Borehole strain observations in eastern Taiwan

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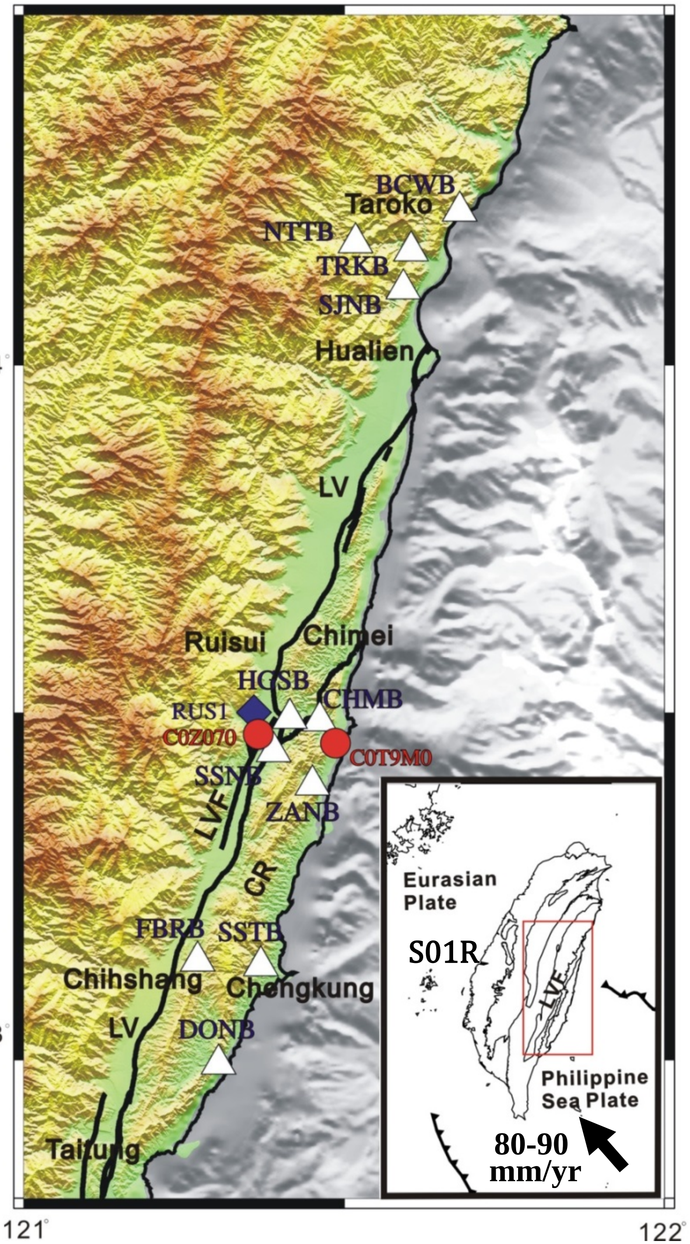
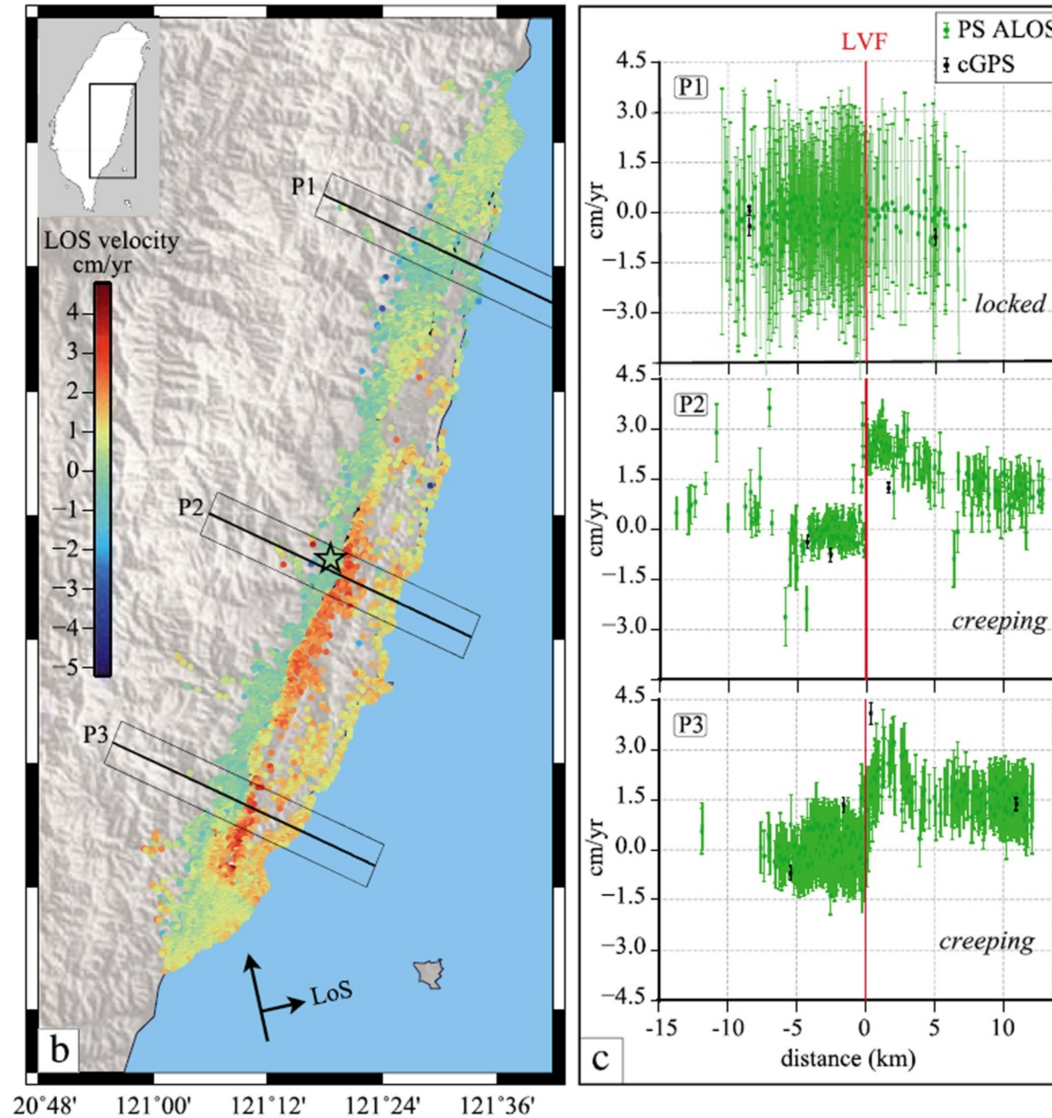
Outlines

