台灣慢地震的觀測
Unlock the secrets of slow earthquakes in Taiwan?

陳卉瑄

國立臺灣師範大學 地球科學系

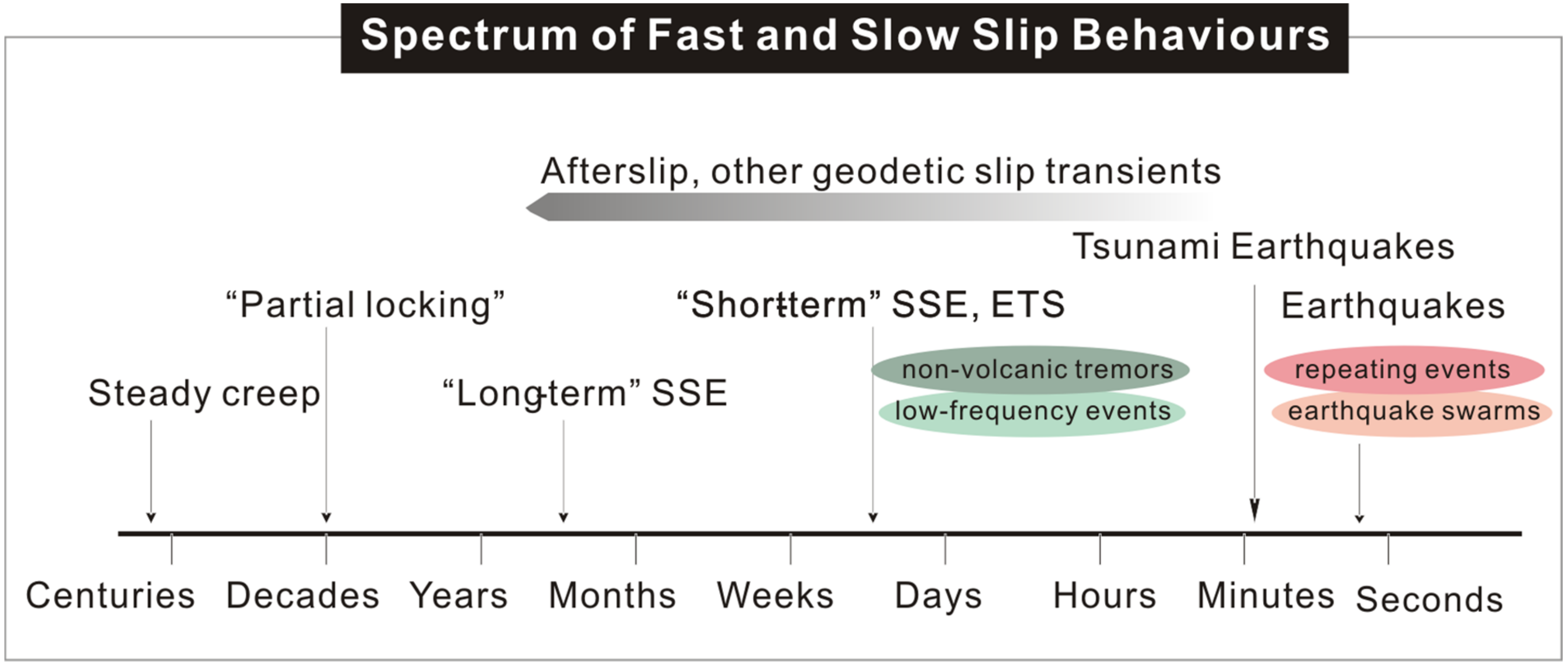
莊育菱、戴心如、萬晉宇

彭葦、呂莛鈺、葉庭禎

葉庭禎，2010，台灣地震與長微震之動態誘發，國立台灣大學地質科學所碩士論文。
莊育菱，2012，台灣非火山長微震半自動化偵測系統，國立台灣師範大學地科學所碩士論文。
呂莛鈺，2012，非火山低頻群震之時空特性，國立台灣師範大學地科學系專題。
彭葦，2012，中央山脈下方群震和長微震的時空相關性，國立台灣大學地質科學系。
戴心如，2013，長微震活動周期與潮汐力的相關性研究，國立台灣師範大學地科學系專題。
萬晉宇，2013，台灣非火山長微震訊號之頻率特徵分析，國立台灣師範大學地科學系專題。
Chung

Slow earthquakes

- 近年來在孕震區更深部的下部地殼，慢滑移事件(slow slip event)和長微震事件(tremor)的發現，將我們對斷層活動方式的理解推入了新紀元。這種活動介於一般地震數十秒的快速破裂、和數年的緩慢蠕變(creeping)之間，稱為慢地震(slow earthquake)。

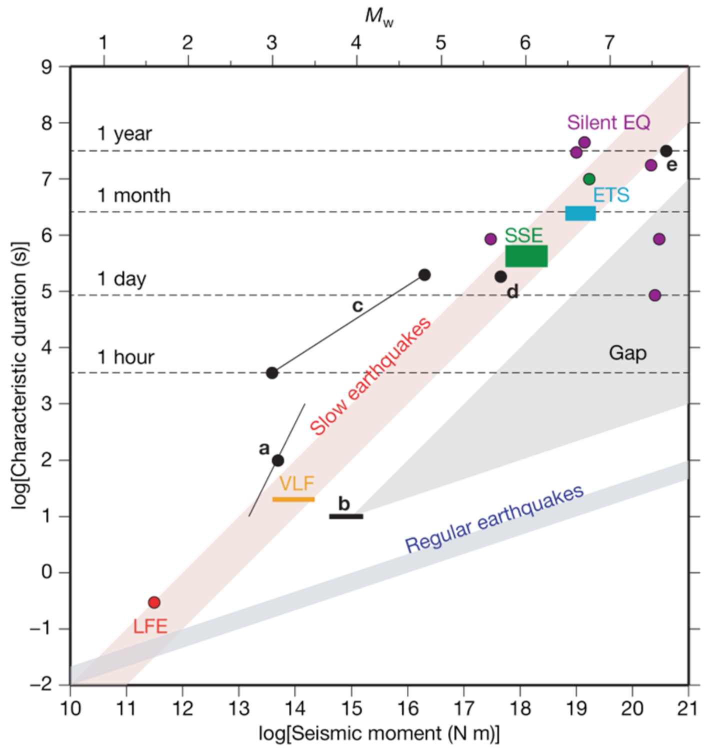


- (Modified from Kelin Wang, 2010, Investigating thermal tectonic conditions for ETS and similar events)

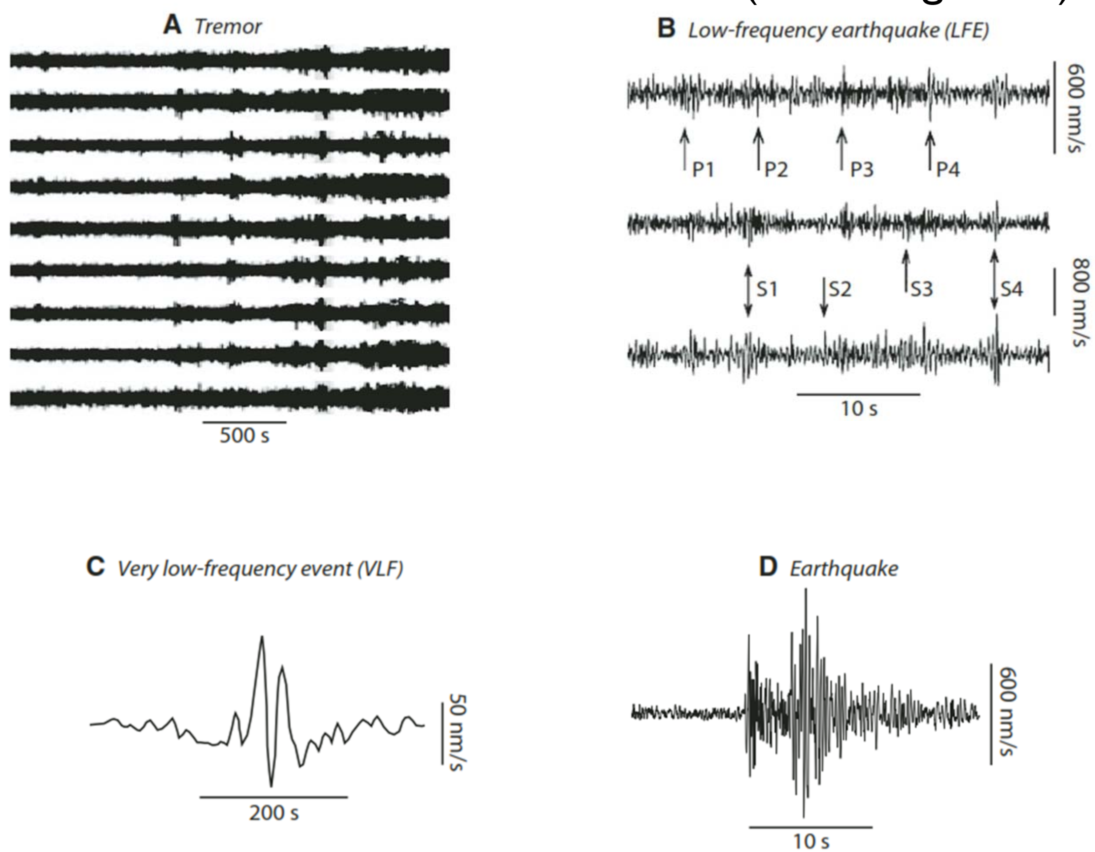
Slow earthquake family

- 他們發生的深度和一般地震不一樣
- 由地震波特徵，他們有不同的存在形式(持續時間、頻率)
- 但是，不同型態的慢地震其地震矩和持續時間有相同的線性關係。

(Gomberg, 2010)

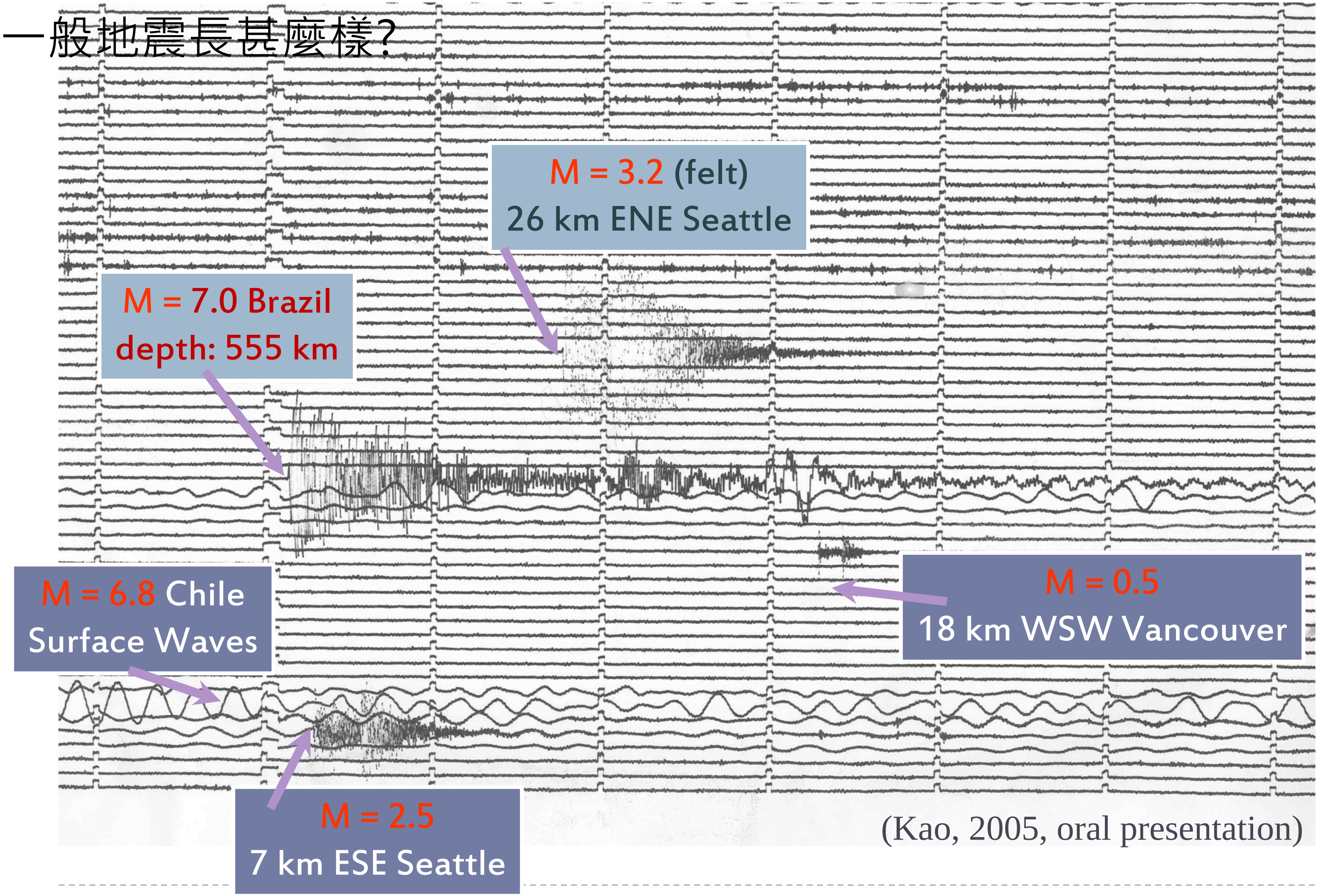


(Ide et al., 2007)



Ordinary earthquake records

一般地震長甚麼樣?

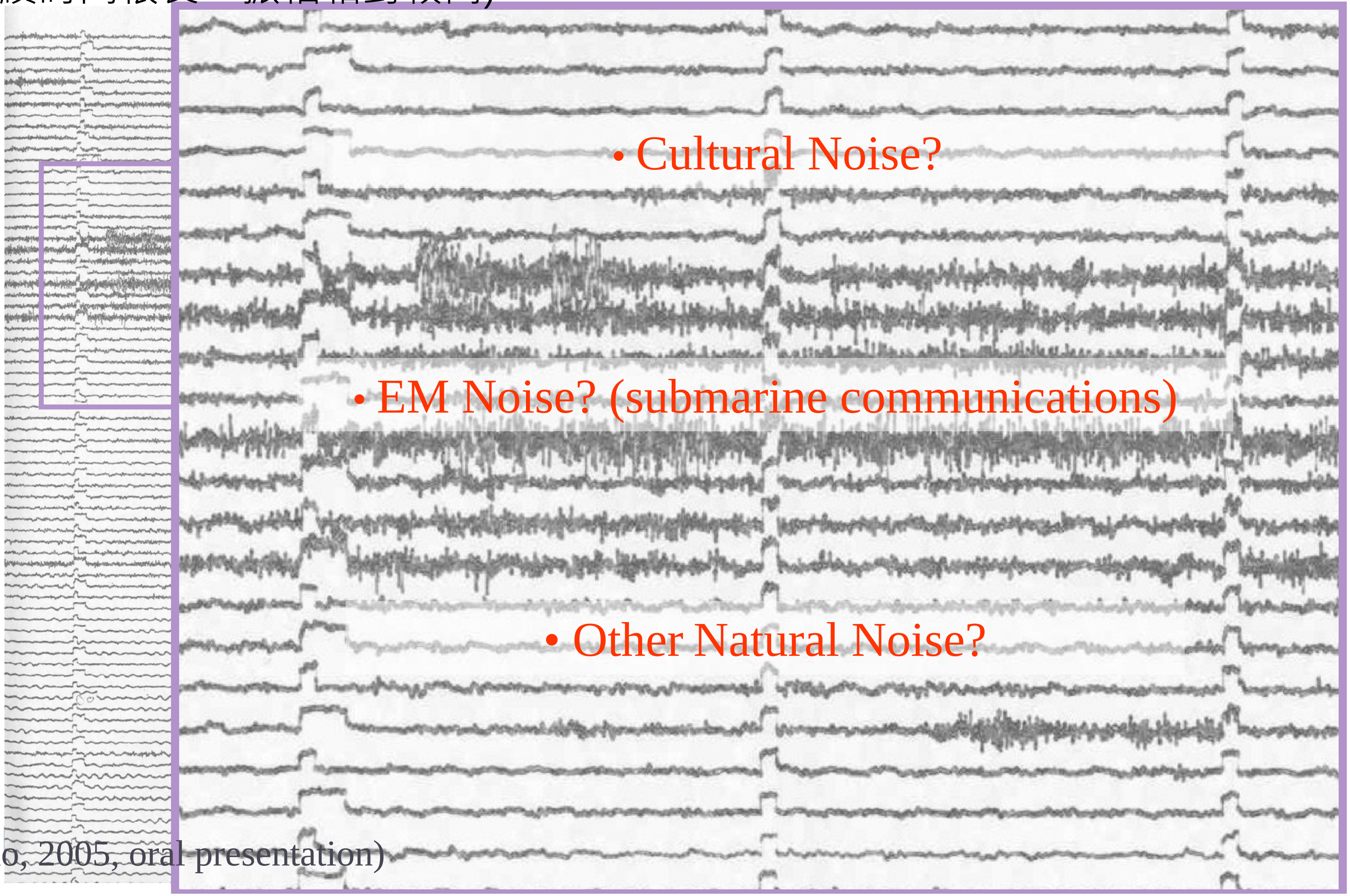


(Kao, 2005, oral presentation)

- *Typical earthquake signals observed at PGC station*

Long-lasting, large amplitude "Noise"

在連續紀錄中，事實上埋著特殊的雜訊
(持續時間很長、振幅相對較高)

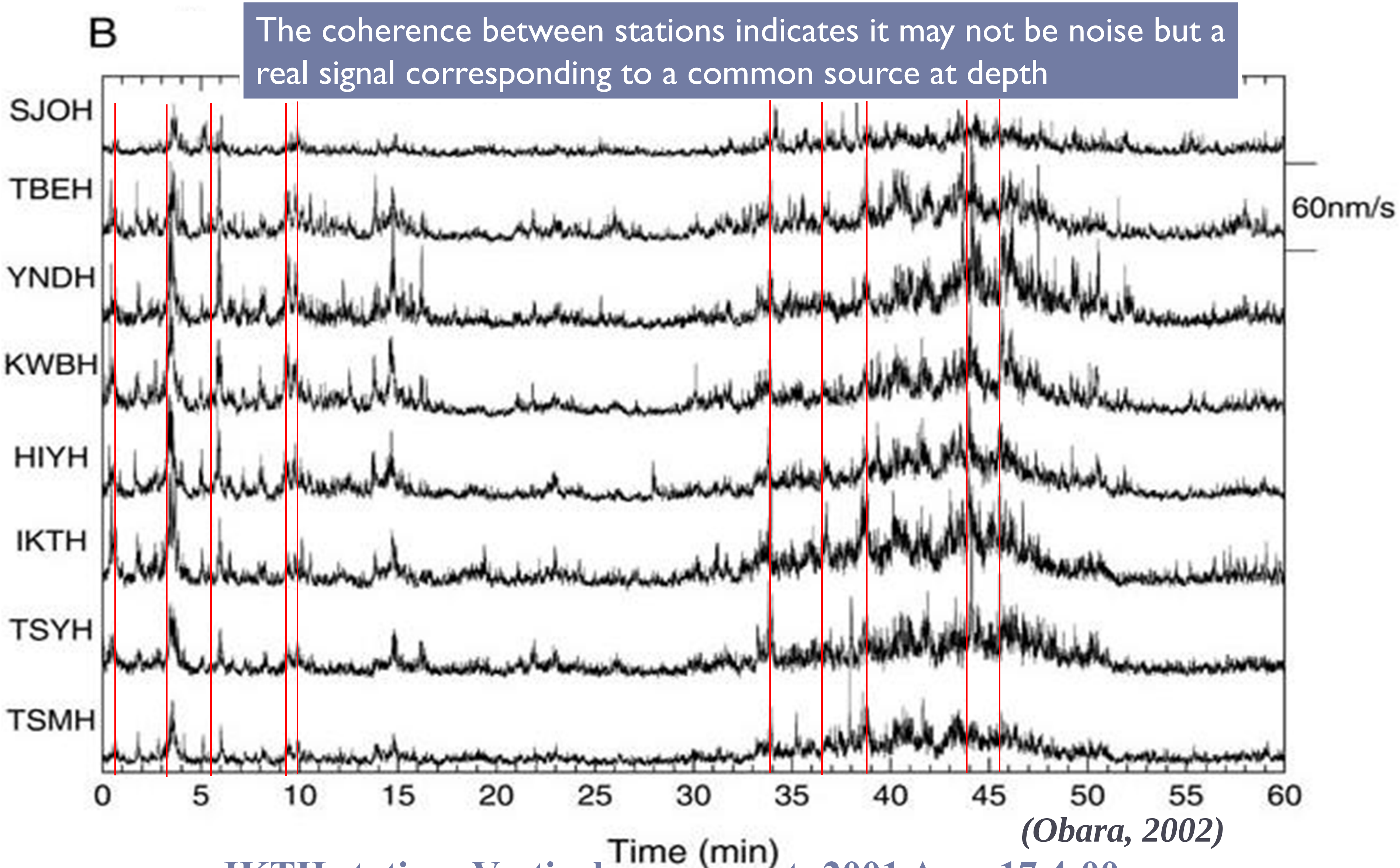


(Kao, 2005, oral presentation)

The noise-like signals turn out to USEFUL

這些特殊雜訊，竟然在不同測站具有一致到時!

The coherence between stations indicates it may not be noise but a real signal corresponding to a common source at depth



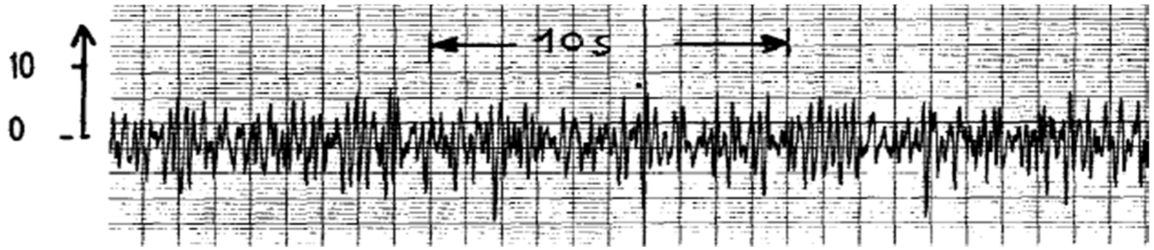
(Obara, 2002)

IKTH station; Vertical component; 2001 Aug. 17 4:00 am

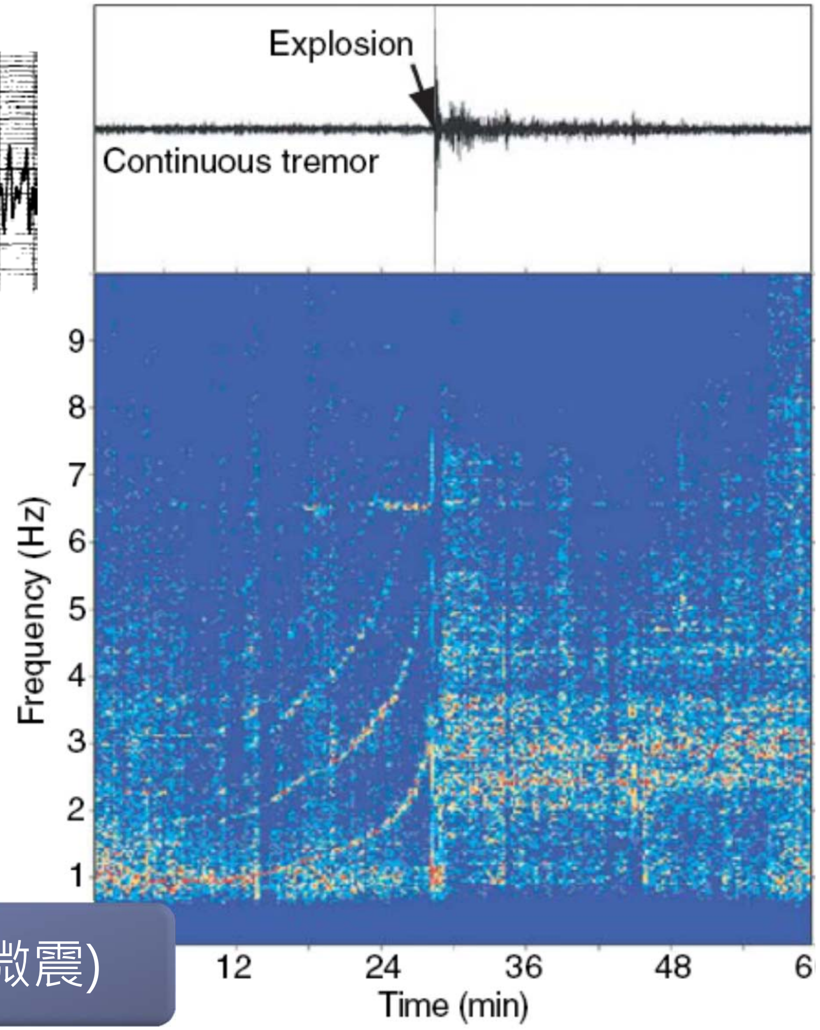
Similar feature with volcanic tremor

其波形特性和火山地區常見的tremor(長微震)類似

At volcanoes, more or less continuous ground vibrations often occur, called "volcanic tremor", which is an important indicator of volcanic activity.



