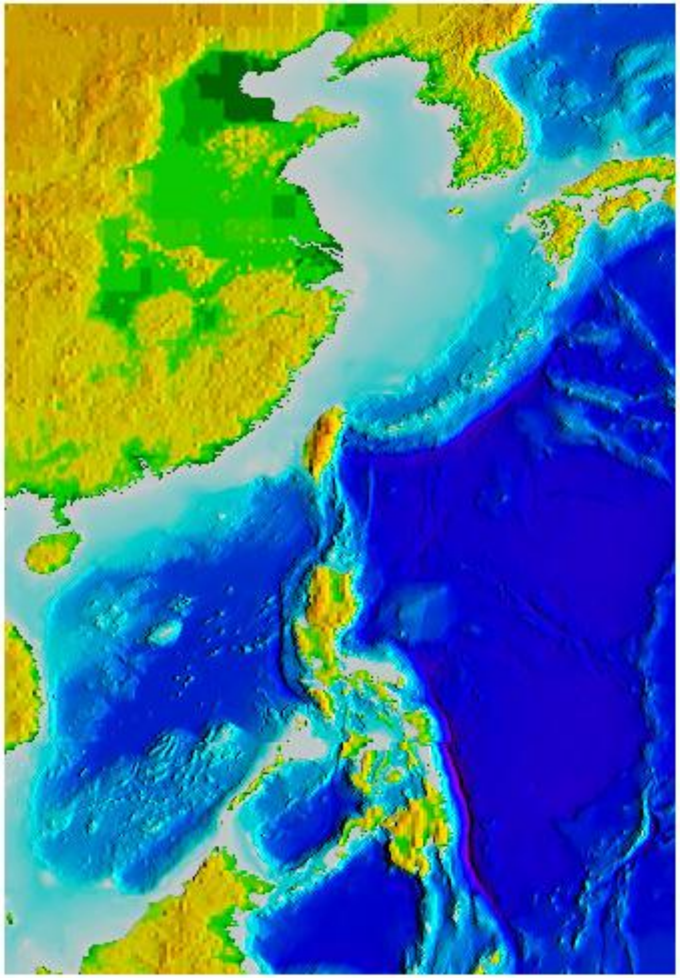
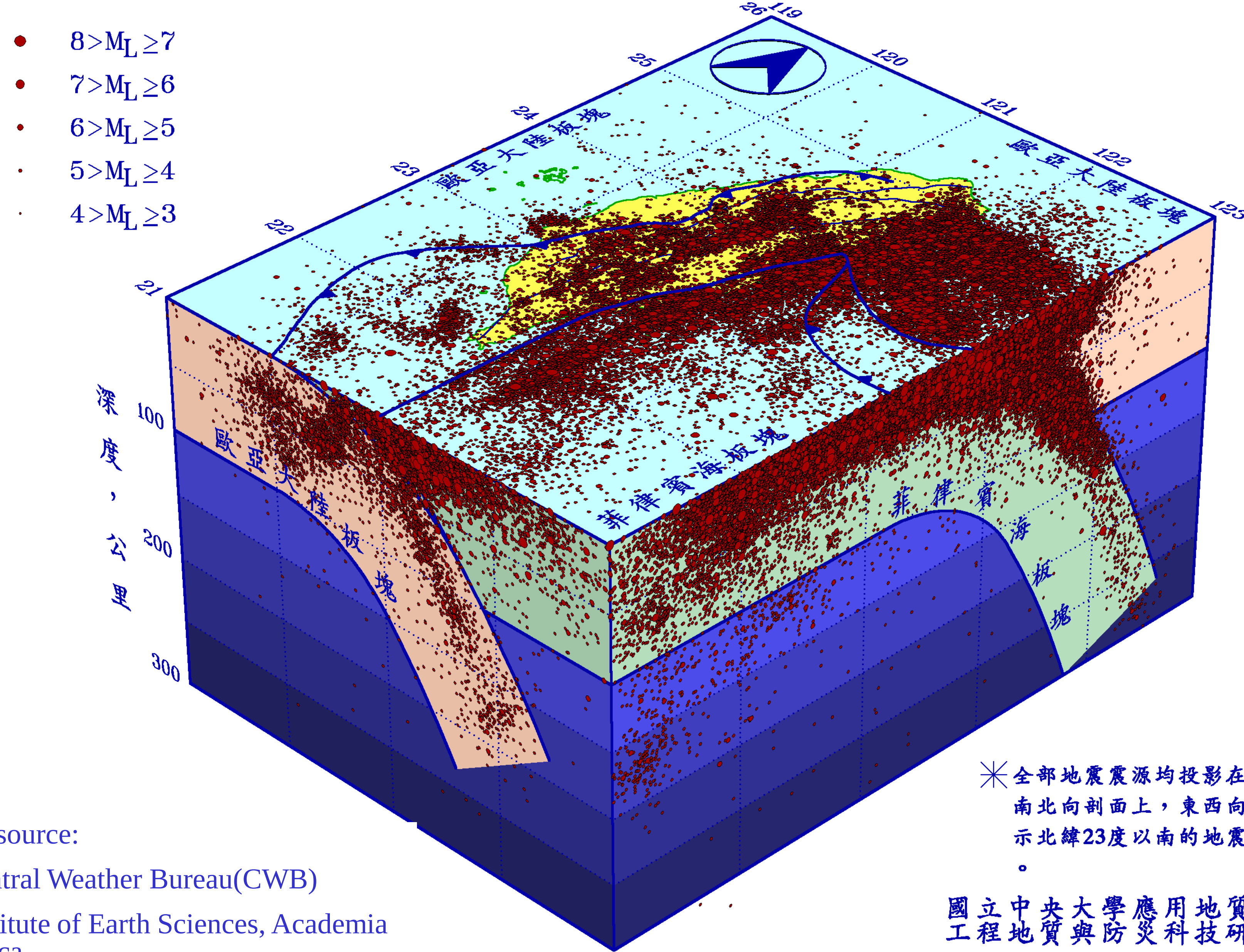


Plate Tectonics in Taiwan

Seismotectonic framework of Taiwan

(1900–2007)



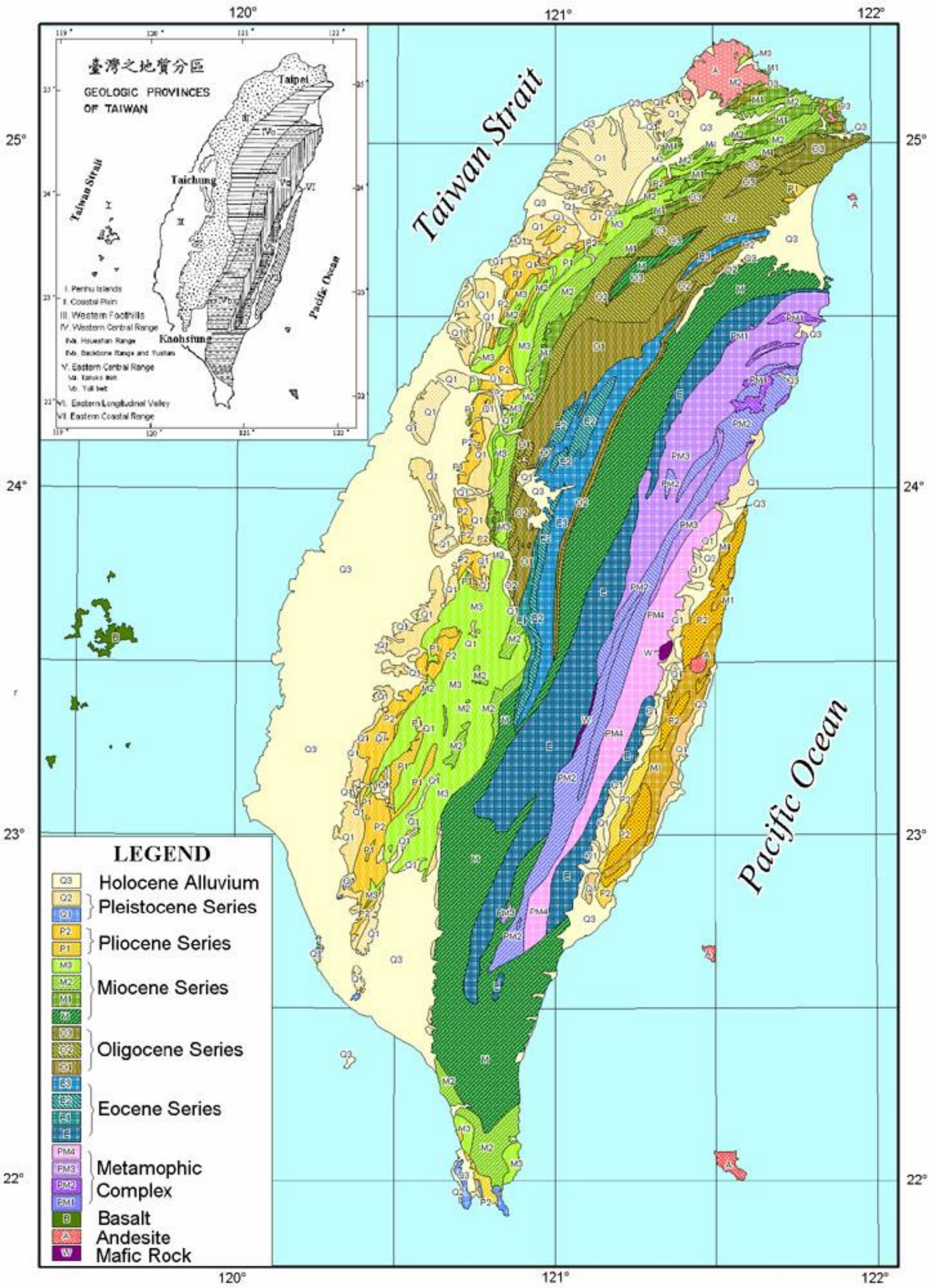
✳全部地震震源均投影在水平面及南北向剖面上，東西向剖面僅表示北緯23度以南的地震震源投影。

Data source:

1.Central Weather Bureau(CWB)

2.Institute of Earth Sciences, Academia Sinica

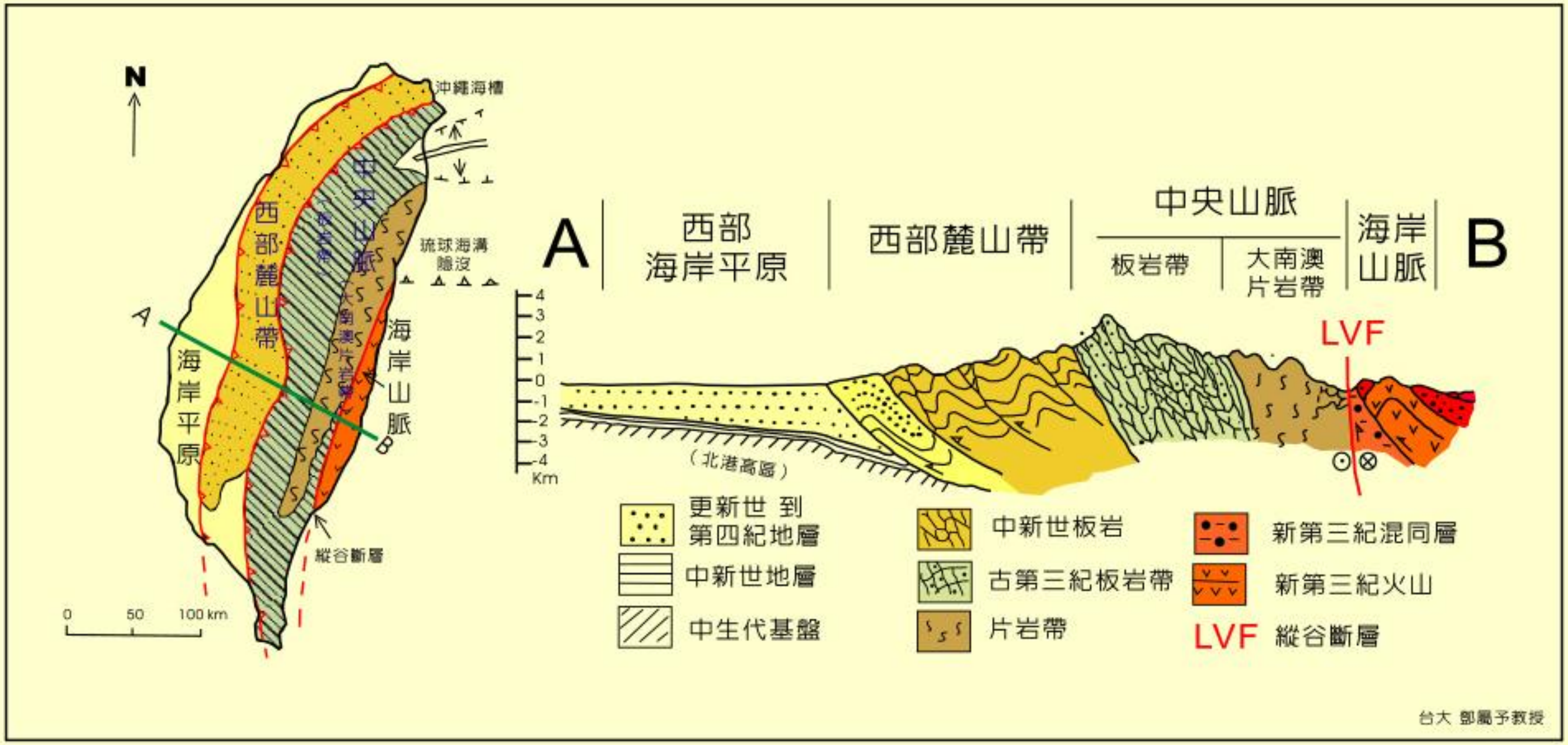
國立中央大學應用地質研究所
工程地質與防災科技研究室印製



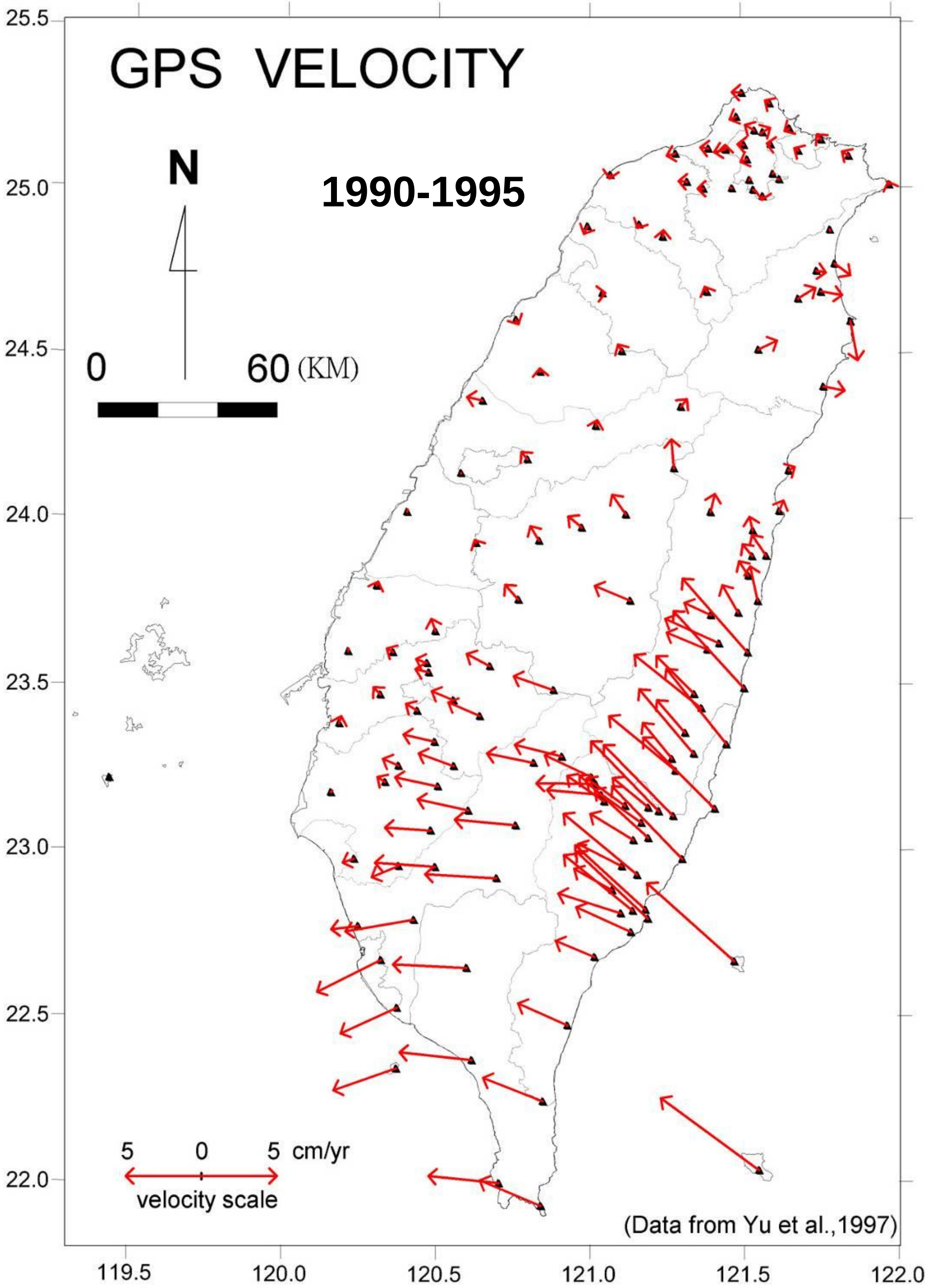
Geology of Taiwan

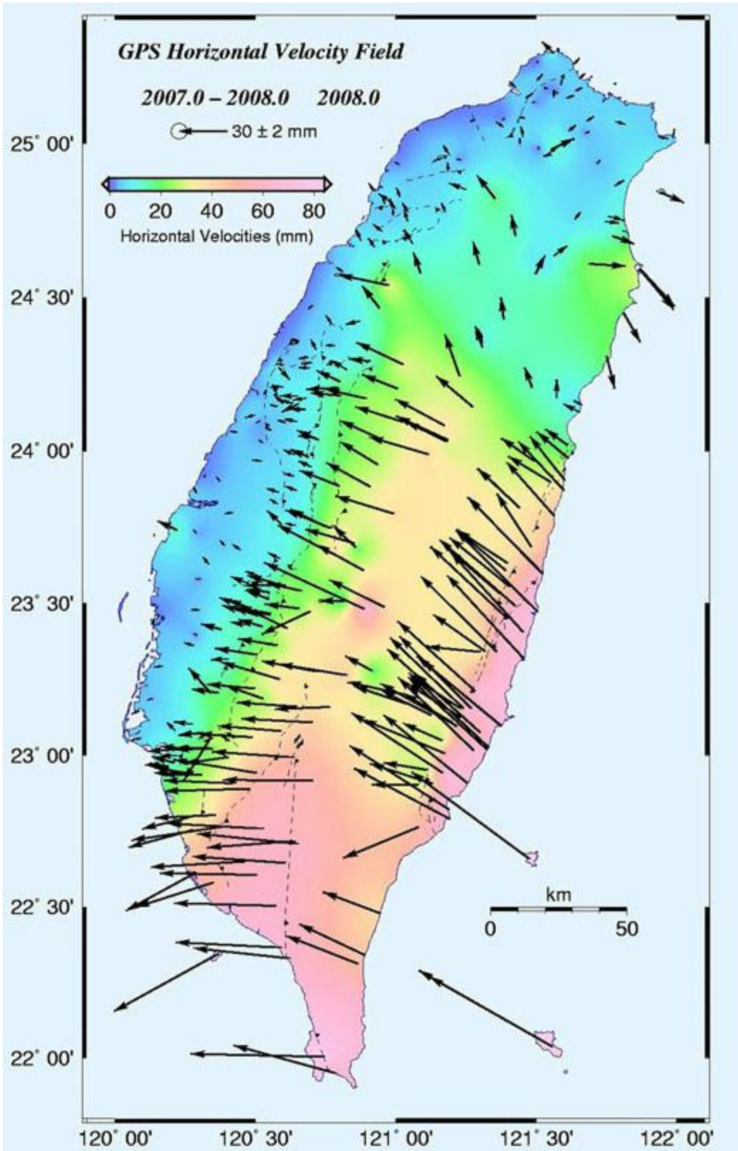
- Taiwan orogeny started at Late Miocene and is presently active.
- The Central Range consists of metamorphic complex and a Paleogene slate belt.
- Bordering the Central Range is the Western Foothills, consisting of Neogene sedimentary formations, and the Eastern Coastal Range, which is also made of Neogene sedimentary strata.
- The Longitudinal Valley located between the Central Range and the Eastern Coastal Range is the suture zone between two plates.

横過台灣島東西向之地質構造剖面圖

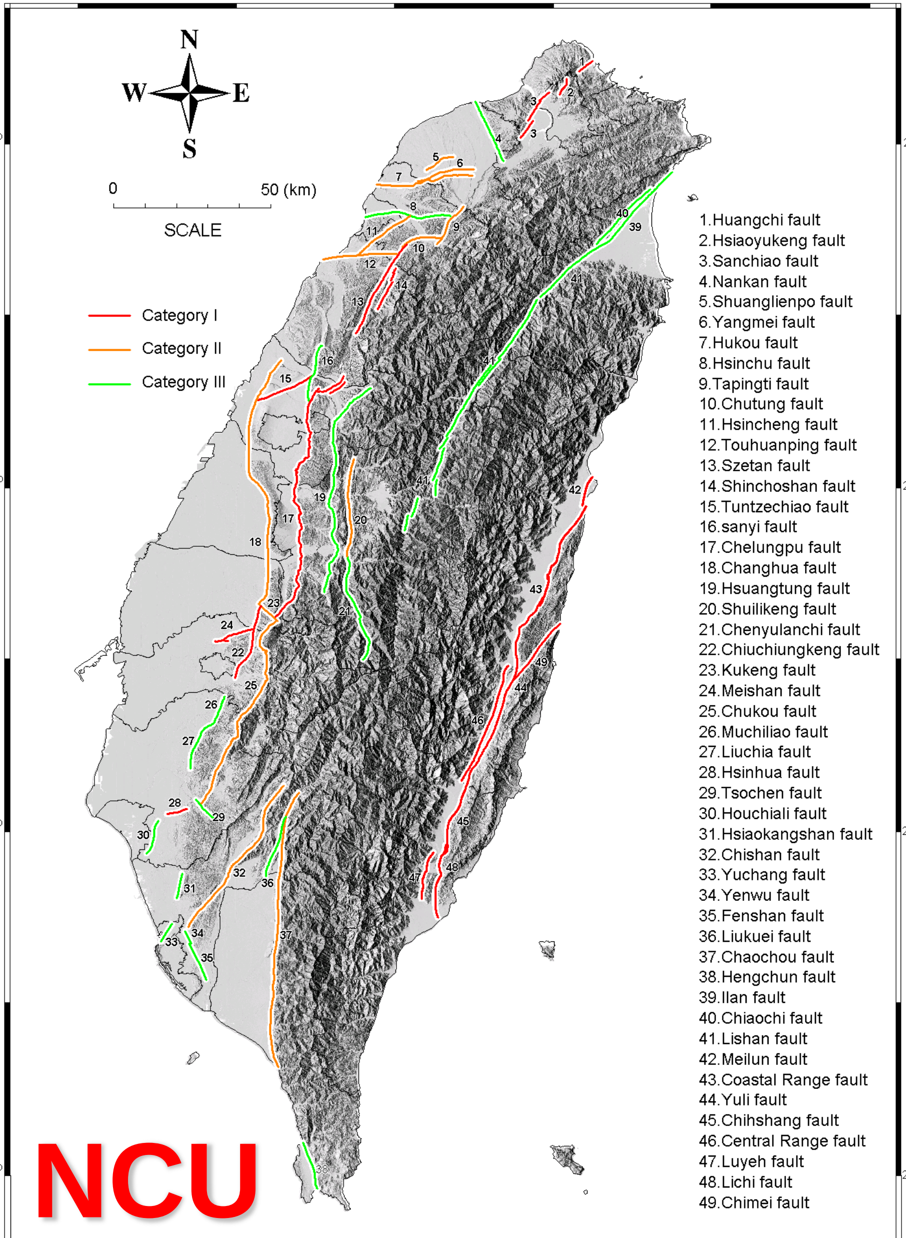


台灣地區各GPS站相對於澎湖站之移動速度

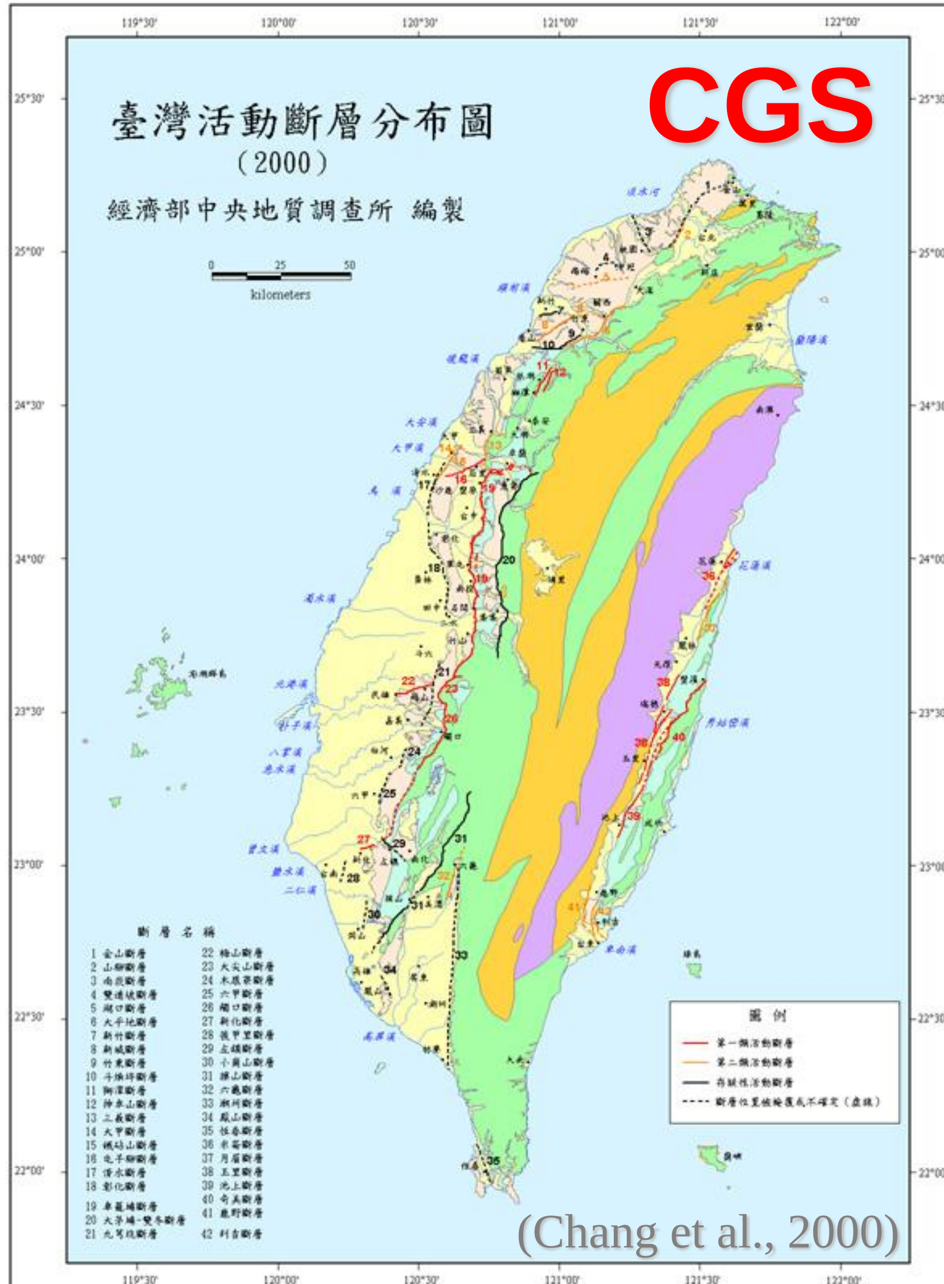




中研院GPS監測成果統合資料



(Modified from Lee, 1999)



(Chang et al., 2000)

Earthquake Sources

Source Categories	Source Geometry	Earthquake Recurrence model
Shallow Crustal Sources; Deep Sources	Regional/ Areal Sources	Truncated Exponential Model
Subduction Zone Sources (Interface sources; Intraslab sources); Active Faults	Planar/3D Sources	Characteristic Eqk. Model