- Borehole strain data processing
- Strain responses to environmental disturbances
- Relations between precipitation-induced strain and tectonic-origin motions
- Borehole strain recorded during the 2013 M_w 6.2 Ruisui, Taiwan EQ
- Precursory strain and earthquake nucleation

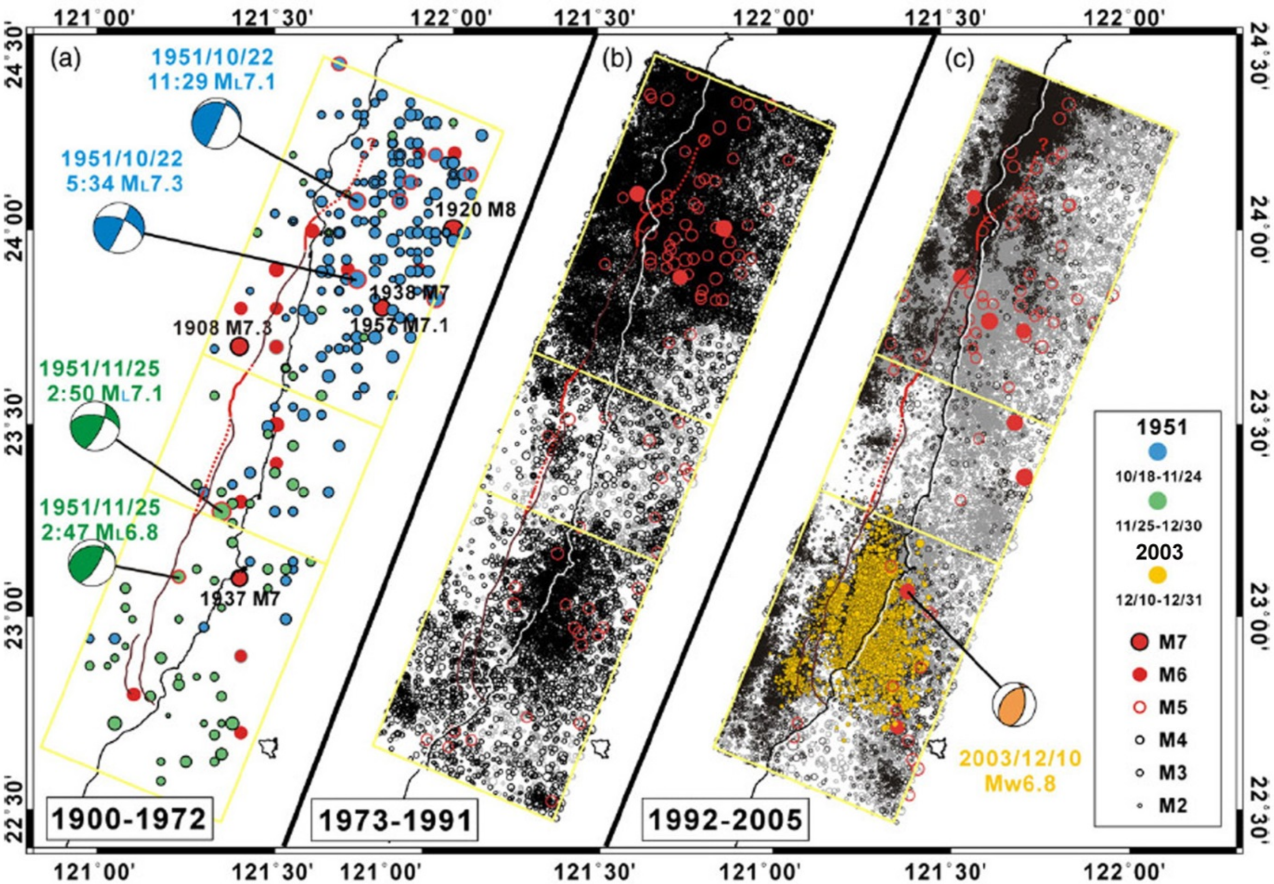
Borehole strainmeter array



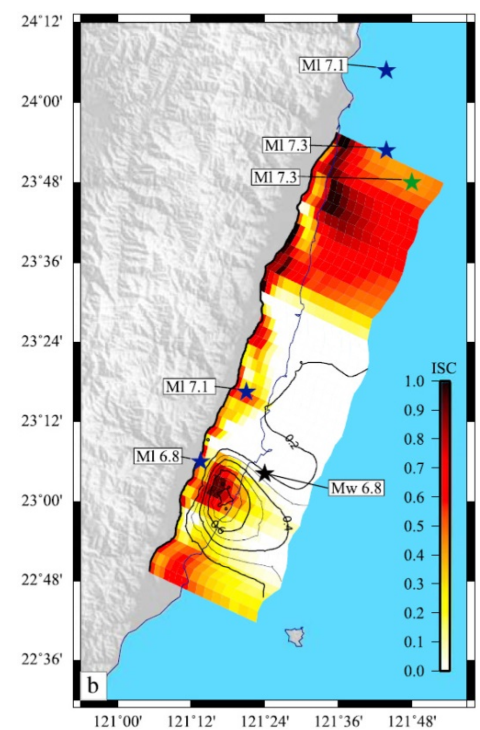