(Schick,1988)



Persistent seismic signal that is observed only near active volcanoes, lasting from several minutes to several days, preceding and/or accompanying most volcanic eruptions

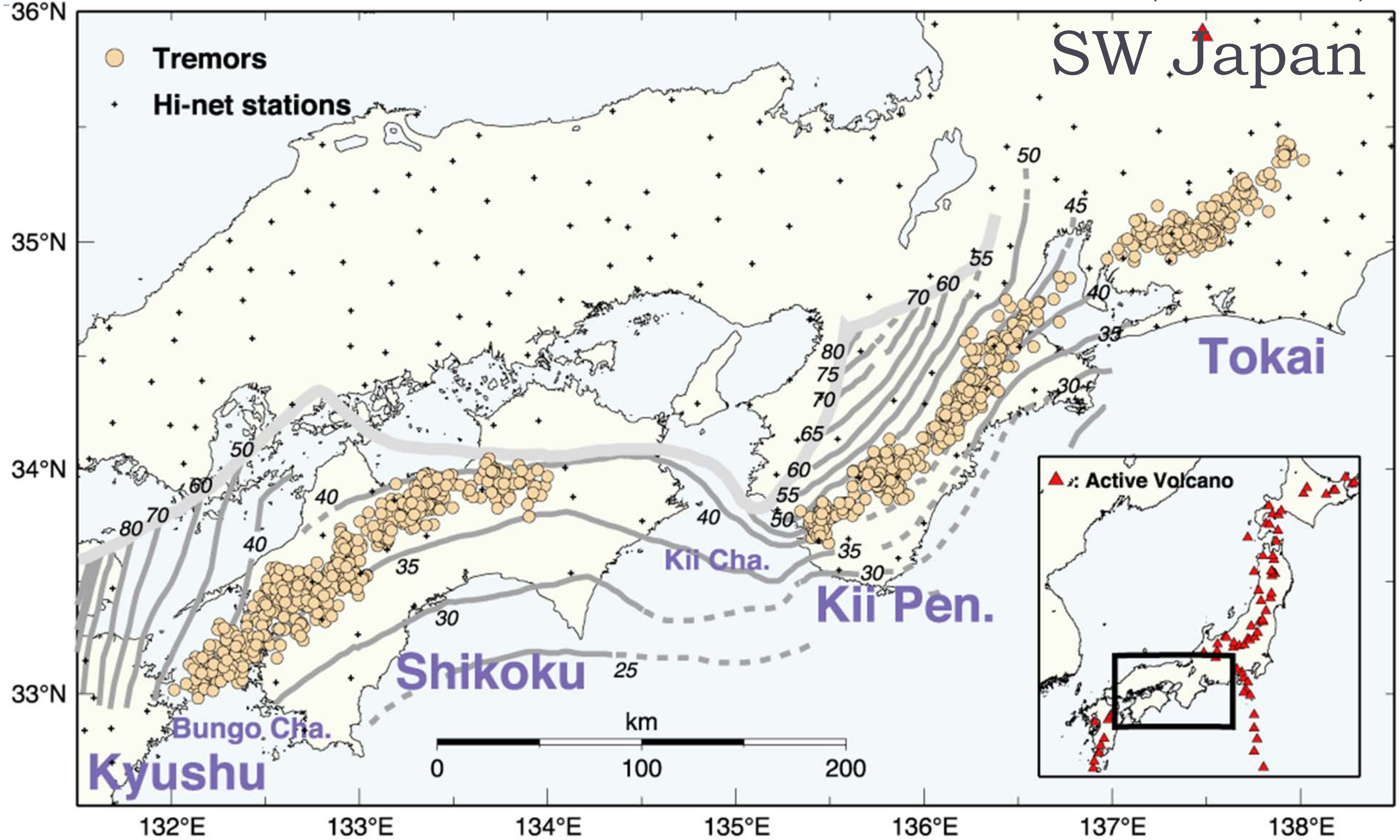
(Fehler, 1983; Julian, 1994; Ripepe, 1996; Me.taxian et al., 1997).

因此命名為non-volcanic tremor(非火山長微震)

Spatial distribution of tremors

定位後，這些*似雜訊源*在空間上有規則的分布

(Obara, 2002)



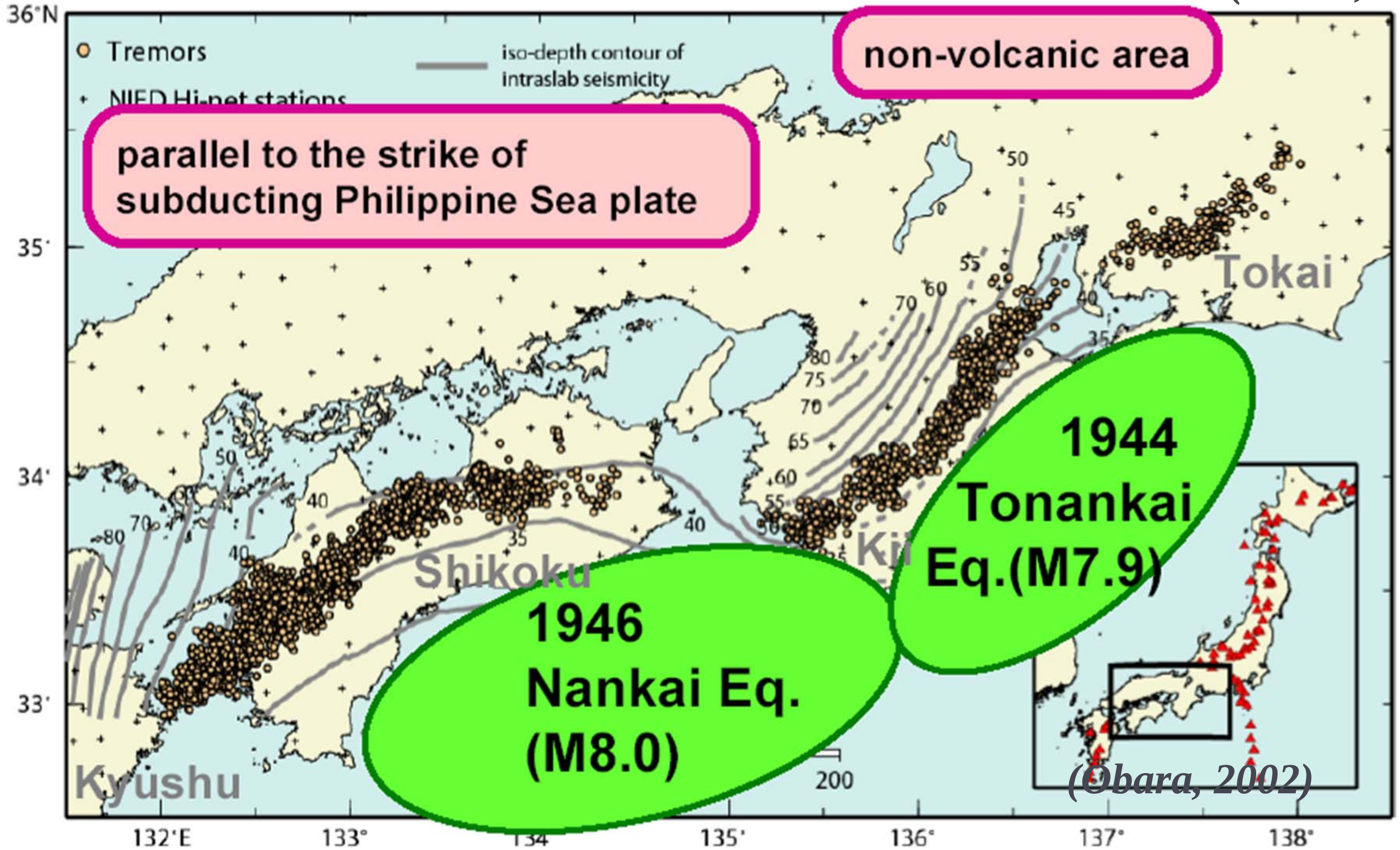
The shape and position agreement → the vibrations are of tectonic origin.

Wide source area over 600 km in length (along-strike, underneath the seismogenic zone)

平行於海溝排列，表示這個*似雜訊源*有構造上的起源

長微震發生在孕震帶更深處

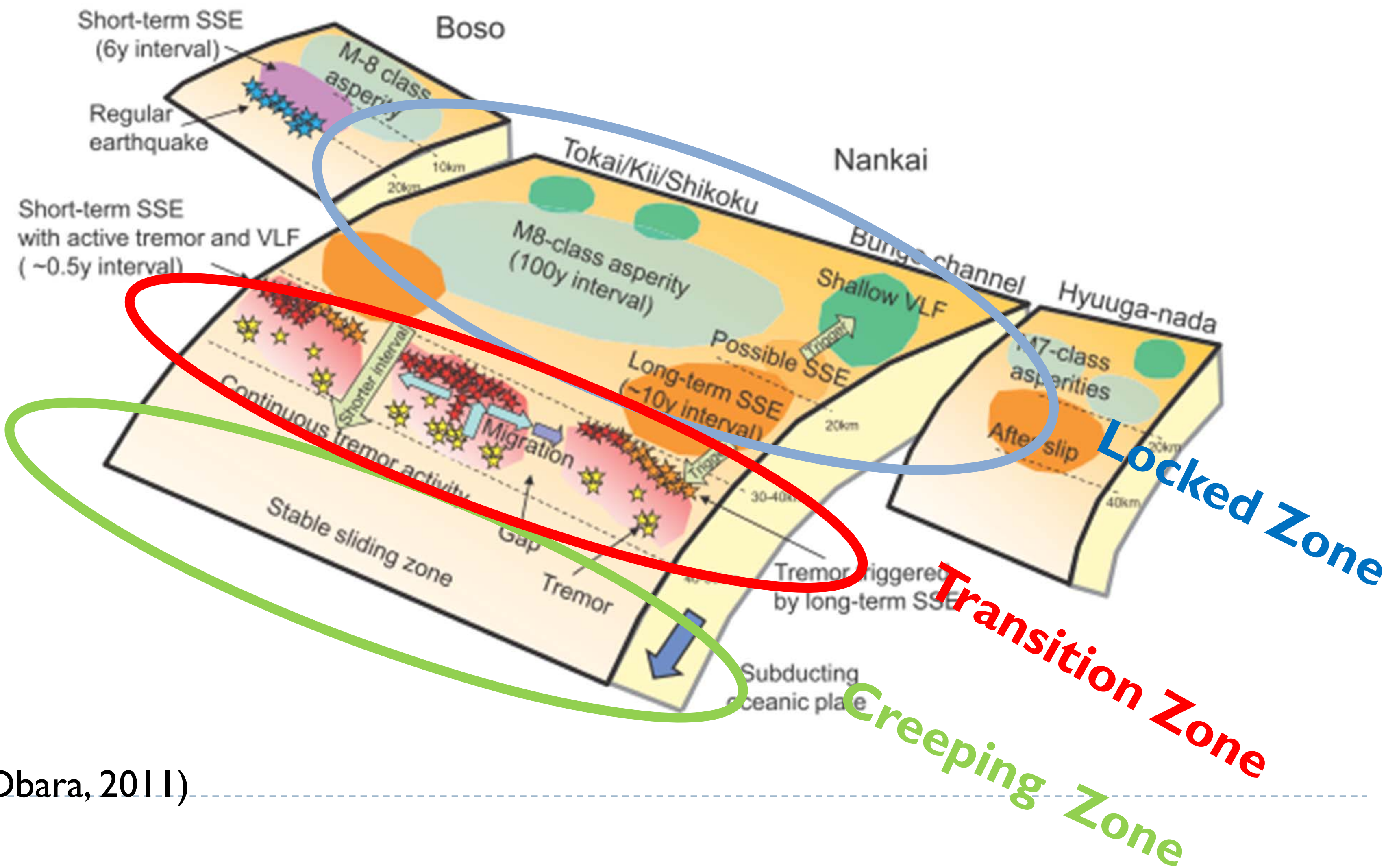
(Obara, 2002)



- Tremors are located at the deeper part of the slip distribution of megathrust earthquakes, therefore they might reflect a part of the subduction process.

Non-volcanic tremor

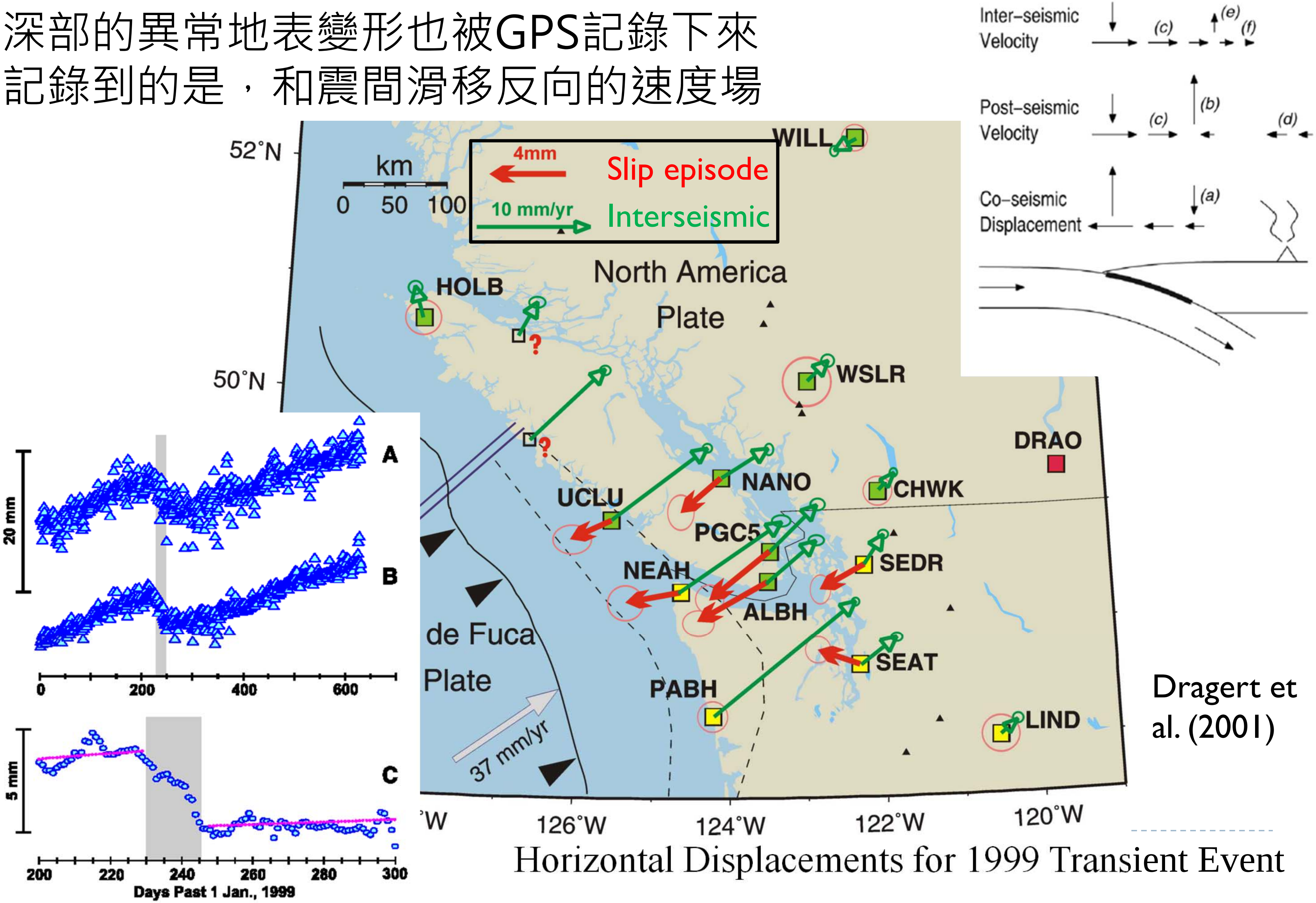
The deep-seated, non-volcanic tremors serve as an indicator for slow slip below the base of the seismogenic zone



(Obara, 2011)

Slow slip event

深部的異常地表變形也被GPS記錄下來
記錄到的是，和震間滑移反向的速度場



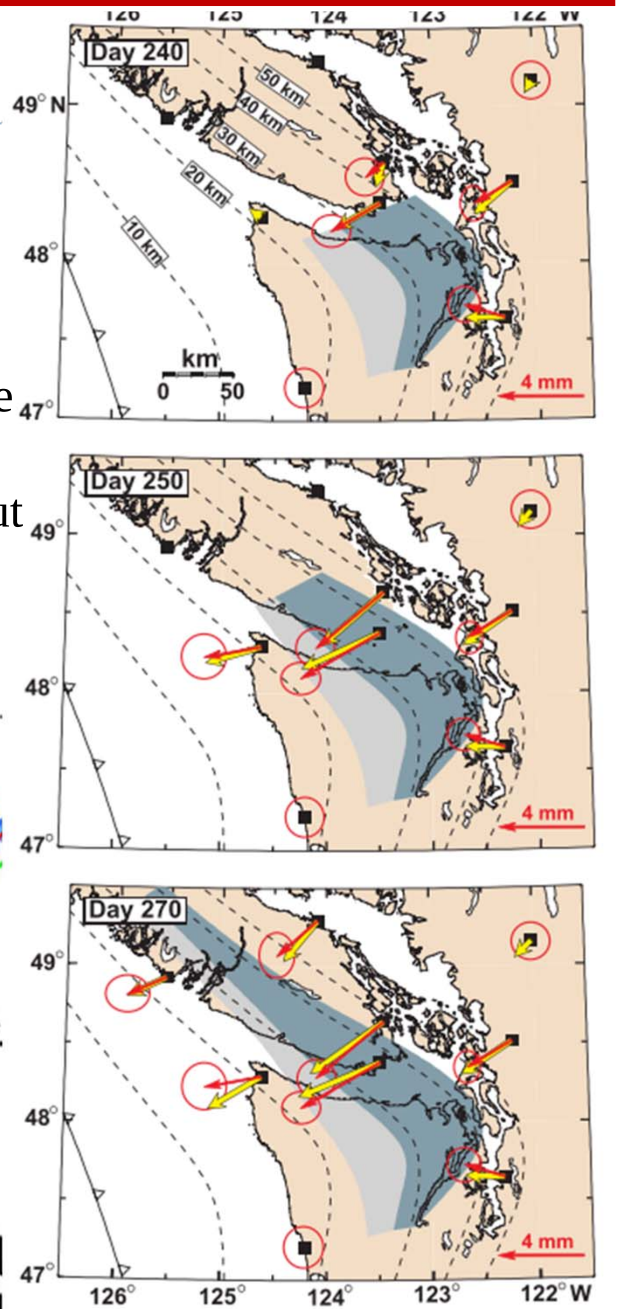
Horizontal Displacements for 1999 Transient Event

Dragert et al. (2001)

Slow slip event

在深部必須要有滑移事件的發生，才能產生地表反向速度場

- ★ signal propagation parallel to the strike of the sunduction slab (6km/day)
- ★ These brief reversals can be explained by slip on the deep Cascadia subduction fault, 20 to 40 km below the surface of the Earth
- ★ These slip events occur at surprisingly regular intervals of about 14 month

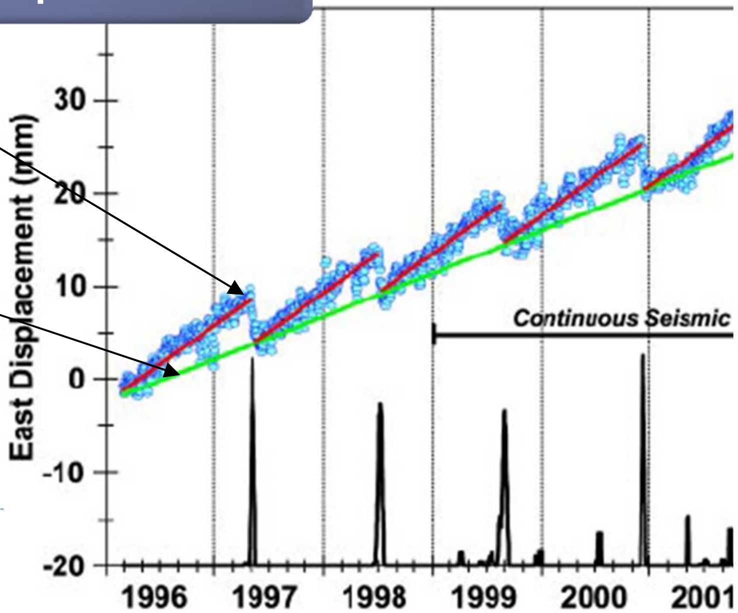


Tremor and slip 同步

East component of the GPS site ALBH

Inter-seismic eastward motion of the site

Total number of hours of tremor activity



Dragert et al. (2001)

Non-volcanic tremor | Slow slip event

時間、空間上同步，證實了兩種觀測可能描述著同一物理現象:
慢速滑移行為(慢地震)

Tremor and slip 發生在同一斷層嵌塊上(fault patch)

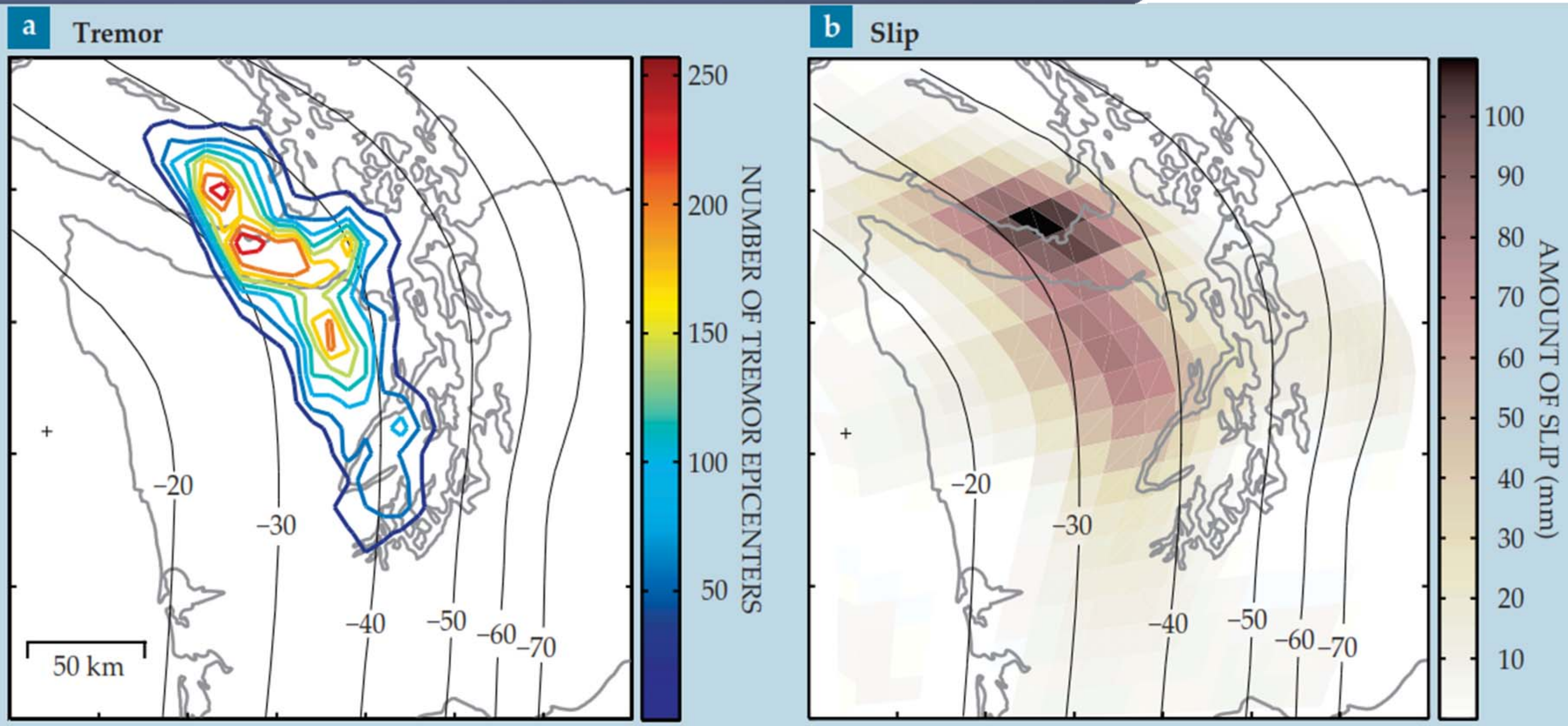
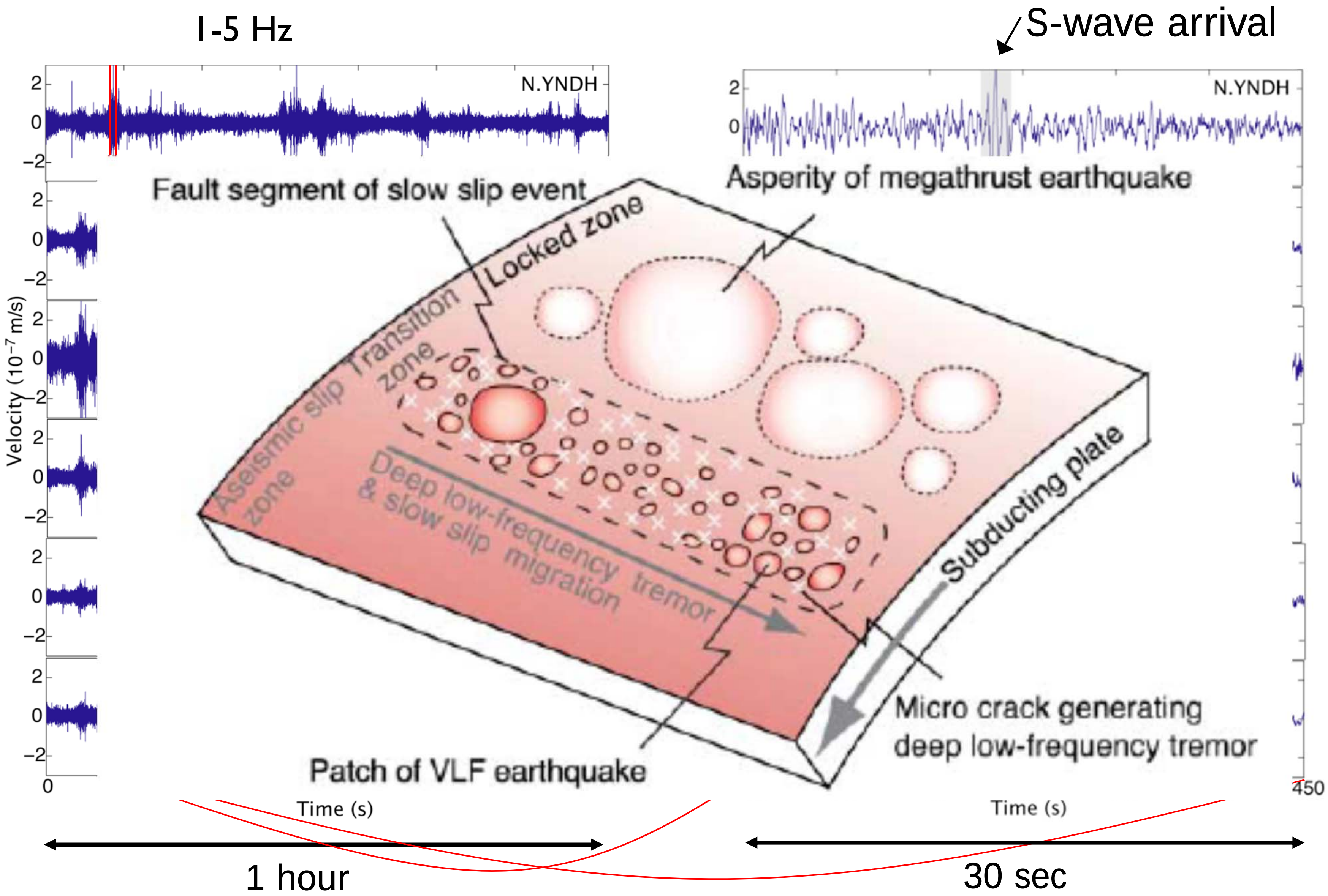


Figure 2. Tremor and slip are usually observed on the same patch of fault during a slow-slip episode. **(a)** Tremor, observed by seismometers and quantified as the number of tremor epicenters per 0.1° × 0.1° bin, summed over four slow-slip episodes in the Cascadia subduction zone from 2004 to 2008. **(b)** Total slip, measured by GPS, for the same four episodes. The contours in both panels show the depth of the plate interface. (Adapted from ref. 15.)

(Vidale and Houston, 2012)

Non-volcanic tremor | Slow slip event



the signal is indeed weak, but that the S-wave arrivals are visible.

Why slow slip events important?

