Short and long-period crustal strain observations along eastern Taiwan

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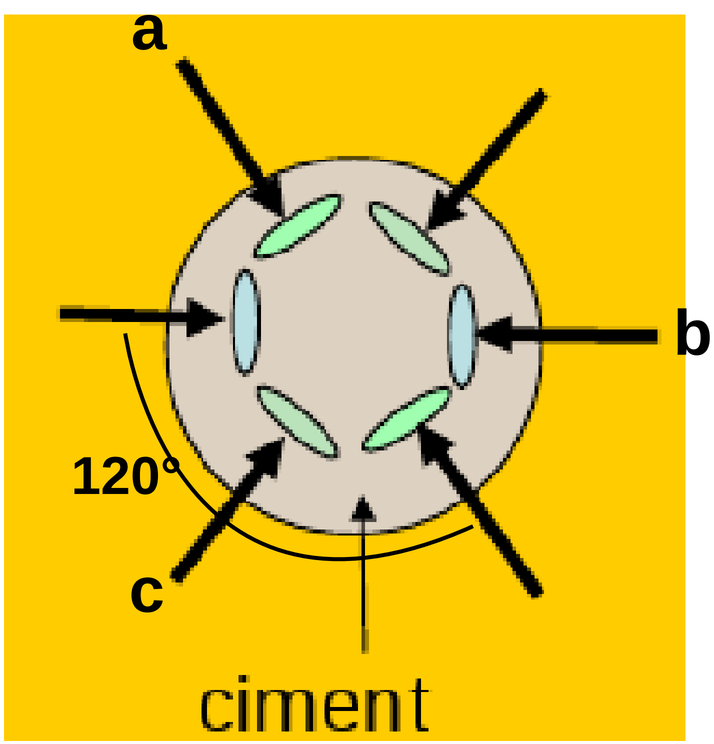
Summary :

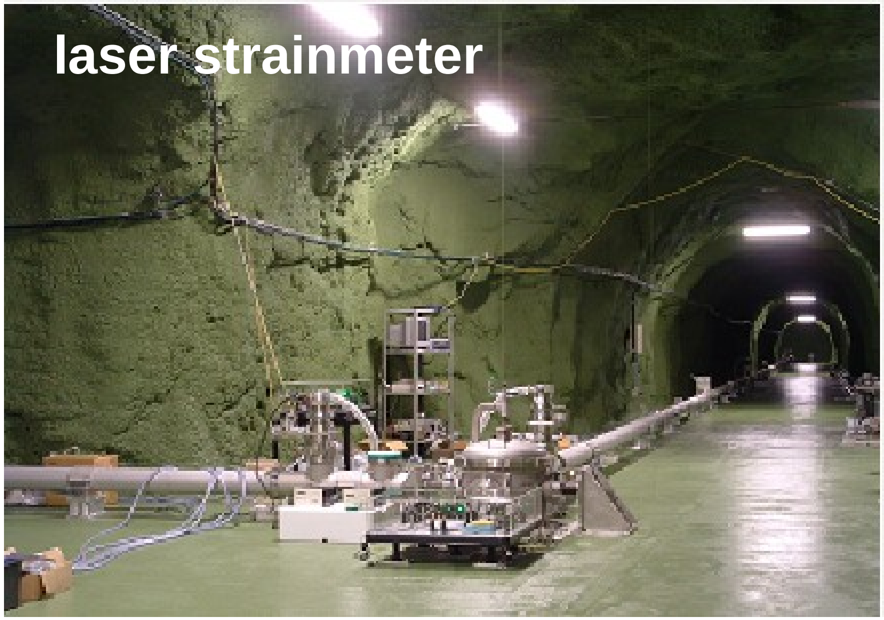
1. **Borehole strain measurements :** generalities, instrumentation, …

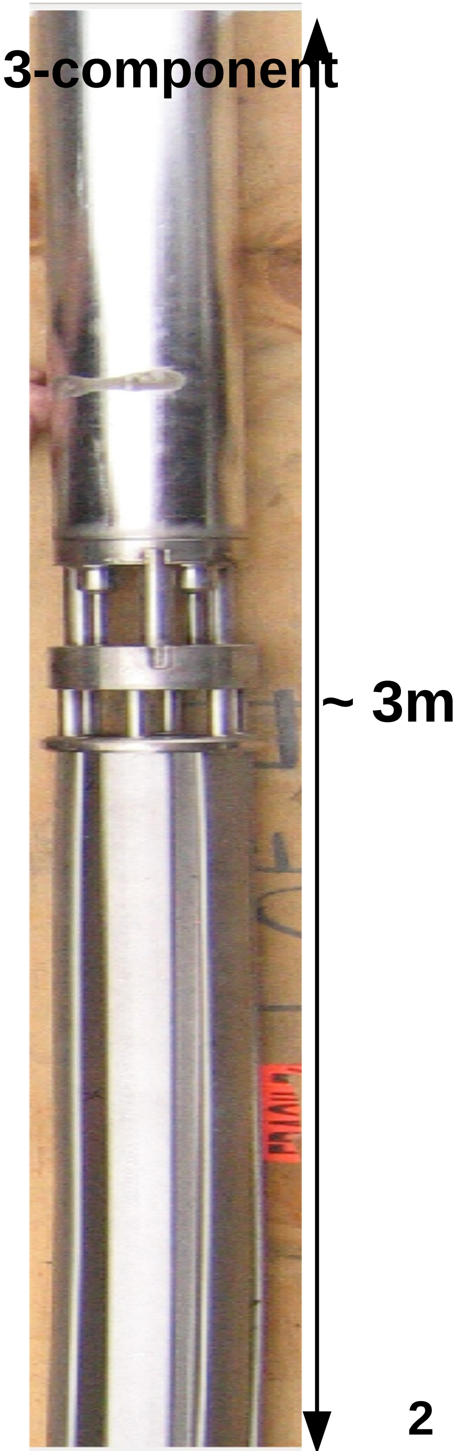
2. **Short-period strain observation :** complete crustal strain field of the 2013 October M6.2 Rueisuei earthquake

3. **Long-period strain observation :** aseismic creep sequence during April 2010 along the Chihshang fault

What is a dilatometer/strainmeter ?

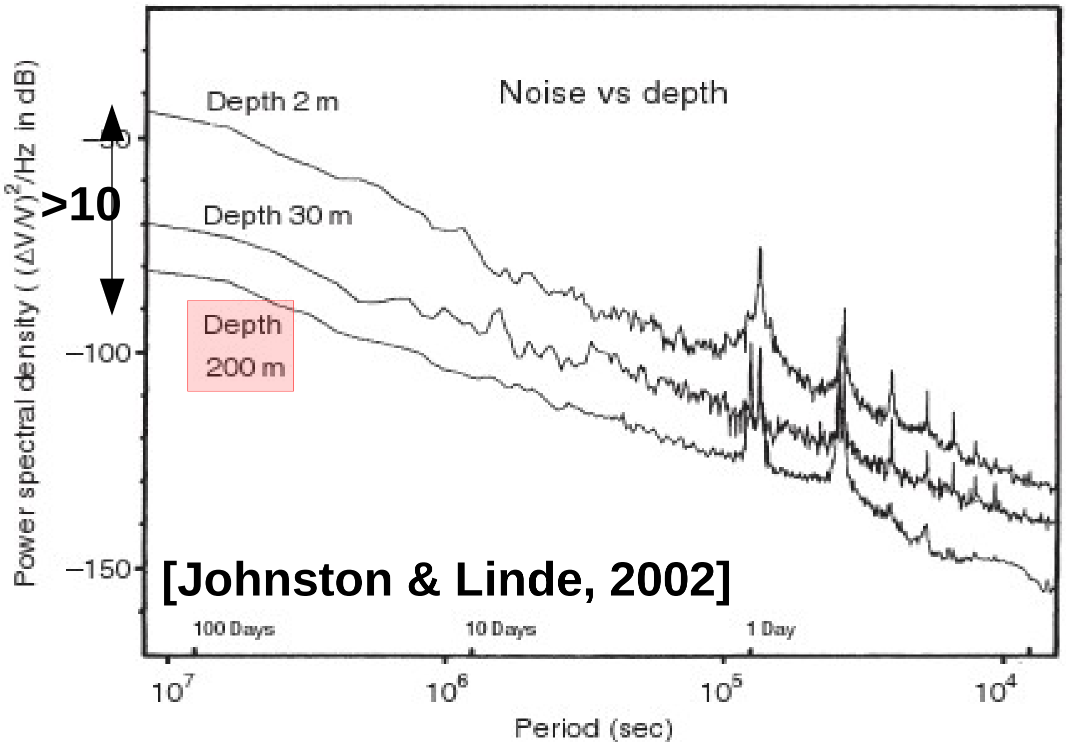




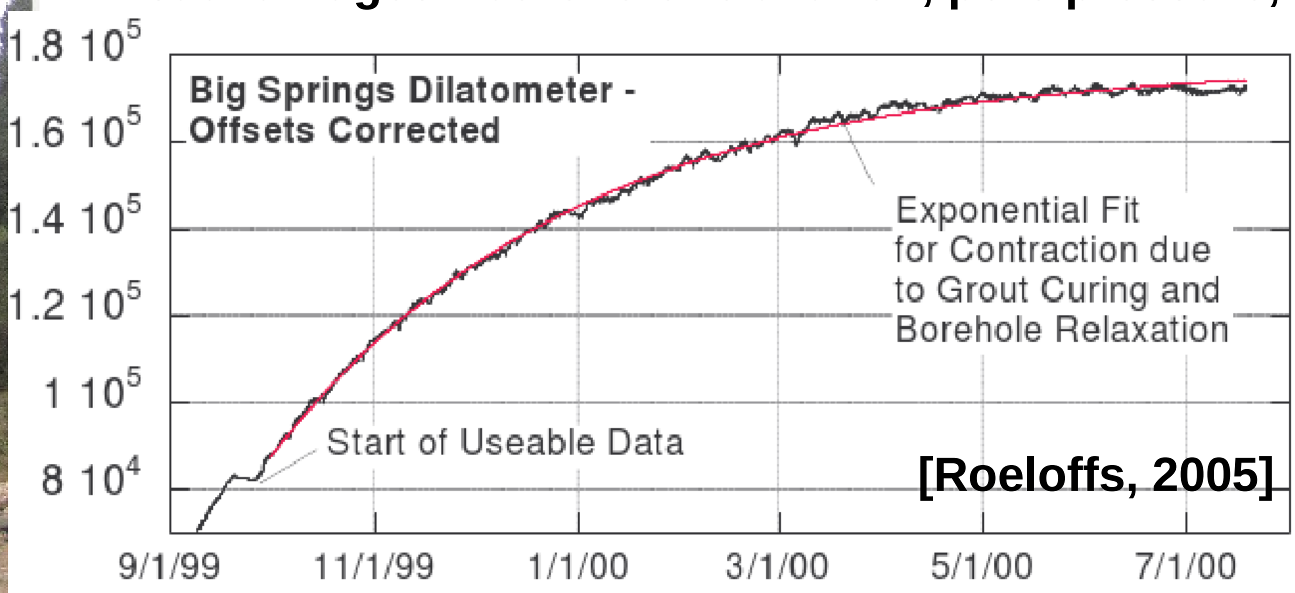


Installation in a borehole

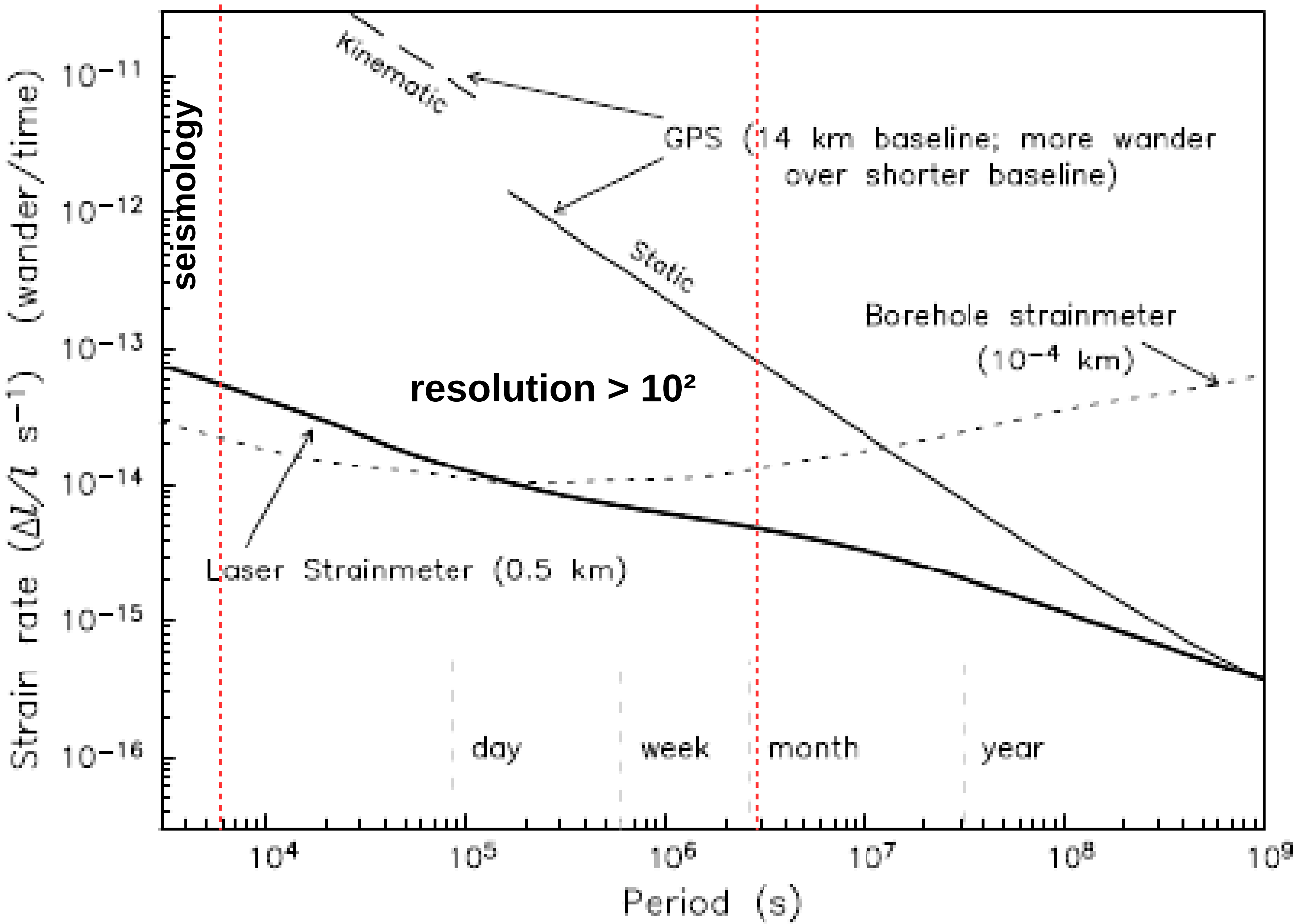
Advantages : isolation, noise reduction, ...



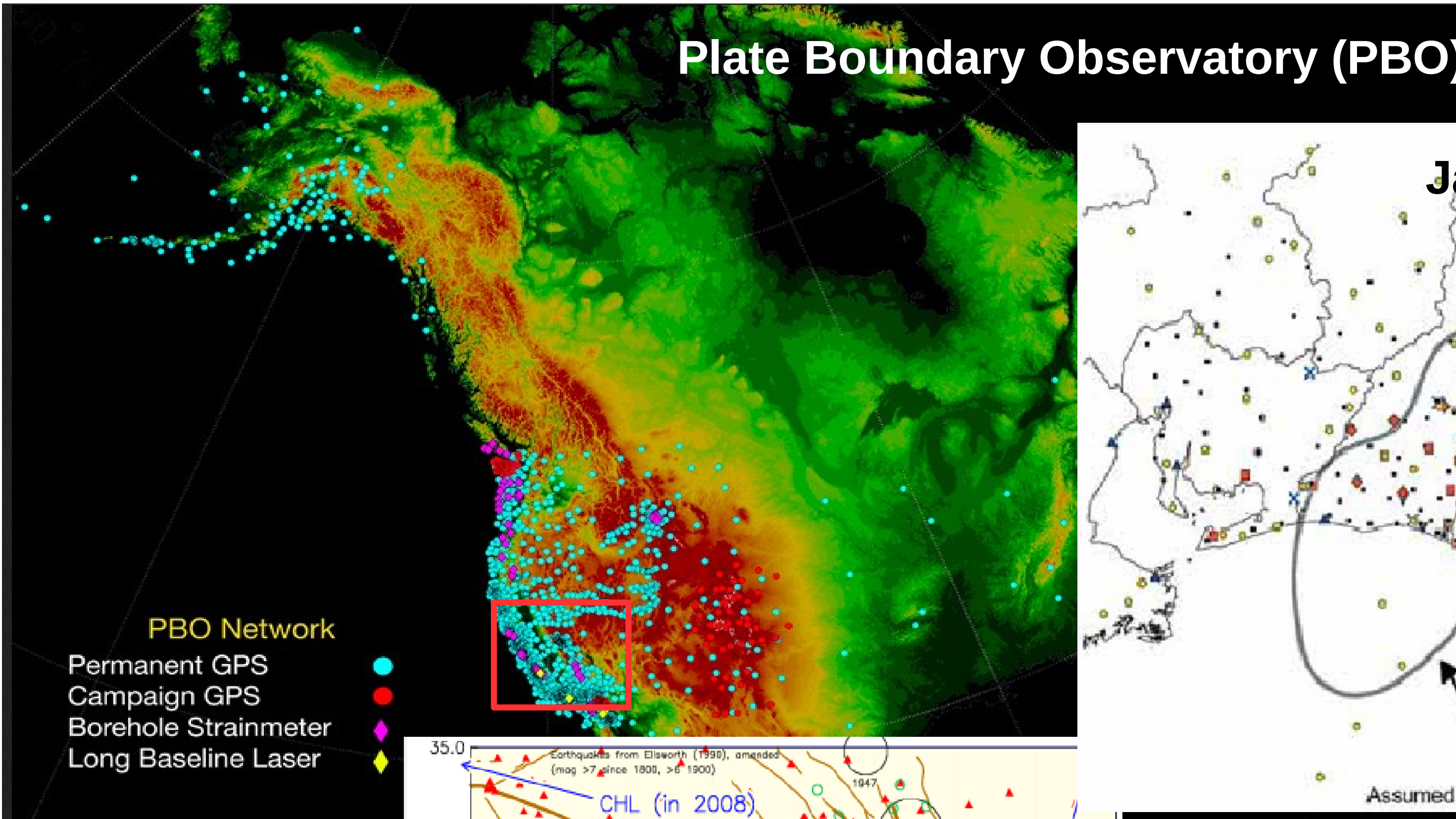
Disadvantages : borehole relaxation, pore pressure, ...

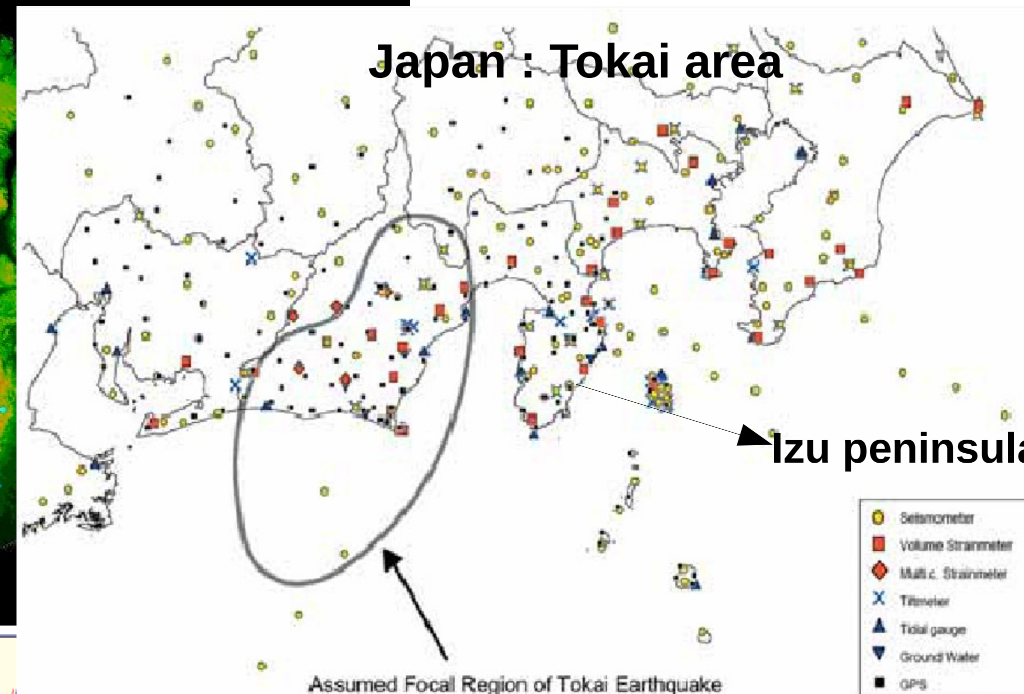


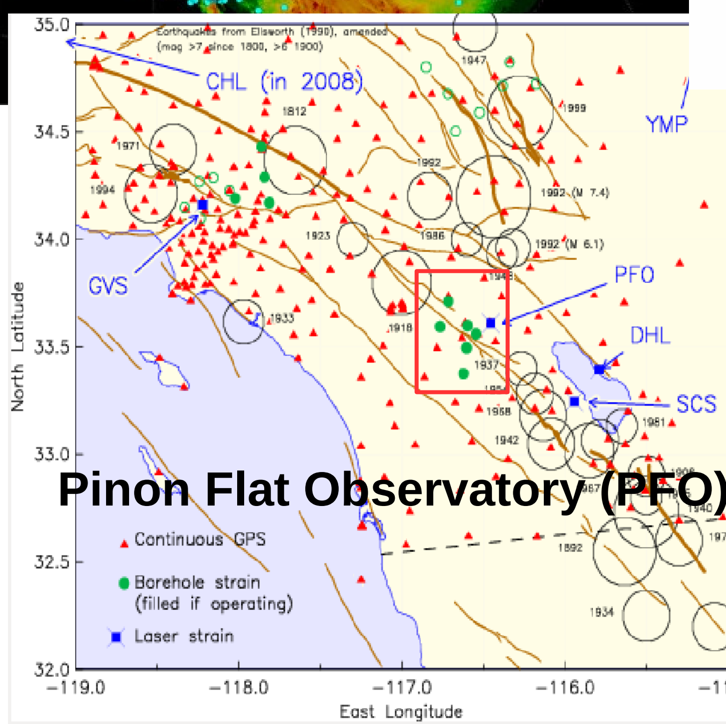
Interest : filling the gap between seismology and GPS measurements