(Thomas et al., 2014)

Seismicity and fault coupling on the Longitudinal Valley fault



(Chung et al., 2008)

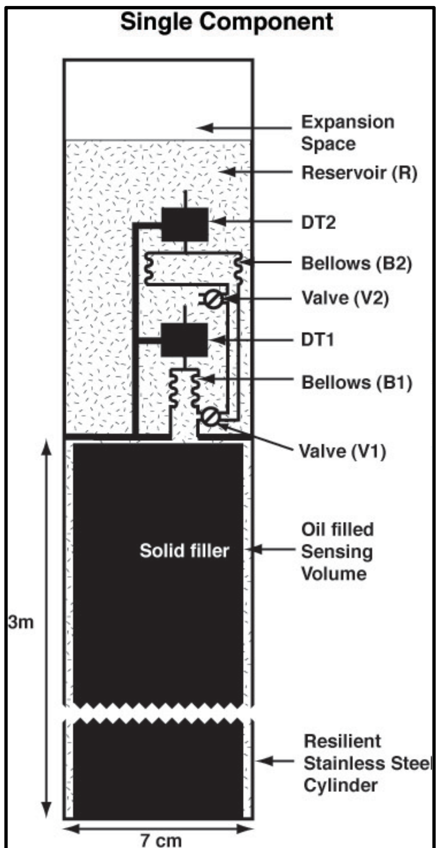


(Thomas et al., 2014)

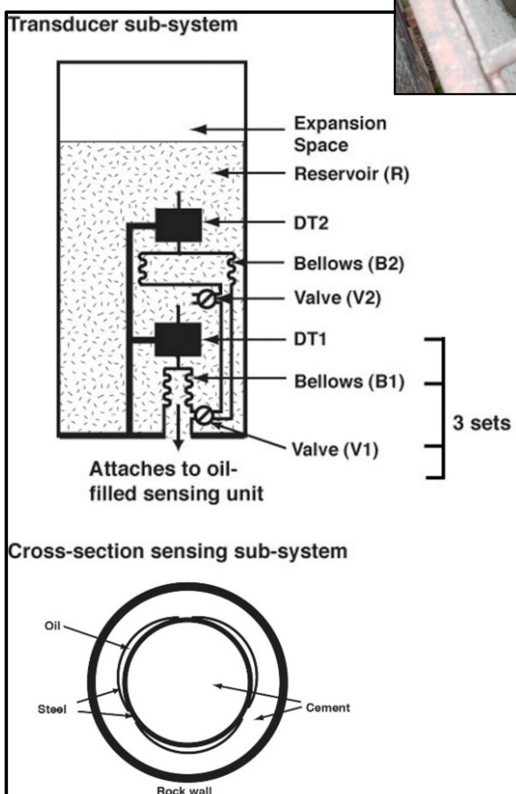
Sacks-Evertson borehole strainmeter

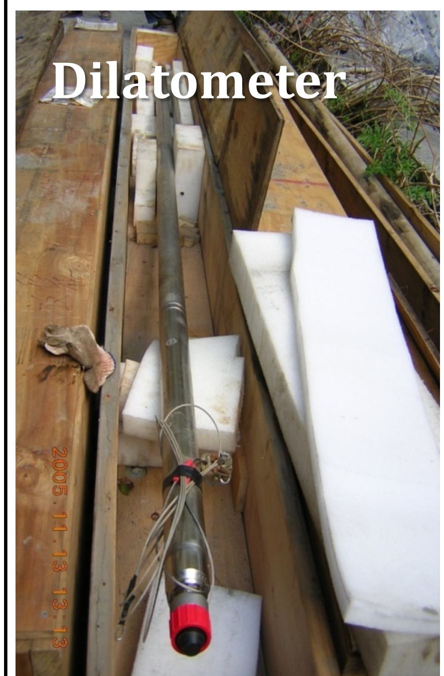
in collaboration with the DTM,
Carnegie institution of Washington