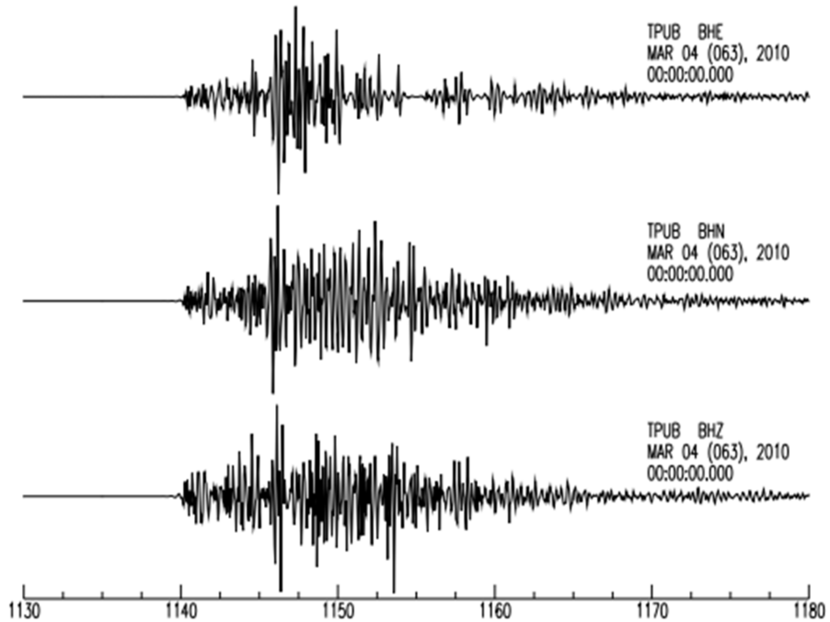
- **The moment magnitude of event can go up to M6.7** (Dragert et al., 2001)
- **Slow slip events are found to lead up LARGE EARTHQUAKE**
- **Very sensitive to small stress changes, therefore can be used as an indicator of temporal change in crustal property before/after big quake**

Importance of tremor & its characteristics

在GPS無法解析時，可能的慢速滑移事件，就依賴tremor的發現和分析!

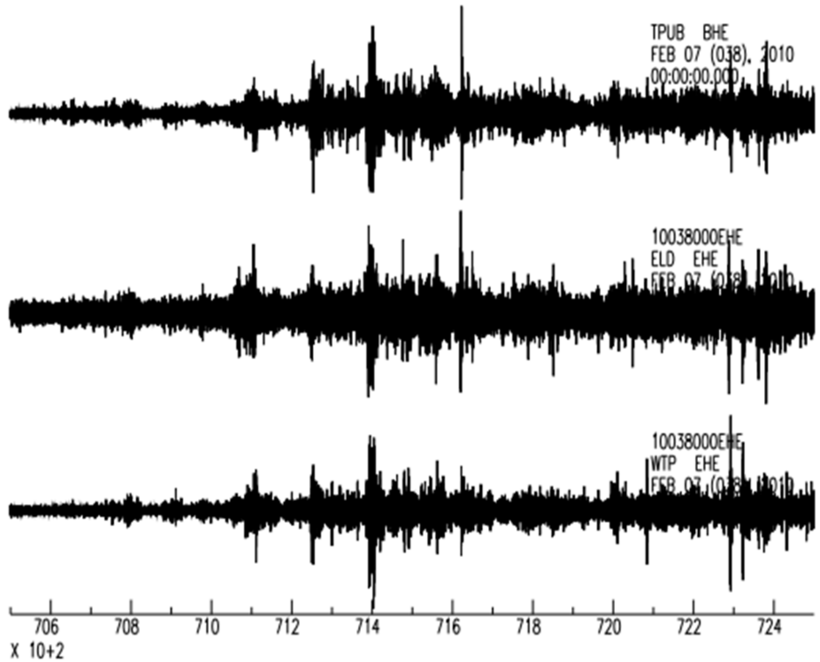
(1) 貌似雜訊
(2) 主頻率2-8 Hz
(3)無明顯P波、S波到時
(4)能量持續時間長、數分鐘到數月不等
(5)能在相距數公里至數十公里不等的測站具近乎一致之到時

Ordinary Earthquake



(Ide, 2012) 20s

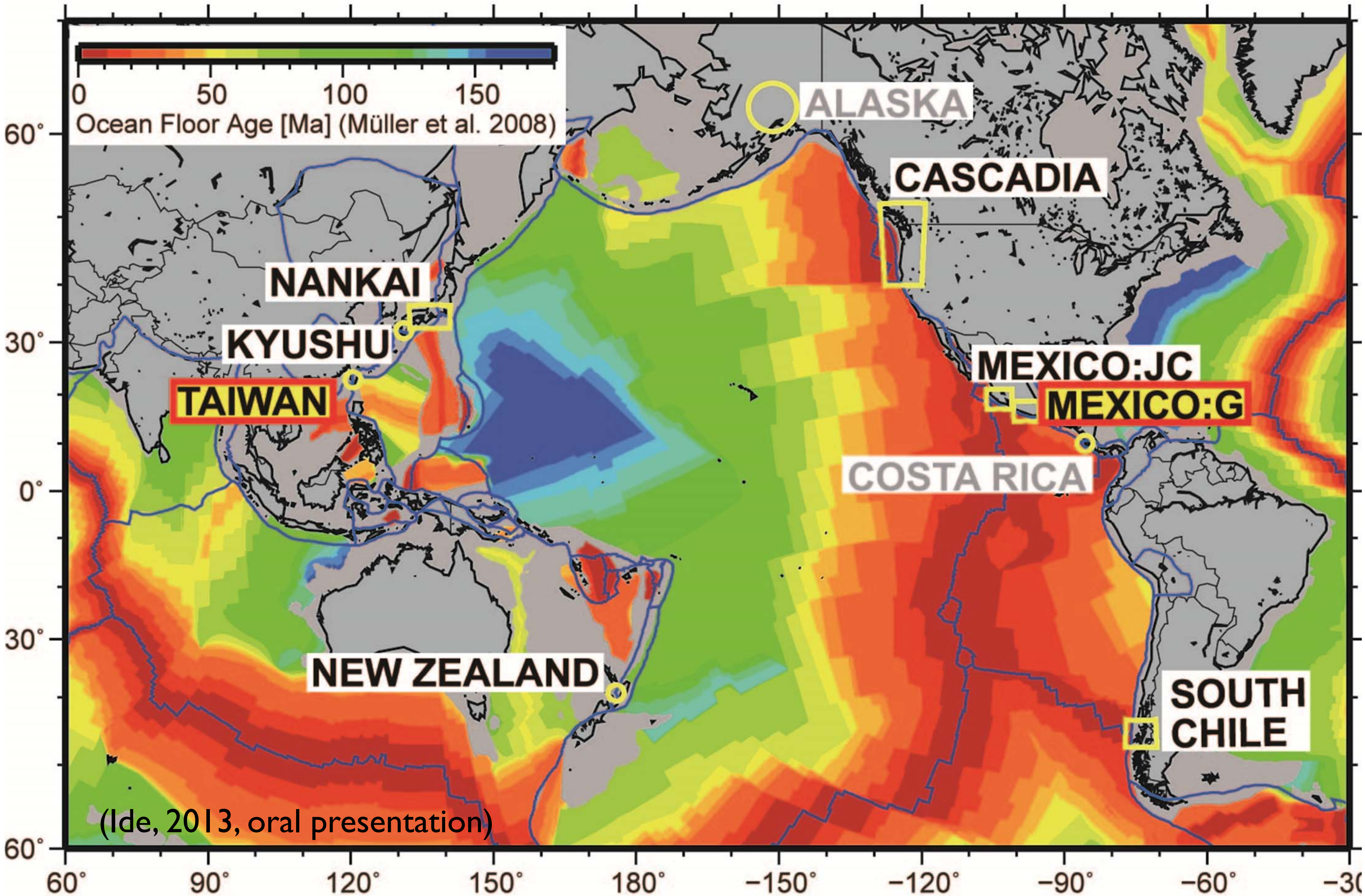
Non-volcanic tremors, NVT



800s

After Ide (JGR, 2012)

Worldwide tremors



(Ide, 2013, oral presentation)

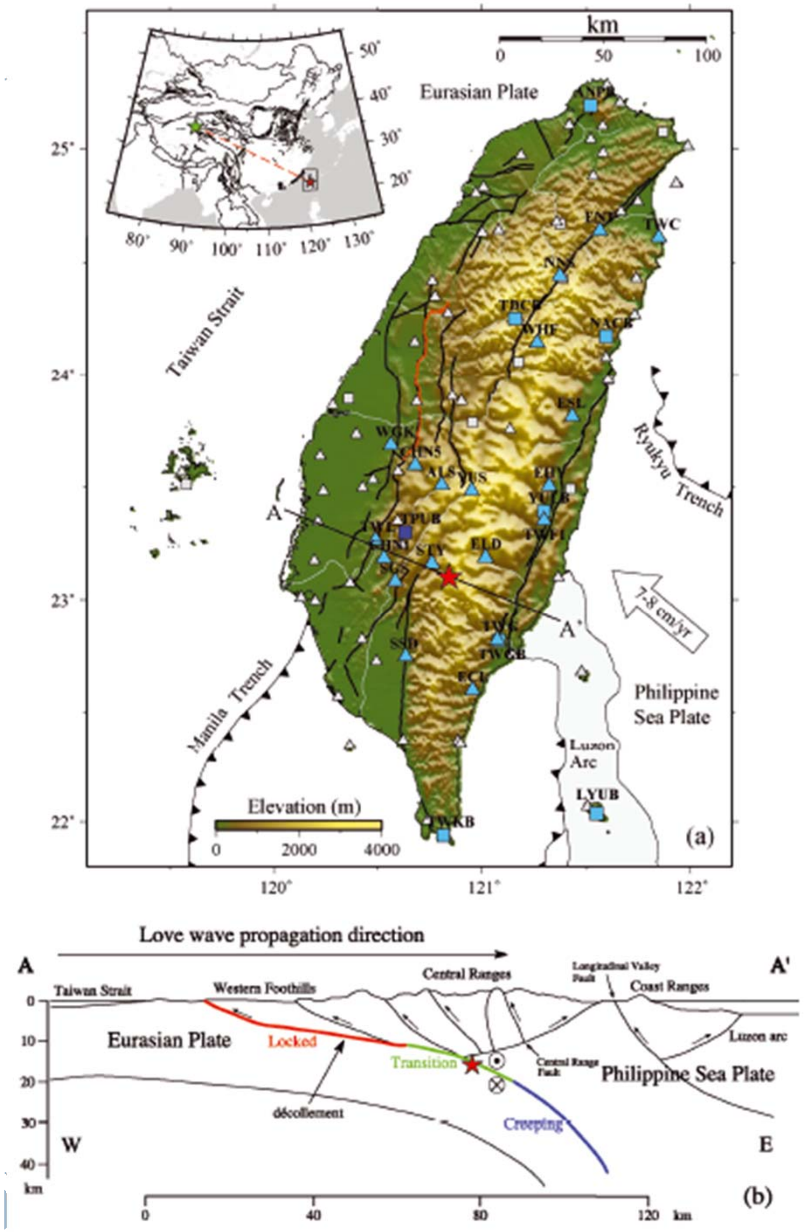
Questions

- **What controls the location of tectonic tremor?**
  - Subduction zone (P-T condition, presence of metamorphic dehydration reaction)
  - San Andreas fault (high pore-fluid pressures at depth)
  - active collisional mountain belts?

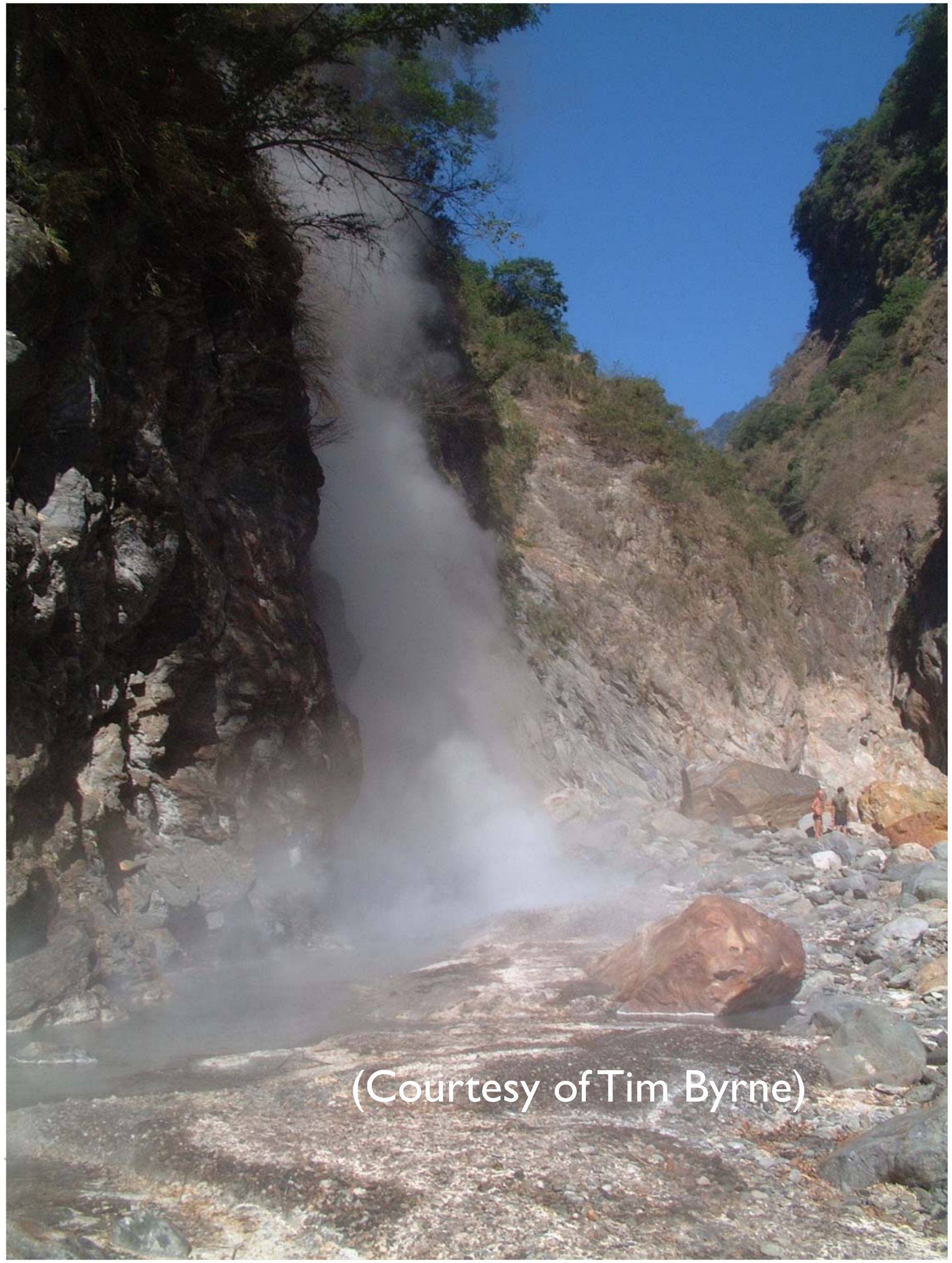
- **What controls their recurrence time?**
  - tremor duration
  - composition of geologic terranes (strength variation)
  - tidal effect

- **What control the timing of their occurrence?**
  - distant earthquakes
  - local major earthquake
  - local seismicity?

Triggered tremors in Taiwan



(Peng and Chao., 2008)

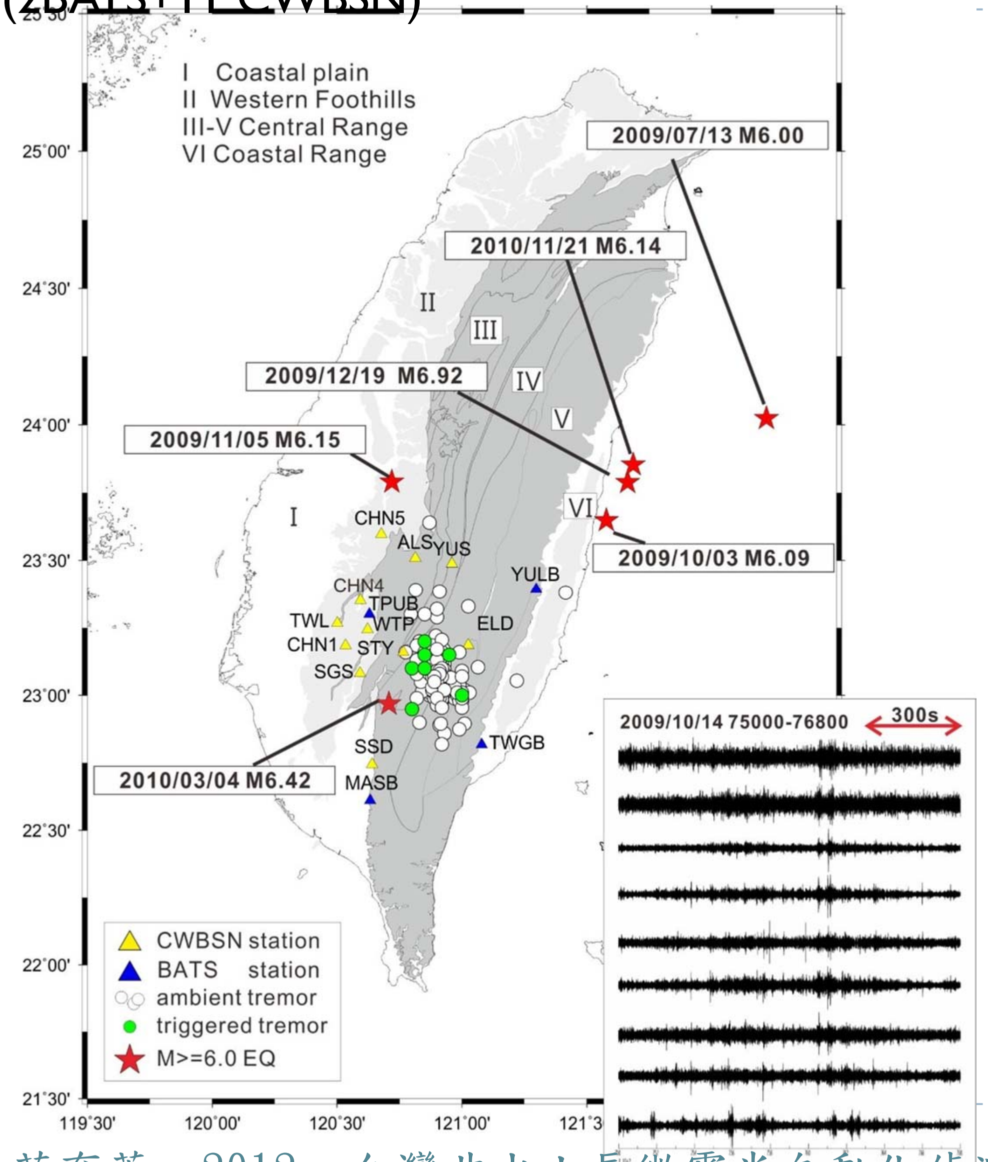


(Courtesy of Tim Byrne)

Ambient tremor in Taiwan

13 stations
(2BATS+11 CWBSN)

自發型長微震自動偵測之建置及分析



Waveform cross-correlation

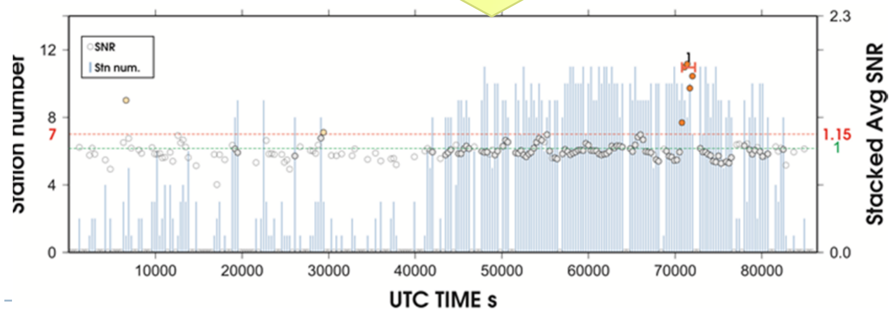
cc> 0.95 at 7+ stations

Signal to noise ratio

SNR> 1.15

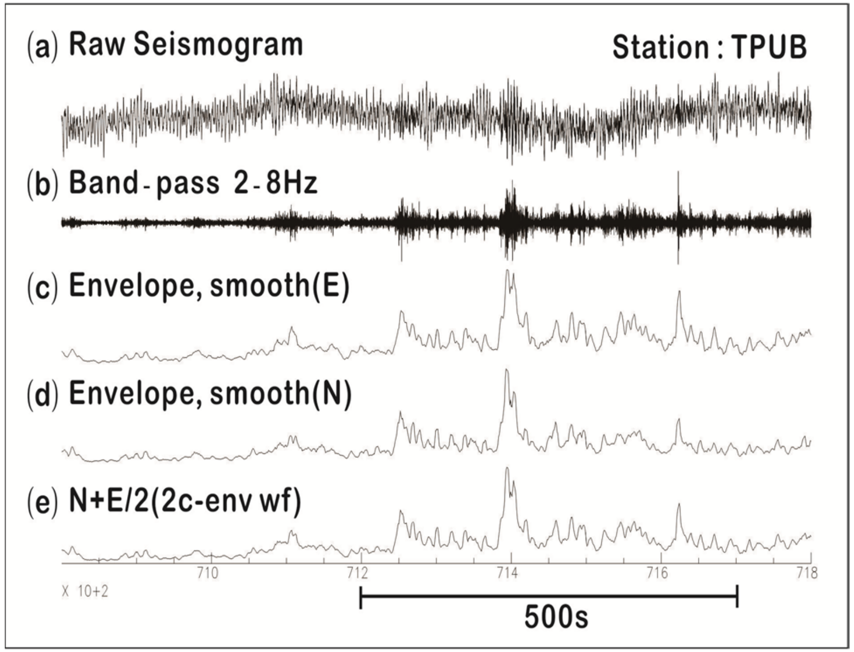
Event duration

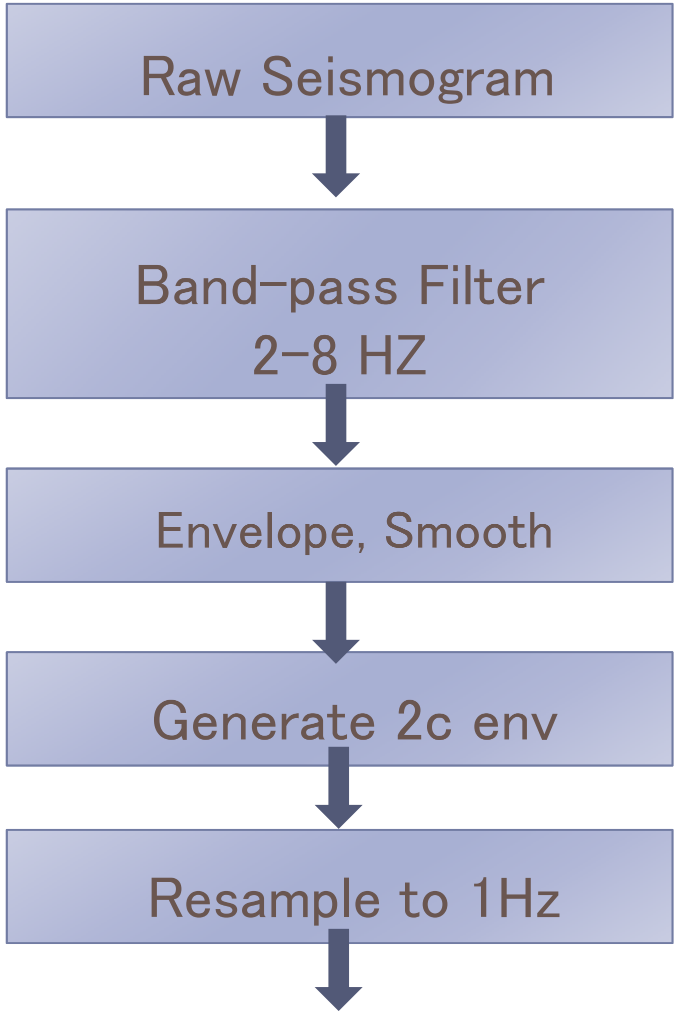
Duration > 600s



莊育菱，2012，台灣非火山長微震半自動化偵測系統，國立台灣師範大學地科學所碩士論文。

第零階段: 前置處理





Auto-detection system

第一階段: 波形相似度比對

要求: 不同測站有一致波形

Pre-processed envelope data

↓

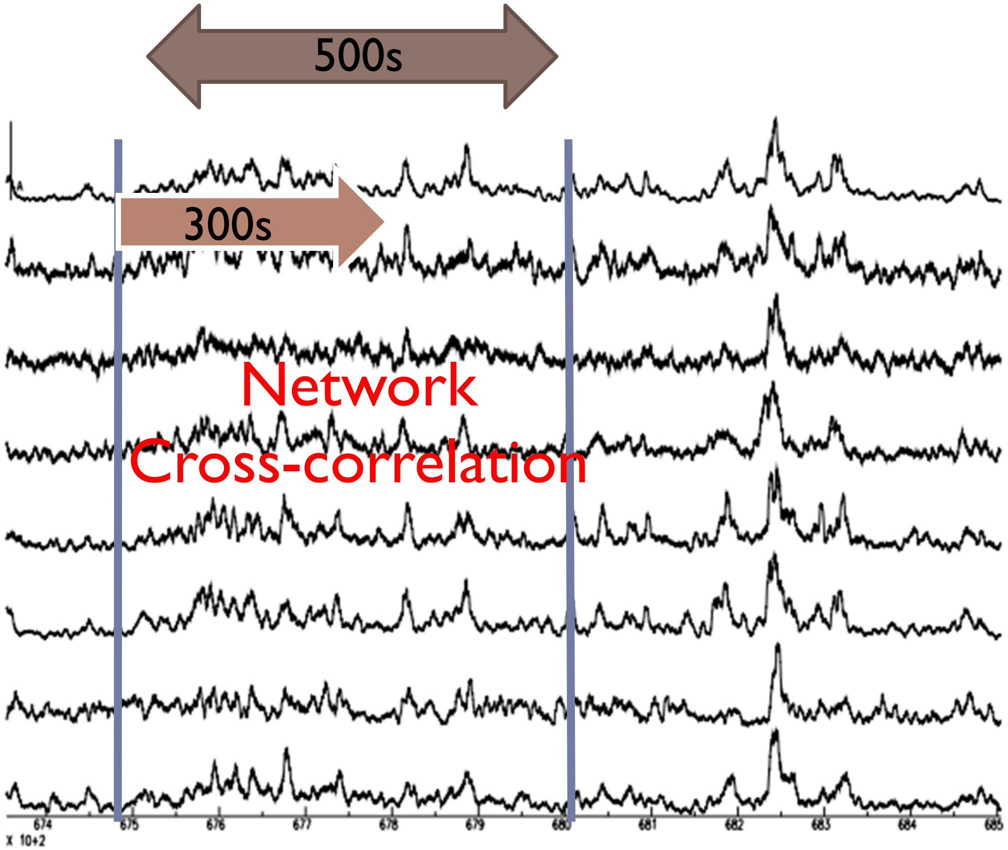
500s time window,300s moving window length, Network cross-correlation

