Earthquake forecasting and probabilistic seismic hazard assessment: applications to Taiwan

- Development of seismicity rate evolution model
- Development of probabilistic seismic hazard assessment
- Applications to Hualien and both Meishan & Jiashian cases

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威力彩

Rate of 1st prize: **1/22,085,448**

Expected value: **ca. 44 NTD**

大樂透

Rate of 1st prize: **1/13,983,816**

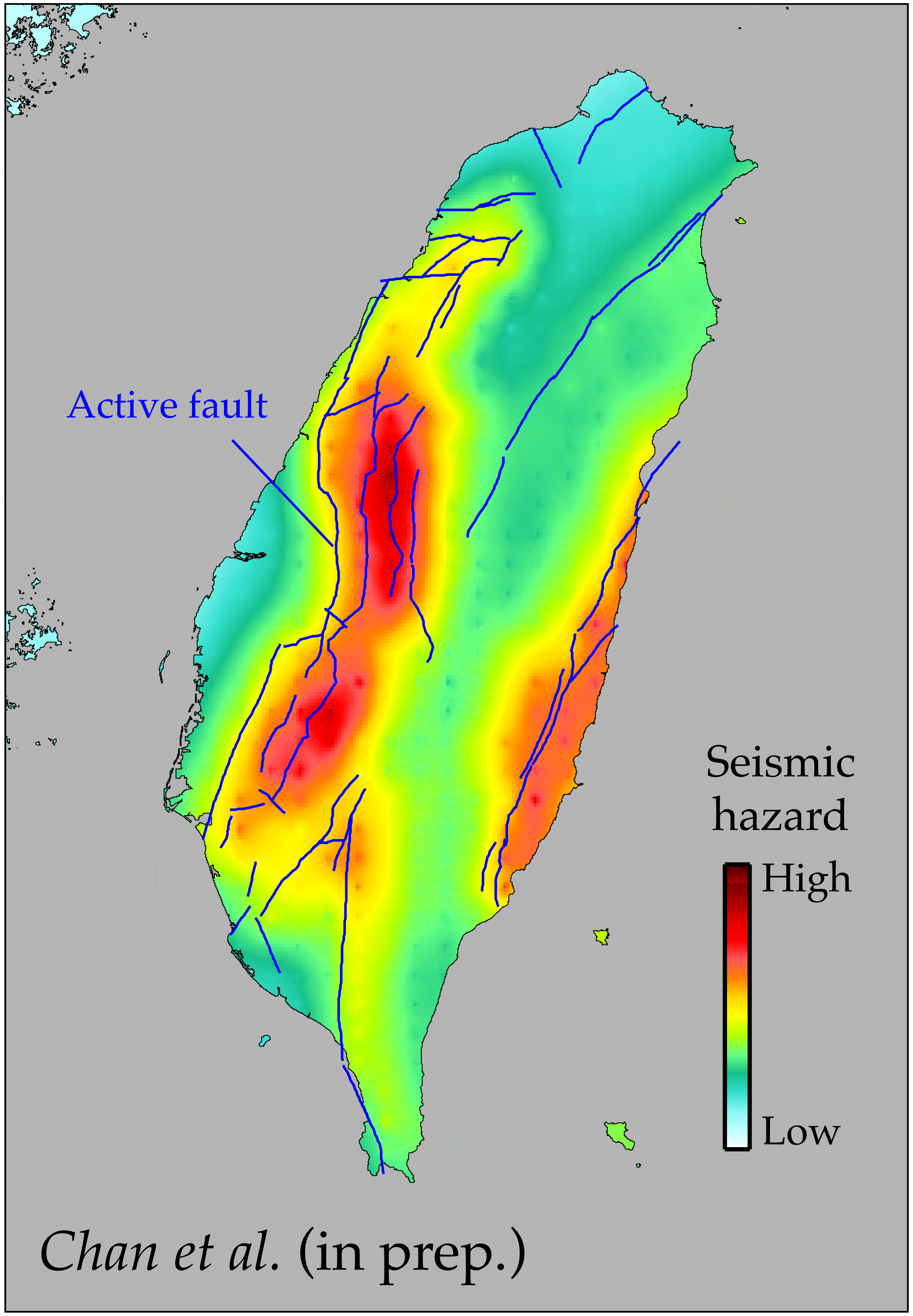
Expected value: **ca. 27.5 NTD**

Daily fatality rate due to car accident in Taiwan: **ca. 1/4,000,000**

Use ***weather forecast*** to decide if an umbrella is necessary

Risk of precipitation is shown in ***probability*** ▶

Probabilistic Seismic Hazard Assessment (PSHA) is....



Reference for seismic hazard mitigation policies

- Building codes
- Site selection of structures

nuclear power plant.....

Is 4th Nuclear Power Plant safe from seismic hazard?

確保核安 斷層呢 核四豈真安全

【記者郭玉屏台北報導】政府到底要怎麼確保核安？立委林佳龍昨(13)天與海洋大學名譽教授李昭興召開記者會，林

澳底斷
斷層帶
質學會
顯示，
中間的

台電重申核四廠附近區域並無任何活動斷層

(中央社訊息服務20130313 16:50:24)針對外界關心「核四廠附近是否有活動斷層」，台電重申表示，龍門(核四)電廠地基開挖深達26公尺，廠房座落在堅實岩盤上，其下方並未發現斷層；民國99年中央地質調查所頒行之台灣活動斷層分佈圖，亦顯示核四廠半徑40公里附近區域並無任何活動斷層。

核四座落斷層破碎帶　台電挨轟說謊

2013年03月13日12:38 讚 144 +1 4

立委林佳龍與海洋大學名譽教授李昭興今召開記者會，指出核四附近澳底斷層、貢寮斷層、枋寮斷層等經過，而台電1994年委託中國地質學會所作「透地雷達施測」更顯示，核四廠第1、2反應爐中間的地層下方有破碎帶經過，台電還敢說廠房坐落在堅實岩盤上，公然說謊，呼籲台電立即重啟調查，他也說，證據已顯示核四不安全，足以停建核四與停公投。林說，將把相關資料送監察院、地檢署舉發。

即時新聞 》雪山斷層影響核四？ 將勘查地質狀況

Breaking news

【台灣醒報／記者郭琇真／台北報導】 2013.03.13 05:20 pm

距核四廠16公里的雪山隧道，其下方斷層近年來不斷活動且有向核四廠延伸的跡象，海洋大學地質學者李昭興13日強調，核四廠下方除了有破碎帶的安全疑慮外，從雪隧延伸出來的斷層也應該重啟地質勘查。對此，地調所回應說，目前立院以附帶決議要求地調所勘查，地調所將盡量於年底公投前完成。

Tohoku case.....

What can we know priori to the 2011 Tohoku earthquake?

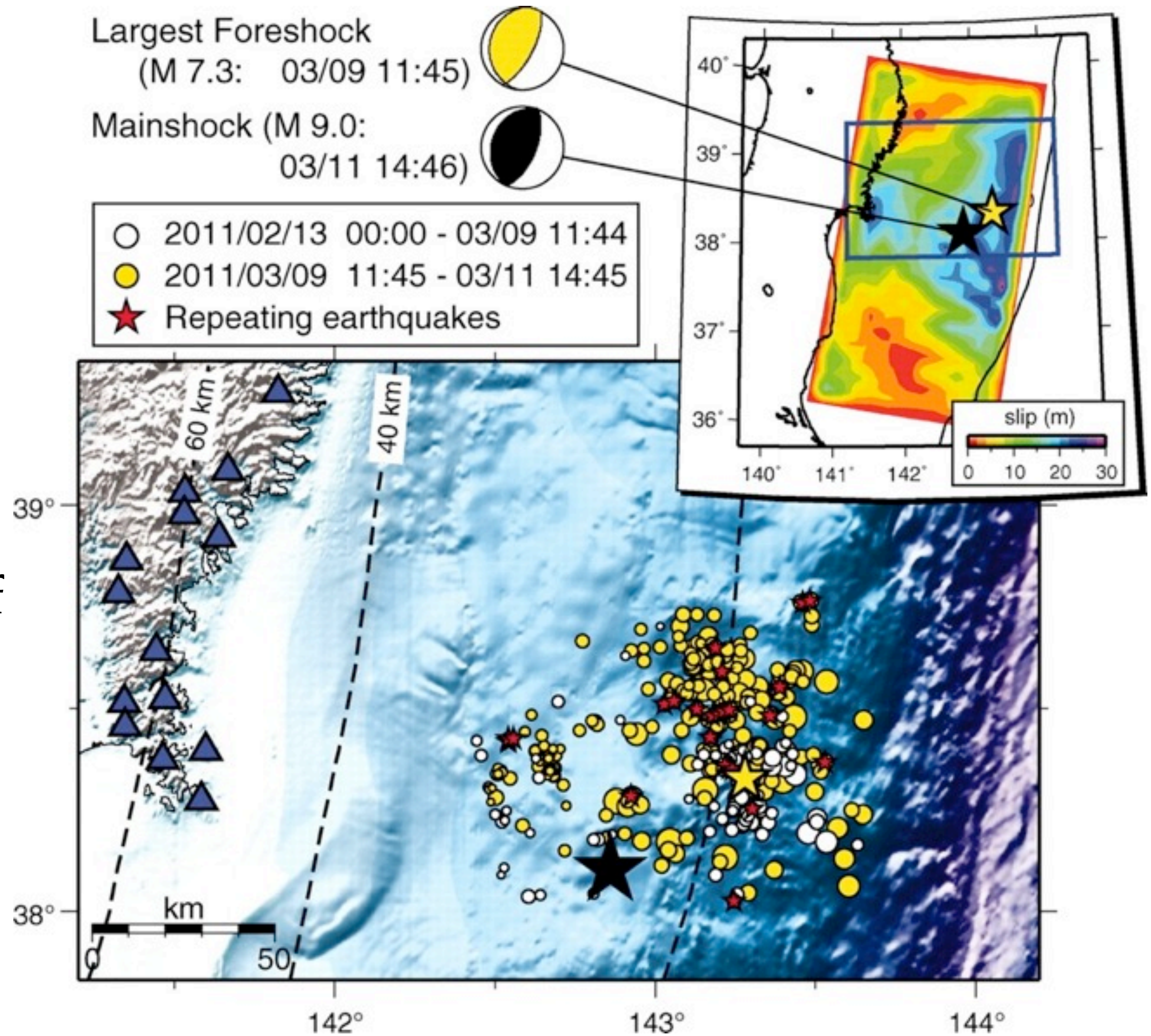
Loss: US $235 billion*

Explosion of the nuclear power plant

*The most expensive natural disaster in world history.

The 2011 M9.0 Tohoku-Oki earthquake follows a ***foreshock*** sequence

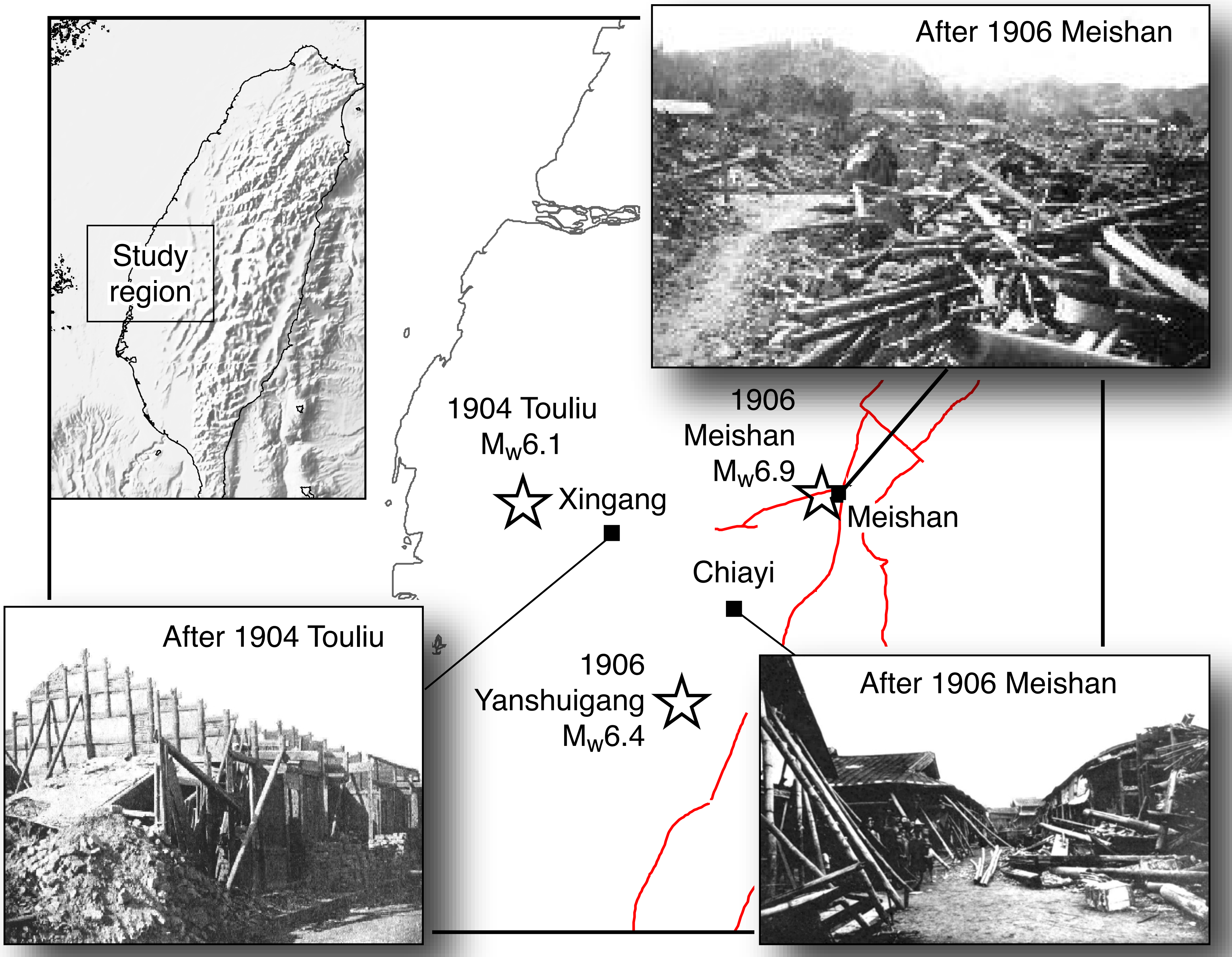
It might be forecasted if ***foreshock-mainshock*** behaviors are well-understood.



by *Kato et al.*, 2012

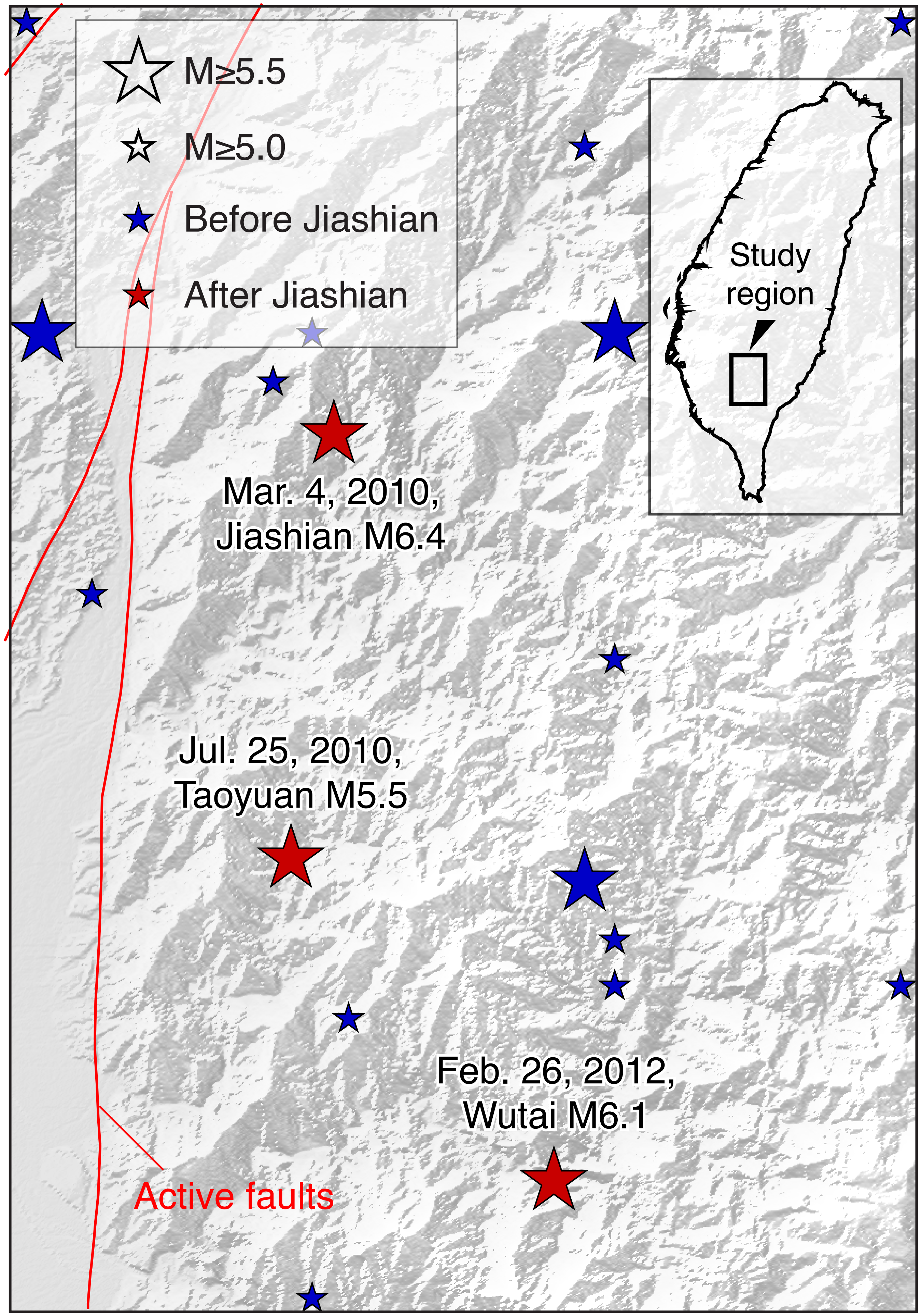
Meishan case....

All the three events in the Meishan sequence caused casualties in the Chiayi region



Chan et al., 2013

Jiashian case…



Higher seismicity rate after Jiashian

Before Jiashian:

M≥5.5 events: 3 (0.03 event/year)

M≥5.0 events: 12 (0.11 event/year)

After Jiashian:

M≥5.5 events: 3 (1.00 event/year)

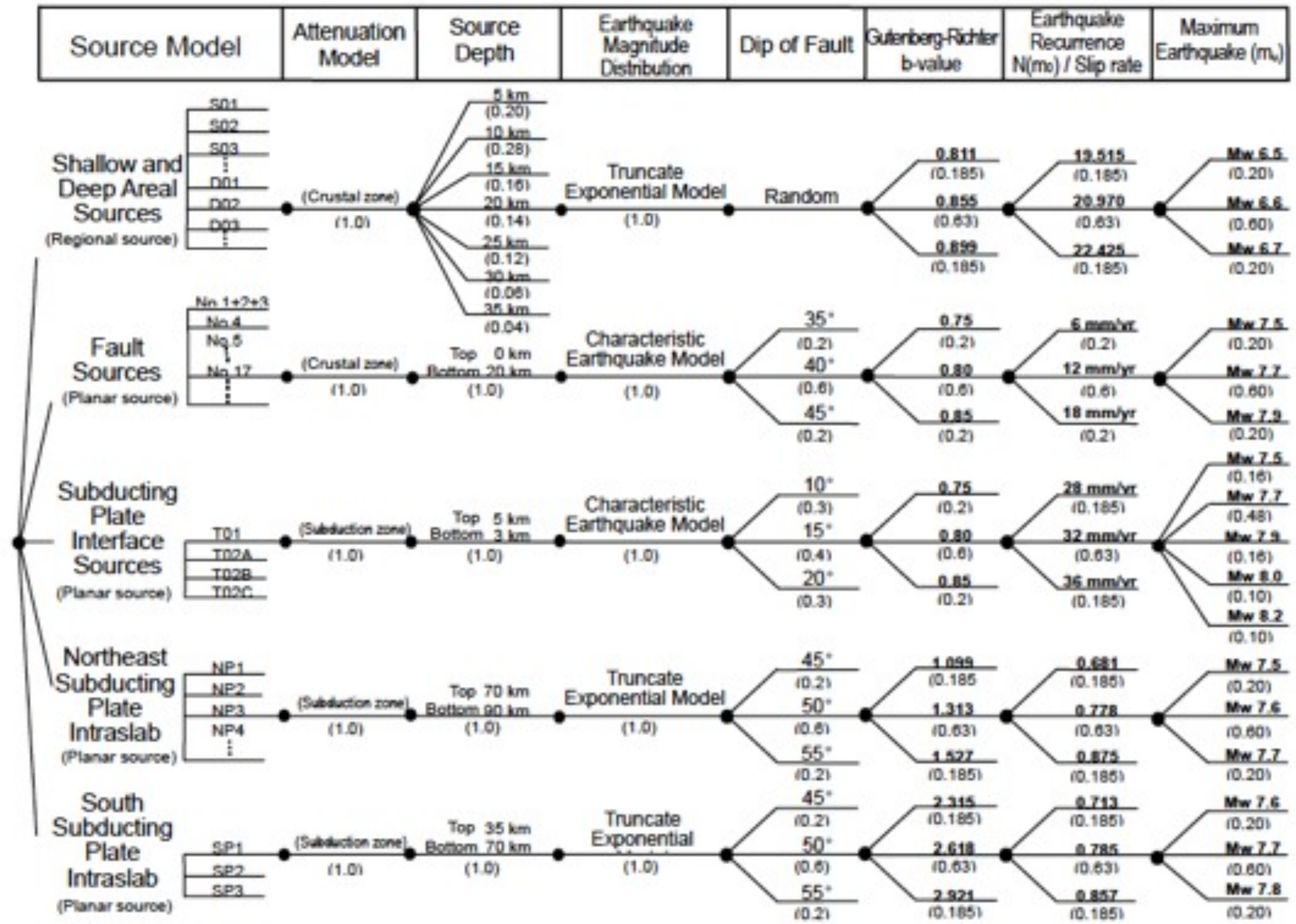
M≥5.0 events: 3 (1.00 event/year)

Chan & Wu, 2012

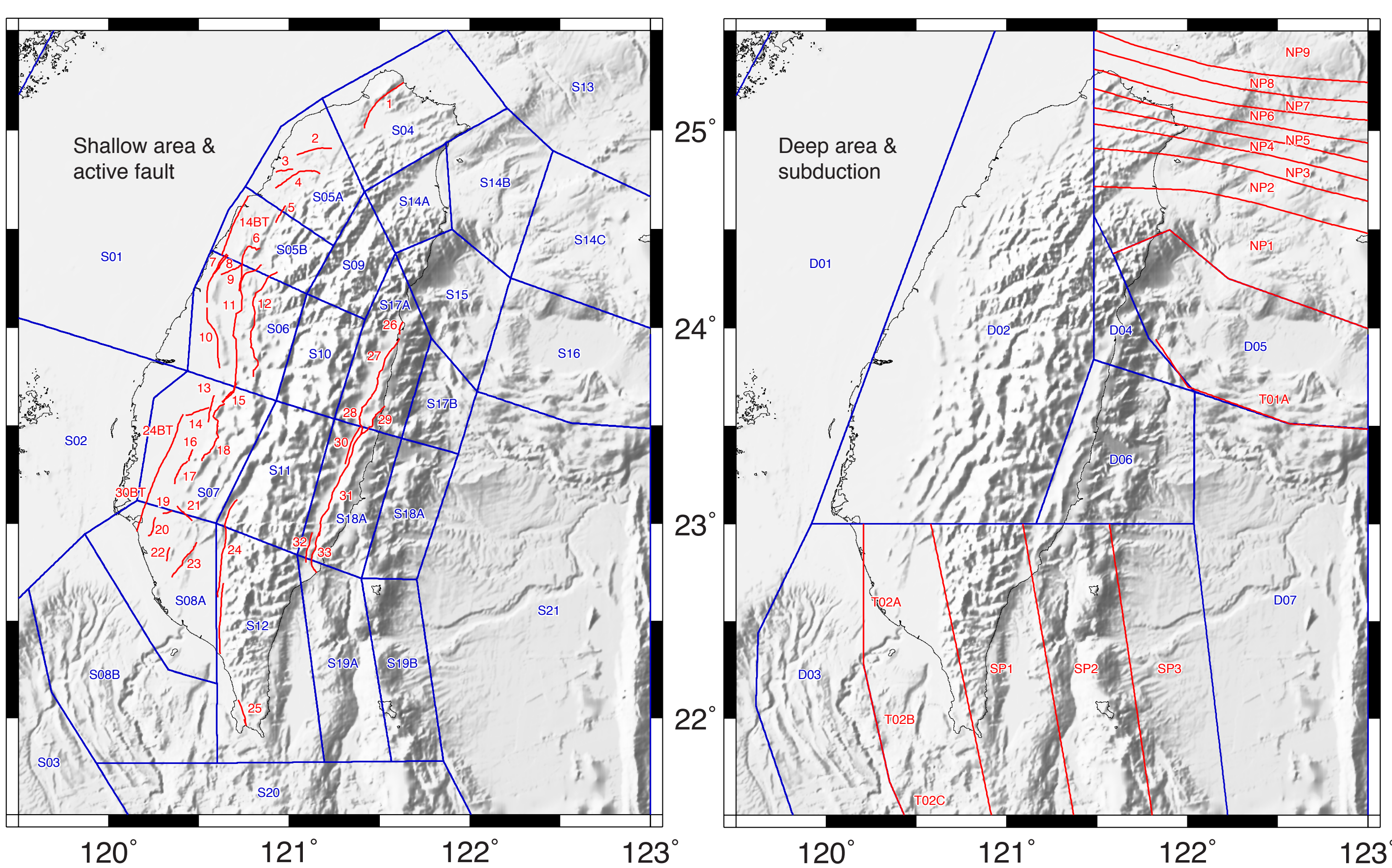
traditional PSHA.....

Traditional PSHA is difficult for implementation in a ***real-time***

- Time consuming
- declustered catalog



▲ Logic tree



◀ Seismog. sources

Cheng et al. (submitted)

Outlines.....

Outlines

- Earthquake forecasting models
  - Long-term rate by a smoothing Kernel
  - Rate evolution by ΔCFS & rate/state model
- Probabilistic seismic hazard assessments
- Applications
  - Hualien City during 2006-2010
  - The Meishan sequence during 1904-1906
  - The Jiashian sequence during 2010-2012

Kernel.....

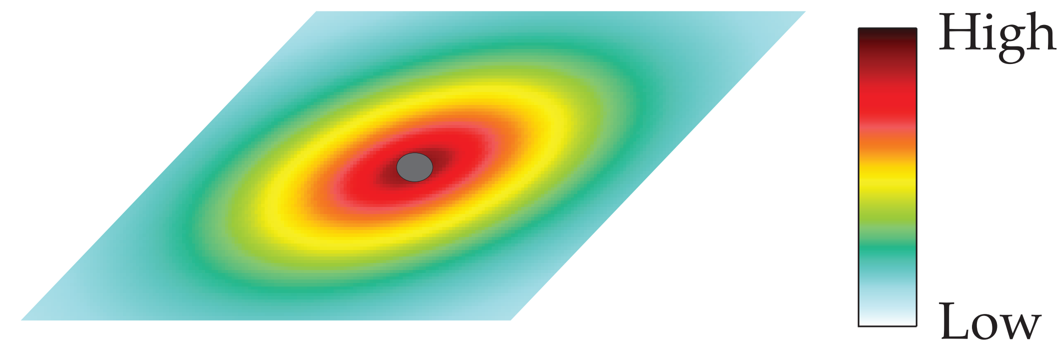
Distribution of seismicity density in the surrounding area

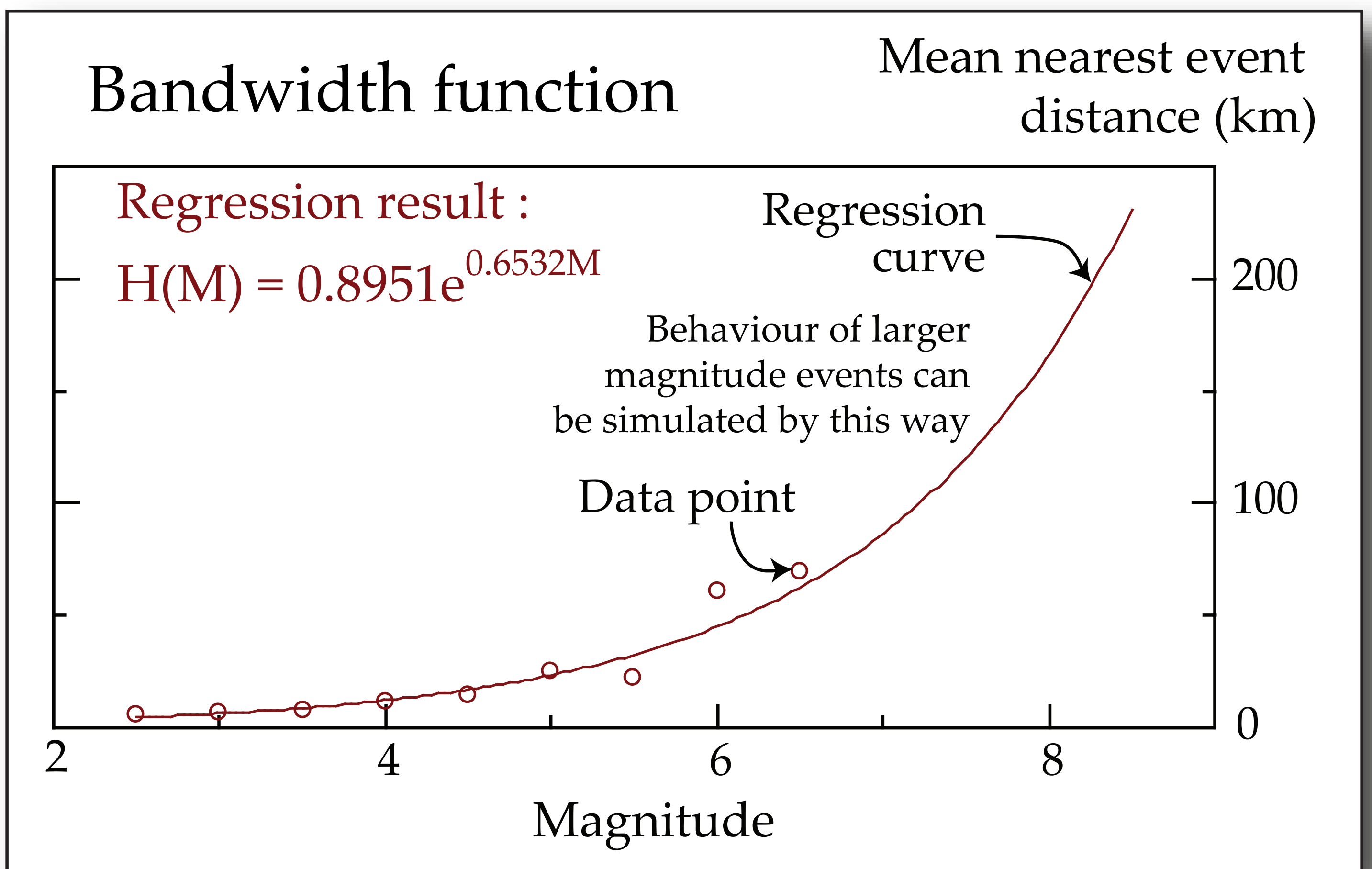
Smoothing Kernel function

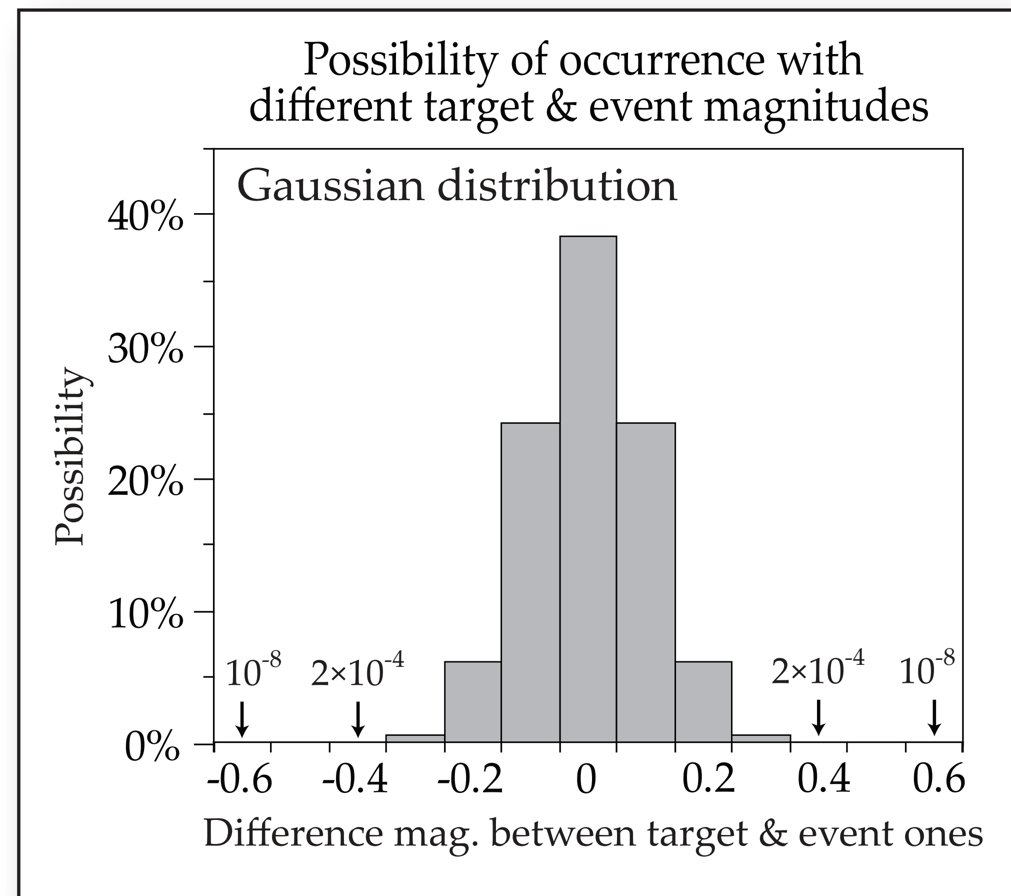
$$K(M,r)=\frac{PL-1}{\pi\ H^2(M)}\left(1+\left(\frac{r}{H(M)}\right)^2\right)^{-PL}$$

Power Law index (1.5-2.0)

Bandwidth function



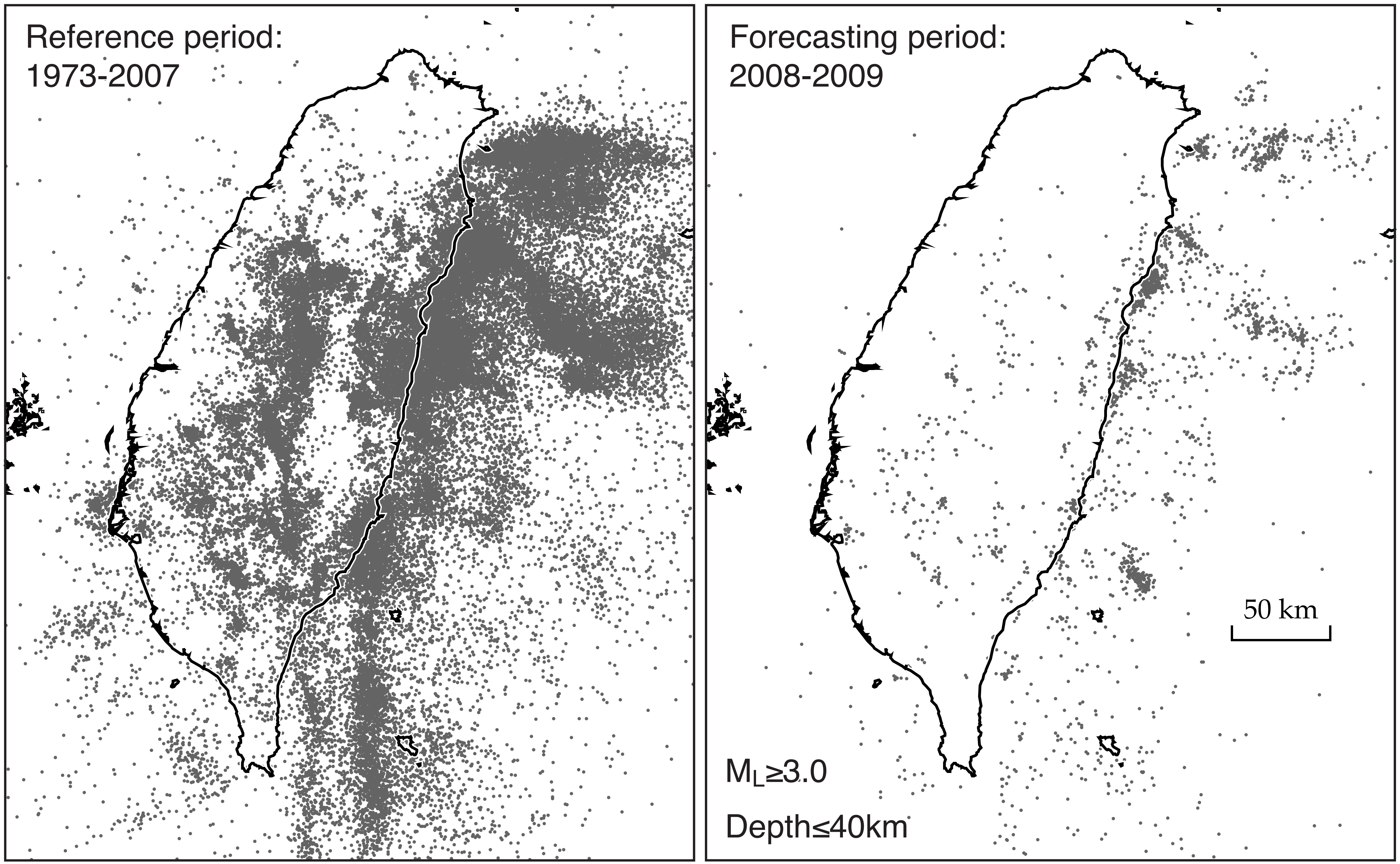




Traditional zoneless approach (*Wu, BSSA*, 1996)

Apply to Taiwan...

