Disaster triggers disaster: Earthquake triggering by wet tropical cyclones

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Presentation content

- **Introduction –**

  Earthquakes and cyclones
- **Observations**
- **Temporal analysis**
- **Coulomb stress change calculations**
- **Triggering analysis**
- **Summary**

Are the two disasters related?

No. 248

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A Science Service Feature

? WHY THE WEATHER ?

Dr. Charles F. Brooks,
of Clark University.
discusses:

EARTHQUAKES AND STORMS

The coincidence of earthquakes and intense cyclones has often been noted. Where conditions are ripe for an earthquake the earth's crust is in an unstable condition. It is possible that the stresses accompanying the passage of a severe cyclone may be sufficient to initiate the quake.

It is clear that tropical cyclones subject the earth's crust to an appreciable and relatively sudden strain, especially on coasts. A drop of two inches in barometric pressure means that a load of about two million tons is removed from each

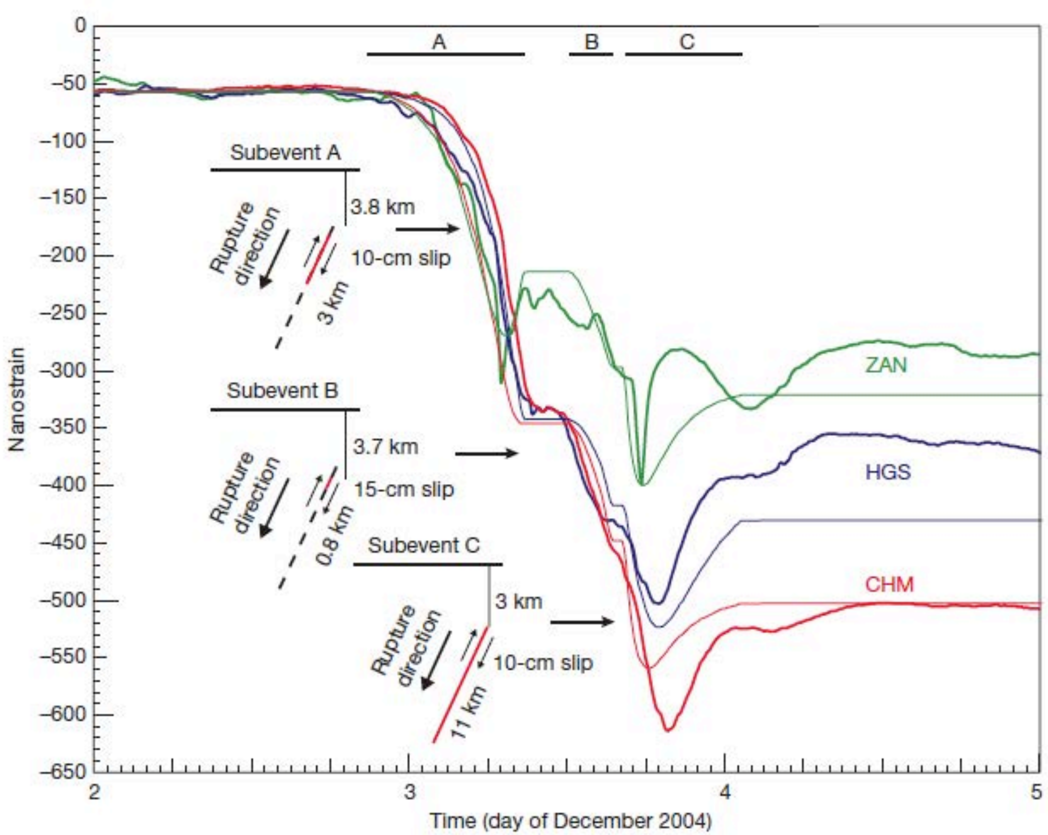
Brooks (1924)

Are the two disasters related?

Slow earthquakes triggered by typhoons

ChiChing Liu[1], Alan T. Linde[2] & I. Selwyn Sacks[2]

Nature 2009



Slow strain release 2-3 days after the typhoon.

Mechanism:
The typhoon's lower pressure results in a very small unclamping of the fault that must be close to the failure condition for the typhoon to act as a trigger.

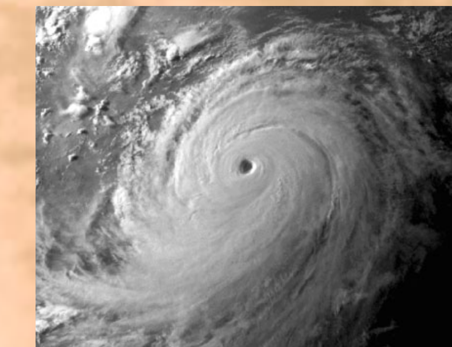
Devastating earthquakes - Wet tropical cyclones

1999 M=7.3 Chi Chi (Taiwan)

2010 M=7.0 Haiti earthquake

2010 M=6.4 Kaohsiung (Taiwan)

1996 Typhoon Herb
(1987 mm in 2 days)



2008 severe hurricane season (Fay, Gustav, Hanna and Ike)

2009 Typhoon Morakot
(2855 mm in 5 days)

Triggering mechanism

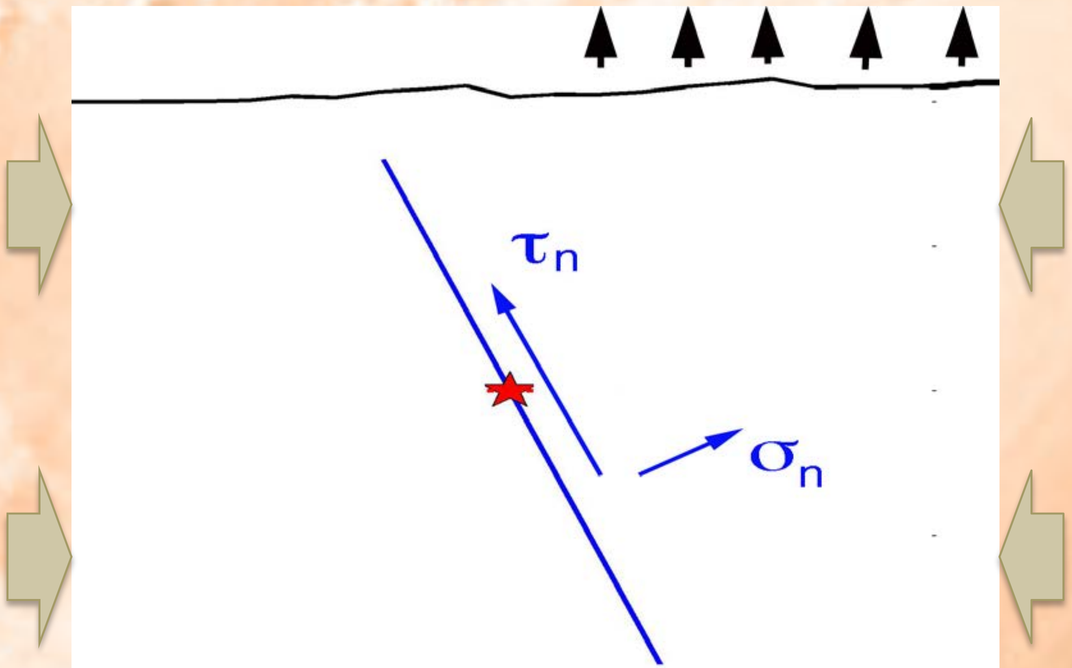
Wet Tropical Cyclones → Rapid erosion ⇔ Surface unloading

↓

Stress change at hypocenter

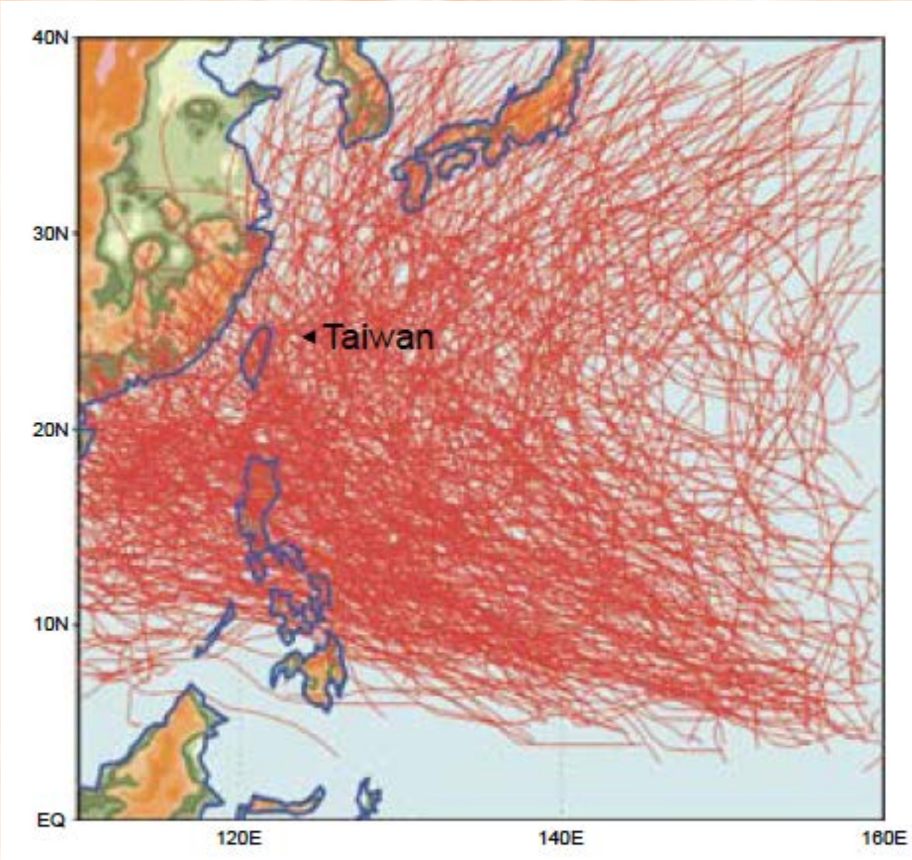
↓

Earthquake triggering

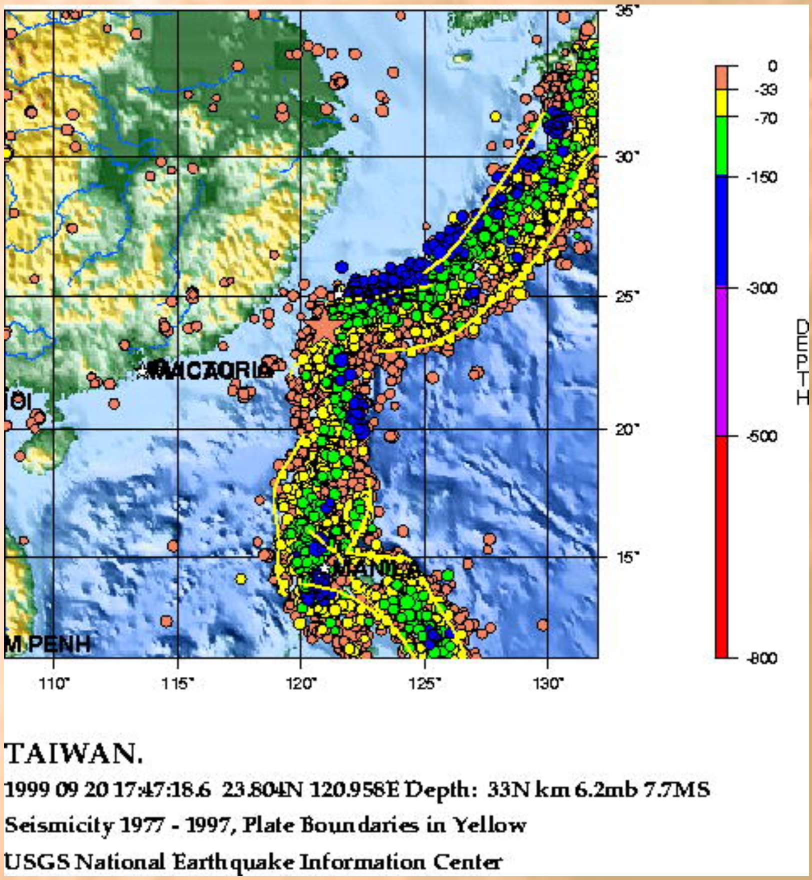


Stress accumulation due to tectonic loading

Taiwan: typhoons and earthquakes



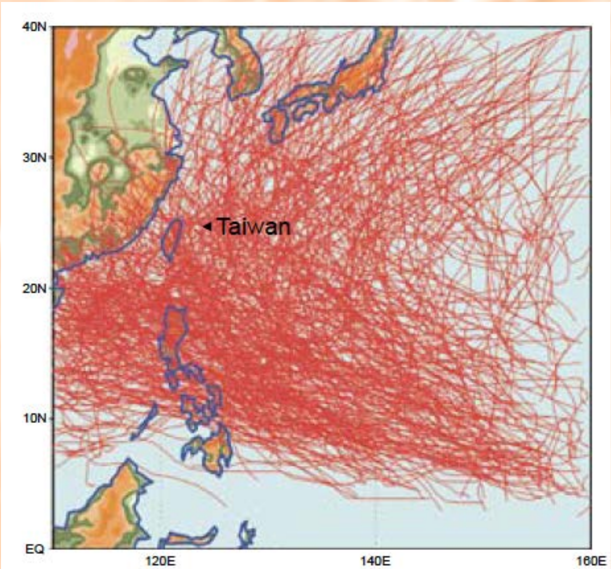
Typhoon tracks 1980-2005



Earthquakes M>4.5
(1976-1999)

Environmental Protection Administration
Executive Yuan, R.O.C. (TAIWAN)
http://www.epa.gov.tw

Taiwan: wettest typhoons



Typhoon tracks 1980-2005

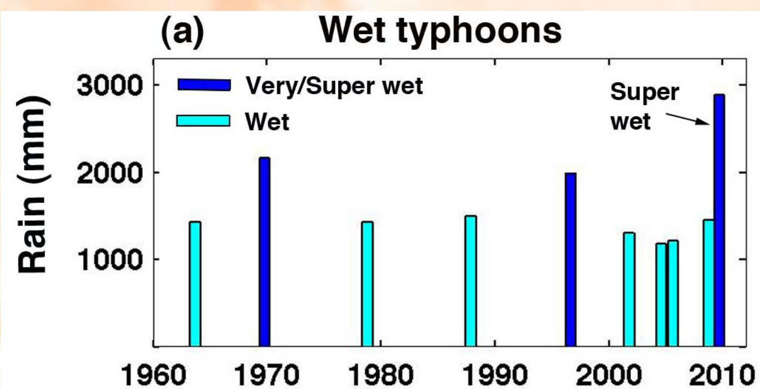


Table 1. Record of the 10 highest typhoon accumulation rainfalls during the last 50 years. Stations' elevation for A-Li station, An Pu and Chu Tze Hu are 2413 m, 826 m and 607 m, respectively. (TC: Tropical Cyclone, NE: Northeasterly, SW: southwesterly).

Typhoon name (CWB warning period)	Intensity classification* Characteristics	Accumulation rainfall in mm (duration) station	Casualties including Death and missing
MORAKOT 2009/08/5–10	Intermediate TC Traversing CMR+ SW monsoon	2855 mm (100 h) A-Li Shan	695
FLOSSIE 1969/10/1–7	Intermediate TC nearby + NE monsoon	2162 mm (120 h) An Pu	105
HERB 1996 07/29–08/01	Strong TC Traversing CMR	1987 mm (48 h) A-Li Shan	73
LYNN 1987/10/23–27	Strong TC nearby + NE monsoon	1497 mm (96 h) Chu Tze Hu	63
SINLAKU 2008/09/9–17	Strong TC Traversing CMR	1458 mm (96 h) A-Li Shan	21
ORA 1978/10/11–14	Intermediate TC nearby + NE monsoon	1434 mm (96 h) Chu Tze Hu	7
GLORIA 1963/9/8–13	Strong TC nearby + NE monsoon	1433 mm (96 h) A-Li Shan	363
NARI 2001/9/6–20	Intermediate TC Traversing CMR	1304 mm (72 h) Chu Tze Hu	104
HAITANG 2005/7/16–20	Strong TC Traversing CMR	1216 mm (72 h) A-Li Shan	15
MINDULLE 2004/06/28–07/02	Intermediate TC Traversing CMR	1182 mm (72 h) A-Li Shan	45

* The CWB's classification of typhoons is based on the maximum wind speed: the light typhoon: 17.2–32.6 m/s; the intermediate typhoon: 32.7–50.9 m/s; the severe typhoon: ≥51 m/s.