Dilatometer

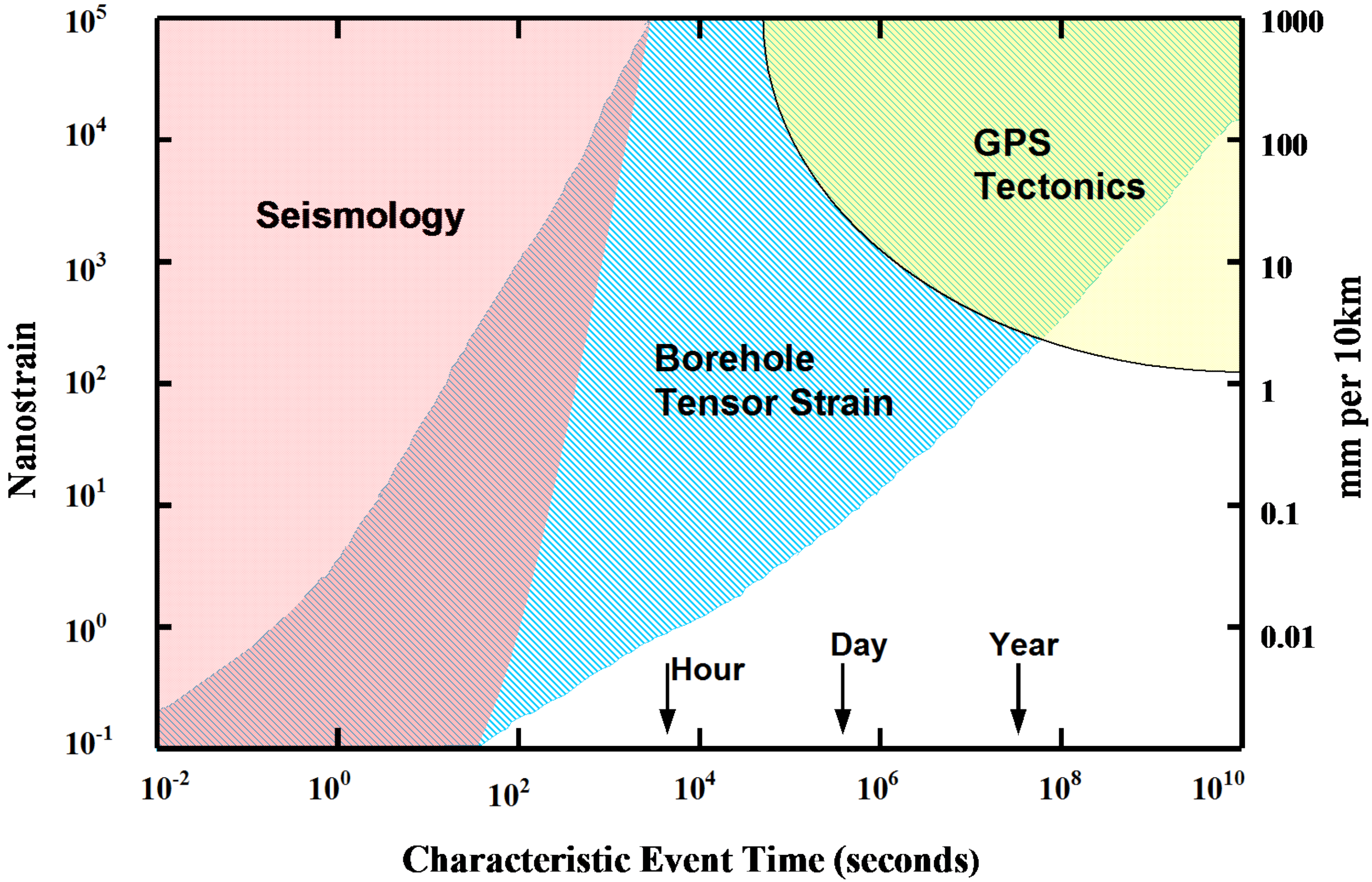


3-component

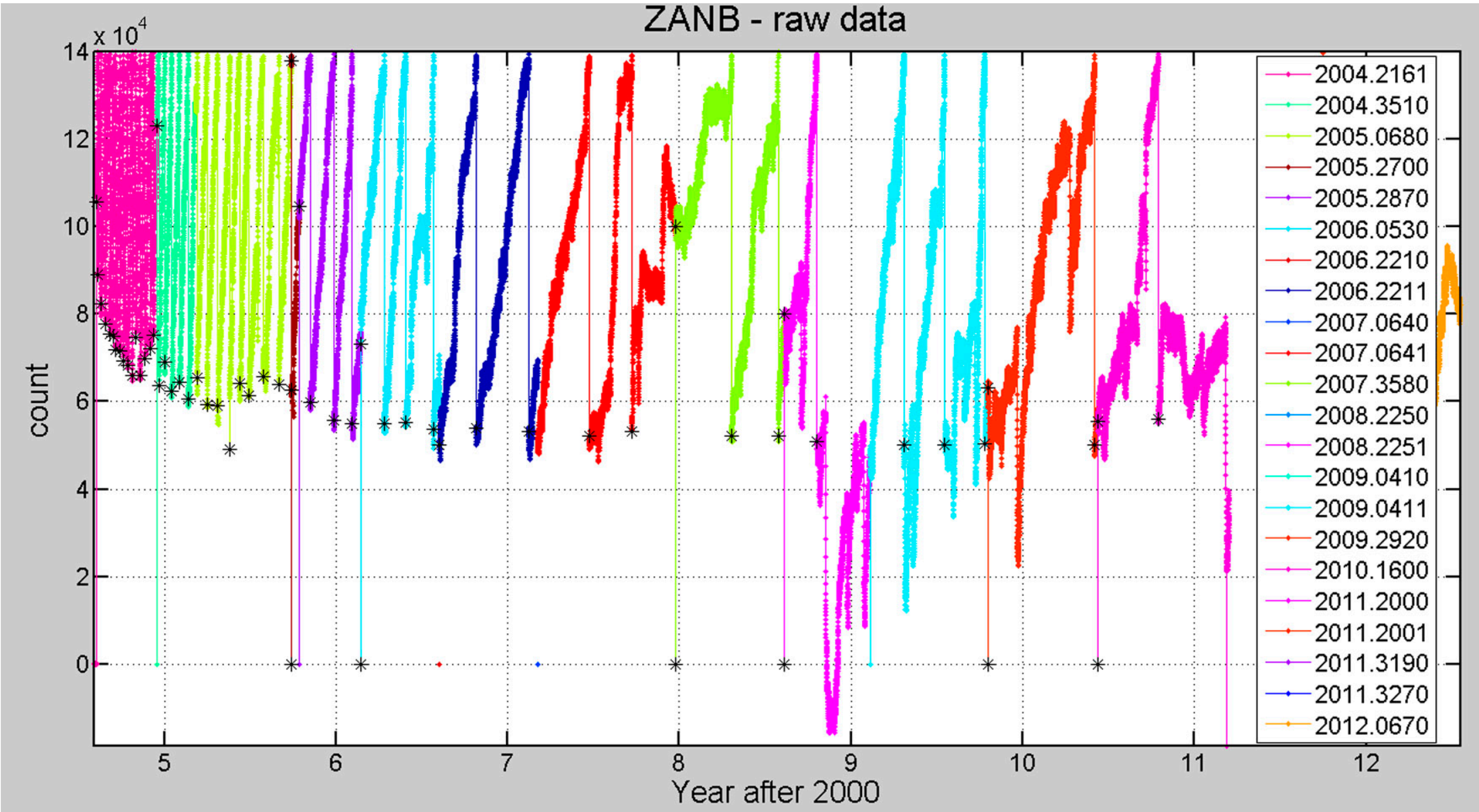




Sensitivities of borehole strainmeter



Borehole strainmeter data



Data processing