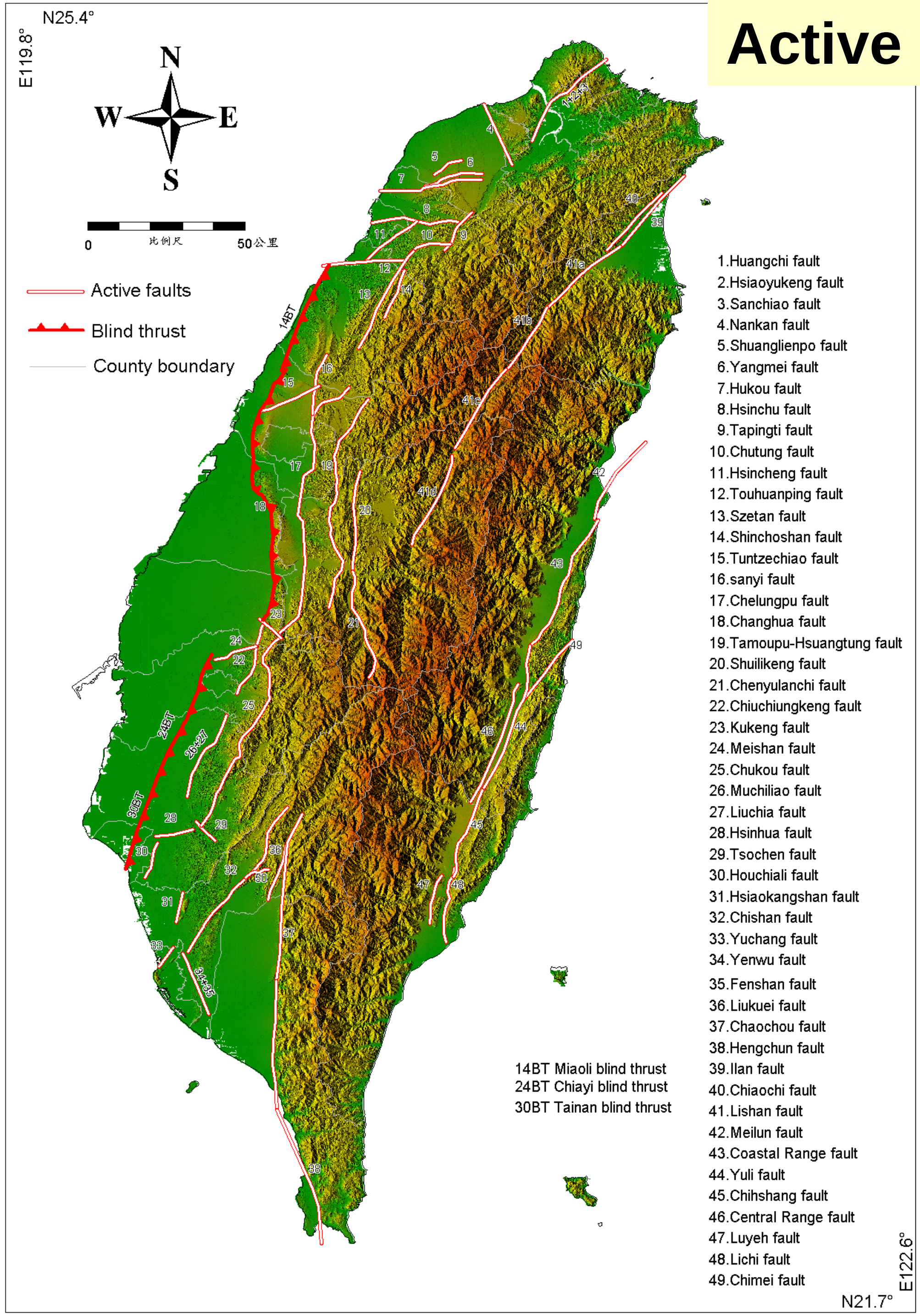
Source Categories

- Shallow Crustal Sources
- Deep Sources

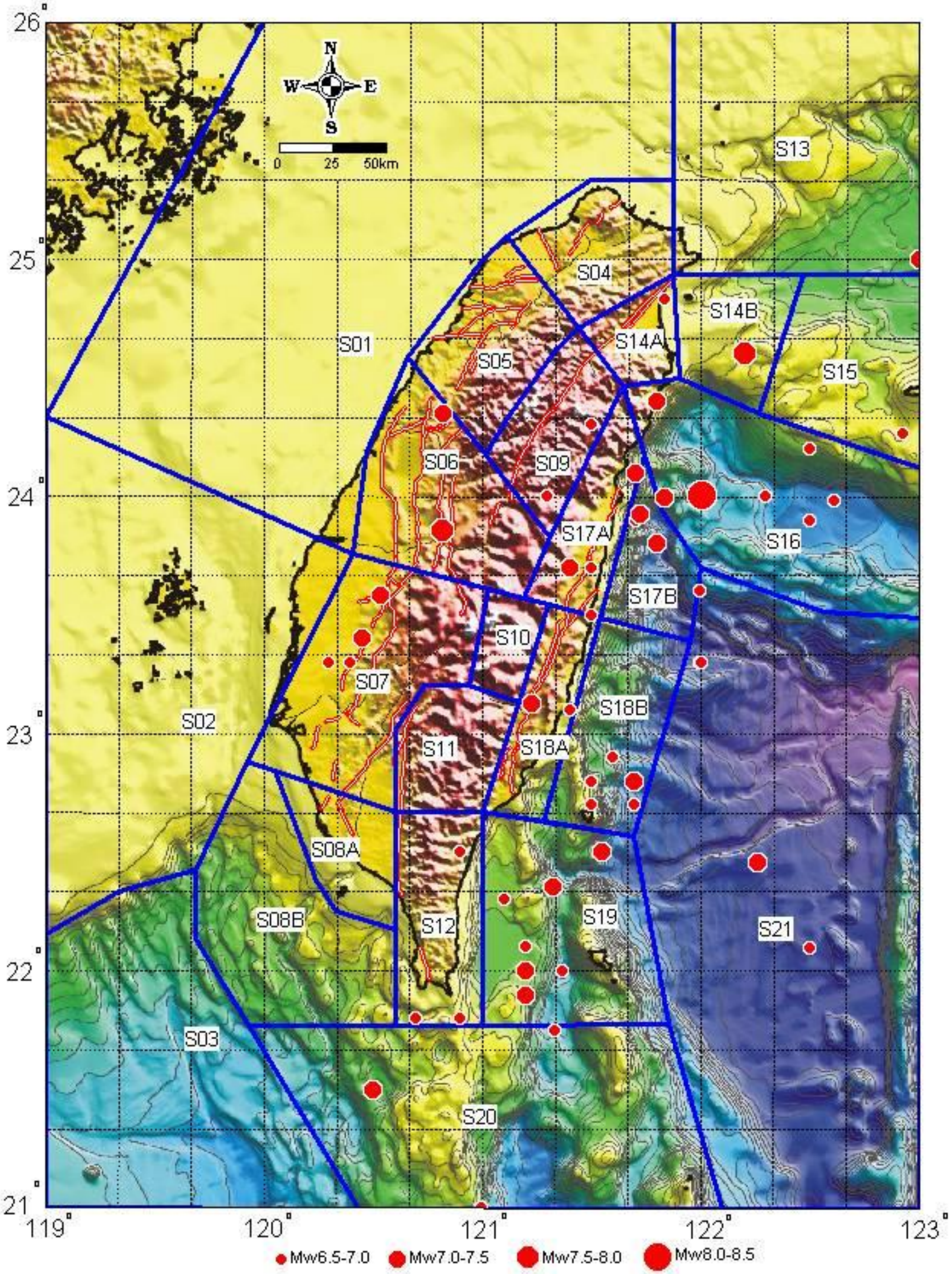
- Subduction Zone Sources
  - Interface sources
  - Intraslab sources
- Active Faults

Active Faults Map of Taiwan

Active Fault (#47)



Shallow crustal sources（depth≦35km)(# 25)



Shyu et al. (2005)

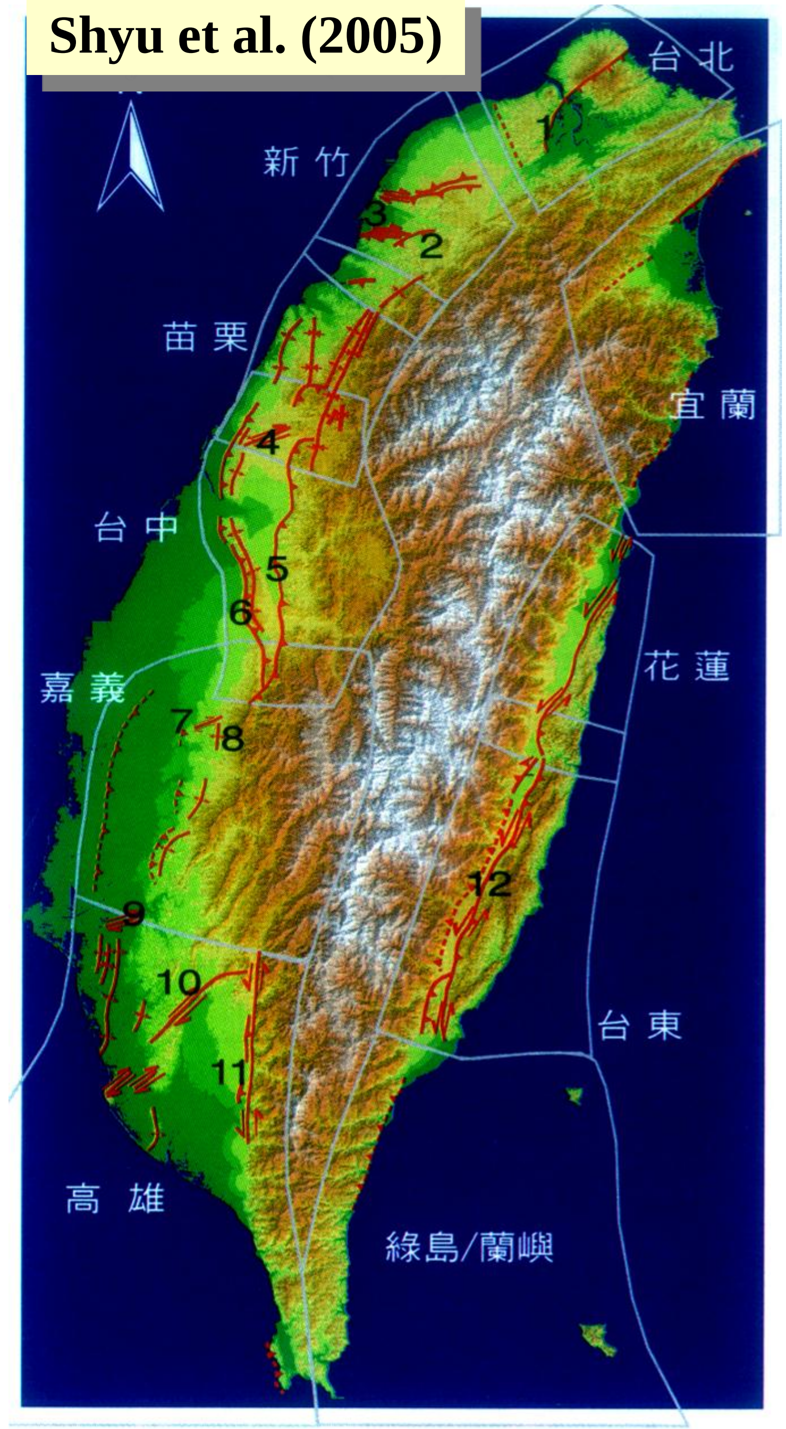
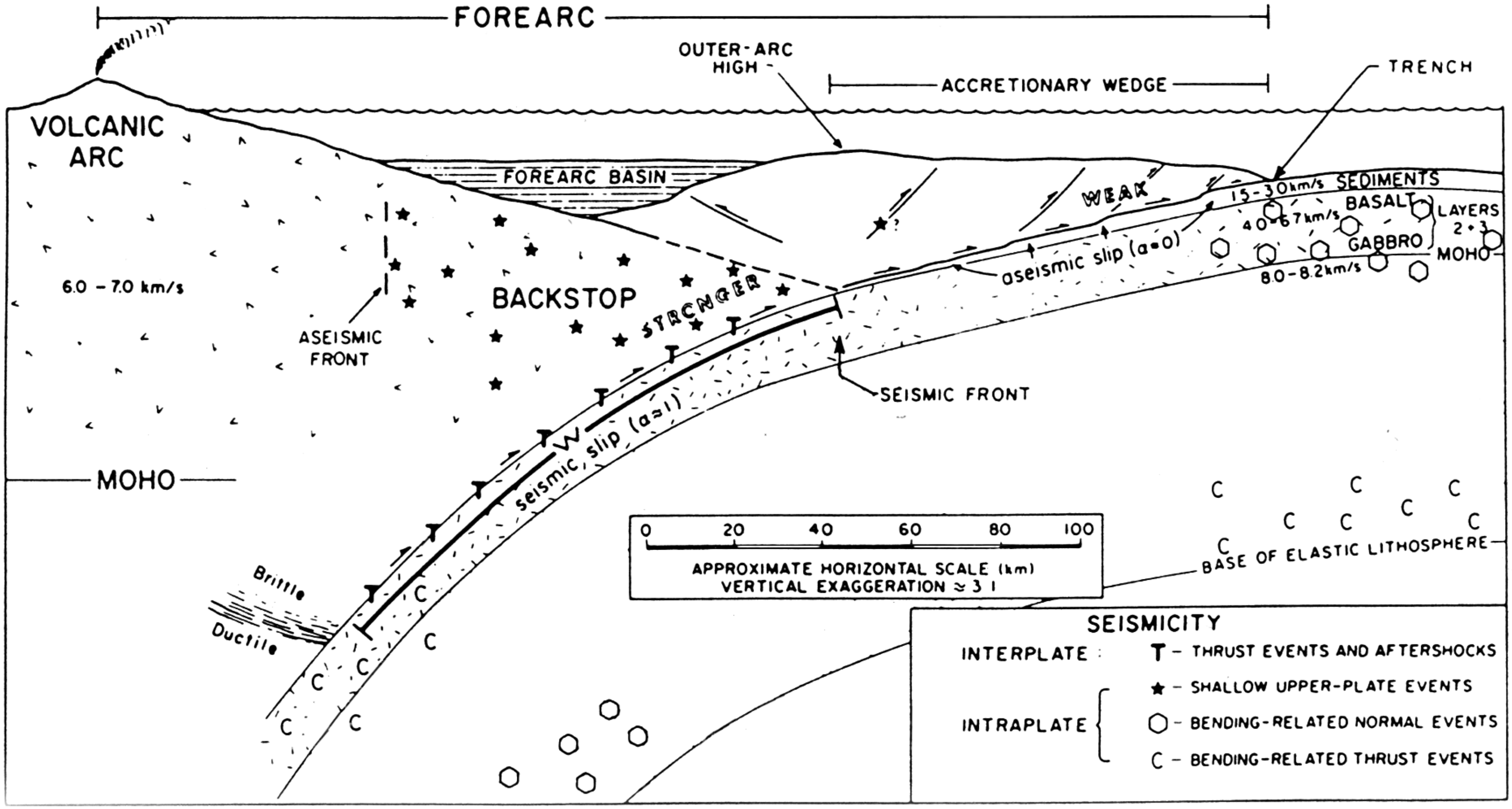
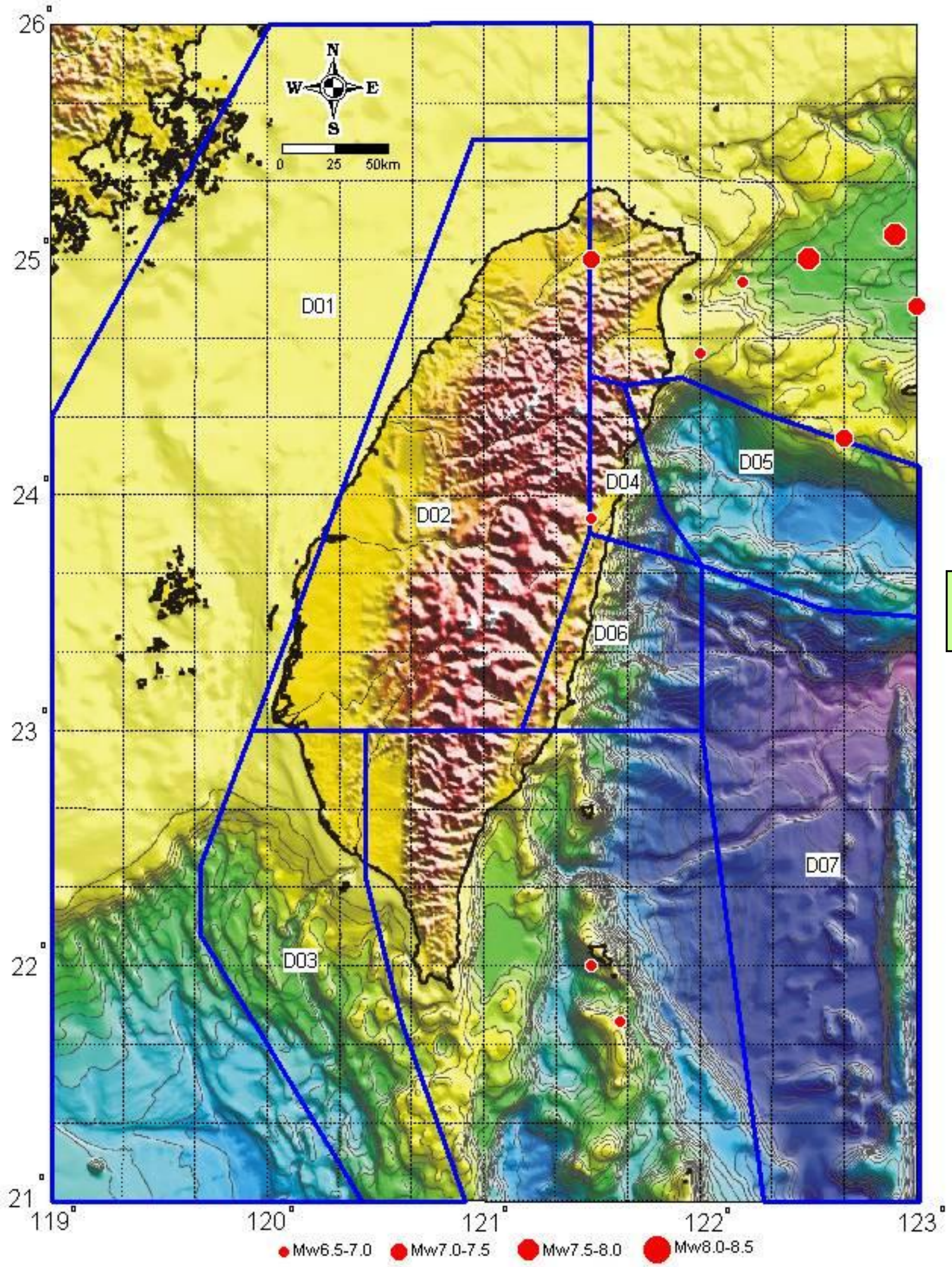


Illustration of Subduction zone system

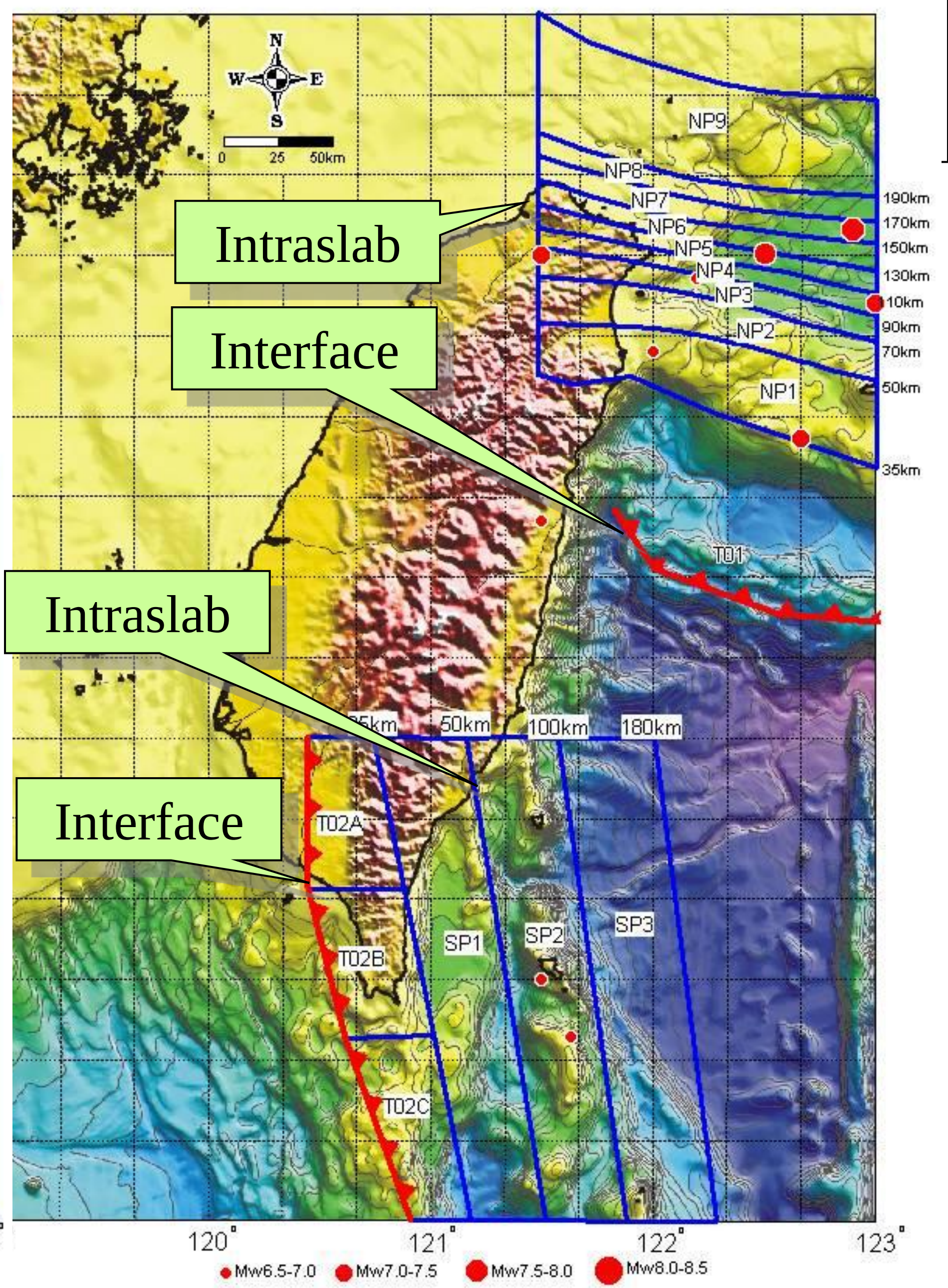


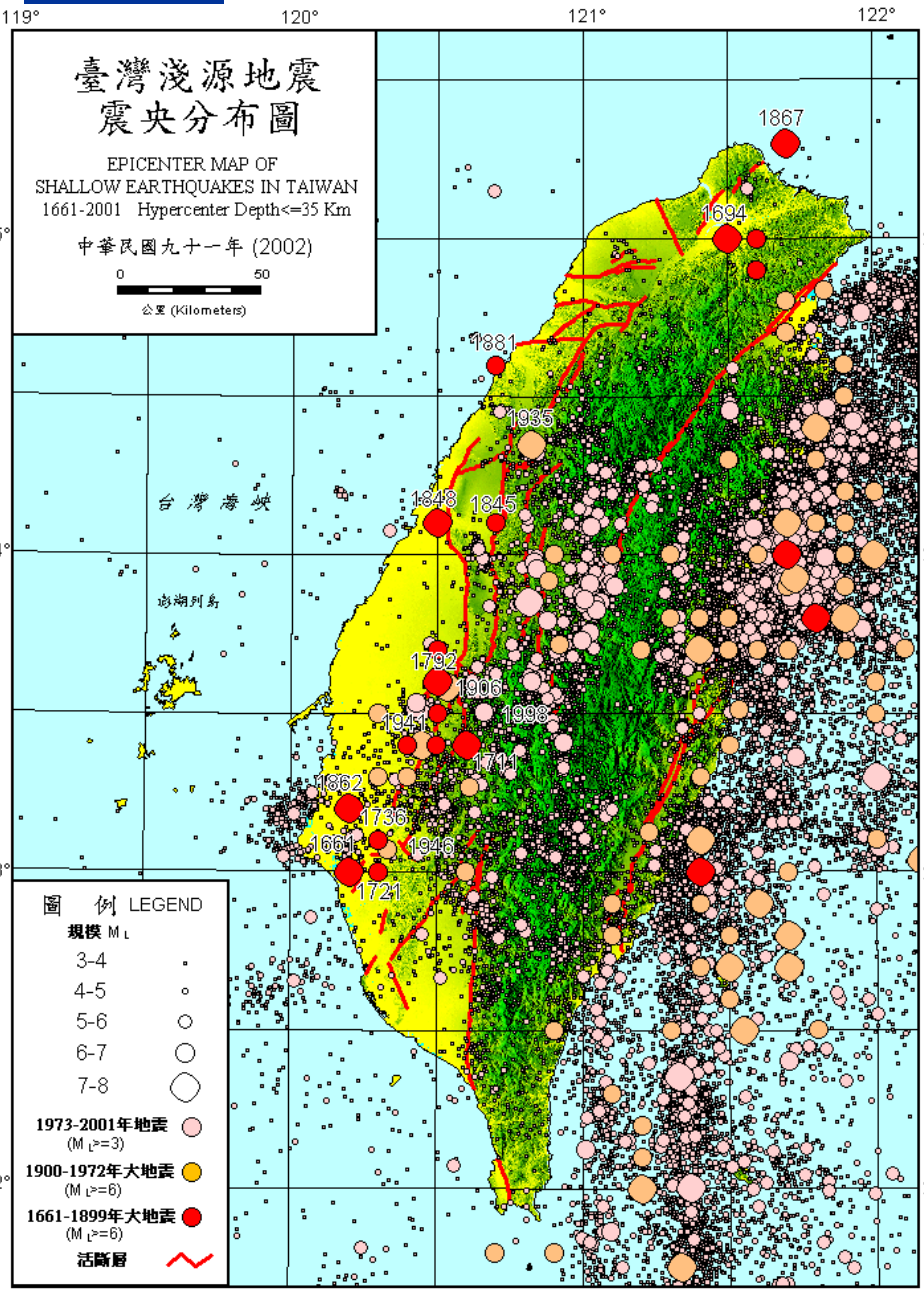
(Byrne et al., 1988)

Deep sources (depth>35km)(#7)

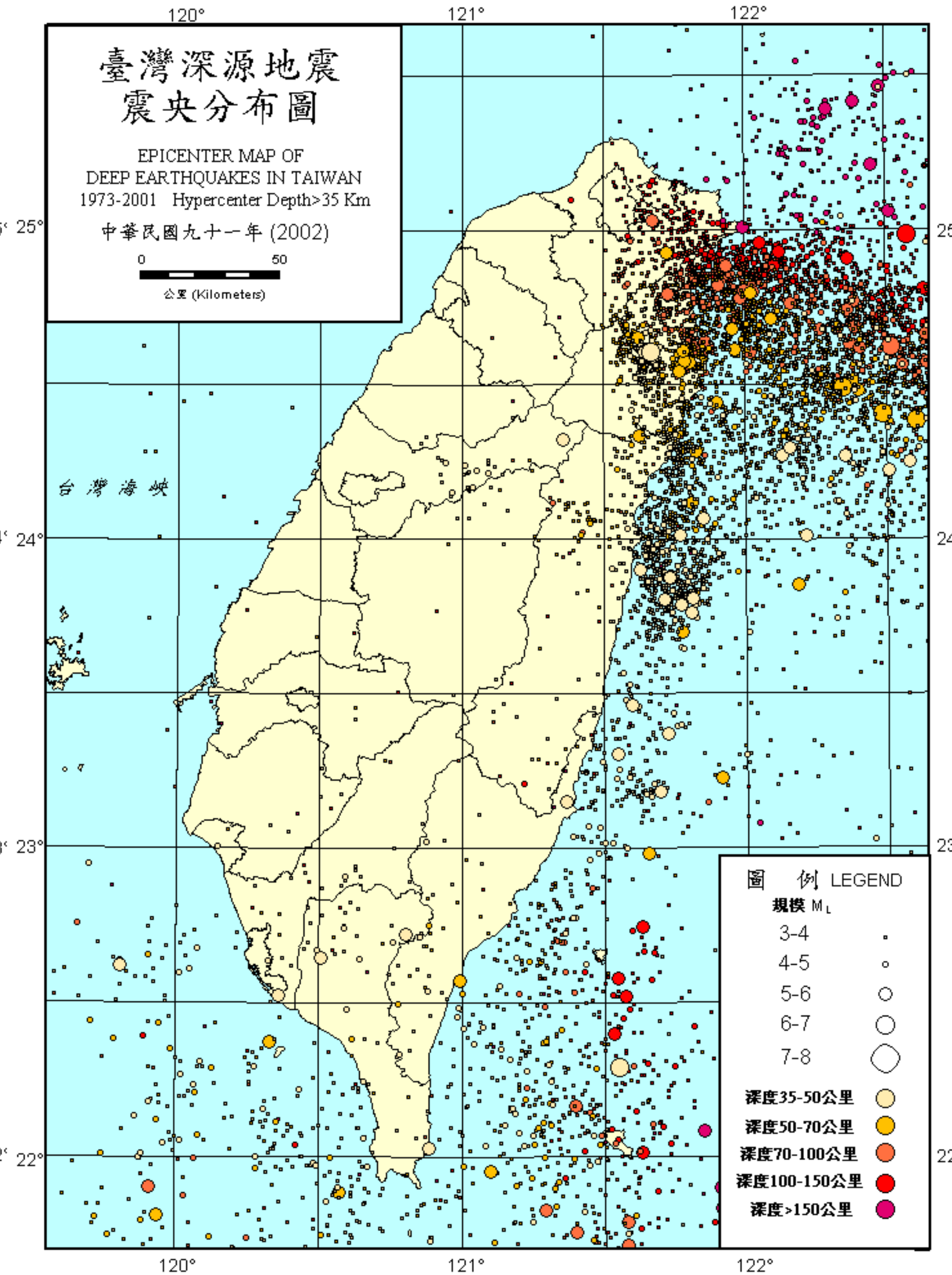


Subduction Zone Sources (#16)





臺灣淺源地震
震央分布圖
EPICENTER MAP OF
SHALLOW EARTHQUAKES IN TAIWAN
1661-2001 Hypercenter Depth<=35 Km
中華民國九十一年 (2002)
0 50
公里 (Kilometers)
台灣海峽
澎湖列島
1867
1694
1881
1935
1848
1845
1792
1906
1998
1941
1711
1862
1736
1661
1946
1721
圖例 LEGEND
規模 M L
3-4
4-5
5-6
6-7
7-8
1973-2001年地震 (M L>=3)
1900-1972年大地震 (M L>=6)
1661-1899年大地震 (M L>=6)
活斷層
119°
120°
121°
122°
25°
24°
23°
22°



臺灣深源地震
震央分布圖
EPICENTER MAP OF
DEEP EARTHQUAKES IN TAIWAN
1973-2001 Hypercenter Depth>35 Km
中華民國九十一年 (2002)
0 50
公里 (Kilometers)
台灣海峽
圖例 LEGEND
規模 M L
3-4
4-5
5-6
6-7
7-8
深度35-50公里
深度50-70公里
深度70-100公里
深度100-150公里
深度>150公里
120°
121°
122°
25°
24°
23°
22°

Completeness of Catalogue

- **Adopt the earthquake catalogue 1900~1999**
- **Eqk. Magnitude convert to M_W**
- Catalogue divided into four stages
  - (Yeh et al., 1995 and Tsai, et al., 2000)
  - **Seismic Monitoring Network**
    - ✓distribution density of instrument
    - ✓accuracy of instrument

