Detection of slow slip events underneath Taiwan orogenic belt

Wei Peng
[1]Dept. of Earth Sciences, National Taiwan Normal University, Taiwan

Kate Huihsuan Chen[1], Roland Bürgmann[2], YaJu Hsu[4], Zaccaria El Yousfi[3], Mathilde Radiguet[3], Erwan Pathier[3], YanHong Chen[4]

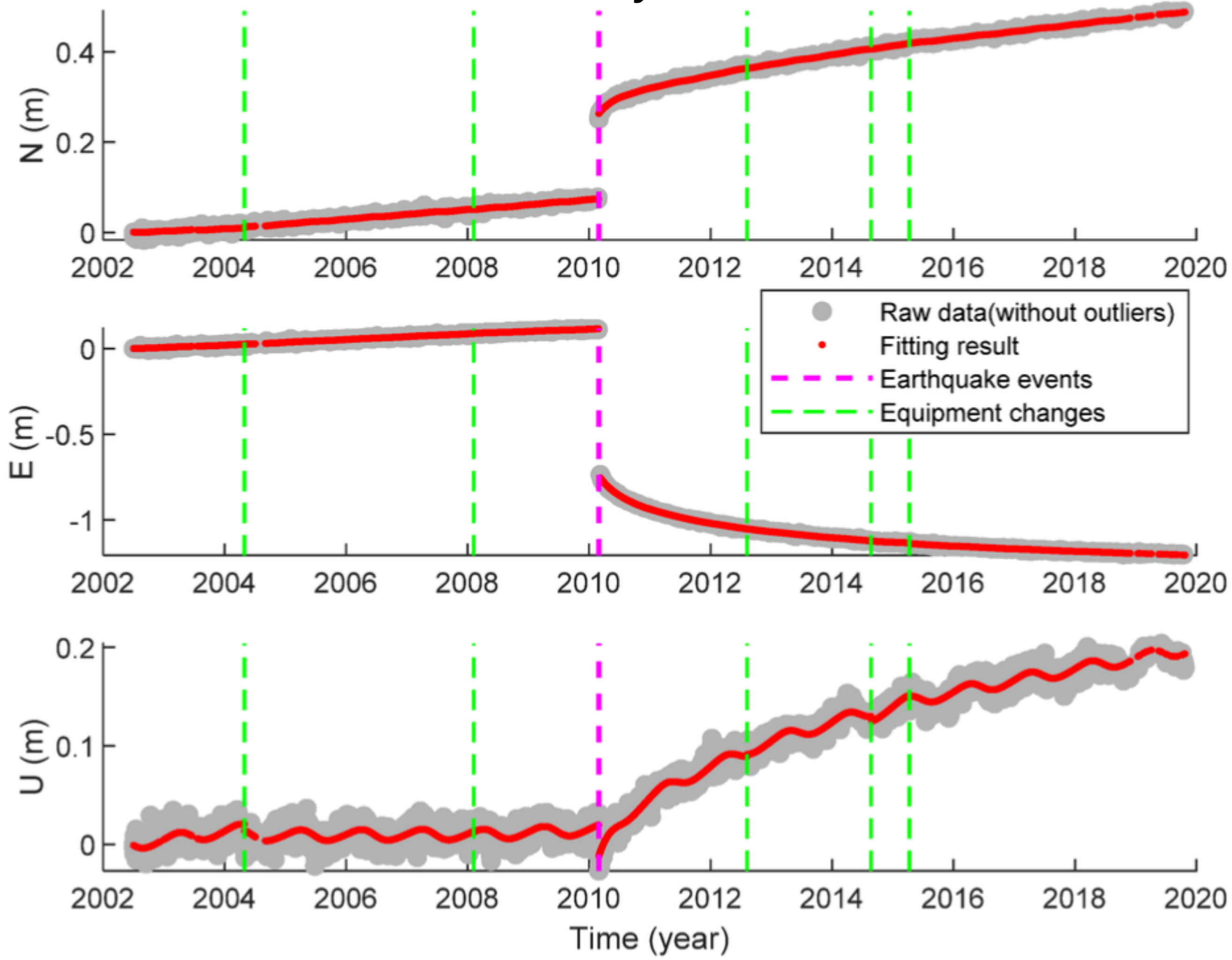
[2]Department of Earth and Planetary Science, University of California, Berkeley, California, USA
[3]Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, Univ. Gustave Eiffel, ISTerre
[4]Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan

Regular earthquake versus Slow earthquake

The difference of SPEED

Regular earthquake

1 day

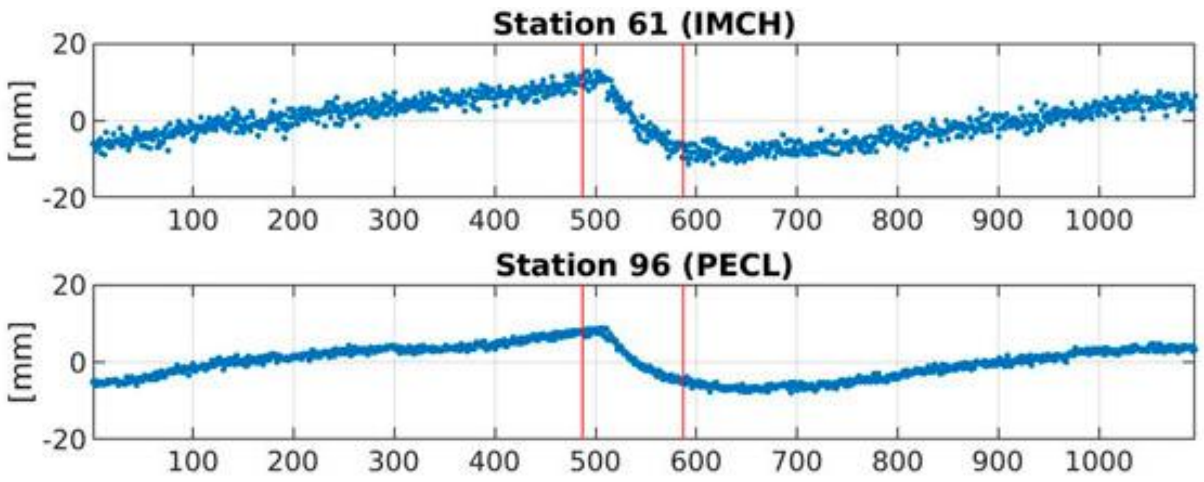


Ren et al., (2021)

Slow earthquake

Slow slip event

100 day

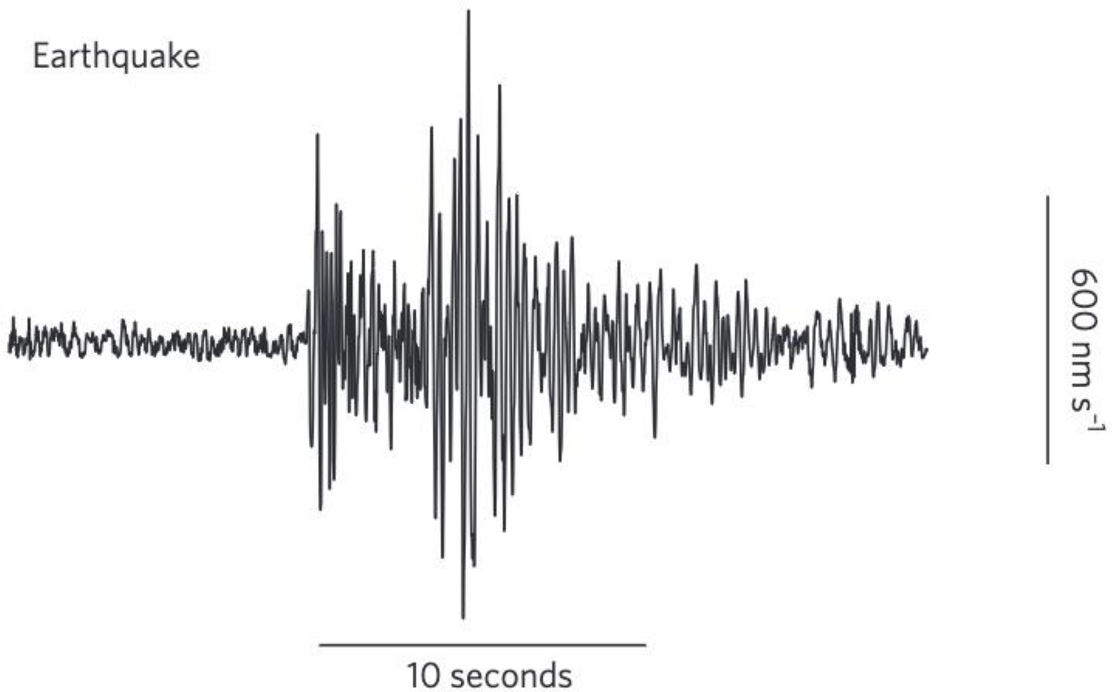


Donoso et al., (2021)

Regular earthquake versus Slow earthquake

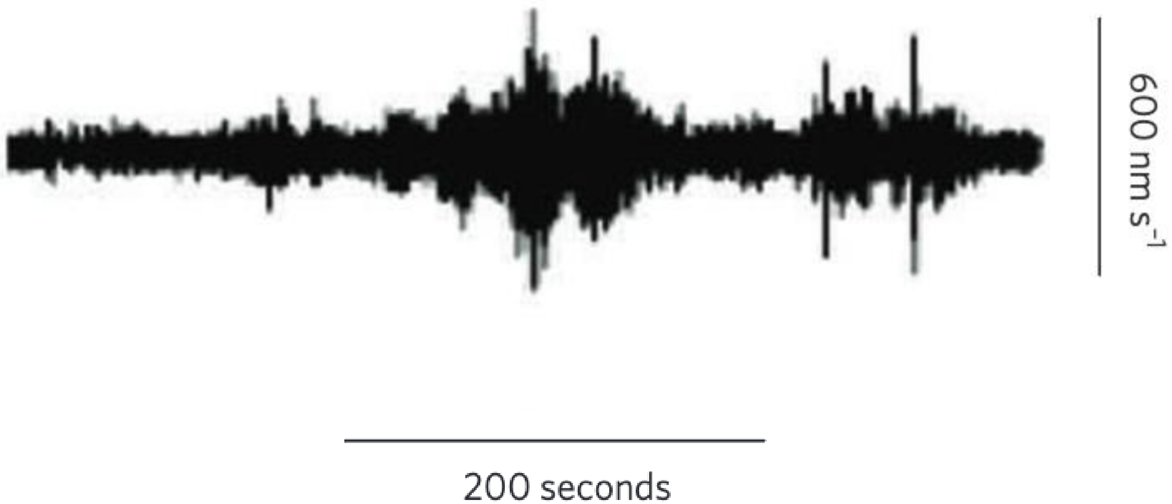
The difference of SPEED

Regular earthquake



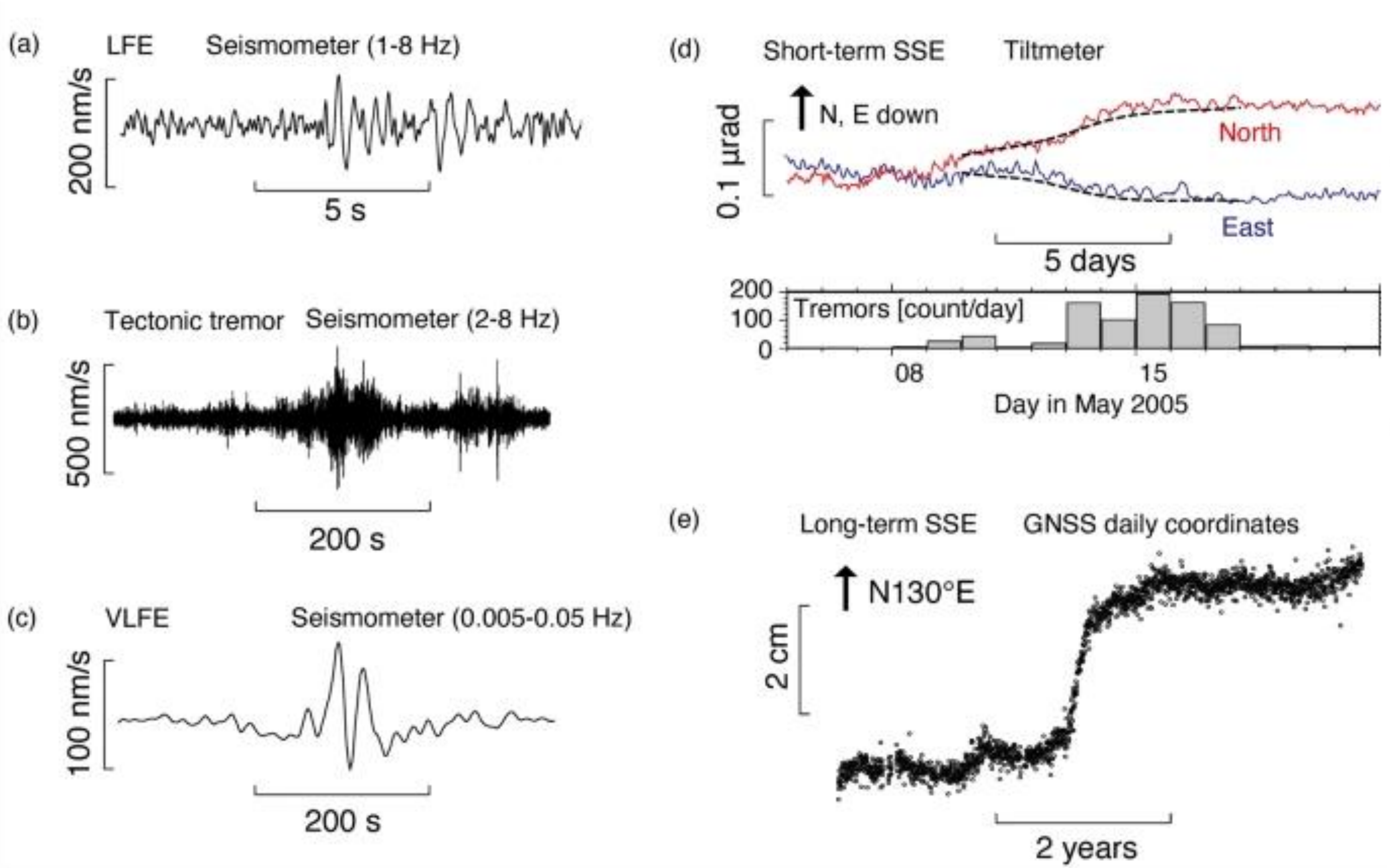
Slow earthquake

Non-volcanic tremor

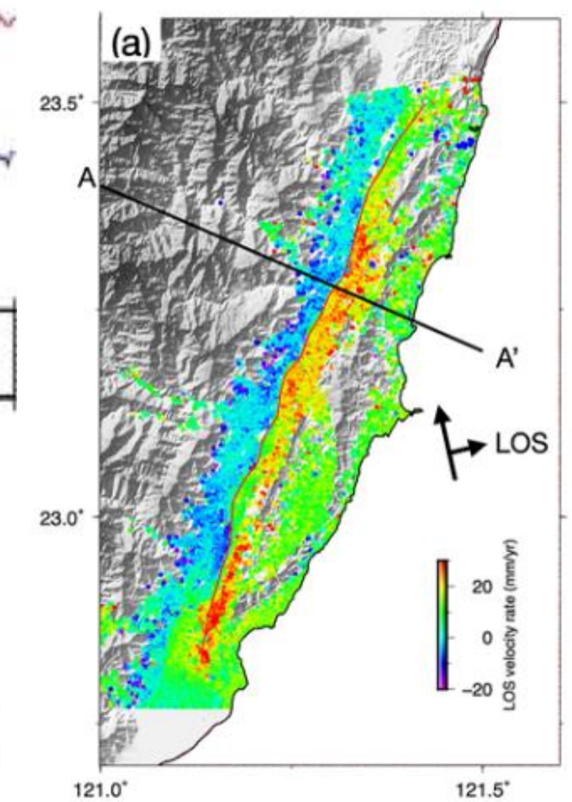


Peng and Gomberg (2010)

Family of Slow earthquake (aseismic slip)



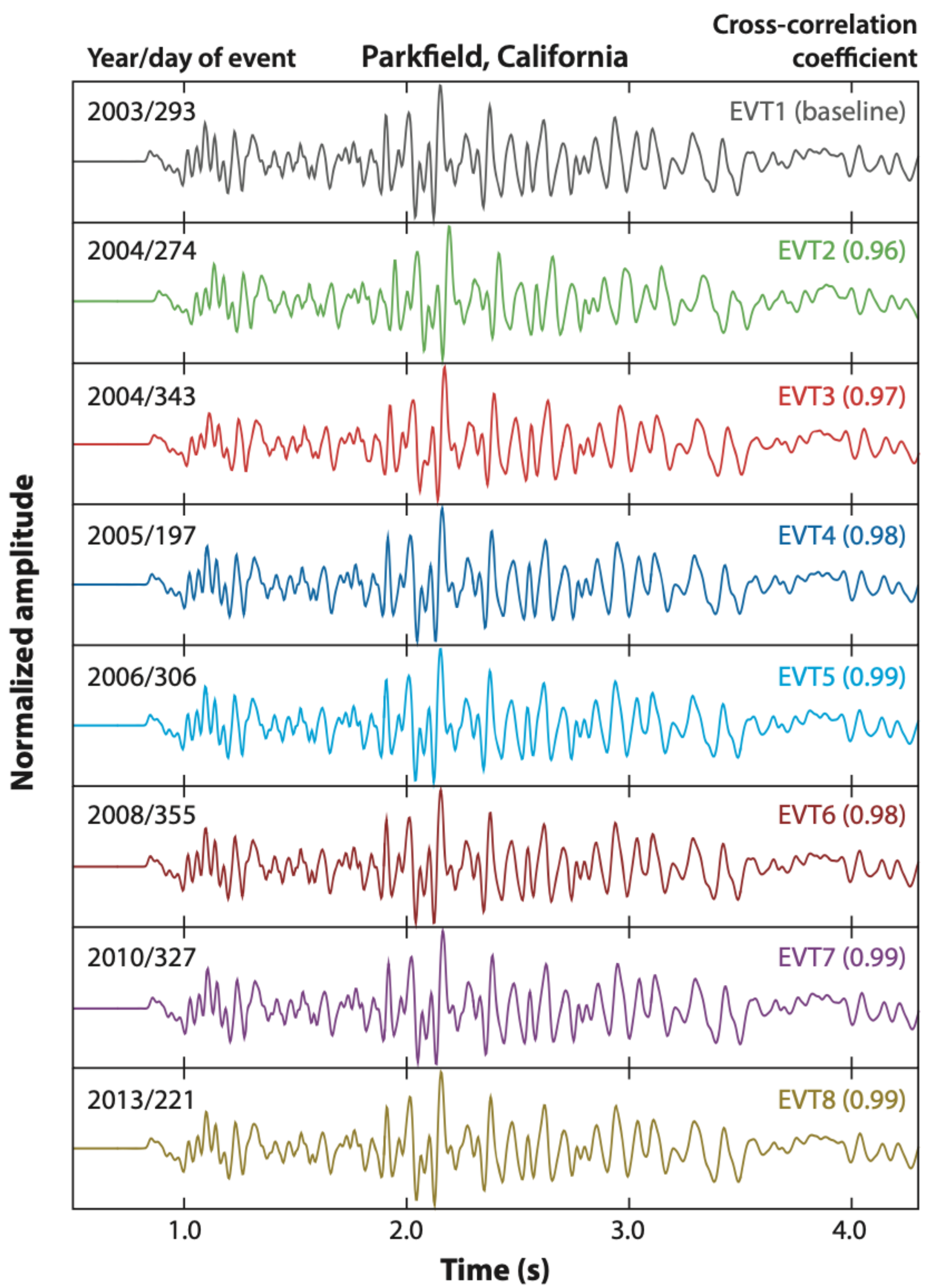
(f) surface creep



Nishikawa et al., (2023)

Strain on a fault that is released aseismically (aseismic slip) could be referred to as a slow earthquake

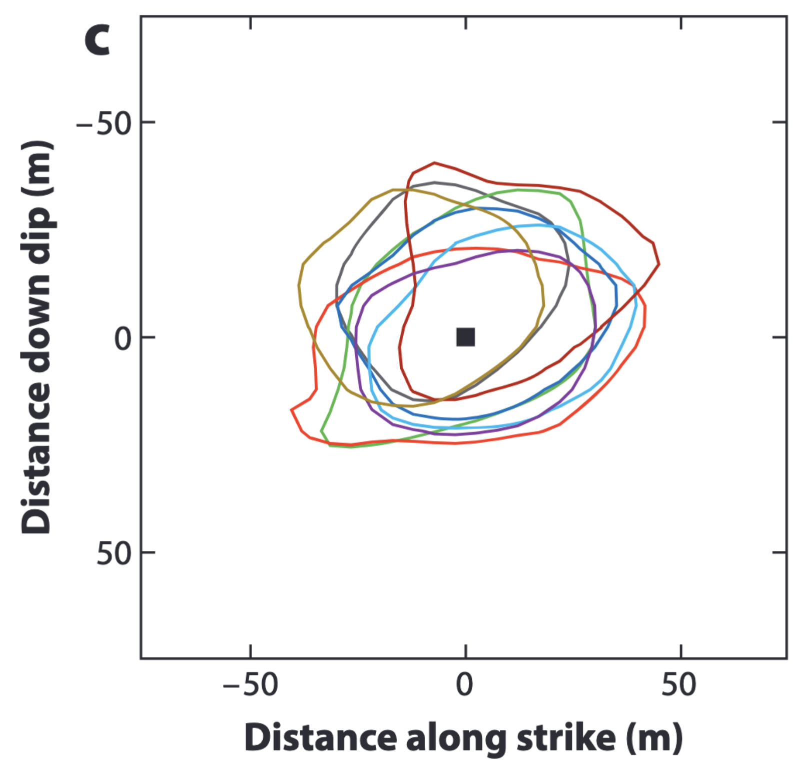
Other seismic events that associated with aseismic slip



Uchida (2019)

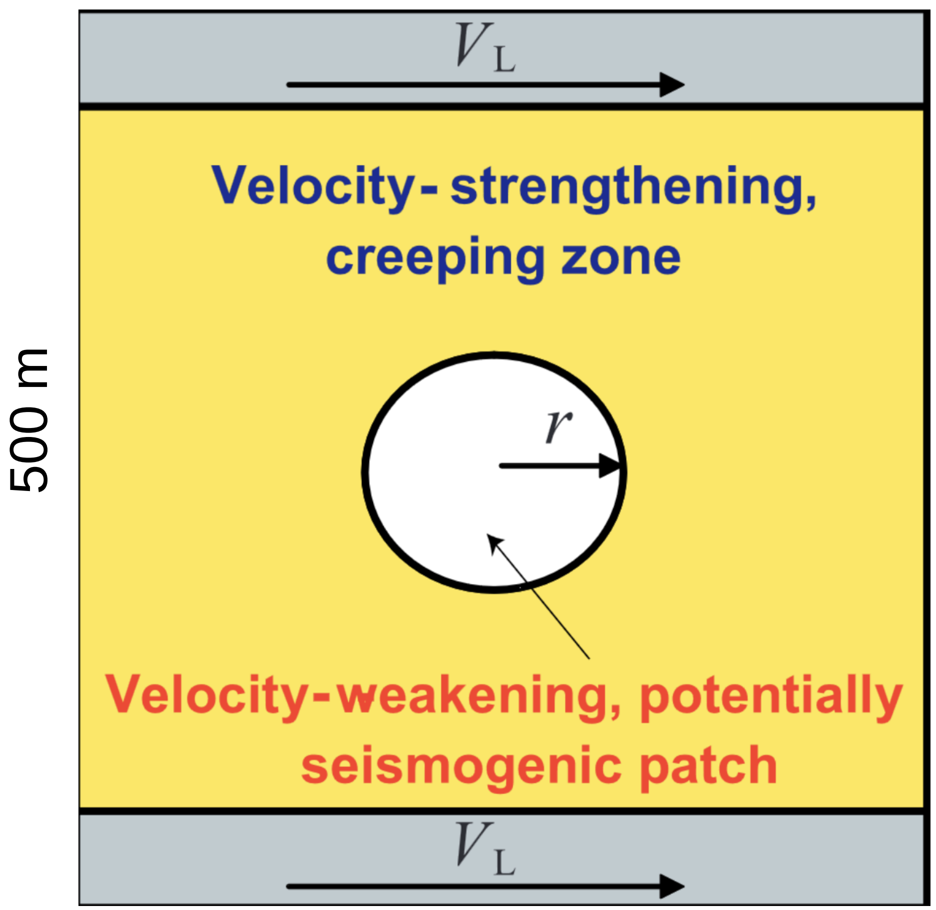
Repeating earthquake : rupture of seismic asperities embedded in creep fault

1) highly similarly in waveform or spectrum coherency. 2) rupture overlap

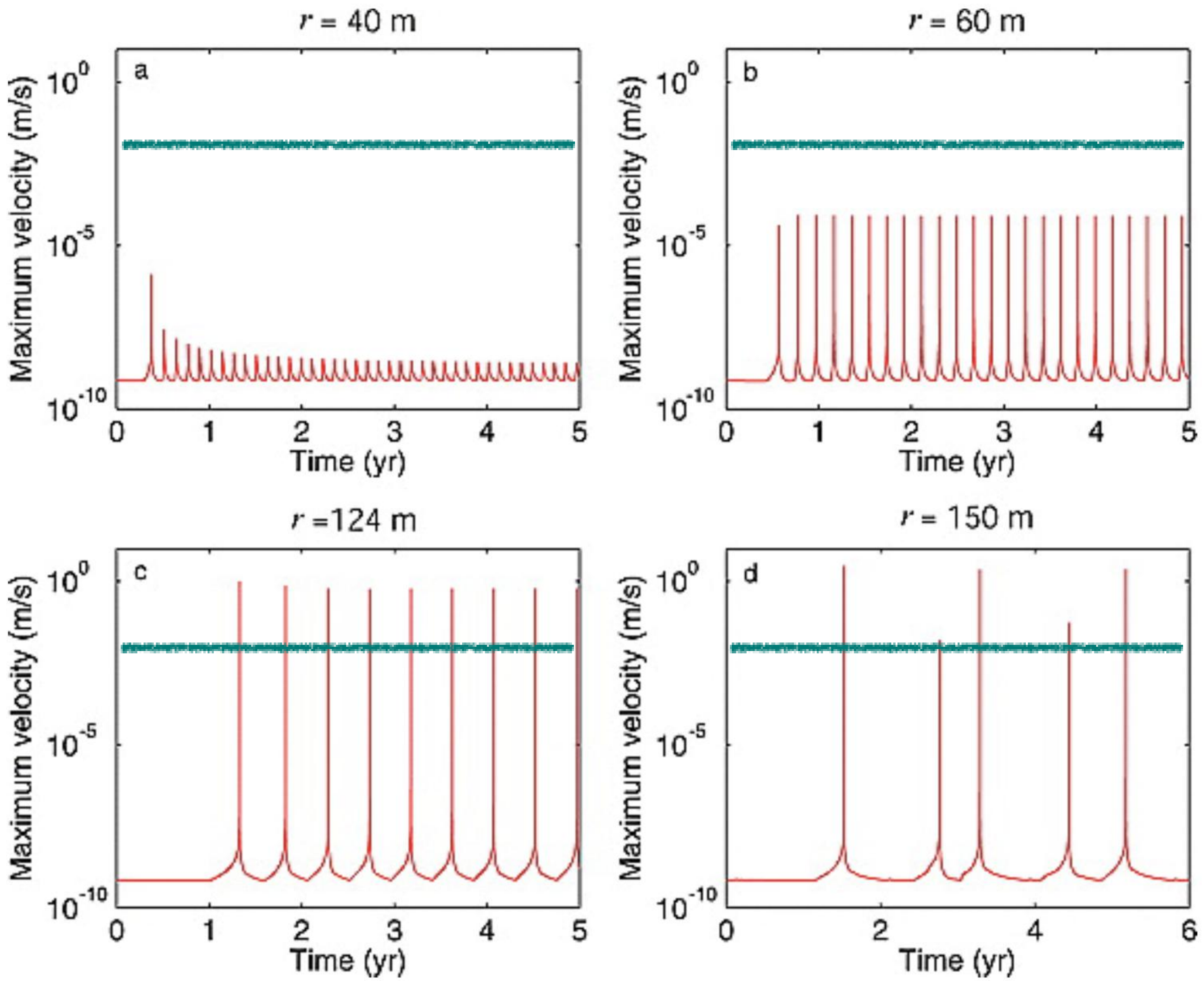


To generate repeating earthquakes, it requires aseismic creep

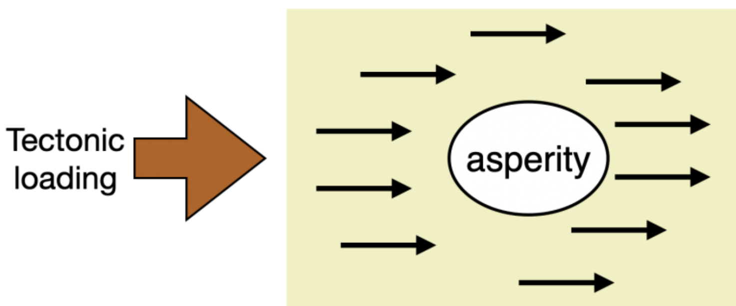
Assuming Vmax ≥ 10^{-3} as a seismic event, repeating behavior only appears under certain conditions

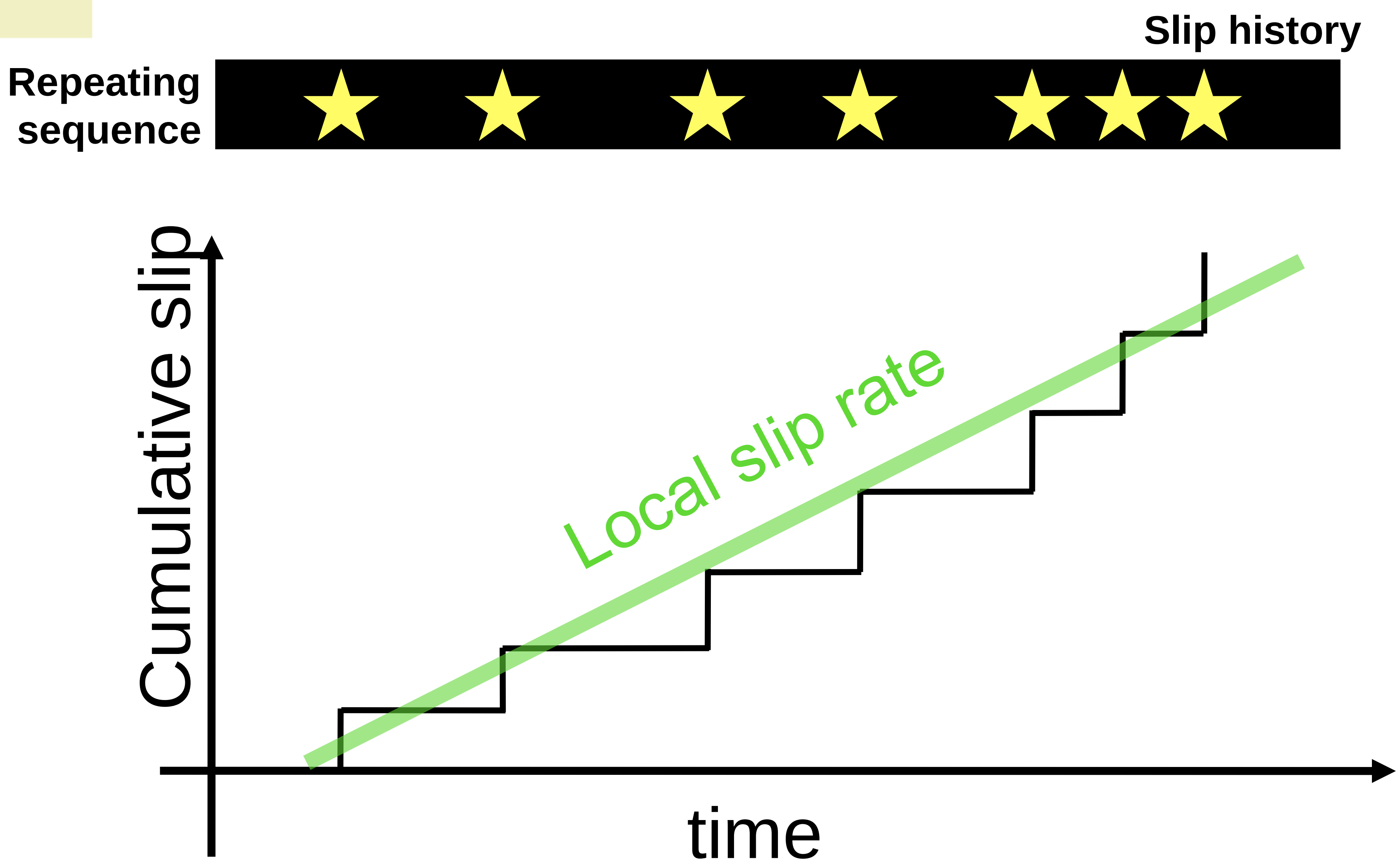


Chen and Lapusta (2009)



By assuming a constant loading rate, we can estimate a local aseismic slip rate from repeating earthquakes





For a sequence

$$A = \frac{\dot{\tilde{M}}}{\mu \dot{\tilde{d}}} = \frac{M_{av}}{\mu \dot{\tilde{d}}\, T_i}$$

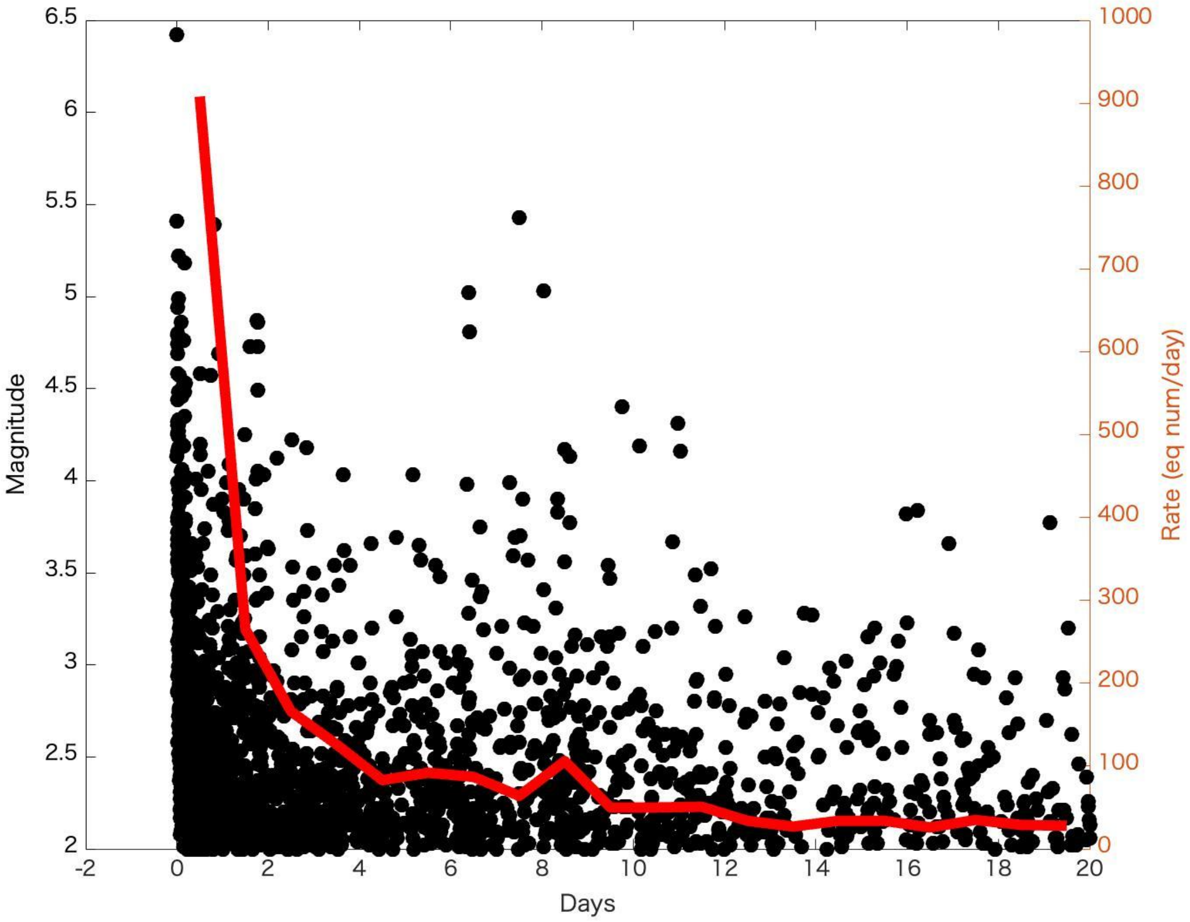
For each event in a seq.

$$d = \frac{M}{\mu A}$$

Other seismic events that associated with aseismic slip

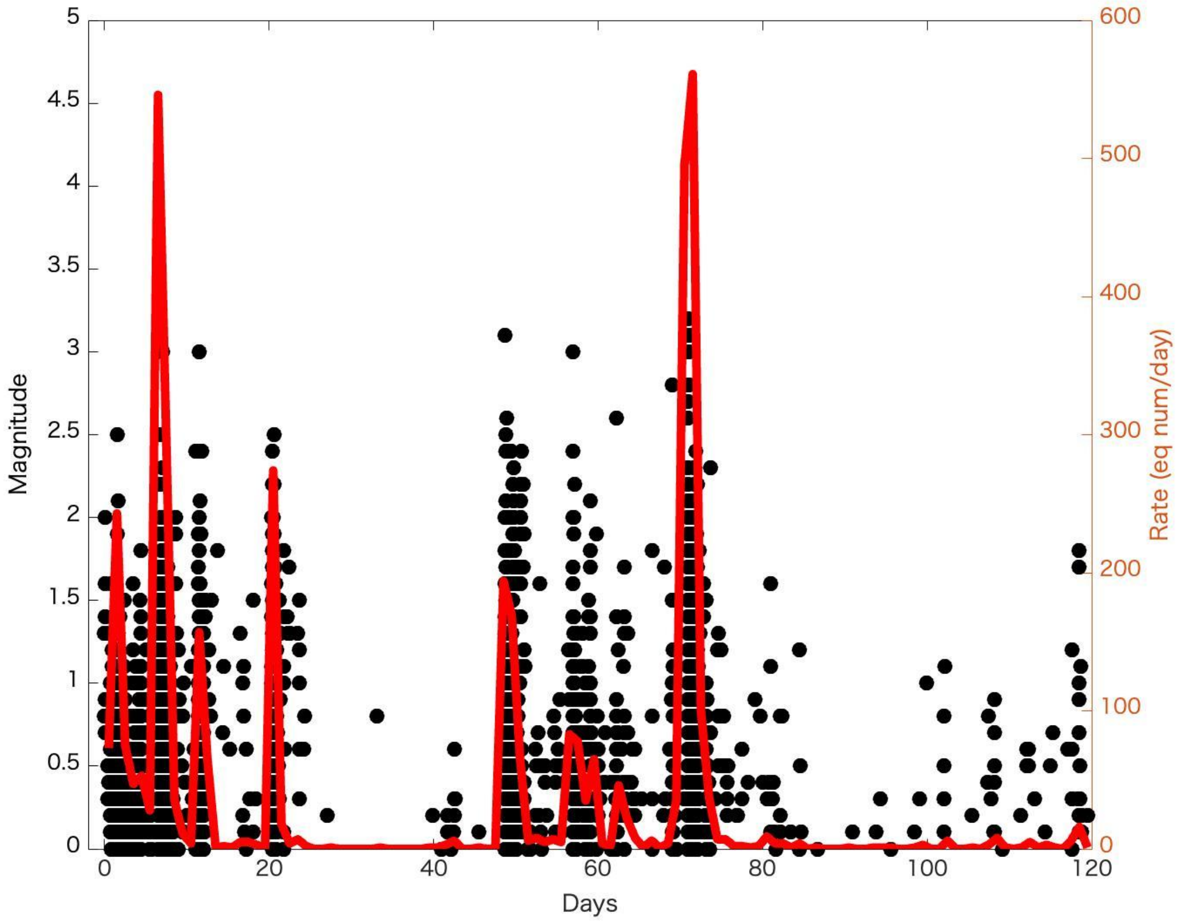
Earthquake swarm: An earthquake cluster whose spatial-temporal characteristics are distinct from mainshock-aftershock sequences, usually occurring in volcanic areas.