Distribution of seismicity for ***reference*** & ***forecast periods***



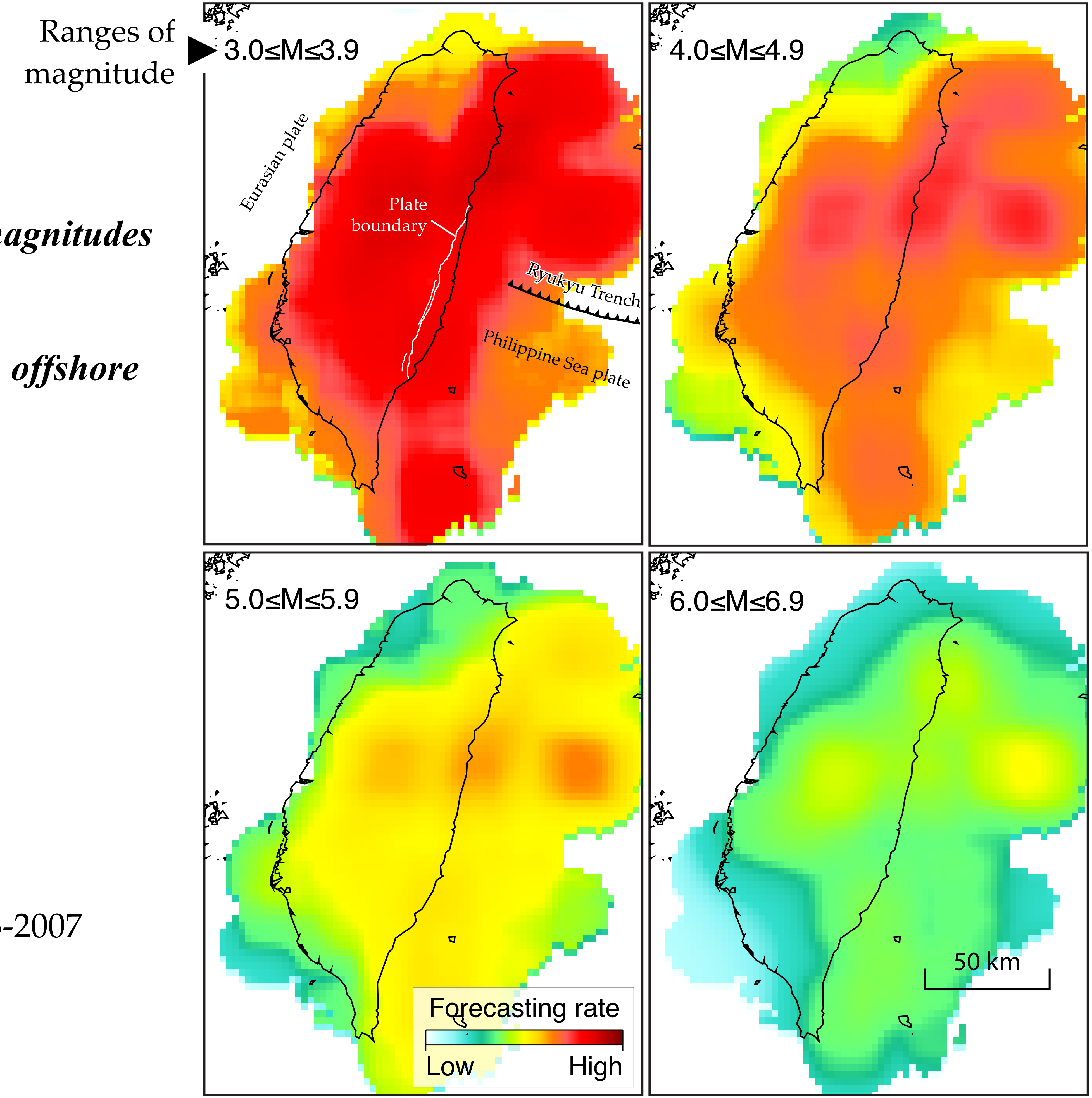
1973-1993 M≥4.0 TTSN catalog;
1994-2009 M≥3.0 CWBSN catalog.

forecast result...

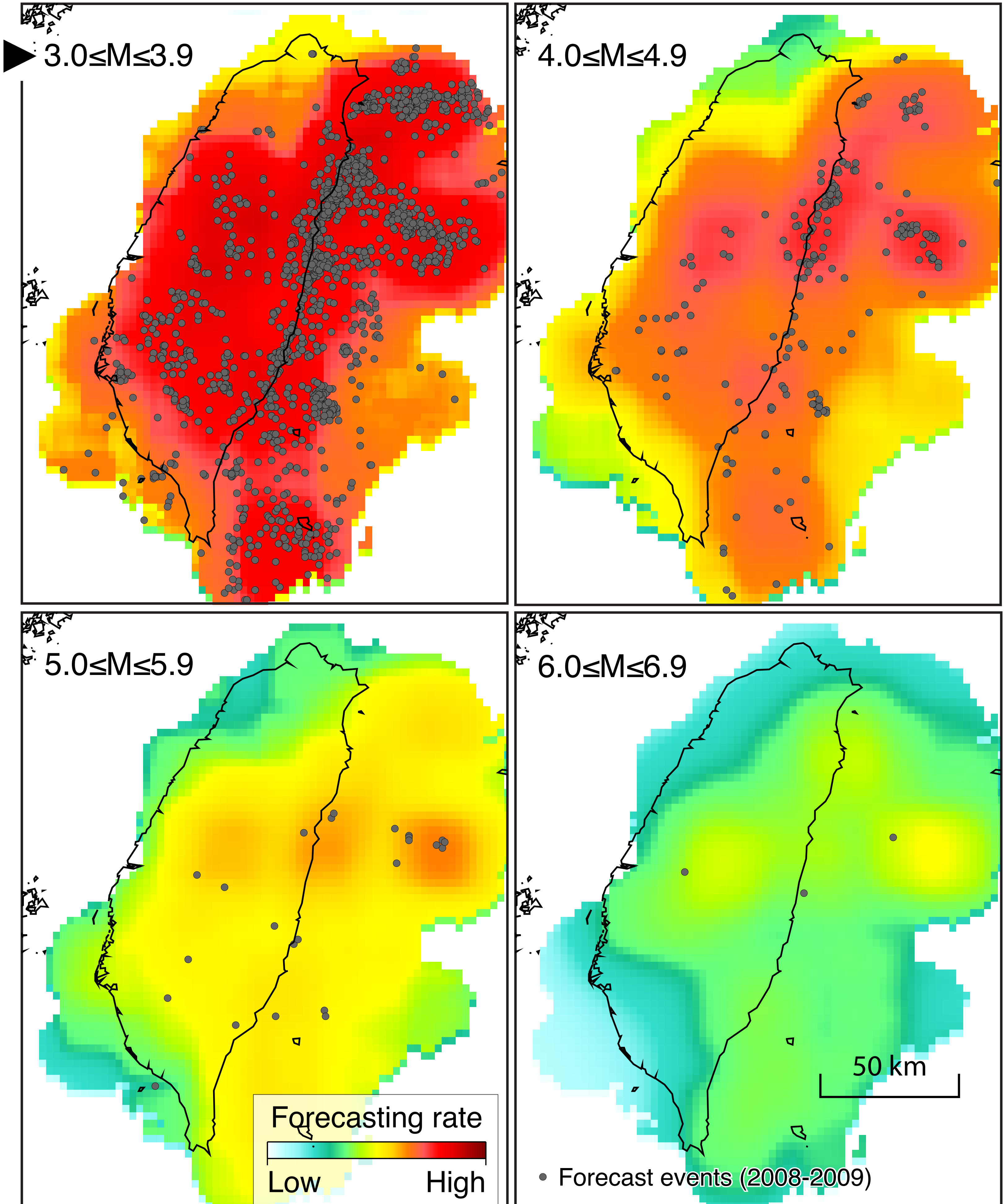
Higher rate for ***smaller magnitudes***
- Follow G-R Law

Higher rate at the ***eastern offshore***
- The plate boundary

Reference period: 1973-2007



Ranges of magnitude



Higher rate for ***smaller magnitudes***
- Follow G-R Law

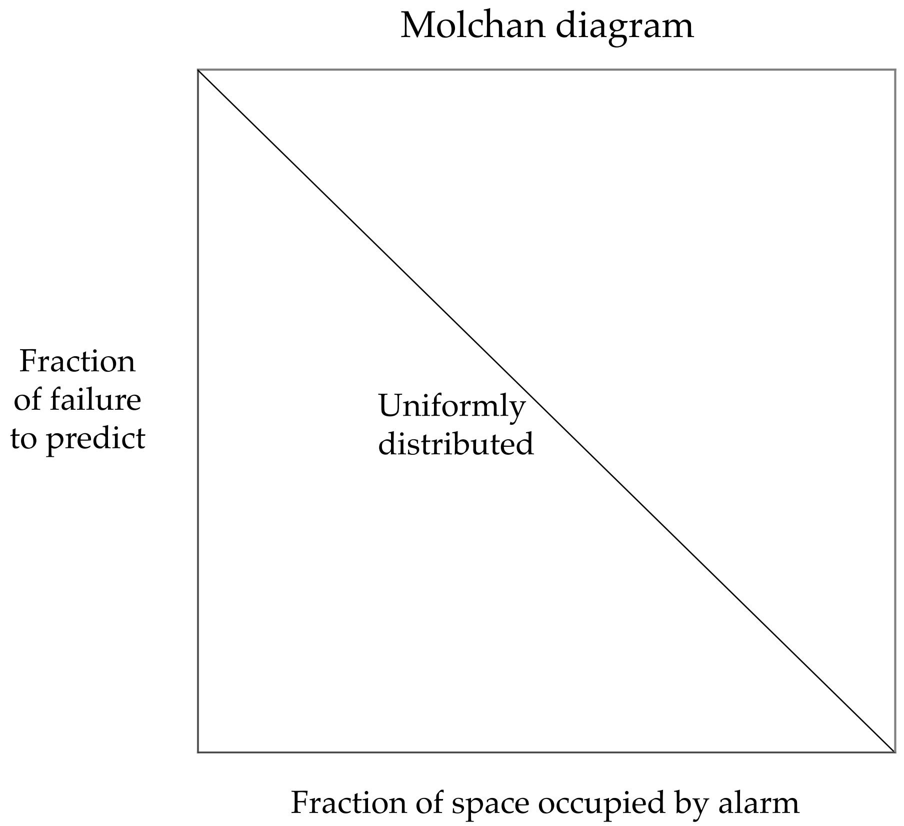
Higher rate at the ***eastern offshore***
- The plate boundary

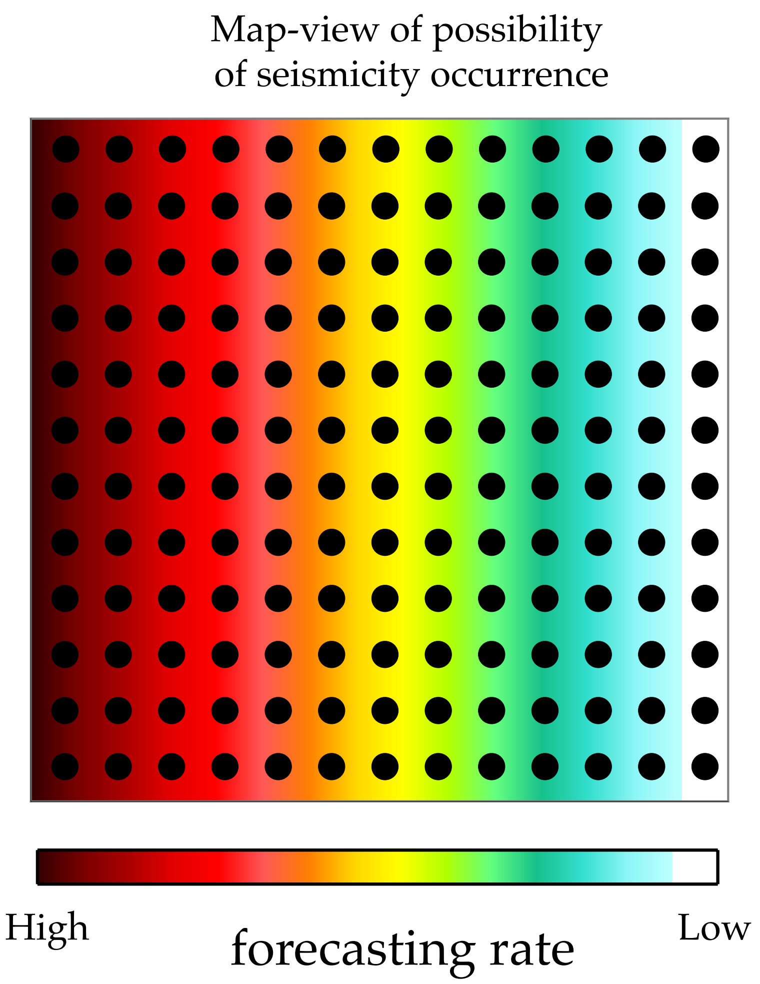
Good correlation with the forecasting event distribution

Reference period: 1973-2007
Forecast period: 2008-2009

Molchan diagram...

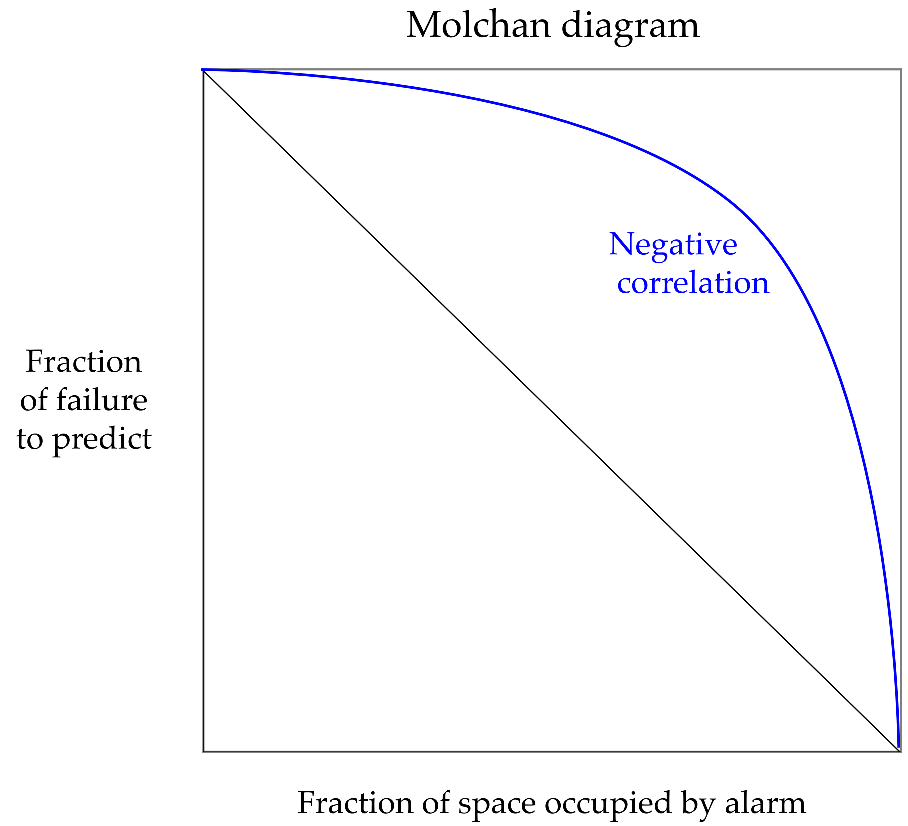
Molchan diagram represents....

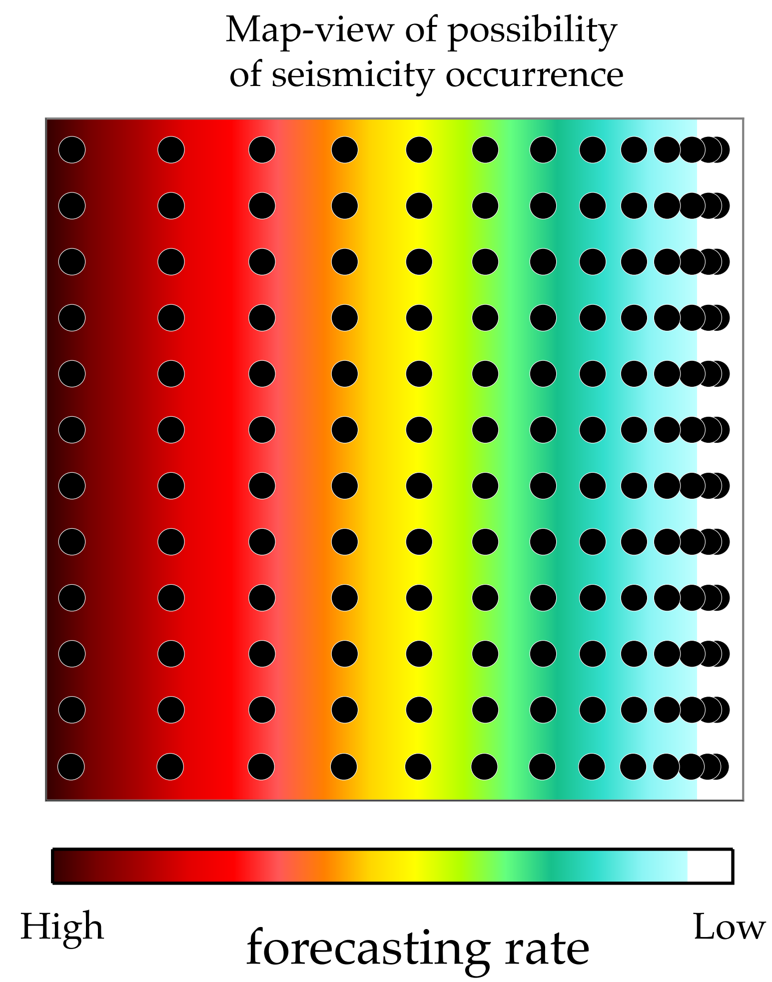




diagonal if no correlation

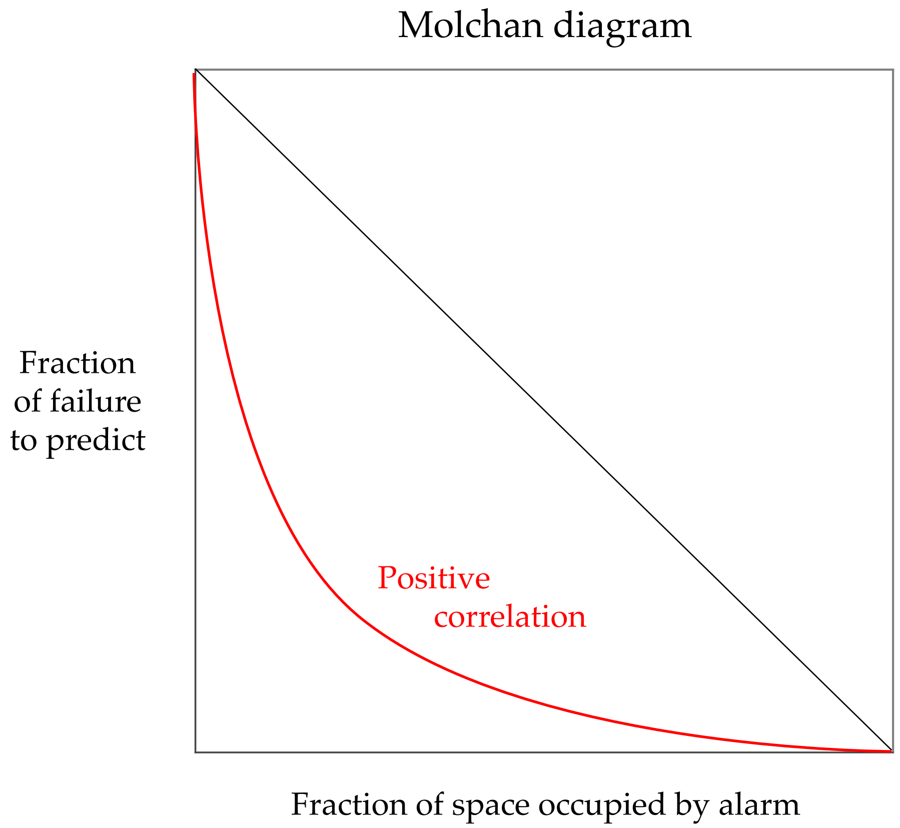
Molchan diagram represents....

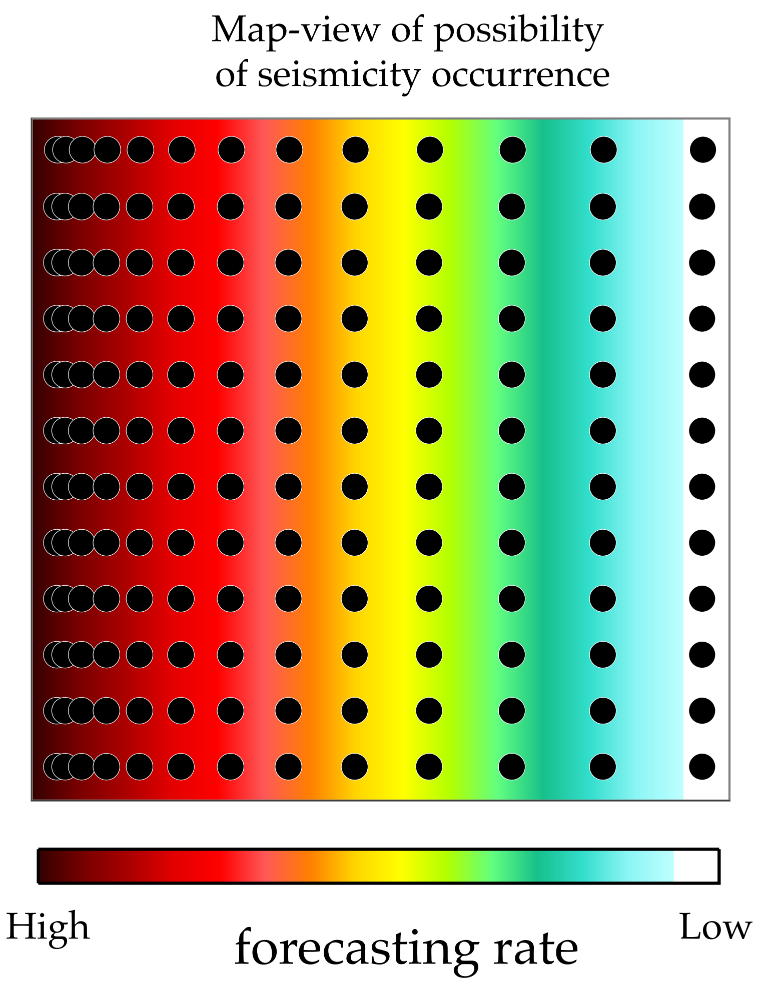




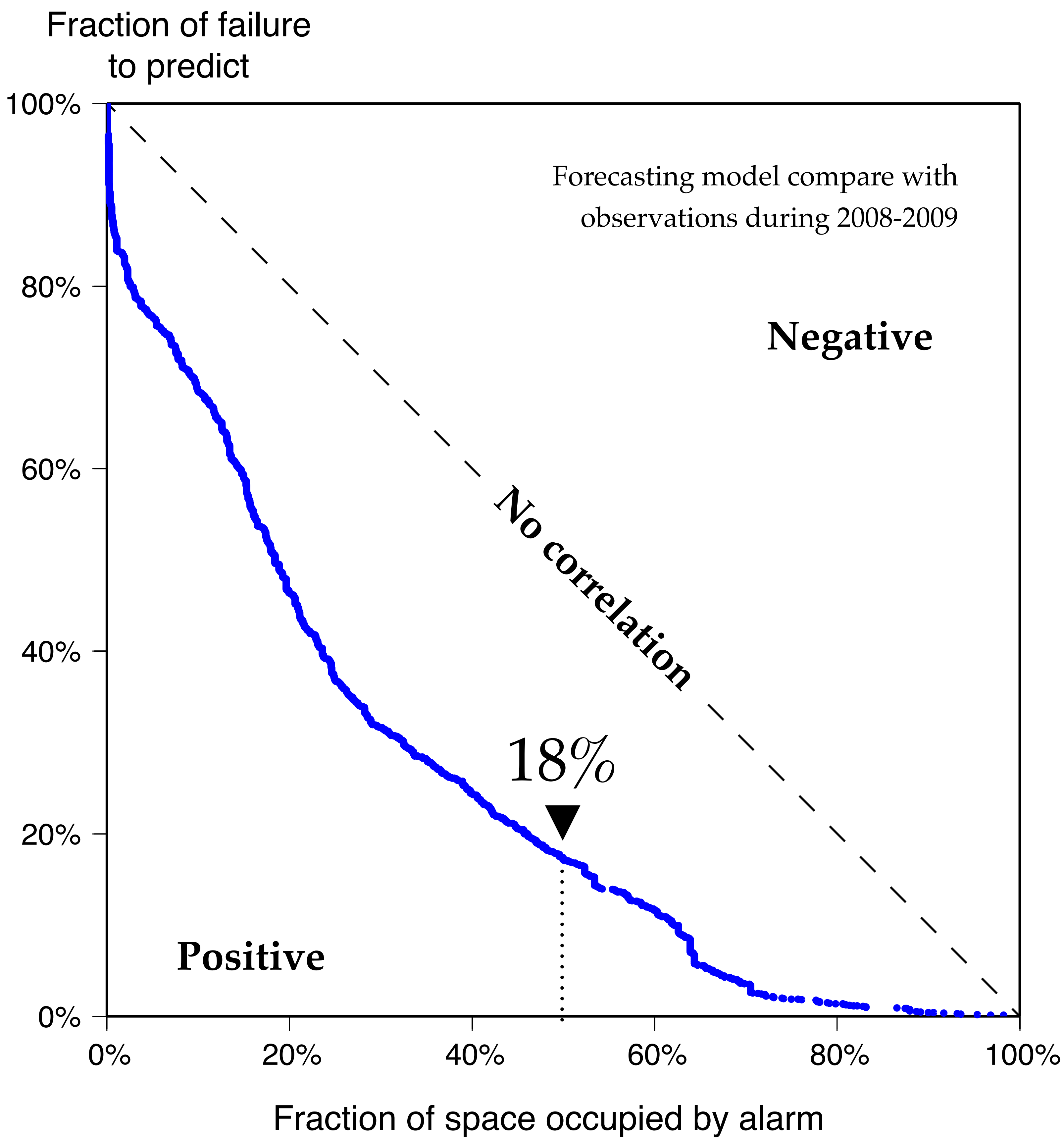
convex arc if negative correlation

Molchan diagram represents....





concave arc **if positive correlation**



Only ***18%*** events occurred in the ***half*** lowest density region

Reference period: 1973-2007

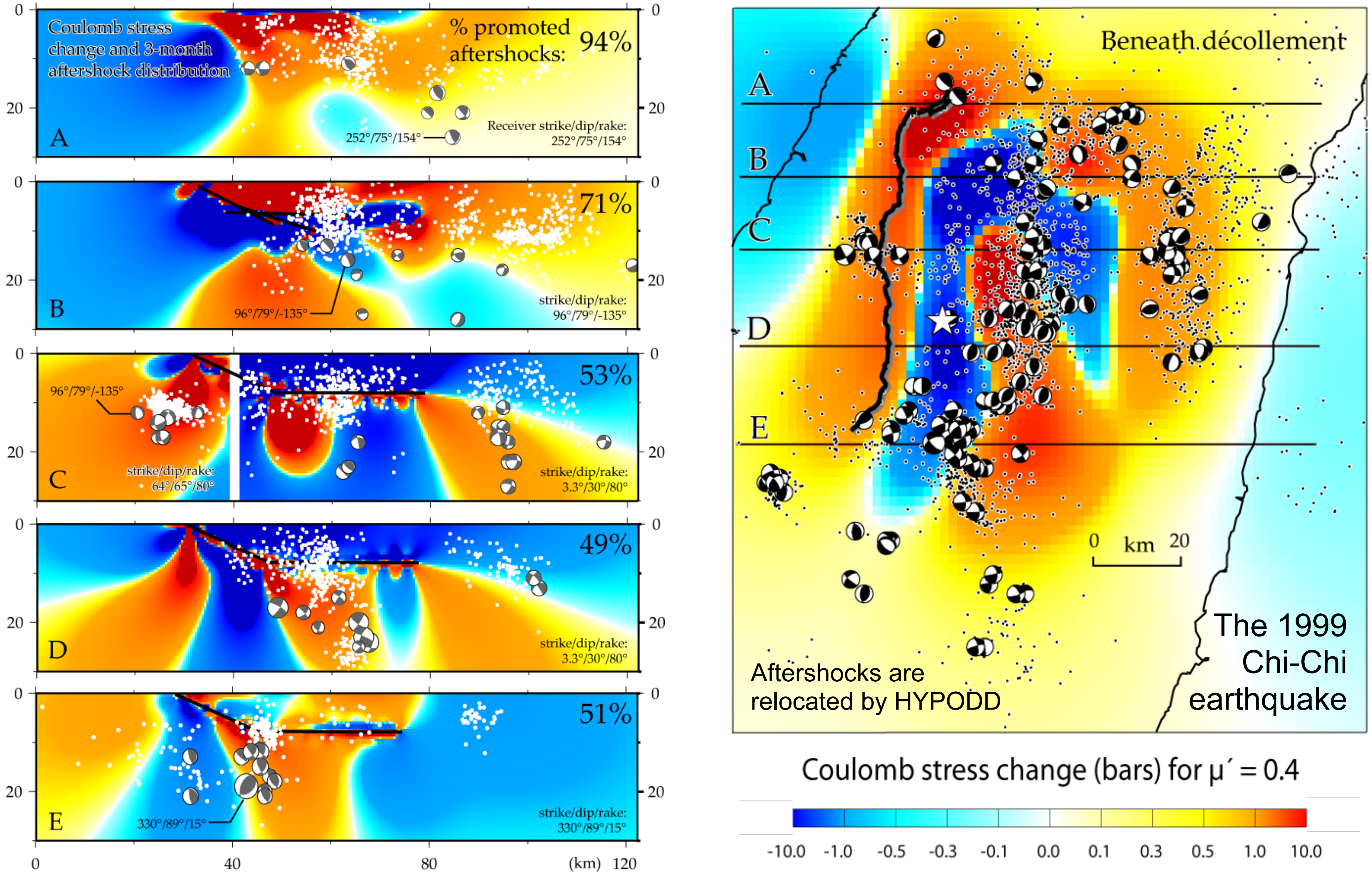
Forecast period: 2008-2009

ΔCFS....