Ten wettest typhoons (1960-2010)
[Lin et al., 2010]

Typhoon Morakot (2009)

Typhoon name (CWB warning period)	Intensity classification* Characteristics	Accumulation rainfall in mm (duration) station	Casualties including Death and missing
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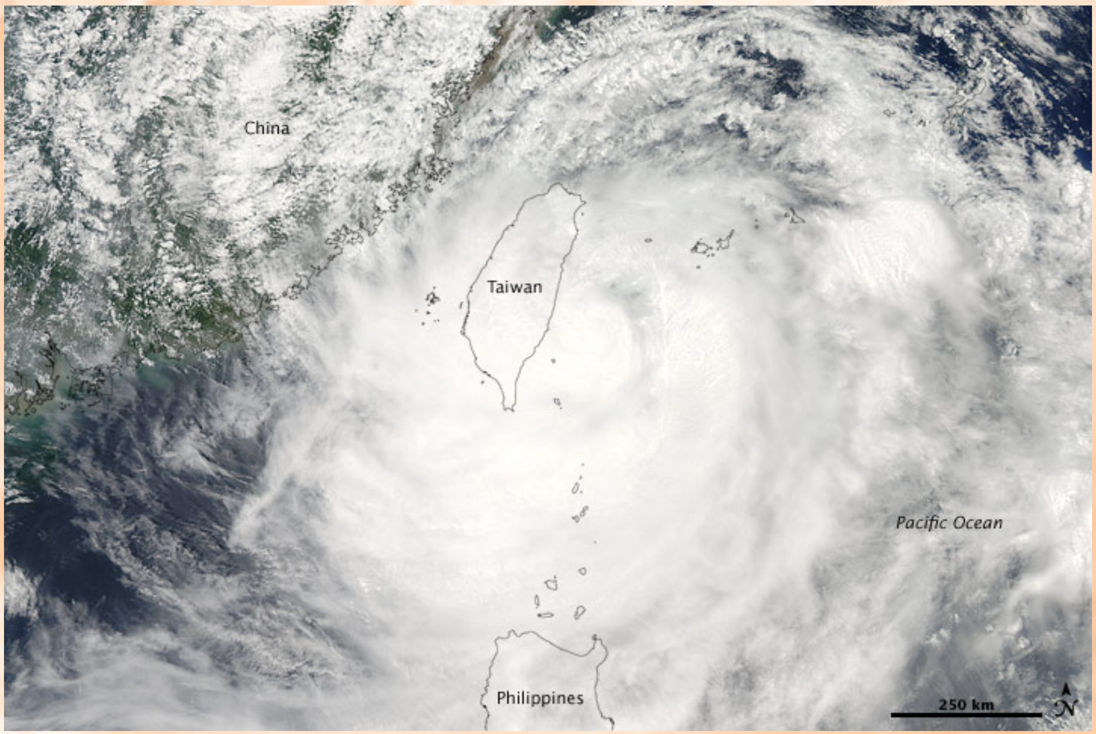

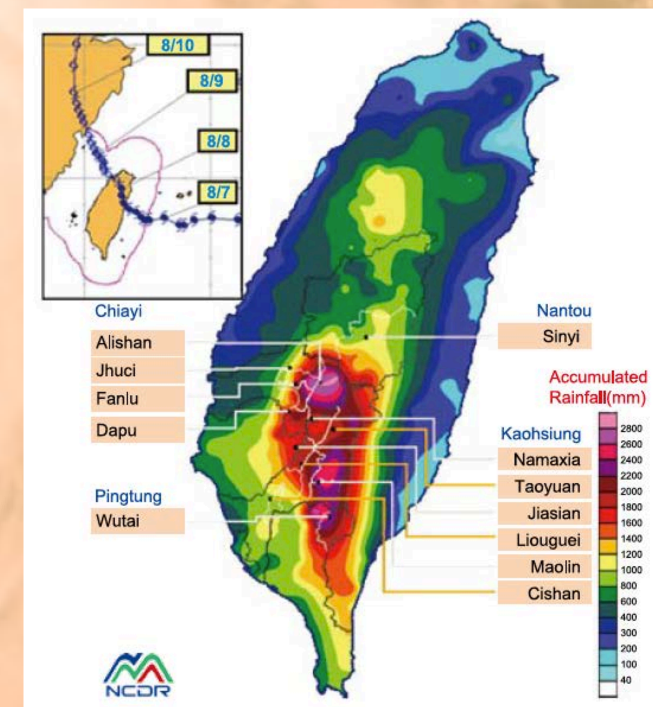

NASA, MODIS image – August 7, 2009

Environmental Protection Administration
Executive Yuan, R.O.C. (TAIWAN)
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Typhoon Morakot (2009)

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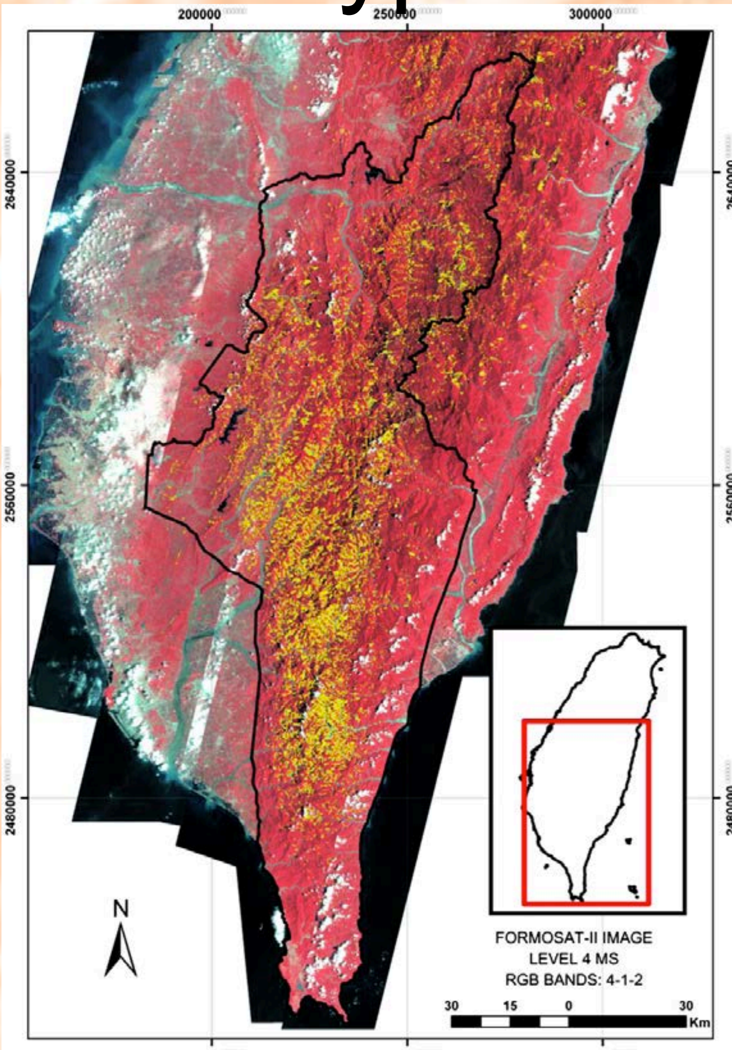
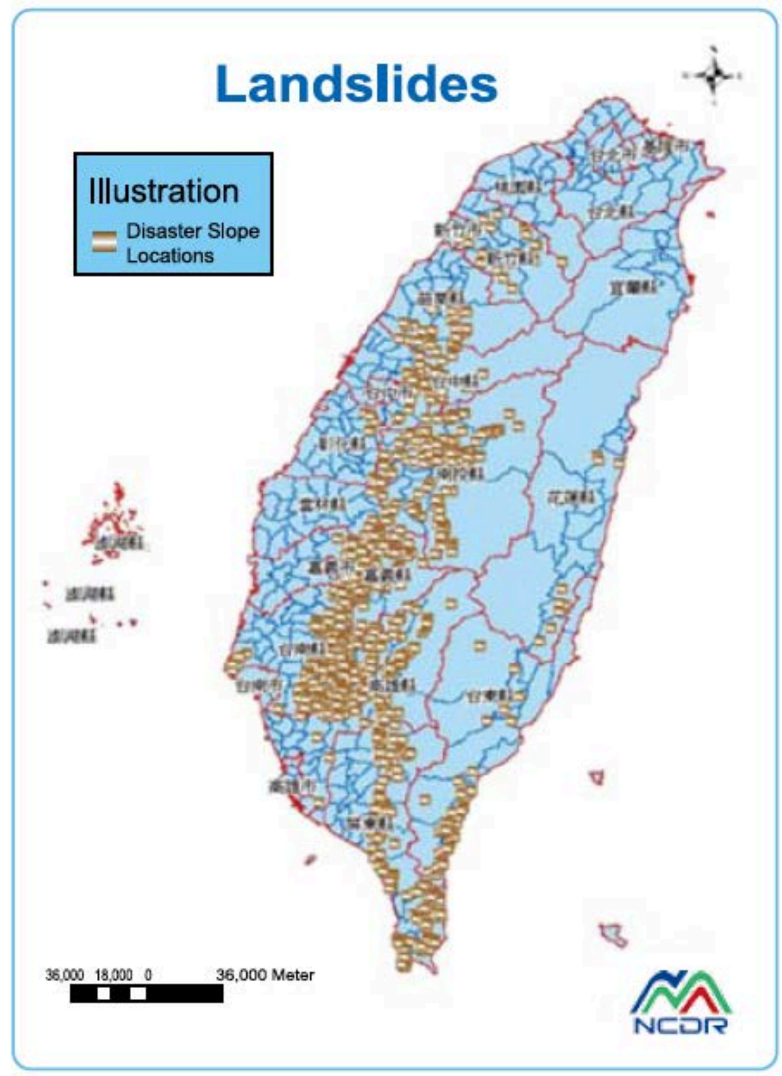
Typhoon Morakot (2009)





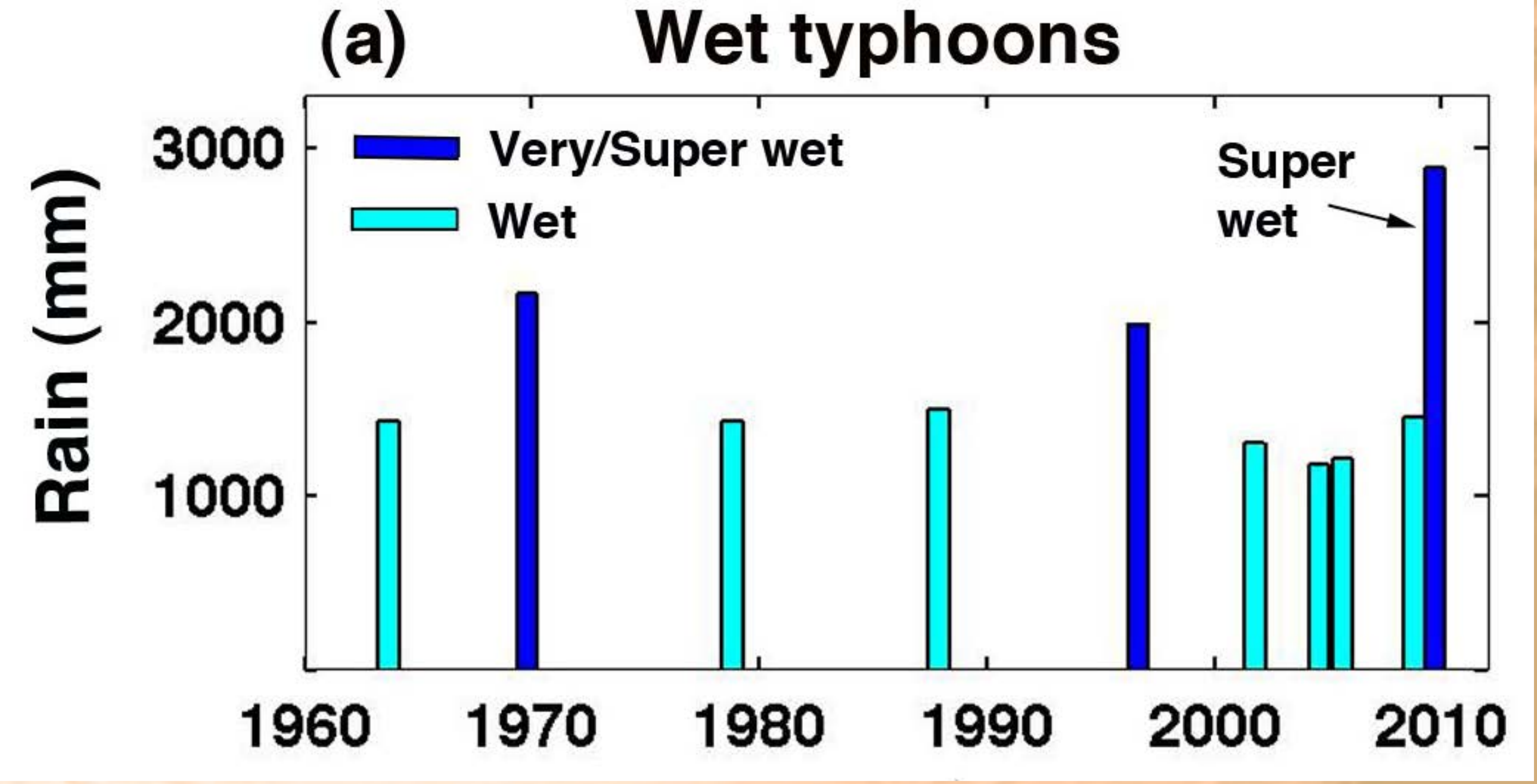
Triggered landslides
(at least 22,705)
[Lin et al., 2011]

Environmental Protection Administration
Executive Yuan, R.O.C. (TAIWAN)
http://www.epa.gov.tw

Typhoon Morakot: landslide around Xiaolin village

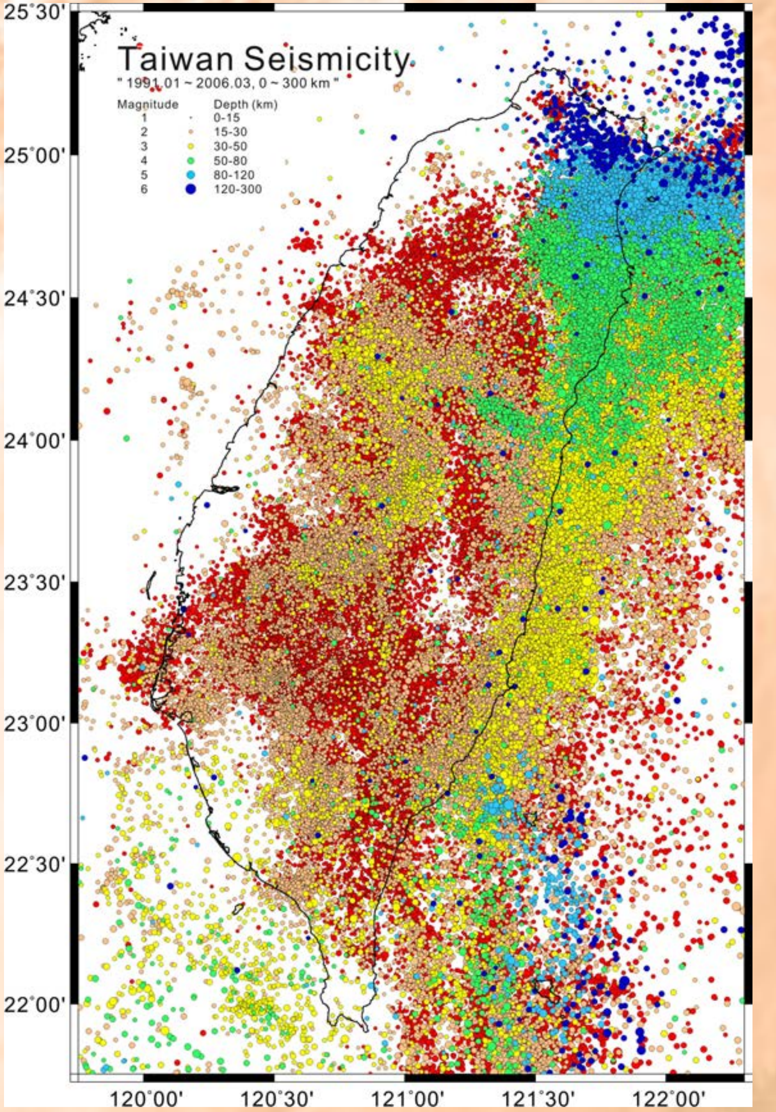
[Lin et al., 2010]

