Seismic Hazard Analysis with Geological and Historical Earthquake Data

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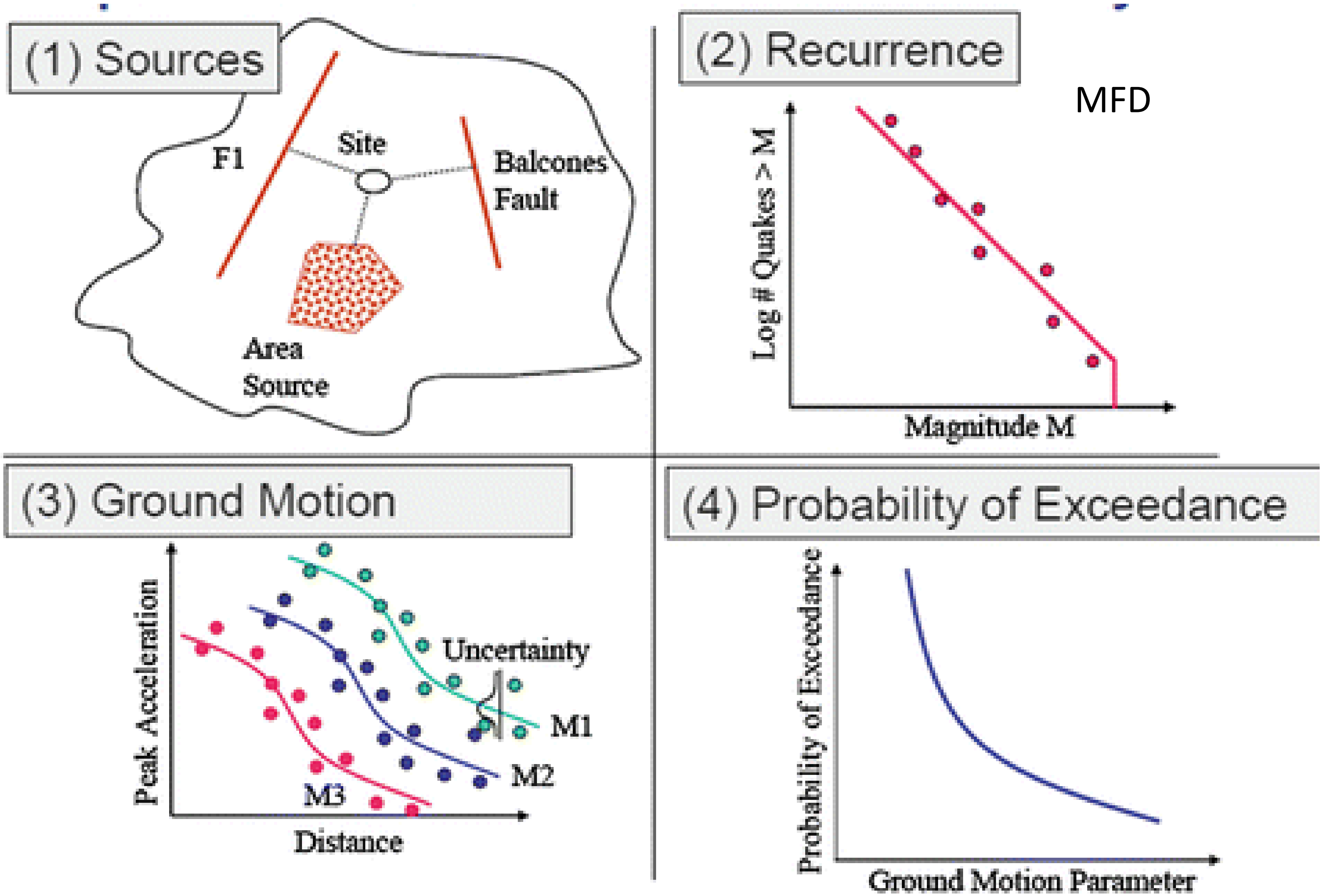
Four steps in PSHA



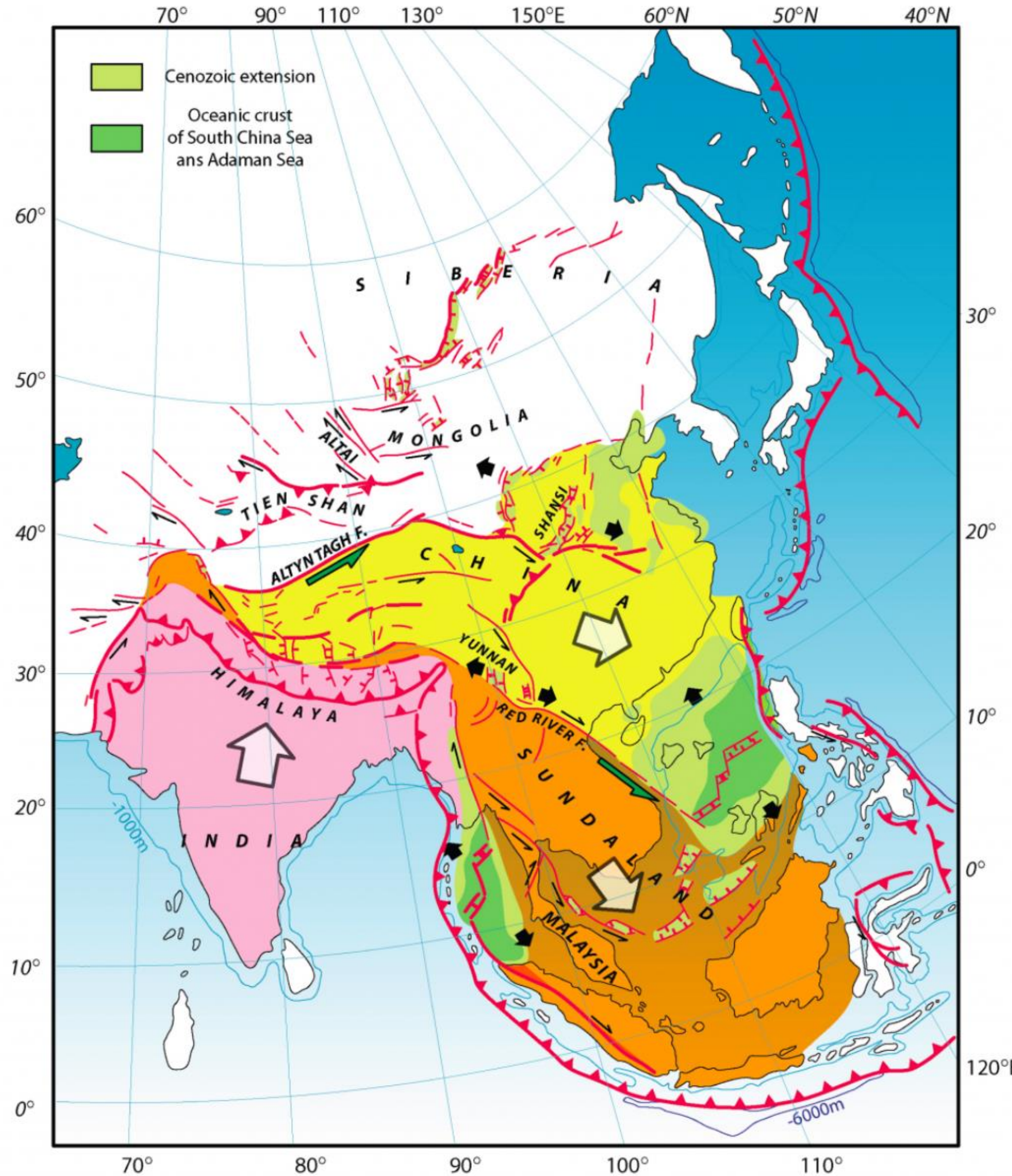
Active faults in China

Cenozoic tectonic deformation Of China and SE Asia

After the collision between the Indian plate and the Eurasian plate, the eastern extrusion of crustal deformation denominates the southeastern Tibetan plateau and the southeast Asia.

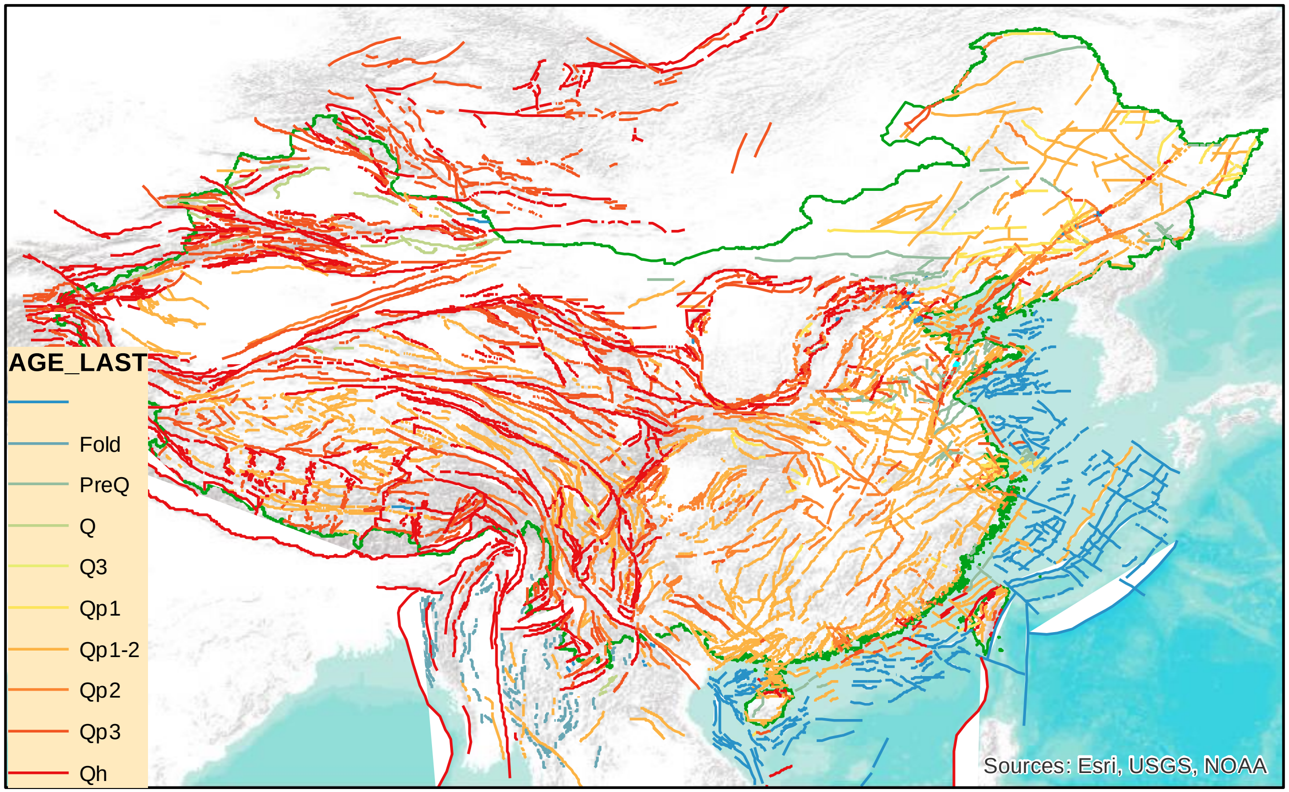
By Paul Tapponnier et al., 1982

Might be even more complex, also should consider the subduction of the Pacific plate and compression from the Siberia region.



PSHA work for mainland China

Compile active faults, collect parameters, and simplify fault traces



- Original fault data from Prof. Xu of CEA
- About 6000 mapped fault traces
- Need to simplify them and collect slip rates, fault types, dipping angles etc. for earthquake modeling
- Slip rates and other parameters are collected from:
    - ~1000 published papers
    - An unpublished book by Prof. Xu et al. (1000+ pages)

Xu et al., 2016, http://www.activefault-datacenter.cn/

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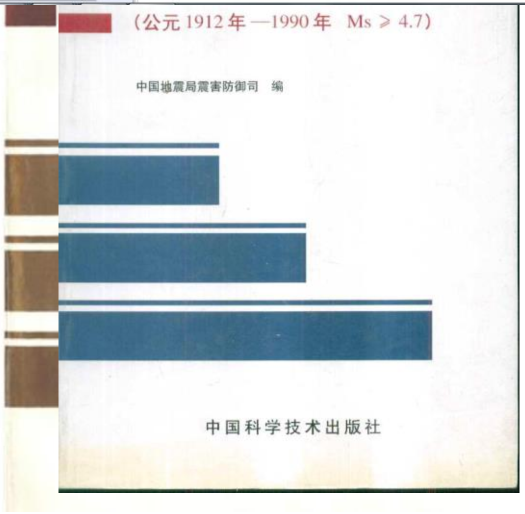
Mw Earthquake Catalog

Highlights of the three China Ms catalogs

- **China Historical Strong Earthquakes (780 B.C. – 1911 A.D.)**
  - 1,034 earthquakes with Ms≥4.7
  - Only two earthquakes in the catalog before 780 BC
  - magnitudes were converted from intensity maps
- **China Present Earthquakes (1912 – 1990)**
  - 4,289 earthquakes with Ms≥4.7
  - some of them were instrumentally recorded
- **CENC catalog (1970 – 2015, published online)**
  - more than 10,000 with Ms≥4.0
  - All of them were instrumentally recorded

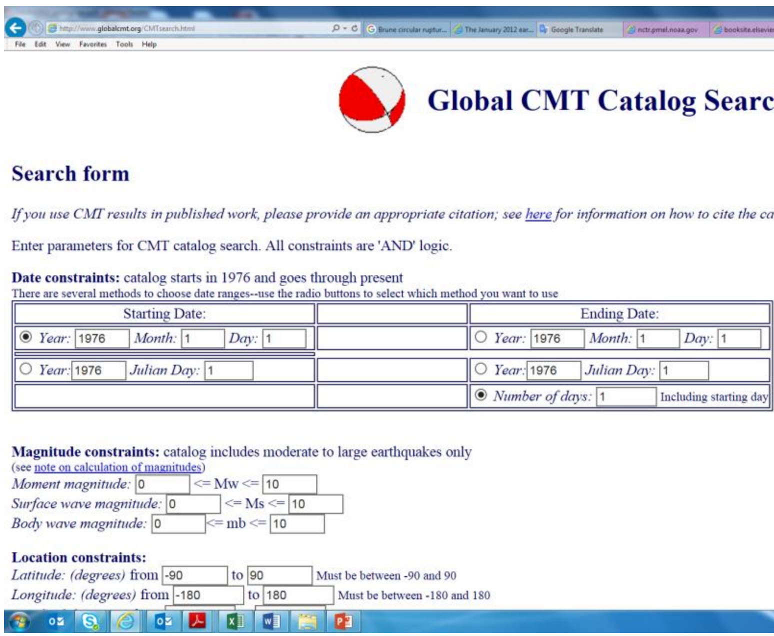


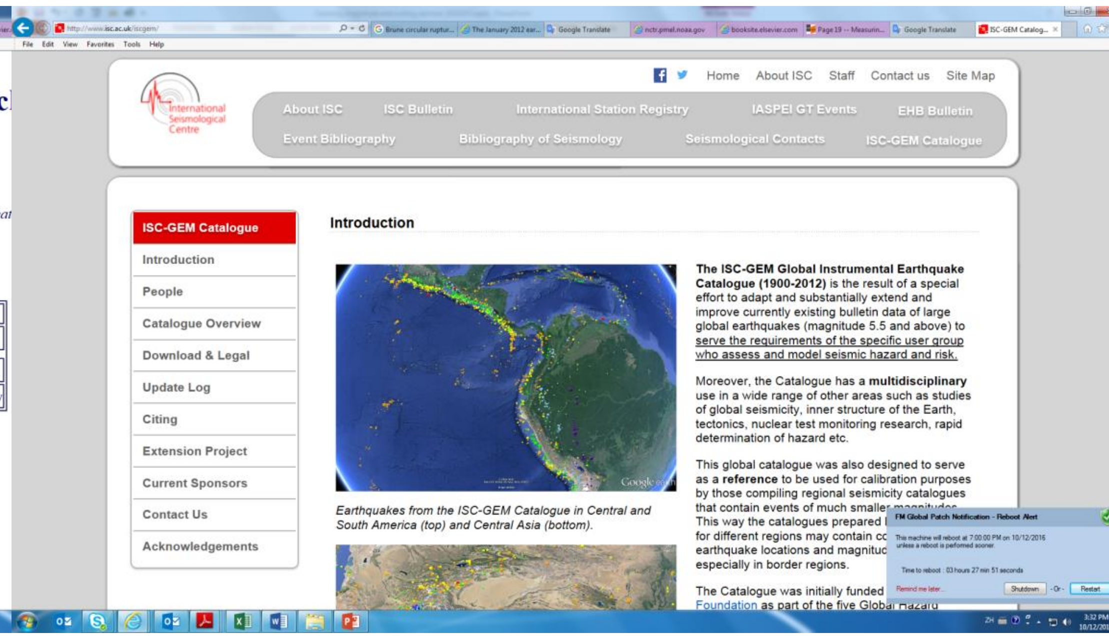
China Historical Strong Earthquakes 2,300 B.C.-1911 A.D.

China Present Earthquakes 1912-1990

Mw Earthquake Catalog

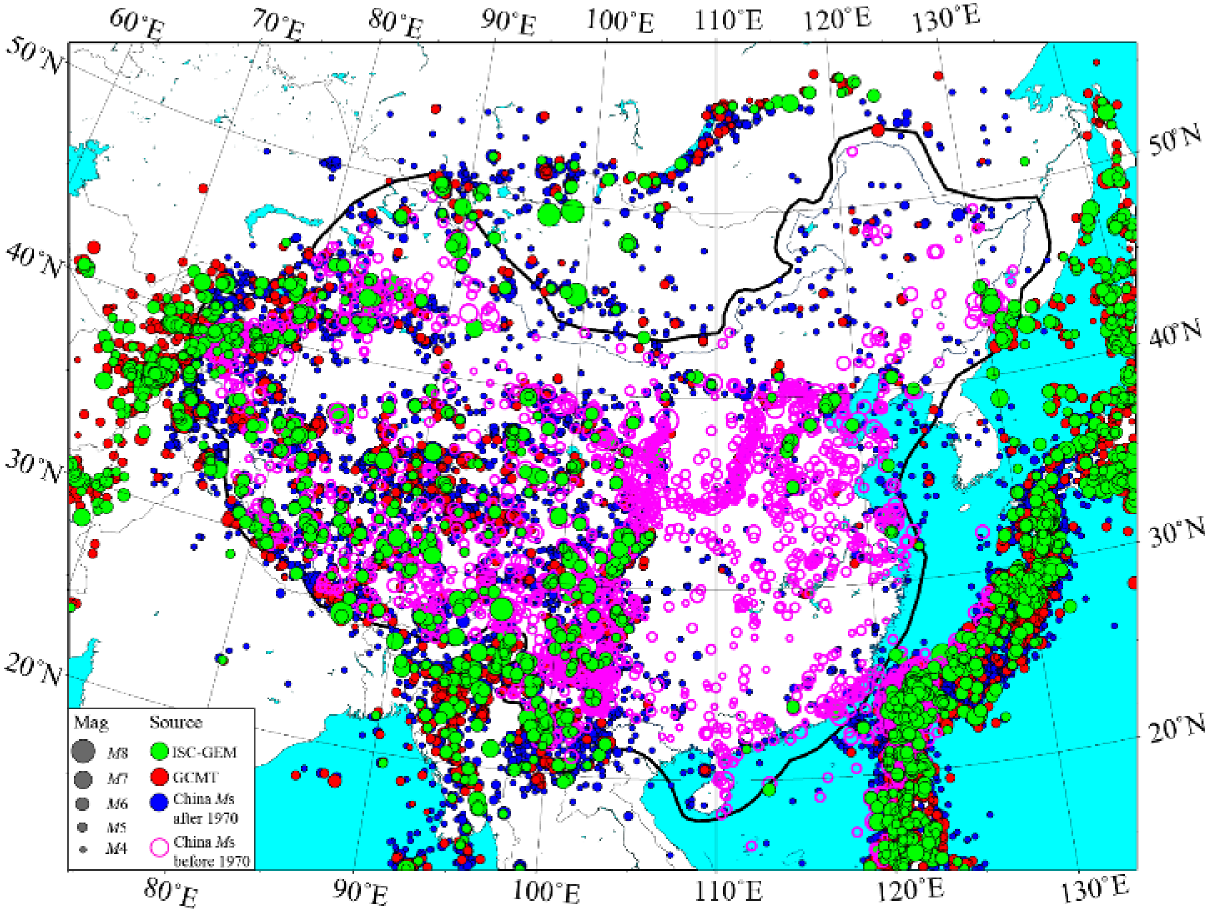
4) 1976-present National coverage of China seismograph stations; Mw-based Global CMT catalog is available. Mw-based ISC-GEM catalog has more precise locations for the events from 1900-2011.





Mw Earthquake Catalog

historical earthquake catalogs



Red : Global CMT catalog (1976-2015).
Green: ISC-GEM catalog (1900-2013).
Blue: Chinese earthquake catalog (1970-2015)
Pink: Chinese earthquake catalog (780 BC to 1969)

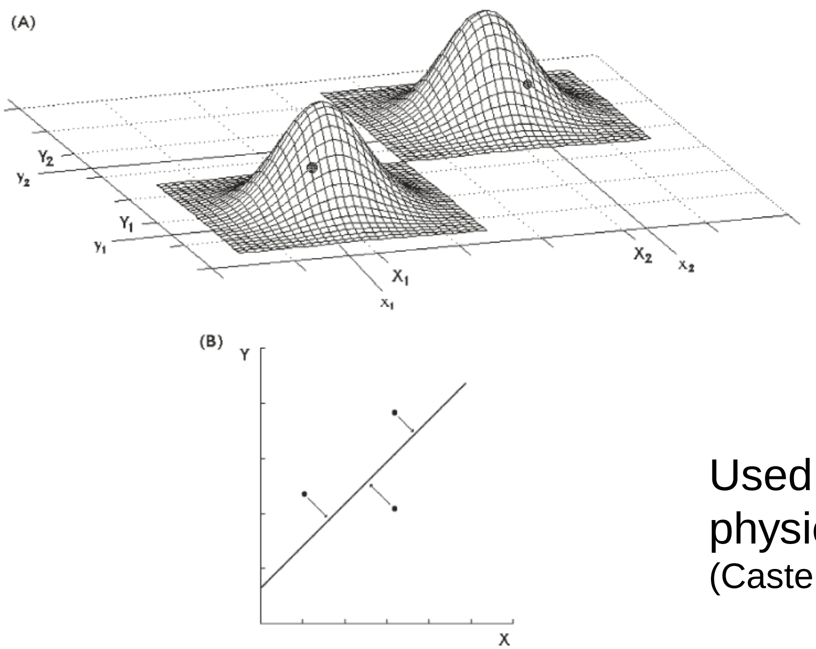
Mw Earthquake Catalog

Before 1900	1900-1965	1966-1975	1976-2015
• Intensity based magnitude	• ≥Ms 7.0 • <Ms 7.0	• ≥Ms 7.0 • <Ms 7.0	• ≥Ms 7.0 • <Ms 7.0

For M_S ≥ 7.0 and <M_S 7.0：

Large earthquakes (M_S ≥ 7.0) magnitude often re-evaluated by the CENC. Magnitude of the Wenchuan earthquake (2008) revised by CENC from M_S 7.8 to 8.0 five days after its occurrence.

General Orthogonal Regression (GOR)



$$\sum_{i=1}^{n}\left[\frac{(y_i - a - bX_i)^2}{\eta} + (x_i - X_i)^2\right]$$

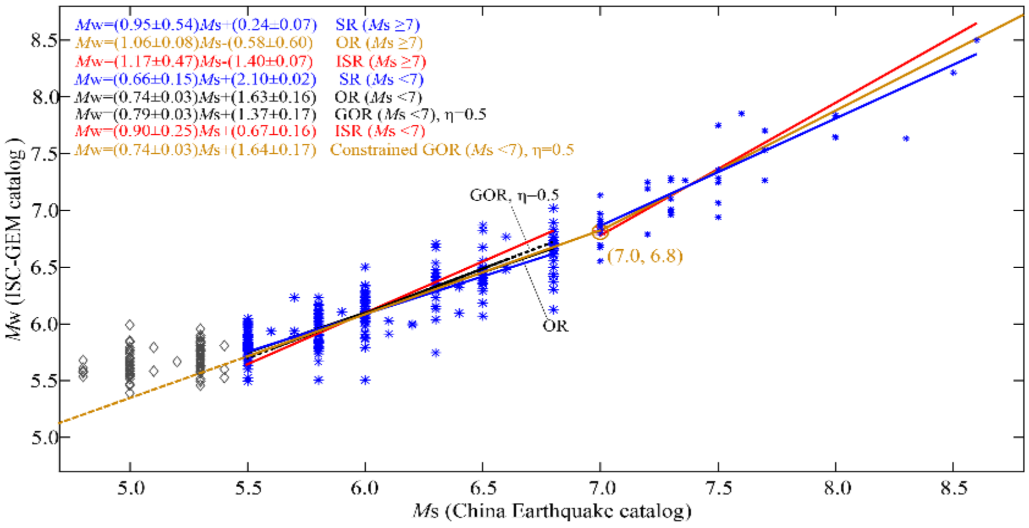
$\eta = \sigma^2_y / \sigma^2_x$ (mostly not given)

Used when the variables are related by fundamental physical laws

(Castellaro et al.,2006;2007; Wason., 2012; Das., 2011).

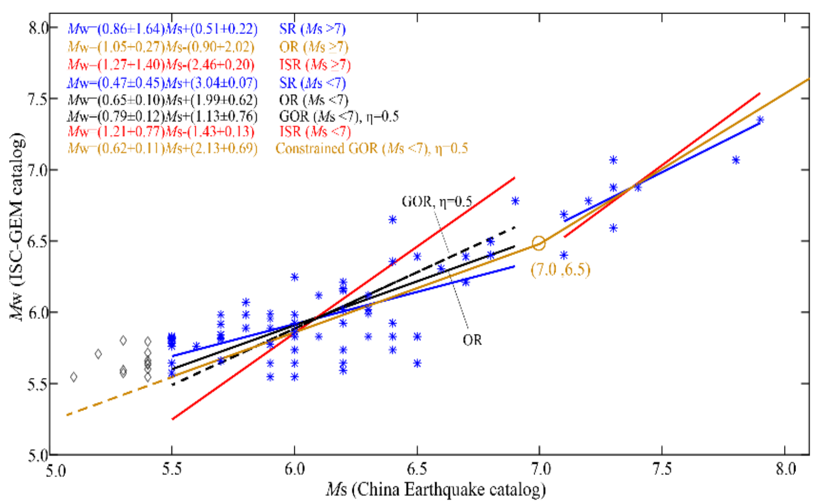
We used the common events in the China Ms catalog and the combined Mw catalog (ISC-GEM catalog with Global CMT catalog) to derive the regression relationships between Ms and Mw.

Mw Earthquake Catalog

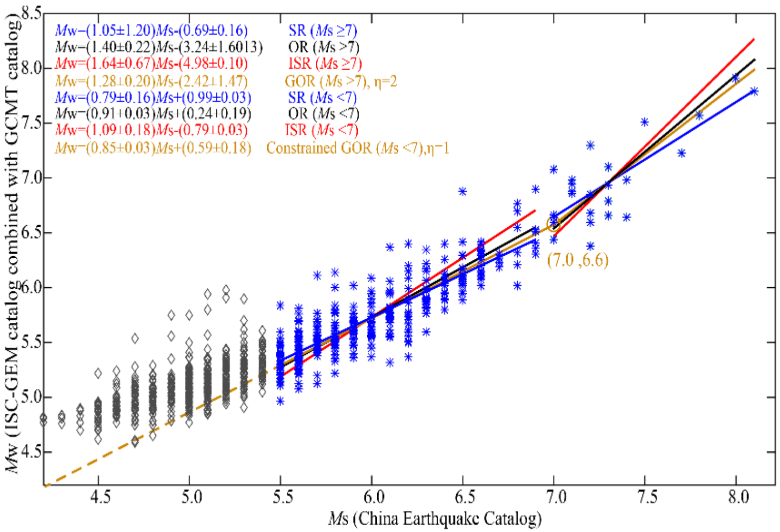


1900-1965

Using the method of Casterllaro (2007) to select the value of η

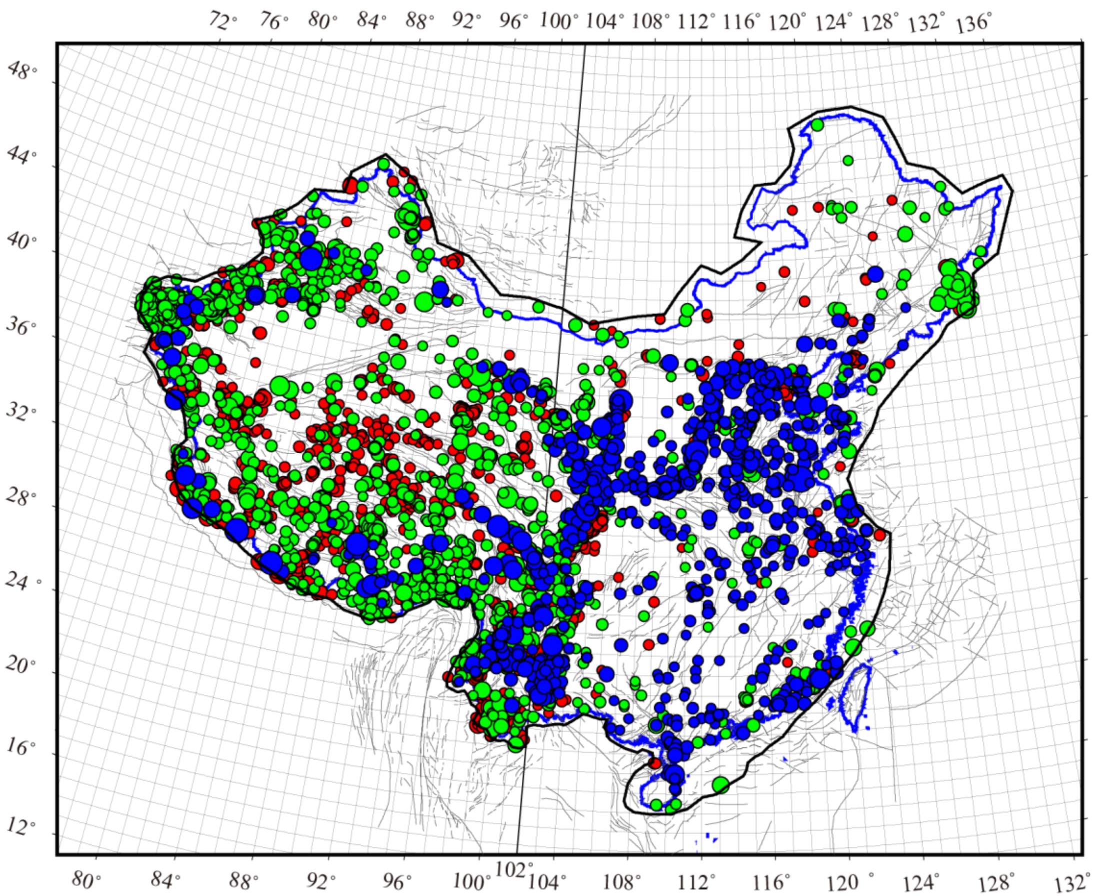


1966-1975



1976-2015

New catalog (M_W≥4.0)



Eastern China (>102°E) has a better record of historical earthquakes than western China.