Short-term seismicity rate evolution

- The Coulomb stress change
- The rate-and-state friction model

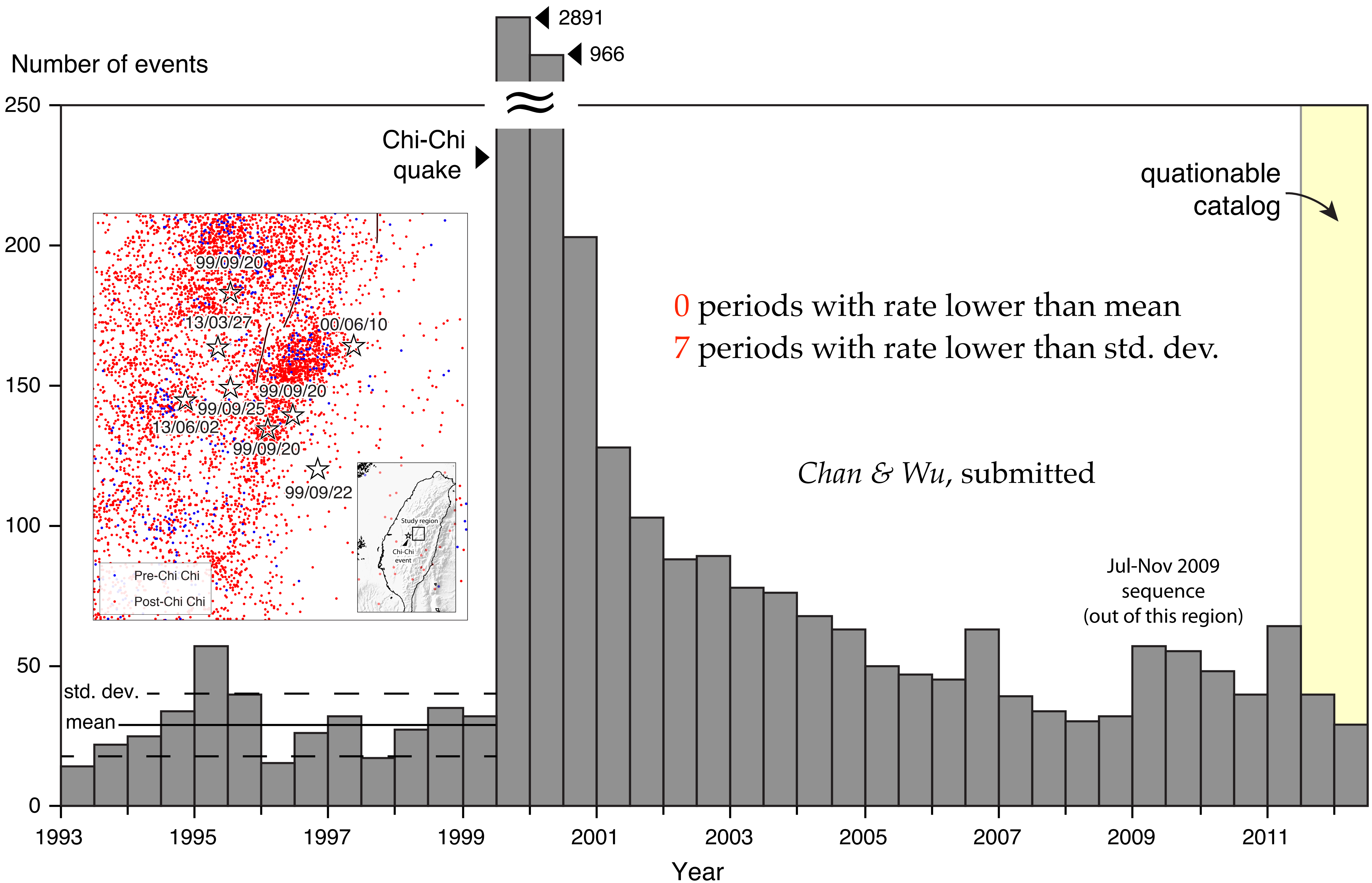
Depth dependency & *mechanism heterogeneity* should be considered for the near-real-time ΔCFS calculation



Chan & Stein, 2009

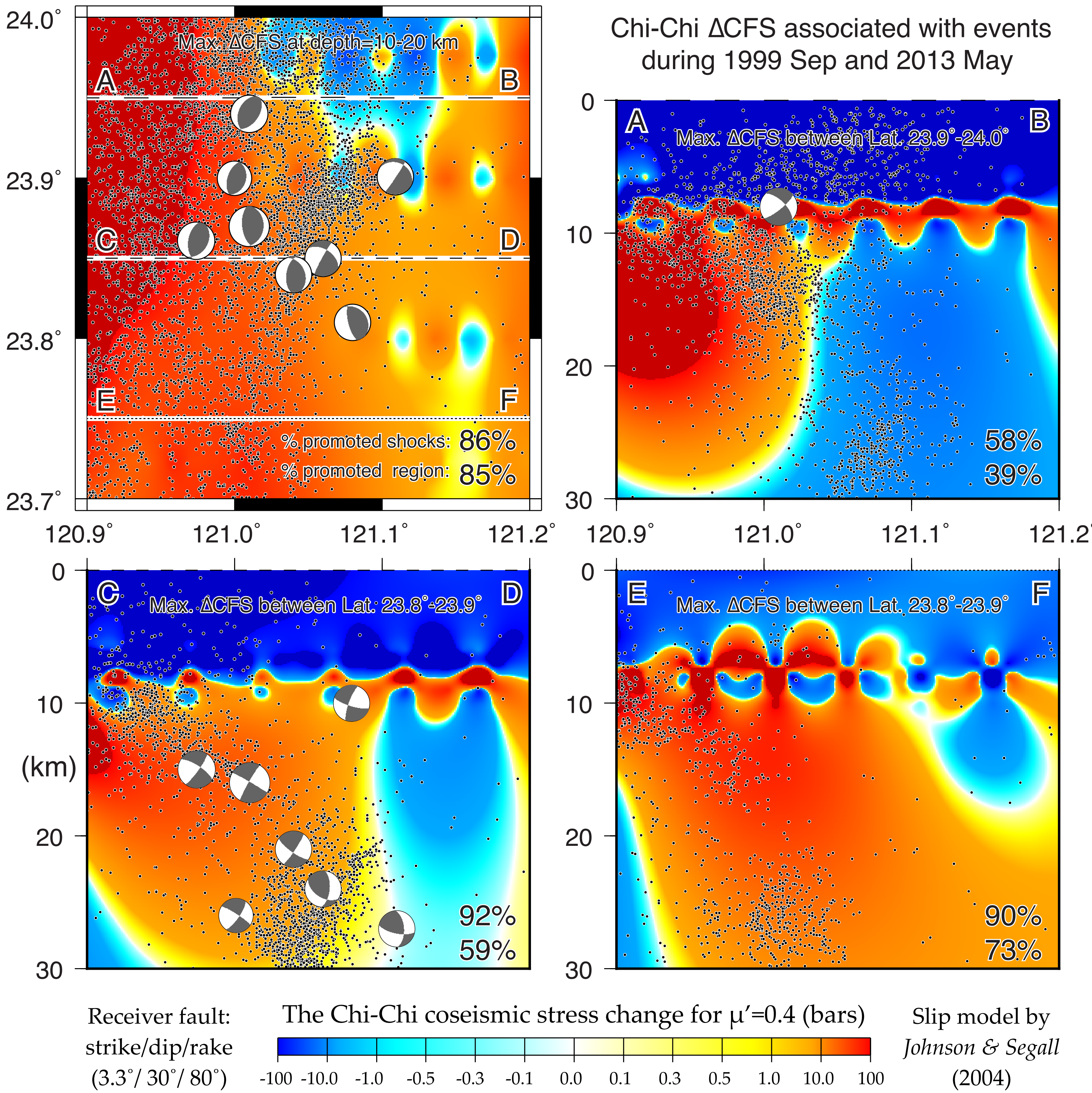
Nantou case…

Seismicity activity cannot simply be explained by ***the Omori decay***



The seismicity rate in Nantou ***keeps high*** after Chi-Chi

ΔCFS…



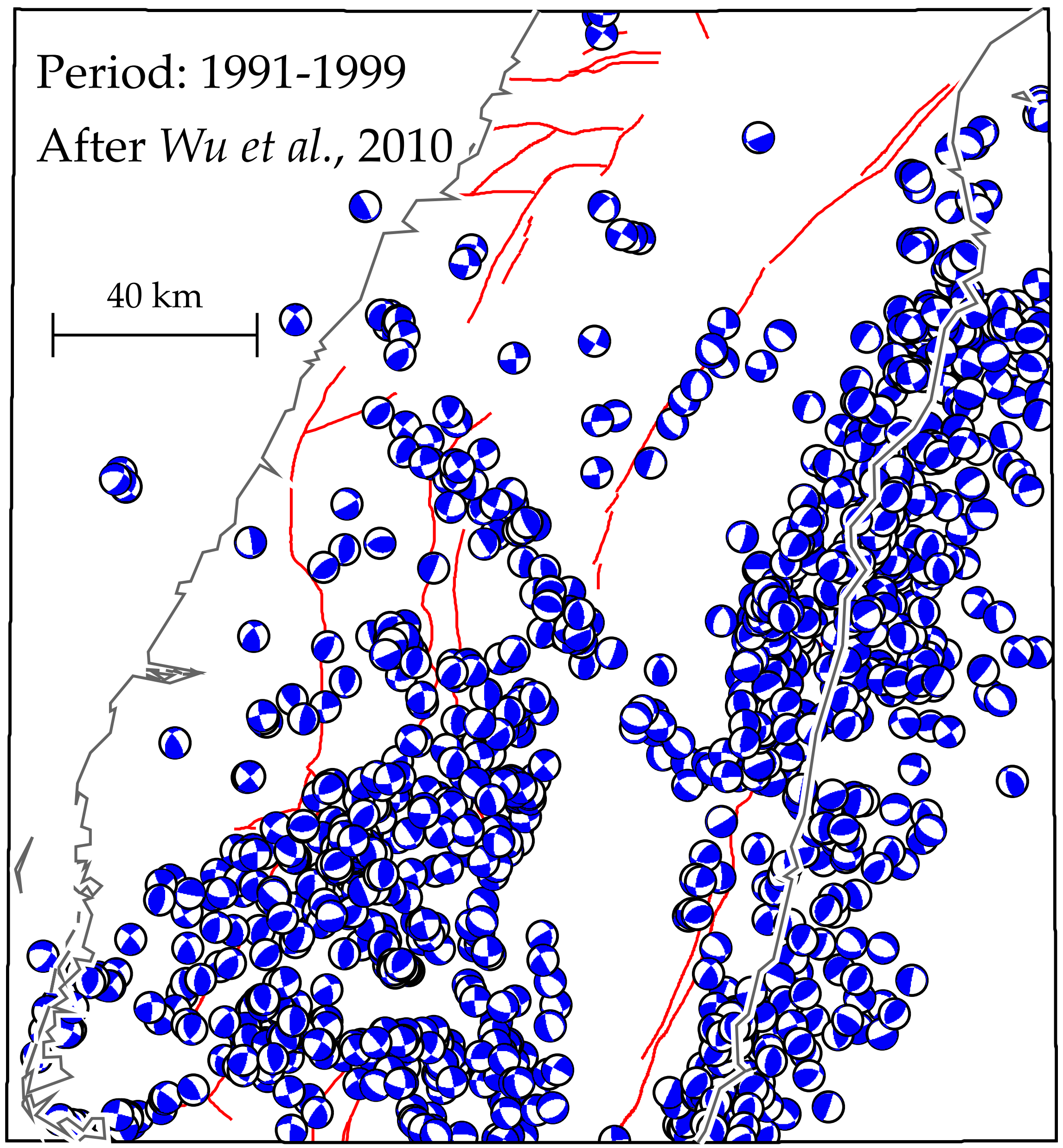
The stress beneath the décollement is ***enhanced***

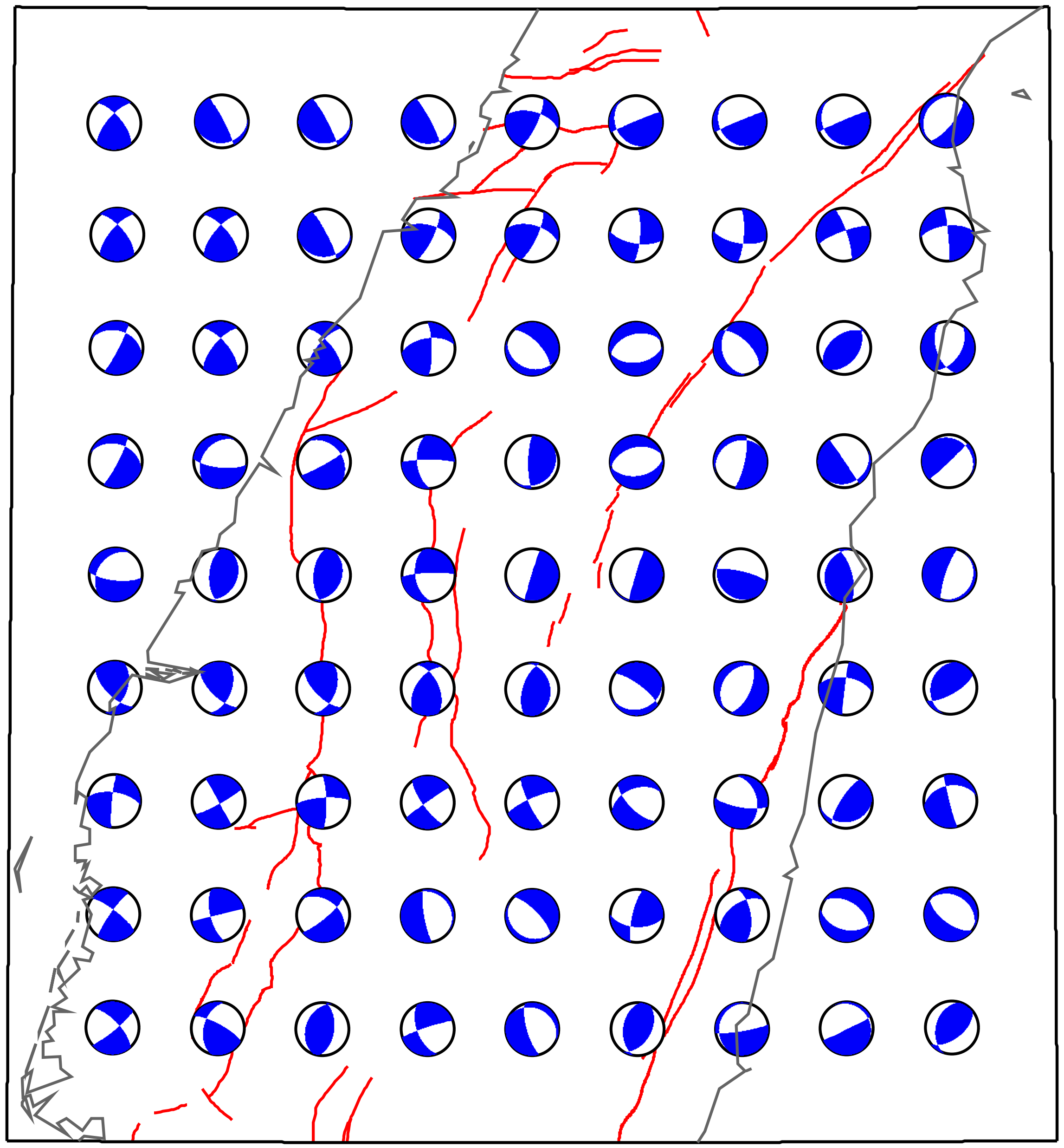
The seismic pattern can be associated with ***ΔCFS***

Chan & Wu, submitted

spatial variable receiver....

Assumed the same focal mechanisms as nearest references for ΔCFS calculations



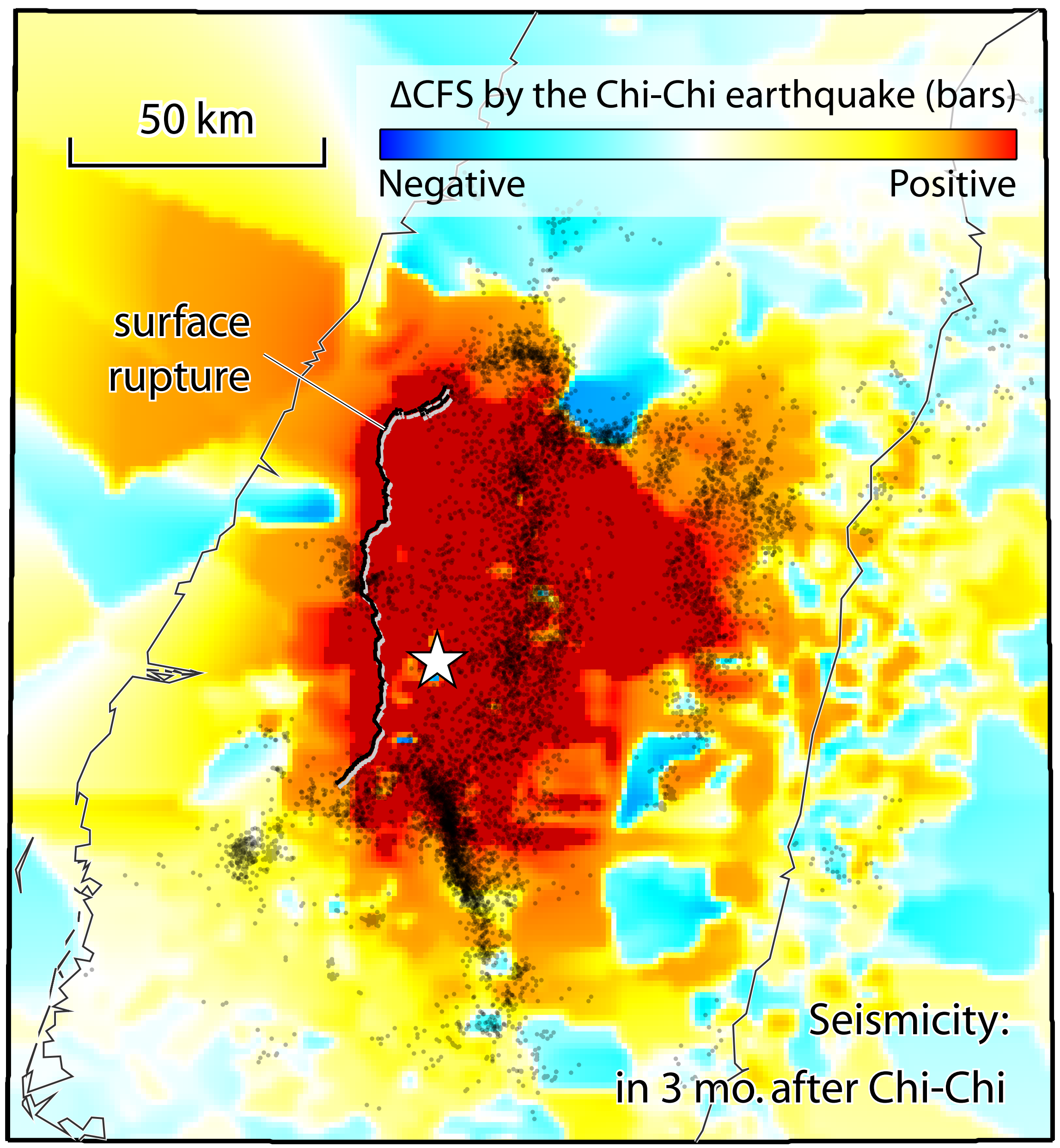


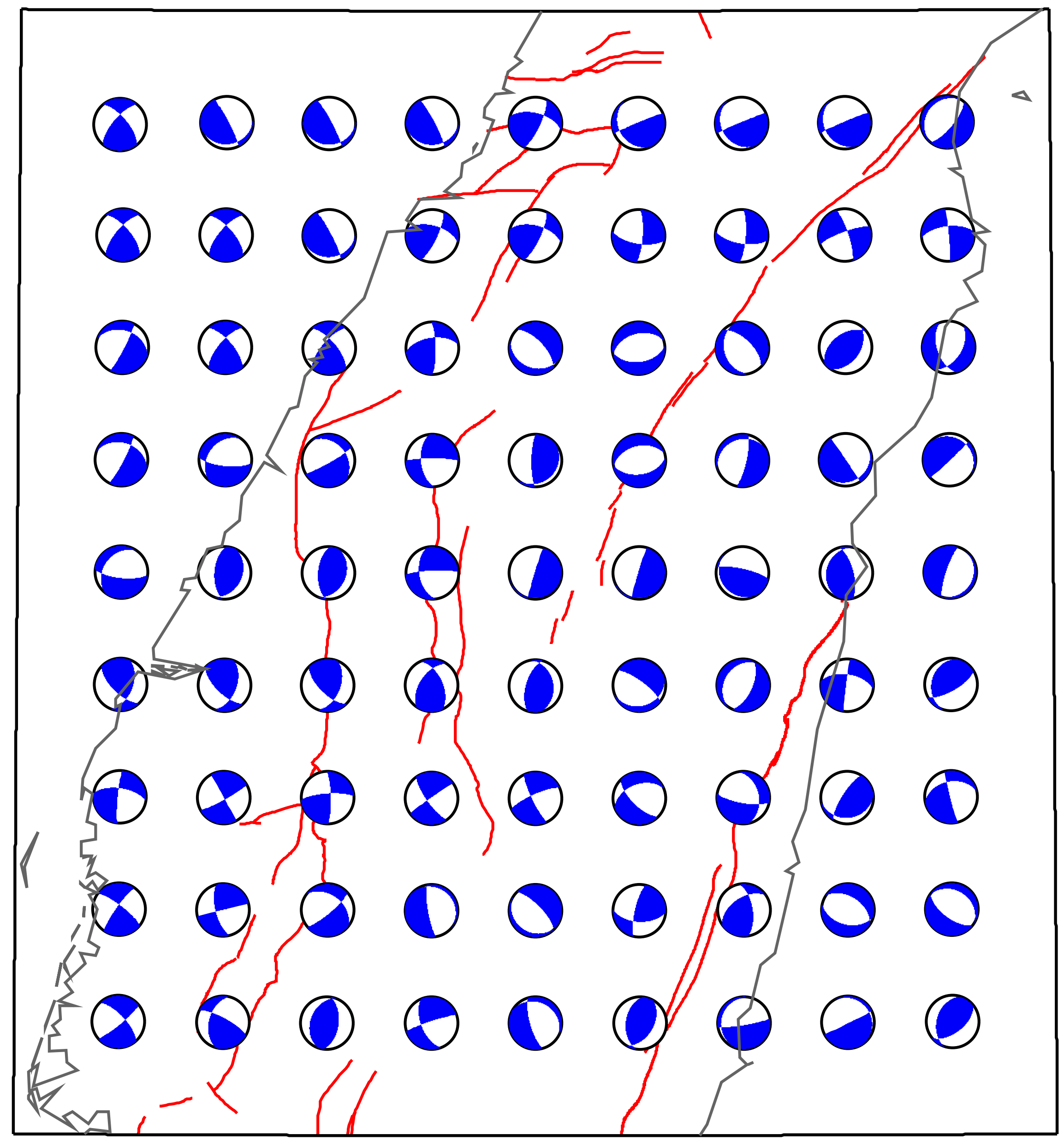
Catalli & Chan, 2012

Good forecasting ability by ***spatial variable receiver faults*** & ***Max. ΔCFS*** among entire seismogenic zone

ΔCFS compares with aftershocks

Assumed receiver faults for ΔCFS calculation



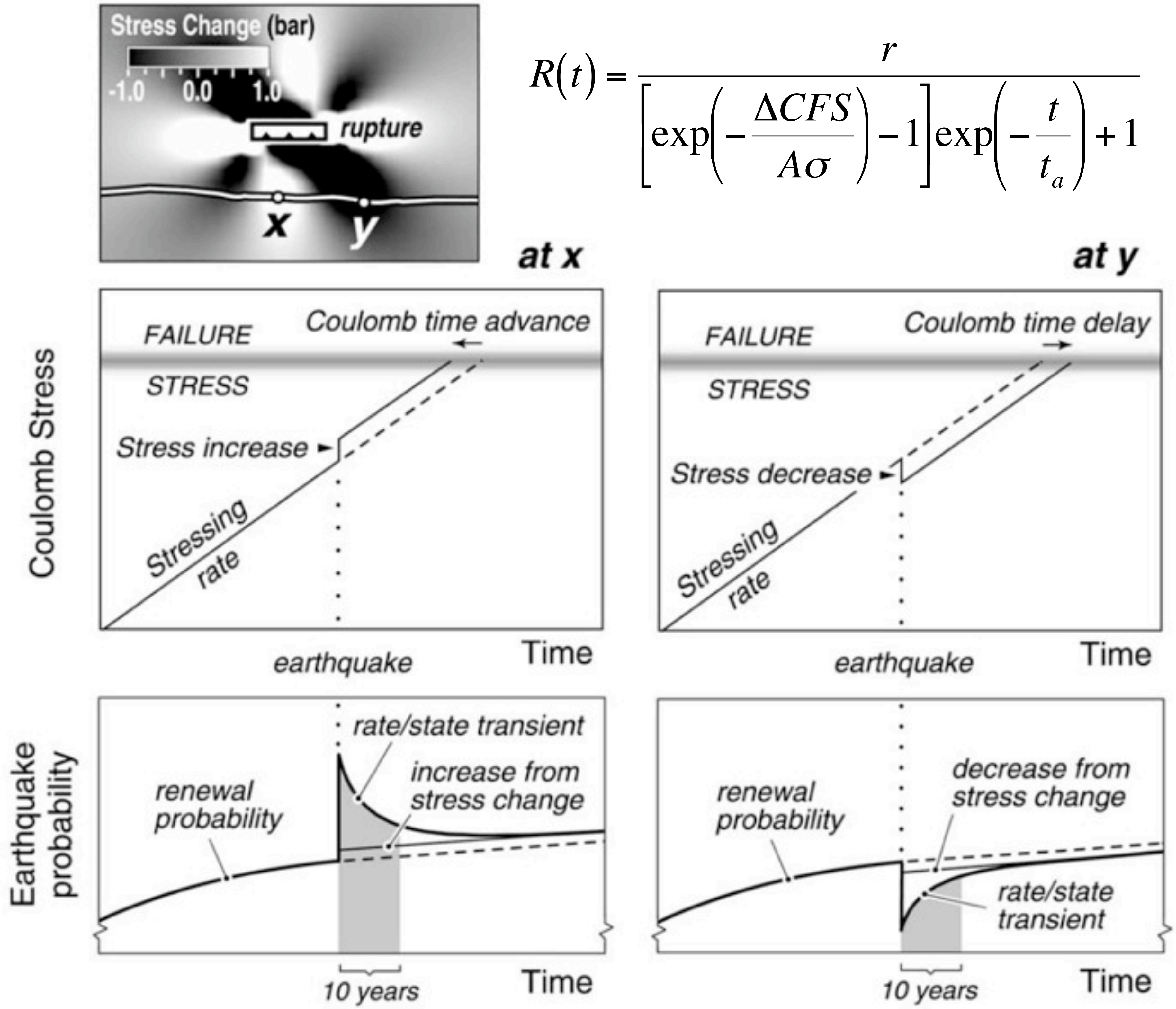


Catalli & Chan, 2012

rate/state....

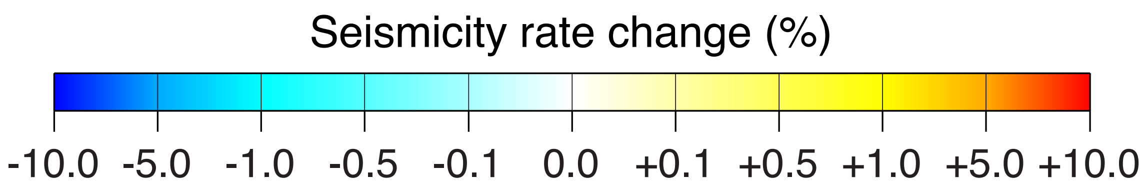
The rate-and-state friction model (*Dieterich*, 1994)

$$R(t) = \frac{r}{\left[\exp\left(-\frac{\Delta CFS}{A\sigma}\right) - 1\right]\exp\left(-\frac{t}{t_a}\right) + 1}$$

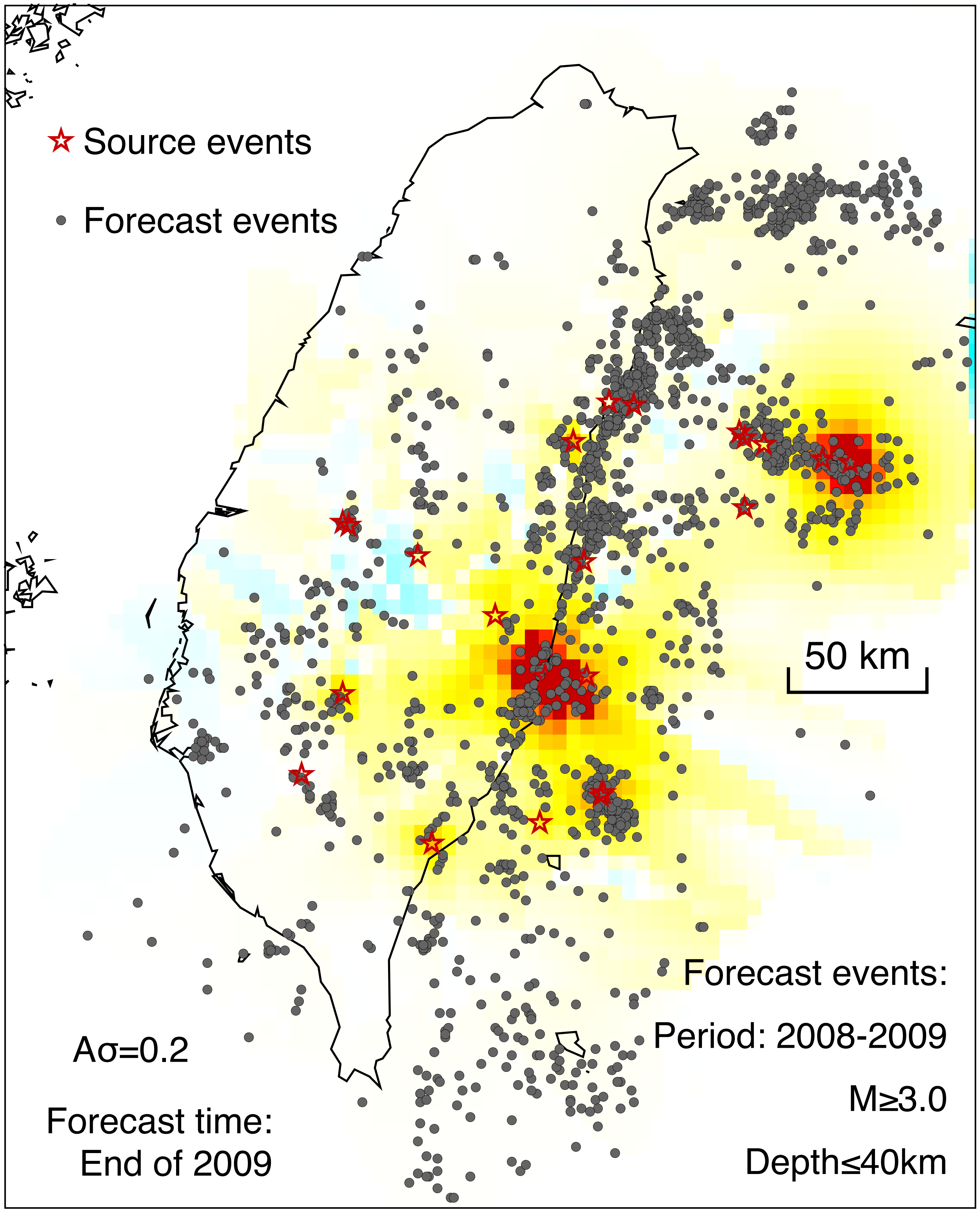


Illustrated by *Toda & Stein*, 2003

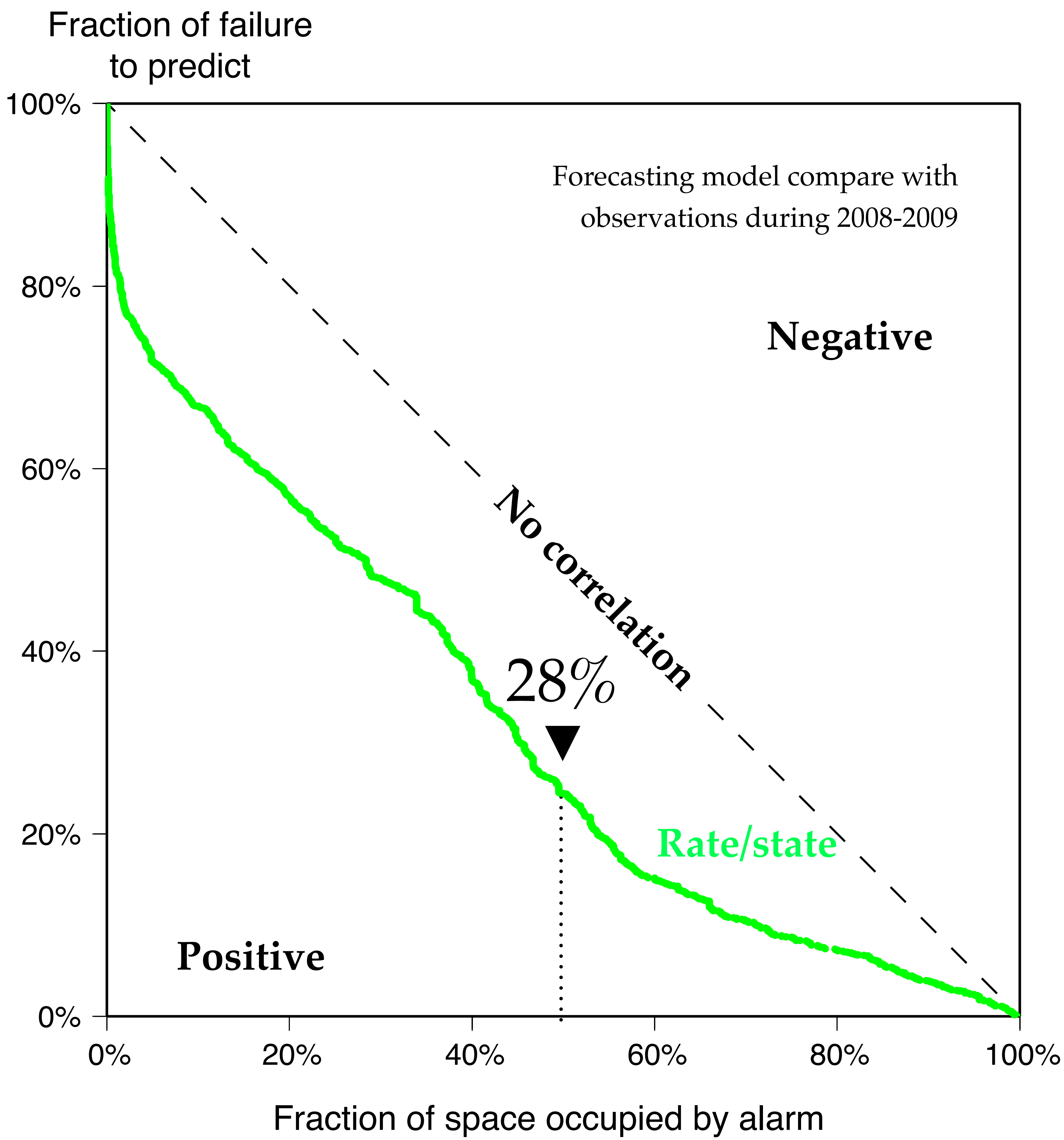
Most events occurred in the rate ***enhanced*** region



