Testing tidal triggering of earthquakes in Taiwan

Seminar at the Department of Earth Sciences
National Central University

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also with
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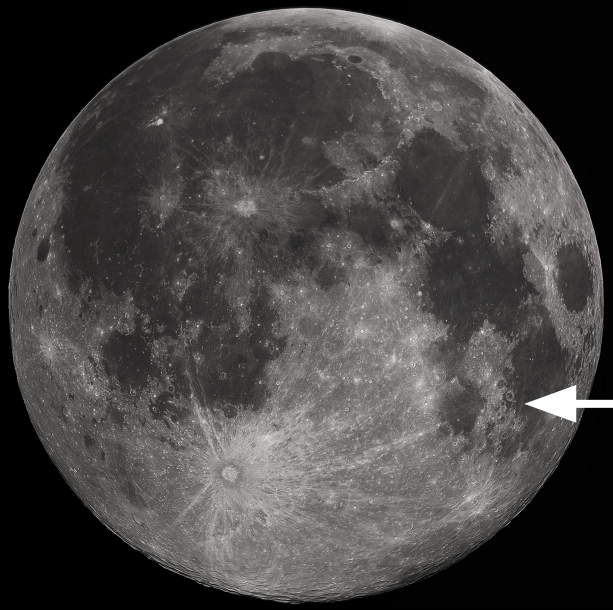
Statements and question

The gravitational fields of the Moon, the Sun (and other celestial objects) periodically deform the Earth.

In the Earth's crust: Deformation → Stress

⇨ **Could this stress trigger fault's rupture?**

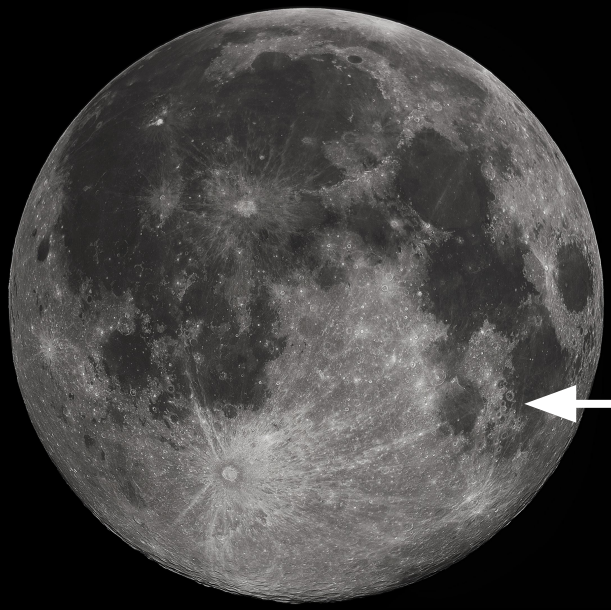
Tidal triggering in the Solar system



Moon seismicity
(Lammlein et al., 1974
Toksöz et al., 1977)

Pictures from http://commons.wikimedia.org/

Tidal triggering in the Solar system



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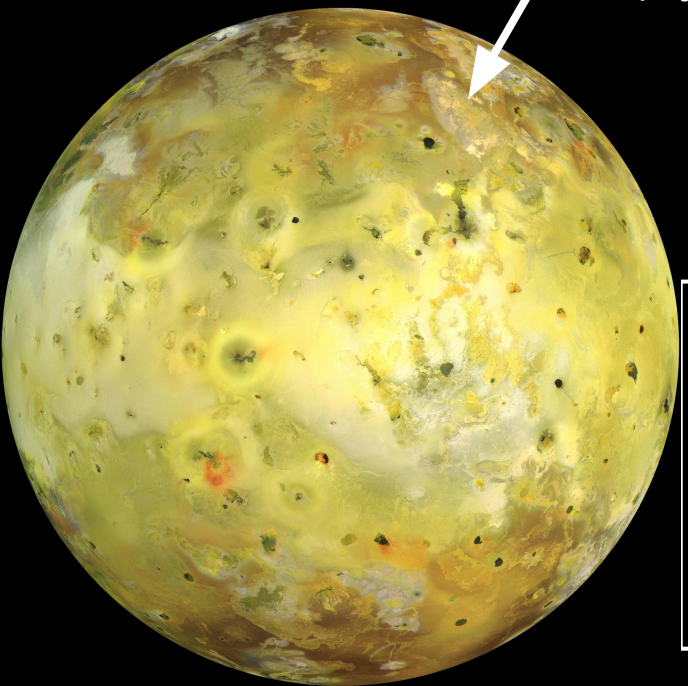
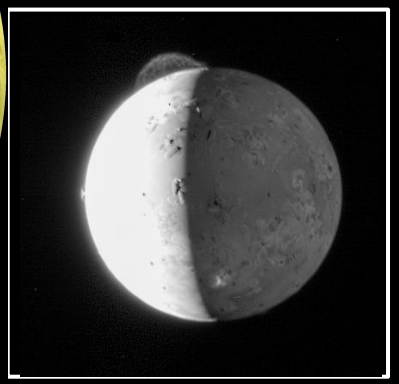
Io volcanism
(Ojakangas & Stevenson, 1986)





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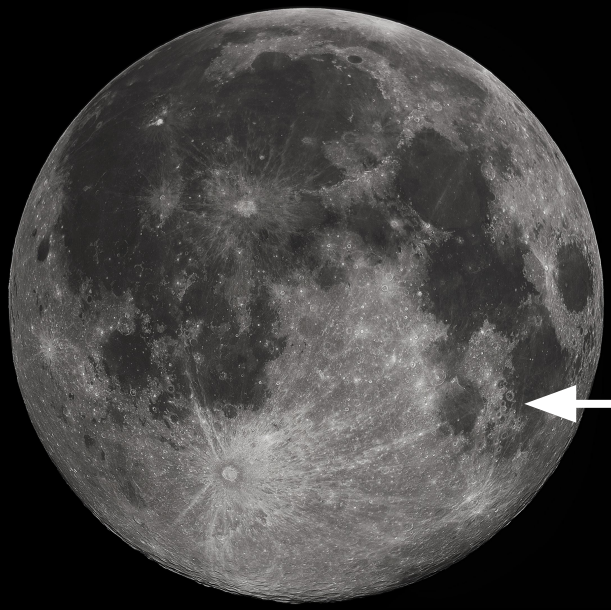

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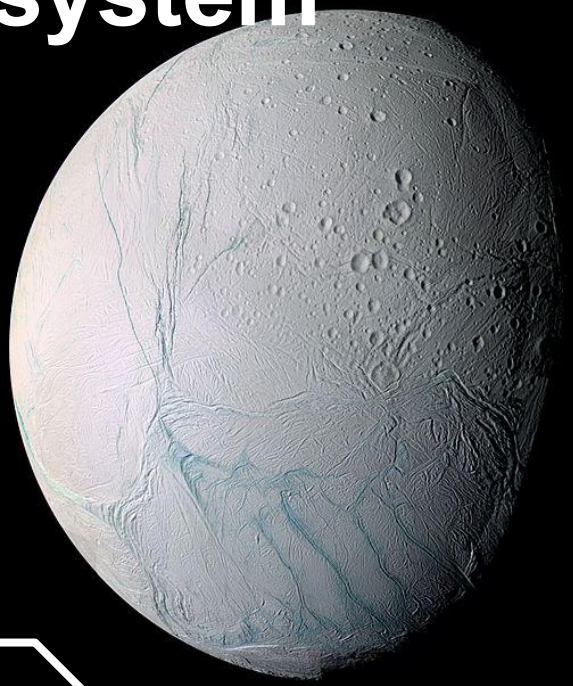

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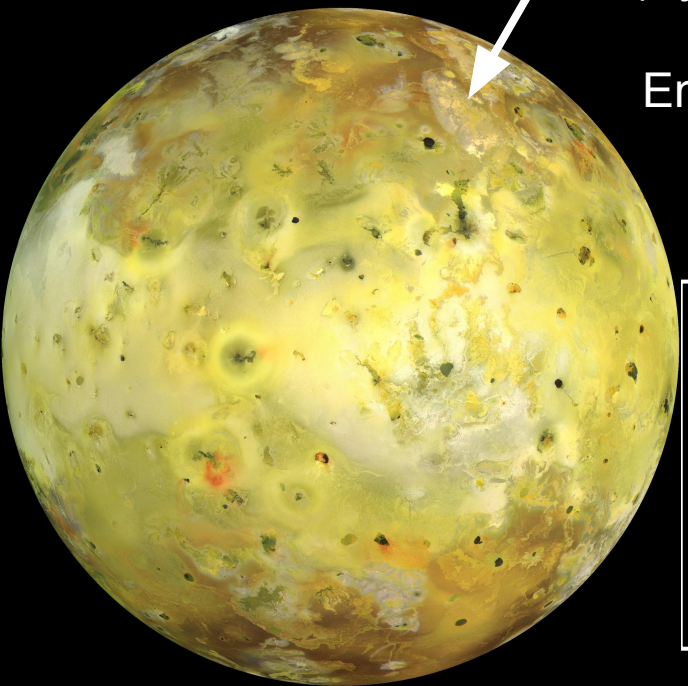
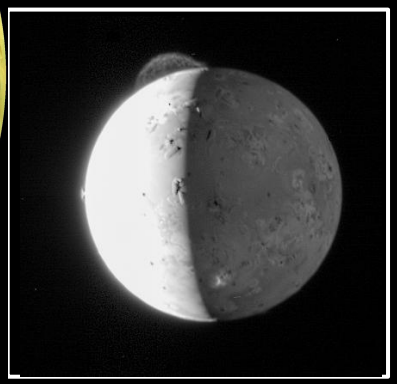
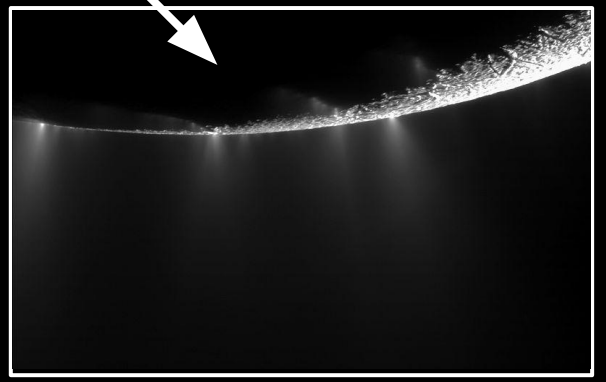


Enceladus water vapor plumes
(Hedman et al., 2013)





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Back on Earth

The question of tidal triggering of earthquakes has been discussed since the middle of the 19th century, at least (review by Varga & Denis, 2009).

Before plate tectonics discovery → Create earthquakes?

After plate tectonics discovery → Trigger earthquakes?