Major networks



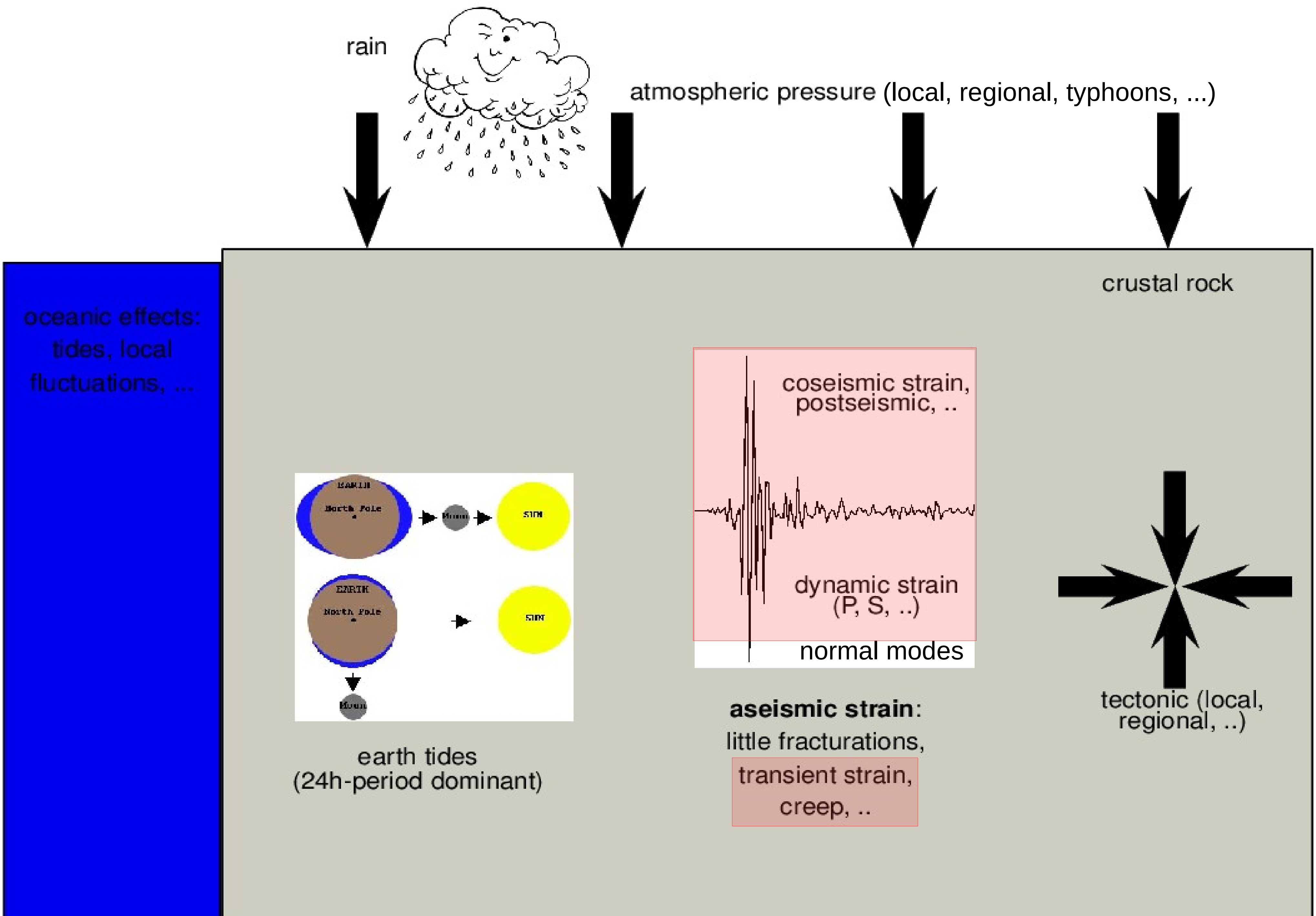




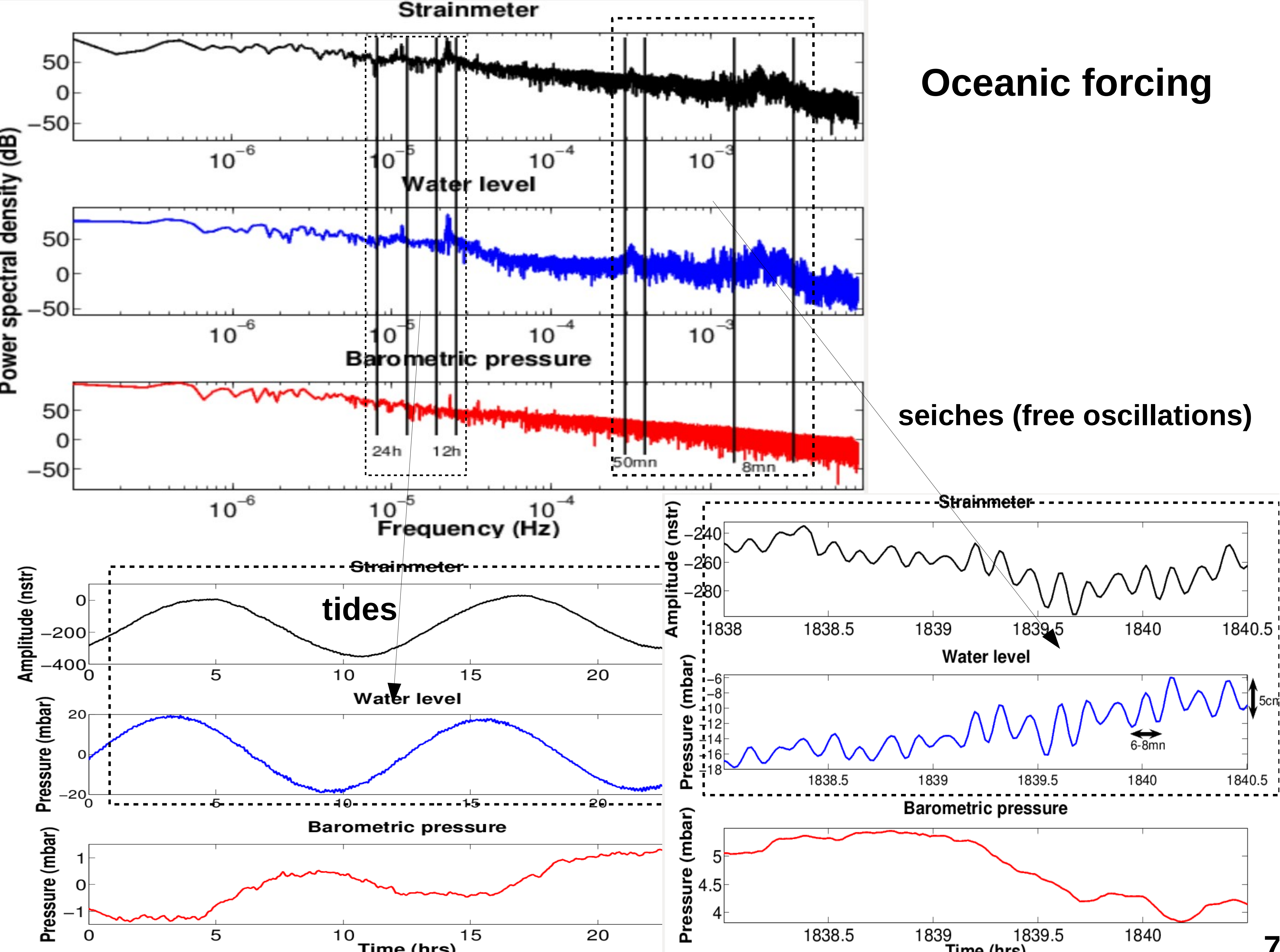
+ Europe : Greece (Gulf of Corinth), Italy (Etna, Vesuvio, Friuli, …), Iceland (Hekla), Germany (Black Forest)

+ Montserrat, Russia, China, ...

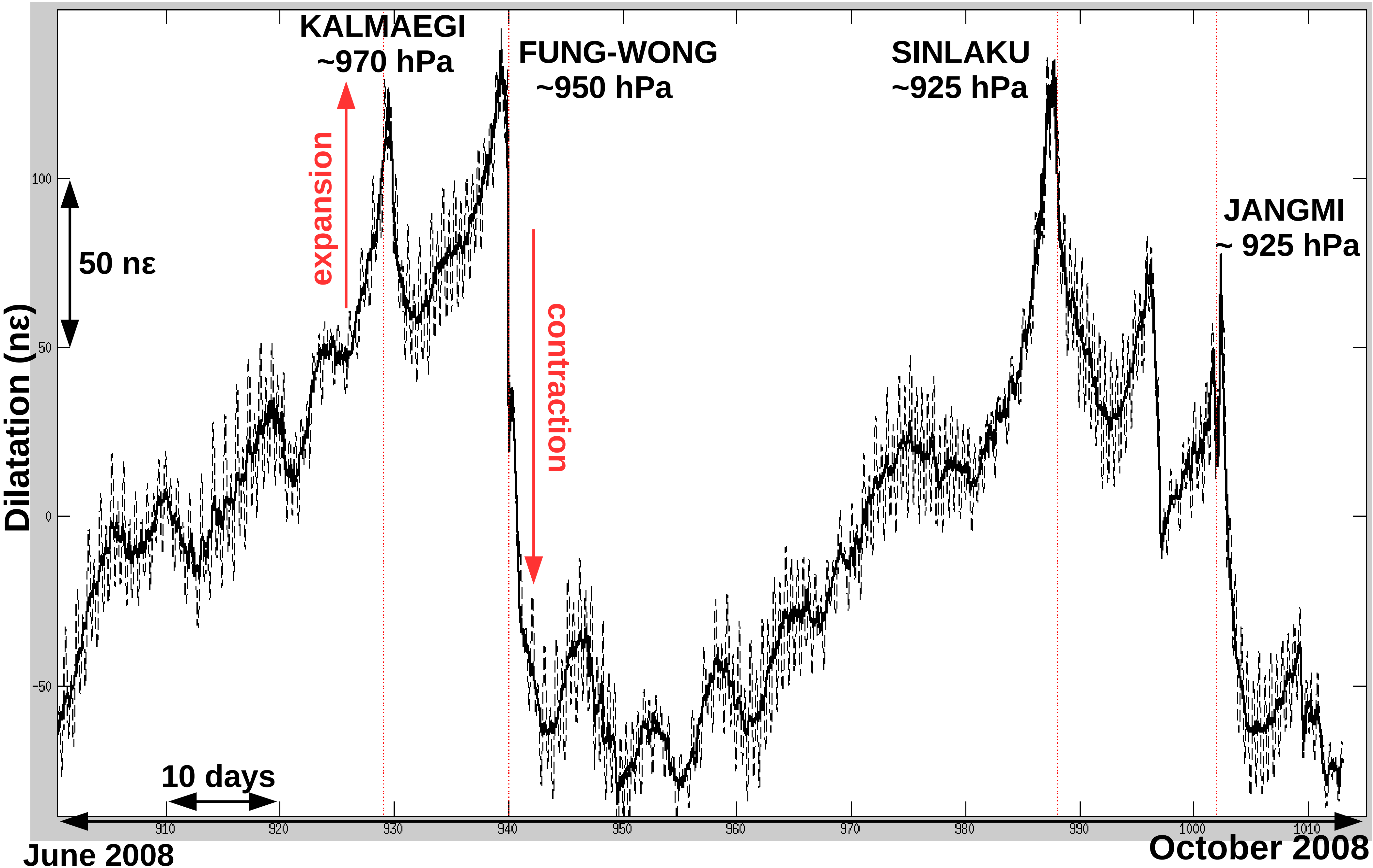
What does it record ?



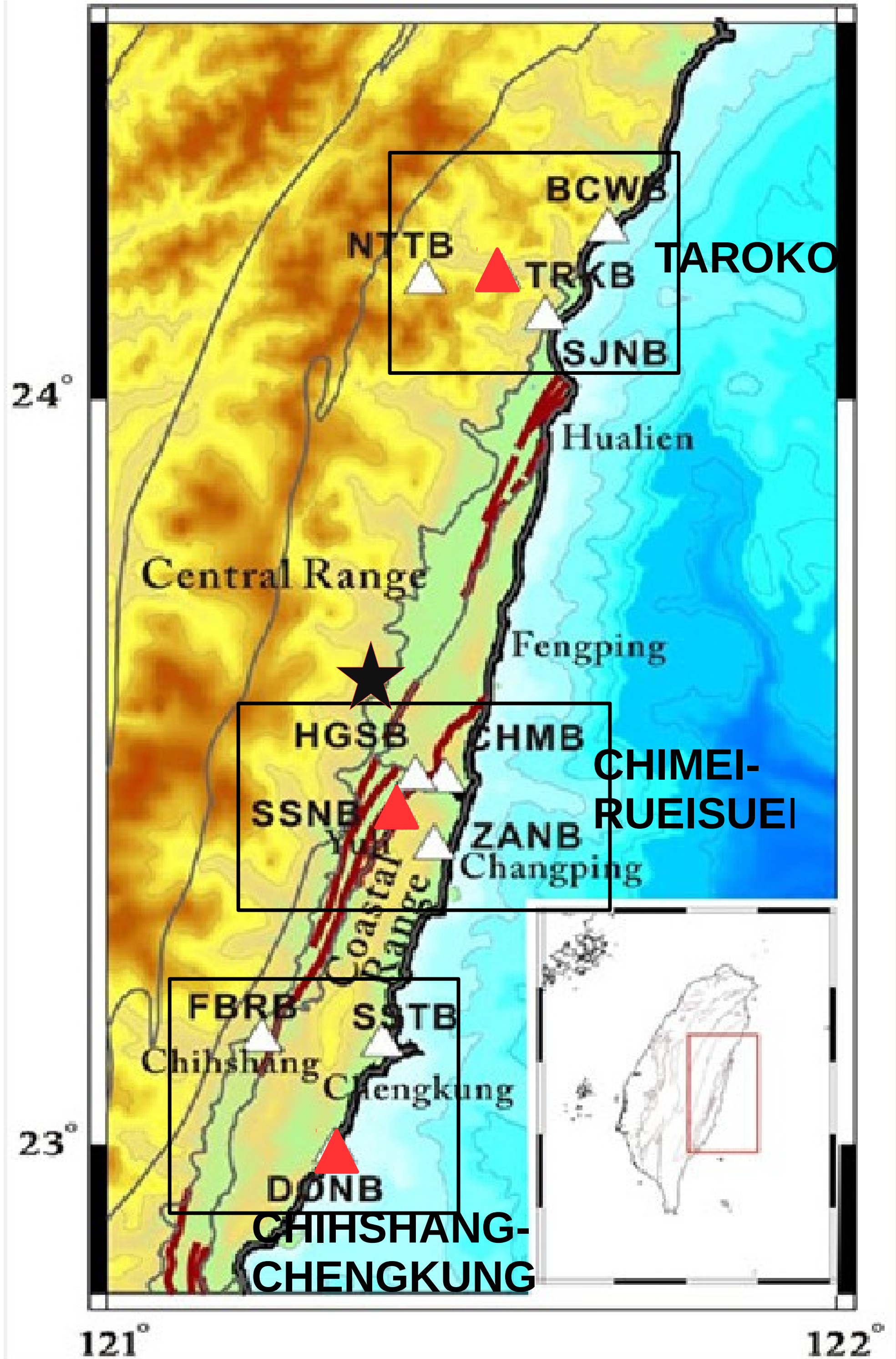
Oceanic forcing



Crustal deformations induced by typhoons

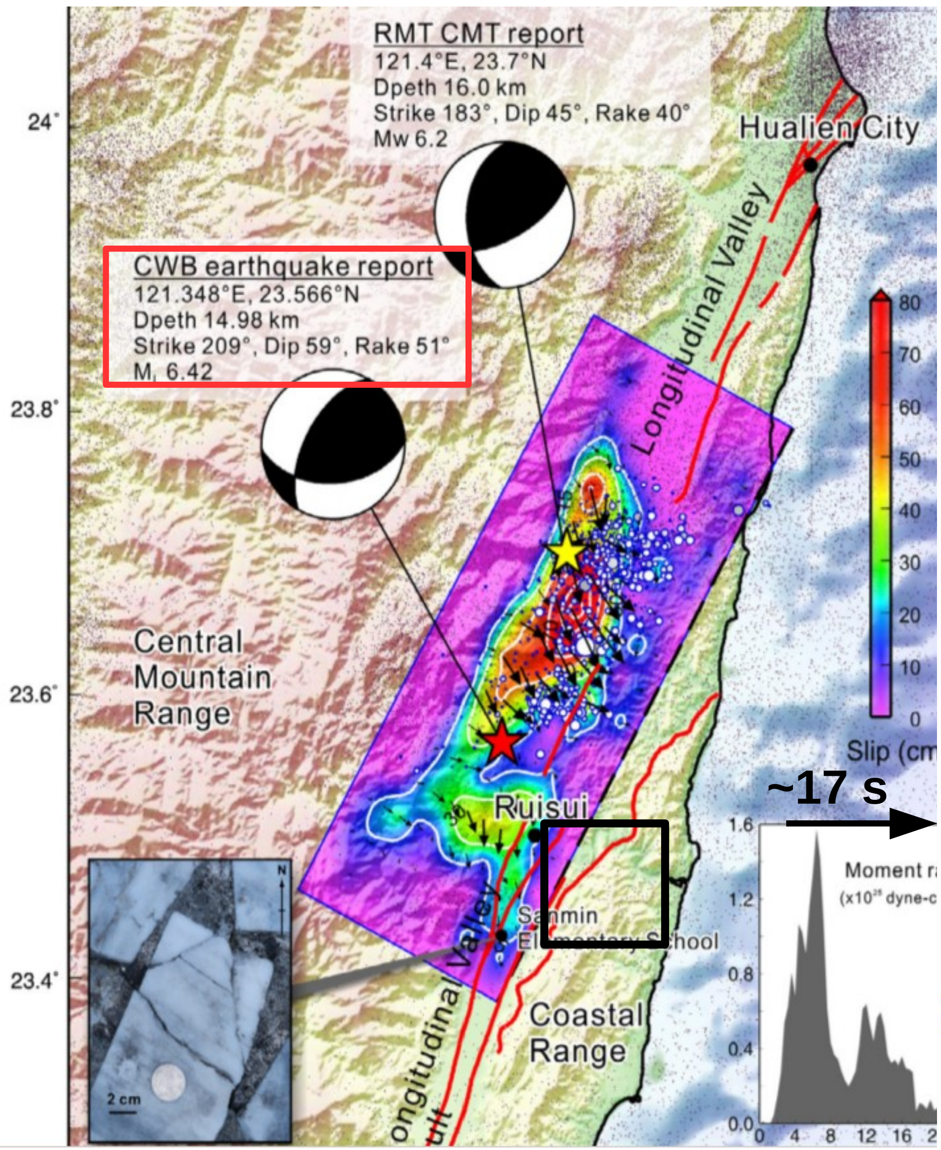


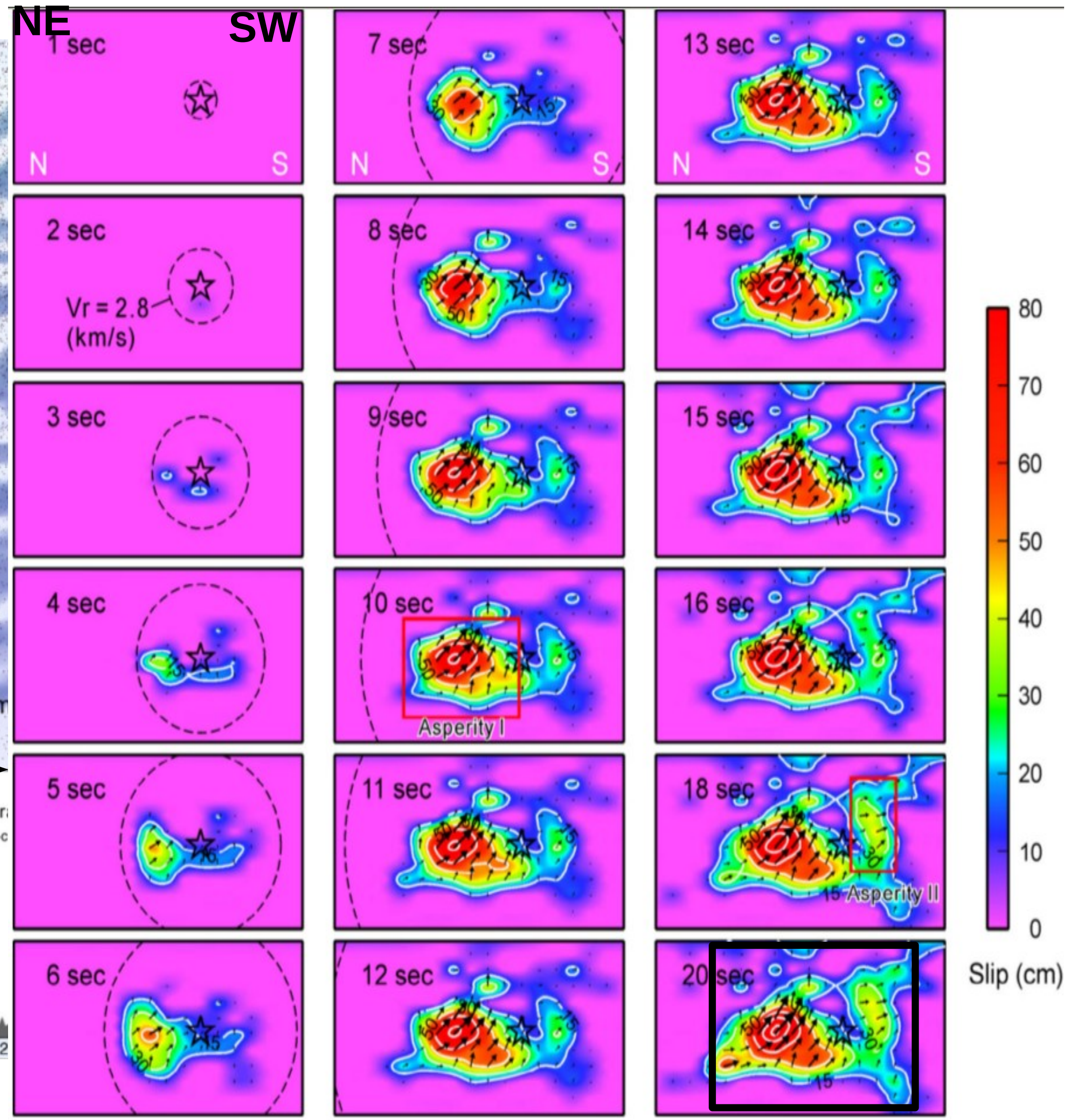
Borehole strainmeter network established along eastern Taiwan



Near-field dilatation observation : the October 2013 Ruisui earthquake

Numerical simulations 5-20 s





30 x 30 km²

[Lee et al., 2014]

Motivations :

- Preliminary dynamic strain observations [Sacks et al., 1971, Gomberg & Agnew, 1996] have pointed out the capability of dilatometers on recording accurately high-frequency seismic waveforms, but no attempt on modeling the complete crustal strain field as recorded by dilatometers has been proposed so far

  - The October 2013 Ruisui earthquake is one of the rare worldwide strain observation of a moderate shock occuring in the near-field of a dilatometer network

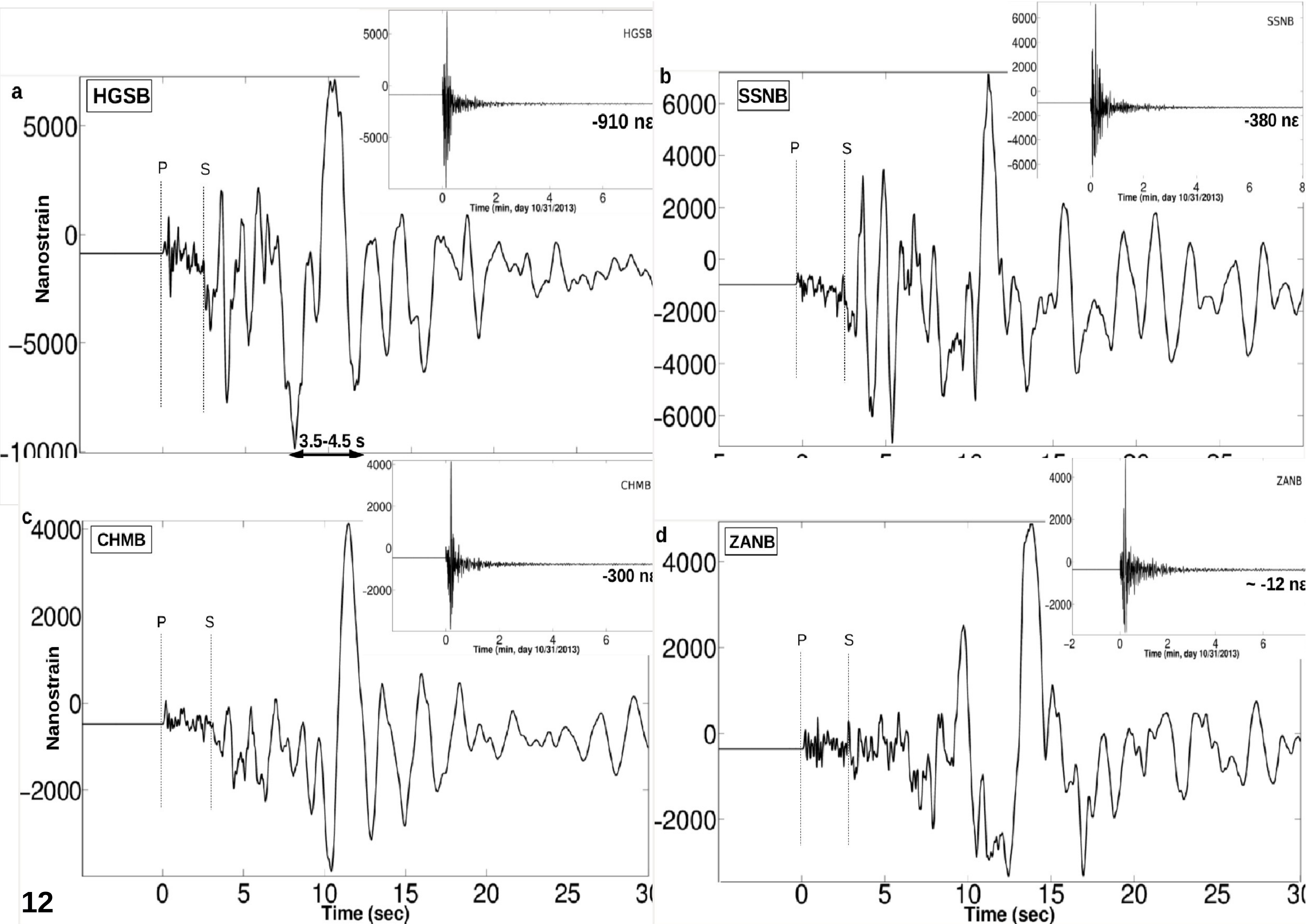
    - It provides presumably the highest resolution strain data since the instrument installations (one decade ago) and allows to constrain location and seismic source process through the use of different component of the crustal strain field (e.g. dynamic, static and permanent near-field)

    - Such an inversion is challenging as we deal with few sites and invert for 3 different components of the crustal strain field at each site (and thus different processes of a seismic rupture). We thus do not performed a full inversion and conducted the study into 2 steps :