Taiwan: wettest typhoons



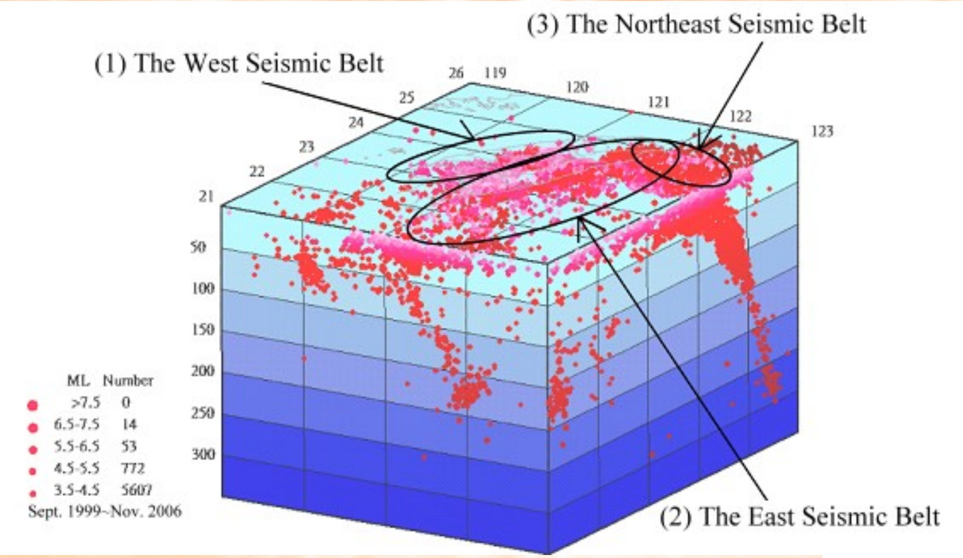
Ten wettest typhoons (1960-2010)
[Lin et al., 2010]

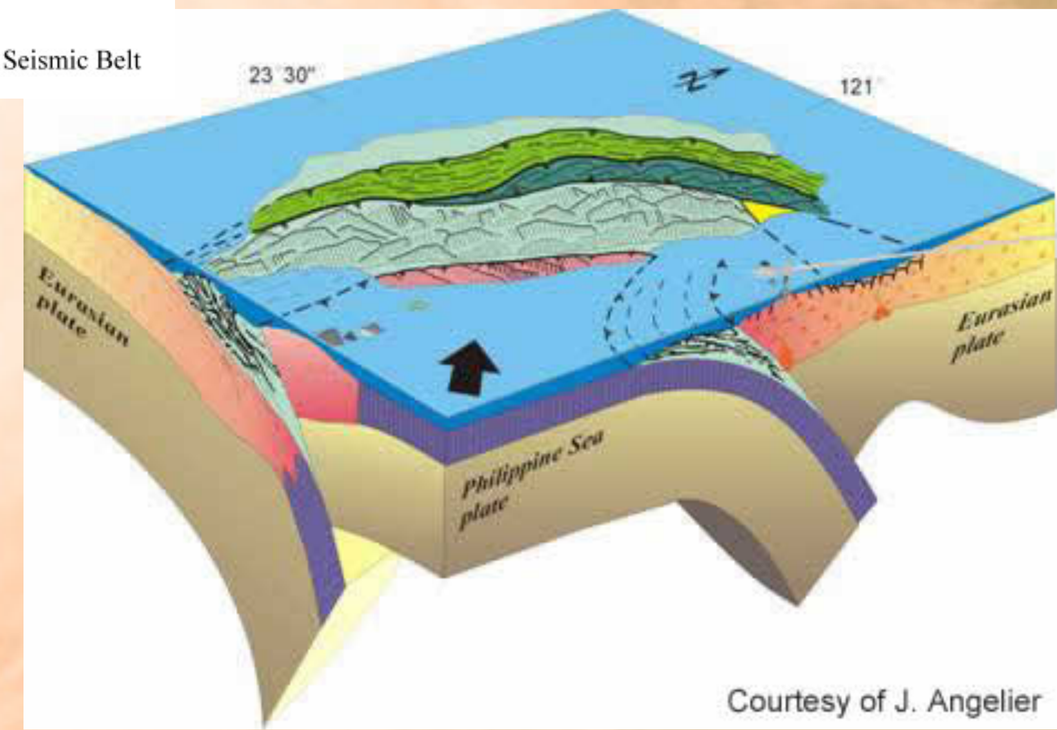
Taiwan: seismicity (1991-2006)



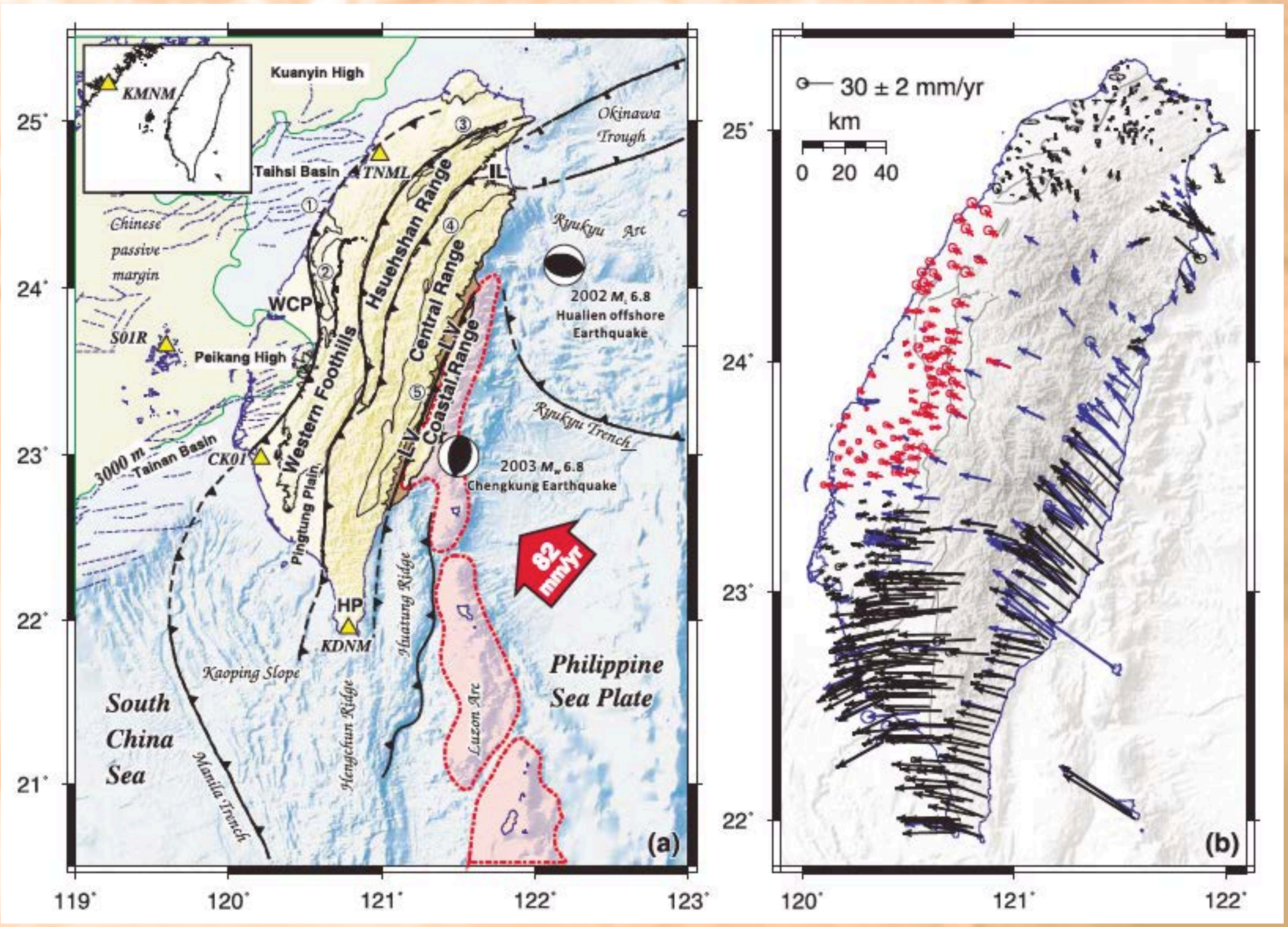
[Hsu, 2009]

Taiwan: seismicity and tectonics



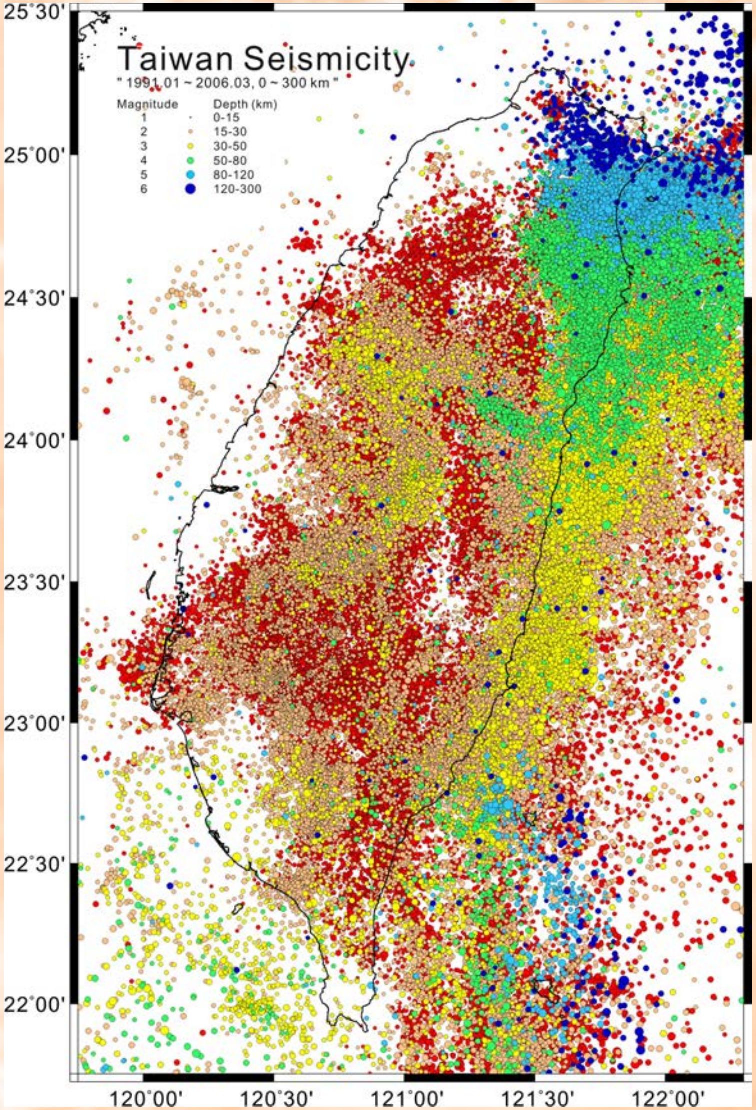


Taiwan: crustal deformation

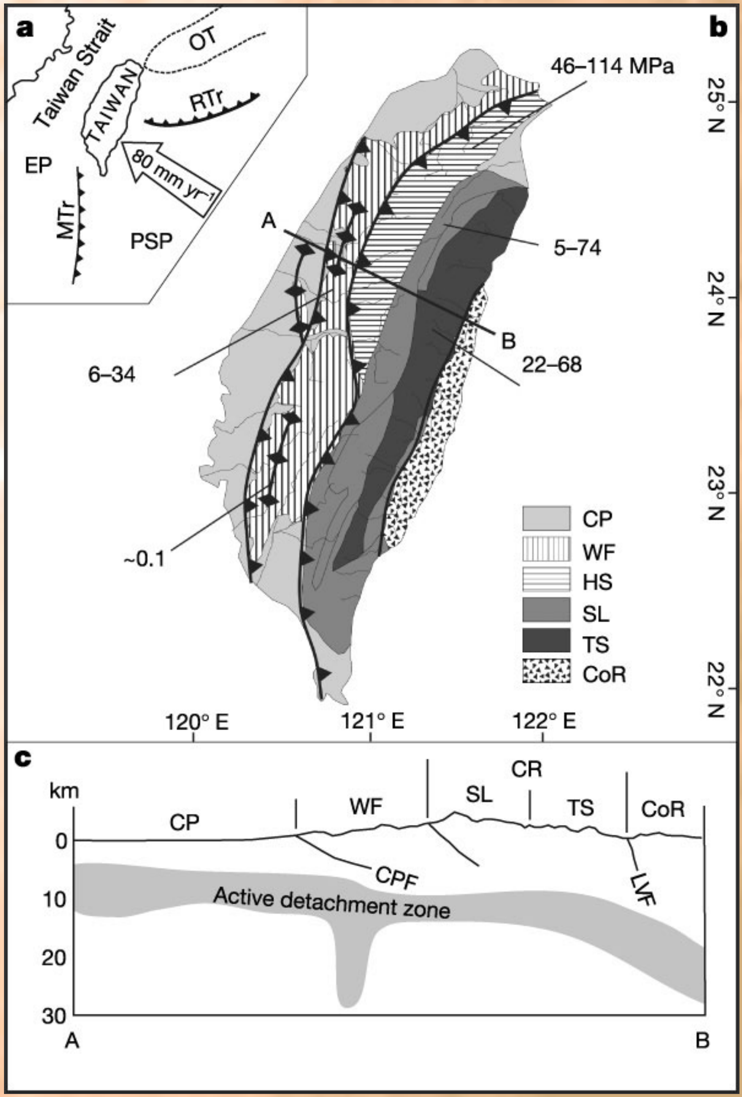


Ching et al. (2011)

Taiwan: seismicity and faults



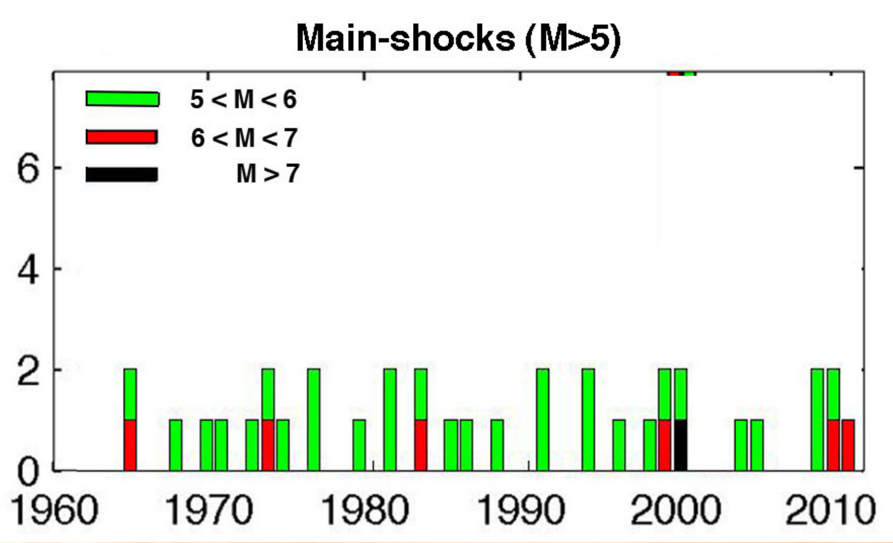
[Hsu, 2009]



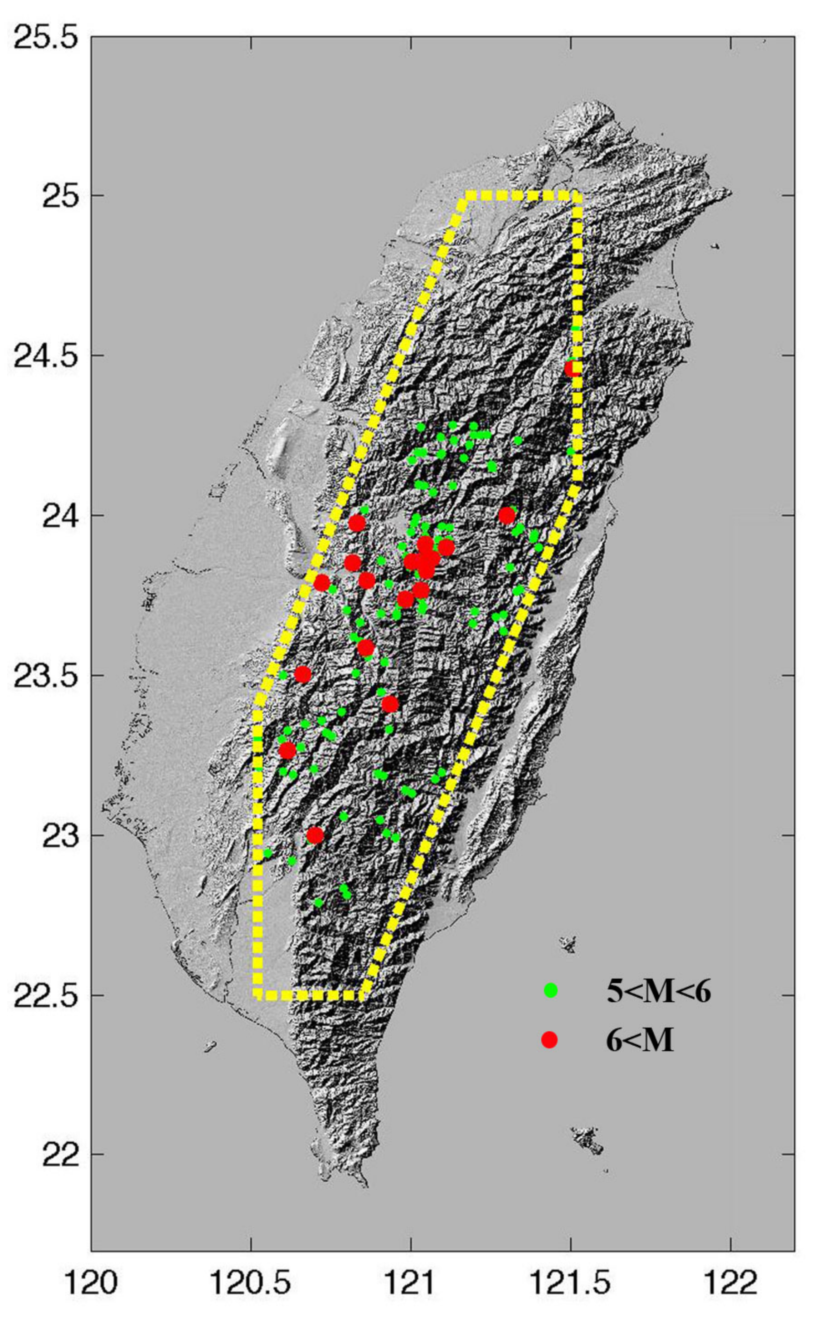
[Dadson et al., 2004]