(e.g. Allen, 1936)

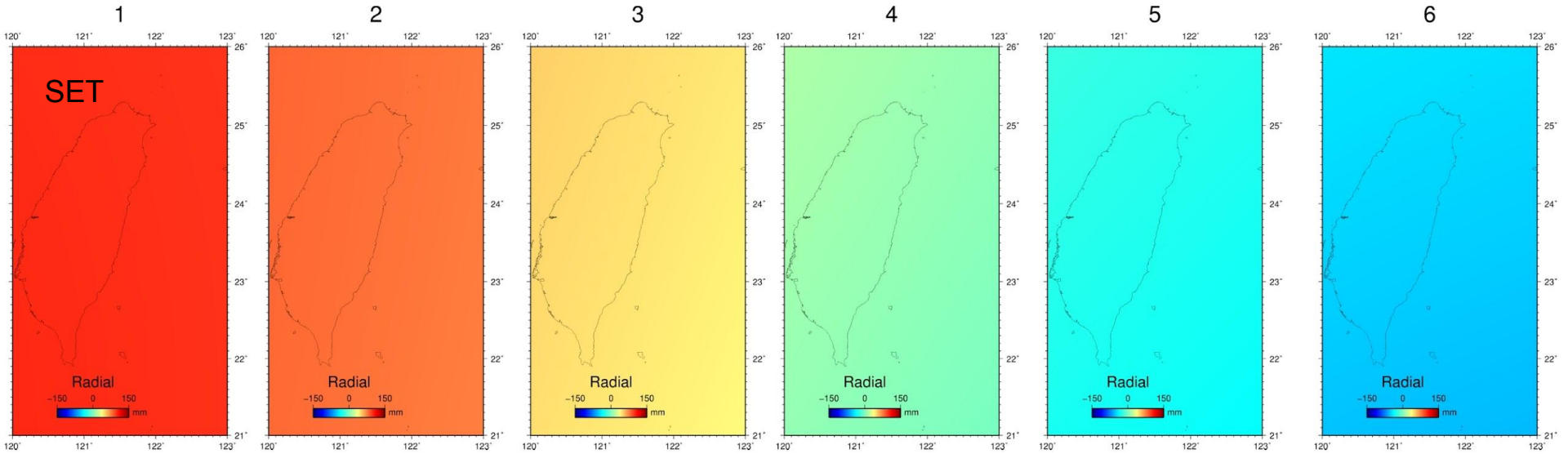
Two conclusions… (not always the same method)

Can trigger	Cannot trigger
Cotton, 1921	Knopoff, 1964 (California)
Allen, 1936 (South California)	Lomnitz, 1974
Bloxsom, 1974 (San Fernando fault, CA)	Heaton, 1975 (Global)
Sadeh, 1978 (Alaska, Central America)	Young & Zürn, 1979 (Jura)
Souriau et al., 1982 (Pyrenees)	Hartzell & Heaton, 1989 (California)
Tsuruoka et al. 1995 (Global)	Vidale et al., 1998 (California)
Tanaka et al., 2004 (Japan)	Beeler & Lockner, 2003 (lab)
Métivier et al. 2009 (Global)	

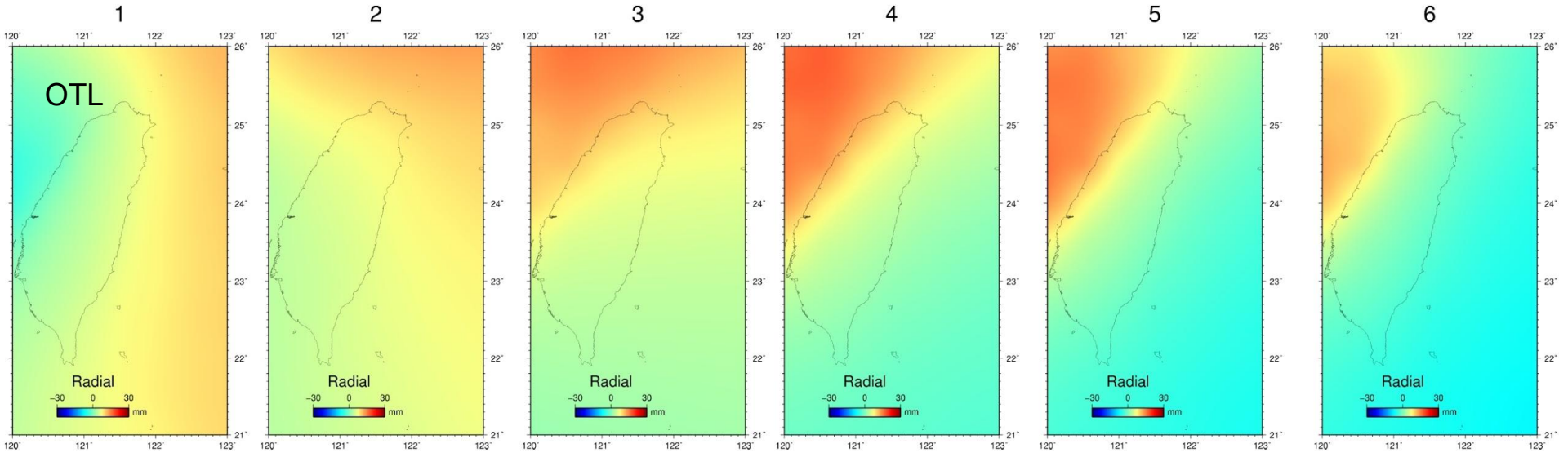
after Varga & Denis, 2009

Earth deformation = **Solid Earth Tides** (SET).

Tides redistribute oceanic masses = **Ocean Tide Loading** (OTL)



Radial displacement, every hour



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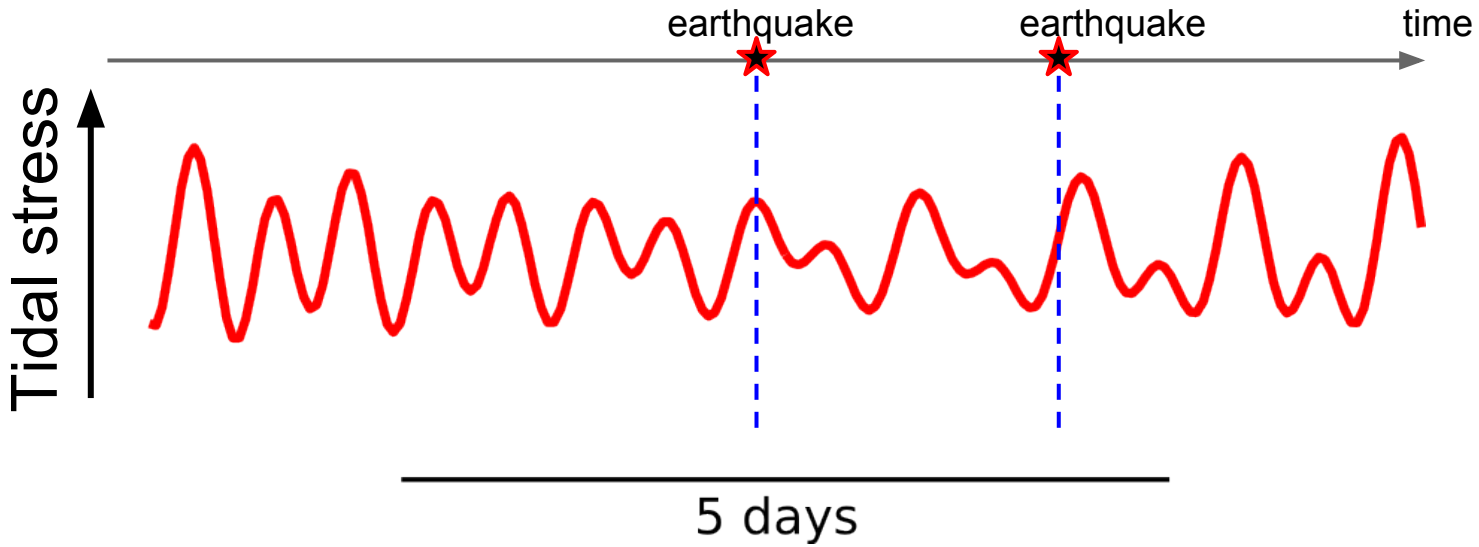
With ocean loading effect

Without ocean loading effect

after Varga & Denis, 2009

Usual method

Compare the time of earthquake occurrence with the time of peak tidal stress, then make statistics on the **tidal phase**