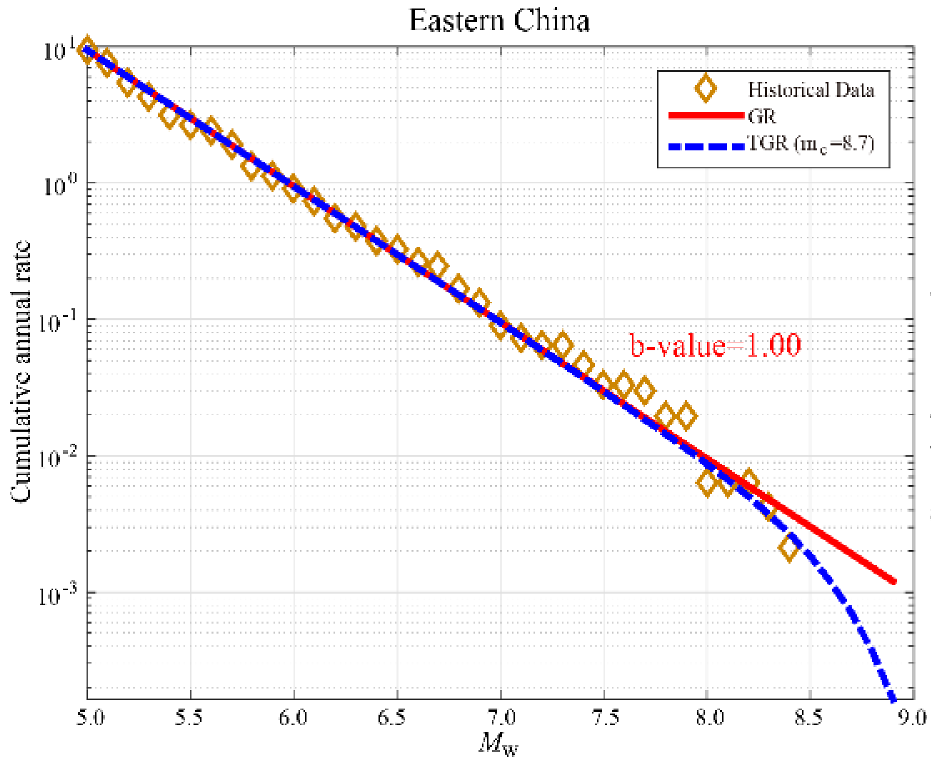
Before 1900
1900-1969
1970-2015

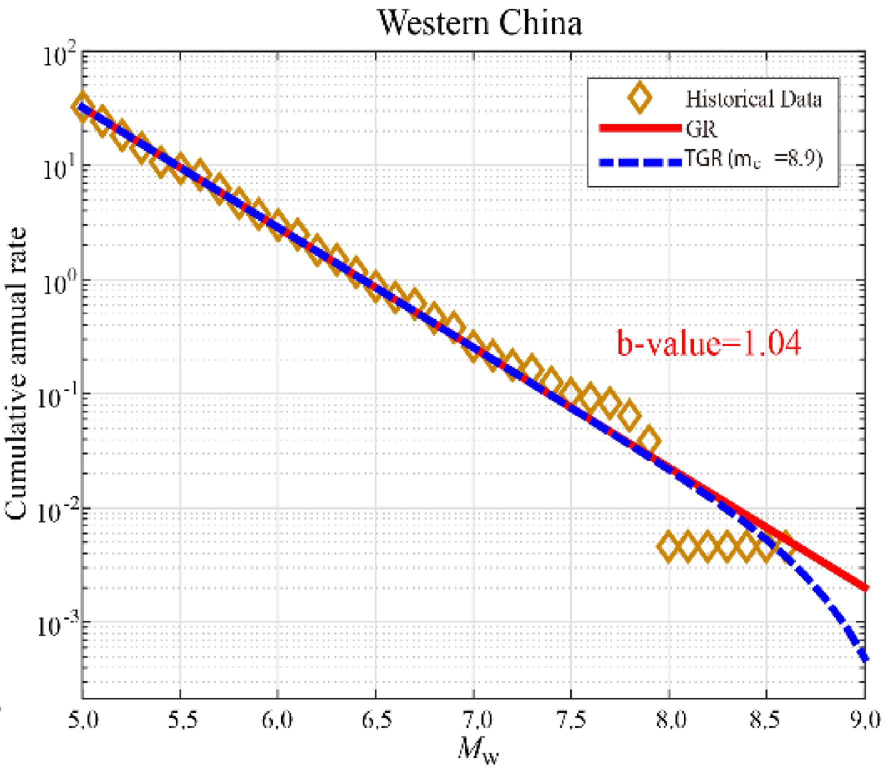
Cheng et al., 2017, BSSA

MFD

✓We got a Mw-based earthquake catalog

✓G-R relationships for eastern and western China show good results





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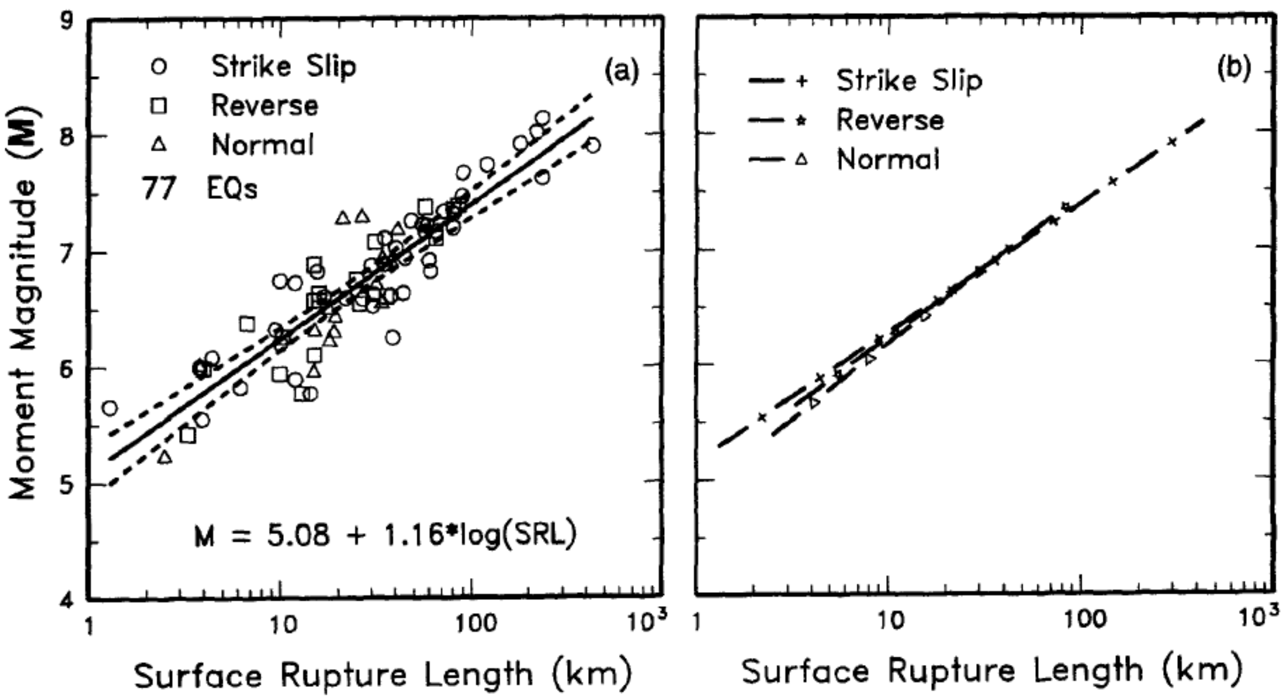
Rupture Scaling for the earthquakes in China

Surface Rupture Length, SRL~*M*w (WC94)

(evaluate the magnitude from fieldwork data)



Wells and Coppersmith ,1994

Blaser et al.,2010, GOR method was used

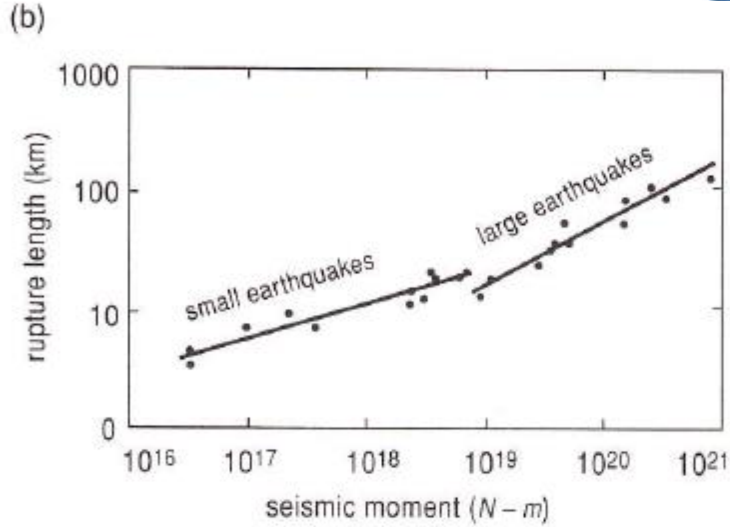
Leonard, 2014, bilinear regression line

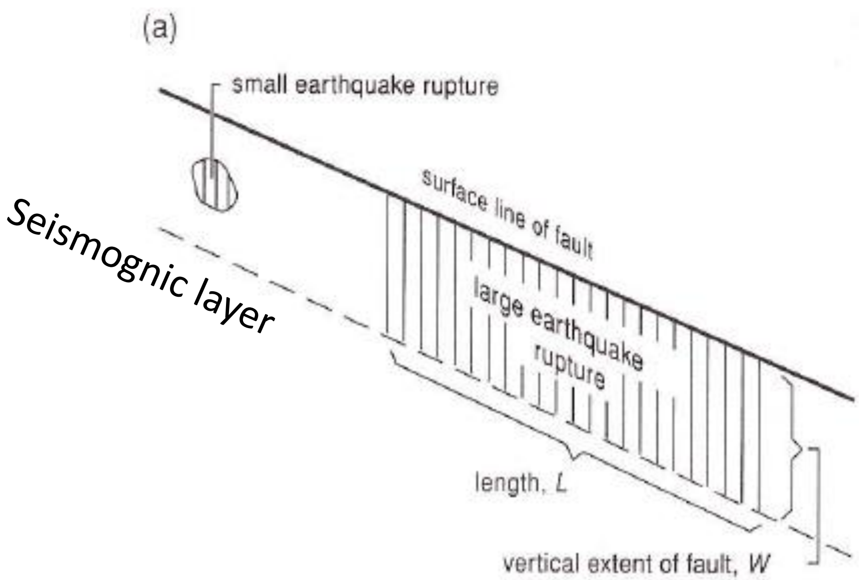
Rupture Scaling for the earthquakes in China

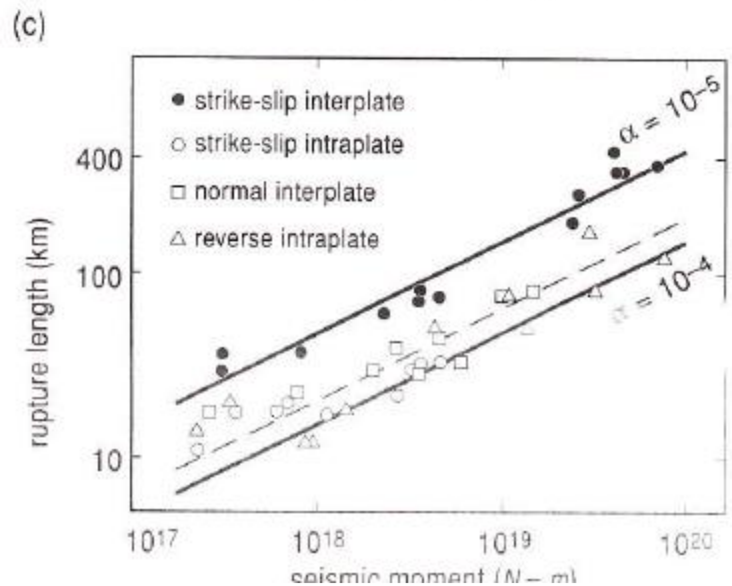
Whether the global scaling relations can be used in mainland China?

What is a scaling?

It means that big displacements do NOT happen on small fault plane area!







Ben Dueker, ppt

Rupture Scaling for the earthquakes in China

Whether the global scaling relations can be used in mainland China?

Scaling Relations for Global Earthquakes

Tectonic regime		Recommended Scaling relations
Plate boundary crust	A1: Fast plate boundary faults (> 10 mm/yr)	Hanks and Bakun (2002;2008);Wesnousky (2008);Leonard (2014)
	A2: Slow plate boundary faults (< 10 mm/yr)	Yen and Ma (2011); Hanks and Bakun (2002;2008) ; Stirling et al. (2008) (New Zealand-oblique-slip) Wesnousky (2008)(strike slip)
Stable continental		Anderson et al. (1996);Nuttli (1983)
subduction	Continental	Strasser et al. (2010)(interface)
	Marine	Blaser et al. (2010) (subduction)
	Intraslab	Ichinose et al. (2006)
Volcanic		Villamor et al. (2007); Wesnousky (2008) (normal)

Recommended by Stirling and Goded (2012) and Stirling et al. (2013), by tectonic regime.

Short of the samples from the intraplate earthquakes

Theoretical frameworks for the rupture parameters and magnitude

$$M_W = \frac{2}{3}(logM_0 - 9.05)$$

$$M_0 = \mu \cdot RA \cdot \overline{D}$$

$$\Delta\sigma = C\mu\frac{\overline{D}}{\tilde{L}}$$

For large strike slip earthquakes (RW is a constant) :

Three types of scaling relations

Self-similarity scaling $RLD \propto M_0^{\frac{1}{3}}$, $RW \propto M_0^{\frac{1}{3}}$, and $\overline{D} \propto M_0^{\frac{1}{3}}$

$\Delta\sigma$ constant

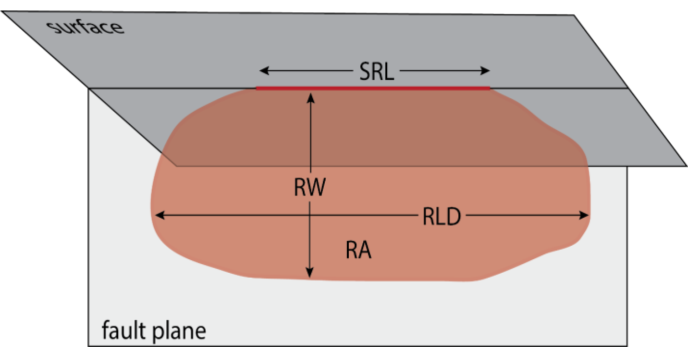
L-model (Scholz, 1982) $\overline{D} \propto RLD$ $RLD \propto M_0^{1/2}$

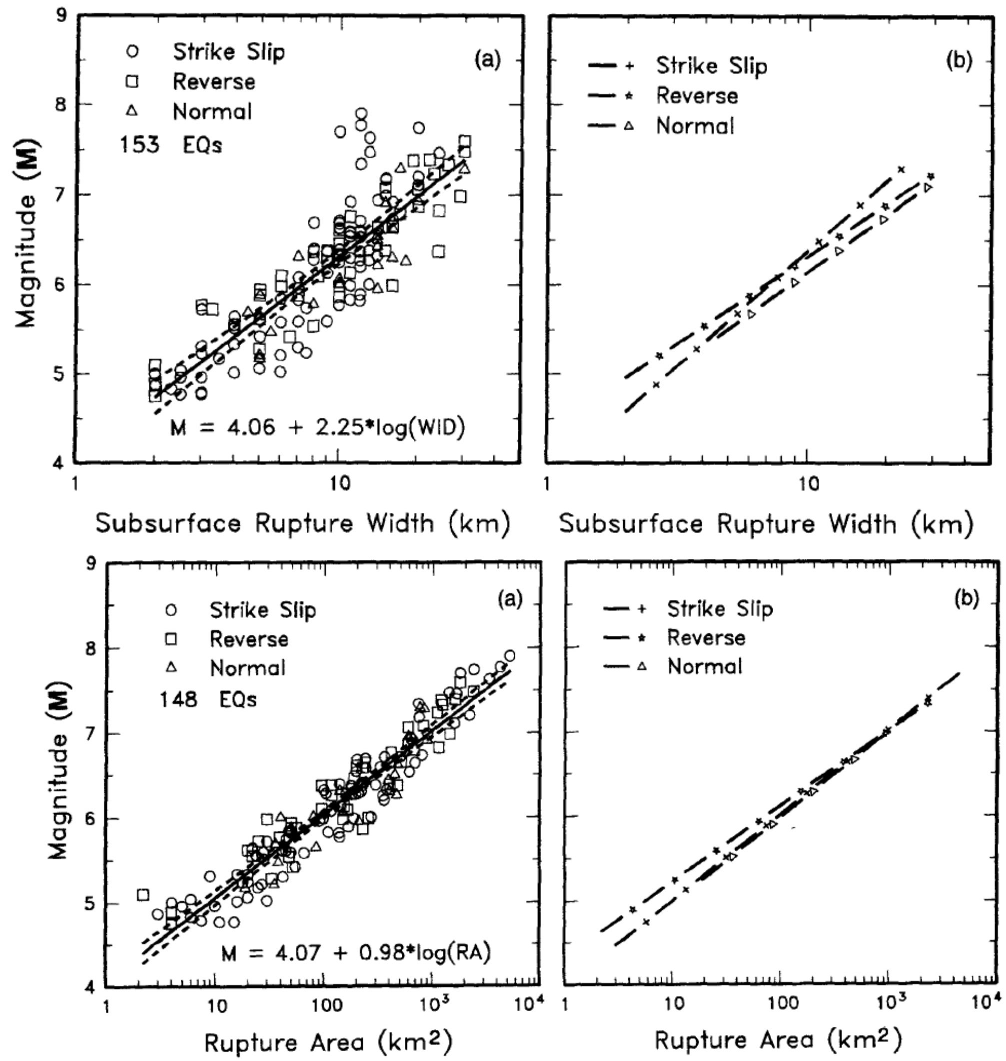
$\Delta\sigma$ magnitude-dependent

W-model (Romanowicz, 1992) $RLD \propto M_0$ $\Delta\sigma$ magnitude-independent

Subsurface Rupture Length, RLD~Mw (WC94)

(To evaluate the magnitude or rupture parameters for calculation)



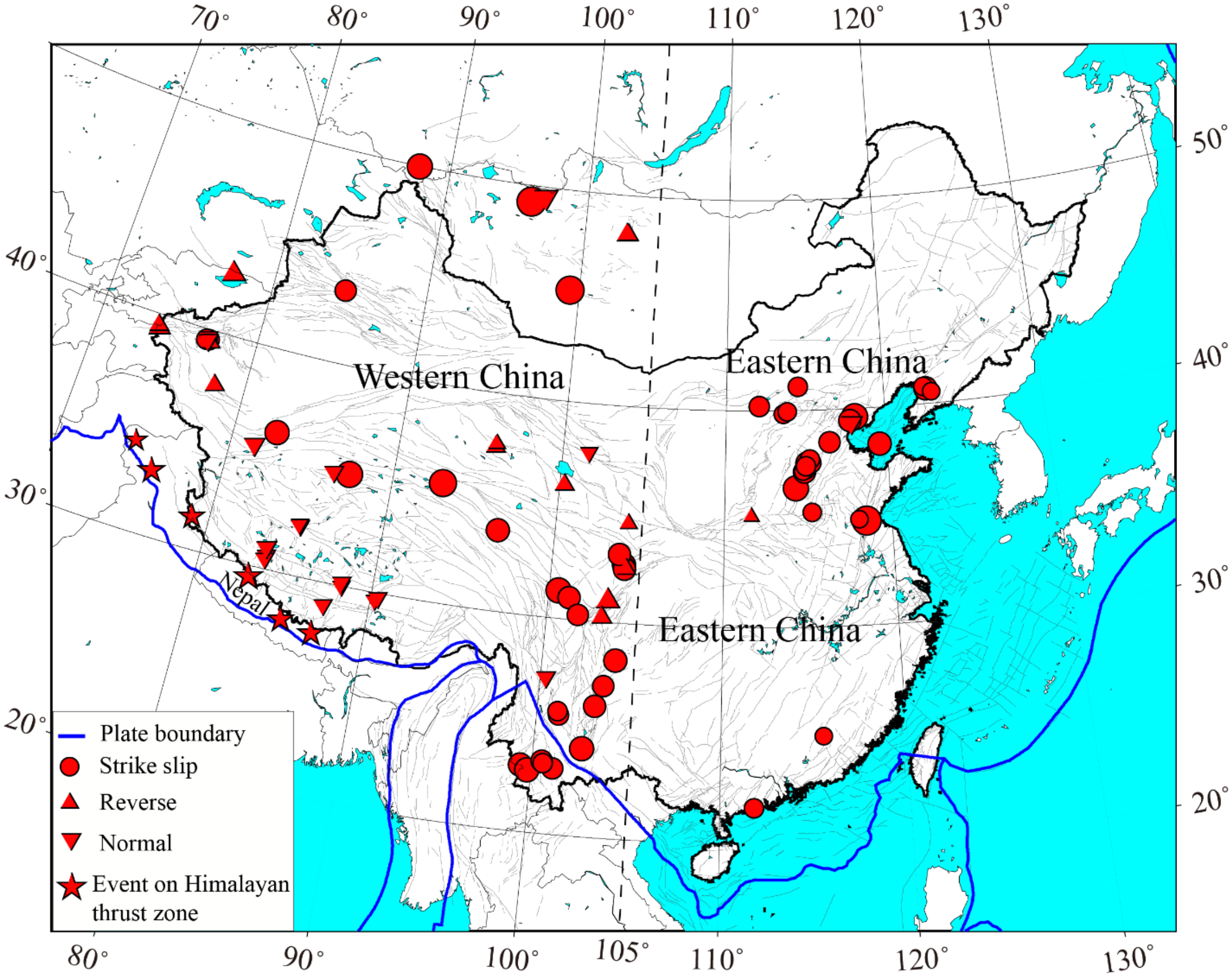


SRL provides a minimum estimate of RLD.

(Wells and Coppersmith, 1994)

Rupture Scaling for the earthquakes in China

Rupture parameters (intraplate environment)



We will use the RLDs and Mw data in mainland China to get the scaling relations.

Different methods for the source parameters

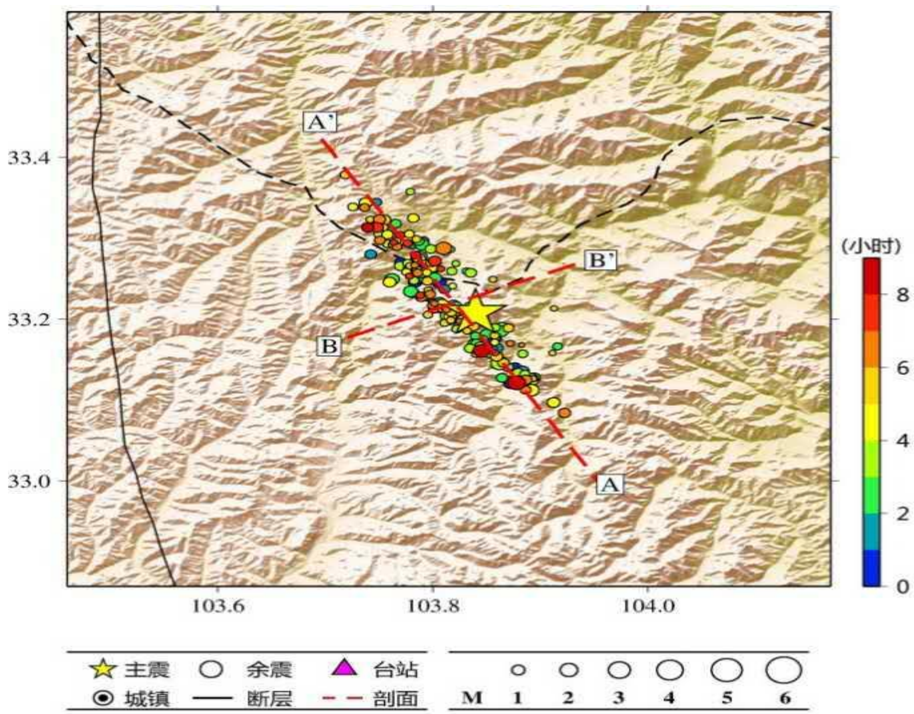
1. Aftershock relocation

2. Seismic data inversion

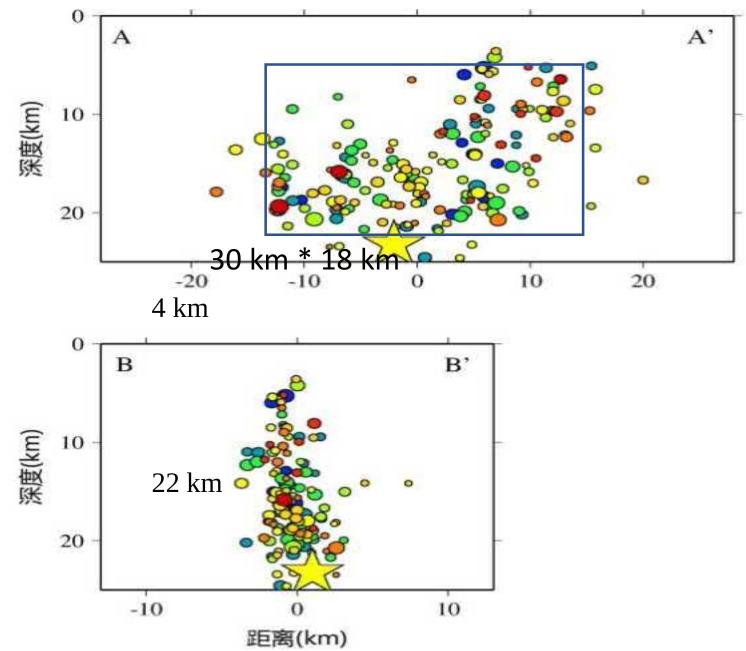
3. Geodetic data inversion

Aftershock Relocation

Mw6.5 Jiuzhaigou EQ in 2017



中国地震局地球物理研究所 房立华、王未来、杨婷提供



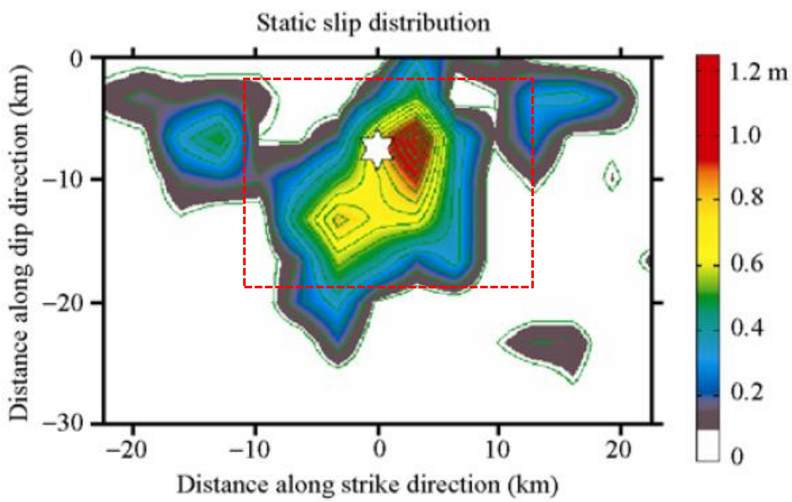
截止2017年08月09日06时59分，重定位后得到了196个余震的位置。余震主要呈北北西向分布，震源深度集中在6-26km。

Recommend by Wells and Coppersmith,1994

(Fang et al.,2017)

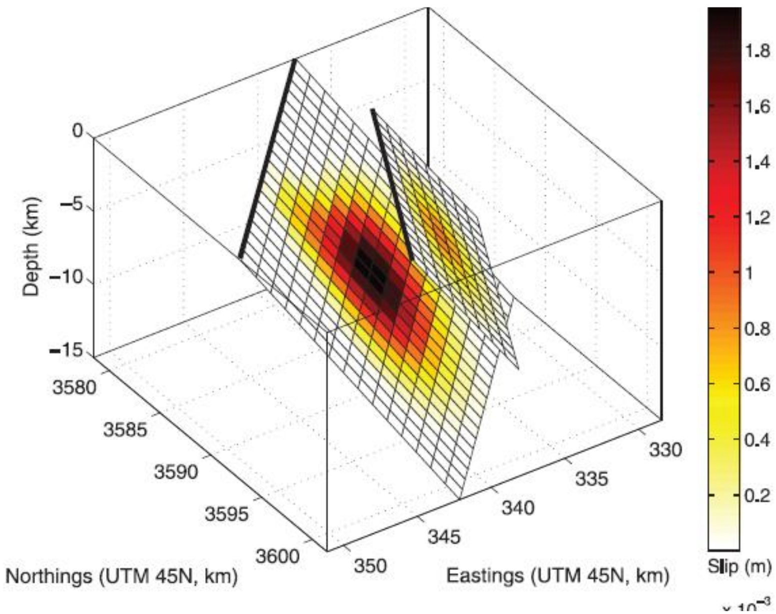
Rupture Scaling for the earthquakes in China