Mainshock aftershock sequence
2003 ChengKung



Seismicity rate decay with time

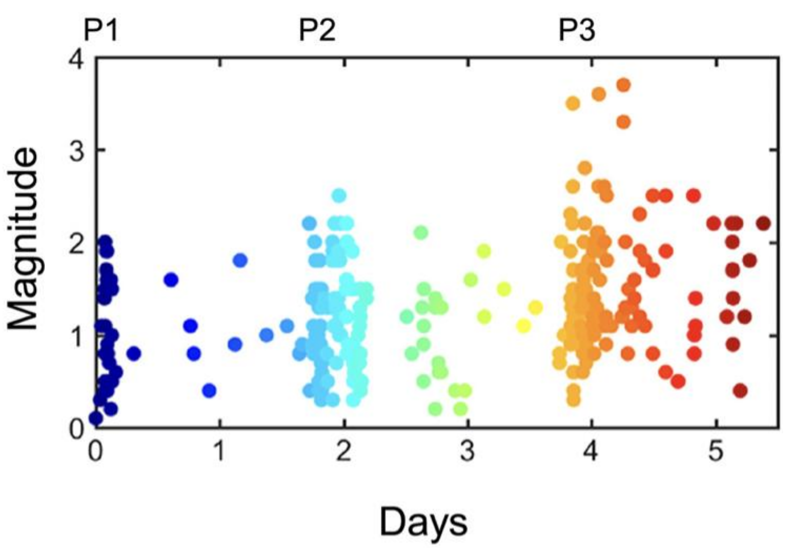
Swarm sequence
2000 West Bohemia/Vogtland

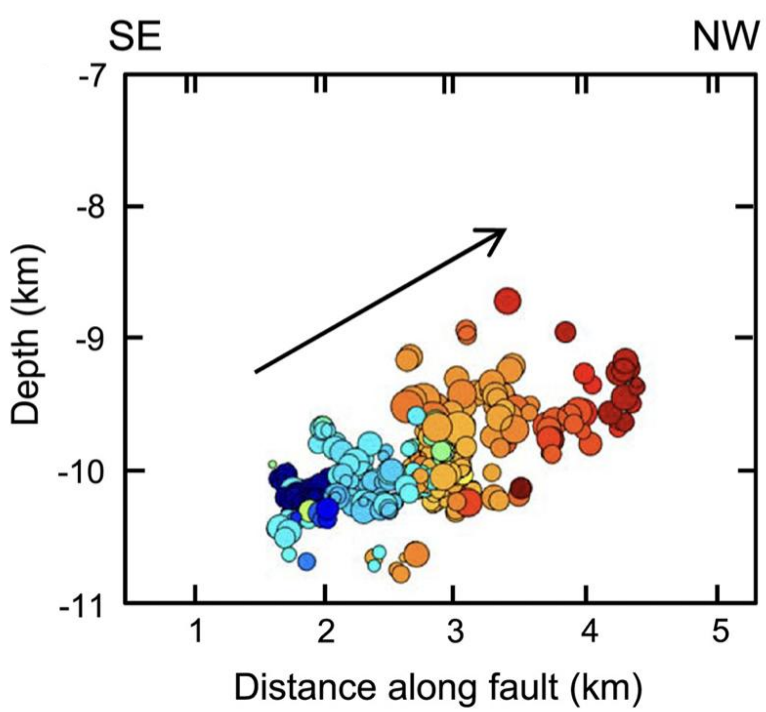


No common features

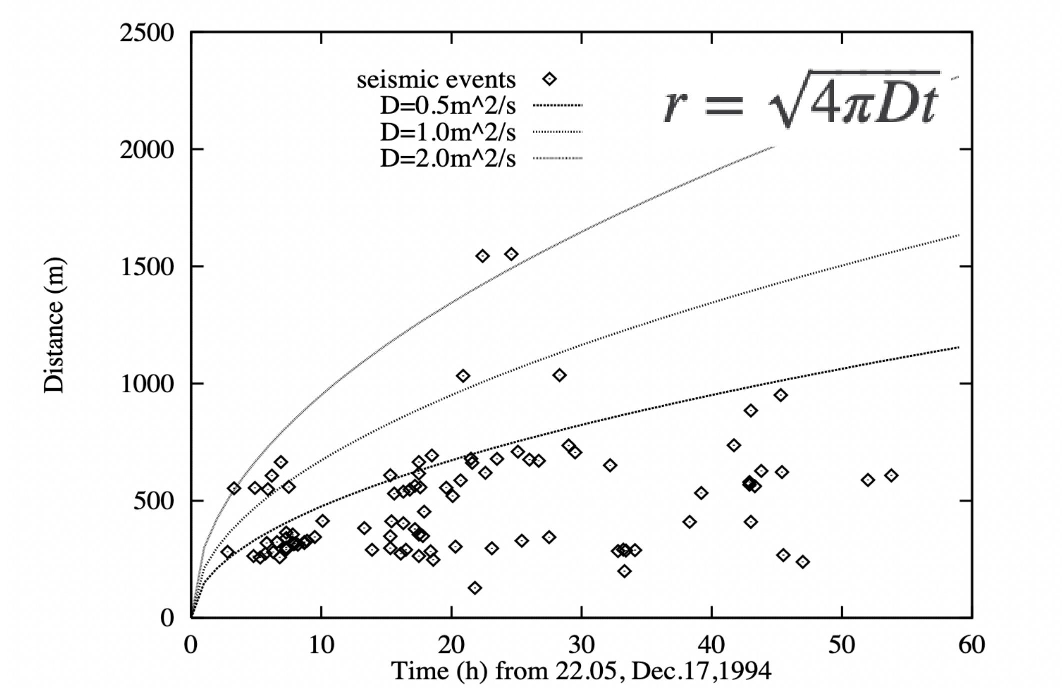
Earthquake swarm is often relate to fluid migration or slow slip transient

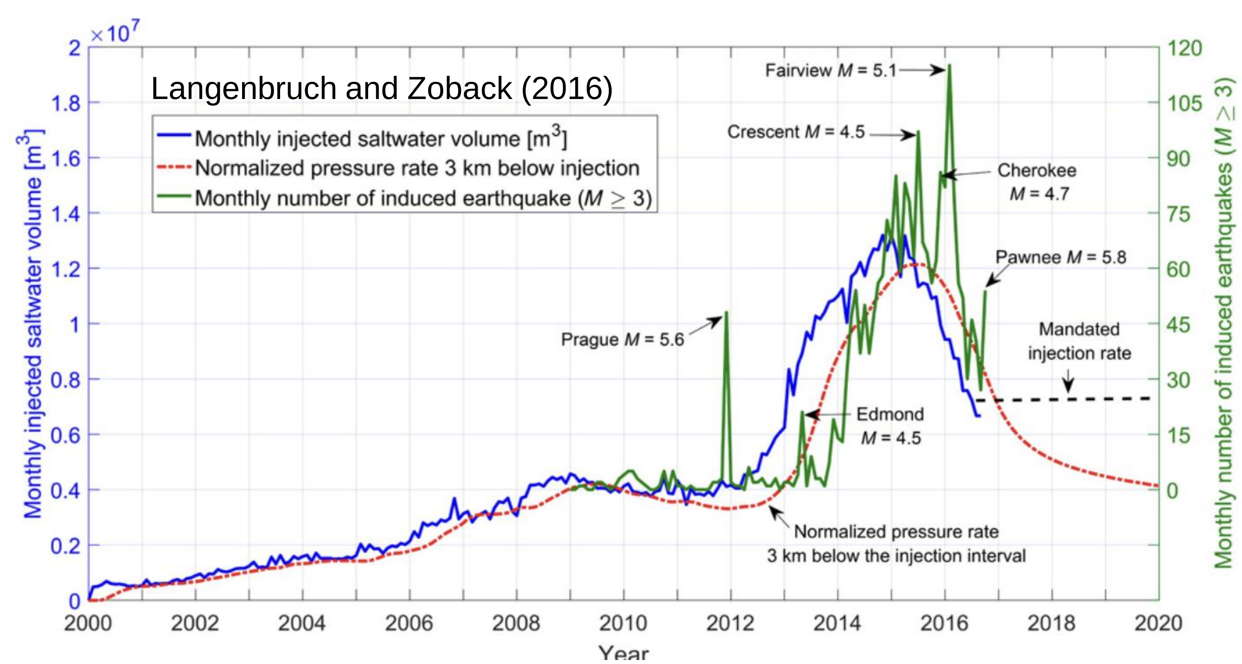
West Bohemia/Vogtland region
(Vavryčuk and Hrubcová 2017)



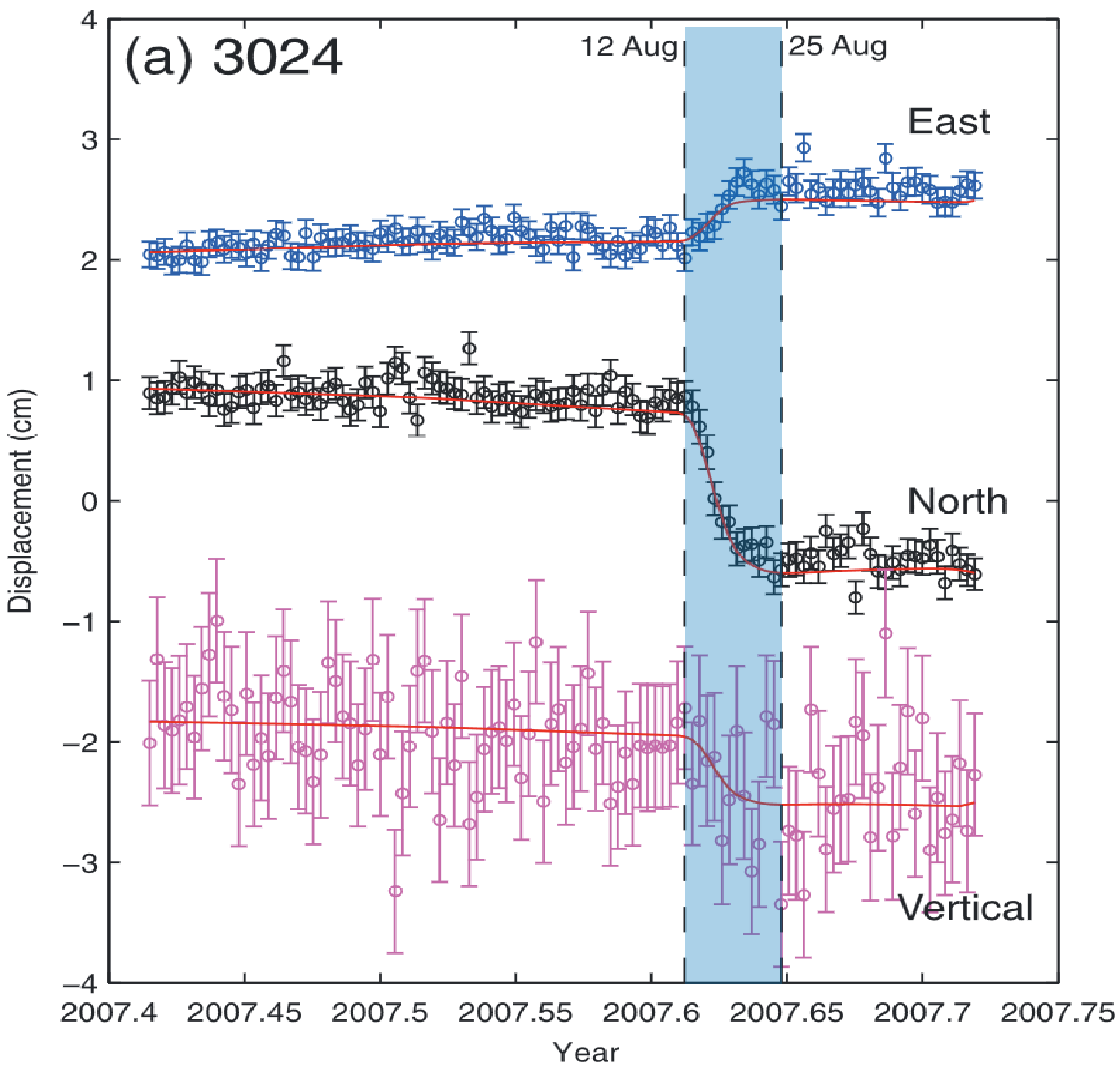


German, water injection
(Shapiro et al., 1997)

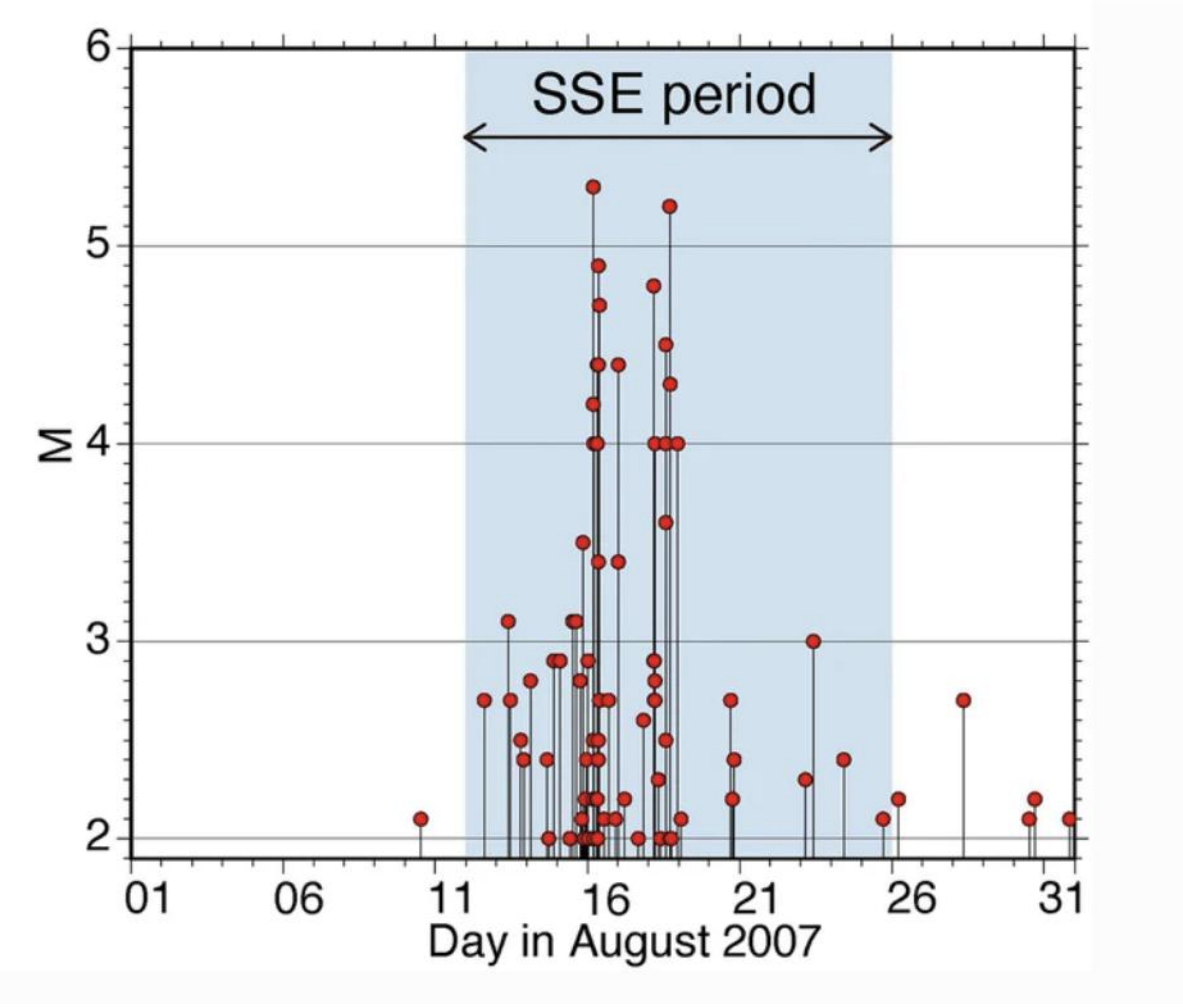




Earthquake swarm is often relate to fluid migration or slow slip transient

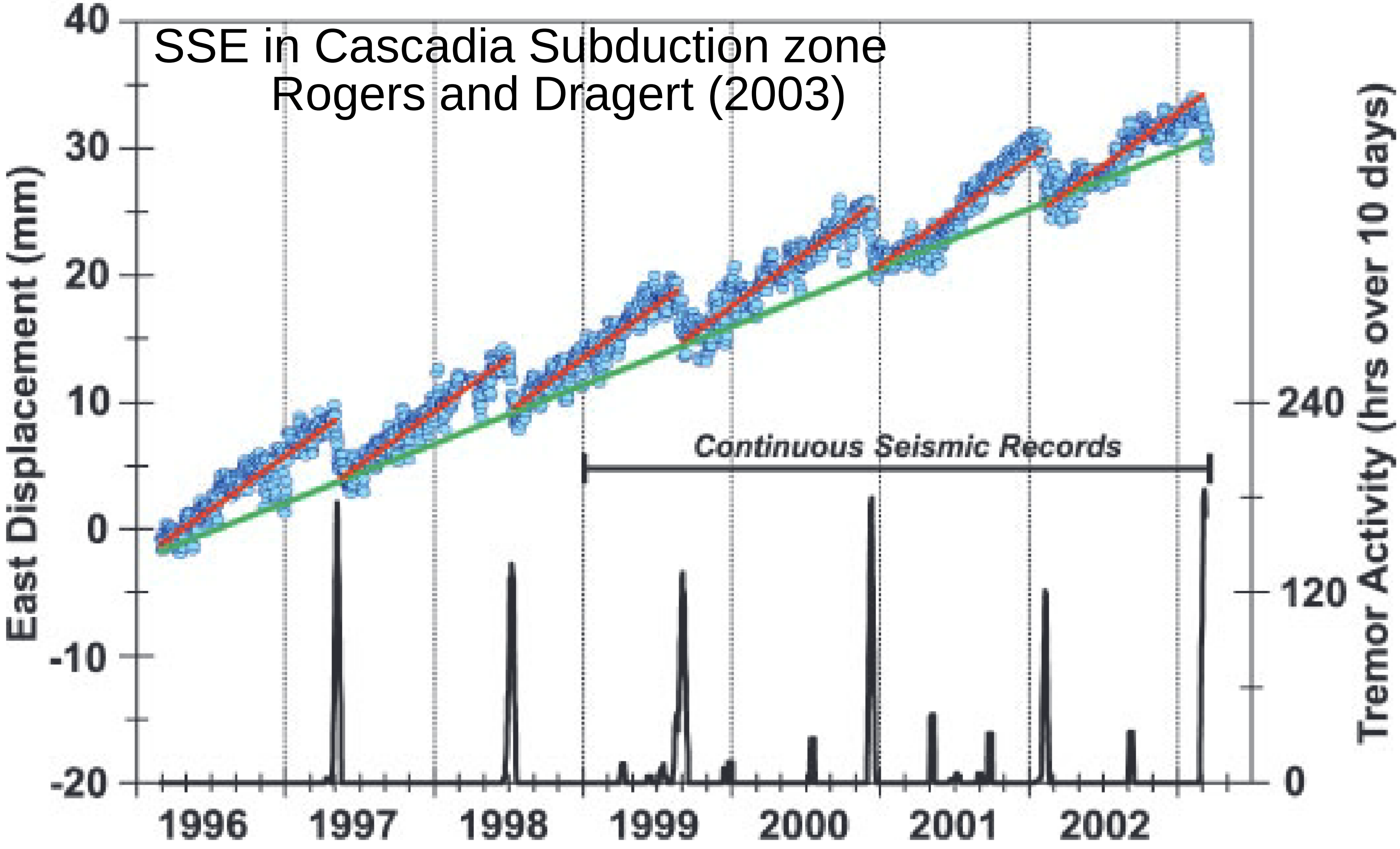


Earthquake swarm occurred along with SSE



Nishikawa et al. (2023)

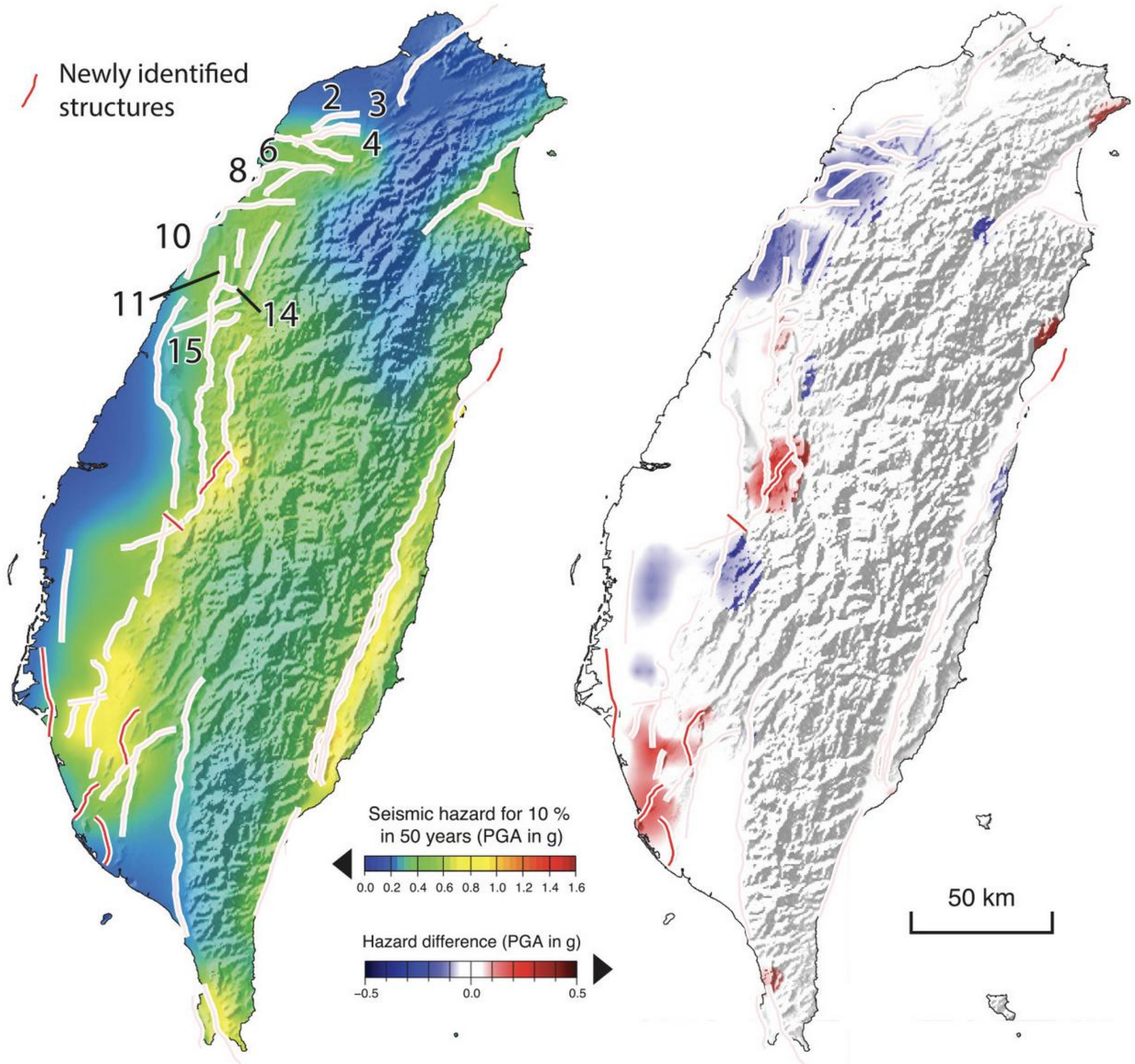
In general, tremors and slow slip events are temporally coincided



Why do we care ?

By monitoring/capturing slow slip events, we could understand more about fault slip during the interseismic period.

By knowing about fault slip during the interseismic period, we can estimate the slip deficit to quantify how much strain is accumulating.

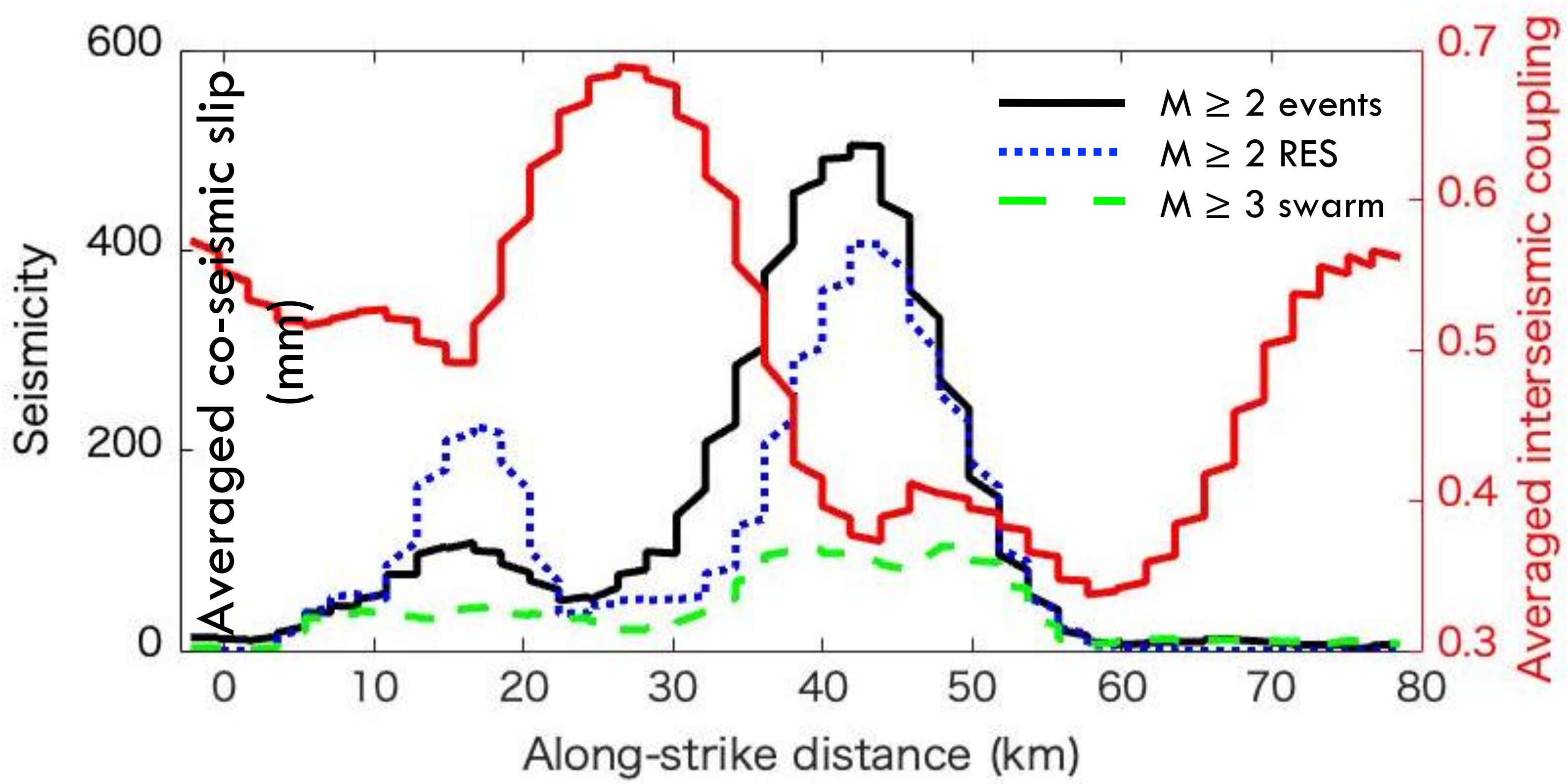


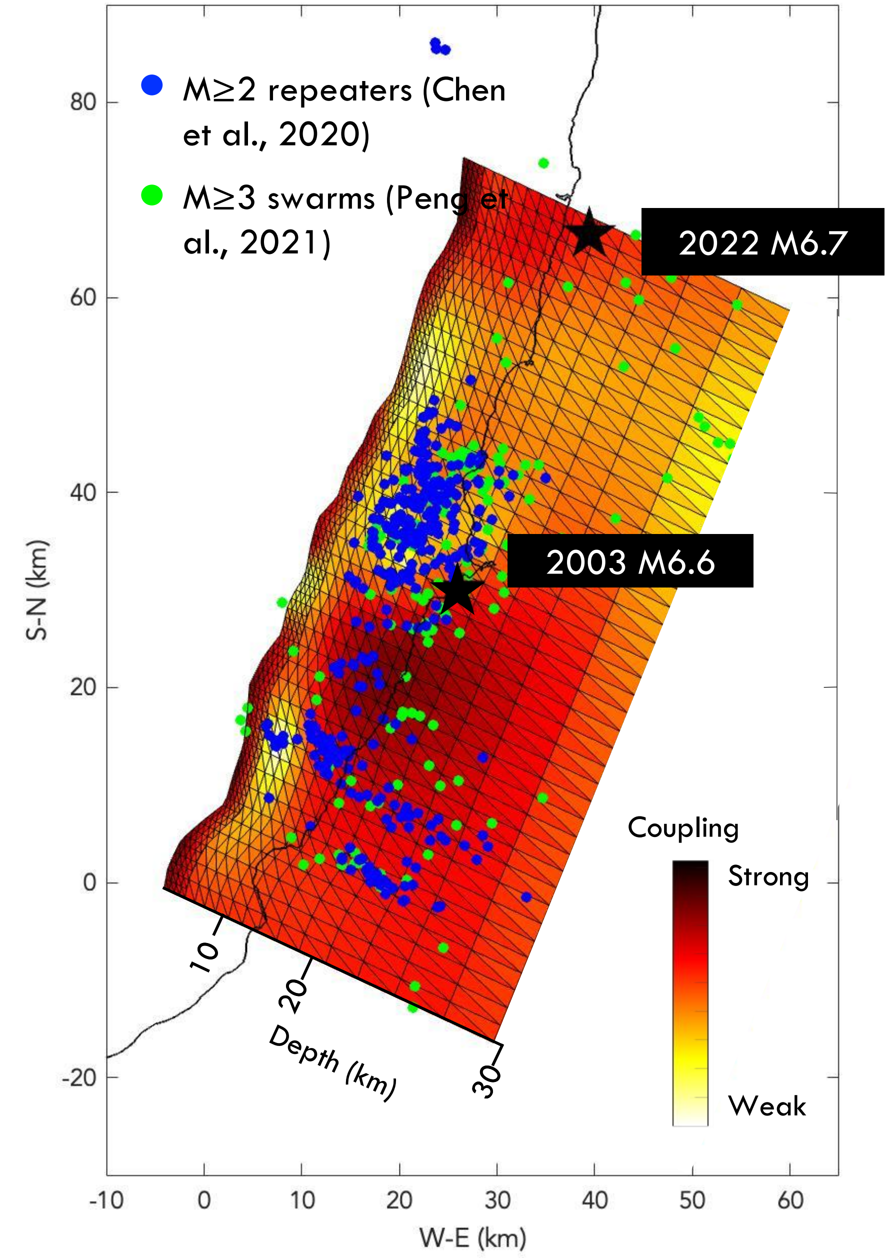
Chan et al (2020)

Interseismic coupling estimated using geodetic and repeating earthquake

The spatial variation of seismicity in general, shows an anti-correlation with that of the interseismic coupling.

In higher coupling areas however, seismicity patterns are distinct from those with weak coupling.



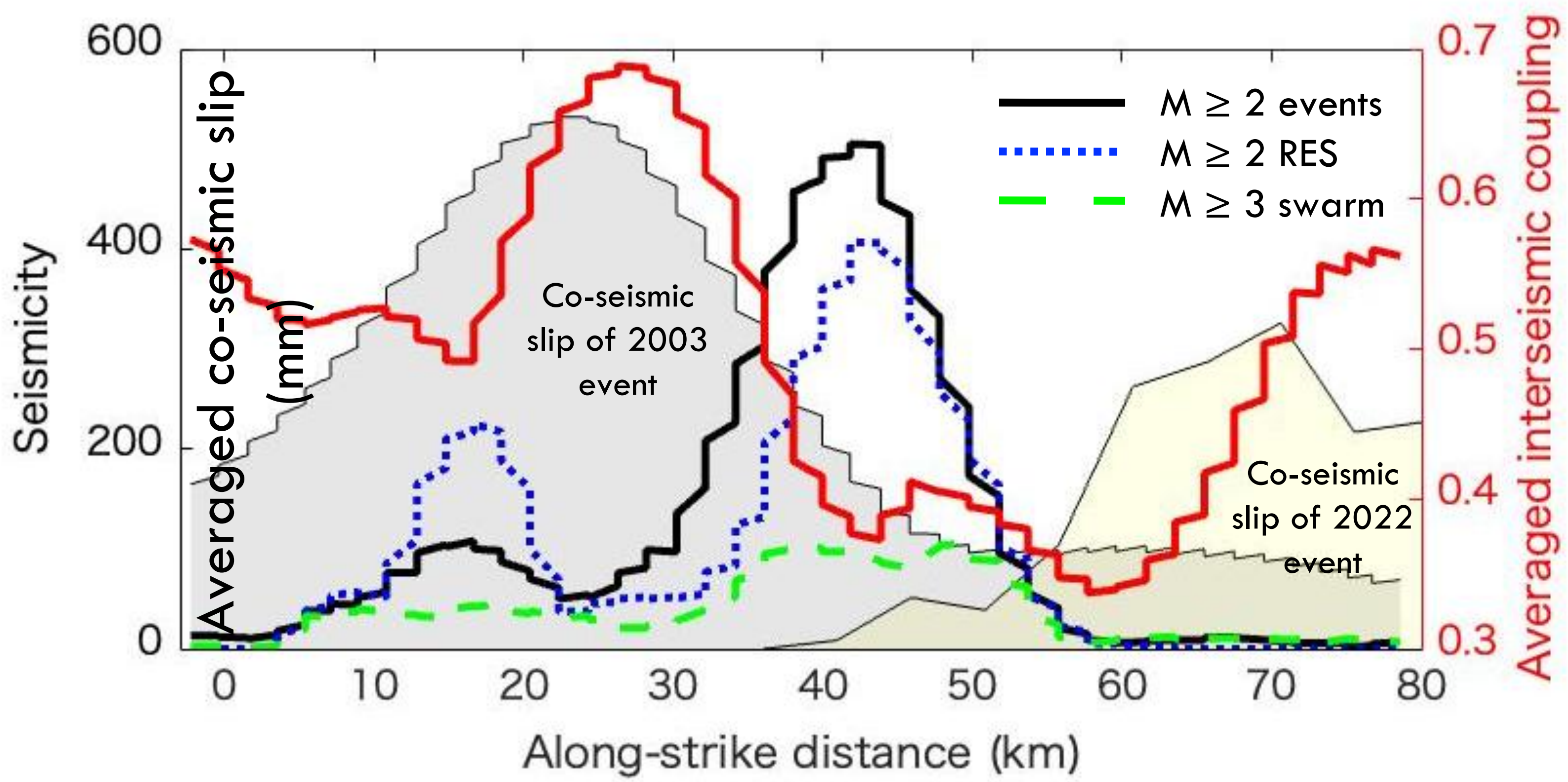


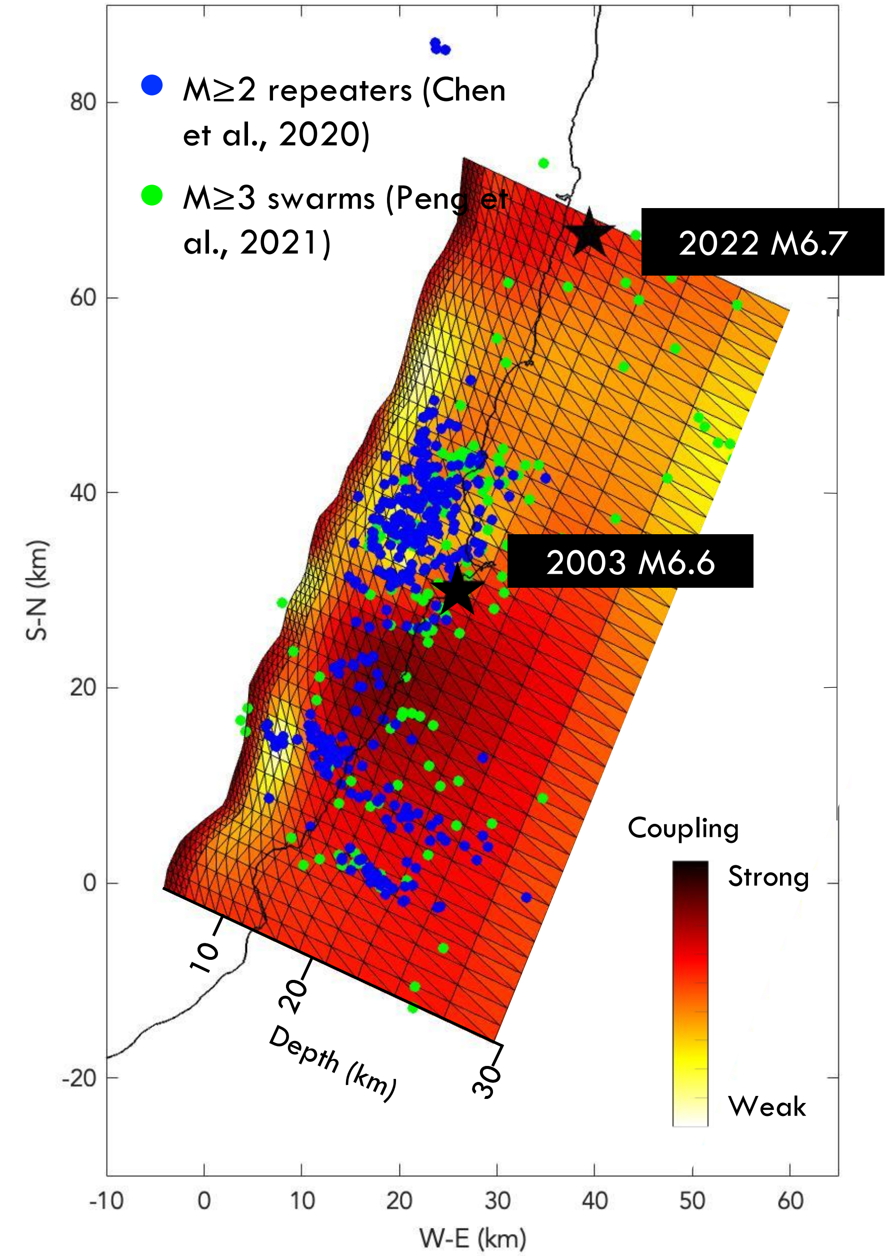
Peng et al., (2023)

Interseismic coupling estimated using geodetic and repeating earthquake

The spatial variation of seismicity in general, shows an anti-correlation with that of the interseismic coupling.

In higher coupling areas however, seismicity patterns are distinct from those with weak coupling.