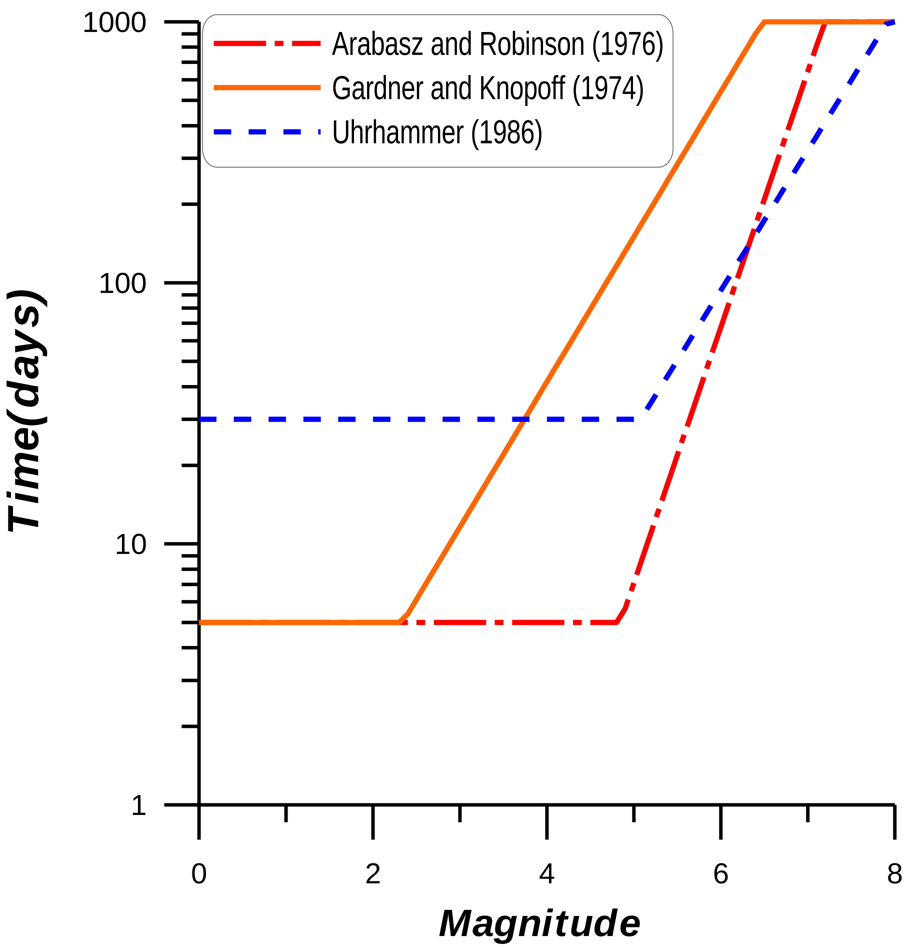
(1) 1900~1935：whole region M_w6.0；

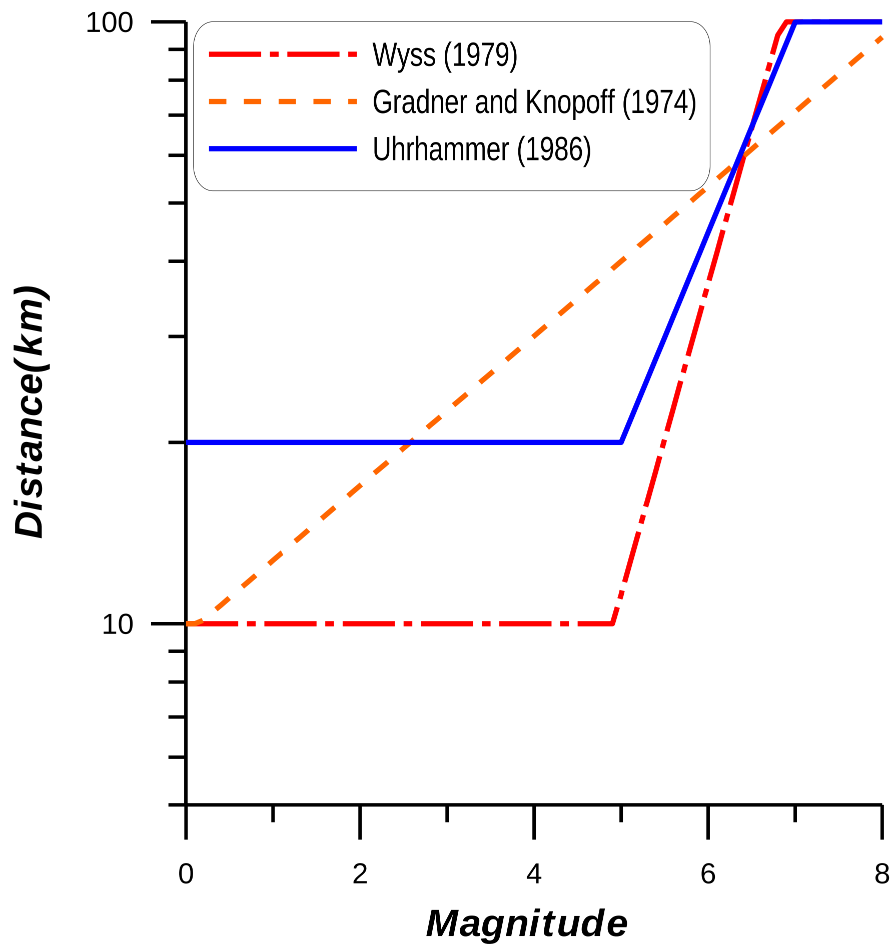
(2) 1936~1972：inland M_w5.0，offshore M_w5.5；

(3) 1973~1991：inland M_w3.5，offshore M_w4.0；

(4) 1992~ ：inland M_w2.5，offshore M_w3.5。

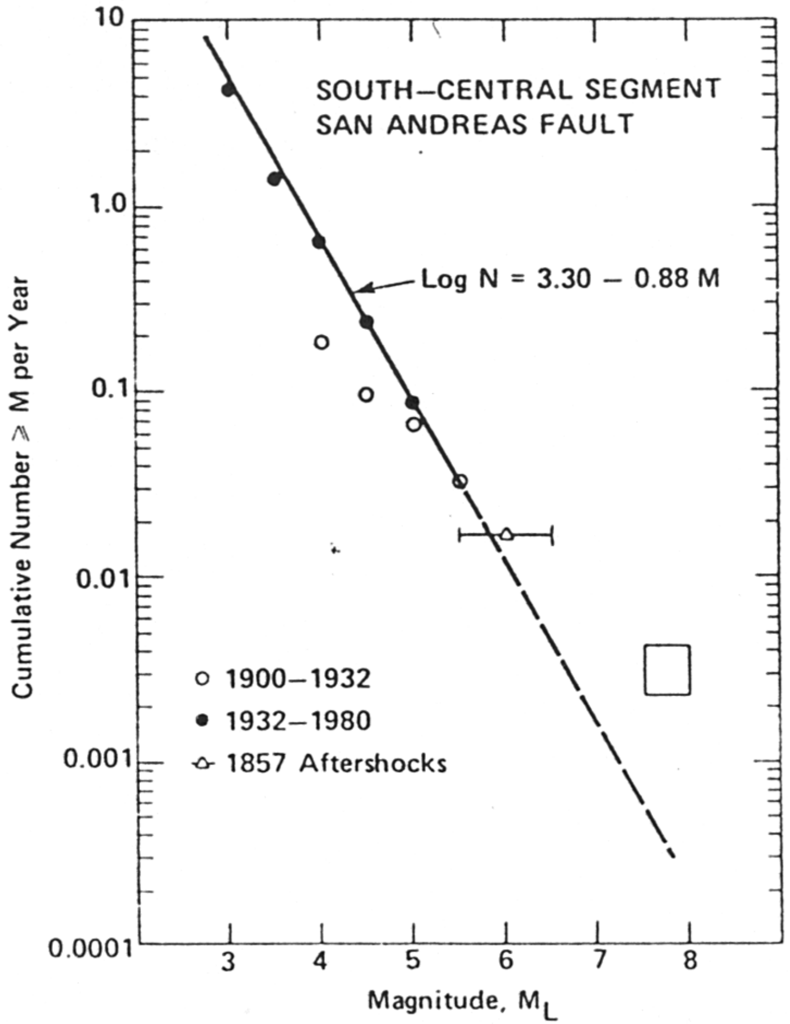
Foreshock and Aftershock Removal

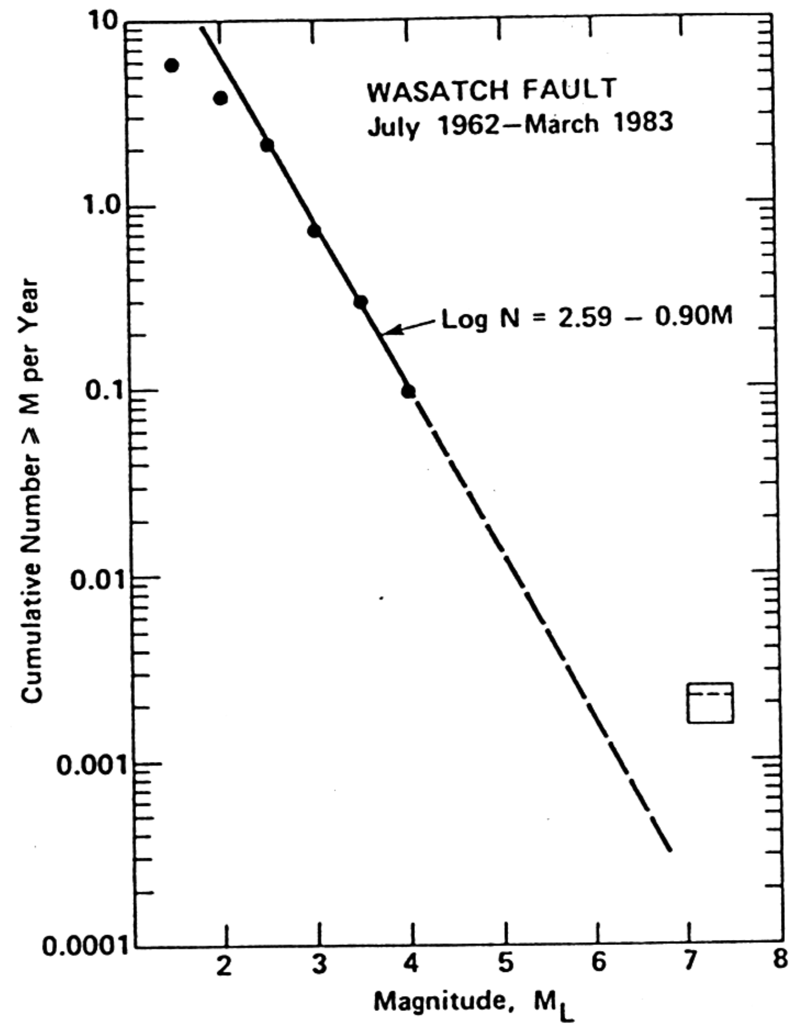




國外常用的(a)時間域與(b)空間域上的去除前震及餘震的地震序列經驗準則。

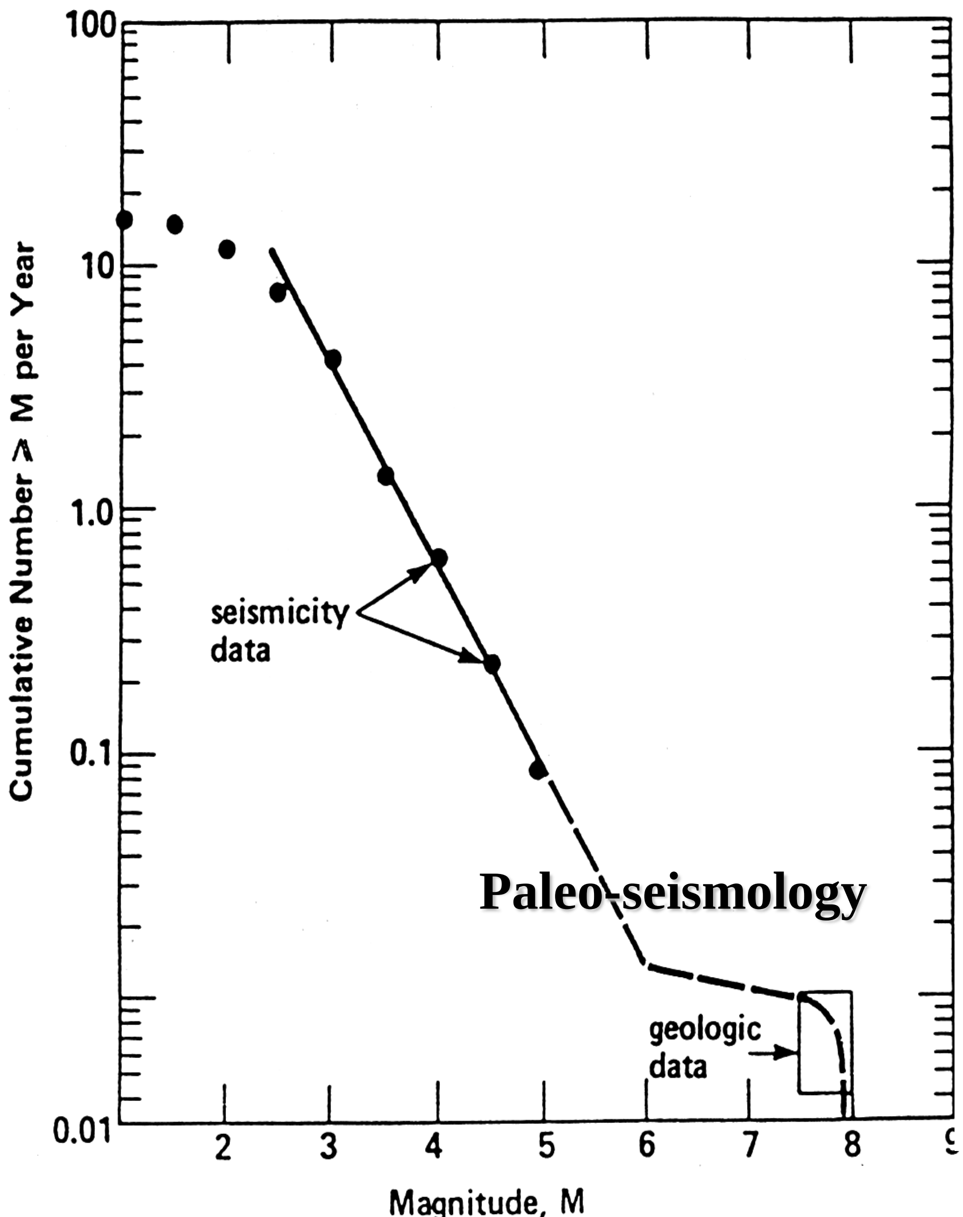
Estimate fault activity / recurrence rate

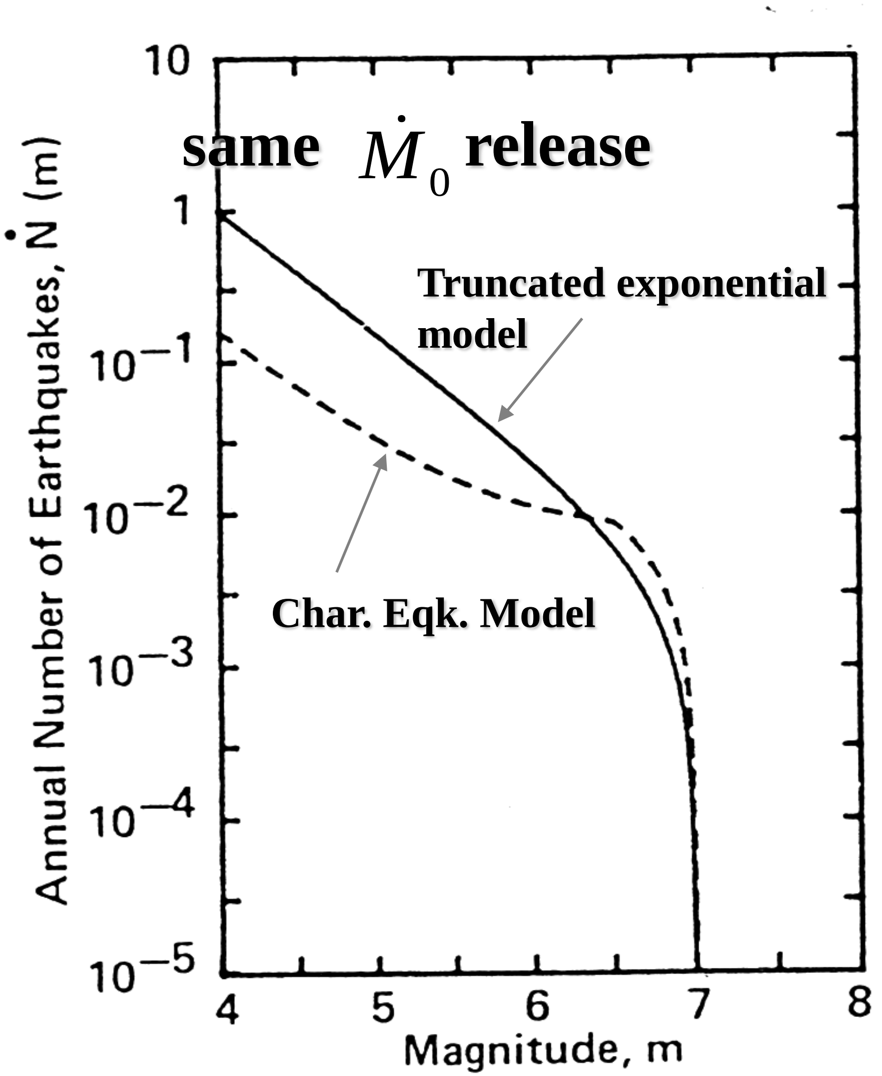




(Schwartz與Coppersmith, 1984)

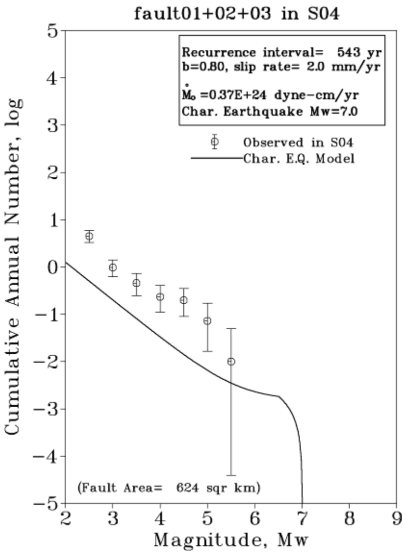
Estimate fault activity / recurrence rate

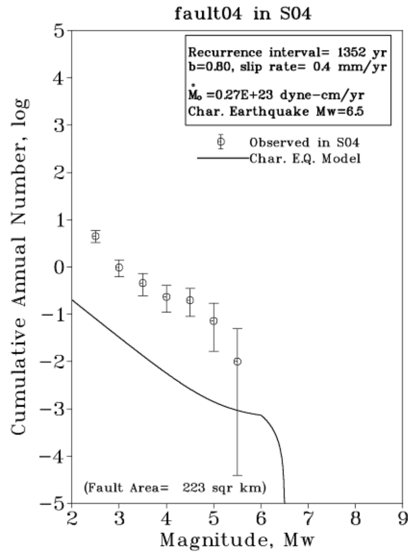


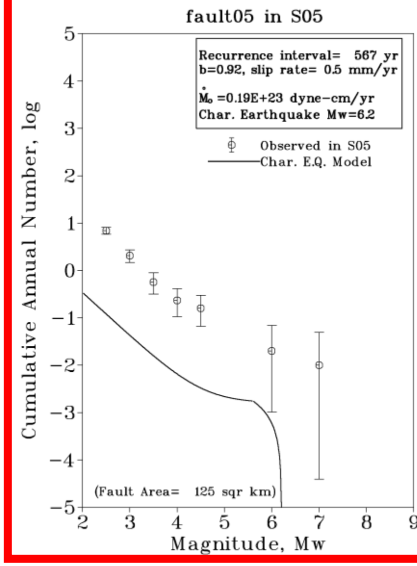


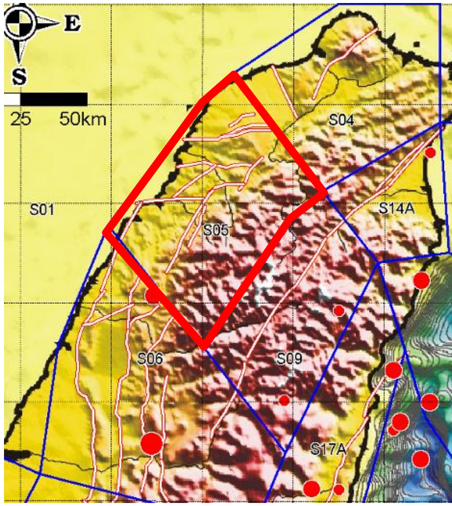
(Youngs and Coppersmith, 1985)

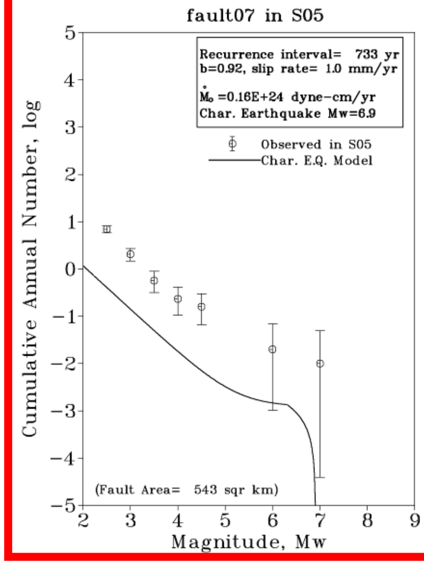
Characteristic Earthquake Model for Interface/Active Fault Sources

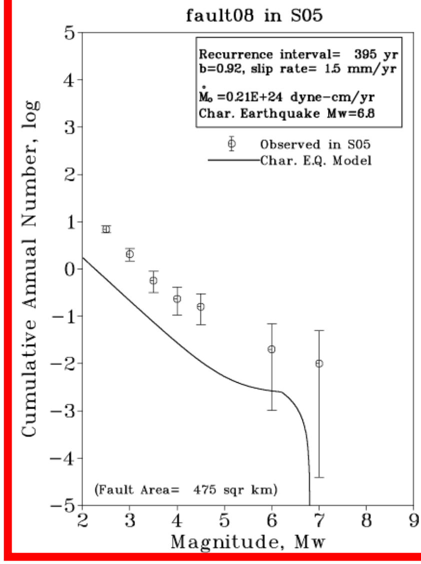


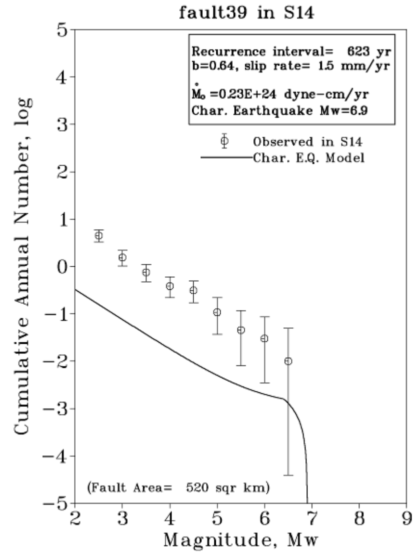


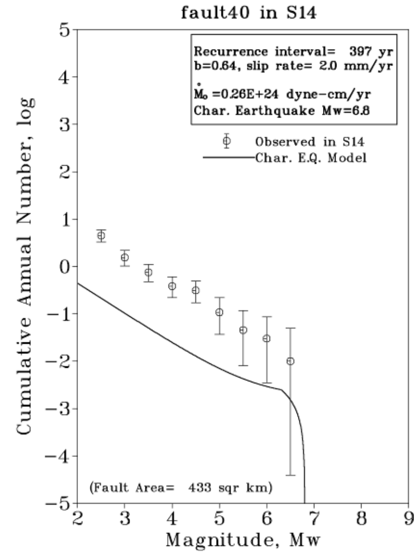












Summary of Active Faults in Taiwan

Fault No.	Fault Name	Fault Category	Strike	Dip (degree)	Length (km)	Fault mechanism	Stratigraphic throw (m)	Youngest reference horizon offsetted	Displacement of reference horizon (m)	Age of reference horizon (10^3yr)	Long-term slip rate (mm/yr)	Short-term slip rate (mm/yr)	Maximum earthquake magnitude recorded	Magnitude of last earthquake	Elapsed time (yr)	Activity	References
1	Huangchi	I	NNE	SE	6	Normal	600+	Holocene Alluvium	?	10	?	?	7.1	7.1	132	A	1
2	Hsiaoyukeng	I	NNE	SE	6	Normal	?	L. Pletstocene Volcanic cone	?	?	?	?	5.1	5.1	10	A	1
3	Sanchiao	I	NNE	SE	18	Normal & Sinistral	700	Holocene Alluvium	20	10	2	?	7.0	7.0	305	A	1,2,3
4	Nankan	III	NNW	NW	22	Normal & Dextral	?	LH[*1]	?	120	?	?	?	?	?	?	4,5,6,7,8
5	Shuanglienpo	II	ENE	SE	11	Reverse	?	LT[*2]	?	50	?	?	?	?	?	B	5,6,7,8,9
6	Yangmei	II	ENE	NW	19	Reverse	?	LT	10	33	0.3	?	?	?	?	B	5,6,7,8,9
7	Hukou	II	ENE	50SE	32	Thrust	300	LT	25	33	0.8	?	?	?	?	B	5,6,7,8,9,10
8	Hsinchu	III	E-W	55S	27	Thrust	700	Toukoshan F.	700	1000±	0.7	?	?	?	?	B	11,12,13,14
9	Tapingti	II	NNE	SE	15	Thrust	?	LT	?	33	?	?	?	?	?	B	6,14,16
10	Chutung	II	NE	SE	13	Reverse	500	FT[*3]	?	10	?	?	?	?	?	B	6,11,12,13,14,15,16
11	Hsincheng	II	N40E	40SE	21	Thrust	700	LT	?	33	?	?	?	?	?	B	6,11,12,13,14,15,16,17
12	Touhuanping	II	E-W	90	24	Dextral	600	FT	?	10	?	?	?	?	?	B	6,7,11,12,13,14,15,17,18
13	Seztan	I	N10E	75W	35	Reverse	?	Ground surface	V=3 H=0.6	0	?	?	7.1	7.1	64	A	19,20
14	Shinchoshan	I	N10E	E	16	Reverse	?	Ground surface	V=0.6	0	?	?	?	?	64	A	19,20
15	Tuntzechiao	I	N60E	90	20	Dextral	?	Ground surface	V=0.6 H=1.5	0	?	?	7.1	7.1	64	A	19,20
16	Sanyi	III	NNE	15E	18	Thrust	?	Toukoshan F.	?	?	?	?	?	?	?	?	21,22,23,24,25,26,27
17	Chelungpu	I	N-S	30E	90	Thrust	?	Ground surface	V=7.8 H=9.5	0	?	?	7.6	7.6	3	A	5,6,16,25

Summary of Active Faults in Taiwan (Lee, 1999)

18	Changhua	II	NNS	?	85	Thrust	?	LT	25-145	?	?	?	?	?	?	?	5,6,16,25,28
19	Tamopu-Hsuan gtung	III	N-S	55E	50	Thrust	5000	Toukoshan F.	?	Pleistocene	?	?	?	?	?	?	5,6,16,25,29
20	Shuilikeng	II	N-S	E	32	Thrust	5000	FT		20?	?	?	?	?	?	?	6,50
21	Chenyulanchi	III	N-S	E	34	Thrust	5000	?			?	?	?	?	?	?	30
22	Chiuchiungkeng	I	NNE	30E	24	Thrust	1200	FT	?	<10	?	?	?	?	?	A	31,59
23	Kukeng	II	NW	90	9	Sinistral	?	?	?	?	?	?	?	?	?	A	31
24	Meishan	I	N75E	90	13	Dextrtal	?	Ground surface	H=2.4 V=1.8	0	?	?	7.1	7.1	93	AA	32,33,35
25	Chukou	II	NE	60E	65	Thrust	3000	Toukoshan F.	?	?	?	?	?	?	?	A	36,37,38
26	Muchiliao	III	NNE	SE	7	Thrust	?	Tainan F.?	?	Holocene	?	?	?	?	?	?	6,16,33,34
27	Liuchia	III	NNE	SE	10	Thrust	10	Liushuang F.	10	M.Pleistocene	?	?	?	?	?	?	39
28	Hsinhua	I	N70E	90	6	Dextrtal	0.76	Ground surface	H=2.0 V=0.8	0	?	?	6.3	6.3	53	A	40
29	Tsochen	III	NW	90	9	Sinistral	?	?	?	?	?	?	?	?	?	?	6,16,41
30	Houchiali	III	NNE	W	11	Normal	>30?	Tainan F.?	>30?	Holocene	?	?	?	?	?	?	6,16,42
31	Hsiaokangshan	III	NNE	SE	9	Reverse	?	Tainan F.?	?	Holocene	?	?	?	?	?	?	16,42,43
32	Chishan	II	NE	W	60	Thrust	?	?	?	?	?	?	?	?	?	A	6,16,36,42,44,50
33	Yuchang	III	NE	?	7	Reverse	?	Holocene S.?	?	Holocene	?	?	?	?	?	?	6,16,43
34	Yenwu	III	NW	?	5	Reverse	?	Holocene S.?	?	Holocene	?	?	?	?	?	?	6,16,43
35	Fenshan	III	NW	?	13	Reverse	?	Holocene S.?	8?	Holocene	?	?	?	?	?	?	6,16,43
36	Liukuei	III	NE	?	20	Reverse	3000	Liukuei F.	?	Pleistocene	?	?	?	?	?	?	6,16,36,50
37	Chaochou	II	N-S	E	110	Reverse	6000	LT	?	30±	?	?	?	?	?	A	6,16,45,46,50
38	Hengchun	III	NNW	70E	17	Reverse	?	Kenting F.	?	M.Pleistocene	?	?	?	?	?	?	16,42,43,47,48,49
39	Ilan	III	NE	SE	30	Normal	?	?	?	?	?	?	?	?	?	?	50
40	Chiaochi	III	NE	SE	24	Normal	?	?	?	?	?	?	?	?	?	?	50
41	Lishan	III	NNE	?	110	Normal	?	?	?	?	?	?	?	?	?	?	50,51
42	Meilun	I	N30E	60E	>12	Reverse & Sinistral	>170	Ground surface	H=2.0 V=1.2	0	?	?	7.1	7.1	38	AA	52,53,54,55

Summary of Active Faults in Taiwan

43	Fenglin East	I	N30E	60E	45	Reverse & Sinistral	?	?	?	?	?	?	?	?	?	AA	16,55
44	Yuli	I	N30E	60E	48	Reverse & Sinistral	?	Ground surface	H=1.6 V=1.3	0	?	30	7.3	7.3	38	AA	6,16,54,55,56
45	Chihshang	I	N25E	60E	30	Reverse & Sinistral	?	Ground surface	?	0	?	20	7.3	7.3	38	AA	6,16,54,55,56
46	Yuli West	I	NNE	?	40	Reverse	?	Ground surface	?	0	?	?	?	?	?	A	16
47	Luyeh	I	N-S	?	17	Reverse	?	FT	?	?	?	?	?	?	?	A	55,57
48	Lichi	I	N-S	60E	24	Reverse & Sinistral	?	FT	?	?	?	?	?	?	?	AA	16,51
49	Chimei	I	N40E	80E	>25	Reverse & Sinistral	?	FT	?	4~5	?	?	5.2	5.2	27	AA	58

***Note:** 1.LH: Lateritic Horizon, Middle to Late Pleistocene. 2.LT: Lateritic Terrace, Late Pleistocene. 3..FT: Fluvial Terrace, Holocene.