Chan et al., 2012



Molchan diagram…

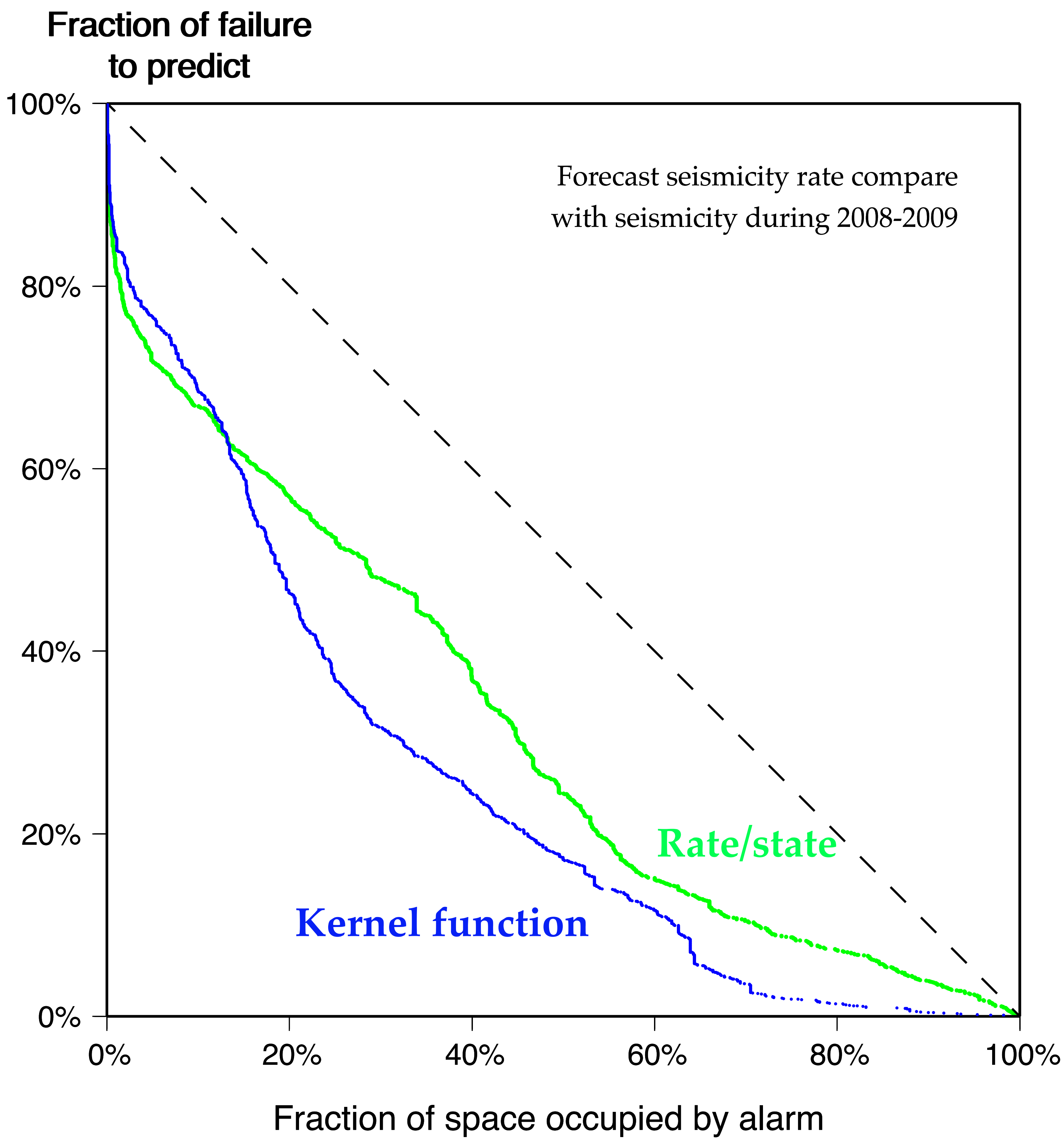


Only ***28%*** events occurred in the ***half*** lowest density region

Reference period: 1973-2007

Forecast period: 2008-2009

Chan et al., 2012



Only ***28%*** events occurred in the ***half*** lowest density region

Not as good as forecast model by the Kernel function

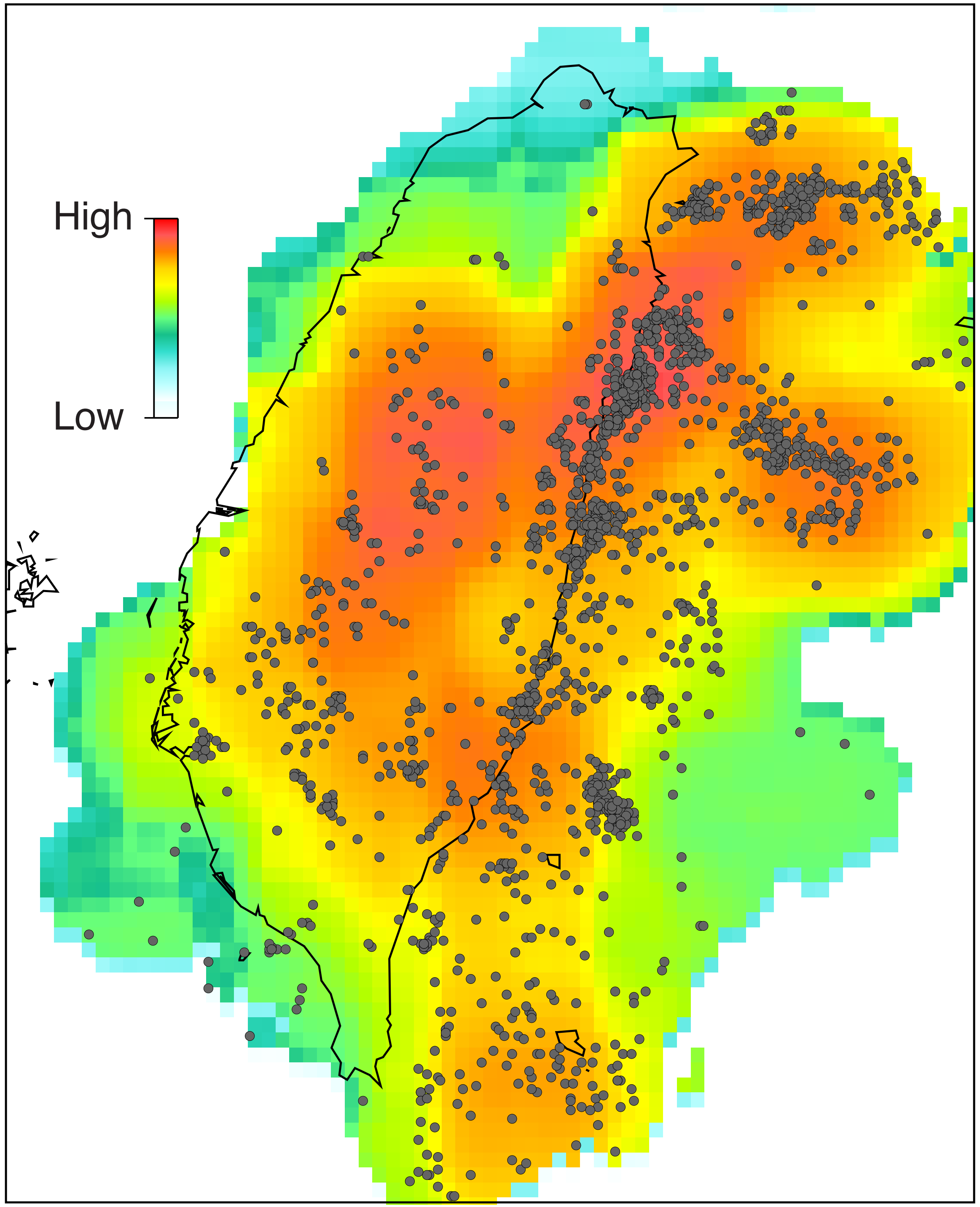
Reference period: 1973-2007

Forecast period: 2008-2009

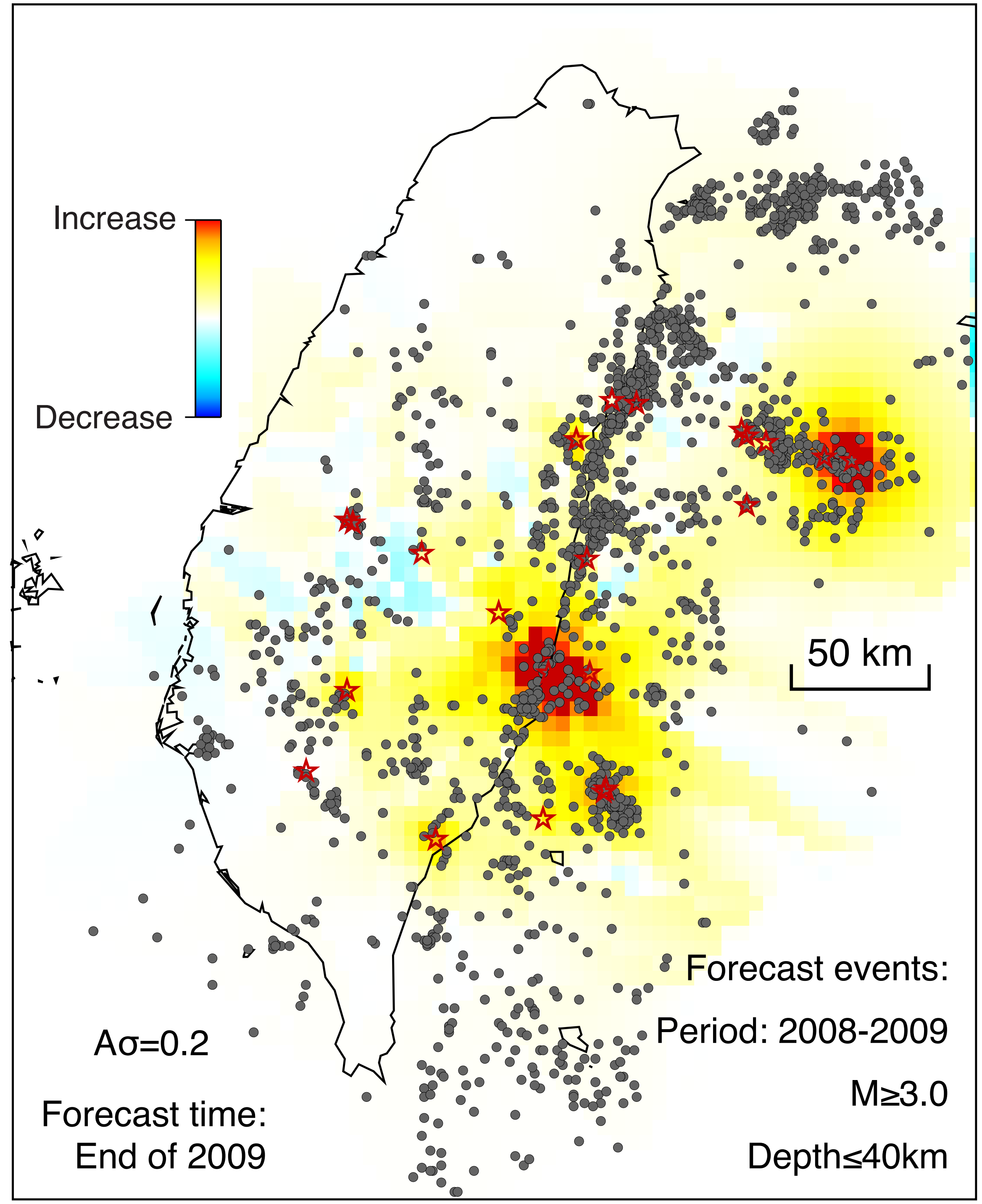
Chan et al., 2012

Combination….

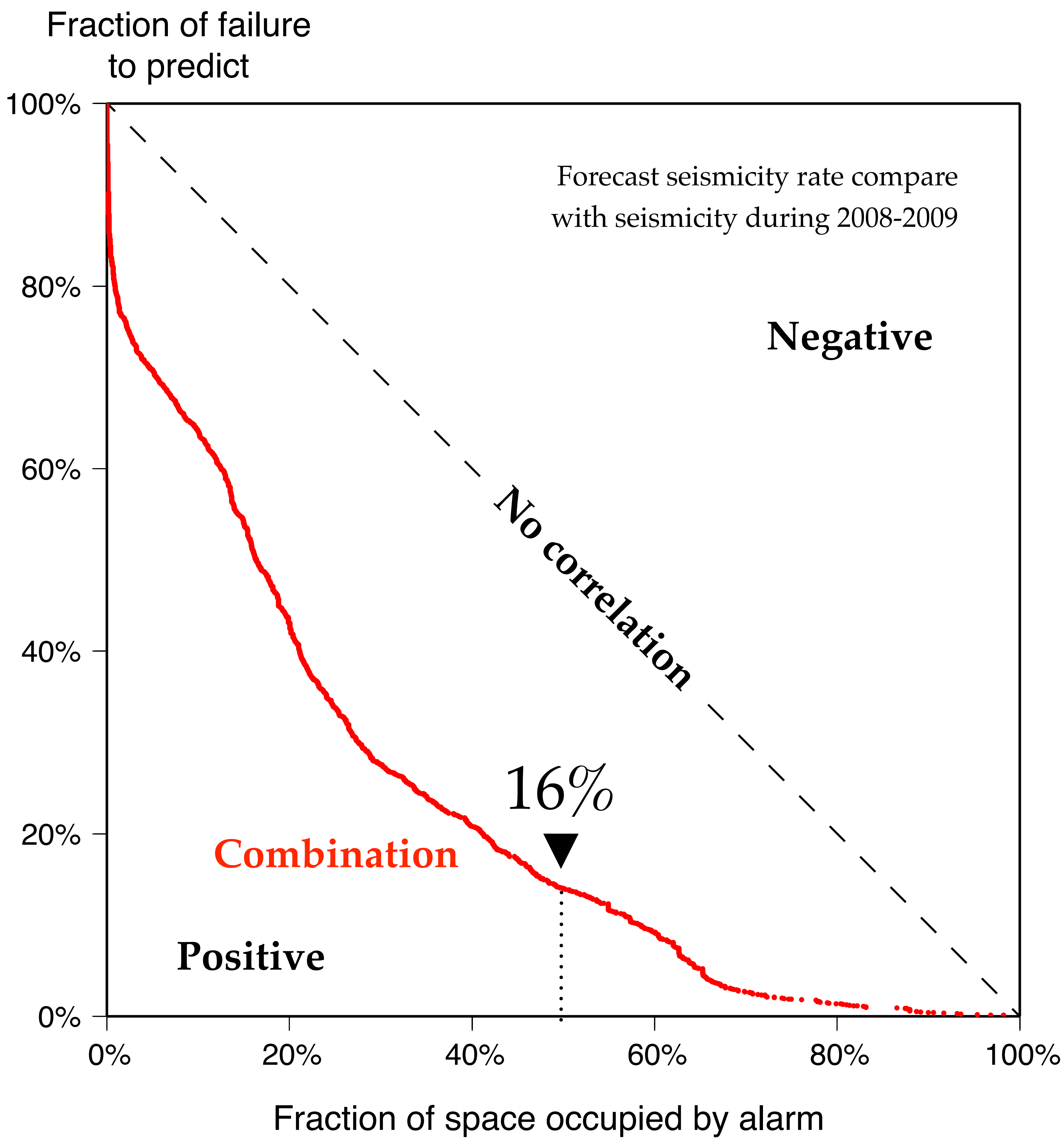
Combine the two models for another forecasting model



The Kernel function



The rate/state friction model



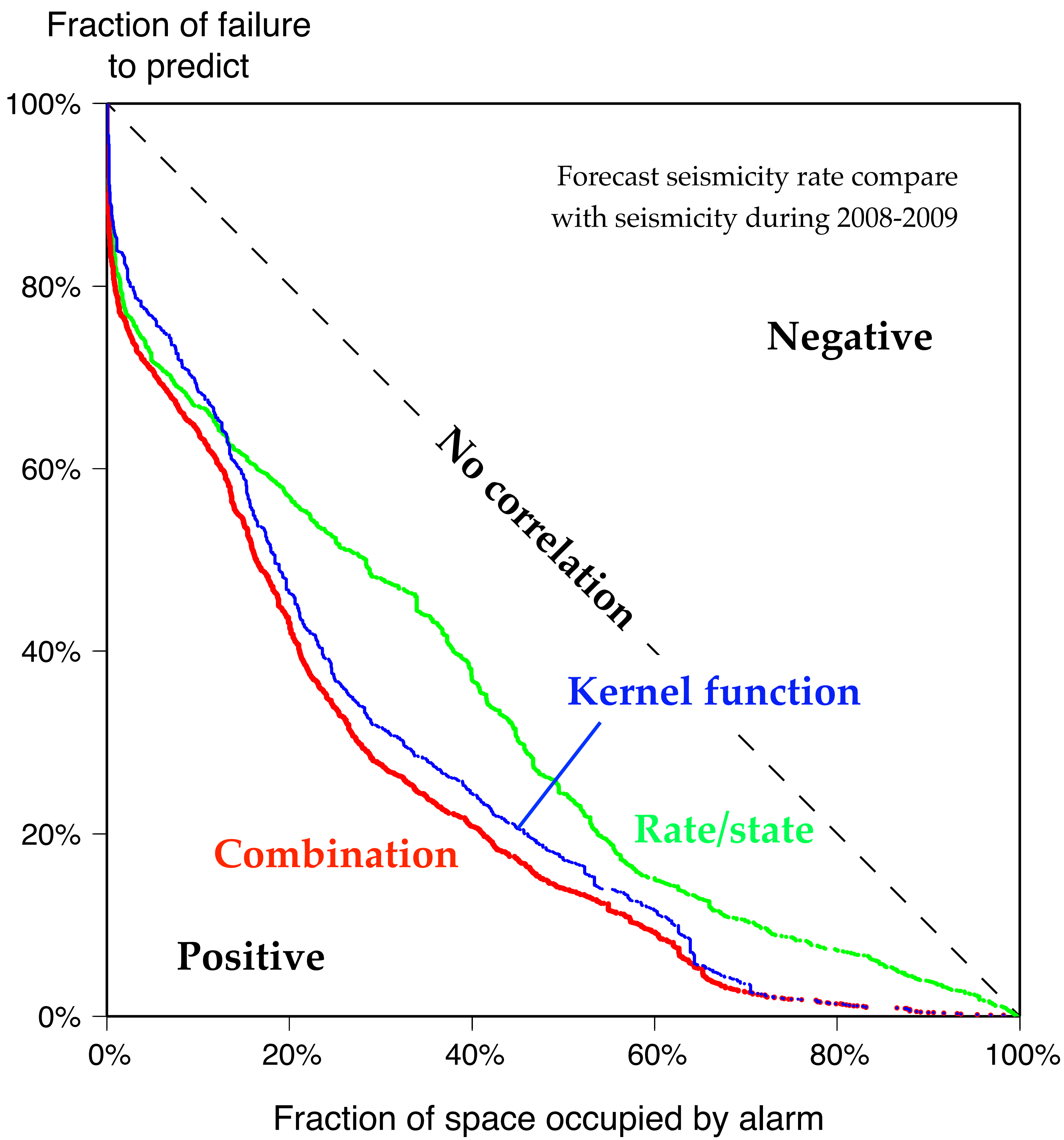
Only ***28%*** events occurred in the ***half*** lowest density region

Reference period: 1973-2007

Forecast period: 2008-2009

Chan et al., 2012

Compare with other results….



Only ***28%*** events occurred in the ***half*** lowest density region

Combination of the two models has ***the best forecasting ability***

Reference period: 1973-2007

Forecast period: 2008-2009

Chan et al., 2012

PSHA….

Application of the Probabilistic Seismic Hazard Assessment (PSHA)

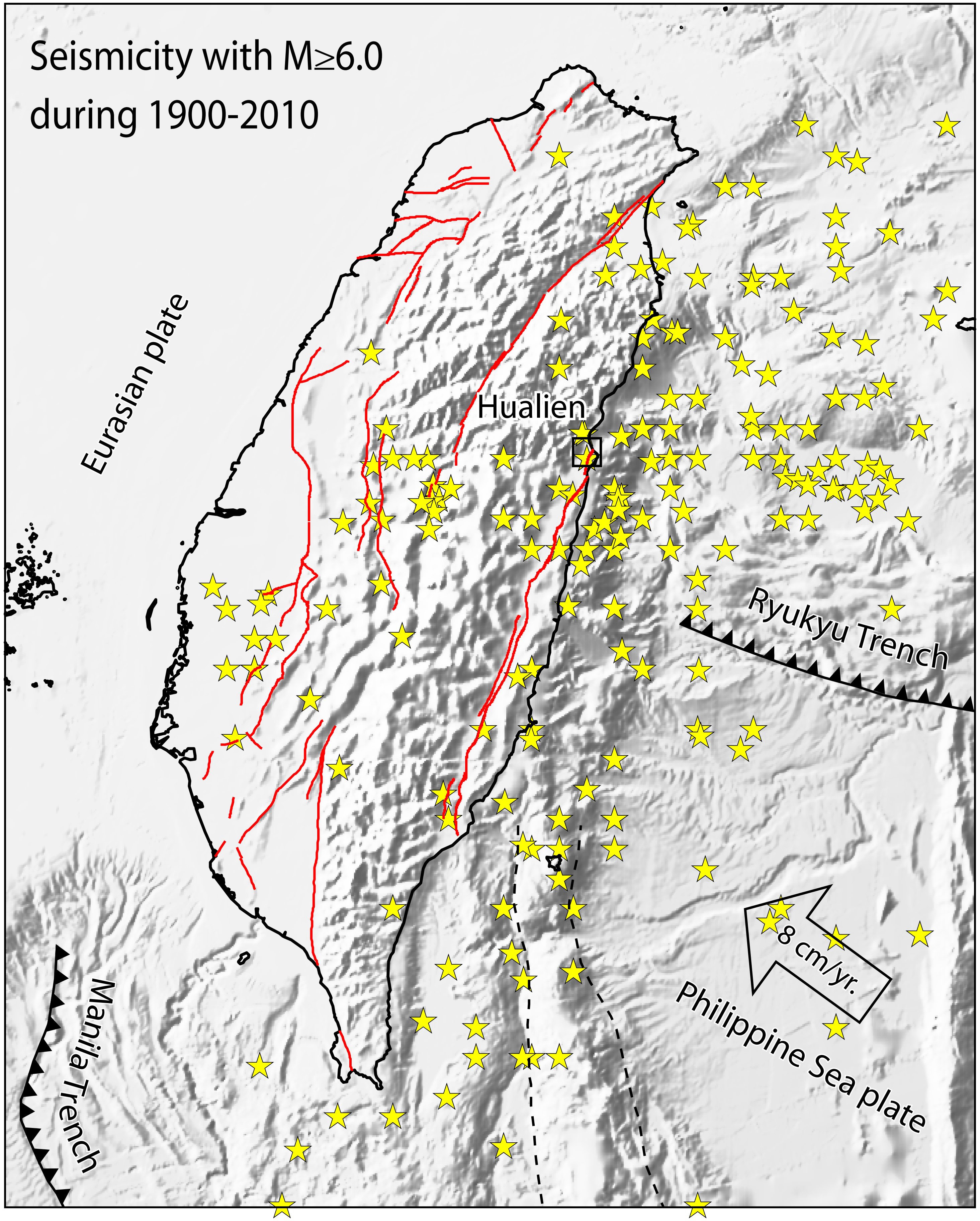
- Long-term & short-term seismicity density rate
- Considering ground motion prediction equations
- Application to Hualien City

why Hualien....


花蓮芋

Most of the ***large earthquakes*** take place along the east coast

Hualien is one of the most ***populated*** cities along the east coast

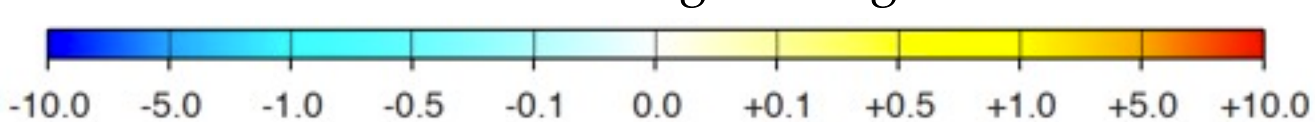


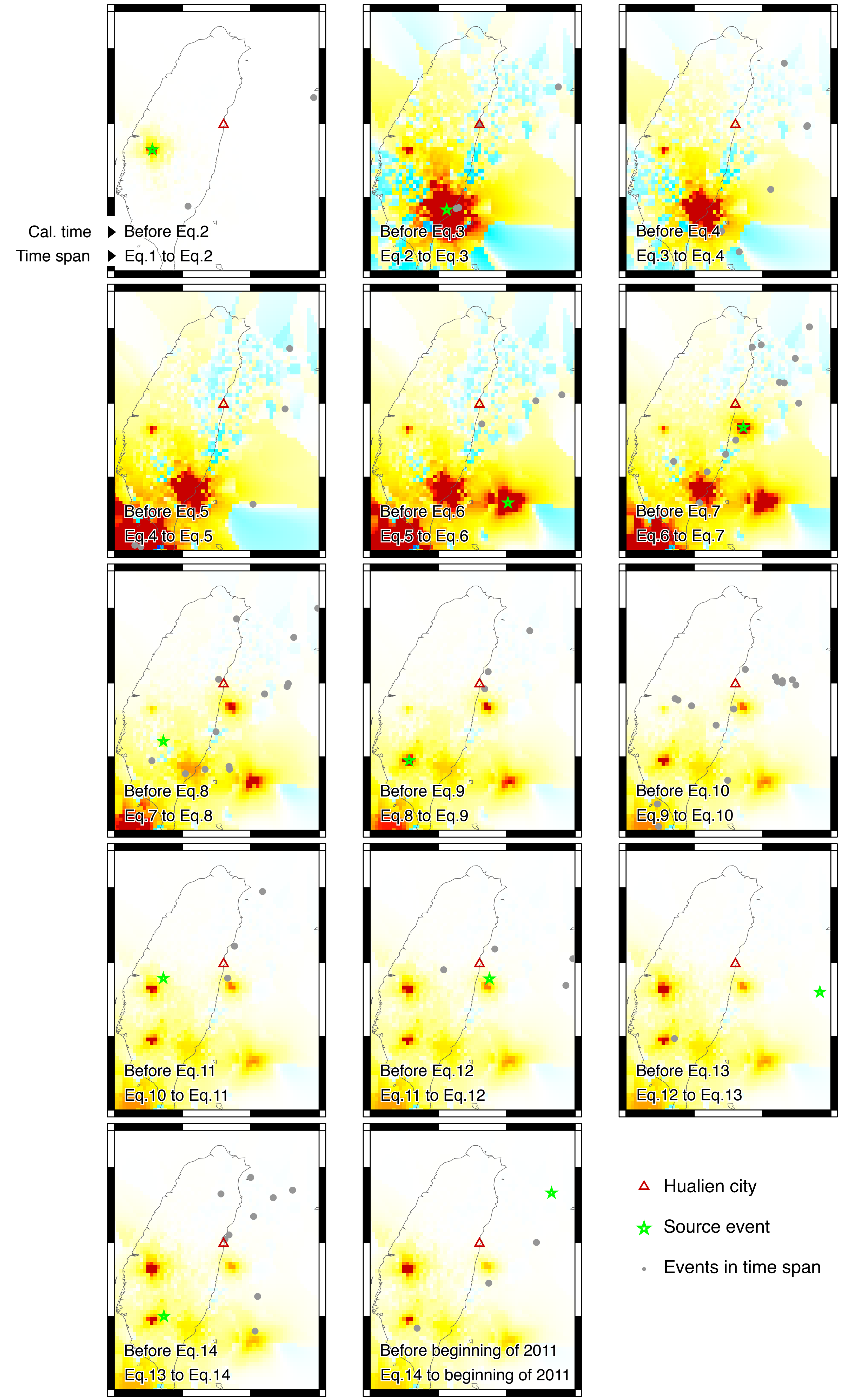
Rate evolution.....

Evolution of seismic rate during 2006-2010

according to the rate / state friction model

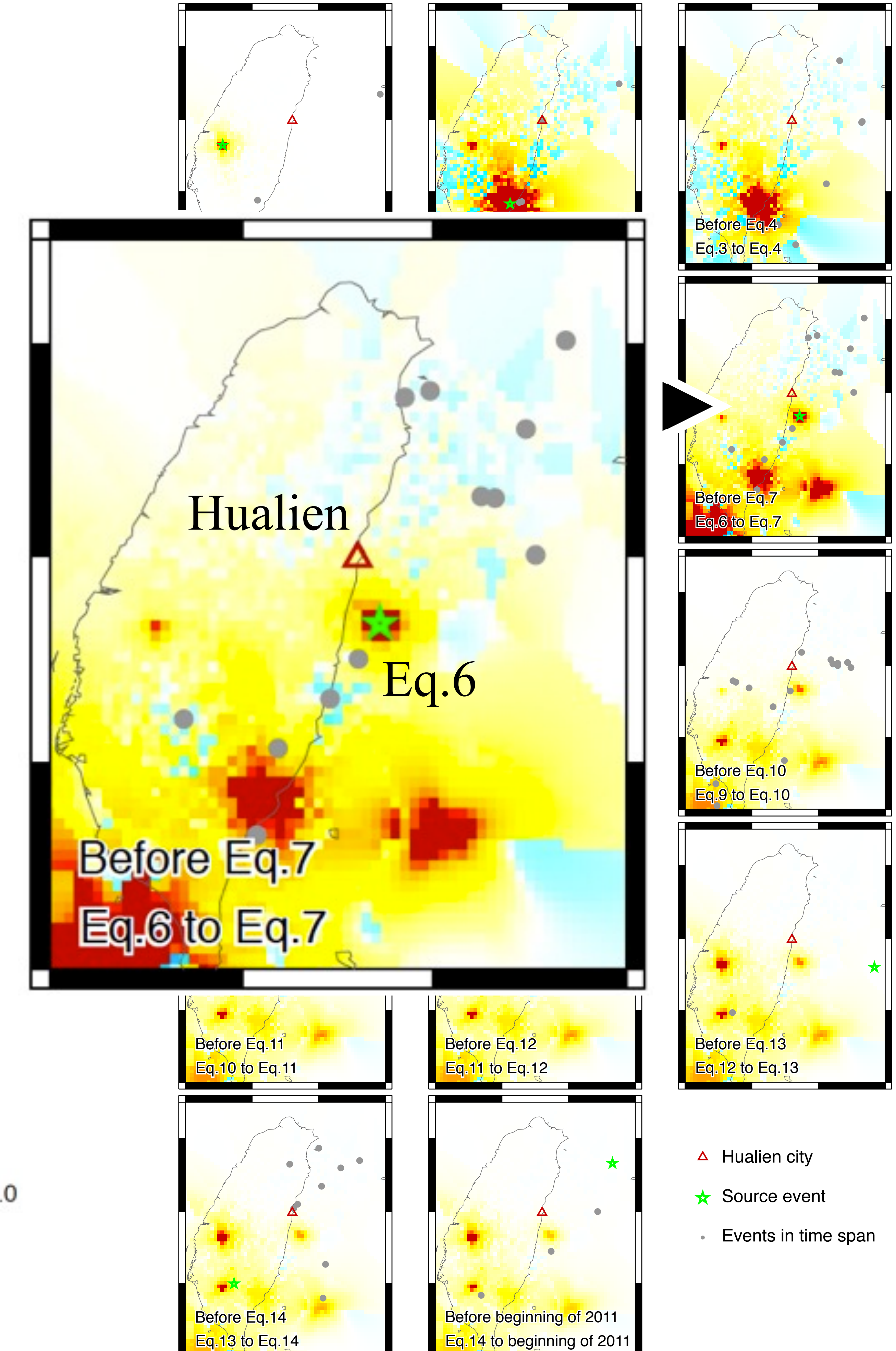
Evolution of rate change during 2006-2010



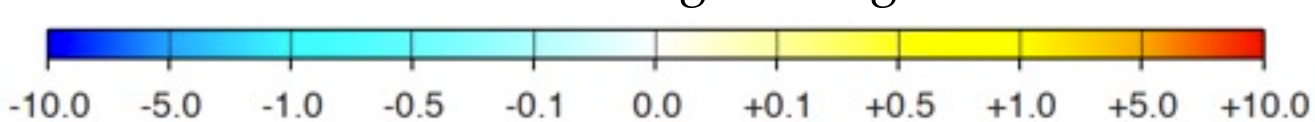


Evolution of seismic rate during 2006-2010

Significant rate increase near Hualien after **eq.6 (M5.1)**

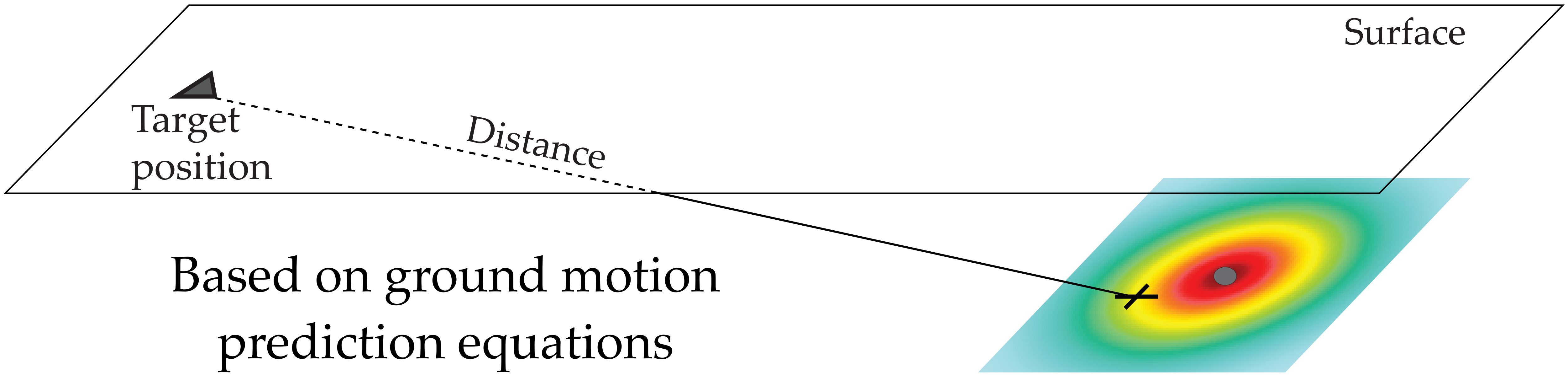


Evolution of rate change during 2006-2010



GMPEs......