Teleseismic inversion



Ning’er earthquake in 2007 **Zhang et al.,2008**

Geodetic data inversion



Gerze earthquake in 2008 **Elliott et al.,2010**

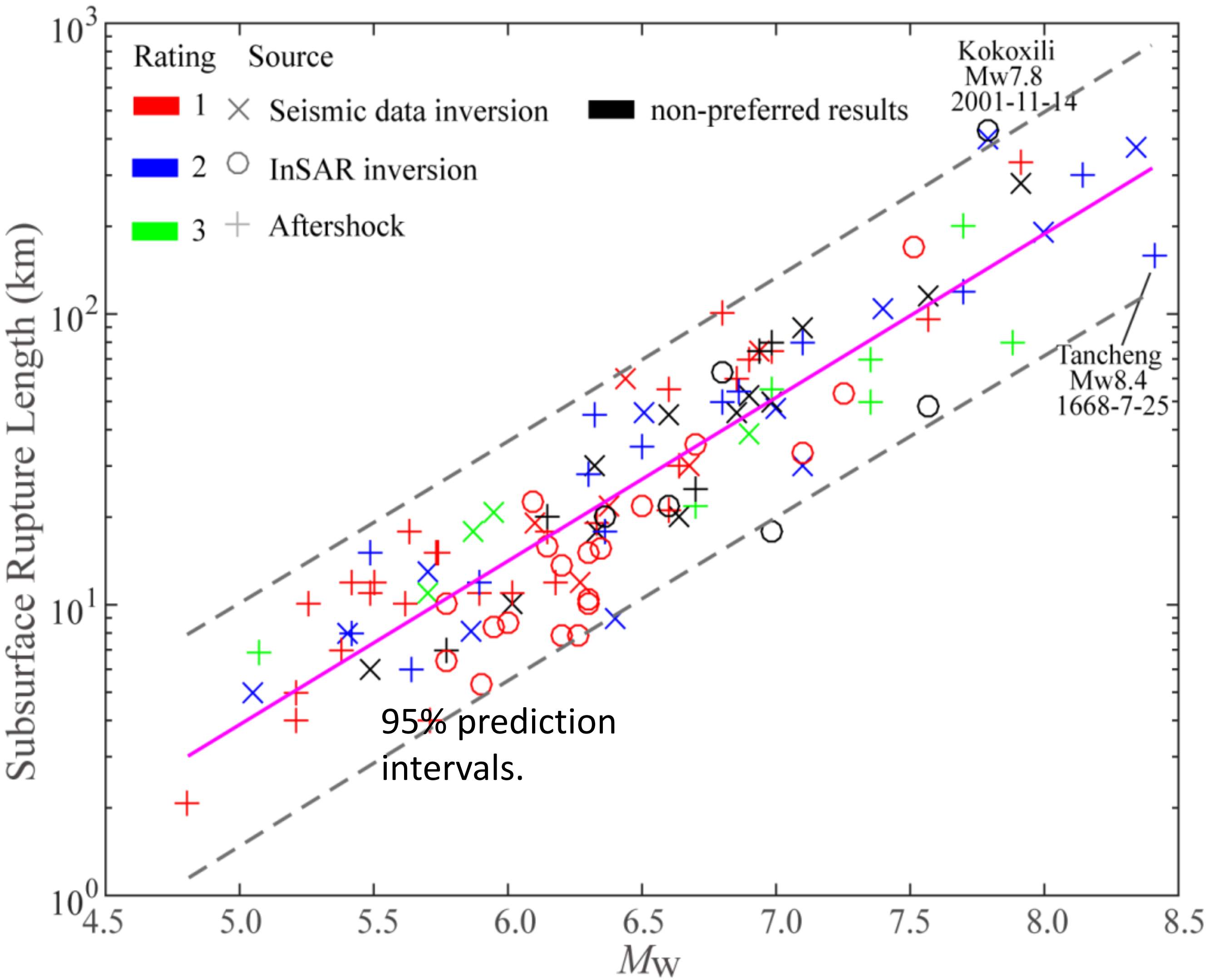
For some earthquakes, rupture lengths estimated from these methods **are much shorter than rupture lengths** measured from the distribution of aftershocks.

Estimates of subsurface rupture length based on geodetic modeling or source time functions are accepted for regression analysis **only when independent estimates of rupture length are available for corroboration.**

(Wells and Coppersmith, 1994)

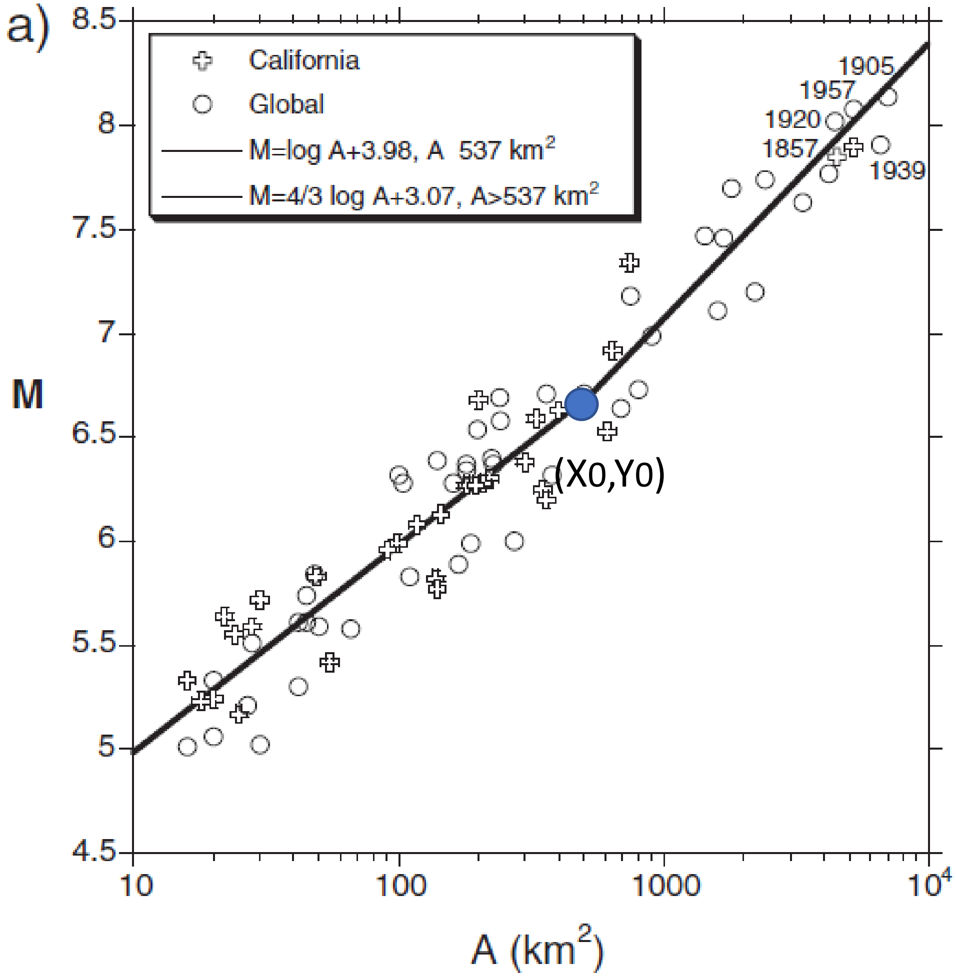
Rupture Scaling for the earthquakes in China

Comparison of different sources of the rupture length relative to M_W



The result shows that the source model from the three methods can be used together.

Bilinear regressions for strike slip earthquakes



Fault rupture is width limited by the seismogenic Depth.

$$\hat{\alpha} = \bar{y} - \hat{\beta}\bar{x}$$

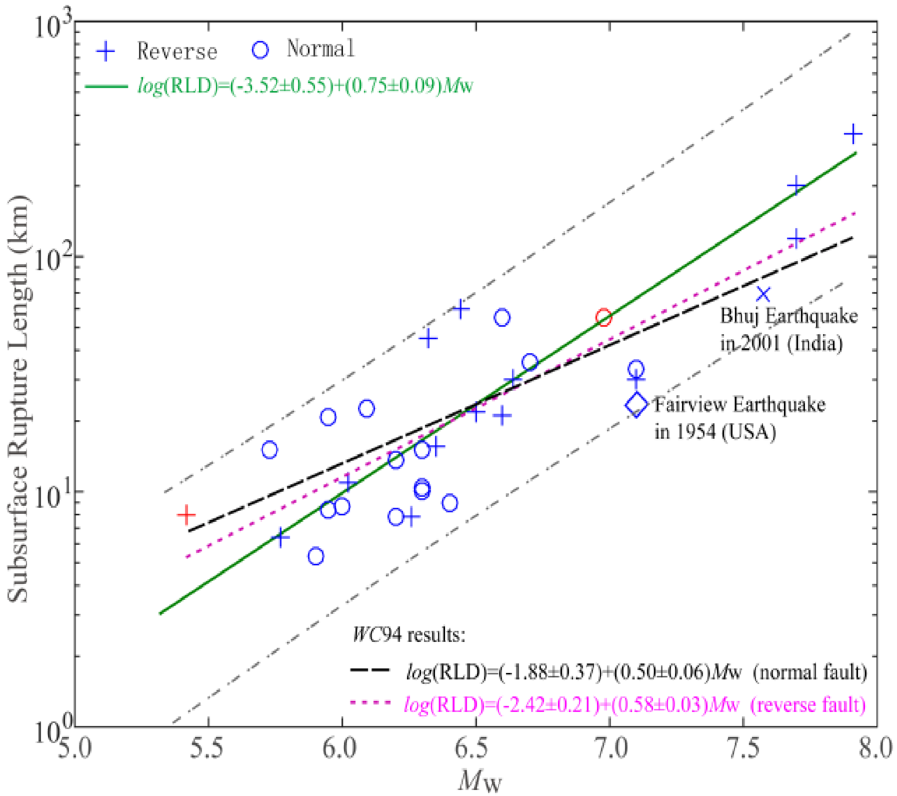
$$\begin{bmatrix} \hat{\alpha} \\ \hat{\beta} \\ \lambda \end{bmatrix} = \begin{bmatrix} 1 & \bar{x} & 1 \\ \bar{x} & \bar{x}^2 & x_0 \\ 1 & x_0 & 0 \end{bmatrix}^{-1} \begin{bmatrix} \bar{y} \\ \overline{xy} \\ y_0 \end{bmatrix}$$

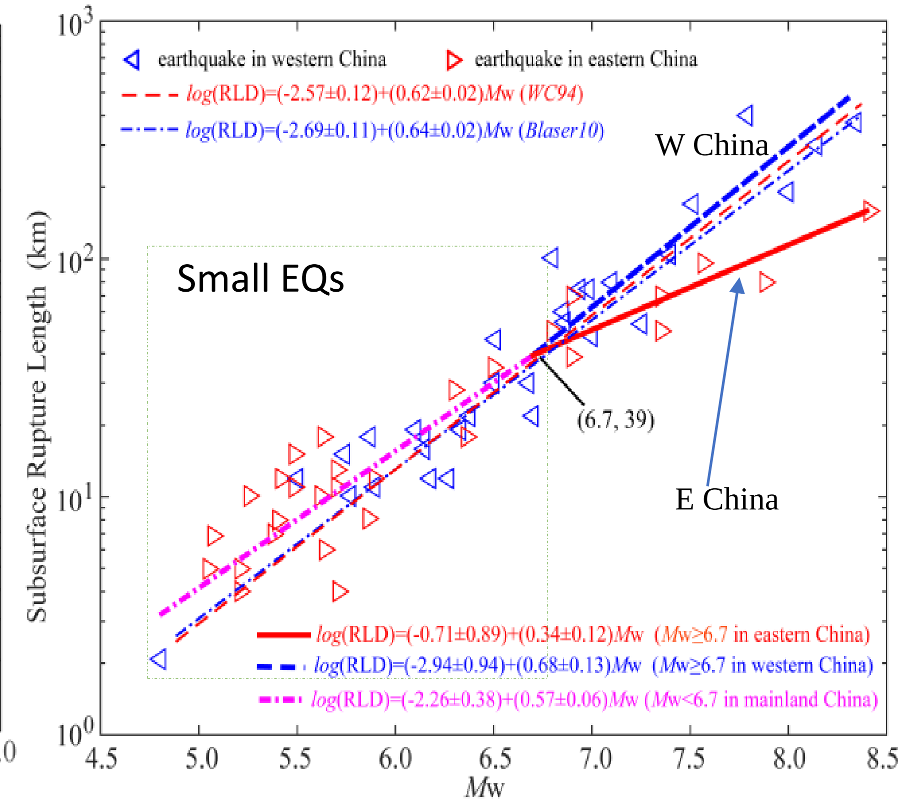
(x_0, y_0) is the constraining point.

Menke, 1989

We use *M*w6.7 as the divided point (Hanks and Bakun, 2002)

Regression relations of *RLD* with M_W for dip-slip and strike-slip earthquakes.





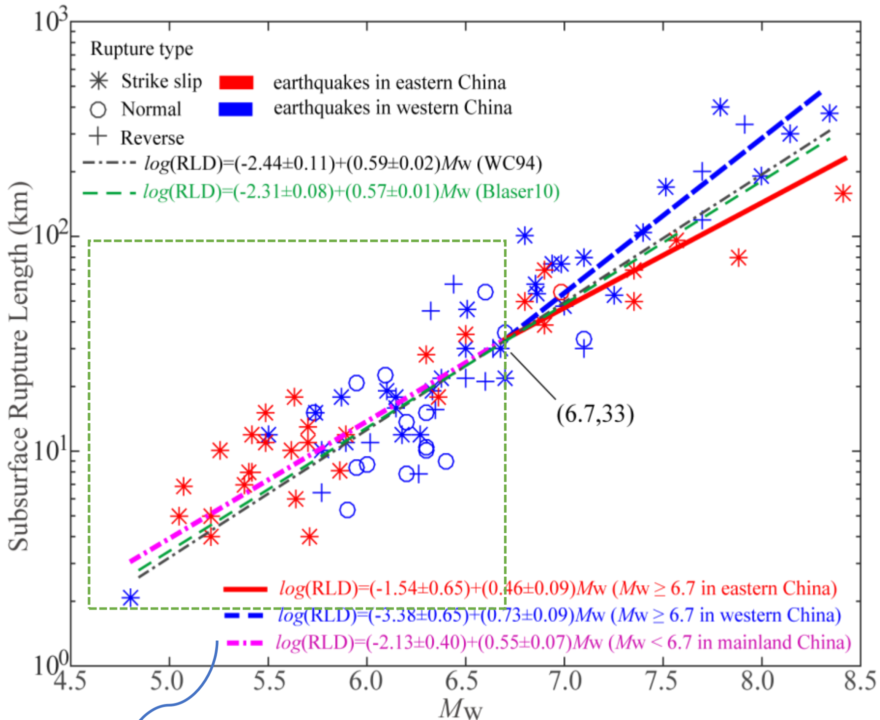
Data sample is relatively small.
Only two dip-slip events (Luanxian 7.1 in 1976 and Yuanqu 5.4 in 1965) in eastern China

F-tests show M_W≥6.7 strike-slip earthquakes in eastern China is much smaller than those from *WC94* and *Bls10*.

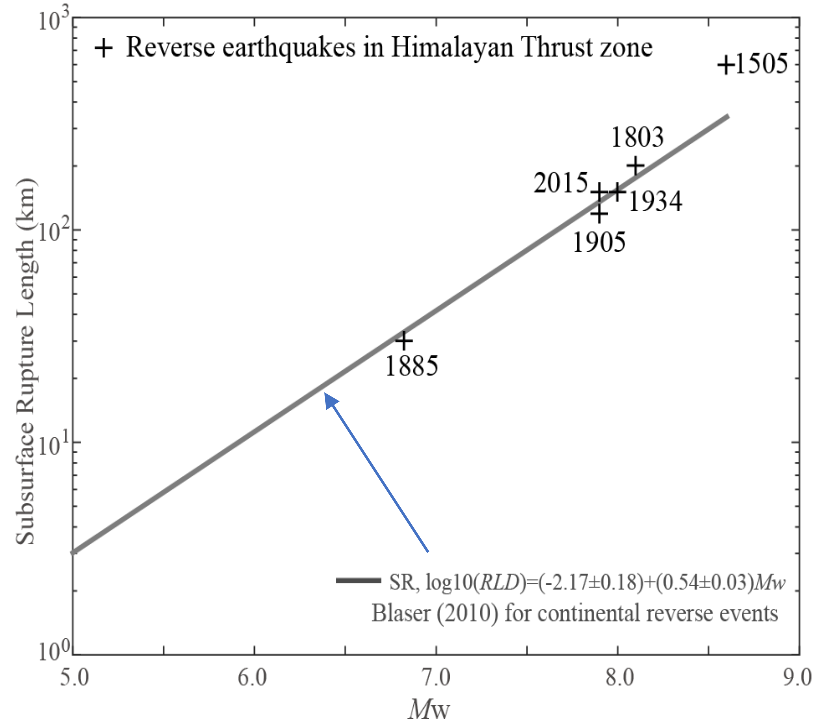
Rupture Scaling for the earthquakes in China

Regression relations of *RLD* with M_W for dip-slip and strike-slip earthquakes.

All types of earthquakes (intraplate EQs)



Earthquakes in Himalayan thrust zone (interplate EQs)



W China: $M_0 = 10^{15.98} \cdot RLD^{2.05}$

E China: $M_0 = 10^{14.10} \cdot RLD^{3.29}$

Small EQs $M_0 = 10^{14.92} \cdot RLD^{2.75}$

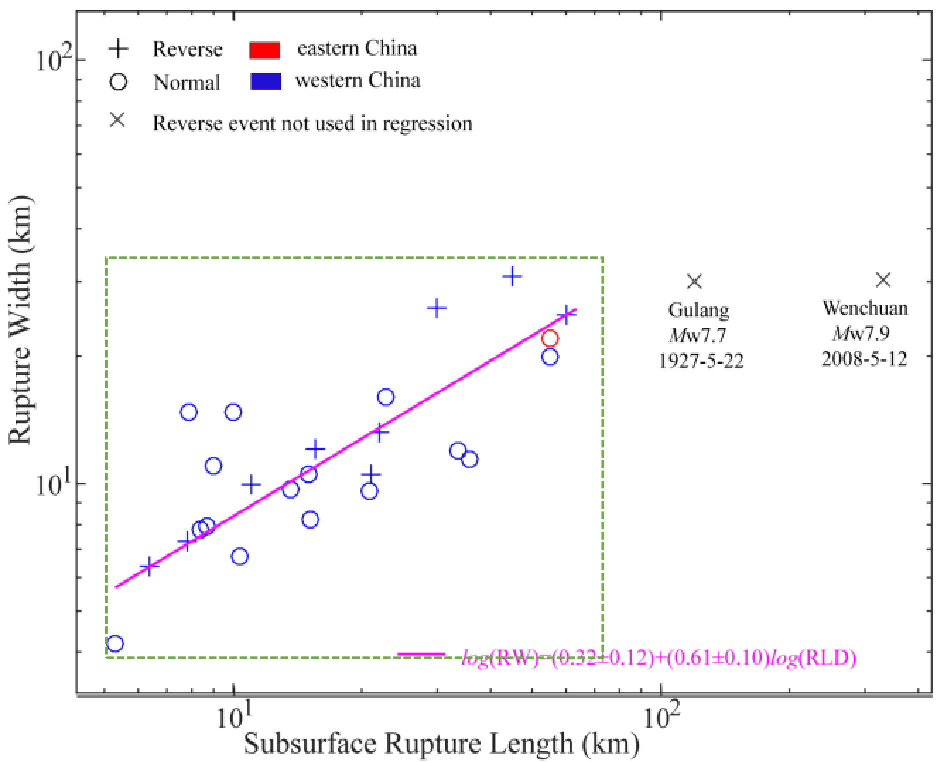
L model?

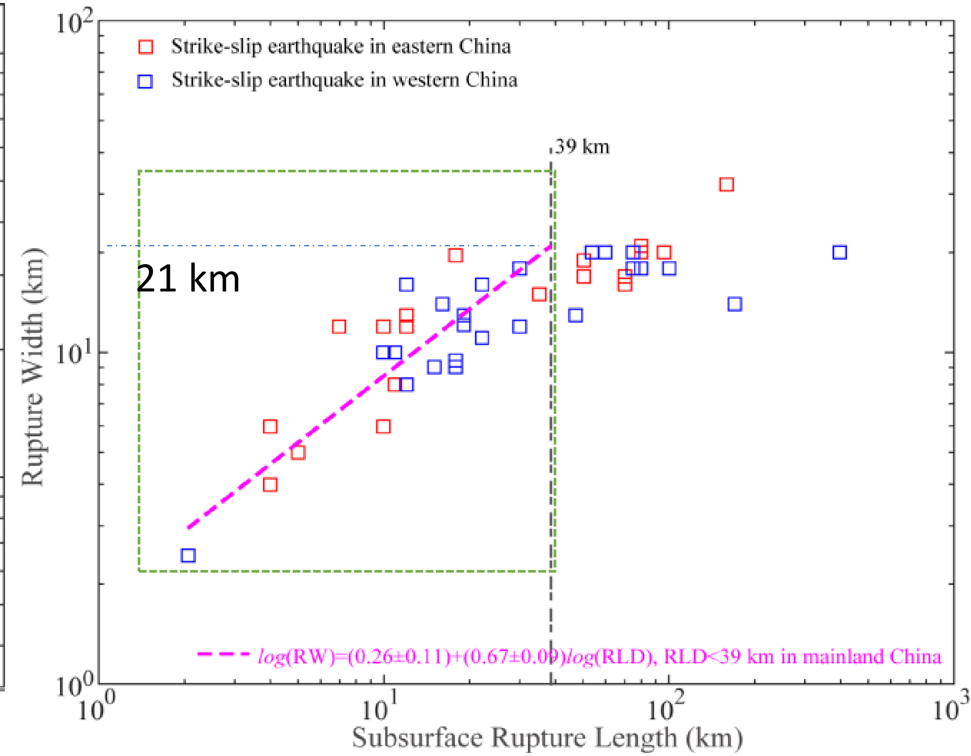
Self-similarity scaling ?

Only 2015 Gorkha earthquake from instrumental data inversion; Others are interpreted from the isoseismal maps

Rupture Scaling for the earthquakes in China

Regression relations of *RLD* with *RW* for dip-slip and strike-slip earthquakes.





Gulang EQ in 1927 and Wenchuan EQ in 2008 large obviously deviate from the line.

$$RW = 2.10 * RLD^{0.61}$$

$$RW = 1.83 * RLD^{0.67}$$

Different from the **Self-similarity scaling. But similar to the results of Leonard 201**

$W = C_1 L^{\beta}$,

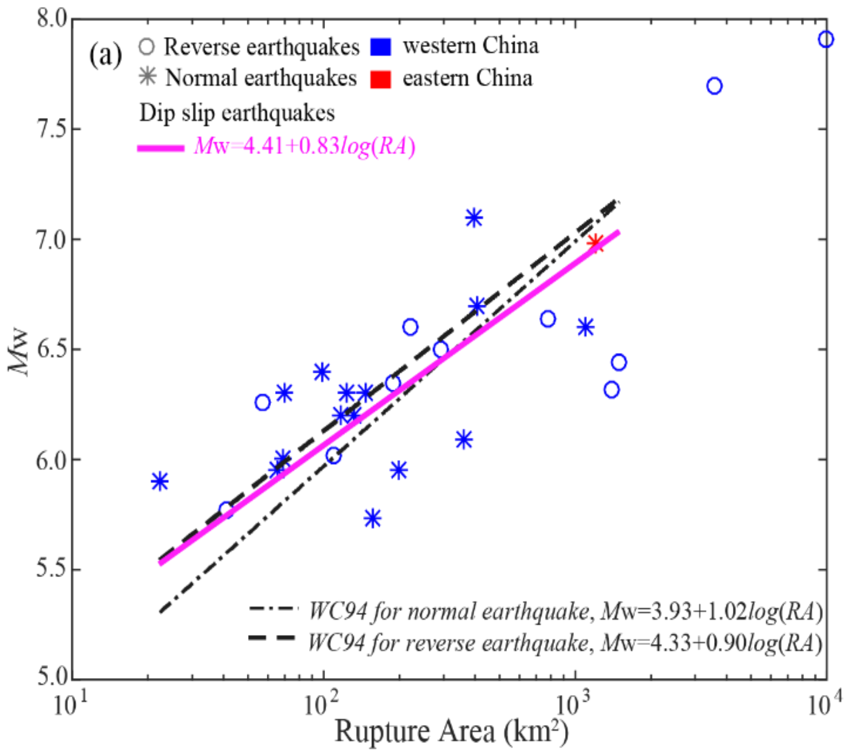
β=2/3

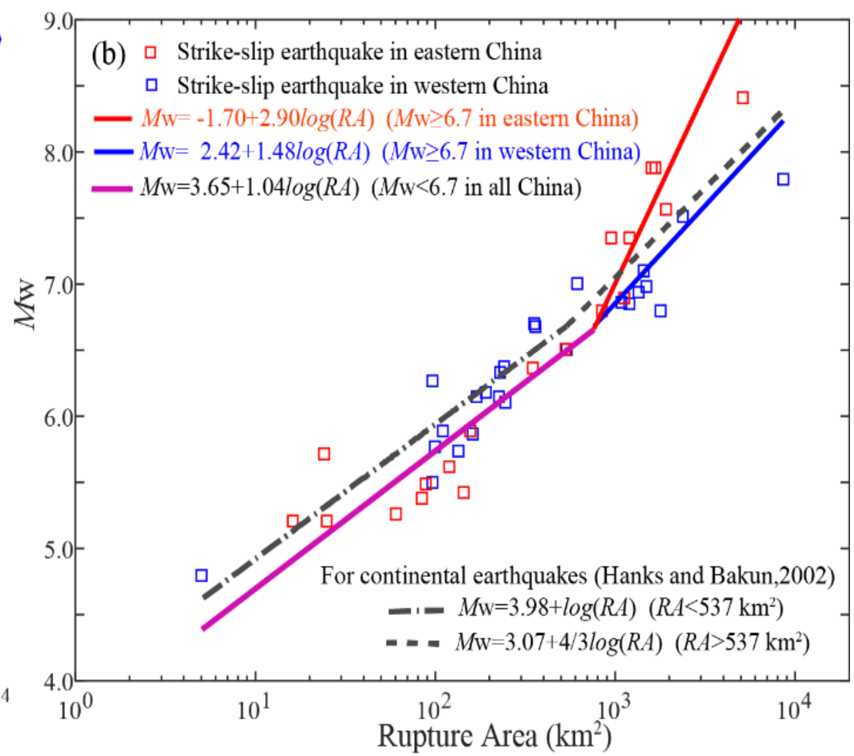
Rupture Scaling for the earthquakes in China

$W = C_1 L^{\beta}$, (beta=2/3)

Regression relations between *RA* and M_W

Dip-slip (with large error) | Strike-slip





Hanks and Bakun, 2002

Different from the L model

Small SS $\mathbf{M} = \log A + 2/3 \log \Delta\sigma - 10.958.$ **Self-similarity scaling**

$\mathbf{M} = 4/3 \log A + 3.03$ ($\bar{u} = \alpha L$) *L*-model

Cheng et al., 2020,SRL

Summary

We compiled rupture parameters for 91 earthquakes in and around mainland China, and we derived earthquake magnitude-rupture scaling relations using these data.

- **For western China, Mw~ RLD scaling relations are not statistically different from global results (WC94, and Blaser et al.,2010)**
- **For eastern China, large strike-slip earthquakes is smaller than those for western China.**

- **For RLD~RW, we obtained the relation of *RW* $\propto (RLD)^{2/3}$ for all types of earthquakes, similar to *Leonard* for all M_W > ~5 earthquakes.**
- **Our M_W-*RA* relations are close to those from *WC94* and *Hanks and Bakun* except for large strike-slip earthquakes in eastern China, where we have a different M_W-*RLD* relation from those based on global data.**

- **Our relations for dip-slip earthquakes are close to the *L*-model.**
- **For smaller strike-slip earthquakes, our relations are between the *L* and self-similarity models.**
- **Larger earthquakes in western China is consistent with the *L*-model,**
- **Larger earthquakes in eastern China is close to the self-similarity model.**

Rupture Scaling for the earthquakes in China

Earthquake scaling relations are also suitable for southeast Asia

Earthquake Rupture Scaling Relations for Mainland China

Jia Cheng*[1], Yufang Rong[2], Harold Magistrale[2], Guihua Chen[3], and Xiwei Xu[1]

Abstract

Magnitude-rupture scaling relations describe how the length, width, and area of fault rupture vary with earthquake magnitude. These parameters are required in seismic hazard models to fit the models' earthquakes onto faults and to define the site-rupture distances needed in ground-motion prediction equations. We collected the magnitude and rupture parameters of 91 earthquakes in Mainland China and nearby regions to study magnitude-rupture scaling relations. We find no systematic deviations for the subsurface rupture length (RLD) obtained from different methods versus earthquake magnitude. We performed regressions of RLD versus magnitude and versus rupture width using general orthogonal regression. Then, we derived the relations between rupture area and magnitude. Our relations are not statistically different from the results derived by others using global datasets, if the parameters of the five pre-1900 great earthquakes in eastern China are not used. However, if the five earthquakes are used, the magnitude-rupture length scaling relation for large strike-slip earthquakes in eastern China gives shorter rupture lengths than earthquakes in western China and other plate boundary regions in the world.