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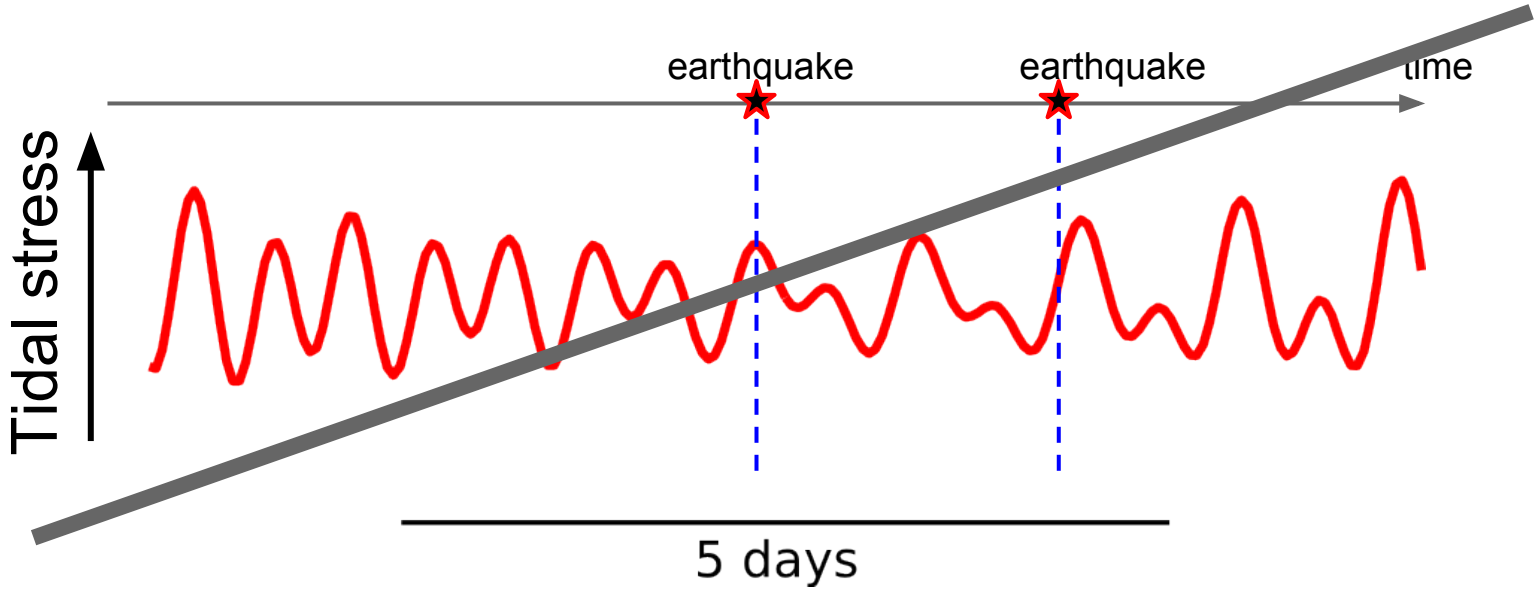
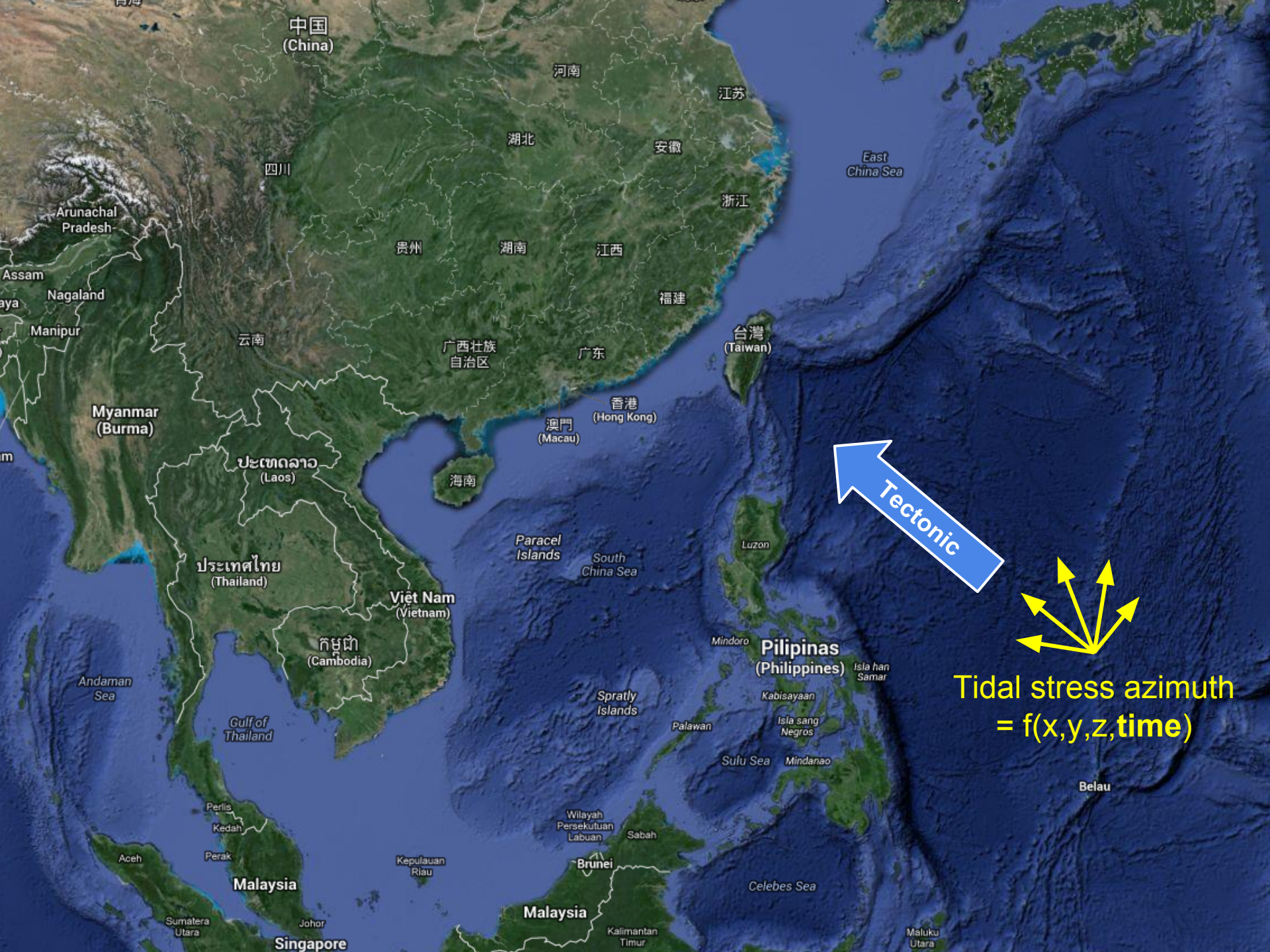


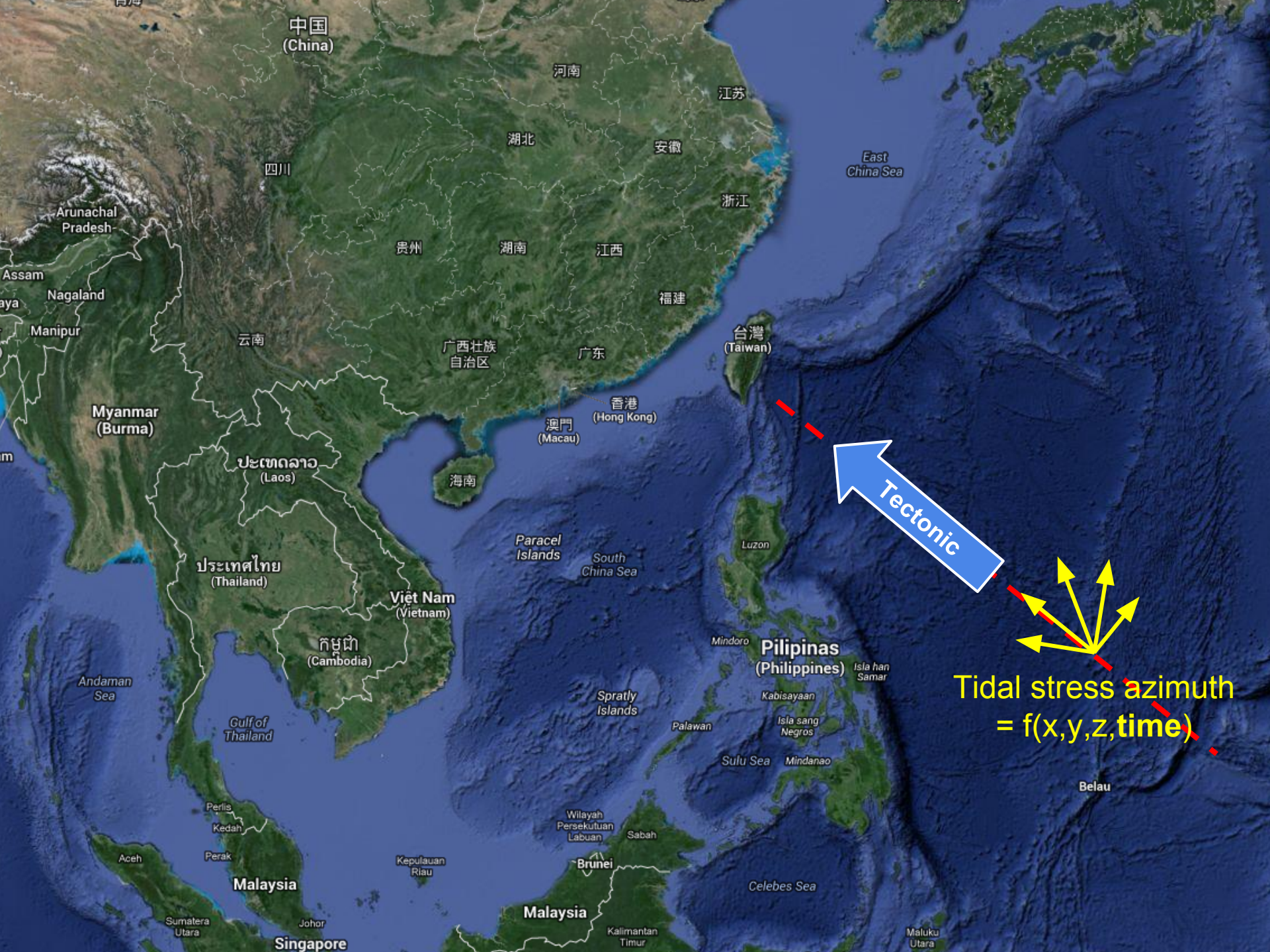
Here, focus on the **azimuth of the tidal stress**
Tanaka et al. (2004) suggest:

"The tidal stress may encourage earthquake occurrence when it acts in the direction to increase the regional tectonic stress." [in Japan]

We test this hypothesis for Taiwan



Tidal stress azimuth
= f(x,y,z,**time**)


中国
(China)
河南
江苏
湖北
安徽
四川
East
China Sea
浙江
Arunachal
Pradesh
贵州
湖南
江西
Assam
Nagaland
福建
Manipur
台灣
(Taiwan)
云南
广西壮族
自治区
广东
香港
(Hong Kong)
Myanmar
(Burma)
澳門
(Macau)
ประเทศลาว
(Laos)
海南
Tectonic
Paracel
Islands
South
China Sea
Luzon
ประเทศไทย
(Thailand)
Việt Nam
(Vietnam)
Mindoro
Pilipinas
(Philippines)
Isla han
Samar
Andaman
Sea
กัมพูชา
(Cambodia)
Spratly
Islands
Kabisayaan
Gulf of
Thailand
Palawan
Isla sang
Negros
Sulu Sea
Mindanao
Belau
Perlis
Kedah
Wilayah
Persekutuan
Labuan
Sabah
Aceh
Perak
Kepulauan
Riau
Brunei
Malaysia
Celebes Sea
Malaysia
Sumatera
Utara
Johor
Kalimantan
Timur
Singapore
Maluku
Utara
Tidal stress azimuth
= f(x,y,z,time)

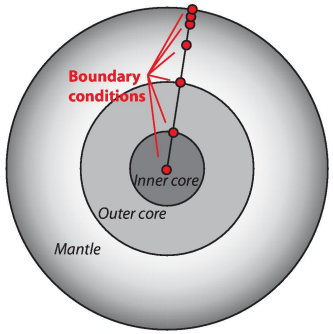
Method

1. Compute the tidal stress

2. Look for tidal triggering of earthquakes:
   → Do earthquakes occur randomly in comparison with the azimuth of the tidal stress

3. Compare tidal and tectonic stresses

Spheroidal deformations of the Earth
Alterman et al., 1959
Farrell, 1972
Takeuchi & Saito, 1972