Considering ***ground motion prediction equations*** for probabilistic seismic hazard assessment



Based on ground motion prediction equations

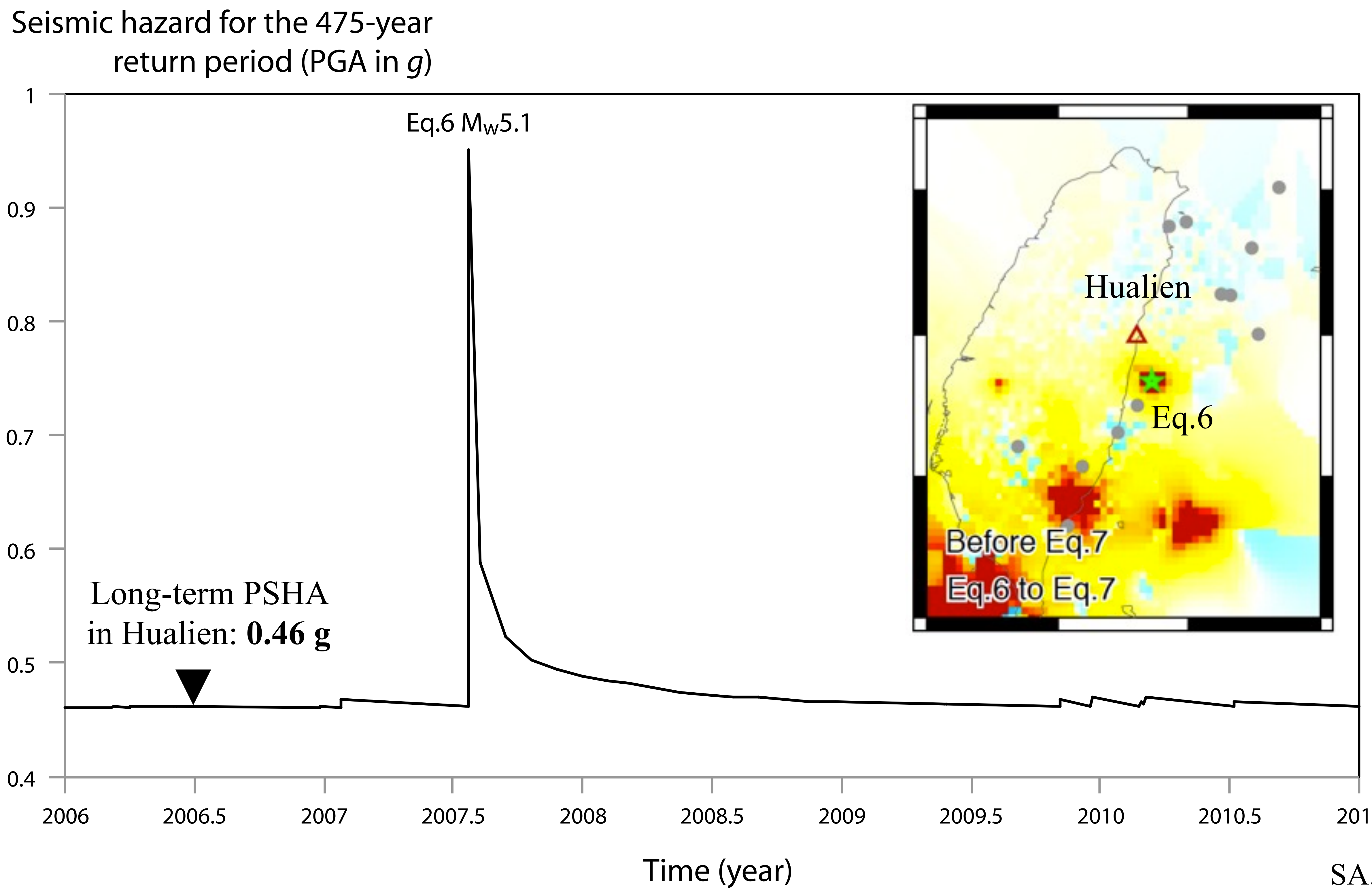
Ground motion prediction equations used in this study:

Crustal events	$\ln y = -2.5 + 1.205 M_W - 1.905 \ln\left(R + 0.51552 \exp\left(0.63255 M_W\right)\right) + 0.0075 H$	Lin & Lee, 2008
Interface events	$\ln y = -0.9 + 1.0 M_W - 1.9 \ln\left(R + 0.99178 \exp\left(0.52632 M_W\right)\right) + 0.004 H$	Lin et al., 2011
Intraslab events	$\ln y = -0.9 + 1.0 M_W - 1.9 \ln\left(R + 0.99178 \exp\left(0.52632 M_W\right)\right) + 0.004 H + 0.31$	

R: distance to the site; H: hypocentral depth

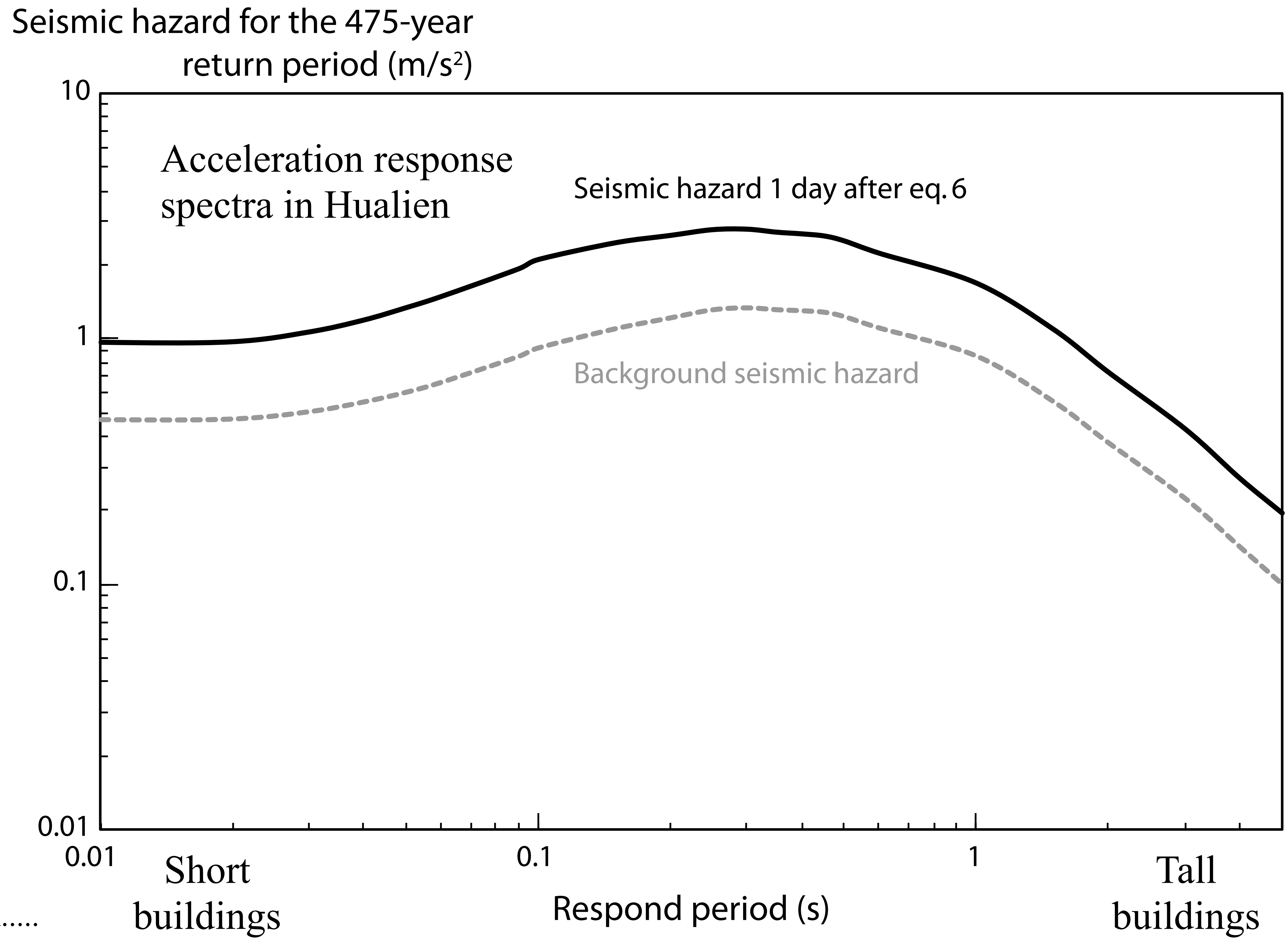
*GMPEs for the footwall and soil sites

Significant rise of seismic hazard after eq.6



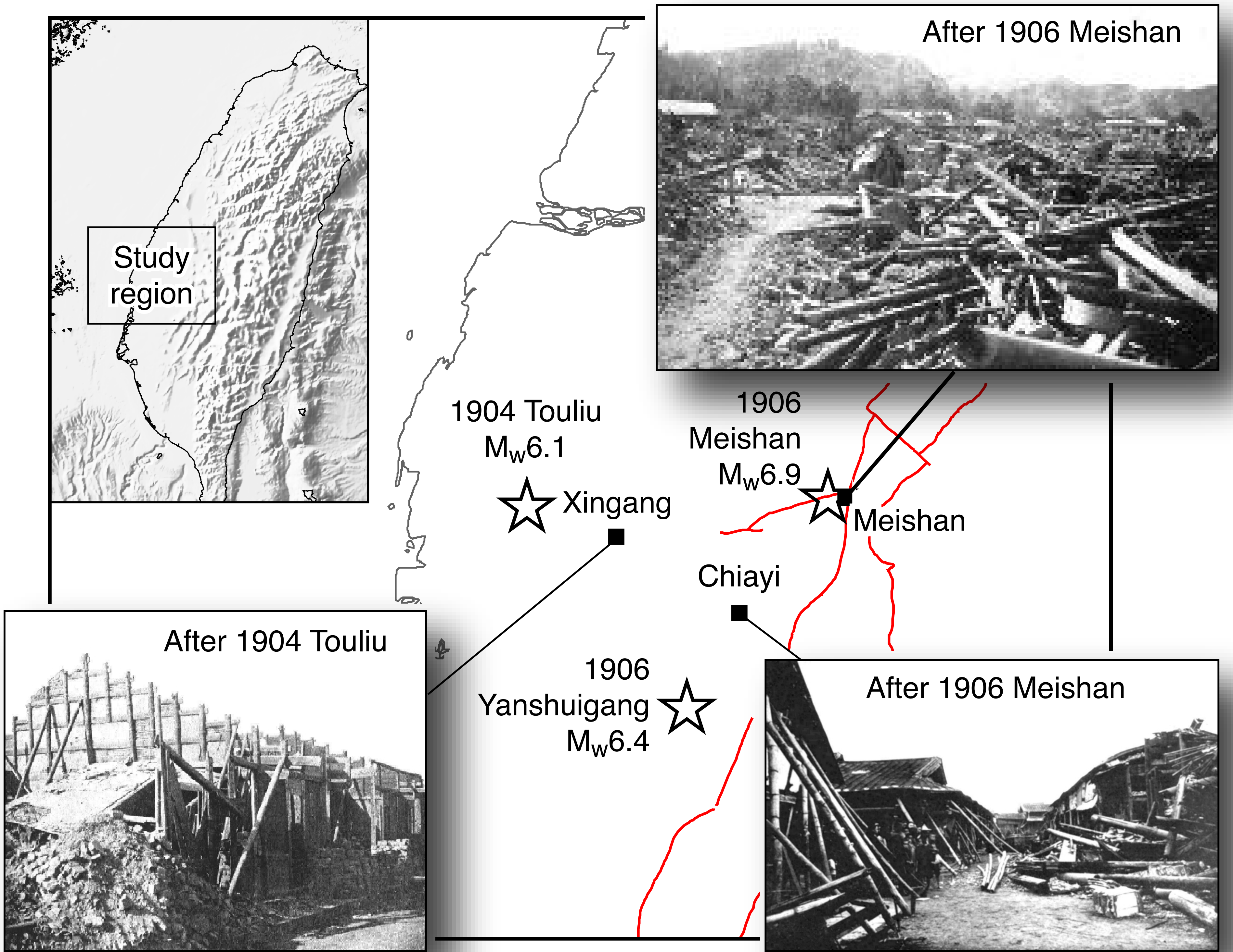
SA.....

Twice of seismic hazard is evaluated after eq. 6
Larger differences for the ***shorter*** response periods



Meishan.....

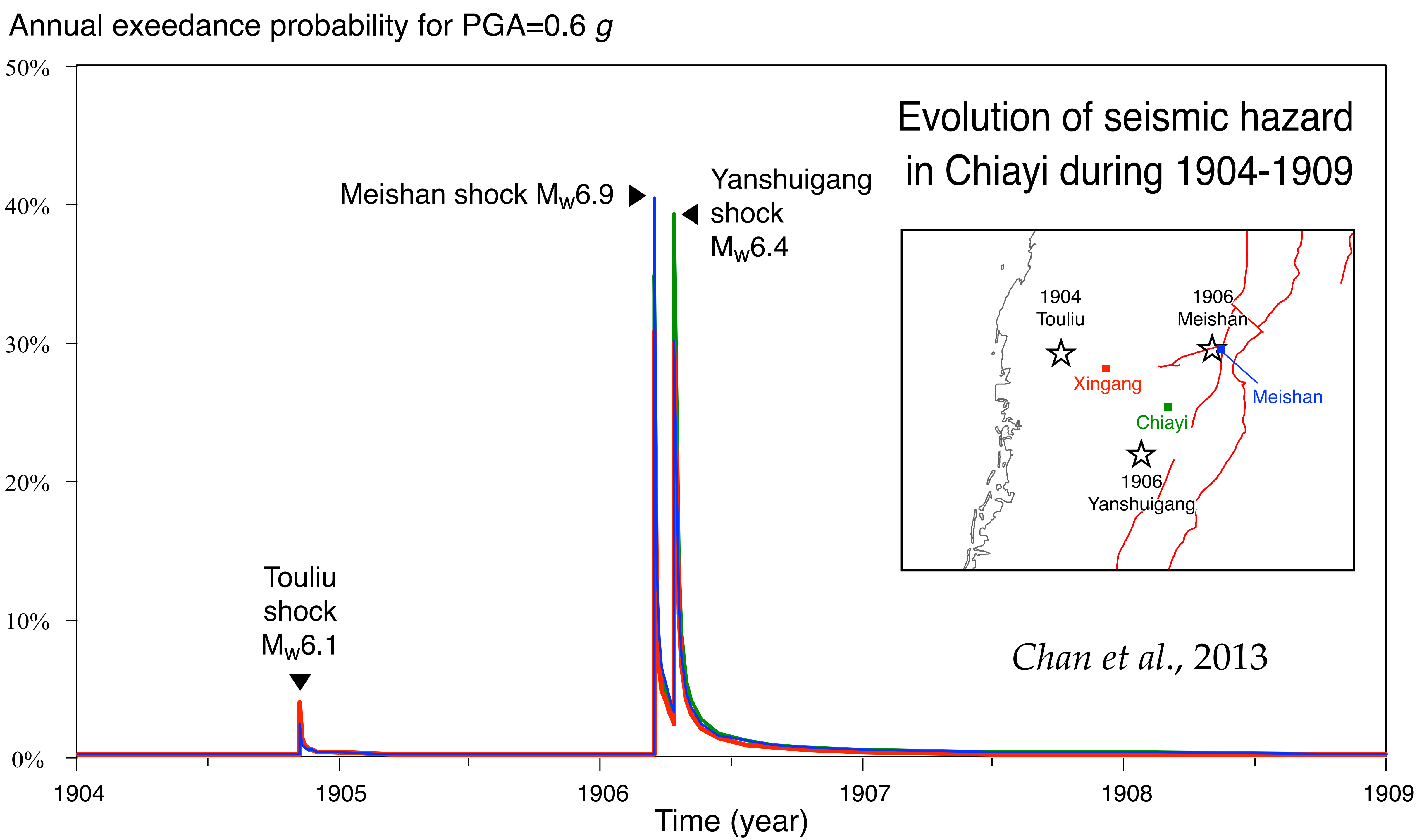
The time-dependent PSHA can be applied to the Meishan sequence



Chan et al., 2013

hazard evolution.....

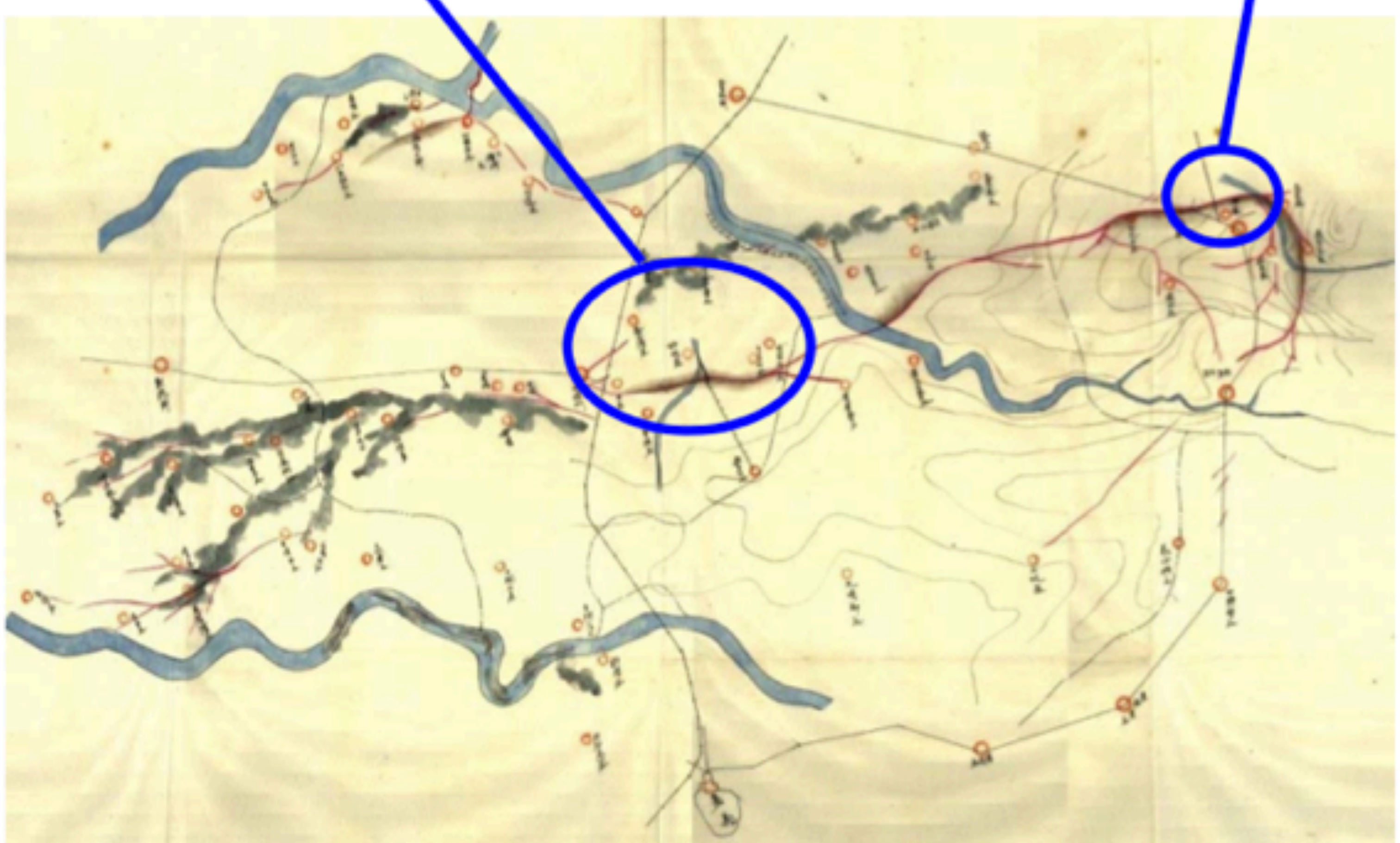
Higher hazard after each earthquake
Higher hazard in the neighboring city



Importance of seismic hazard preparation near the Meishan fault
Our results provided information on the seismogenic fault system

Ta-mao: Lu-chu-pon (蘆竹畔莊)
the floor subside more than a foot,
the ground outside the north wall
uplifted more than a foot.
rice field subside

Ta-mao: Mei-tze-keng(梅仔坑)
The ground opened suddenly,
one firewood collector dropped
into the fissure. Then the ground
closed.

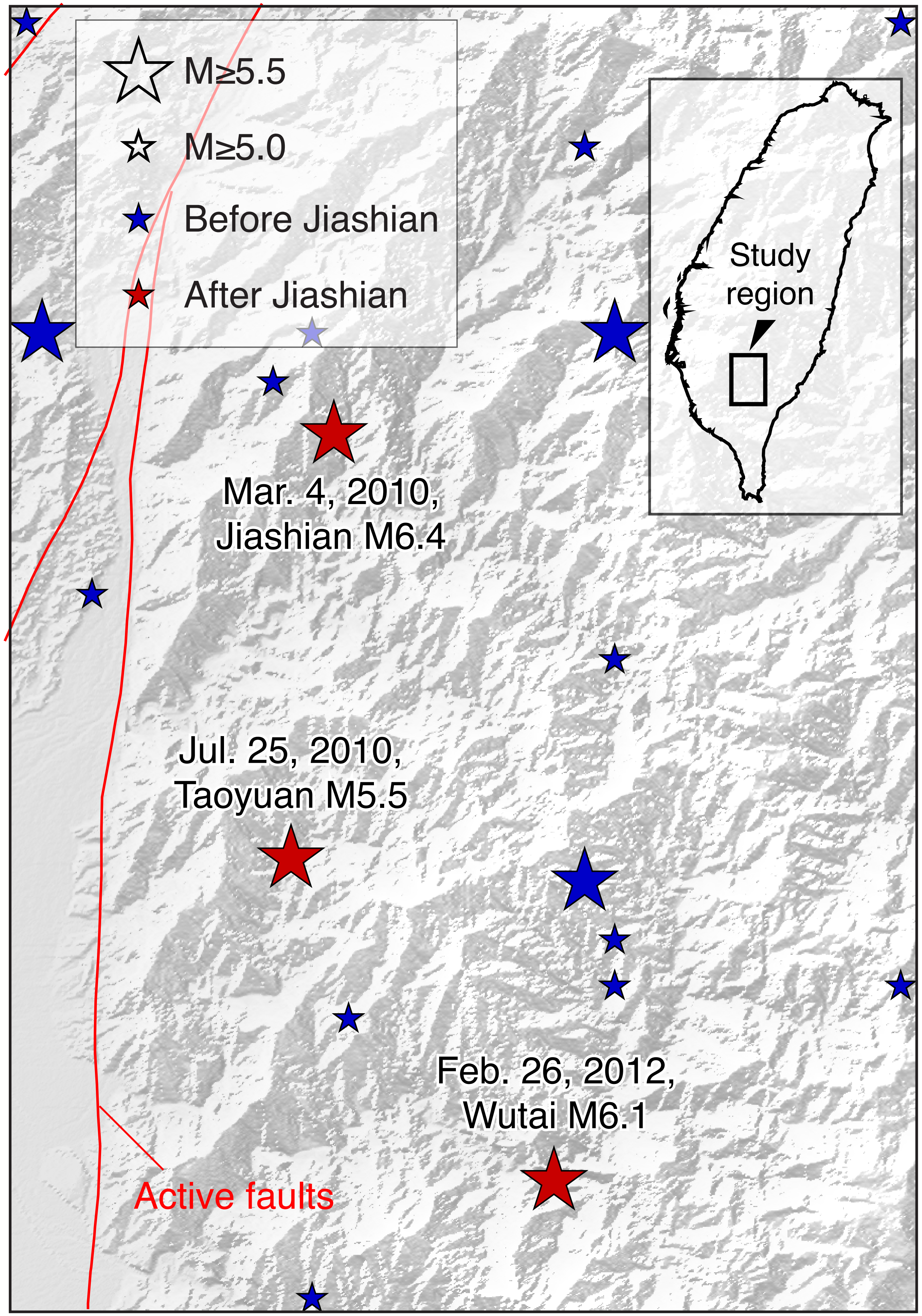


The Meishan Fault (1906 Meishan Earthqauke)

1792
| - **114 yr.**
1906
| - **108 yr.**
2014 **???**

By Prof. S.N. Cheng

Jiashian case....



Higher seismicity rate after Jiashian

Before Jiashian:

M≥5.5 events: 3 (0.03 event/year)

M≥5.0 events: 12 (0.11 event/year)

After Jiashian:

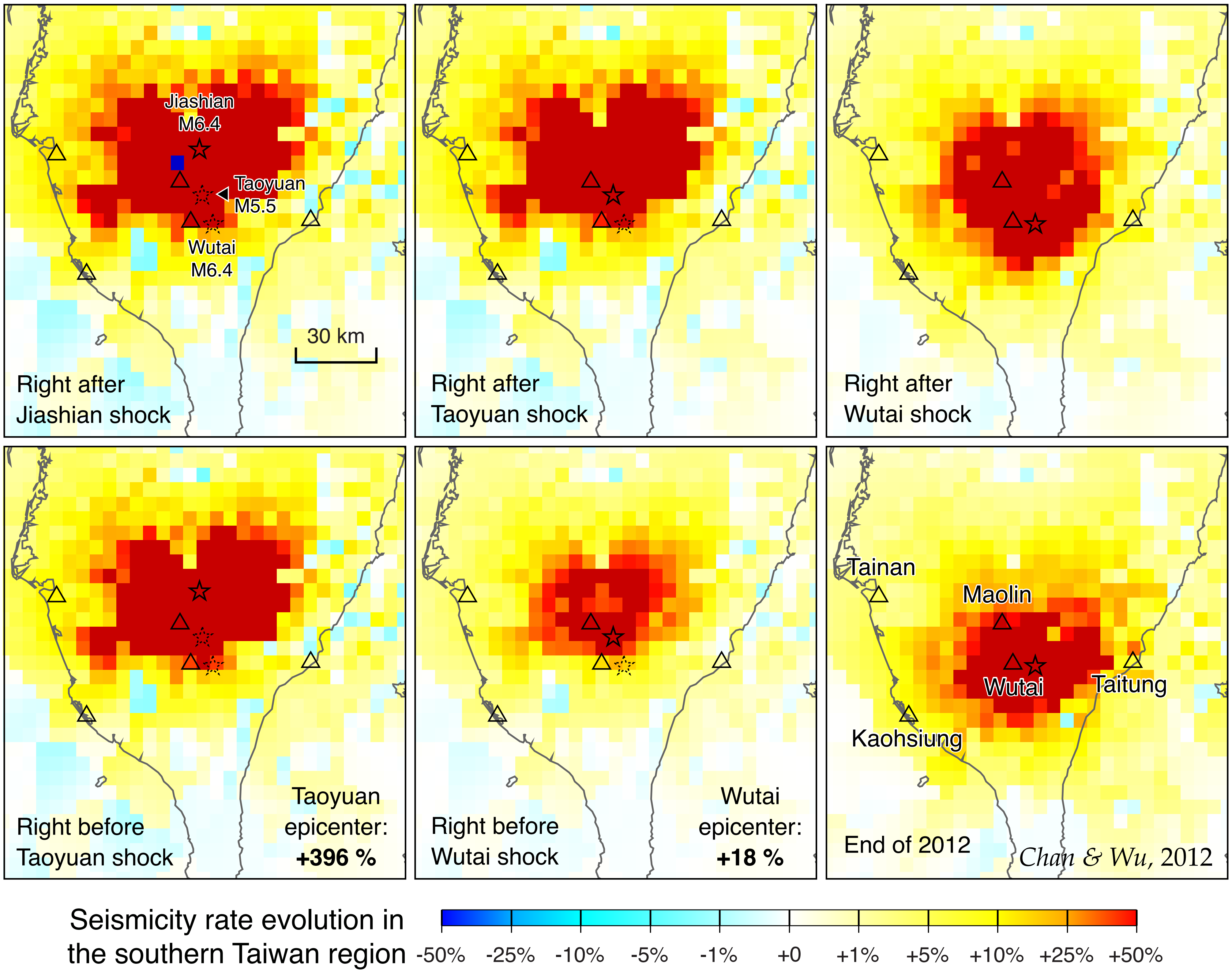
M≥5.5 events: 3 (1.00 event/year)

M≥5.0 events: 3 (1.00 event/year)

Chan & Wu, 2012

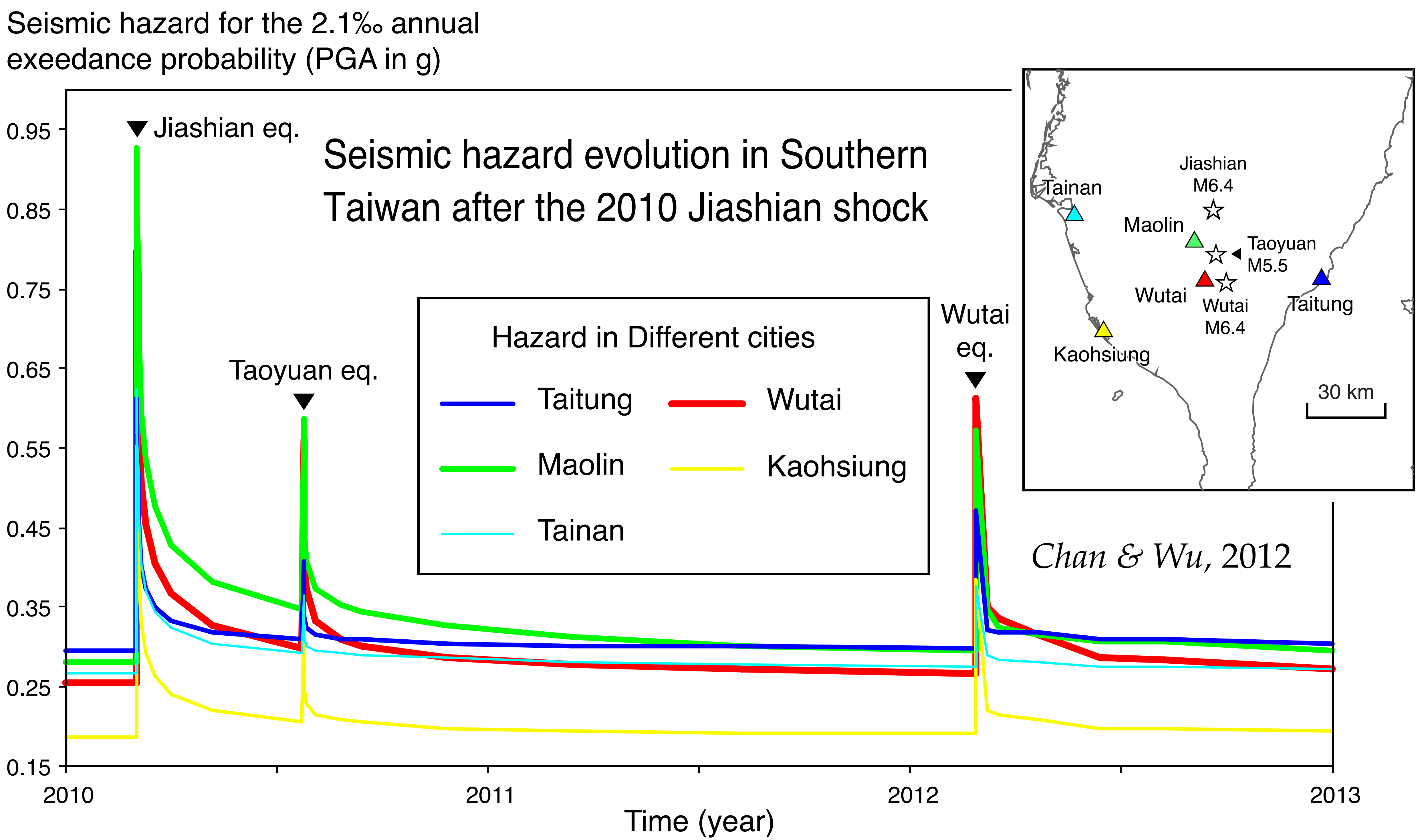
rate evolution.....

Higher rate is expected near epicenters
Consequent events can be ***forecasted***



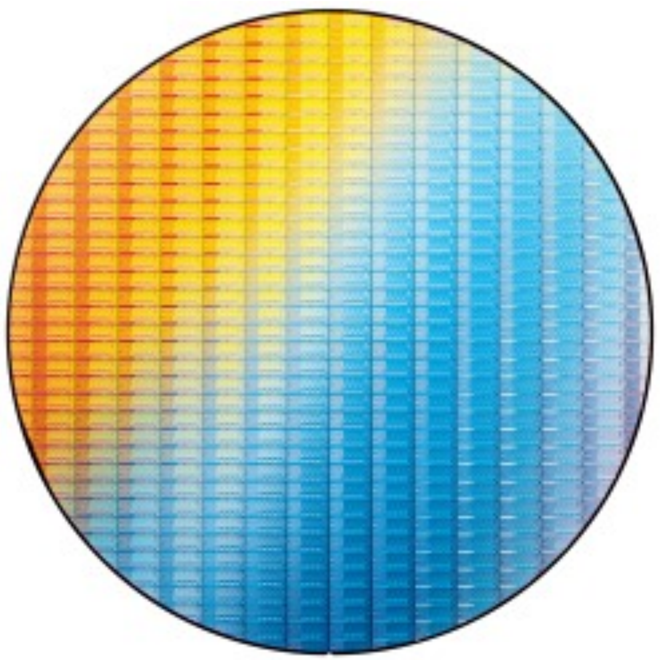
hazard evolution.....