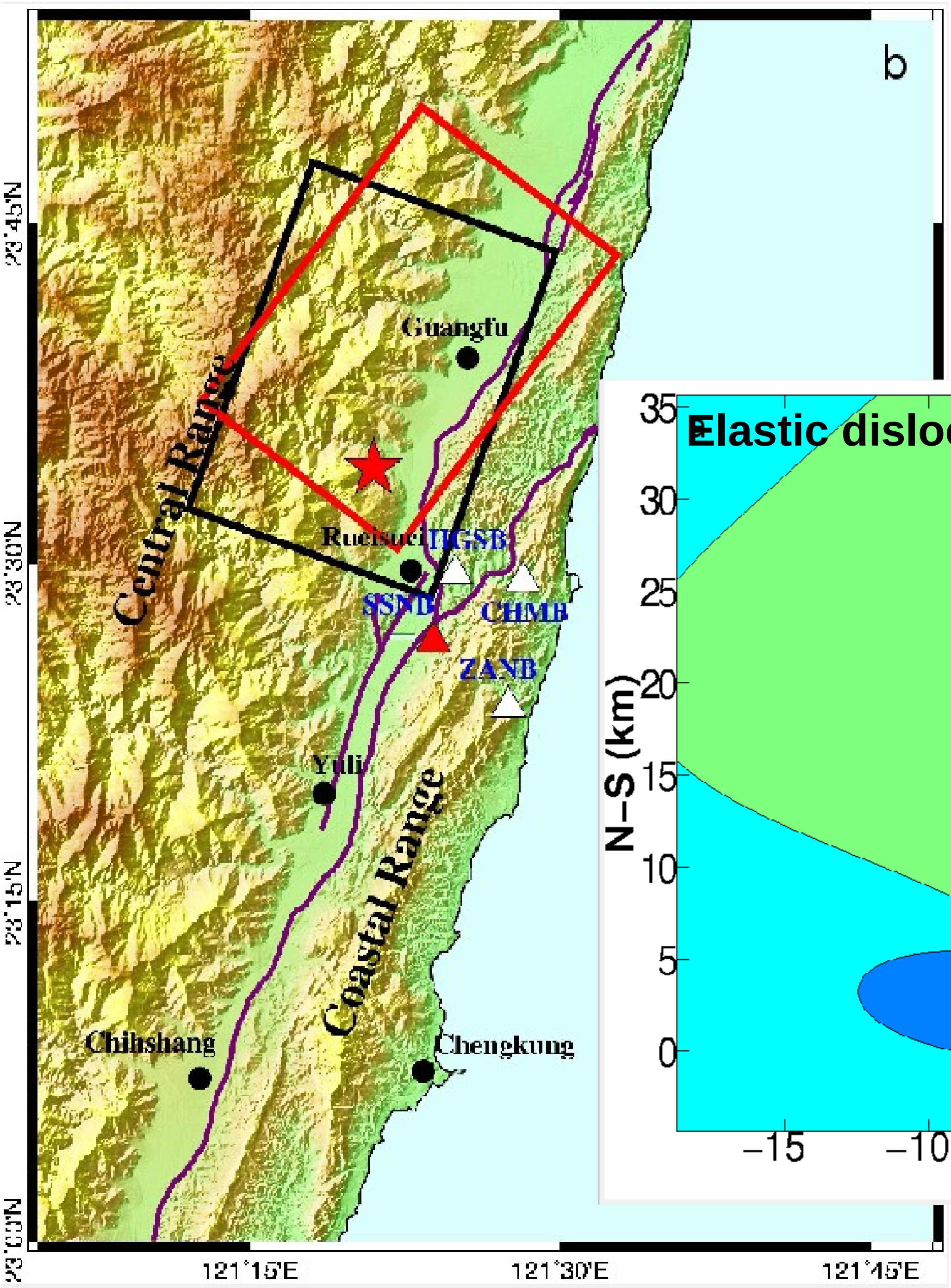
      - Inversion of the static signals only to assess the source location and fault source parameters

      - Use the previous parameters to invert for the source process and also model the complete crustal strain field

Near-field dilatation signals

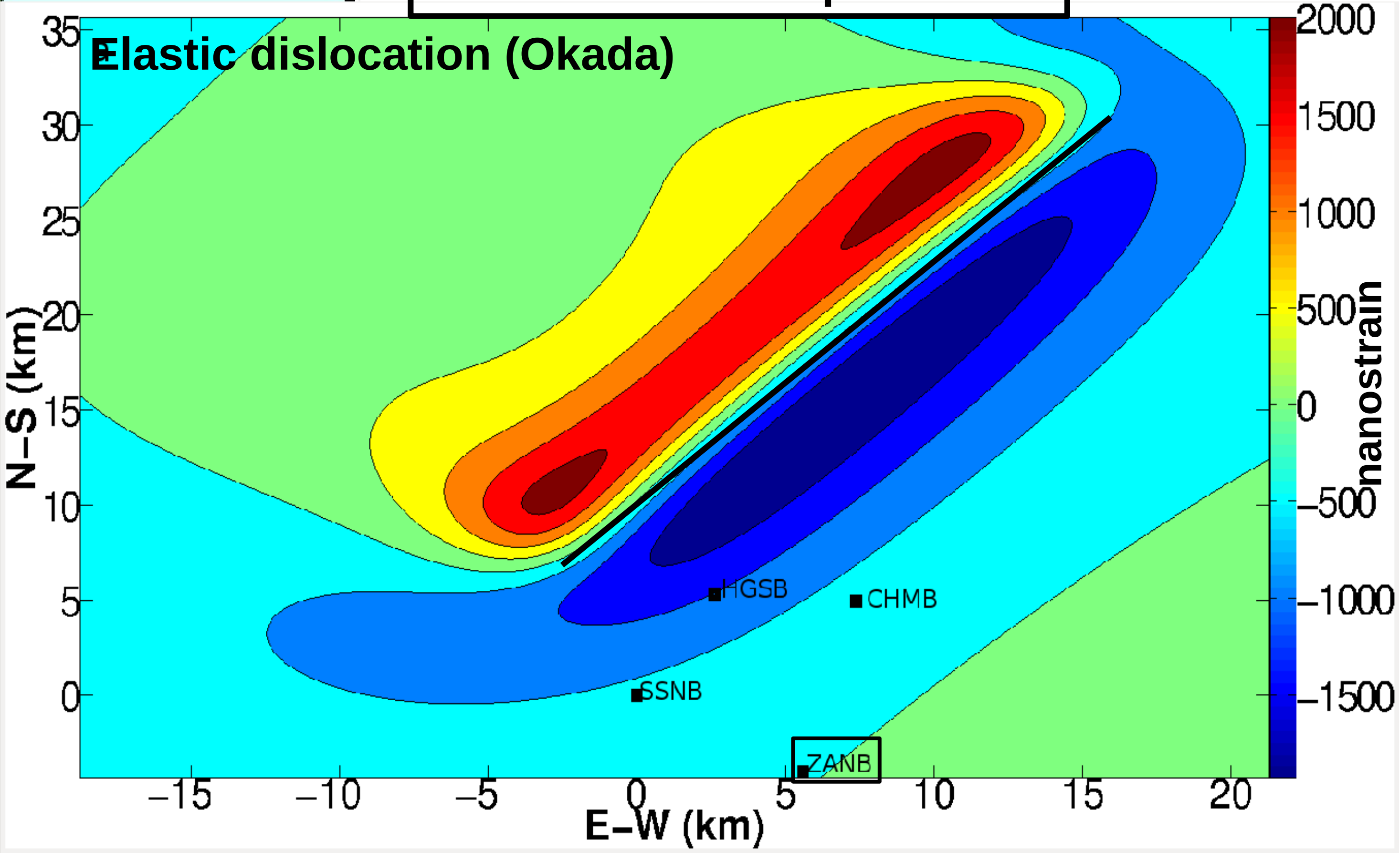


Best source fault model inferred from static signals

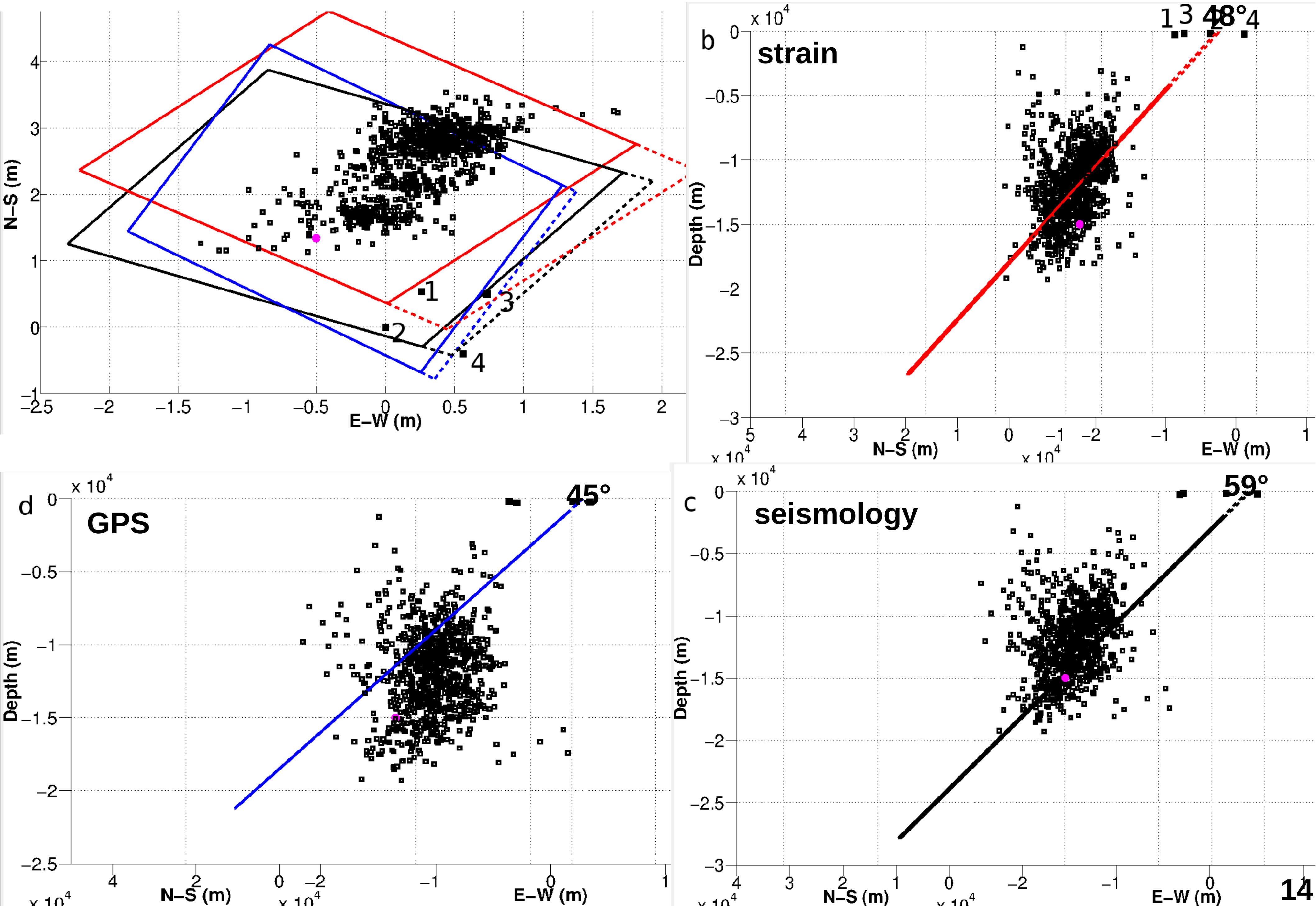


- grid search by inverting 6 parameters : azimuth, dip ,rake + position of centroid
- strong constraints on depth (±500m), azimuth (±2°) and dip (±3°)

217°/48°/49° - Depth : 15 km



Comparison with aftershock location

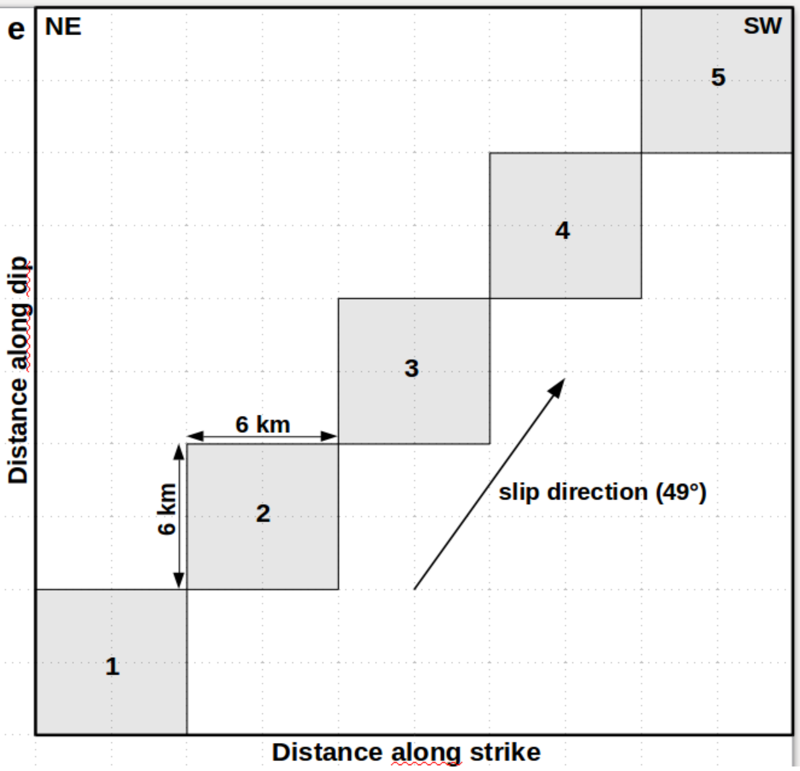


Modeling the complete dilatation strain field of the Ruisui event

- Inversions are performed with AXITRA's 3D reflectivity code of dislocation (Coutant, 1989). Modeling of the seismic source is performed with point sources embedded in a medium with layers (9 layers [Chen, 1995]). The full wavefield Green's functions are calculated by the discrete wavenumber method (Bouchon, 1979)

- Limit the calculation of the dynamic field to about 4-5 s period as a 30 km-long fault requires a minimum of 4-5 sources (dimensions of about 6 x 6 km²) to be triggered sequentially for a reasonable waveform estimation

- 5 sources are convoluted using a triangle-like source as moment-rate function and the computation of the (N, E, Z) displacements at the corners of an infinitesimal cube surrounding each instrument position are estimated



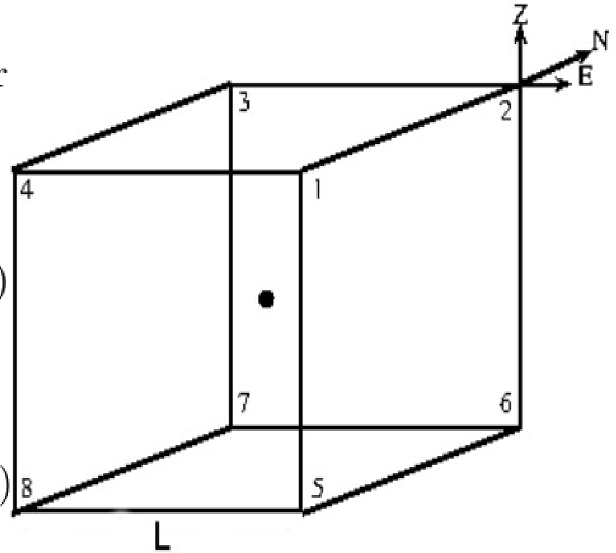
- Simulations are performed by using as a-priori constraints the fault parameters (217°/48°/ 49°) and location (depth varies)

- Allow the slip to vary over the fault patches when invert for triggering sequence, subevent timing, rise-time (constant) and depth of the fault plane

- Fit the 3 components of the strain field at each site by trial and errors

Under the assumption of a homogeneous-linear-elastic medium and by considering a (E, N, Z) reference, the tensor of deformation may be expressed as a linear combination of displacements, as follows :

$$\epsilon = \begin{bmatrix} \epsilon_{EE} & \epsilon_{EN} & \epsilon_{EZ} \\ \epsilon_{NE} & \epsilon_{NN} & \epsilon_{NZ} \\ \epsilon_{ZE} & \epsilon_{ZN} & \epsilon_{ZZ} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 2\frac{\partial u_E}{\partial E} & \frac{\partial u_E}{\partial N} + \frac{\partial u_N}{\partial E} & \frac{\partial u_E}{\partial Z} + \frac{\partial u_Z}{\partial E} \\ \frac{\partial u_N}{\partial E} + \frac{\partial u_E}{\partial N} & 2\frac{\partial u_N}{\partial N} & \frac{\partial u_N}{\partial Z} + \frac{\partial u_Z}{\partial N} \\ \frac{\partial u_Z}{\partial E} + \frac{\partial u_E}{\partial Z} & \frac{\partial u_Z}{\partial N} + \frac{\partial u_N}{\partial Z} & 2\frac{\partial u_Z}{\partial Z} \end{bmatrix} \quad (1)$$



The volumetric strain ϵ_V, which represents the trace of the strain tensor ϵ, is:

$$\epsilon_V = \epsilon_{EE} + \epsilon_{NN} + \epsilon_{ZZ} = \frac{\partial u_E}{\partial E} + \frac{\partial u_N}{\partial N} + \frac{\partial u_Z}{\partial Z} \quad (2)$$

$$\epsilon_V \sim \frac{\Delta u_E}{L} + \frac{\Delta u_N}{L} + \frac{\Delta u_Z}{L} \quad (3)$$

where Δu_E, Δu_N and Δu_Z are the total displacements in the East, North and Vertical directions, respectively. By considering expansion as positive, their expressions may be explicited as follows:

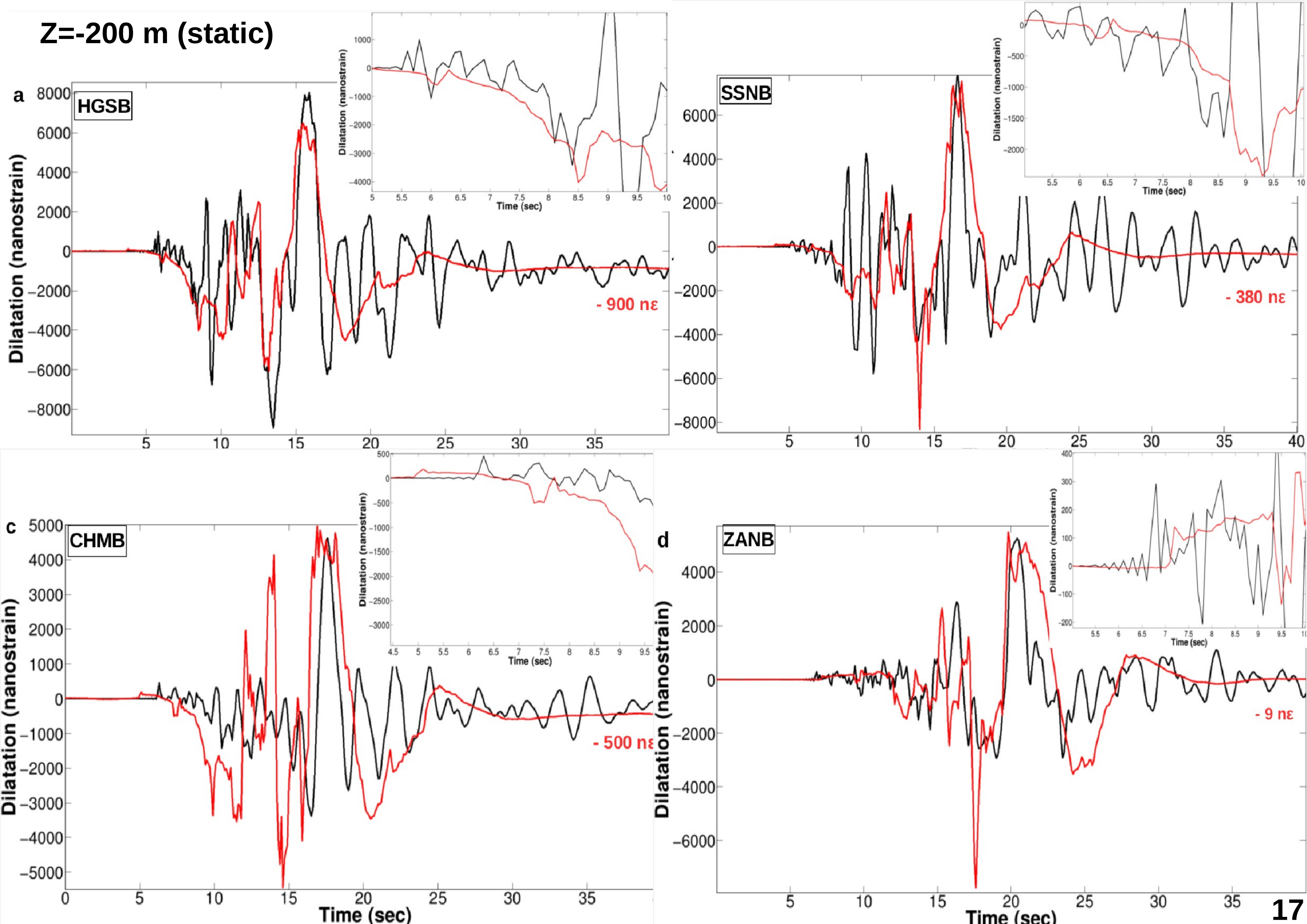
$$\Delta u_E = (u_{1E} - u_{4E}) + (u_{2E} - u_{3E}) + (u_{5E} - u_{8E}) + (u_{6E} - u_{7E}) \quad (4)$$

$$\Delta u_N = (u_{2N} - u_{1N}) + (u_{3N} - u_{4N}) + (u_{6N} - u_{5N}) + (u_{7N} - u_{8N}) \quad (5)$$

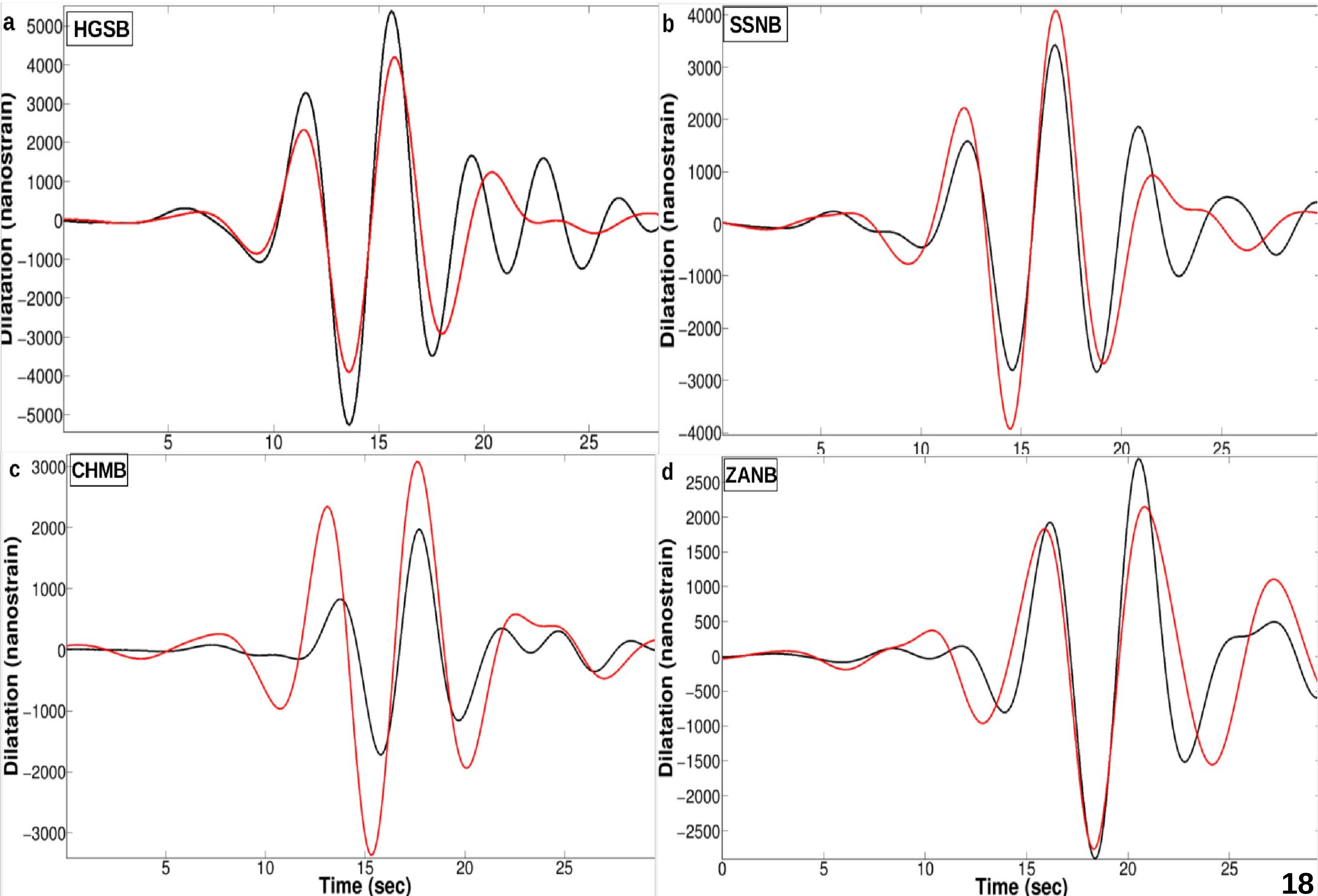
$$\Delta u_Z = (u_{1Z} - u_{5Z}) + (u_{2Z} - u_{6Z}) + (u_{4Z} - u_{8Z}) + (u_{3Z} - u_{7Z}) \quad (6)$$

where u_{4E} is the displacement component in the East direction at virtual station 4, for instance.