$$s(t) = a_0 + a_1 e^{-t/\lambda_1} + a_2 e^{-t/\lambda_2} + a_3 t$$

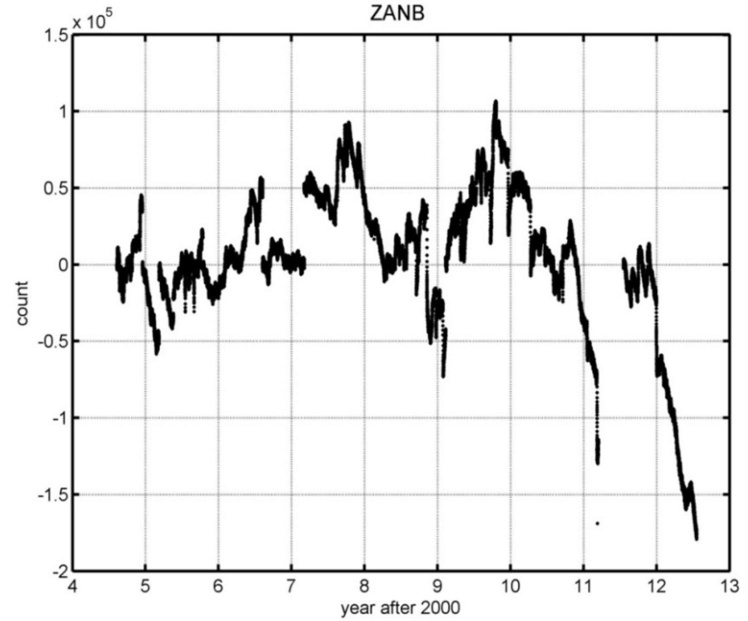
$s(t)$: strainmeter data

a_0 : constant

$a_1 e^{-t/\lambda_1}$, $a_2 e^{-t/\lambda_2}$: strain changes associated with the hole relaxation and grout curing