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Supplemental Material

Introduction

Scaling relations associate earthquake size (magnitude M_w or scalar moment M_0) with fault rupture parameters. Fault rupture parameters include surface rupture length (SRL), subsurface rupture length (RLD), rupture width (RW), rupture area (RA), and average slip ($\bar{D}$). In the past decades, many versions of earthquake magnitude-rupture scaling regression relations have been developed for regional or global seismic hazard analysis (e.g., Hanks and Bakun, 2002; Wesnousky and King, 2007; Leonard, 2010; Stirling *et al.*, 2013; Konstantinou, 2014). Most of these studies have included at least some large earthquakes occurring in Mainland China (e.g., Wells and Coppersmith, 1994; Manighetti *et al.*, 2007). The most widely used scaling relations were empirically developed by Wells and Coppersmith (1994; hereafter, WC94). However, the relationships of WC94 did not distinguish intraplate and plate boundary events. Leonard (2010, 2014) developed a set of self-consistent scaling relations between M_0, RA, RLD, RW, and $\bar{D}$. Hanks and Bakun (2002; hereafter, HB02) used a bilinear source scaling model to interpret the relations between M_w and RA. For earthquakes with $M_w \le 6.63$, they assumed an average $\Delta\sigma$ of 2.67 MPa. For larger events, they used *L*-model scaling. Blaser *et al.* (2010; hereafter, Bls10) found that the scaling relations differ for different slip types, and the continental and subduction zone thrusts have the same scaling. Thingbaijam *et al.* (2017) derived a set of earthquake rupture scaling relations using general orthogonal regression (GOR) and the database of finite-fault earthquake rupture models (Mai and Thingbaijam, 2014). They found that RLD and $\bar{D}$ are correlated. Dowrick and Rhoades (2004) discussed the regional variation of the relations. They concluded that the regression results from New Zealand data are significantly different from those from California, China, and Japan. The small number of events from China included in their study did not show a different trend from the events of Japan and California. Here, we address the regionalization issue by comparing our results from earthquakes in China and vicinity with those from global earthquakes (e.g., Wells and Coppersmith, 1994).

Faulting in China is caused primarily by the collision of the Indian and Eurasian tectonic plates. The collision caused the uplift and crustal thickening of the Tibetan plateau and high-intraplate deformation in much of Mainland China. Western China is more tectonically active than eastern China and can be described as a diffuse plate boundary. North China block is the most active region in eastern China and is one of the most active intraplate seismic regions in the world (Liu *et al.*, 2007). Many regression scaling relations have been developed for different regions within China. Some of the studies used SRL measured during fieldwork (e.g., Deng *et al.*, 1992; Ran, 2011), and some used aftershock or other seismic data to infer rupture parameters (e.g., Long *et al.*, 2006). Most of the relations were

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An Assessment of Earthquake Scaling Relationships for Crustal Earthquakes in Indonesia

Endra Gunawan*[1,2]

of dip-slip earthquake events
2011, (e) L2014, (f) T2017,
ling relationship for dip-slip
iagnitude for normal faults,
uncertainty of each model.
able 1, in which triangles

Conclusion

I have investigated previously published earthquake scaling relationships applied to crustal earthquake cases in Indonesia. I found that for strike-slip and dip-slip faulting regime, the scaling relationship proposed by Cheng *et al.* (2020) generates smaller misfit than the other scaling relationships considered. For dip-slip faulting regimes, one could use the all dip-slip relationships by Cheng *et al.* (2020) to avoid miscalculation of earthquake magnitude because it is applicable to dip-slip faulting regime in general. Preferably, one may use different scaling relationships for the possible faulting styles on a logic tree with appropriate weights. The recommended weight for strike-slip faulting regime is 0.11 for Wells and Coppersmith (1994) and Wesnousky (2008), 0.12 for Yen and Ma (2011) and Brengman *et al.* (2019), 0.13 for Mai and Beroza (2000) and Leonard (2014), and 0.14 for and Thingbaijam *et al.* (2017) and Cheng *et al.* (2020). Whereas for the dip-slip faulting system in Indonesia, one could weigh the scaling relationship of 0.11 for Wesnousky (2008); 0.12 for Yen and Ma (2011), Thingbaijam *et al.* (2017), and Brengman *et al.* (2019); 0.13 for Wells and Coppersmith (1994), Mai and Beroza (2000), and Leonard (2014); and 0.14 for Cheng *et al.* (2020).

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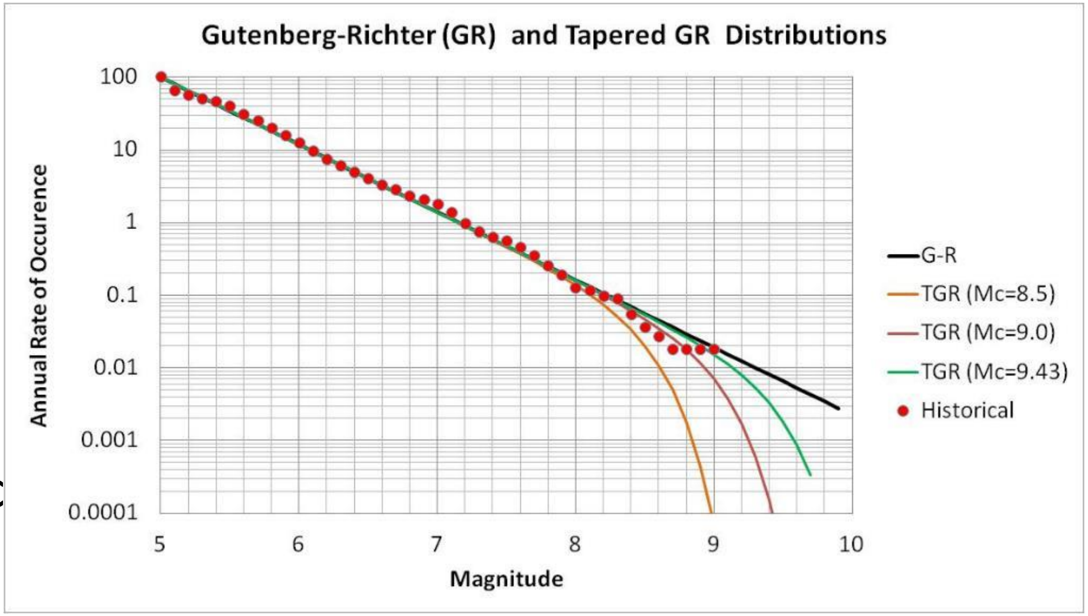
A new method for modeling earthquake rate and distribution

- Traditional method
  - Identify area source zones and faults
  - Model earthquake rates for each of them
  - The total rate will be the sum of them
- Drawbacks
  - Assume the rates are uniformly distributed within each source zone
  - Faults are not complete and earthquake recurrence rates on fault are very uncertain, thus the total rate can be very off at large magnitudes
  - Strain rate data are not explicitly used

- New method
  - Delineate large source zones
  - Model earthquake rates using historical earthquakes and constrained by strain rate
  - Distribute the total rates to known faults and area sources
- Values
  - Honor the knowledge of known faults
  - Earthquake rates do not need to be uniformly distributed
  - Strain rate data provide moment budget
  - Capture the possible large earthquakes that may be missed by using the traditional method

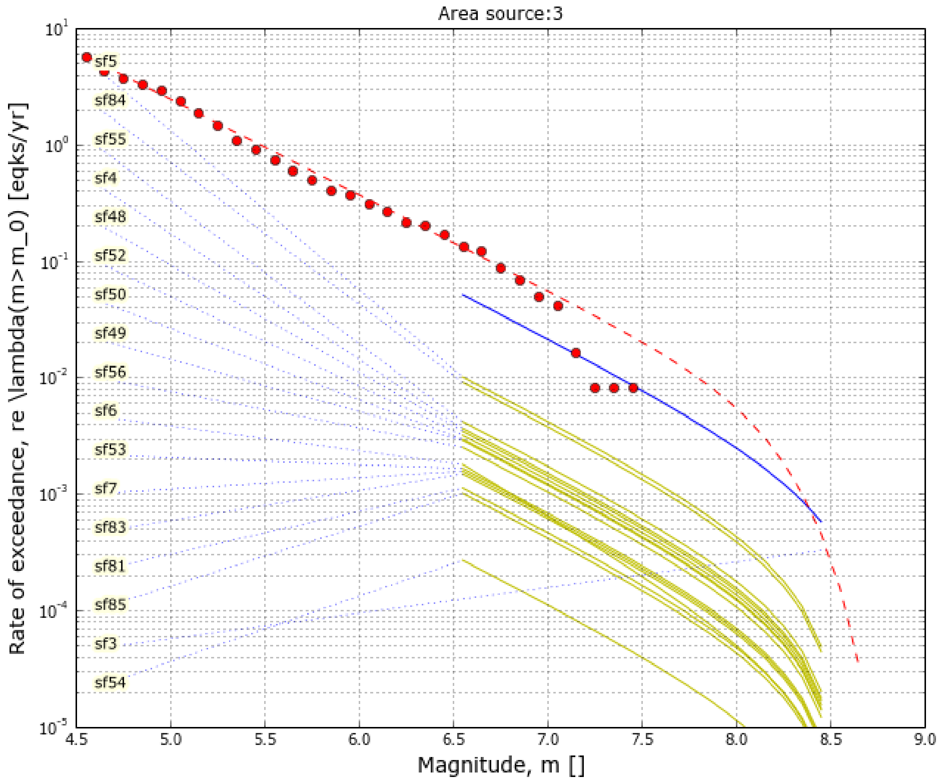
Modeling total seismicity rates for a zone

- Use Tapered Gutenberg-Richter (TGR) to model seismicity rate
- Derive TGR a- and b-values from historical catalogs
- Constrain TGR corner magnitude (m_c) using seismic moment rate from strain



Yufang Rong et al., 2020, EQ spectra

Example of distributing earthquake rates to area source and faults

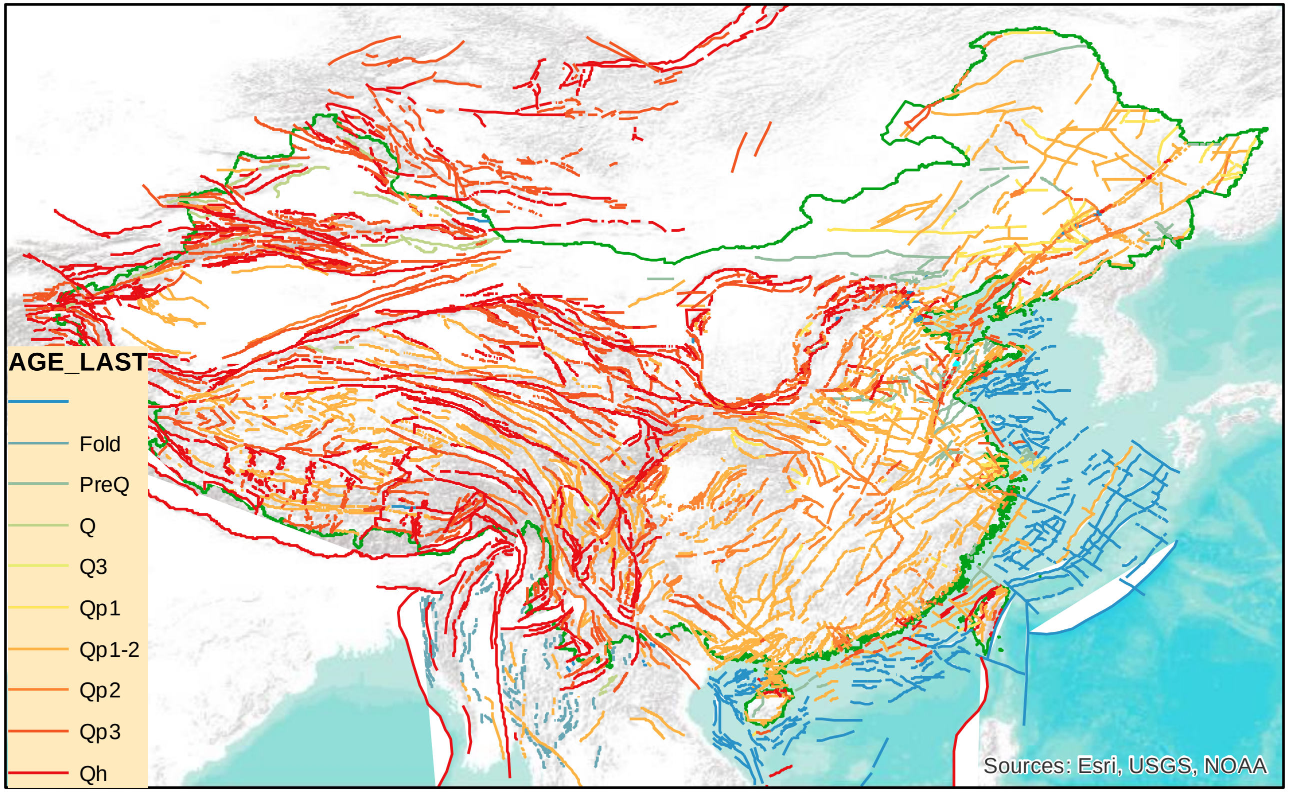


- Developing the software tool with GEM
- Figure legend:
  - Red dashed line: total modeled earthquake rates for the zone
  - Red dots: historical rates
  - Lime: earthquake rates on each of the faults
  - Blue: sum rates on faults
  - Rate distributed to area source: red dashed line minus blue

Yufang Rong et al., 2020, EQ spectra

Seismic hazard analysis for mainland China

Compile active faults, collect parameters, and simplify fault traces

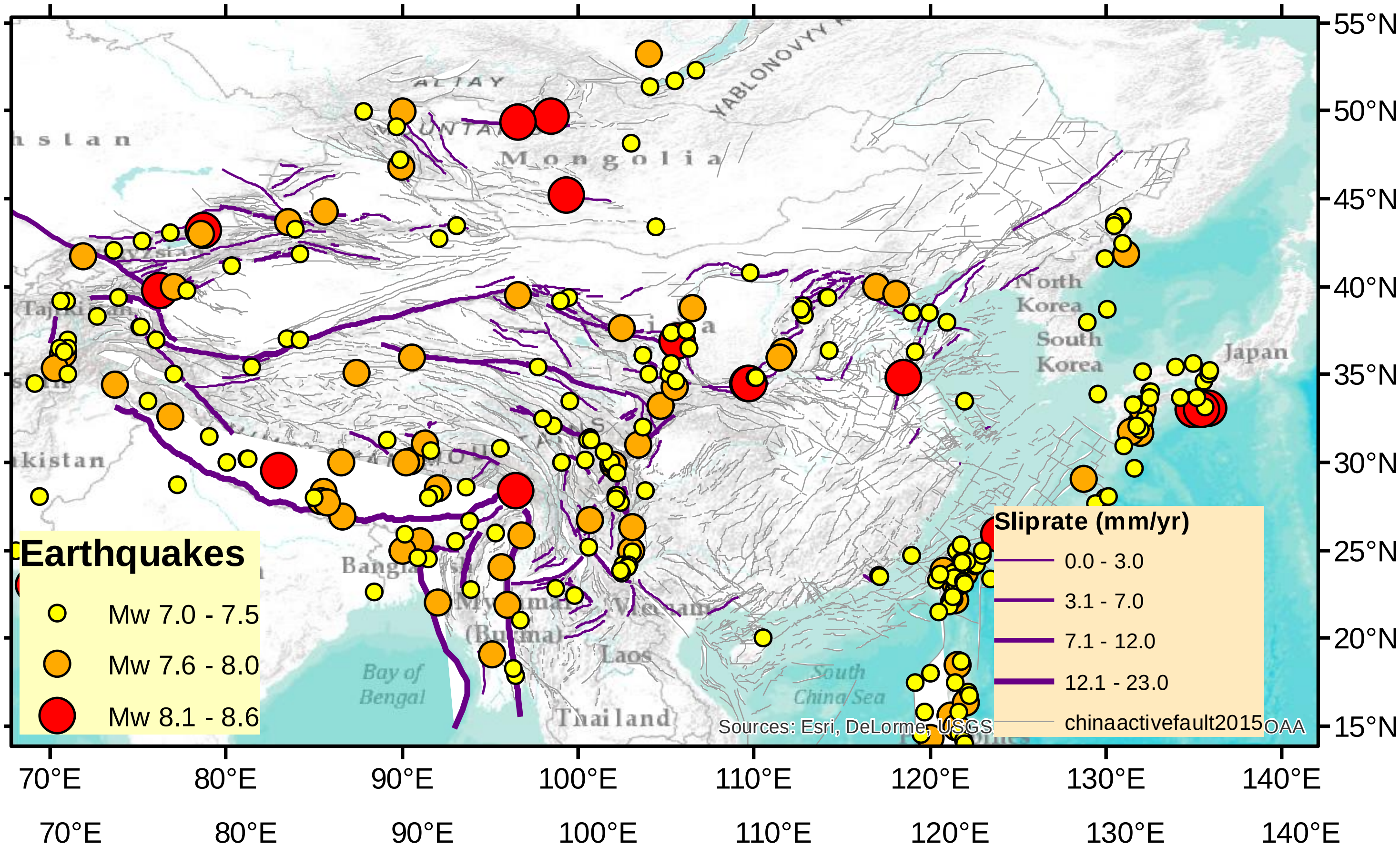


- Original fault data from Prof. Xu of CEA
- About 6000 mapped fault traces
- Need to simplify them and collect slip rates, fault types, dipping angles etc. for earthquake modeling
- Slip rates and other parameters are collected from:
  - ~1000 published papers
  - An unpublished book by Prof. Xu et al. (1000+ pages)

Xu et al., 2016， http://www.activefault-datacenter.cn/

Seismic hazard analysis for mainland China

Active faults: simplify fault traces and collect slip rates

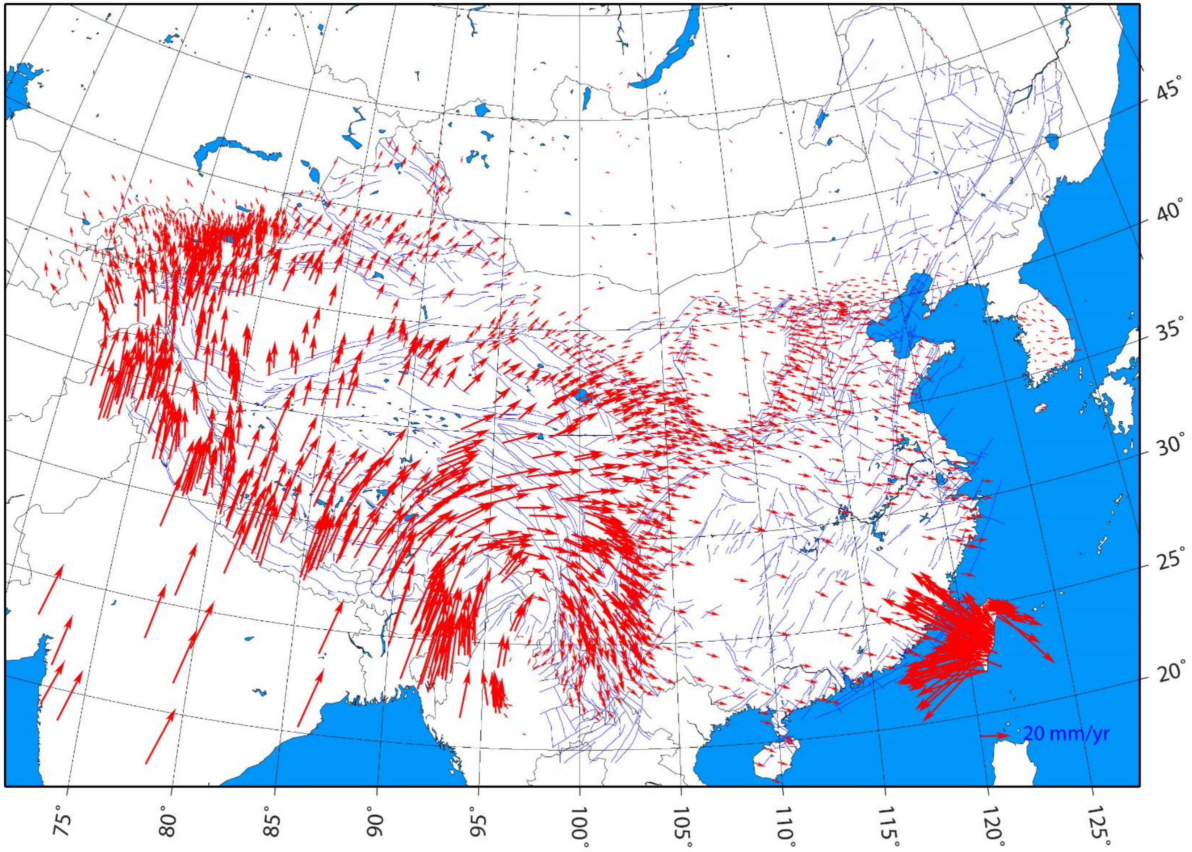


~300 faults with slip rates

Construct strain rate map

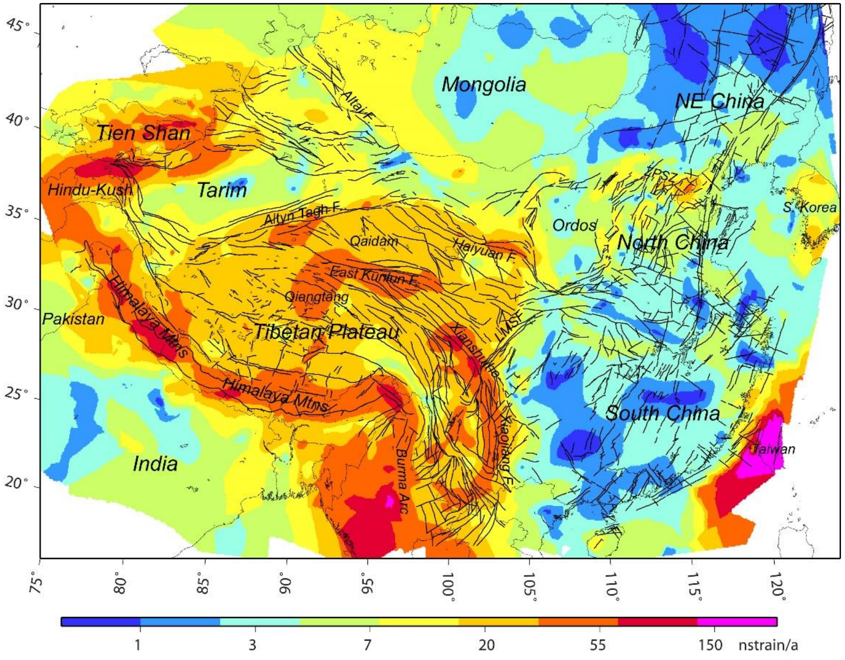
Composition of GPS Velocity Field

- Data sources:
  - Mainland China: CMONOC Phase I + Parts of Phase II data
  - Surrounding regions: compiled from literature
- Solutions are rotated to a common reference frame.
- Data are screened; outliers and redundant sites are removed.
- Total number of stations used: 1898.