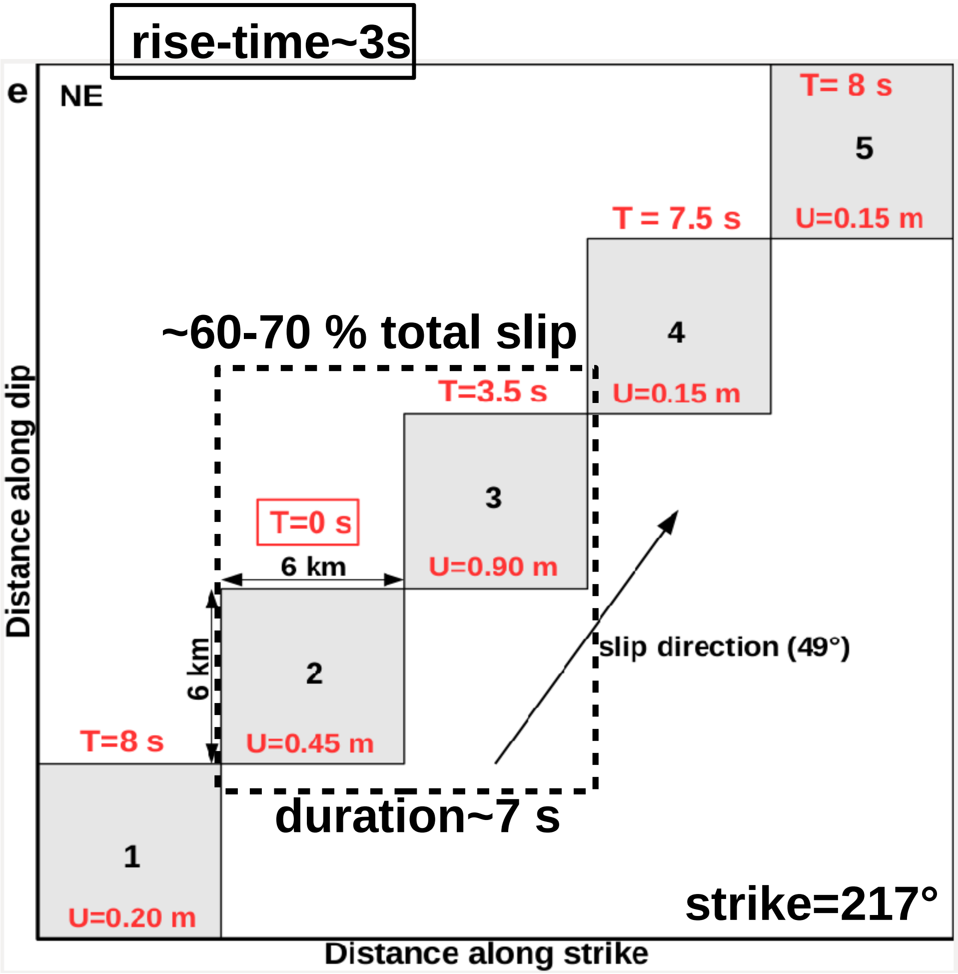
Near- and static dilatation field



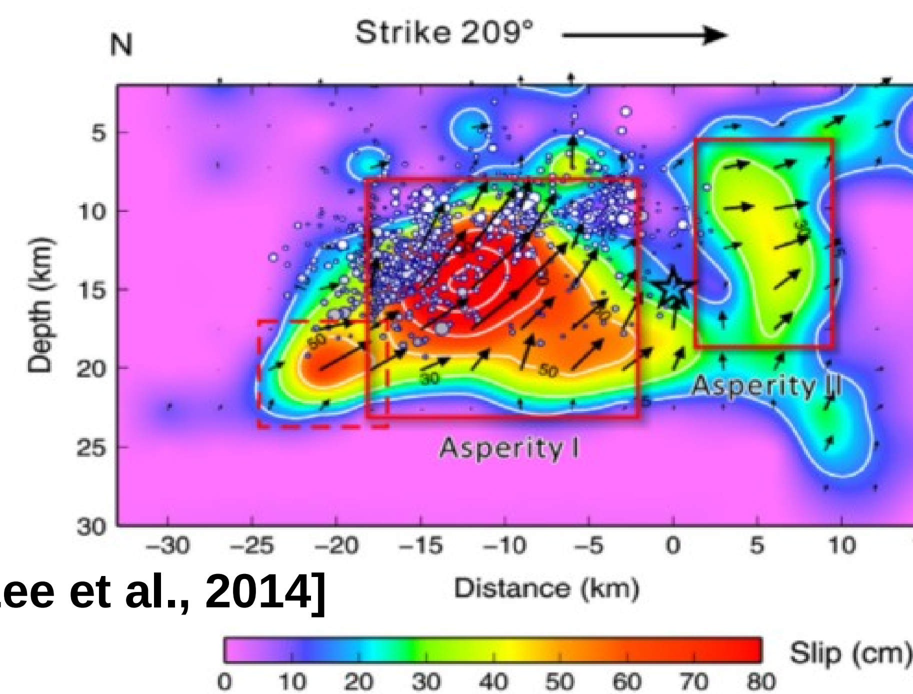
Dynamic pulses (bandpassed 3-7 s)



Rupture process inferred from dilatation data inversion



- Large central asperity (~12x12 km²) which concentrates about 60-70 % of the total Slip (> 1 m)
- After 7-8 s, the asperity spreads to the deepest part and, at the same time, extends to the surface (SW limit : controls the delay of wave arrivals at HGSB)
- Rupture process lasts ~11 s which yields a rupture velocity ~ 2.7 km/s (intraplate earthquake ~ 2.8 km/s)

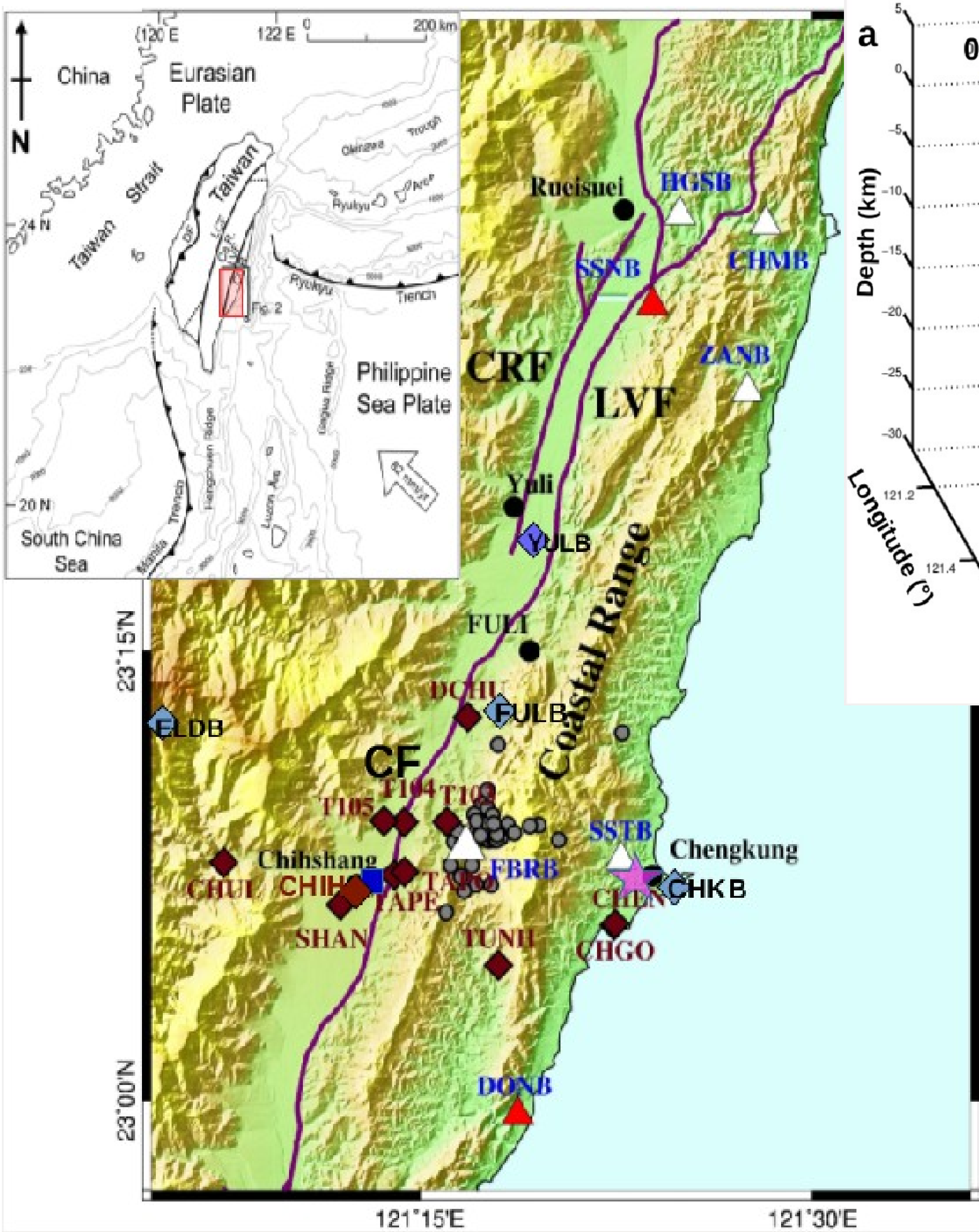


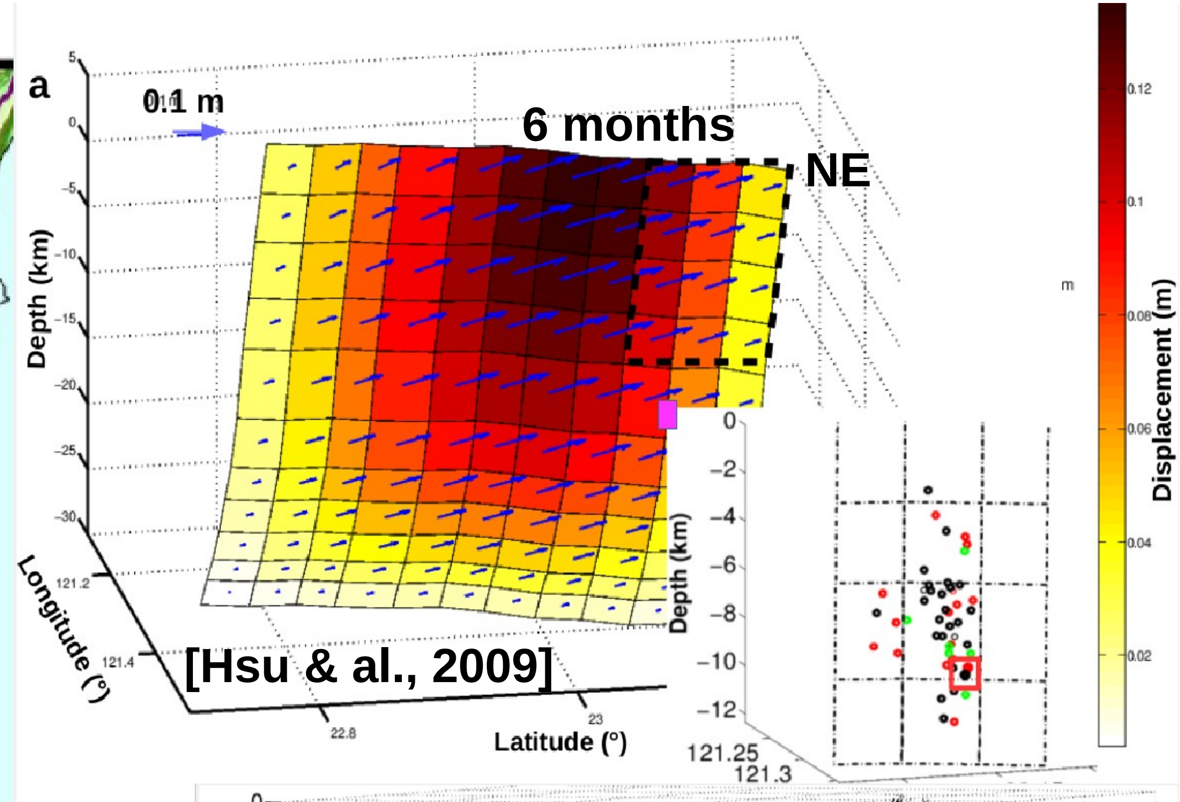
[Lee et al., 2014]

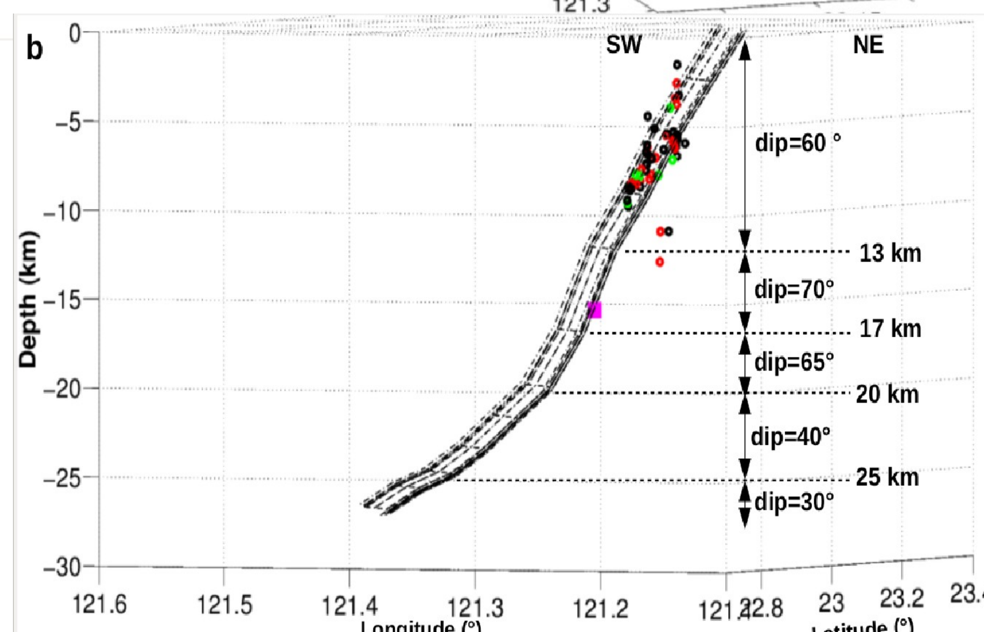
Conclusions & perspectives :

- This study represents the first attempt to model the complete strain field as recorded by strainmeters (in the near field) from only the dilatation data :
  - Very good agreement between the observations and the model for the zero-frequency, permanent static deformation, at 3 sites including the 2 closest ones (HGSB & SSNB)
  - Good estimations of the 5-sec period dynamic waveforms (with ~20 % of discrepancies) at sites HGSB, SSNB and ZANB
  - Discrepancies > 40 % for the 3 components at CHMB site : rupture directivity ? Instrumental calibration issue ?
- Our model is by no means complete or exact but the first order success of this preliminary effort indicates the potential value of high frequency strain records
  - Add constraints to the seismic source inversions as for instance, depth (static field depends strongly on the depth of buried sources), zero-frequency near-field observation (resolution, instrument correction, ..)
  - Investigating crustal structure (strain is spatial differential of displacement)
  - Dynamic triggering of earthquakes, tremors, SSEs, ...

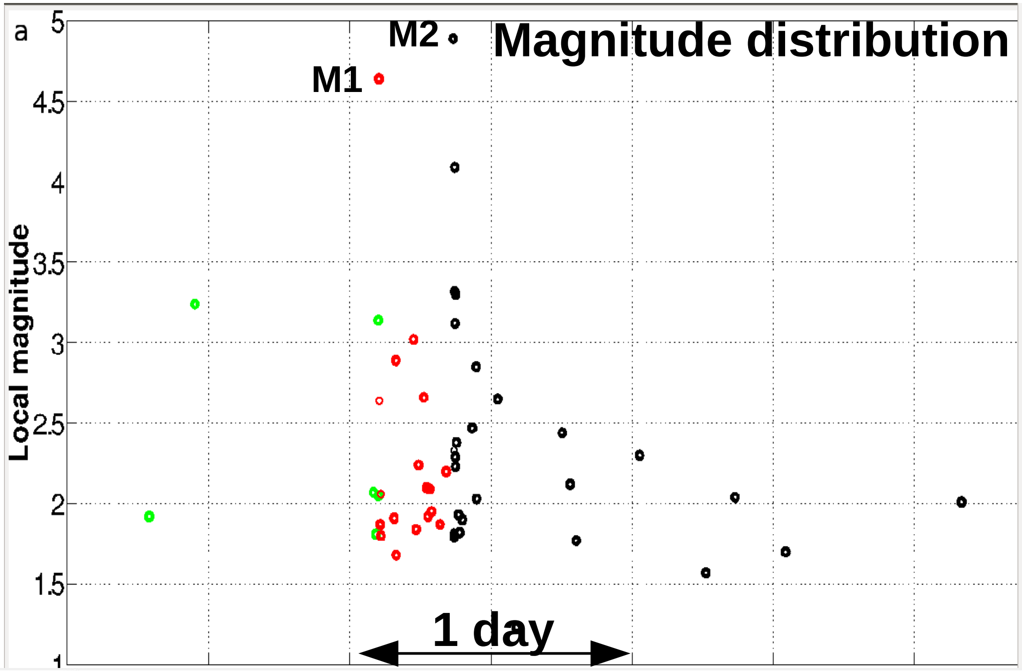
Long-period observation : April 2010 seismic crisis on Chihshang fault