References:

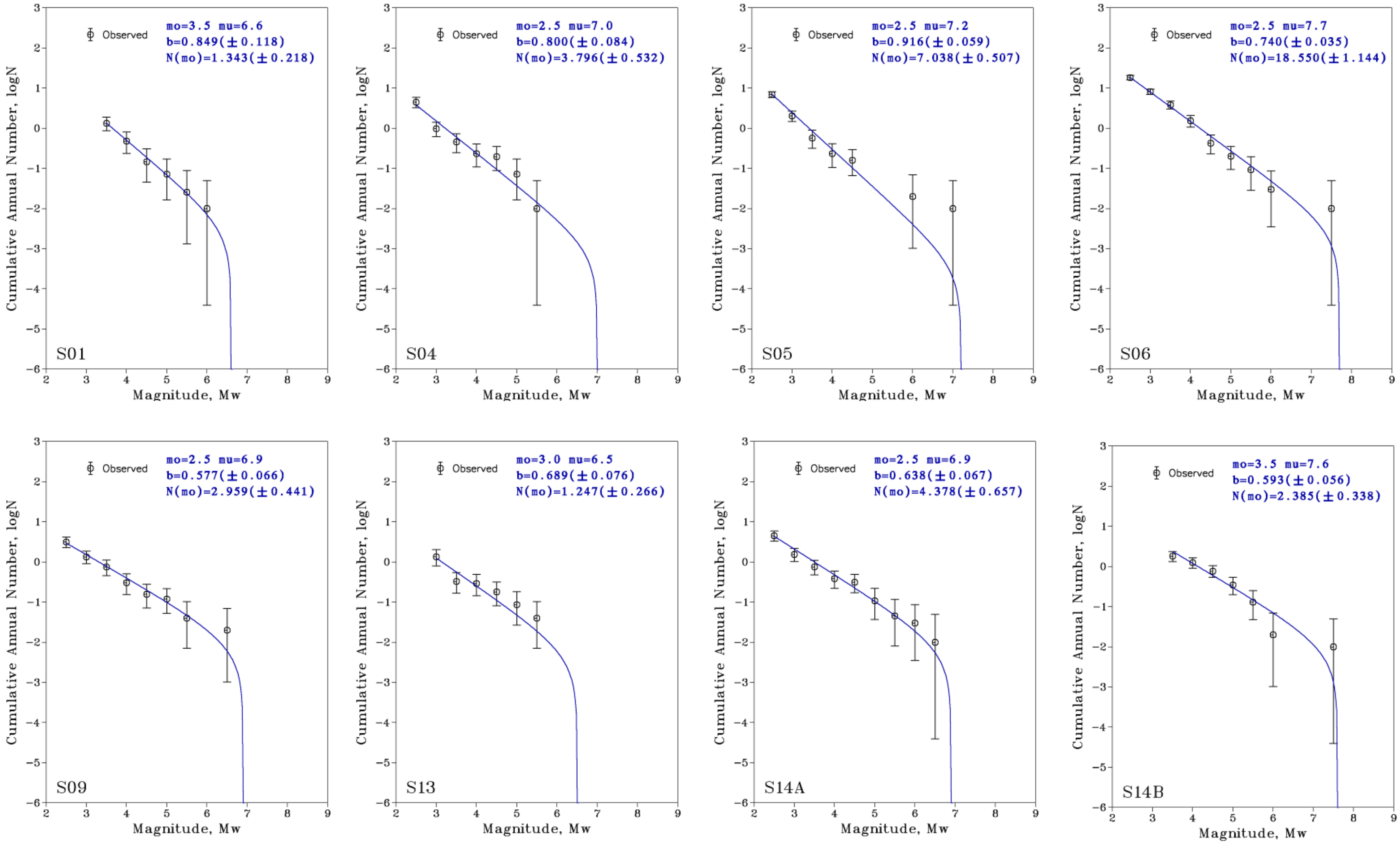
1.Lee et.al., (1995); 2.Wang, C.Y., & Lee, C.T., (1997); 3.Lee, C.T., (1998); 4.Chen et.al., (1994); 5.Ku, C.C. (1963); 6.Bonilla, M.G. (1975); 7 Shih et.al. (1983); 8.Hanal, S., (1929); 9.Lee, C.T., (1996); 10.Tang, C.H., (1964); 11.Tang, C.H., (1968); 12.Tang, C.H. & Hsu, C.H., (1970); 13.Chang, S.L., (1972); 14.Shih et.al., (1985); 15.Chen, J.S., (1974); 16.Hsu, T.L. & Chang, H.C., (1979); 17.Huang, C.S., (1984); 18.Chiang, S.C., (1970); 19.Earthquake Research Institute (1936); 20.Ooe, Z., (1936); 21. Chang, L.S., (1951); 22.Chiu, H.T., (1962); 23.Meng, C.Y., (1963); 24.Tang, C.H., (1969); 25.Chang, S.L., (1971); 26.Shih et.al., (1984); 27.Lee, J.F., (1994); 28.Chang, H.C., (1994); 29.Chiu, H.T., (1972); 30.Lee. C. T., (1996); 31. Chinese Petroleum Corporation (1986); 32.Omori, F., (1907); 33.Sun, S.C., (1970); 34.Sun, S.C., (1971); 35.Lee et.al., (1994); 36.Tsan, S.F. & Keng, W.P., (1968); 37.Sinotech Engineering Consultants, Inc.(1989); 38.Huang et.al., (1994); 39.Shih et.al., (1986); 40.Chang et.al., (1947); 41.Chinese Petroleum Corporation (1989); 42.Yang, G.S., (1986); 43.Sun, S.C., (1964); 44.Hsieh, S.H., (1970); 45.Tomita, Y., (1955); 46.Hsu, C.M., (1986); 47. Ishizaki K., (1942); 48.Pan, Y.S., (1968); 49.Cheng, Y.M. & Huang, C.Y., (1975); 50.This study; 51.Bonilla, M.G., (1976); 52.Cheng, K.C., (1960); 53.Hsu, M.T., (1971); 54.Hsu, T.L., (1962); 55.York, J.E., (1976); 56.Ku, C.C., (1964); 57.Hsu, T.L., (1976); 58.Chen et.al., (1991); 59.Lin et.al., (1999)

Characterization of Active Fault Sources in Taiwan

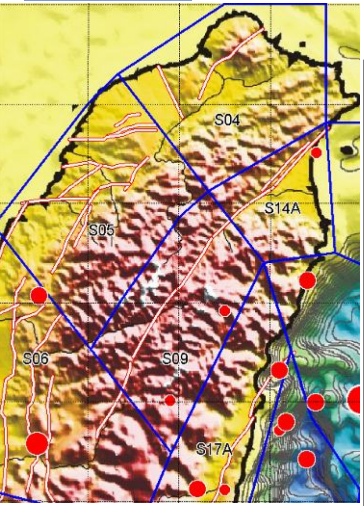
Weighting inside the parentheses

Reginal source	Fault No.	Fault Name	Strike	Dip (Degree)	dip	Fault mechanism	Fault length (km)	fault rupture depth(km)		fault rupture width(km)	displacement (m)	Max. rupture area(km^2)	fault slip rate(mm/yr) Associated Weights (in Parentheses)	Max. Magnitude Mu Associated Weights (in Parentheses)	Characteristic Earthquake recurrence interval(year)		
								Top	Bottom						Younngs and Coppersmith, 1985	Matsuda, 1975	Bolina, 1970
S04	01+02+03	Huangchi + Hsiaoyukeng + Sanchiao	NNE	60SE	60	Norma & Sinistral	36	0	15	17	1.8	624	1.0(0.2) 2.0(0.6) 3.0(0.2)	6.8(0.2) 7.0(0.6) 7.2(0.2)	543	746	568
	04	Nankan	NNW	80NW	80	Normal& Dextral	22	0	10	10	0.7	223	0.2(0.2) 0.4(0.6) 0.6(0.2)	6.3(0.2) 6.5(0.6) 6.7(0.2)	1352	1896	1492
S05	05	Shuanglienpo	ENE	50SE	50	Reverse	12	2	10	10	0.4	125	0.2(0.2) 0.5(0.6) 0.8(0.2)	6.0(0.2) 6.2(0.6) 6.4(0.2)	567	1036	831
	06	Yangmei	ENE	50NW	50	Reverse	20	2	10	10	0.8	261	0.2(0.2) 0.5(0.6) 0.8(0.2)	6.4(0.2) 6.6(0.6) 6.8(0.2)	1082	1704	1334
	07	Hukou	ENE	45SE	45	Thrust	32	0	12	17	1.5	543	0.5(0.2) 1.0(0.6) 1.5(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	733	1362	1041
	08	Hsinchu	E-W	45S	45	Thrust	28	0	12	17	1.4	475	0.8(0.2) 1.5(0.6) 2.3(0.2)	6.6(0.2) 6.8(0.6) 7.1(0.2)	395	832	639
	09	Tapingti	NNE	45SE	45	Thrust	15	0	12	17	0.8	255	0.3(0.2) 0.6(0.6) 0.9(0.2)	6.3(0.2) 6.5(0.6) 6.8(0.2)	653	1378	1080
	10	Chutung	NE	50SE	50	Reverse	14	0	12	16	0.7	219	0.3(0.2) 0.6(0.6) 0.9(0.2)	6.3(0.2) 6.5(0.6) 6.7(0.2)	760	1249	983
	11	Hsincheng	N40E	45SE	45	Thrust	22	0	12	17	1.1	373	1.0(0.2) 2.0(0.6) 3.0(0.2)	6.5(0.2) 6.7(0.6) 7.0(0.2)	267	532	412
	12	Touhungping	E-W	80S	80	Dextral	27	0	12	12	1.0	329	1.3(0.2) 2.5(0.6) 3.8(0.2)	6.5(0.2) 6.7(0.6) 6.9(0.2)	242	392	304
	13	Szetan	N10E	75W	75	Reverse	35	0	12	12	1.3	435	1.3(0.2) 2.5(0.6) 3.8(0.2)	6.6(0.2) 6.8(0.6) 7.0(0.2)	259	471	362
	14	Shinchoshan	N10E	60E	60	Reverse	16	0	12	14	0.7	222	1.3(0.2) 2.5(0.6) 3.8(0.2)	6.3(0.2) 6.5(0.6) 6.7(0.2)	180	302	238
	14BT	Miaoli blind thrust	N10E	30E	30	Reverse & Dextral	37	2	15	26	2.6	962	2.5(0.2) 5.0(0.6) 7.5(0.2)	7.0(0.2) 7.2(0.6) 7.4(0.2)	223	397	298
S06	15	Tuntzechiao	N60E	90	90	Dextral	20	0	15	15	0.9	300	1.3(0.2) 2.5(0.6) 3.8(0.2)	6.4(0.2) 6.6(0.6) 6.8(0.2)	226	368	287
	16	Sanyi	NNE	40E	40	Thrust	22	0	15	23	1.5	513	0.5(0.2) 1.0(0.6) 1.5(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	940	1313	1005
	17	Chelungpu	N-S	40E	40	Thrust	90	0	20	31	6.8	2800	8(0.2) 15(0.6) 23(0.2)	7.5(0.2) 7.7(0.6) 7.9(0.2)	182	268	194
	18	Changhua	NNS	30E	28	Thrust	85	2	15	28	5.4	2354	8(0.2) 15(0.6) 23(0.2)	7.4(0.2) 7.6(0.6) 7.8(0.2)	153	226	165
	19	Tamopu-Hsuangtung	N-S	45E	45	Thrust	70	0	15	21	3.8	1485	0.4(0.2) 0.8(0.6) 1.2(0.2)	7.2(0.2) 7.4(0.6) 7.6(0.2)	2282	3306	2444
	20	Shuilikeng	N-S	50E	50	Thrust	32	0	15	20	1.8	627	0.3(0.2) 0.6(0.6) 0.9(0.2)	6.8(0.2) 7.0(0.6) 7.2(0.2)	1810	2495	1898
	21	Chenyulanchi	N-S	50E	50	Thrust	36	0	15	20	2.0	705	0.4(0.2) 0.8(0.6) 1.2(0.2)	6.8(0.2) 7.0(0.6) 7.3(0.2)	1207	2023	1533
S14A	39	Ilan	NE	60SE	60	Normal	30	0	15	17	1.5	520	0.8(0.2) 1.5(0.6) 2.3(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	623	882	675
	40	Chiaochi	NE	60SE	60	Normal	25	0	15	17	1.3	433	1.0(0.2) 2.0(0.6) 3.0(0.2)	6.6(0.2) 6.8(0.6) 7.0(0.2)	397	587	452
	41a	Lishan(a)	NNE	60E	60	Normal	30	0	15	17	1.5	520	0.8(0.2) 1.5(0.6) 2.3(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	623	882	675
S09	41b	Lishan(b)	NNE	60E	60	Normal	25	0	15	17	1.3	433	0.6(0.2) 1.2(0.6) 1.8(0.2)	6.6(0.2) 6.8(0.6) 7.0(0.2)	666	978	753
	41c	Lishan(c)	NNE	60E	60	Normal	30	0	15	17	1.5	520	0.5(0.2) 1.0(0.6) 1.5(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	940	1323	1013
	41d	Lishan(d)	NNE	60E	60	Normal	30	0	15	17	1.5	520	0.5(0.2) 1.0(0.6) 1.5(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	940	1323	1013

Truncated Exponential Model for Regional/Areal, Intraslab Sources



Characterization of Shallow Crustal areal Sources in Northern Taiwan Depth less than 35km



Source No.	m_o	$\dot{N}(m_o)$ $(\pm\sigma_{\dot{N}(m_o)})$	$b(\pm\sigma_b)$	m_u (Associated Weights in Parentheses)	The largest recorded M_W
S01	3.5	1.343(±0.218)	0.849(±0.118)	6.5 (0.2) 6.6 (0.6) 6.7 (0.2)	**6.2**
S04	2.5	3.796(±0.532)	0.800(±0.084)	6.4(1.0)	**5.6**
S05*	2.5	7.038(±0.507)	0.916(±0.059)	5.0(1.0)	**7.1**
S06*	2.5	18.550(±1.144)	0.740(±0.035)	6.5(1.0)	**7.6**
S09*	2.5	2.959(±0.441)	0.577(±0.066)	6.5(0.0)	**6.7**
S13	3.0	1.247(±0.266)	0.689(±0.076)	6.3(0.2) 6.5(0.6) 6.7(0.2)	**5.8**
S14A*	2.5	4.378(±0.657)	0.638(±0.067)	6.5(1.0)	**6.5**
S14B	3.5	2.385(±0.338)	0.593(±0.056)	7.4 (0.2) 7.6 (0.6) 7.8 (0.2)	**7.5**
S15	3.5	9.262(±0.8031)	0.658(±0.045)	7.4 (0.2) 7.6 (0.6) 7.8 (0.2)	**6.6**
S16*	3.5	9.885(±0.828)	0.644(±0.039)	7.0 (1.0)	**8.2**
S17A*	3.5	1.328(±0.293)	0.520(±0.086)	6.5(1.0)	**7.2**
S17B	3.5	3.790(±0.516)	0.681(±0.070)	7.3 (0.2) 7.5 (0.6) 7.7 (0.2)	**7.2**

*There was at least one active fault within the areal source. Any magnitude of events were larger than m_u (maximum magnitude) would be triggered by active faults as characteristic earthquakes. Therefore, magnitude of event bellow ***m***u assumed as background earthquakes.

Characterization of deep areal Sources in Northern Taiwan
Depth large than 35km

Source No.	m_o	$\dot{N}(m_o)$ $(\pm\sigma_{\dot{N}(m_o)})$	$b(\pm\sigma_b)$	m_u (Associated Weights in Parentheses)	The largest recorded M_W
D01	3.5	3.311(±0.543)	1.043(±0.132)	6.5 (0.2) 6.6 (0.6) 6.7 (0.2)	**6.0**
D02	3.0	3.808(±0.373)	0.896(±0.080)	6.5 (0.2) 6.6 (0.6) 6.7 (0.2)	**6.0**
D04	3.5	1.702(±0.244)	0.734(±0.090)	7.0 (0.2) 7.2 (0.6) 7.4 (0.2)	**6.7**
D05*	3.5	5.312(±0.436)	0.707(±0.049)	6.8 (0.2) 7.0 (0.6) 7.2 (0.2)	**6.3**
D06	3.5	2.107(±0.275)	0.764(±0.081)	6.8 (0.2) 7.0 (0.6) 7.2 (0.2)	**6.3**

Note: D05 and S16 are located in the same Top-View place, but their focal depth are different. Focal depth of D05 is greater 35km and S16 is bellow 35km.

Characterization of Subduction Zone Sources in Northern Taiwan

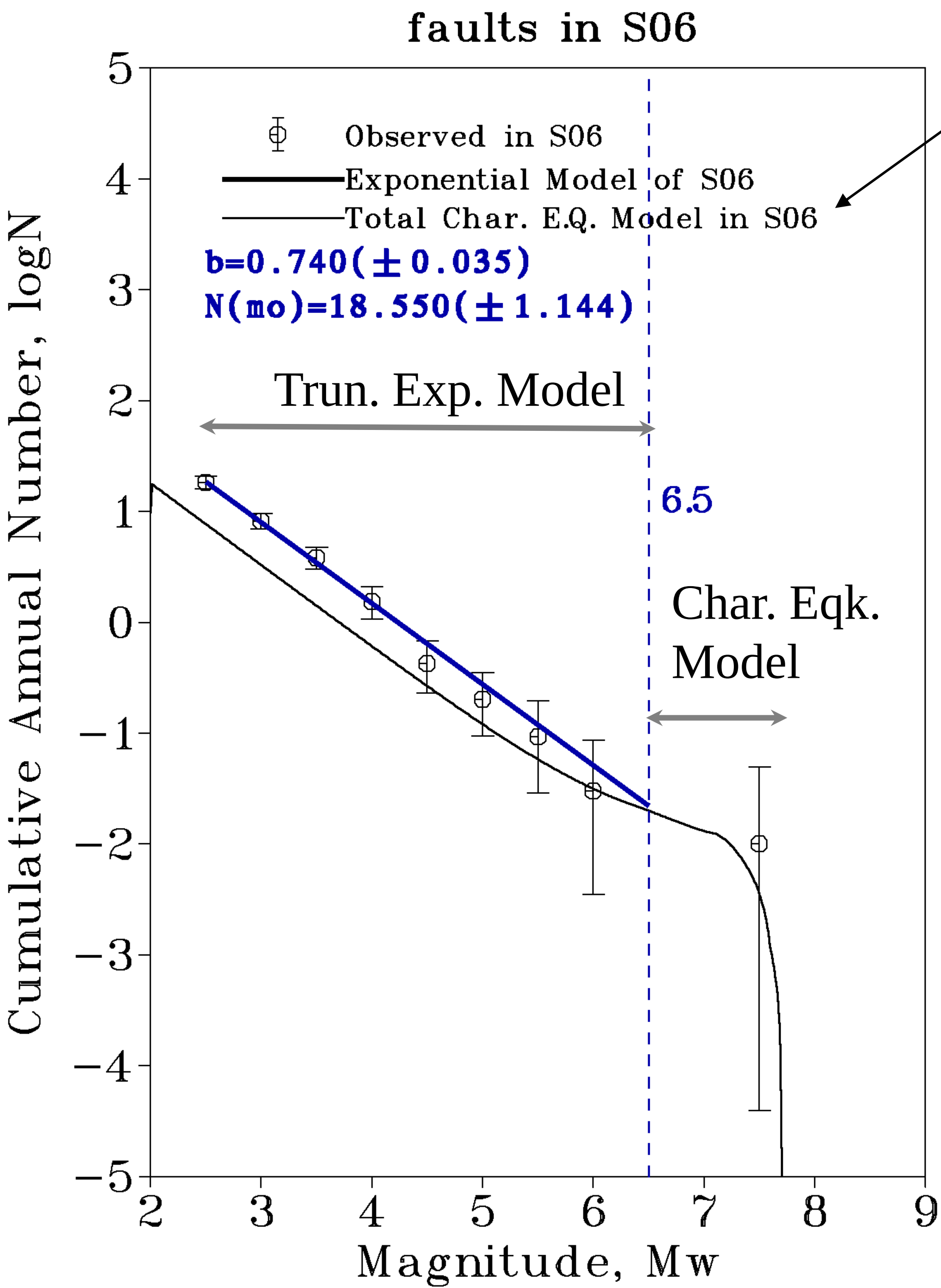
Interface Earthquake source

NO	Name	m_o	Slip rate (mm/yr)	Dip-angle (degree)	Seismogenic depth	b	m_u	The largest recorded M_W
T01*	Interface	6.5	30(0.2) 40(0.6) 50(0.2)	18(0.3) 20(0.4) 22(0.3)	10~40km	0.7	7.8 (0.2) 8.0 (0.6) 8.2 (0.2)	8.2

- T01 interface source is within regional source S16. The earthquakes would be assumed as interface source while the magnitude is grater than MW6.5.
- The dip-angle of interface-plate was illustrated by the depth distribution of seismicity.
- The slip-rate was estimated by **Kao et al.(1998) and Kao et al.(2000).**

Intraslab Earthquake sources

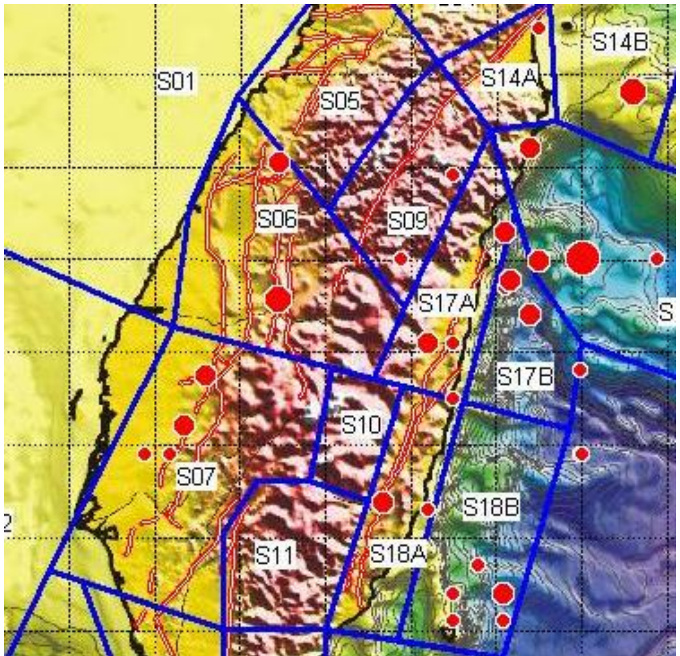
NO	Depth Range	m_o	$\dot{N}(m_o)$ ($\pm\sigma_{\dot{N}(m_o)}$)	$b(\pm\sigma_b)$	m_u			The largest recorded M_W
NP1	35-50km	4.0	3.000(±0.318)	0.884(±0.077)	7.6 (0.2)	7.7 (0.6)	7.8 (0.2)	7.4
NP2	50-70km	4.0	2.441(±0.294)	0.826(±0.085)	7.6 (0.2)	7.7 (0.6)	7.8 (0.2)	6.2
NP3	70-90km	4.0	1.313(±0.214)	0.778(±0.097)	7.6 (0.2)	7.7 (0.6)	7.8 (0.2)	7.2
NP4	90-110km	4.0	0.576(±0.133)	0.797(±0.068)	7.7 (0.2)	7.8 (0.6)	7.9 (0.2)	7.3
NP5	110-130km	4.0	0.309(±0.103)	0.824(±0.071)	7.7 (0.2)	7.8 (0.6)	7.9 (0.2)	7.6
NP6	130-150km	4.0	0.282(±0.0998)	0.861(±0.071)	7.7 (0.2)	7.8 (0.6)	7.9 (0.2)	6.0
NP7	150-170km	4.0	0.409(±0.118)	0.801(±0.070)	7.7 (0.2)	7.8 (0.6)	7.9 (0.2)	7.6
NP8	170-190km	4.0	0.410(±0.114)	0.894(±0.070)	7.7 (0.2)	7.8 (0.6)	7.9 (0.2)	5.4
NP9	190km~	4.0	0.870(±0.174)	0.884(±0.067)	7.7 (0.2)	7.8 (0.6)	7.9 (0.2)	5.9



To summary the annual number of all active faults within areal source S06.

To avoid double counting the rate of seismicity:

- **M>6.5, Char. Eqk. Model, related to active fault**
- **M<=6.5, trun. Exp. Model,** related to background seismicity

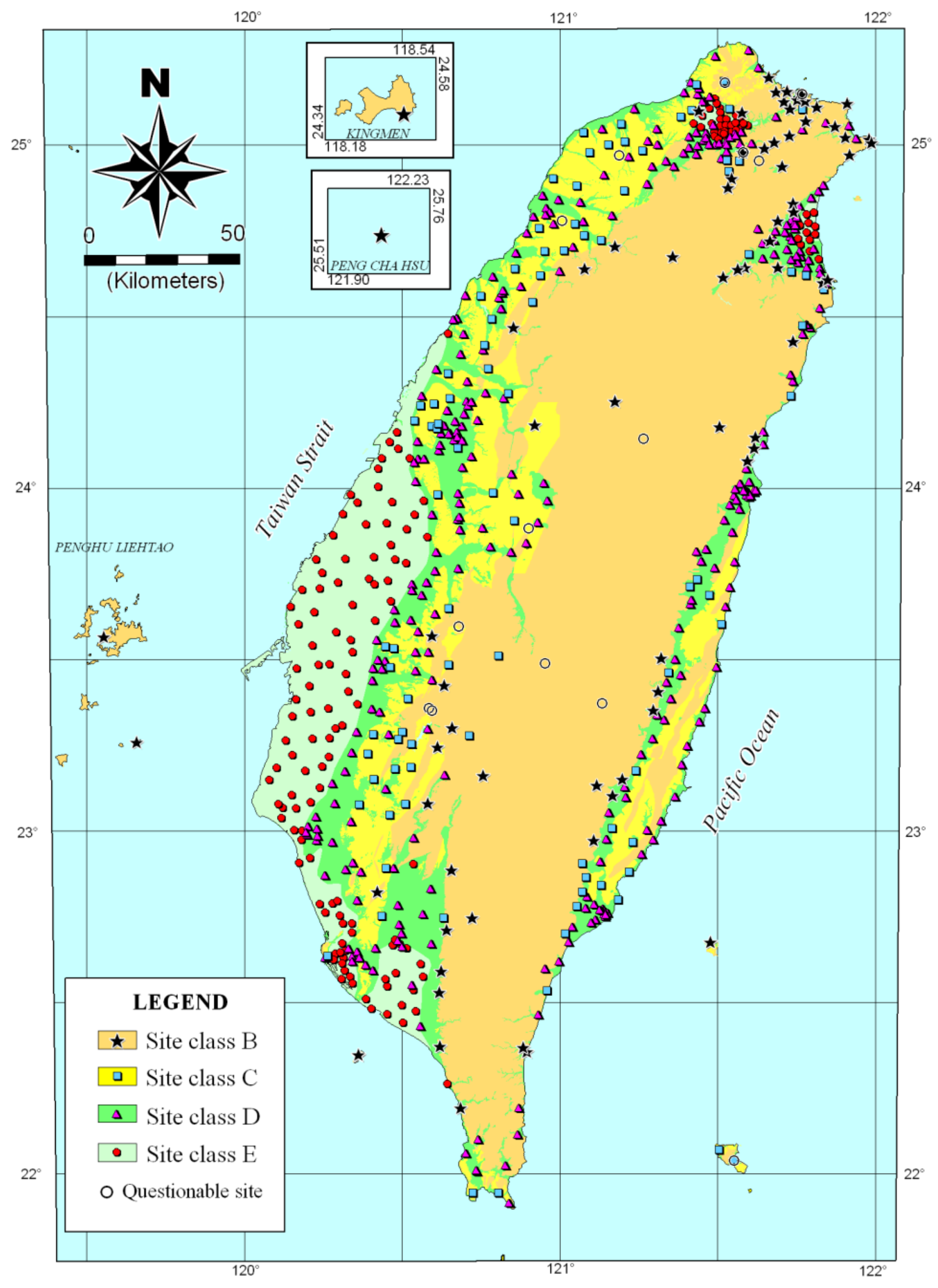


Ground-Motion Estimation after Chi-Chi

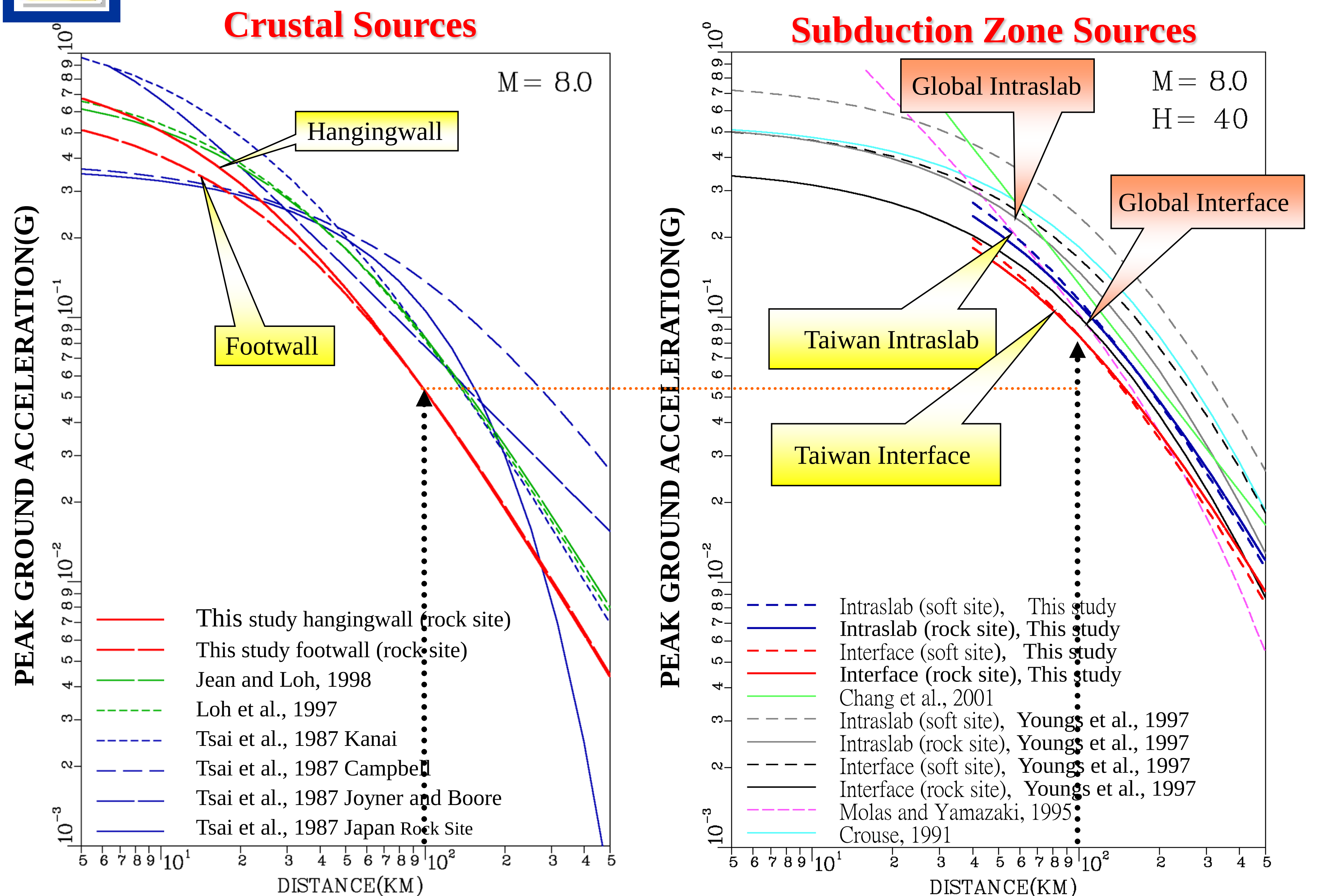
- Chi-Chi earthquake and its after shock provide a great number of ground motion data recorded by TSMIP.
- Site Classification Vs30
  - Average shear-wave velocity of the top 30m of soil NEHRP's drilling of TSMIP stations
  - Site categories B, C, D, E, F (Lee et al., 2001)
- Near fault ground motion data are very valuable for developing ground motion prediction model.