PREM, Dziewonski & Anderson, 1981
SNREI Earth

Tidal force VS ocean load:
one different boundary condition at the surface

Tidal stress computation

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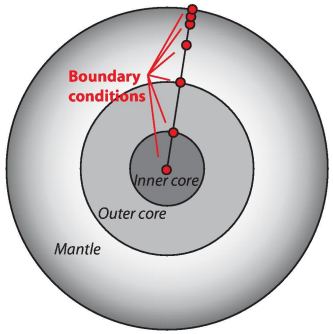

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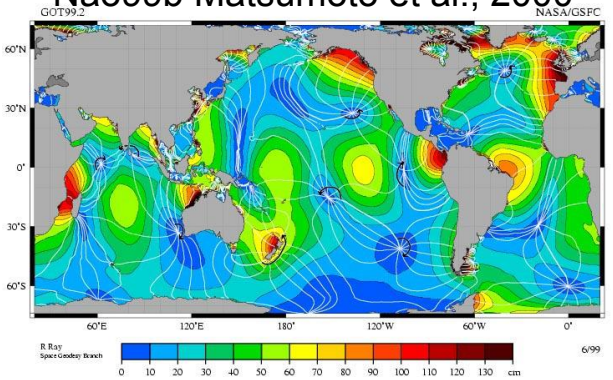
Tidal force VS ocean load:
one different boundary condition at the surface

Stress **Green functions** for a point mass load *f(location)*

*

Tide model *f(time)*
Nao99b Matsumoto et al., 2000



Tidal stress computation

Solid Earth tide stress tensor
f(location,time)

Oceanic tide stress tensor
f(location,time)

Spheroidal deformations of the Earth
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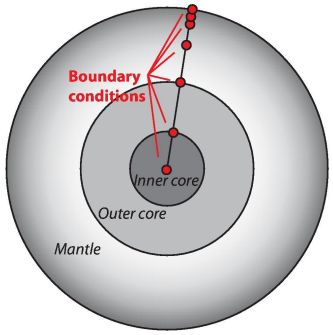

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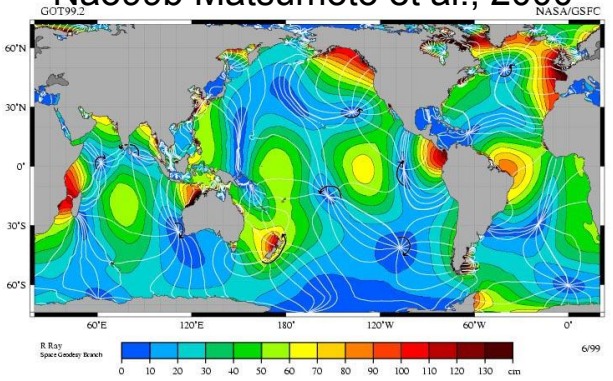


Tidal stress computation

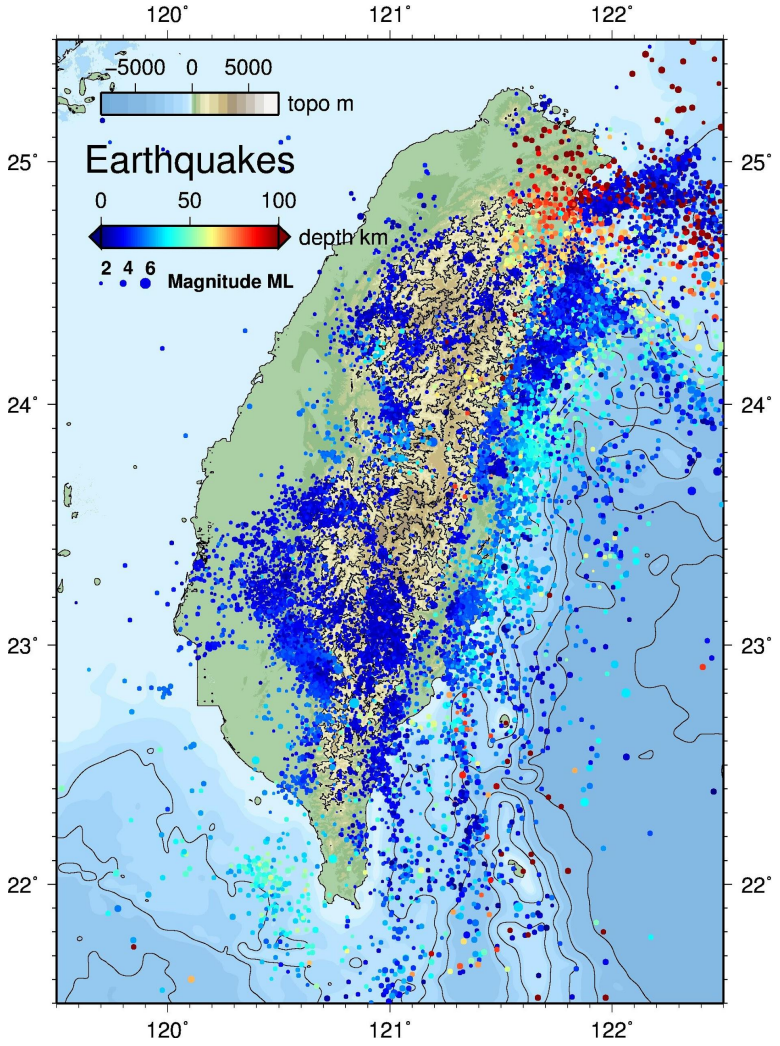
Solid Earth tide stress tensor
f(location,time)

+

Oceanic tide stress tensor
f(location,time)

Tidal stress tensor
f(location,time)

Tidal stress tensor = *f(location,time)* → Uses earthquakes



Central Weather Bureau catalog, 1994 to 2012.

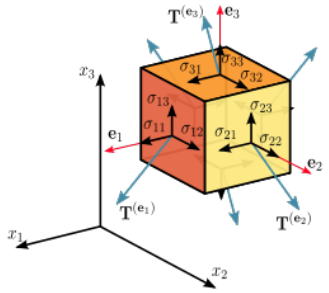
Magnitude of completeness >= 2.0

Declustering using Reasenberg (1985) method, implemented by ZMAP software (Wiemer, 2001)

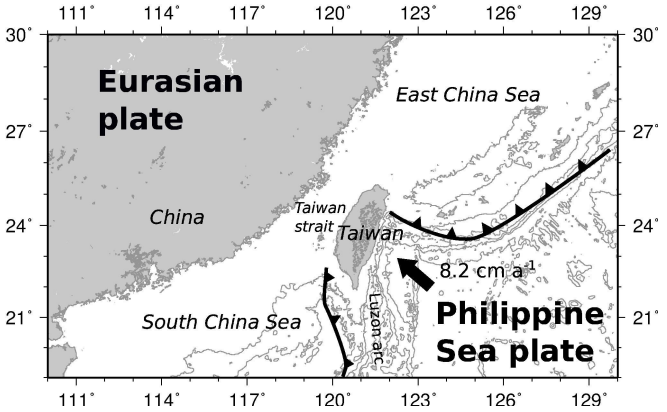
Total ~ 118 000 earthquakes

Check point

We have: Tidal stress tensor for every earthquake in Taiwan since 1994



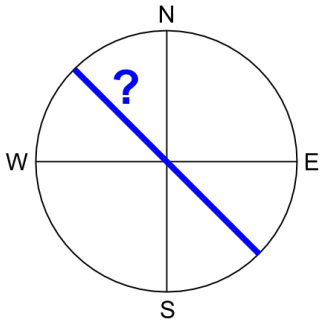
Question: does the tidal stress encourage earthquake occurrence when it acts in the direction to increase the regional tectonic stress?



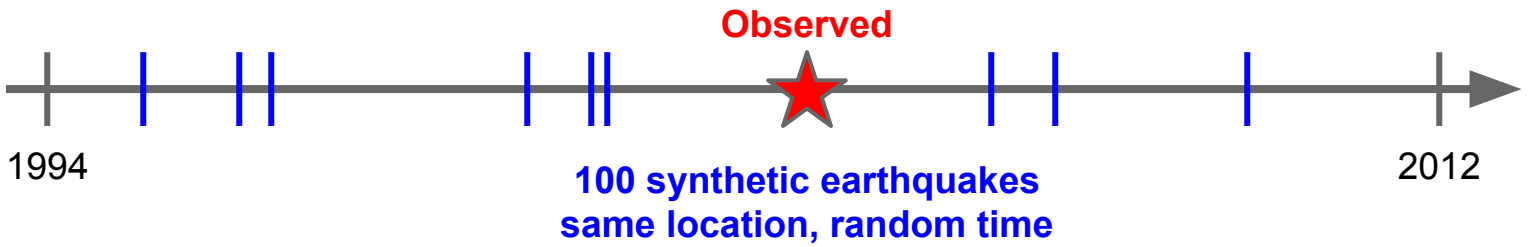
STATISTICS

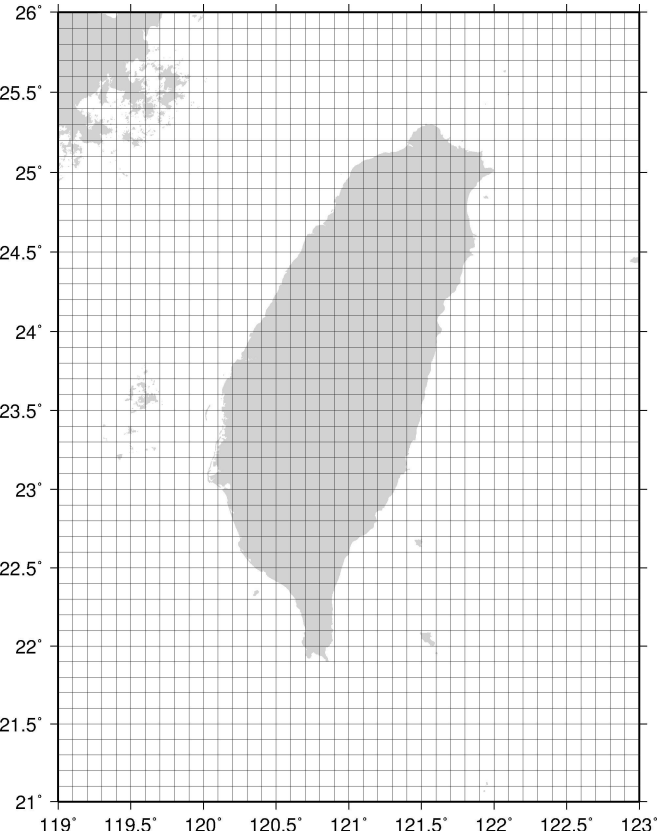
We need: Azimuth of the tidal principal axis of maximal compression for:

1. these earthquakes
2. synthetic random earthquakes



Statistical method





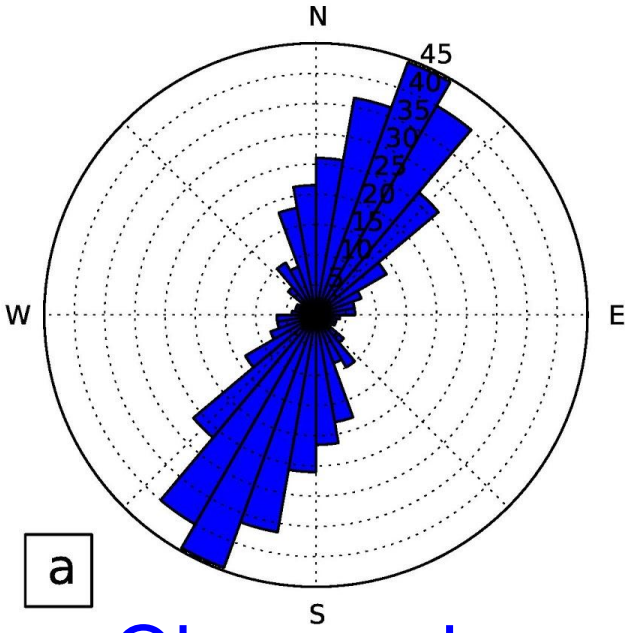
118 000 observed earthquakes **O**
→ 11 800 000 synthetics **S**

Sorted in 0.1x0.1 degrees regions
depth [0-15] and [15-30] km

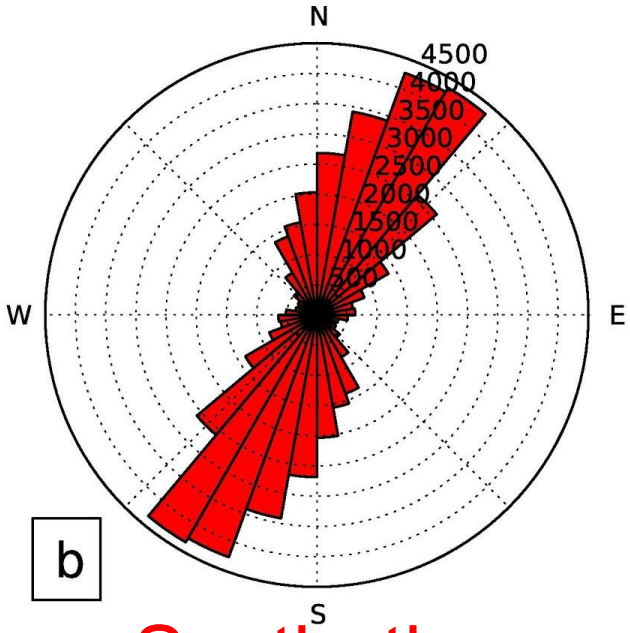
For each region with >100 observed earthquakes:

1. Compute azimuth of the tidal principal axis of maximal compression, for O and S
2. Test if O is a representative sample of S, using Fisher's exact test

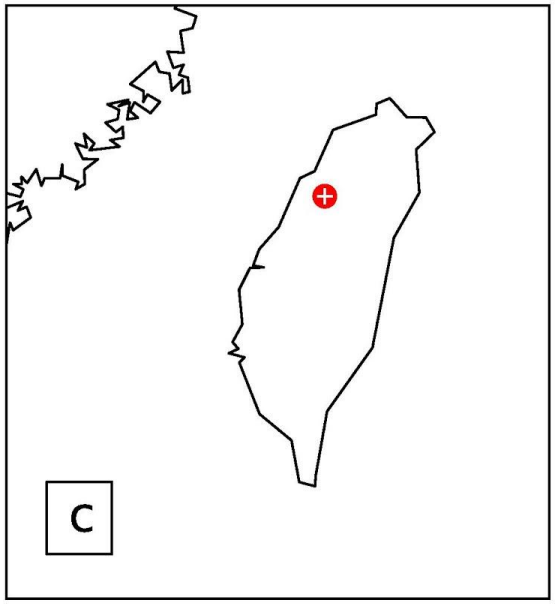
Example of azimuths of the principal axis of maximal compression for one region



Observed



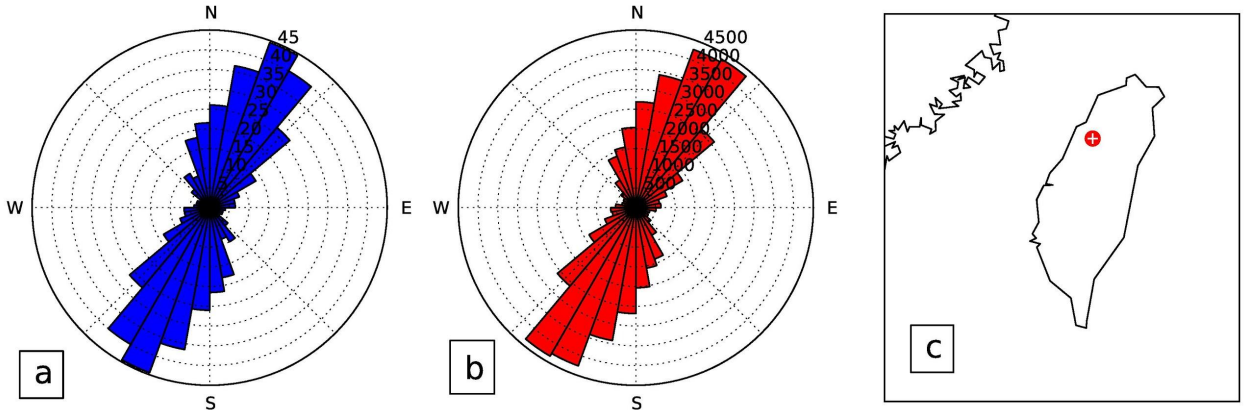
Synthetic



Location

The Fisher exact test tells us the probability that O and S are equally distributed. If not, then we evidence a possible tidal triggering.

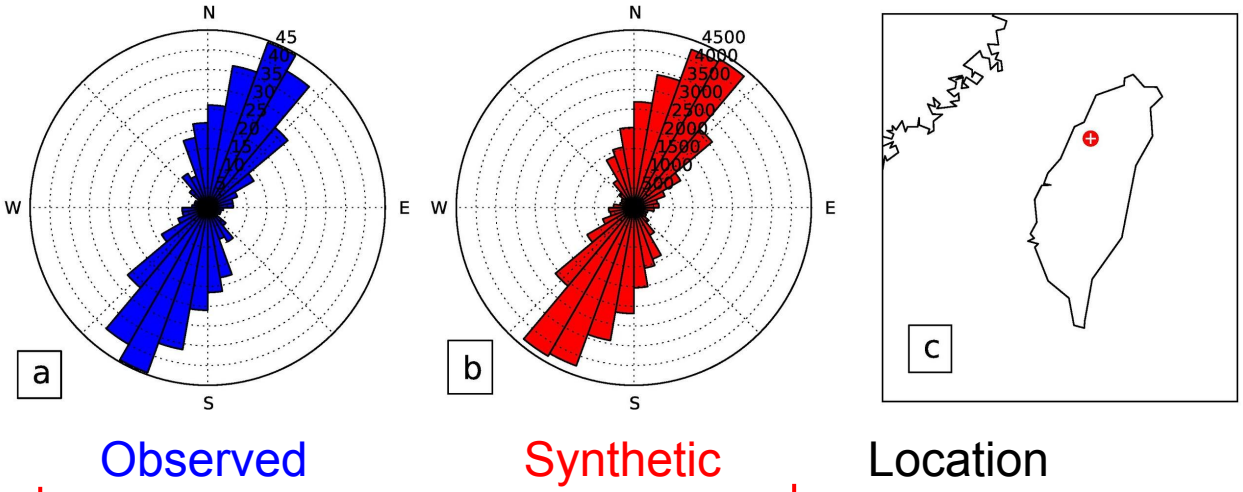
Example of azimuths of the principal axis of maximal compression for one region



Observed Synthetic Location

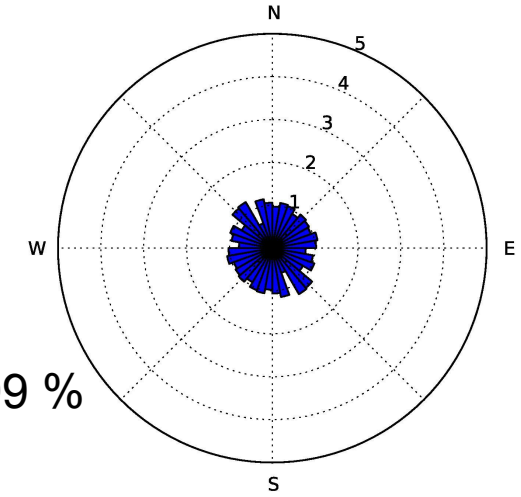
Result of the Fisher's exact test p = 99 %
O and S are equally distributed

Example of azimuths of the principal axis of maximal compression for one region



Observed Synthetic Location

graphic ratio O/S



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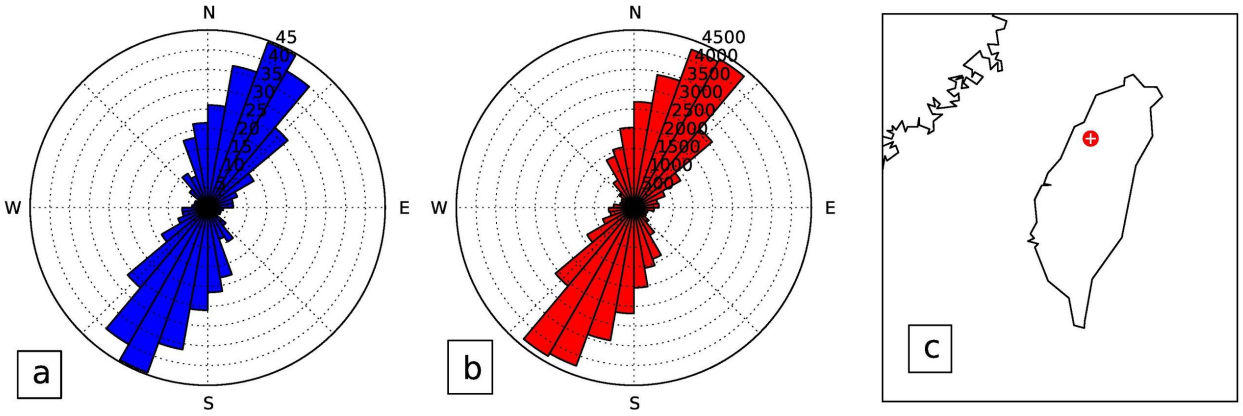