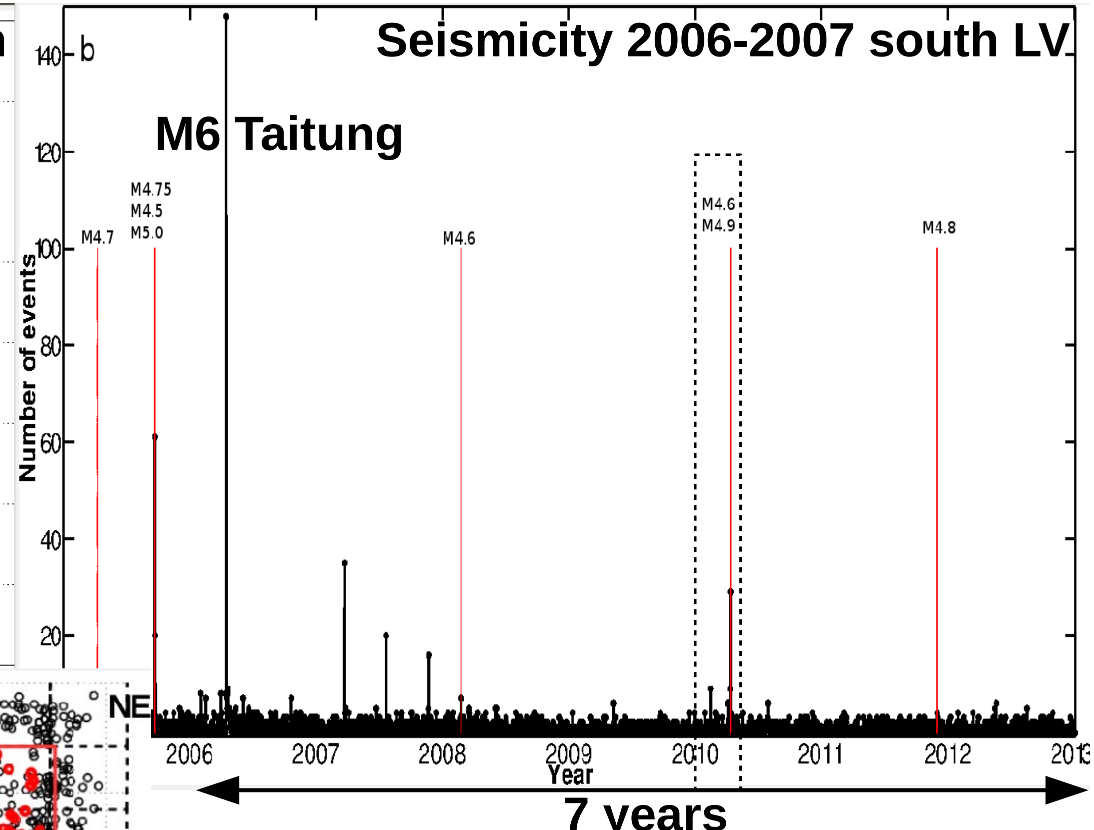


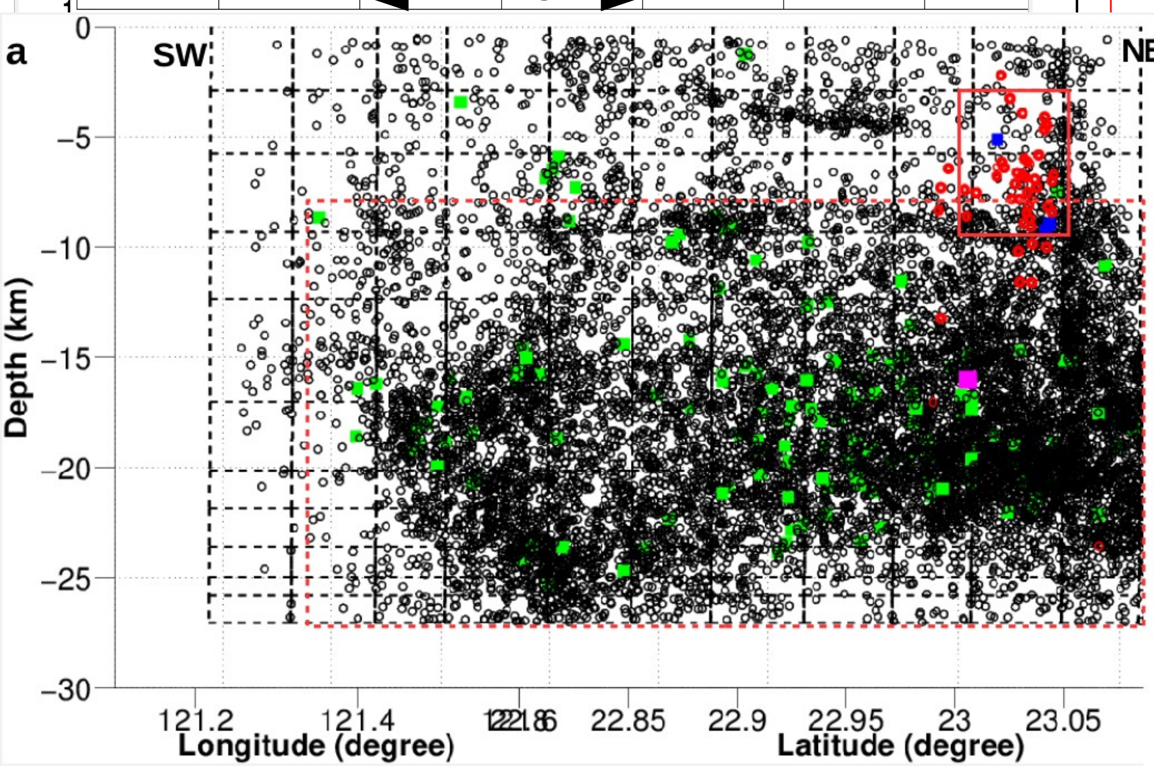




Seismicity



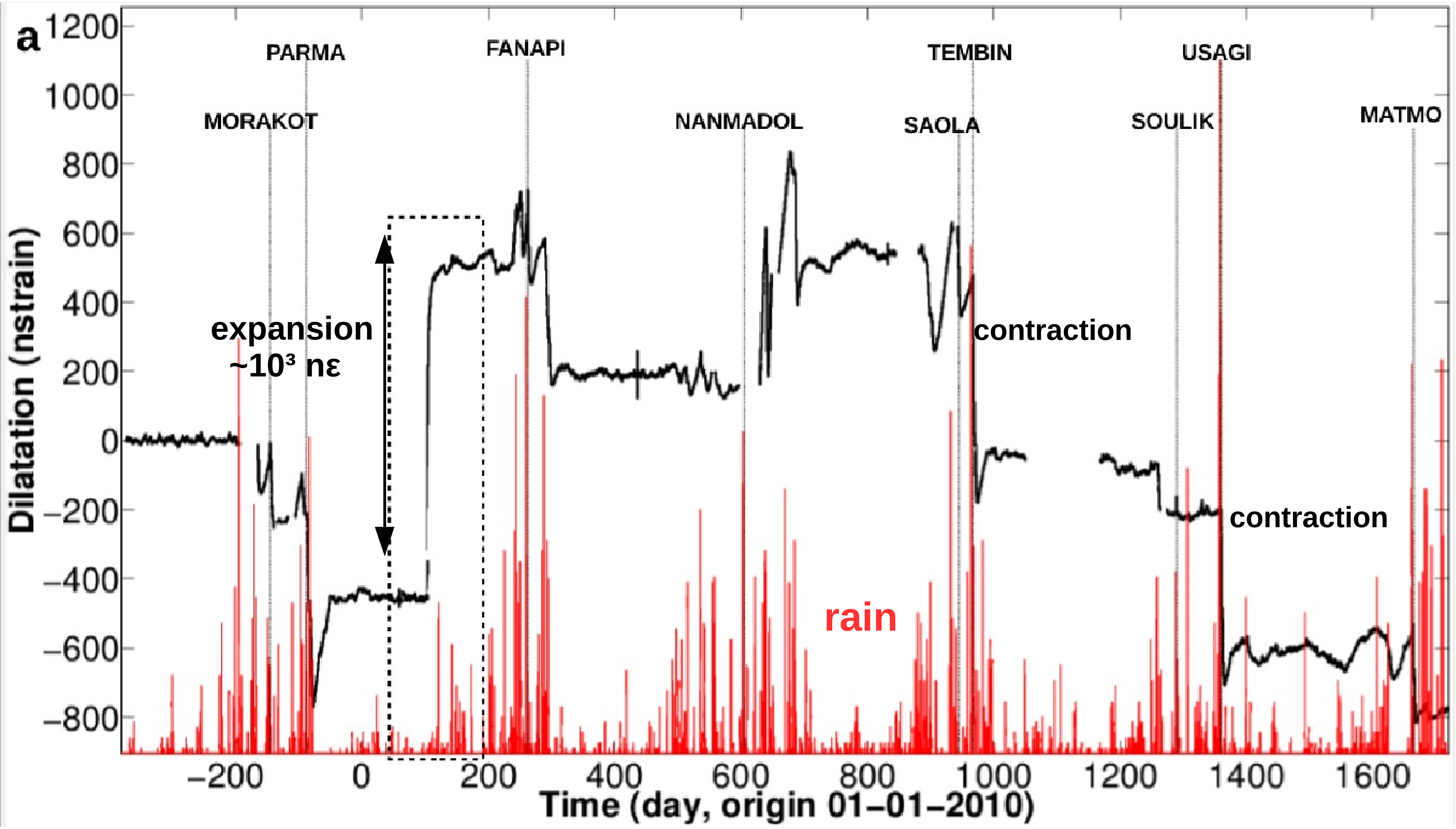




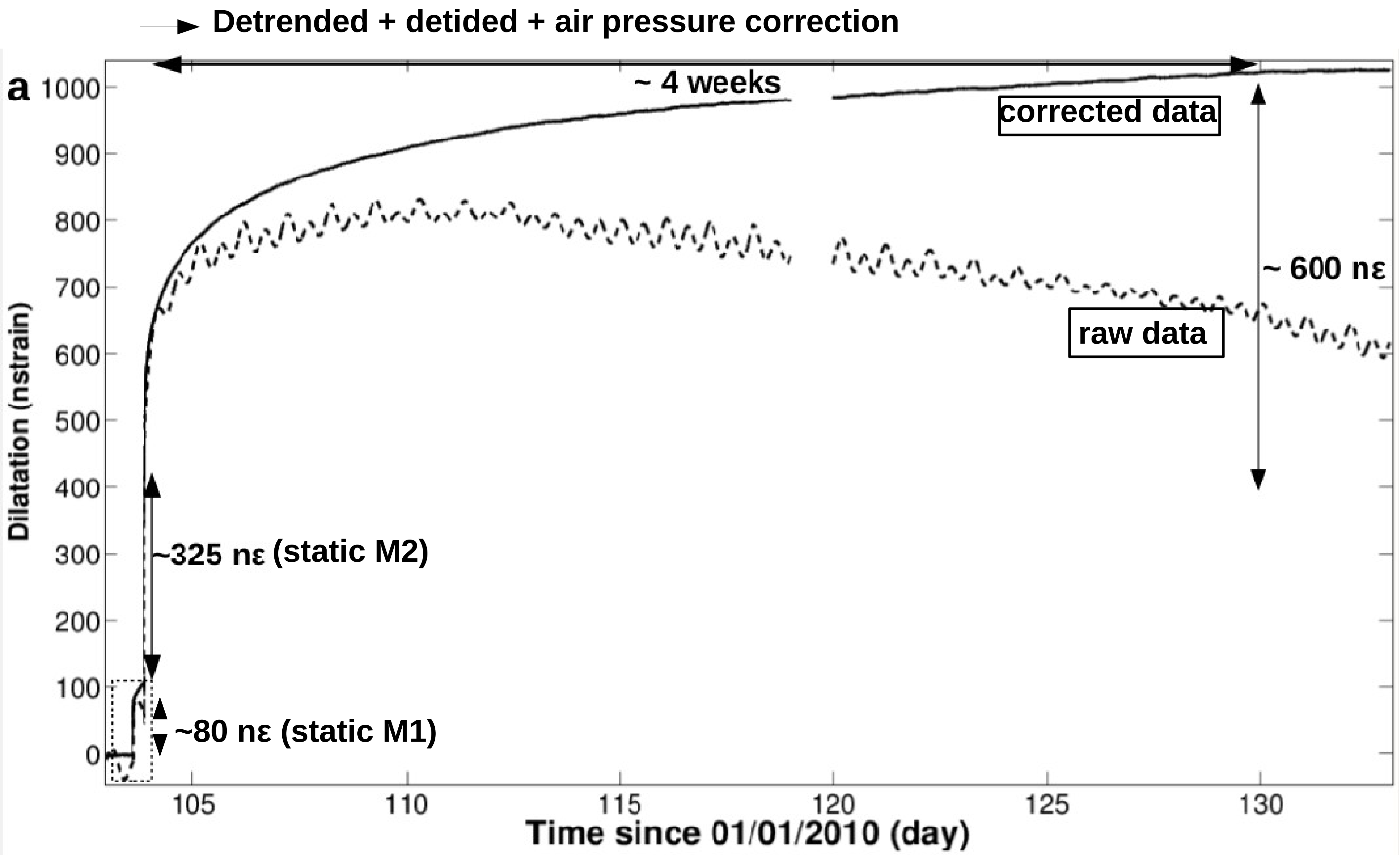
1992-2014 seismicity

2009 - 2014 dilatation signal recorded by FBRB dilatometer

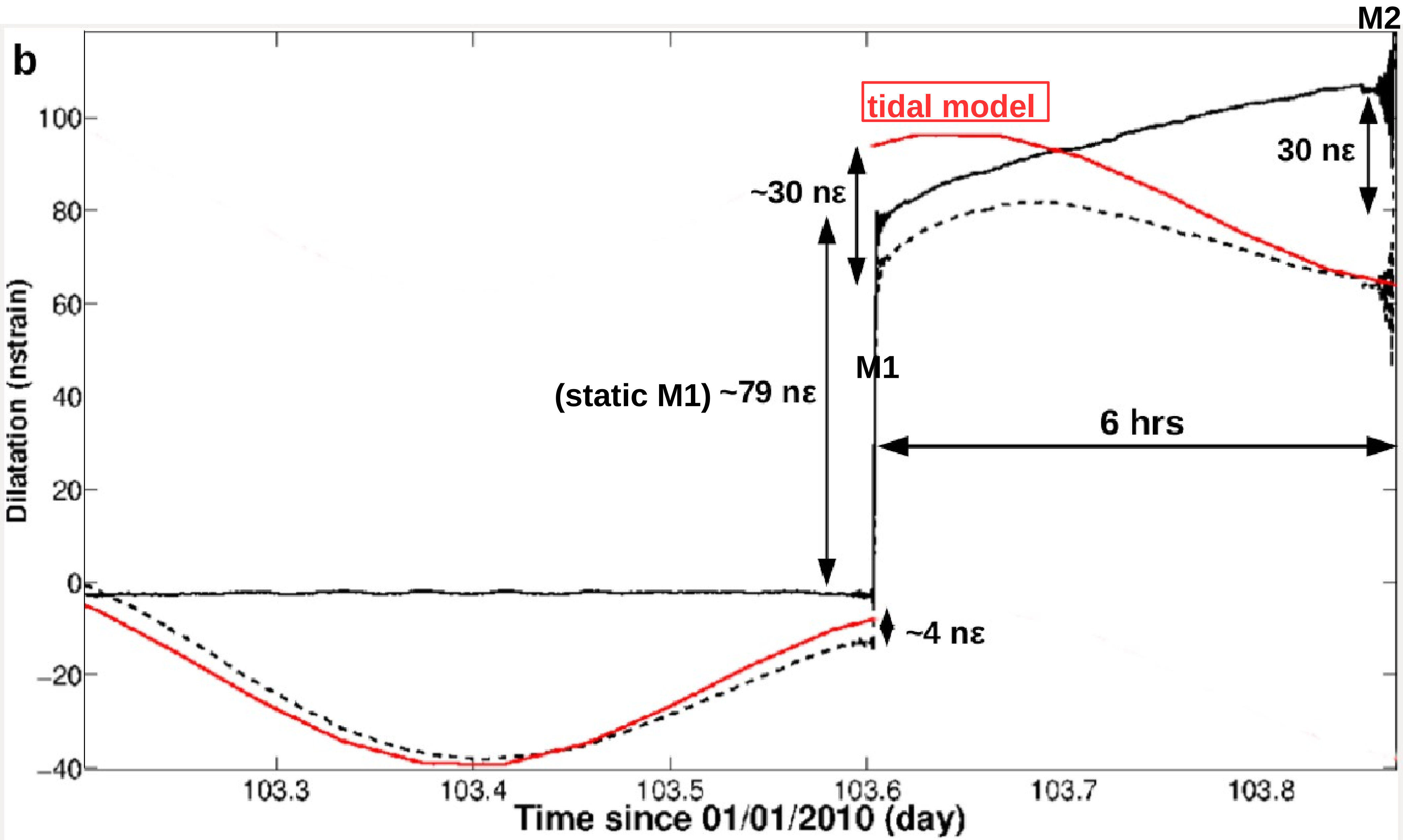
detrended & detided (solid+oceanic)



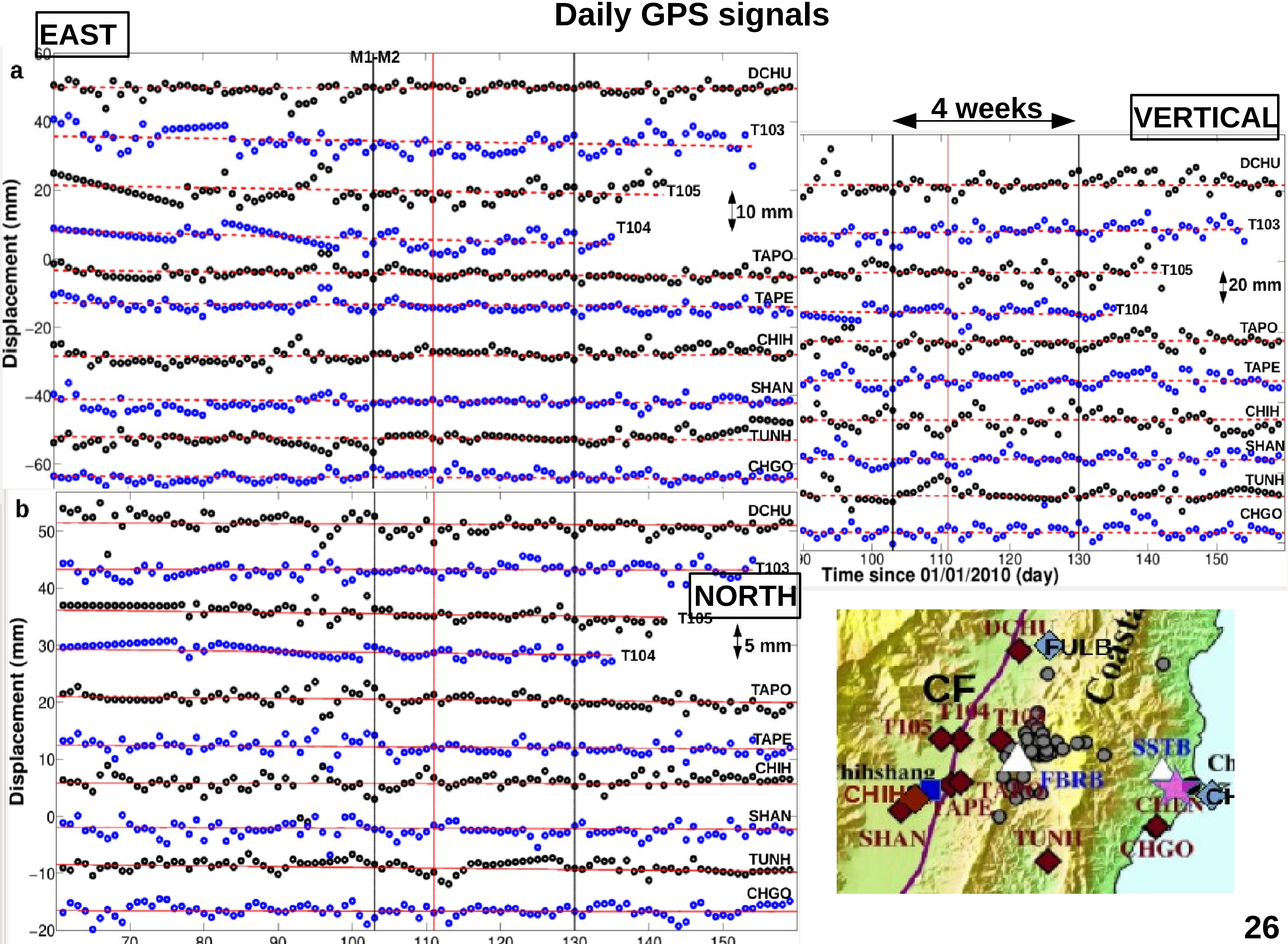
Slow relaxation



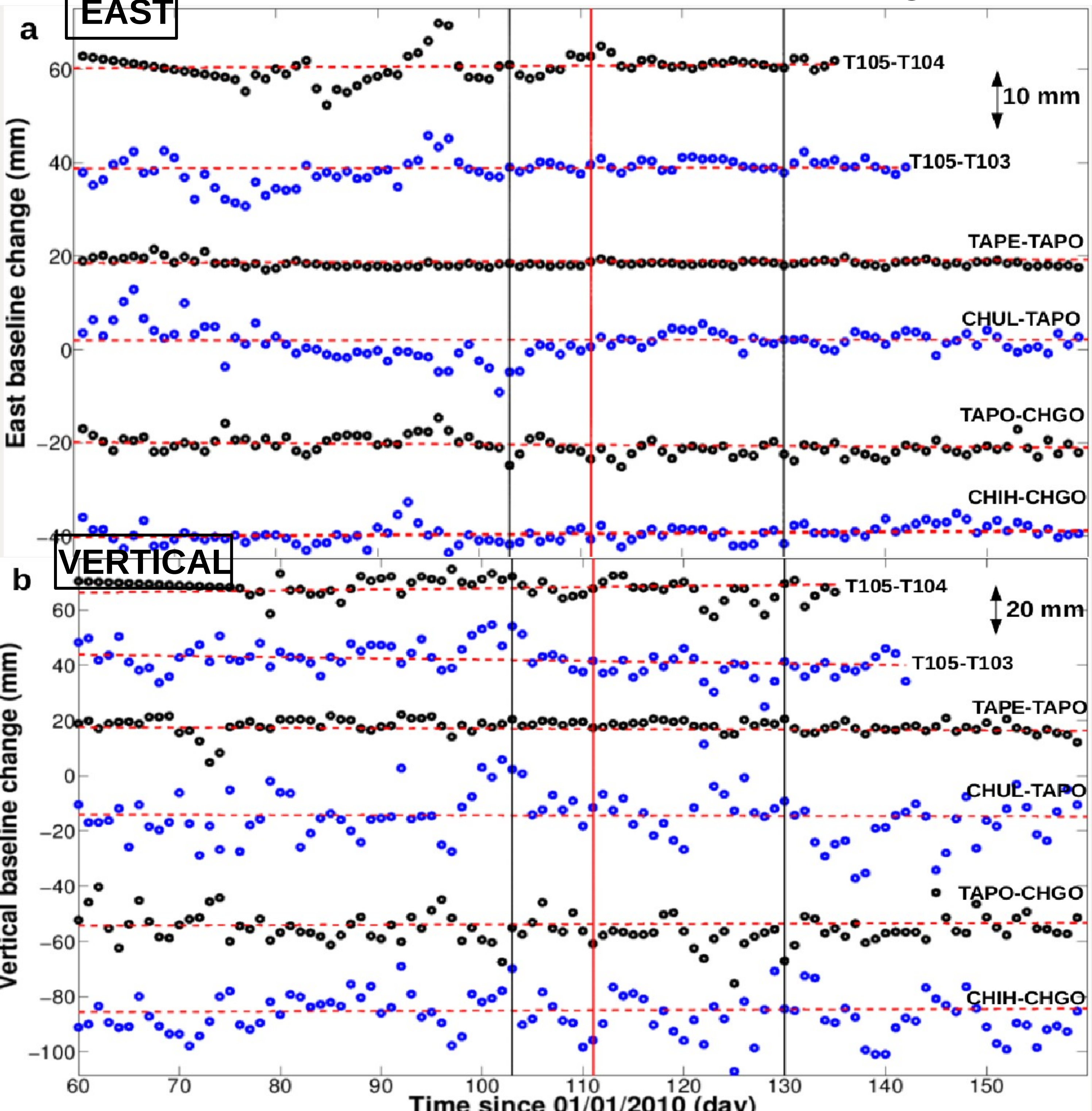
Relaxation initiation

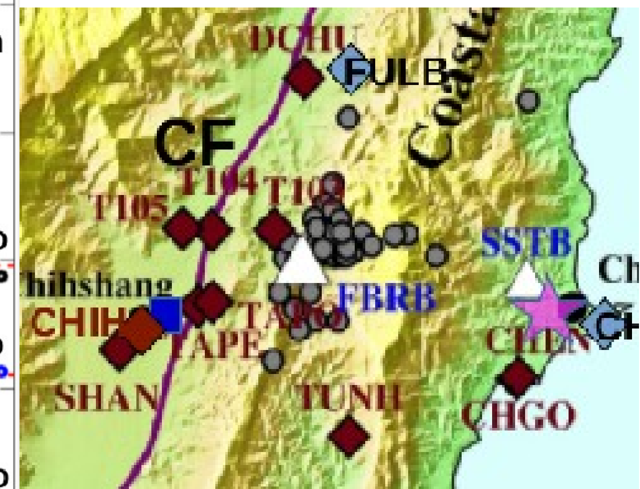


Daily GPS signals



GPS baseline changes

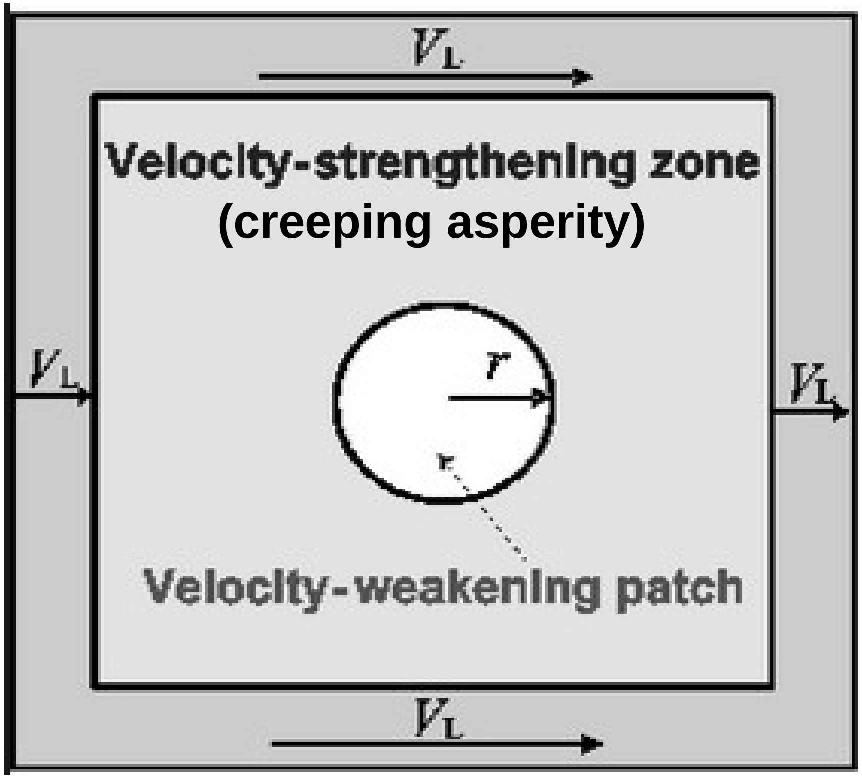




No coherent surface displacements revealed on GPS time-series

Microseismicity : Search for highly-similar signals (multiplets)

- Seismic repeaters/multiplets may represent the repeated ruptures of the same fault asperity (or neighbouring asperities) by constant loading from aseismic creep on the surrounding fault surface [Nadeau and McEvilly, 1999]

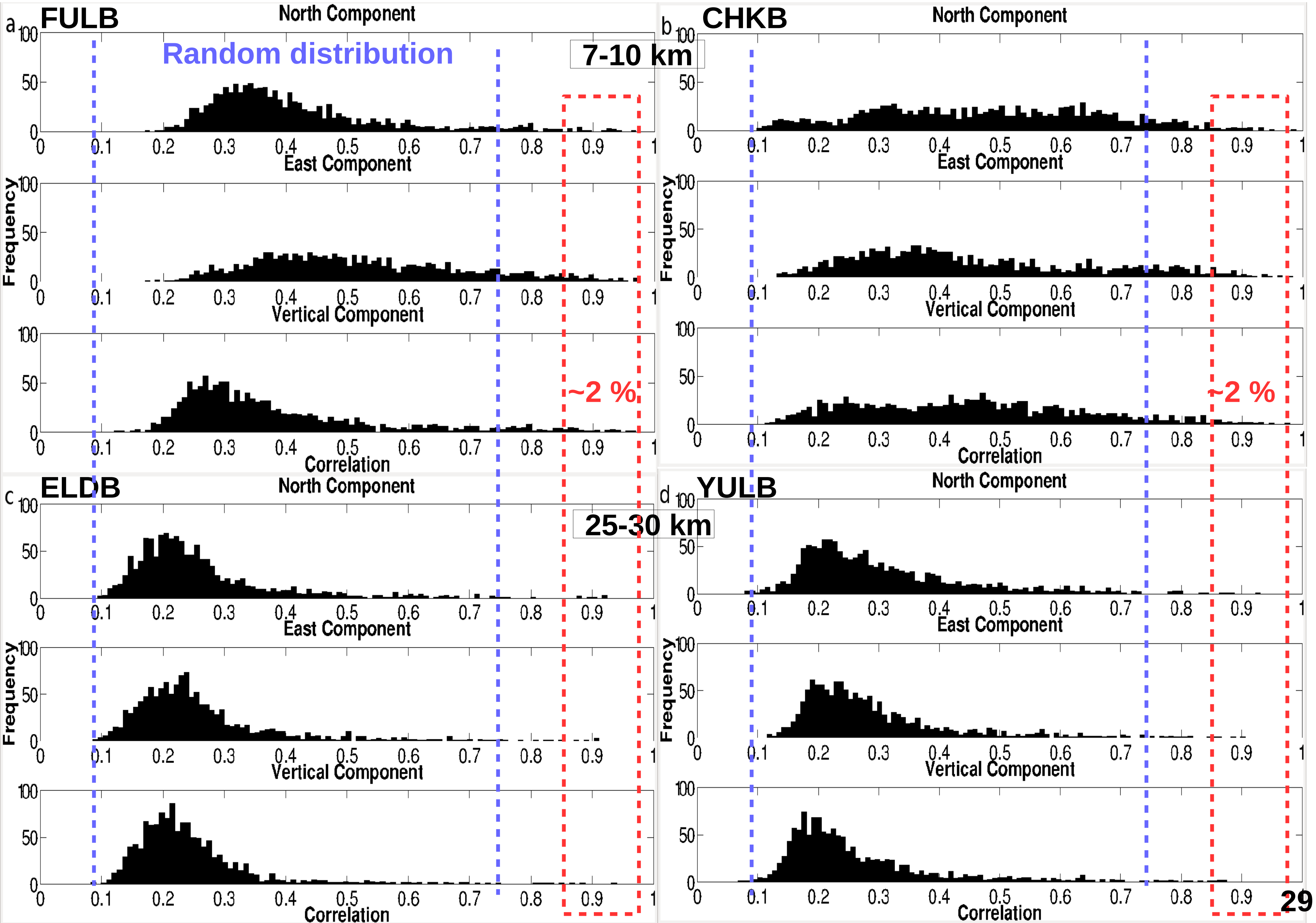


- Take advantage of the evidence of the aseismic creep to investigate the possibility of occurrence of repeaters/multiplets during the small crisis (~50 events)