Higher seismic hazard is evaluated after occurrence of each large earthquake



Chan & Wu, 2012

Application: ***Warnings*** for precise industries



A wafer

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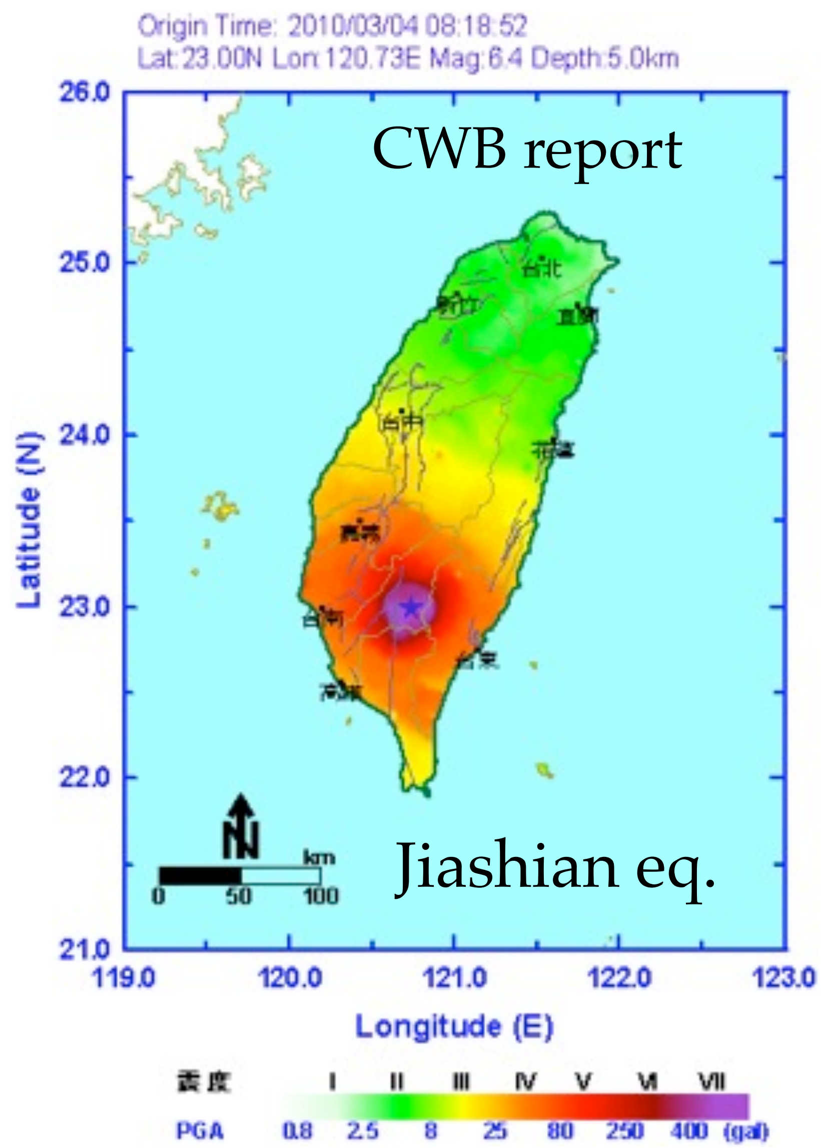
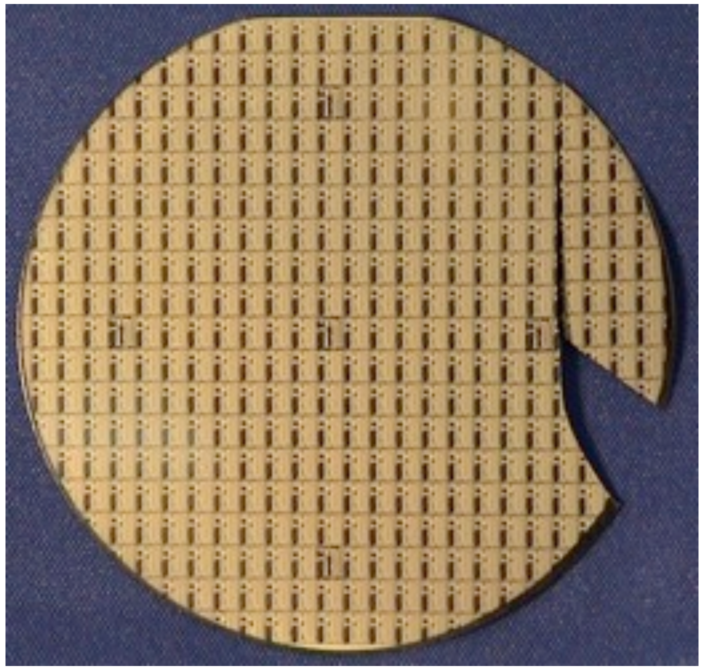


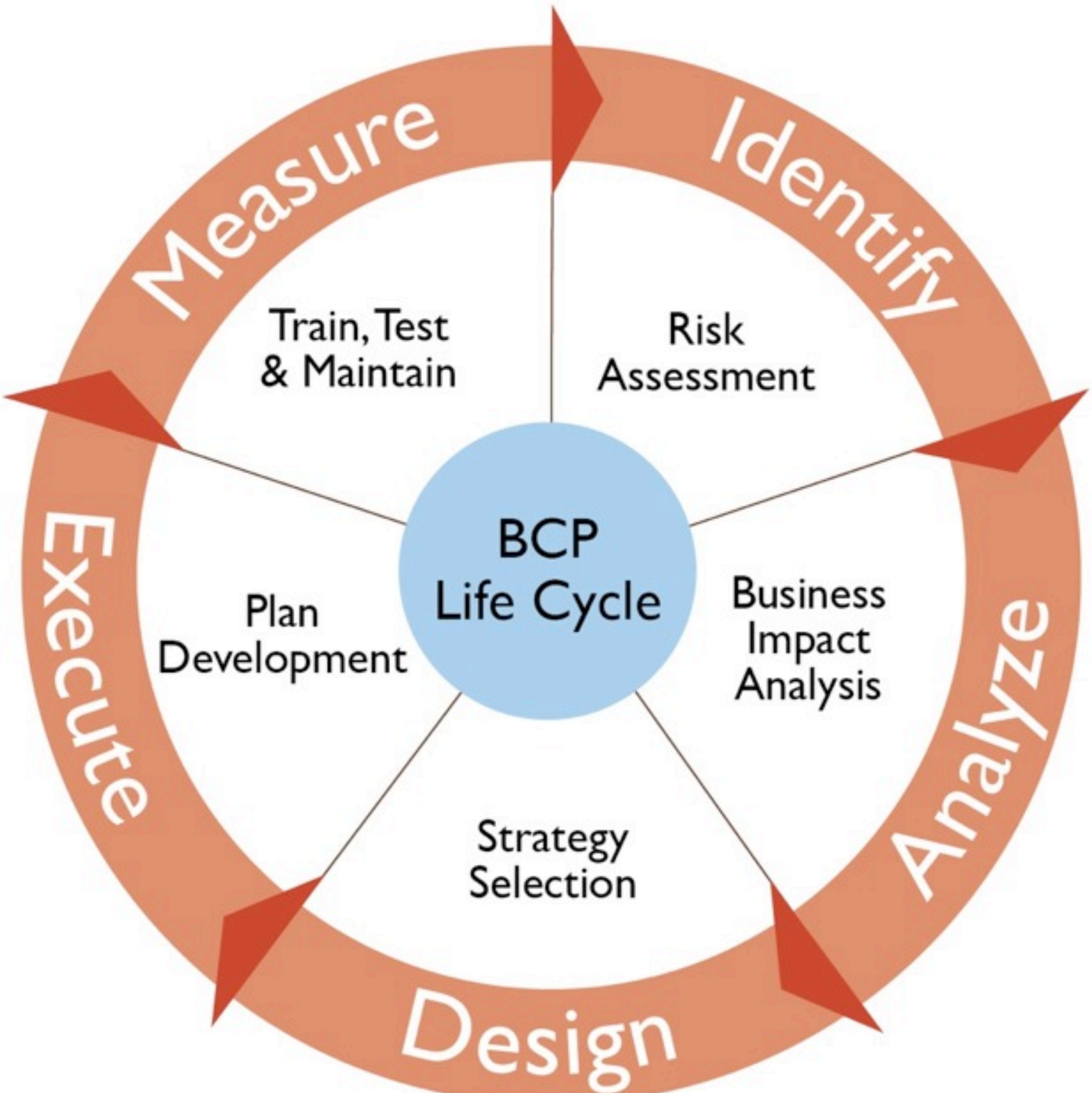
Earthquake

=



A broken wafer

Application: To determine ***Business Continuity Planning***



e.g.,

Disaster recovery management;

Earthquake resistant design;

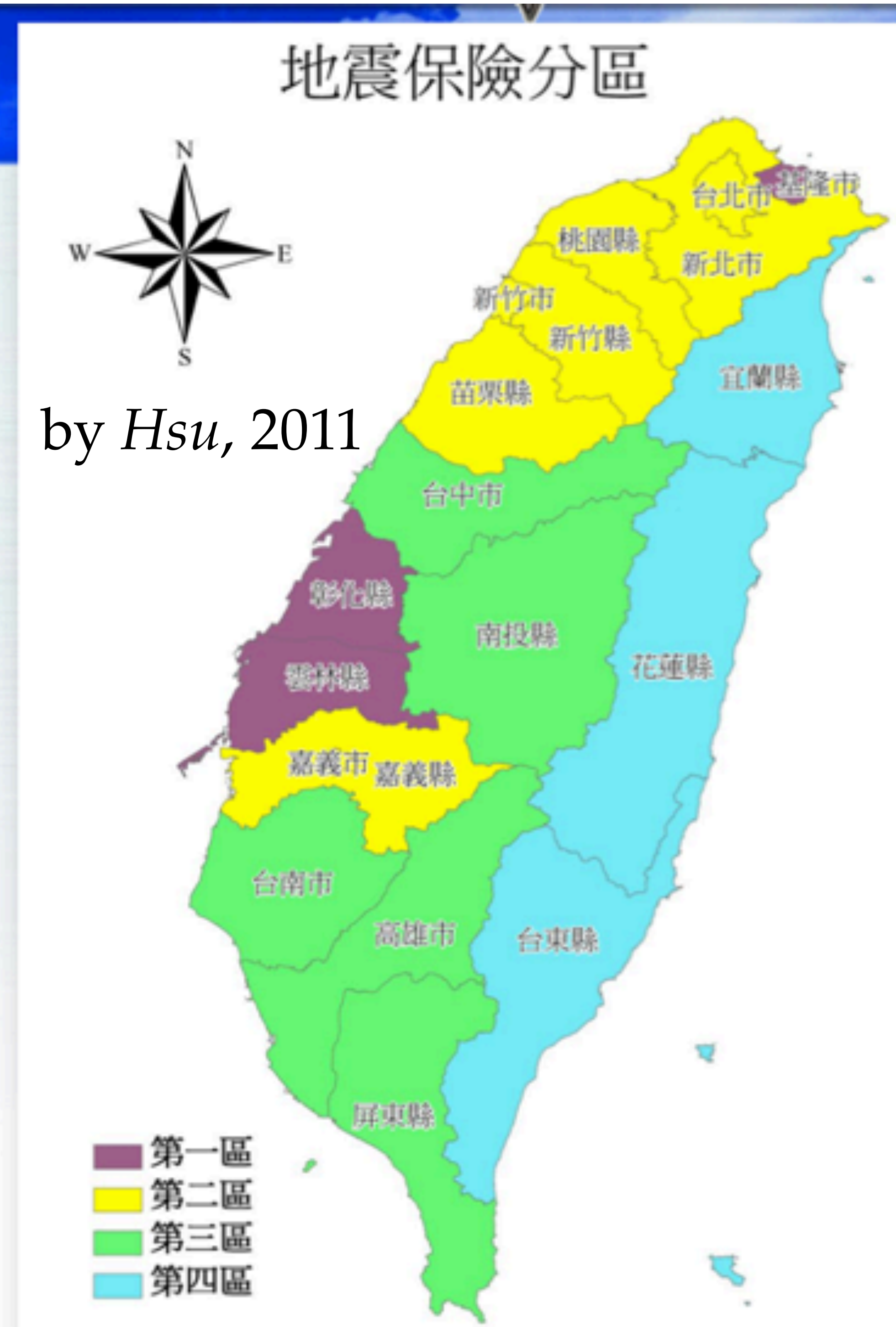
Insurance essentiality;

Application: To determine ***insurance rate categories***

Rate of Expanded Residential Earthquake Insurance

地區	基本危險費率（‰）		
	結構等級		
	A	B	C
第一區	0.64	1.01	1.57
第二區	0.97	1.55	2.41
第三區	1.57	2.49	3.88
第四區	2.86	4.56	7.09

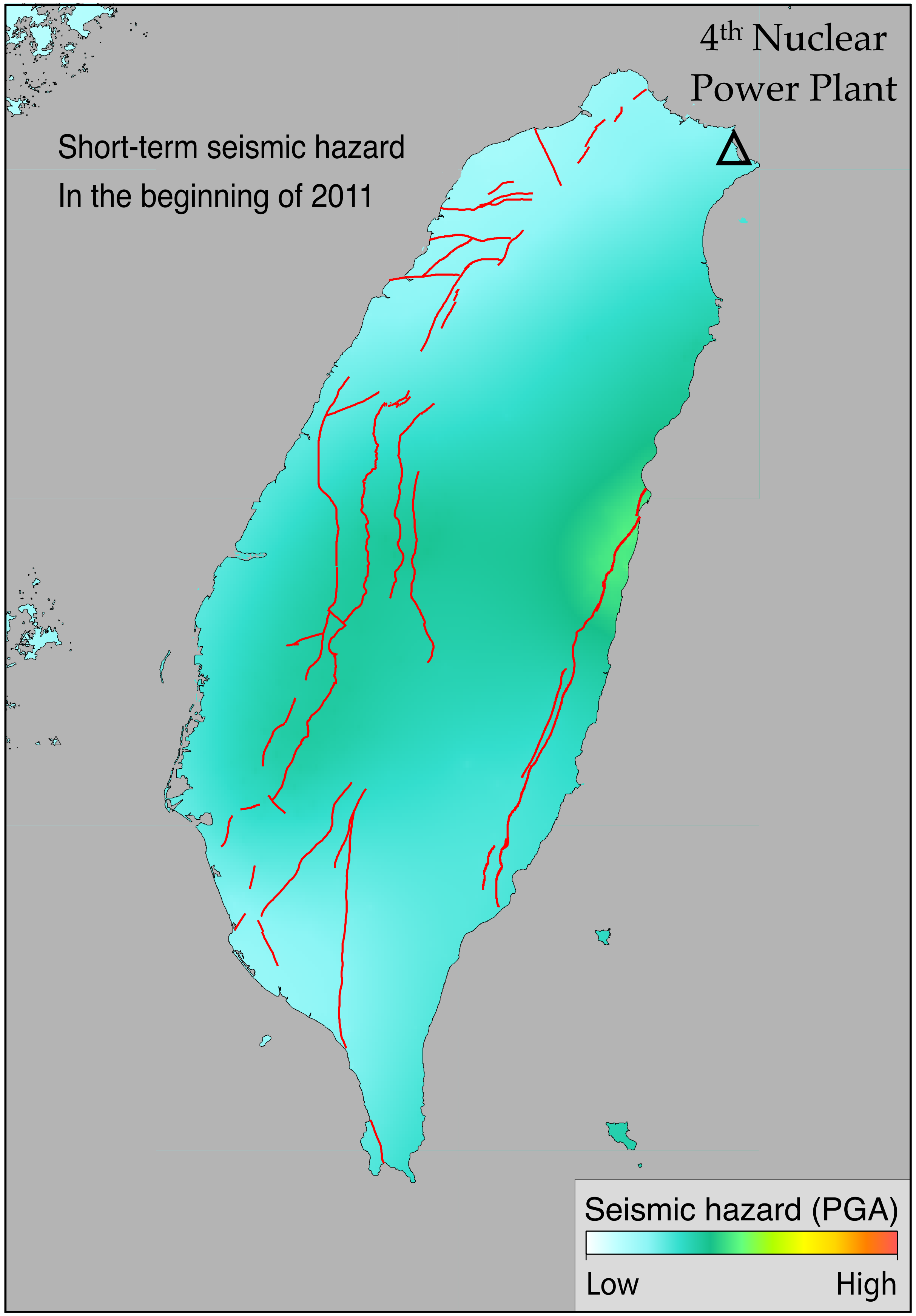
結構等級說明	
A	鋼架、外牆為金屬板或石棉板造之建築物；但牆腳若以鋼筋水泥造或磚造者，應自地面起以不超過一公尺為限
A	鋼骨水泥造或鋼筋水泥造，外牆為玻璃帷幕、無磚或石牆之建築物
A	木造平房
B	鋼骨水泥造或鋼筋水泥造，外牆全部或部份為磚、空心磚或石造之建築物
C	上列A、B級以外其他之建築物



by *Hsu*, 2011

Based on ***hazard maps*** and ***Vulnerability models***

Is 4th Nuclear Power Plant safe from seismic hazard?



Our result: **0.23 g** with 10% in 50 yr

Seismic design: **0.40 g**

<u>What we have obtained:</u>

- Low hazard in the site
- Might safe from seismic hazard

<u>Crucial future works:</u>

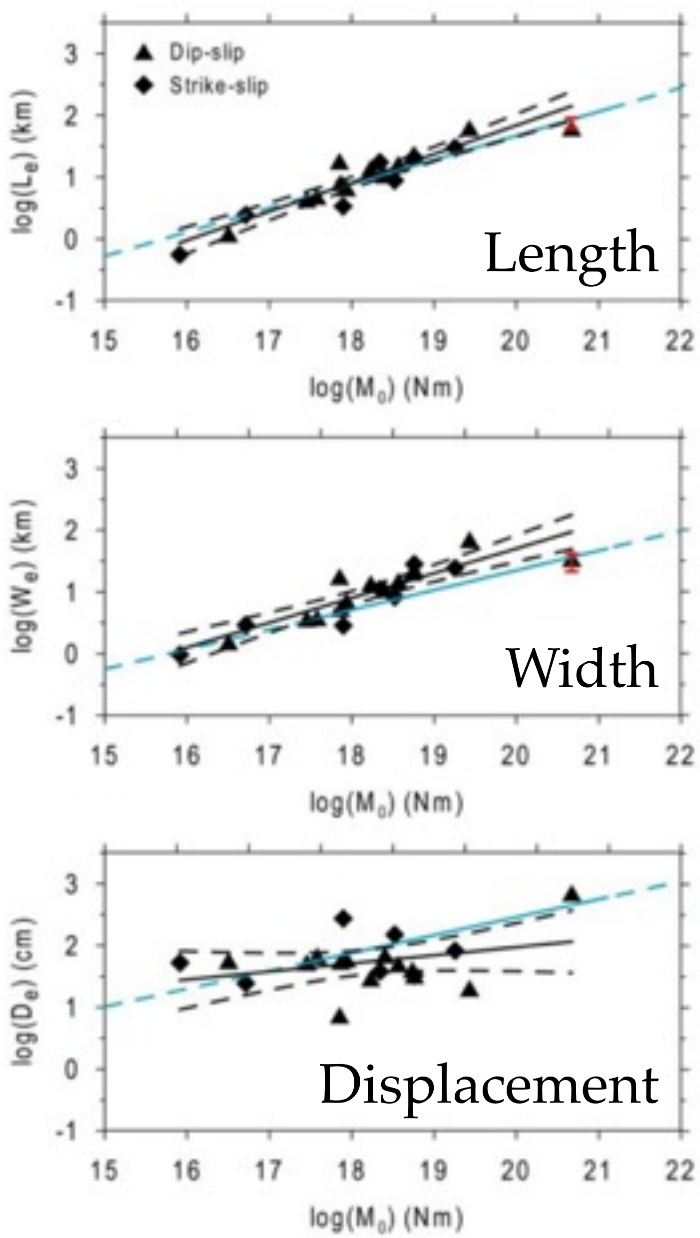
- Consider active faults for PSHA
- Investigate site condition
- Implement waveform simulations
- Investigate historical earthquakes
- Assess seismic risk

Thanks!

References:

Catalli & Chan, GJI, 2012	Rapid ΔCFS calculation
Chan & Stein, GJI, 2009	Chi-Chi ΔCFS
Chan & Wu, JAES, 2012	Jiashian sequence
Chan et al., NHESS, 2012	Forecasting models
Chan et al., Tectonophy., 2012	Stress state in Taiwan
Chan et al., NHESS, 2013	PSHA in Taiwan
Chan et al., TAO, 2013	Meishan sequence

Source slip model for each earthquake by the ***scaling law***



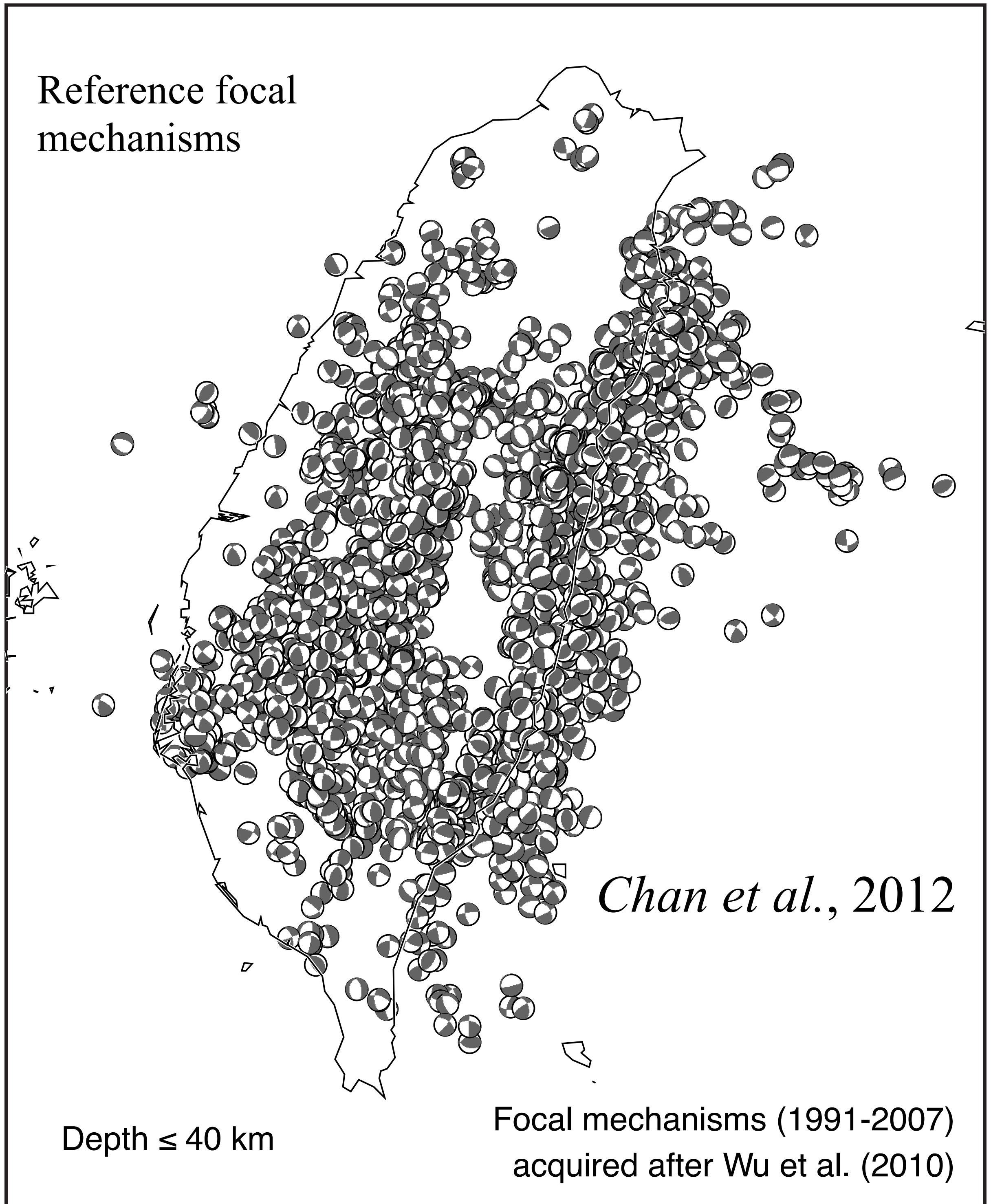
After *Yen & Ma*, 2011

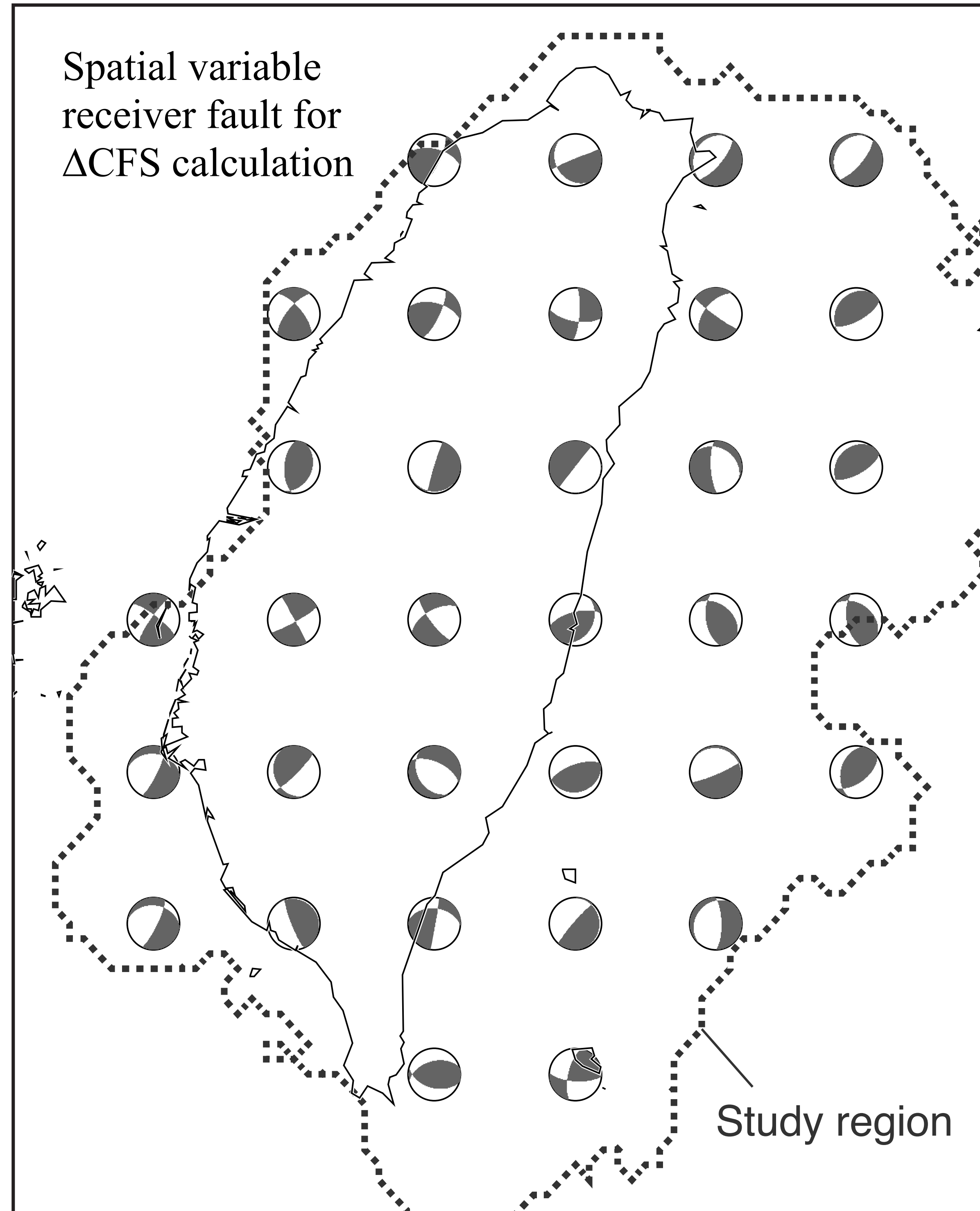
Year	Month	Day	Longitude (˚)	Latitude (˚)	M_W	Depth (km)	Strike (˚)	Dip (˚)	Rake (˚)
2008	2	17	121.45	23.28	5.0	19	8	45	54
2008	2	29	122.55	23.99	4.8	31	304	20	145
2008	3	4	120.72	23.22	4.9	18	208	42	83
2008	4	14	121.43	22.79	4.7	23	289	32	-101
2008	4	23	121.66	22.89	5.6	13	241	64	159
2008	4	23	121.65	22.88	4.7	12	233	55	150
2008	5	10	122.45	24.00	5.4	25	324	36	165
2008	5	13	121.04	22.72	4.9	17	265	40	147
2008	8	1	121.55	24.06	4.7	27	68	27	121
2008	12	2	121.60	23.28	4.9	26	359	46	54
2008	12	7	122.17	23.84	4.6	26	193	39	108
2008	12	23	120.57	22.95	4.9	18	326	41	84
2009	1	3	121.68	24.19	4.9	24	248	13	104
2009	6	28	121.77	24.18	4.8	19	240	29	101
2009	7	13	122.17	24.07	5.8	21	321	48	166
2009	7	16	122.15	24.09	5.0	31	59	80	9
2009	7	16	122.24	24.05	4.6	26	335	64	171
2009	7	26	120.99	23.68	4.6	23	321	41	38
2009	7	26	121.27	23.48	4.7	27	91	54	153
2009	10	3	121.59	23.66	5.7	17	244	46	122
2009	11	5	120.72	23.79	5.1	22	230	57	145
2009	11	5	120.74	23.78	4.8	18	203	44	122

Form the BATS catalog

rate/state....

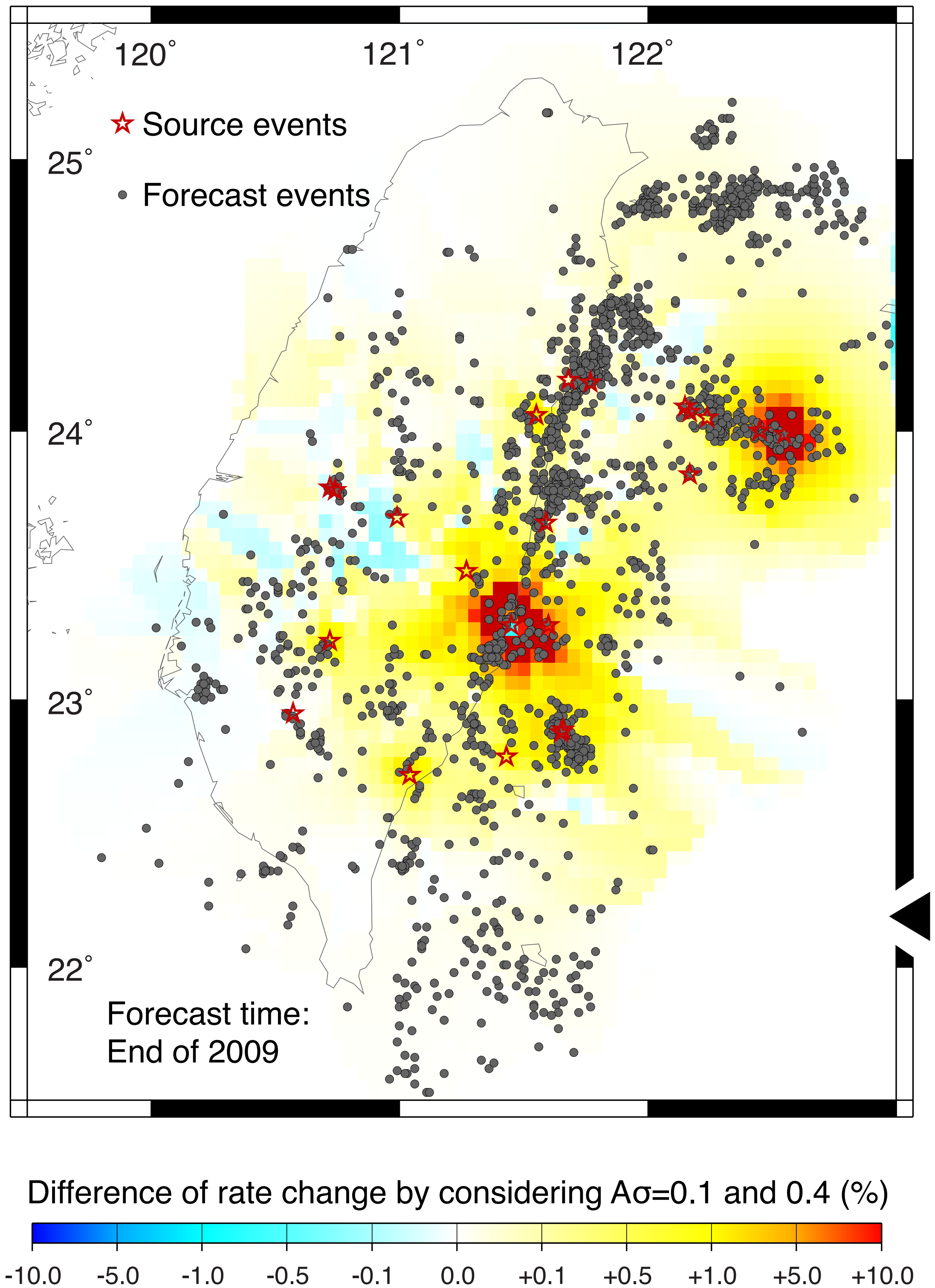
Assumed the same focal mechanisms as nearest references for ΔCFS calculations

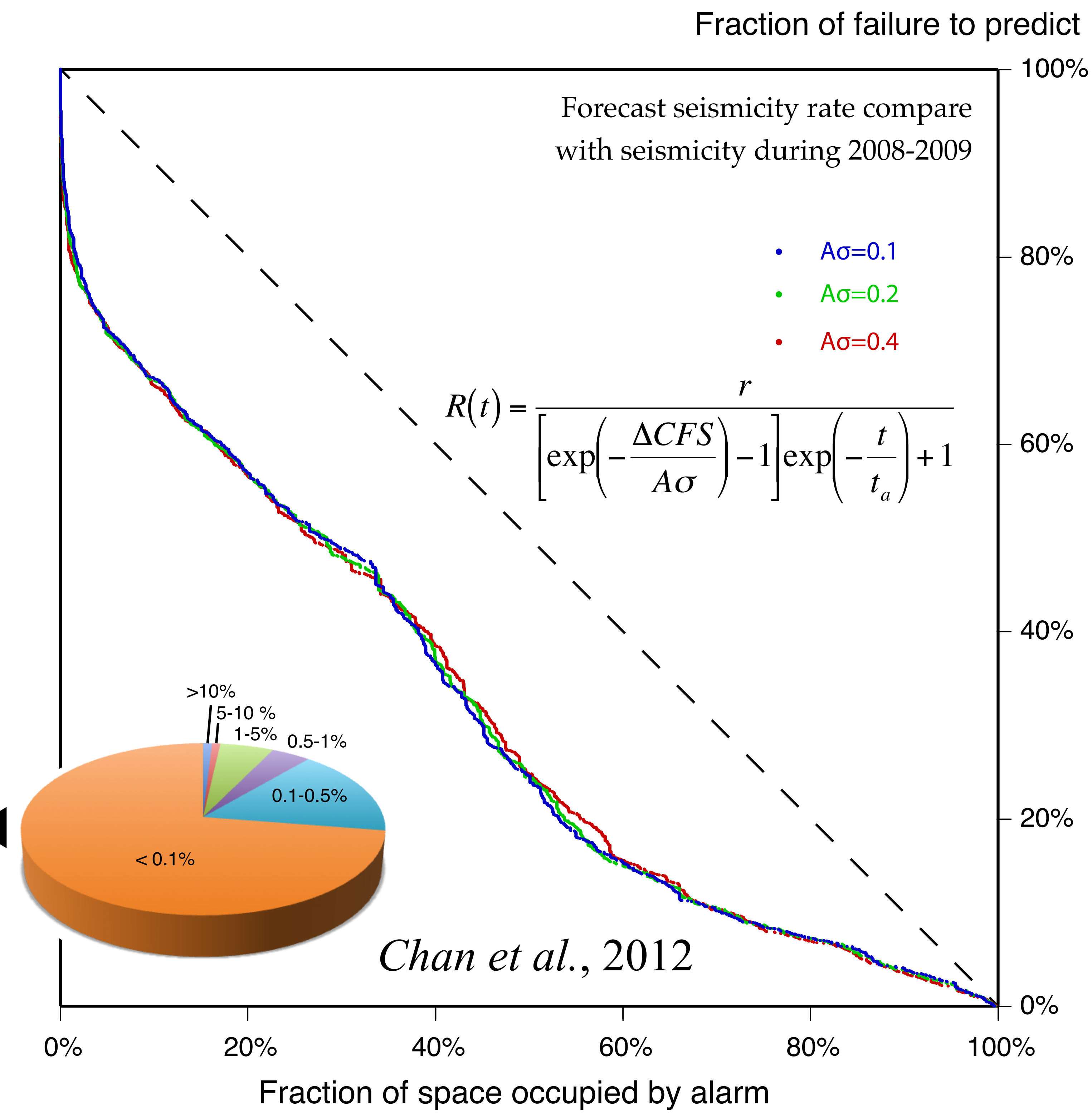




Source eqs….