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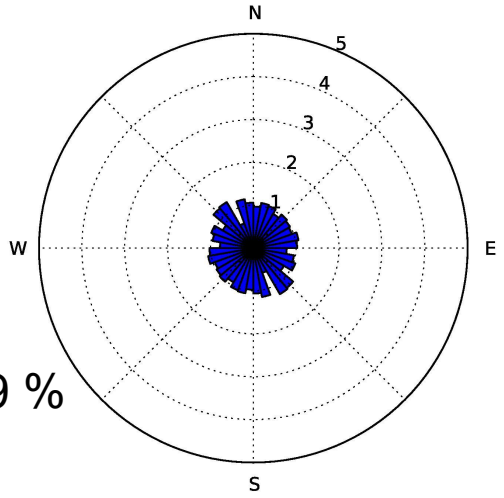

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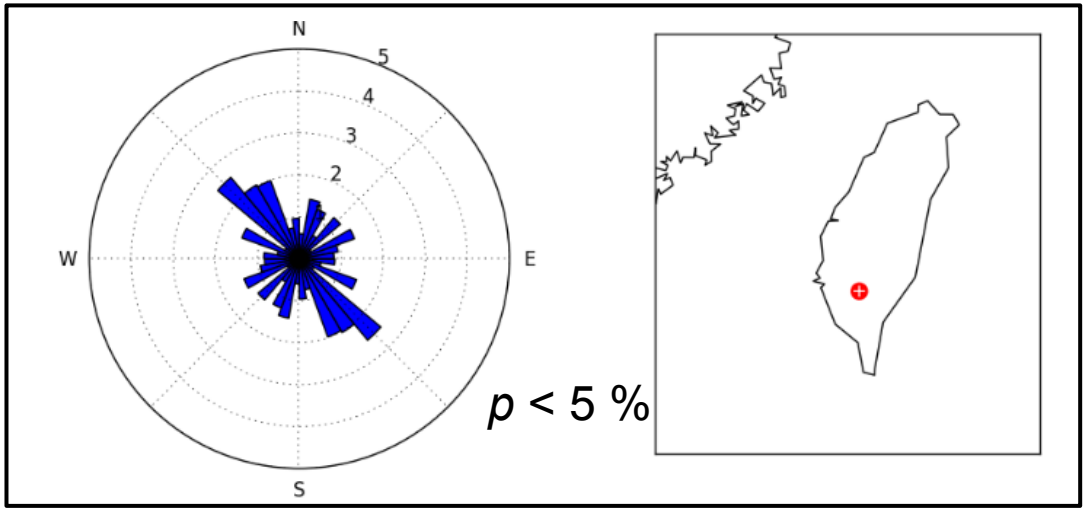
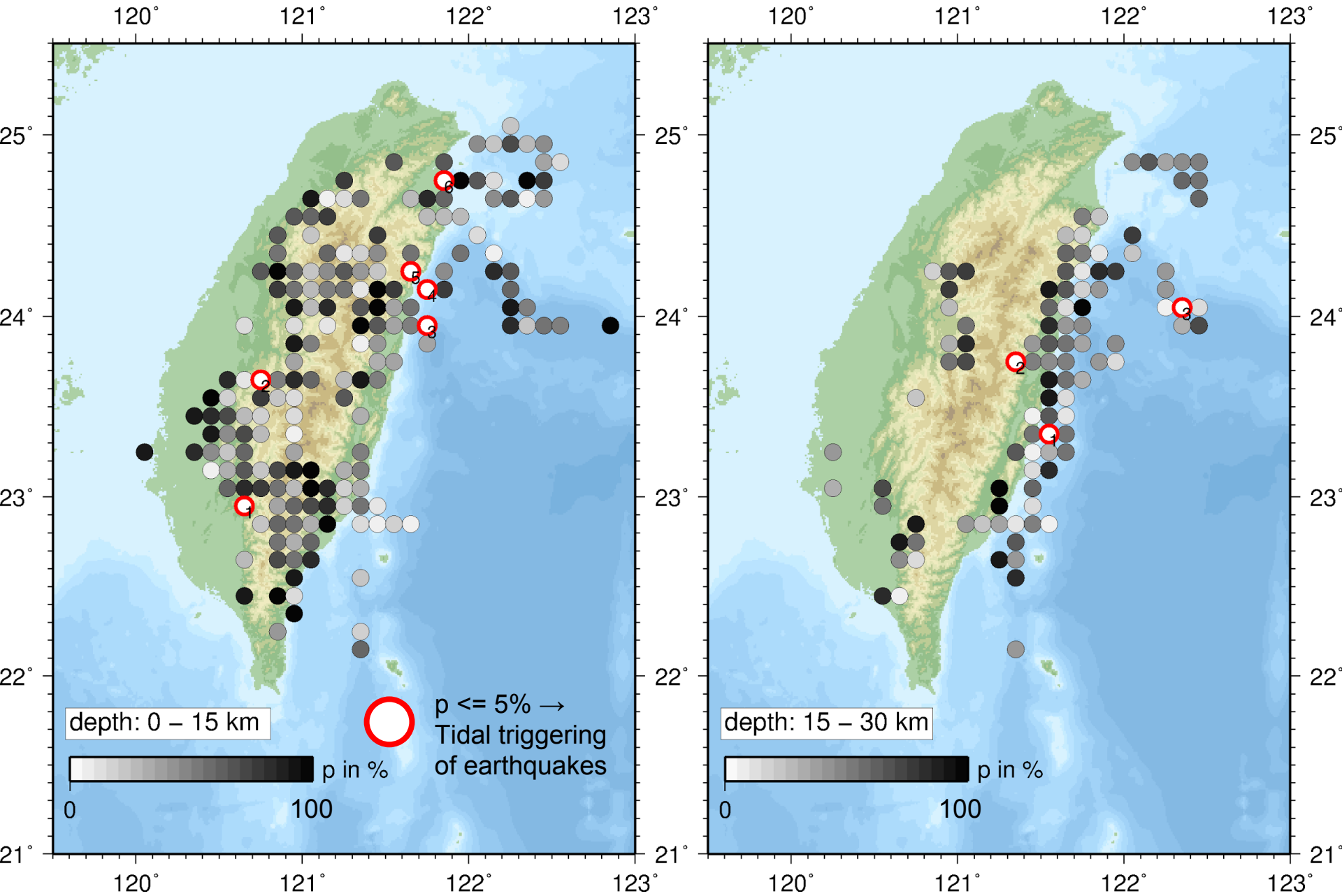
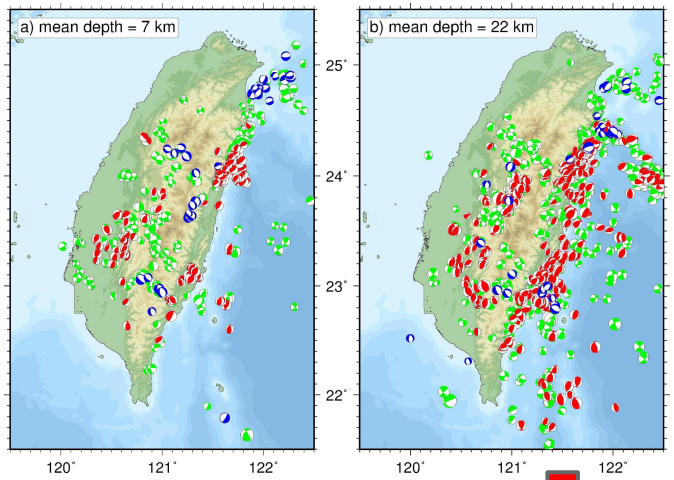