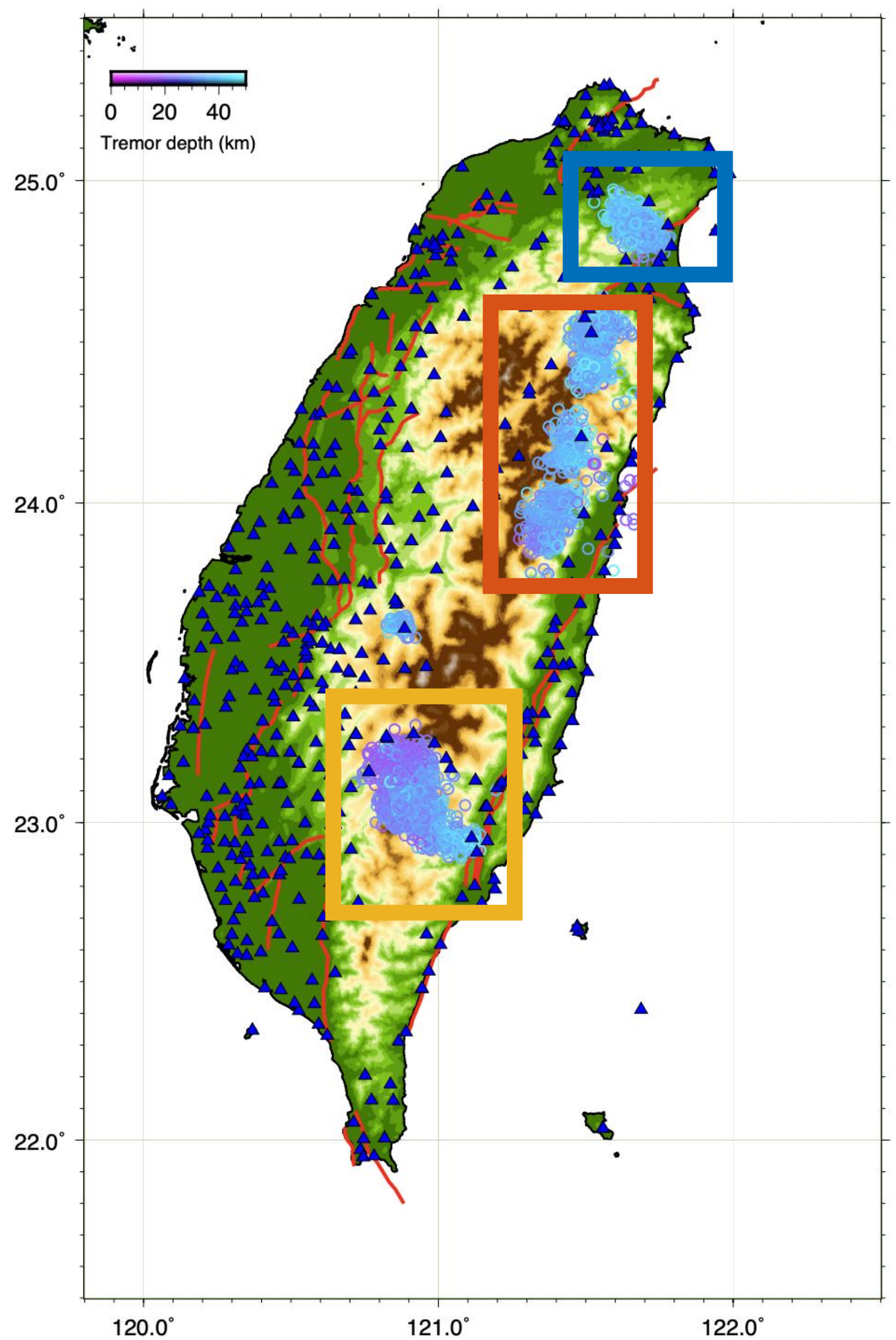


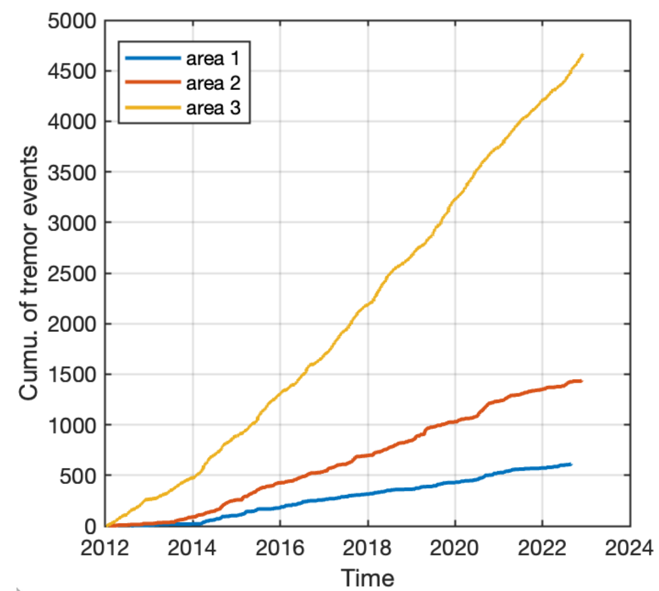
Peng et al., (2023)

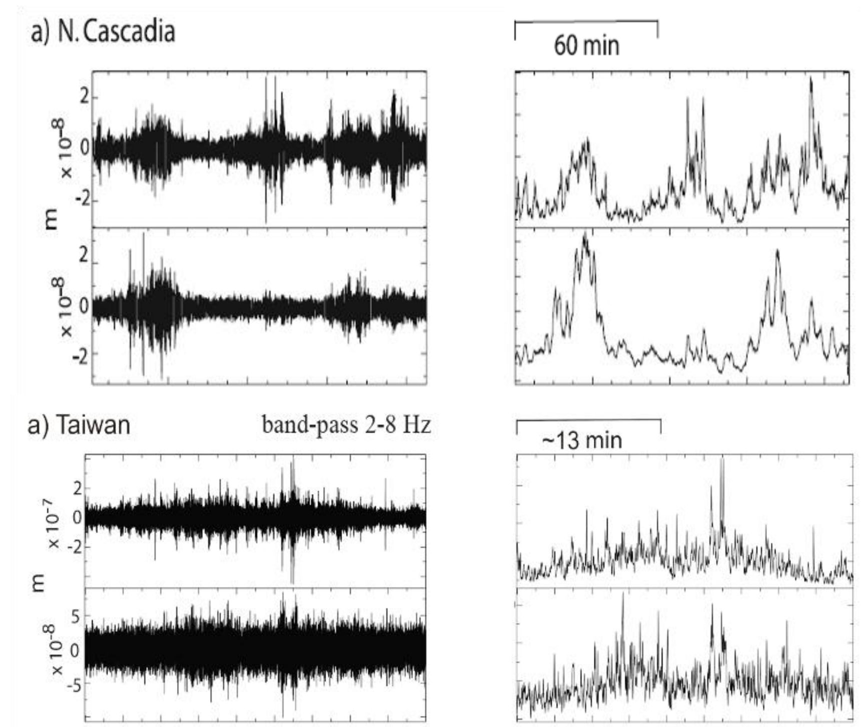
Slow slip events in Taiwan are difficult to identify because…

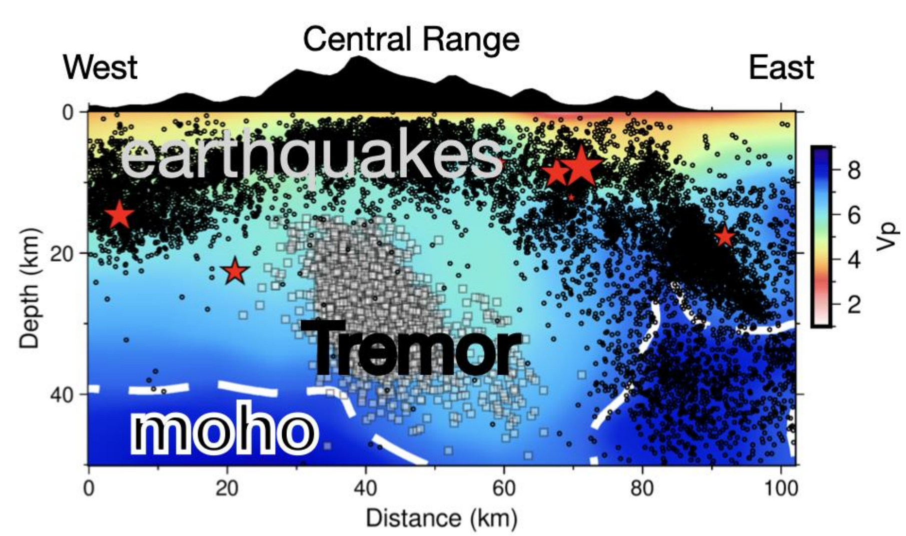
1. Most of the tectonic tremors are short and (mean duration less than 3 minutes) occur at depths greater than 30 km

Tremor map

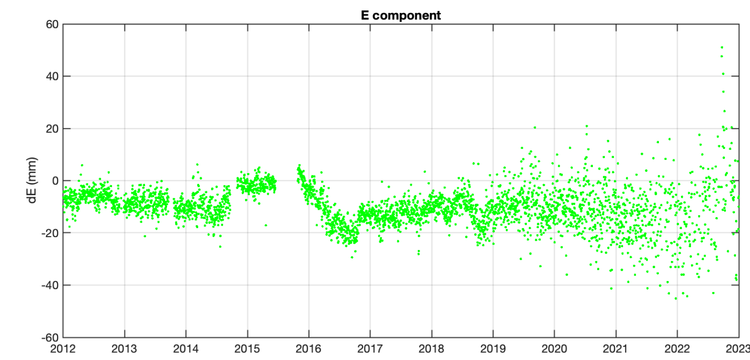






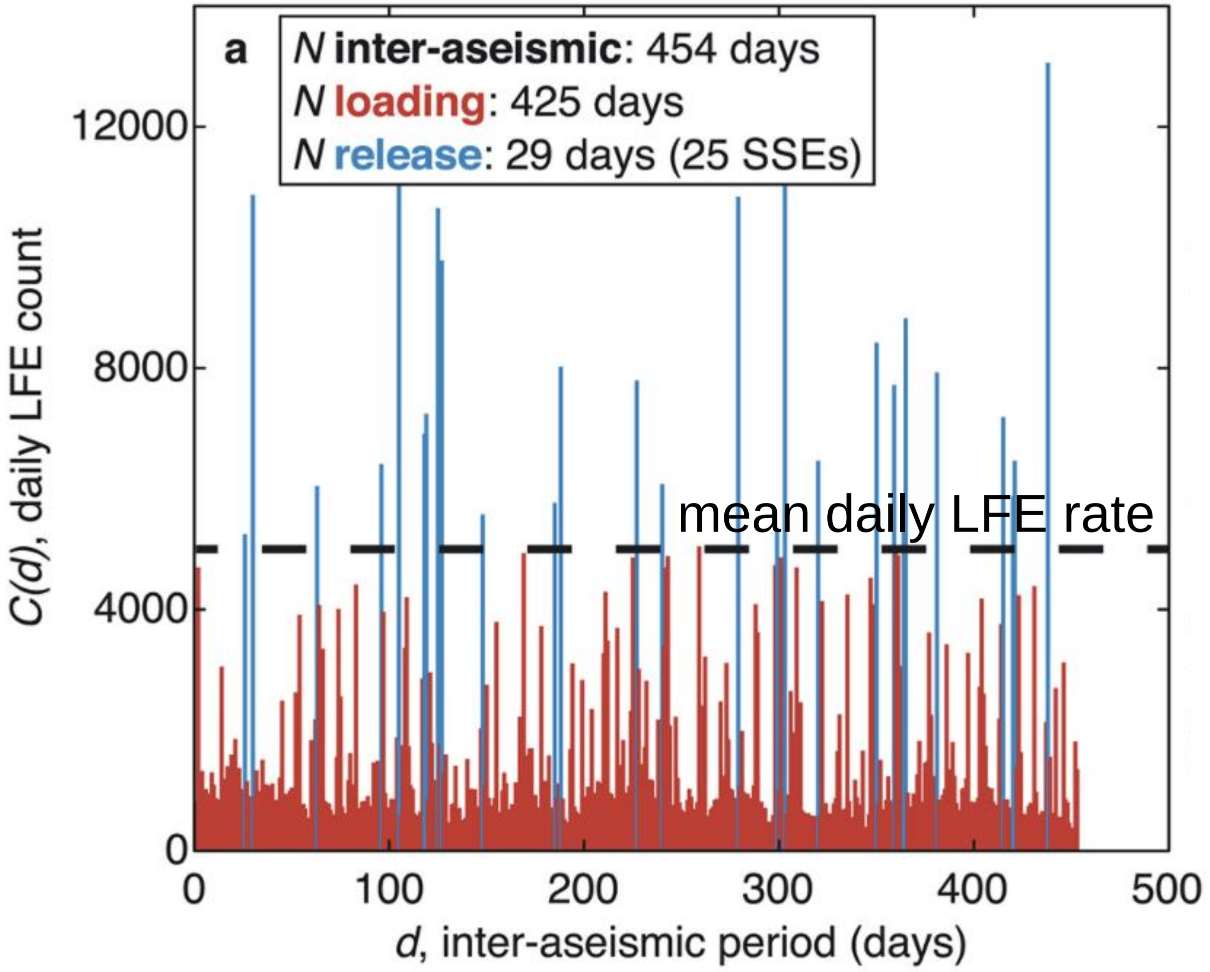


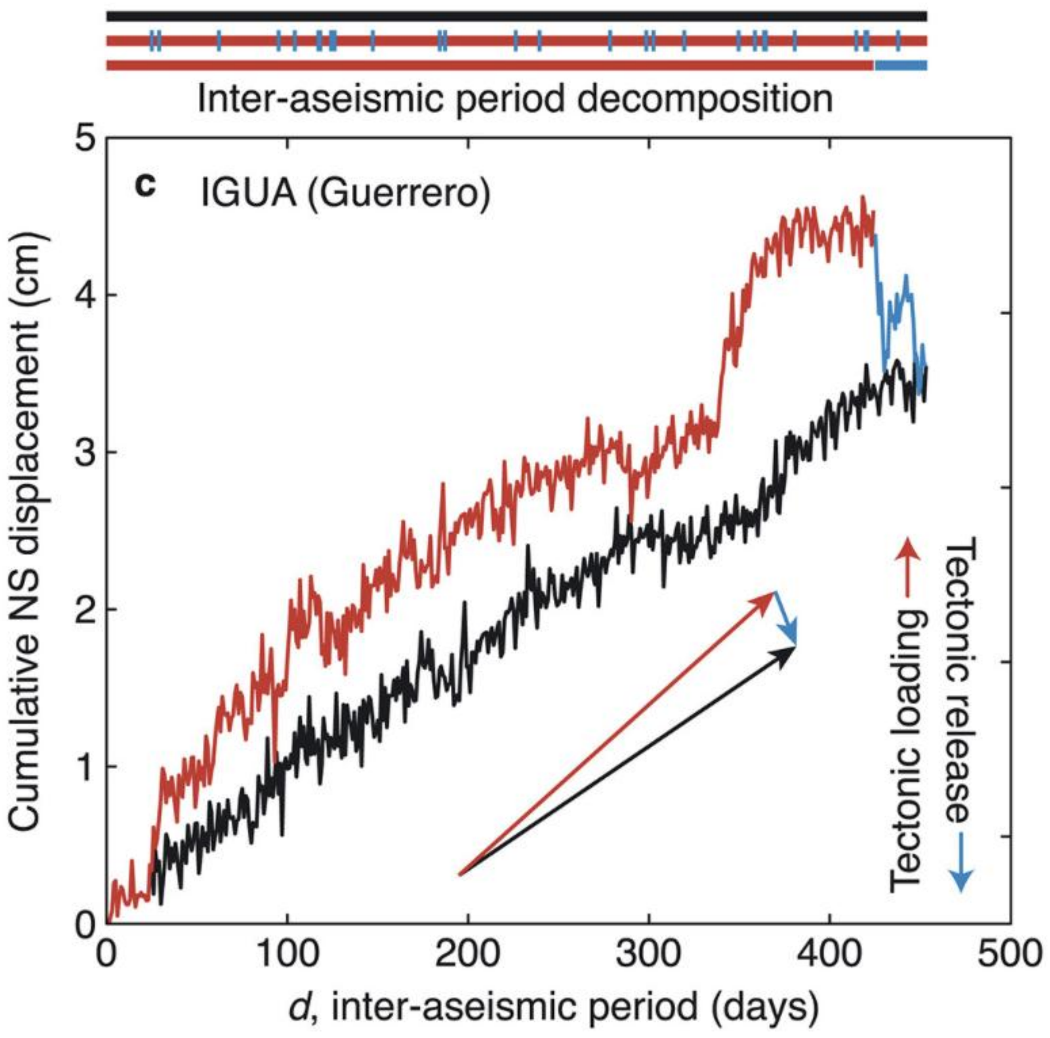
2. GNSS signal is usually contamination from other noise.



For such small perturbations associated with tremor, one possible way is to stack the deformation during the tremor period

Guerrero, Mexico





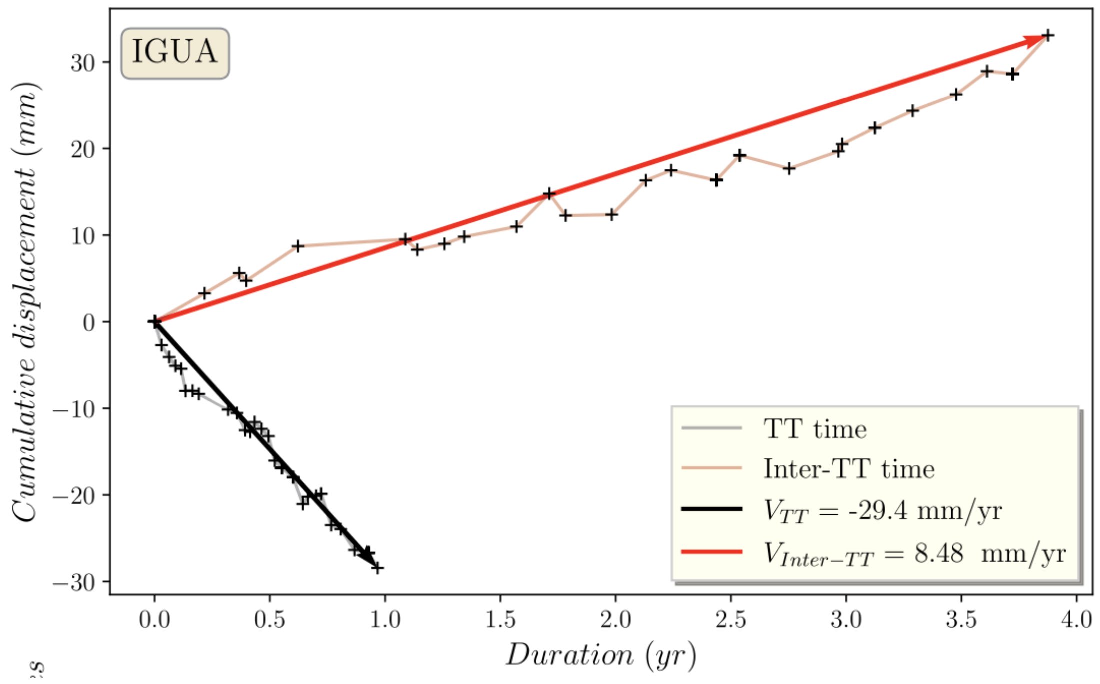
Frank (2016)

Concepts of decomposition :

Estimate the cumulative offset between during tremor and inter-tremor period

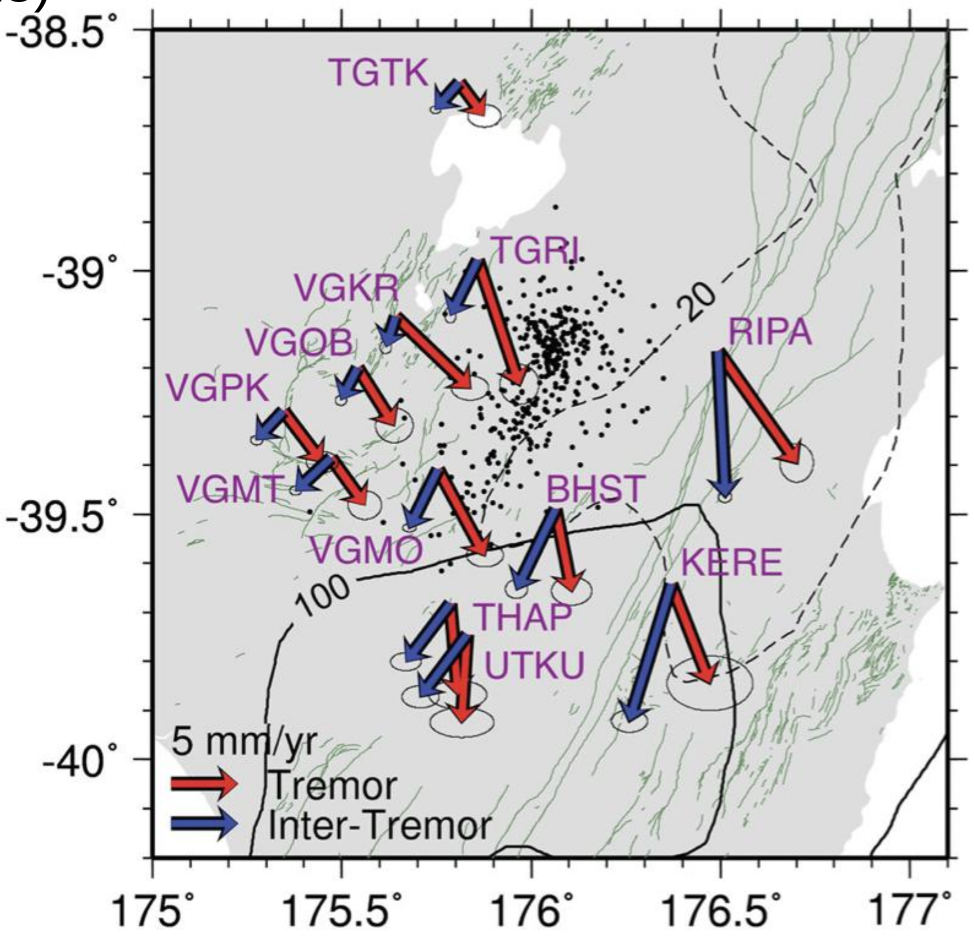
Mexico

El Yousfi et al. (2023)



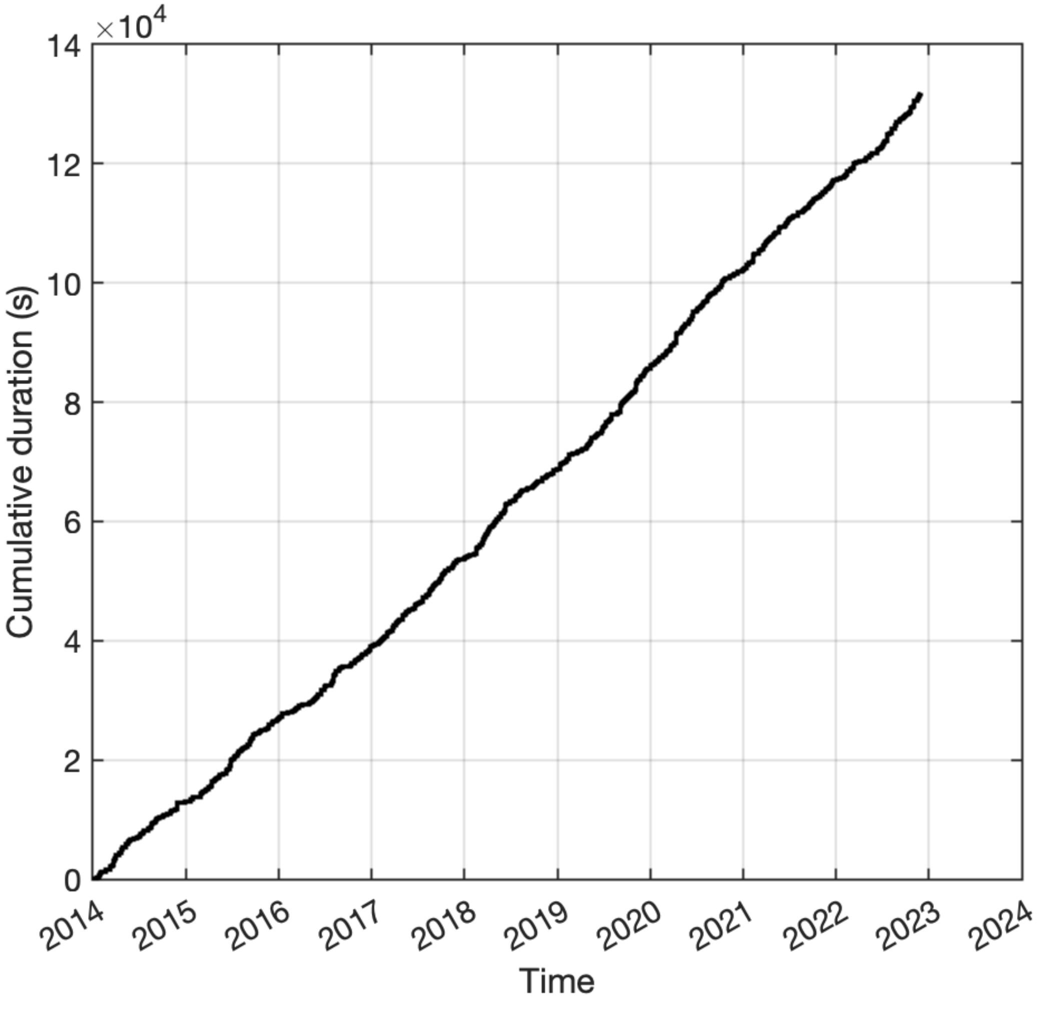
New Zealand

Fasola et al. (2023)



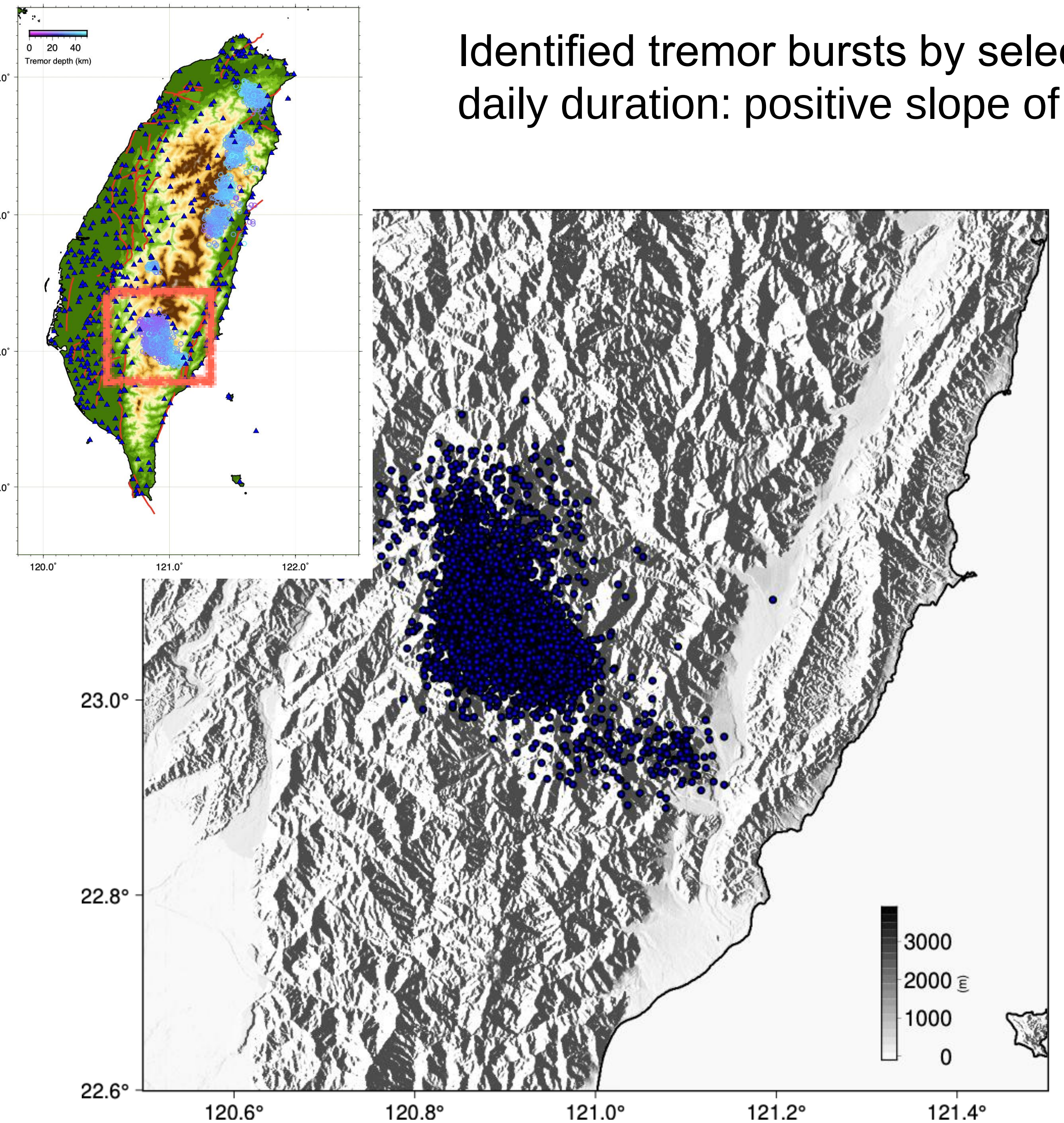
Three steps to estimate slow slip through decomposition:

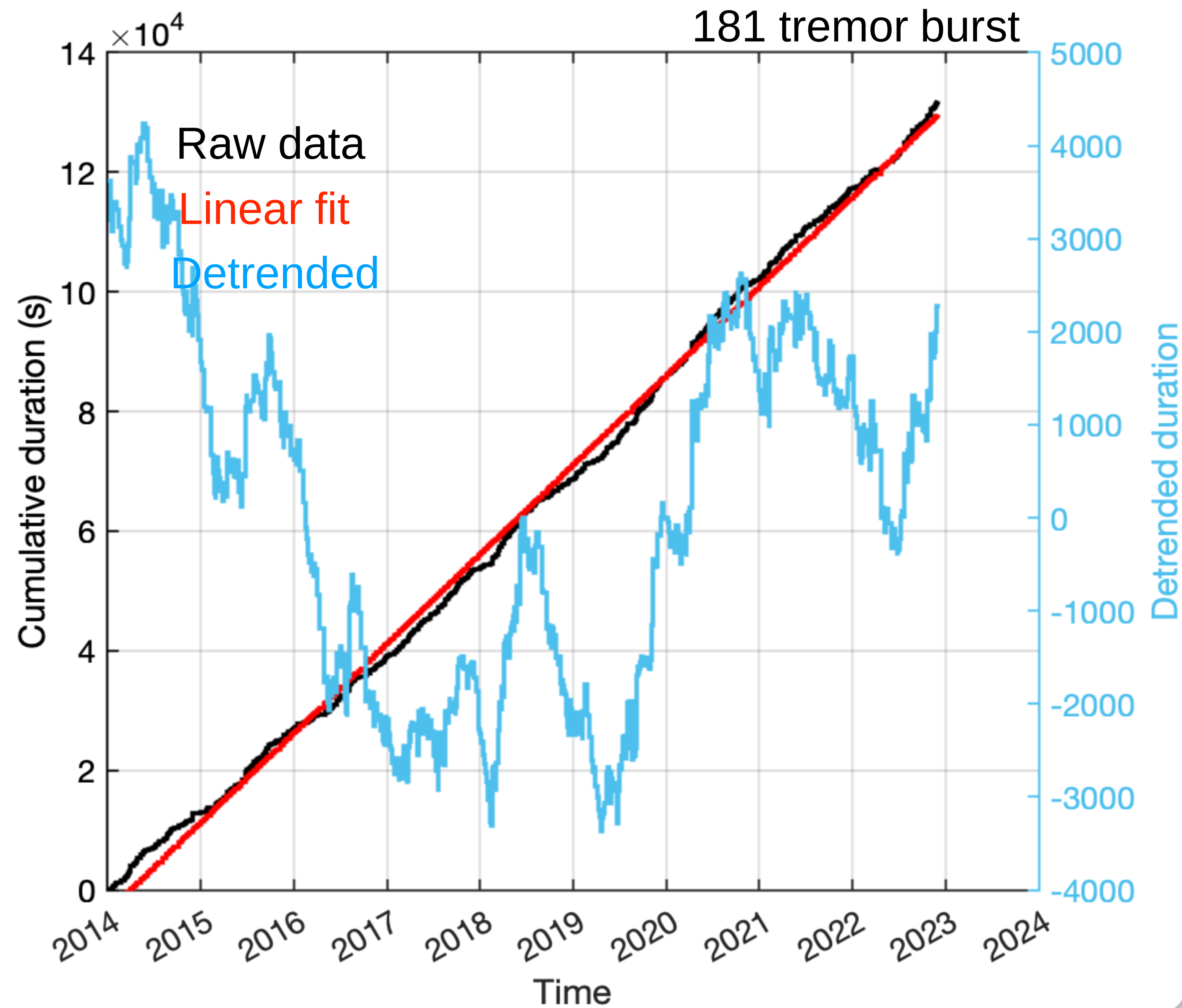
1. Tremor burst identification
2. GNSS time series correction
3. Decomposition



Tremor burst identification : searching for enhanced tremor activity

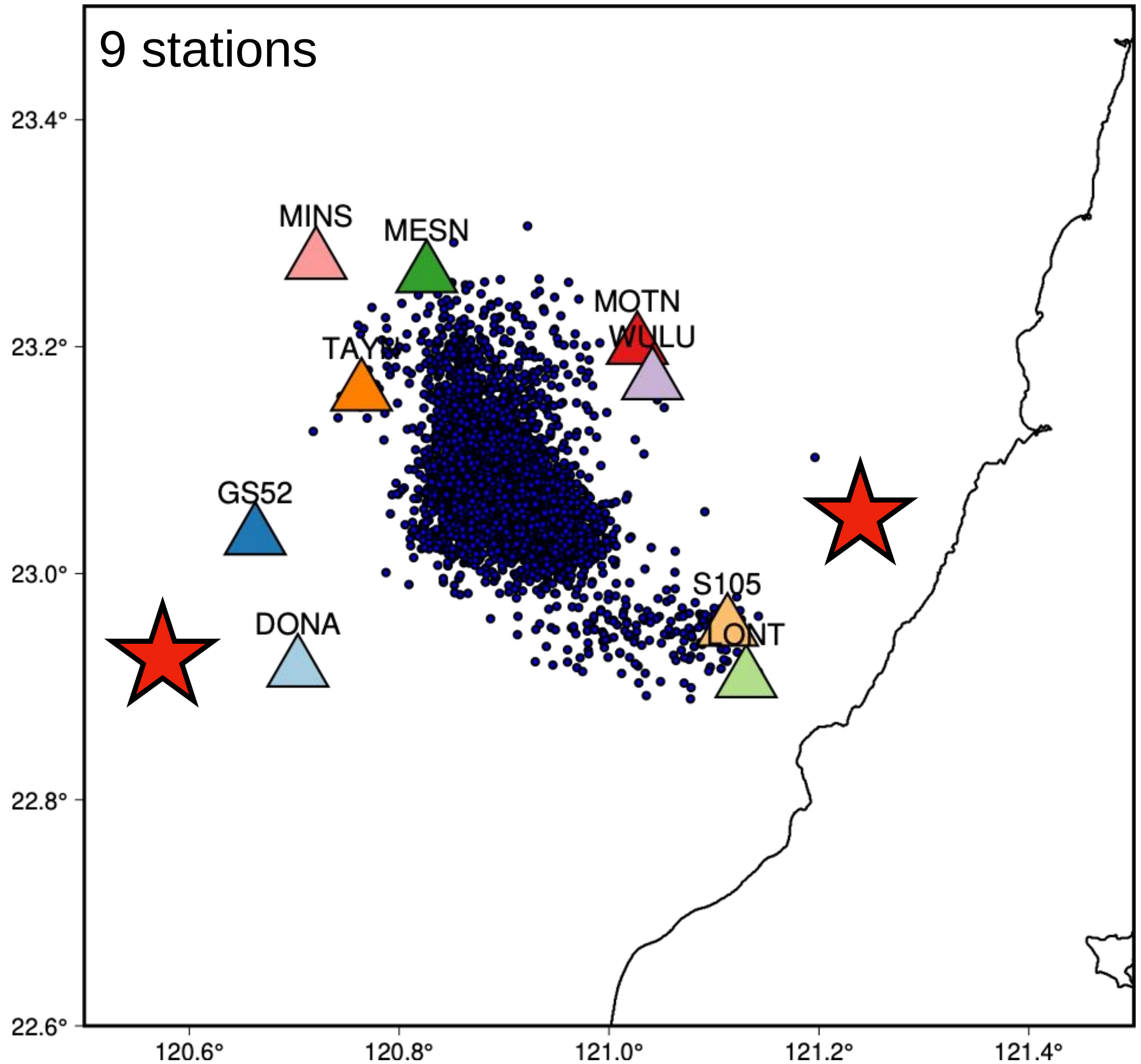
Identified tremor bursts by selecting the days when daily tremor duration ≥ mean daily duration: positive slope of the detrended data

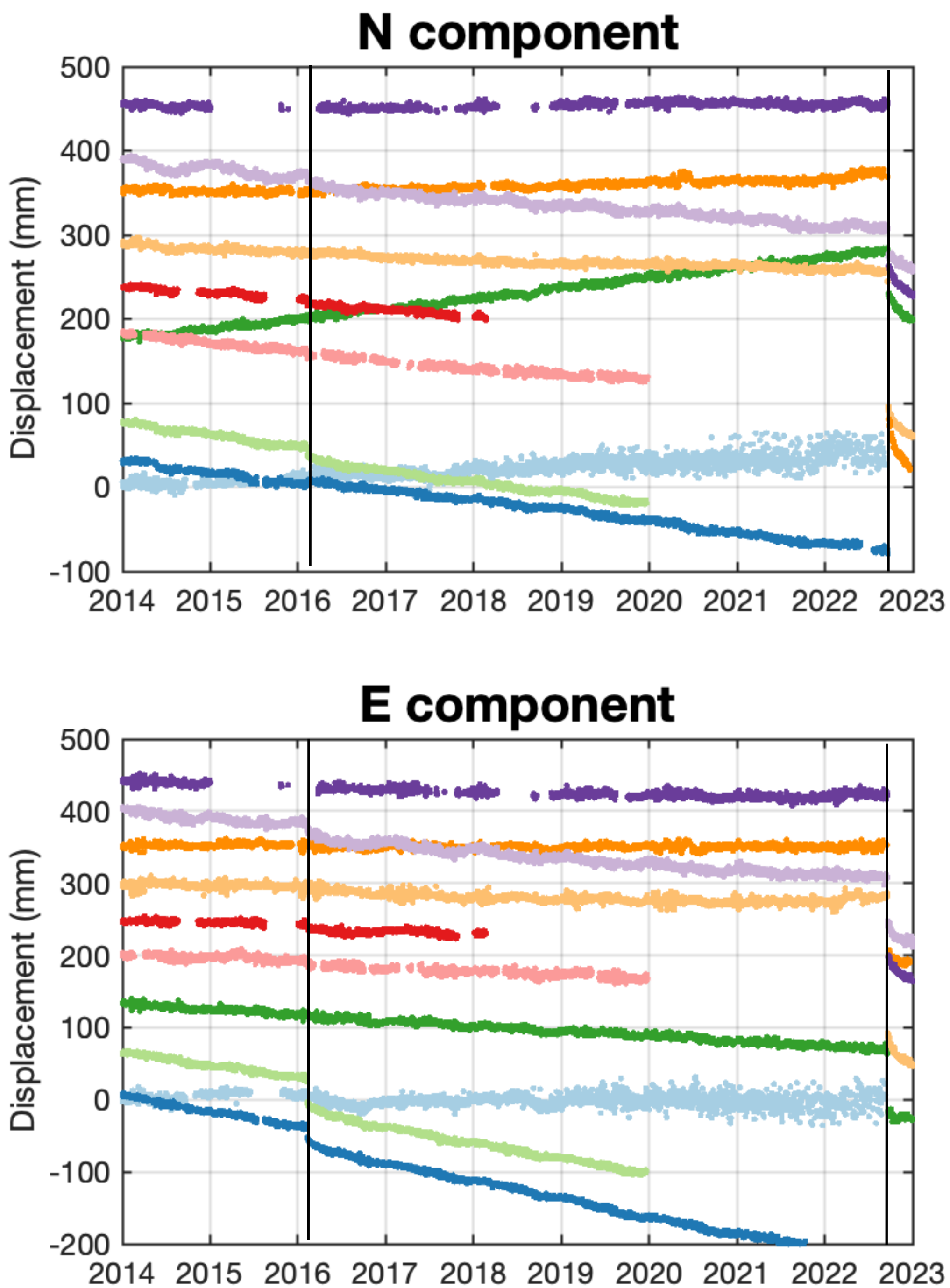




GNSS time series correction : Removing co-seismic effect

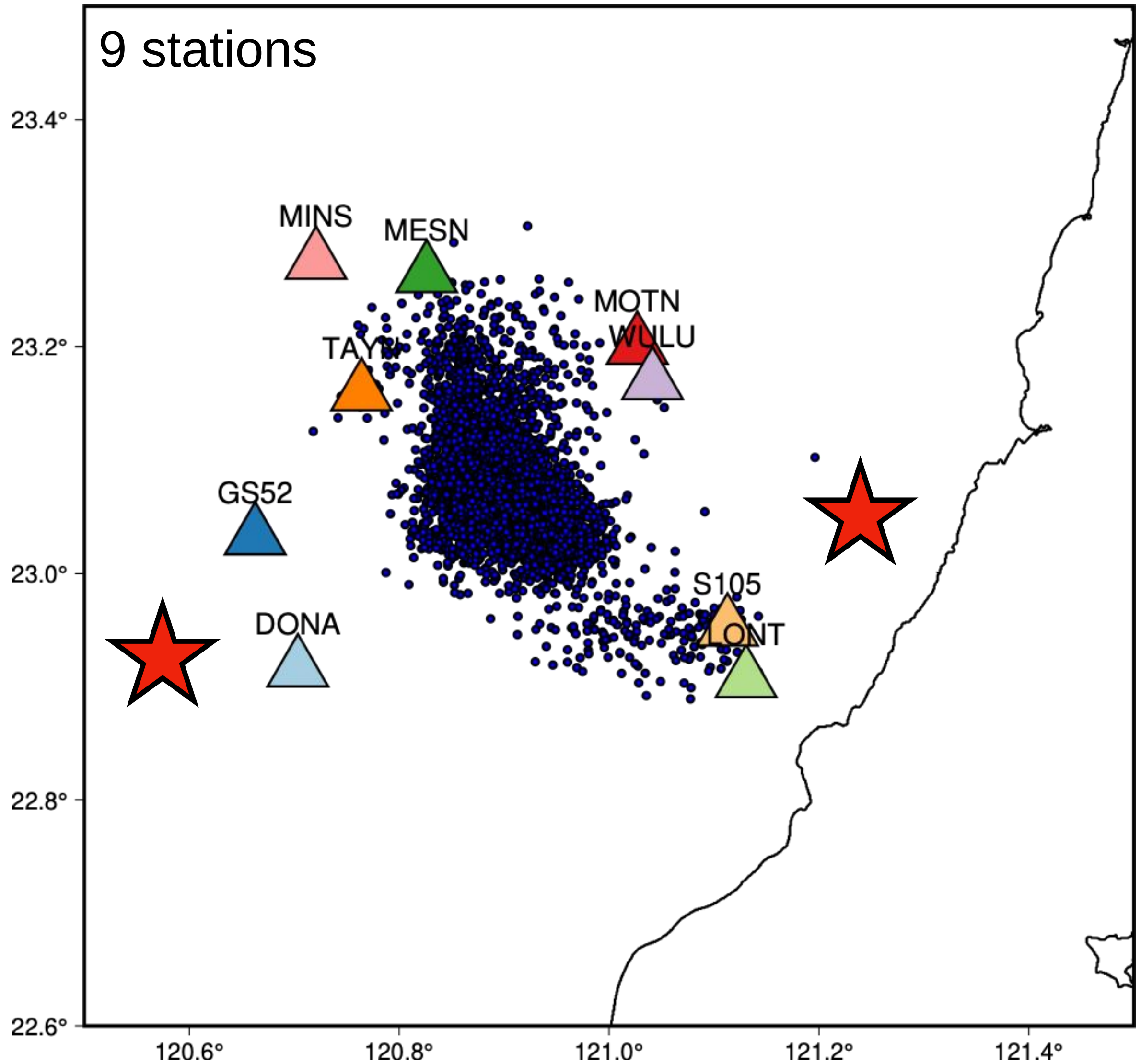
$$y(t_i) = a + bt_i + \sum_{j=1}^{n_j} g_i H(t_i - T_{gi}) + \beta$$