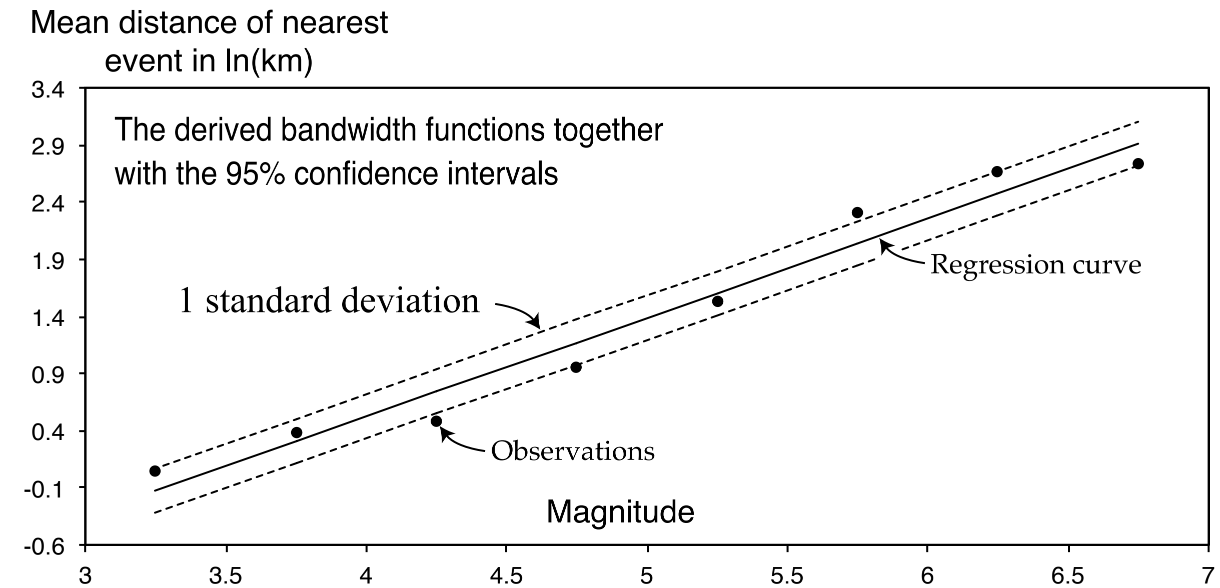
Insignificant different when variations of $A\sigma$ are assumed

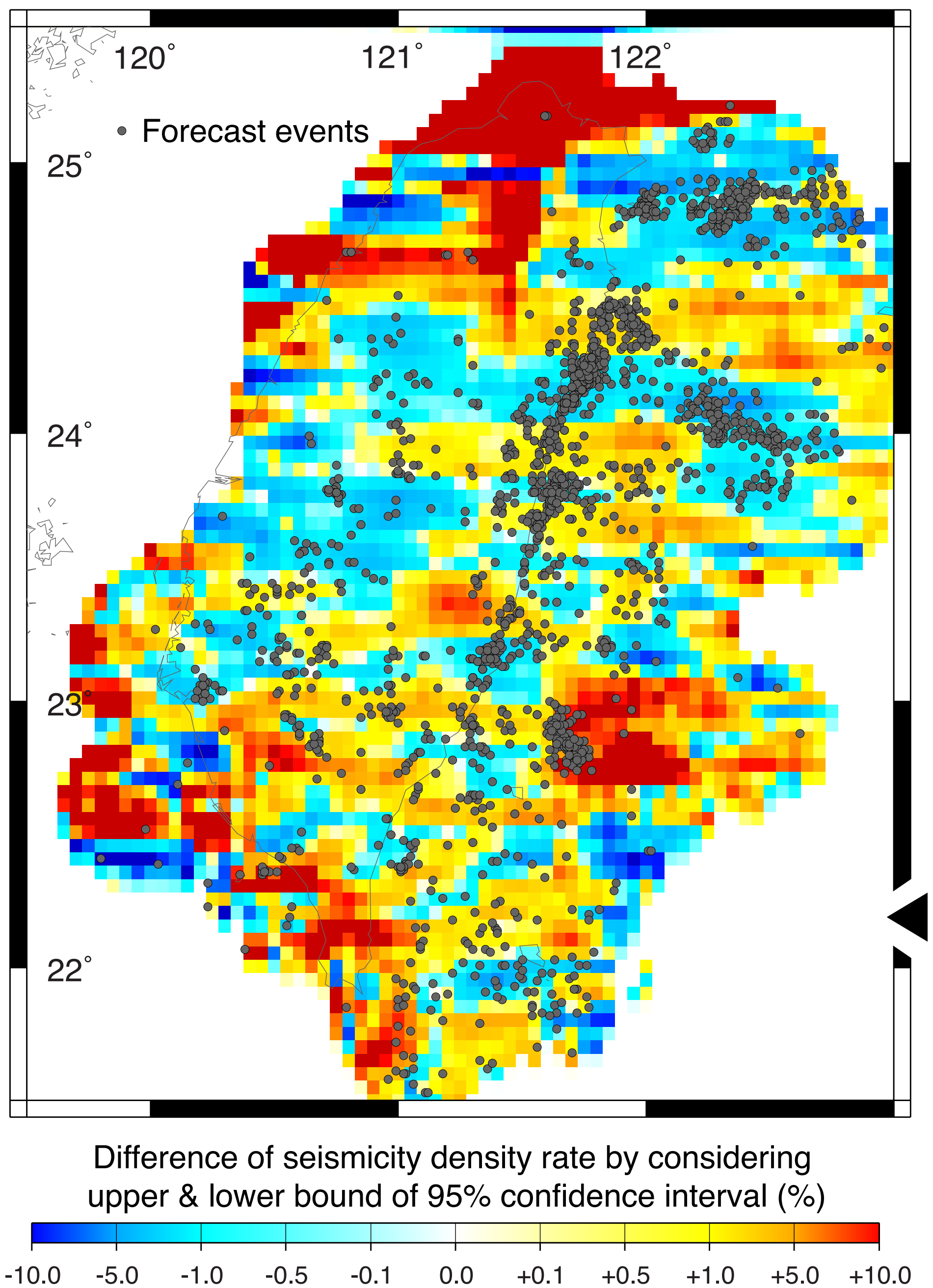


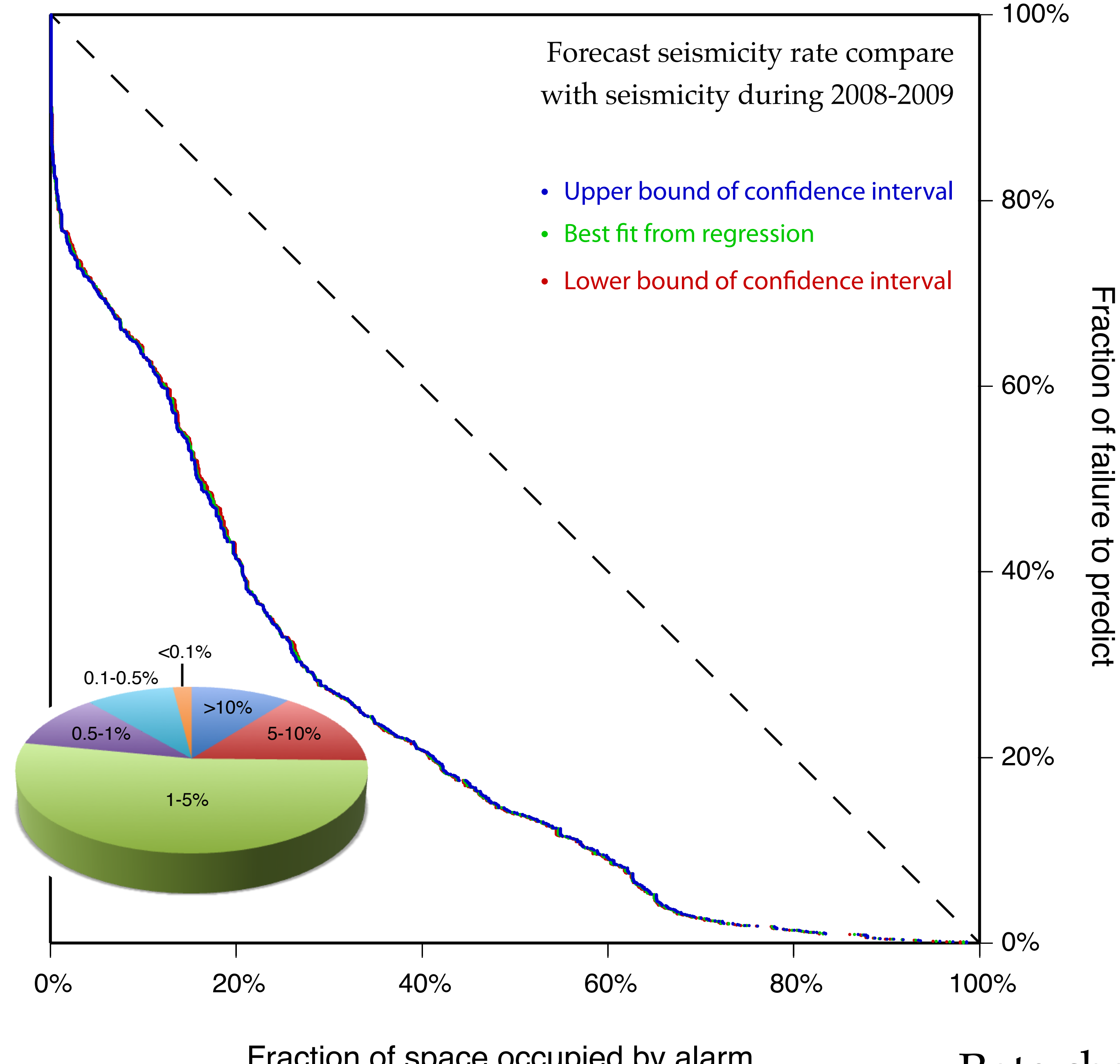


Combination model....

Insignificant different when ***bandwidth function*** are in the confidence interval

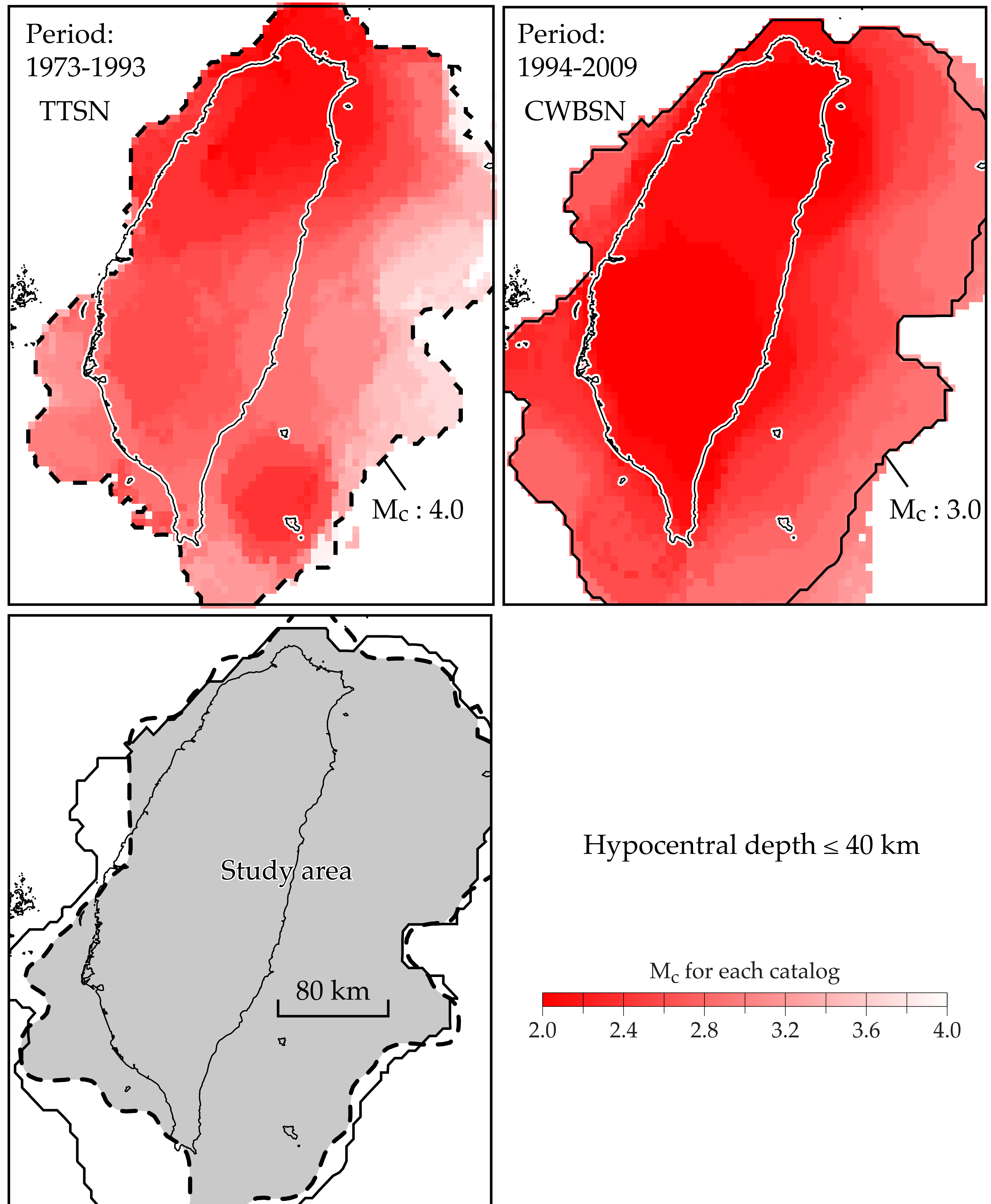




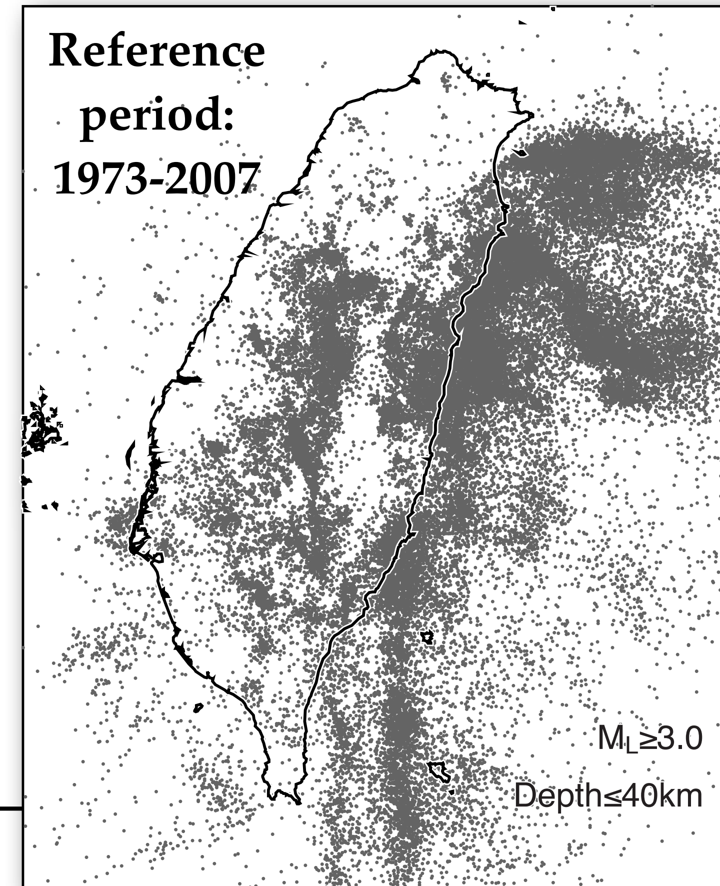


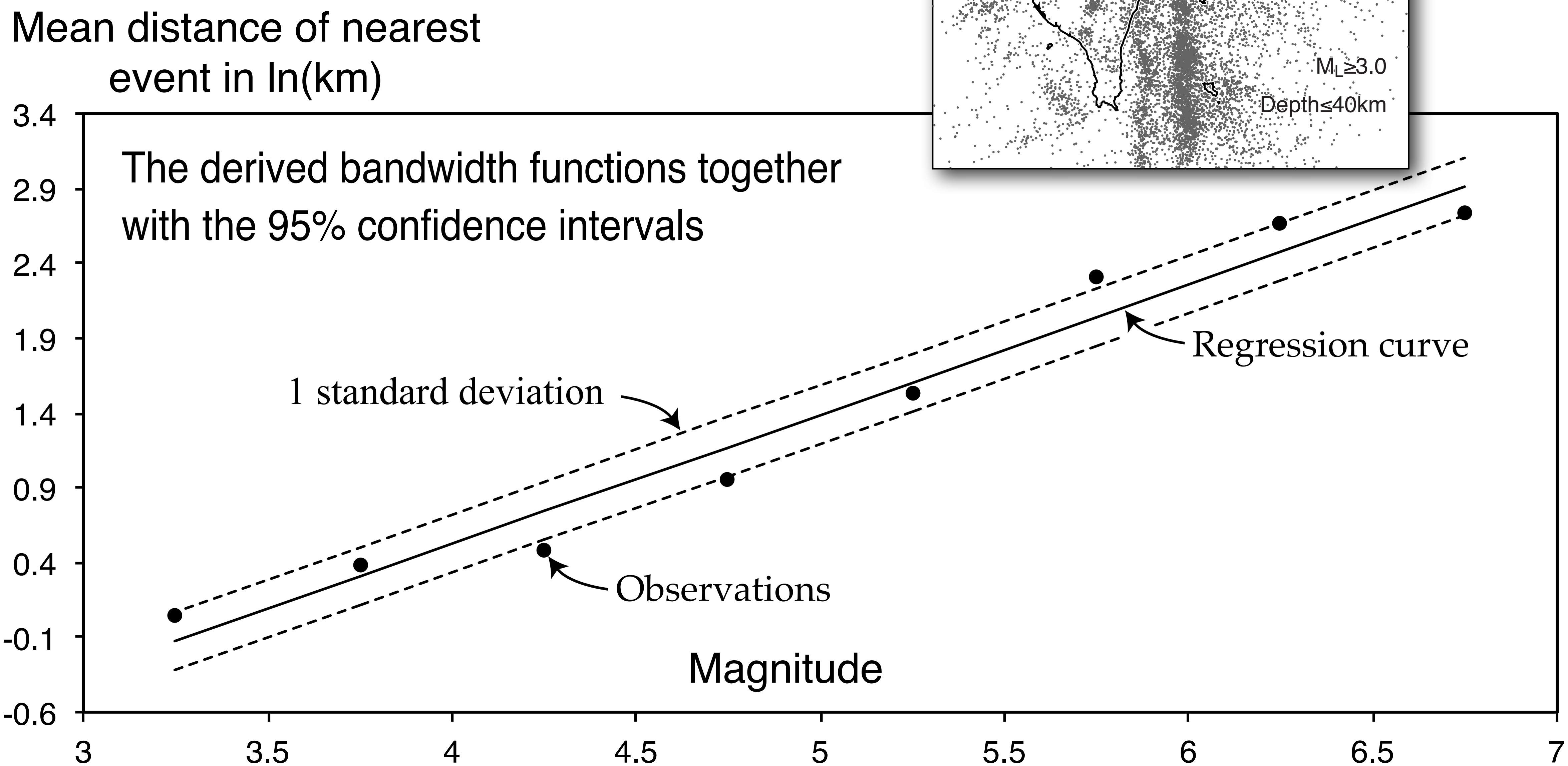
Rate change….

Assume the ***intersectional*** regions with ***Mc≤4.0 for TTSN*** & ***Mc≤3.0 for CWBSN*** as the study area



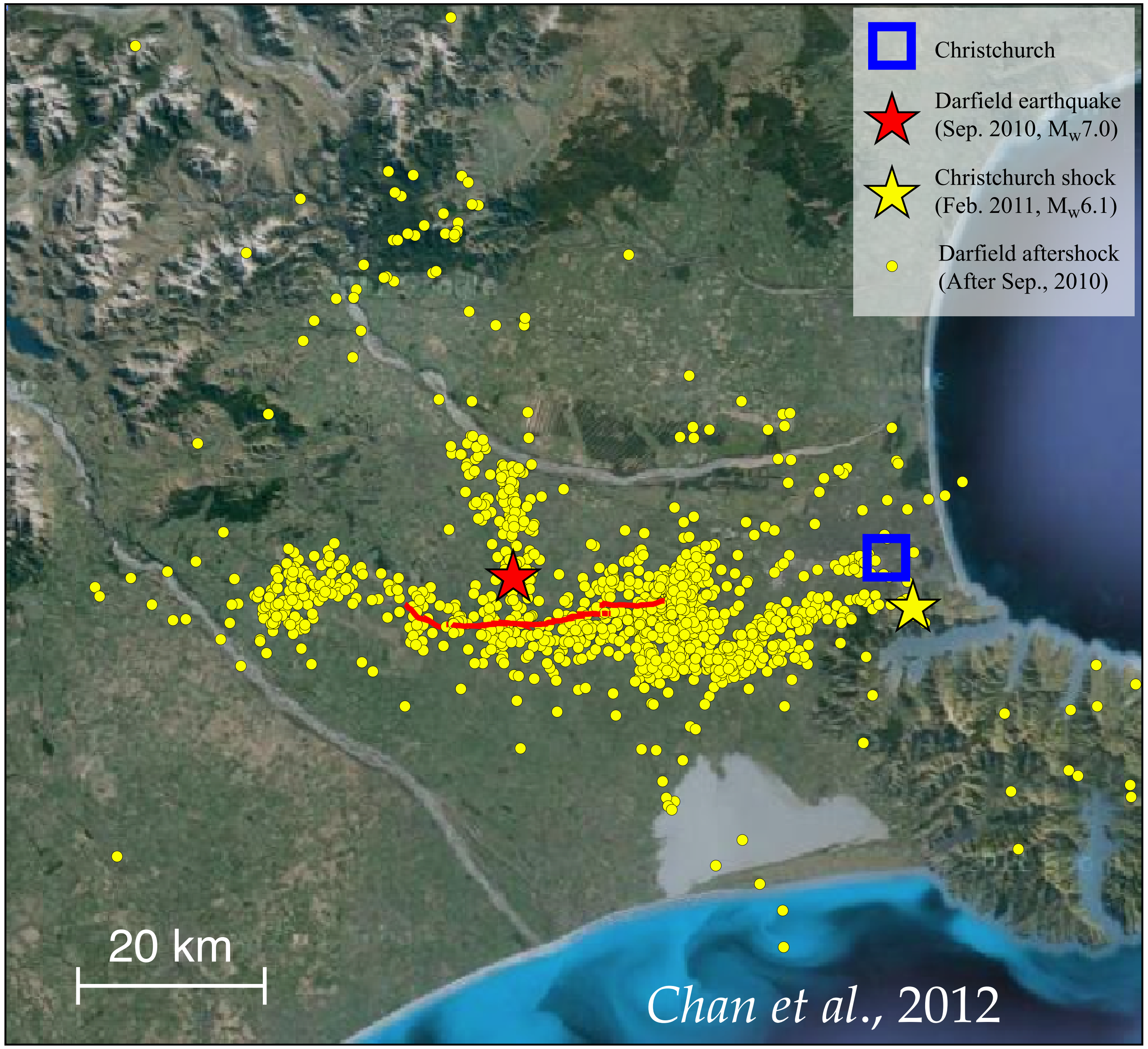
Bandwidth functions acquired from the distribution of reference earthquakes





Forecasting results...

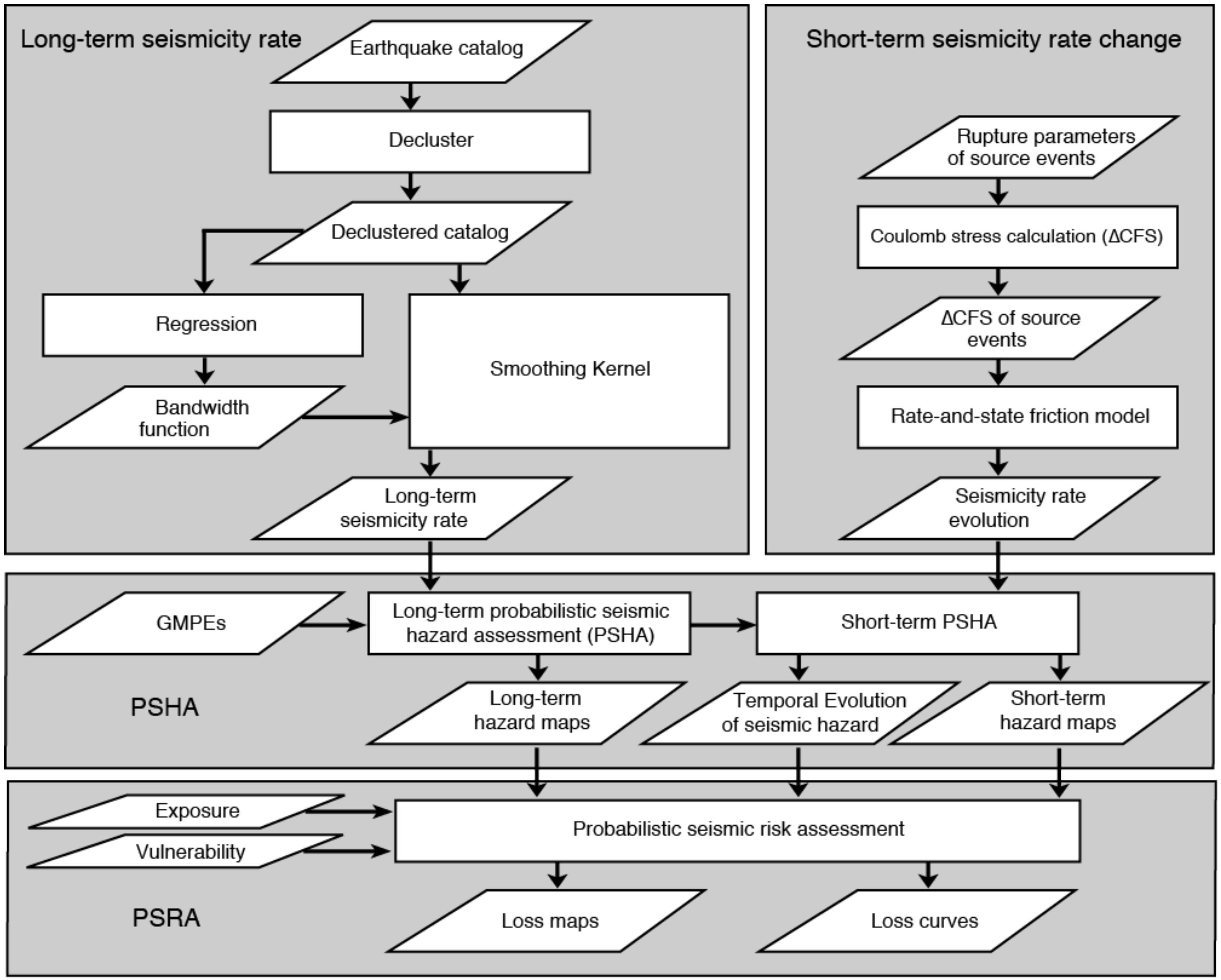
Why *time-dependency* should be implemented for risk assessment?



- ***Consequent events*** may result in larger damage
- For ***short-term*** needs: ***relief*** & ***shelter***
- For ***mid-term*** needs: ***recovery*** & ***reconstruction***

Earthquake	Distance to Christchurch	PGA in Christchurch
2010 Darfield	40 km	0.30 g
2011 Christchurch	5 km	1.88 g

The proposed flow chart for PSRA

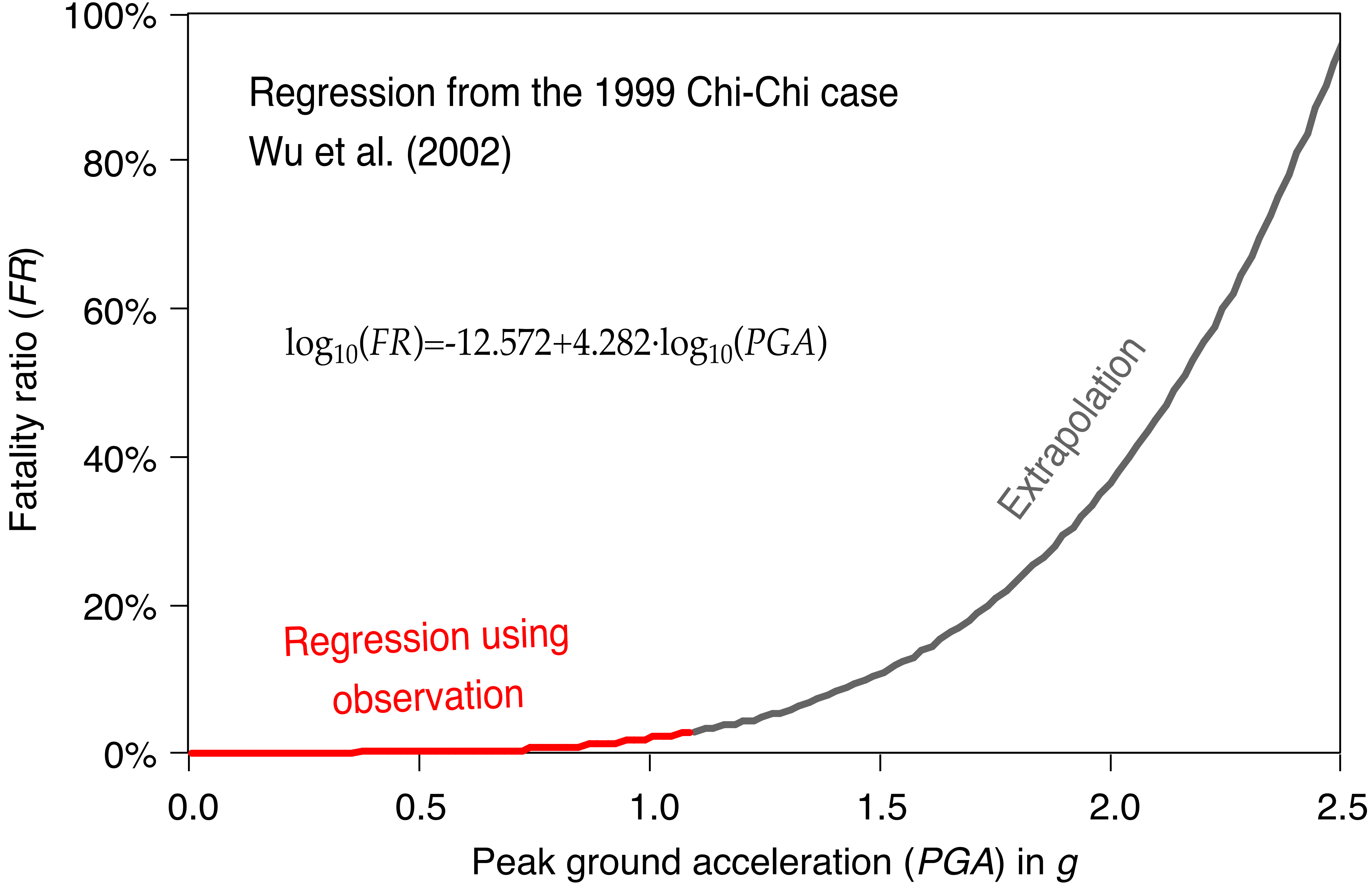


ΔCFS.....