Site Classification for TSMIP Stations (Lee et al, 2001)

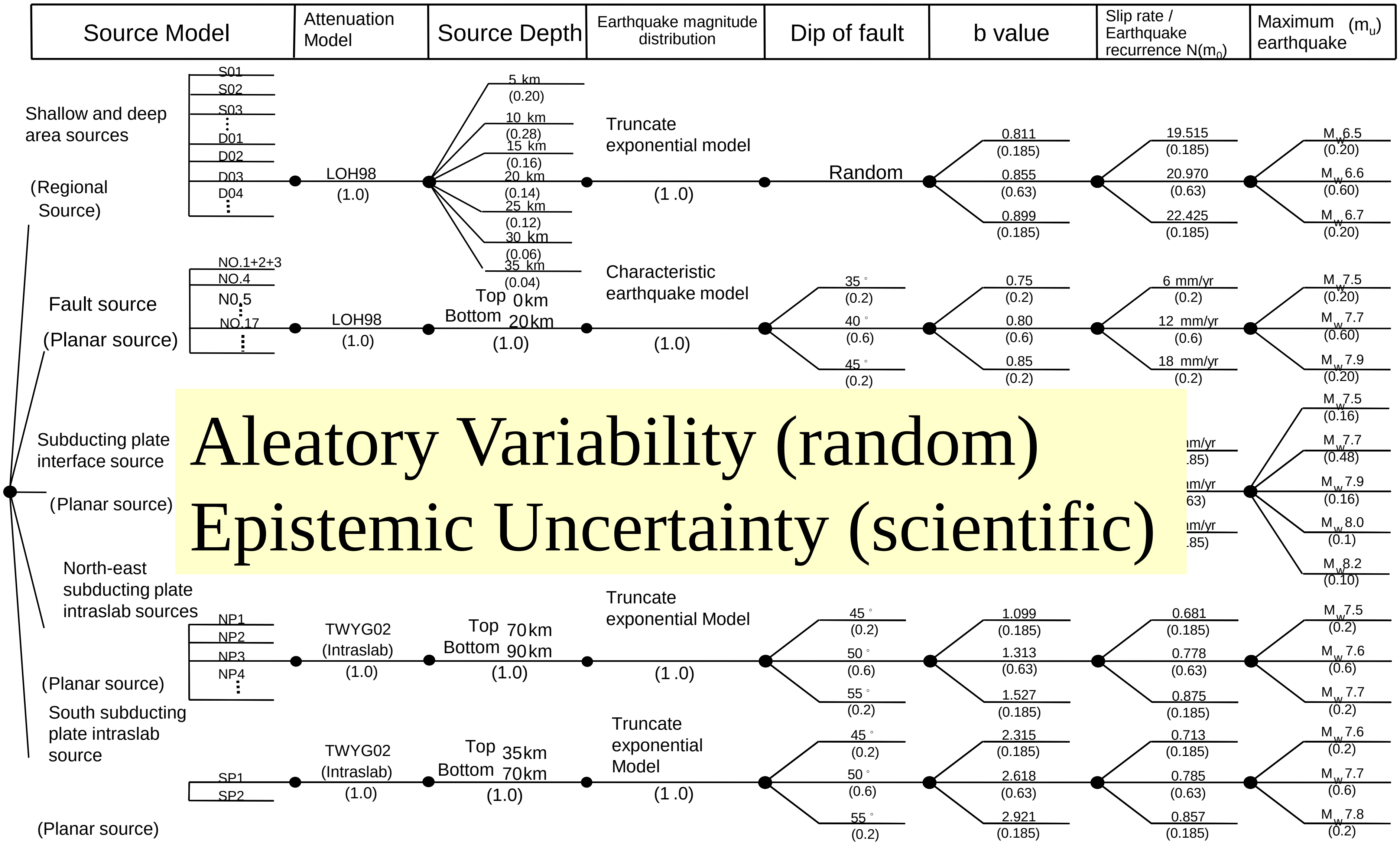
- Capture stable differences in velocity through site categories
  - Surficial geology
    - Rock vs. Soil
    - Age, depositional environment, texture
- Vs_{30} (Average shear-wave velocity of the top 30m of soil) (NEHRP)



Comparison of PGA Attenuation Relations

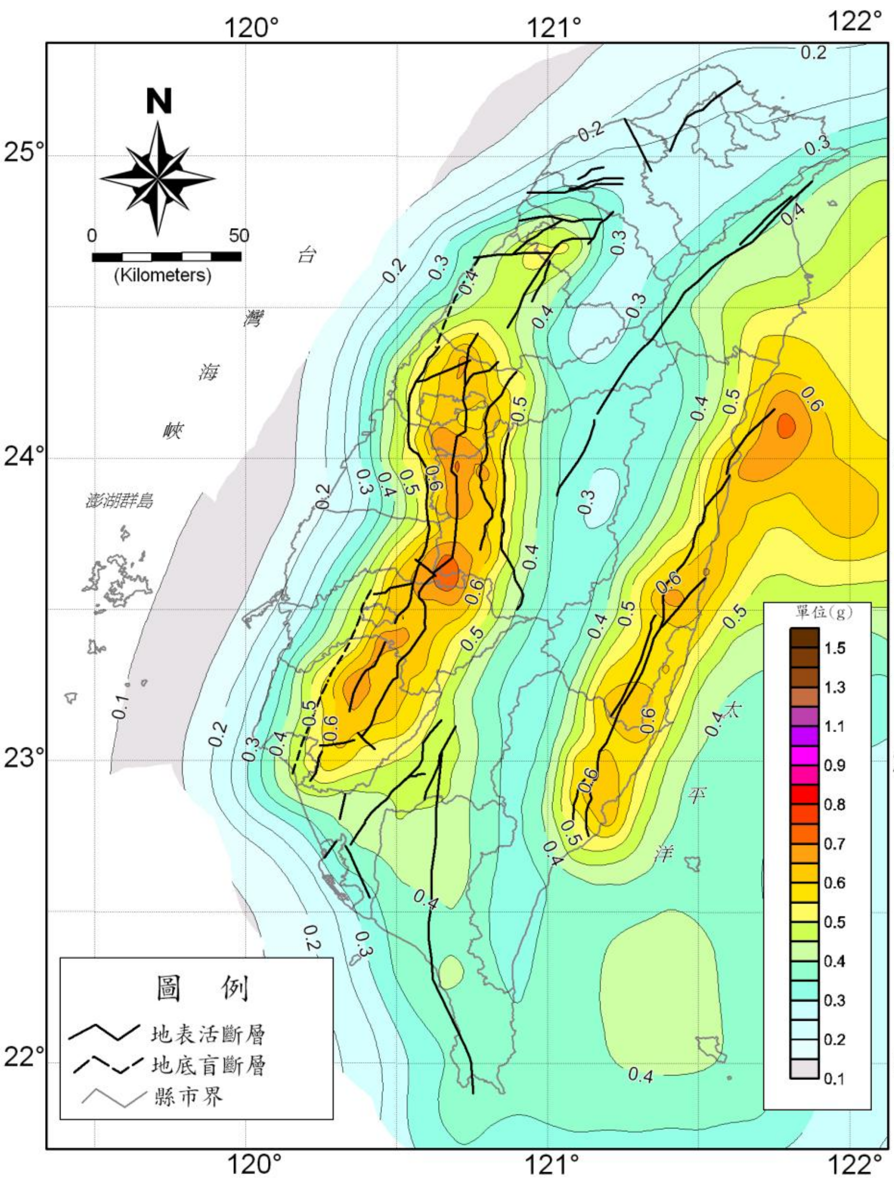


Logic tree used in the PSHA for handling the uncertainty of parameters and models

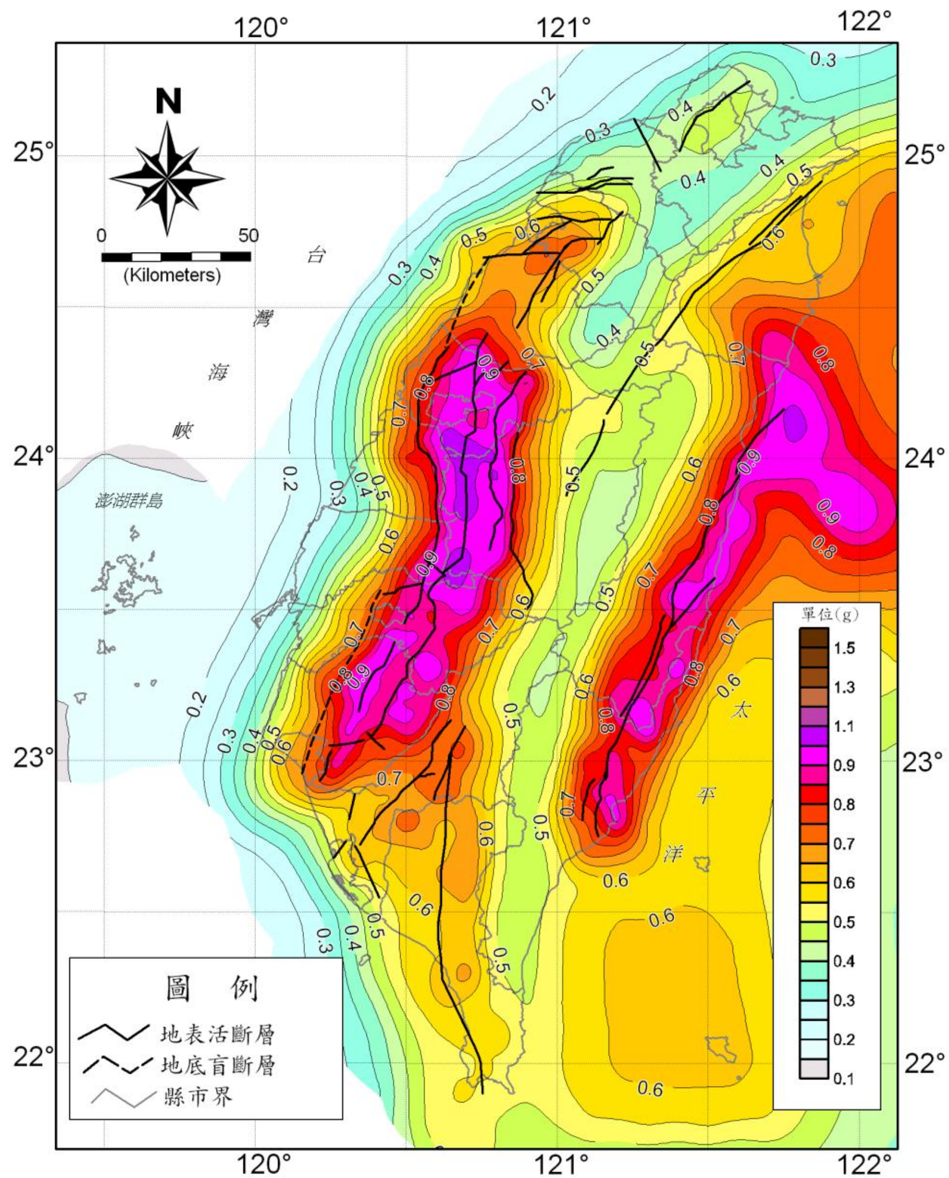


PSHA Result (PGA , rock site)

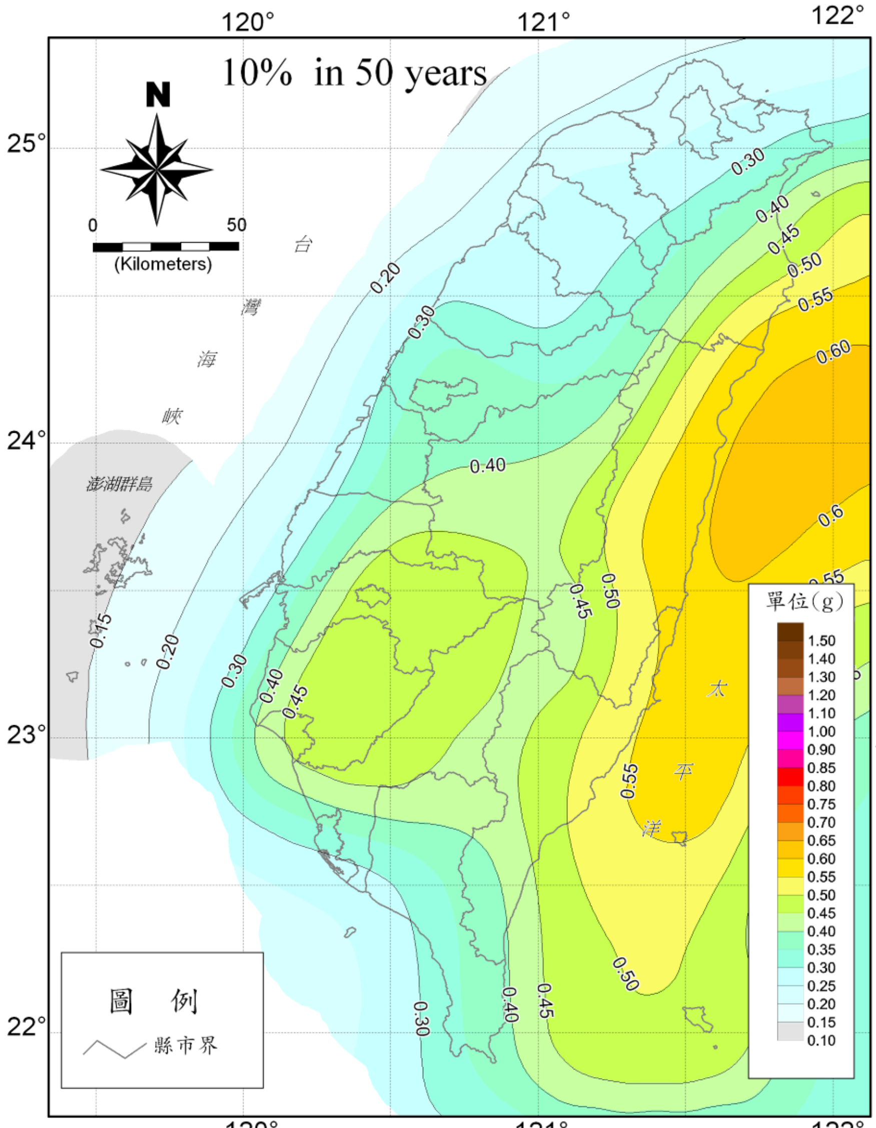
10% Prob. of Exceedance in 50 years



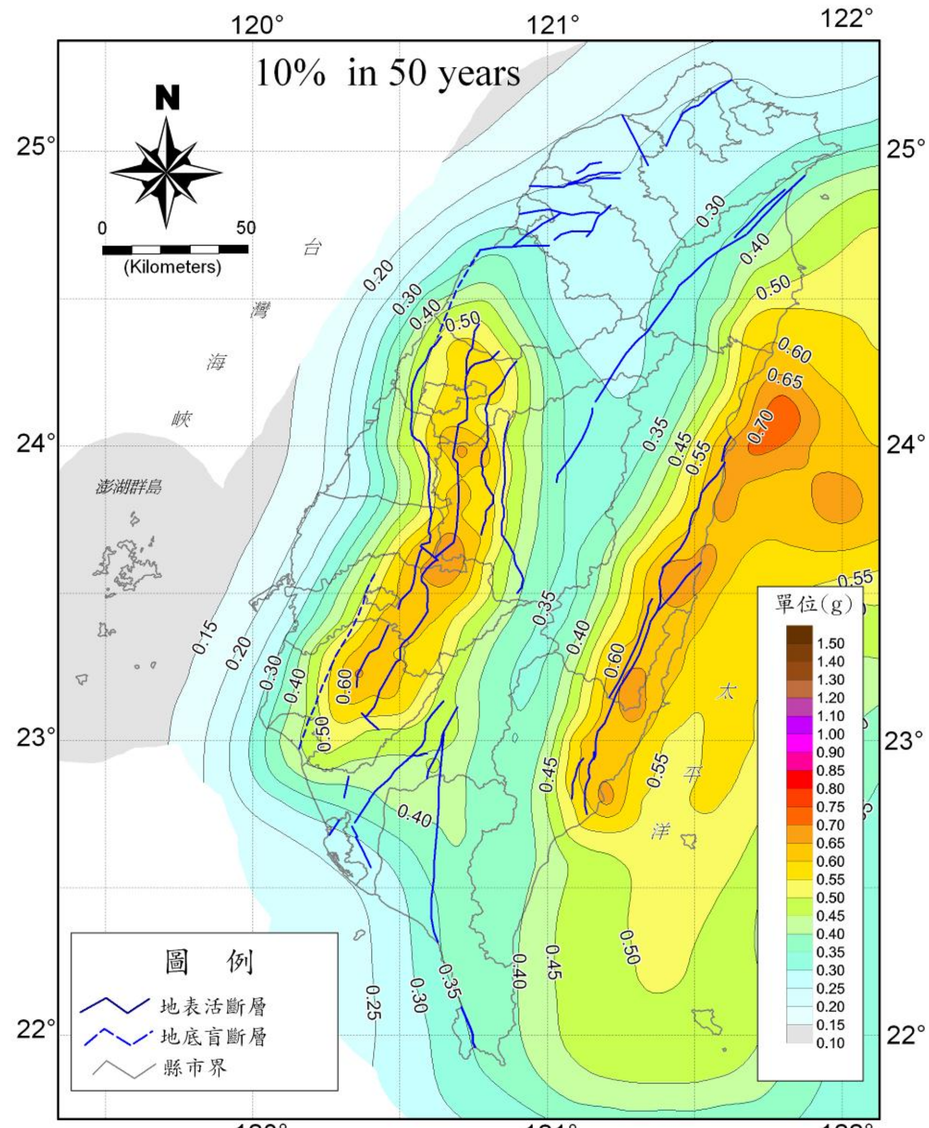
2% Prob. of Exceedance in 50 years



PSHA Result (Fault Sources are Important)



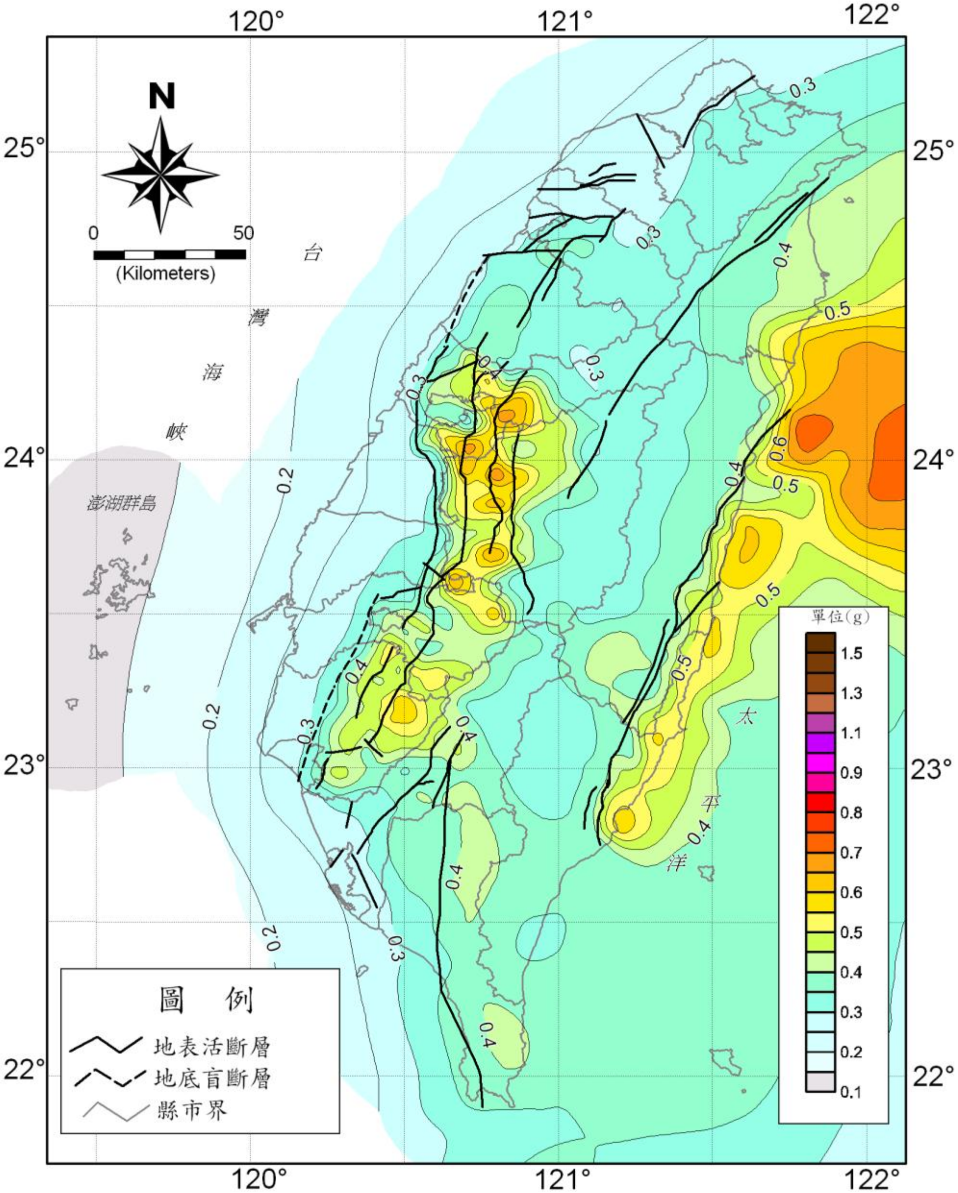
Result of PSHA without considering fault source



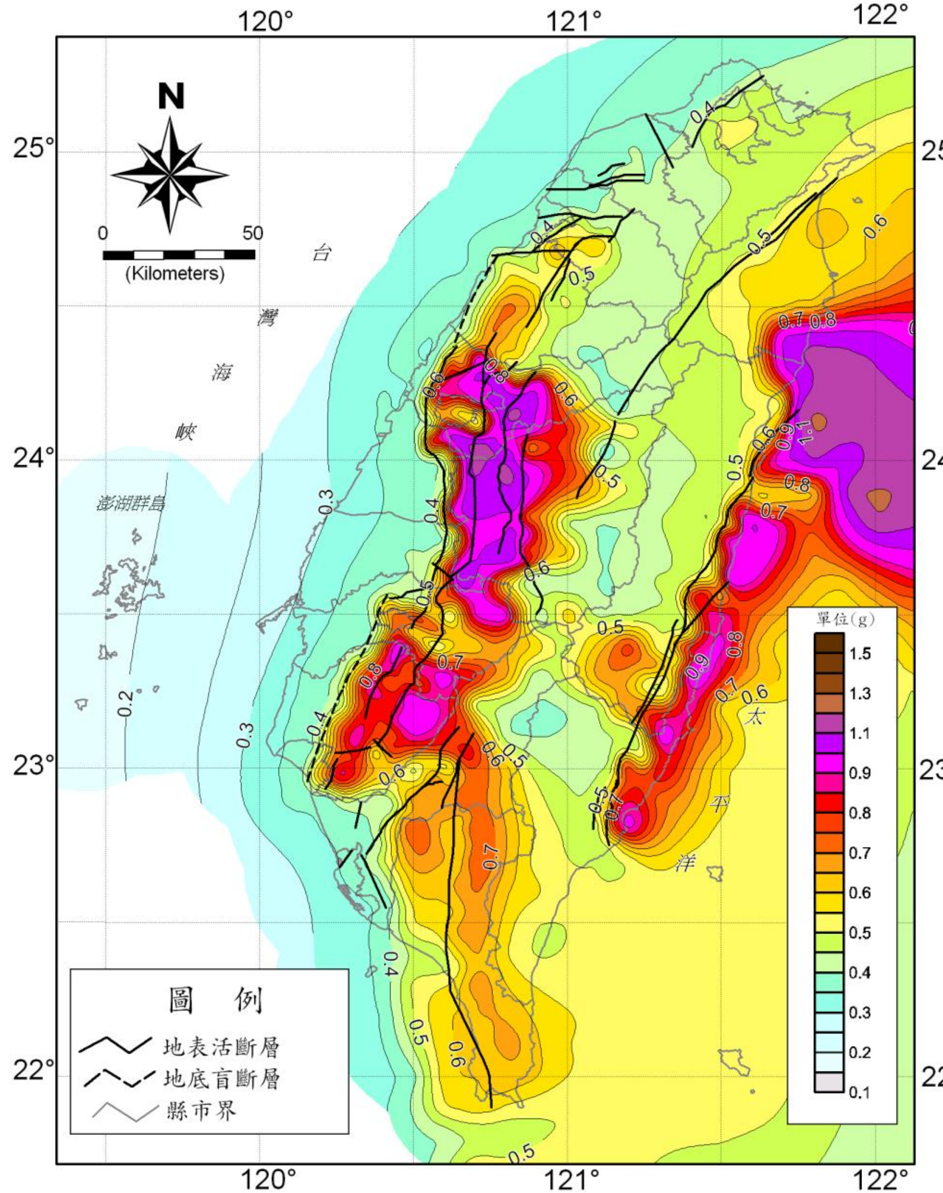
Result of PSHA considering fault source

PSHA Result (Sa=1.0sec, rock site)

10% Prob. of Exceedance in 50 years

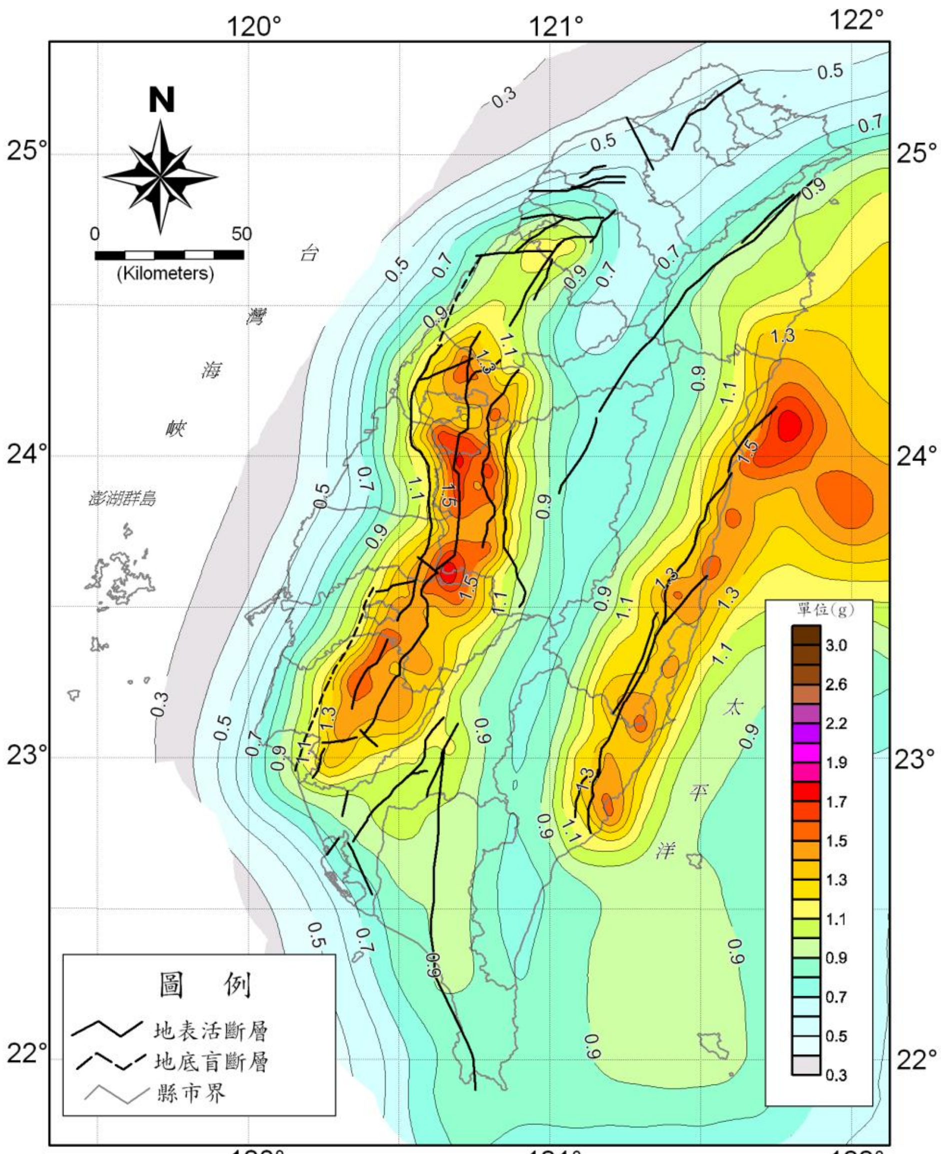


2% Prob. of Exceedance in 50 years

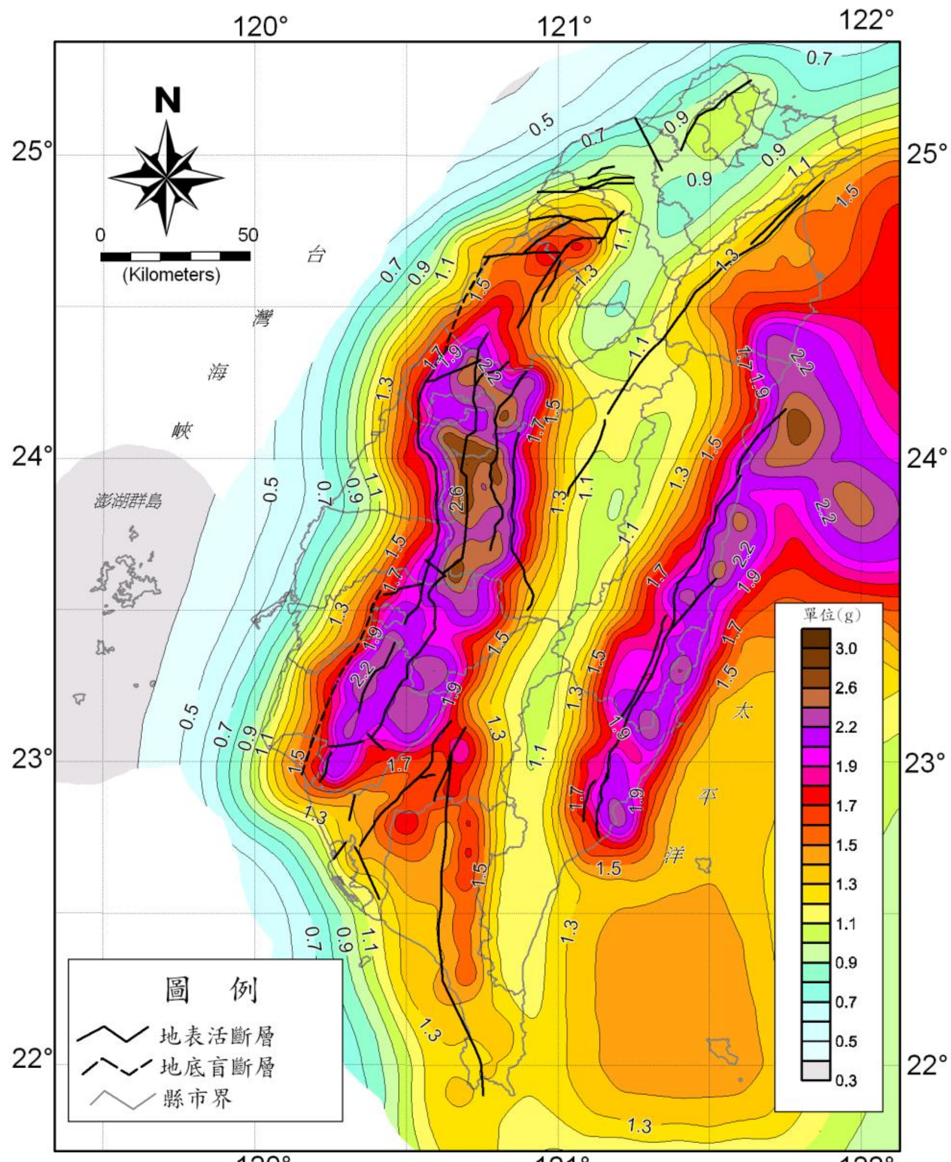


PSHA Result (Sa=0.2 sec, rock site)