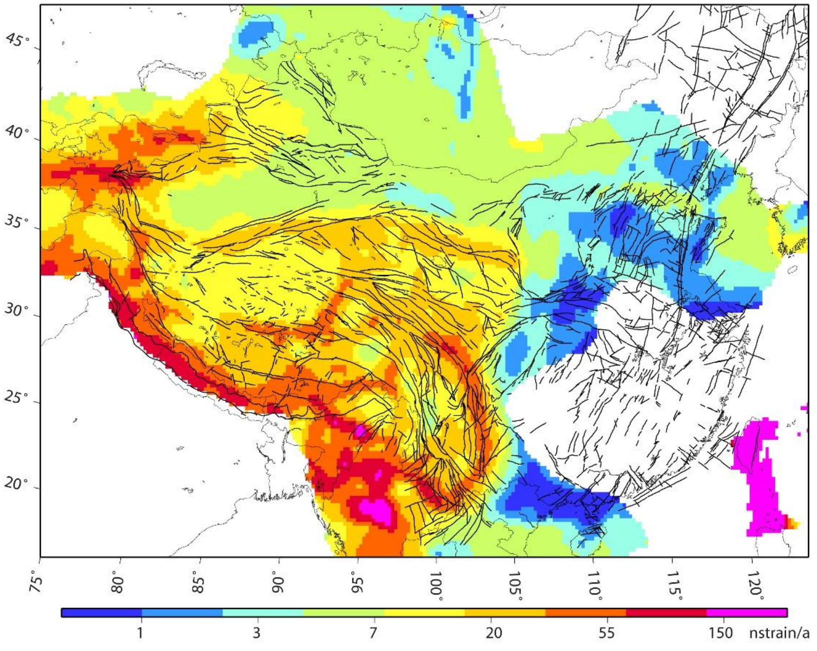


Wang and Shen, 2020

Strain rates derived from GPS velocities



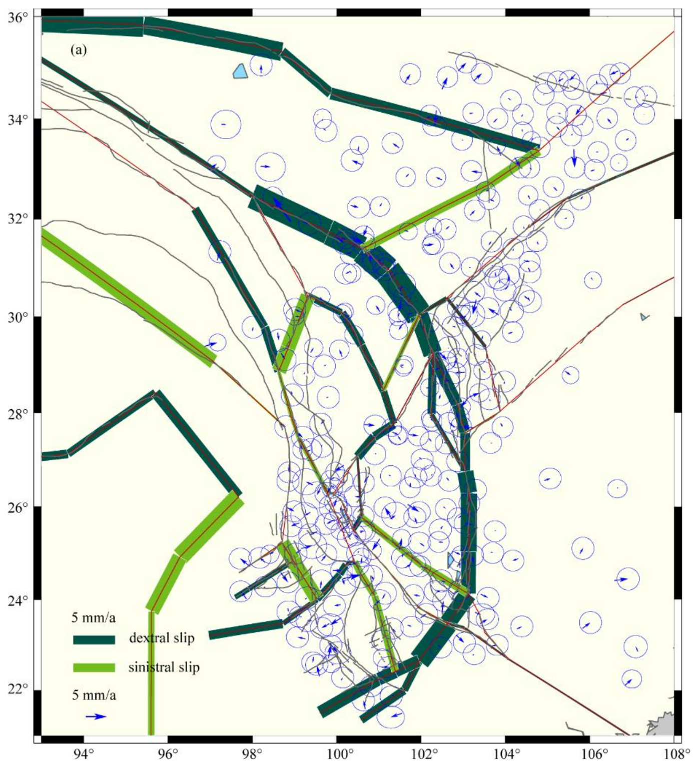
Z. Shen for this project



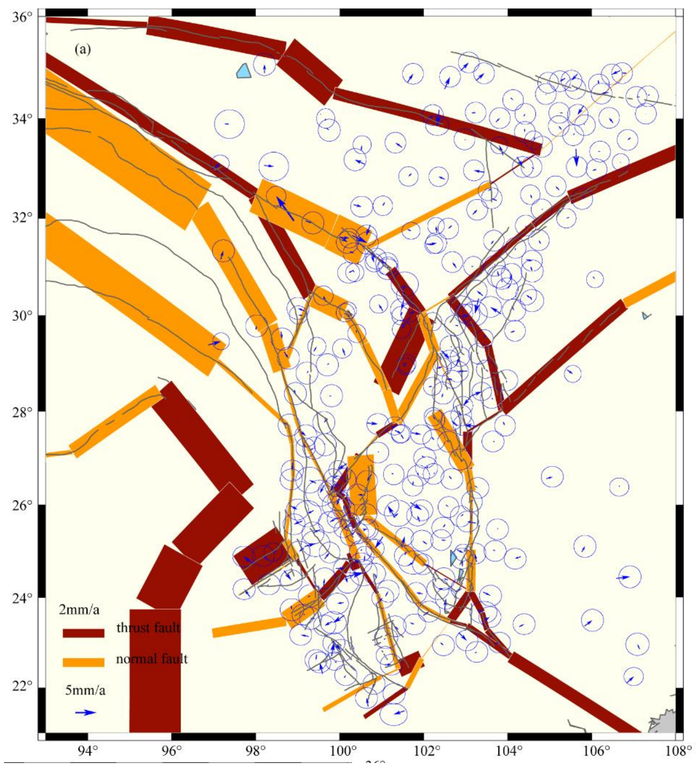
Global Strain Rate Model from GEM

Wang and Shen, 2020

Constrain fault slip rates using geodetic data



Strike slip

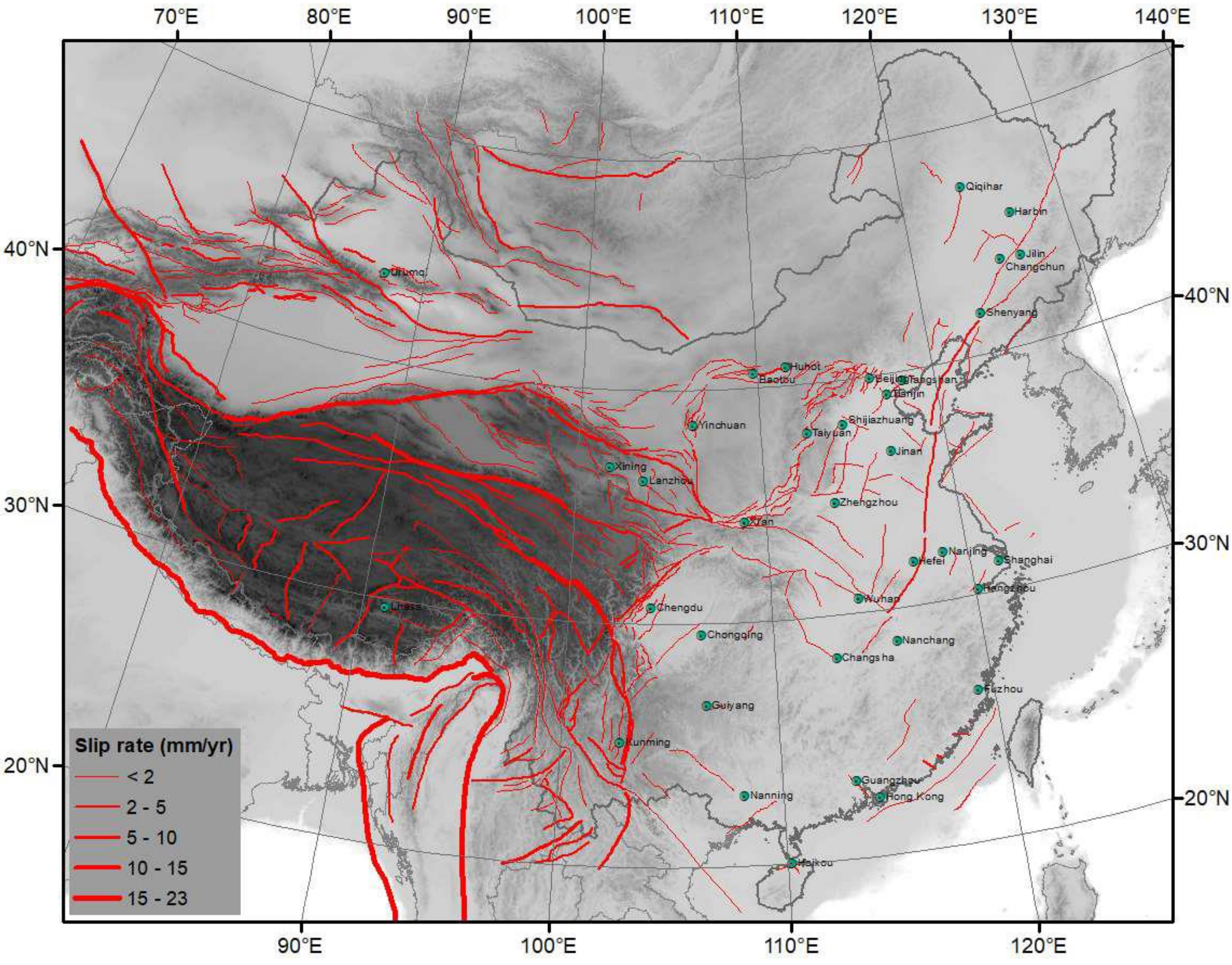


Compression/extension

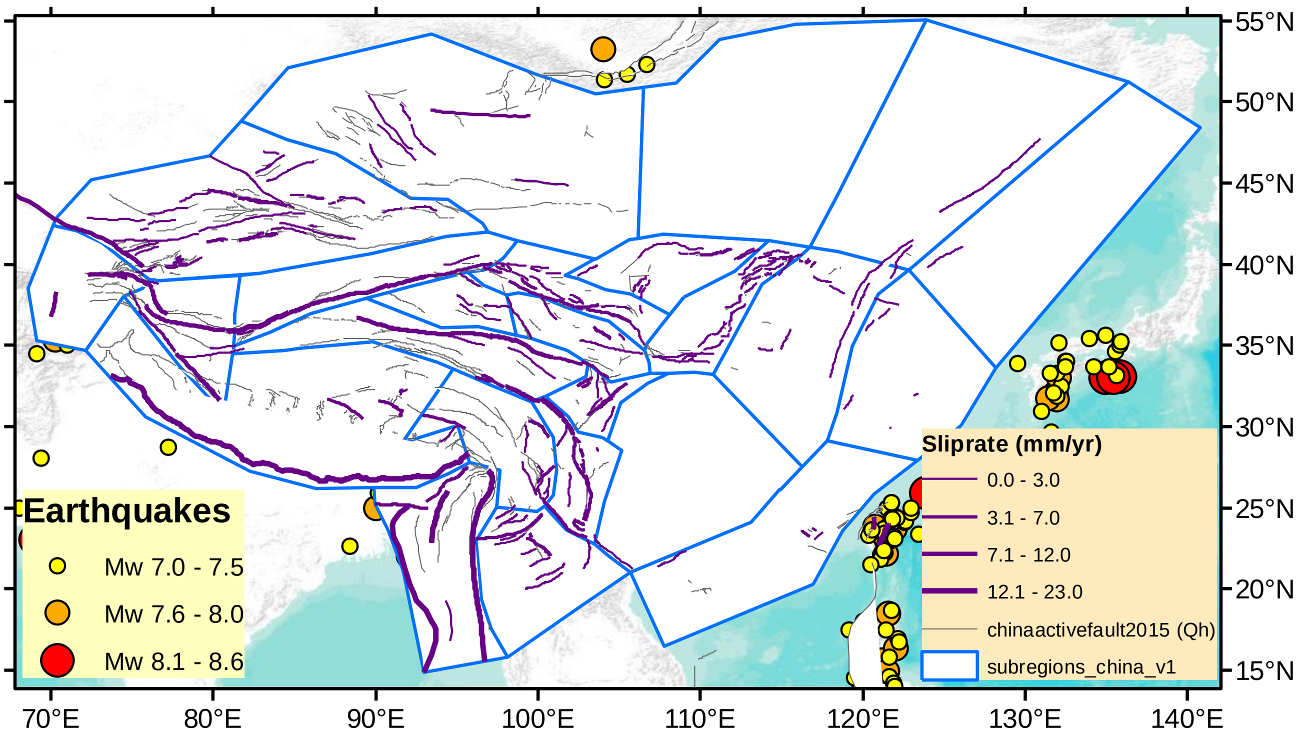
(Wang et al., Sci. China, 2008; Wang et al. JAES, 2015)

Seismic hazard analysis for mainland China

Slips rate from geological and geodetic data

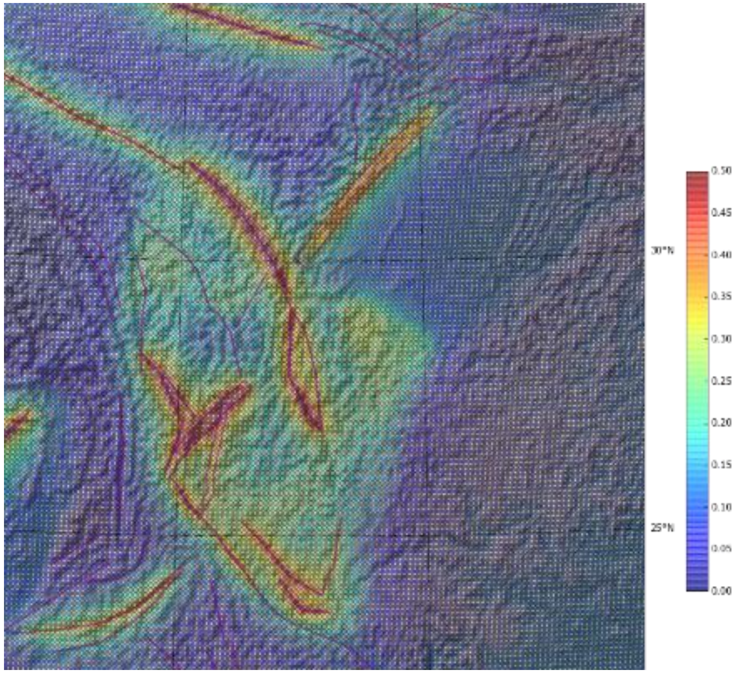


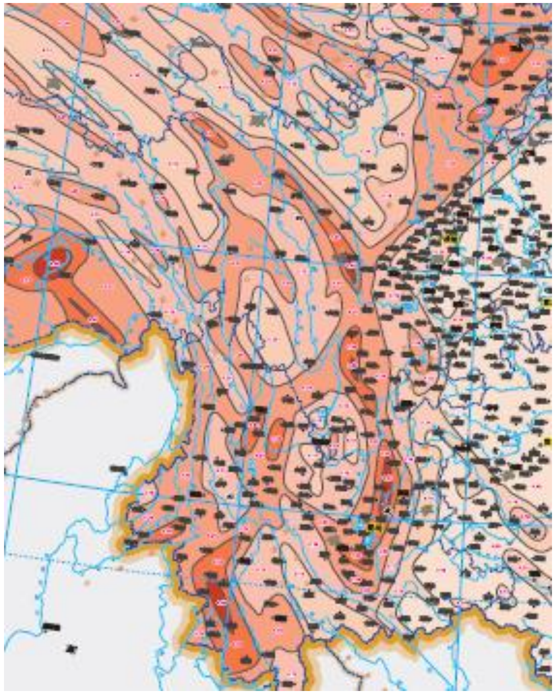
Delineate seismic source zones



- Each source zone capture similar tectonics;
- Zones are delineated based on seismotectonics, geological faults, and historical earthquakes;
- Earthquake magnitude-frequency distributions will be modeled for each zone

10. Calculate seismic hazard and create maps



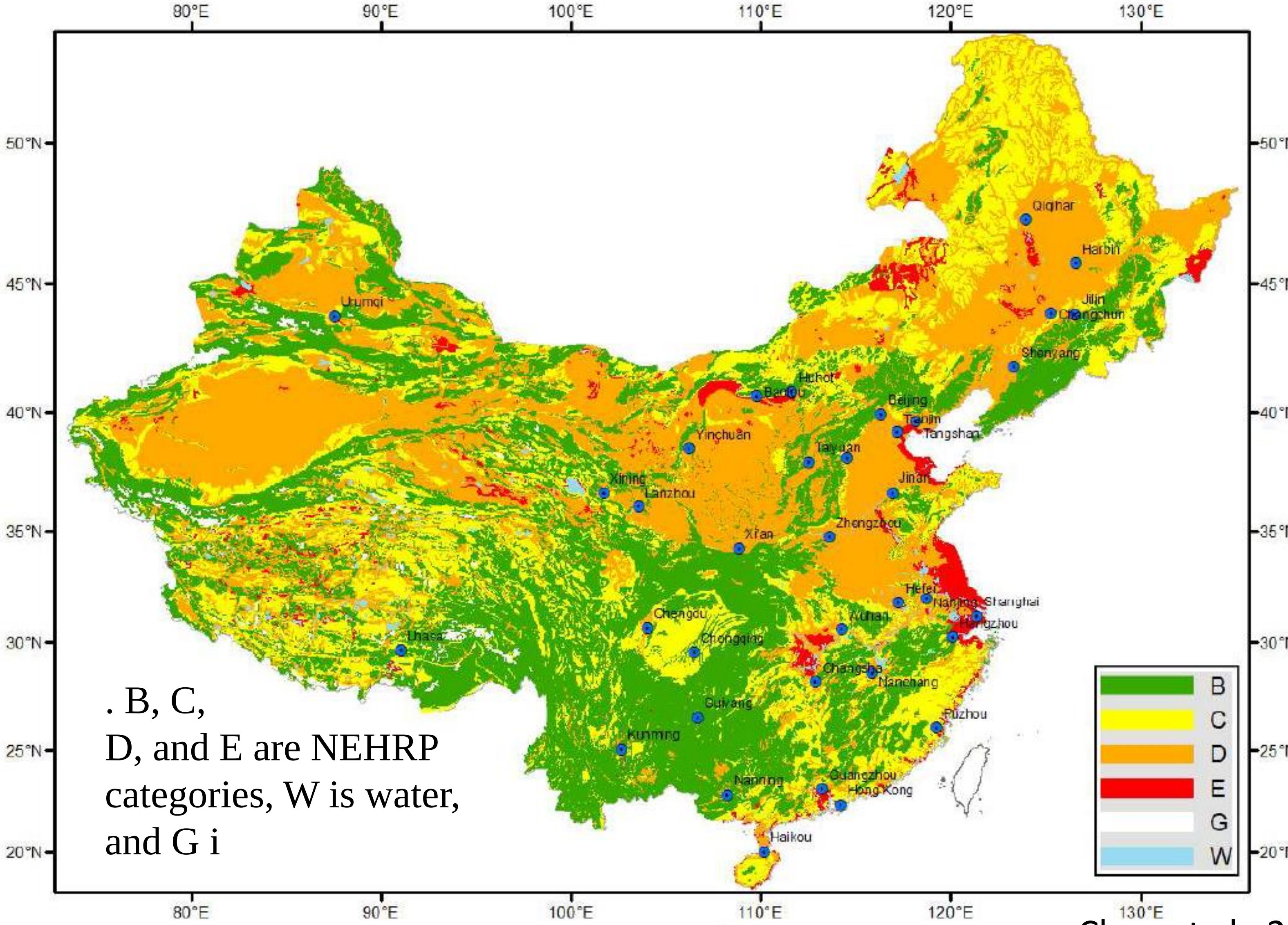


- Example 500-year PGA calculated using OpenQuake and test data (not complete)
- Results are promising!

Yufang Rong et al., 2020, EQ spectra

Seismic hazard analysis for mainland China

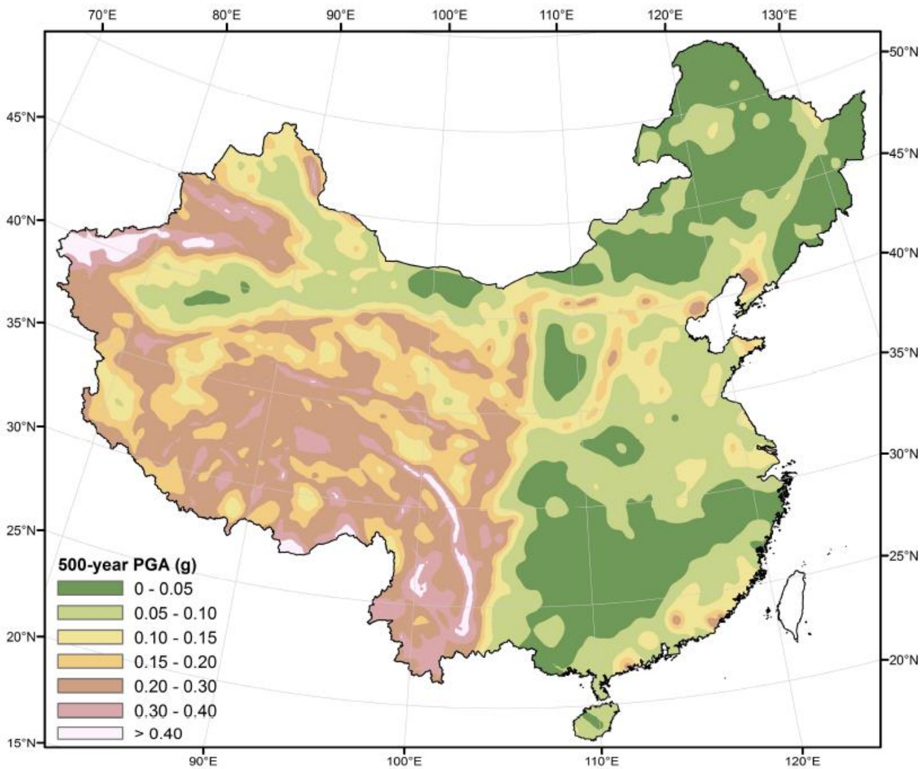
Seismic site condition map
(the bedrock geology database and the Quaternary map)

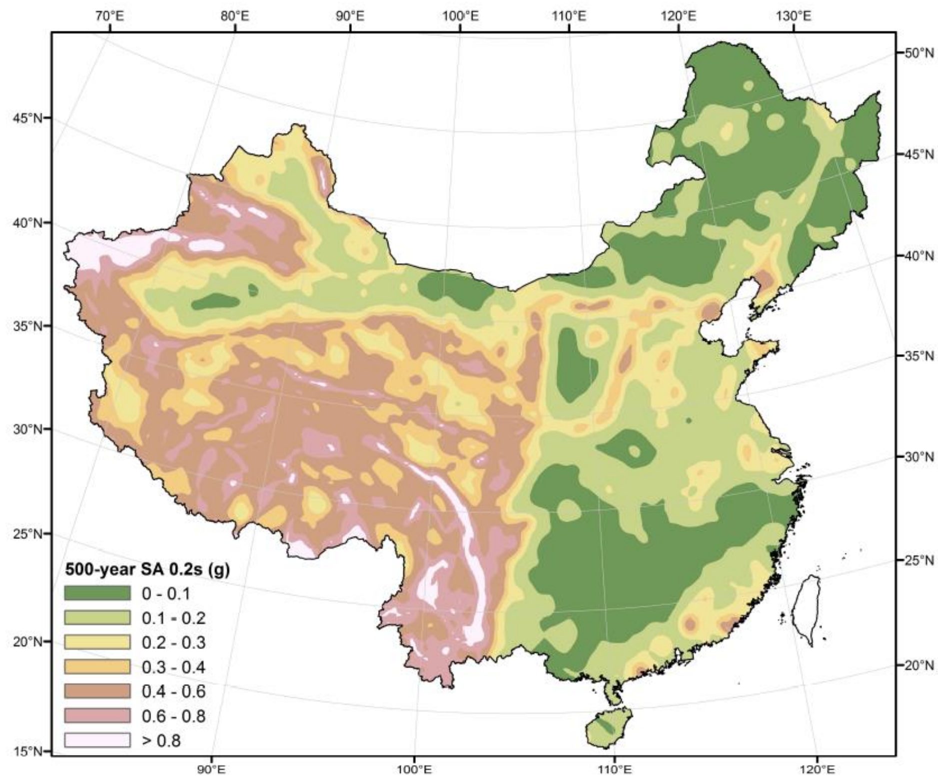


. B, C,
D, and E are NEHRP
categories, W is water,
and G i

Chen et al., 2021, SRL

Seismic hazard analysis for mainland China





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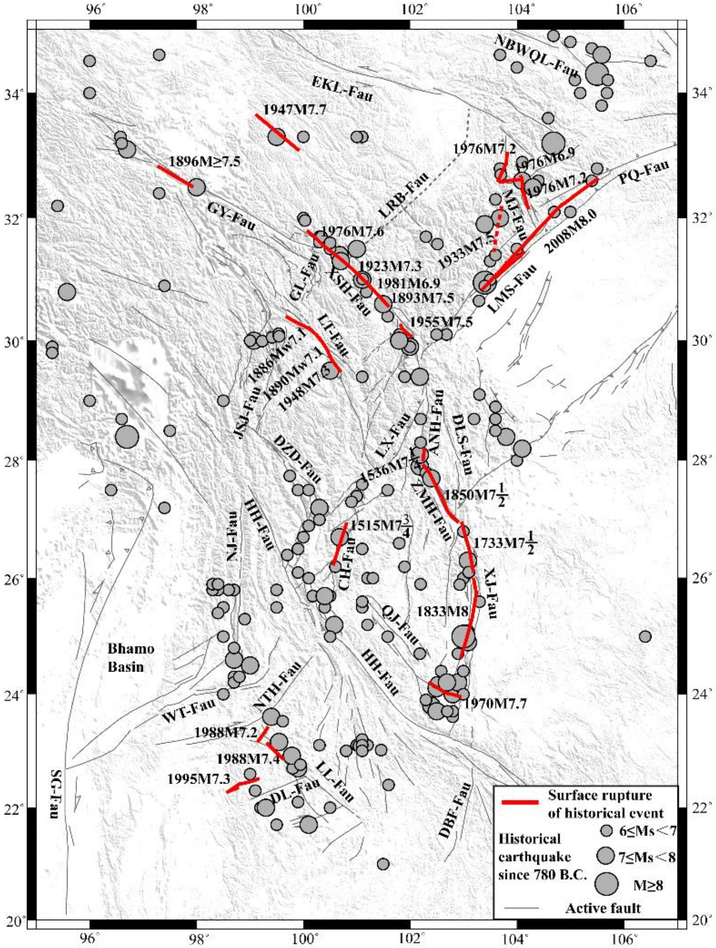
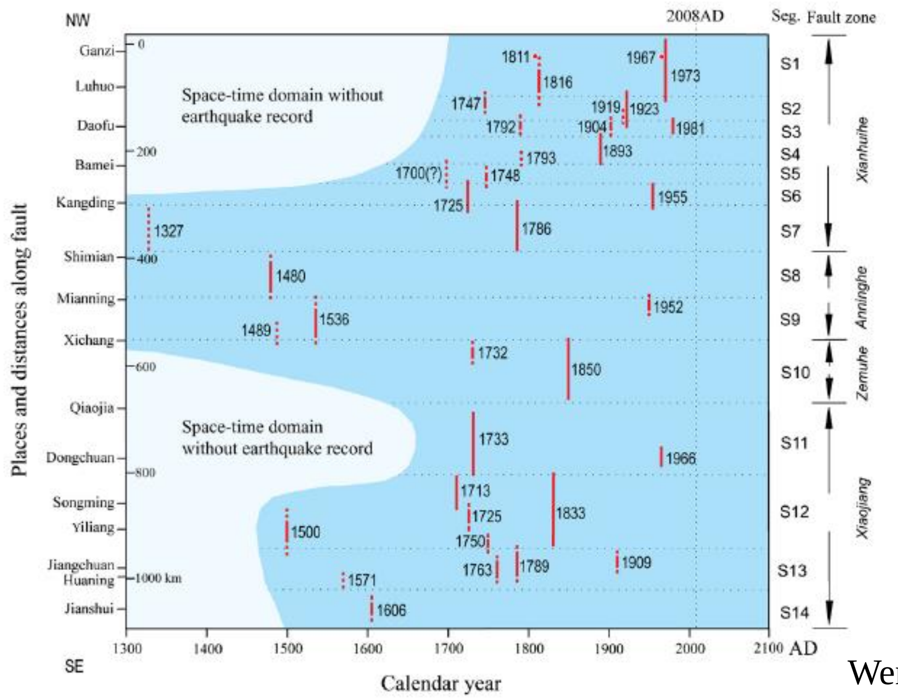
Seismic hazard analysis for main strike slip faults



Why we study the Xianshuihe-Xiaojiang fault?
Xianshuihe fault is the most dangerous faults in China with earthquake hazard.

Since 1327 AD, at least 18 >M7 earthquakes have occurred on the Xianshuihe-Xiaojiang fault zone.



Wen et al., 2008

Seismic hazard analysis for main strike slip faults

Multisegment rupture could cause catastrophic earthquake hazard.

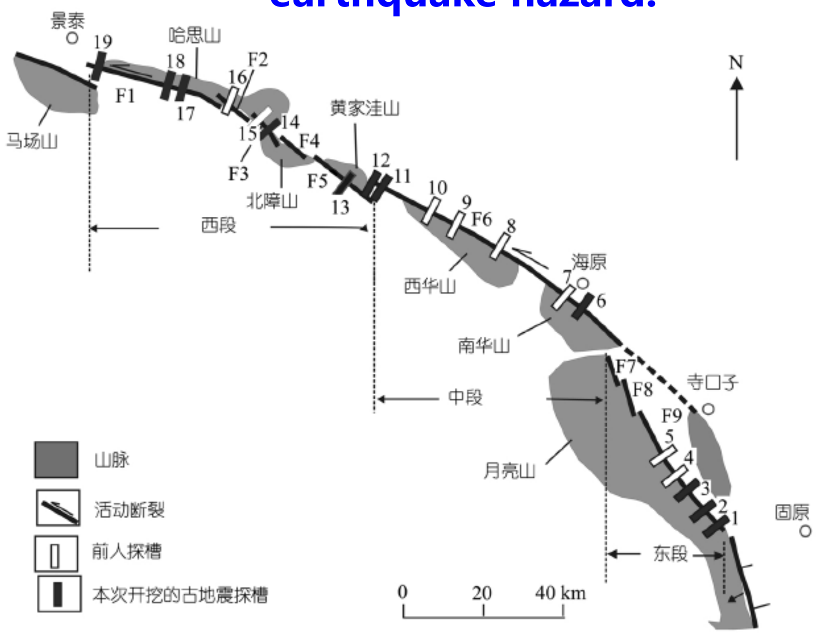
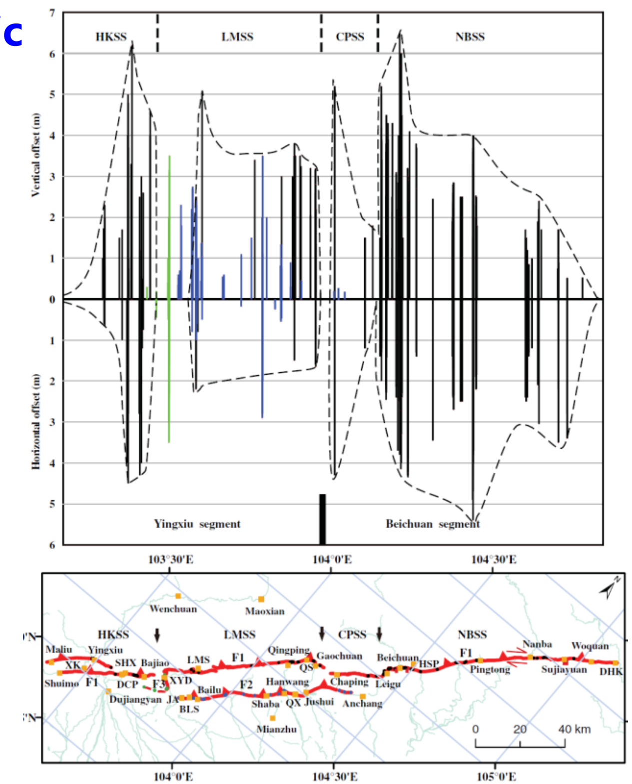


图 1 海原断裂带的几何结构、分段和探槽分布图

3 sections with 9 segments ruptured in the Haiyuan 1920 M8.5 earthquake, caused at least 282,000 death toll.

Zhang P et al., 2003



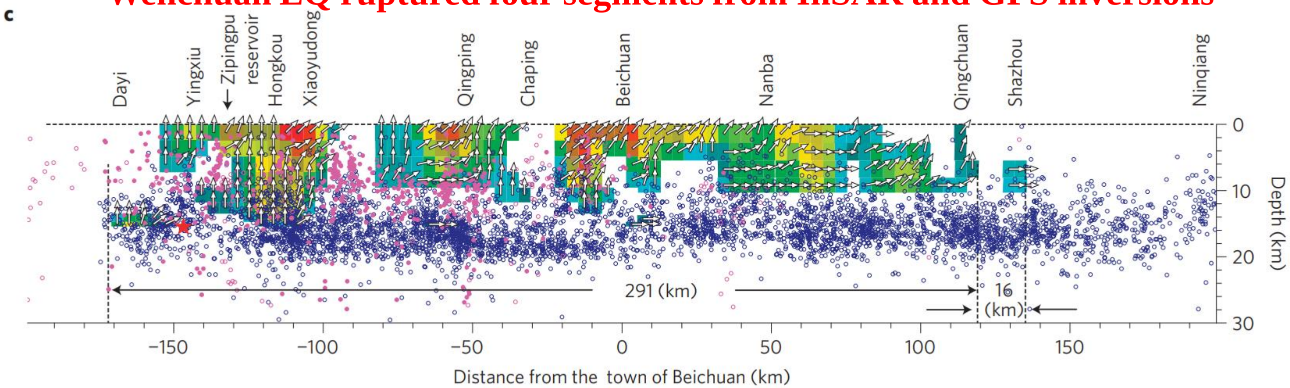
Wenchuan earthquake in 2008 ruptured 4 segments of >M7.0 earthquakes, with >80,000 death and missing

Yu et al., 2010, BSSA

Seismic hazard analysis for main strike slip faults

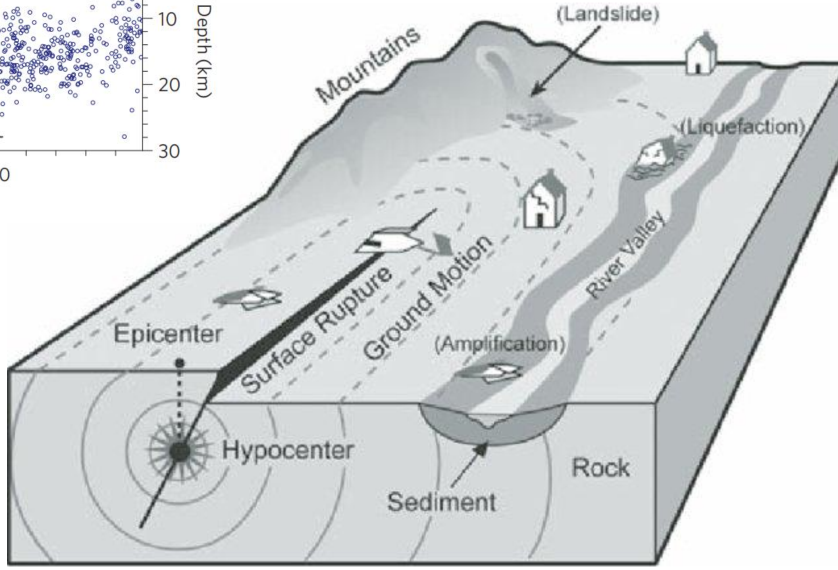
Multisegment rupture could cause catastrophic earthquake hazard.

Wenchuan EQ ruptured four segments from InSAR and GPS inversions



Wang et al., 2011, Nature Geosciences

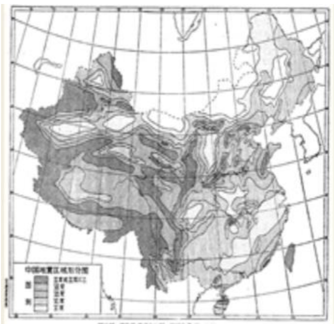
Four segments rupture simultaneously could cause even larger hazards and geological disasters than the total of the four single ruptures.



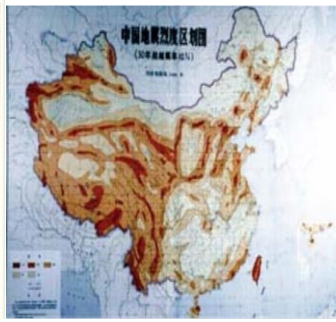
Crawford et al., 2016, GSA special paper

Seismic hazard analysis for main strike slip faults

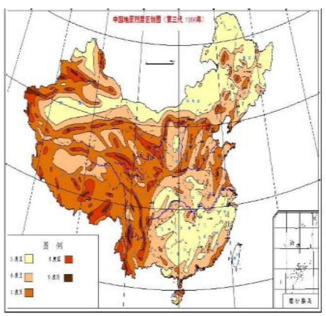
The compilation of NSHM of China should also consider the multi-segment rupture hazard.