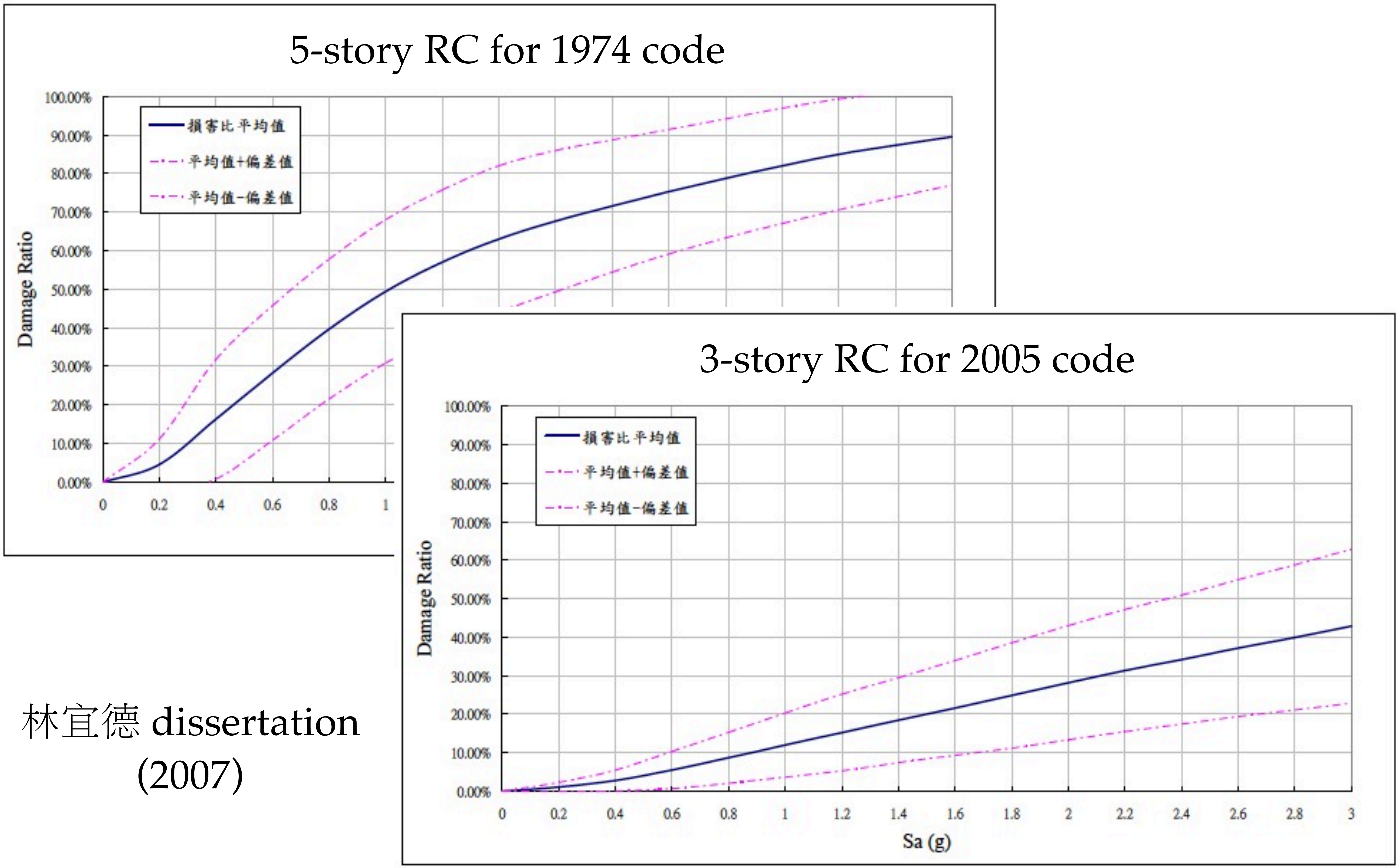
Concerns of this model:

No data for PGA > 1.3 g;

Distribution (log-log) is ***different*** from building vulnerability model

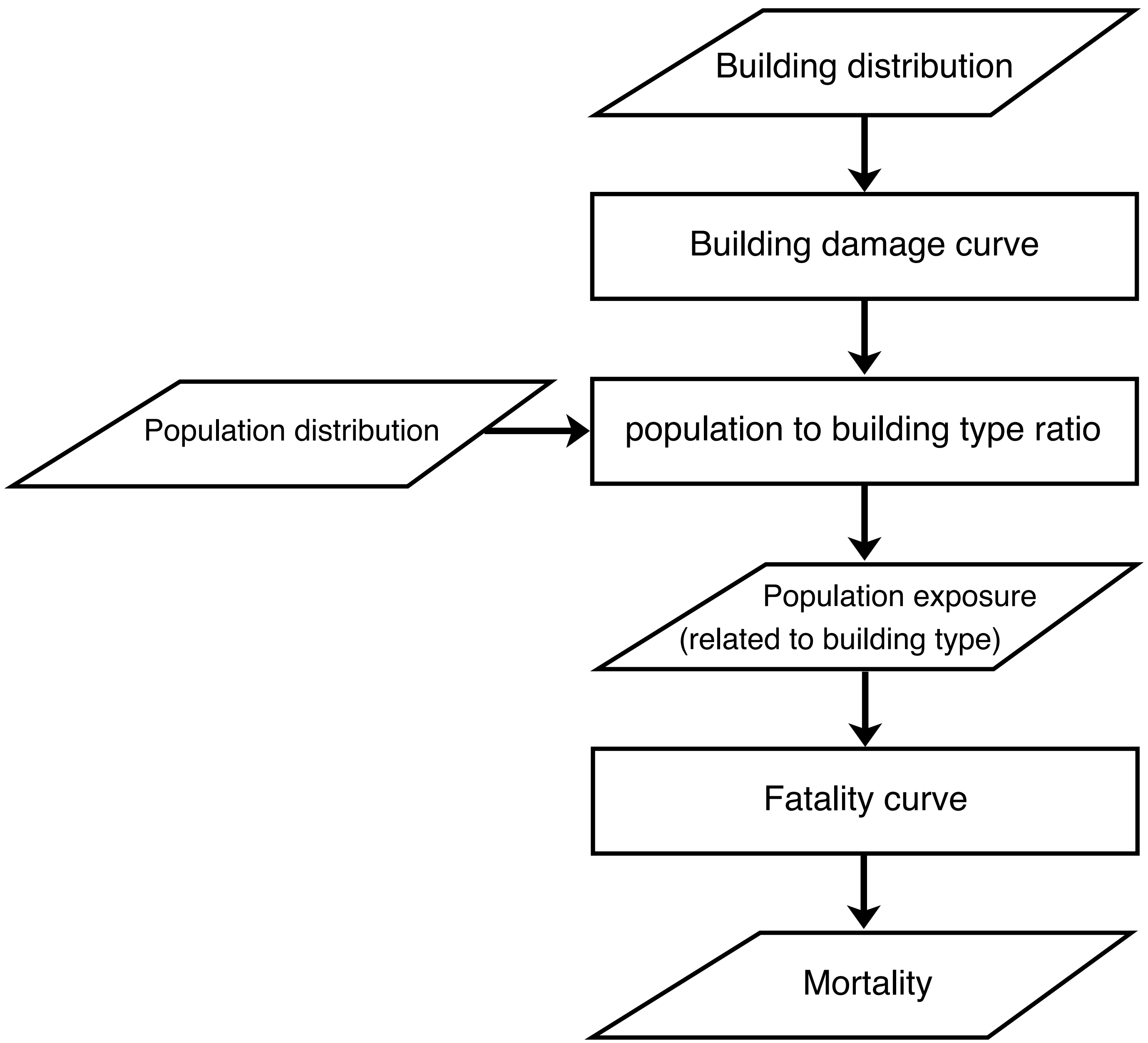


Vulnerability models for different building types types for varies building codes

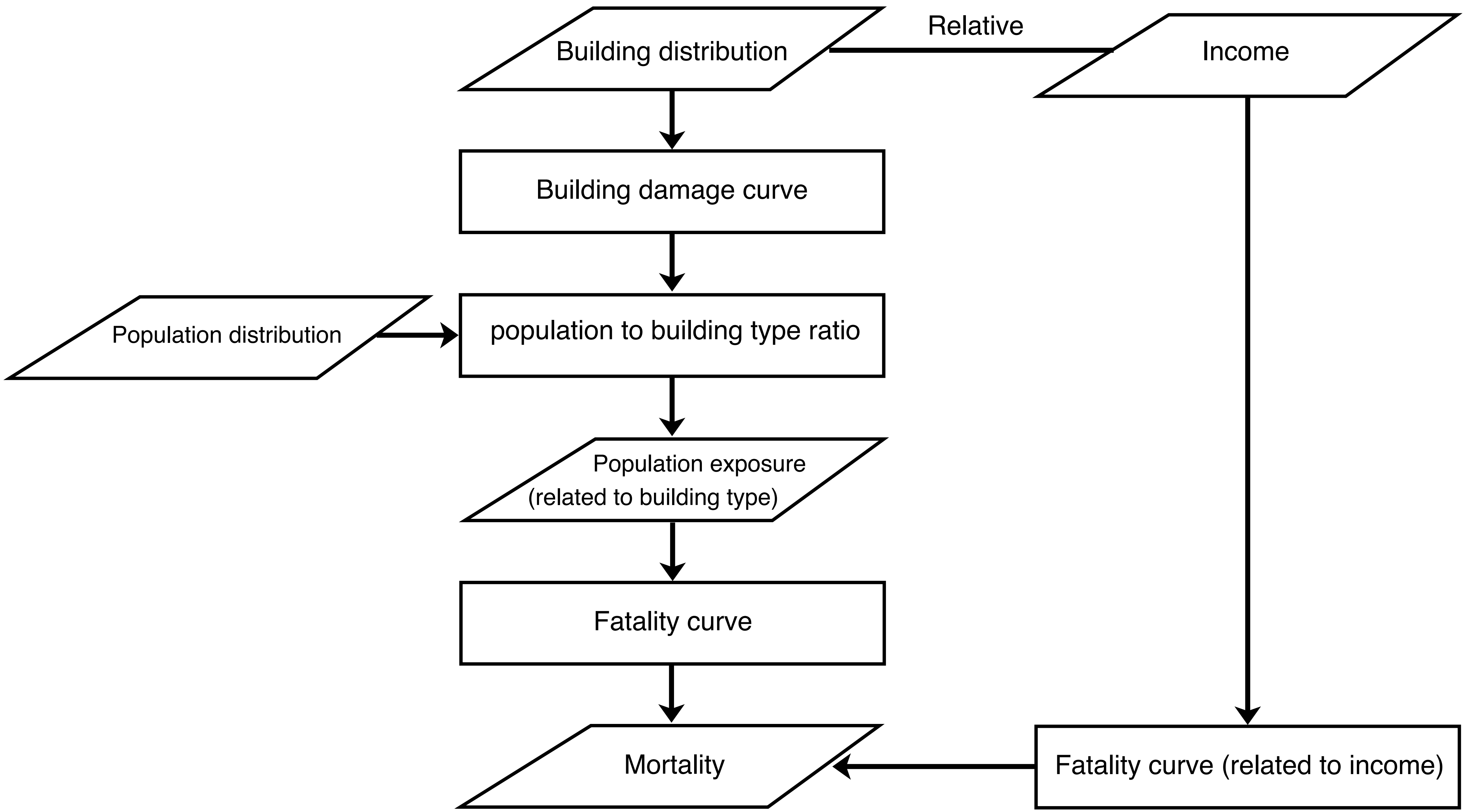


林宜德 dissertation (2007)

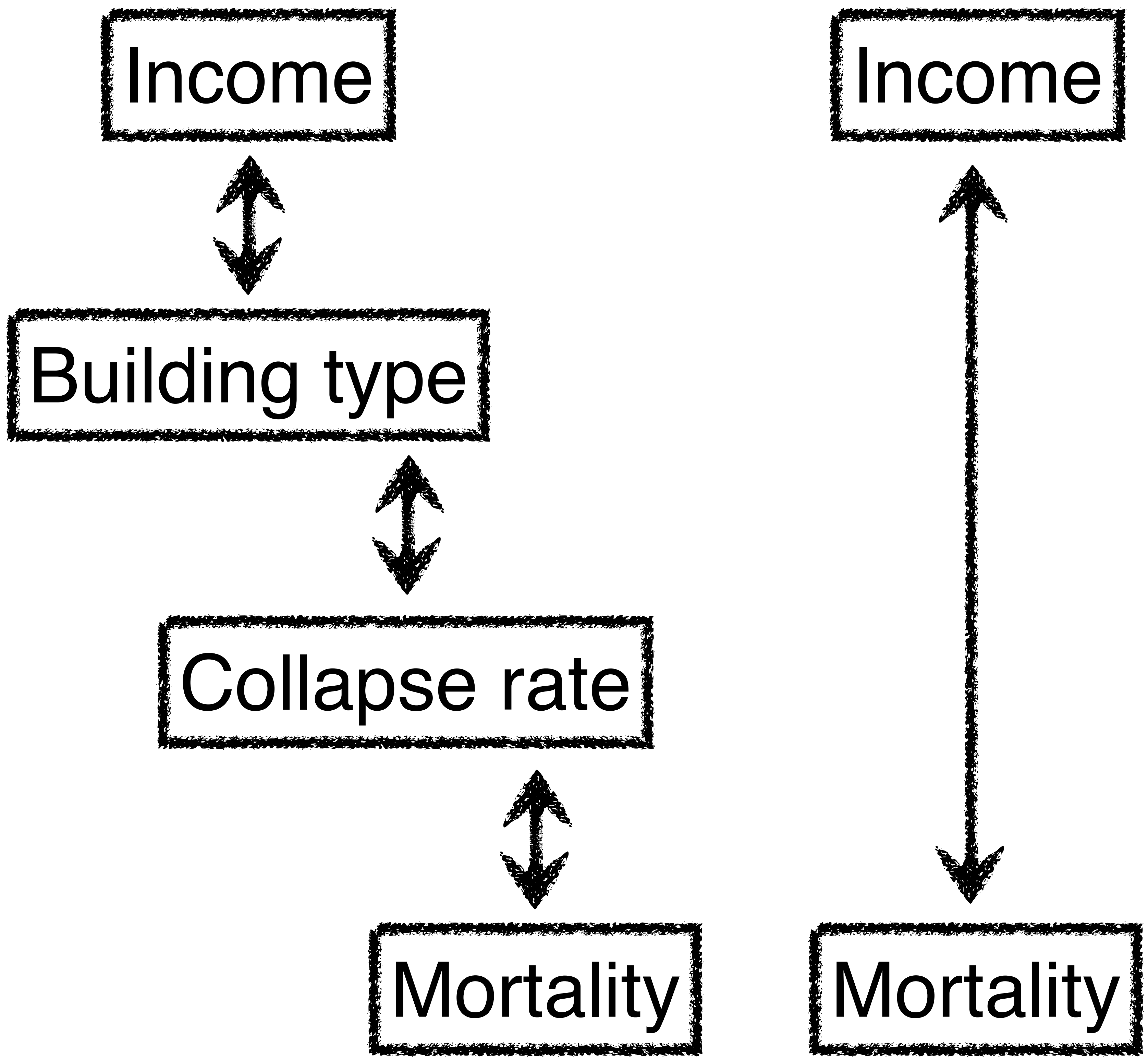
Alternative procedures for mortality estimation



Alternative procedures for mortality estimation

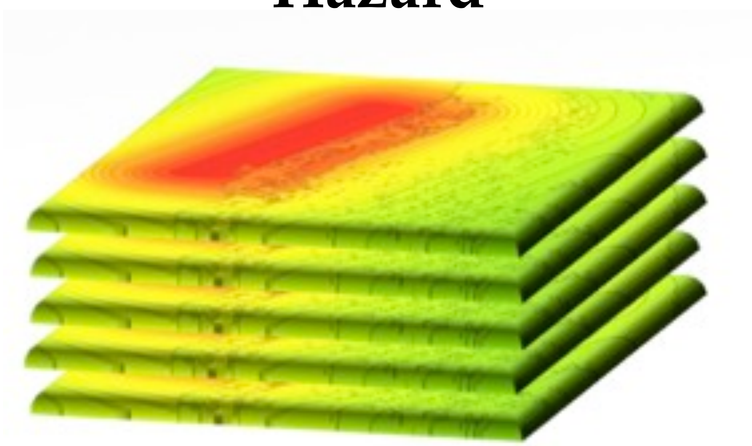


Analysis the relations between each other



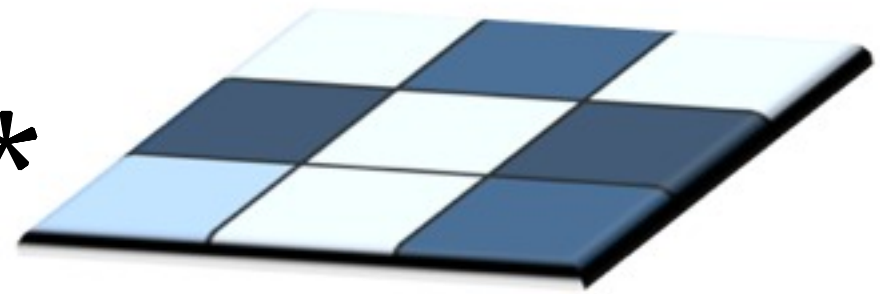
Further application: seismic risk assessment

Hazard



*

Exposure



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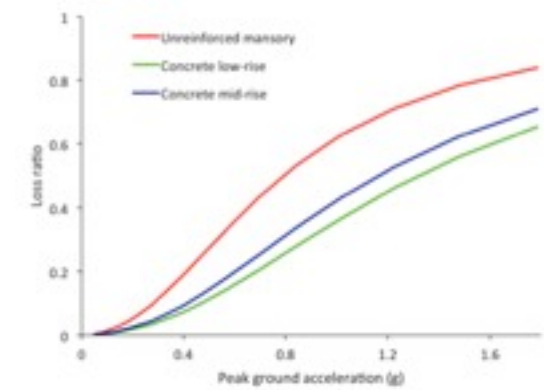
Vulnerability

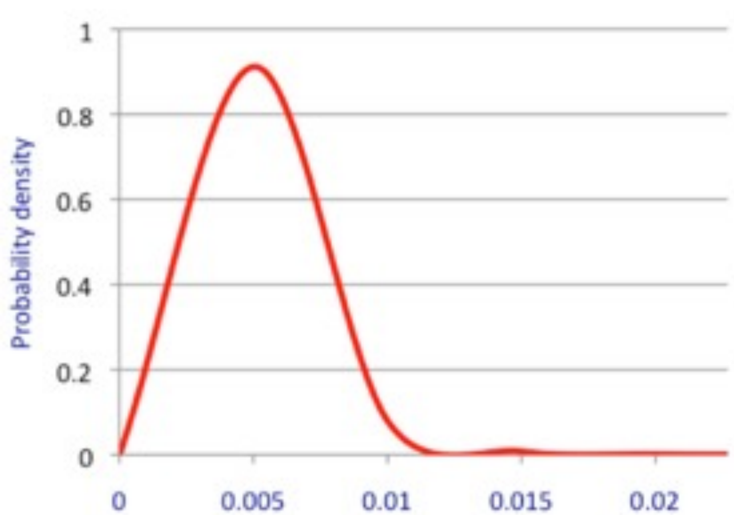


Hazard curves
Hazard maps

Population/Building distribution

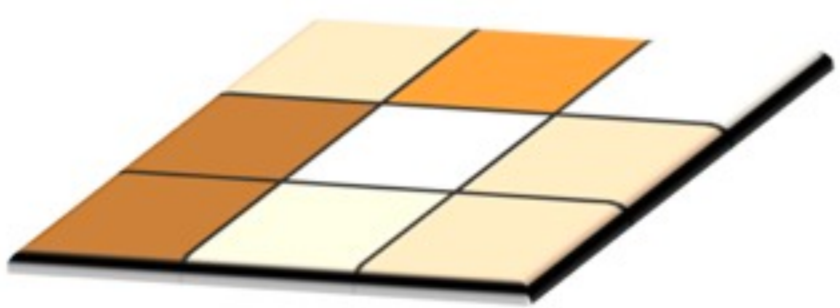
Loss ratios

Loss curve



or/and

Loss map



IPCC, 2012

.... Meishan eq

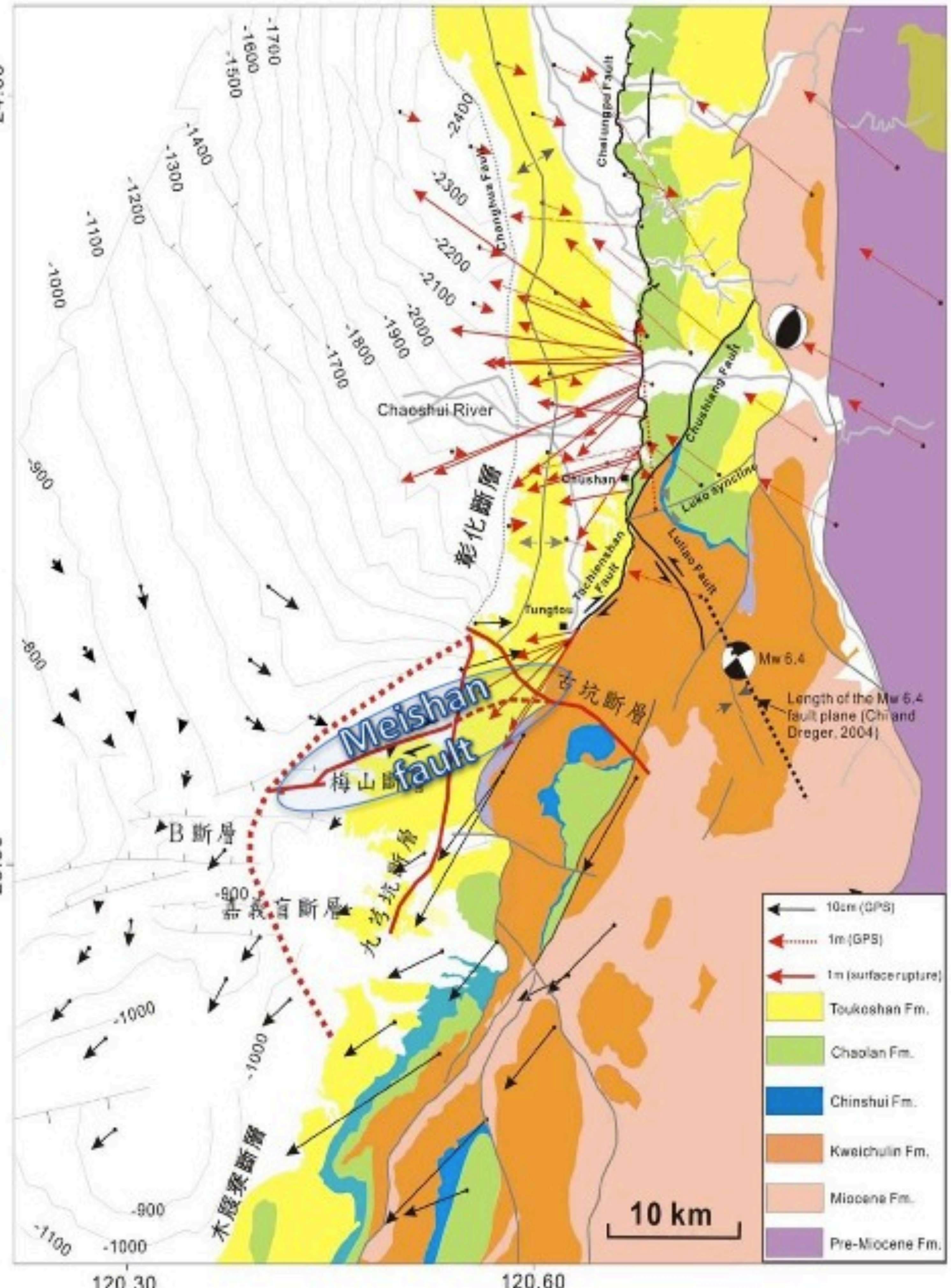
1906 Meishan Earthquake Scenario

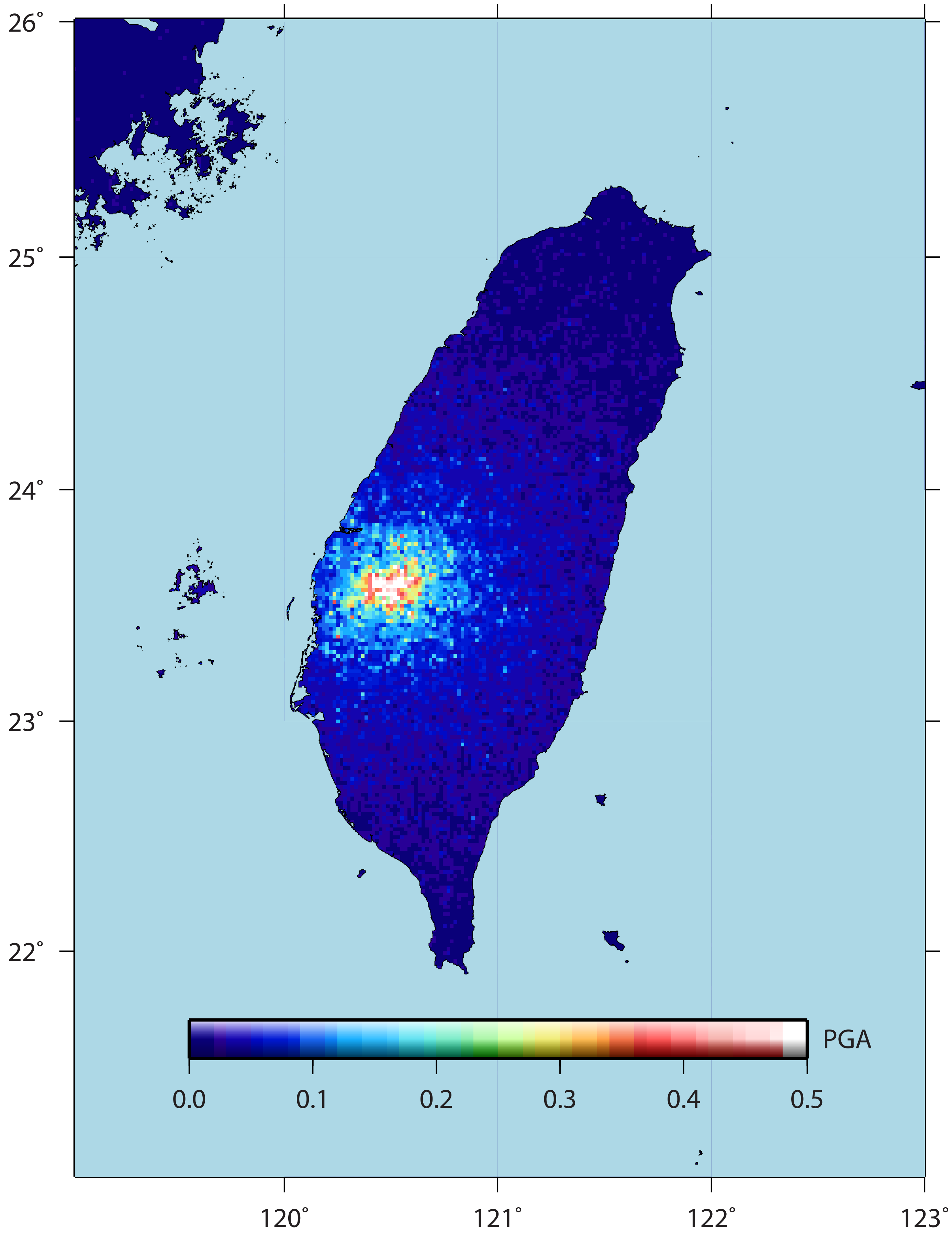
Prof. Lee
1906 Meishan eartqhuake
-Meishan fault

-Compilation of the subsurface structure, seismic-reflection, logging, micro-temors
-Simulation (Dr. Lee, and Dr. Yen)

-Literature data (Prof. Cheng)

=>Validation the TEM Exercise
HAZARD, RISK, SOCIAL IMPACT



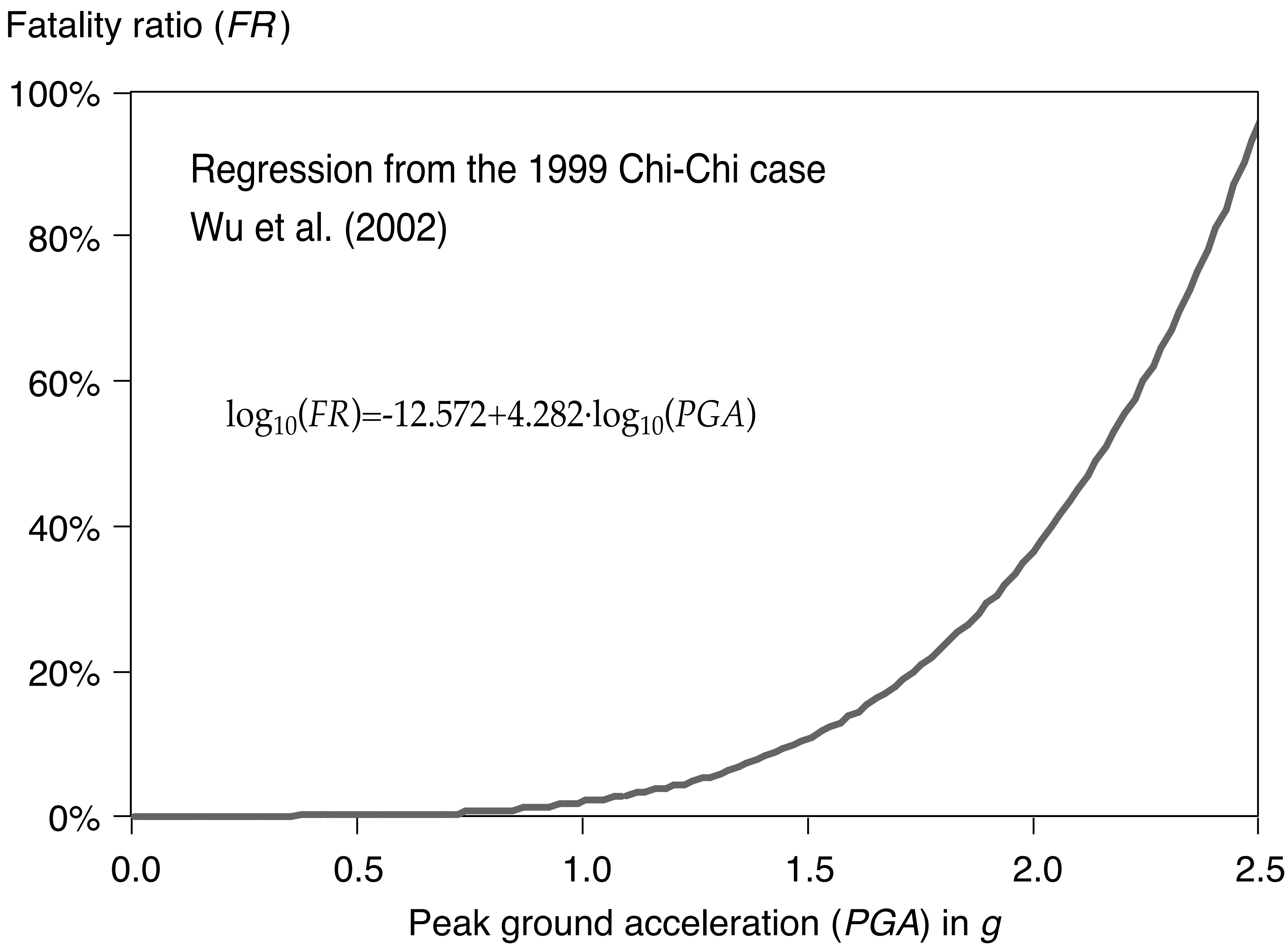


Ground shaking of the Meishan Scenario

Can be regarded as an input for ***risk*** assessment

Ground shaking from ***other approaches*** can also be inputs of OQ

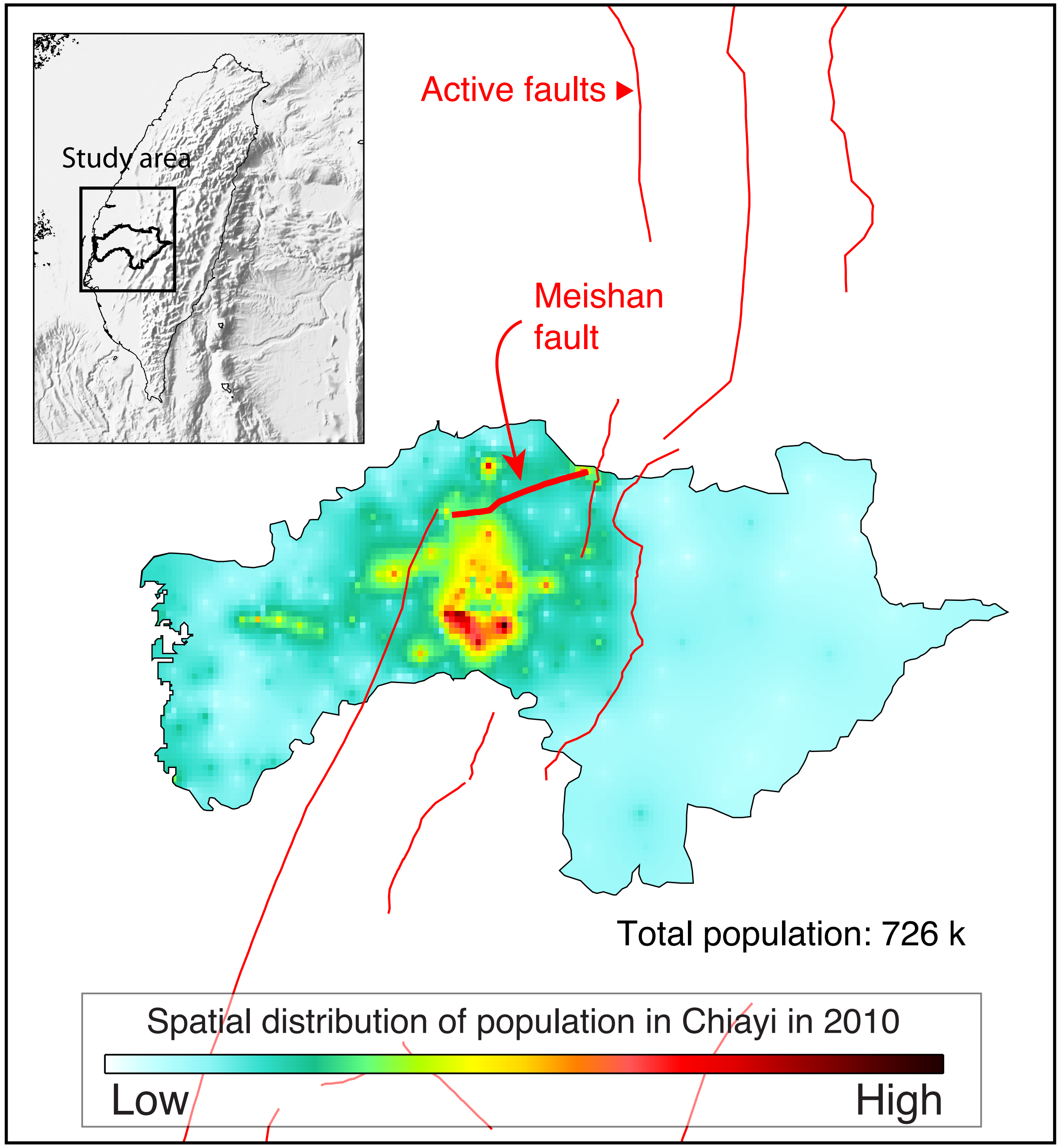
Considering ***Fatality rates*** as a function of ground shaking from the 1999 Chi-Chi case



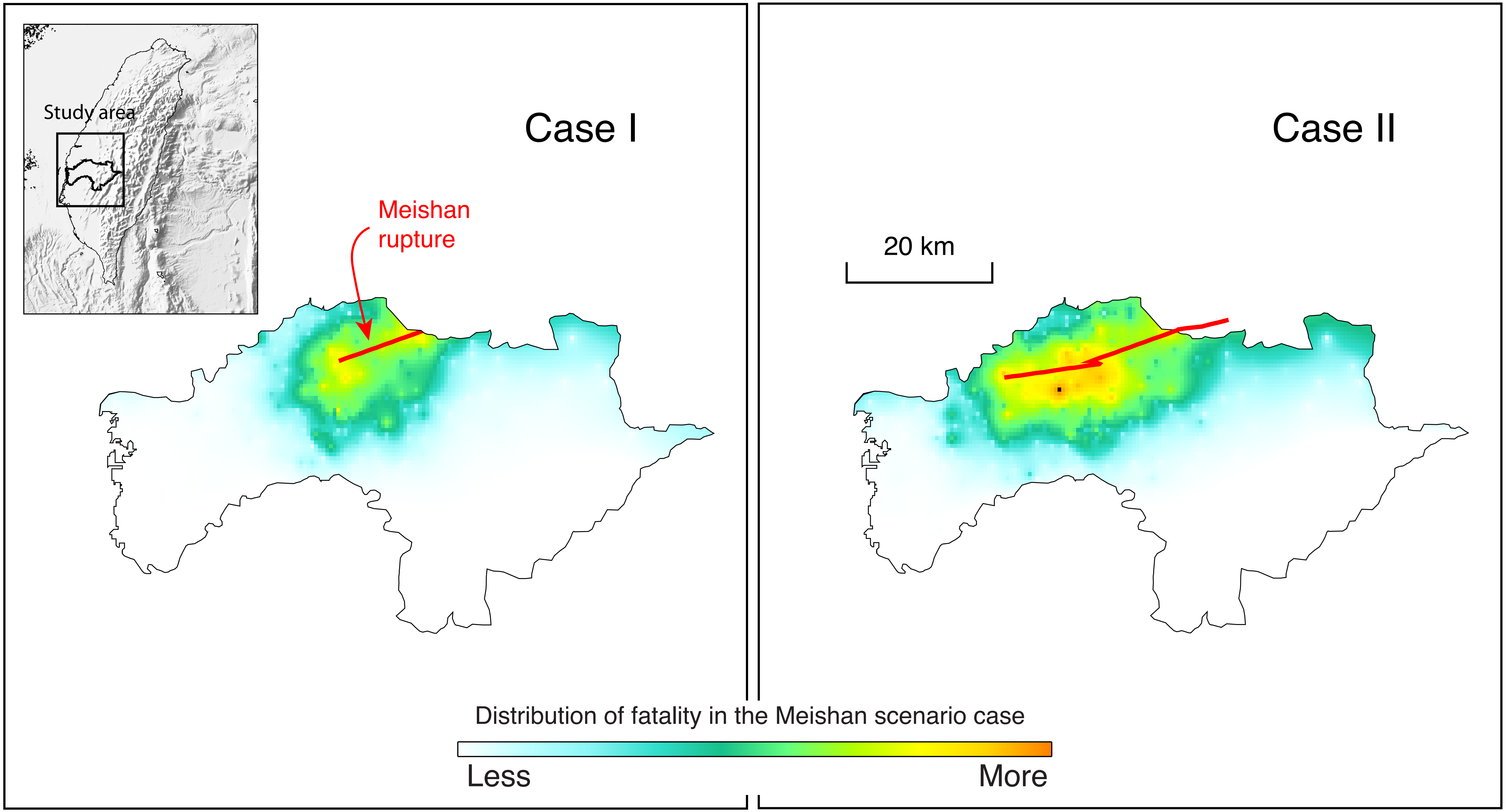
Advantage: Can be ***rapidly*** implemented

Distribution of population

Scenario case in respect of fatality



Case II may attributes more fatality in a wider range than Case I



Rupture alignment in 1906

Rupture alignment in 1906, blind fault, and liquefaction region