10% Prob. of Exceedance in 50 years

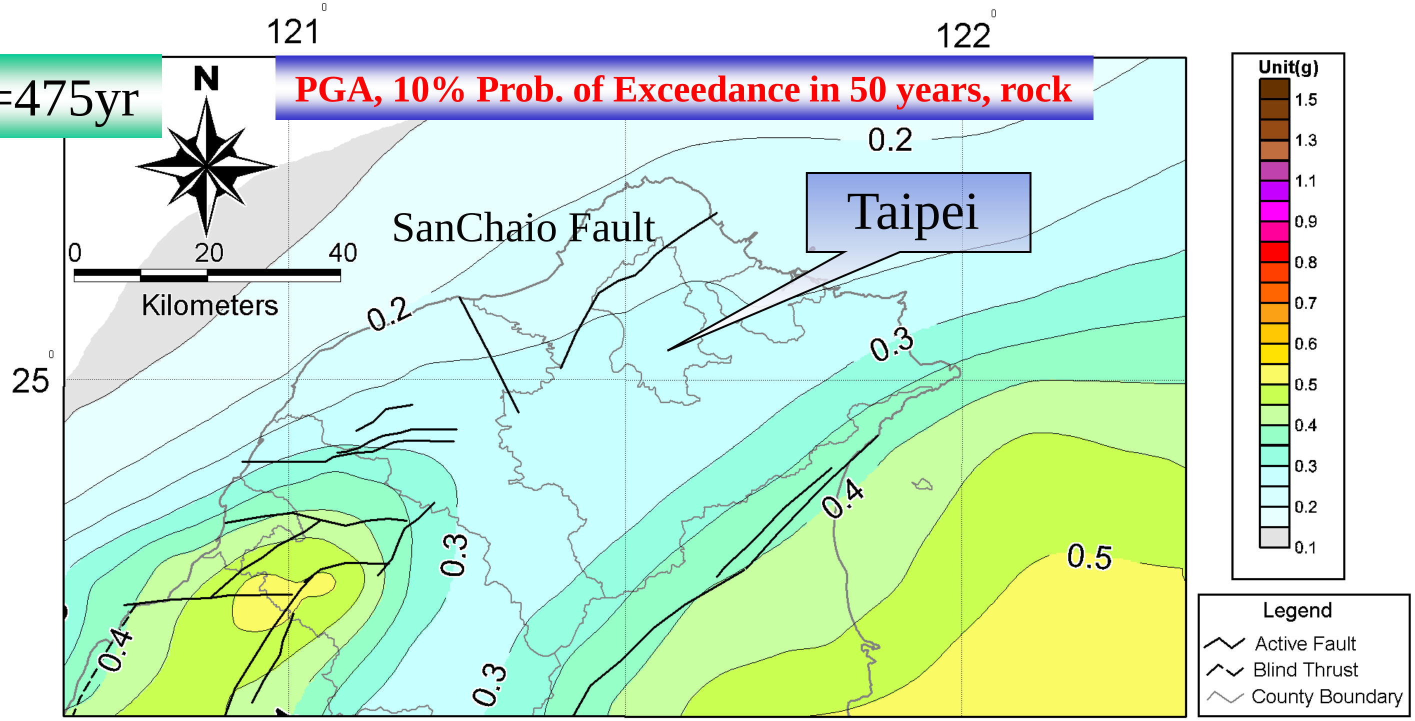


2% Prob. of Exceedance in 50 years

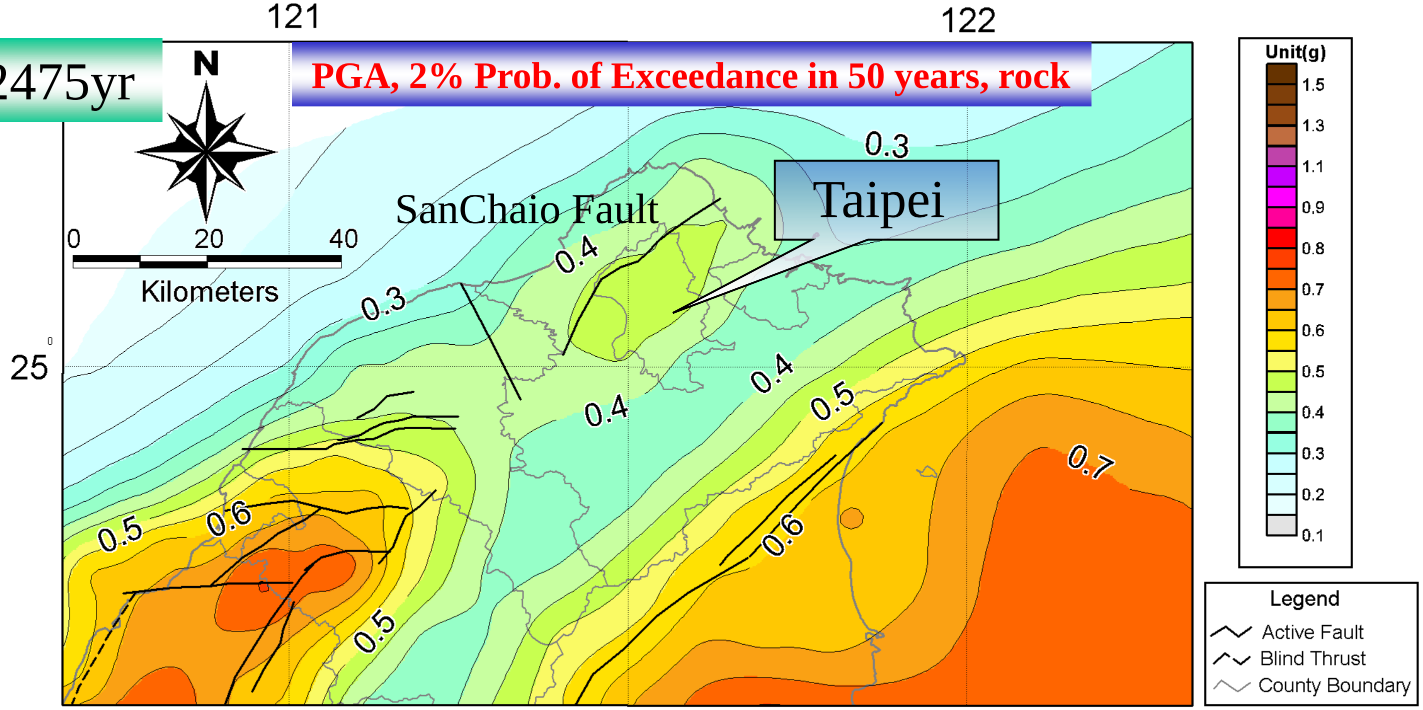


PSHA of Northern Taiwan

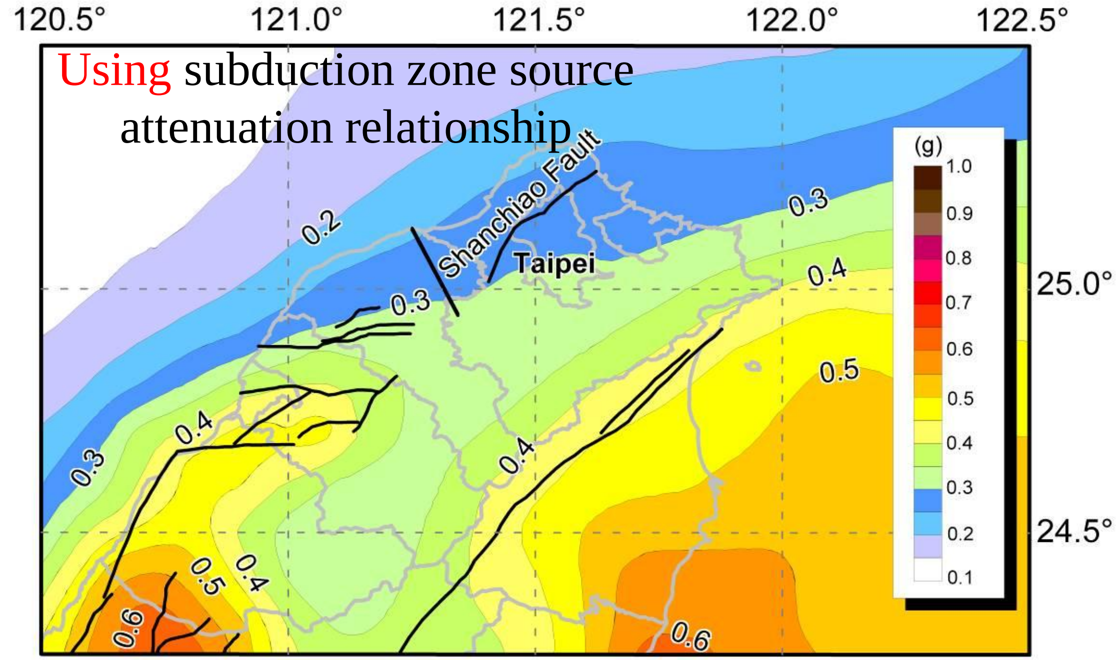
RTP=475yr

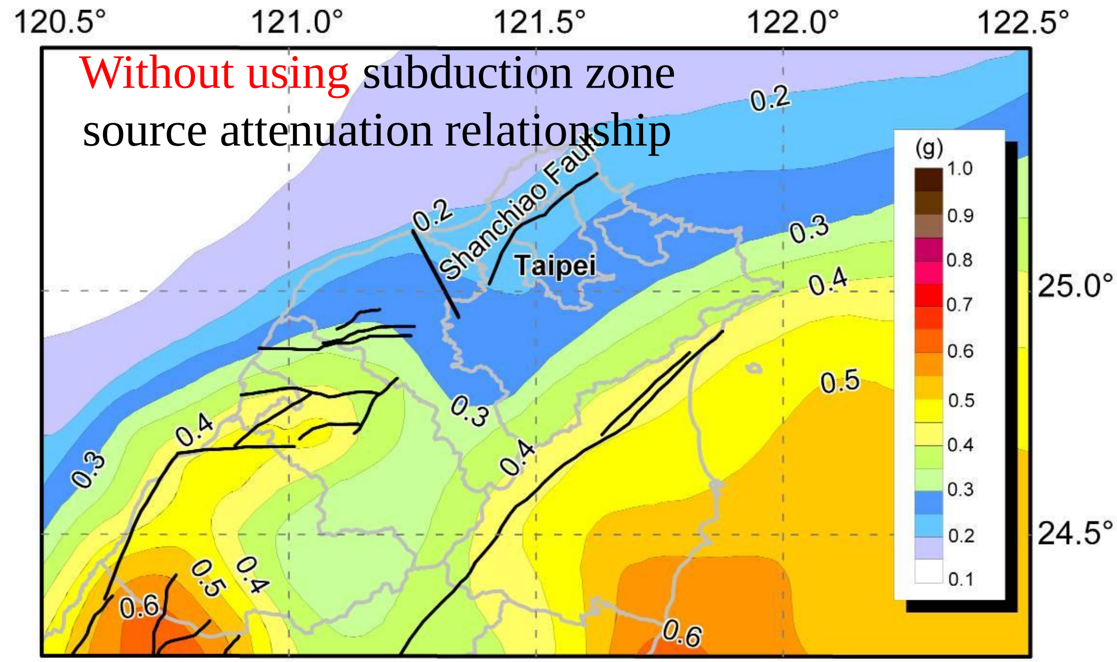


RTP=2475yr

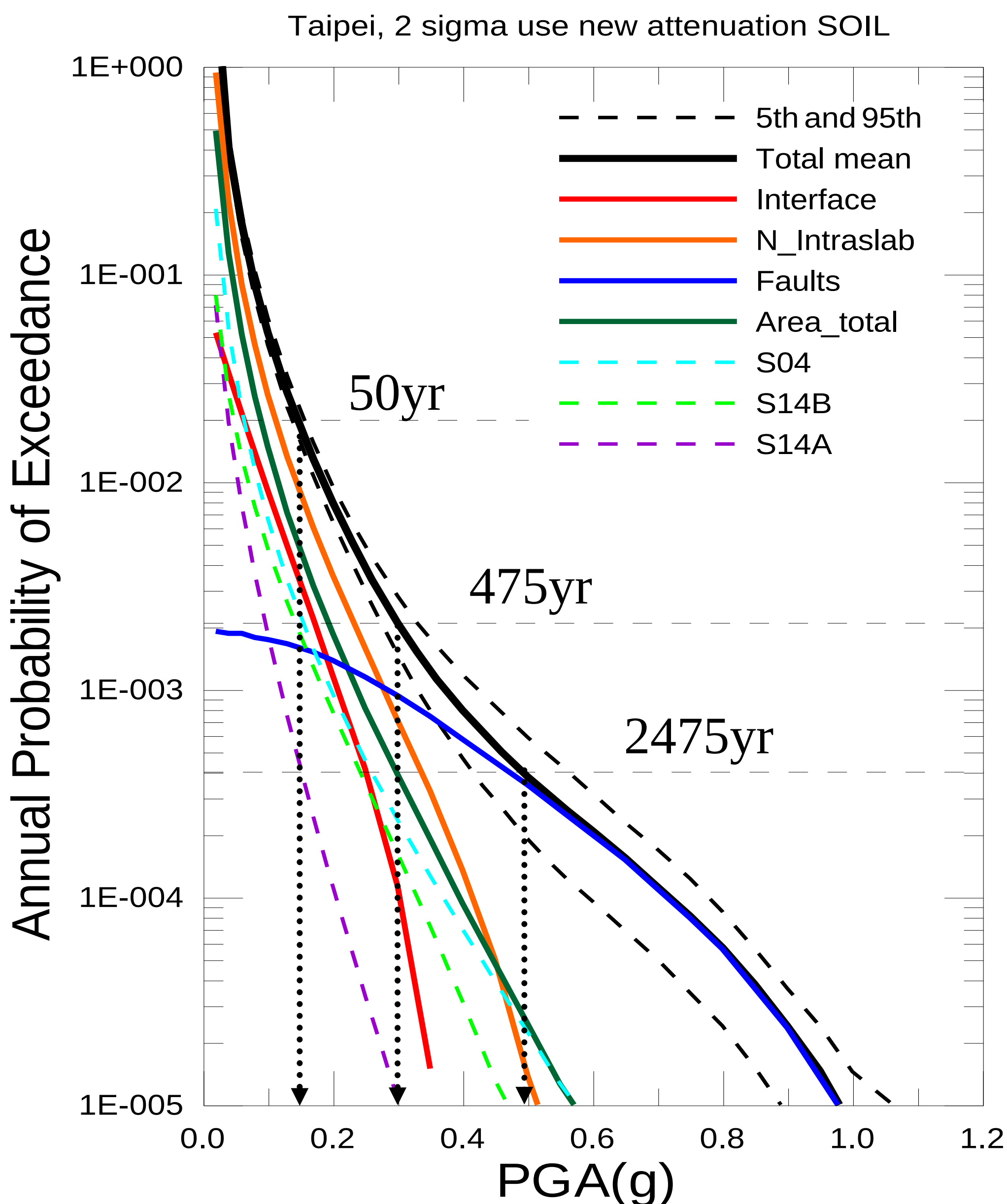


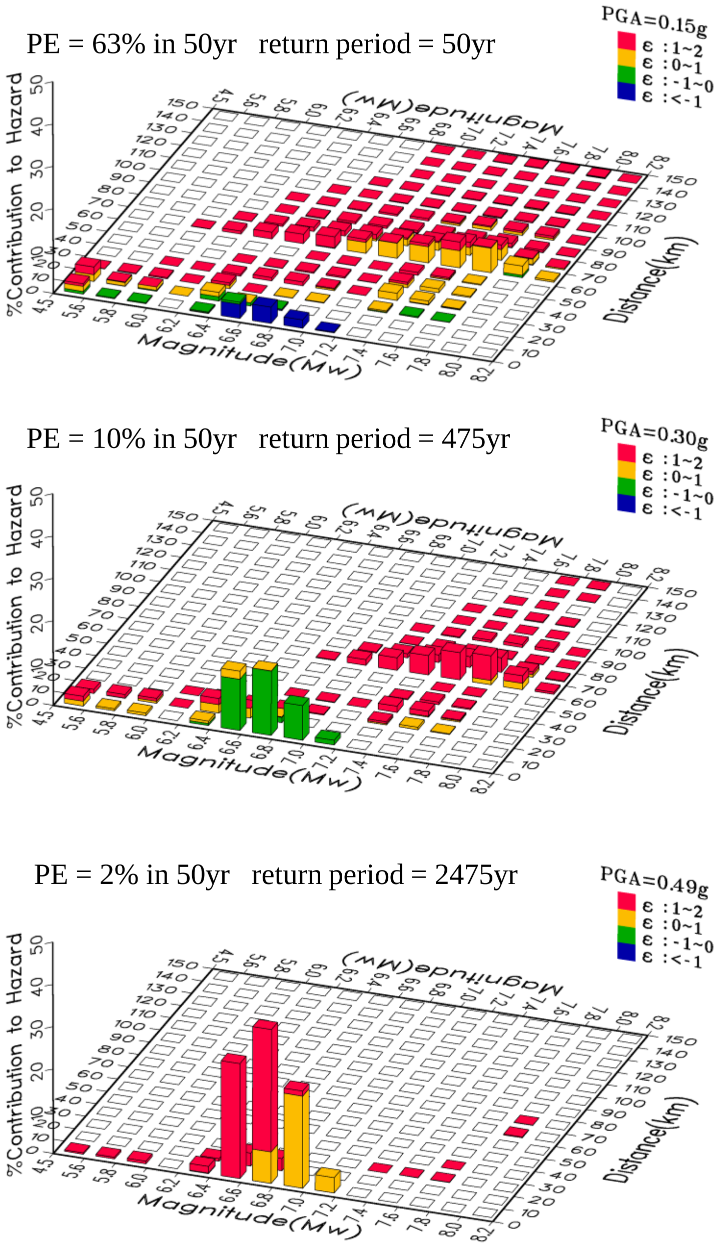
Subduction zone attenuation relationship need to be considered individually





PSHA of Taipei Metropolis





Future Tasks
Next Generation of
Taiwan Earthquake Hazard Map

Future Tasks

- Revision of Seismogenic/Areal Source
- Develop the spatial and temporal relationship of mainsock and aftershock
- Analysis the completeness of earthquake catalogue
- Historical earthquake research
- Development of Taiwan GMPEs (TNGA)
- Max magnitude of Subduction zone (Mega-thrust)
- Active fault parameters (geometry, slip rate) updating
- Time-dependent earthquake probability models (WGCEP, NIED)

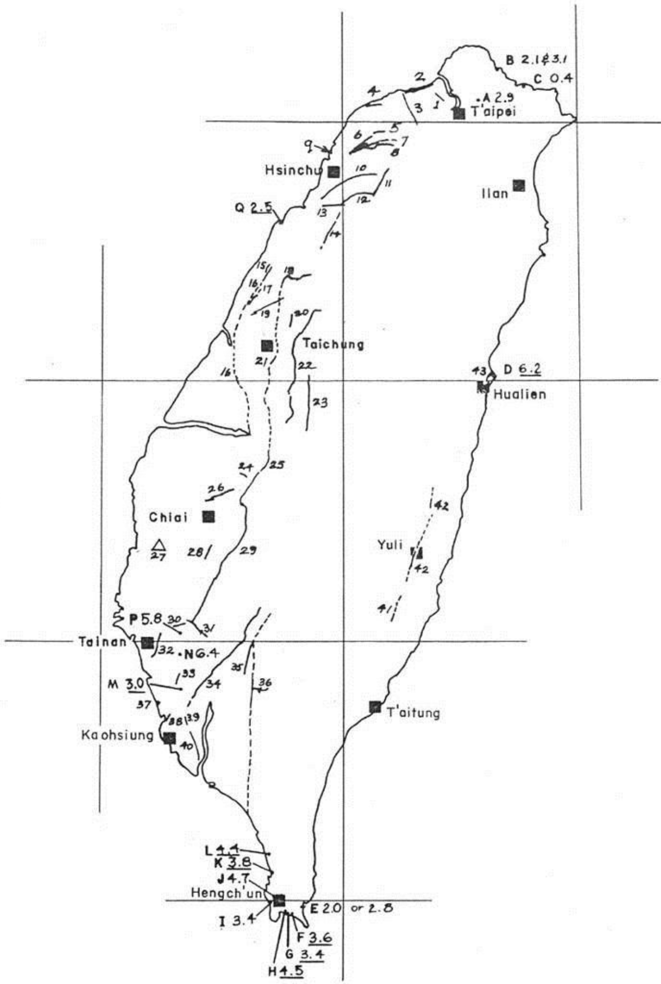
Reference

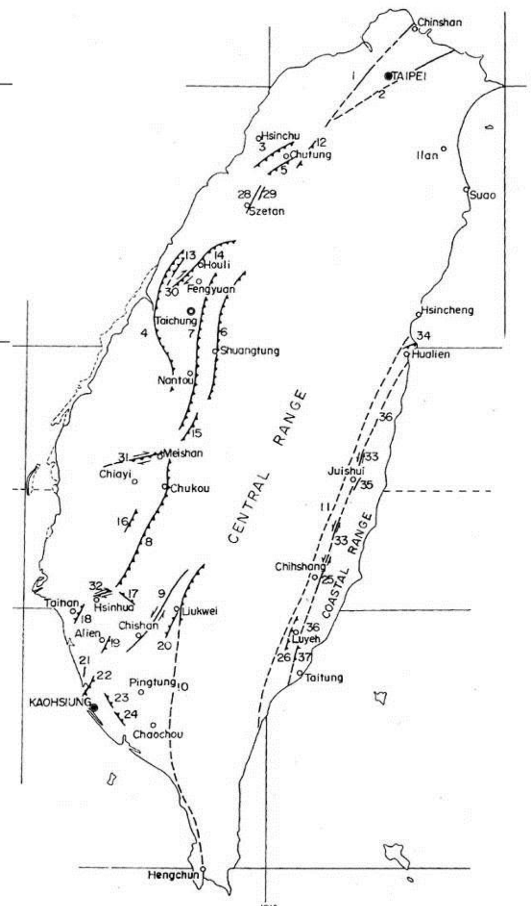
- 鄭錦桐(2002)台灣地區PSHA的不確定分析與參數拆解，中央大學地球物理研究所博士論文，共227頁。
- Lee, C. T. (1999). “Neotectonics and active faults in Taiwan,” *Workshop on Disaster Prevention/ Management and Green Technolgy*, Foster City, CA, U.S.A., 61-74.
- Lee, Chyi-Tyi, Cheng, C.T., Liao, C. W., Tsai, Yi-Ben (2001)Site Classifications of Taiwan Free-Field Strong-Motion Stations, 2001 Bull. Seism. Soc. Am., 91(5), 1283-1297. (SCI)
- Cheng, Chin-Tung, Chiou, Shian-Jin, Lee, Chyi-Tyi, Tsai, Yi-Ben (2007) Study on probabilistic seismic hazard maps of Taiwan after Chi-Chi earthquake, Journal of GeoEngineering, Vol. 1, No. 2. (EI)
- Cheng, Chin-Tung, Lee, Chyi-Tyi, Lin, Po-Shen, Lin, Bor-Shiun, Tsai, Yi-Ben, Chiou, Syi-Jang (2009) Probabilistic Earthqauke Hazard in Taipei Metropolis and Its Surrounding Regions. TAO (Terrestrial, Atmospheric and Ocecnic Sciences), Vol. 21. (SCI)
- Lin, P.S., Lee, Chyi-Tyi (2008) Ground-motion attenuation relationships for subduction zone earthquakes in northeastern Taiwan, Bulletin of the Seismological Society of America, 98(1), 220-240, February, 2008. (SCI)
- Lin, P.S., Lee, Chyi-Tyi, Cheng, C.T., Song, C.H. (2011) Response spectral attenuation relations for shallow crustal earthquakes in Taiwan, Engineering Geology, 121, 150-164. (SCI)

Thanks for Your Attention

Thomas, Chin-Tung Cheng Ph. D. (鄭錦桐)
Email: ctcheng@sinotech.org.tw
TEL: +886-2-27580568#237
http://dptrc.sinotech.org.tw
Disaster Prevention Technology Research Center
Sinotech Engineering Consultants, INC., Taipei, Taiwan