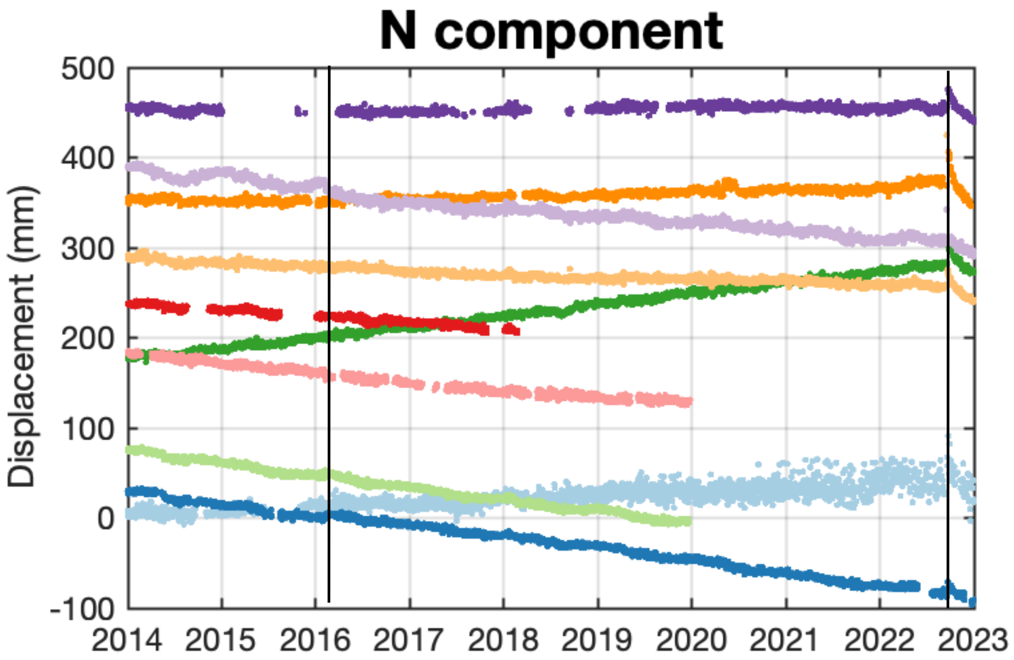


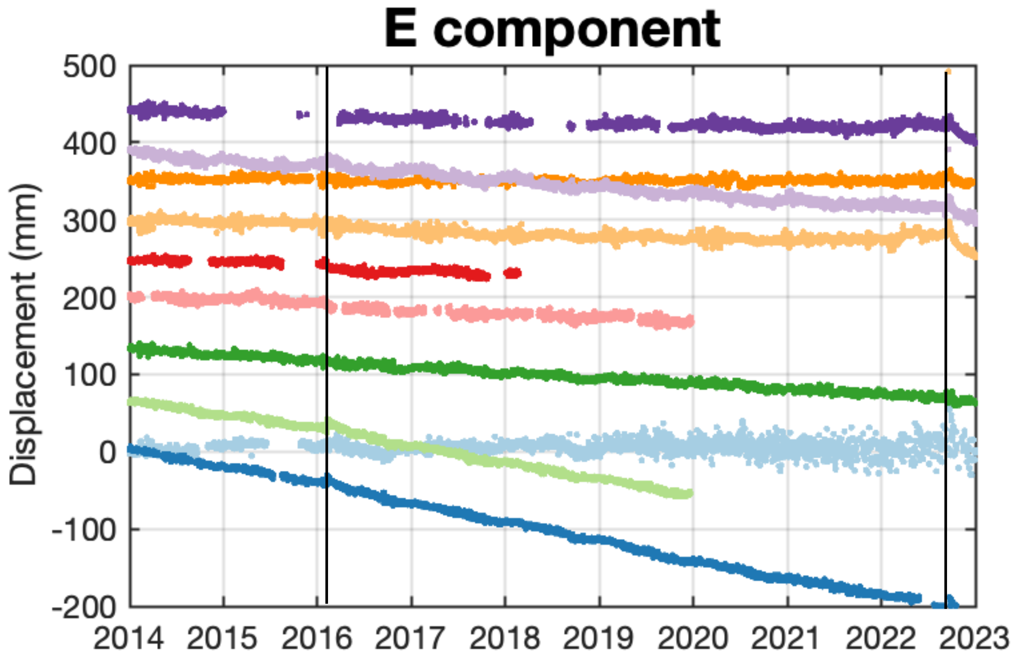


GNSS time series correction : Removing co-seismic effect

$$y(t_i) = a + bt_i + \sum_{j=1}^{n_j} g_i H(t_i - T_{gi}) + \beta$$

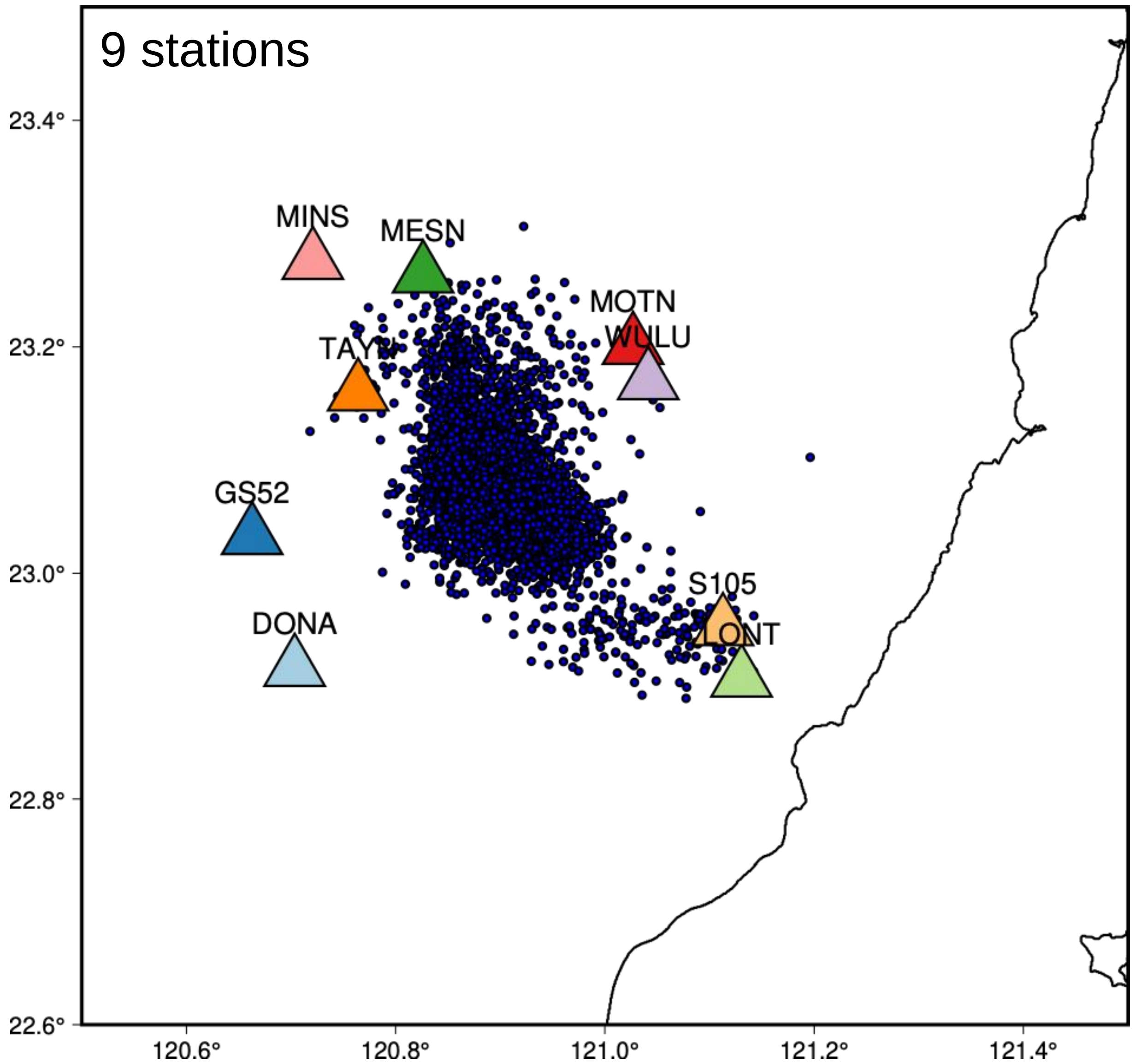


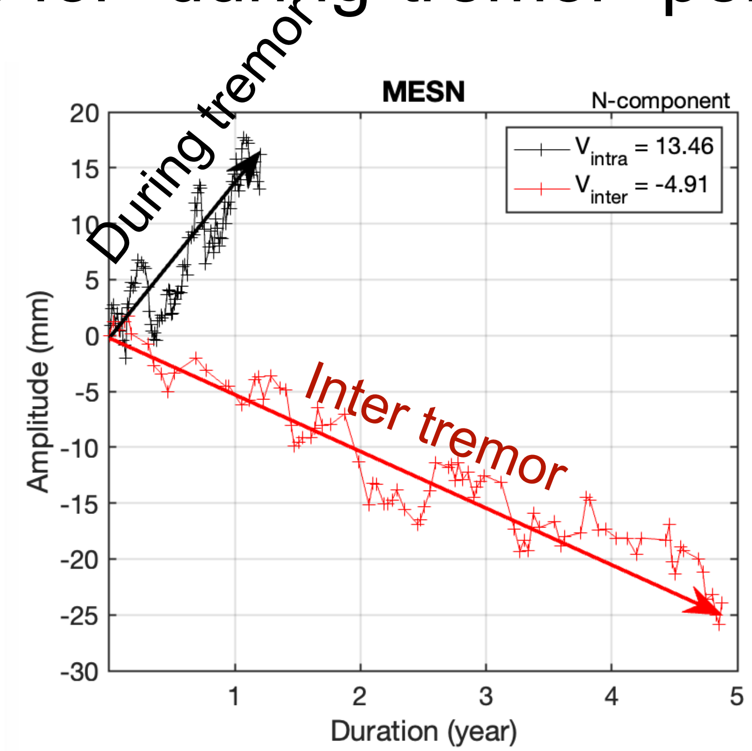


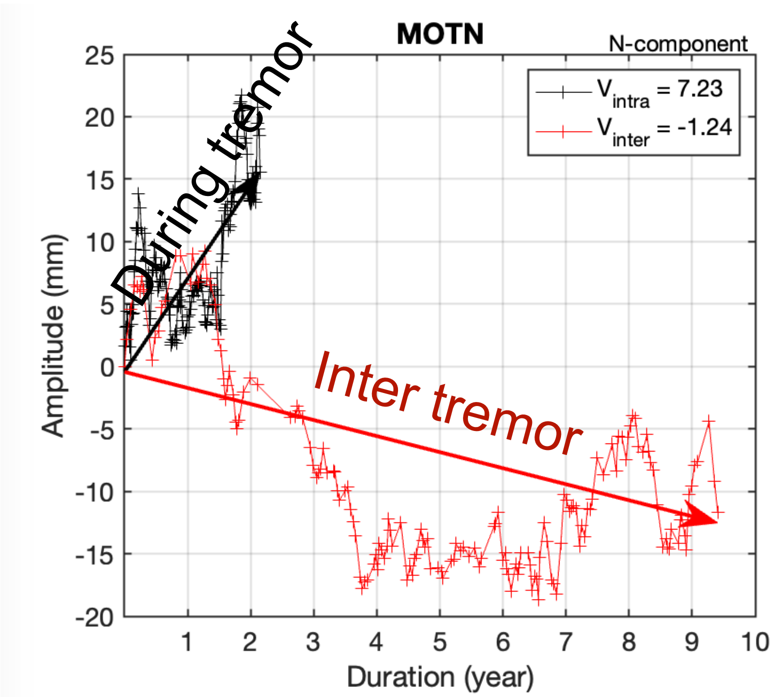


Results of GNSS decomposition

181 tremor burst (mean duration of 1.78 days) from 2014 to 2022 are considered, to extract GNSS time series for “during-tremor” period.

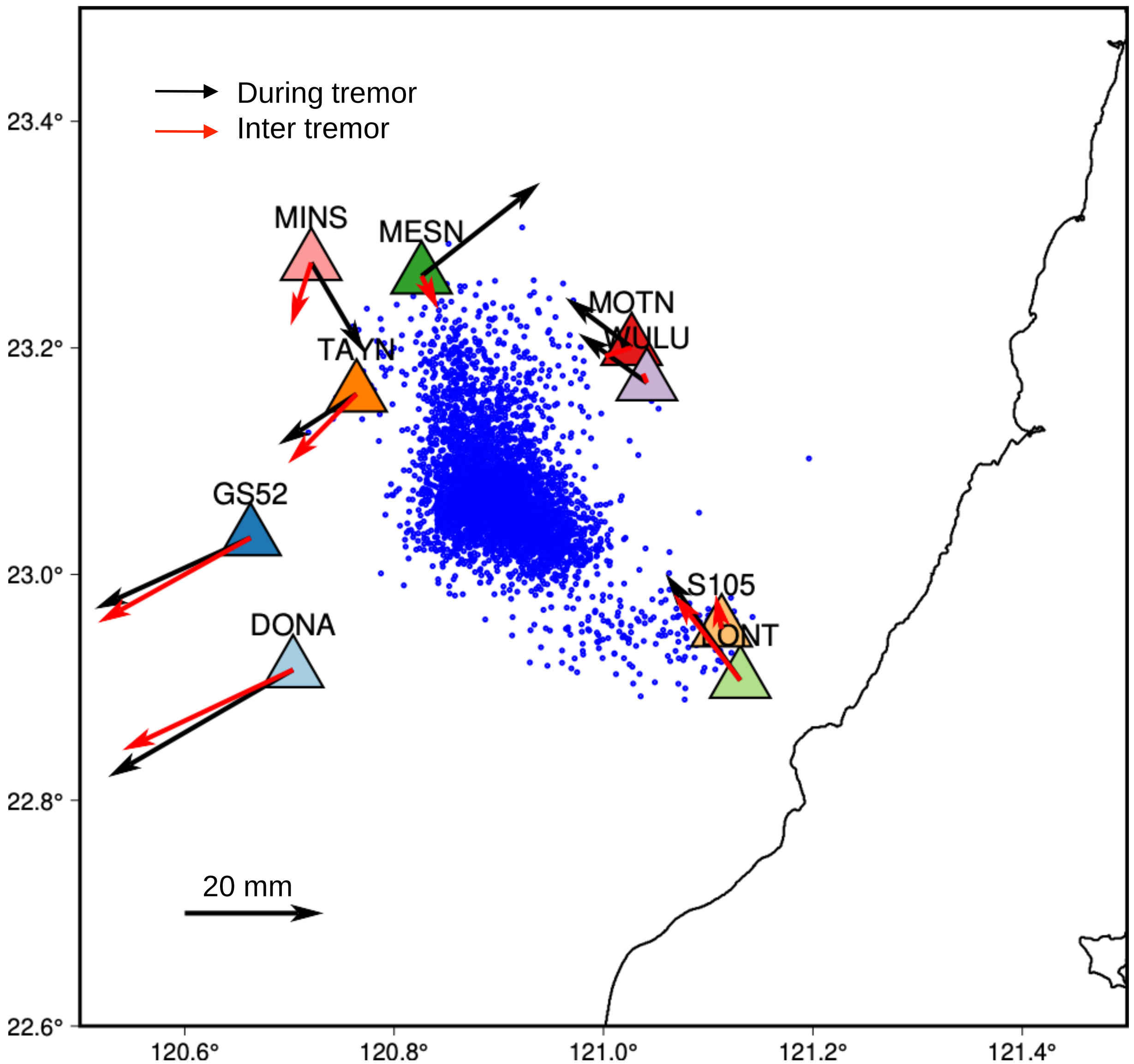


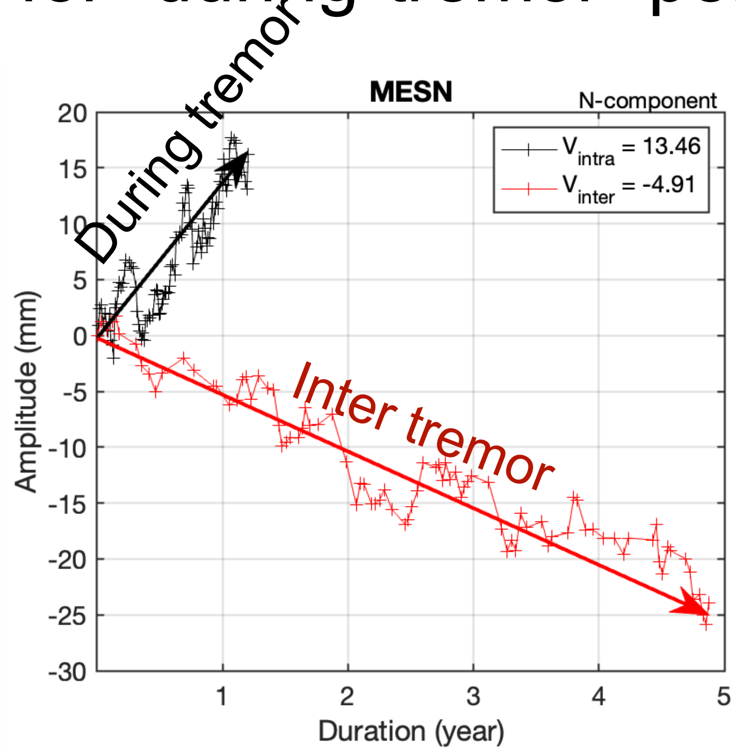


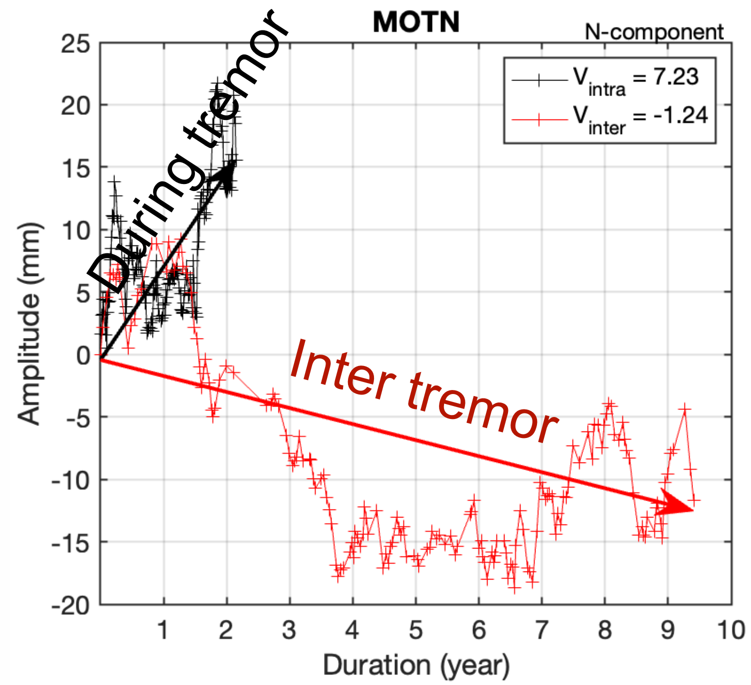


Results of GNSS decomposition

181 tremor burst (mean duration of 1.78 days) from 2014 to 2022 are considered, to extract GNSS time series for “during-tremor” period.

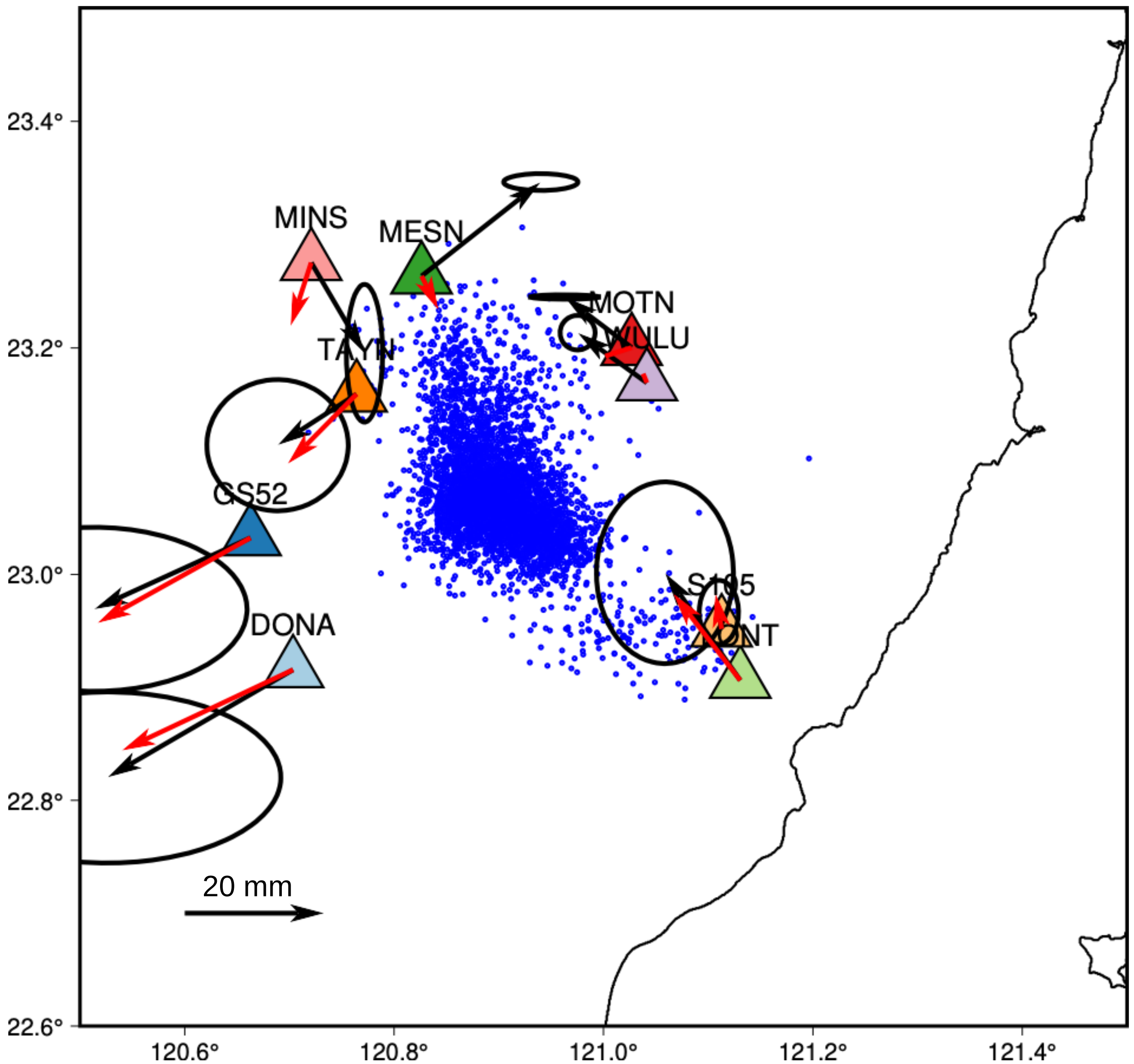


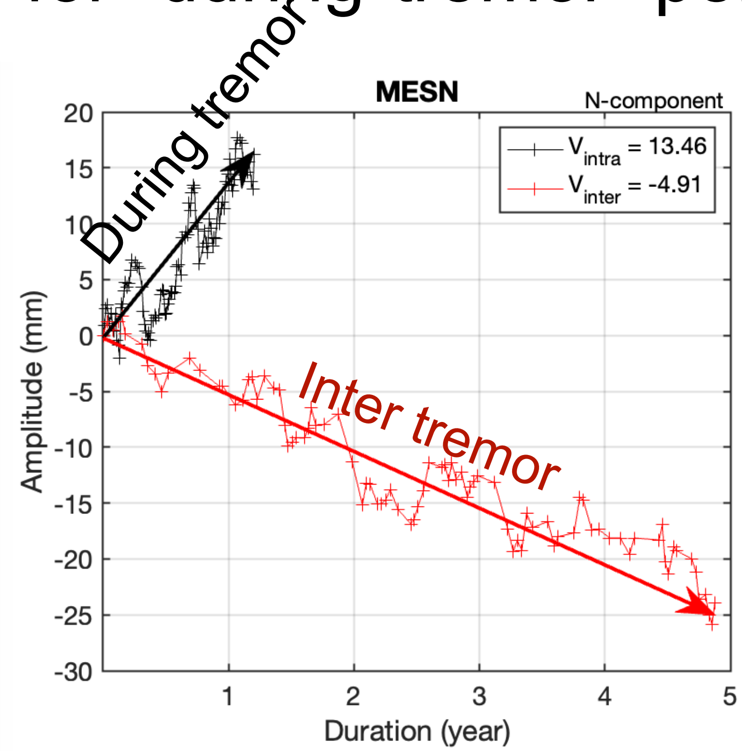


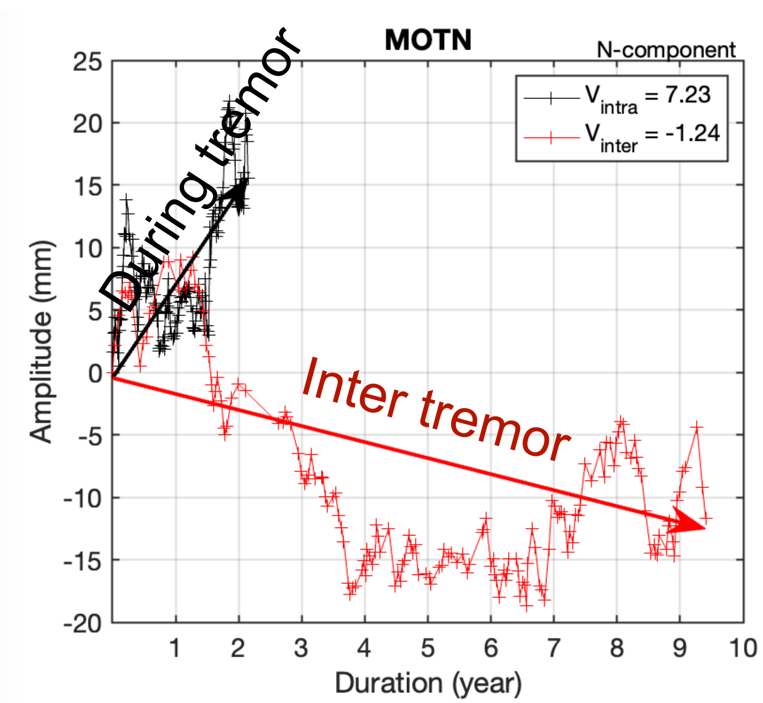


Results of GNSS decomposition

181 tremor burst (mean duration of 1.78 days) from 2014 to 2022 are considered, to extract GNSS time series for “during-tremor” period.



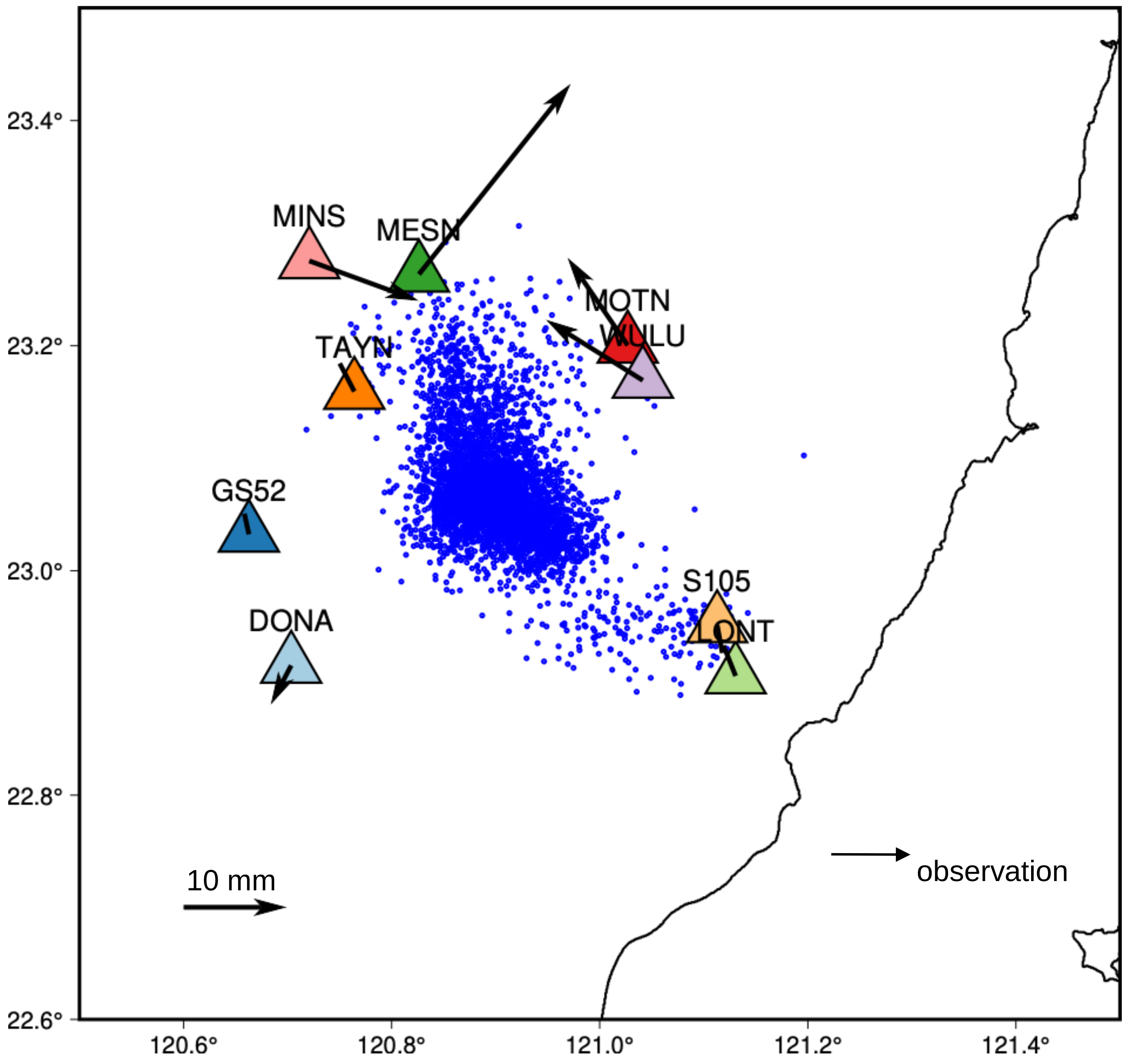




Determination of SSE fault parameters

The optimal fault orientation obtained by the grid search is refers to high angle east-dipping thrust fault.

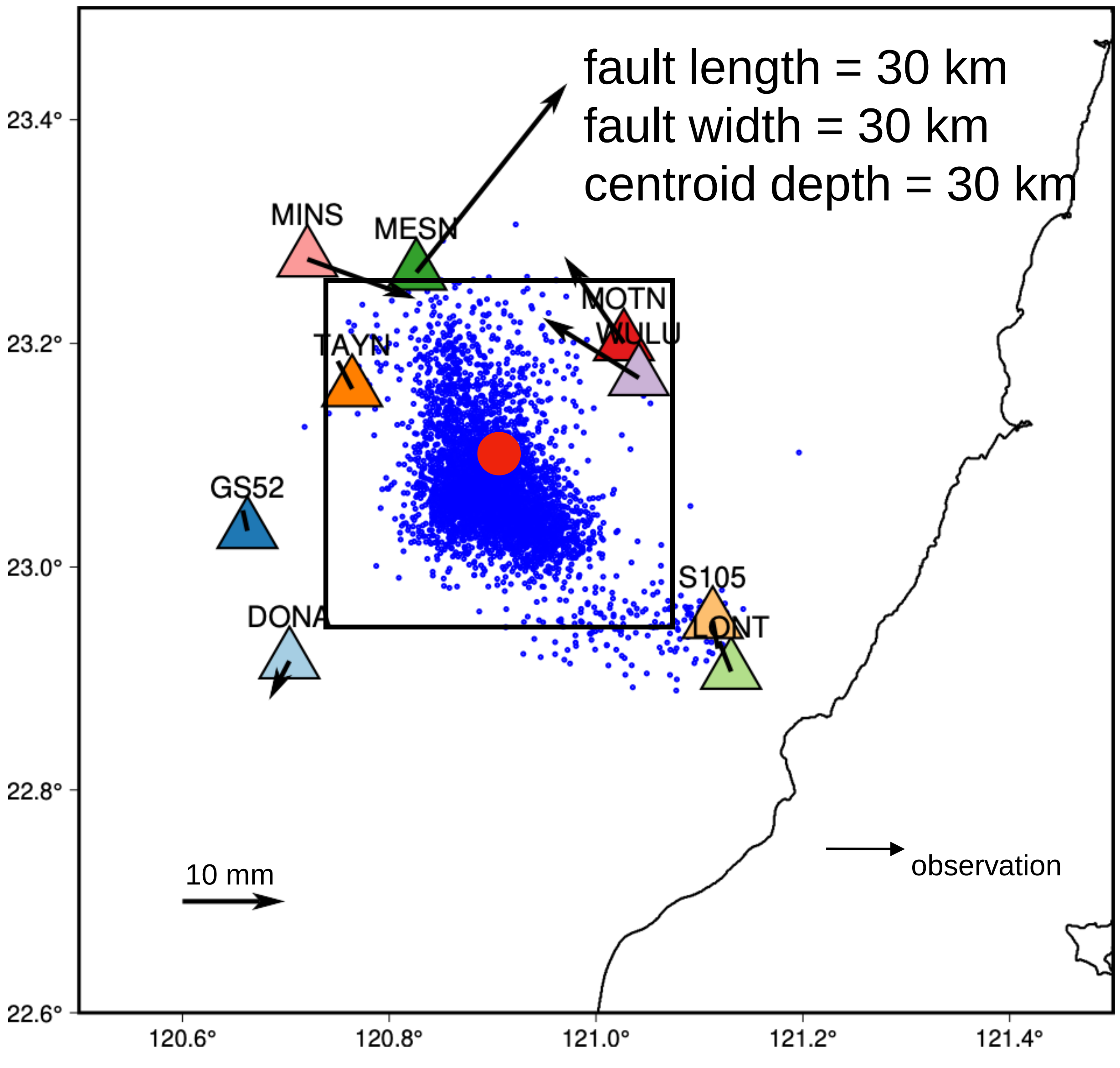
During tremor - inter tremor



Determination of SSE fault parameters

The optimal fault orientation obtained by the grid search is refers to high angle east-dipping thrust fault.

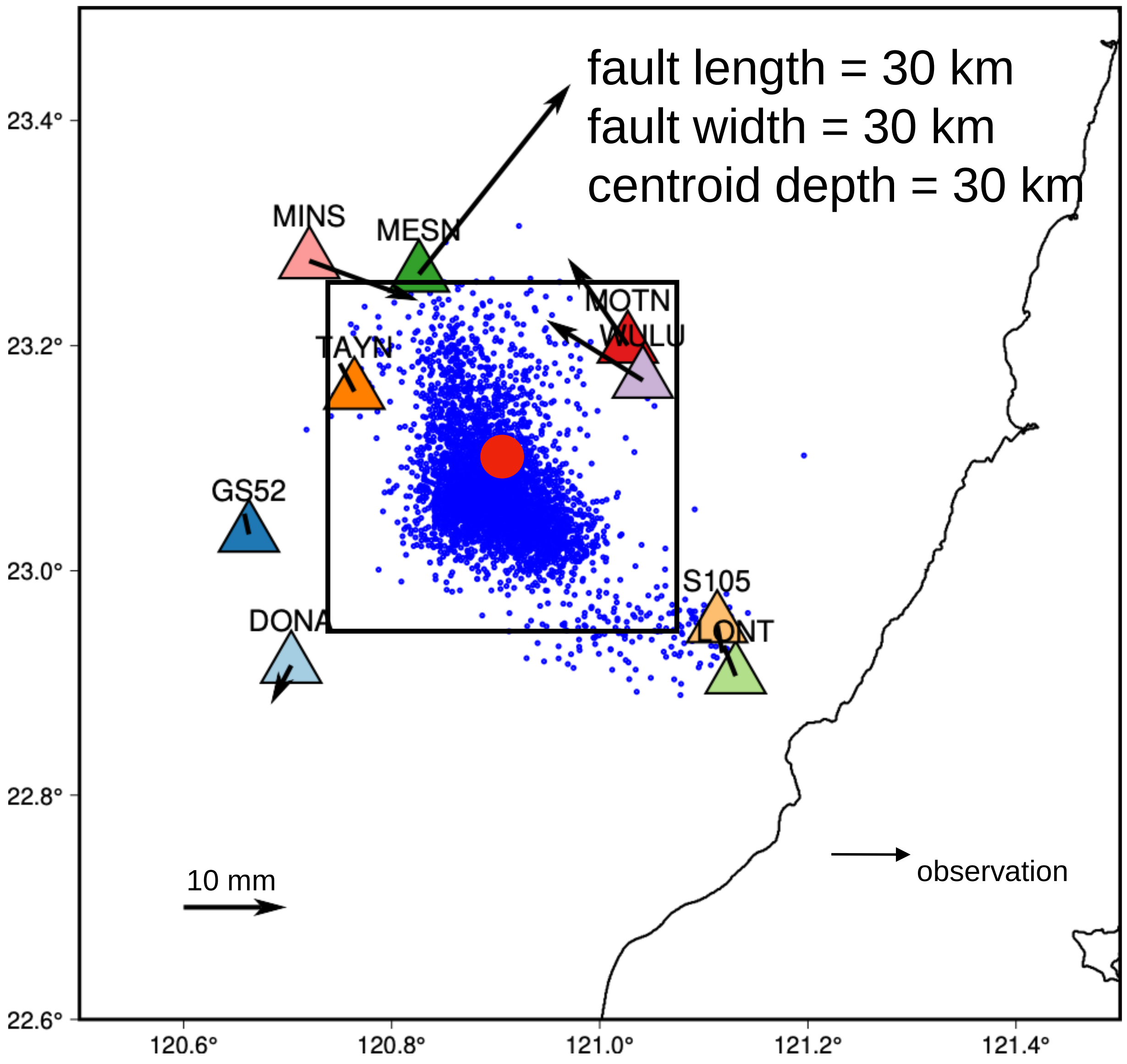
During tremor - inter tremor

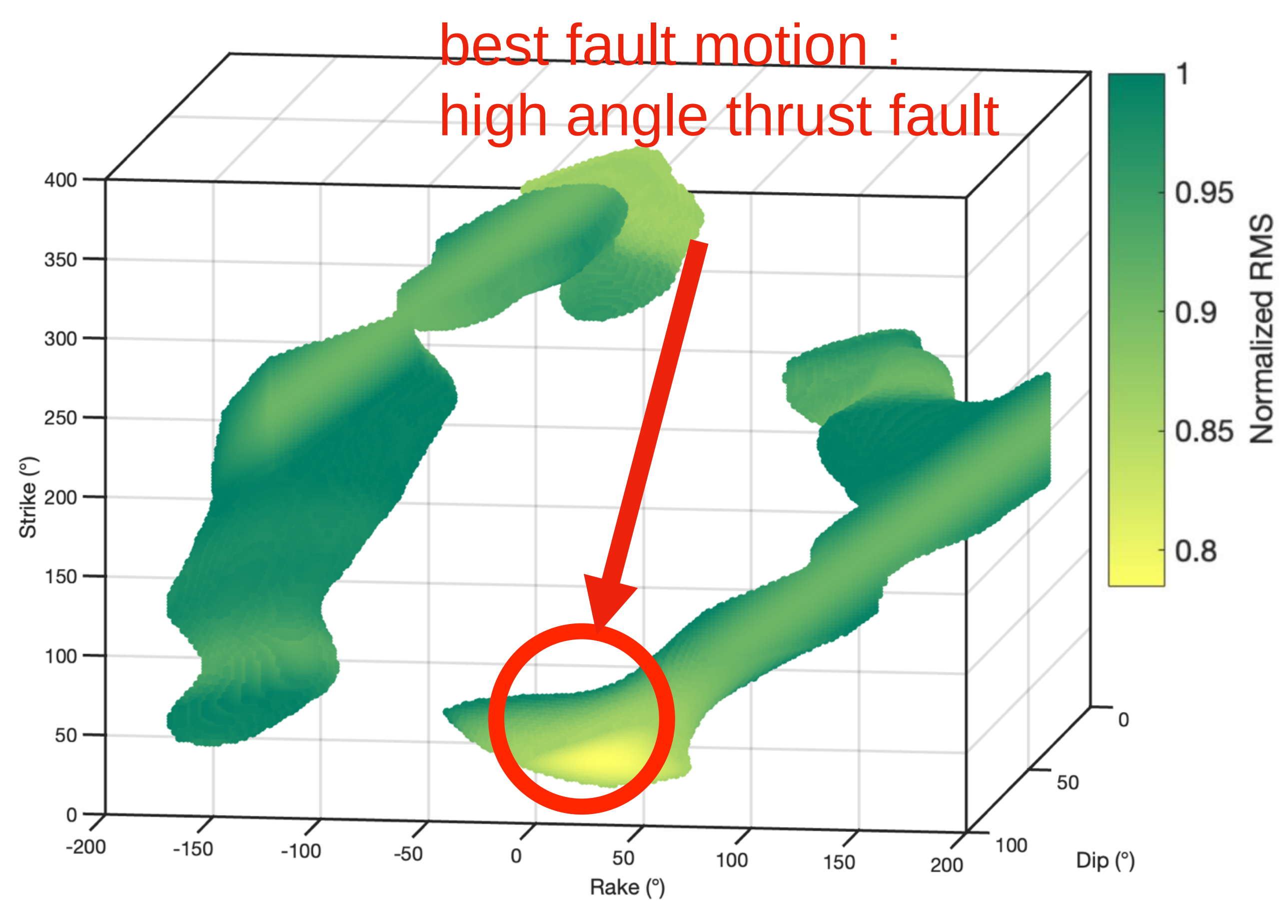


Determination of SSE fault parameters

The optimal fault orientation obtained by the grid search is refers to high angle east-dipping thrust fault.

During tremor - inter tremor

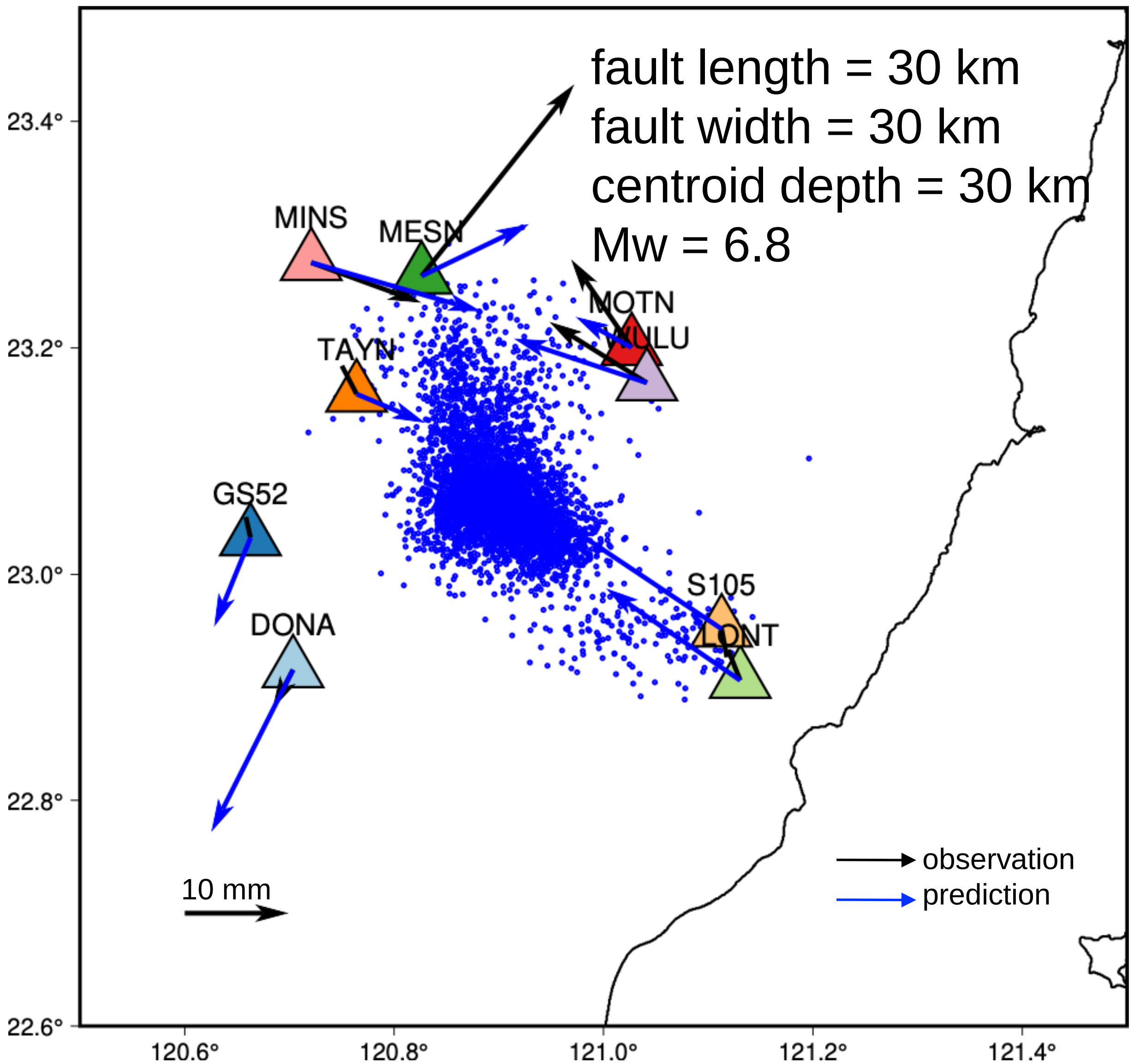


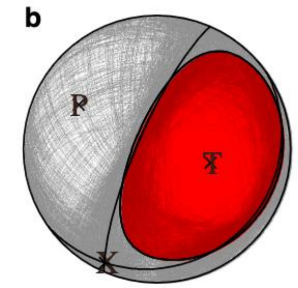


Determination of SSE fault parameters

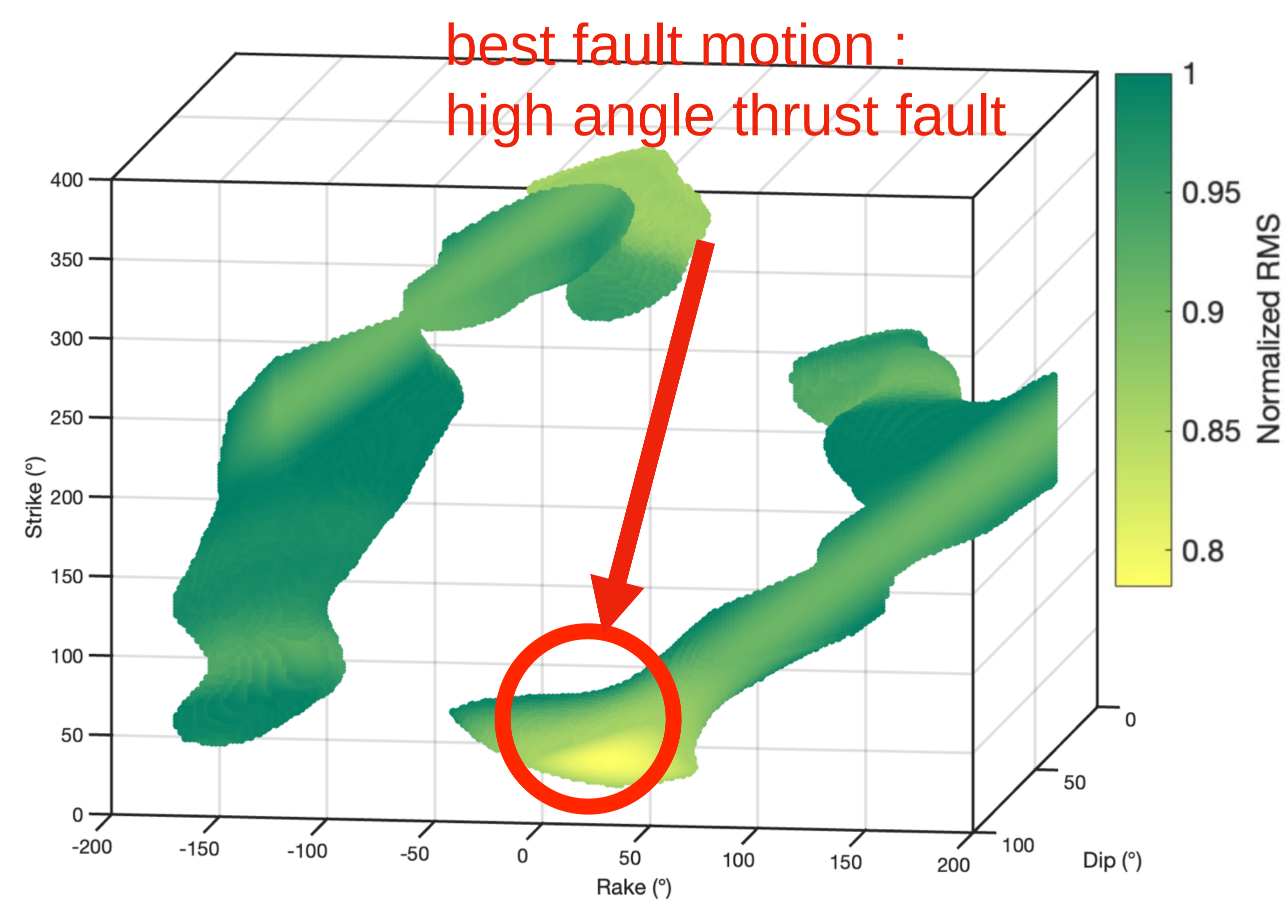
The optimal fault orientation obtained by the grid search is refers to high angle east-dipping thrust fault.