↓

More than 7 stations cc value >0.95

↓

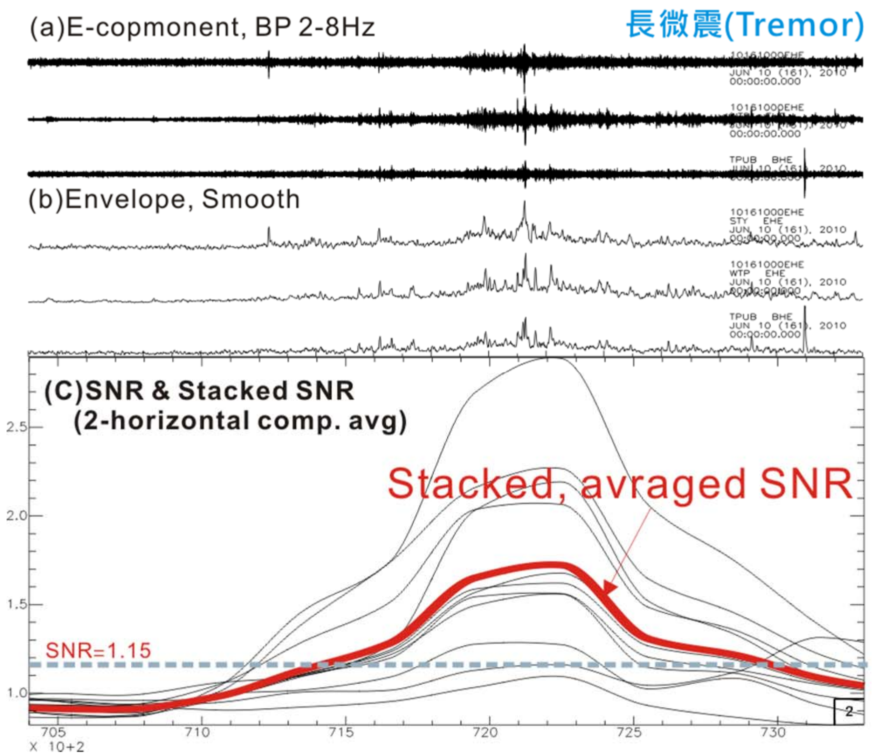
Stage2 : SNR selection

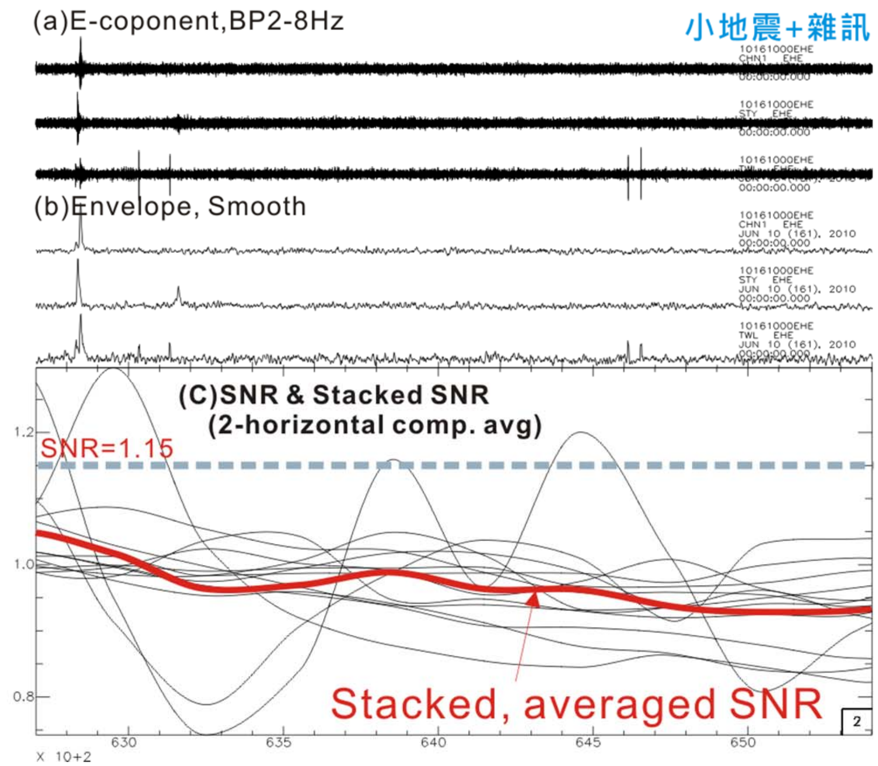


以每500秒視窗且移動300秒進行測站間相關係數計算。若有7個以上測站彼此間相關係數大於0.95則通過檢驗。

第二階段: 波形訊噪比(SNR)檢驗

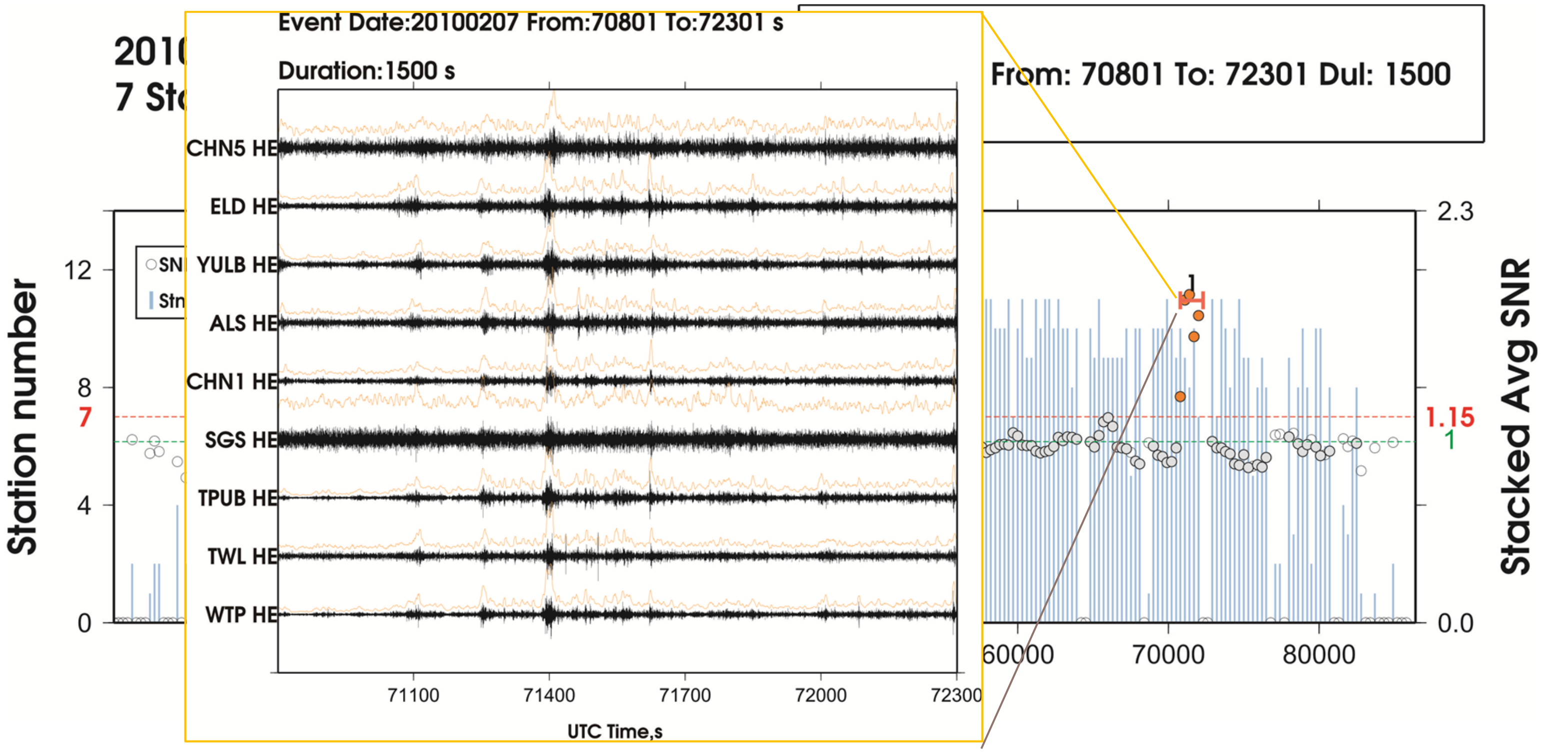
要求: 振幅要大於背景雜訊





第三階段: 持續時間檢驗

要求: 持續時間要夠長



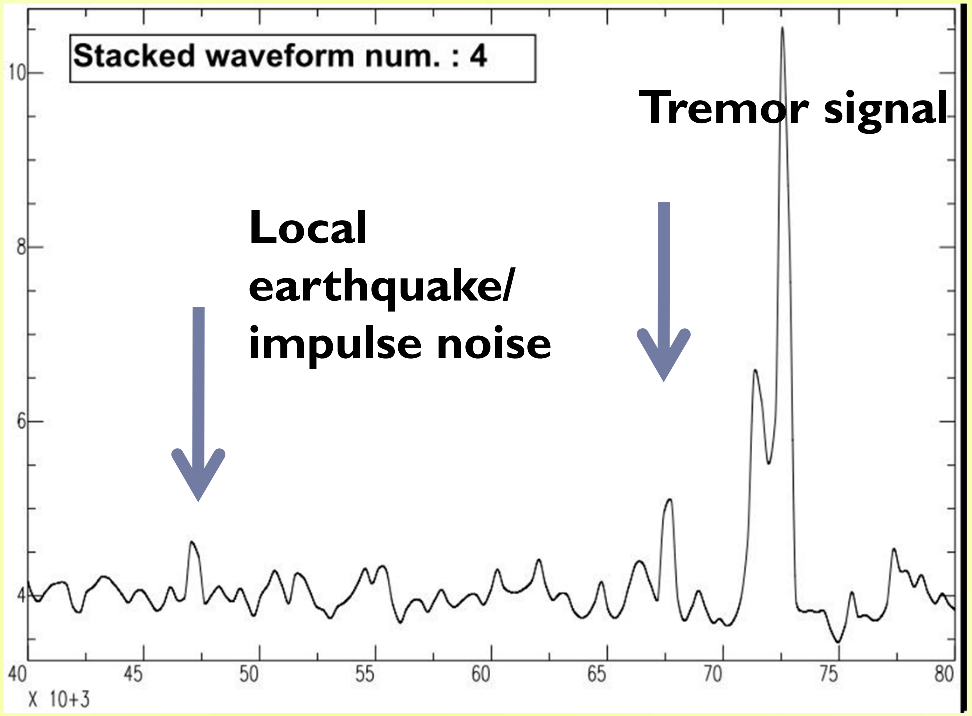
本階段為分離(1)持續時間較短但訊噪比高的特殊雜訊事件(2)尾波較長的區域地震，因此限制連續兩個偵測(持續時間需大於600秒)才判定為可能的長微事件。

Stacking amplified the tremor signals

SNR time series of each station

1.Stacked similar waveform

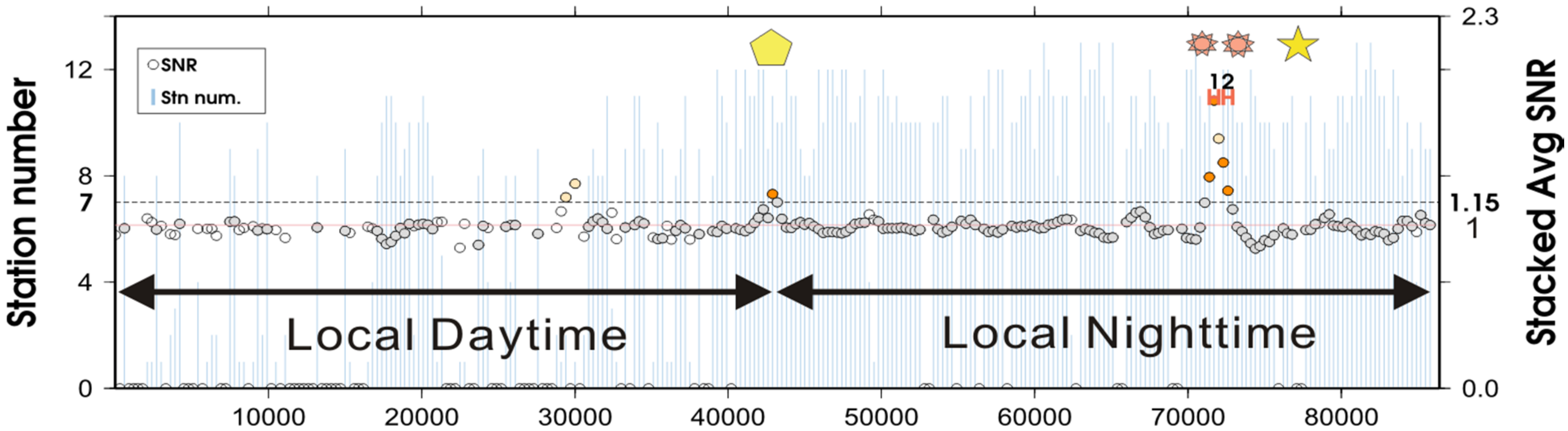
2. Take average amplitude of stacked waveform



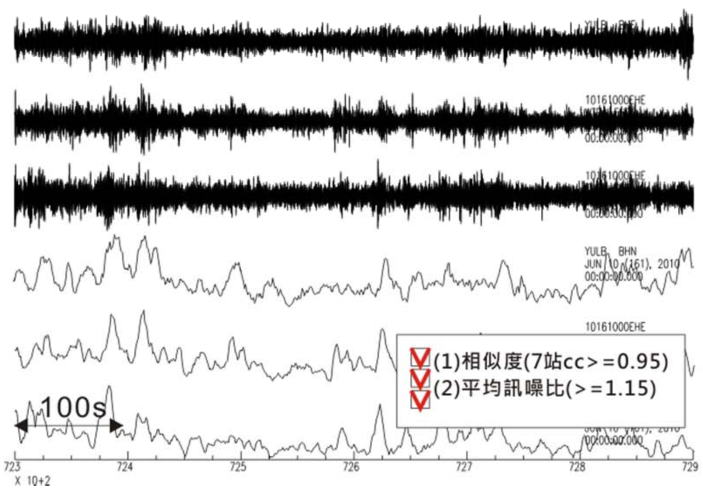
Diagnostic characteristic for tremors

2010.06.10
7 Station CC 0.95 SNR 1.15 Dul 600 s

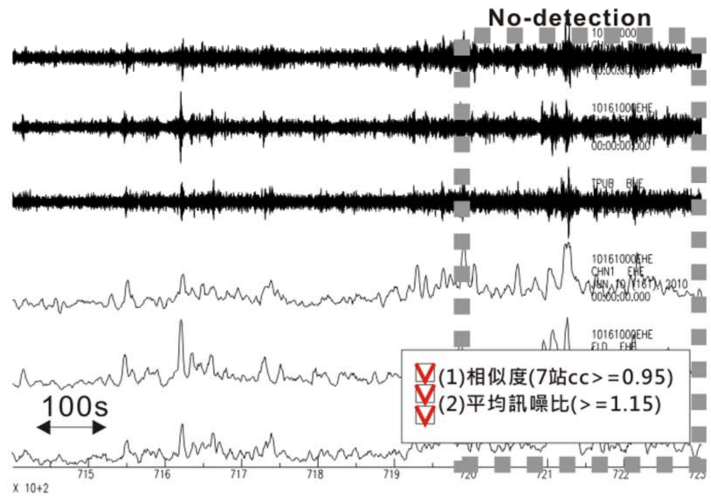
#Event2 From: 72301 To: 72901 Dul: 600
#Event1 From: 71401 To: 72001 Dul: 600



ambient tremor



ambient tremor



What controls the location and timing of tectonic tremor?

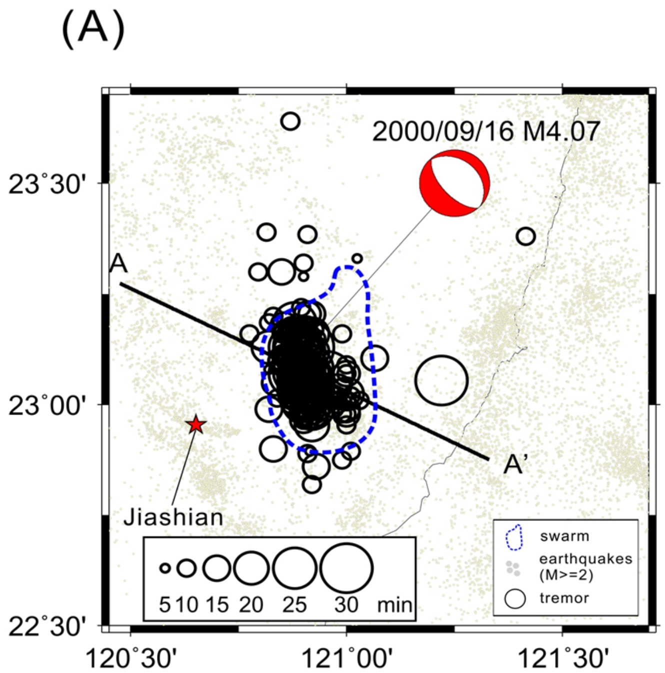
莊育菱，2012，
台灣非火山長微震半自動化偵測系統，國立台灣師範大學地科學所碩士論文。
Chung et al., 2013,
Ambient tremors in a collisional orogenic belt, GRL, in revision.

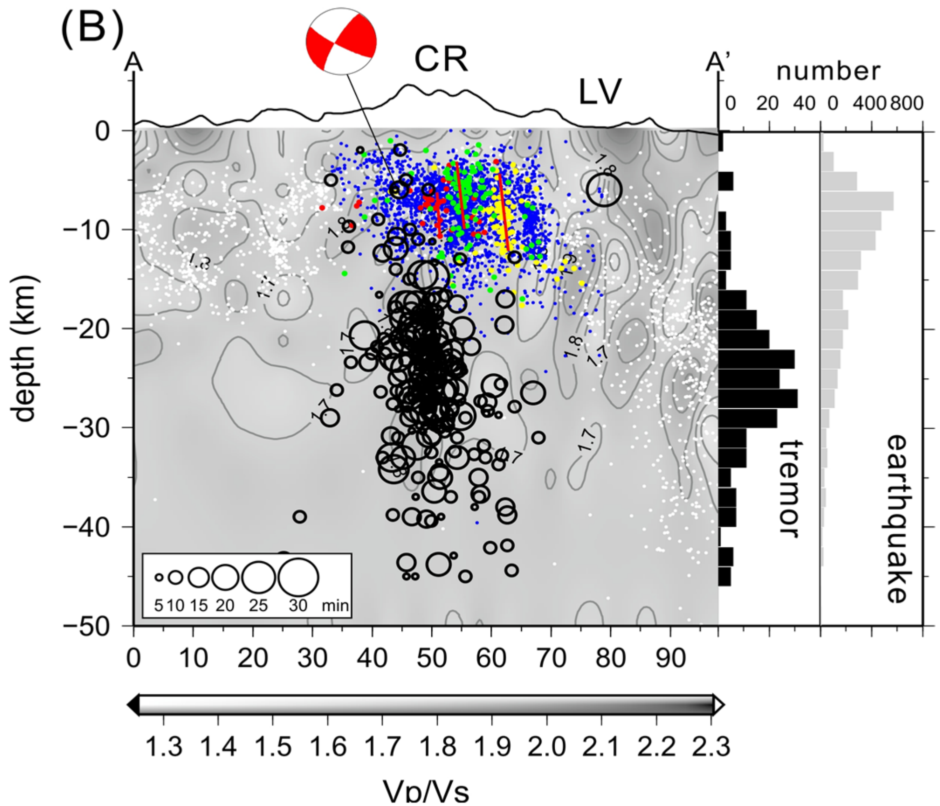
Detection of ambient tremors

Data:
January, 2008 to December, 2011
Detection:
231 ambient tremor episodes with durations ranging from 5 to 30 minutes

1. Most of the detected ambient tremors are confined in a 50 x 50 km^2 area in southern Central Range with nearly vertical structure

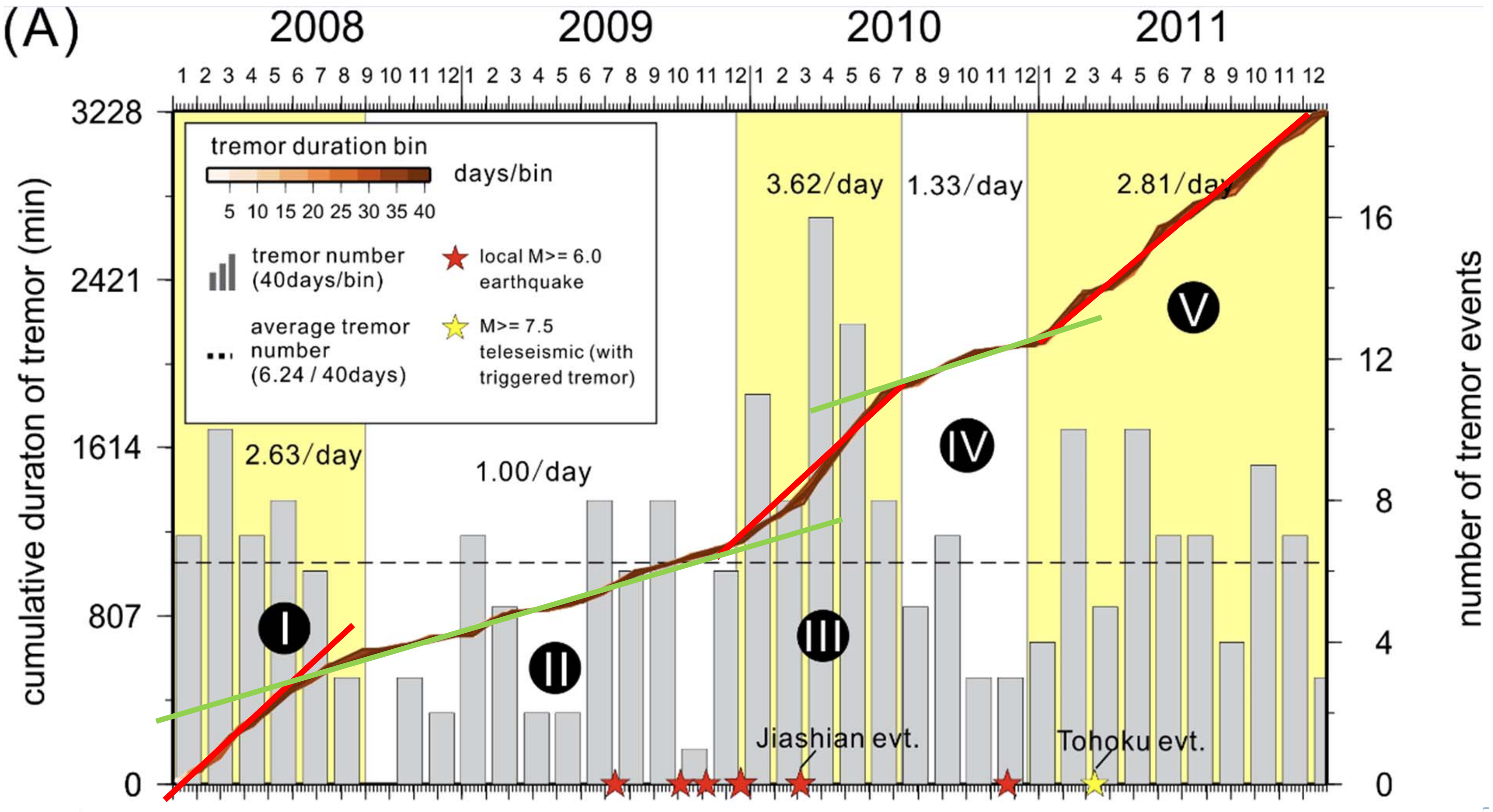
2. 68% of the 231 events occurred at a depth range of 17-34 km, below where the seismicity is concentrated