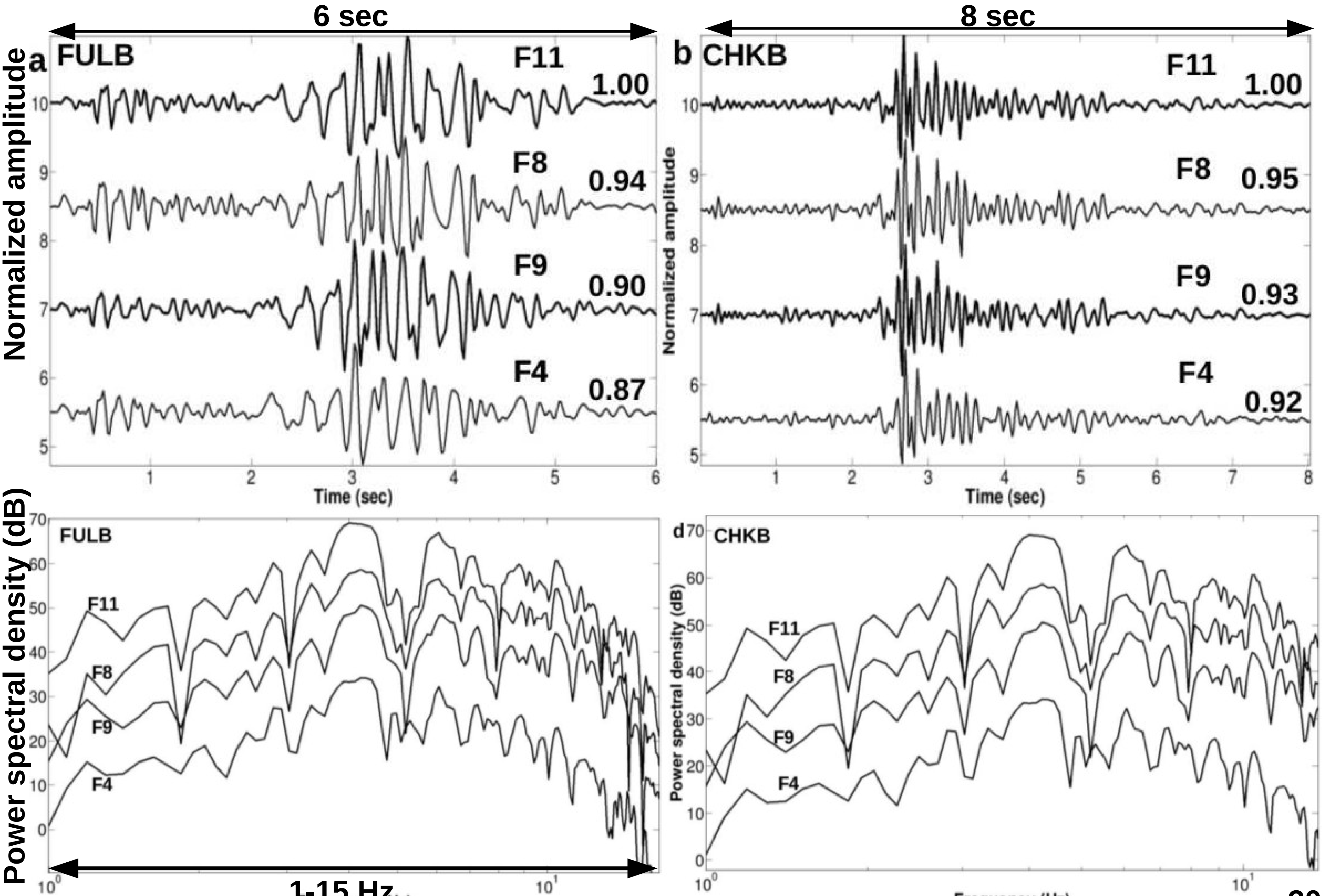
- Cross-correlation of the seismic waveforms (~50 events, filtered 1-15 Hz) recorded at 4 nearby stations (~7 to 30 km)

- Existence of repeaters has already been reported on the northern section of the Chihshang fault [Chen, 2007, 2008]

Frequency distribution of cross-correlation coefficients between pairs

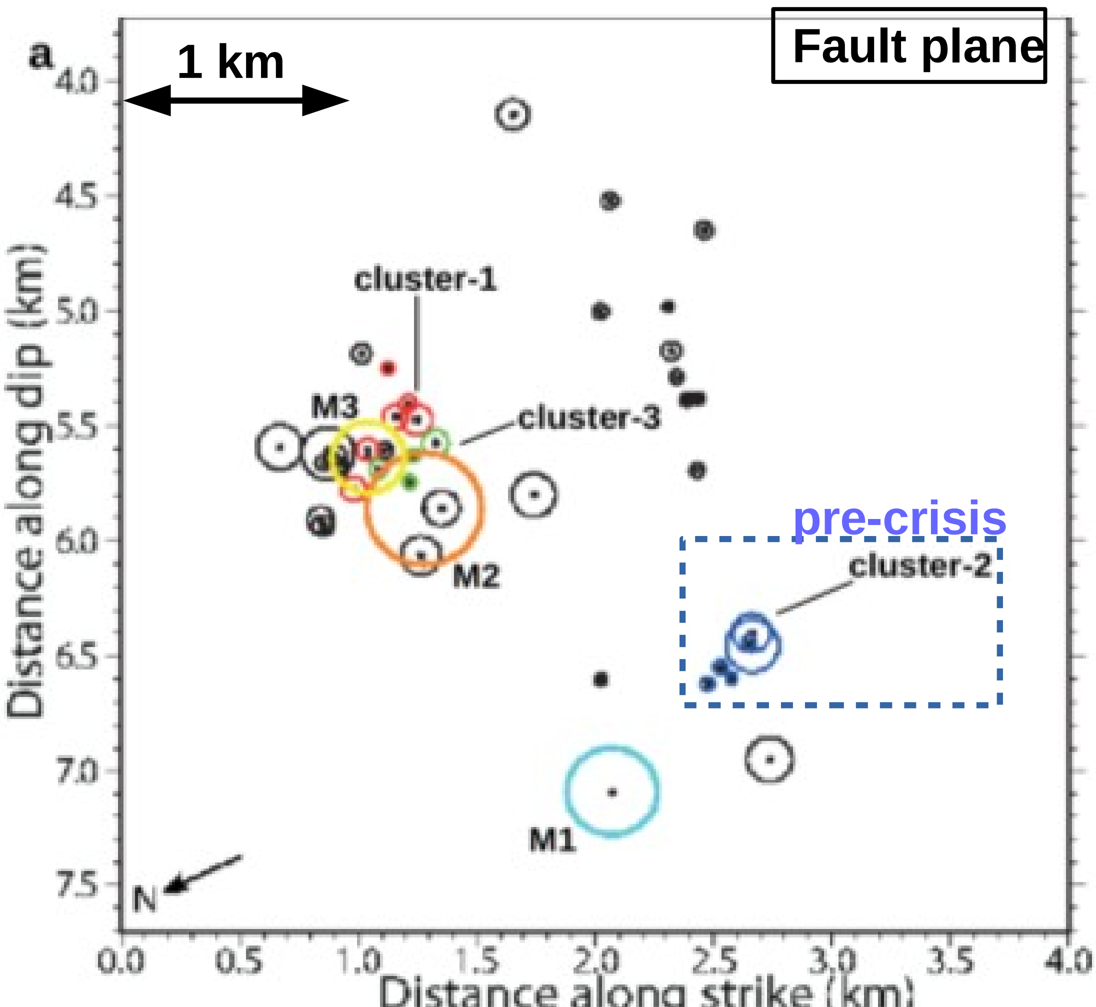


Examples of highly correlated waveforms



Relocation of microseismicity

- Relocate seismicity by double difference algorithm [Waldhauser and Ellsworth, 2000]
  - Manual pick P/S waves absolute time + relative P delay times from cross-correlations at 4 stations (cc >0.75 on vertical component)



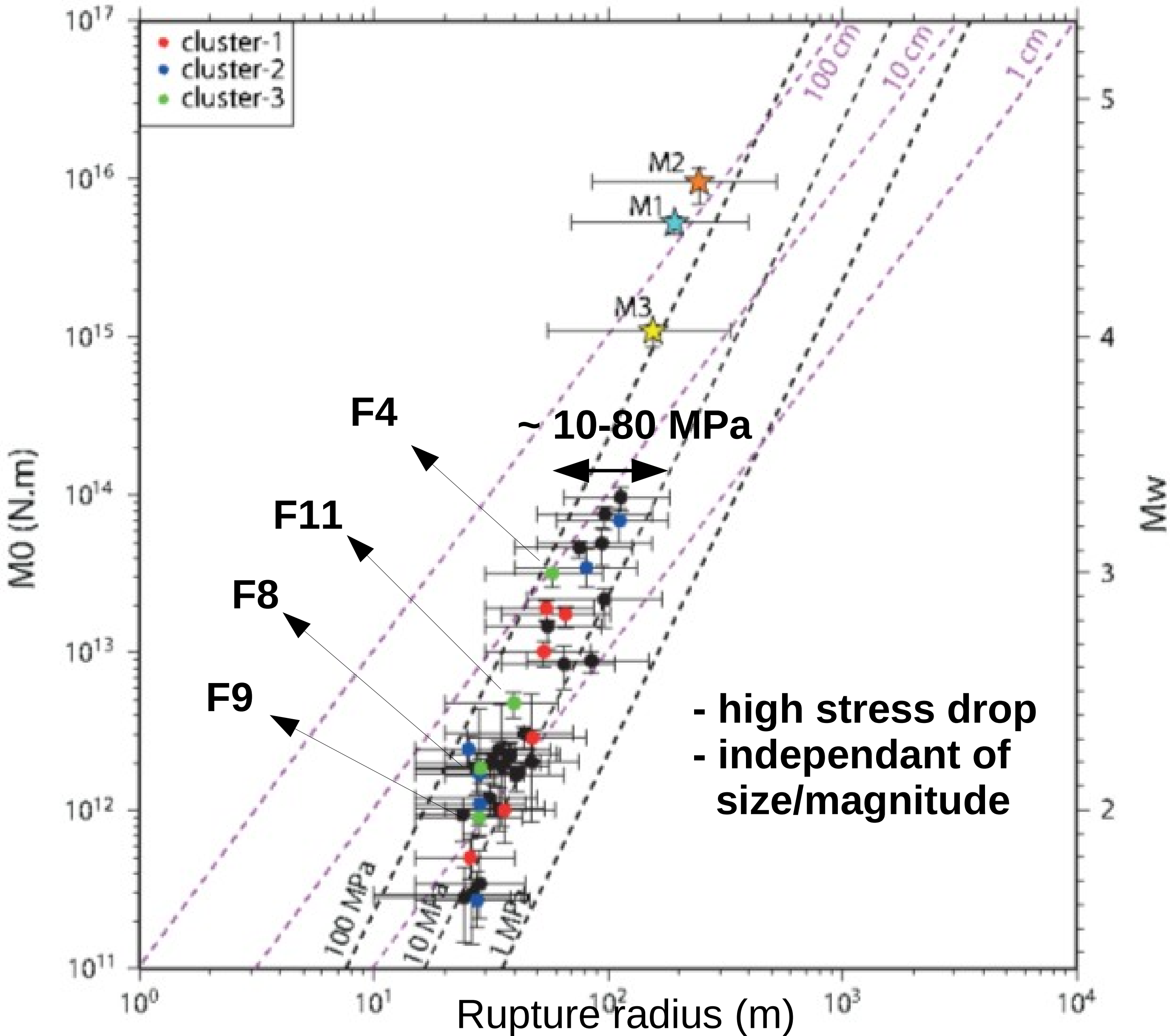
- 3 clusters are build : number of cross-correlations and stations does not allow to resolve any overlapping of the seismic source

- We only consider cluster-3 (4 events) made by Highly-correlated events (cc >0.9) occuring between shocks M1 & M2

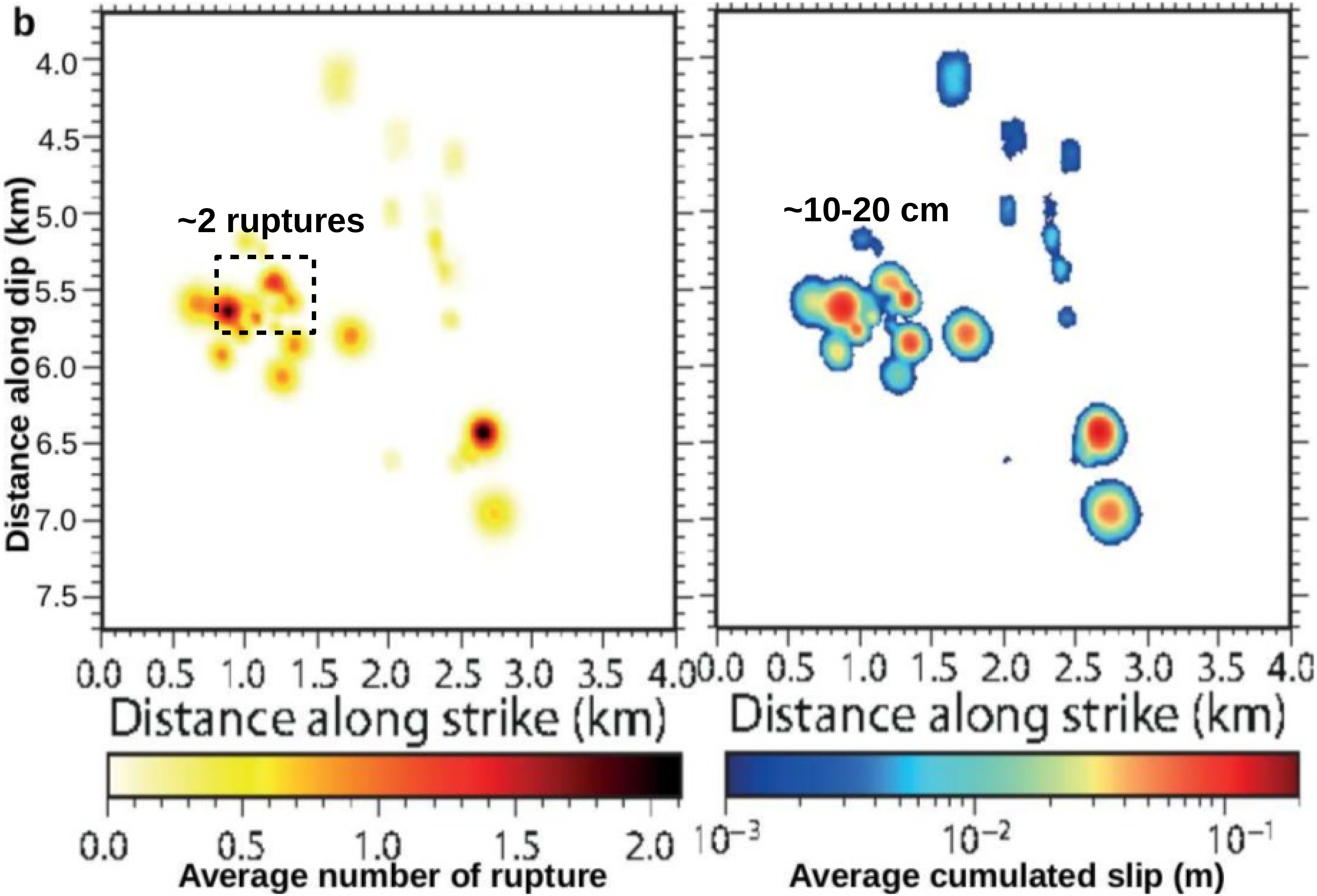
Source parameter estimation : Bayesian approach

→ **Estimations of source parameters such as size of rupture, coseismic slip and static stress drop are estimated through Bayesian approach [Godano et al., 2015]**

(radius estimation down to 20 cm due to inversion limit (at 100 Hz))

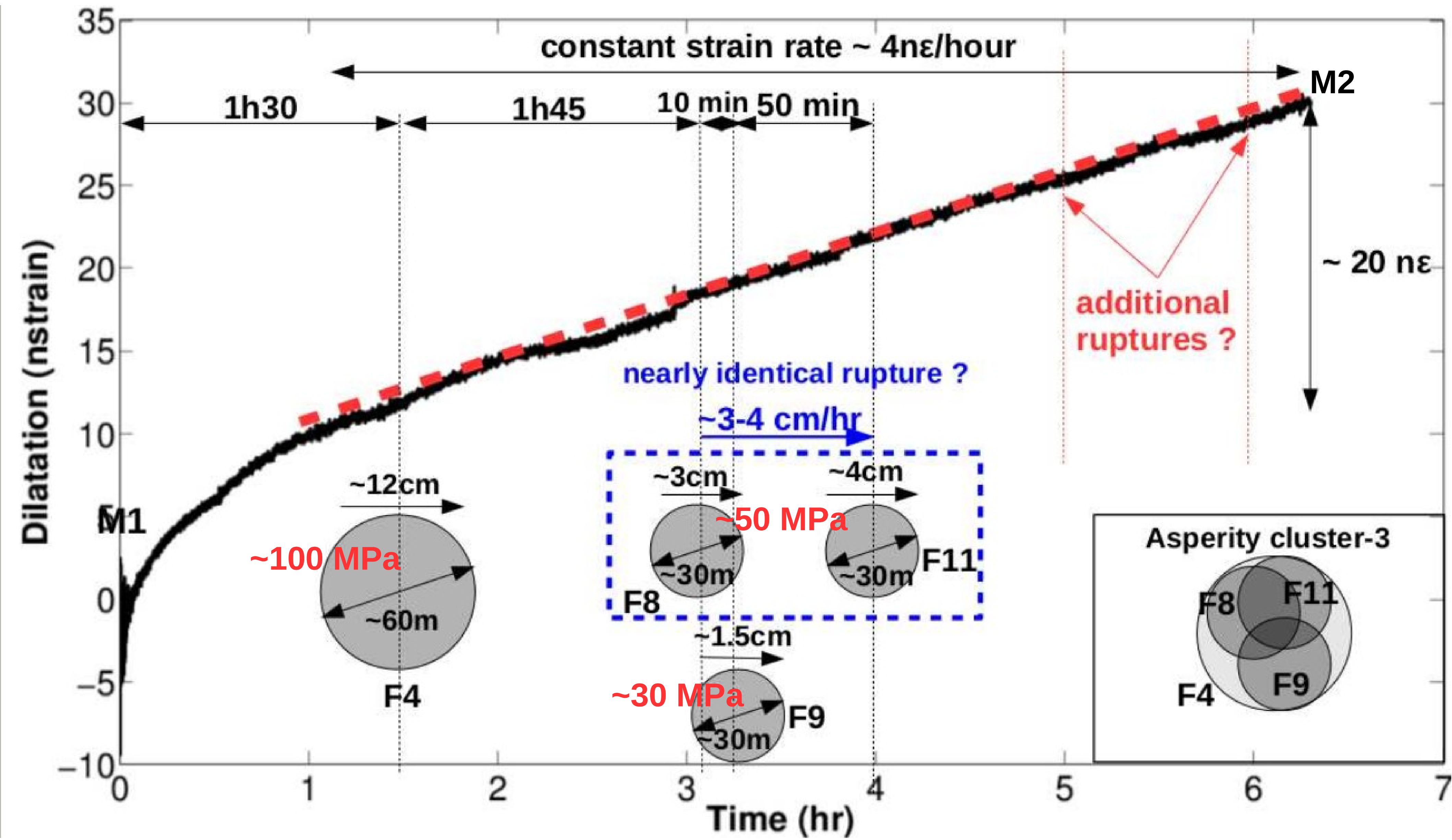


1rst order estimation of repeated rupture characteristics

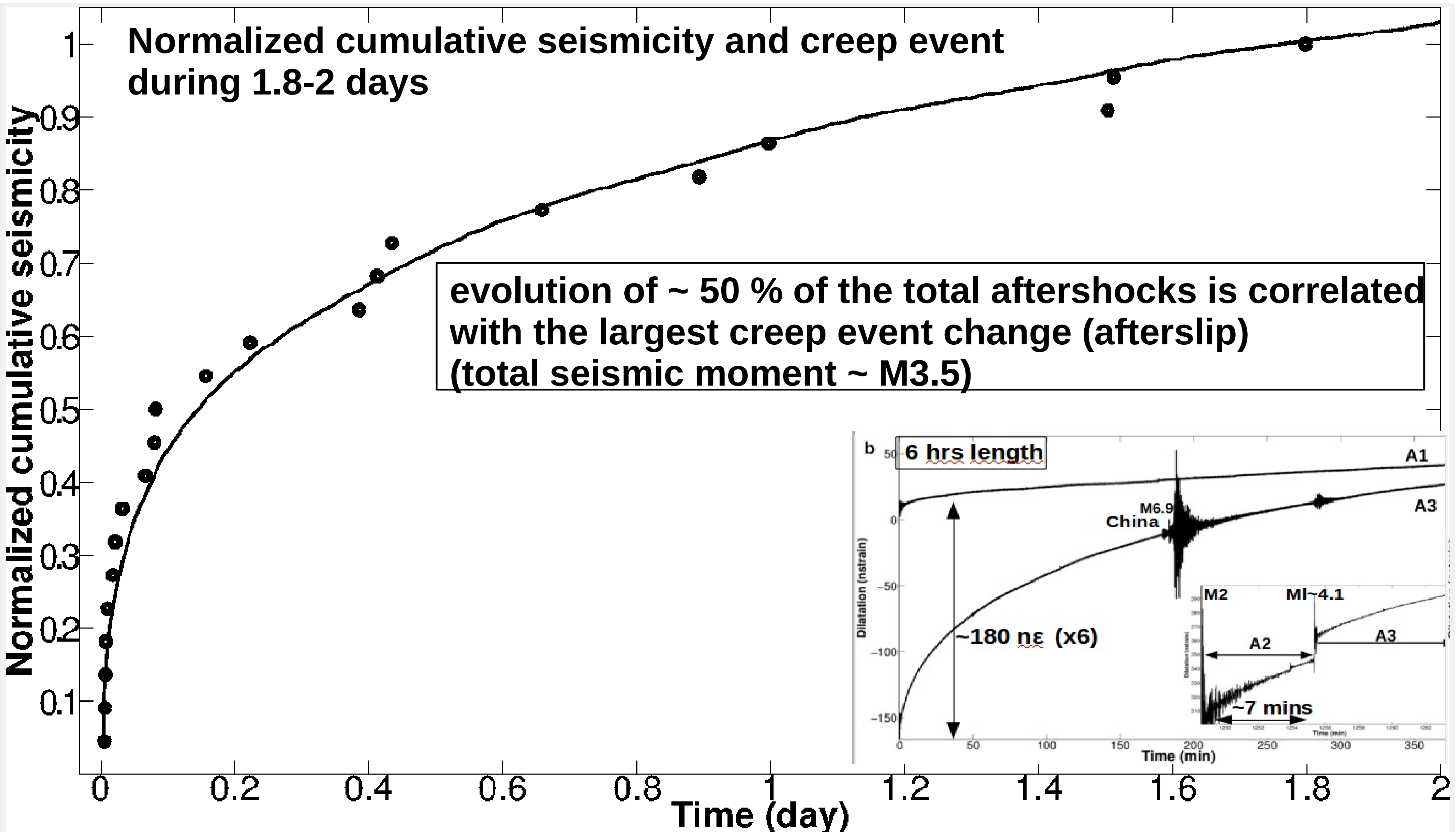


Rupture of cluster-3 (asperity) along with the aseismic loading

→ **Estimation of the cumulated aseismic slip during M1-M2 ~ 20-30 cm**



Aftershocks driven by brittle creep (slow shear failure)

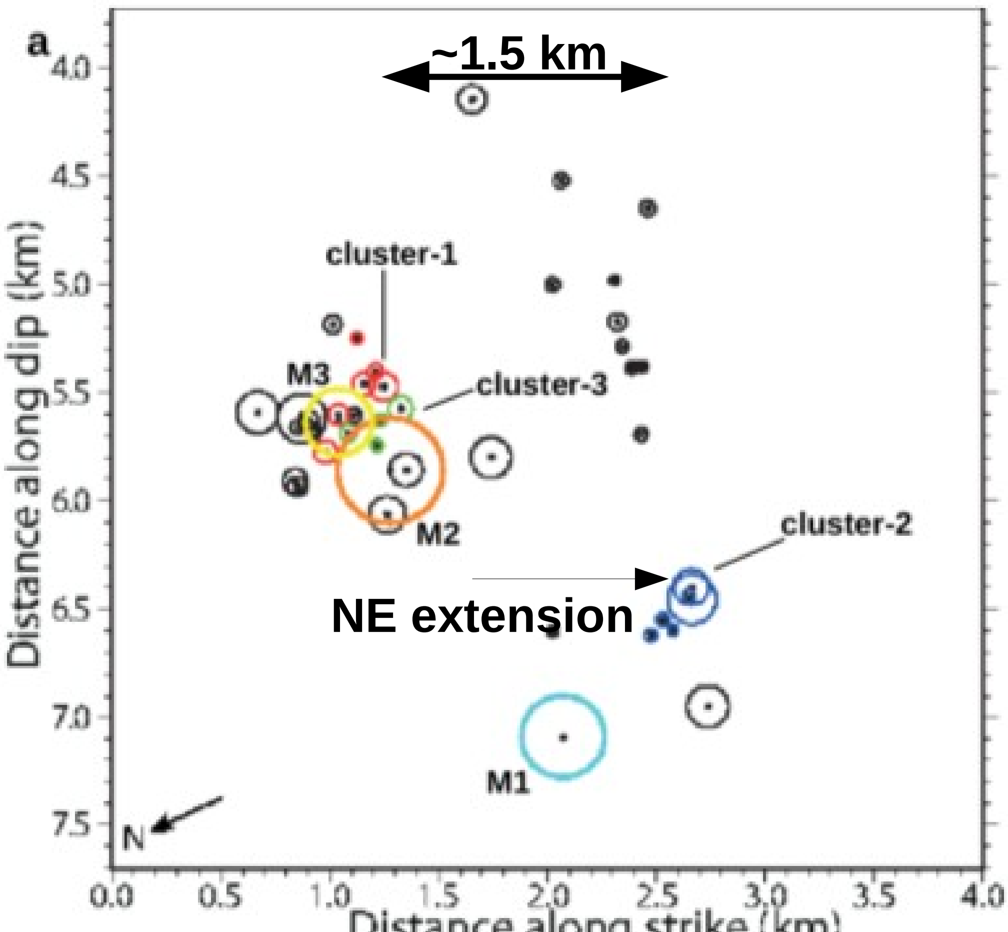


Constraints on the aseismic creep structure

► Use simultaneous geodetic and seismological observation of aseismic creep to constrain (1rst order) its source characteristics (location, dimension, moment)