Seismicity in the mountainous area

M > 5
1960-2010

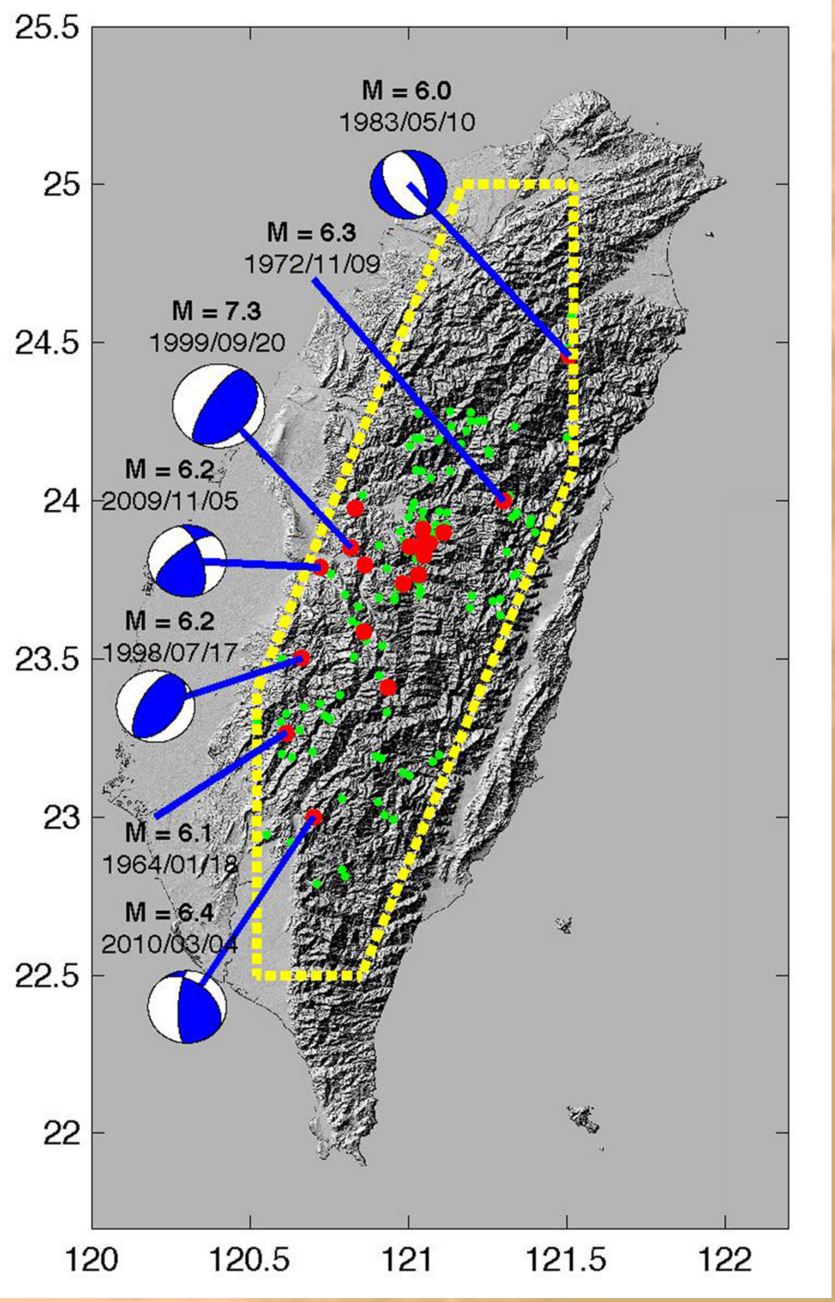


[Source: Taiwan Event Catalog]



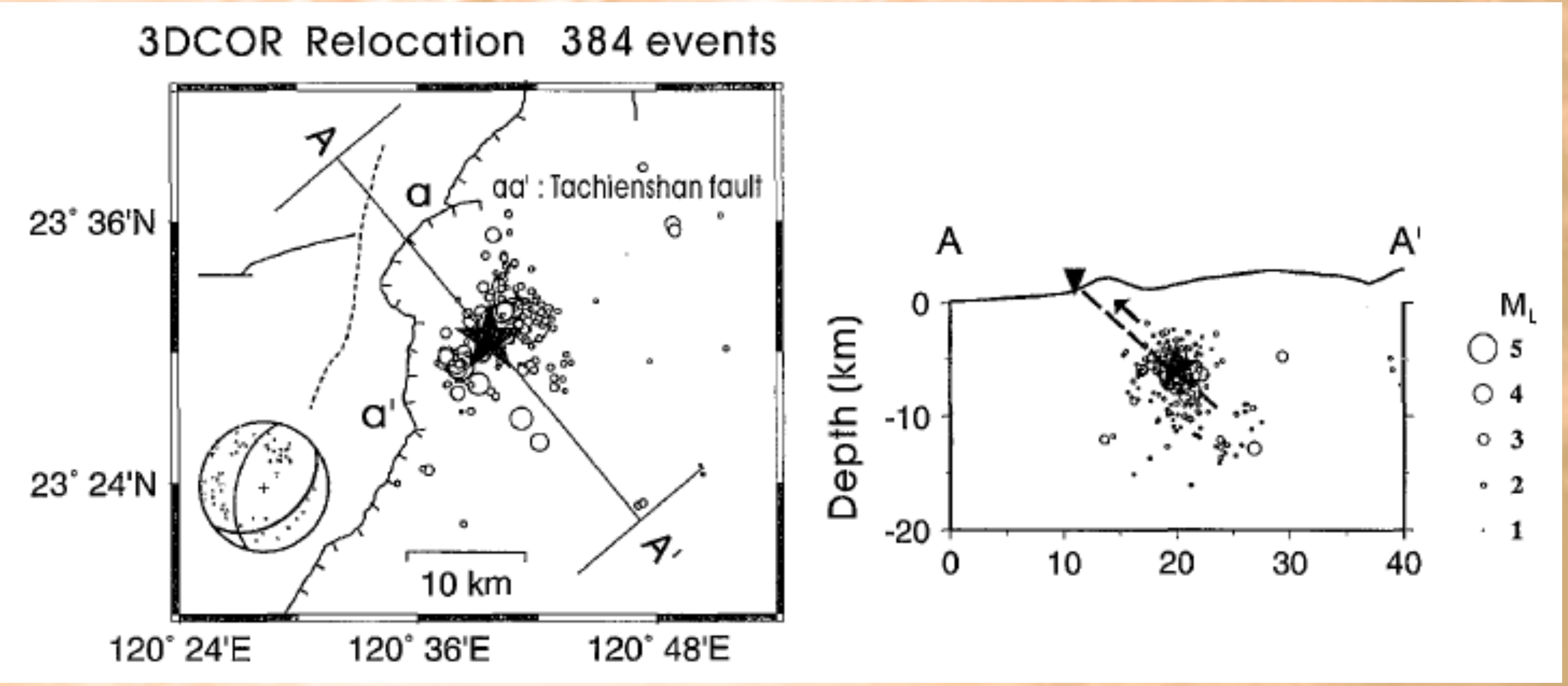
Seismicity in the mountainous area (M>6)

Name	Date	Mag.	Depth	Casualties
	1964-01-18	6.1	18.0	
	1972-11-09	6.3	10.0	
	1983-05-10	6.0	1.2	
Rueyli	1998-07-17	6.2	5.6	
Chi Chi	1999-09-20	7.3	8.0	> 2,000 death
Nantou	2009-11-05	6.2	24.1	
Kaohsiung	2010-03-04	6.2	24	96 injuries



[Source: Taiwan Event Catalog]

The M=6.2 Rueyli earthquake

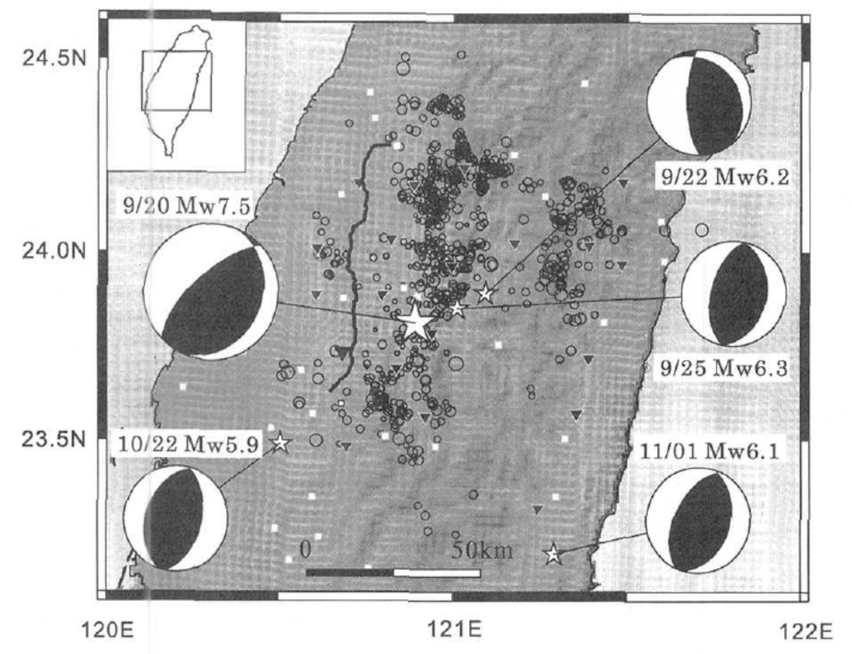


Wu et al. (2003)

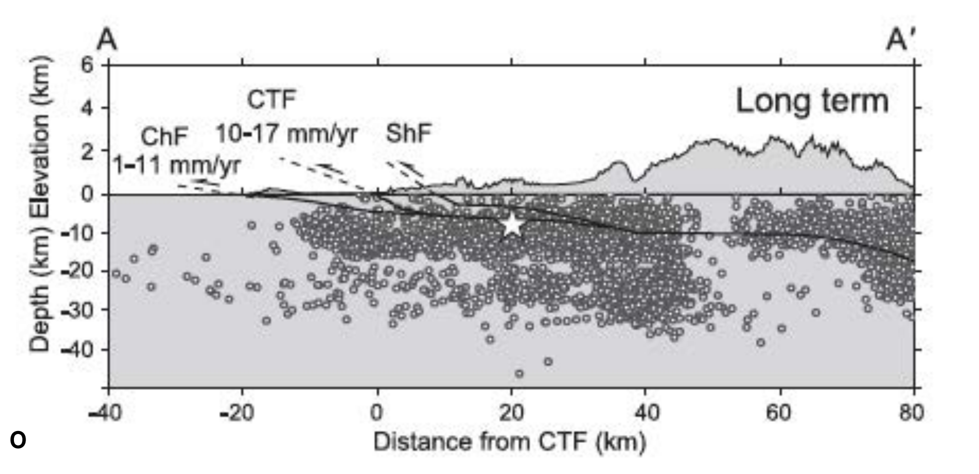
The earthquake ruptured the Tachienshan Fault

Magnitude: 6.2
Depth: 5.6 km
Dip: 40º

The M=7.3 Chi Chi earthquake



Kikuchi et al. (2000)



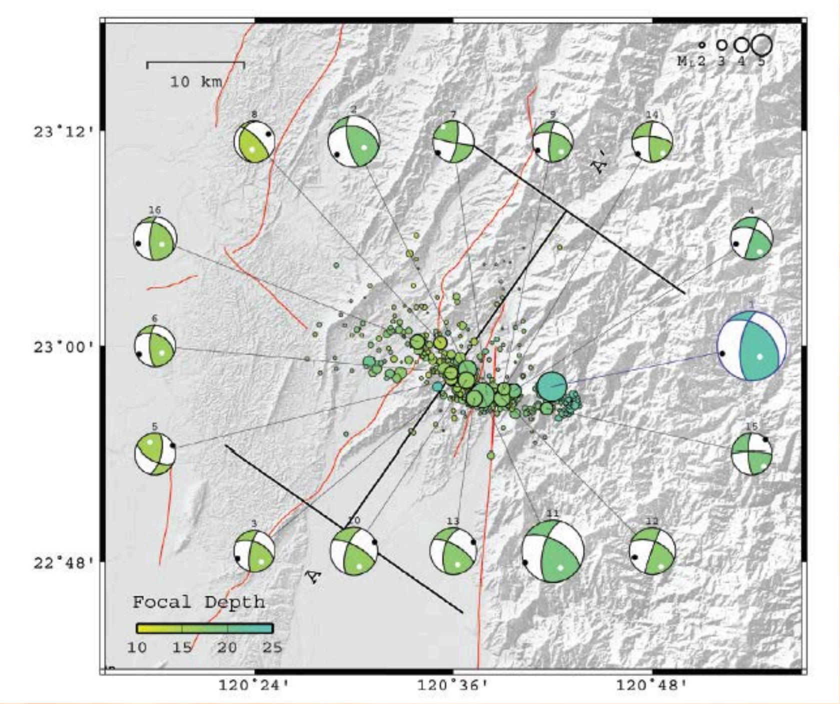
o

Cattin et al. (2004)

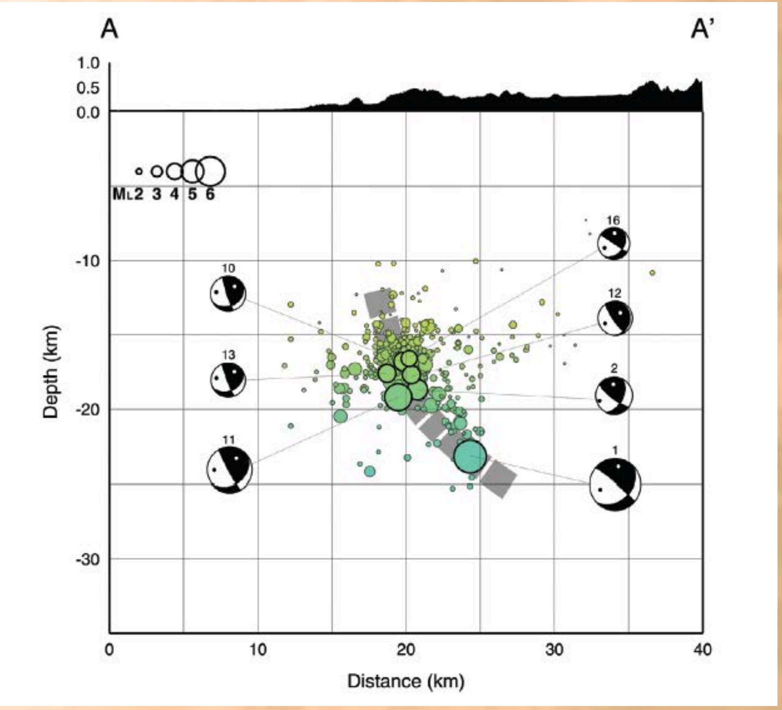
The earthquake ruptured the Chelungpu Thrust Fault (CTF)

Magnitude: 7.3
Depth: 12 km
Dip: 22º

The M=6.2 Kaohsiung earthquake



Huang et al. (2011)



The earthquake ruptured a blind thrust

Magnitude: 6.2
Depth: 24 km
Dip: 41º

Strong earthquake hits Taiwan; 64 people injured

Associated Press

Buzz up! 563 votes | Send | Share | Print

By PETER ENAV, Associated Press Writer – Thu Mar 4, 7:14 am ET

AP – Firemen battle a blaze at a textile factory that started shortly after a strong earthquake jolted the ...

TAIPEI, Taiwan – A powerful 6.4-magnitude earthquake rocked southern Taiwan on Thursday, terrifying residents, disrupting communications and triggering at least one large fire. Sixty-four people were injured, the National Fire Agency said.