$a_3 t$: linear trend

$$\frac{ds(t)}{dt} = -\frac{a_1}{\lambda_1} e^{-t/\lambda_{11}} - \frac{a_2}{\lambda_2} e^{-t/\lambda_{12}} + a_3$$



(Hsu et al., 2015)

Table 2. Optimal Values for Parameters in Equation (1), λ_1 and λ_2, Are the Relaxation Time of Two Exponential Terms; a_1 and a_2 Are Amplitudes of Two Exponential Terms; a_3 Is the Amplitude of Long-Term Linear Trend

Site	λ_1 (day)	λ_2 (day)	a_1 (strain)	a_2 (strain)	a_3 (strain/yr)
CHMB	365	1460	−3.4E-6	−3.0E-4	−3.2E-6
HGSB	110	620	−1.9E-5	−4.3E-5	−2.0E-6
ZANB	73	256	−2.1E-7	−1.7E-5	−1.4E-6
SSNB	110	840	−8.7E-6	−3.7E-5	−1.9E-6

Strainmeter calibration and tidal responses

SPOTL (Agnew, 1996)

Estimate strains of M2 and O1 tides produced by the solid Earth tides and the ocean loading

M2/O1 (Period:12.4206/25.8194 hour)

Baytap08 (Tamura and Agnew, 2008)

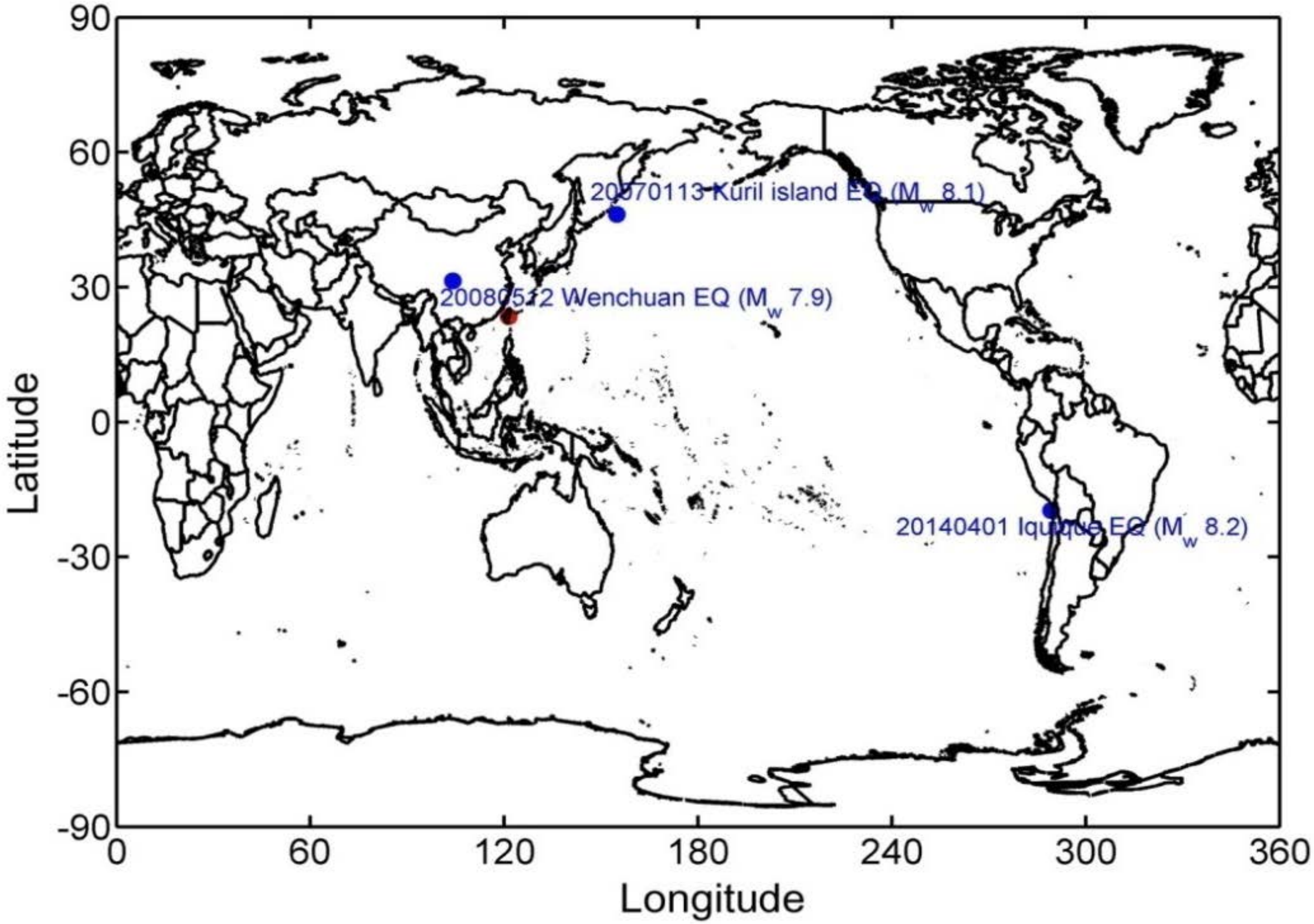
- Using a Bayesian modeling procedure to analyze time series that contain both tidal and other variations
- Estimate tide and air pressure responses to strain data