► As regards to the large stress drops (>10 MPa) we consider that the asperity is embedded in the creeping structure [Nadeau and Johnson, 1998]

► For location, we add 2 geometric constraints :

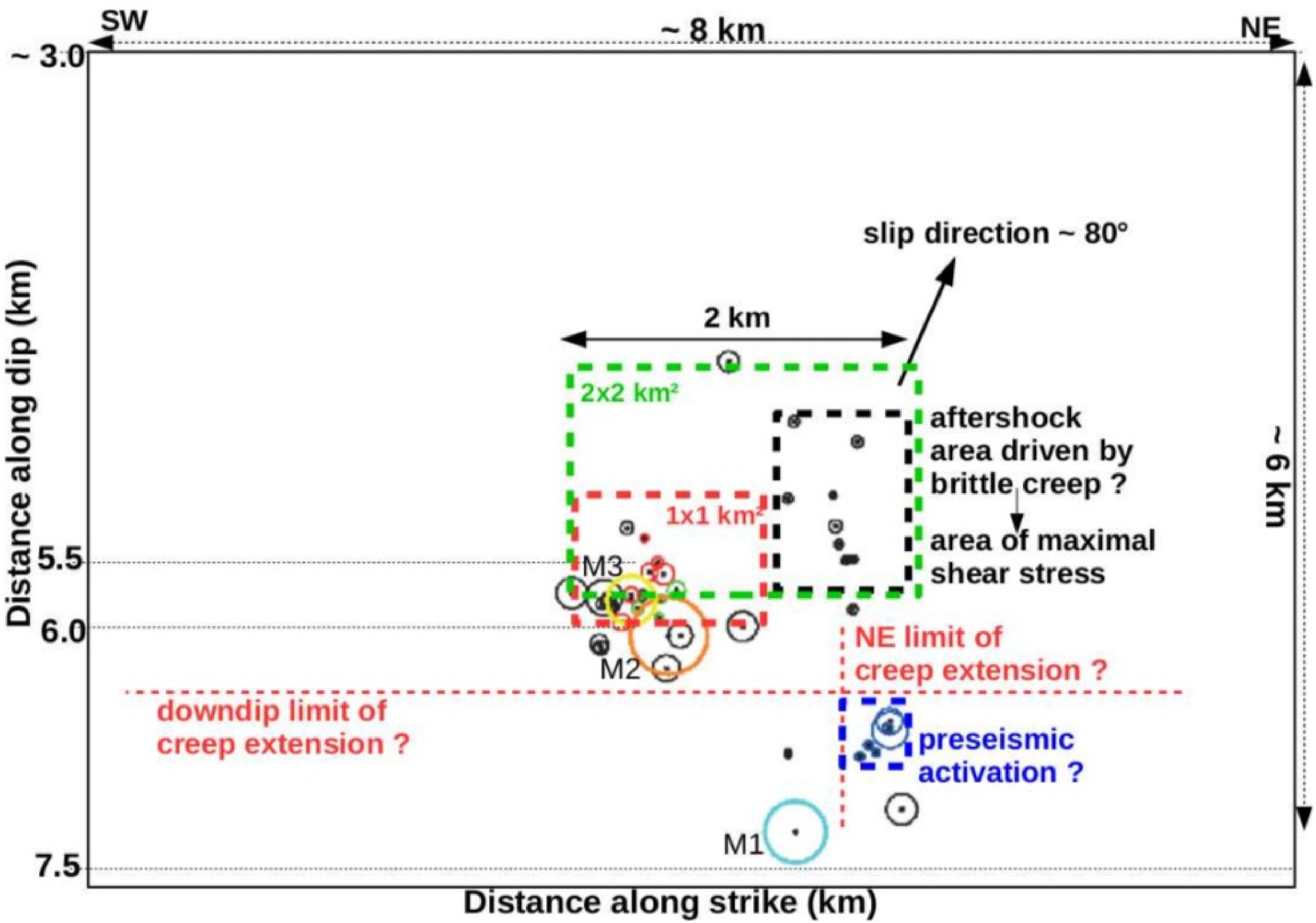


► Aseismic structure encompasses cluster-1 and cluster-2 (as triggered after M1) : minimum 0.5-1 km²

► Cluster-2 is not embedded in the structure (it has been activated before M1 and not reactivated after)

► We roughly know final aseismic slip after M1 (~20 cm in 6 hrs), also we scale the dimensions of patch over the strain value at FBRB and estimate the surface displacements at GPS sites (static dislocation)

Scenarii of slow rupture



► Aseismic structure remains unchanged after M2 (slip x20) → slip ~3-4m/1 month (know the final slip through geodesy) ► Very large value

► Structure changes after M2 (dimensions, rake?) as shear stress increases + asperity releases ~0.5-1m of coseismic slip due to 2003 Chengkung earthquake [Thomas et al., 2014] ► ~2x2 km² asperity (propagating creep)

Conclusions & perspectives :

- Study represents a very rare case of simultaneous occurrence of geodetic and seimological signatures of aseismic creep

  - Assess the aseismic slip properties based on the rupture cycle of an isolated asperity under constant loading (i.e. constant strain rate)

- Number of events does not allow to tightly constrain source relocations & parameters

  - Refinement of the creeping asperity properties and a better understanding of its long-term behavior would need additional observations and cross-correlations (use waveforms as template)

- Paucity of moderate to large earthquakes (M>6-6.5) in the LV as regards to the large accumulation of elastic strain (aseismic slip accounts for more than 80% of the long-term slip rate in south LV [Thomas et al., 2014])

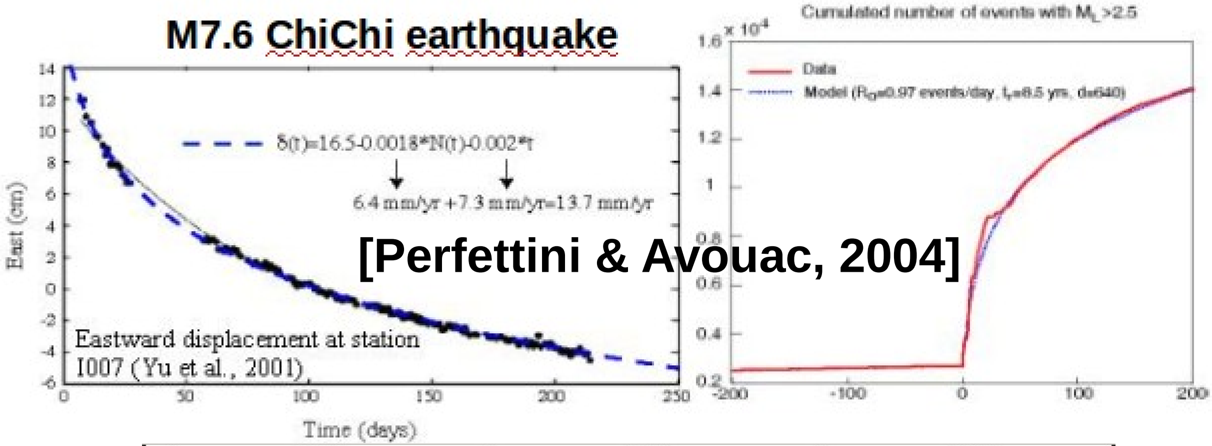
  - Tracking slow slip events and estimating their strength is therefore of major importance in the aim to assess the seismic hazard of the eastern Taiwan and thus to estimate the capability of aseismic slip to evolve into larger and destructive seismic ruptures

→ **In the present case, the aseismic process appears to be complex :**

→ **1rst phase of ~6 hours associated with ~70 % of clusted seismicity (multiplets)**

→ **2nd phase following shock M2 with enhancement of the loading rate and and aseismic slip seems to control the aftershock productivity during the first 2 days (~aftershock duration) through brittle creep**

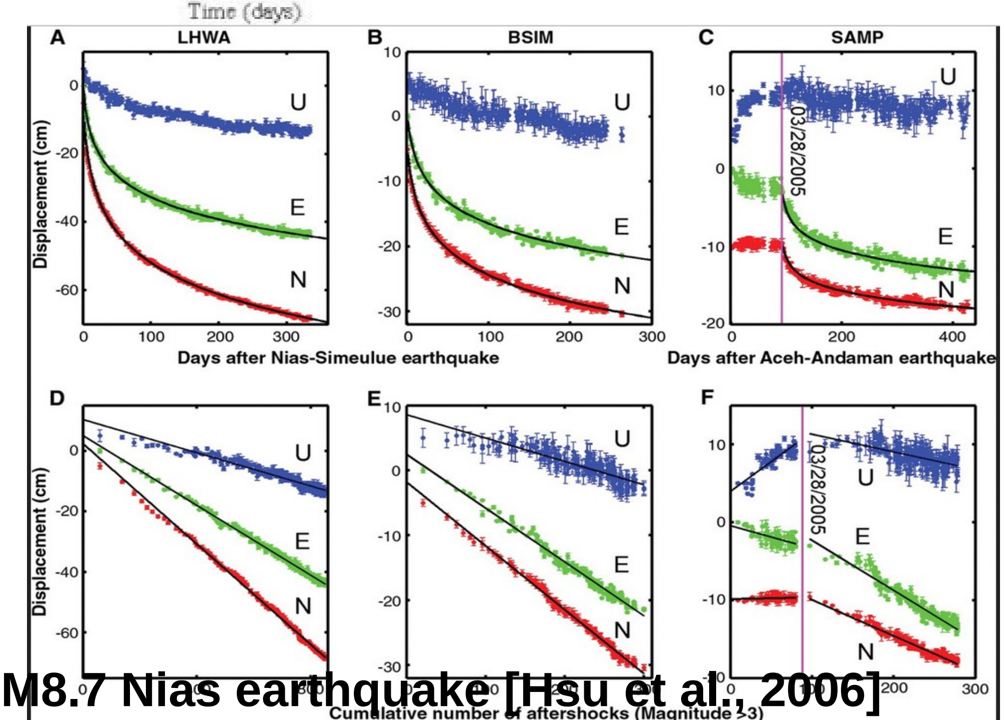
M7.6 ChiChi earthquake



[Perfettini & Avouac, 2004]

→ **For 2 scenarii, the total moment released by aseismic processes ~M5.3**

→ **Larger than magnitude of 2 mainshocks and that the total seismic moment of the crisis**

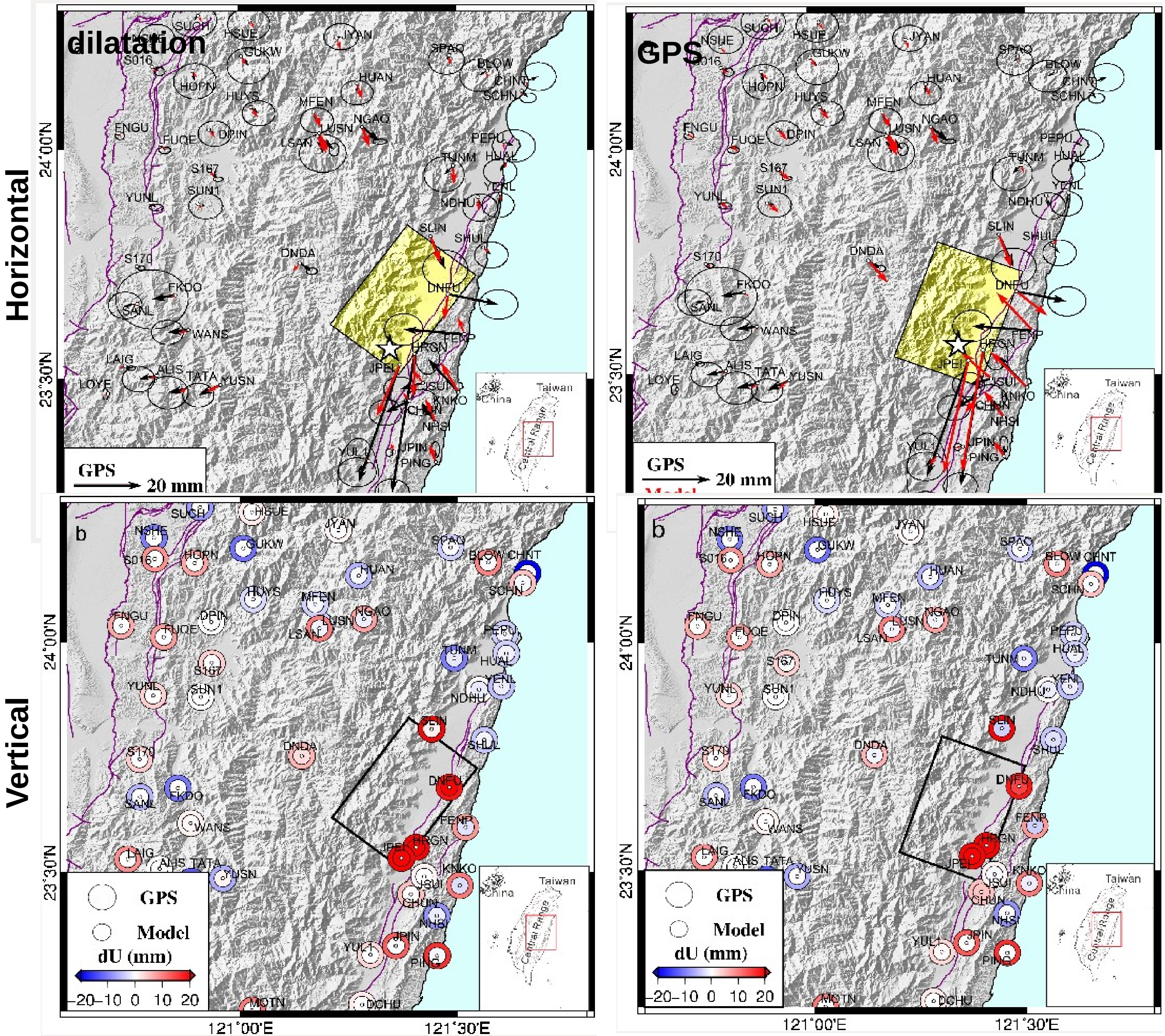


M8.7 Nias earthquake [Hsu et al., 2006]

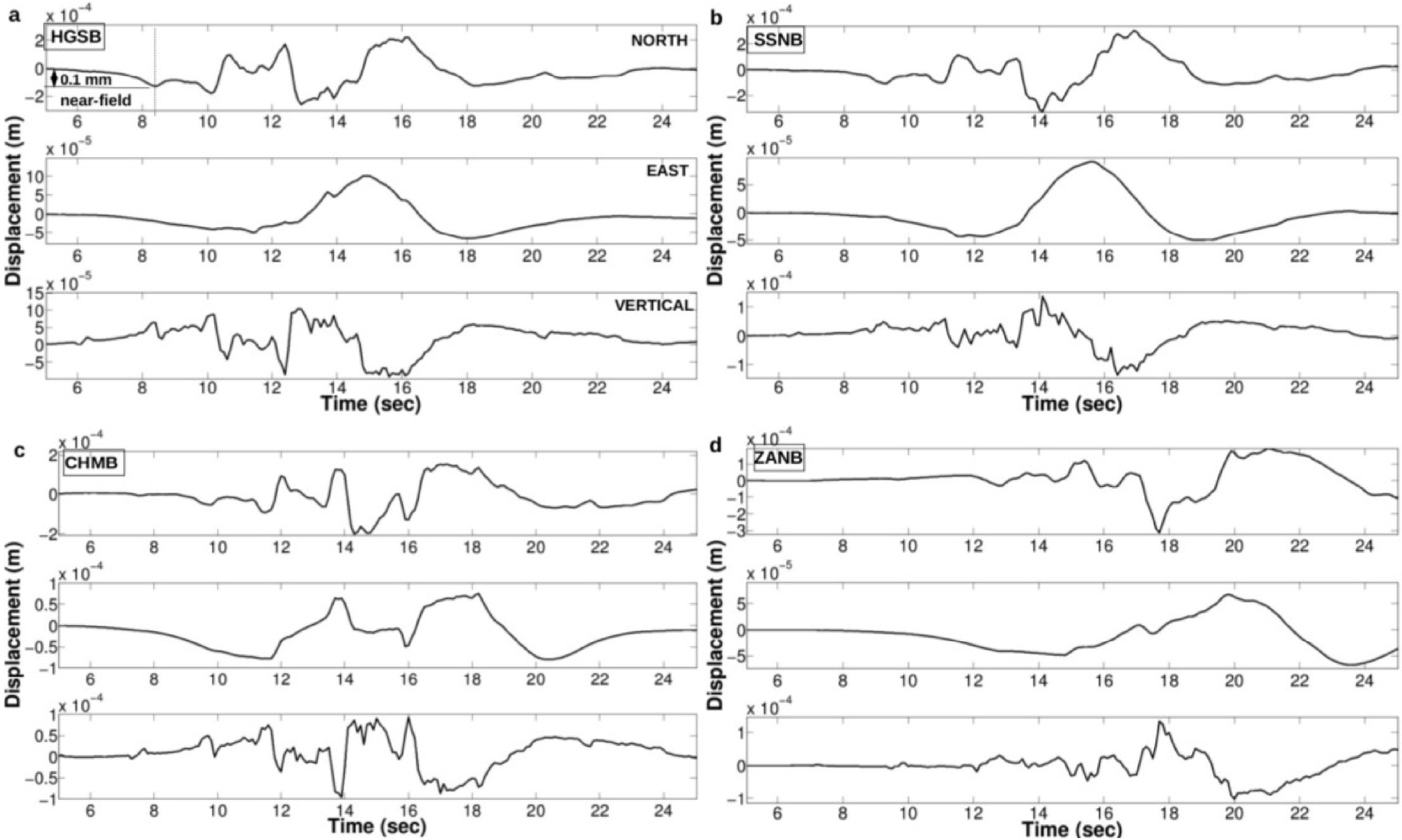
THANK YOU !

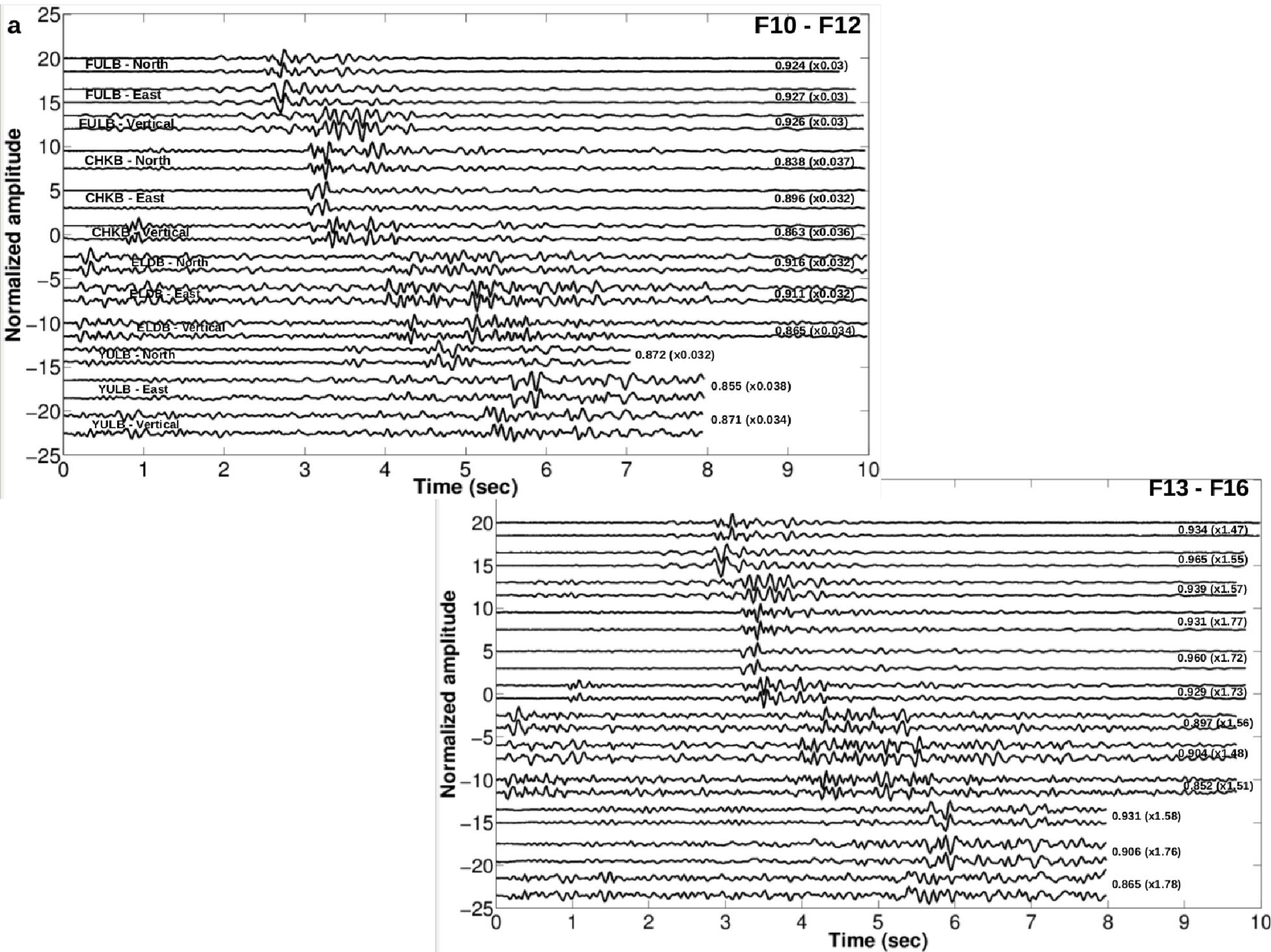
If you're interested on working with strain data, feel free to contact

canitano@earth.sinica.edu.tw


Horizontal
Vertical
dilatation
GPS
b
24°00'N
23°30'N
121°00'E
121°30'E
GPS
20 mm
Model
dU (mm)
−20 −10 0 10 20
Taiwan
China
Central Range

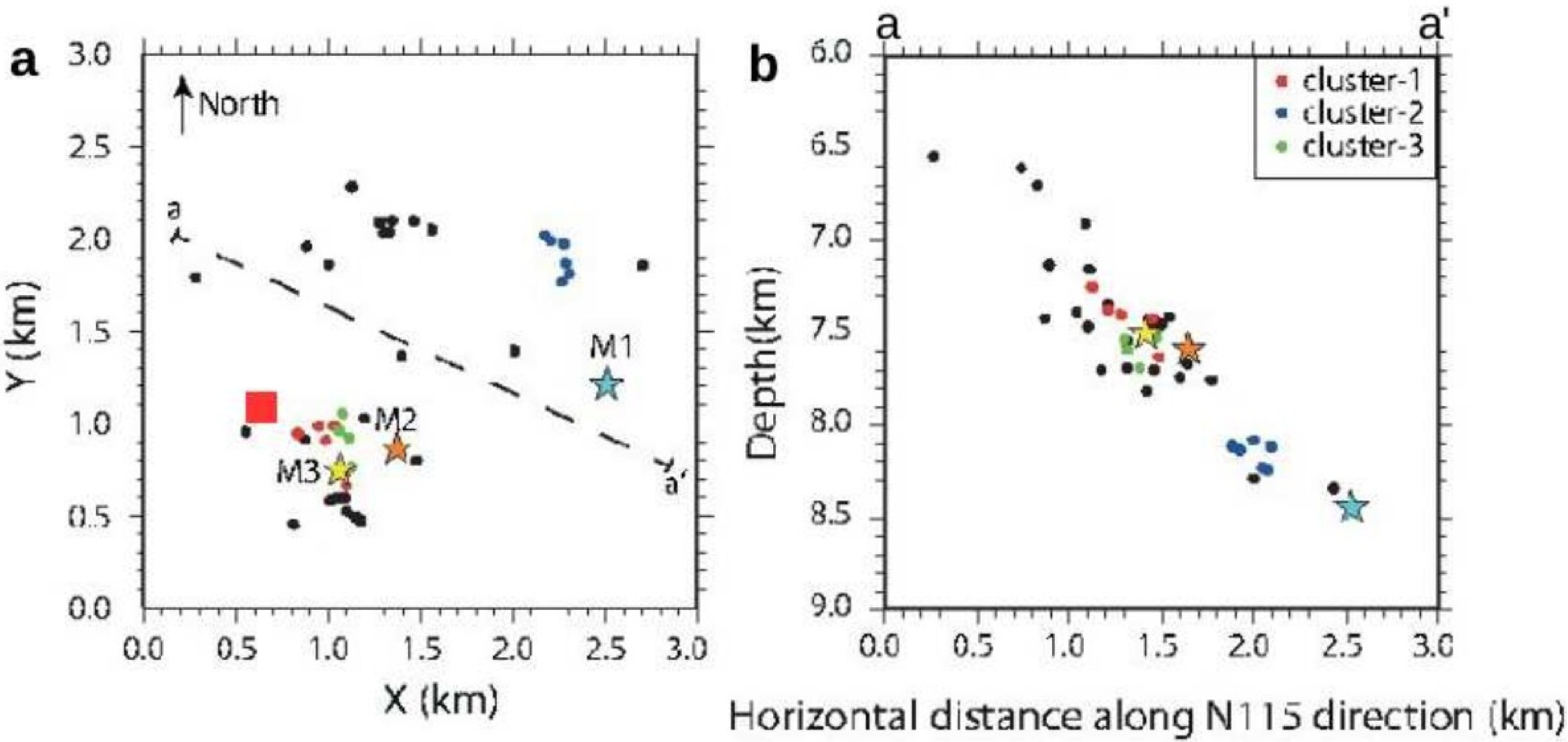
Computed displacements (Axitra)