No tsunami alert was issued. The quake was centered in the same mountainous region of rural Kaohsiung county that endured the brunt of the damage from Typhoon Morakot, a devastating storm that killed about 700 people last August.

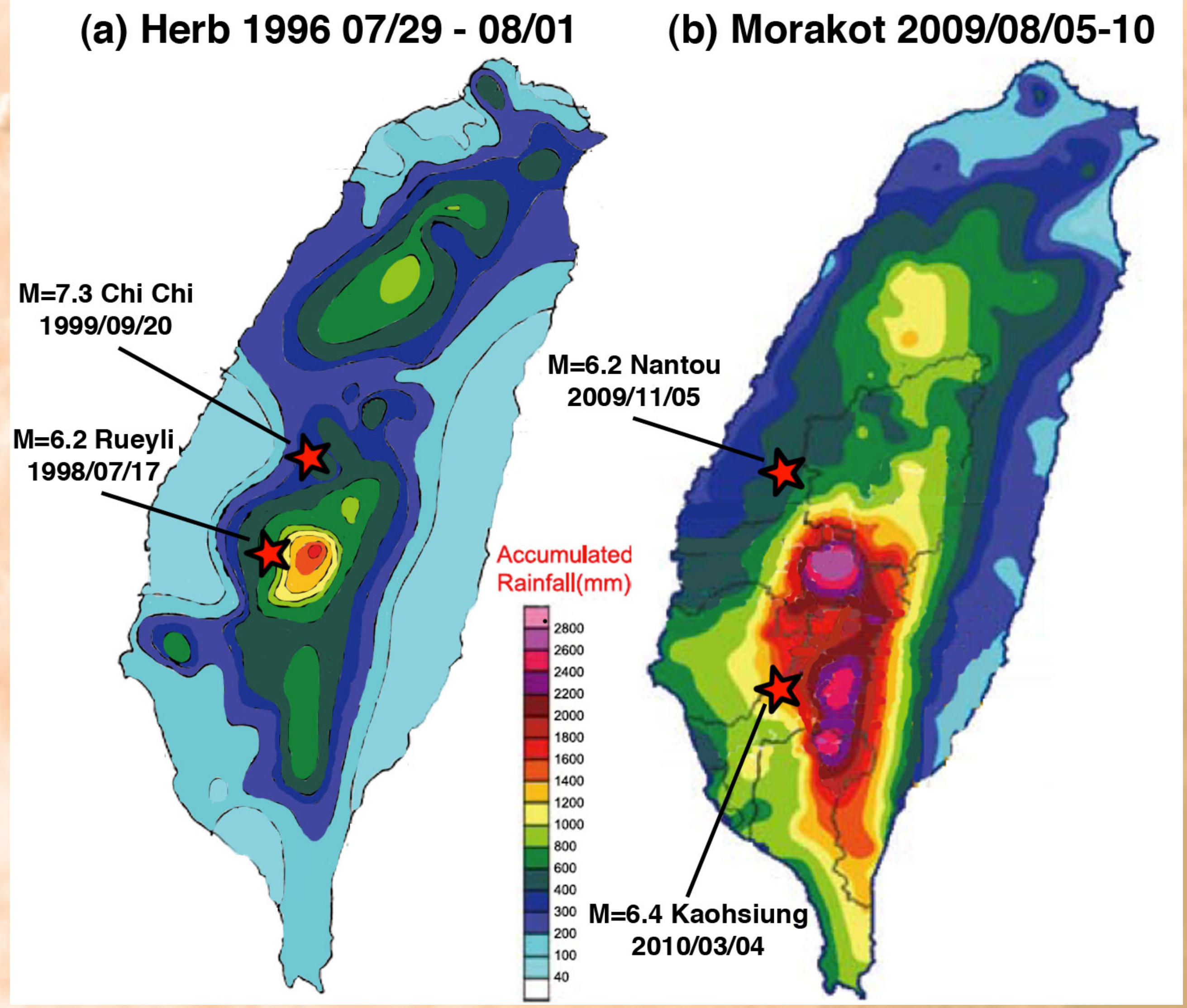
Taiwanese actor Chu Chung-heng said he and other passengers were close to panic when the high-speed train on which they were traveling was dislodged from its track by the quake.

"Many people in my car were screaming," he said. "I was so scared that I couldn't make a sound. The train shook very hard, and I thought it was going to overturn."

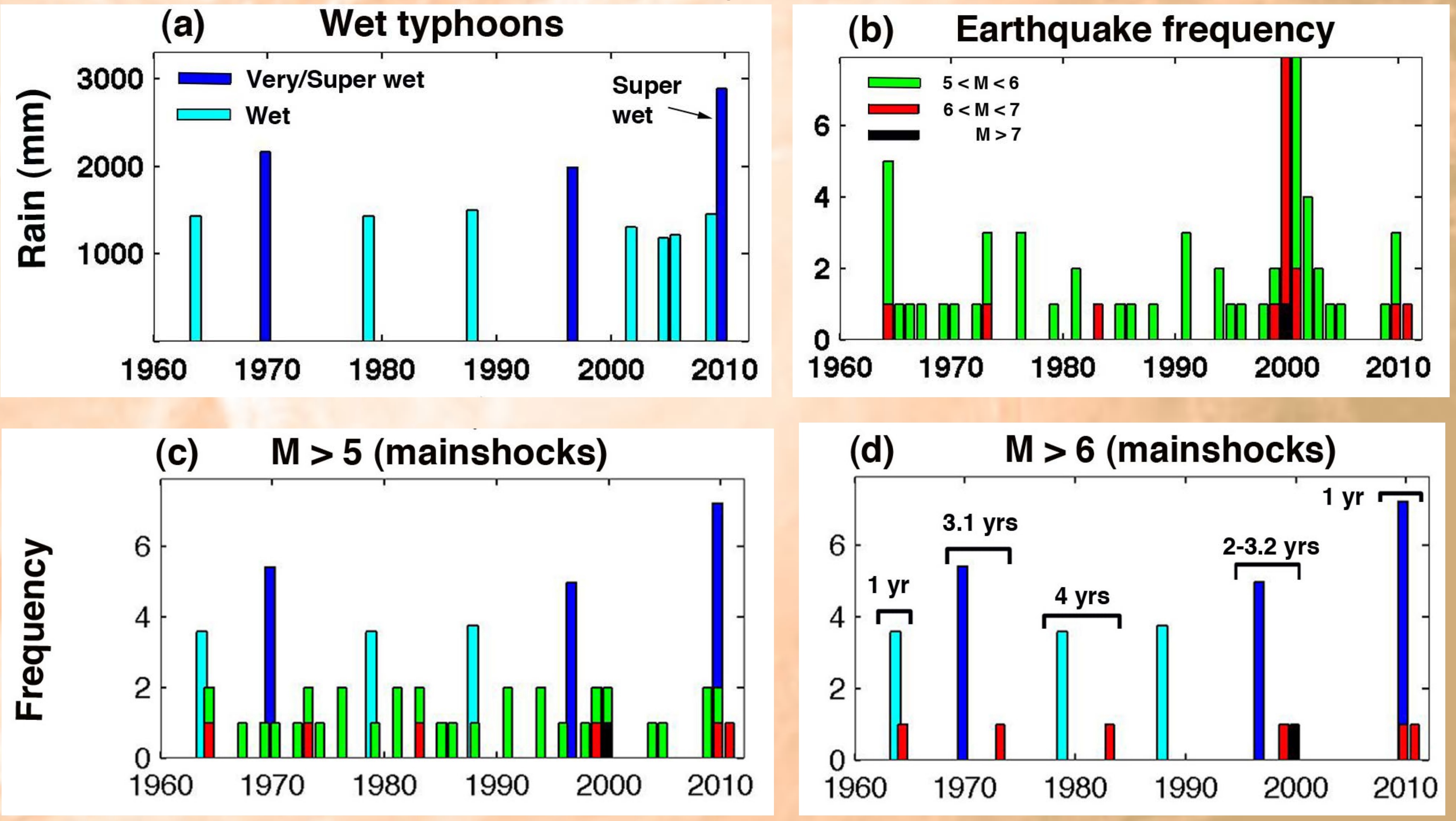
Rail service in southern and central Taiwan was suspended, as was the state-of-the-art subway system in Kaohsiung city, Taiwan's second largest with a population of 1.5 million. Kaohsiung is about 250 miles (400 kilometers) south of Taipei.

The quake's epicenter was near the town of Jiashian, especially hard hit by last year's typhoon. A Kaohsiung county official told CTI TV news that some temporary housing built for typhoon survivors collapsed.

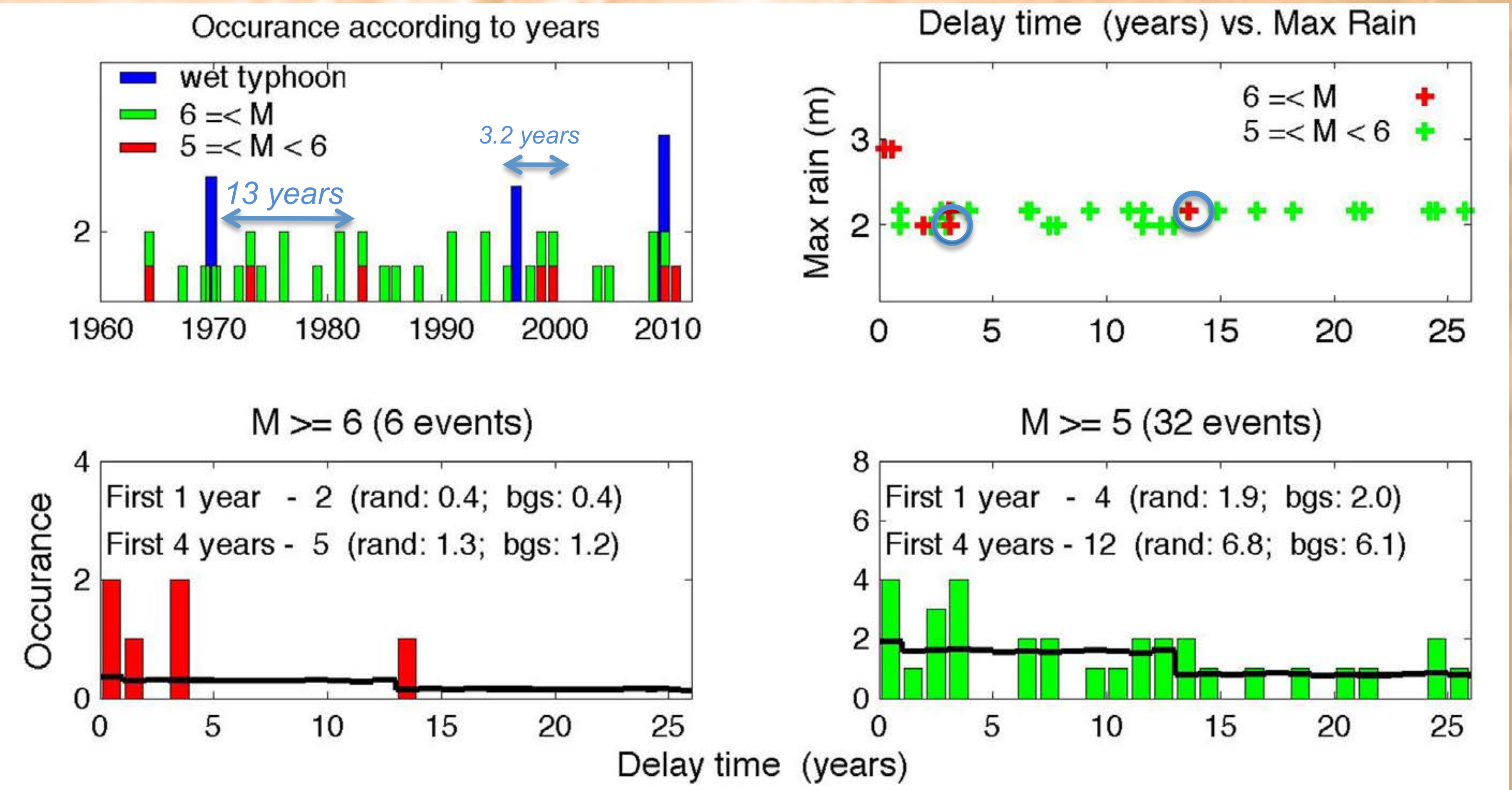
Spatial relations between wet typhoon rainfall and M>6 main-shock epicenters



Seismicity in the mountainous area vs. wet typhoons



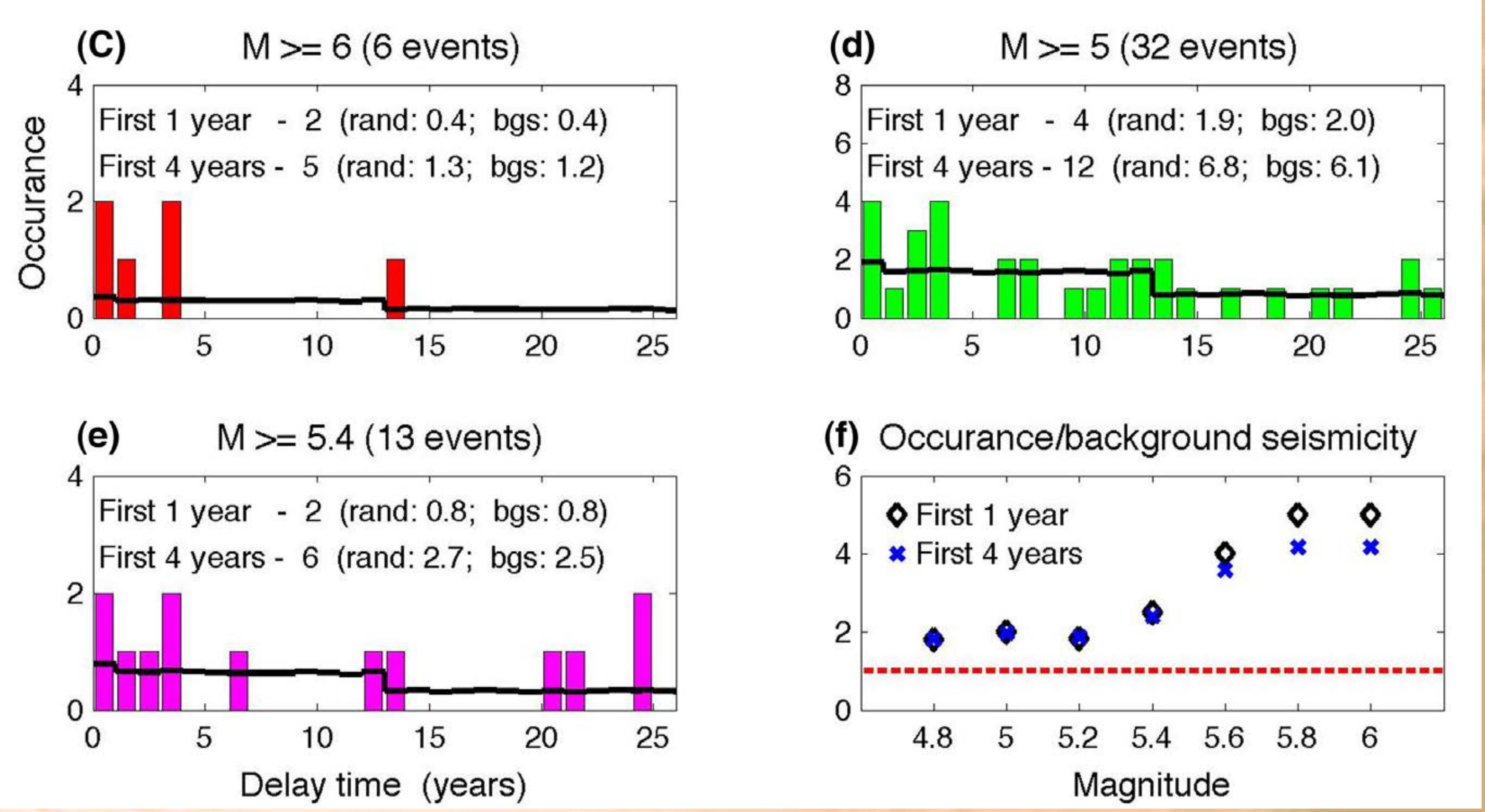
Temporal (delay) analysis



M≥6: 85% of earthquakes occurred within first 4 years (5 times the expected).

M≥5: 35% of earthquakes occurred within first 4 years (twice the expected).