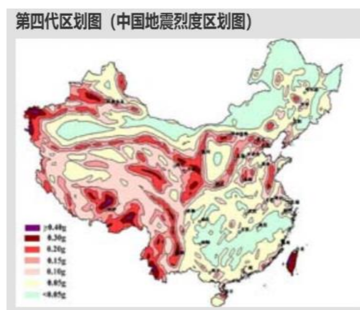
1st version in1957



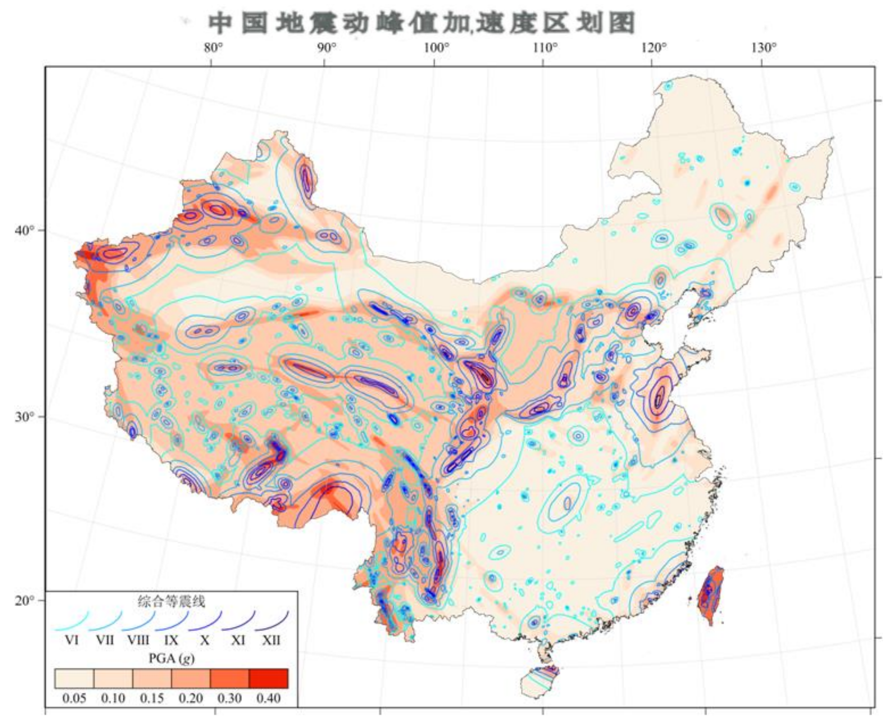
2nd version in 1977



3rd version in 1990



4th version in 2001



The new version in 2015

The 4th version in 2001 started to use ground motion parameters zonation maps rather than the intensity map.

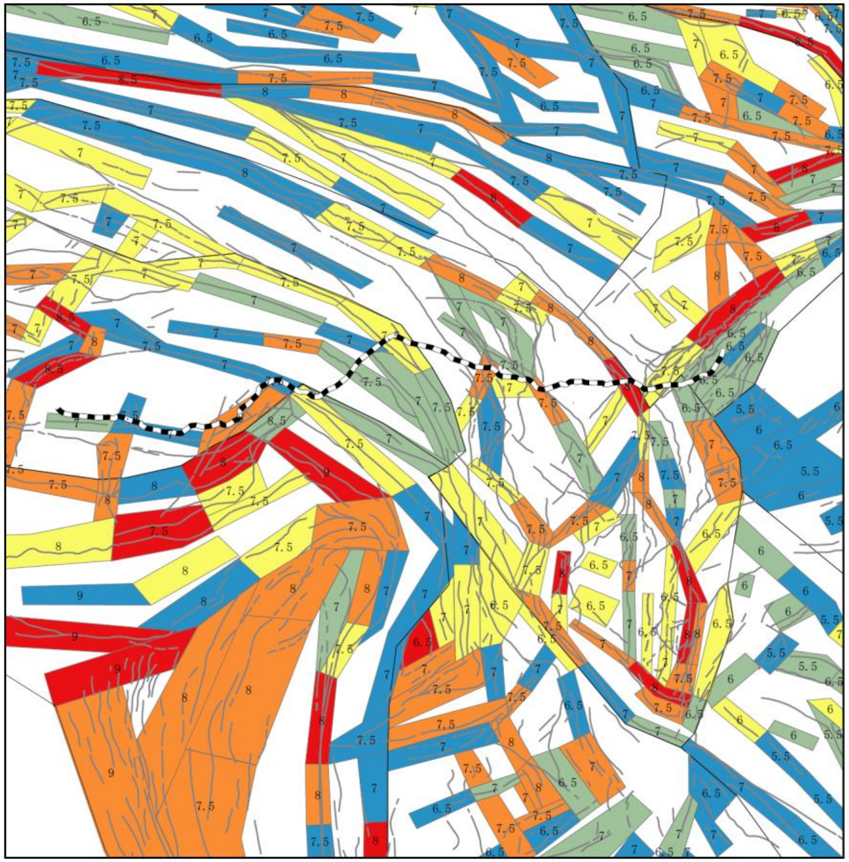
The 5th version applied the three kinds of seismic source model, i.e., seismic zone for MFD, the fault source, and the background source.

Seismic hazard analysis for main strike slip faults

The 5th generation of China NSHM

1. Mainly inferred from historical rupture data, no consideration of the multi-segment hazard.

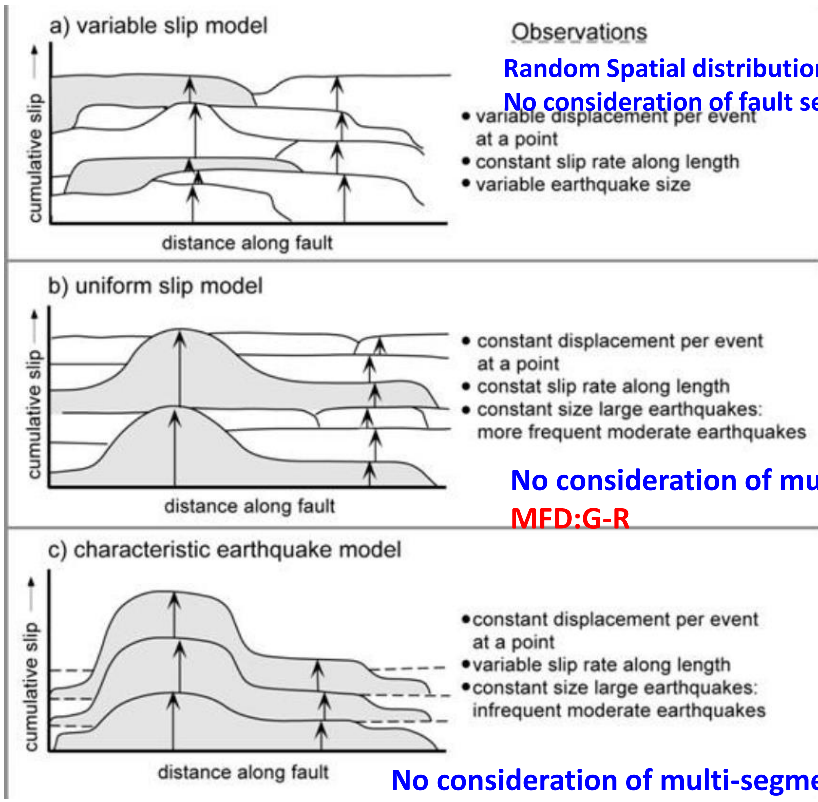
2. The maximum magnitudes in the Xianshuihe-Diandong Seismic Zone and the Dianxi Seismic Zone are both Ms8.0, mainly based on the maximum magnitude from the largest historical earthquakes.



What we do is:
Jump out of the historical earthquake ruptures (intensity maps), to model earthquake hazards based on fault segmentation and present fault slip rates.

Seismic hazard analysis for main strike slip faults

Eq Occurrence Pattern on the fault



Random Spatial distribution of displacement

No consideration of fault segment

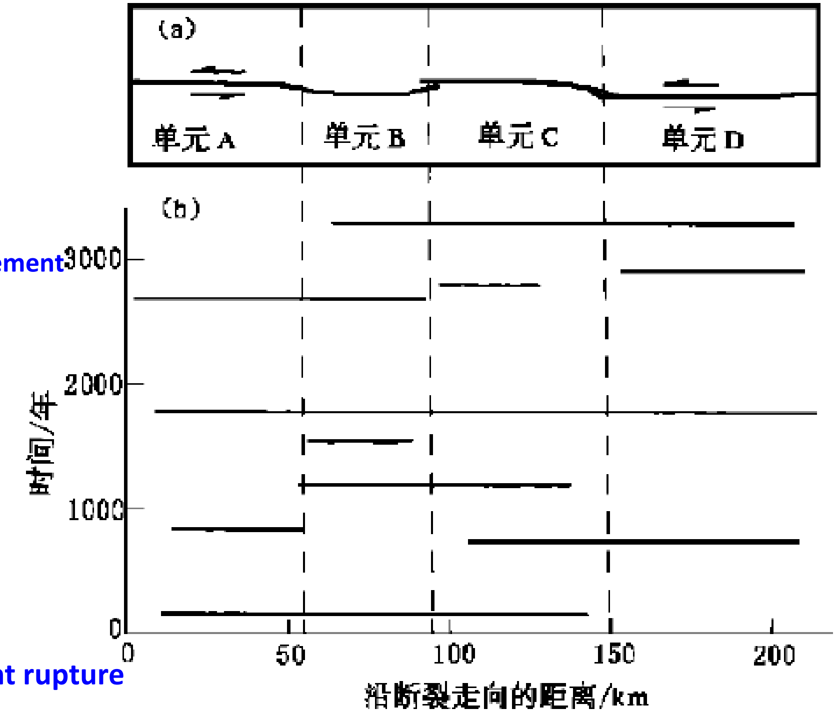
No consideration of multi-segment rupture

MFD:G-R

No consideration of multi-segment rupture

MFD: Characteristic EQ, or Y-C

Schwartz and Coppersmith,1984,JGR

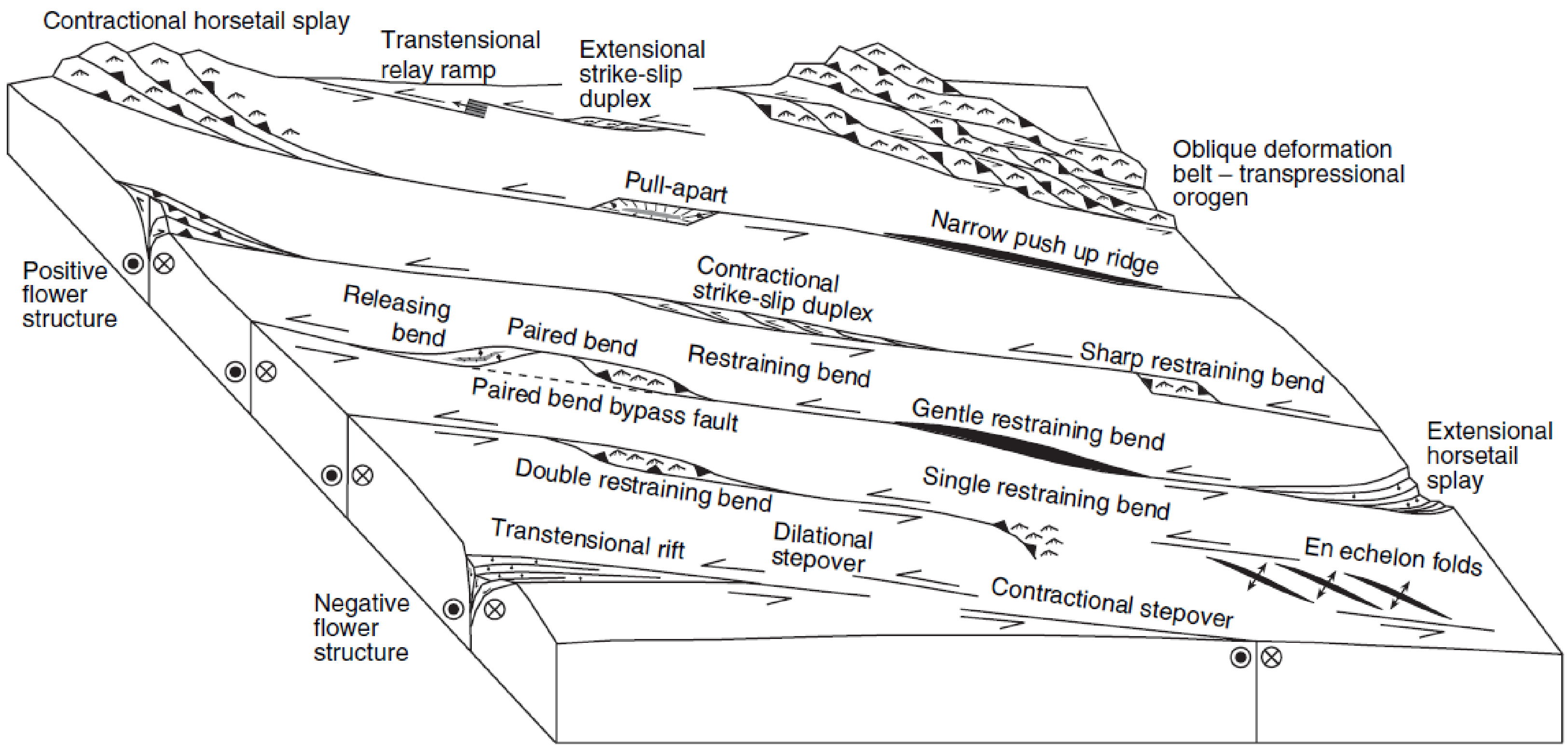


Empirical studies in China show the earthquake sizes for fault segment have some regularity.

This cycle is small, the next cycle is big, the ratio is 0.48.
This cycle is mediate, the next cycle is 0.69 for big or 0.25 for small EQ.
This cycle is big, the next cycle is 0.36 for small , and 0.64 for mediate EQ.

Wen Xueze， 2001， Acta Seismologica Sinica

Segmentation and multi-segment rupture from geological data

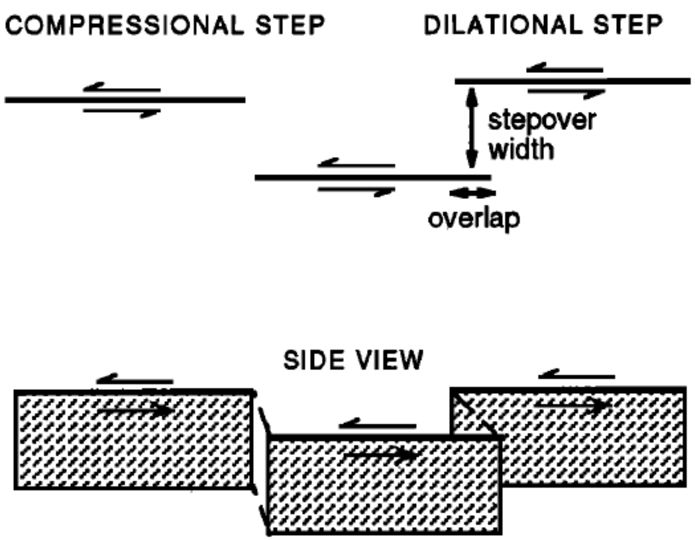


Segmentation are based on the following items：Pull-apart basin/stepovers, restraining or releasing bend, conjugated by oblique faults, strike difference changes, etc (and so forth).

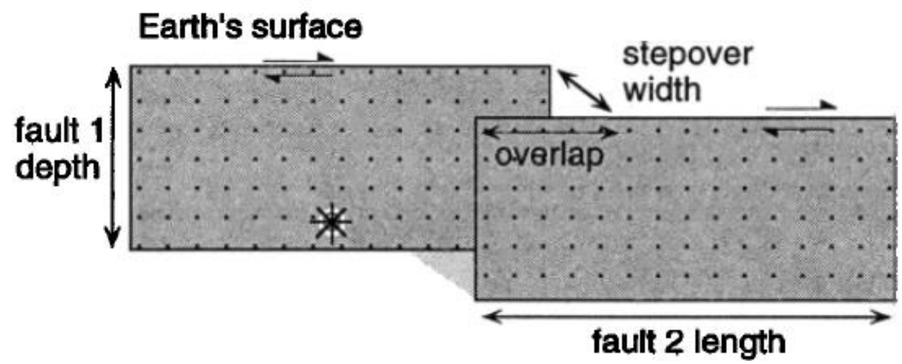
Cunningham and Mann, 2007

Seismic hazard analysis for main strike slip faults

Numerical simulations:
suggested that the rupture process might stop when encountering steps with a 5+ km width

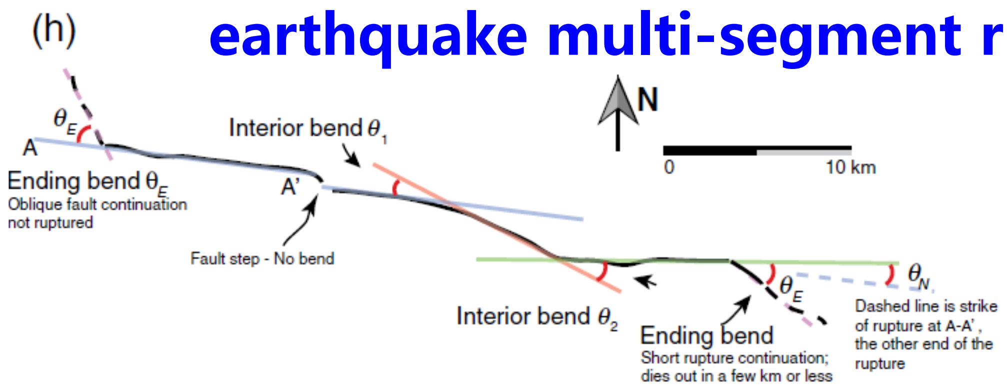


Harris and Day, 1993



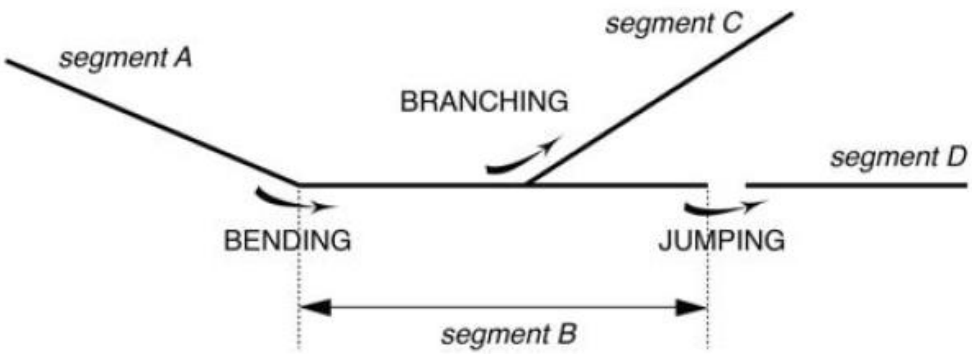
Harris and Day, 1999

Strike-difference: also a indicator for earthquake multi-segment rupture through.



Biasi and Wesnousky, 2017

Cannot rupture when >30° from Global historical rupture data



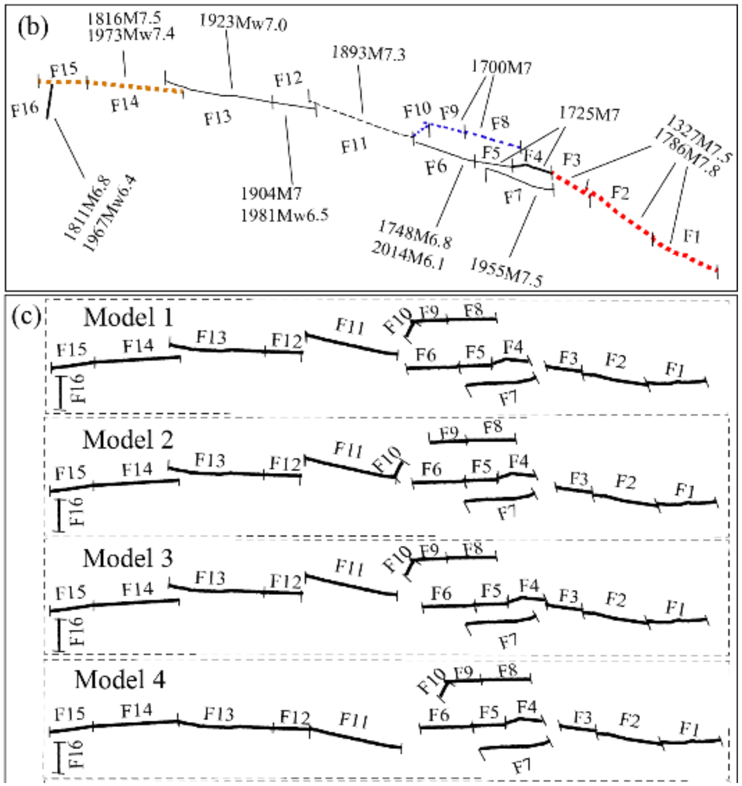
Mignan et al., 2015

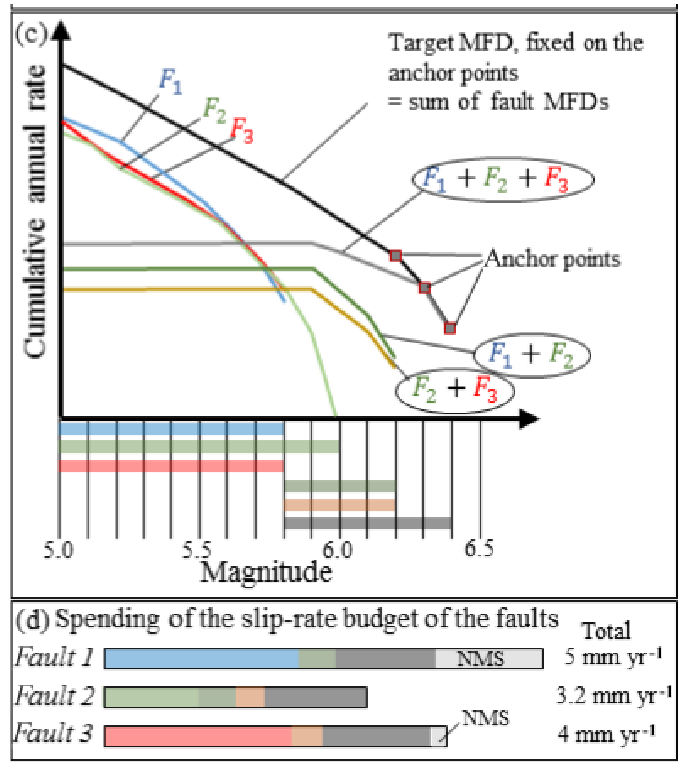
>30° , but should also consider the background stress field

Seismic hazard analysis for main strike slip faults

The Xianshuihe Fault

Seismic hazard analysis for main strike slip faults





- **We established the segmentation model for the Xianshuihe fault. We analyzed the possibilities of the rupture combinations according to Mmax, the width of the stepovers, and the segmenation models.**

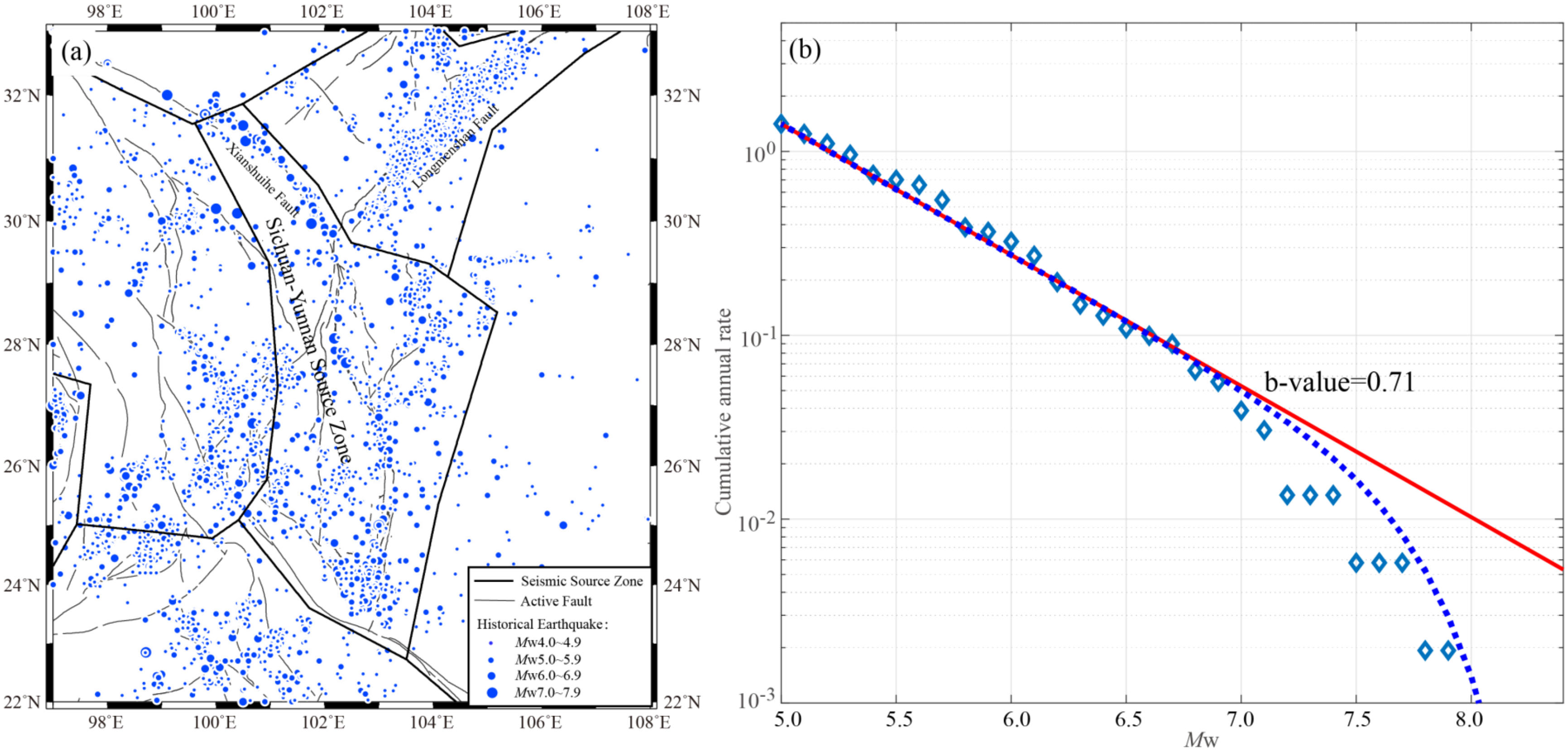
- **We integrated the MFD, fault slip rate, historical earthquake and paleo-earthquake sequence, etc., also considering the creep characteristics of the fault section, to iterate the occurrence rate of multi-segment rupture combinations and single segment ruptures.**

Chartier et al., 2017

Cheng et al., 2021, SRL

Seismic hazard analysis for main strike slip faults

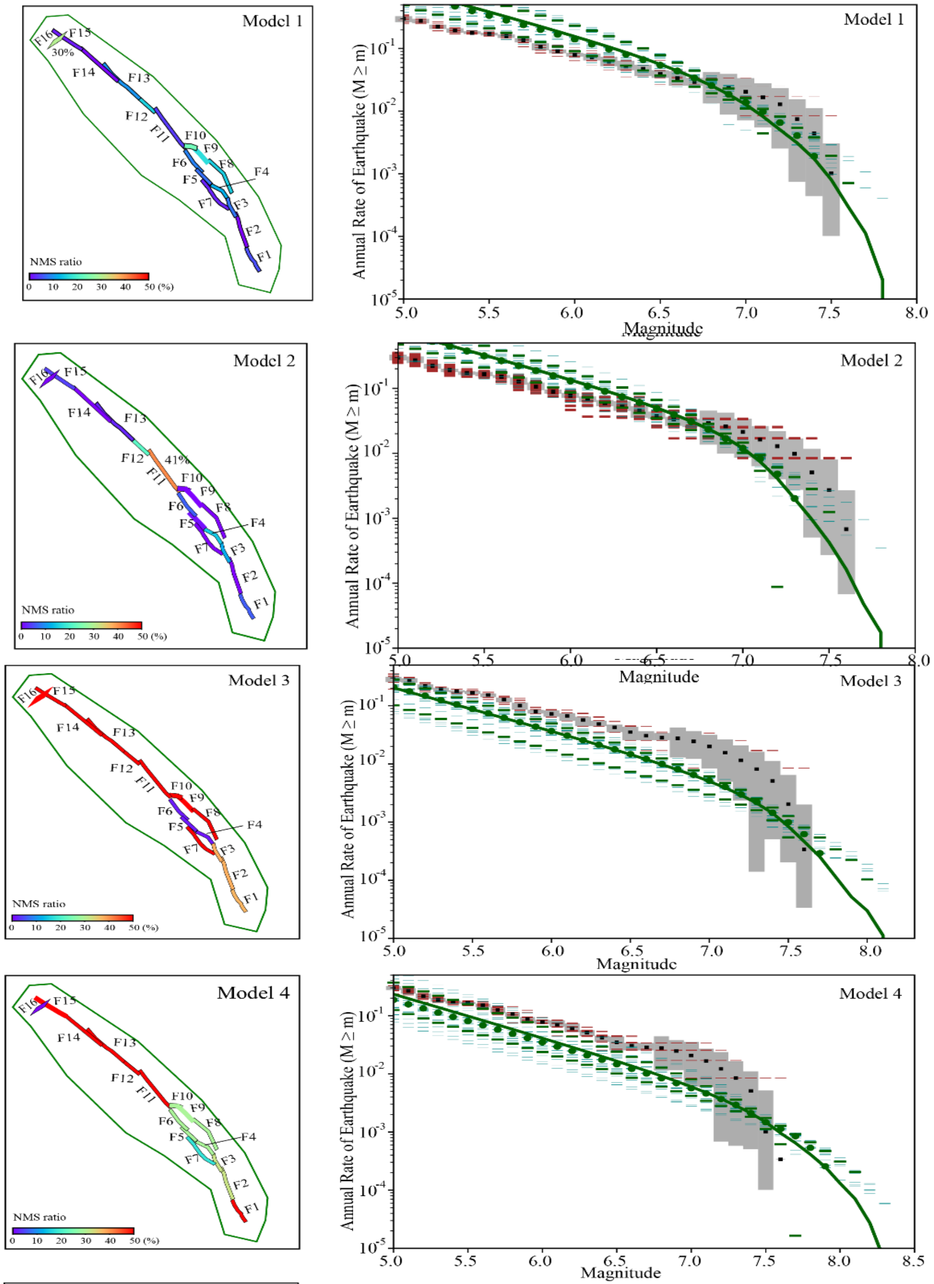
G-R relation in the East Sichuan-Yunnan Region



Cheng et al., 2017

Seismic hazard analysis for main strike slip faults

Xianshuihe fault



NMS ratio：

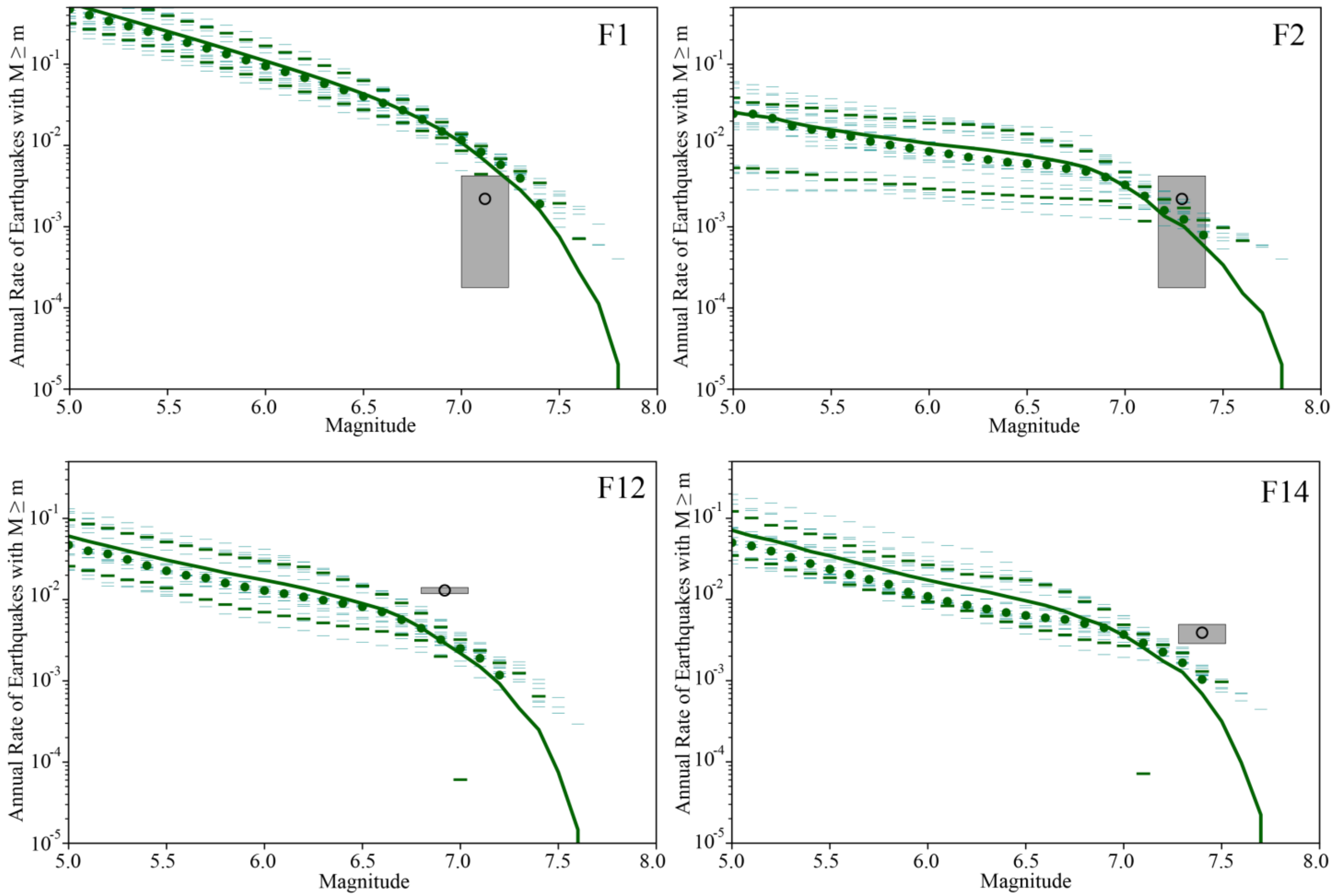
The iteration residual of fault slip rate is seen as the NMS.