During tremor - inter tremor

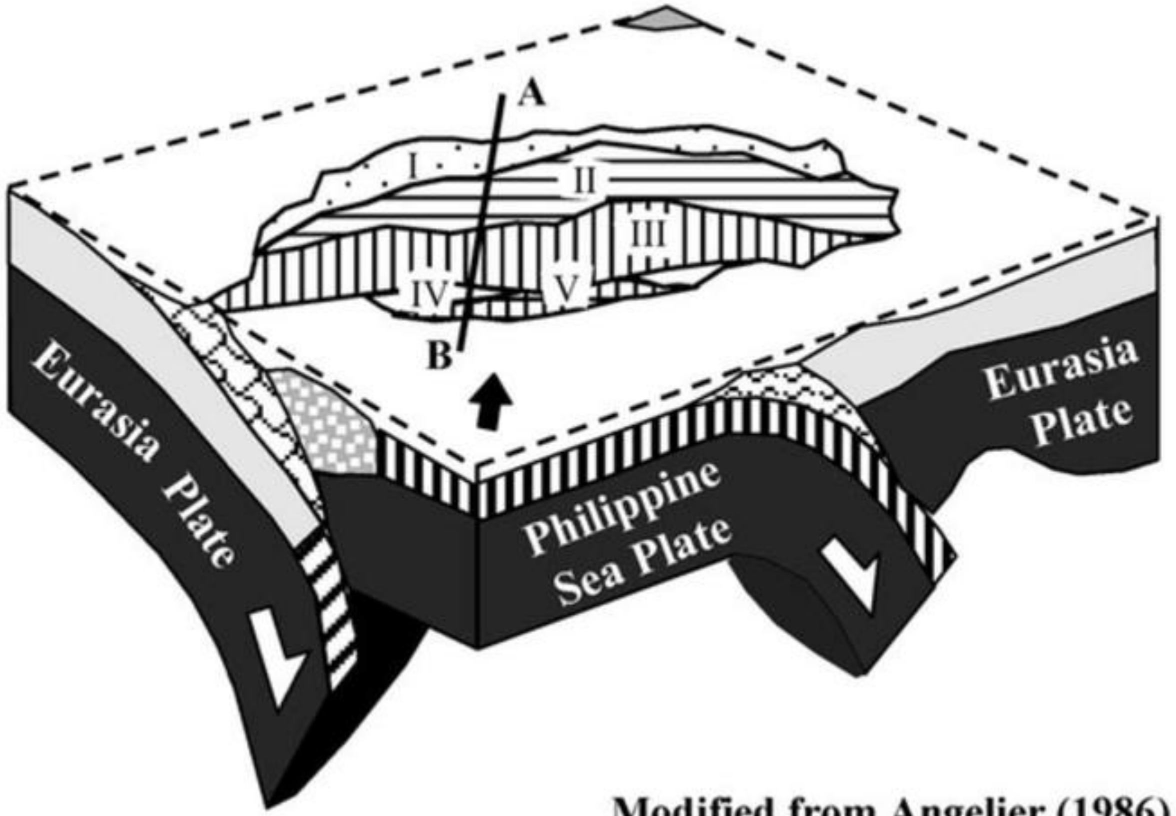




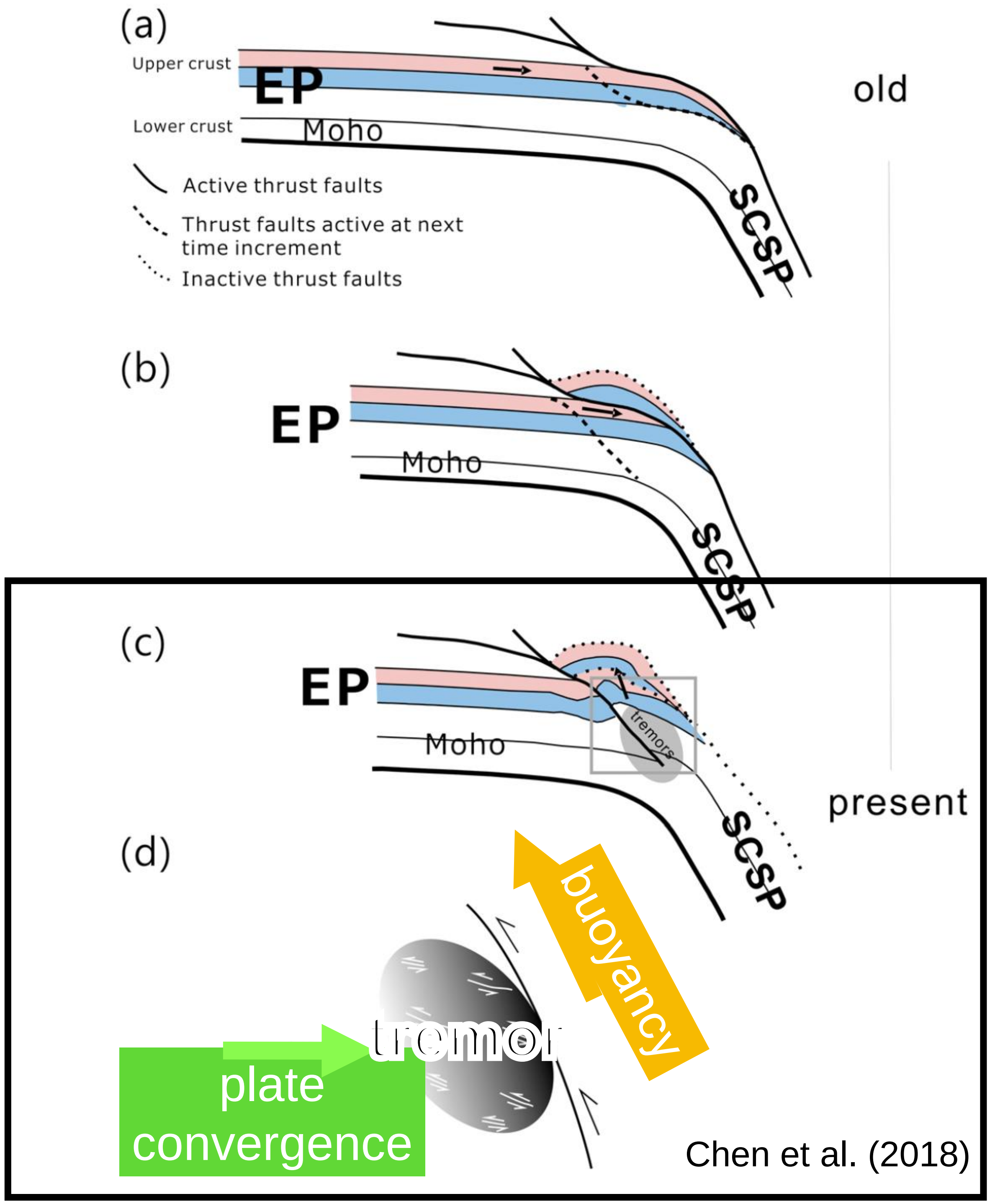
Source inversion of tremor Ide (2015)



Tectonic model for SSE

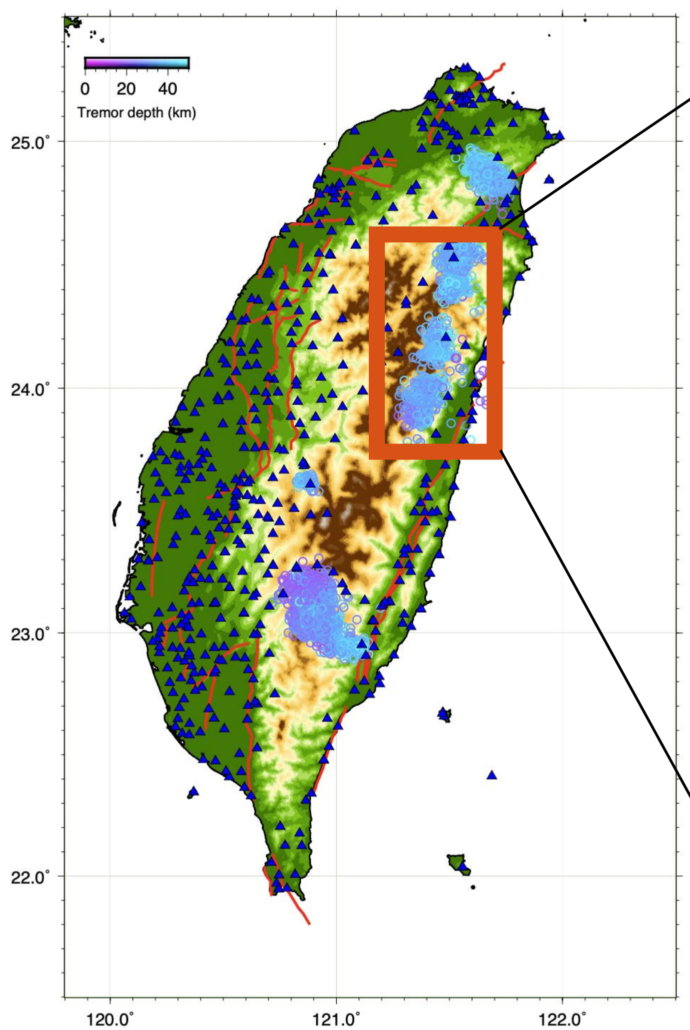


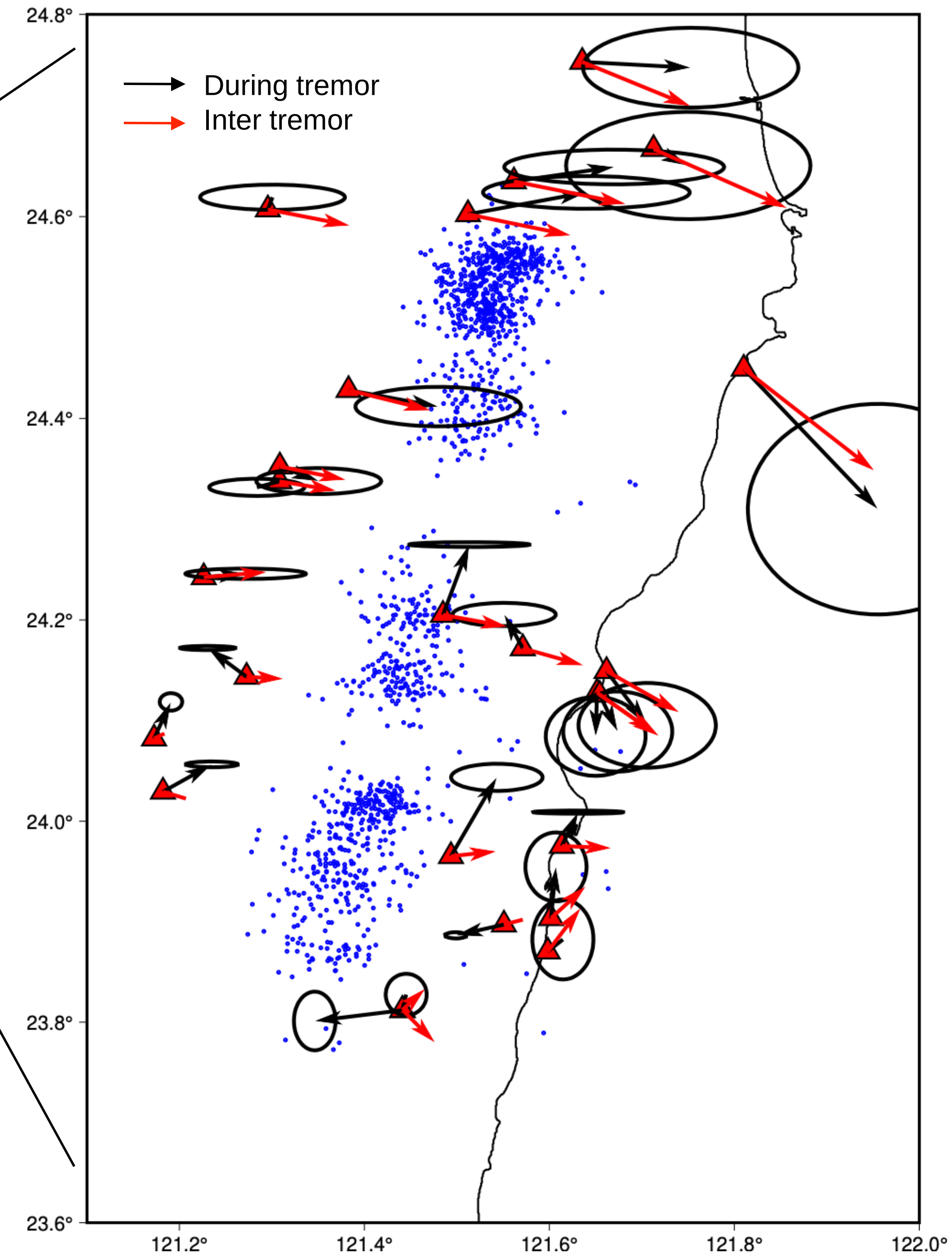
Modified from Angelier (1986)



Chen et al. (2018)

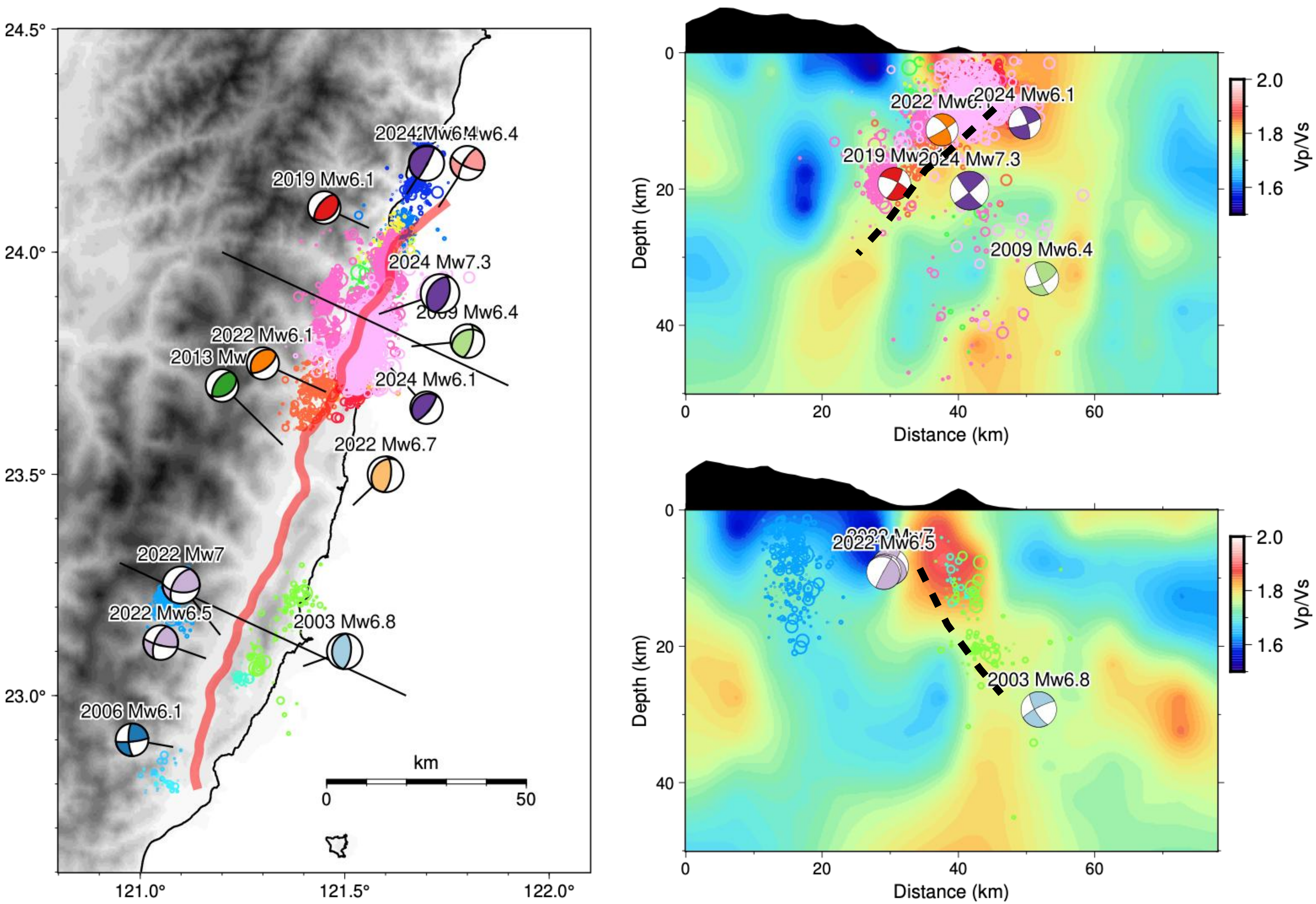
GNSS decomposition shows no siginificant difference between during tremor and inter-tremor period





Earthquake swarm in eastern Taiwan

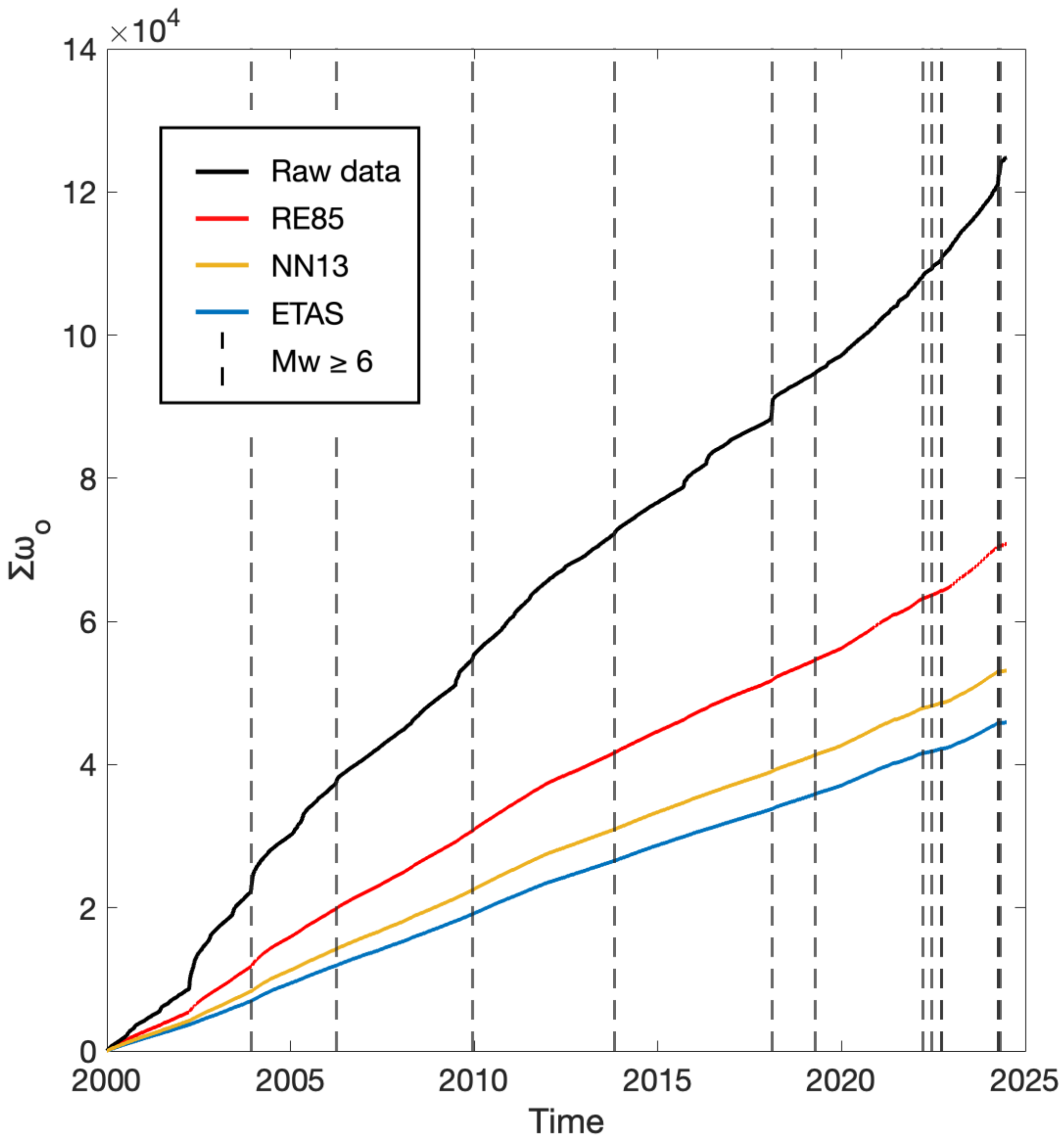
15 swarm sequences located at eastern Taiwan (10 in north longitudinal valley, 5 in south longitudinal valley) in the period of year 2000 to 2024.3



Peng et al,. (2025, under revision)

Earthquake swarm : anomalies in declustered cata

Time series ⟶ Density rate (Marsan et al., 2013)



$$\mu_0(x,y,t) = \sum_i \omega_i e^{-\sqrt{\frac{(x-x_i)^2+(y-y_i)^2}{l}}} e^{-\frac{|t-t_i|}{T}} \times \frac{1}{2\pi l^2 \alpha_i}$$

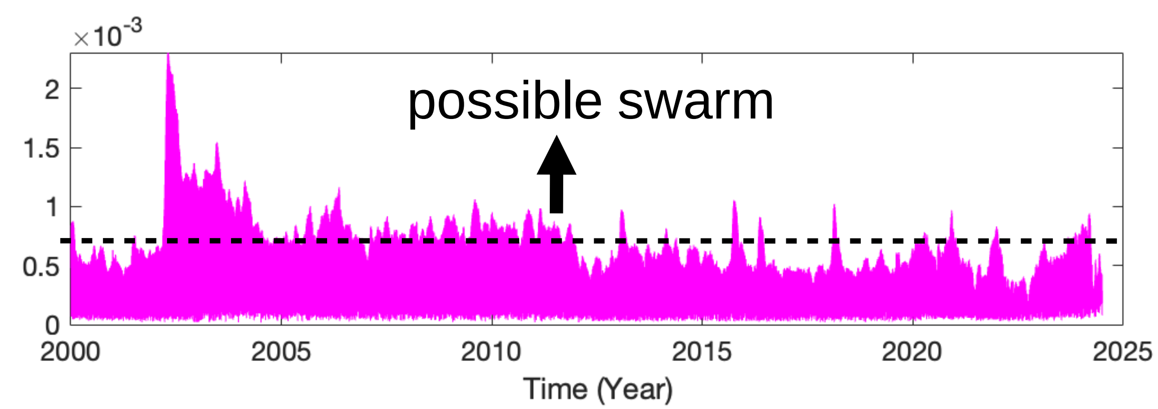
$$\alpha_i = 2T - T\left(e^{-\frac{t_s-t_i}{T}} - e^{-\frac{t_e-t_i}{T}}\right)$$

ω_i : probability as a background event of a earthquake occurred at (xi,yi,ti)

l : patial smoothing parameter (3 km)

T : temporal smoothing parameter (5 days)

α_i : scaling parameter



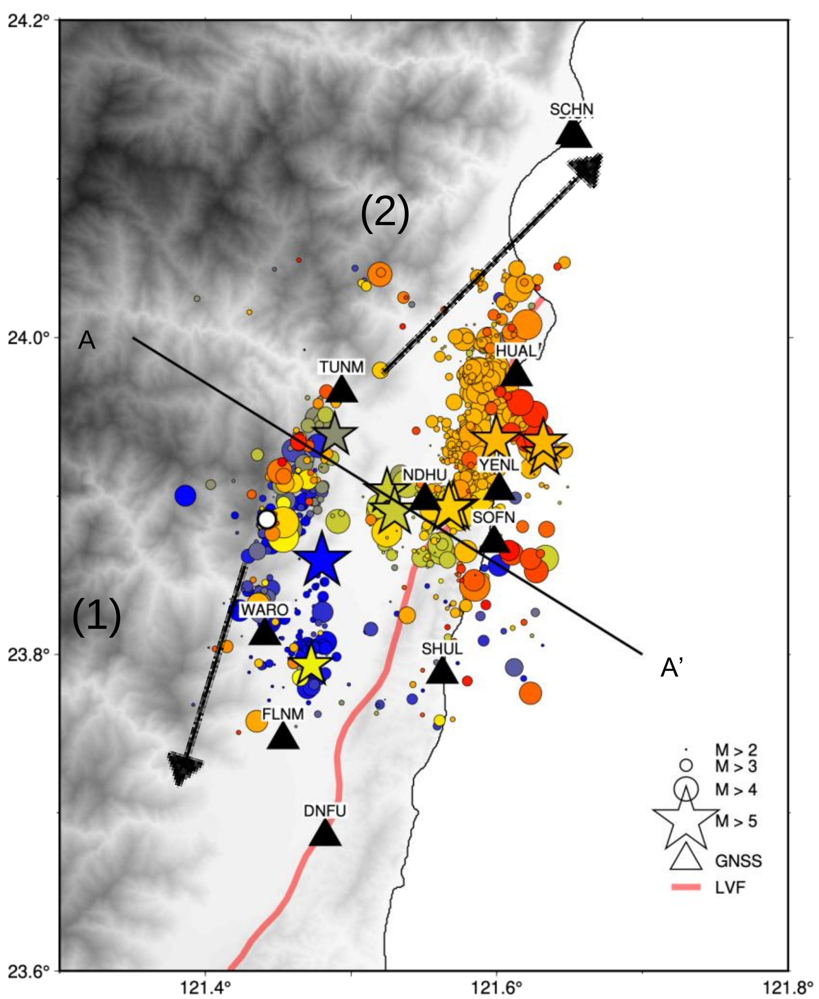
Modified space-time ETAS model (Marsan et al., 2013)
Nearest-neighbor (Zaliapin and Ben-Zion, 2013)
Linking method (Reasenberg, 1985)

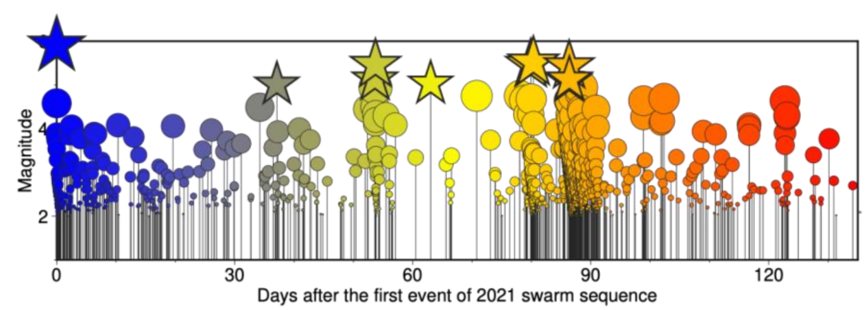
Spatiotemporal characteristics of EQ swarm

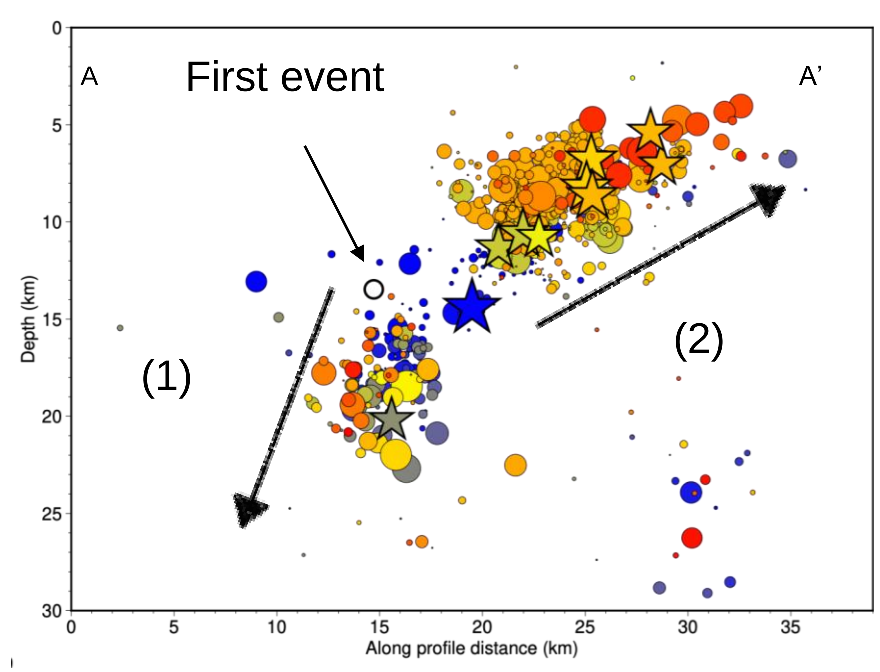
Example of the largest earthquake swarm occurred in 2021:

Start time 2021/04/18, duration 135 days

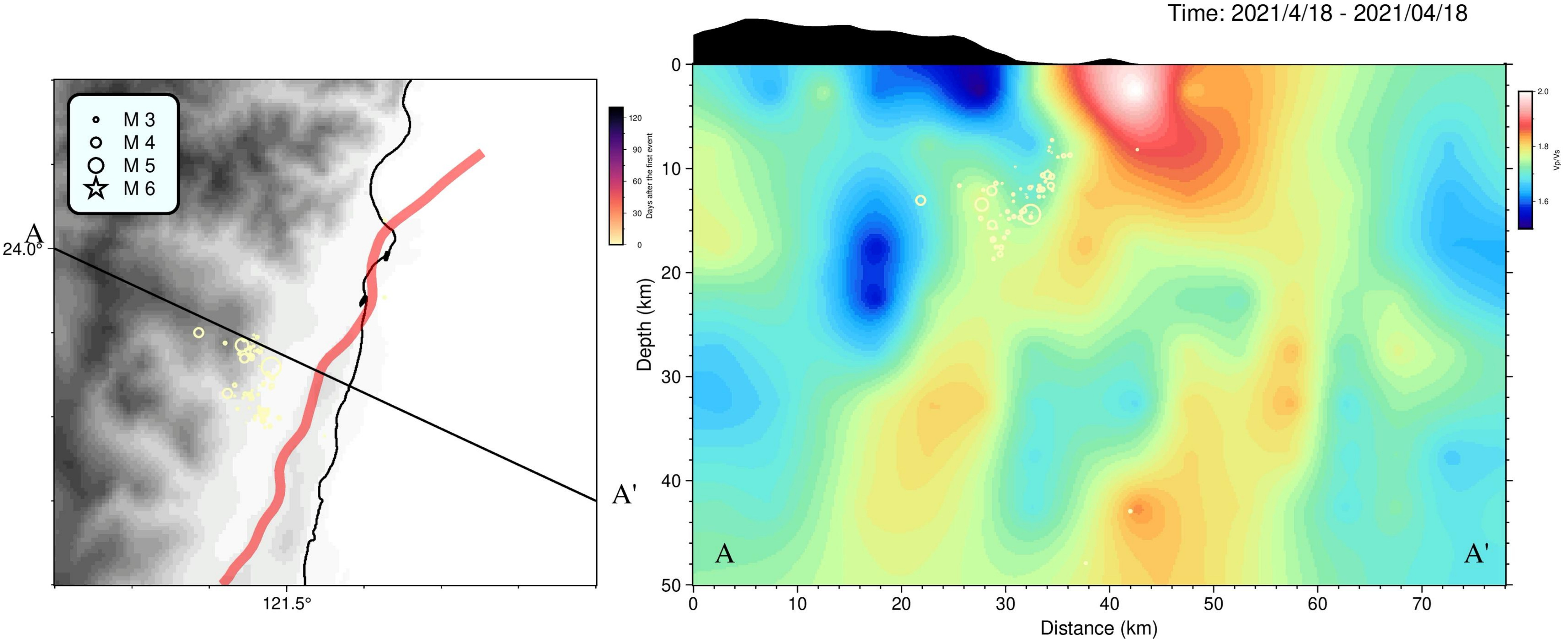
→ Migration pattern







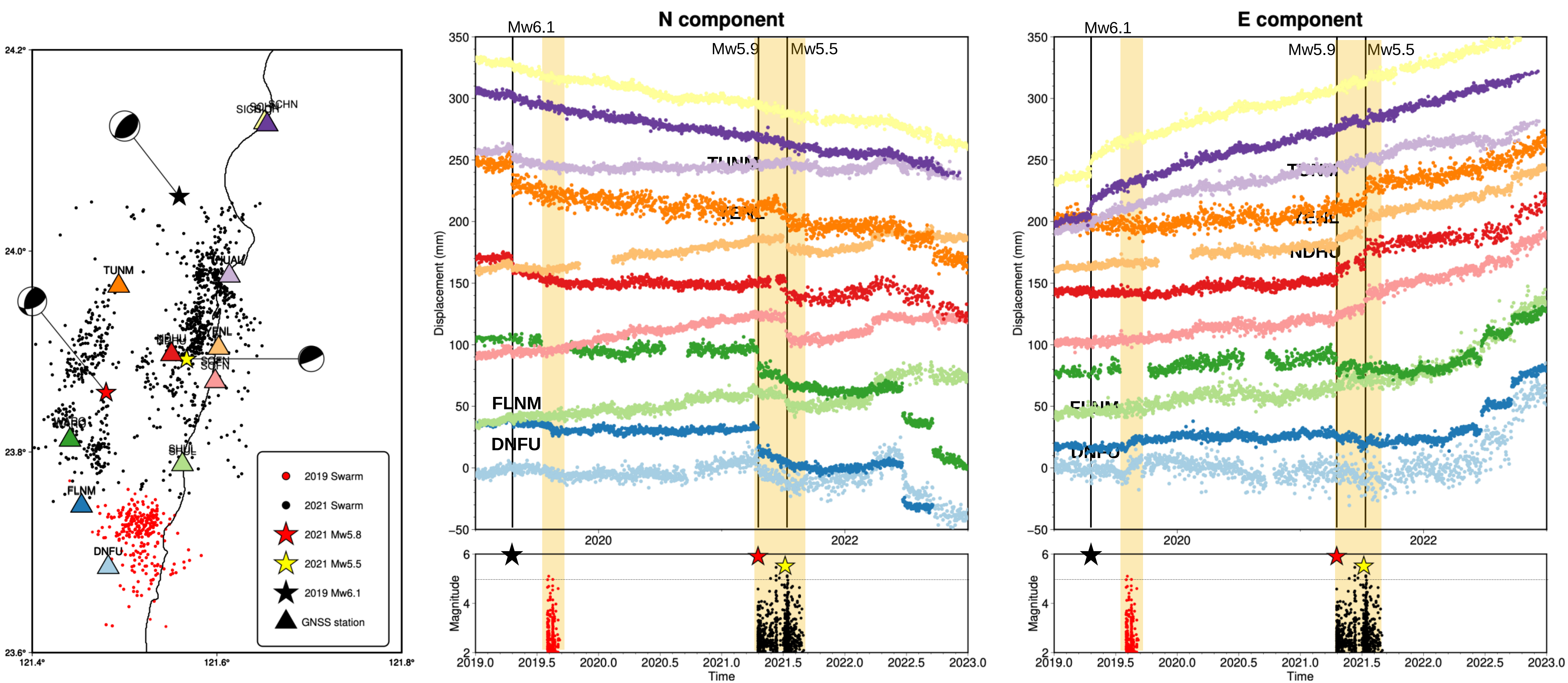
Migration pattern:
(1) Northward and downward migration in first 30 days
(2) Continued northward migration with upward propagation



Time: 2021/4/18 - 2021/04/18
M 3
M 4
M 5
M 6
A
A'
24.0°
121.5°
Days after the first event
0
30
60
90
120
Depth (km)
Distance (km)
Vp/Vs
1.6
1.8
2.0
0
10
20
30
40
50
60
70

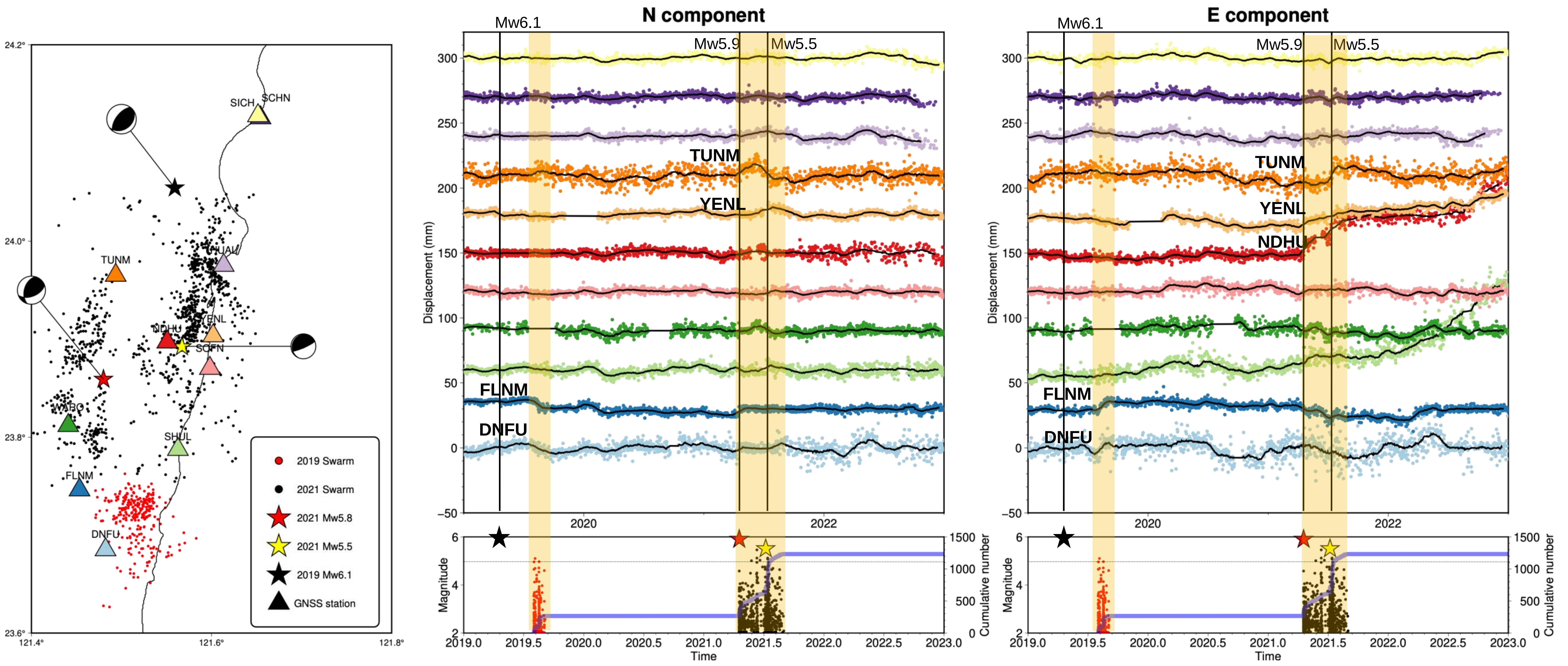
Transient Slow slip evidence associated with EQ swarm

11 GNSS stations in the study area were analyzed after removing the linear trend, seasonal deformation, and co-seismic deformation.