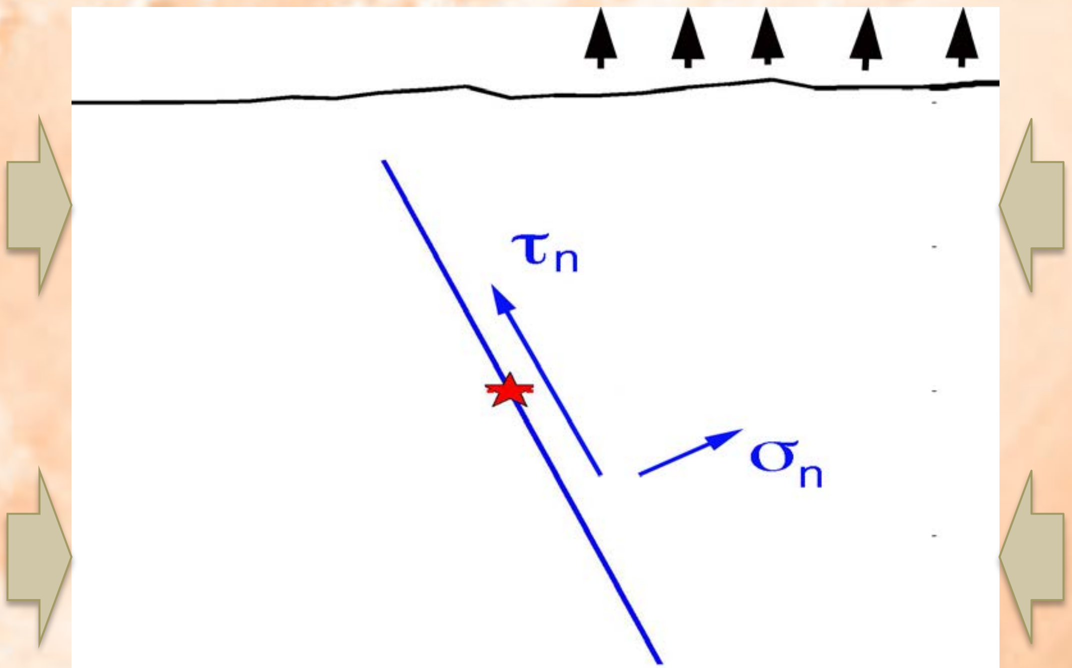
Temporal (delay) analysis



The delay analysis indicates a magnitude dependent temporal clustering.

Triggering mechanism

Wet Tropical Cyclones → Rapid erosion ⬄ Surface unloading



Stress accumulation due to tectonic loading

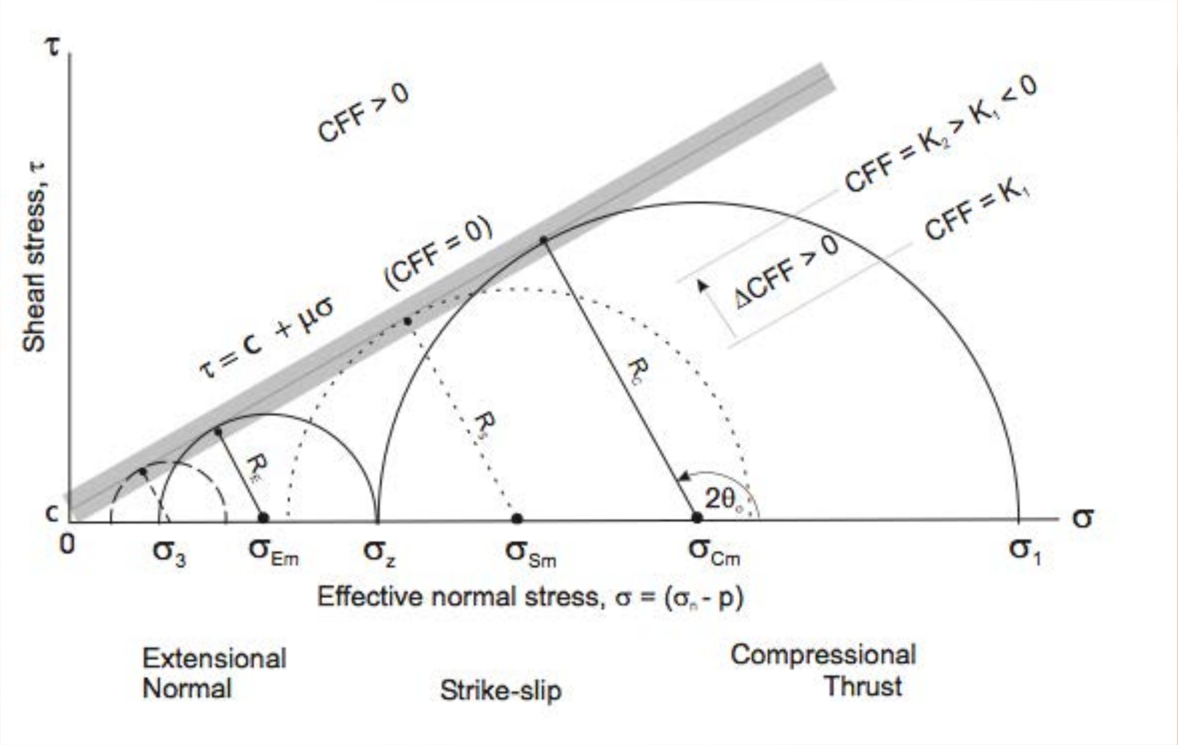
Surface unloading → Stress change at hypocenter → Earthquake triggering

Static vs Dynamic Triggering

- Static Triggering (ST)
  - Displacement along faults caused during an earthquake increases stress nearby
    - Stress then released through an earthquake
    - Possibly advances earthquake cycle
  - Aftershocks are very common and can be thought of as a result of ST
    - Redistribution of stress after the earthquake rupture
  - ST occurs usually within 2 fault lengths of rupture
    - Deformation displacement becomes small outside of this distance
  - Modeled as Coulomb Stress Failure
- Dynamic Triggering (DT)
  - Earthquakes caused by transient seismic signals
    - Seismic waves: Surface waves
    - Role of these waves not fully understood
  - Usually more that 2 fault lengths away from an earthquake fault plane
    - Has been documented to occur 3000 km away from epicenter
  - Early investigations and documentations thought unreliable (see Hill and Prejean, 2007 for discussion)
  - Causes are still being debated: CFF or fluid controlled
  - Numerous investigators now studying phenomena (e.g., Gomberg, Hill, Brodsky, Kilb, etc.)

Static Triggering: Coulomb Stress Failure

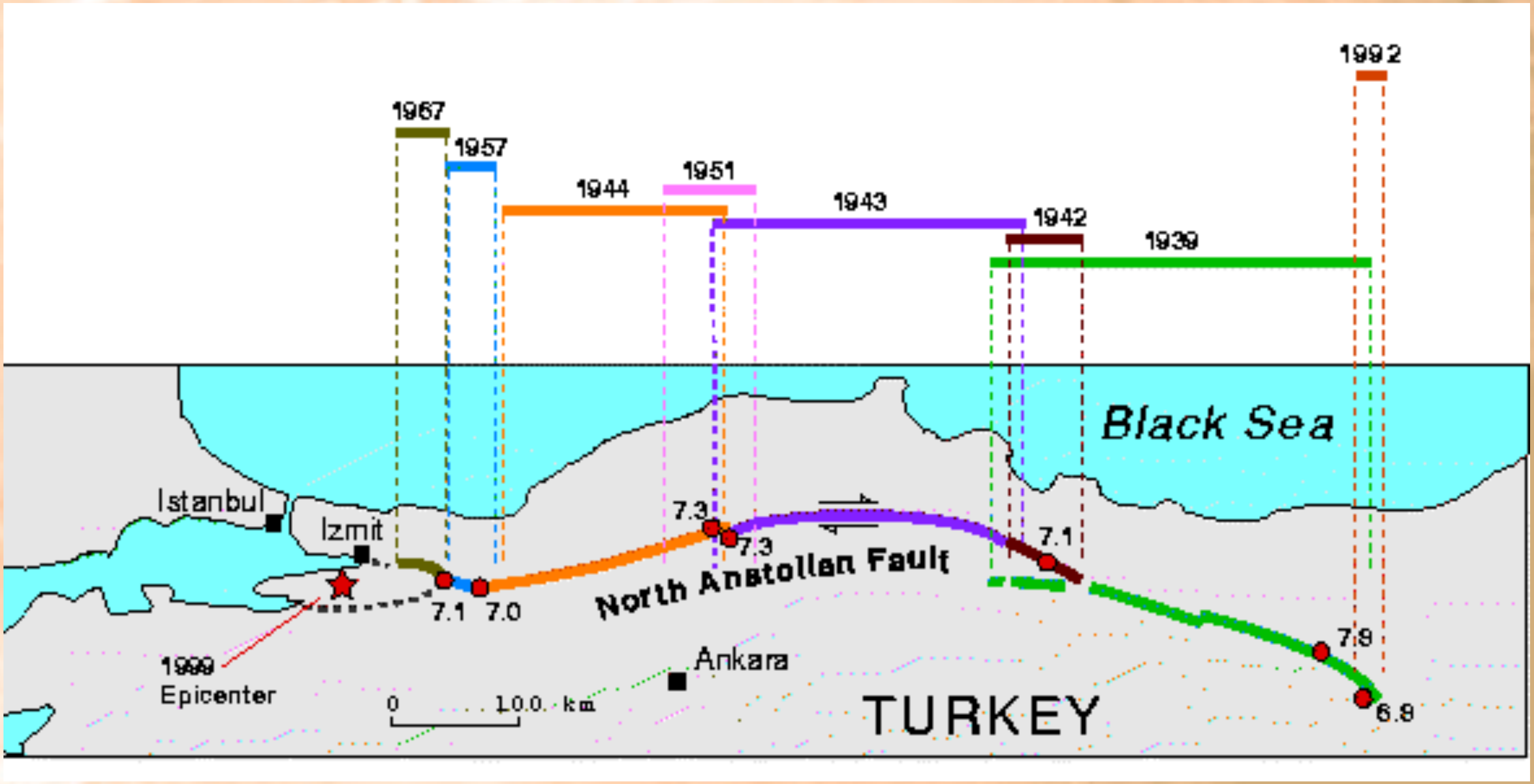
- Mohr Circle
  - Represents amount of shear stress (τ) along with normal stress (σ) to get failure
  - CFF: Coulomb Failure Criteria
  - P: Pore pressure (fluids) which reduce effective normal stress
- Failure depends on stress regime (principle axis orientation)
- In practice, we can only measure absolute stress in boreholes…or can we?

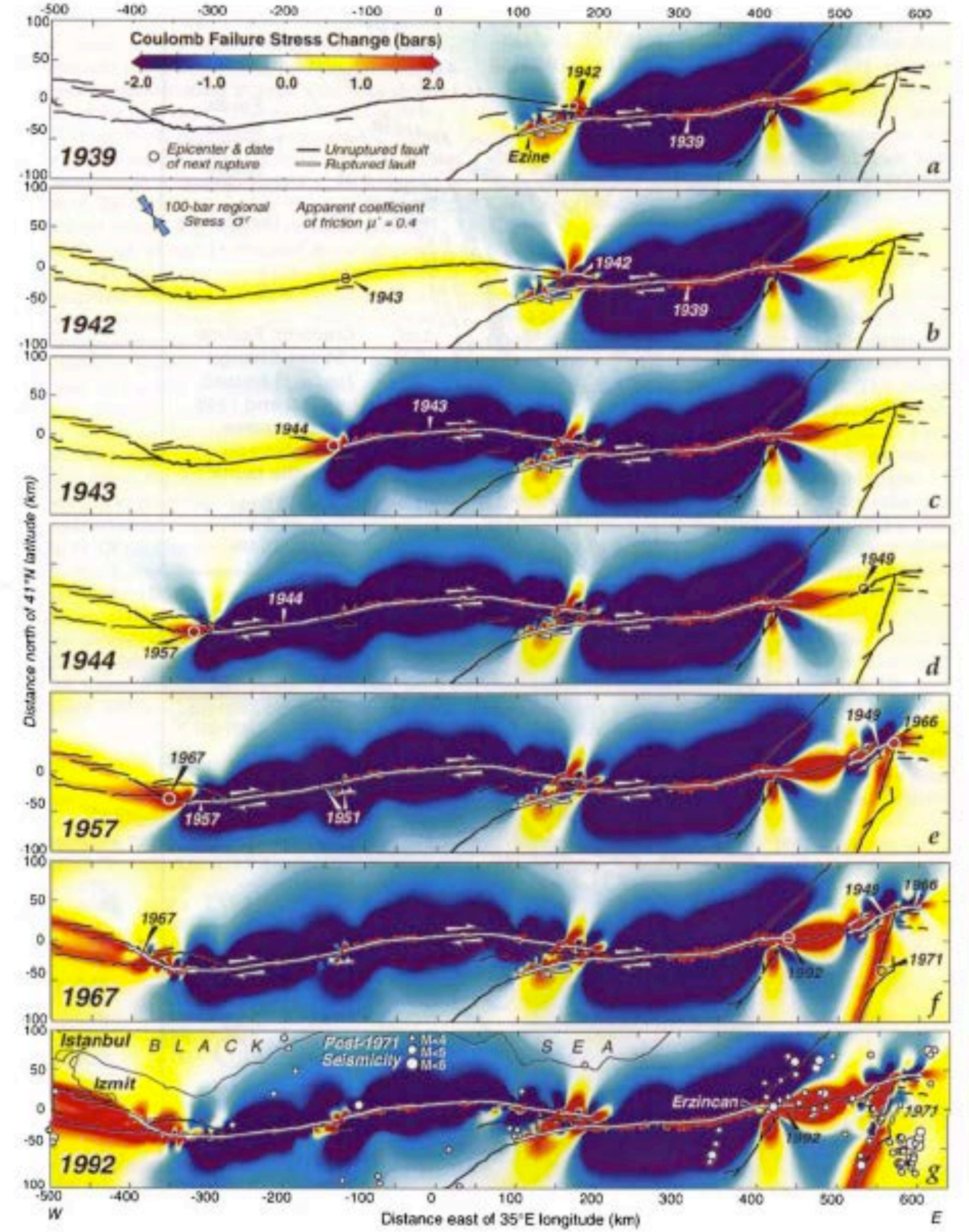


From Hill and Prejean, 2007

North-Anatolian Fault, Turkey

West-ward propagating series of events on the North Anatolian Fault 1939-1999



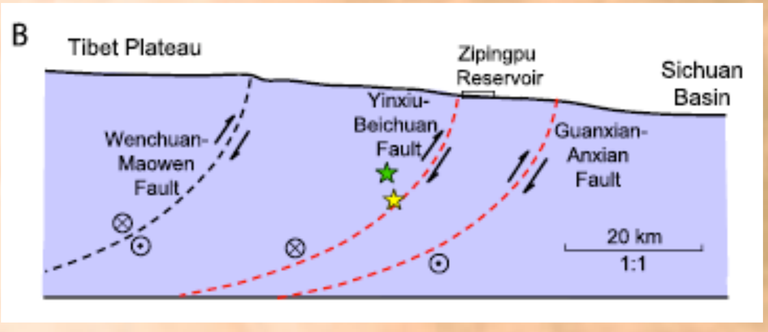


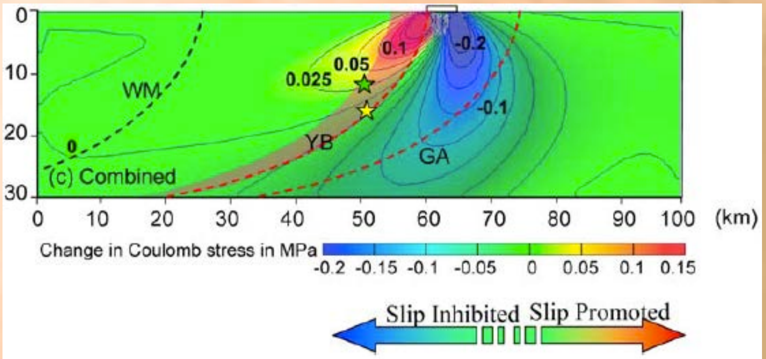
Coulomb failure calculations

[Stein et al., 1997]

Earthquake Triggering Mechanisms

- Earthquakes
- Volcanic eruption
- Dyke intrusion
- Earth tides
- Hydrologic loading
- Atmospheric loading
- Reservoir construction
- Glacier melt