The NMS ratio of ≤30–40% is introduced as a threshold to determine the reasonable multi-segment combination models (Chartier et al., 2019).

Seismic hazard analysis for main strike slip faults

Xianshuihe fault

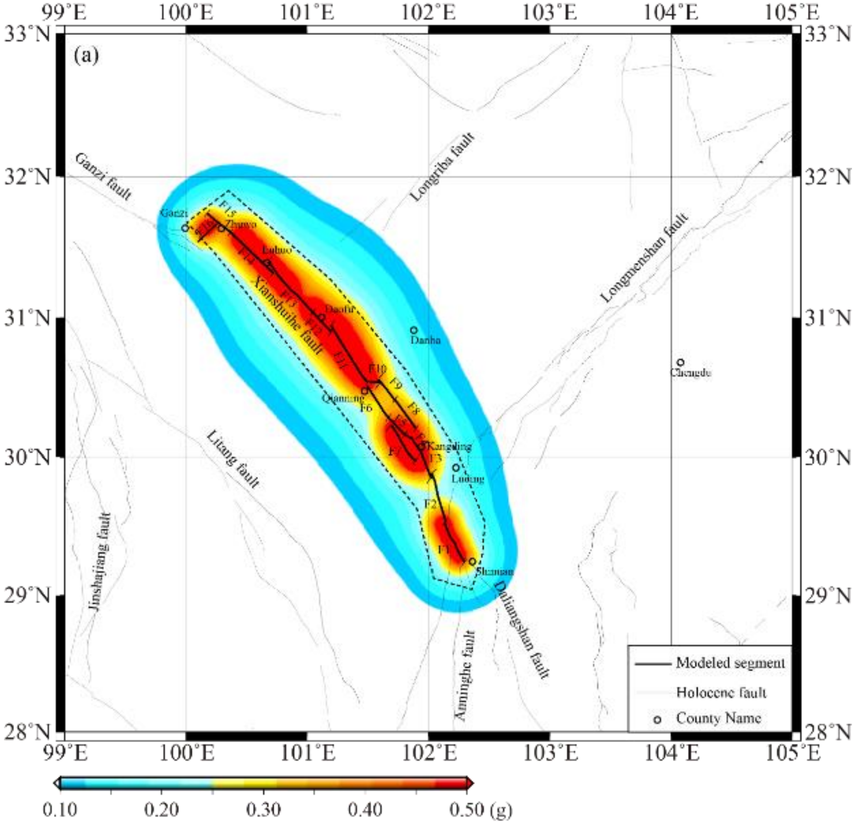
Comparison with the historical recurrence rate



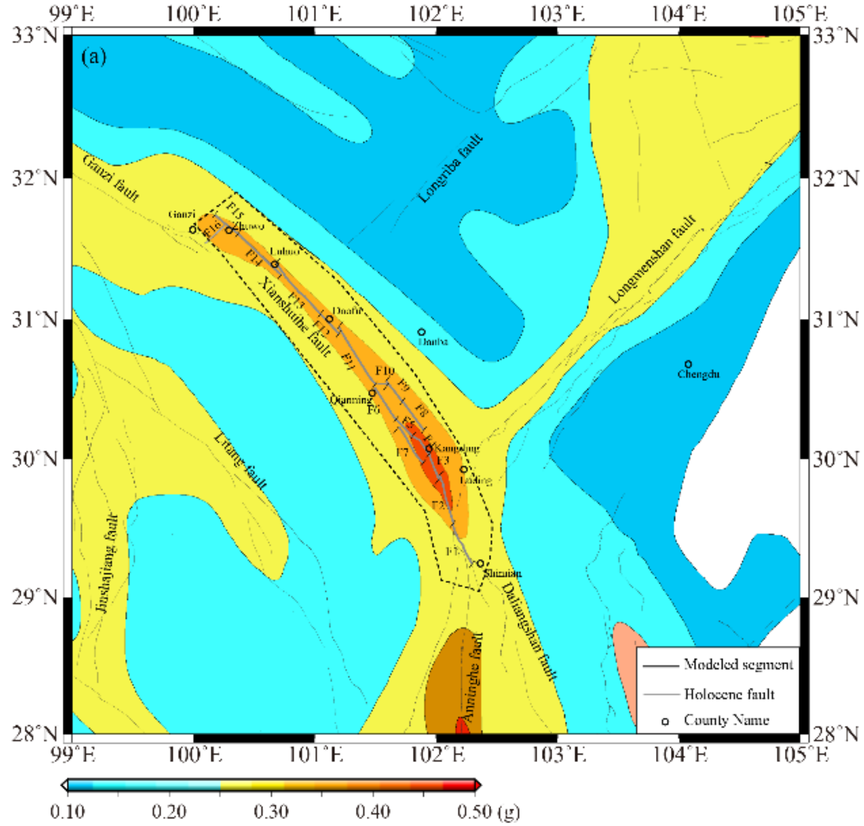
Seismic hazard analysis for main strike slip faults

Xianshuihe fault

Seismic Hazard of the Xianshuihe fault (PGA 475 yr)



Our results



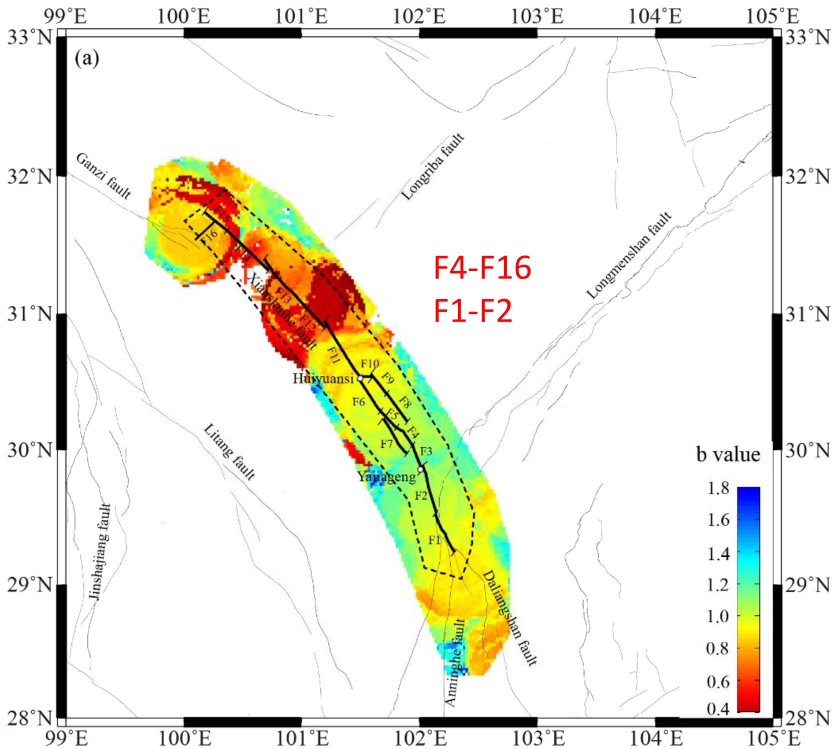
NSHM OF China in 2015

Cheng et al., 2021, SRL

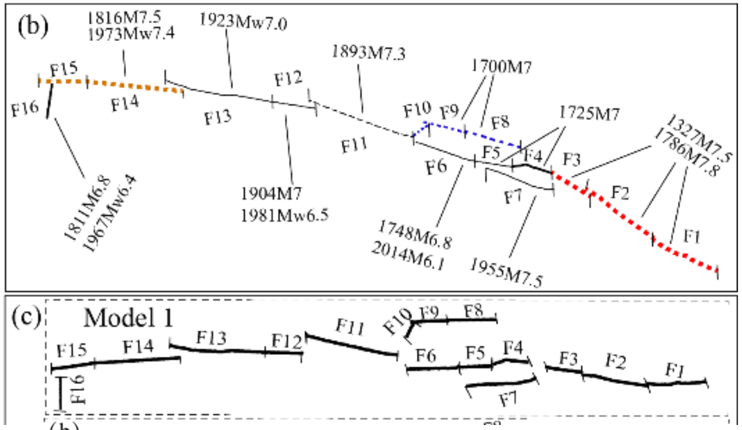
Seismic hazard analysis for main strike slip faults

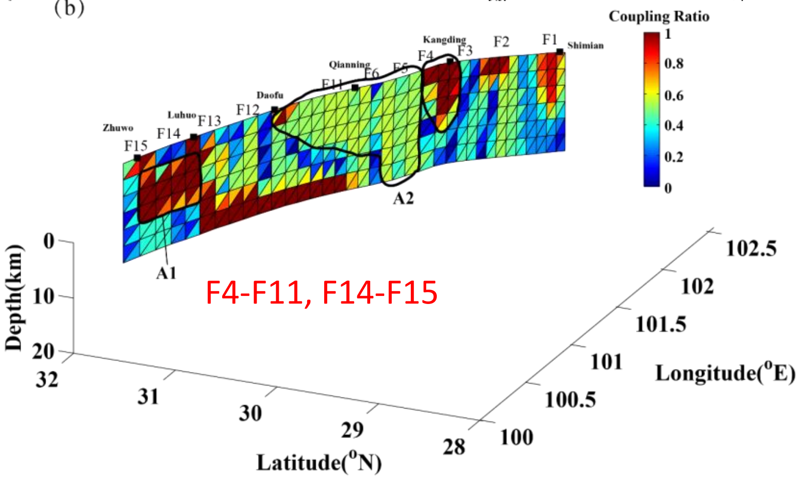
Xianshuihe fault

Low b value- the asperity of the potential earthquakes



Low b values and coupling ratios are around the F4-F11， and most obviously around the F4 segment



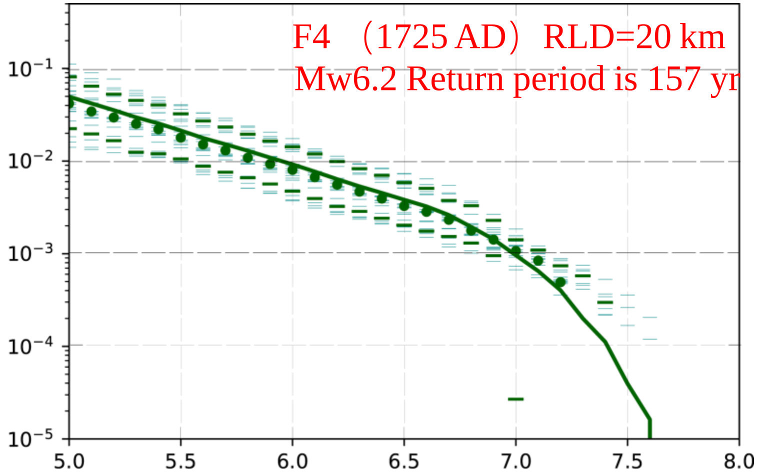


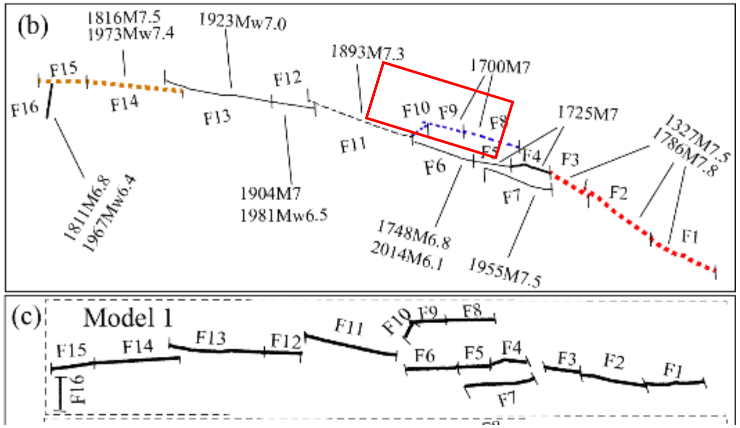
Coupling ratio from the inversion of Insar and GPS

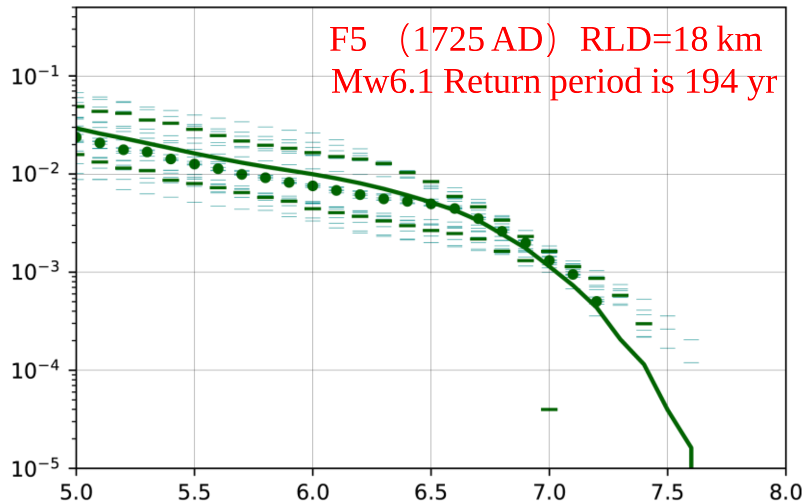
Seismic hazard analysis for main strike slip faults

Xianshuihe fault

G-R







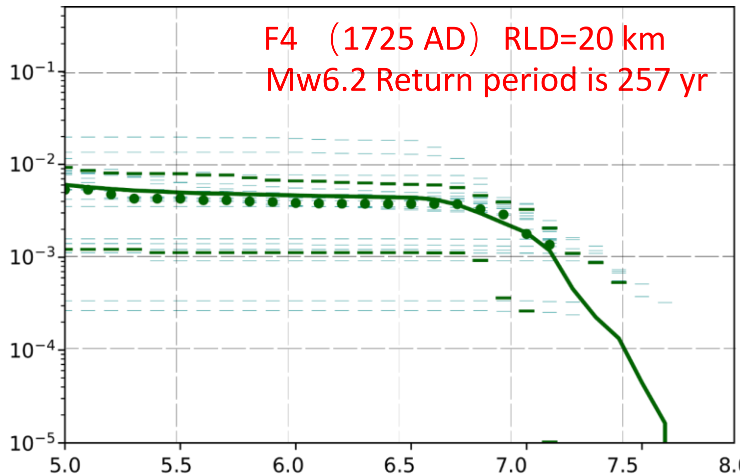
Scaling Law of the Mw and RLD （Cheng et al., 2020）
log(RLD) = (–2.45±0.17) + (0.61 ± 0.03)Mw

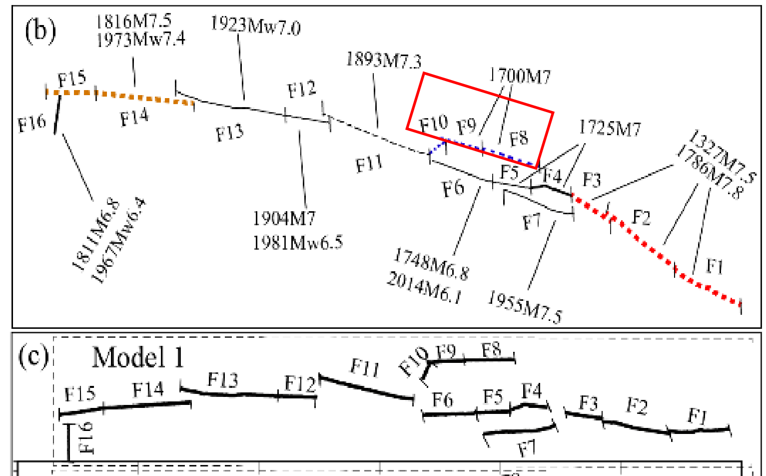
Mw6.7, RLD = 40 km
F4 , Mw6.7 Return period is 381 yr
F5, Mw6.7 Return period is 249 yr

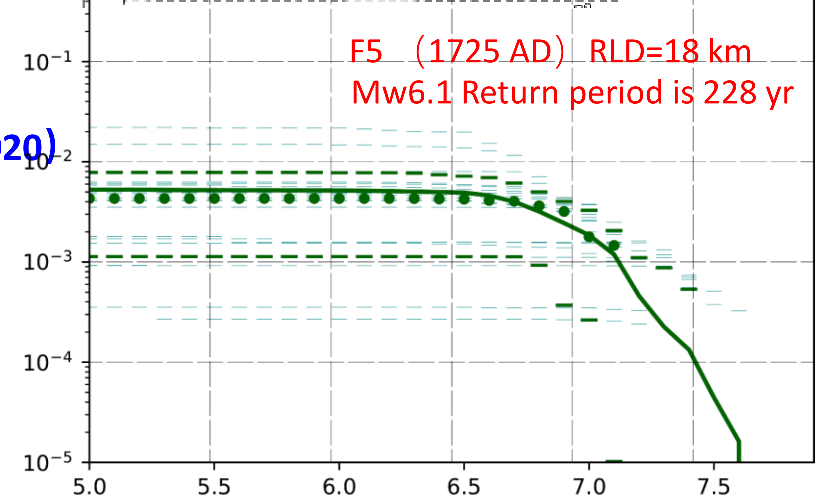
Seismic hazard analysis for main strike slip faults

Xianshuihe fault

Y-C







Scaling Law of the Mw and RLD （Cheng et al., 2020）

log(RLD) = (–2.45±0.17) + (0.61 ± 0.03)Mw

Mw6.7, RLD = 40 km

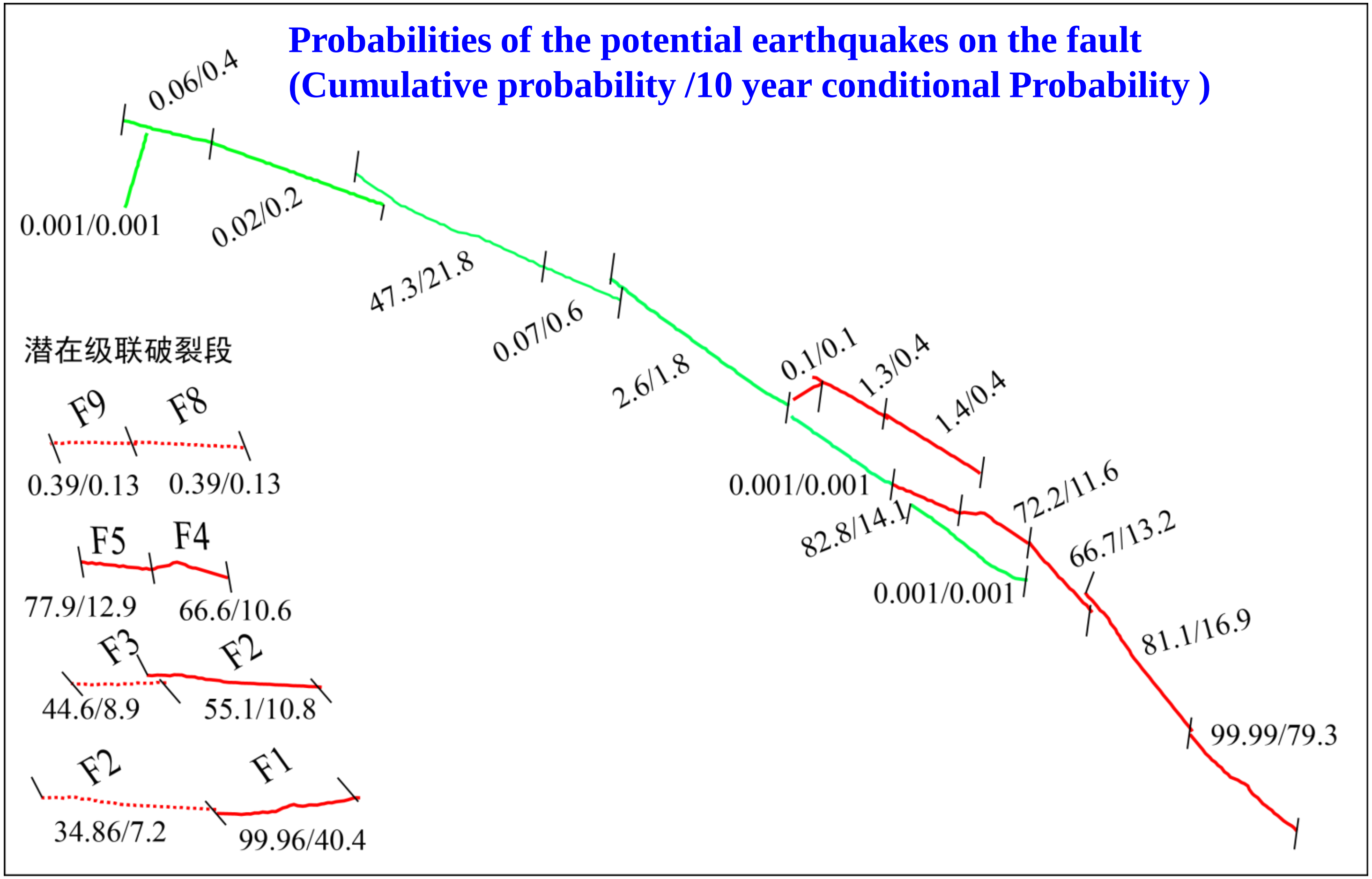
F4 , Mw6.7 Return period is 242 yr

F5, Mw6.7 Return period is 271 yr

Cheng et al., 2021, SRLc

Seismic hazard analysis for main strike slip faults

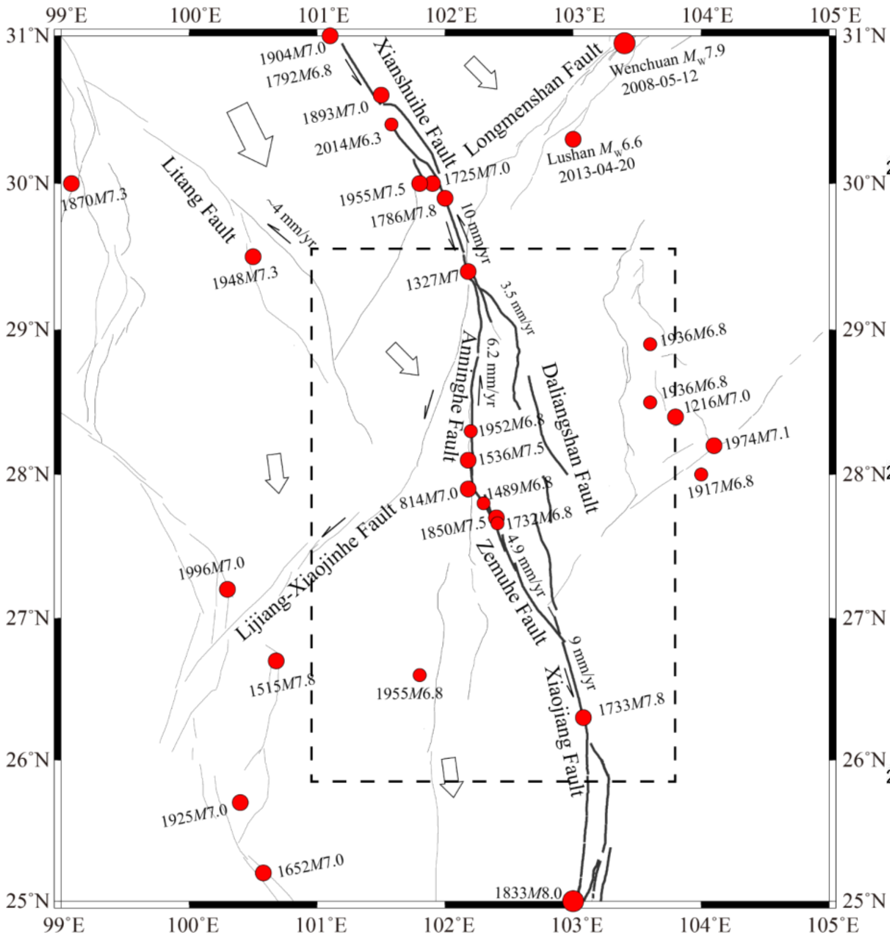
Xianshuihe fault

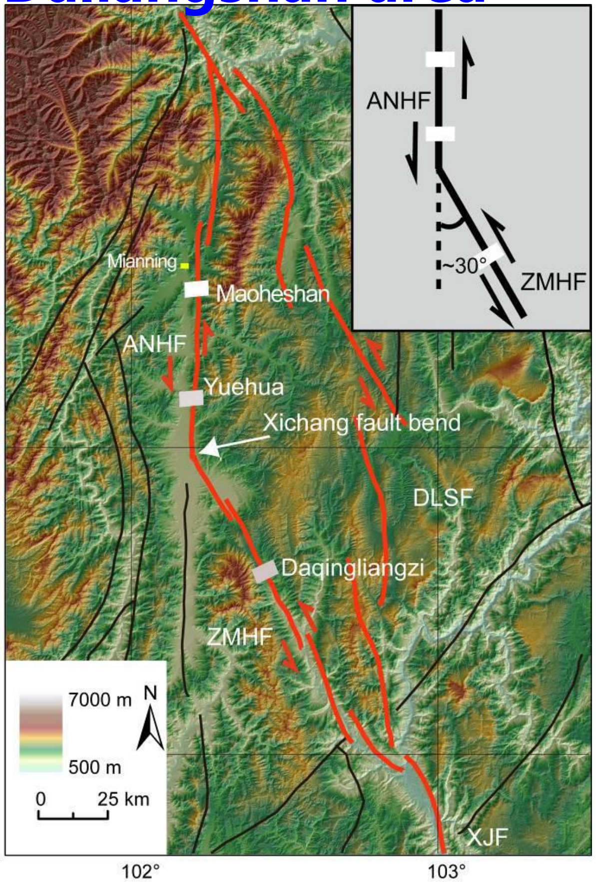


Cheng et al., 2021, SRL

Seismic hazard analysis for main strike slip faults

Aninghe-Zemuhe-Daliangshan area





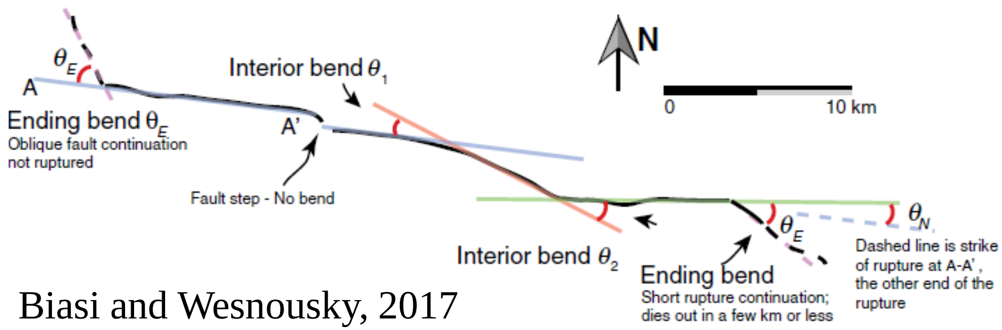
Wang et al., 2014; 2017

Seismic hazard analysis for main strike slip faults

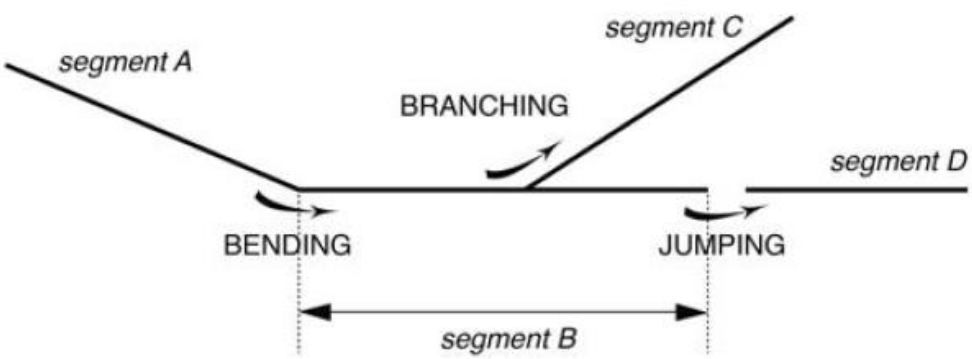
Aninghe-Zemuhe-Daliangshan area

Strike-difference is also a indicator for earthquake multi-segment rupture through.