p < 5 %

Maps of tidal triggering

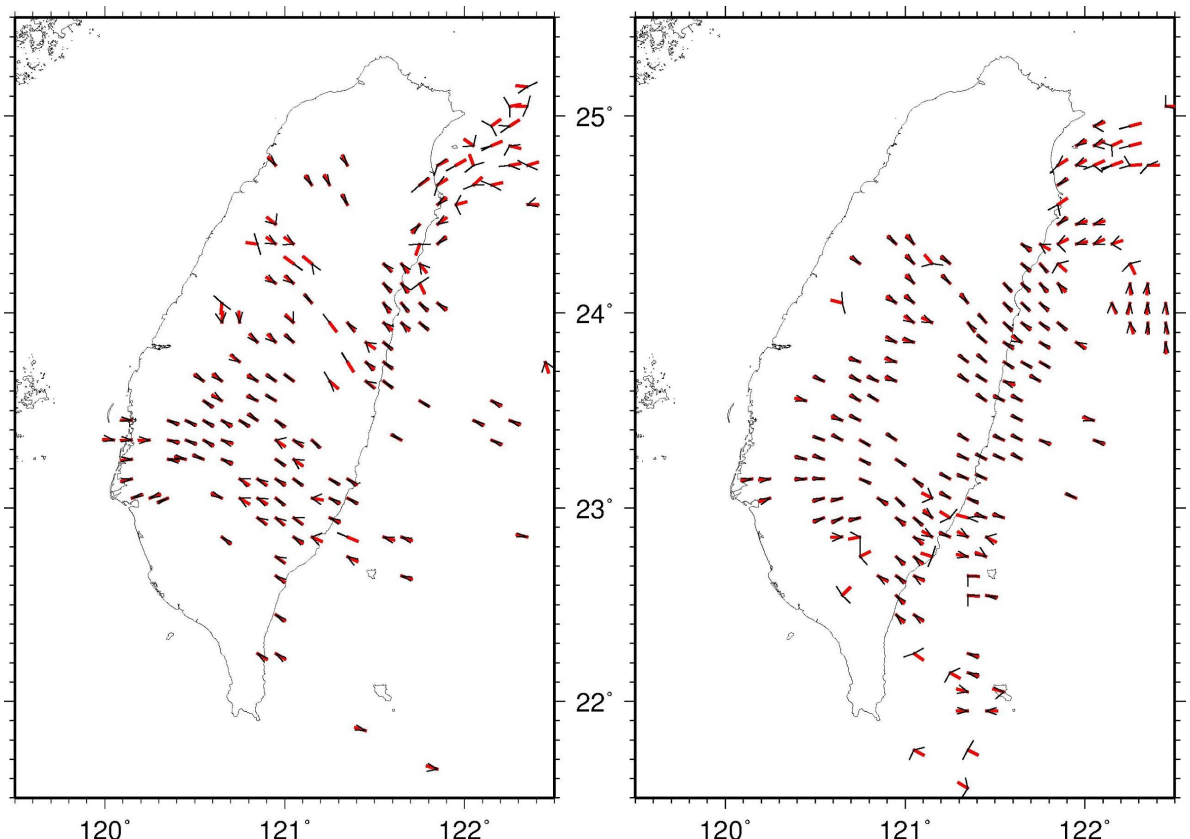


Tectonic stress computation

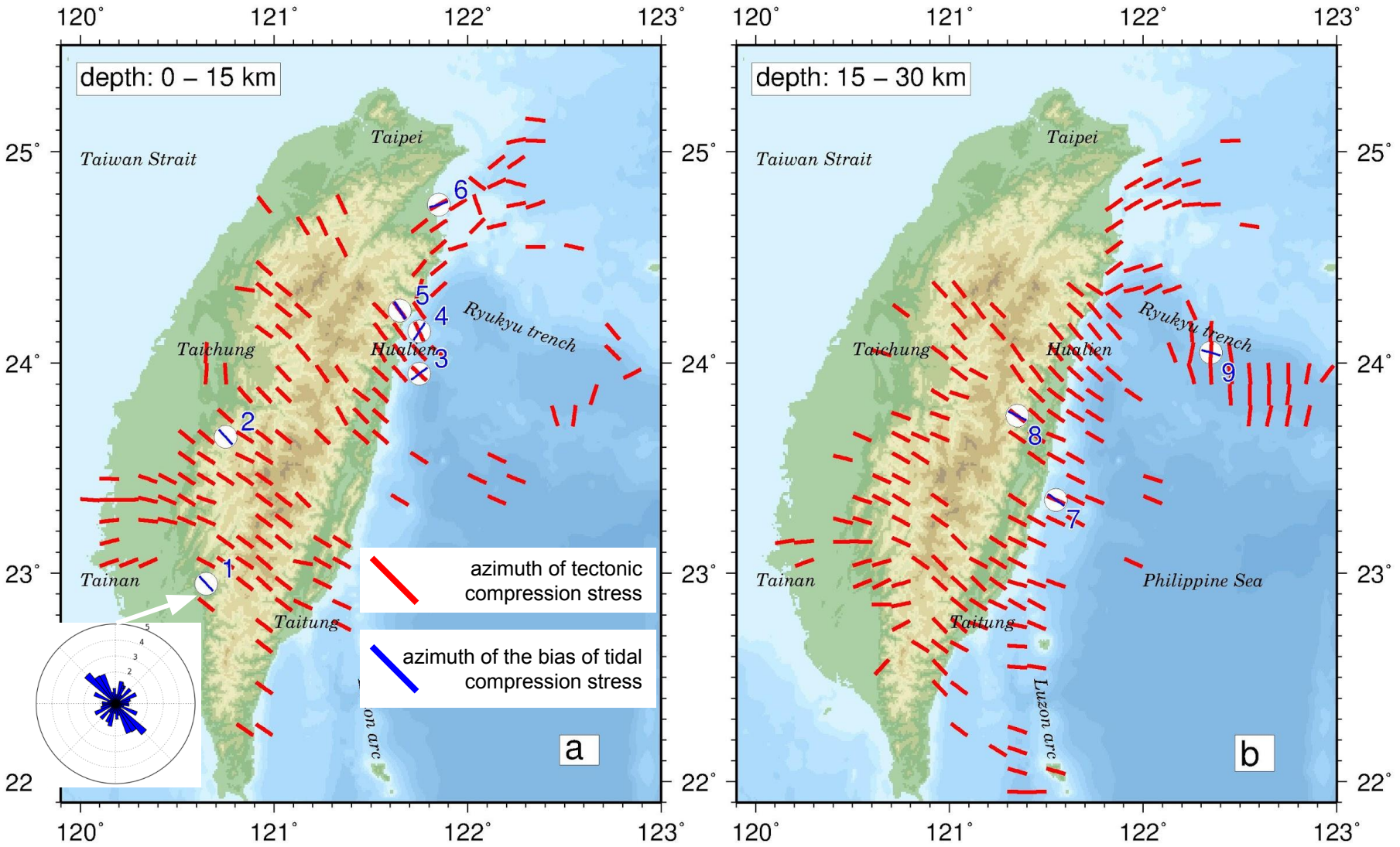


Focal mechanisms from the BATS catalog

Compute the azimuth of the most compressive axis using SATSI code (Hardebeck and Michael, 2006)



Comparison with the tectonic stress



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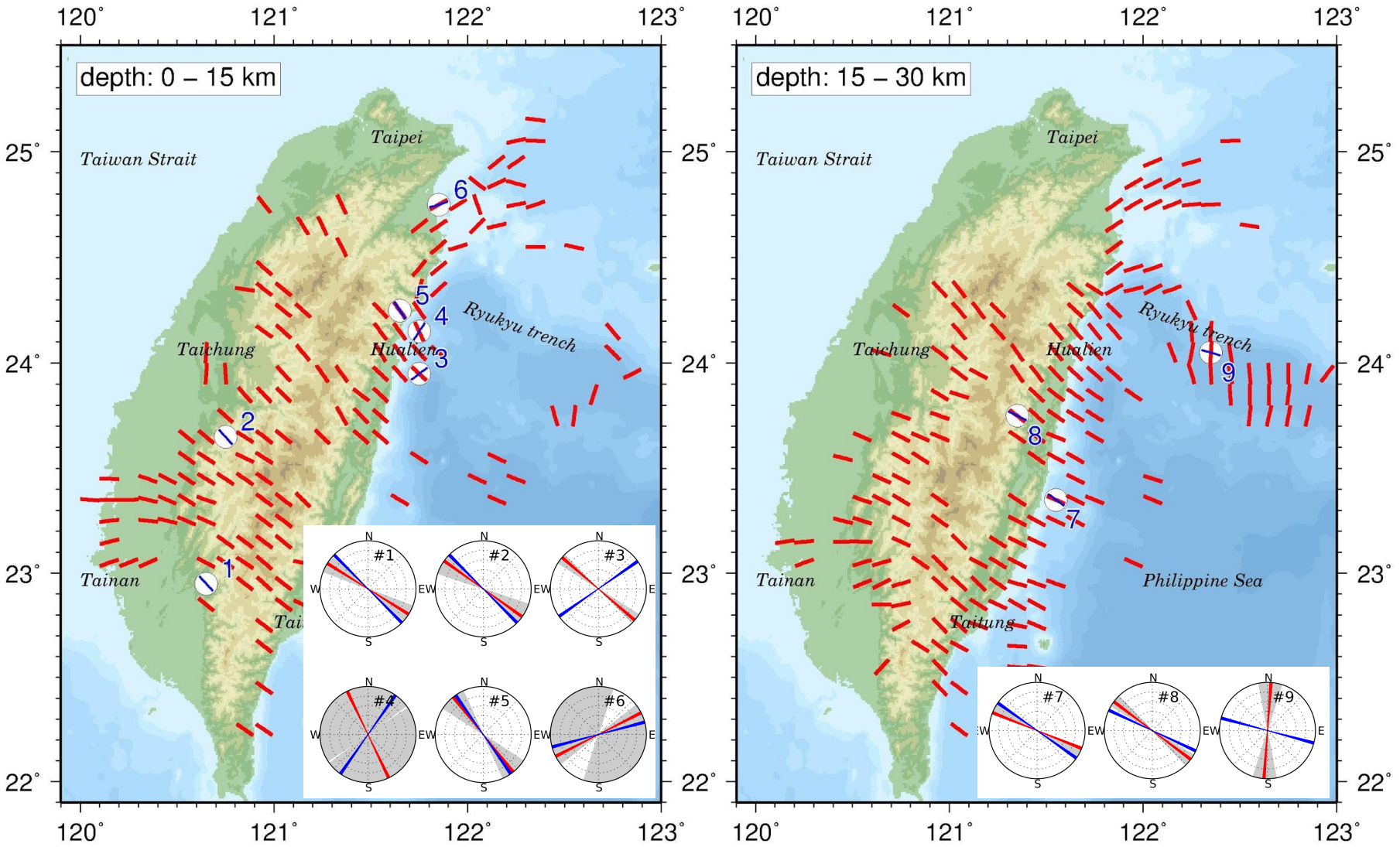
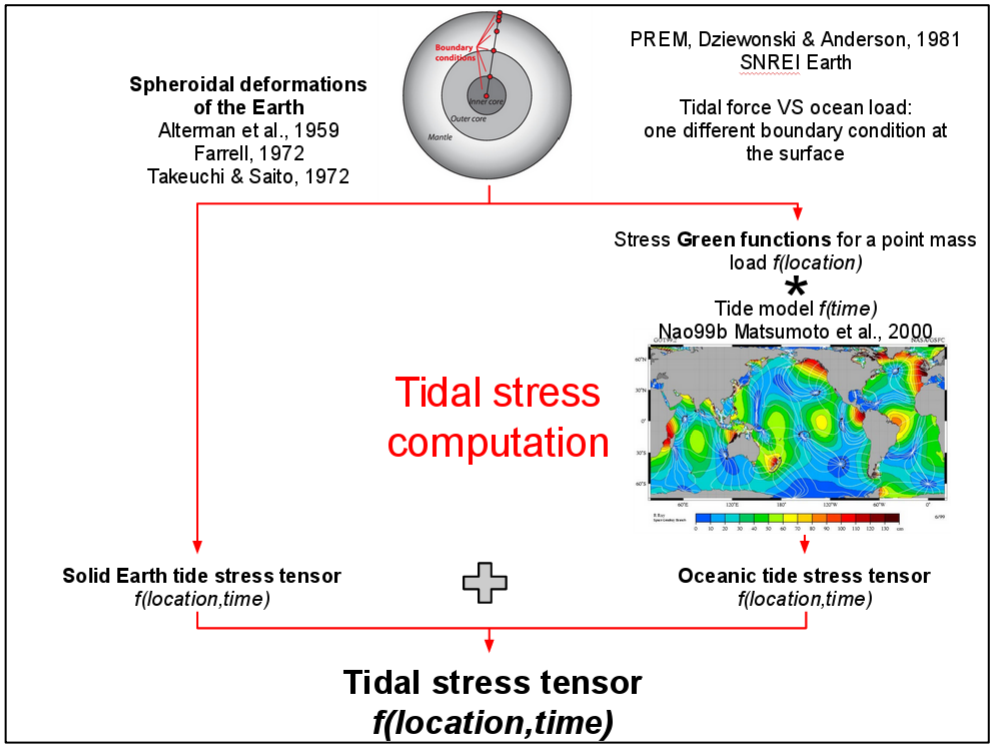


Solid Earth Tides *VS* Ocean Tide Loading

Previously in this presentation...