Transient Slow slip evidence associated with EQ swarm

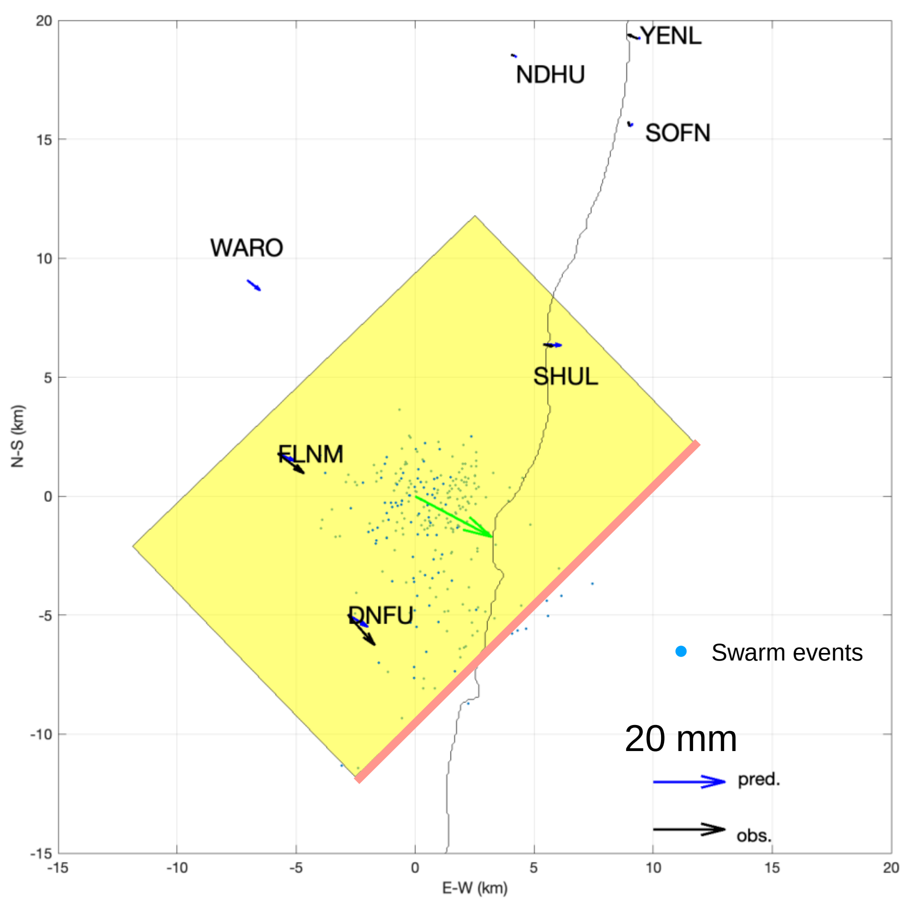
For 2019 swarm : ~20 mm at station FLNM and DNFU
For 2021 swarm : 20 mm at station YENL, ~40 mm at station NDHU



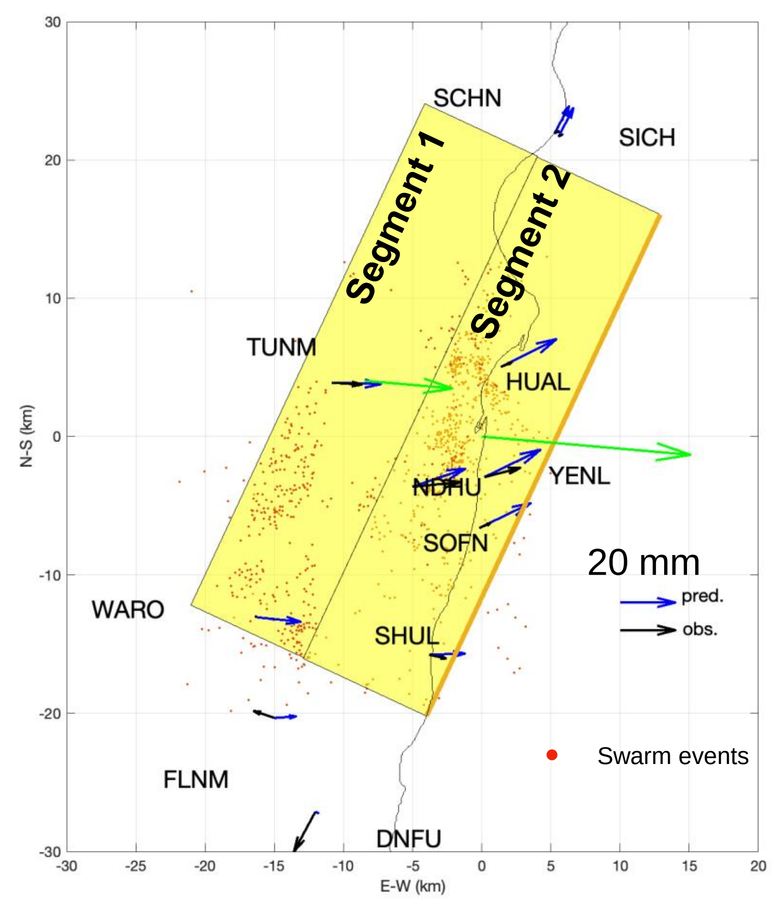
Forward model associated with earthquake swarm

The amplitude of slip imposed on the fault is approximated by the total seismic moment of swarm event

During the 2019 swarm



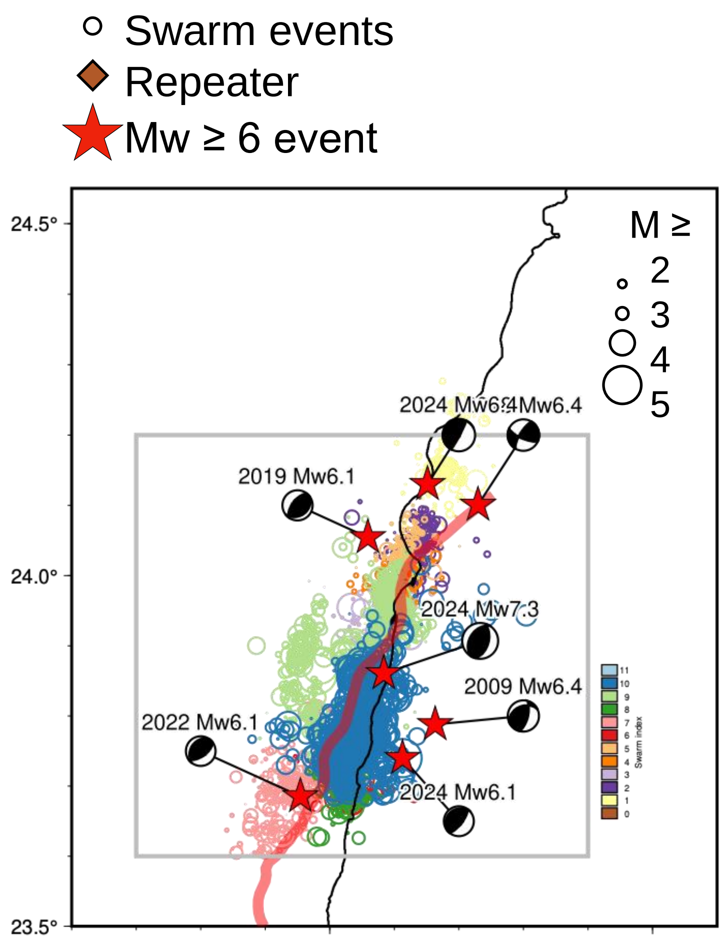
During the 2021 swarm

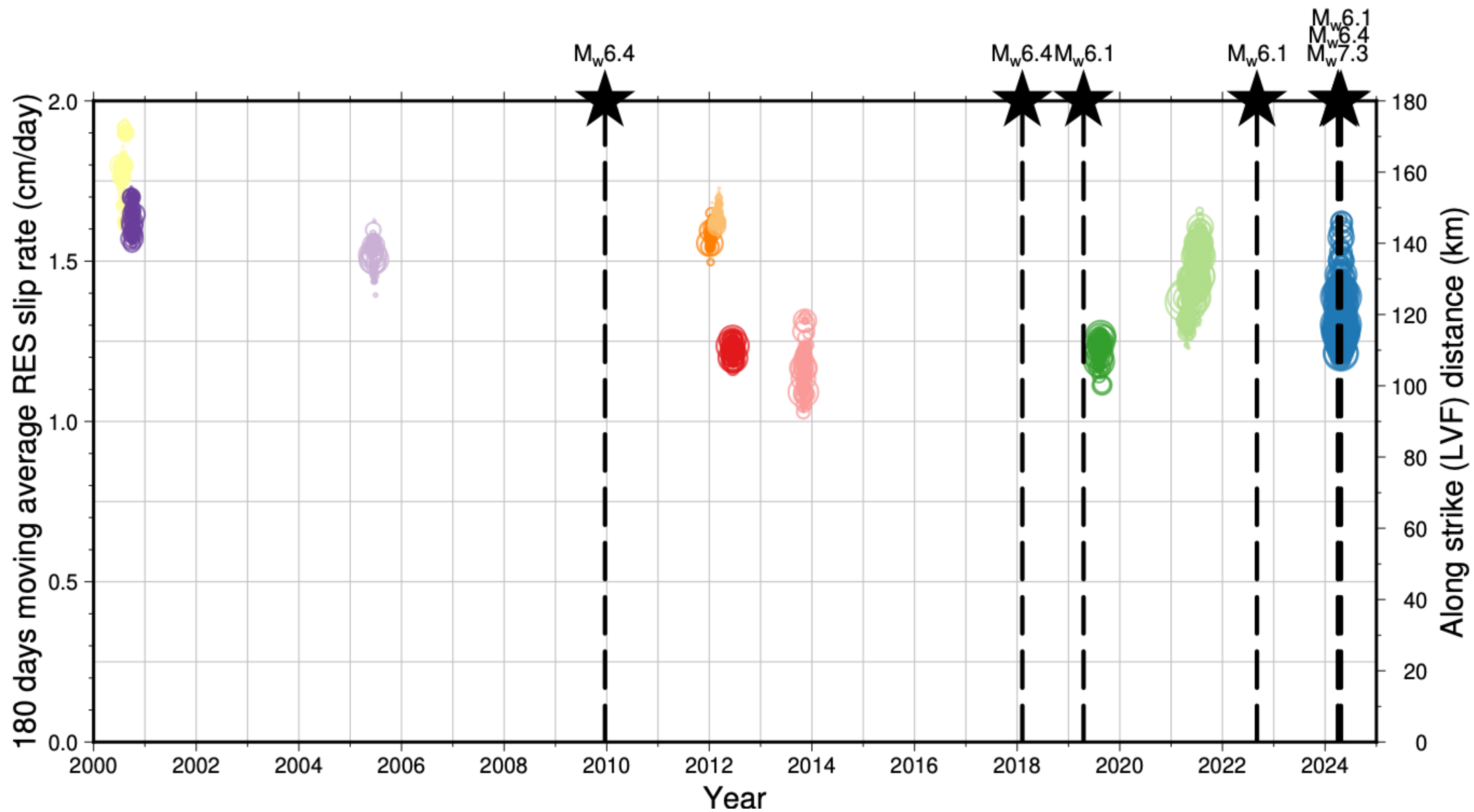


Swarm id (Period)	Swarm period	Total moment released from swarm	Maximun moment estimated from GNSS observation
Seq. 8	2019/08/02-2019/09/05	3.83E+23	9.00E+23
Seq. 9 seg.1	2021/04/17-2021/06/01	1.15E+24	4.32E+24
Seq. 9 seg.2	2021/06/01-2021/08/29	2.28E+24	2.40E+24

Spatiotemporal characteristics of earthquake swarm in Northeast Taiwan

Not associated with nearby Mw ≥ 6 earthquake

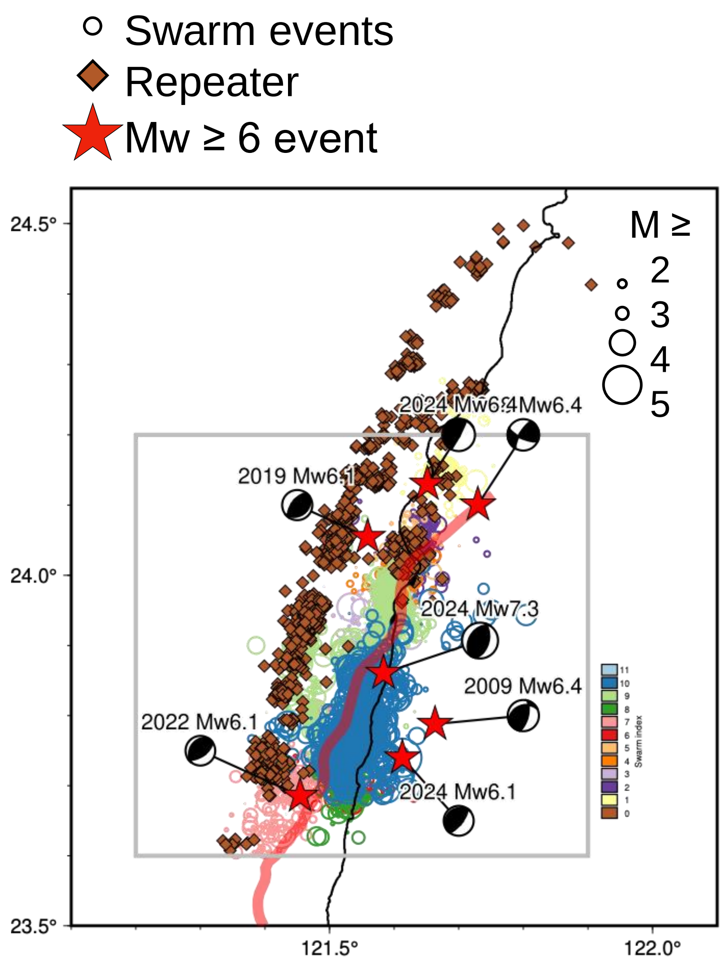


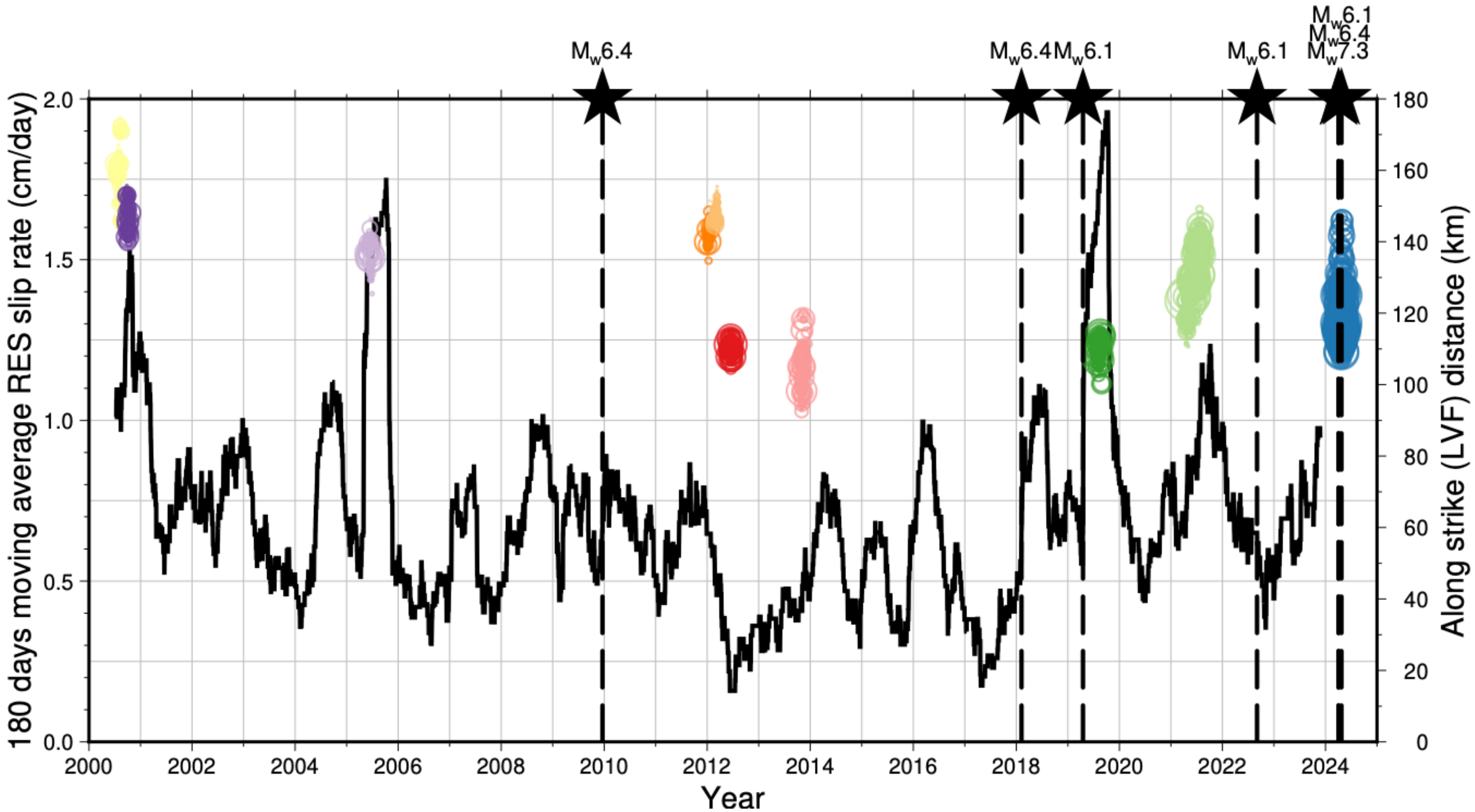


Peng et al,. (2025, under revision)

Spatiotemporal characteristics of earthquake swarm in Northeast Taiwan

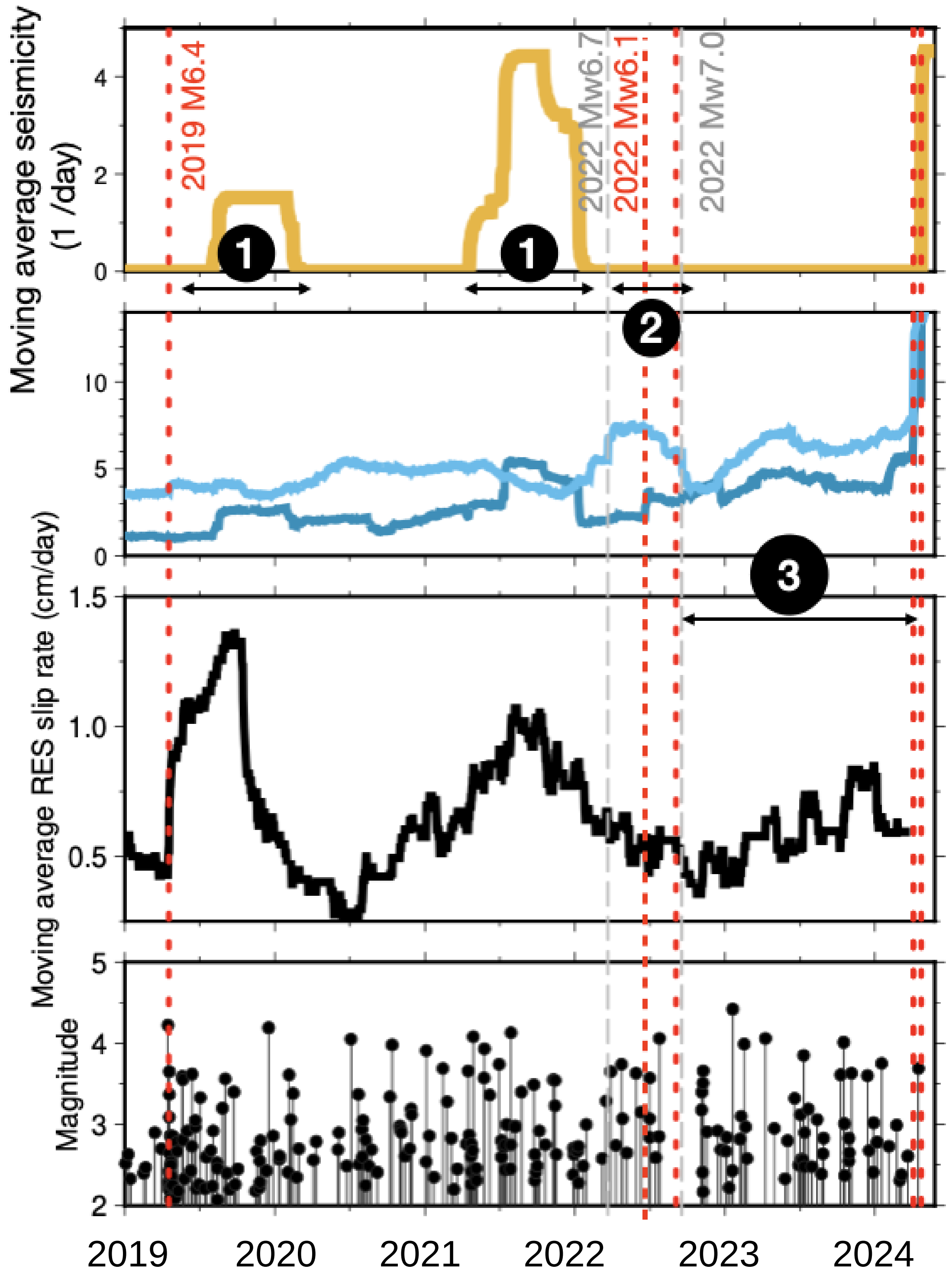
Swarm tend to occur when aseismic slip accelerated





Peng et al,. (2025, under revision)

Interplay of seismic and aseismic slip episodes in northern LV



Swarm events
Seismicity at depth ≤ 15 km
Seismicity at depth > 15 km
RES (Repeating events)

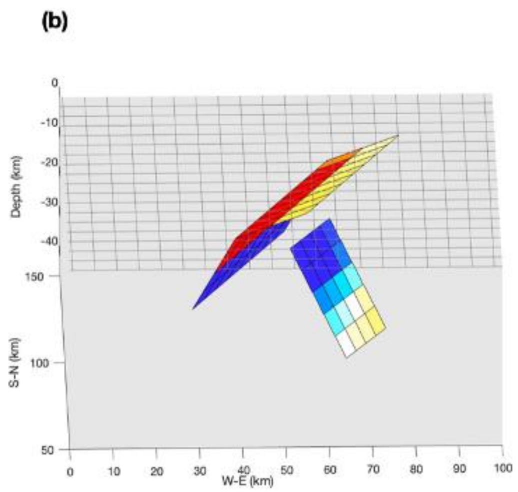
Stage 1: Acceleration of aseismic slip

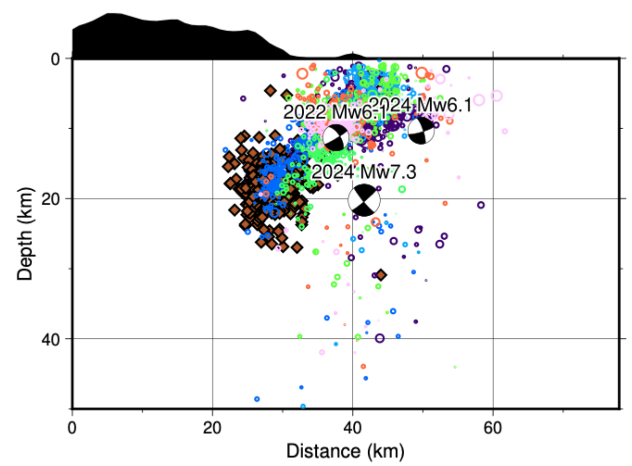
Stage 2: Enhanced seismicity

Stage 3: Gradually accelerated seismic and aseismic slip rate

Stress triggering models

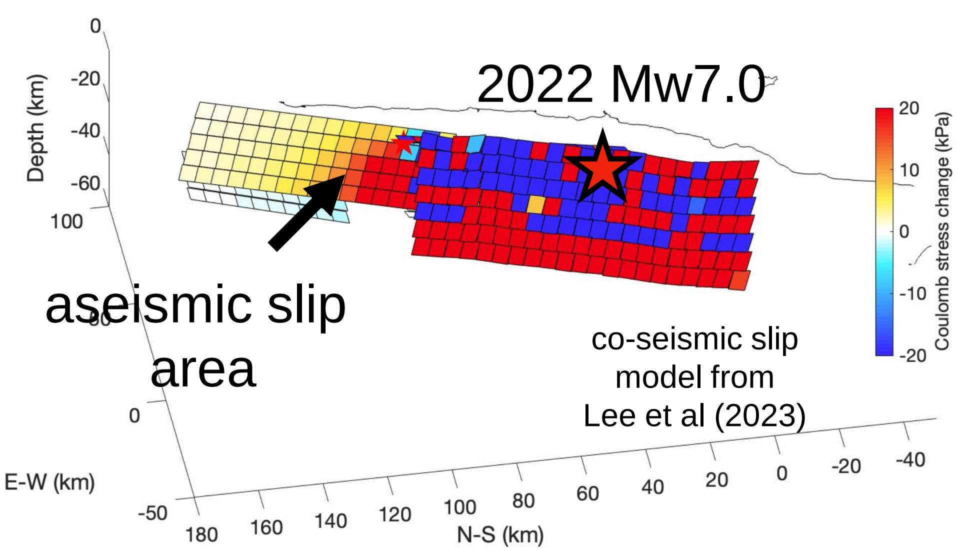
Stage 1: Acceleration of aseismic slip





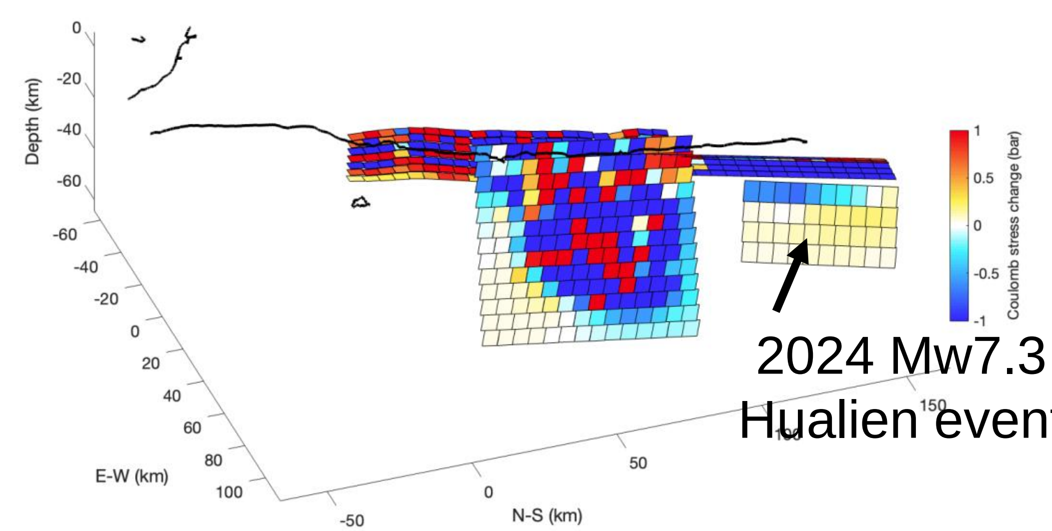
Stress increased about 0-10 kpa

Stage 3: Gradually accelerated seismic and aseismic slip rate after 2022 Mw7.0 event



Stage 4 : Cumulative stress from 2019 to 2022

source : slow earthquake, 2022 March Mw6.7 event, 2022 June Mw 6.1 event, 2022 September Mw 7.0 event

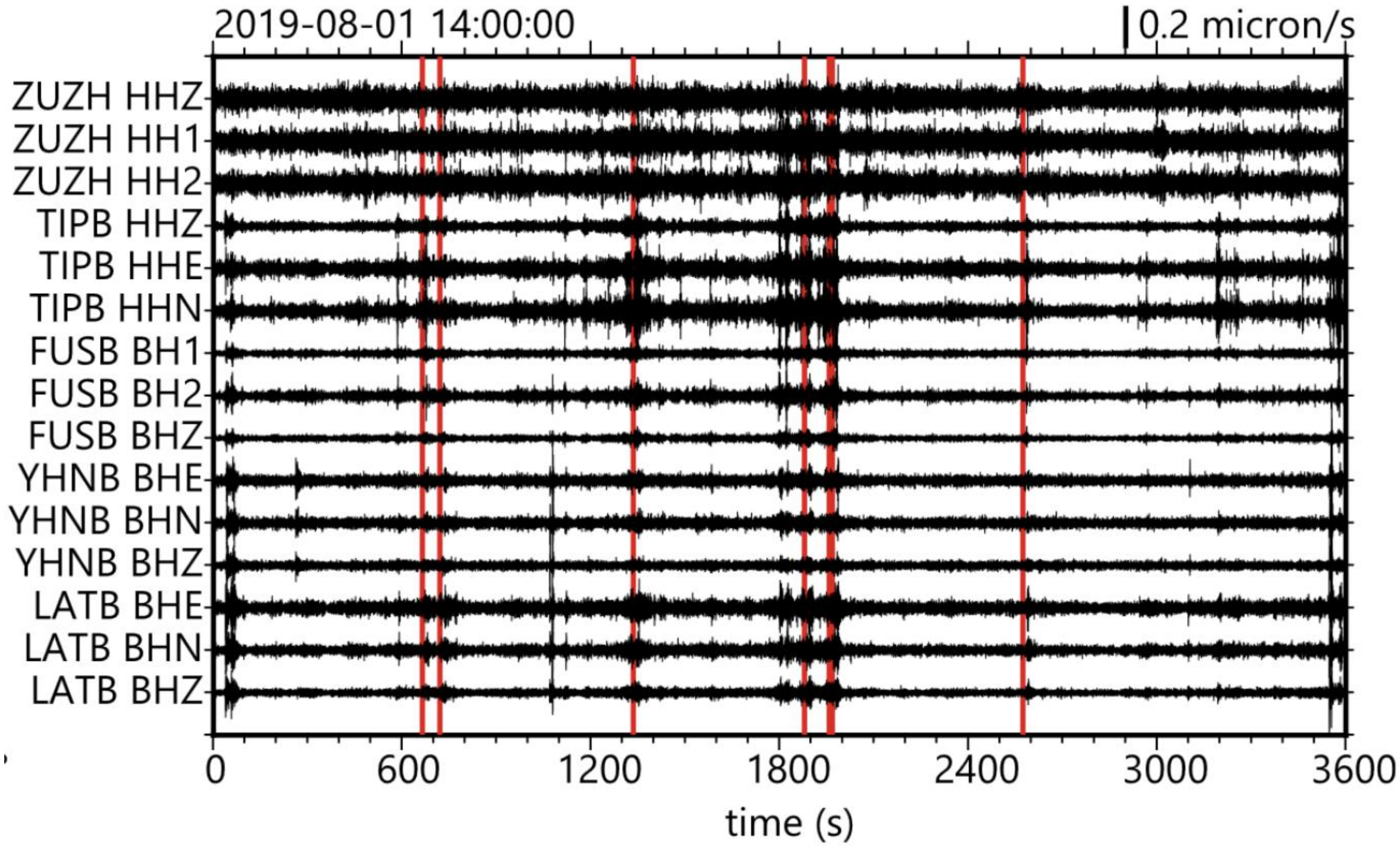


Summary

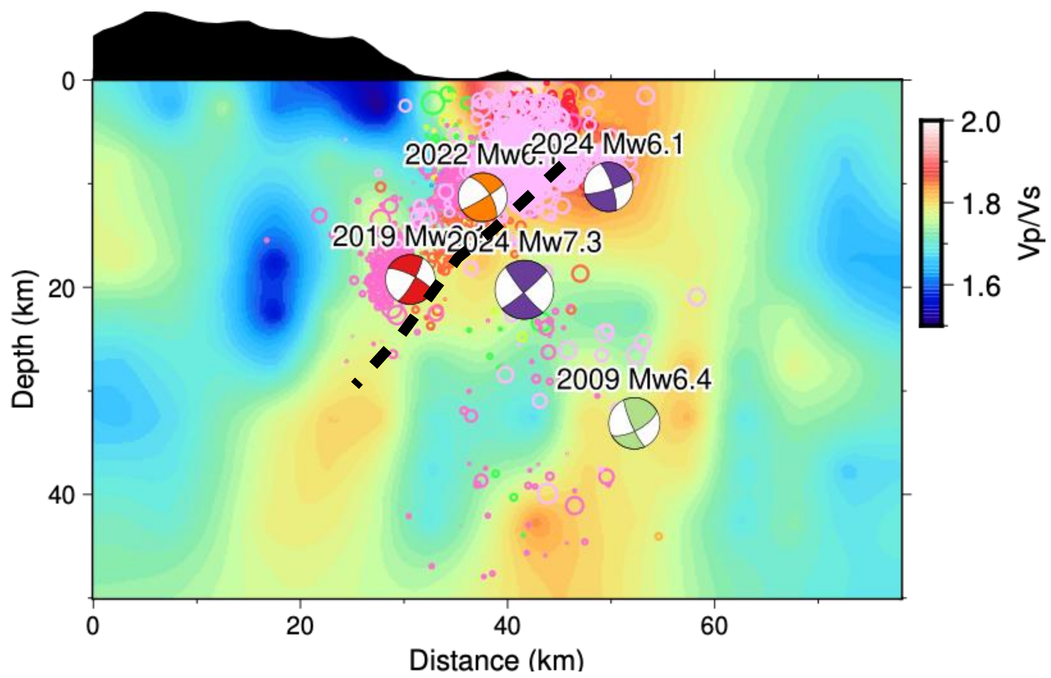
1. Slow slip event associated with tectonic tremor by decomposing GNSS data from during and inter-tremor period.
2. Slow slip associated with earthquake swarm by looking at the corrected GNSS displacement during swarm period.
3. Earthquake swarms in eastern Taiwan (2000-2024) show a connection with aseismic slip episodes, with most swarms occurring near the 2024 M7.3 earthquake epicenter and 90% accompanied by increased aseismic slip rates.
4. A significant aseismic slip episode in mid-2021 featured a four-month swarm with bilateral migration suggesting both fluid pressure and aseismic slip contributions, followed by M6+ earthquakes in 2022 and increasing aseismic slip and seismicity rates in 2023.
5. The 2024 Hualien earthquake demonstrates aseismic slip-induced stress triggering of a major earthquake, highlighting the importance of including aseismic deformation in fault interaction models and earthquake hazard assessment.

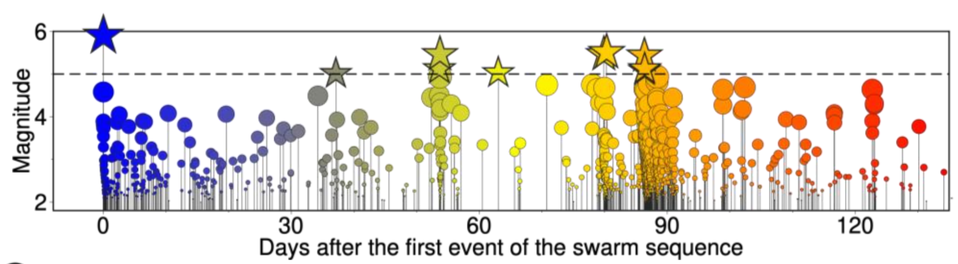
Tremor detection

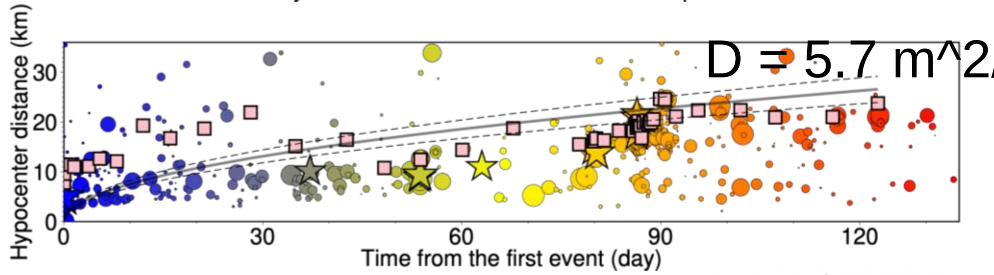
1. bandpass 2-8 Hz
2. Squared, lowpass filtered at 0.1 Hz, and resampled at 1 sps.
3. Envelopes (square root of process 2)
4. 300 s time window (50% overlap)
5. require 30 pairs at least, exclude events with over 1000 pairs (large earthquake).
6. exclude the detection associated with local eq