Table 3. Results of Tidal Analyses for Three Sacks-Evertson Dilatometers (SES-1) and One Three-Component Borehole Strainmeter (SES-3)

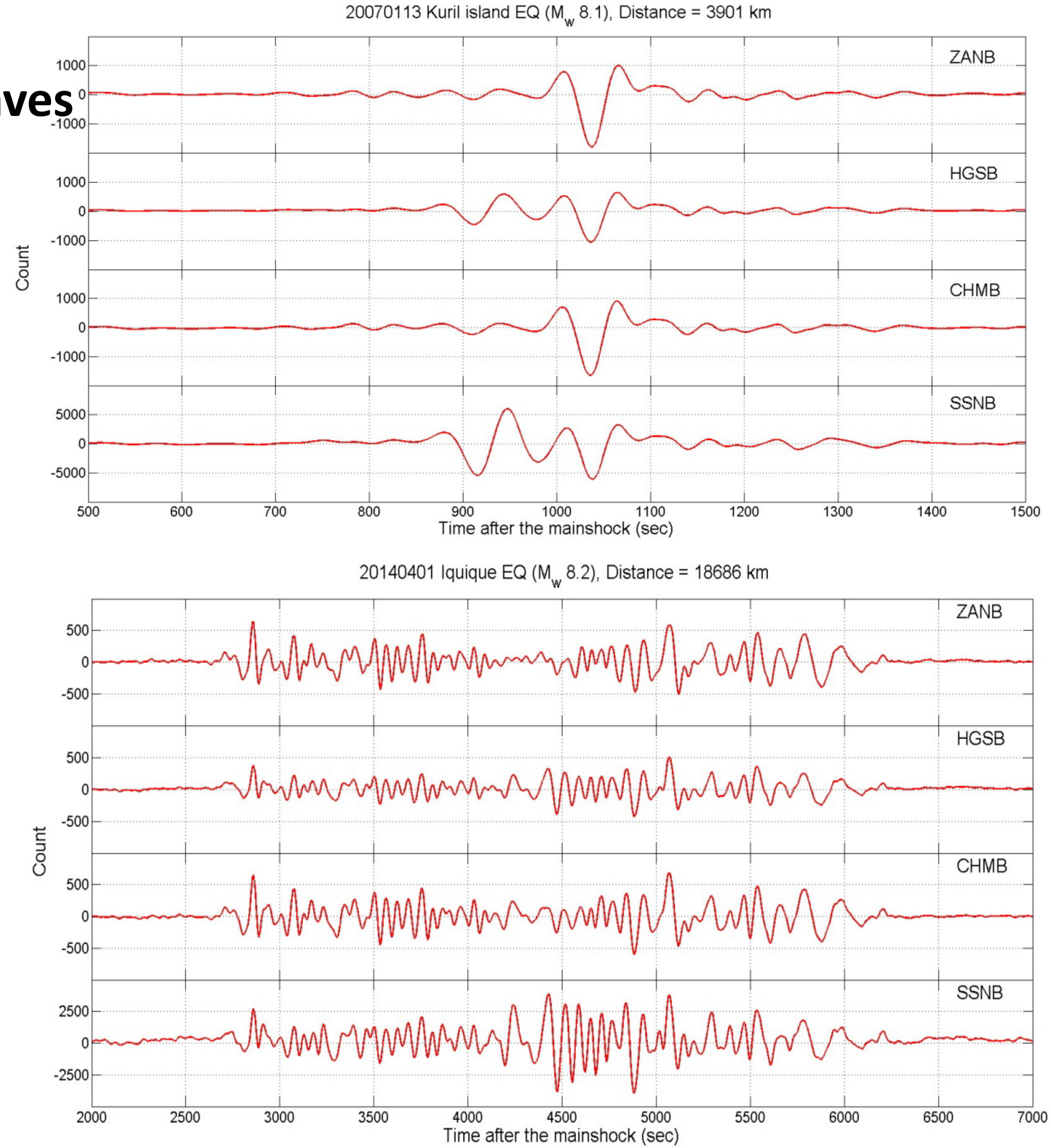
Site	M2_amp (nε, SPOTL)	M2_amp (count)	M2/O1 (SPOTL)	M2/O1 (observed)	M2 Phase (SPOTL)	M2 Phase (observed)	O1 Phase (SPOTL)	O1 Phase (observed)	M2 Admittance (strain/count)	O1 Admittance (strain/count)	BPRC[a] (nε/hPa)
CHMB	12.1	2758	3.3	3.8 ± 0.1	9.6	7.9 ± 0.2	18.0	-7.0 ± 0.9	4.4E-12 ± 1.3E-14	5.0E-12 ± 7.5E-14	-0.9 ± 0.2
HGSB	12.9	1505	3.3	4.4 ± 0.3	9.1	8.2 ± 0.5	15.8	-10.8 ± 3.3	8.5E-12 ± 7.3E-14	1.1E-11 ± 6.2E-13	-3.2 ± 0.5
ZANB	11.9	1657	3.3	3.2 ± 0.1	9.3	8.1 ± 0.4	19.0	8.3 ± 1.4	7.2E-12 ± 4.8E-14	7.0E-12 ± 1.7E-13	-2.8 ± 0.2
SSNB-dil	13.1	14162	3.3	5.1 ± 0.6	8.7	5.4 ± 0.1	15.5	-18.9 ± 0.9	9.2E-13 ± 1.9E-15	1.4E-12 ± 3.8E-14	-2.8 ± 0.1
SSNB-γ_1	18.0	10999	9.3	5.7 ± 0.7	30.6	20.5 ± 0.5	-32.5	-78.2 ± 0.8	1.6E-12 ± 2.6E-14	1.0E-12 ± 1.3E-14	-0.1 ± 0.1
SSNB-γ_2	12.6	3133	2.0	19.1 ± 0.7	-143.1	-138.5 ± 0.3	71.8	-67.3 ± 7.7	4.0E-12 ± 2.0E-14	3.8E-11 ± 1.2E-13	-1.3 ± 0.3