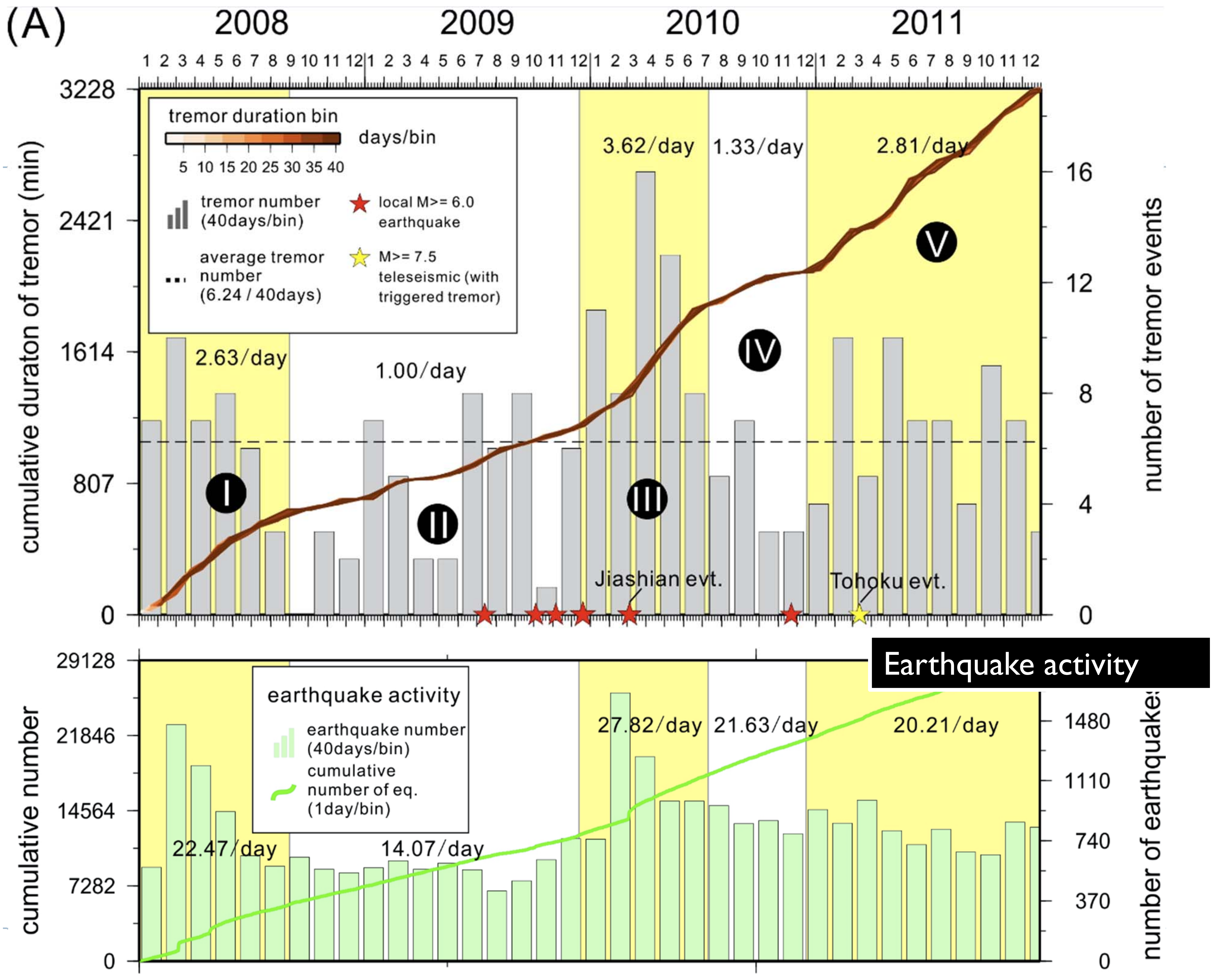


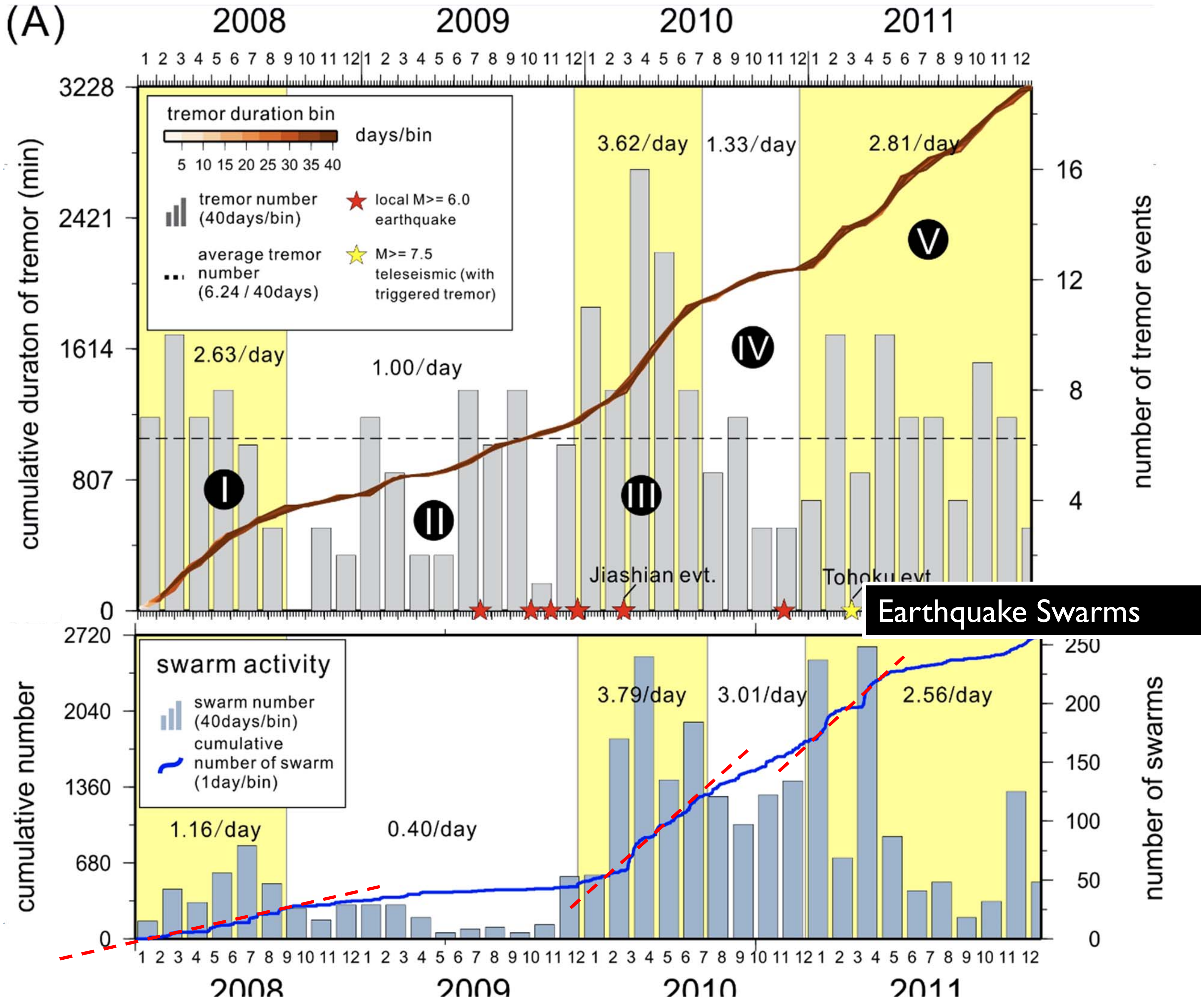


Spatio-temporal evolution of tremors

1. The number of tremors in each 40-day bin is largest at the time of the local 2010/3/4 M6.4 Jiashian earthquake
2. Segments I, III, and VI show a higher rate of tremors at 2.63, 3.62 and 2.81mins per day

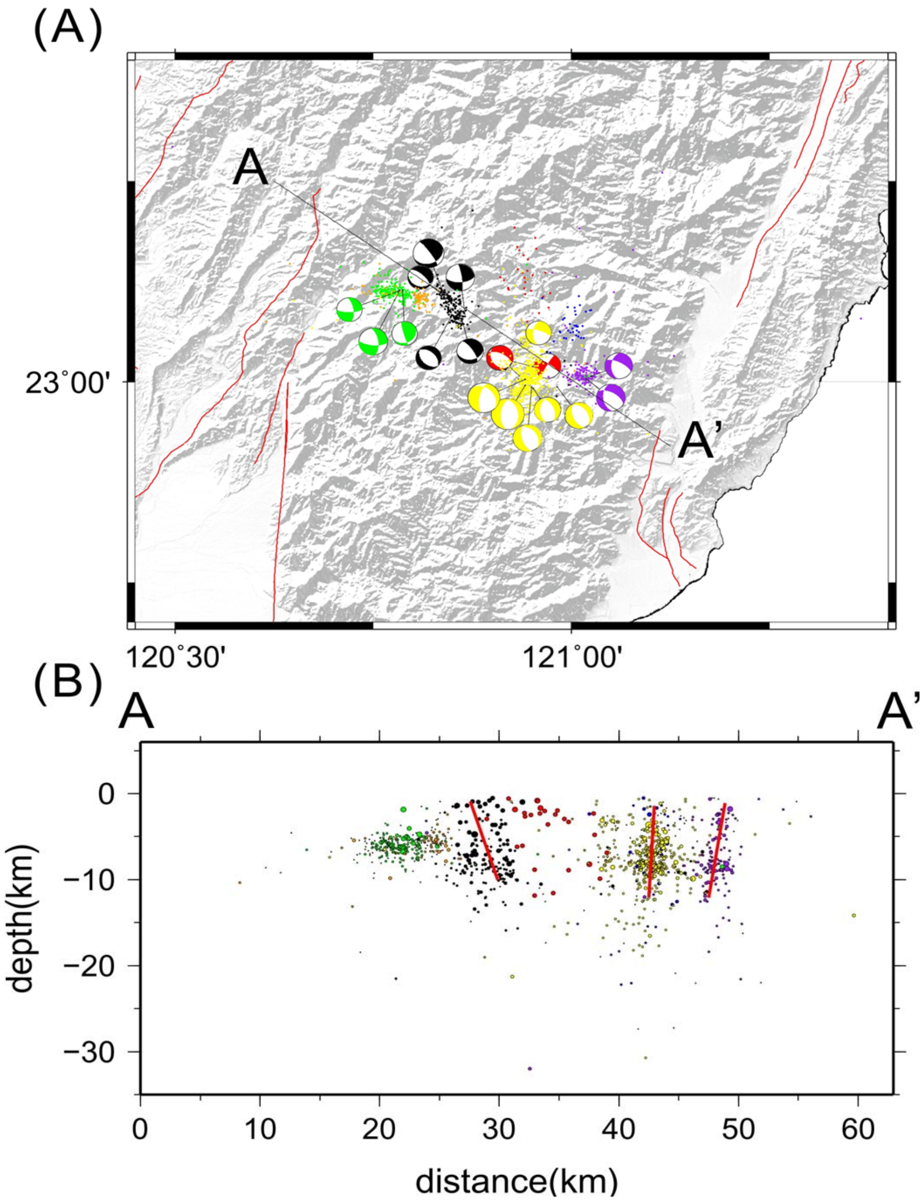



(A)
2008
2009
2010
2011
cumulative duraton of tremor (min)
number of tremor events
tremor duration bin
days/bin
5 10 15 20 25 30 35 40
tremor number (40days/bin)
local M>= 6.0 earthquake
average tremor number (6.24 / 40days)
M>= 7.5 teleseismic (with triggered tremor)
2.63/day
1.00/day
3.62/day
1.33/day
2.81/day
I
II
III
IV
V
Jiashian evt.
Tohoku evt.
cumulative number
number of earthquakes
earthquake activity
earthquake number (40days/bin)
cumulative number of eq. (1day/bin)
22.47/day
14.07/day
27.82/day
21.63/day
20.21/day
Earthquake activity

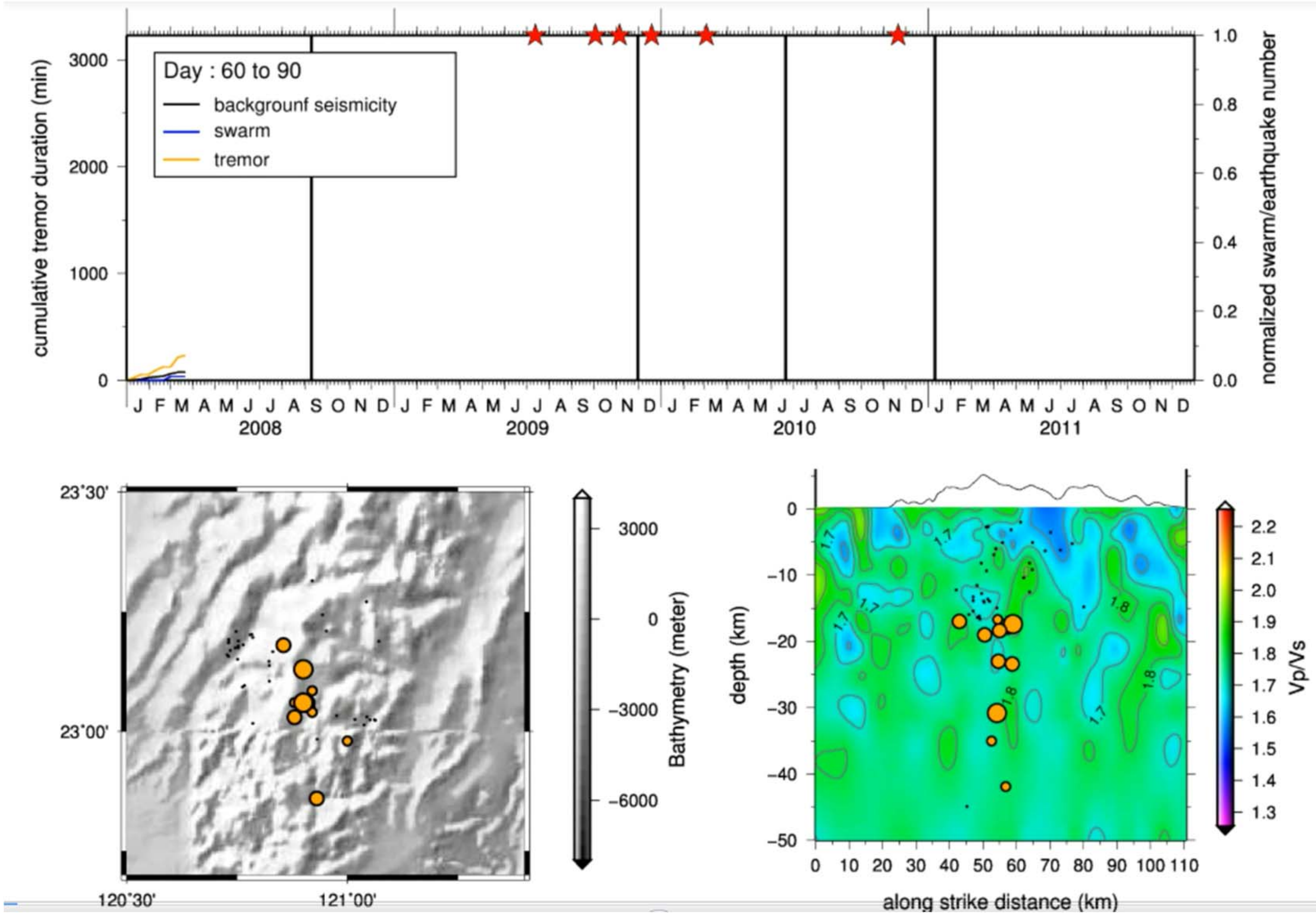

(A)
2008
2009
2010
2011
3228
2421
1614
807
0
cumulative duraton of tremor (min)
number of tremor events
tremor duration bin
days/bin
5 10 15 20 25 30 35 40
tremor number (40days/bin)
local M>= 6.0 earthquake
average tremor number (6.24 / 40days)
M>= 7.5 teleseismic (with triggered tremor)
2.63/day
1.00/day
3.62/day
1.33/day
2.81/day
I
II
III
IV
V
16
12
8
4
Jiashian evt.
Tohoku evt.
Earthquake Swarms
2720
2040
1360
680
cumulative number
number of swarms
swarm activity
swarm number (40days/bin)
cumulative number of swarm (1day/bin)
1.16/day
0.40/day
3.79/day
3.01/day
2.56/day
250
200
150
100
50

Tremor activity is highly correlated with earthquake swarms

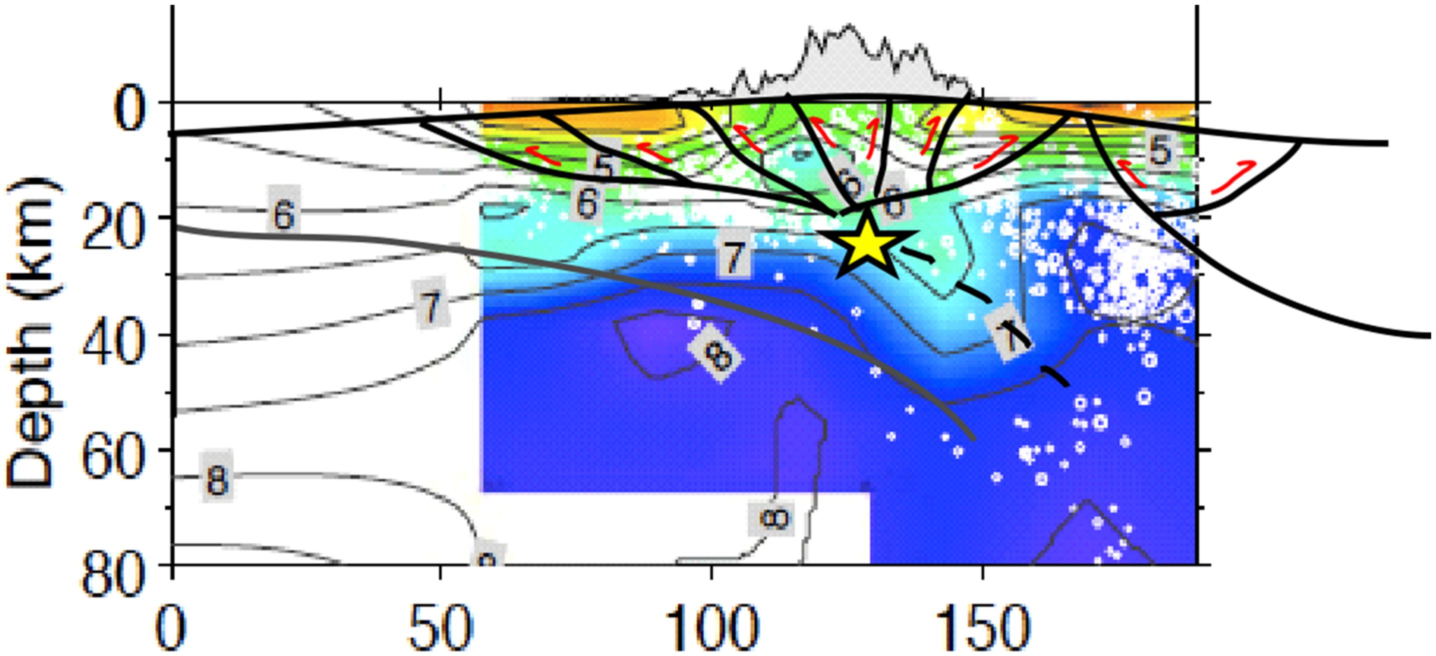
- These swarms, which are composed of normal-faulting *M* 0.7 – *M* 3.9 earthquakes during the study period of 2008-2011, occur above the tremor events at < 20 km depth and delineate a sub-vertical planar structure.
- We find that their activity correlates temporally with tremor as both the tremor and swarm activities are elevated in segments I, III, and VI.



Synchronized activity at shallow and deeper depths?



Possible fault planes for tremor source?

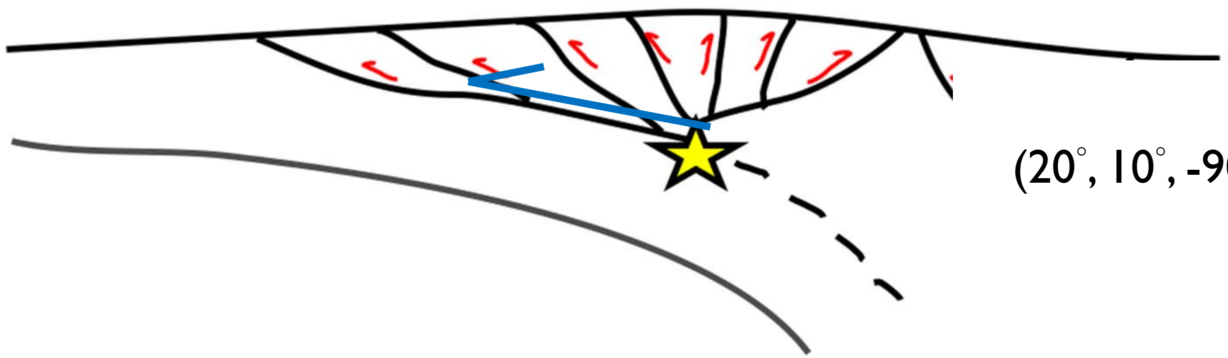


[*Kuo-Chen et. al., 2011*]

Triggering relationship?

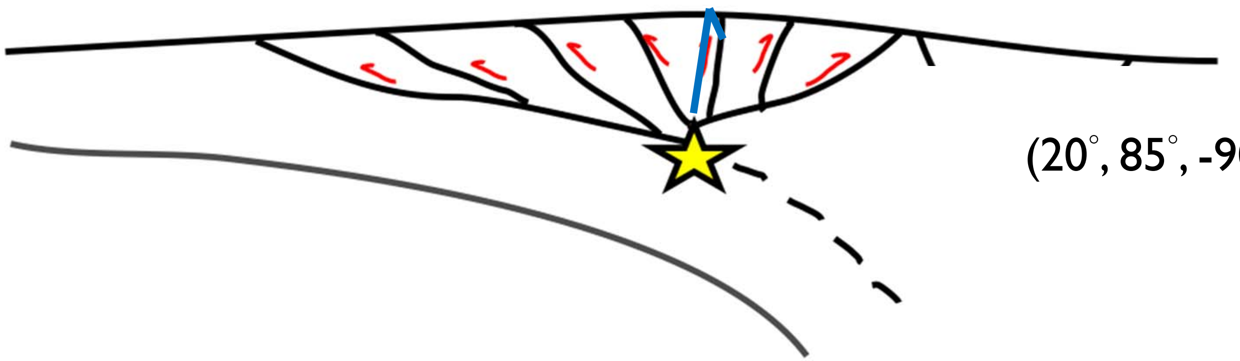
two possible fault planes at the depth of 15-20 km

(1) a thrust fault plane aligned along a décollement suggested by wedge model [*Carena and Suppe, 2002*]



(20°, 10°, -90°)

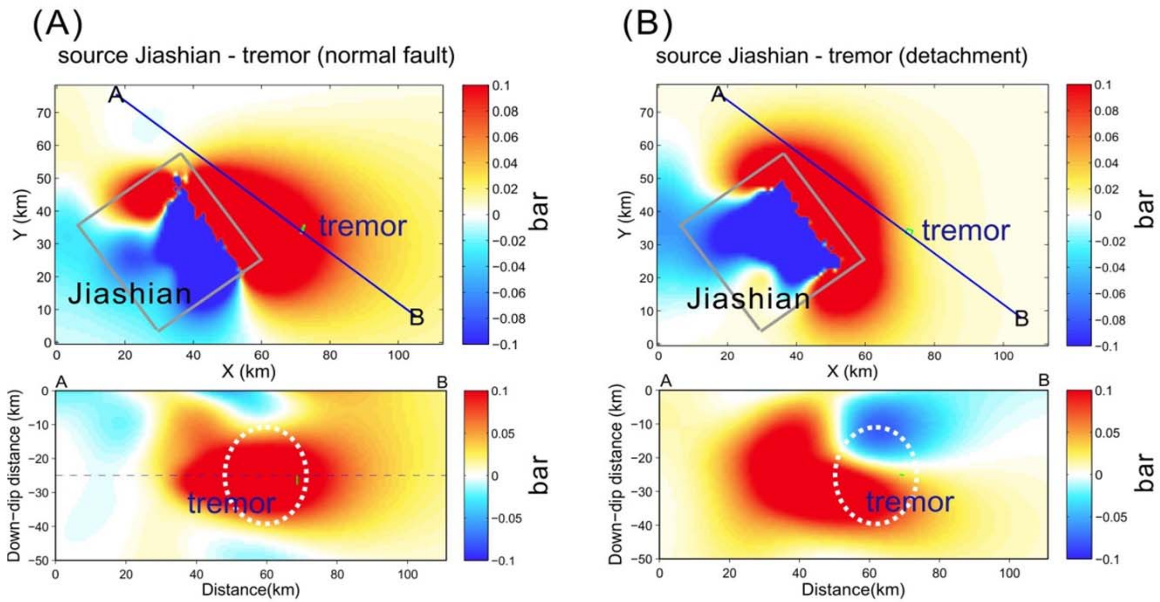
(2) a vertically oriented normal fault plane similar to swarm focal mechanism.



(20°, 85°, -90°)

large earthquake vs. tremor

- static stress transfer induced by the 2010/3/4 Mw 6.4 Jiashian earthquake reveals a ~10 kPa stress change along both the décollement and ~2.5 kPa along a nearly-vertical normal faulting structure.

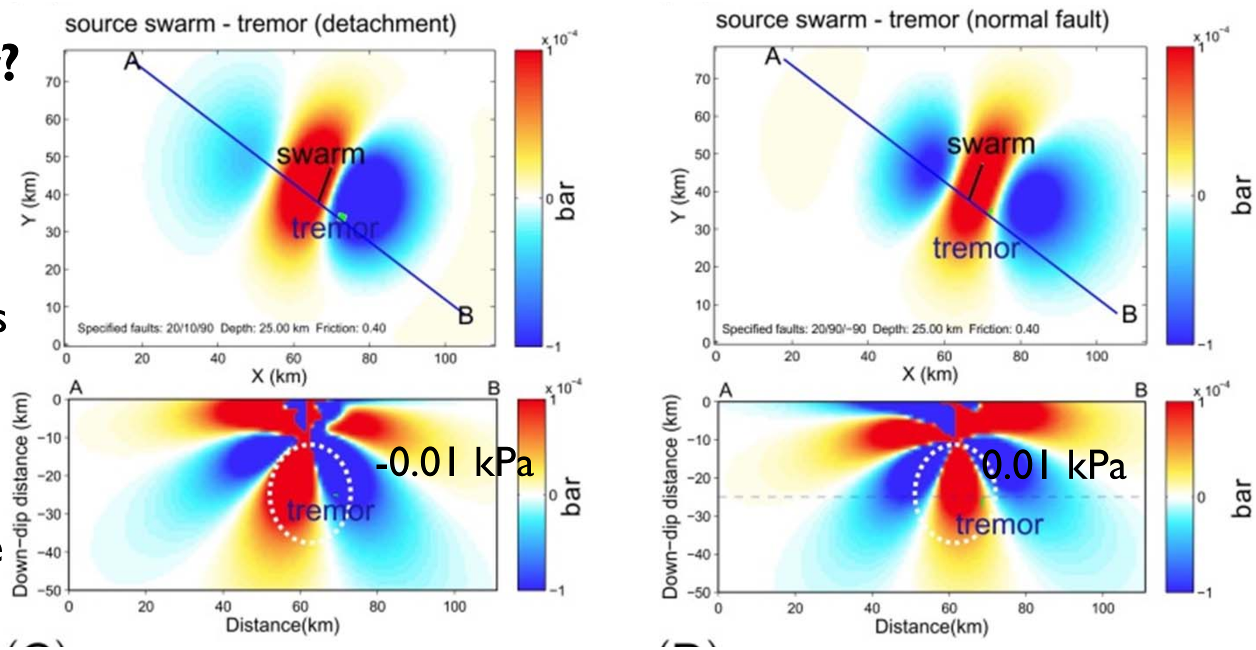


Co-seismic slip induced Coulomb stress change from the Jiashian earthquake can explain tremors at greater depth.

Earthquake swarm vs. tremor

Swarm triggers tremor?

The normal fault slip equivalent to *Mw* 3.9 in the earthquake swarm regions transfer smaller positive stress increase near the normal faulting tremor source region, whereas on the thrust décollement the stress change is negative.



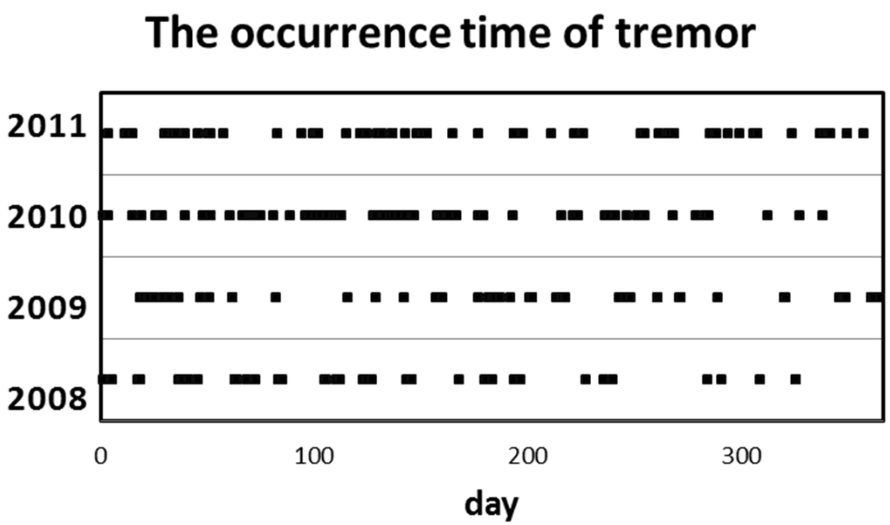
Stress change induced by shallow seismicity controls the tremor acceleration

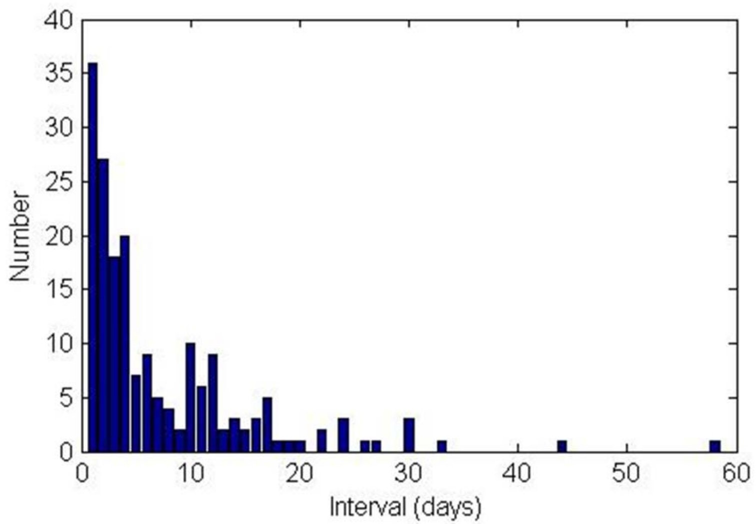
- In addition to the co-seismic slip induced Coulomb stress change from the Jiashian earthquake, the small earthquakes swarms are also possible to triggering relationships with the tremor activity at greater depth.
- Coulomb stress changes on both triggering *scenarios* (*swarm triggers tremor or tremor triggers swarm*), however, only occurs when normal faulting of tremor are applied.
- It is therefore possible that earthquake swarms at shallow depth play a role in elevated tremor activity at deeper levels through a common physical process such as fluid diffusion or underlying aseismic slip.