Origin of earthquake swarm

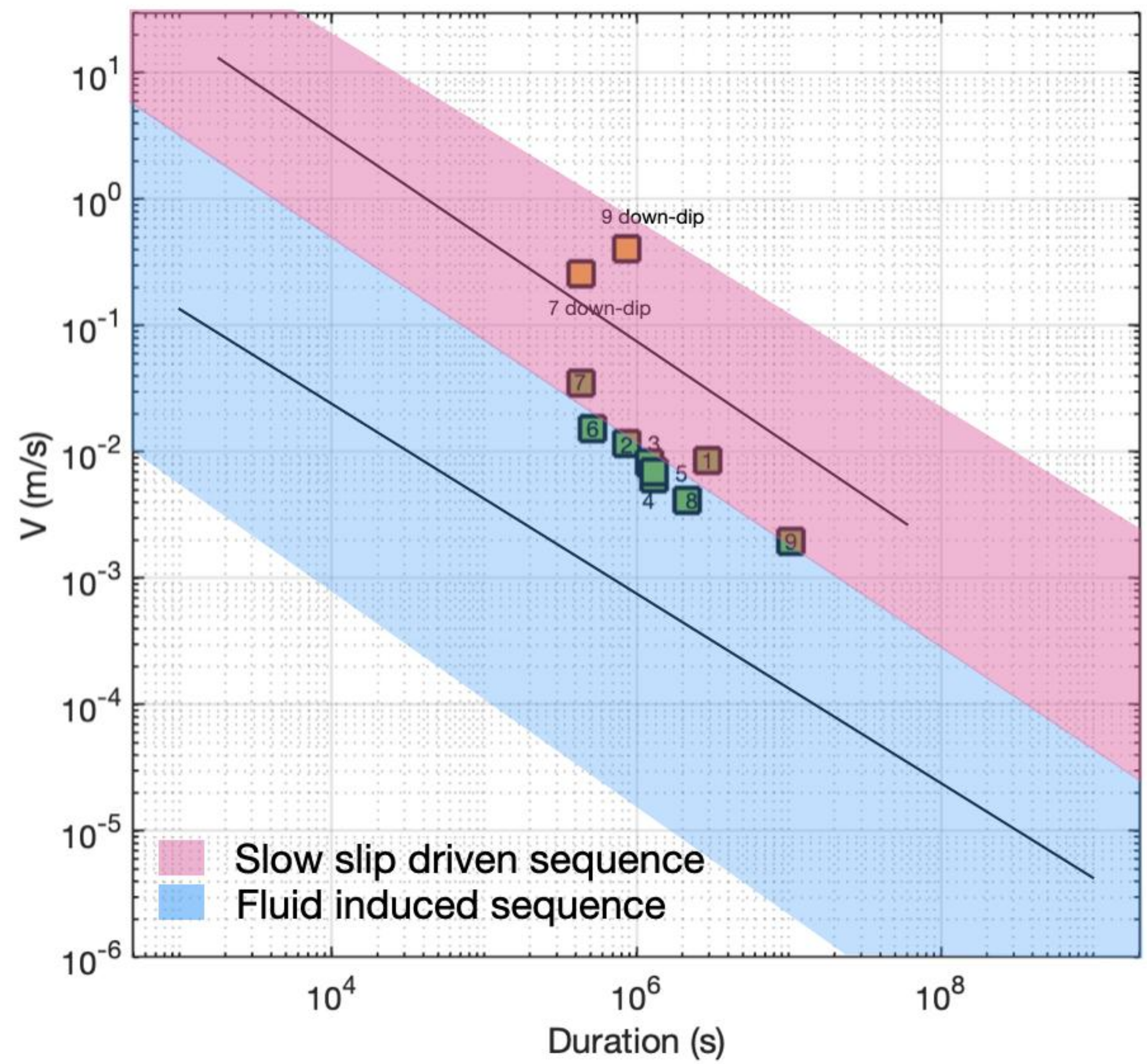






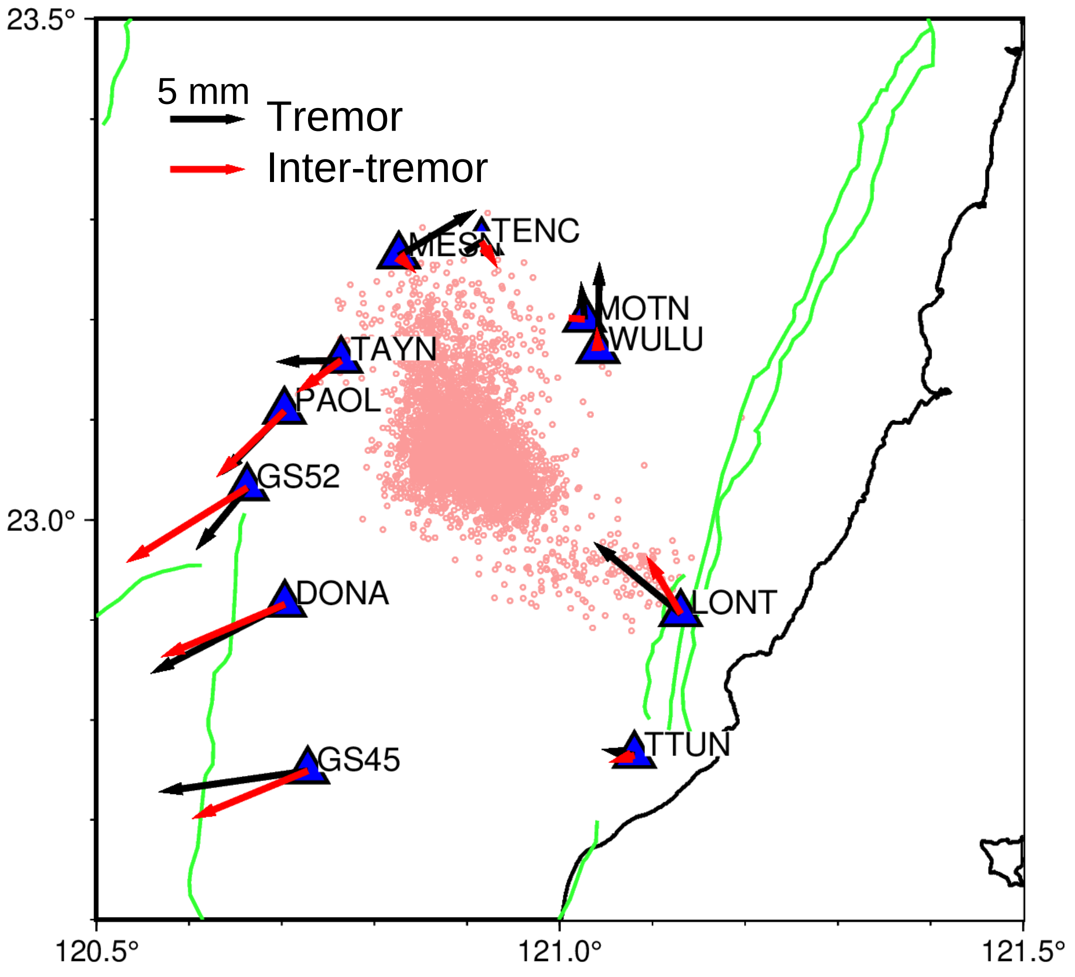
D = 5.7 m^2/s

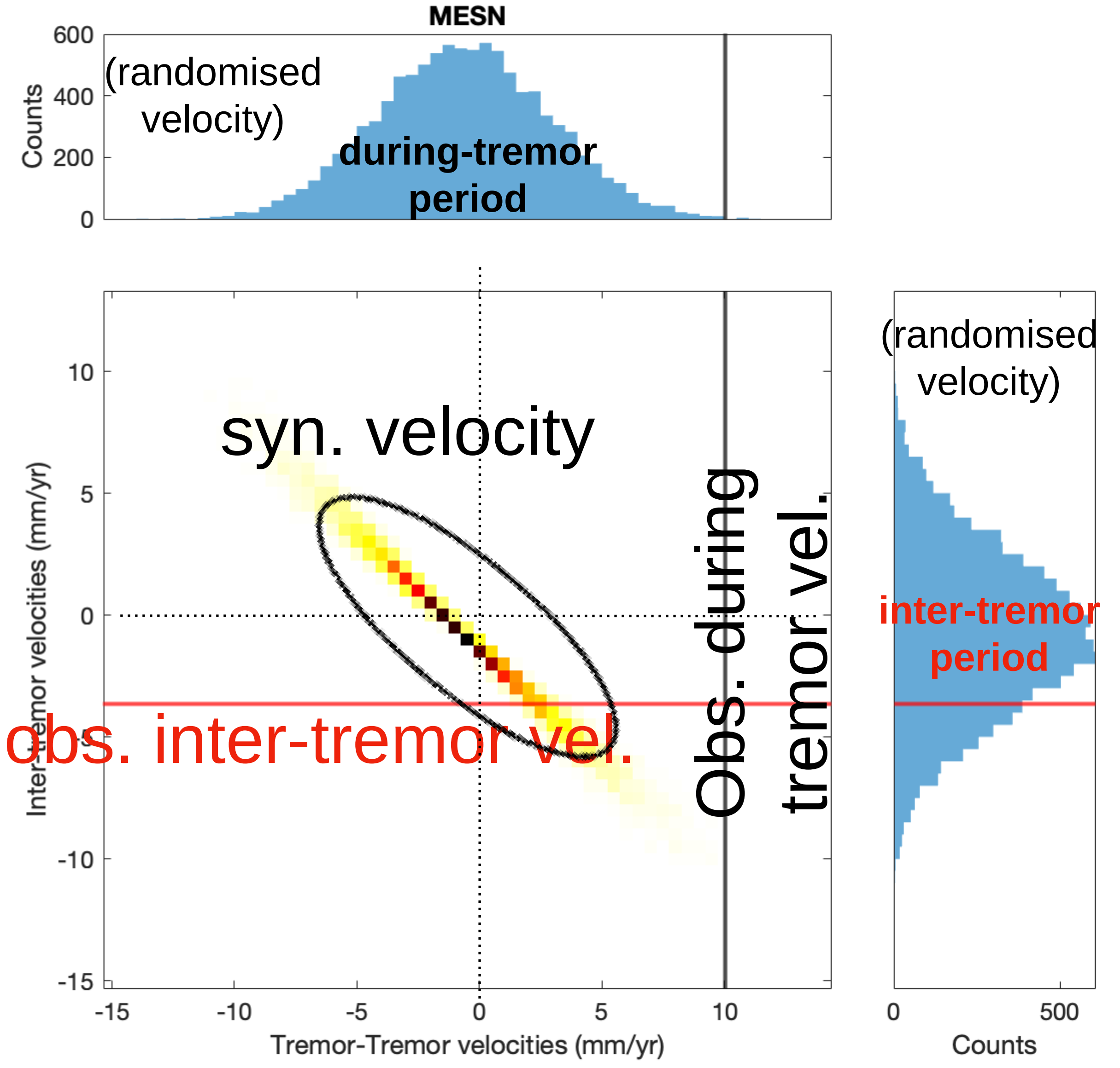
$$r = \sqrt{4\pi D t}$$



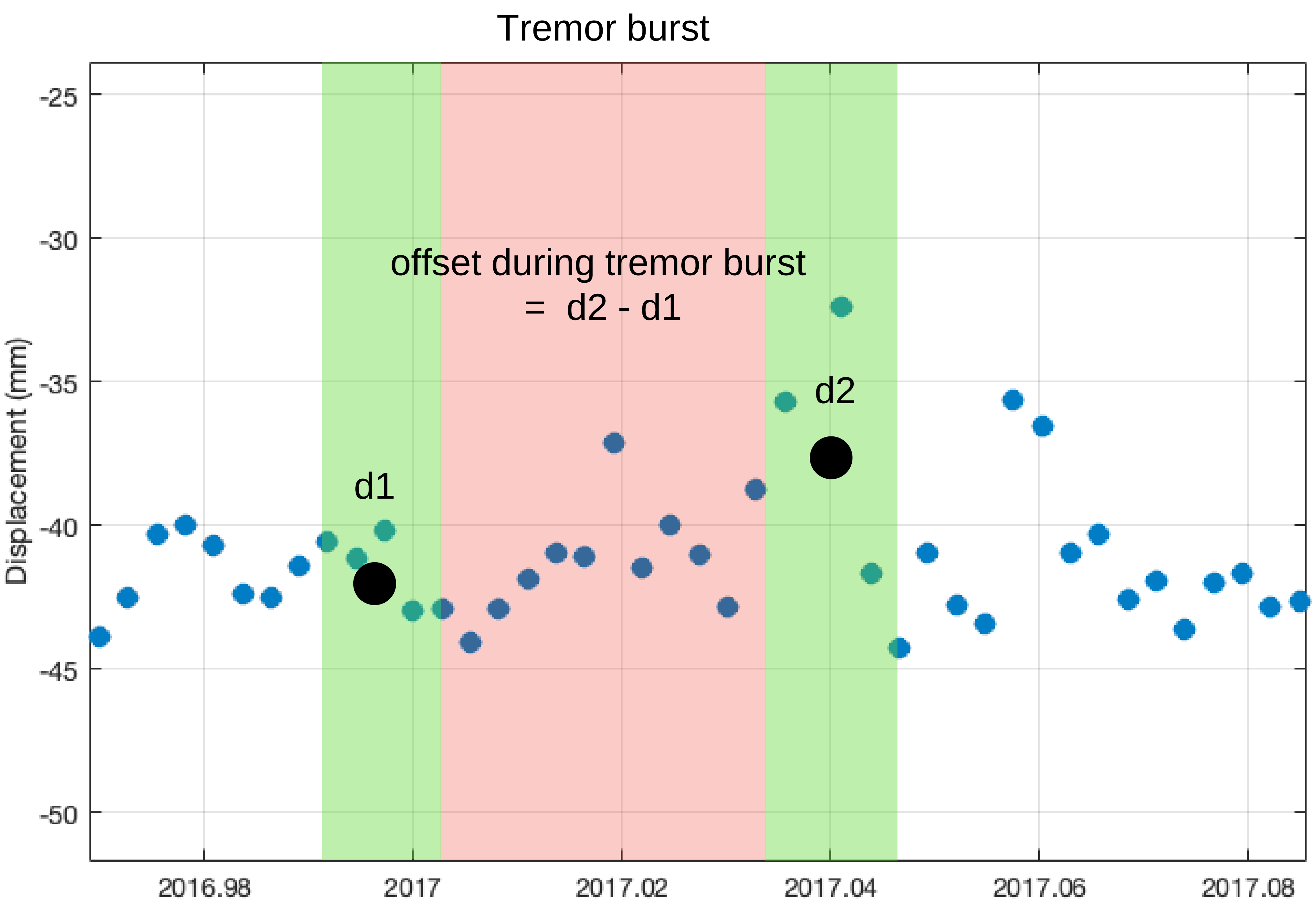
Results of GNSS decomposition

Applying random decomposition for validating data quality.





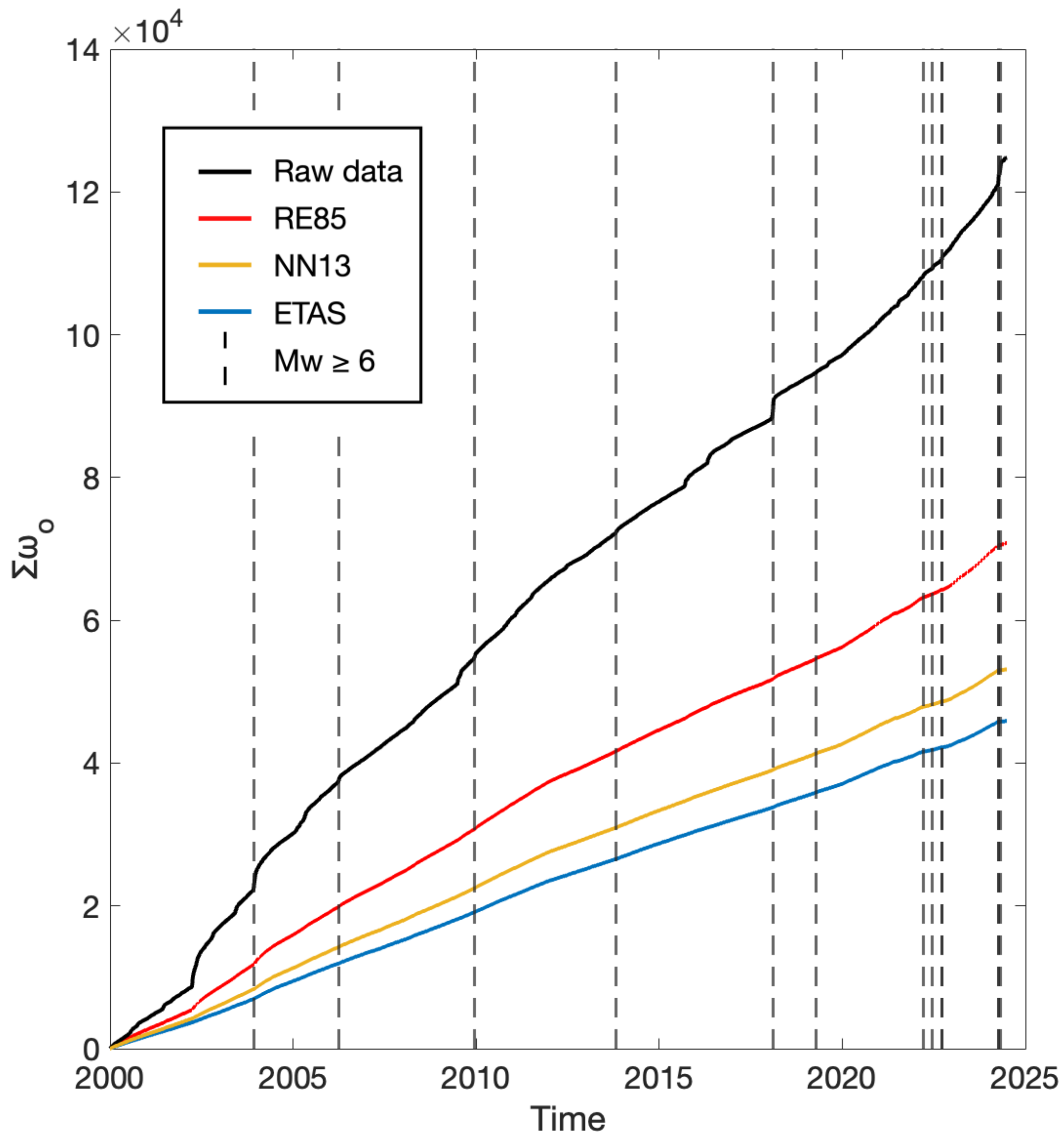
Calculate displacement during tremor and inter-tremor period

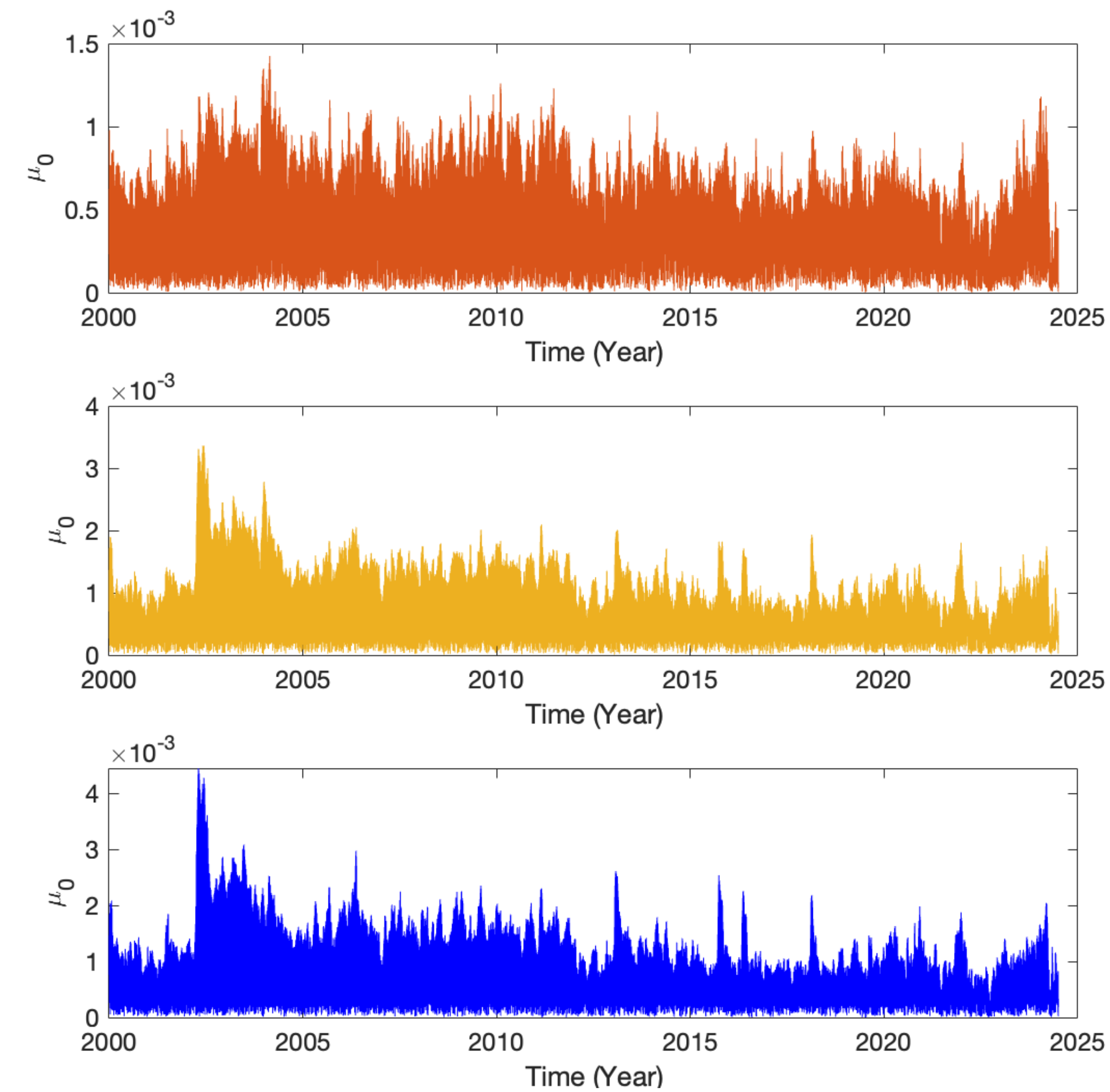


Earthquake swarm : anomalies in declustered cata

Peng et al (2021)

Time series → Density rate (Marsan et al., 2013)





Modified space-time ETAS model (Marsan et al., 2013)
Nearest-neighbor (Zaliapin and Ben-Zion, 2013)
Linking method (Reasenberg, 1985)

$$\mu_0(x,y,t) = \sum_i \omega_i e^{-\sqrt{\frac{(x-x_i)^2+(y-y_i)^2}{l}}} e^{-\frac{|t-t_i|}{T}} \times \frac{1}{2\pi l^2 \alpha_i}$$

$$\alpha_i = 2T - T\left(e^{-\frac{t_s-t_i}{T}} - e^{-\frac{t_e-t_i}{T}}\right)$$

ω_i : probability as a background event of a earthquake occurred at (xi,yi,ti)

l : patial smoothing parameter (3 km)

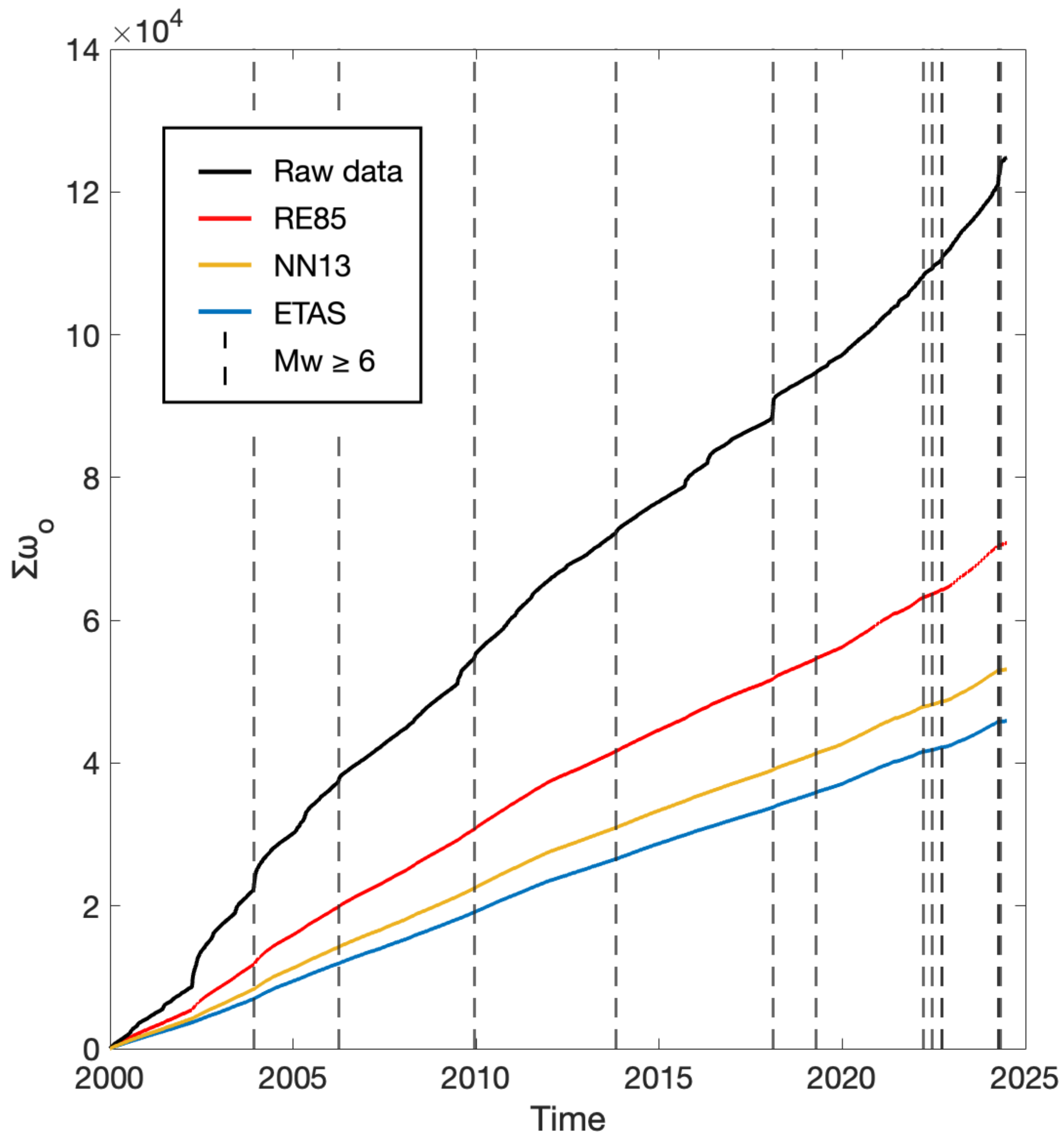
T : temporal smoothing parameter (5 days)

α_i : scaling parameter

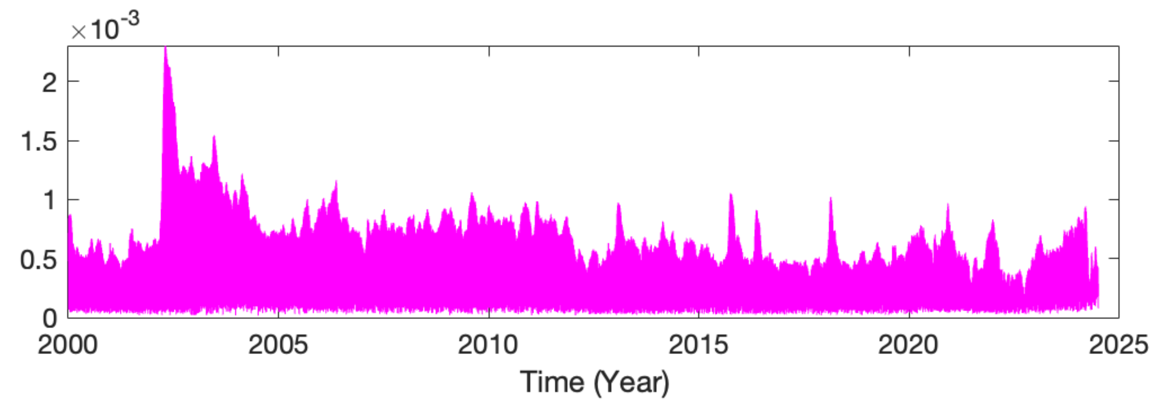
Earthquake swarm : anomalies in declustered cata

Peng et al (2021)

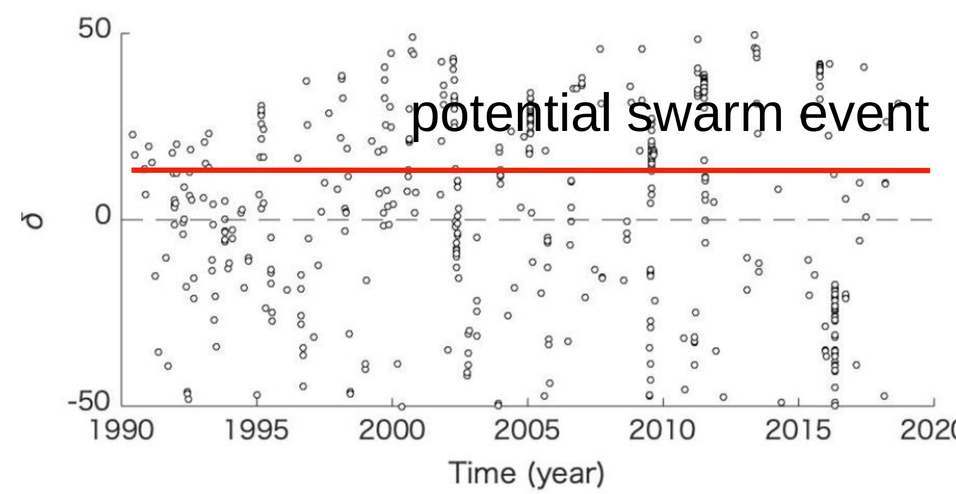
Time series ⟶ Density rate (Marsan et al., 2013)



$$\mu_{0stack}(t) = (\mu_{0etas} \times \mu_{0re85} \times \mu_{0nn13})^{\frac{1}{3}}$$



$$\delta(t) = \frac{\mu_{0stack}(t) - \mu_{0average}(t)}{\mu_{0average}(t)} \times 100$$



Modified space-time ETAS model (Marsan et al., 2013)
Nearest-neighbor (Zaliapin and Ben-Zion, 2013)
Linking method (Reasenberg, 1985)

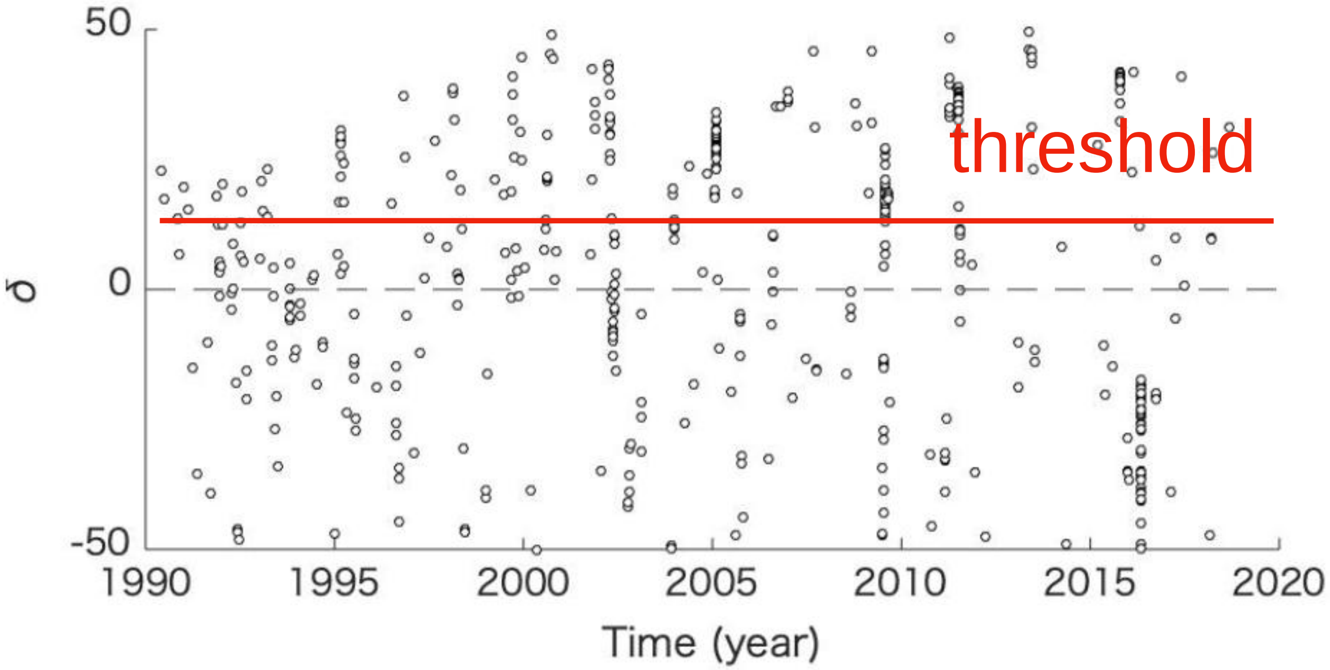
Procedure :

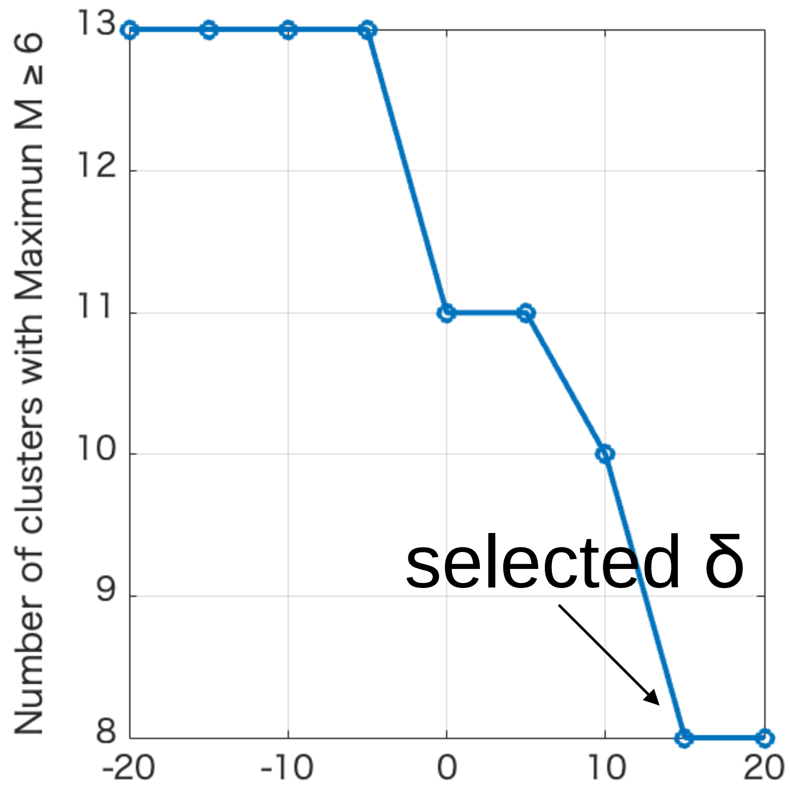
Define threshold for labelling earthquakes as potential swarm events

$$\delta(t) = \frac{\mu_{0stack}(t) - \mu_{0average}(t)}{\mu_{0average}(t)} \times 100$$

Threshold is defined by the abrupt drop of the number of clusters with maximum M ≥ 6

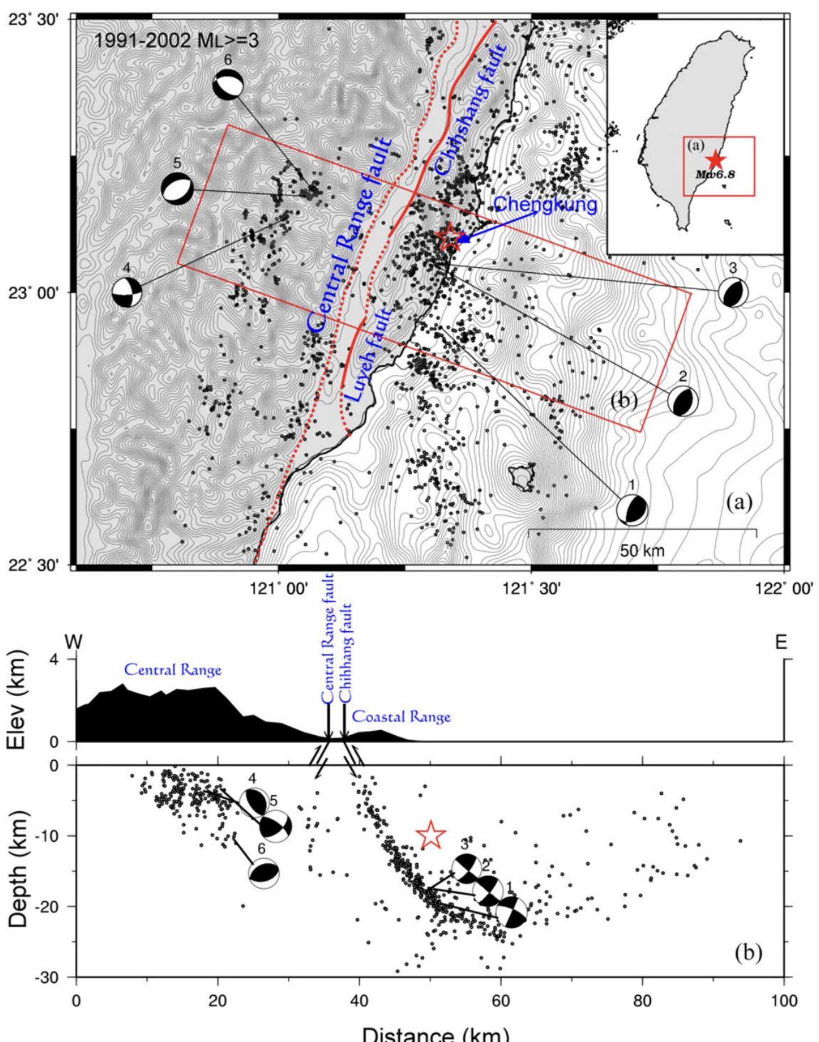
potential swarm event





Dynamic Rupture Simulation of Chihshang fault

2003 Mw 6.8 Chengkung earthquake

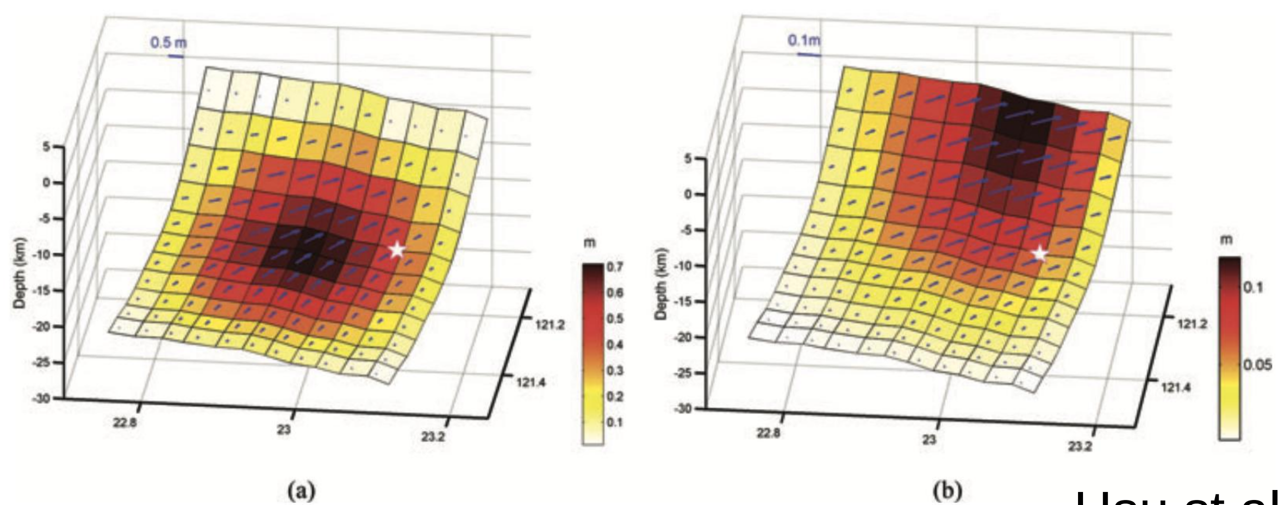


Kuchen et al (2007)

Ozawa et al. (2023)

co-seismic

post-seismic

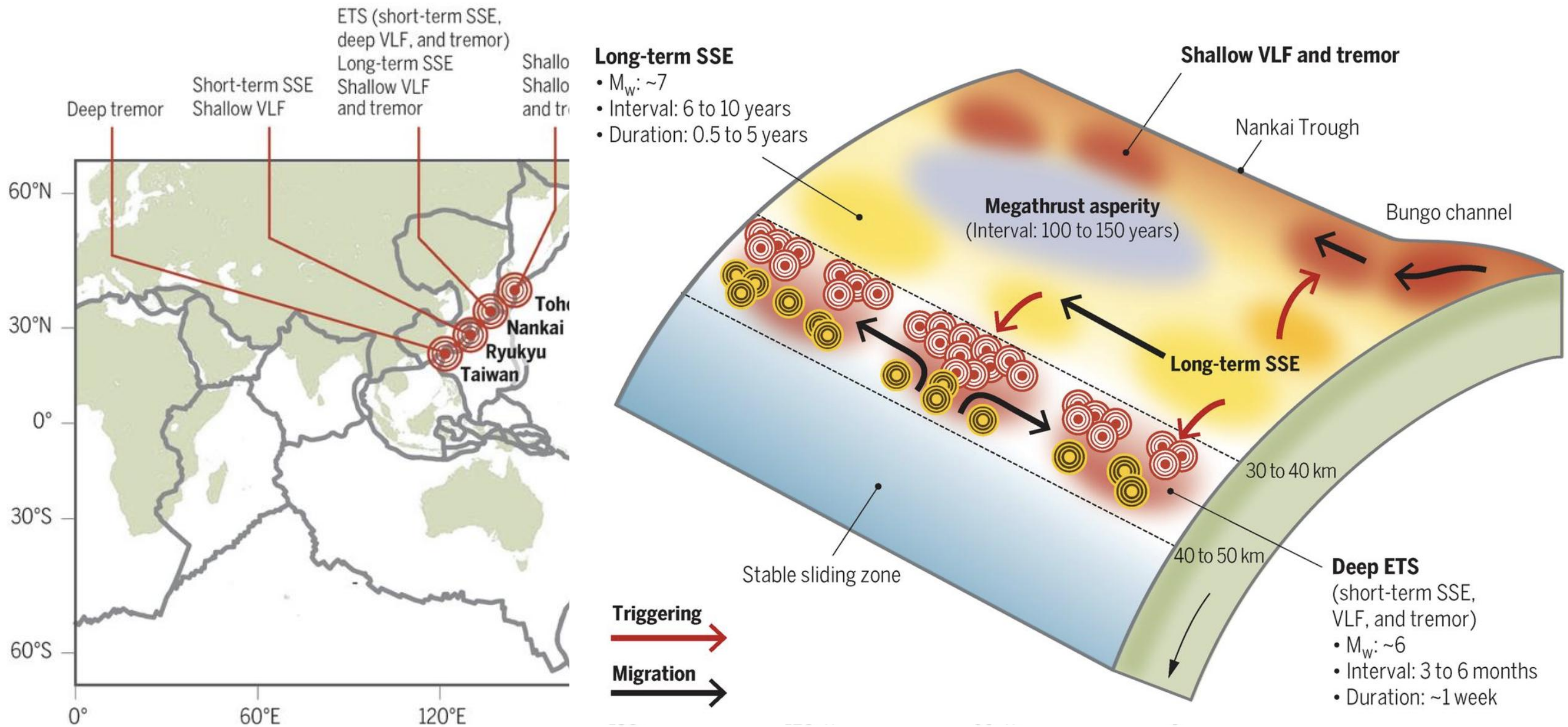


Hsu st al., (2009)

rupture propagate to the shallow depth

triggered seismicity at west-dipping central range fault

And is found to occur only on the up-dip or donw-dip of the megathrust seismogenic zone



Obara and Kato (2016)

Condition to favour slow earthquake generation (from the earthquake m

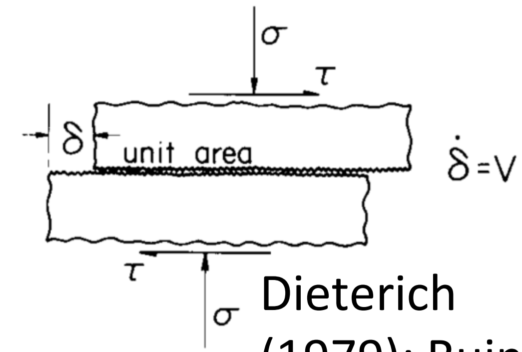
rate and state friction model

$$\mu(V,\theta) = \mu^* + a\ln\frac{V}{V^*} + b\ln\frac{V^*\theta}{D_c}$$

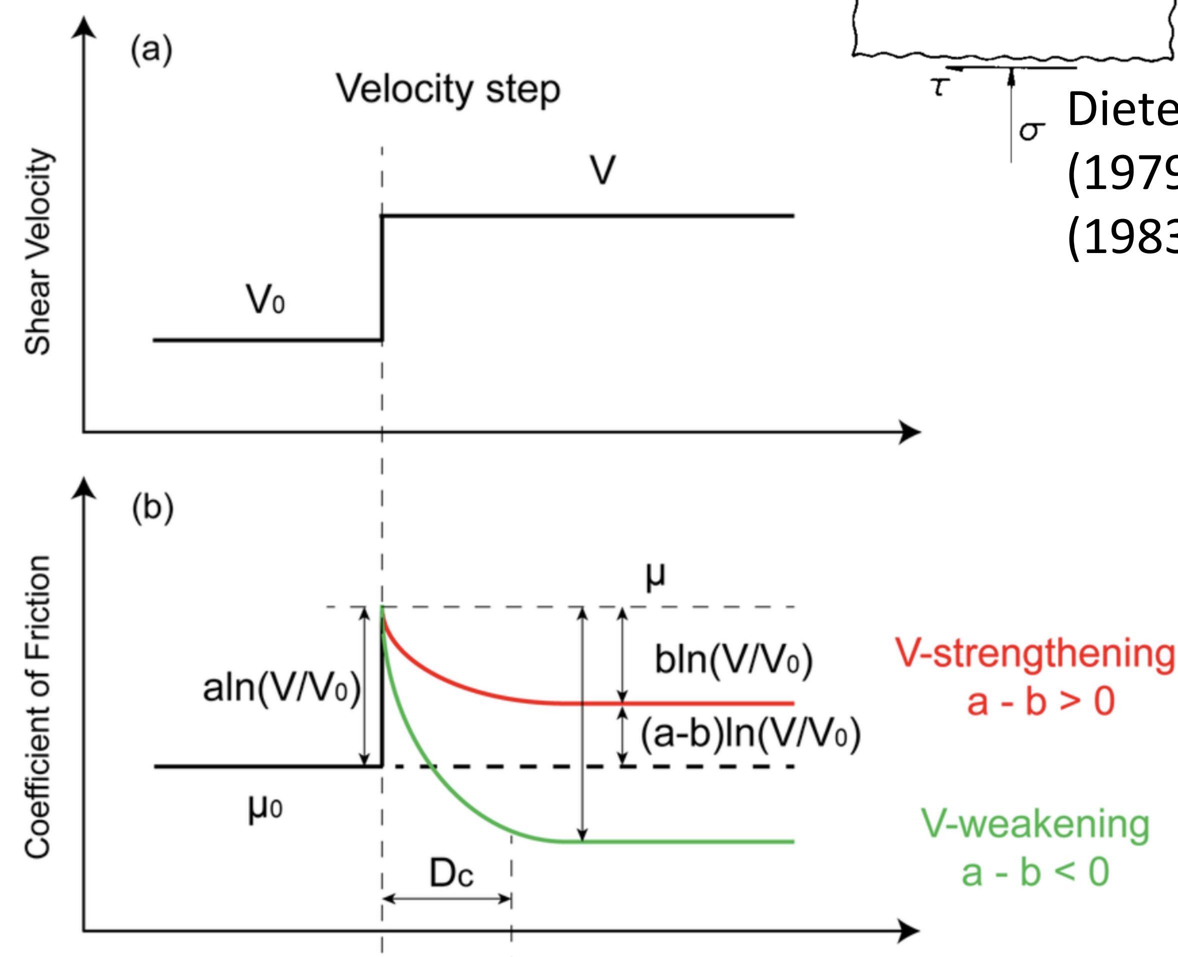
$$L_c = \frac{GD_c}{\sigma(b-a)}$$

L >> Lc : slip seismically
L ~= Lc : slip aseismic
L <= Lc : stable

To generate slow earthquake, we need :
1. Lower normal stress
2. Longer characteristic slip