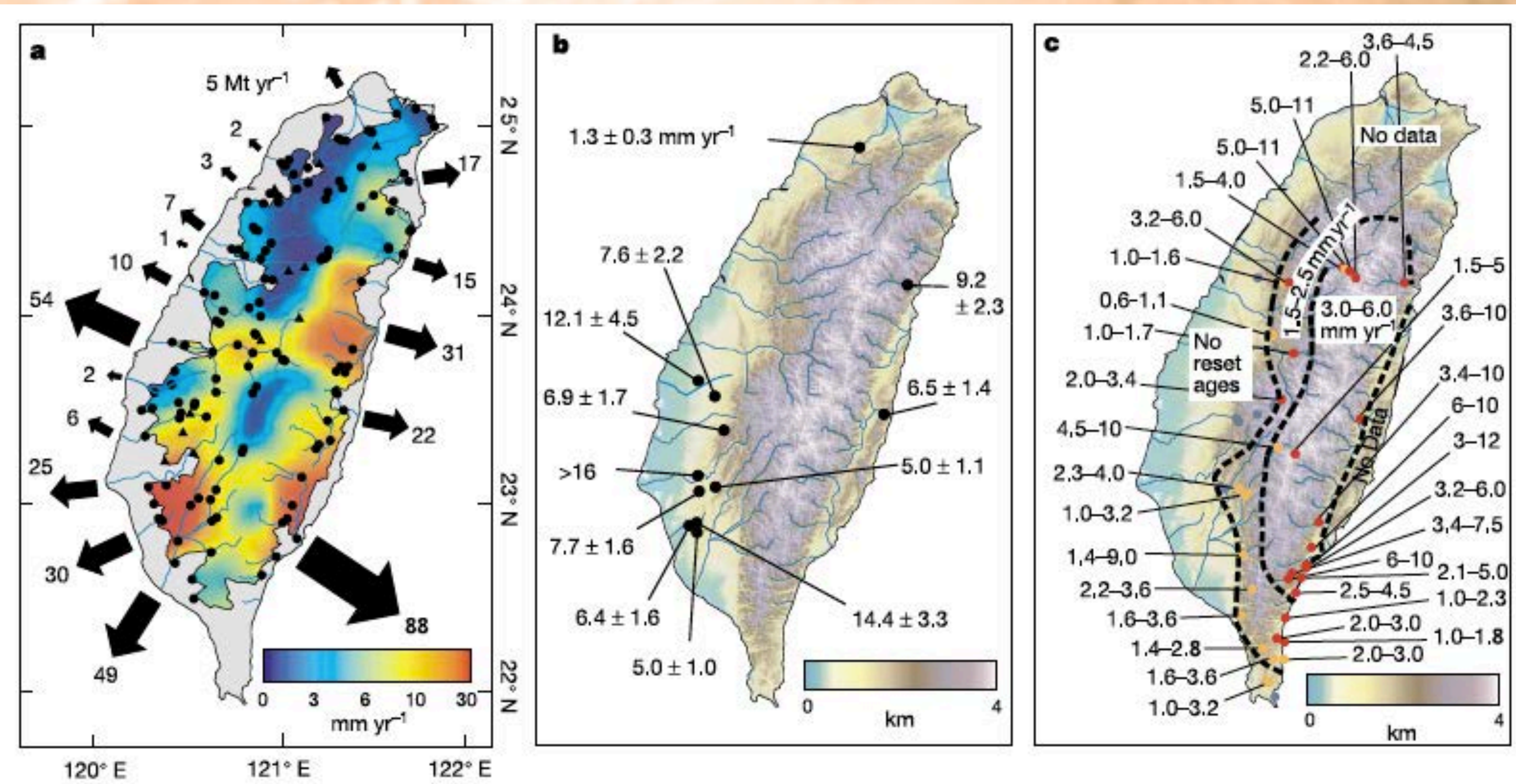


Triggering threshold – 10^4 Pa

Ge et al. (2009)
Did the Zipingpu Reservoir trigger the 2008 Wenchuan earthquake?

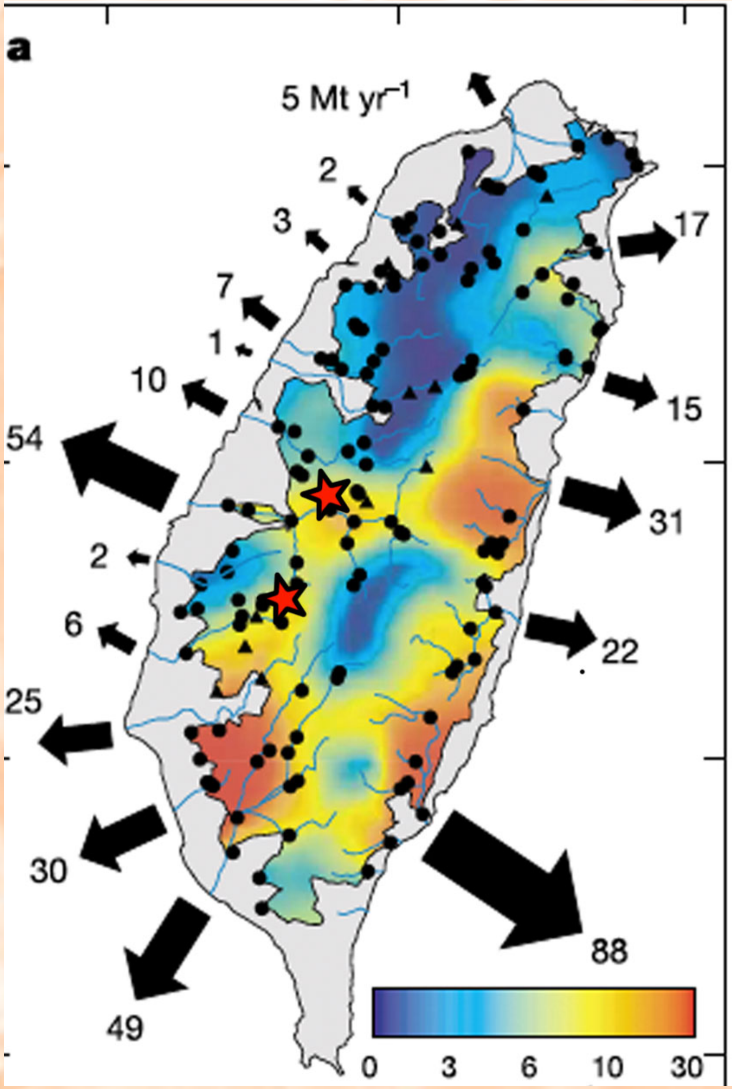
Erosion rates

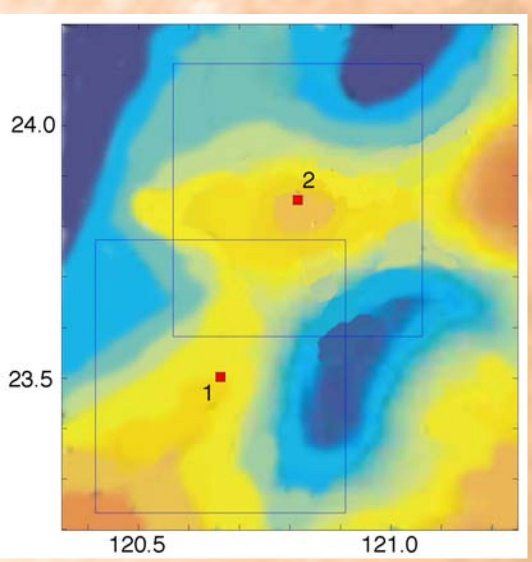
Decadal rate   Holocene rate   Million-year scale rate

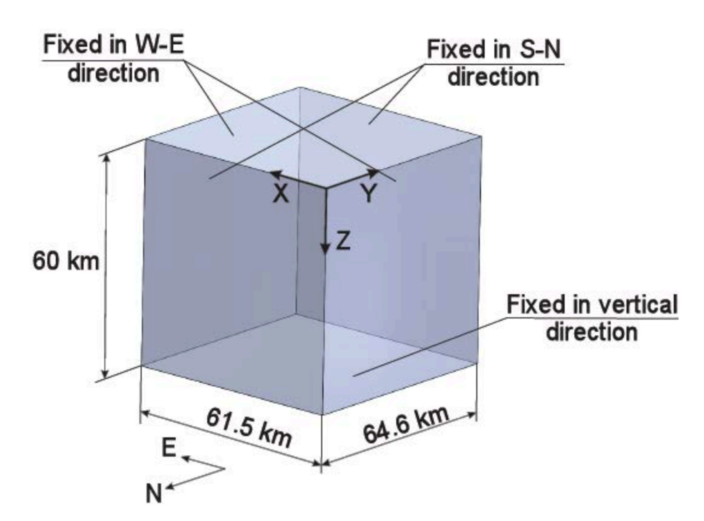


[Dadson et al., 2003]

Model geometry and boundary conditions

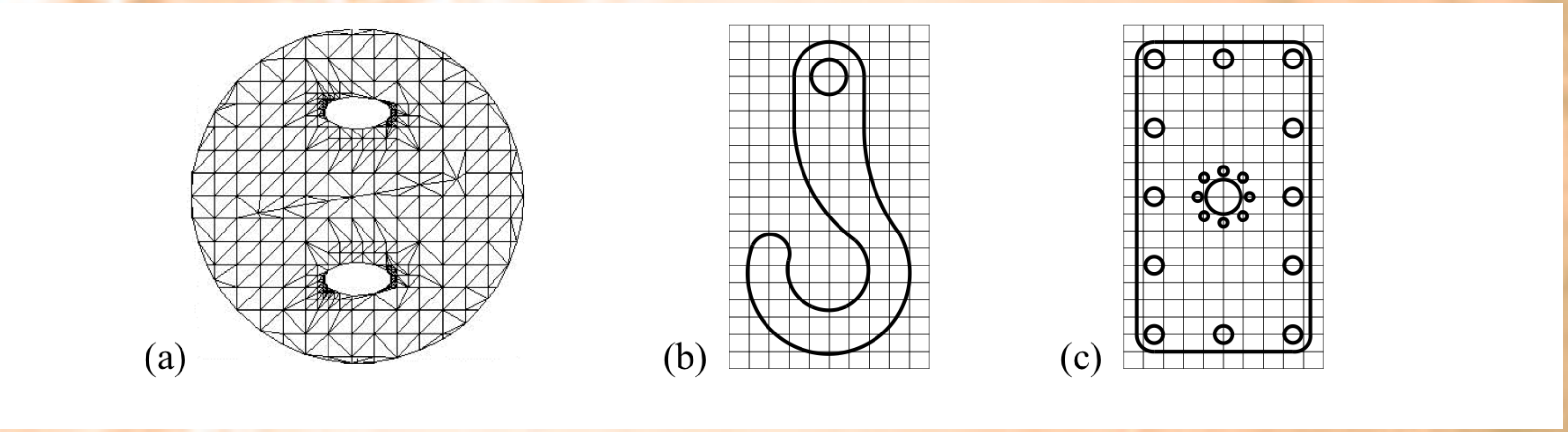






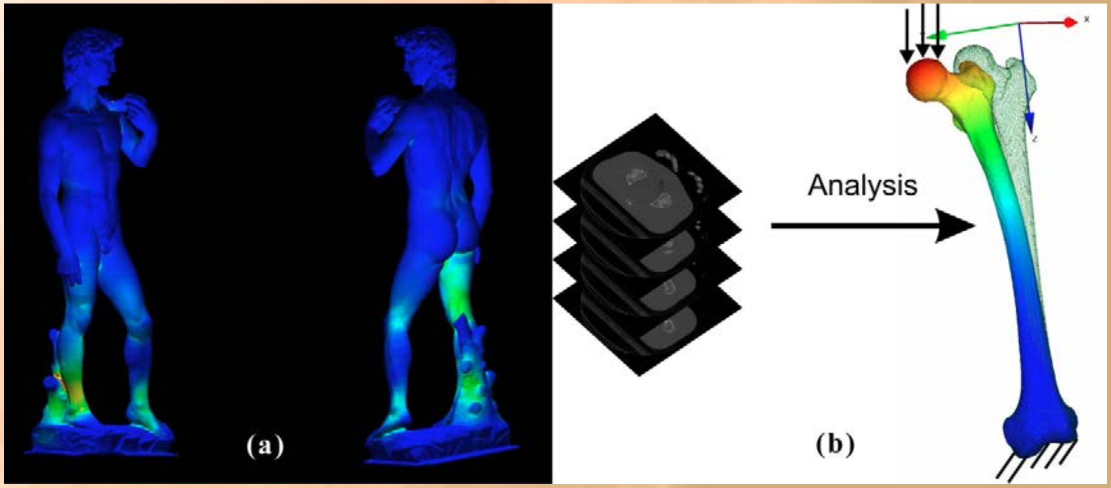
Meshfree finite element modeling

Method of solution: **Mesh-free Finite Element** model

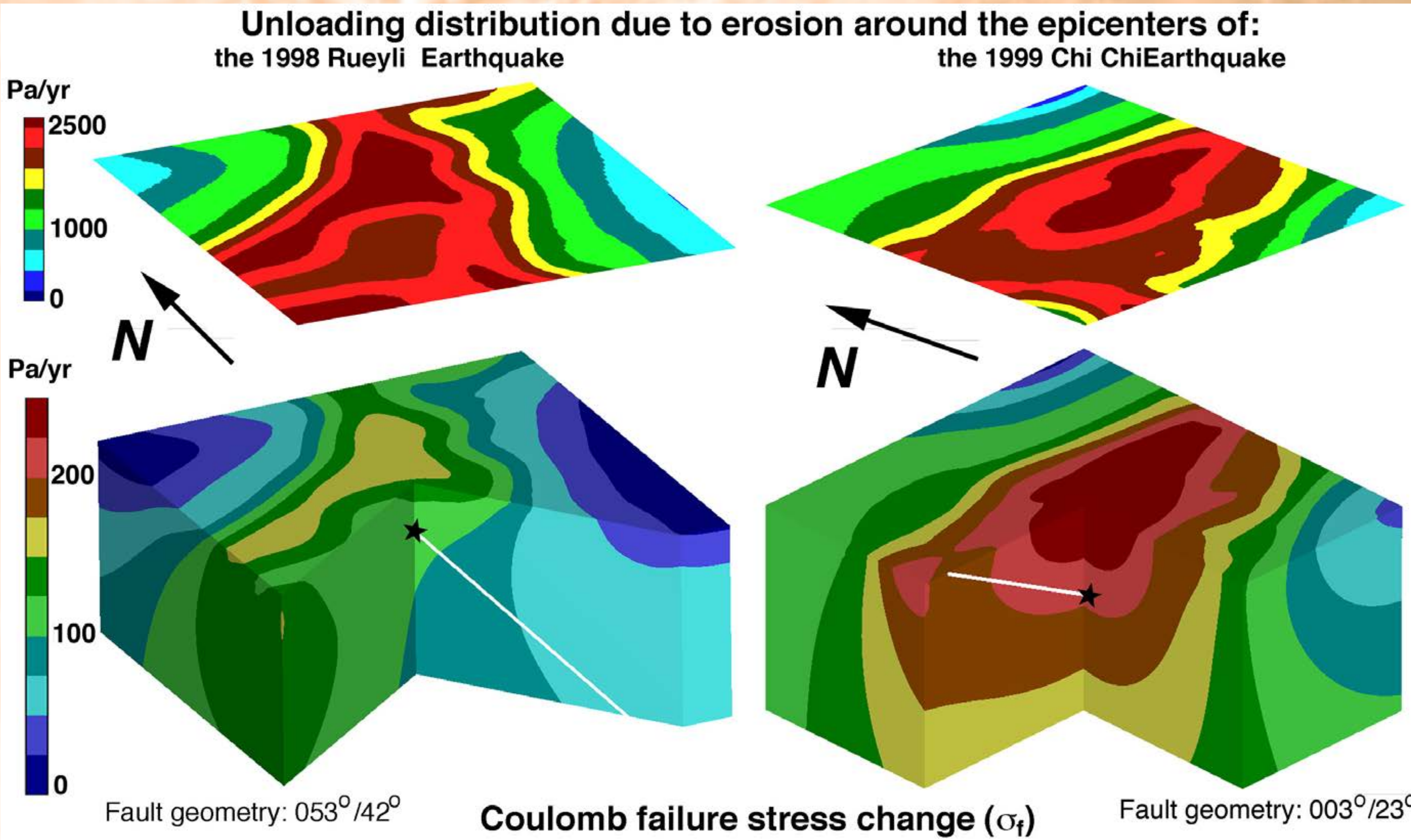


<u>Advantages:</u>

- Complex geometry
- Changing geometries
- “Scan and Solve”
- 3-D



Model results



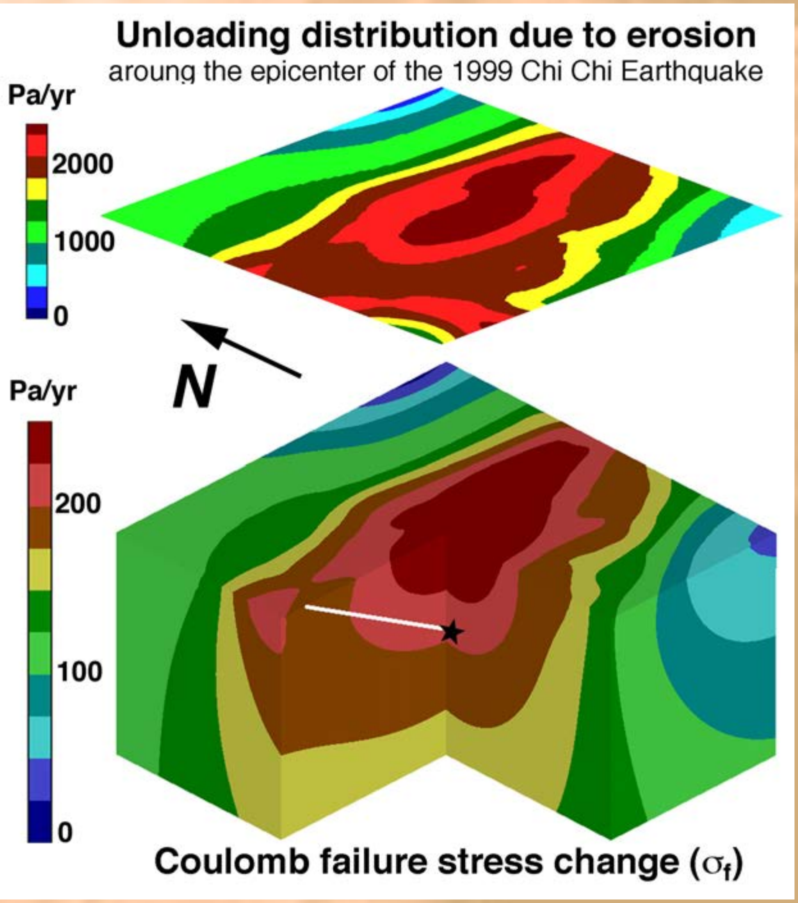
Mean annual stress change (1970-1999)