What controls the recurrence behavior of tectonic tremor?

戴心如，2013，
長微震活動周期與潮汐力的相關性研究，國立台灣師範大學地科學系專題

Temporal distribution of ambient tremors





Do they show a particular recurrence interval?

Among the 231 detected tremor events, 64% of tremor events occur with a interval less than 5 day, whereas 20 % of tremor events occur with a interval less than 1 day.

Calculation of tremor repeat time

- Parameter **s** :

interval of tremor events

$$s = \left| \sum_{i=1,..N} \exp(2\pi i \frac{t_i}{t_0}) \right| / N$$

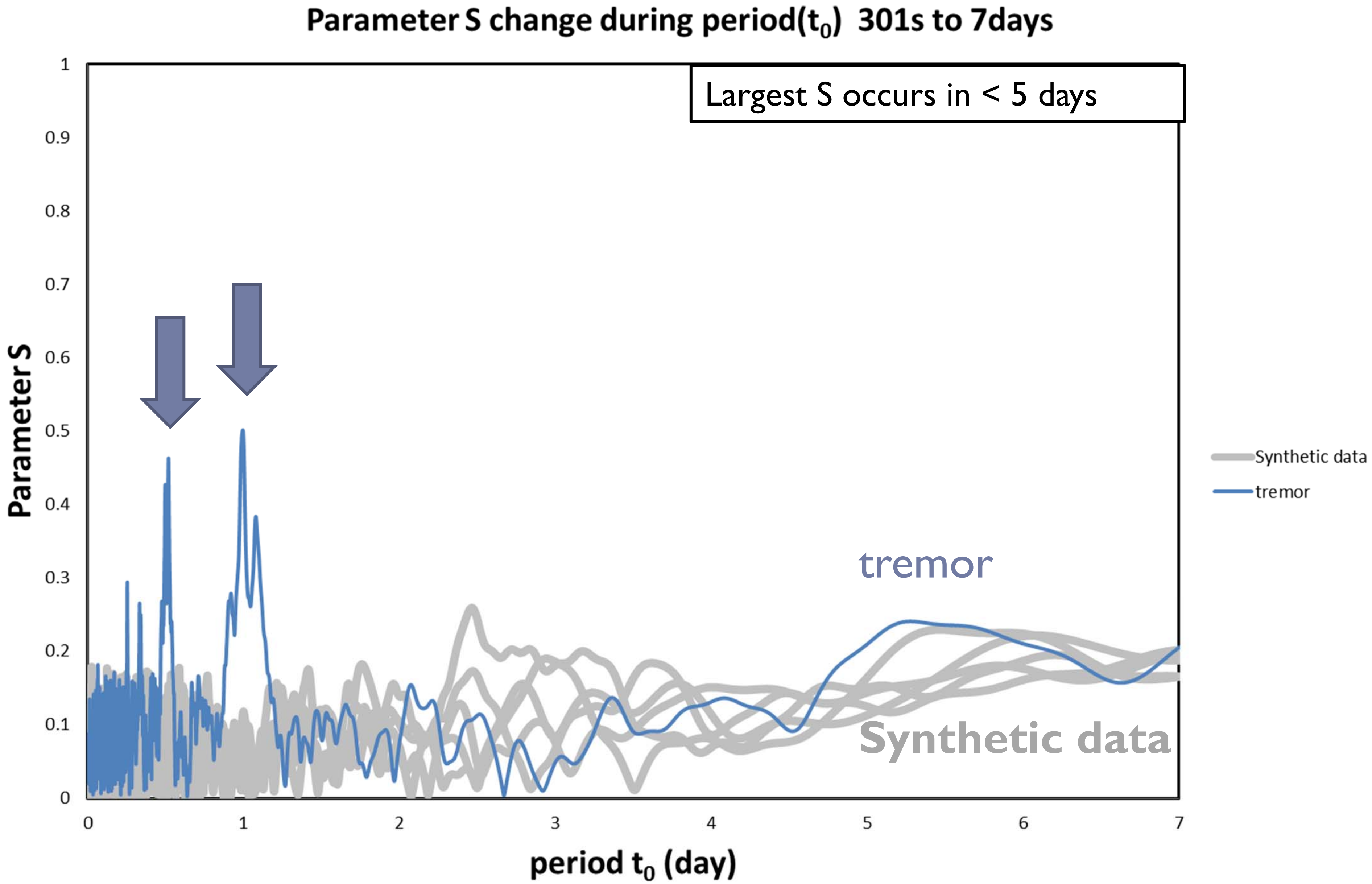
the number of t_i

the period assumed

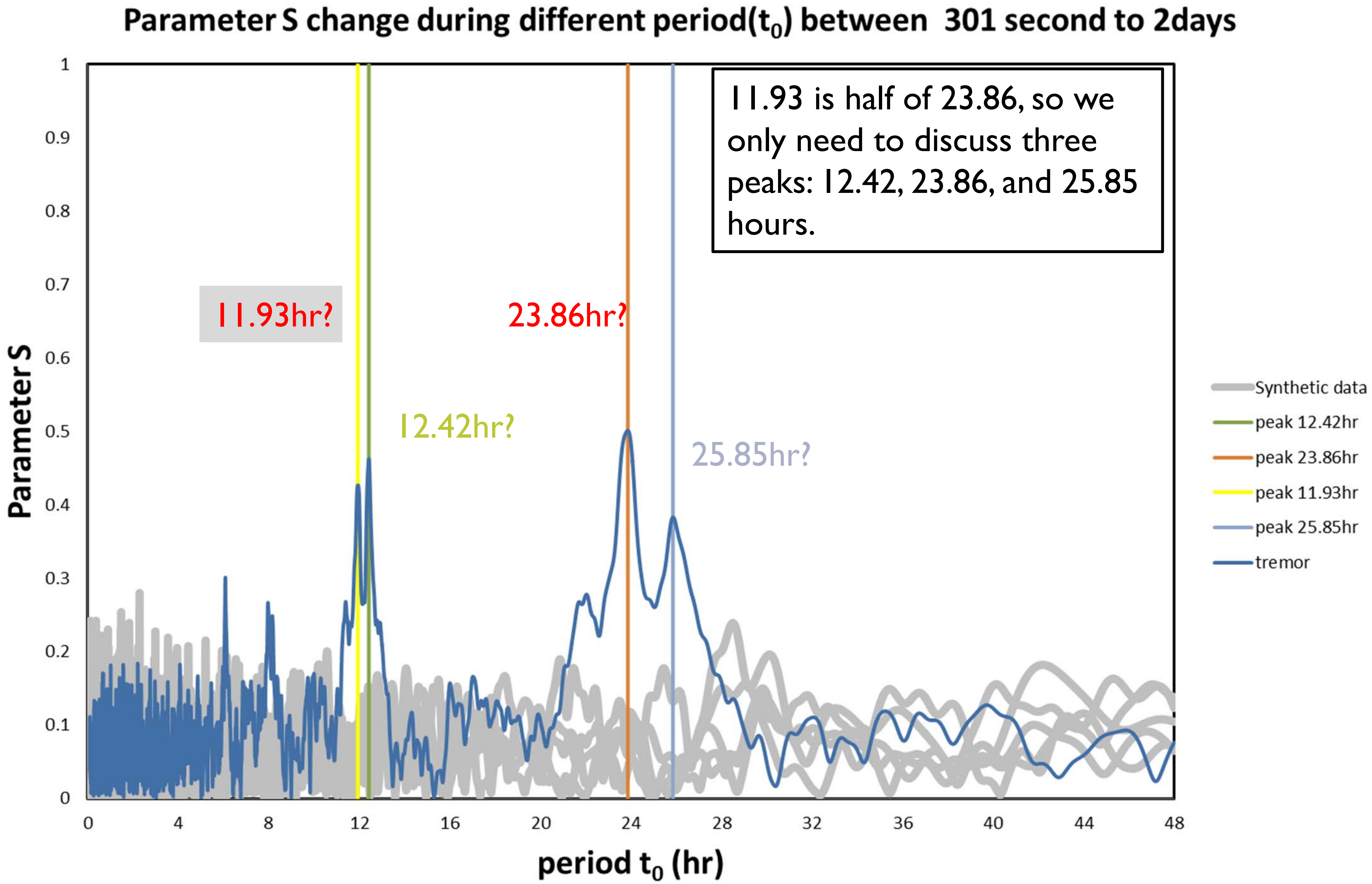
(Ide, 2012)

If the tremor events (sequence) is perfectly periodic, then S = 1

Calculation of tremor recurrence interval

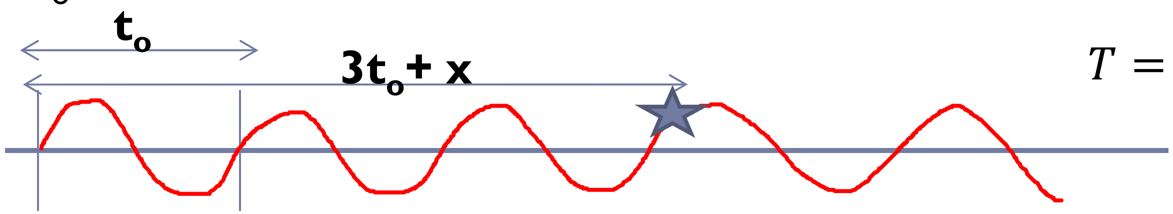


Calculation of tremor repeat time



More precise measure of repeat time

If the real period of tremors = t_o, then the x/t_o of tremors would concentrate at a particular number of x/t_o

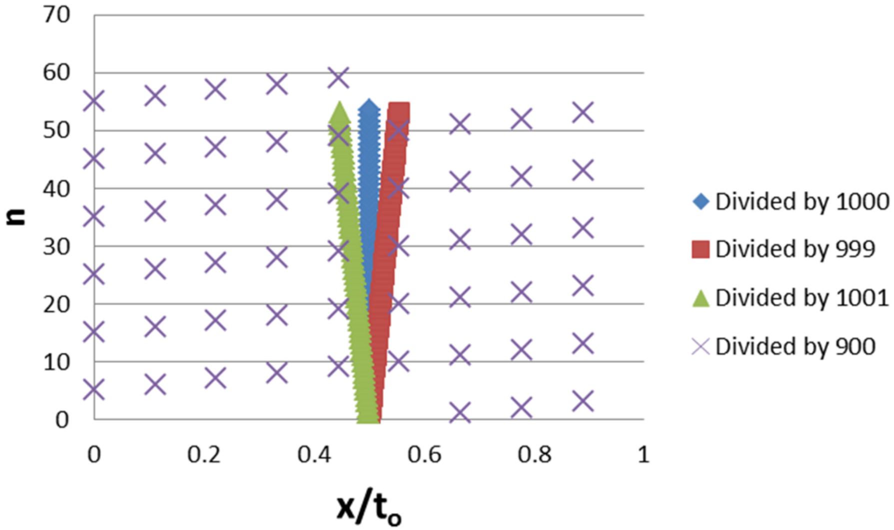


$$T = nt_0 + x$$

T (absolute time of tremor)

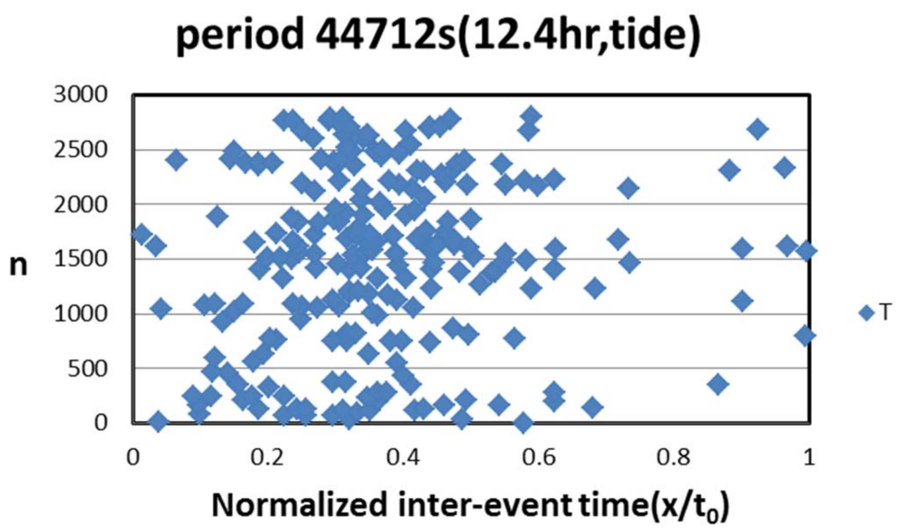
For example, if the real period t_o = 1000, then you will see the vertical blue line corresponding to x=500, therefore x=500/1000=0.5. A very minor difference (t_o =999 or 1001) would lead to a small range of x/t_o, as denoted by red and green lines.

$$T = 1000n + 500 \ \ , n = 1, \ldots 50$$



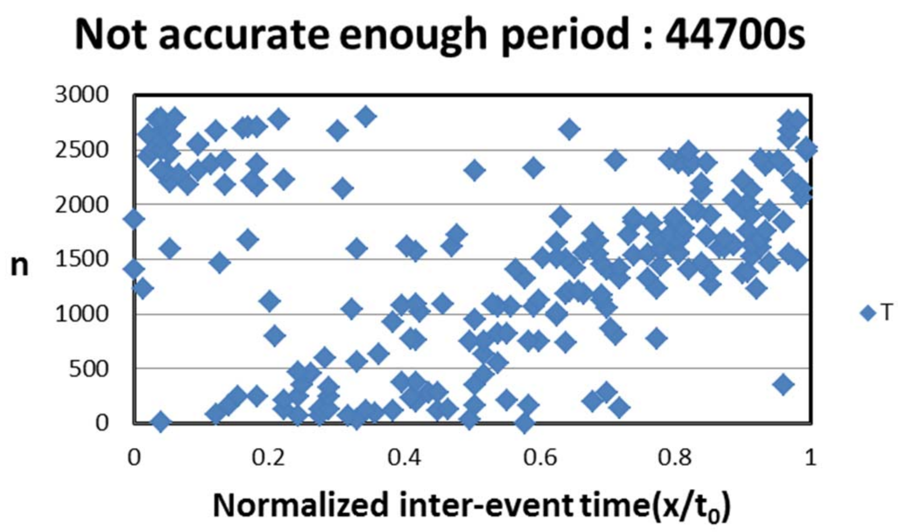
(1) 12.42 hours

(1) Assuming t_0=12.42 hours



Majority of tremor events line up vertically

(2) Assuming t_0=12.417 hours



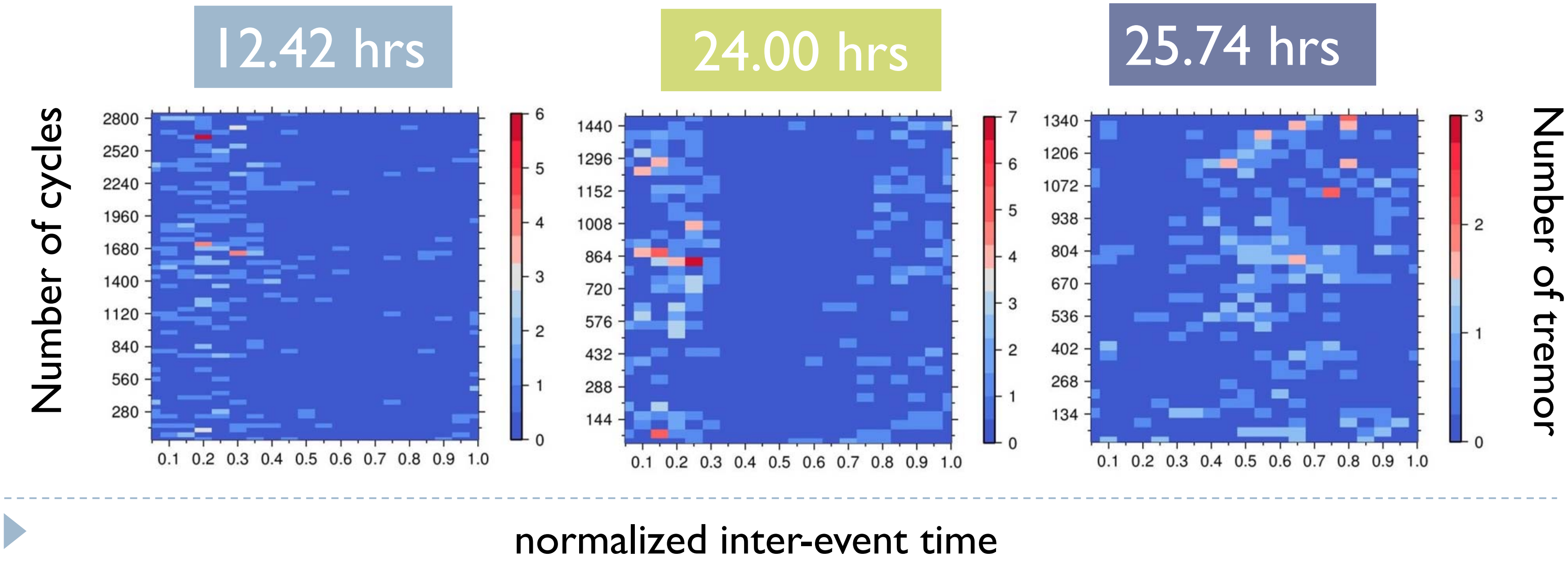
Majority of tremor events line up with NE orientation

So we confirm that the majority of tremors are characterized by the period of 12.42 hours

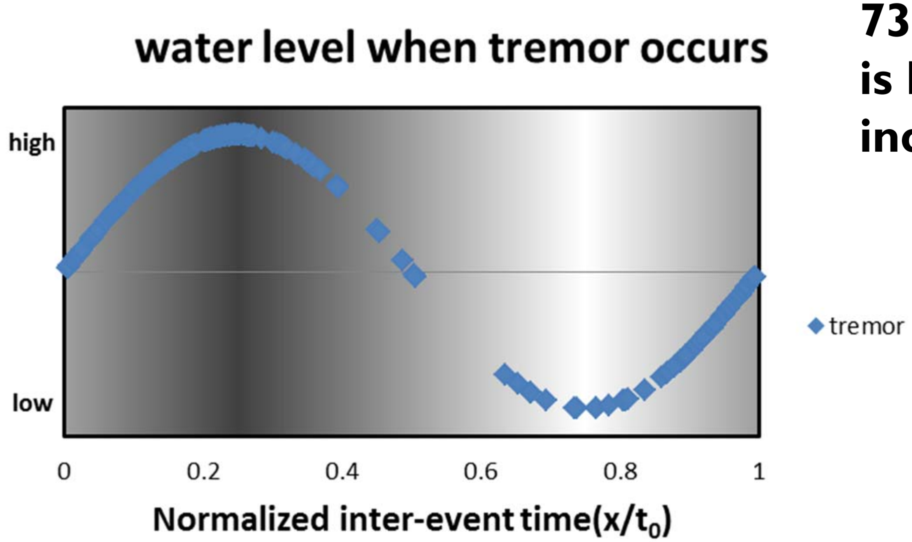
More precise measure of repeat time

To measure a more precise period, we use the occurrence time of tremors divided by t0 of the peaks (or near the peaks) to make sure most of their normalized inter-event time is similar and won't change during the passage of cycles.

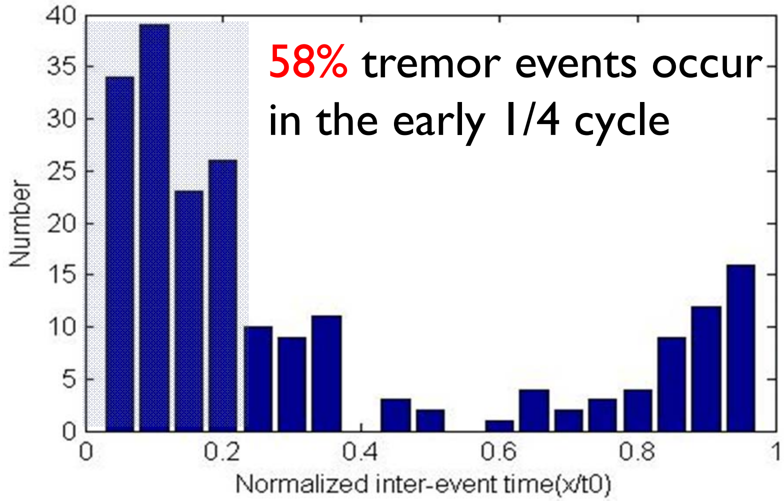
We measure the more precise period for tremor: 12.42, 24,25.74 hrs.

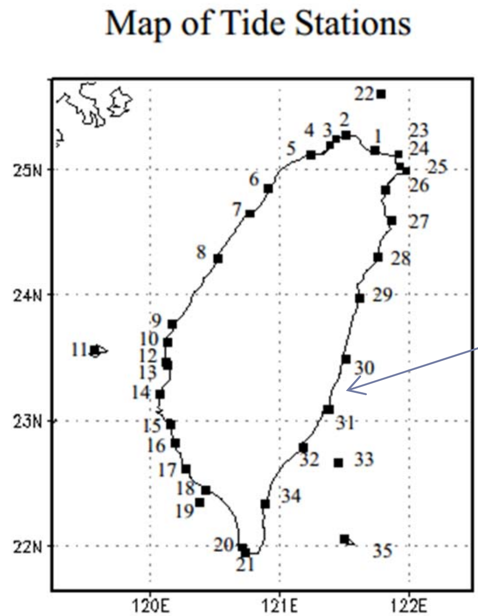


(1) 12.42 h



73 % tremors occurred when water level is high, which is generally high in tidal induced stress.





Chenggong Tidal Station

(成功潮位站),

23°05'50"N

121°22'49"E

(1) 12.42 h

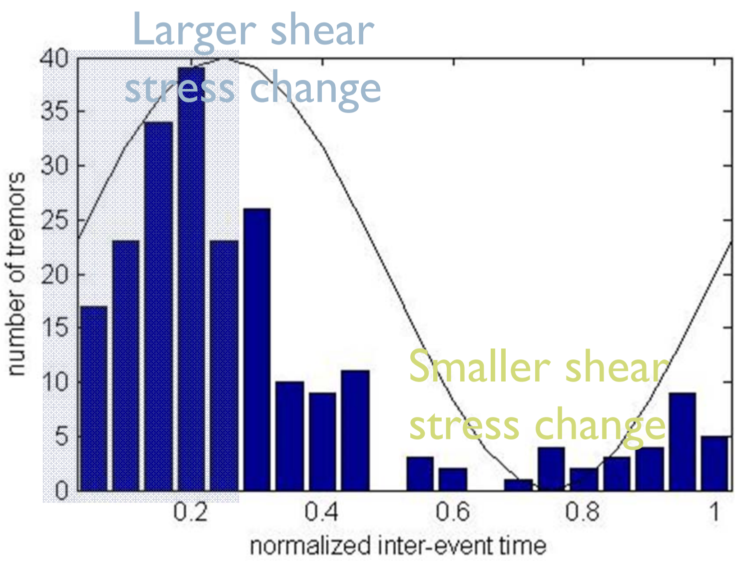
This period is consistent with the semidiurnal principal lunar period of 12.42 h.

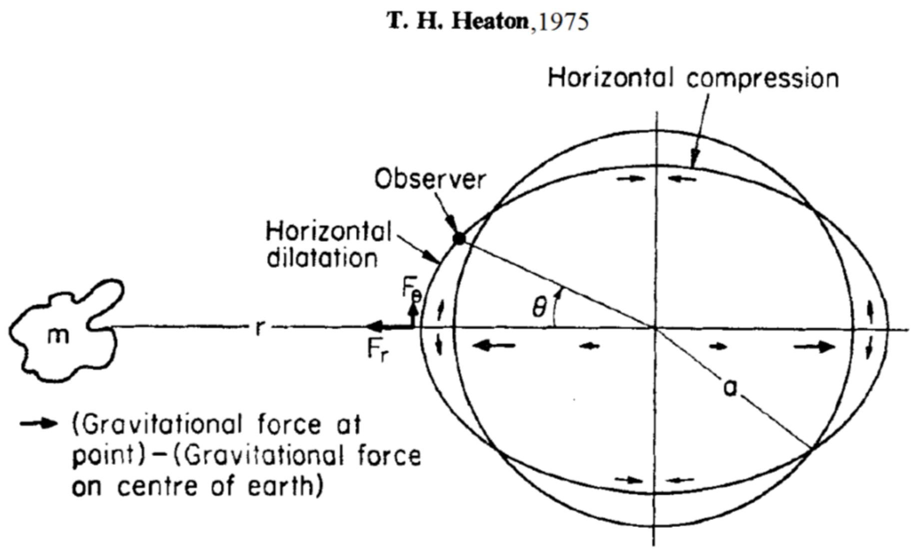
We use location of the Moon to estimate the shear stress change at where tremors occurred.

→ 58% tremor events occurred in the early 1/4 cycle, corresponding to relatively greater shear stress change.

Possible explanation:

12.42 h tremor period is likely a result of gravitation of the Moon

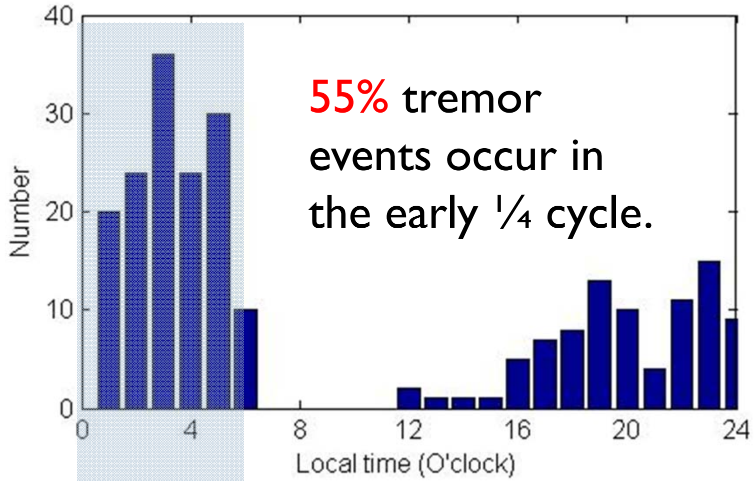




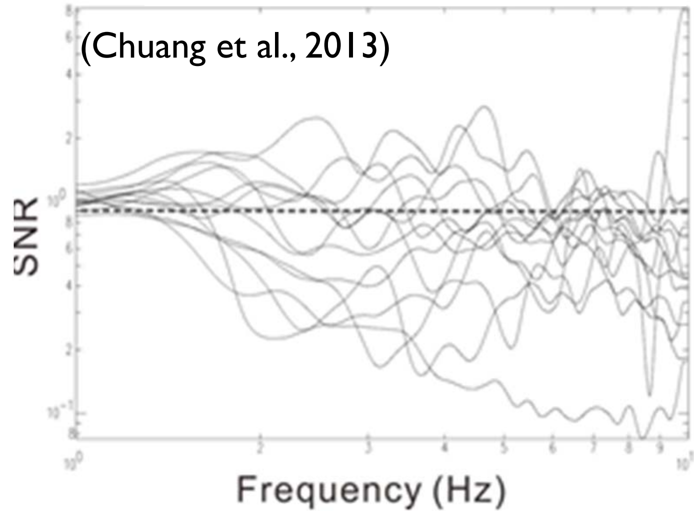
(2) 24.00 h

In Time:

There exists a quiescence between 6-16.
And most of the tremor events occurred at 0-5 AM.