(h)



Biasi and Wesnousky, 2017



Mignan et al., 2015

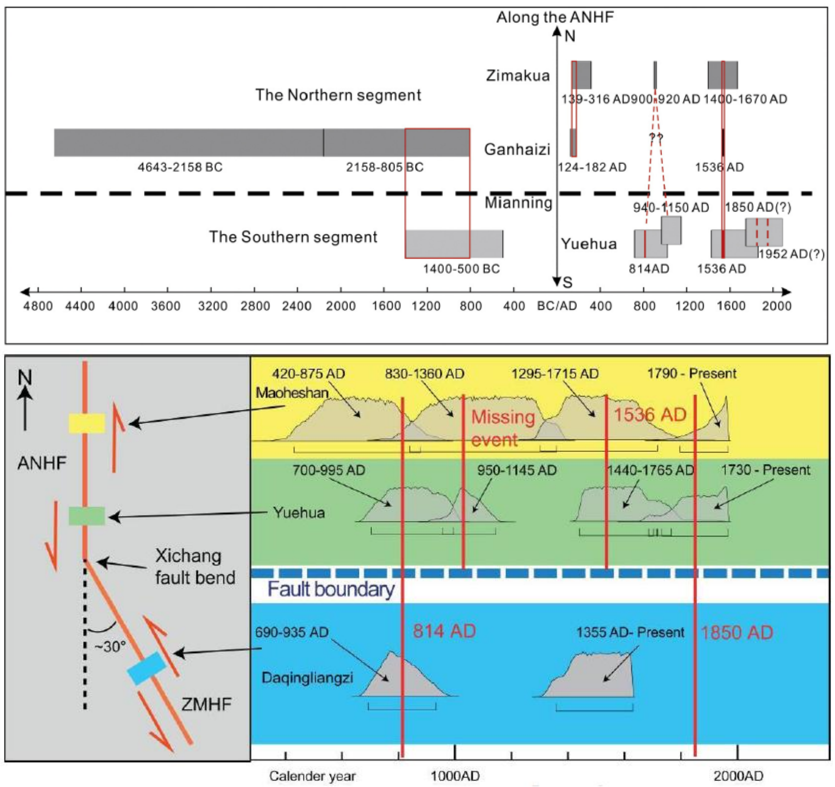
Cannot rupture when >30° from Global historical rupture data

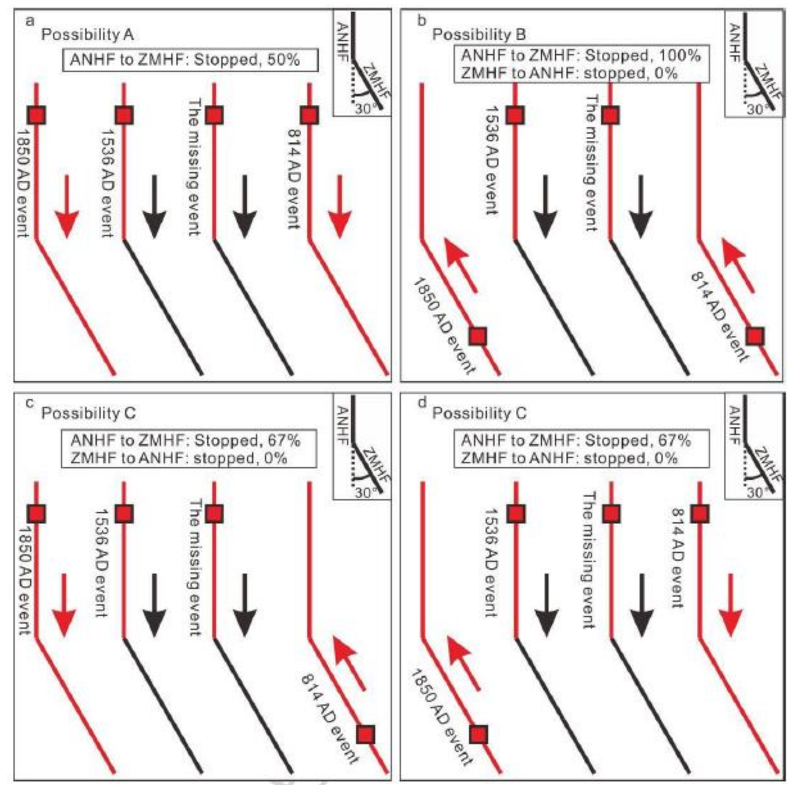
>30° , but should also consider the background stress field

Seismic hazard analysis for main strike slip faults

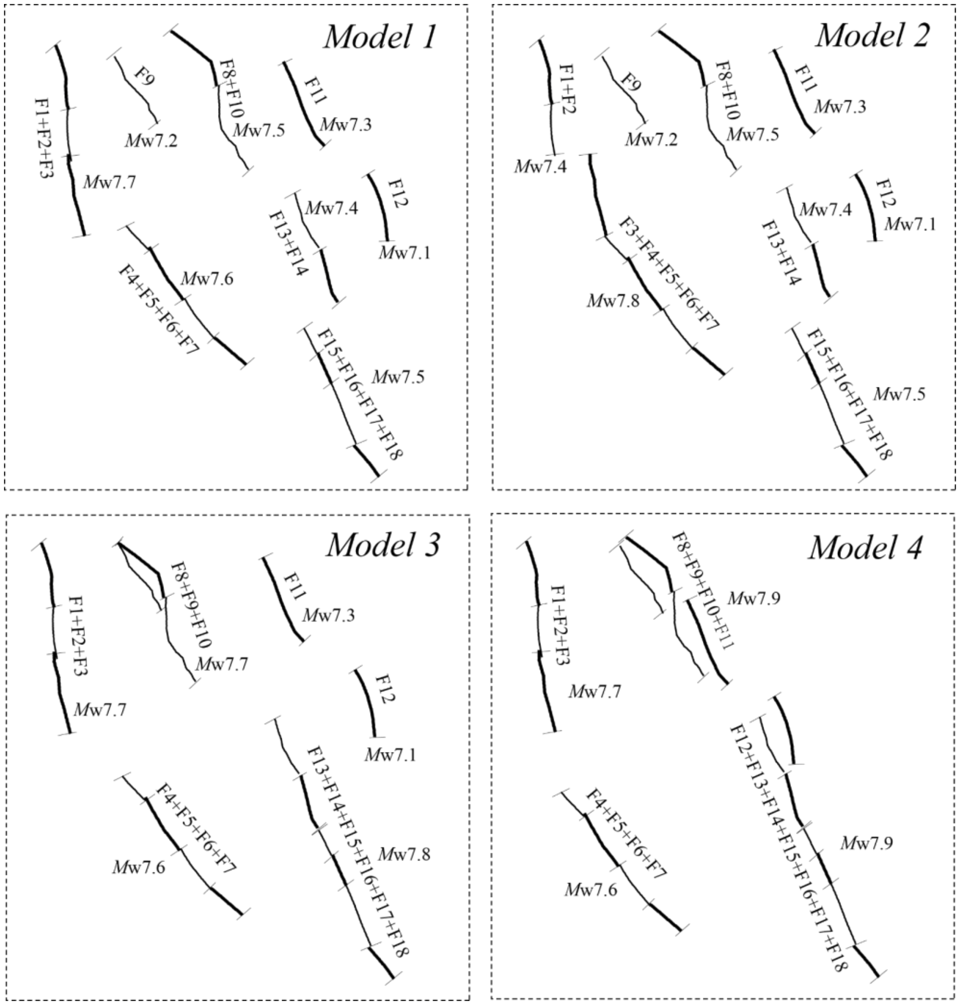
Wang et al. (2014; 2017，tectonophyscis) thought the 1850 earthquake ruptured both the Anninghe and Zemuhe fault with >30° strike difference

Aninghe-Zemuhe-Daliangshan area





Seismic hazard analysis for main strike slip faults



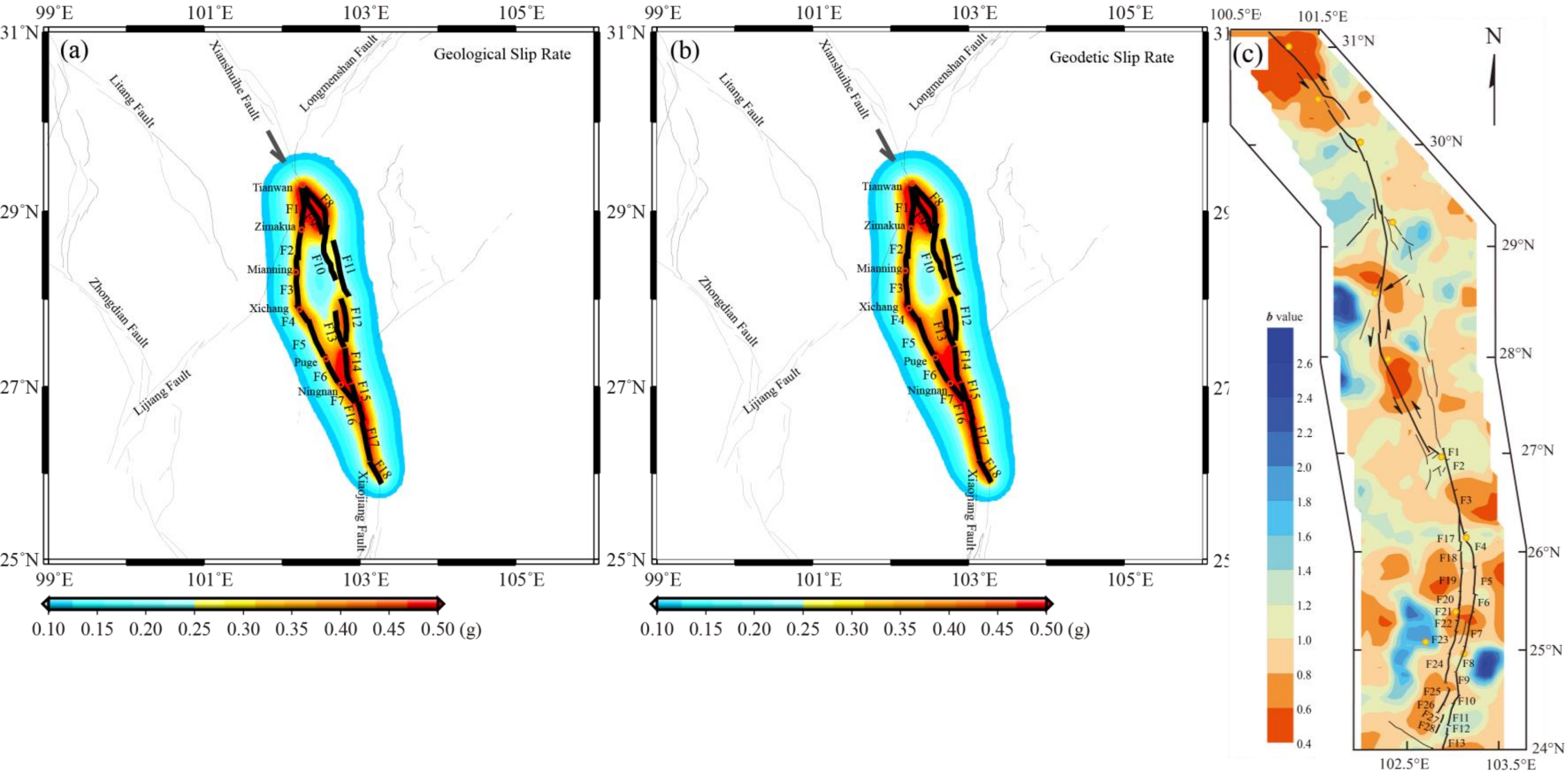
Aninghe-Zemuhe-Daliangshan area

Model 2 is used to check whether the part of the Anninghe fault and part of the Zemuhe fault can rupture together (Wang et al., 2014; 2017).

Model3 and Model4 are used to check whether the multi-segment rupture can occur on the Daliangshan fault.

Seismic hazard analysis for main strike slip faults

Geological Slip Rate **Geodetic Slip Rate**

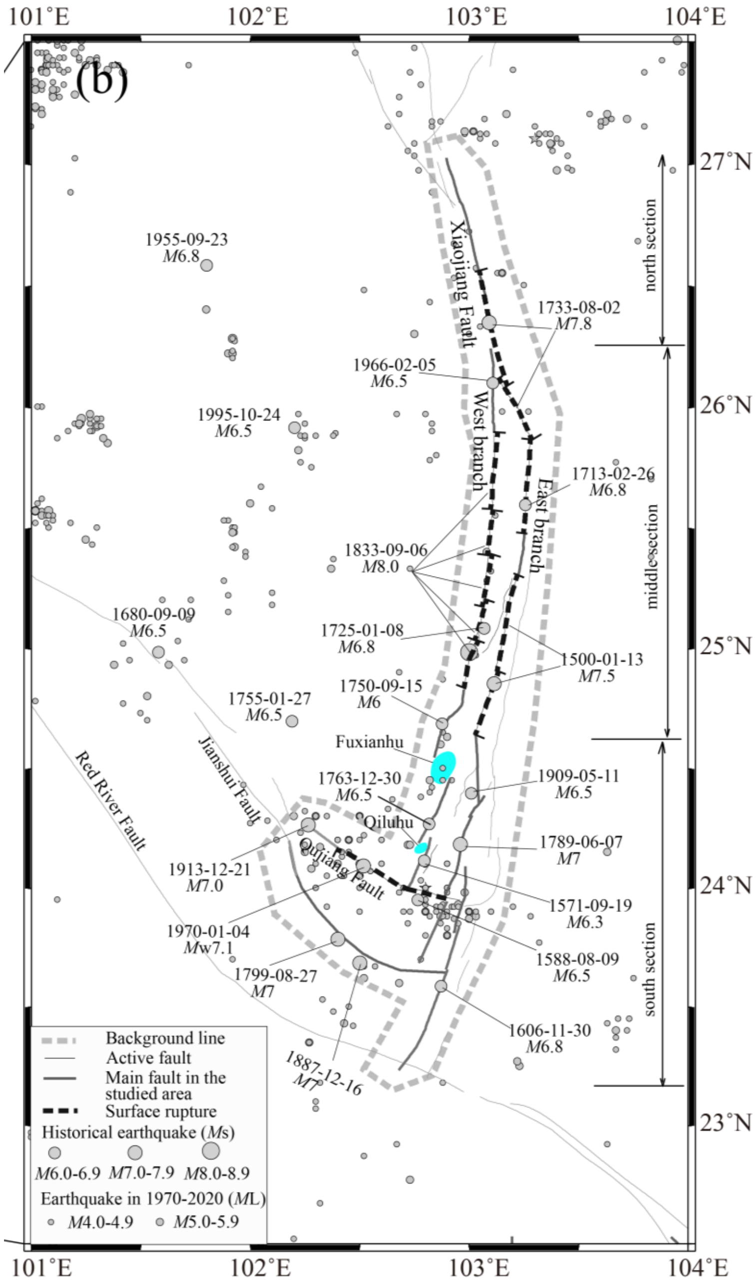


Cheng et al., 2021. Natural Hazards, 107, 1501-1525.

Yi et al., 2008

Cheng et al., 2021, Nhaz

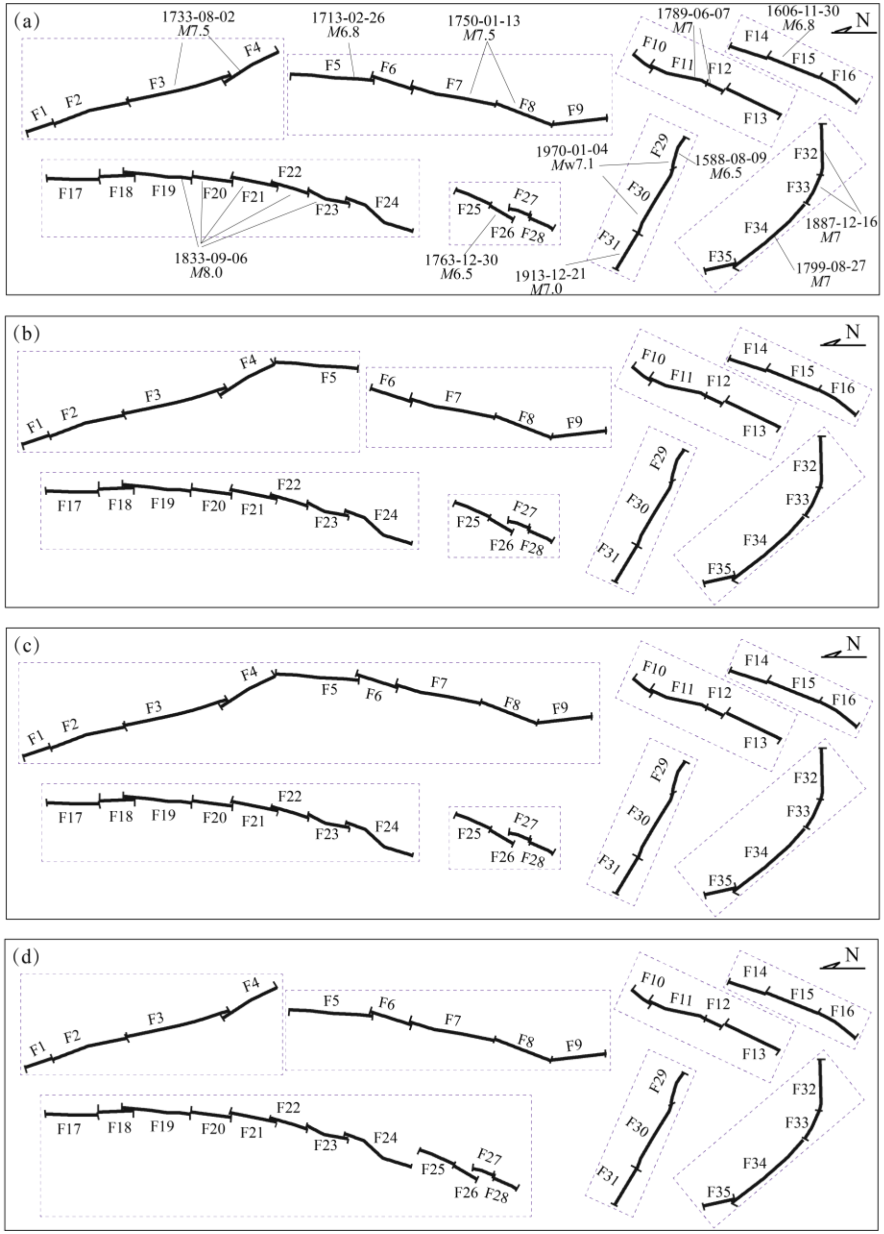
Seismic hazard analysis for main strike slip faults



Xiaojiang Fault

- The Xiaojiang fault is prone to multi-segment ruptures, e.g., the 1833 M8 Songming earthquake on the western branch, and the 1500 M7.5 Yiliang earthquake on the eastern branch.
- Fault Slip rates for the western and eastern branch are both 5 mm/yr.
- Complicate tectonic environment around south part of the Xiaojiang fault, with many small-scale faults around.

Seismic hazard analysis for main strike slip faults



Xiaojiang Fault

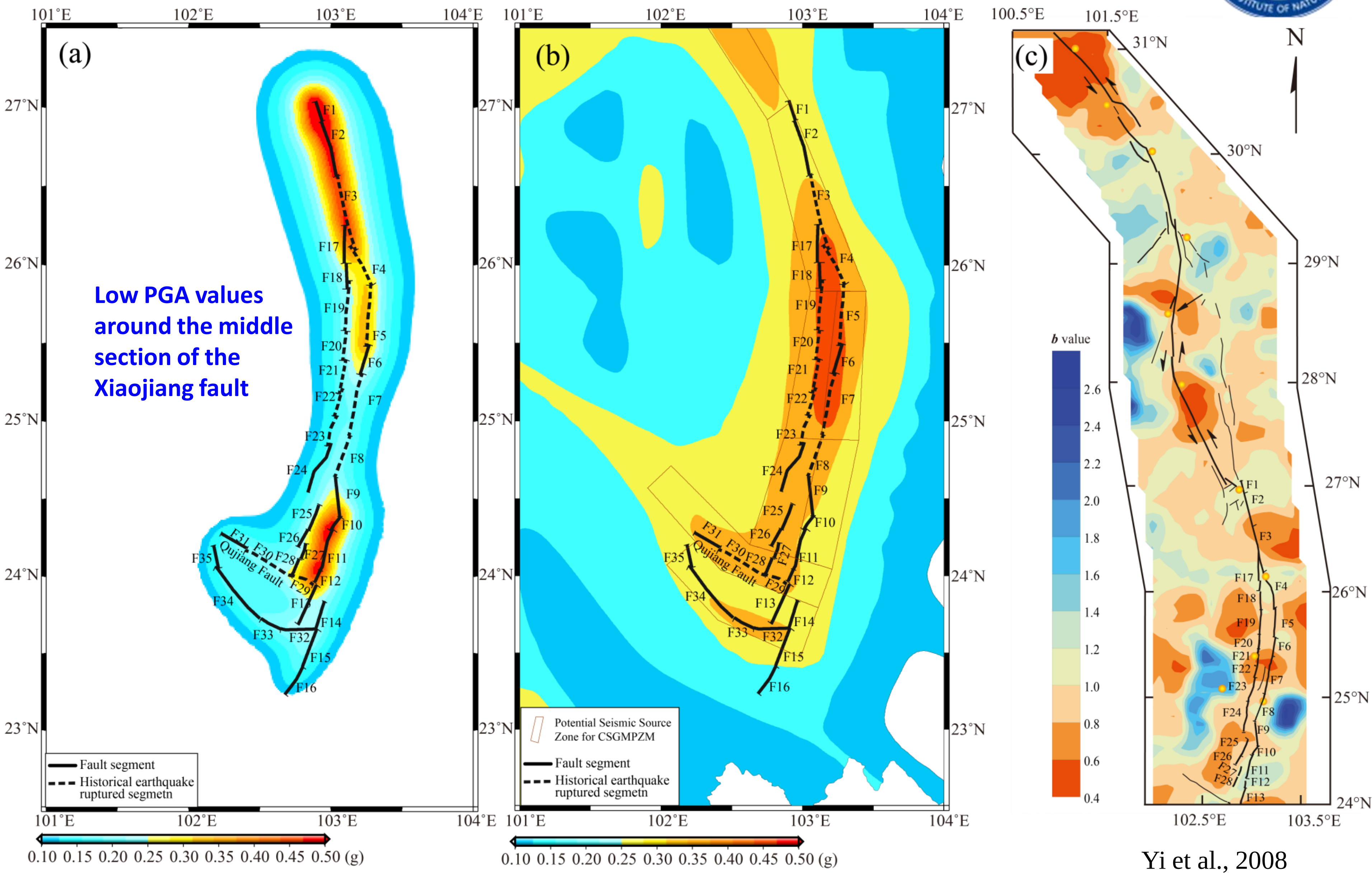
Model 1, from historical rupture data

Model 2, F5 can rupture with F4 with a ~30° strike difference.

Model 3, the eastern branch can rupture together with the northern section.

Model 4, the western branch can rupture through a 12 km step to the segment south to the Fuxianhu Lake

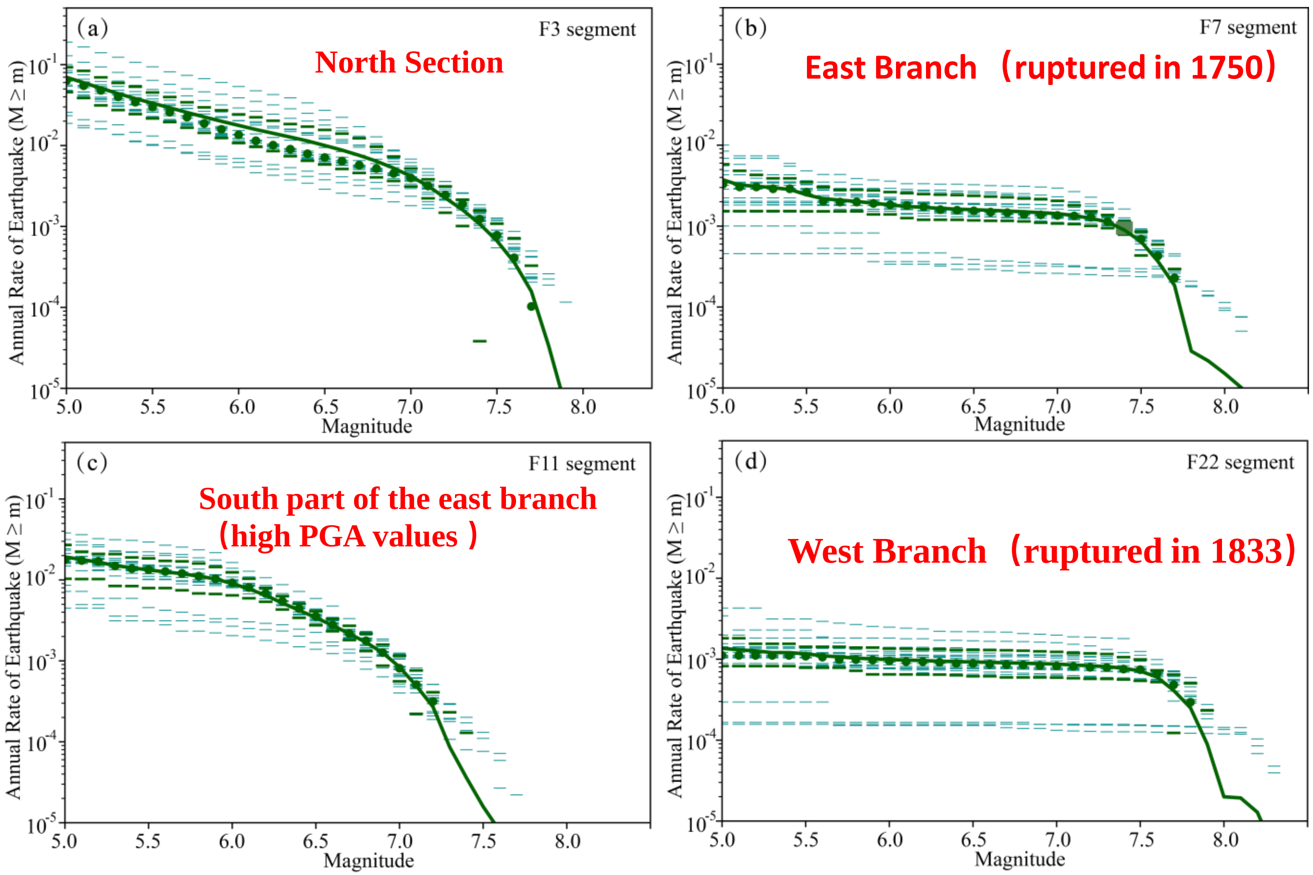
Seismic hazard analysis for main strike slip faults



Yi et al., 2008

Seismic hazard analysis for main strike slip faults

Xiaojiang Fault



The eastern and western branch of the Xiaojiang fault is prone to multi-segment ruptures, and lack of mediate earthquqakes.

Cheng et al., 2021. JAES

Summary

- 1. In PSHA modeling, We use the seismicity rates based on the fault slip rate, which makes the our modeling more reliable.

- 2. Our PSHA modeling is based on the fault segmentation, and also consider multi-segment rupturing which is need to be included in prediction of the future seismic hazard.

- 3. a. The Xianshuihe fault has impending earthquake on the southern section, especially near to the F4~F5 segments.

  b. The Anninghe fault and the Zemuhe fault cannot rupture together.

  c. The southern and northern sections of the Daliangshan fault cannot rupture more than two segments.

  d. The middle section of the Xiaojiang fault is prone to multi-segment rupturing.

Thank you for your attention!