台灣早期不同版本活動斷層分布圖之比較





台灣不同版本活動斷層套疊圖

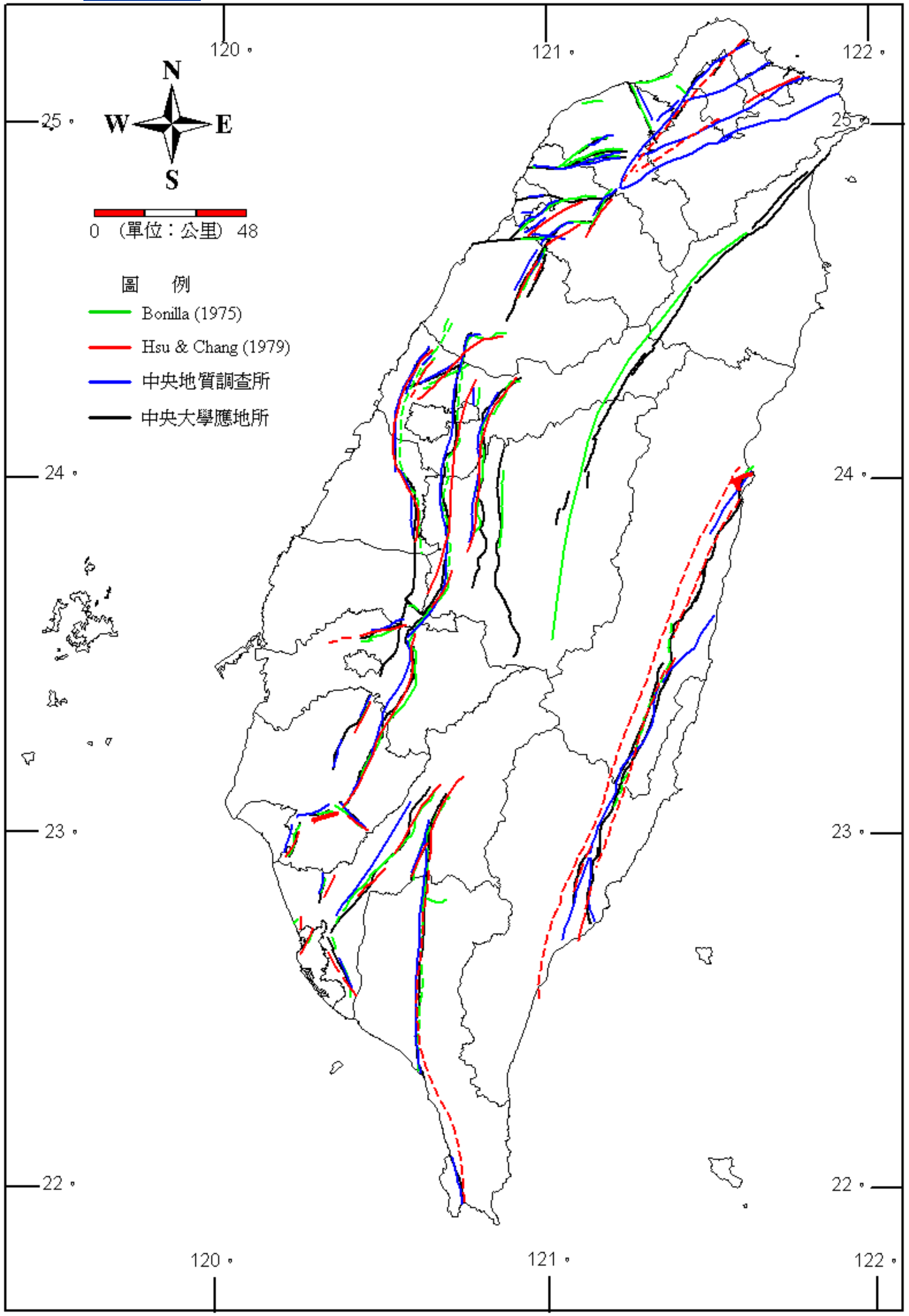
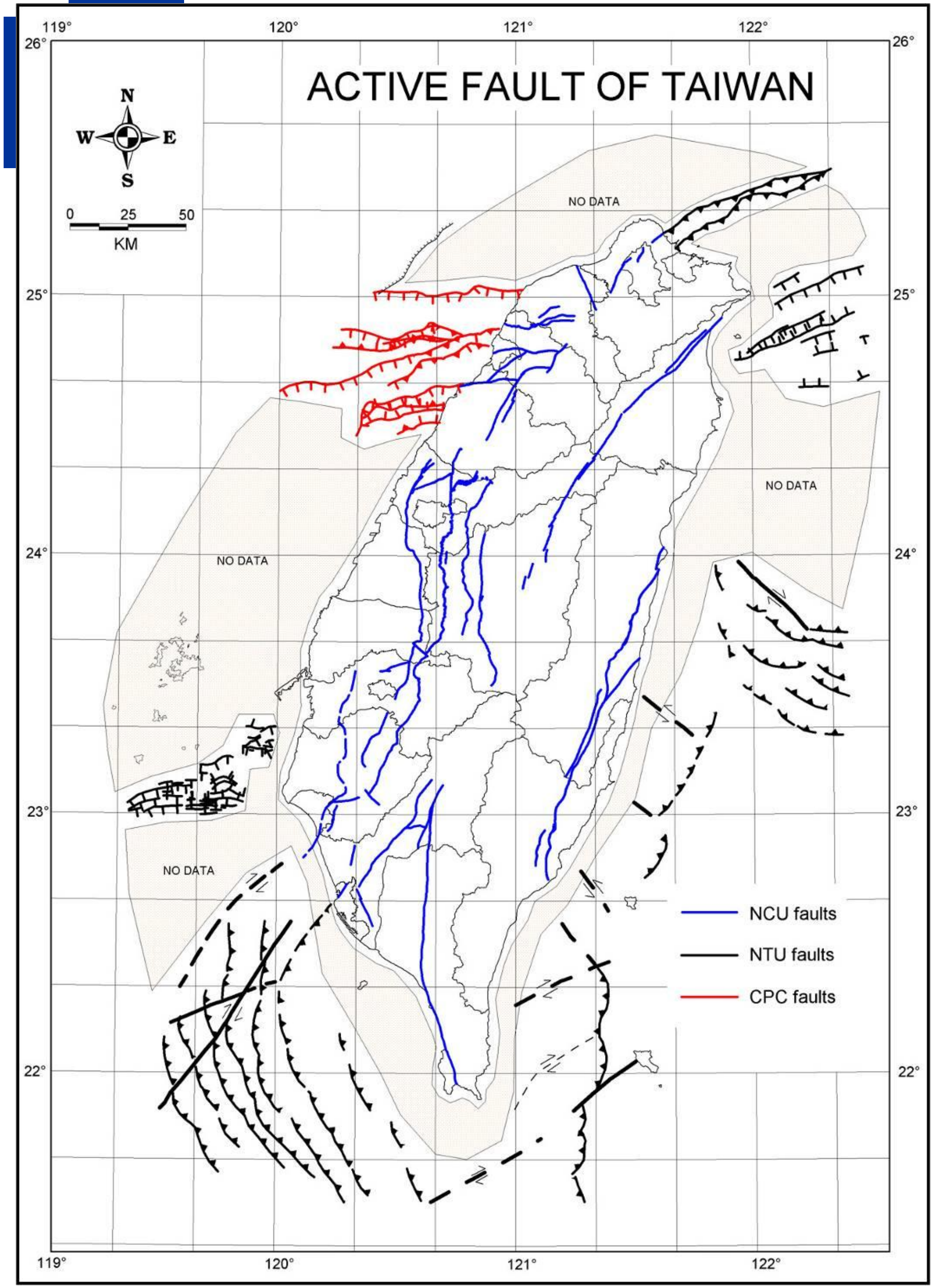


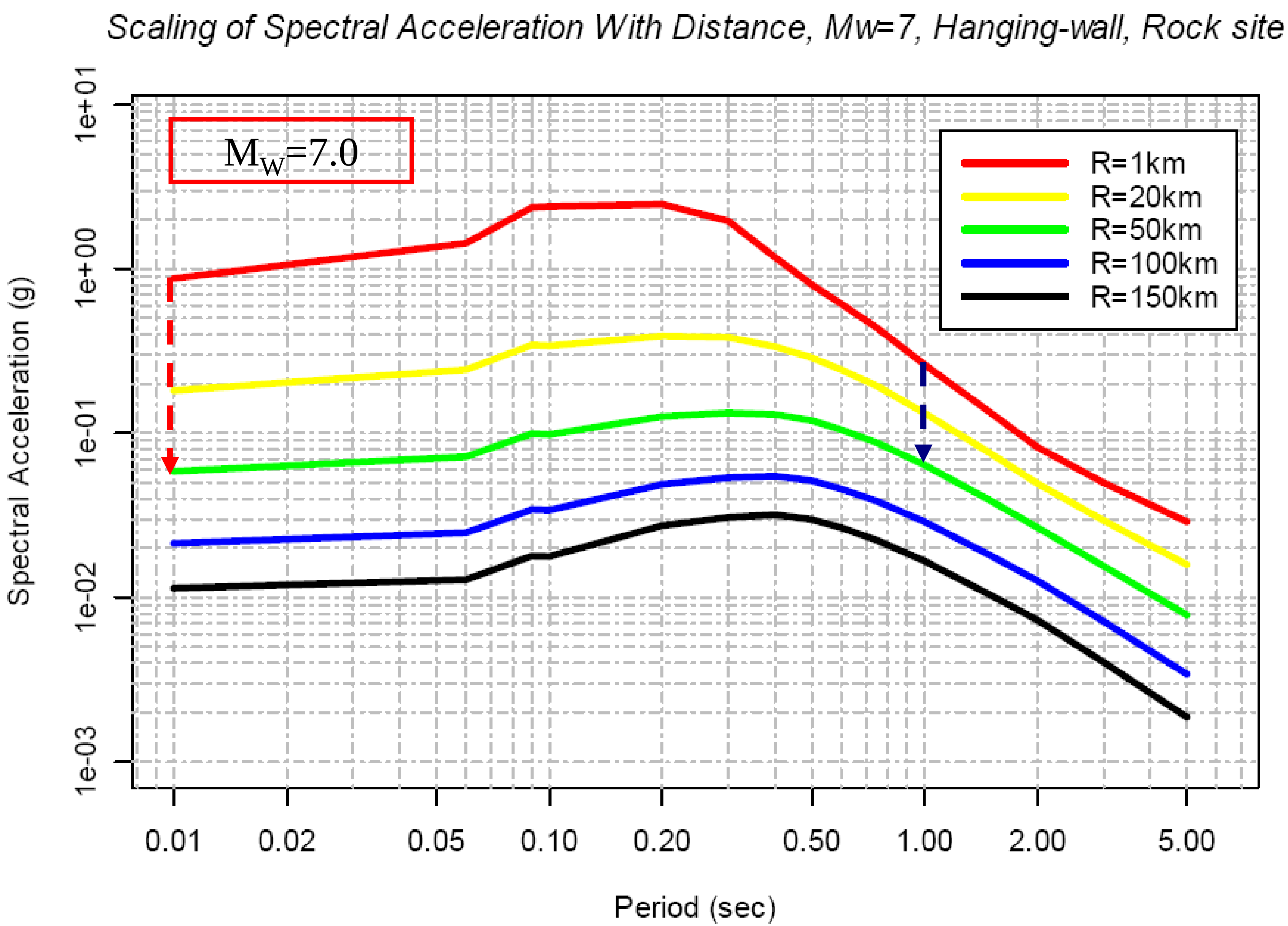
圖　例

- Bonilla (1975)
- Hsu & Chang (1979)
- 中央地質調查所(199
- 中央大學應地所

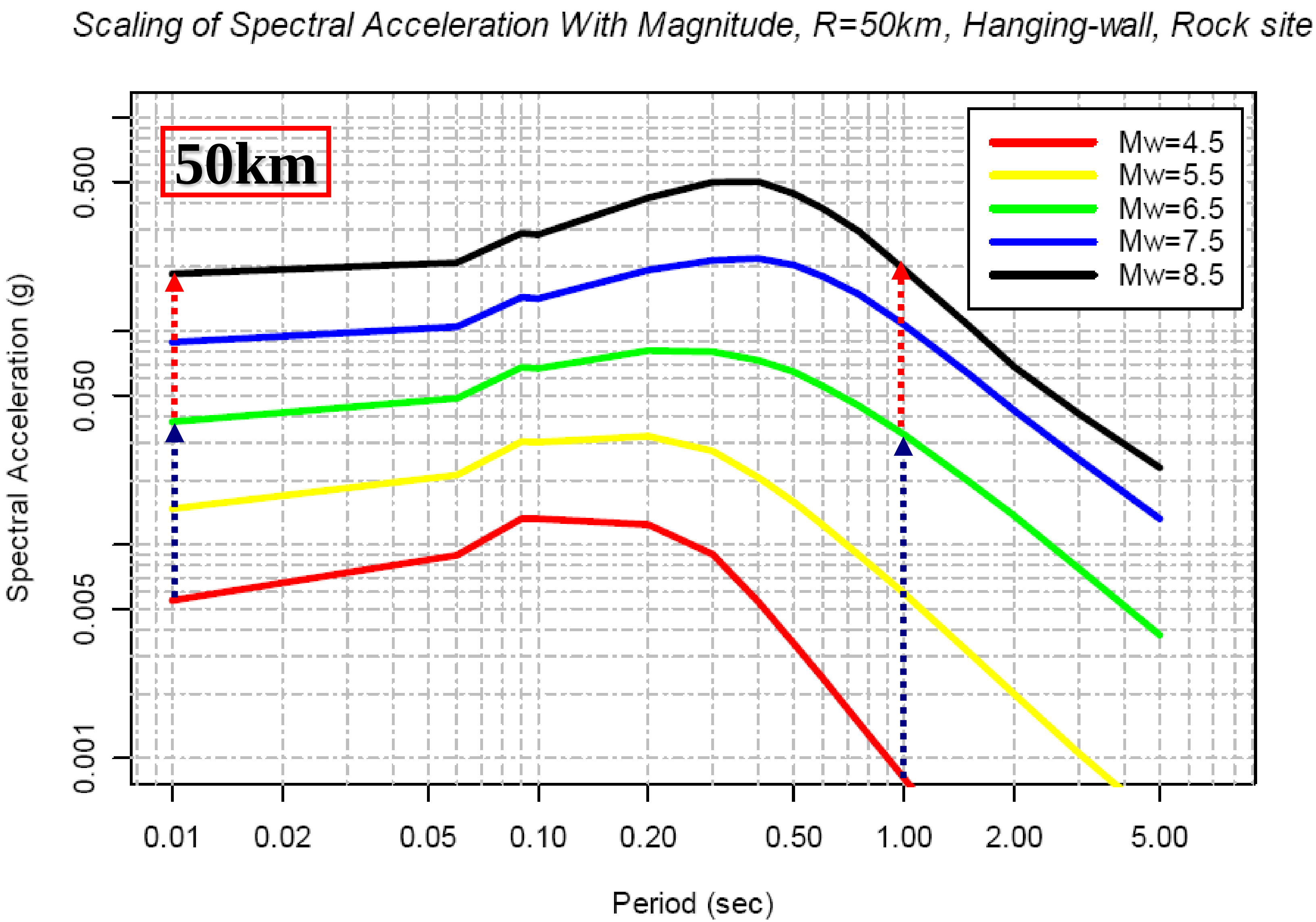
台灣本島及鄰近海域之活動斷層



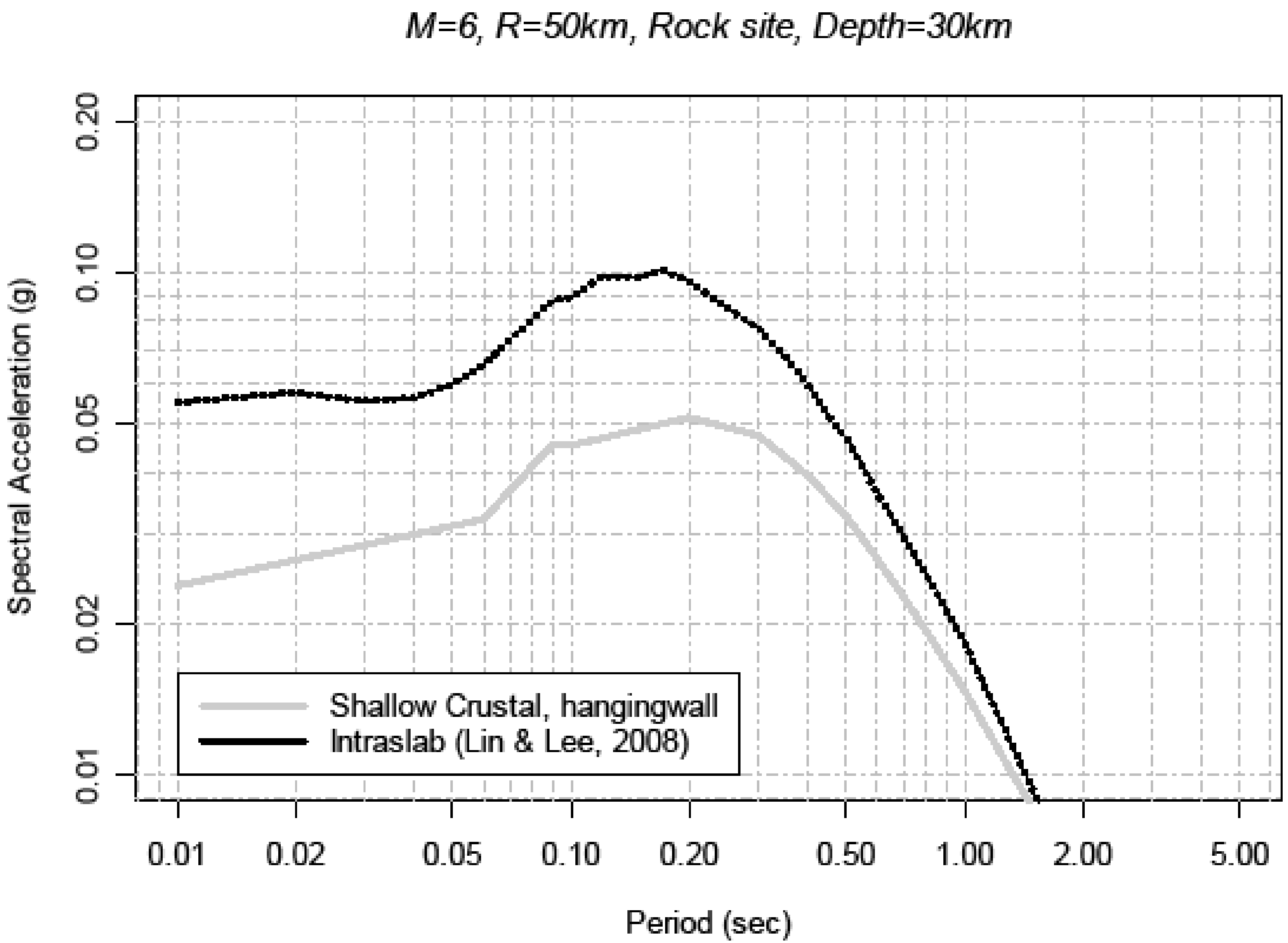
Scaling of Spectral Acceleration
- With Distance-



Scaling of Spectral Acceleration
- With Magnitude -



Scaling of Spectral Acceleration
-With Tectonic Environment -



Epistemic Uncertainty: Example of Unknown Die

- Assume you have not seen the die, but you have seen the results of four previous rolls
  - 2, 3, 3, 4
- What is the model for this die?
  - Assume this is a standard 6 sided die
    Sparse data (4 observations) do not rule out this model
  - Empirical approach
    Assume five sided die, loaded so that 3 comes up most often

「骰子」是甚模樣？

- 目前擲出骰子四次出現點數
  - 3, 4, 4, 5
  - 可瞭解骰子樣式？可建立骰子的統計模型？

- 依據過去的點數統計，預測未來出現各點數的機率？(Aleatory)
- 可能的骰子樣式，六面體？ (Epistemic)

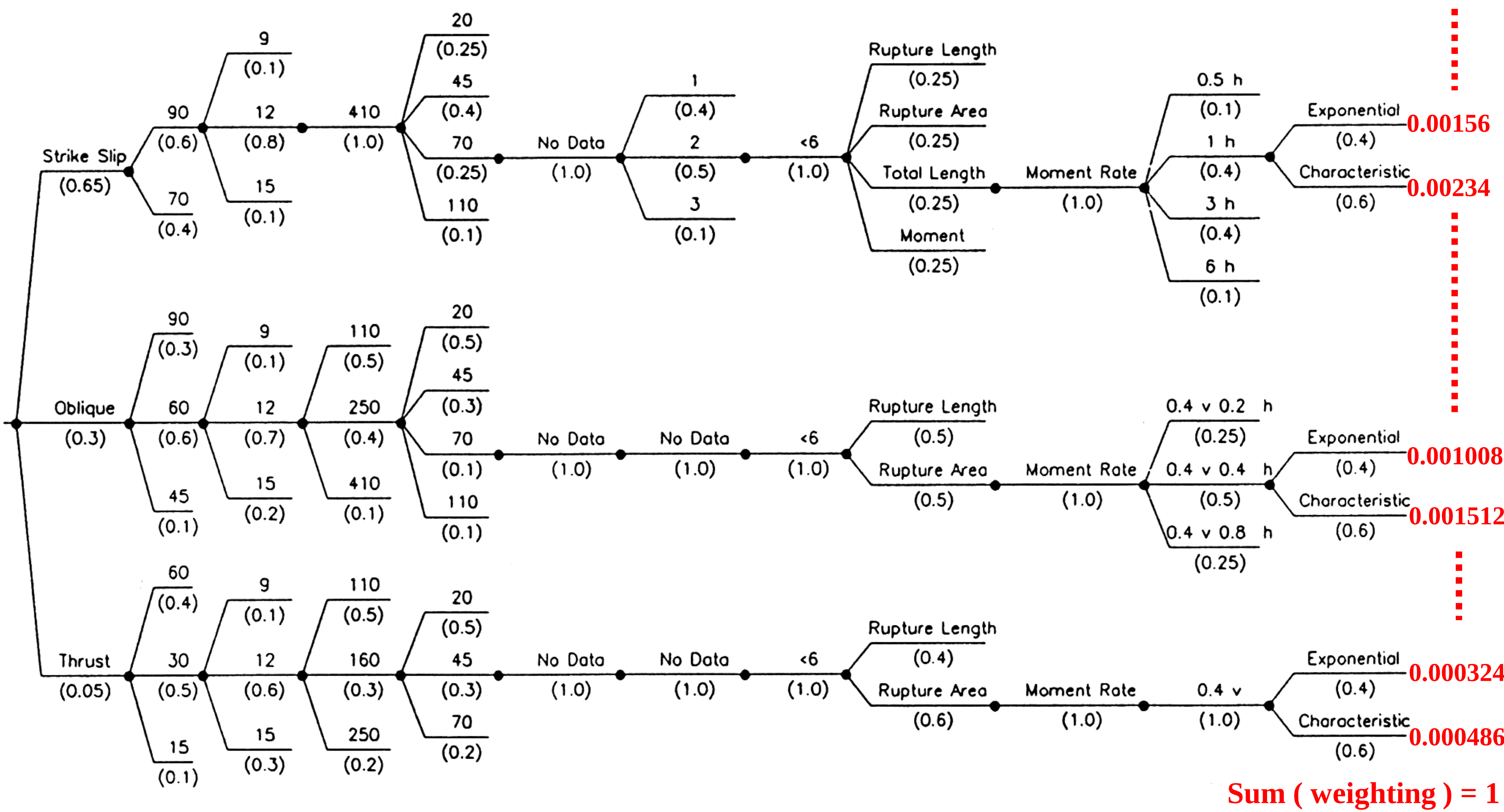
「骰子」是甚模樣？

Roll	Model 1 Global Analog	Model 2 Region Specific	Model 3 Region Specific
1	1/6	0	0.05
2	1/6	0	0.09
3	1/6	0.25	0.18
4	1/6	0.50	0.36
5	1/6	0.25	0.18
6	1/6	0	0.09
7	0	0	0.05

不確定性處理—邏輯樹

美國PG&E電廠進行Diablo Canyon核電廠PSHA時使用邏輯樹結構

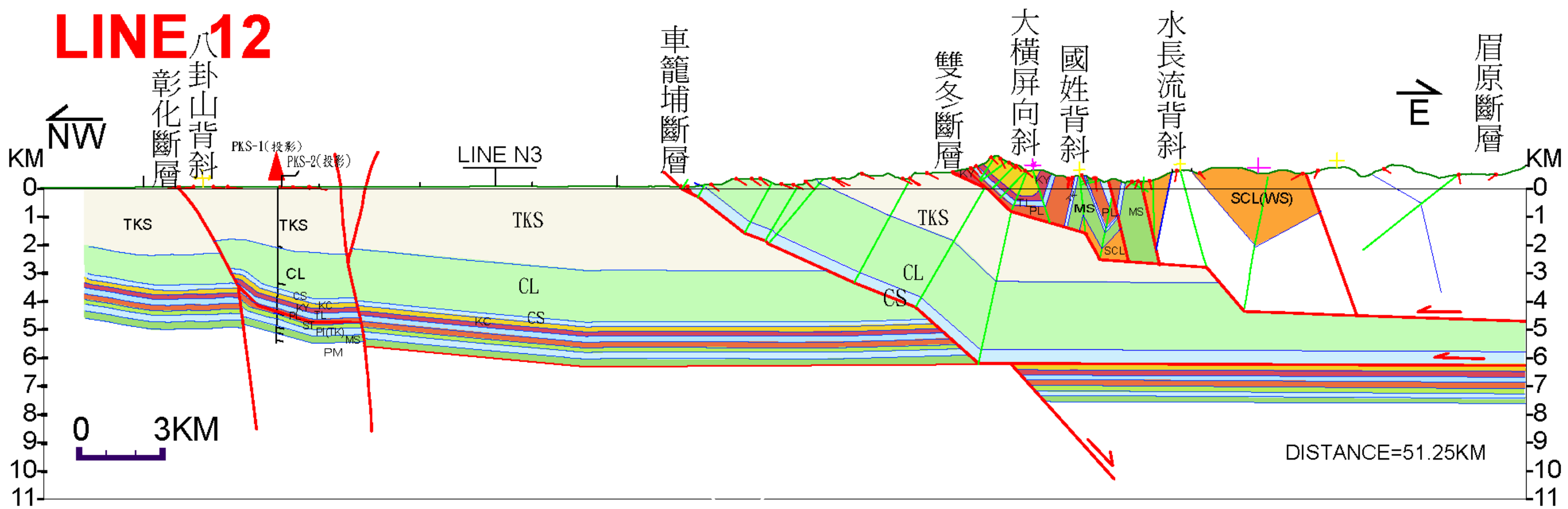
Sense of Slip	Dip (deg)	Maximum Depth (km)	Total Length (km)	Rupture Length (km)	Maximum Displacement (m)	Average Displacement (m)	Maximum Historical	Magnitude Technique	Recurrence Method	Slip Rate (mm/yr)	Magnitude Distribution

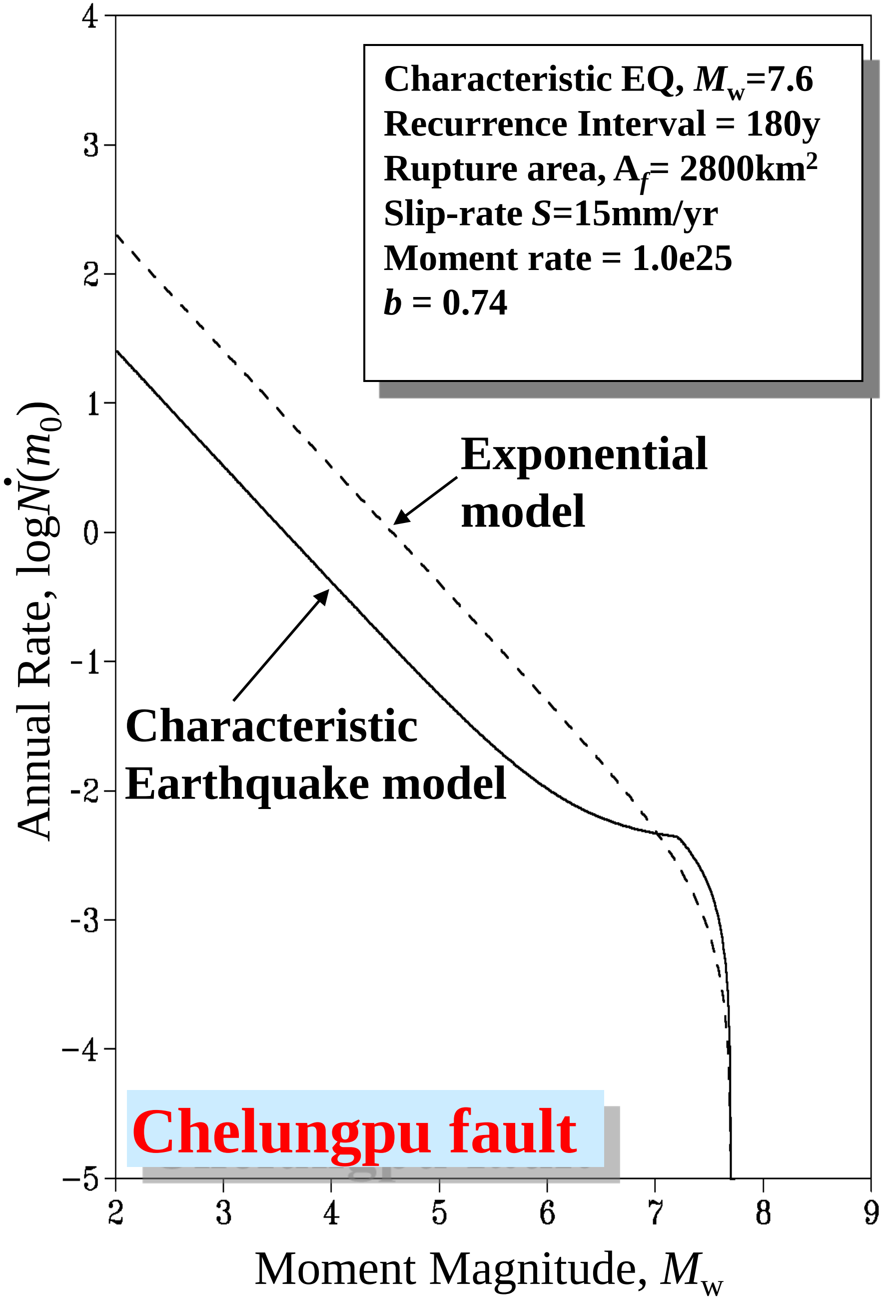


Seismic Hazard Analysis (Cont)

- Estimate likely motion from each potential earthquake source (Mag,Dist,Soil)
  - Use attenuation relation; sometimes simulate motion
  - Consider uncertainty
  - Evaluate potential site effects
    - Conduct site specific 1-D site response analysis (if not generic rock/soil captured by attenuation relation) (SHAKE, RASCALS)
    - Sedimentary basin, topography (FE or FD)
- Consolidate all scenarios and select design motion

傾角


LINE 12
NW
E
彰化斷層
八卦山背斜
車籠埔斷層
雙冬斷層
大橫屏向斜
國姓背斜
水長流背斜
眉原斷層
LINE N3
KM
TKS
CL
CS
KC
PL
MS
SCL
SCL(WS)
PM
0 3KM
DISTANCE=51.25KM



Exponential Model

$$\dot{M}_0 = \mu A_f S = \frac{b\dot{N}(m_0)\cdot\exp(-\beta(m_u-m_0))\cdot M_0(m_u)}{(c-b)(1-\exp(-\beta(m_u-m_0)))}$$

μ is the rigidity, A_f is fault rupture area, S is fault slip-rate,

m_u is upper bound earthquake, m_0 is lower bound earthquake, $\beta = b\ln10$.