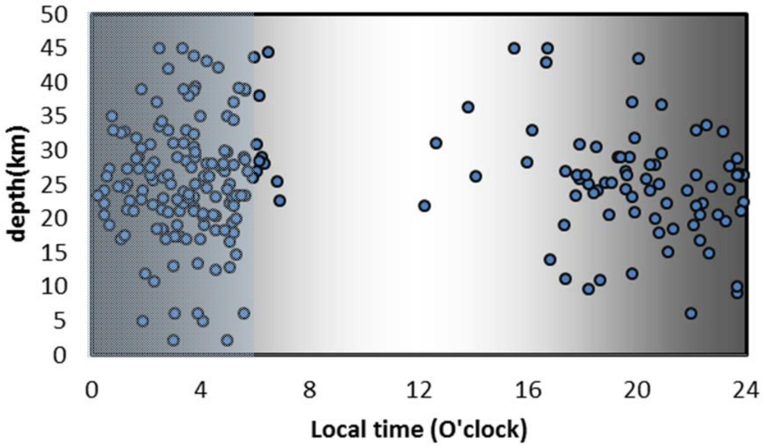


SNR in daytime

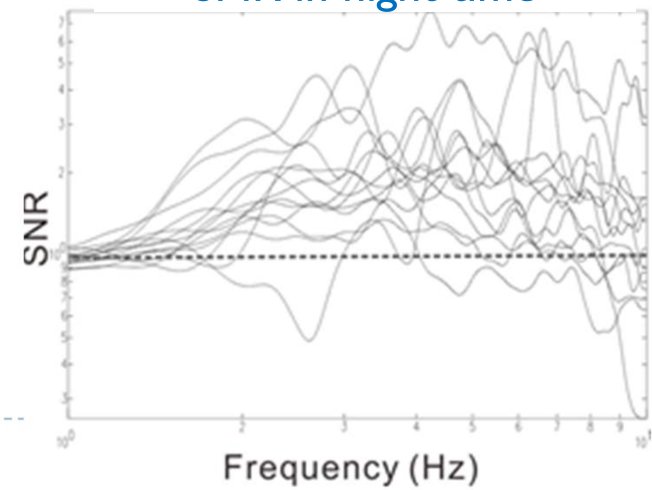


In space:

No clear concentration in space (depth).



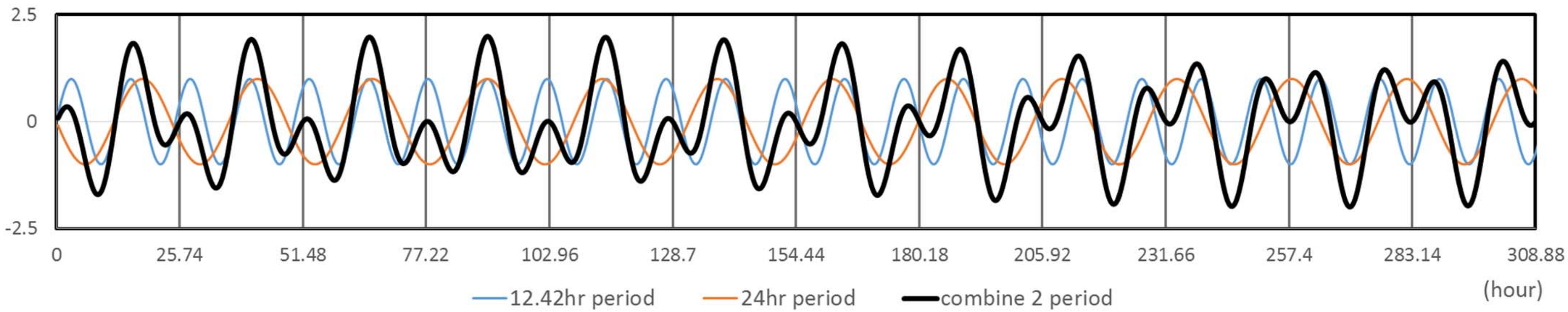
SNR in night time



(3) 25.74 h

The combined effect of 12.42hr and 24hr periods gives the 25.74 h, suggesting the 25.74 h is likely a result of the previous two major tremor periods.

the mechanism needs further study.



Controls of repeat time

- The ambient tremor events in this study are characterized by repeat time of 12.42, 24.00, and 25.74 hours.

- We found that most tremors occurred when moon gravitation induced shear stress change is high. This indicates the correlation between tremor generation and tidal stress. And such correlation explains the 12.42-hr tremors period.

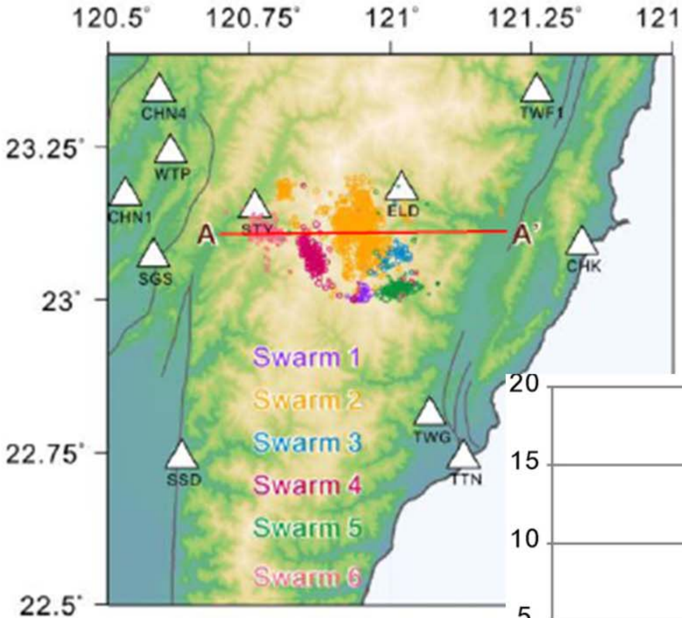
- The 24.00-hr recurrence interval is likely a result of different tremor detectability in daytime and night time, whereas the 25.74-hr period is a combined effect of 12.42 and 24.00 hr periods.

- The tide-tremor correlation follows a universal feature, which is applicable in Japan, Cascadia subduction zones, San Andreas fault, and southern Central Range of Taiwan.

Discussion

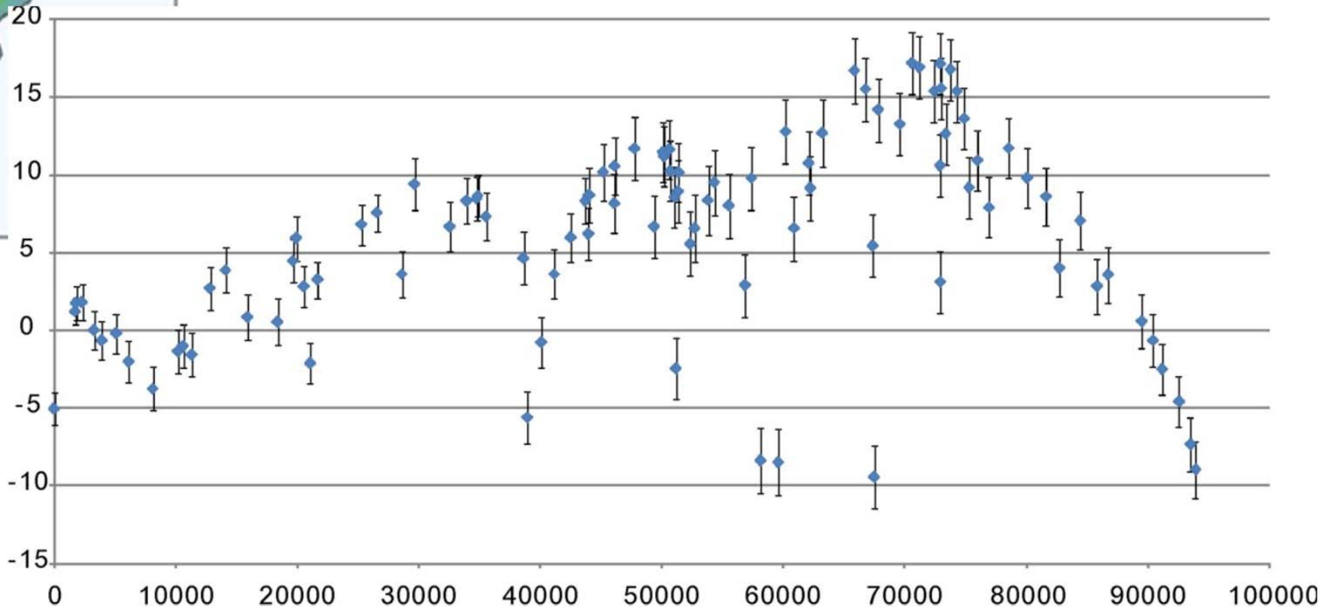
Why southern Central Range?

Why this area special?

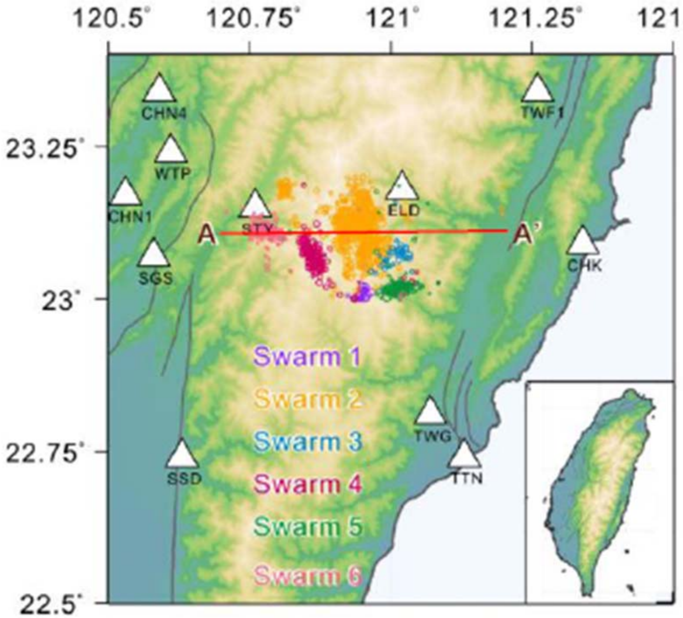


Rapid uplift rate

1-2 cm/yr

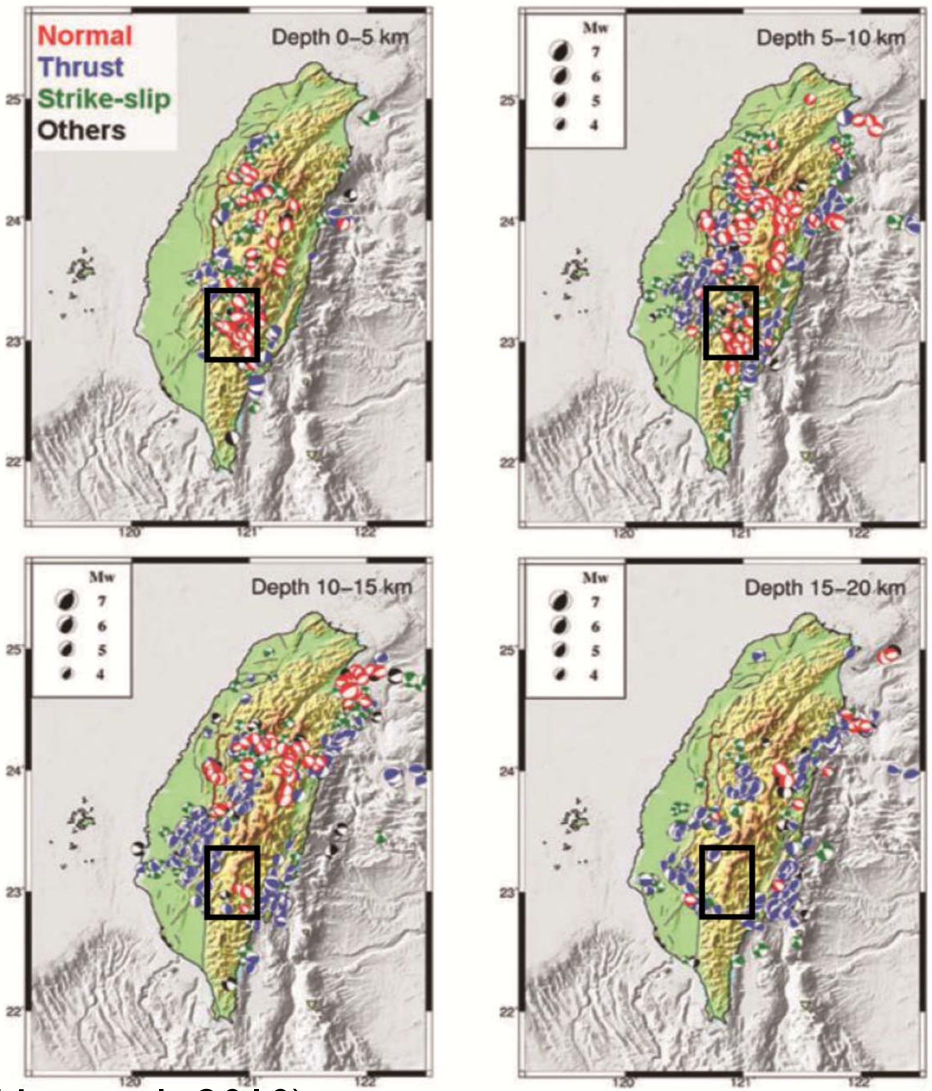


Why this area special?



- Extensional environment

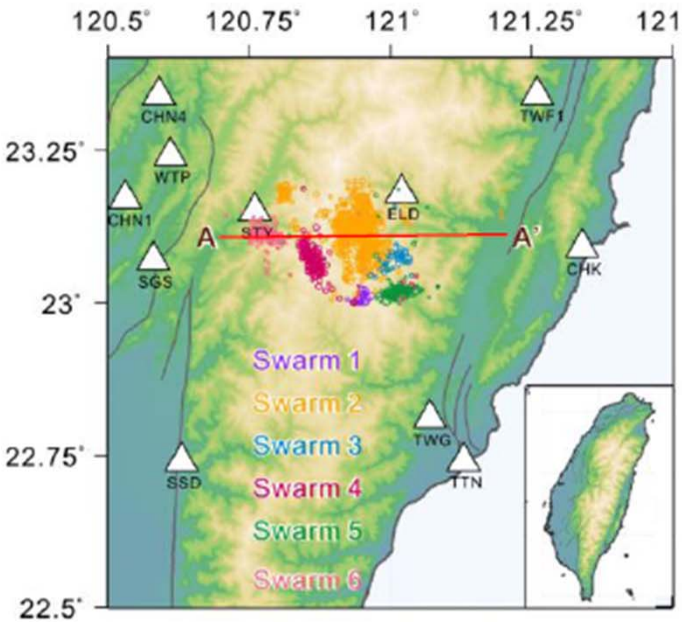
Normal faulting earthquakes

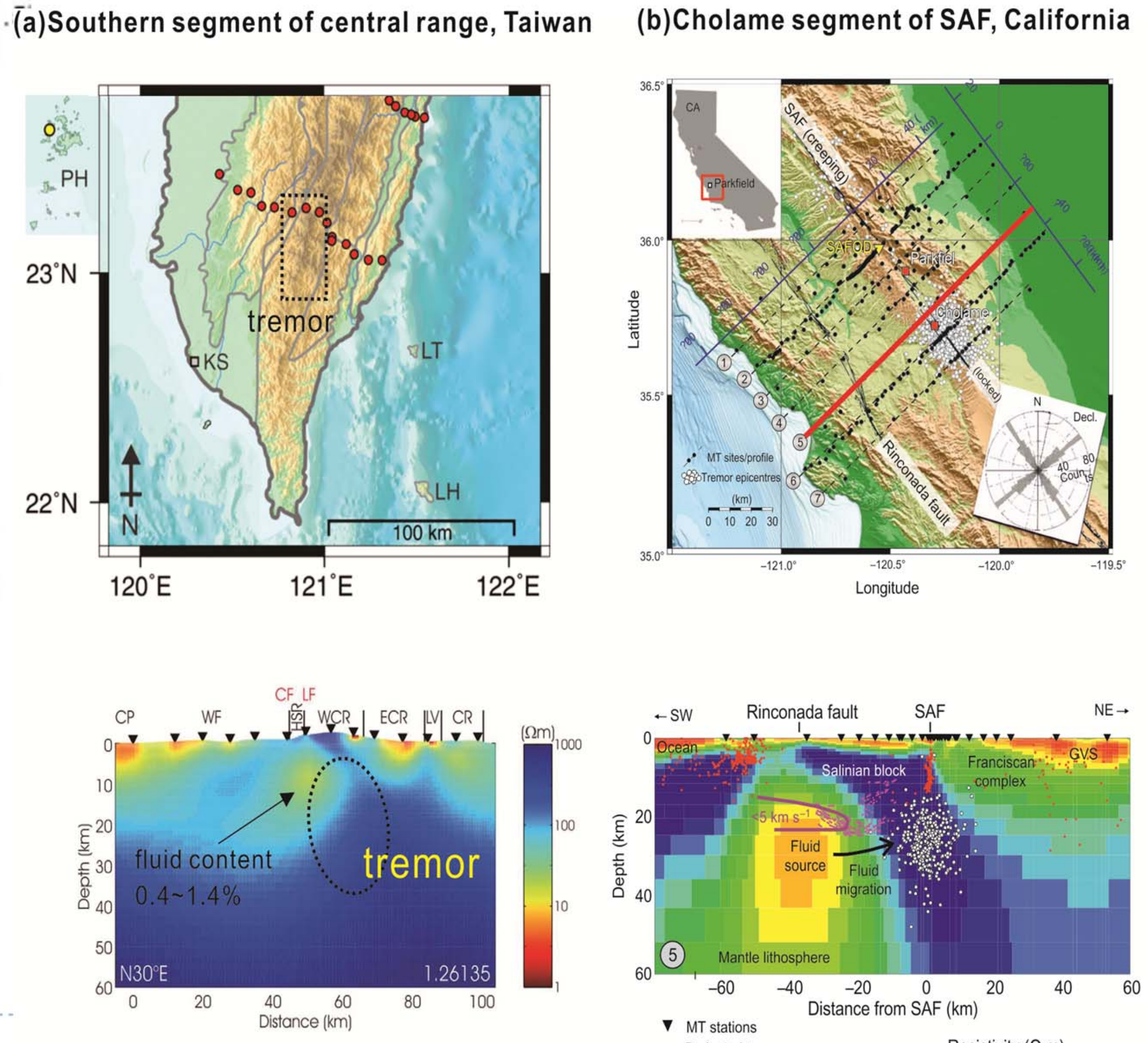


(Hsu et al., 2010)

Why this area special?

Low electrical resistivity



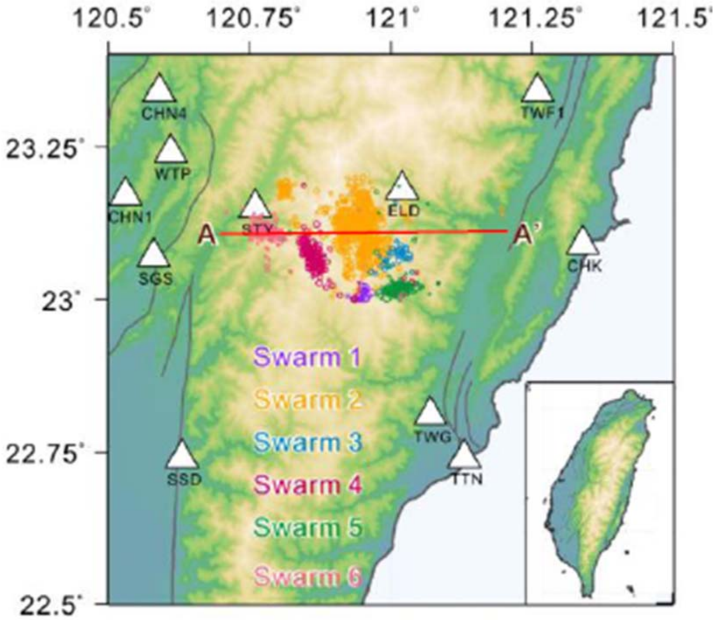


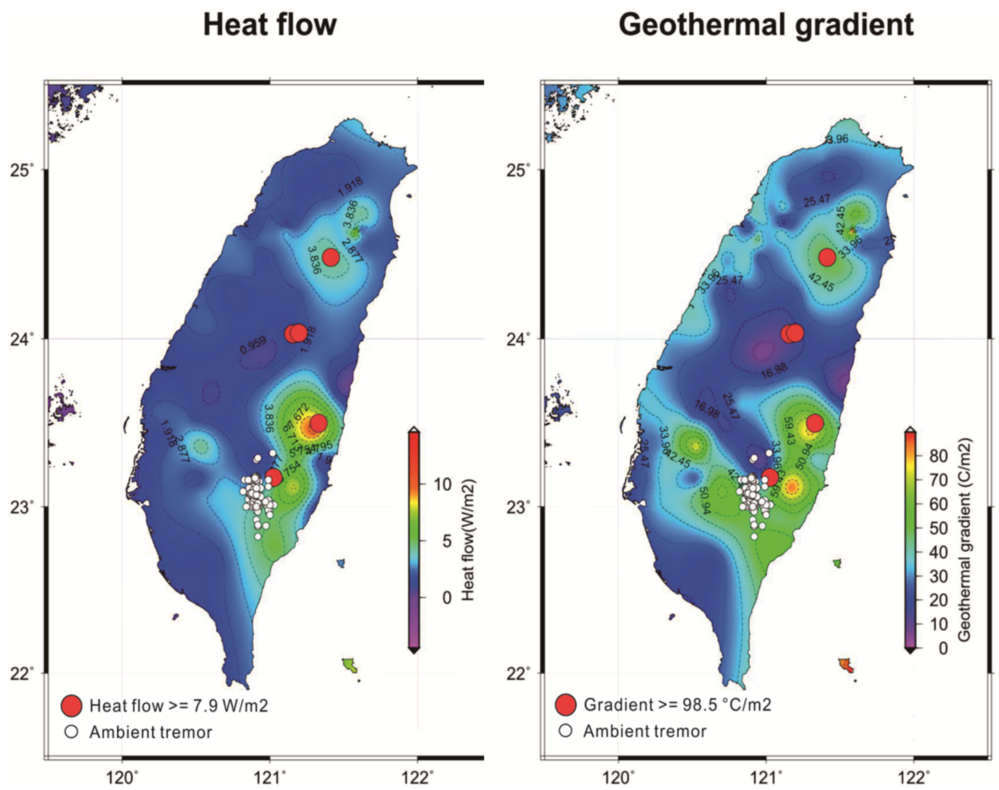
(Bertrand et al., 2012)

- Deep fluid source (0.4~1.4% fluid content)

Why this area special?

greater geothermal gradient





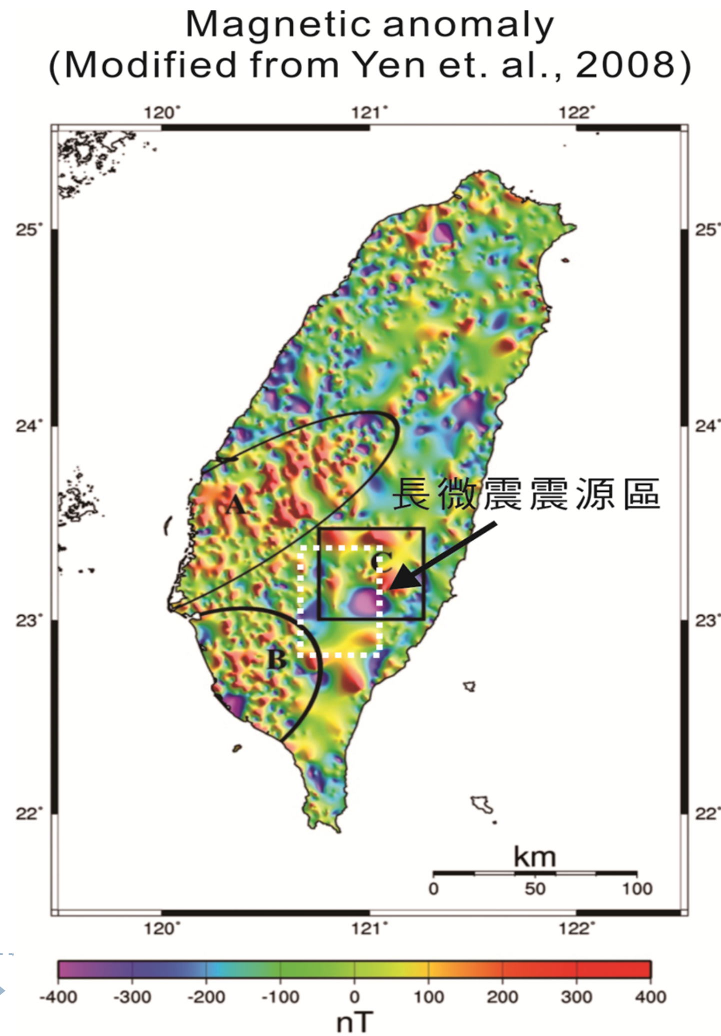
(Chi and Donald, 2008)

- High heat flow (80-250 mW/m^2)and geothermal gradient (30-90°C/km) in the collision zone related to

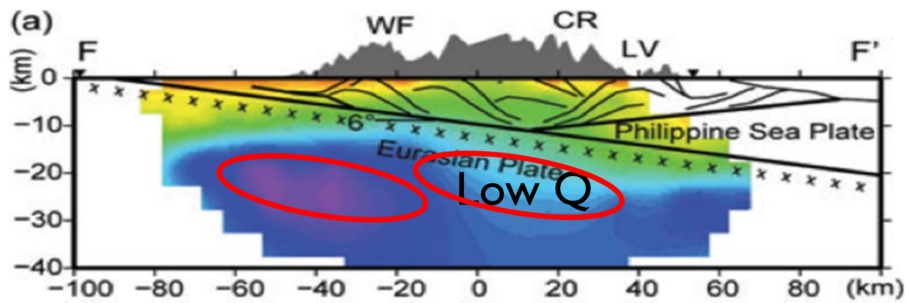
Exhumation, erosion, or collision related upper mantle processes

Why this area special?