Model results

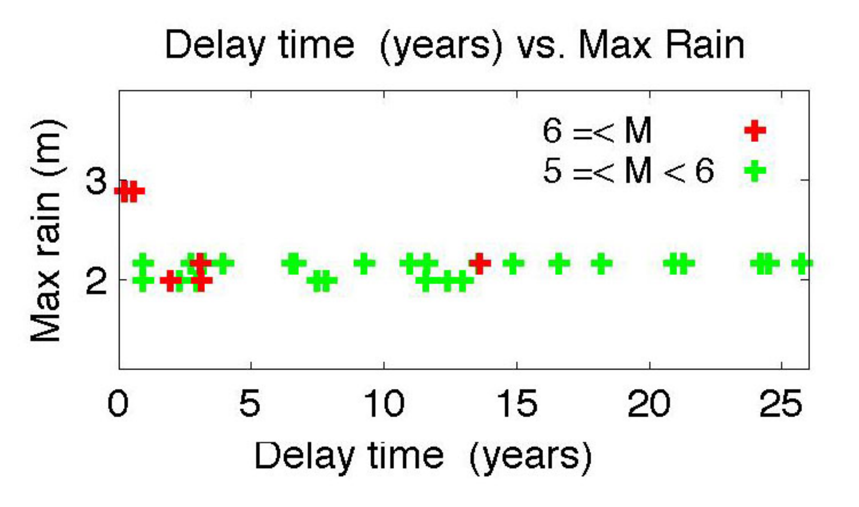
The accumulated stress change over the 30 year is 4-6x10^3 Pa.

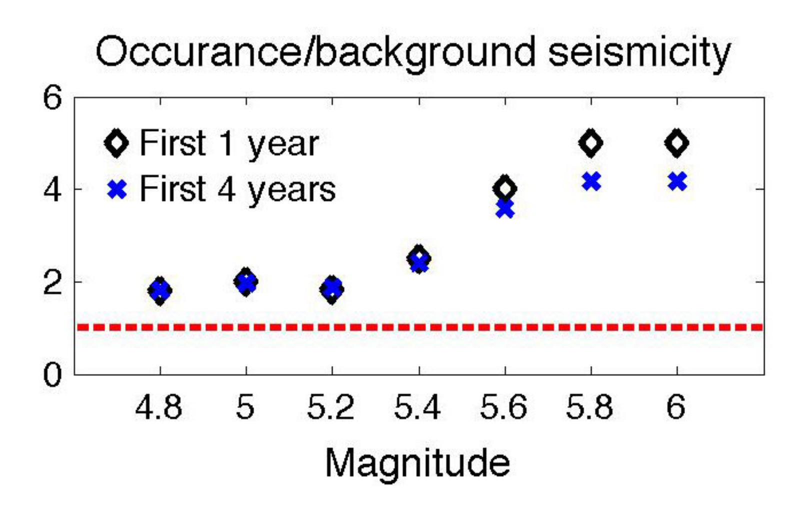
Due to the wet typhoon-induced landslides, we estimate that 30-40% of the stress change occurred after typhoon Herb.

Such stress changes are small, but can trigger an earthquake when added to stresses accumulated along the fault by tectonic loading (tectonic plate motion).



Magnitude dependent temporal clustering

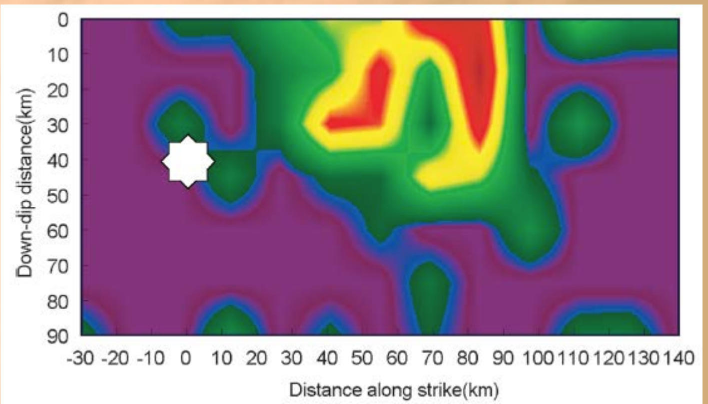




The magnitude dependent clustering suggests that the erosion induce stress reduction affects not only the earthquake nucleation stage, but also the growth stage.

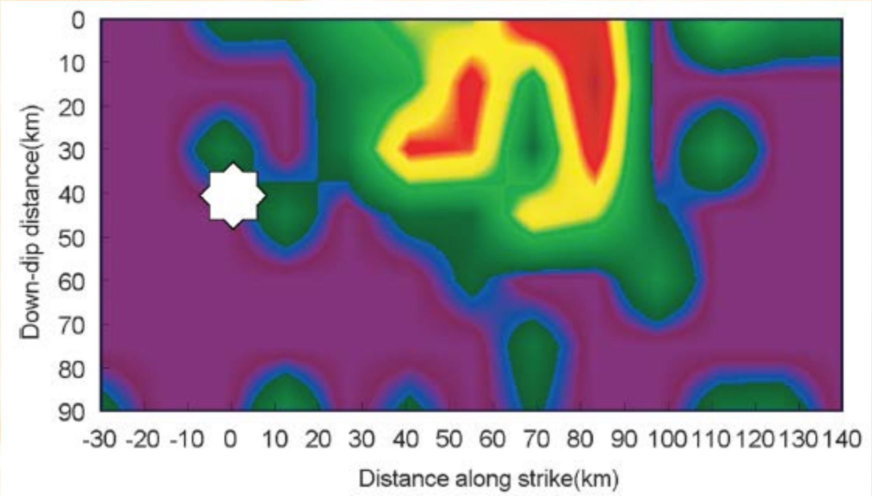
Slip distribution of Chi Chi Earthquake (1999)

[Xu et al, 2002]

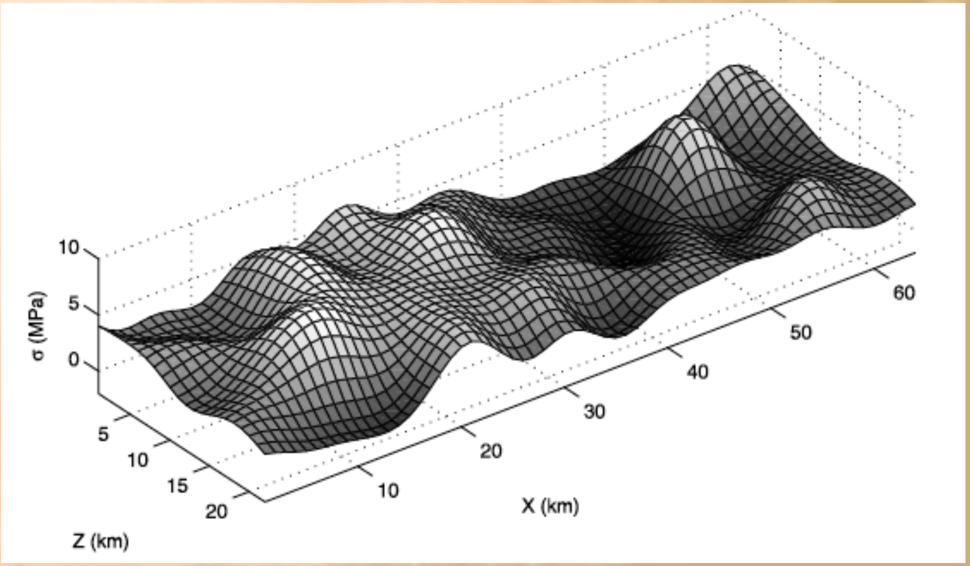


Stress heterogeneities on fault surfaces

- Fault surfaces are not smooth. Stress accumulated on point of contact, known as "asperities".
- Stress changes between asperities and surrounding areas can be very significant (order of magnitude)
- We suggest that the erosion induced stress reduction enable rupture propagation from one asperity to neighbors.



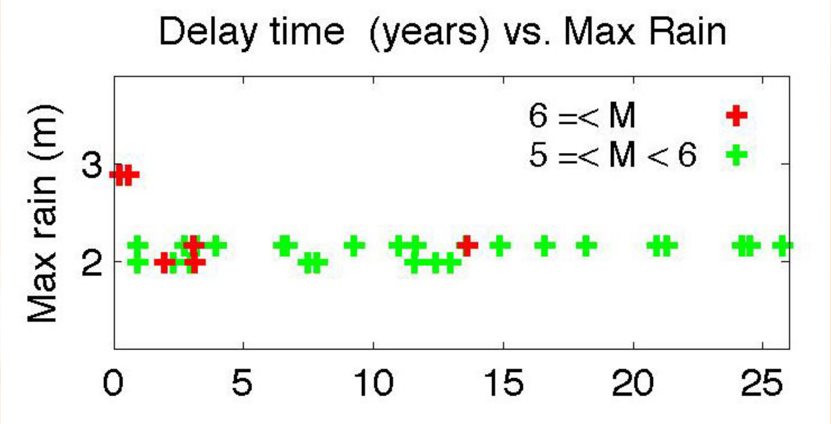
[Xu et al, 2002]

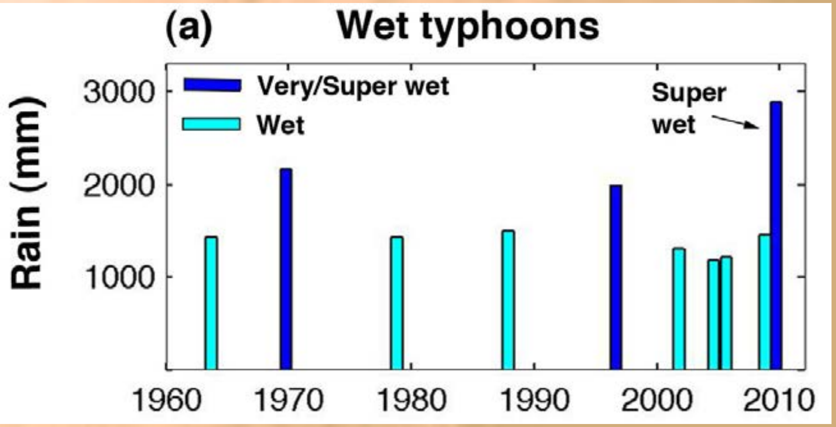


[Schmittbuhlet al, 2006]

Why did the M>6 earthquakes occurred 3-38 months after the wet typhoon?

- Sediment transport from the mountain to the ocean can take its time. Wet typhoons trigger landslides. However, some of the eroded material can transferred afterward.
- Rainfall.
- Previous recent wet typhoons.





Summary (1)

- **Motivation**: We identified three devastating M>6 earthquakes and three additional M>6 events that occurred in tropical mountainous areas shortly (3-38 months) after the same area was subjected to heavy rain induced by very wet tropical cyclone/s.

- **Data**: Seismic (M>5) and wet typhoon records from Taiwan's past 50 years were used to identify temporal relations between the two disaster types.

- **Temporal analysis**: By calculating the time span between the earthquakes and their preceding wet typhoons, we found that 85% of M>6 occurred within the first 4 years after a very wet typhoon (5 times more than expected) and 35% of M>5 events (twice as expected).

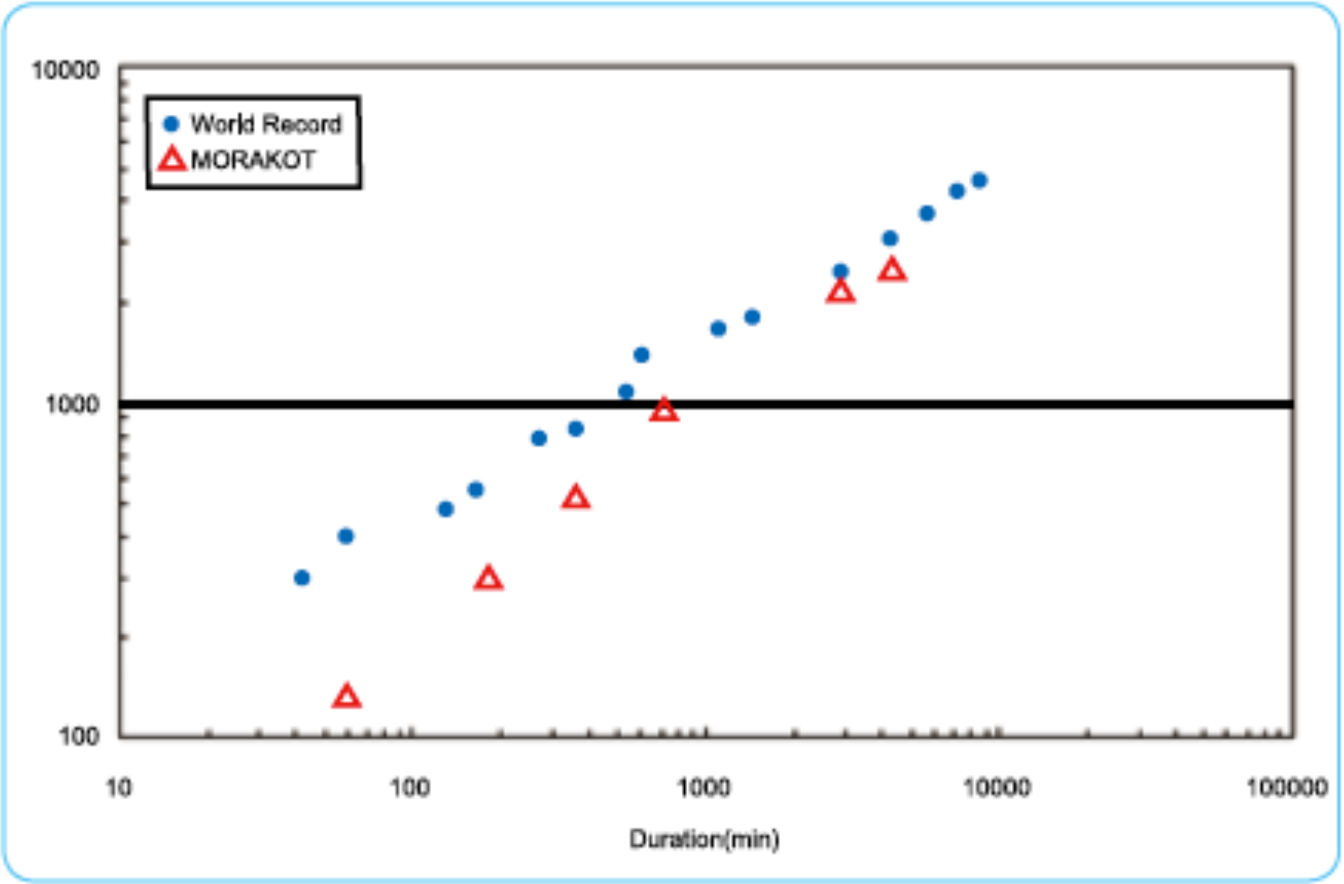
Summary (2)

- **Triggering analysis**: Mechanical modeling indicates that fast erosion induced by Typhoon Herb cause stress changes at the Chi Chi earthquake hypocenter in the range of 2-3x10^3 Pa, which are capable of triggering the earthquakes.

- **Magnitude dependent temporal clustering**: We suggest that the erosion induced stress reduction can promote the ‘growth stage’ of earthquakes by enabling “small” earthquake to rupture several asperities.

Cyclone rainfall

Rain ∝ Duration



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Increased wet typhons and seismicity (M>6) in Taiwan over the past 17 years