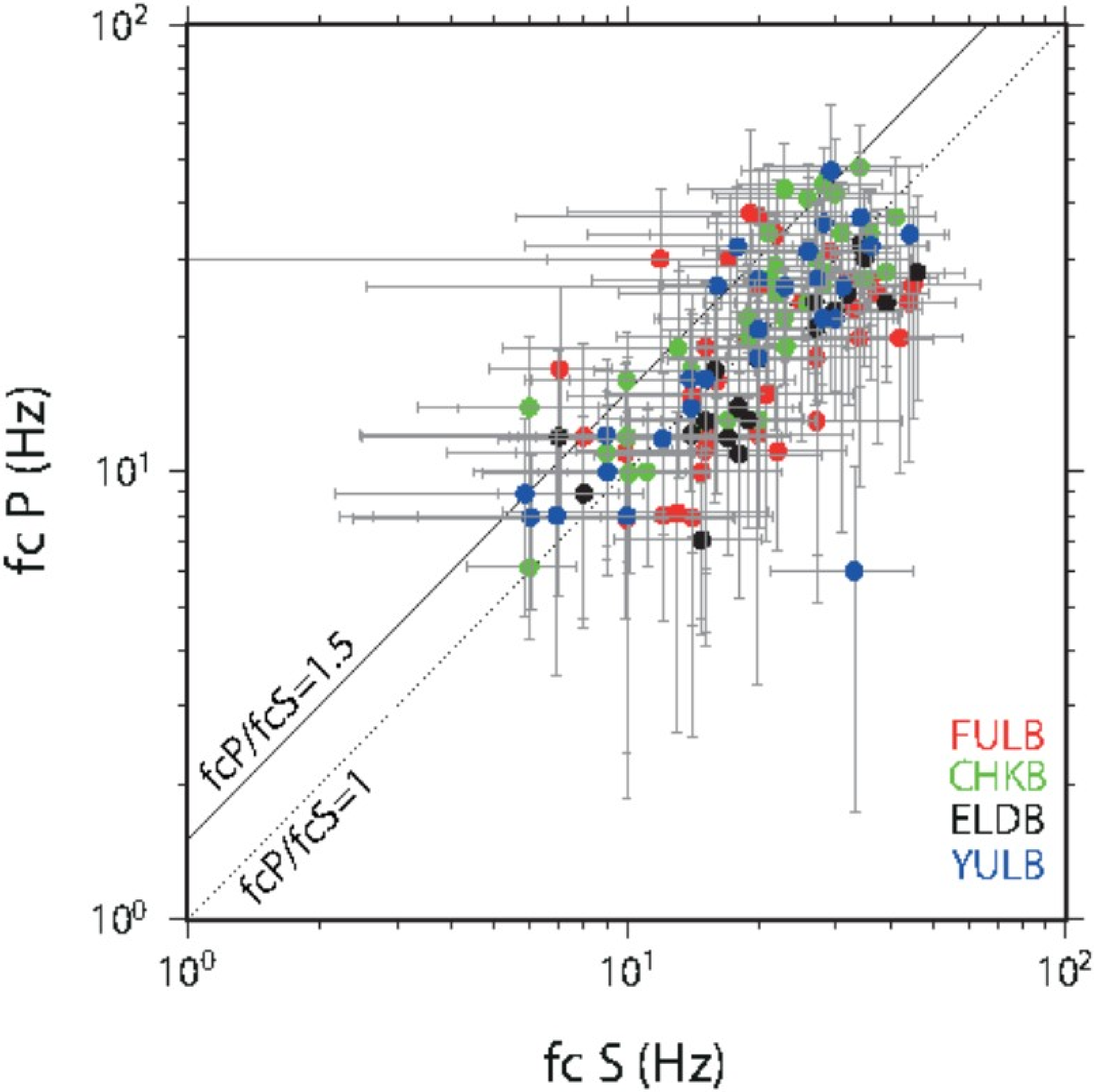


a
F10 - F12
FULB - North
FULB - East
FULB - Vertical
CHKB - North
CHKB - East
CHKB - Vertical
ELDB - North
ELDB - East
ELDB - Vertical
YULB - North
YULB - East
YULB - Vertical
0.924 (x0.03)
0.927 (x0.03)
0.926 (x0.03)
0.838 (x0.037)
0.896 (x0.032)
0.863 (x0.036)
0.916 (x0.032)
0.911 (x0.032)
0.865 (x0.034)
0.872 (x0.032)
0.855 (x0.038)
0.871 (x0.034)
Normalized amplitude
Time (sec)
F13 - F16
0.934 (x1.47)
0.965 (x1.55)
0.939 (x1.57)
0.931 (x1.77)
0.960 (x1.72)
0.929 (x1.73)
0.897 (x1.56)
0.904 (x1.48)
0.852 (x1.51)
0.931 (x1.58)
0.906 (x1.76)
0.865 (x1.78)
Normalized amplitude
Time (sec)

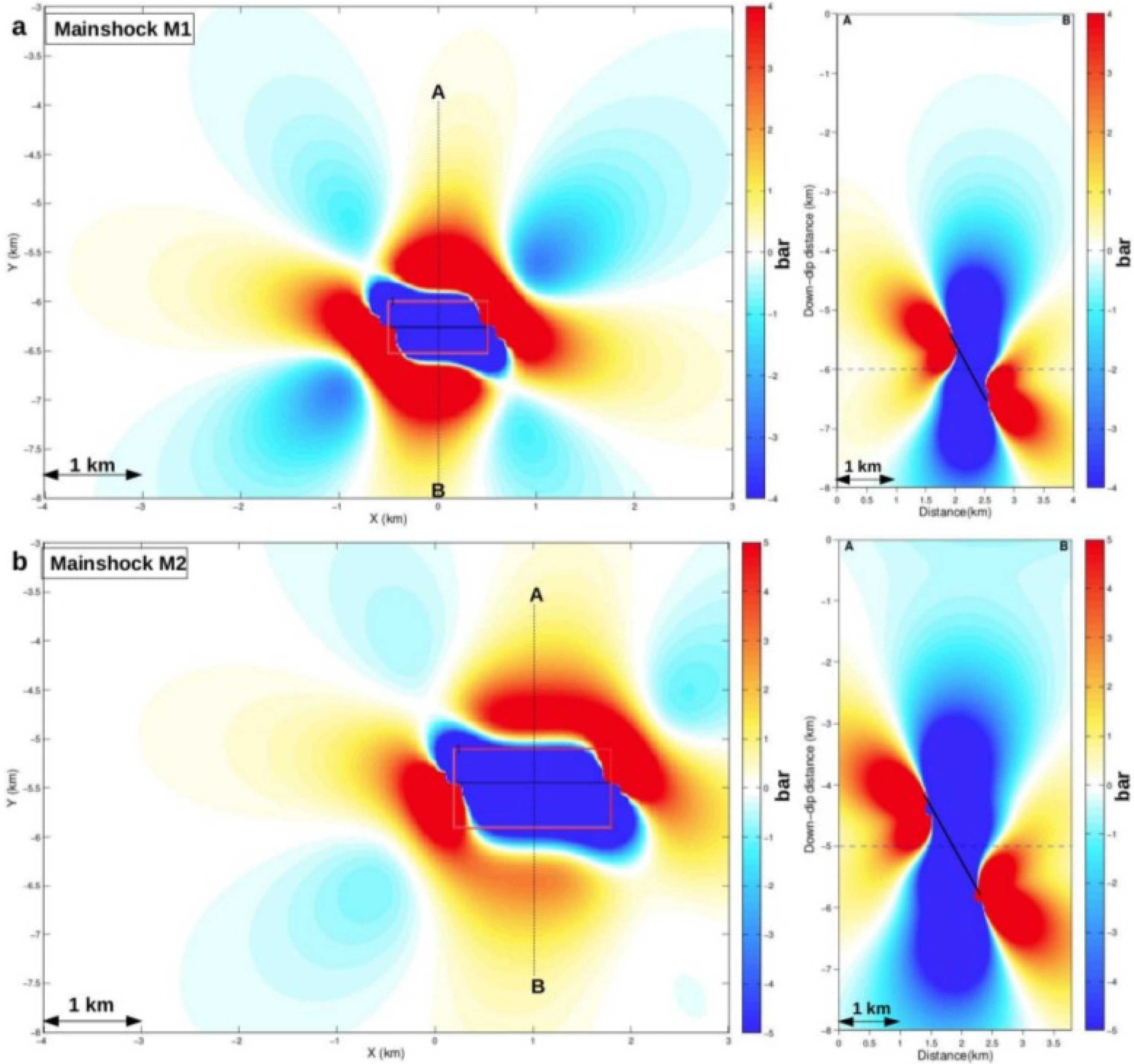
HypoDD relocation of seismicity



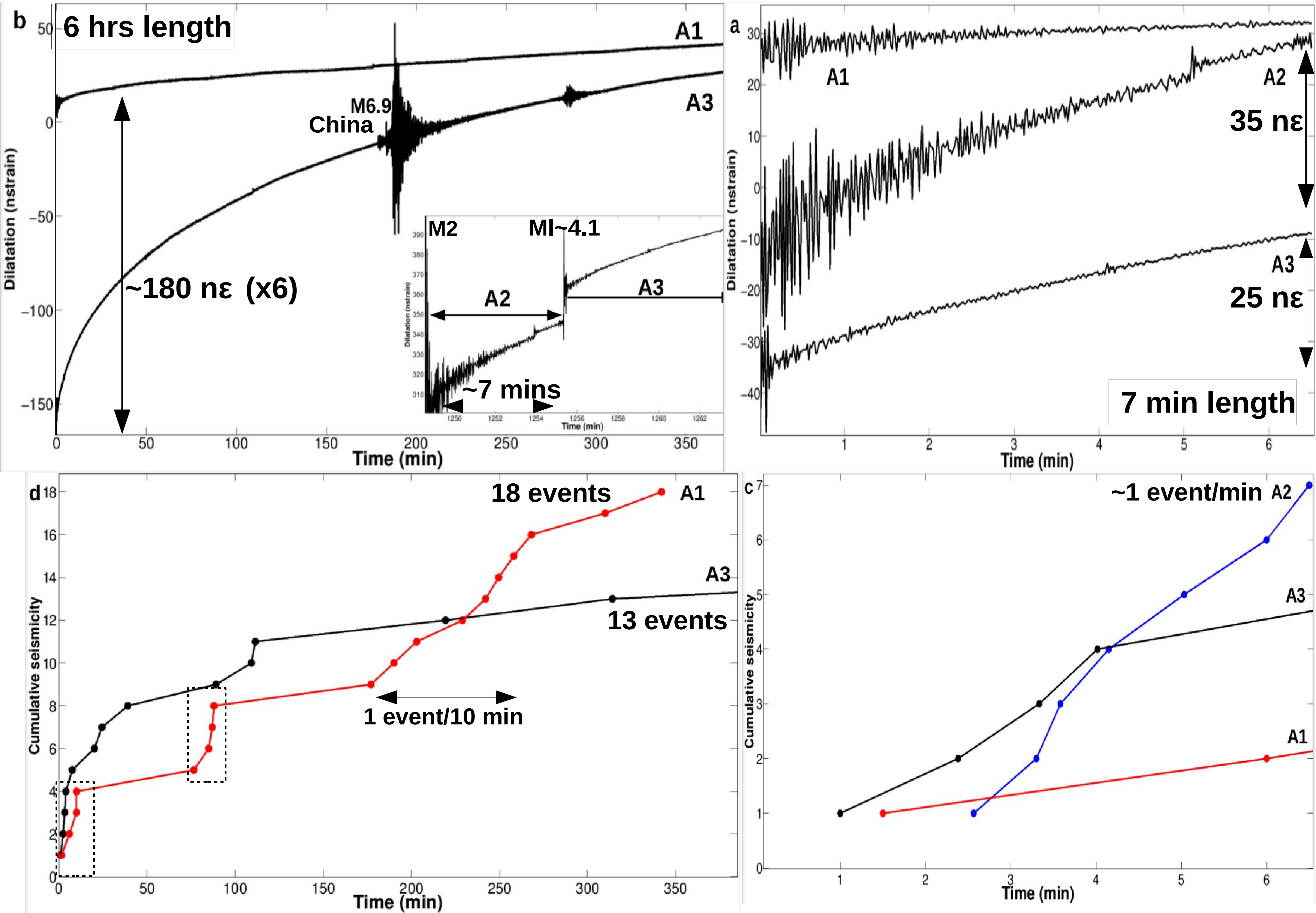
Bayesian approach : results

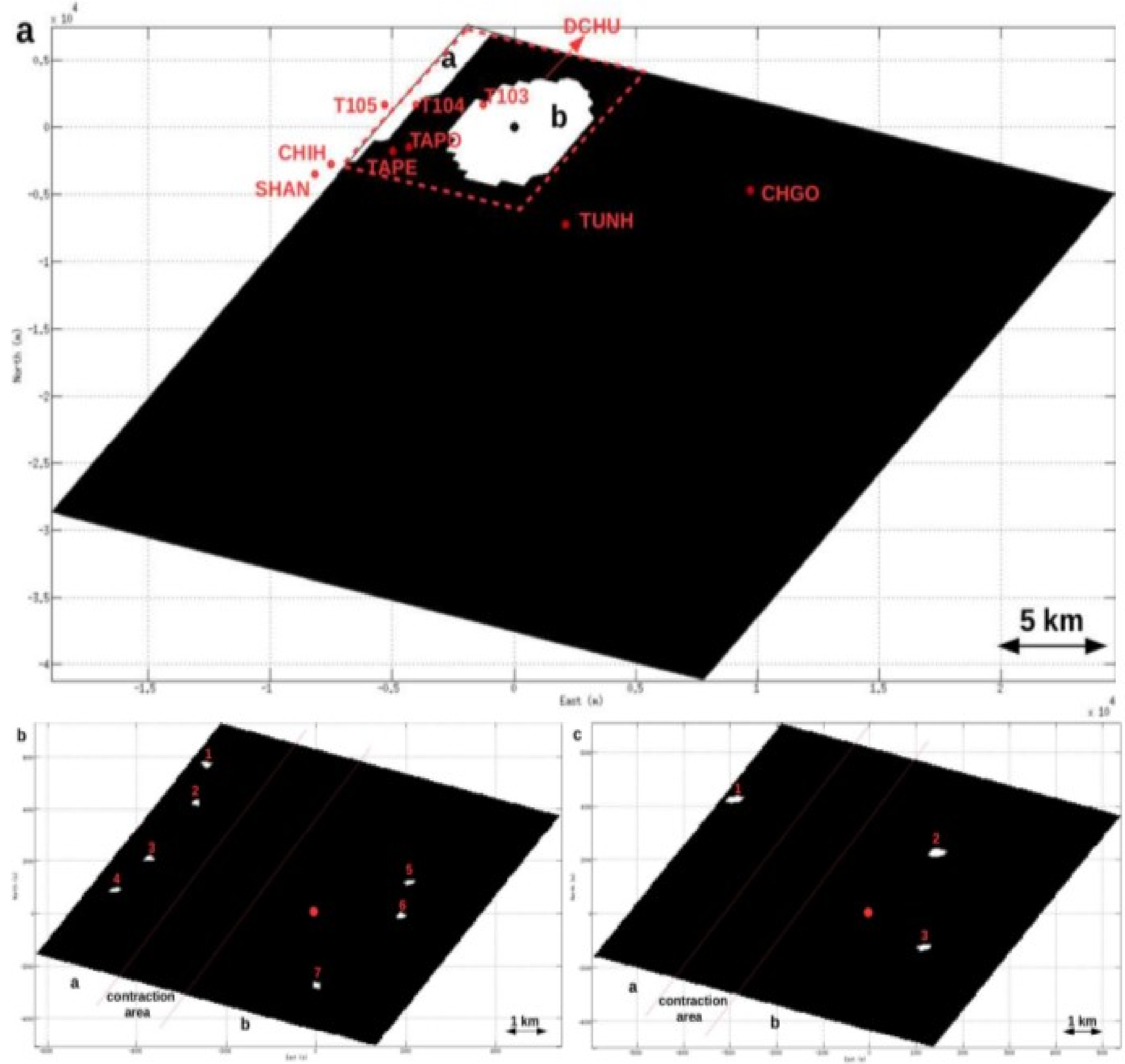


Static shear stress

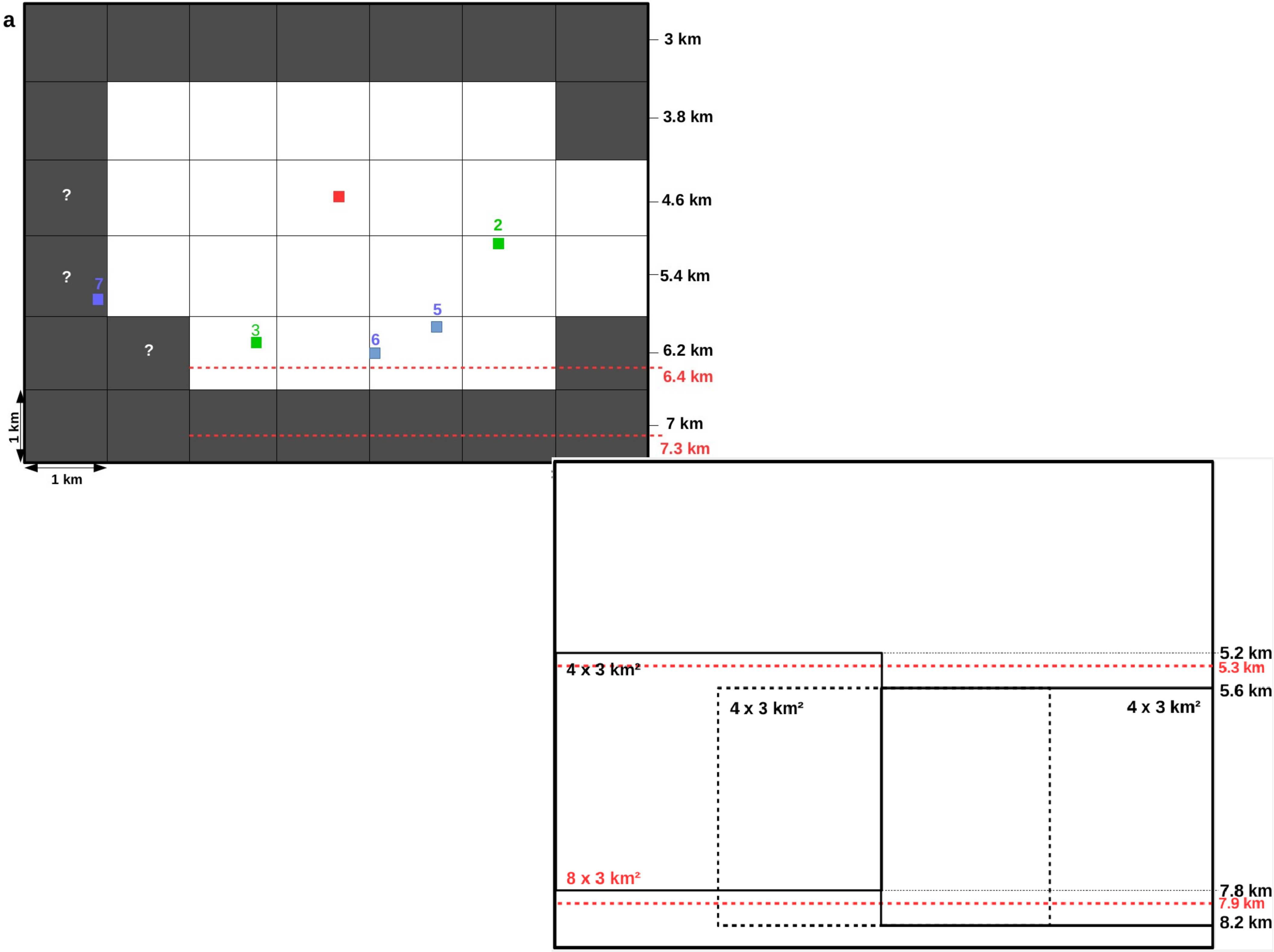


Seismicity and strain observation



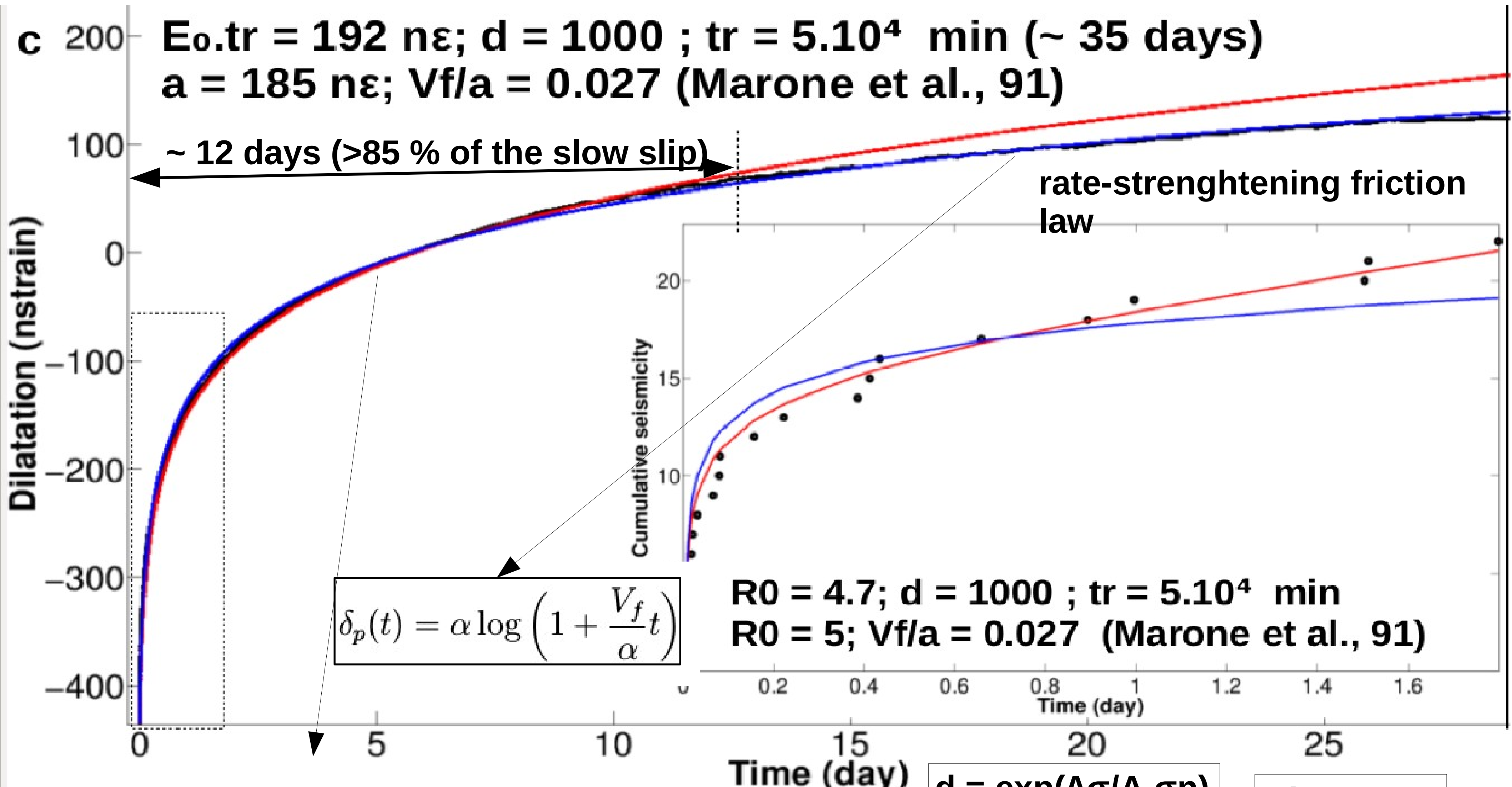


a
DCHU
T105
T104
T103
b
TAPO
CHIH
TAPE
SHAN
CHGO
TUNH
5 km
North (m)
East (m)
b
1
2
3
4
5
6
7
a
contraction
area
b
1 km
c
1
2
3
a
contraction
area
b
1 km



a
3 km
3.8 km
4.6 km
5.4 km
6.2 km
6.4 km
7 km
7.3 km
?
?
?
2
3
5
6
7
1 km
1 km
4 x 3 km²
4 x 3 km²
4 x 3 km²
8 x 3 km²
5.2 km
5.3 km
5.6 km
7.8 km
7.9 km
8.2 km

Rheological parameters of the fault and tectonic



$\epsilon_a(t) = \epsilon_0 t_r \log(1 + d(\exp(t/t_r) - 1))$ → **Eo~2.10³ nε/yr**

strain evolution

$R(t) = R_0 t_r \log(1 + d(\exp(t/t_r) - 1))$ → **Ro~50 event/yr (Ml>1.5-2)**

seismicity productivity

$\boxed{d = \exp(\Delta\sigma / A.\sigma n)}$

A.σn~0.072 MPa

(Δσ~0.5Mpa**)**

A~0.00075

(σn~100MPa)

$\boxed{\dot{\tau} = A.\sigma n / tr}$

T˙~ 0.75 MPa/yr