Magnetic anomaly



Low Q



Huang et al.

- Underthrust block of igneous rocks (probably part of rifted margin) near-surface

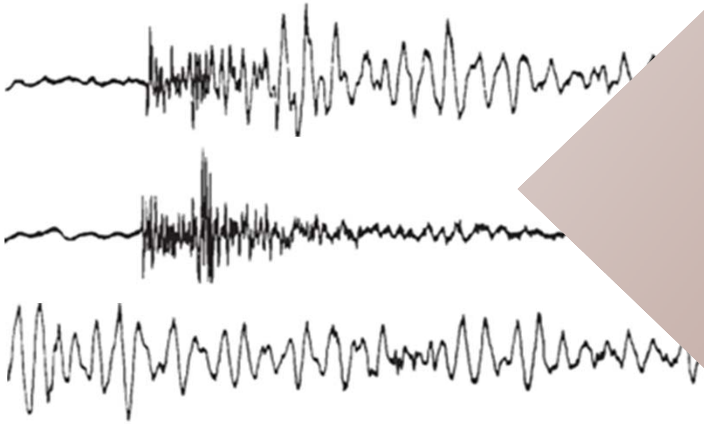
Veins
Hot spring
Uplift rate

Existence of fluid
+ extensional
environment

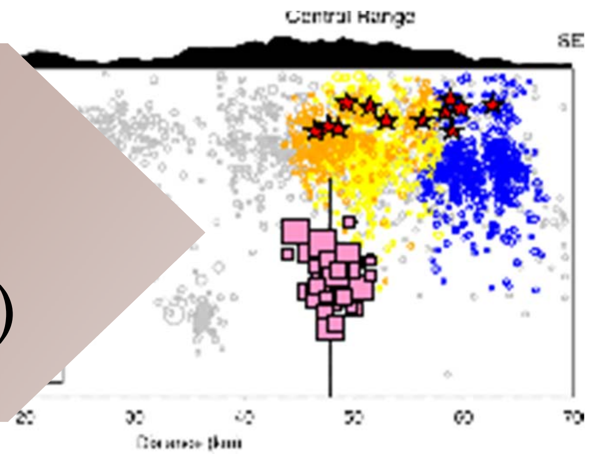
subsurface

Low Qp
Low resistivity
High T
Normal faulting

Connected seismic features



Hybrid event (< 7km)
Swarms (< 15 km)
Tremors (16 – 34 km)



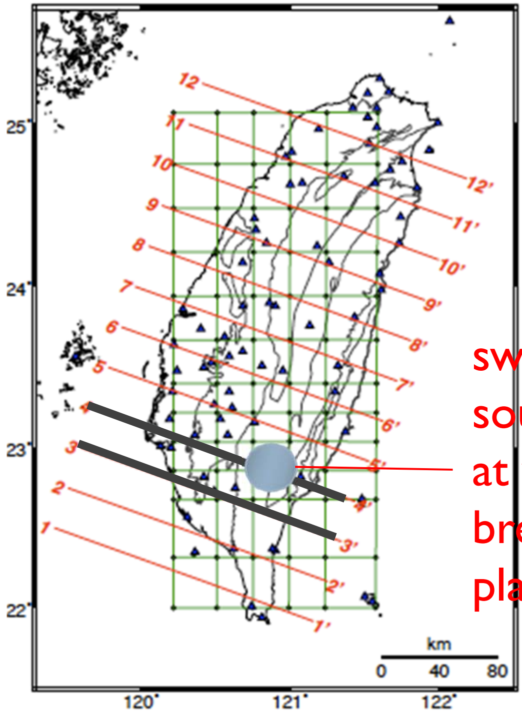
But where the deep water comes from?

Tectonic context

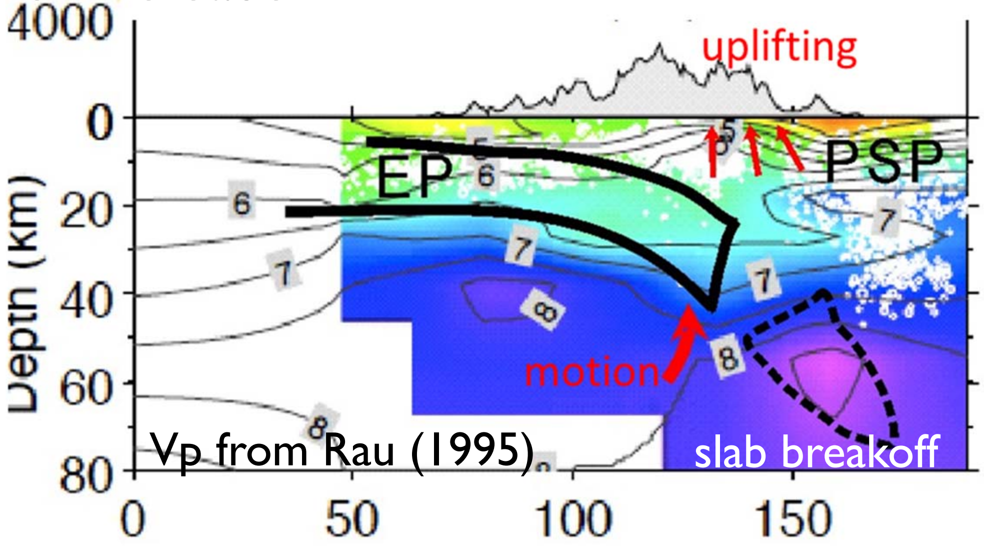
Enough subduction to produce metamorphic fluids

Enough extension to accelerate their release

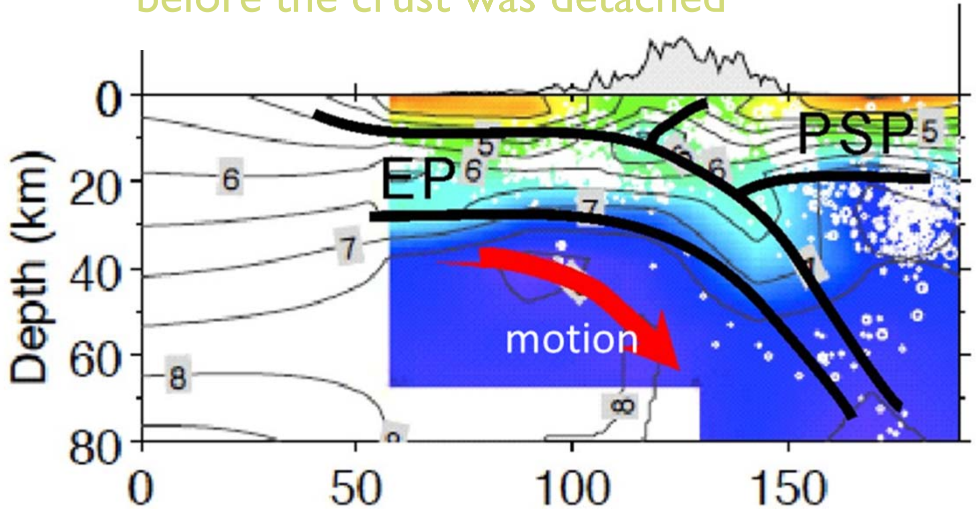
Crustal detachment and extension accelerates the fluid release



swarm/tremor source is located at where slab breakoff took place



The area experienced the most subduction before the crust was detached



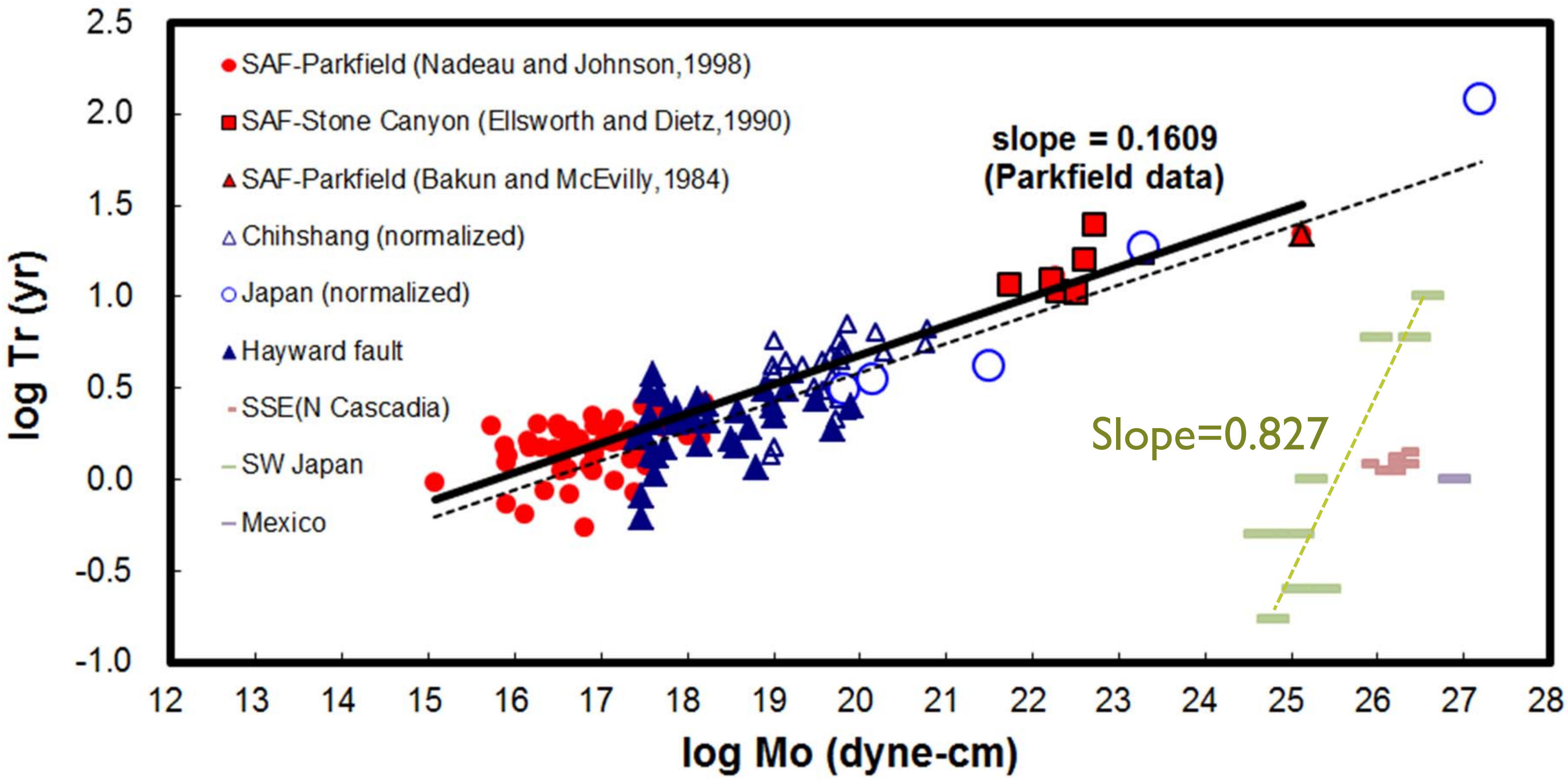
Subduction leads to metamorphism which makes fluids

Discussion

Controls of recurrence behavior?

Recurrence interval vs. Seismic moment

Slow earthquakes is different from ordinary earthquakes



~1/6

~1/1.2

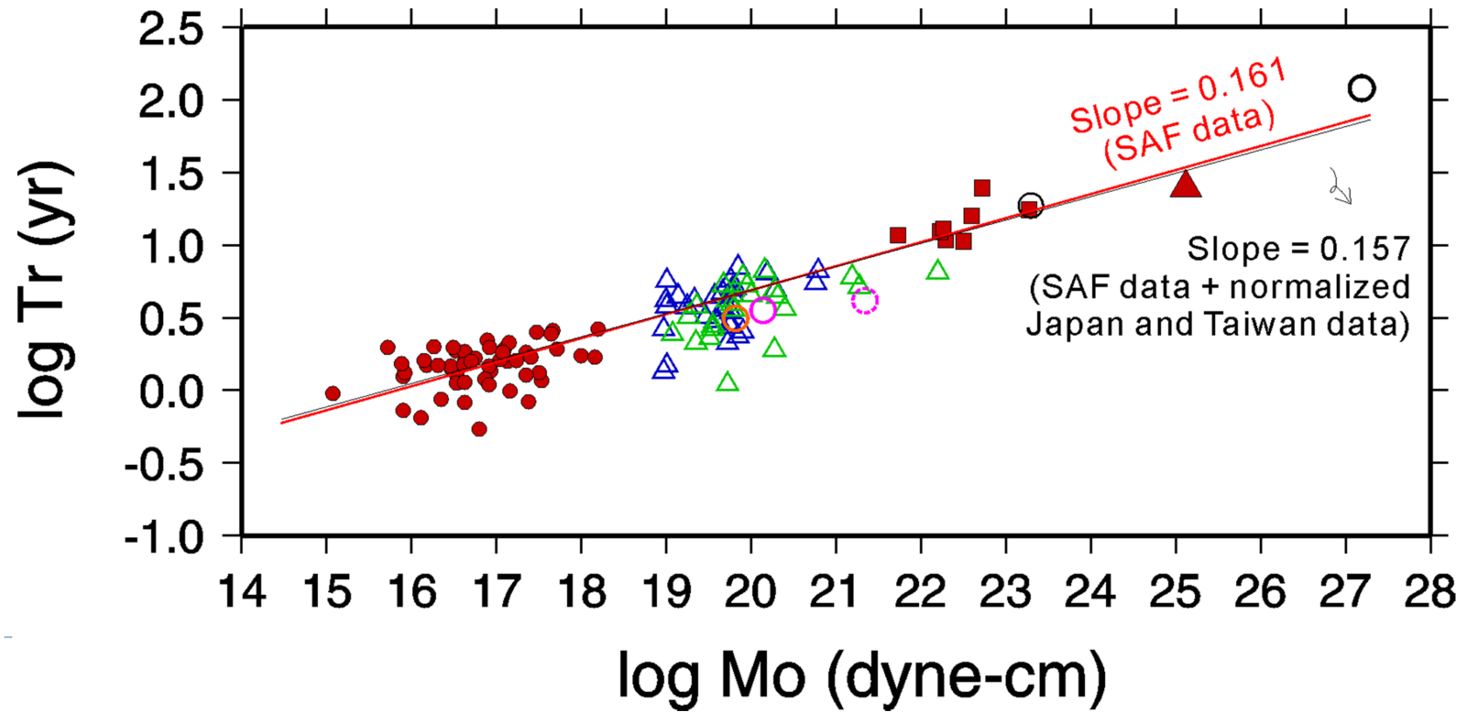
Normalized *Tr-Mo* scaling

How much of regional Tr difference can be explained by differences in long-term tectonic loading rate?

$$T_r \propto 1/V_f$$

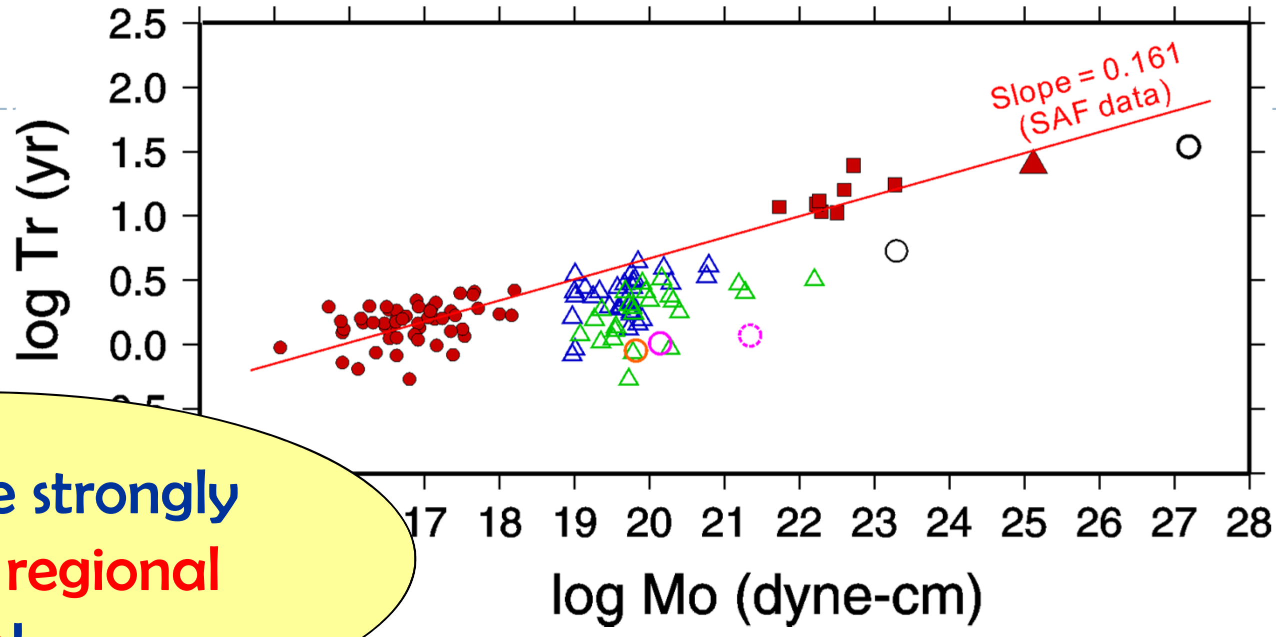
average loading rate on the fault plane

$$T_r^{nor} = \frac{V_f \times Tr}{V_{parkfield}}$$



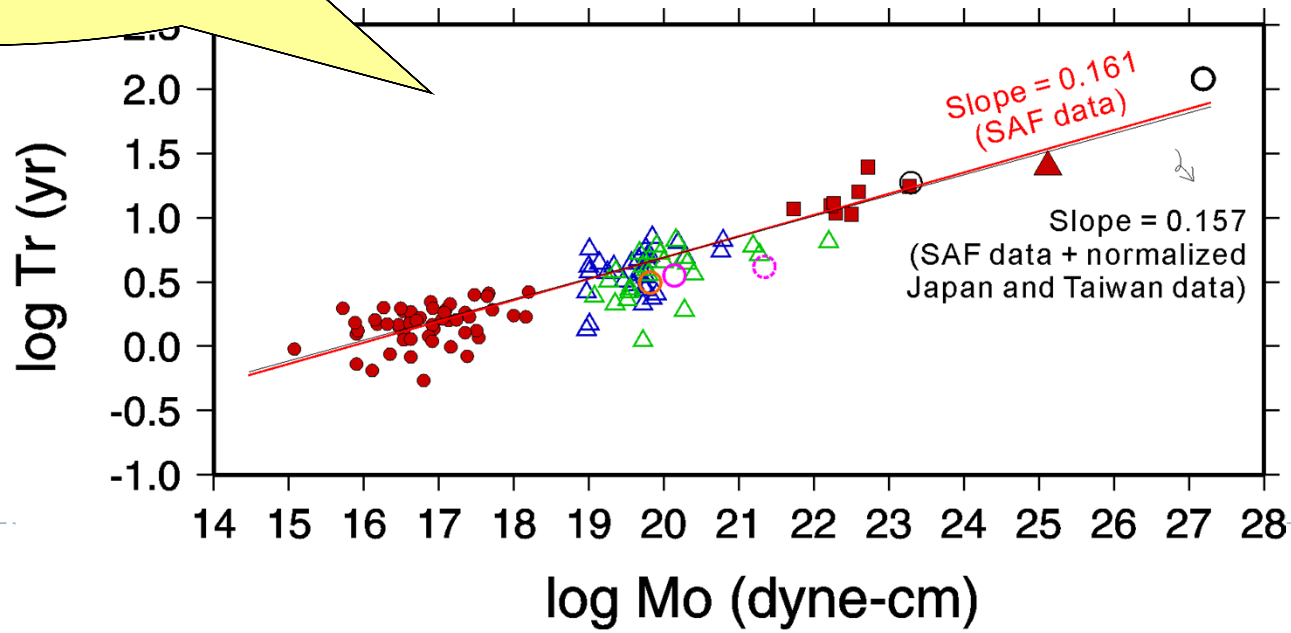
Normalized *Tr-Mo* scaling

Before normalization



Repeat time strongly depends on regional loading rate!

After normalization



Repeating events: Why weak dependency ?

$$T_r = \frac{\Delta\sigma^{2/3} M_0^{1/3}}{1.81 \mu V_d}$$ [Beeler et al., 2001]

Vd = constant

- The relationship $\Delta\sigma \propto (M_0)^{-1/4}$ is required to yield $T_r \propto (M_0)^{1/6}$, that is, the stress drop is inversely proportional to the 1/4th power of seismic moment. In this case, very small repeating events could have very high stress drop [*Nadeau and Johnson*, 1998; *Sammis et al.*, 1999].

Stress drop Δσ= constant

- $V_d \propto (M_0)^{1/6}$ is required to yield $T_r \propto (M_0)^{1/6}$, which implies that the fraction of tectonic load that is released seismically versus aseismically as repeating asperity rupture is size dependent [*Anooshehpoor and Brune*, 2001; *Beeler et al.*, 2001; *Sammis and Rice*, 2001].

Slow slip events: Why strong dependency ?

$$T_r = \frac{\Delta\sigma^{2/3} M_0^{1/3}}{1.81 \mu V_d}$$ [Beeler et al., 2001]

_Vd_ = constant

- The relationship $\Delta\sigma = Mo^{3/4}$ is required to yield $T_r = Mo^{1/1.2}$, that is, the stress drop is proportional to the 3/4th power of seismic moment. In this case, greater SSE could have higher stress drop.

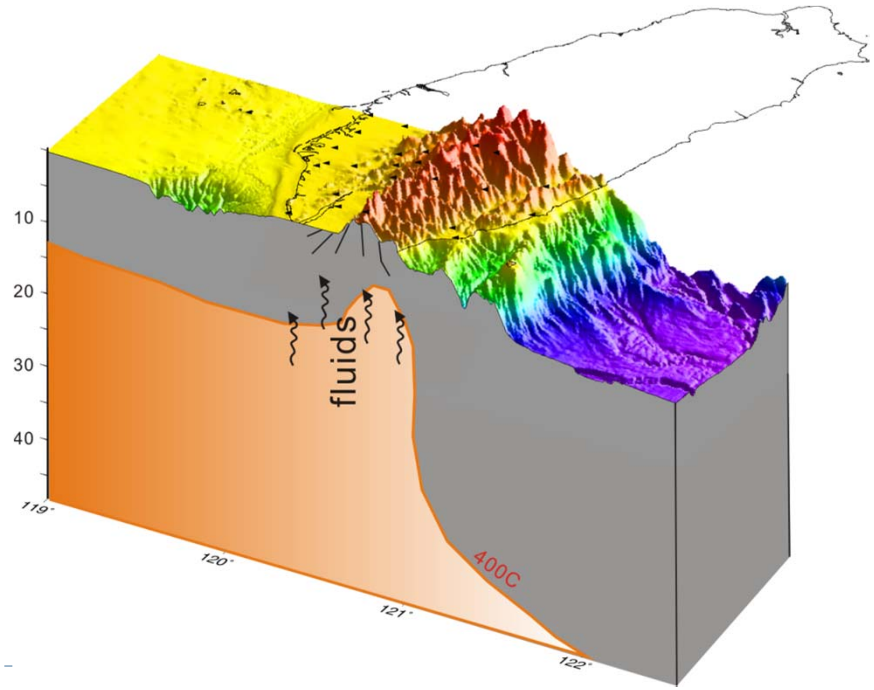
- **Stress drop $\Delta\sigma$ = constant**
- $V_d = Mo^{-1/6}$ is required to yield $T_r = Mo^{1/1.2}$, which implies that the fraction of tectonic load that is released seismically versus aseismically as repeating asperity rupture is size dependent.

Summary

In addition to a co-seismic slip-induced stress change from nearby major earthquake, increased tremor rate is also highly correlated with the active, normal faulting earthquake swarms at the shallower depth.

The ambient tremor events in this study are characterized by repeat time of 12.42, 24, and 25.85 hours. Most tremors occurred when tidal level is high, suggesting the correlation between tremor generation and tidal stress. And such correlation explains the 12.42-hr recurrence interval in tremors.

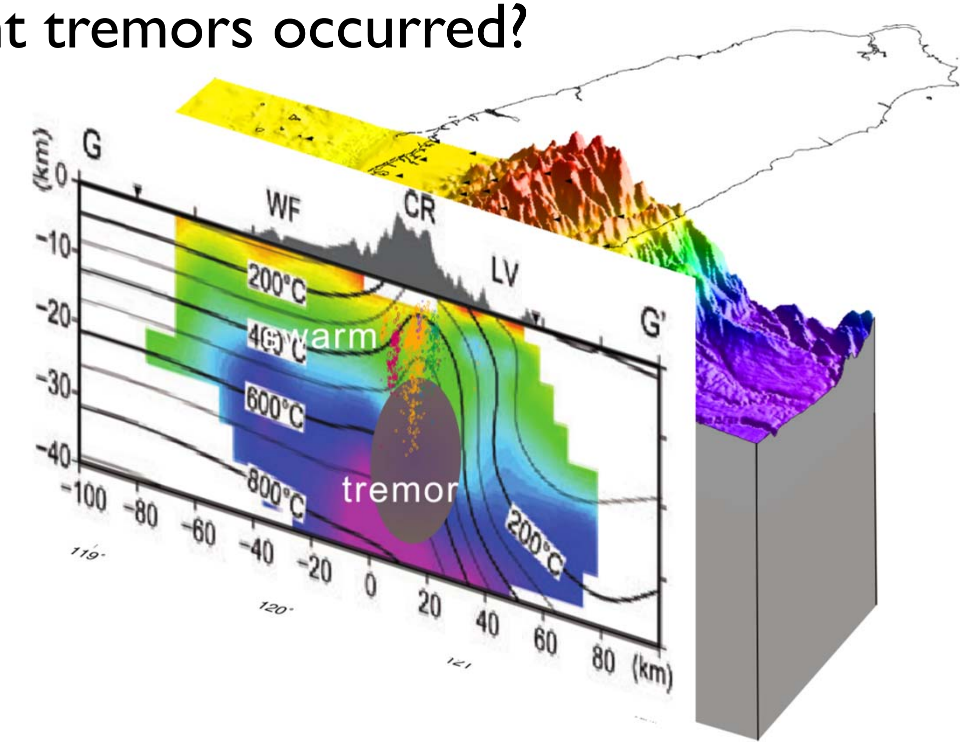
Both the tremor and earthquake swarm activities are confined in a small area where the high attenuation, high thermal anomaly, the boundary between high and low resistivity, and localized veins on the surface are distributed, suggesting the involvement of metamorphic dehydration and fluid flow processes within the orogen.



Future works

Where ambient tremors occurred?

- More precise location of tremor events
- Continues monitoring of deep deformation
- Interaction with nearby earthquakes



Why ➡ / **What (condition)** ➡

Controls of the duration and amplitude?
Controls of the timing of occurrence?
Controls of the recurrence property?
Controls of the tremor location?
Controls of the migration pattern?
Controls of frequency characteristics?