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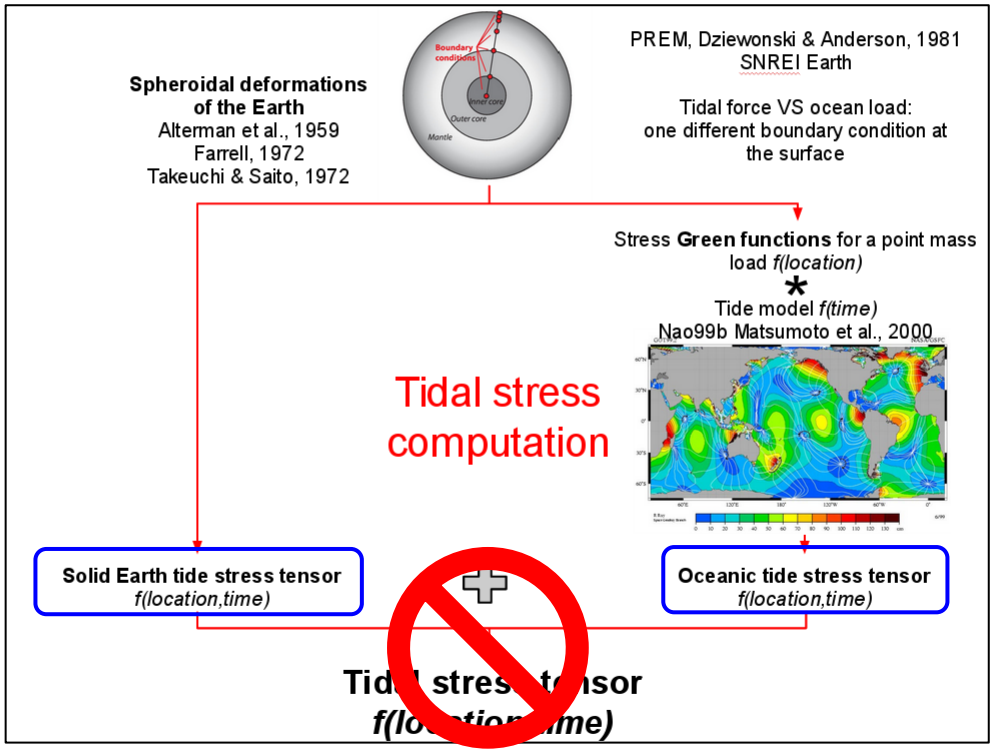
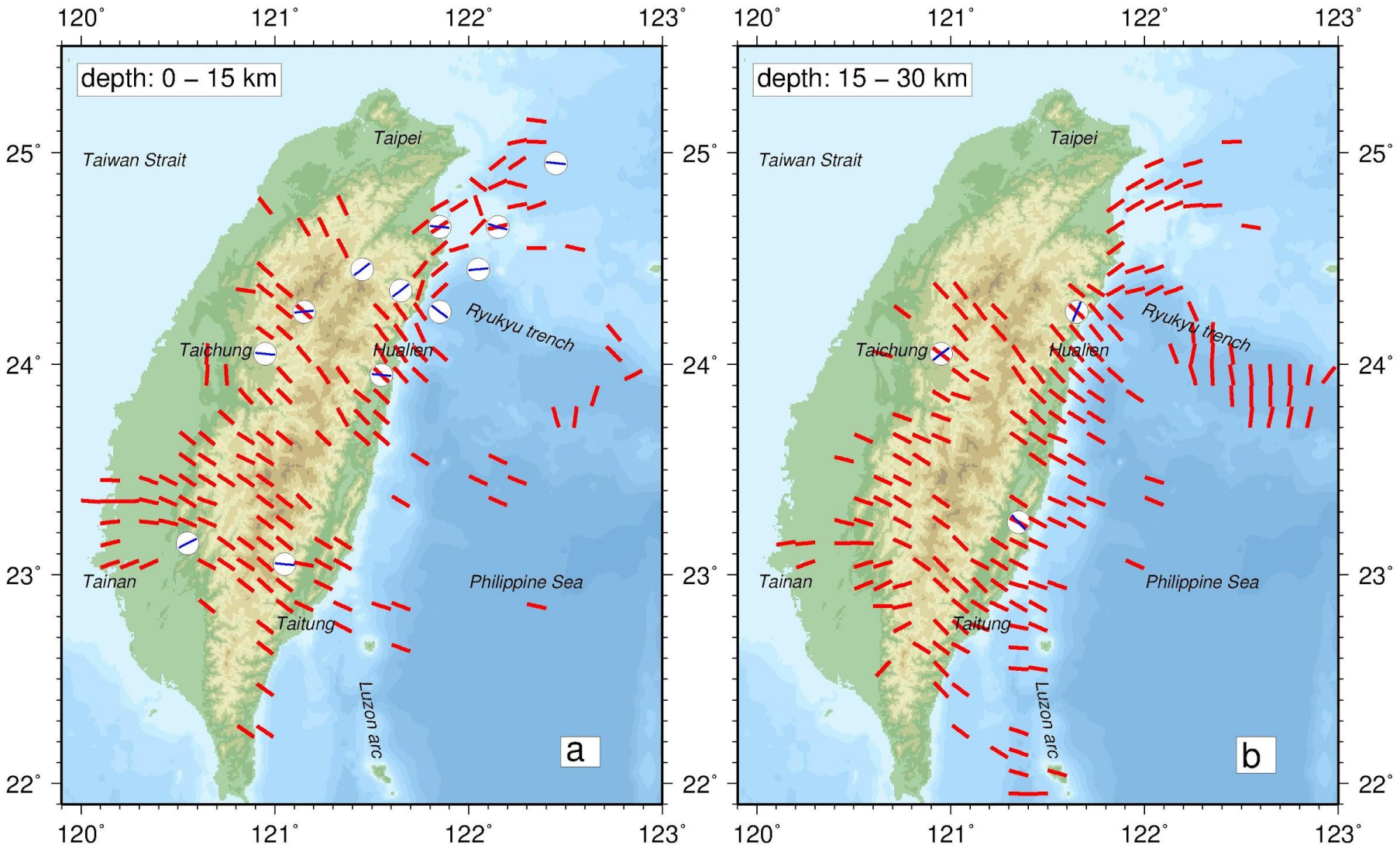


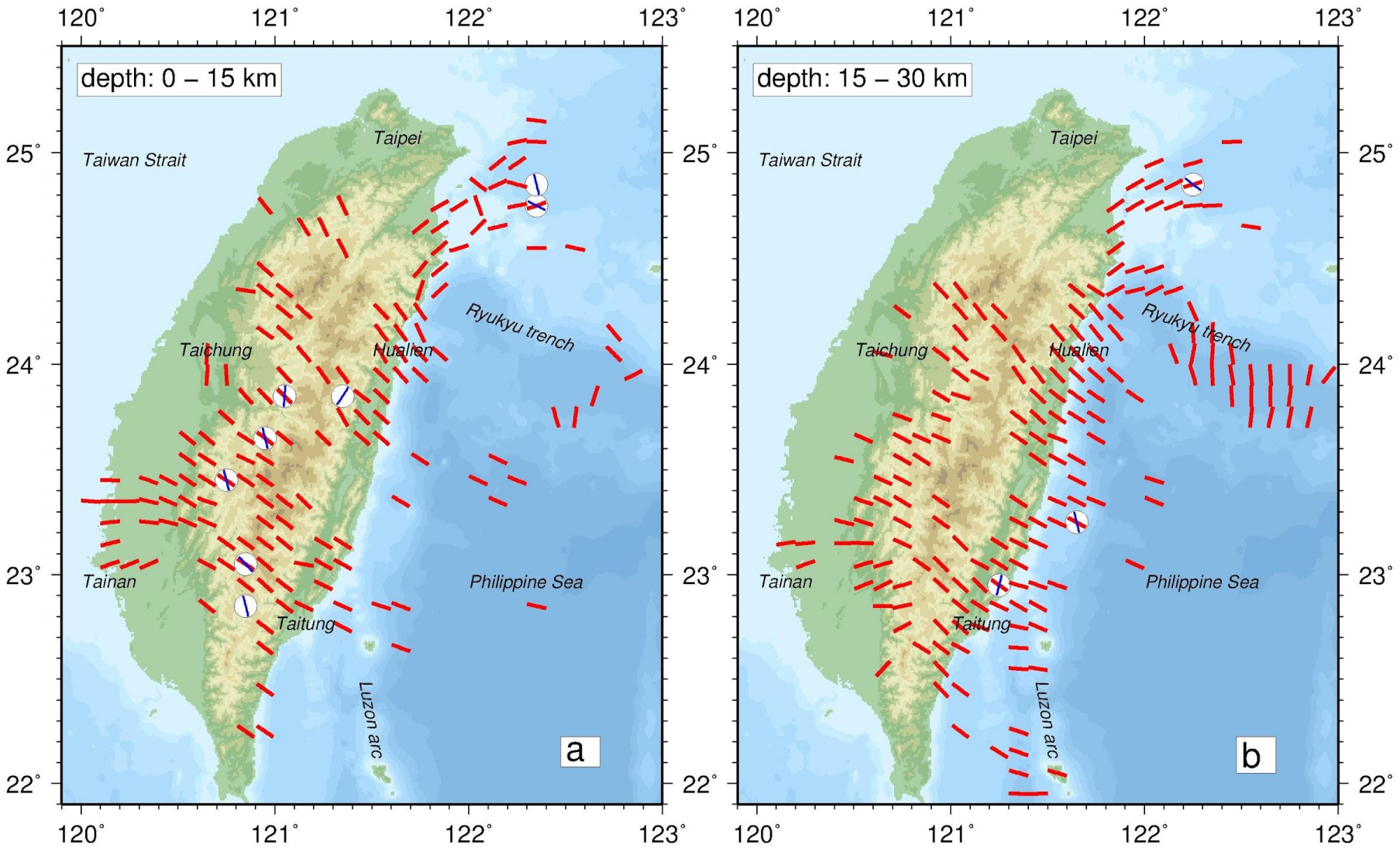
Same method but we **do not sum** the stress tensors of SET and OTL

Study SET and OTL contributions separately.

Only Solid Earth tides



Only Ocean Tide loading



Solid Earth Tides *VS* Ocean Tide Loading

No common zones of tidal triggering

No correlation with the tectonic stress azimuth

This suggests to take into account both effects:

1. Physically more reasonable
2. Tectonic interpretation more consistent

Conclusion

- Tidal triggering of earthquakes is statistically evidenced with 95% confidence at least in Taiwan, mainly on the East coast. But This remain a seldom phenomenon (~3% of the investigated area)

- In most of these locations, the idea that the tidal stress may encourage earthquake occurrence when it acts in the direction to increase the regional tectonic stress is verified

- Both SET and OTL must be taken into account

Perspectives

- Time variability of tidal triggering
- The geological reason for these tide-sensitive areas, if any, has still to be clarified


Thank you !