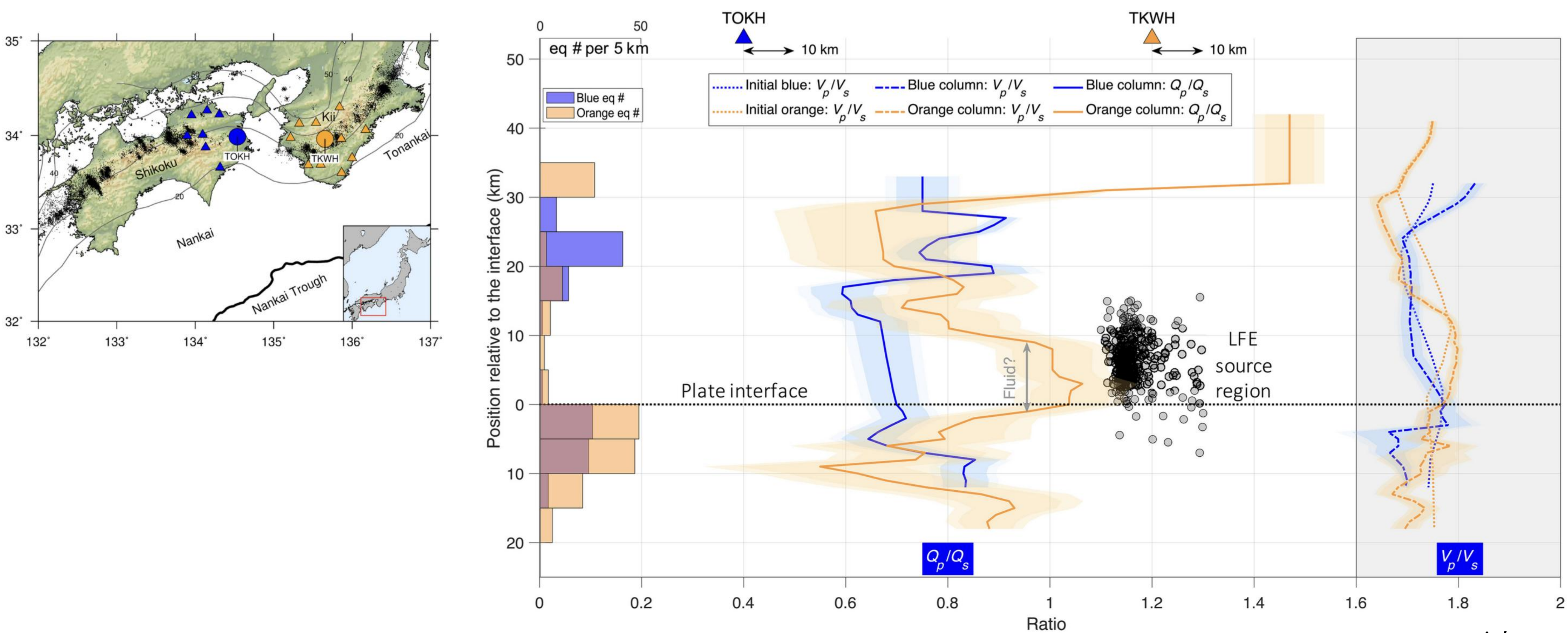


Dieterich (1979); Ruina (1983)



Cui et al. (2023)

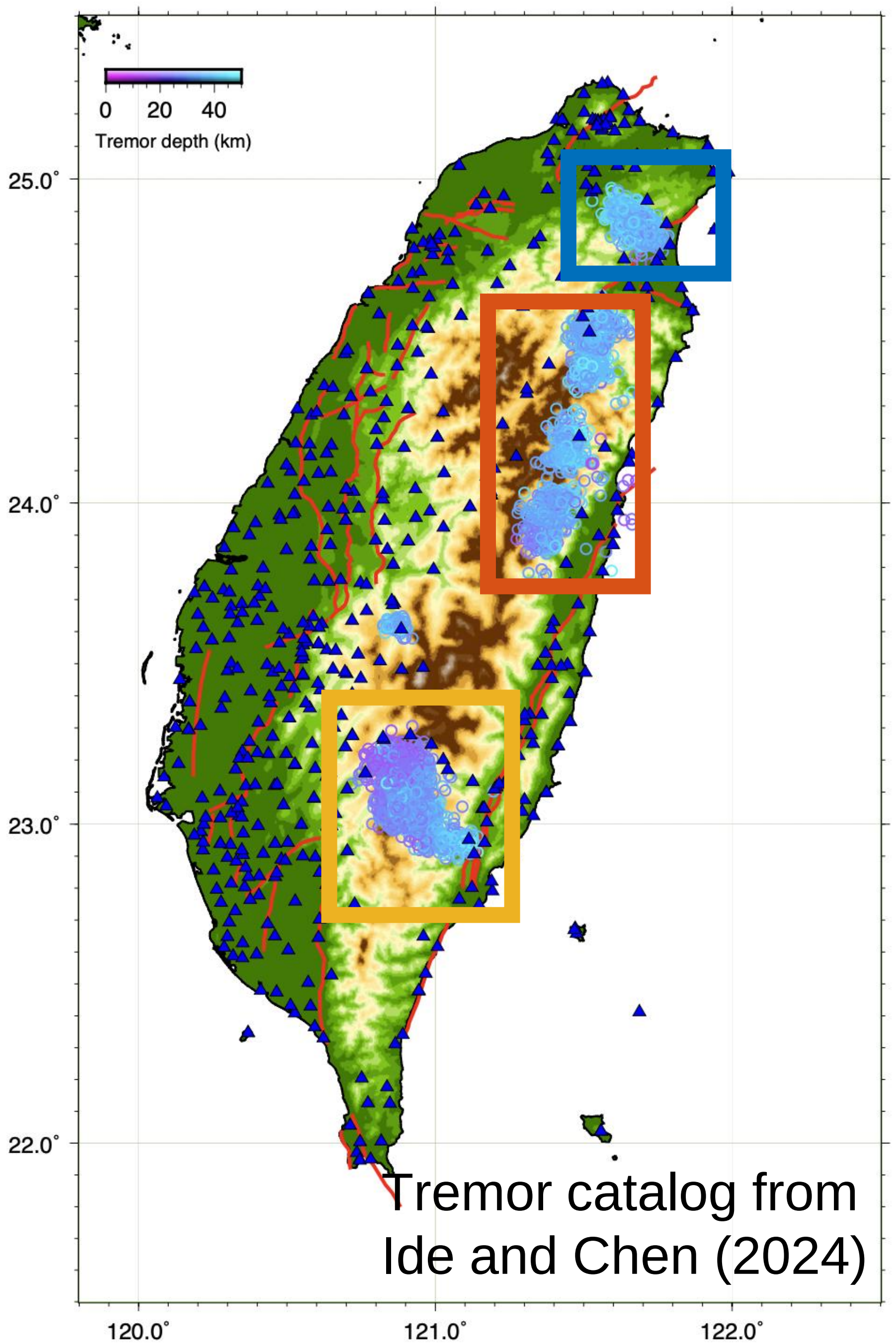
From the observation, slow earthquakes tend to occur on higher Vp/Vs, h



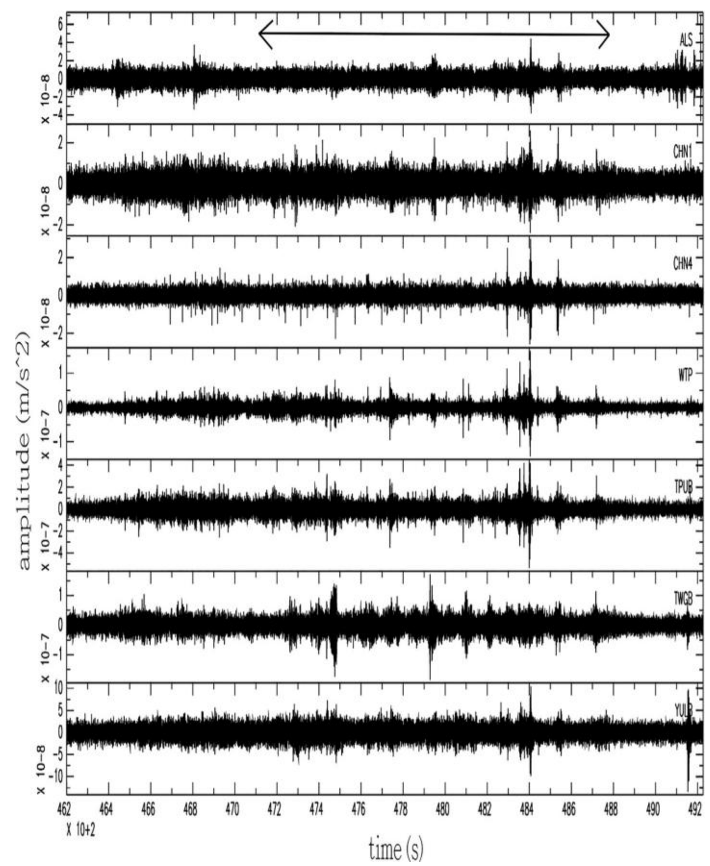
Wang et al (2023)

Tremors in Taiwan are short but frequently

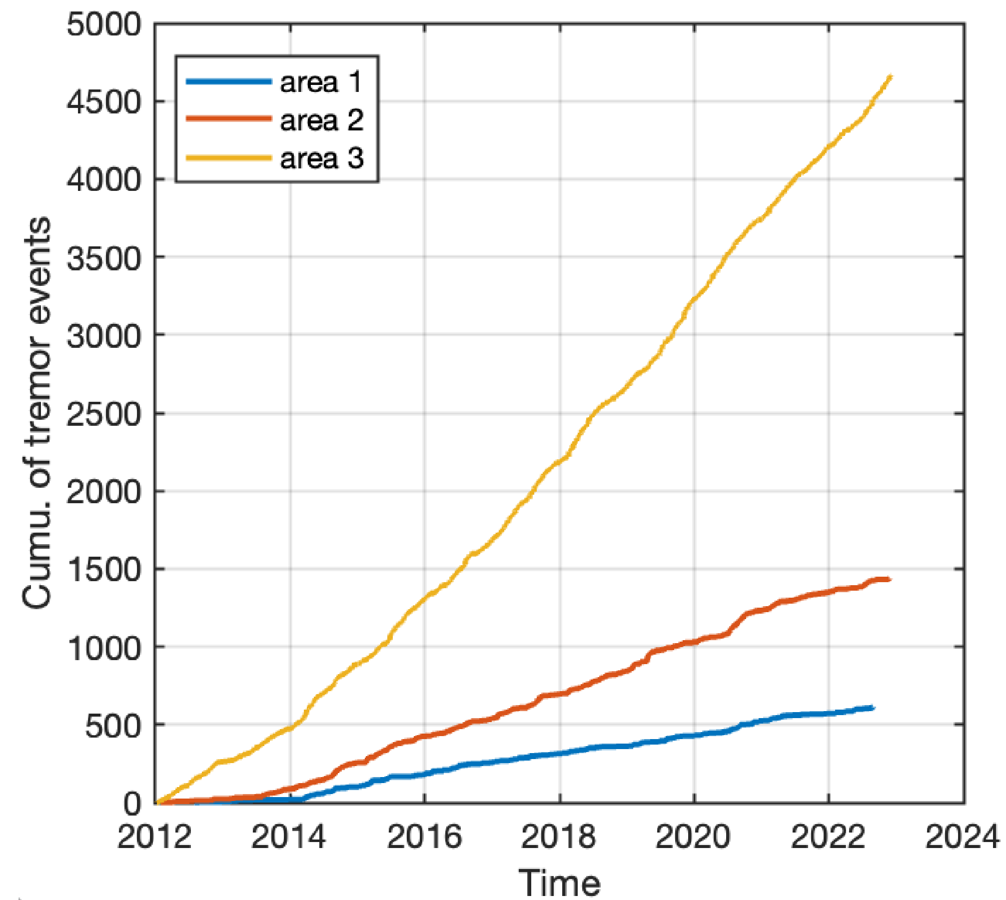
Tremor map



Tremor catalog from
Ide and Chen (2024)

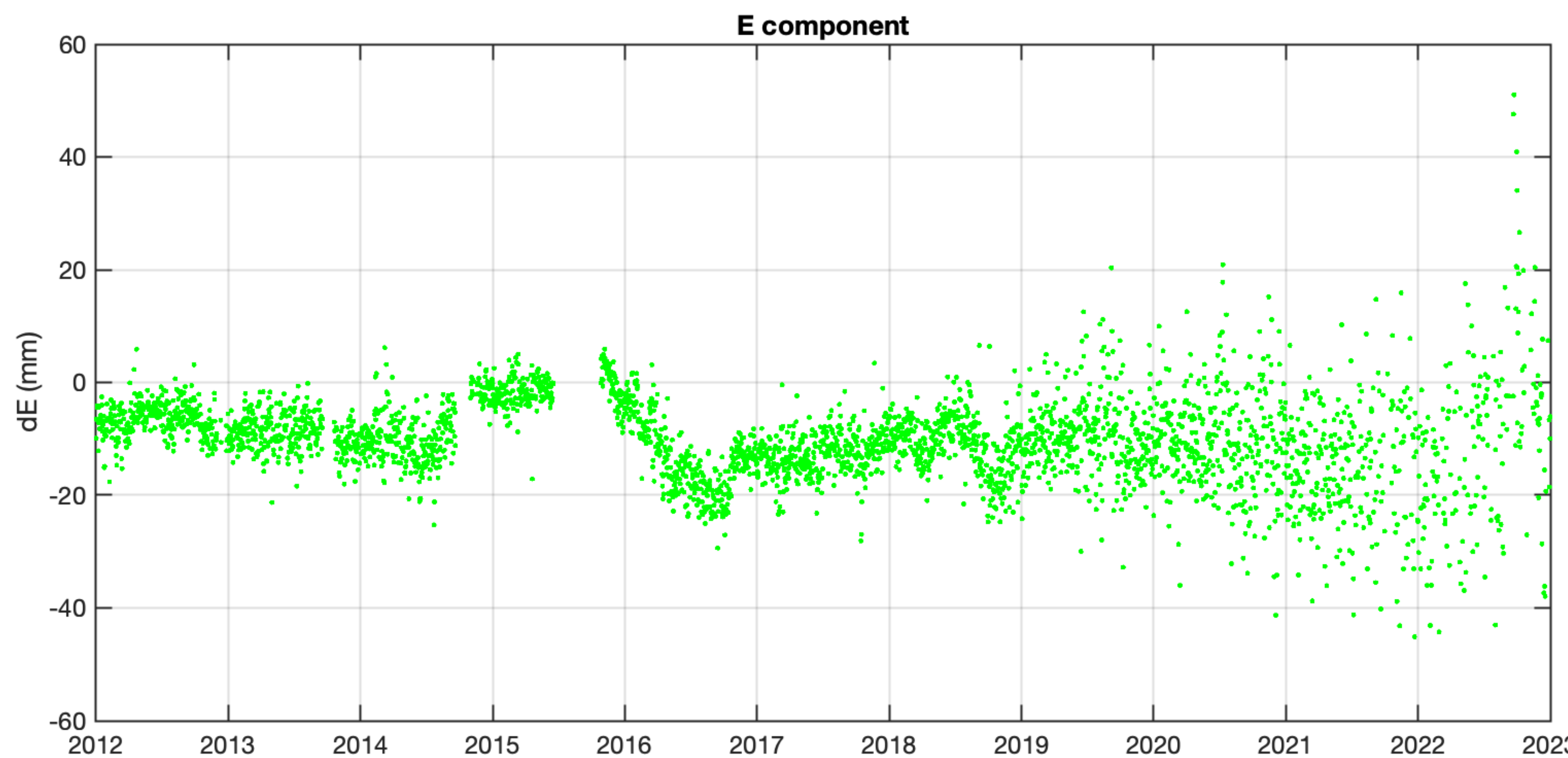


Peng et al., (2019)

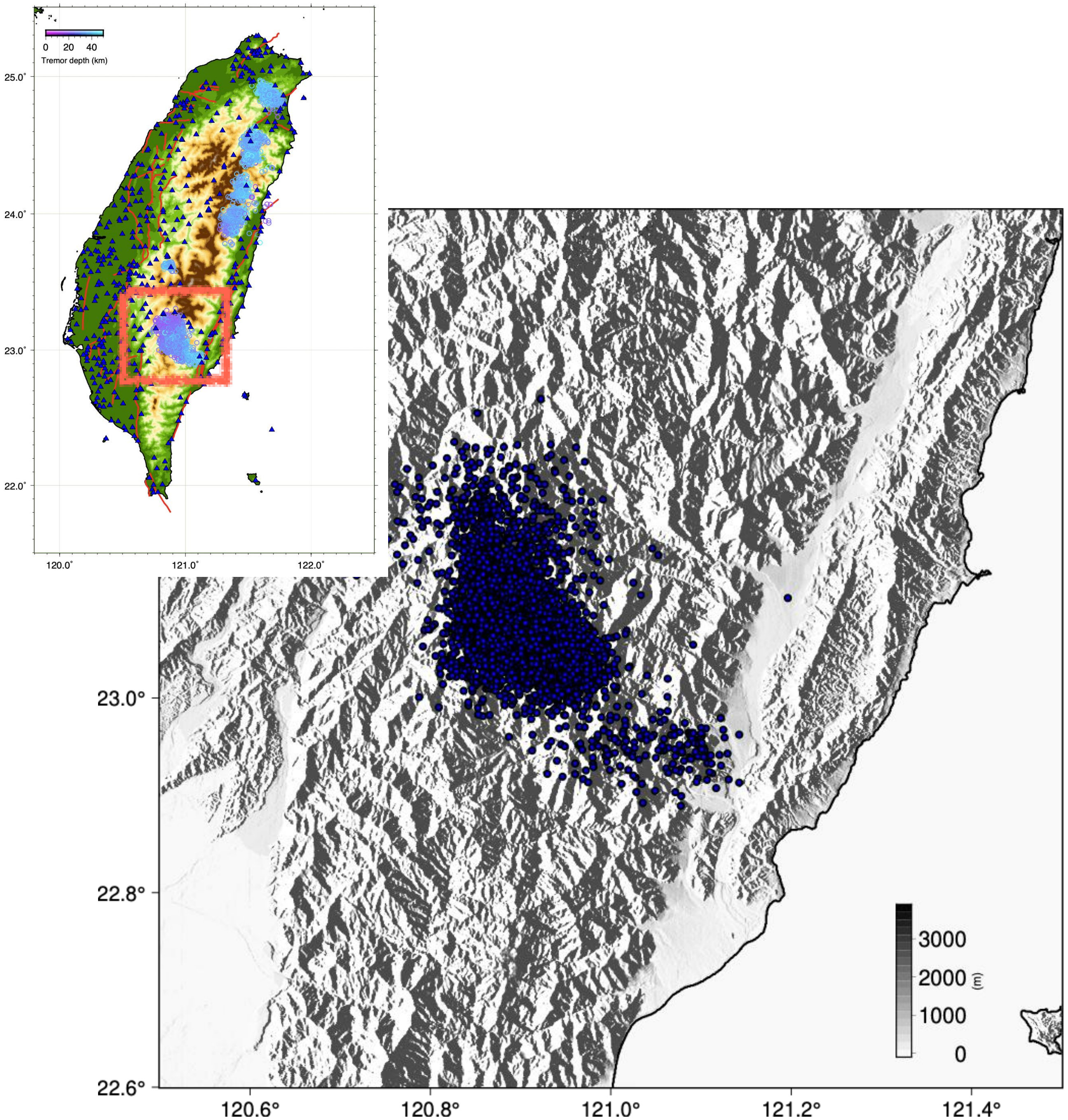


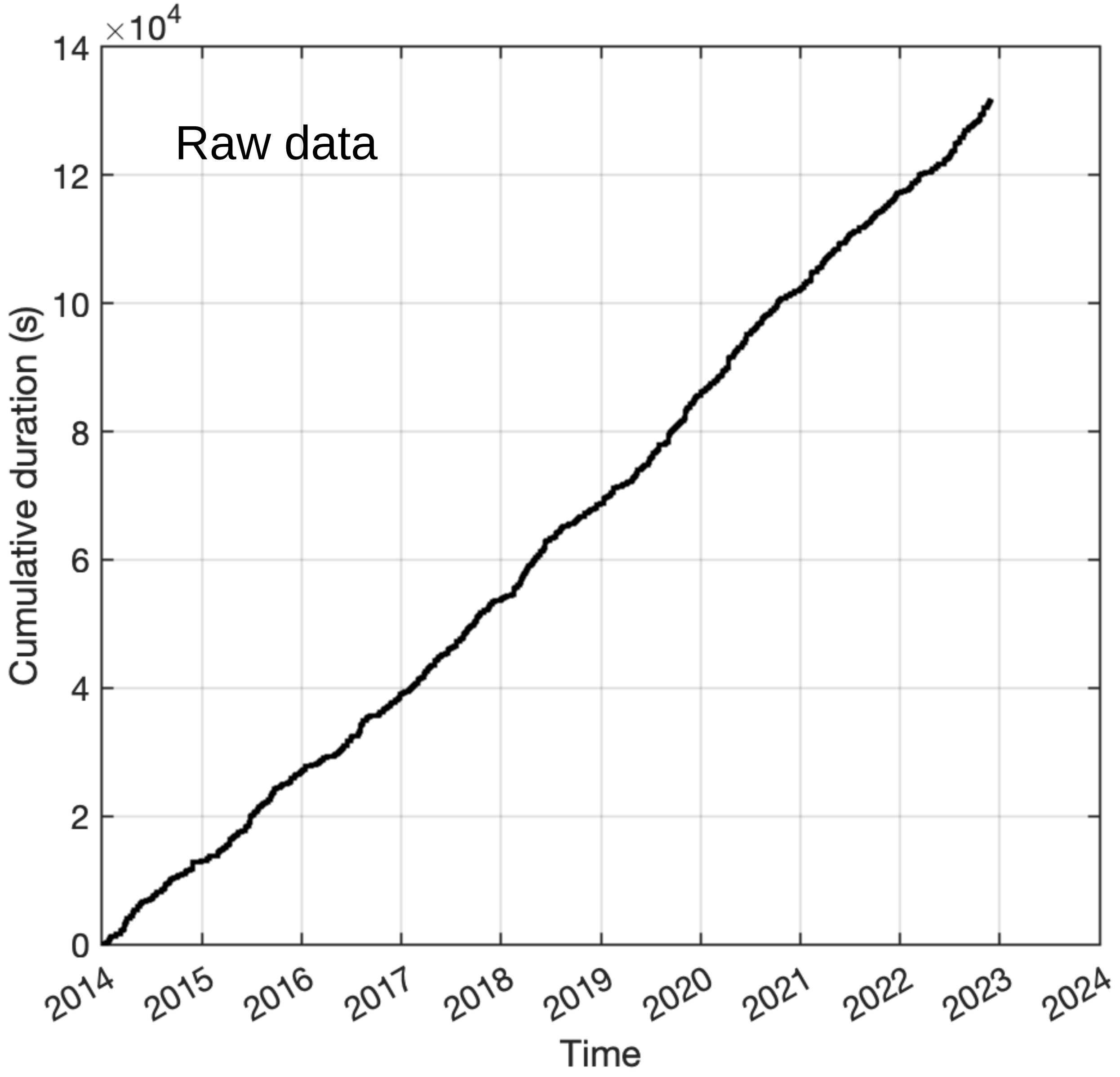
Slow slip events in Taiwan are difficult to identify because…

GNSS signal is usually contamination from other noise.

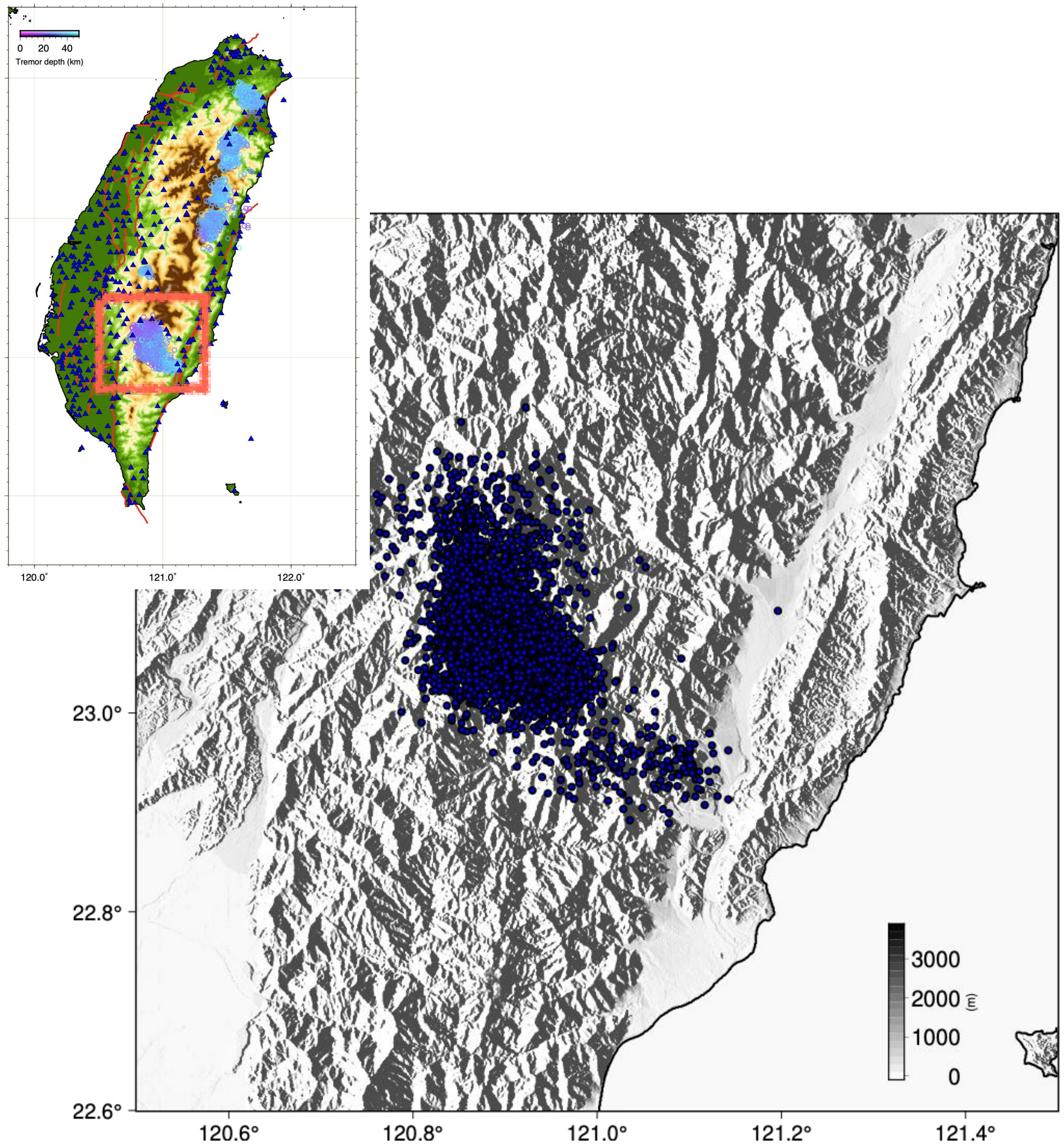


Tremor burst identification : searching enhanced tremor activity

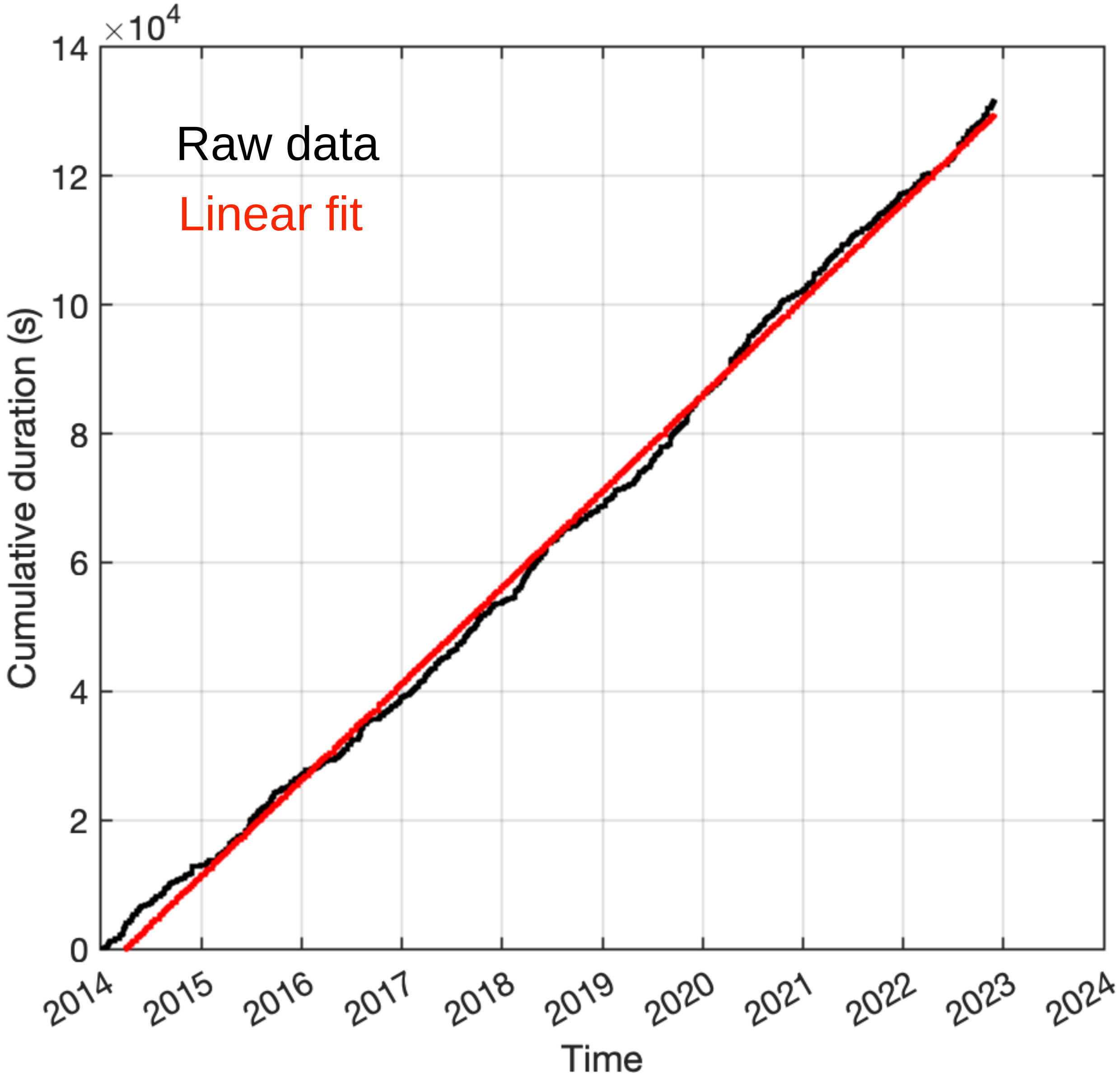




Tremor burst identification : searching enhanced tremor activity



Identified tremor burst by selecting the days when daily tremor duration ≥ mean daily duration



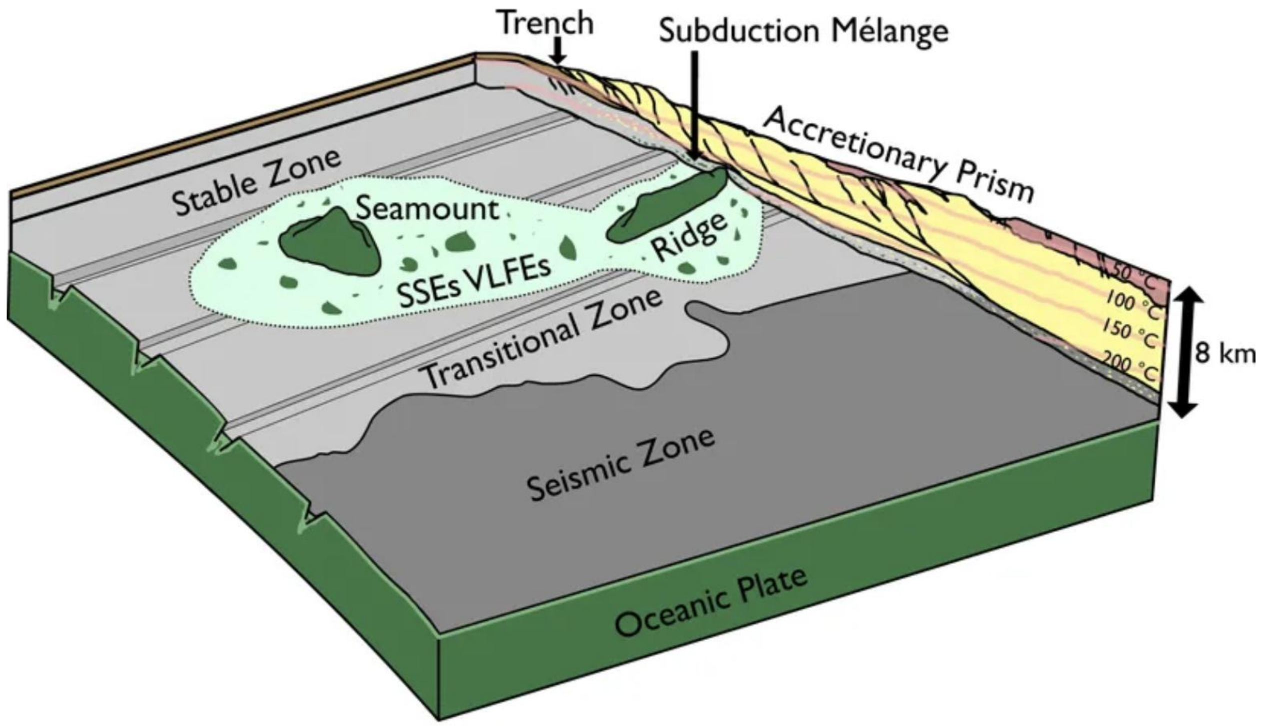
Possible mechanism of slow earthquake

Material rheology : Depth-dependent variability, elastic stiffness (Leeman et al., 2016)

Geochemical process : Pressure resolution (Richard et al., 2014)

Pore fluid press : Metamorphic dehydration, porosity evolution (Peacock,2004; Audet and Burgmann, 2014)

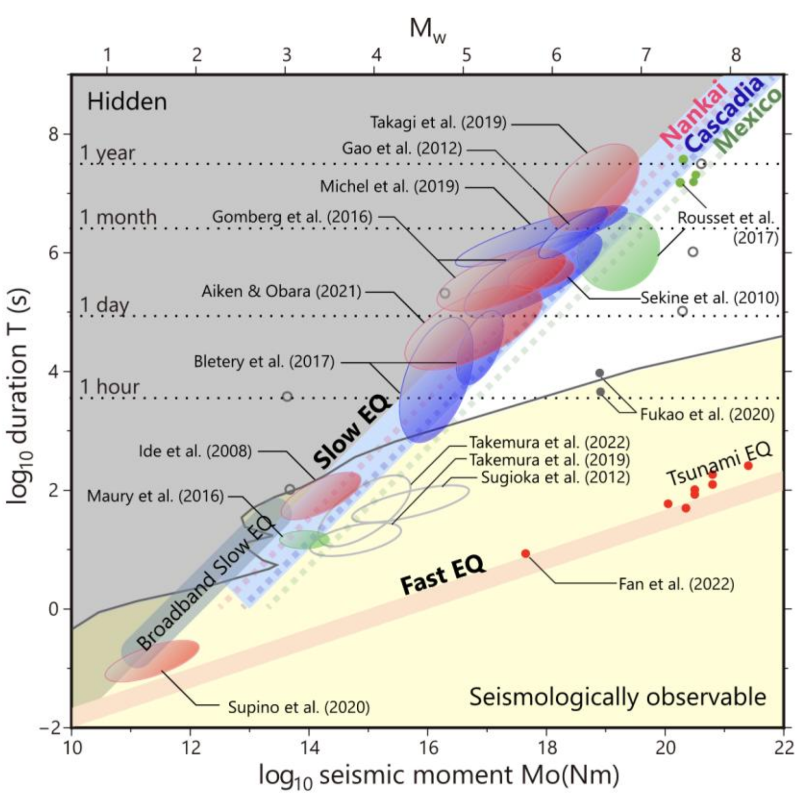
Frictional properties : Velocity-weakening/Velocity-strengthening (Ikari et al., 2013)

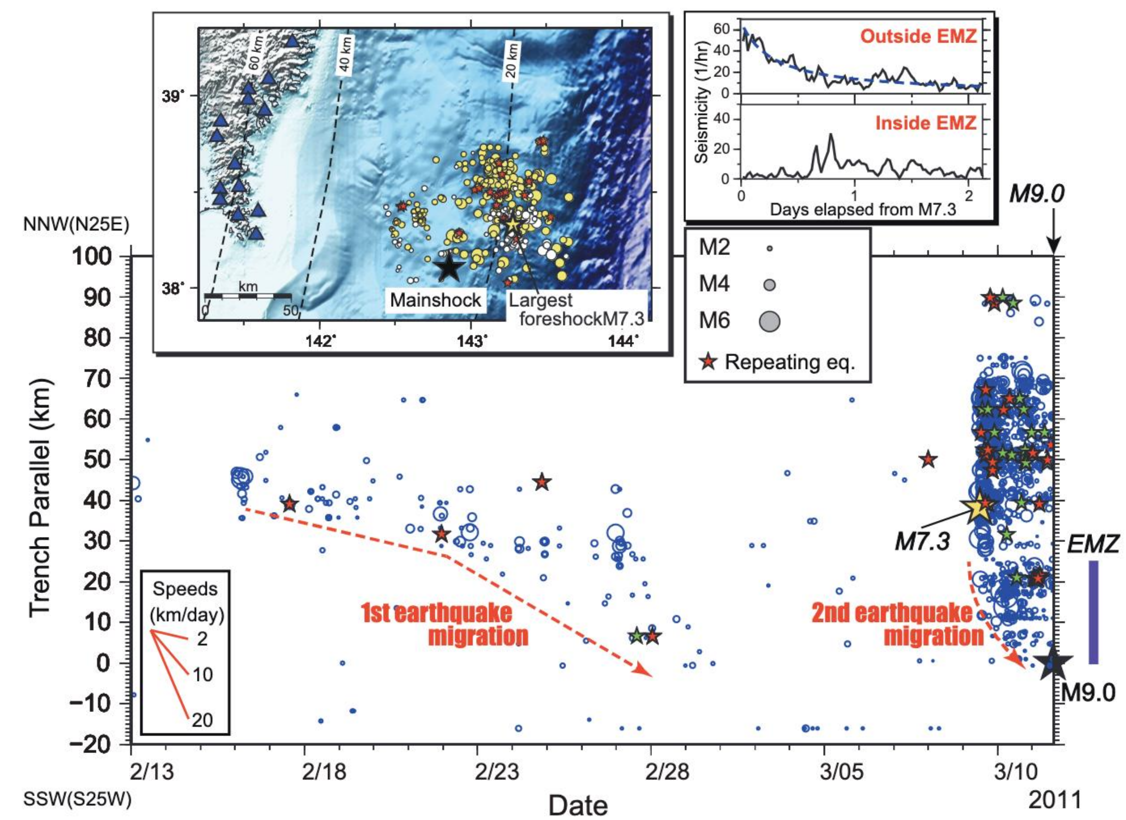


Phillips et al. (2020)

Why do we care ?

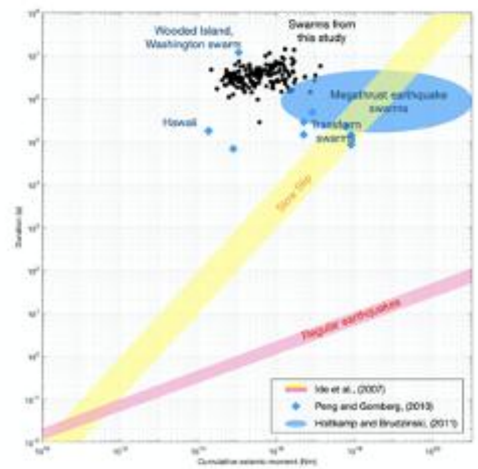
1. Release energy could be equal as Mw ≥ 7 earthquake
2. Some of the slow earthquakes are associated with following large event
3. Very sensitive to small stress perturbation





Kato et al. (2011)

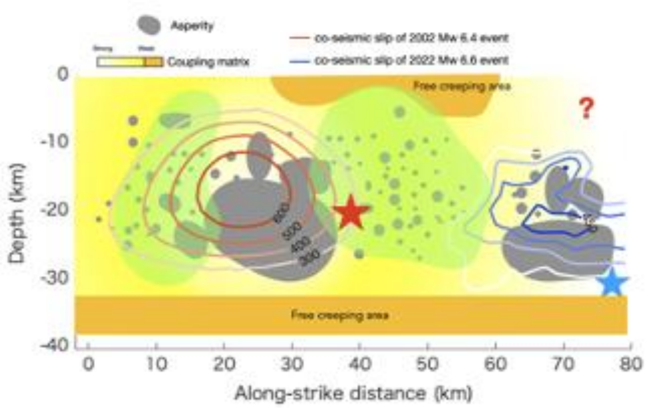
Main research topic :
What and How can we enhance the estimation of seismic hazard?



Previous works:

For aseismic detection (earthquake swarm) :

Using a composite statistical declustering method for swarm detection and its possible mechanism. We found that the possible mechanism for generating earthquake swarm in Taiwan might be dominated by aseismic slip.

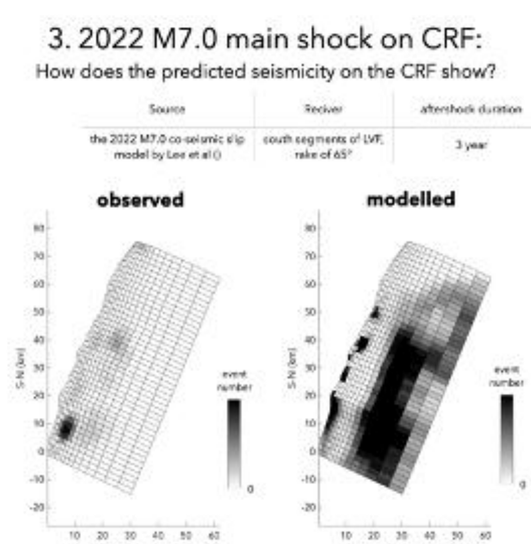


For interseismic slip inversion (geodesy + repeating earthquake) :

We developed a new static inversion method to adopt repeating earthquake data into the slip inversion and established a conception model of Chihshang fault for the future hazard estimation.

For rate/state friction model (Central Range fault, Longitudinal Volley fault)

We found that the 2022 triggering case may require the afterslip on the LVF, to prohibit the triggered of seismicity. This could be further established using post-seismic slip model.



Future research topic :
How the occurrence of slow earthquake affects the earthquake cycle ?

Main questions :

1. How to define statically the spatiotemporal characteristic of aseismic slip on eastern Taiwan?
2. How does the stress evolution of aseismic slip affect the seismic potential of Central Range fault?

Propose works :

1. Employ a machine learning approach to identify the spatiotemporal characteristics of aseismic behavior in Taiwan.
2. Investigate the presence of significant transient slip during tremor activity using GNSS data.
3. Assess the potential stress impact of aseismic behavior on the seismic cycle of the Central Range fault and Longitudinal Valley fault