Characteristic Earthquake model

$$\dot{N}(m) = \dot{N}^e \frac{\exp(-\beta(m-m_0)) - \exp(-\beta(m_u-1/2-m_0))}{1-\exp(-\beta(m_u-1/2-m_0))} + \dot{N}^c, \quad for \quad m_0 \le m < m_u - \frac{1}{2},$$

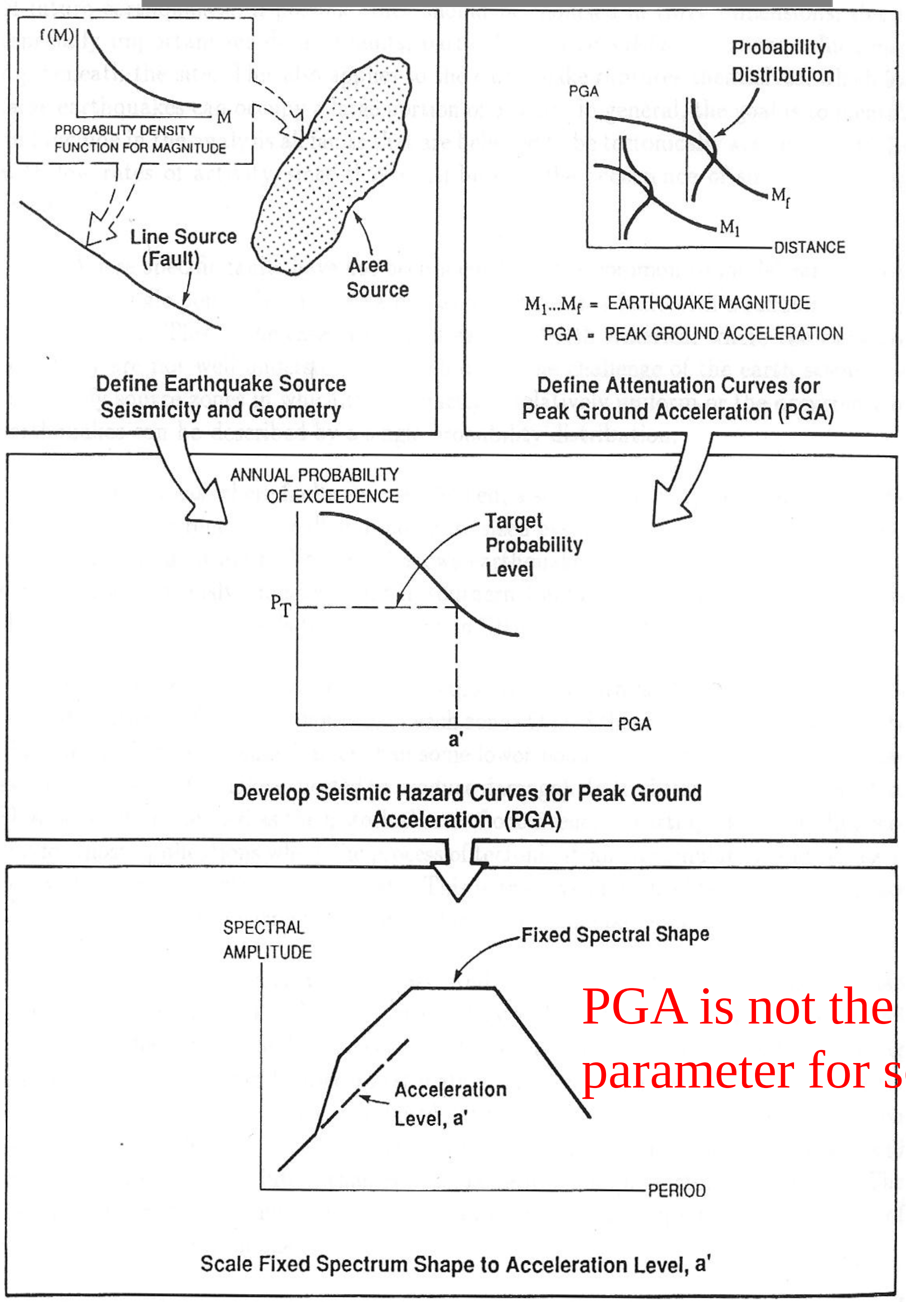
$$\dot{N}(m) = \dot{N}^c \frac{m_u-m}{1/2} \quad for \quad m_u - \frac{1}{2} \le m < m_u,$$

$$\dot{N}^c = \frac{1}{2}\dot{N}^e \frac{b\ln10\cdot\exp(-\beta(m_u-3/2-m_0))}{(1-\exp(m_u-1/2-m_0))}$$

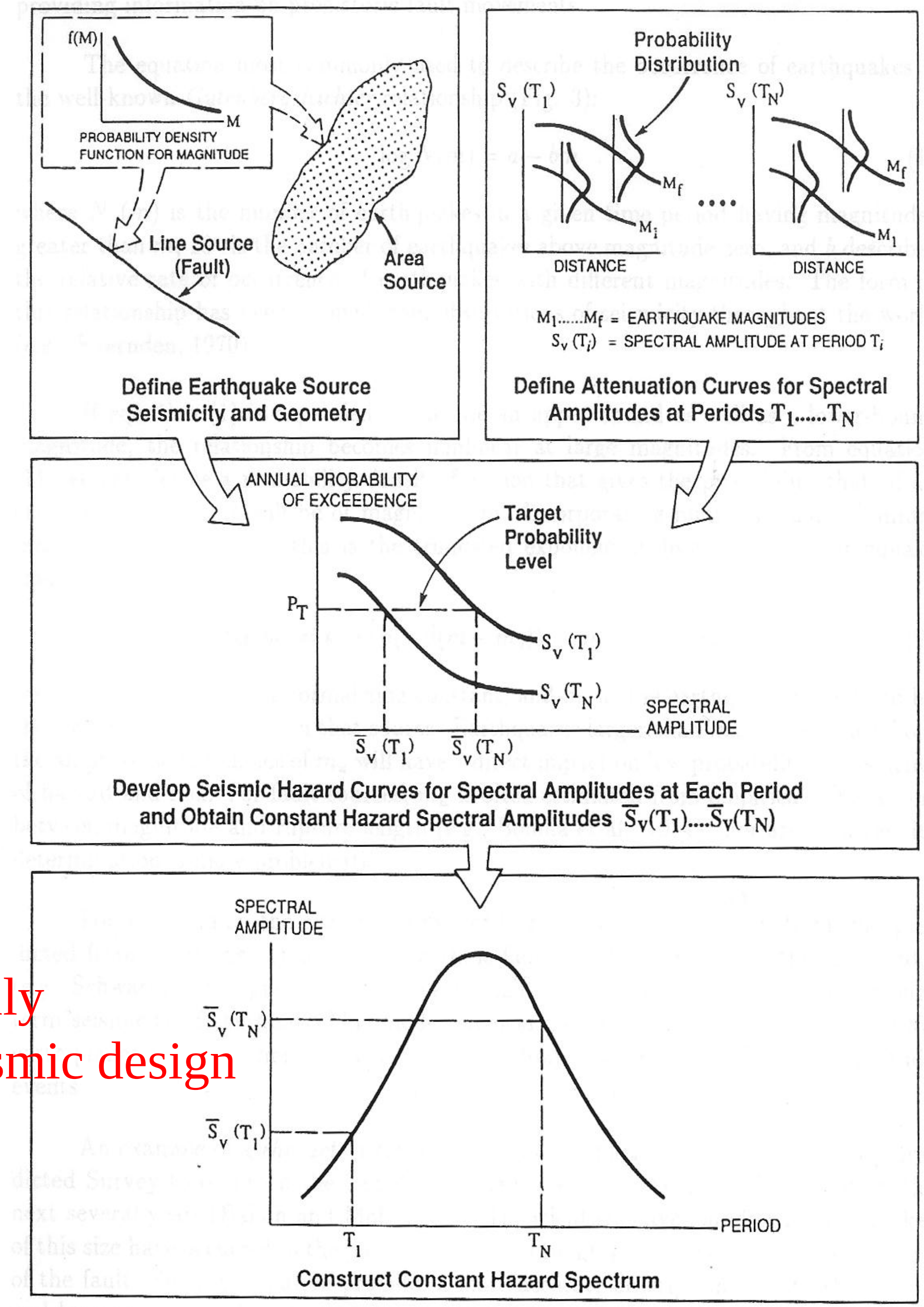
$$\dot{N}^e = \frac{\mu A_f S(1-\exp(-\beta(m_u-m_0-1/2)))}{\exp(-\beta(m_u-m_0-1/2))M_0(m_u)[\frac{b10^{-c/2}}{(c-b)} + \frac{b\exp(\beta)(1-10^{-c/2})}{c}]},$$

Youngs and Coppersmith (1985)

Traditional Method



Uniform Hazard Response Spectrum



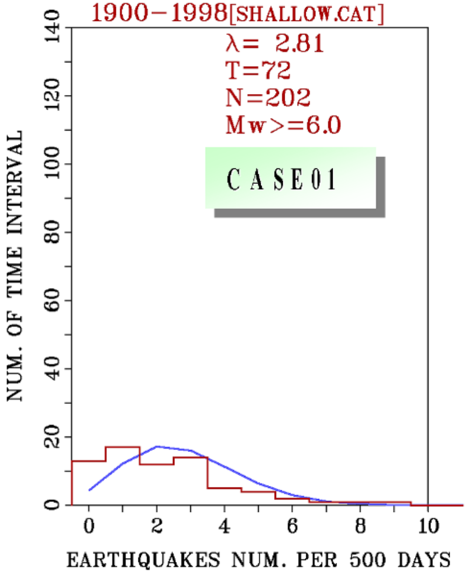
PGA is not the only parameter for seismic design

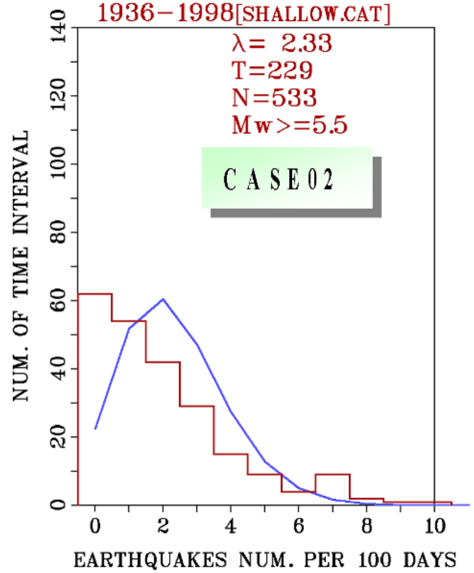
台灣地區強地動加速度衰減式一覽表 (Lee et al, 2001)

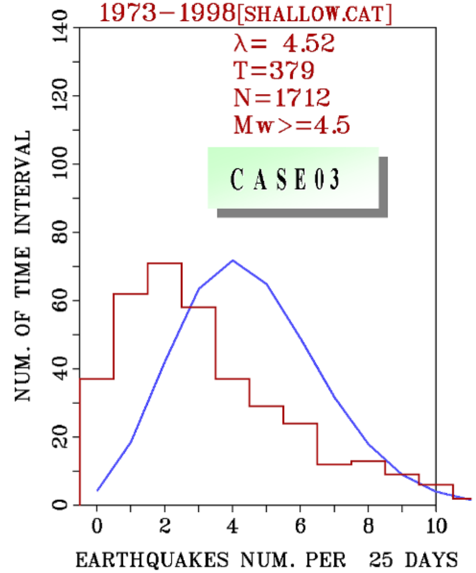
衰減式名稱	衰減式	標準差$\sigma_{\ln y}$
地殼震源堅硬地盤斷層上盤強地動衰減式	$\ln y = -3.25 + 1.075M_W - 1.723 \ln(R + 0.156 \exp(0.62391M_W))$	0.577
地殼震源堅硬地盤斷層下盤強地動衰減式	$\ln y = -3.20 + 1.115M_W - 1.773 \ln(R + 0.206 \exp(0.62888 M_W))$	0.582
地殼震源鬆軟地盤斷層上盤強地動衰減式	$\ln y = -3.55 + 0.925M_W - 1.383 \ln(R + 0.066 \exp(0.66884 M_W))$	0.543
地殼震源鬆軟地盤斷層下盤強地動衰減式	$\ln y = -3.40 + 0.945M_W - 1.433 \ln(R + 0.116 \exp(0.65946 M_W))$	0.552
隱沒板塊介面地震堅硬地盤強地動衰減式	$\ln y = -2.5 + 1.205M_W - 1.905 \ln(R + 0.51552 \exp(0.63255)M_W)) + 0.0075H$	0.526
隱沒板塊介面地震鬆軟地盤強地動衰減式	$\ln y = -0.9 + 1.000M_W - 1.900 \ln(R + 0.99178 \exp(0.52632)M_W)) + 0.004H$	0.627
隱沒板塊內部地震堅硬地盤強地動衰減式	$\ln y = -2.5 + 1.205M_W - 1.905 \ln(R + 0.51552\exp(0.63255)M_W)) + 0.0075H + 0.275$	0.526
隱沒板塊內部地震鬆軟地盤強地動衰減式	$\ln y = -0.9 + 1.000M_W - 1.900 \ln(R + 0.99178 \exp(0.52632)M_W)) + 0.004H + 0.31$	0.627

Chi-Square Test of Mainshock Catalogue

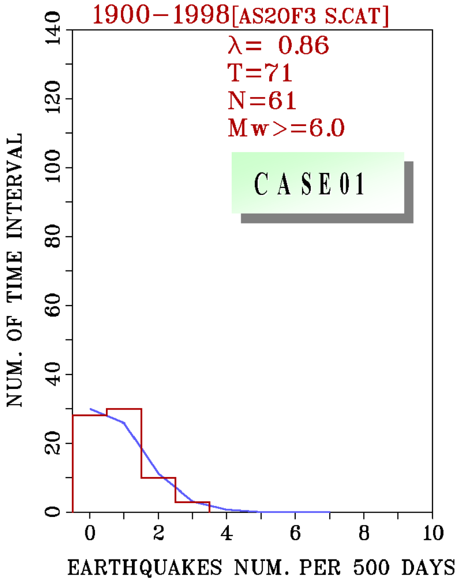
原始地震目錄

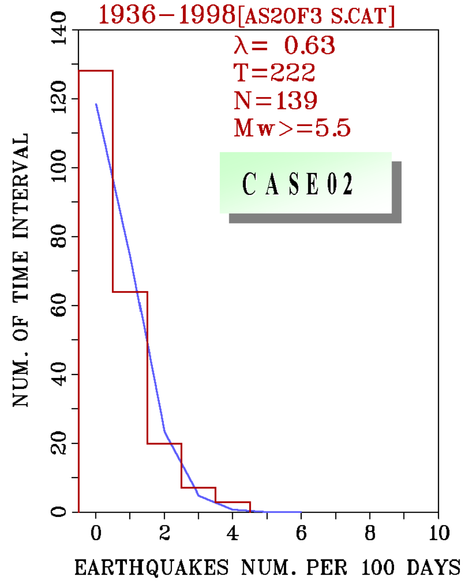


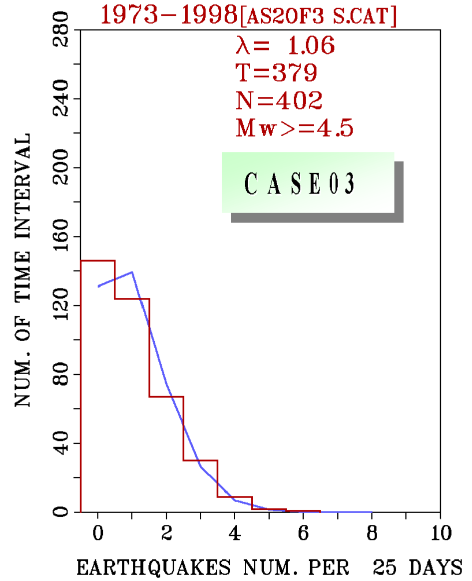




獨立主震目錄

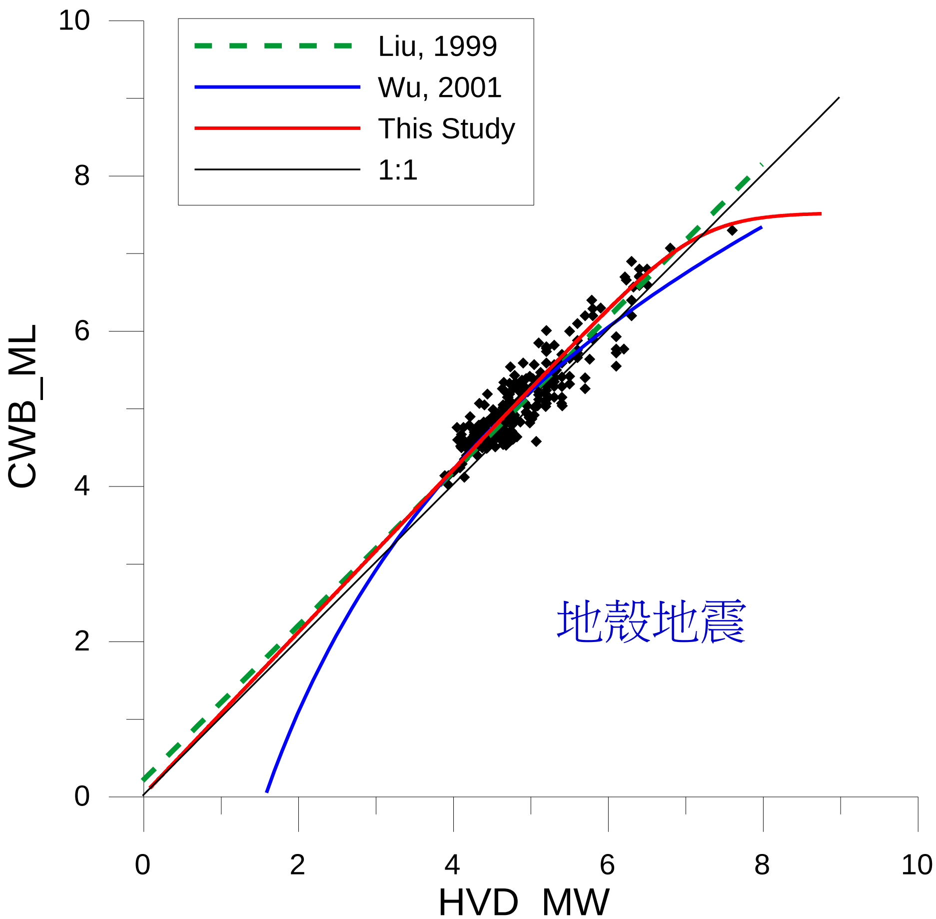




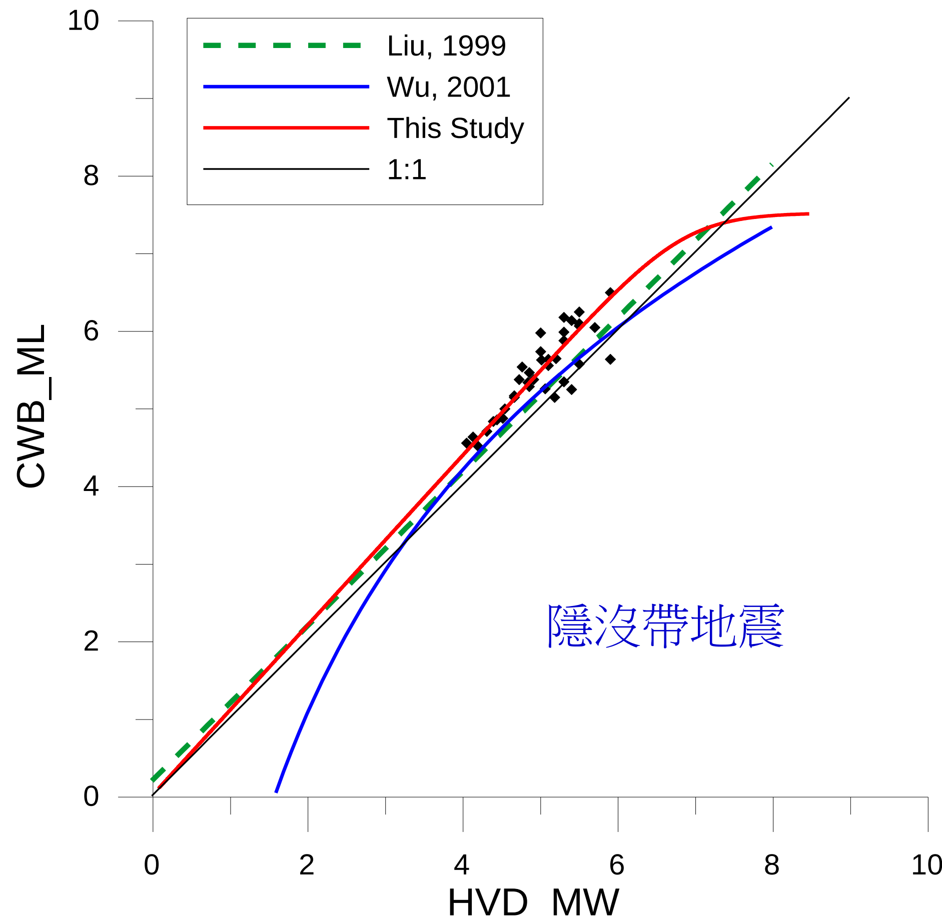


隱沒帶地震與地殼地震M_W與M_L關係式

$M_L \rightarrow M_W$



Shallow earthquake events



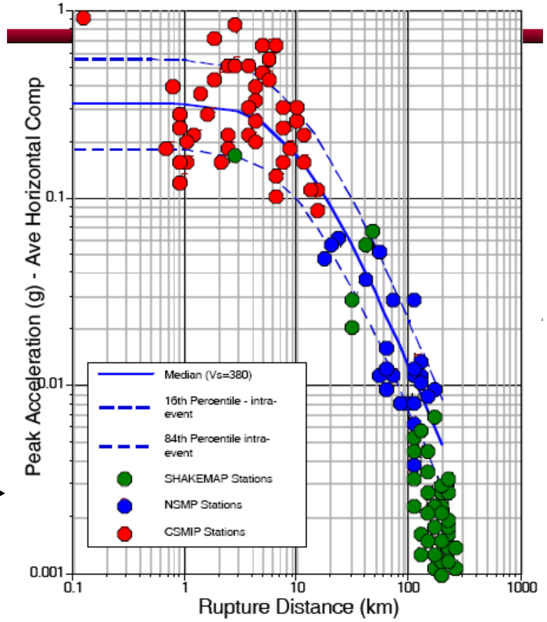
Deep earthquake events

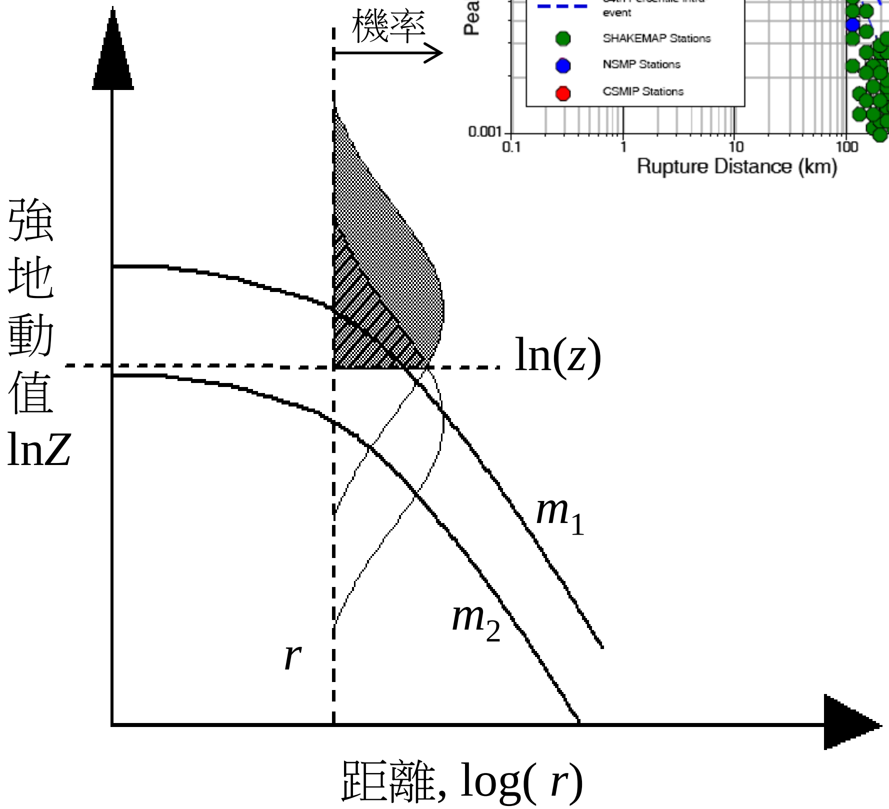
Uncertainties in SHA

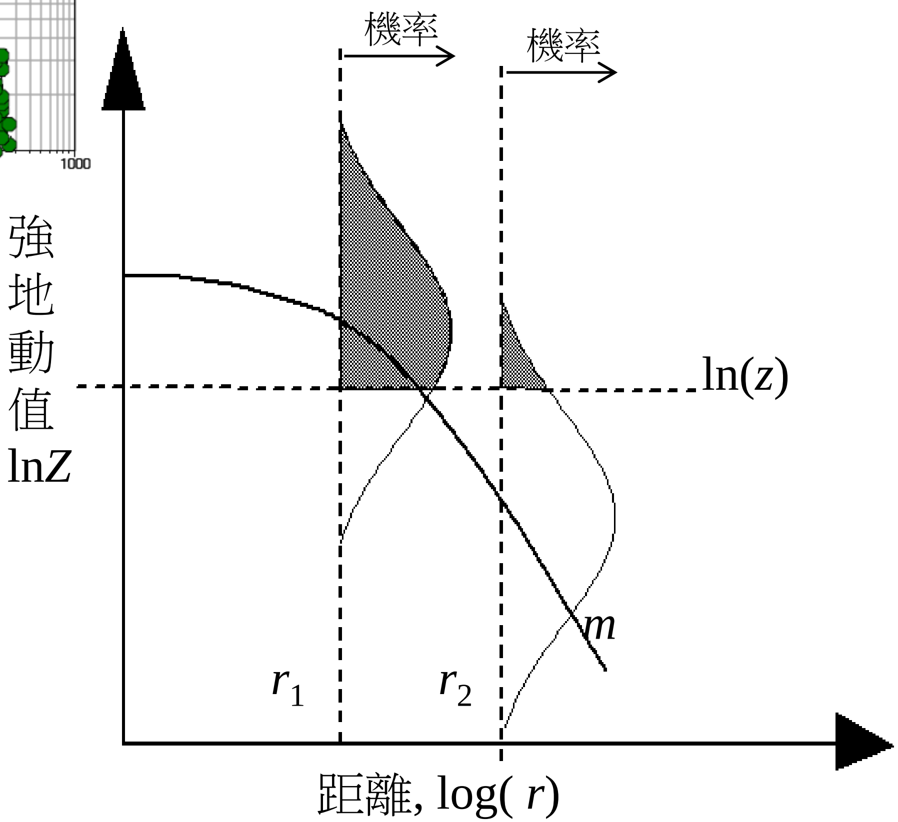
- Uncertainties considered in SHA
  - A fault is active or not (include or exclude from further consideration)
  - Possible magnitudes
    - Rupture the entire fault or part of the fault
  - Likelihood of occurrence of a given magnitude earthquake during the life span of structure -- How often does the earthquake occur? (earthquake recurrence rate)
  - Distance to the earthquake source (location of source)
    - Areal source (random location)
    - Rupture location along the fault

Uncertainties in SHA

- Uncertainties encountered when conducting SHA (cont)
  - Variability of ground motion

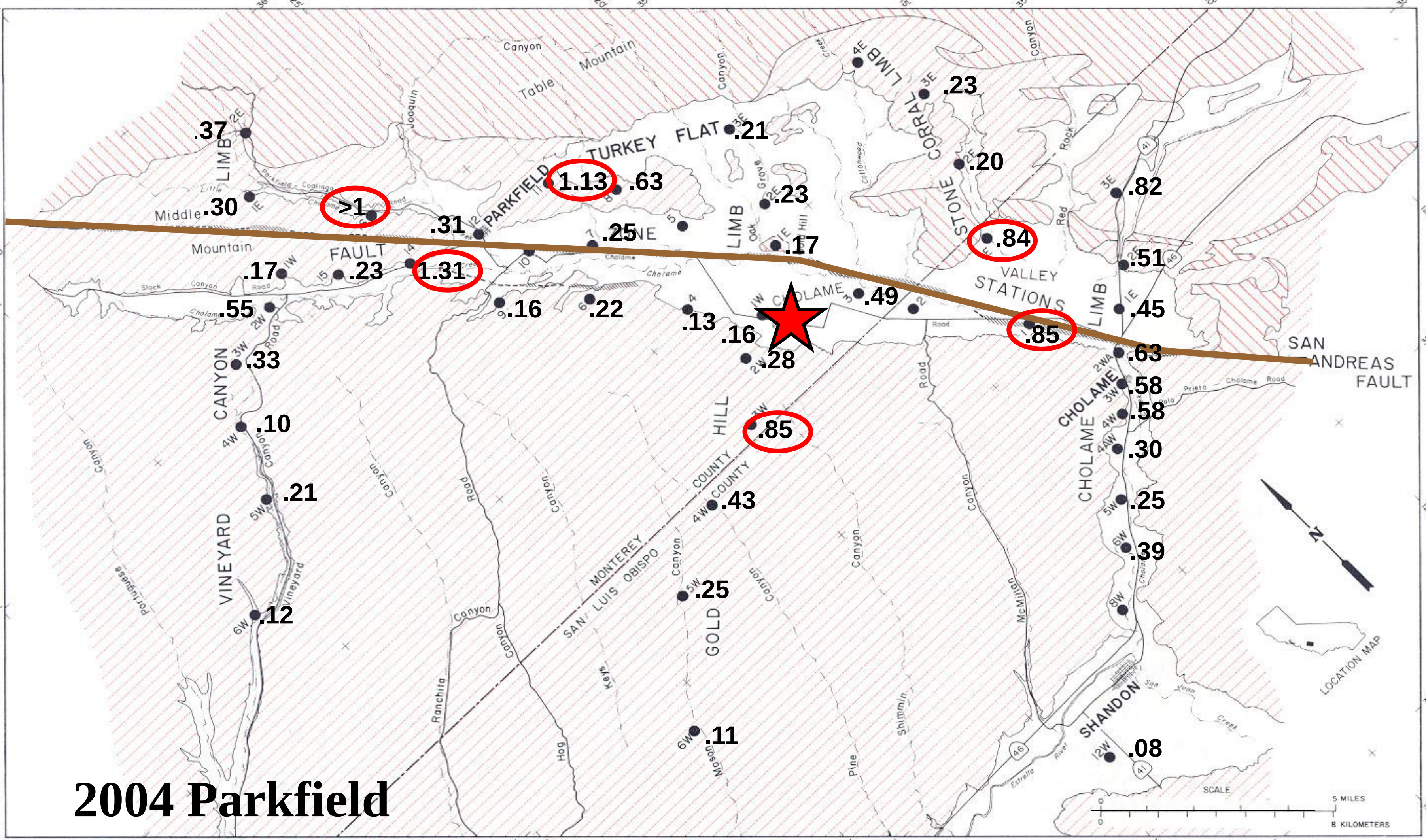






Improvement on Taiwan Seismic Hazard Map

- **Saturation of local magnitude (M_L) :**
  - Chi-Chi earthquake M_L7.3→M_W7.7
  - local magnitude is saturated at a large magnitude.
- **Significant hanging wall effect:** It shows much higher ground motion amplitude at hanging wall than at footwall.
- The need to emphasize the fault source: **fault slip rate (activity) and geometry**.
- The need to **use the closest-distance to fault** plane for ground motion attenuation prediction.
- What's is the **"Worst-case" Ground Motion**, PGA> 1.0g ?
  - Apply PSHA for engineering design
- **PGA is not only one ground motion parameter** for seismic design.
  - **Prediction of spectral acceleration (Sa)** at various periods for seismic design is needed.



2004 Parkfield

(from McJunkin and Shakal, 1983)

Quaternary Deposits
Unconsolidated stream and floodplain deposits of sand, silt, and gravel and terrace deposits of similar composition. Also includes landslide debris.

Cenozoic Rocks and Deposits
Poorly to well indurated predominantly clastic rocks including sandstone, siltstone, and conglomerate of several formations. Most rocks are marine except for the Plio-Pleistocene Paso Robles Formation which underlies the greatest amount of terrain southwest of the San Andreas fault.

Mesozoic Rocks
Moderately to well indurated marine rocks including predominantly sandstone, silton
abundant in Franciscan assemblages. Also includes tabular and lenticular bodies of s

Courtesy of N. Abrahamson

Motivation To Conduct a PSHA

- Why don't we design for the "worst-case" peak acceleration (> 1.2 g)?
  - ex. **2004 Parkfield earthquake in CA.** (PGA> 1.2 g)
- Because it is "unreasonable"
  - Occurrence of "worst-case" motion is **too rare** **AND** it is **too costly** to design for