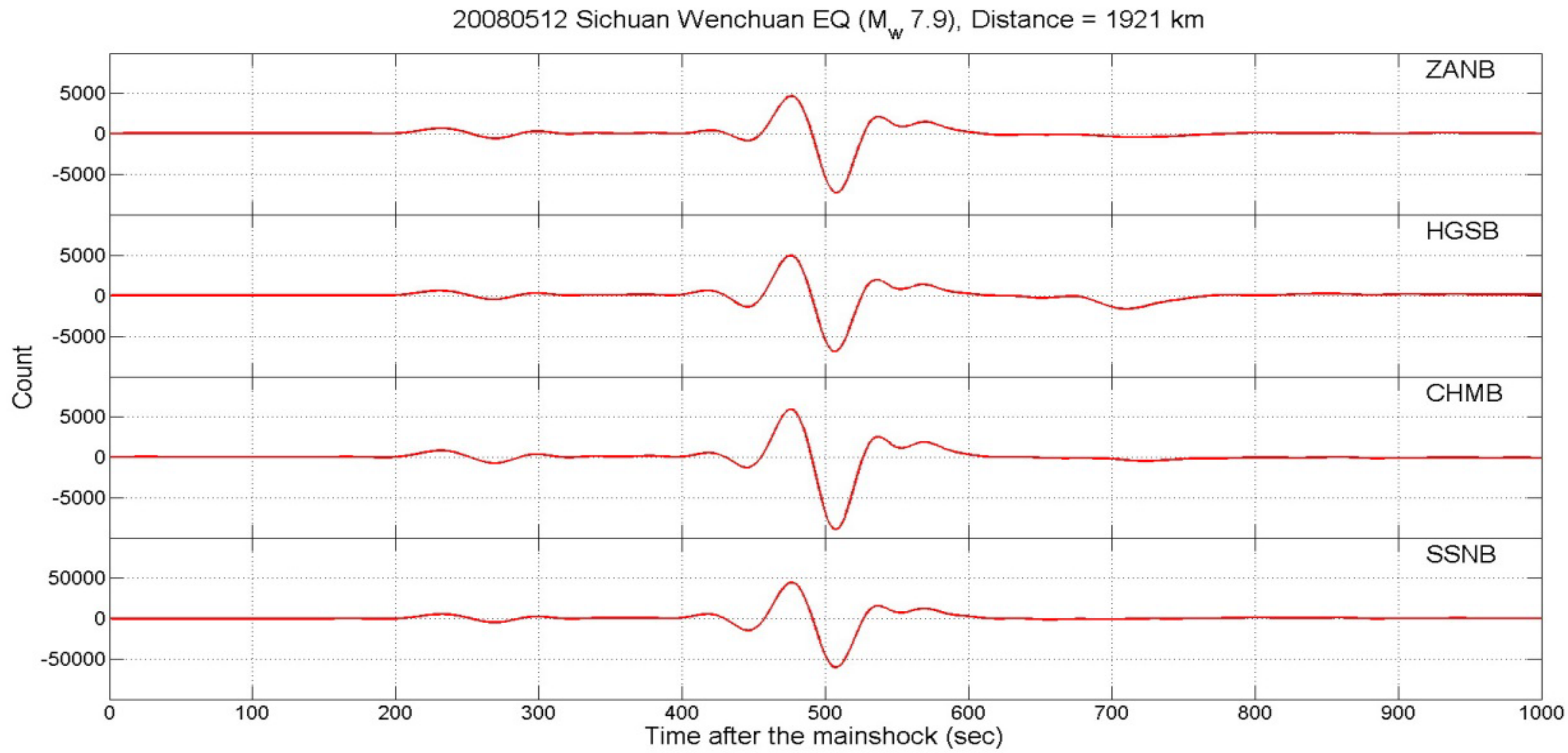
[a]Barometric pressure response coefficient (BPRC)

Strainmeter calibration using long-period surface waves



50-s surface waves



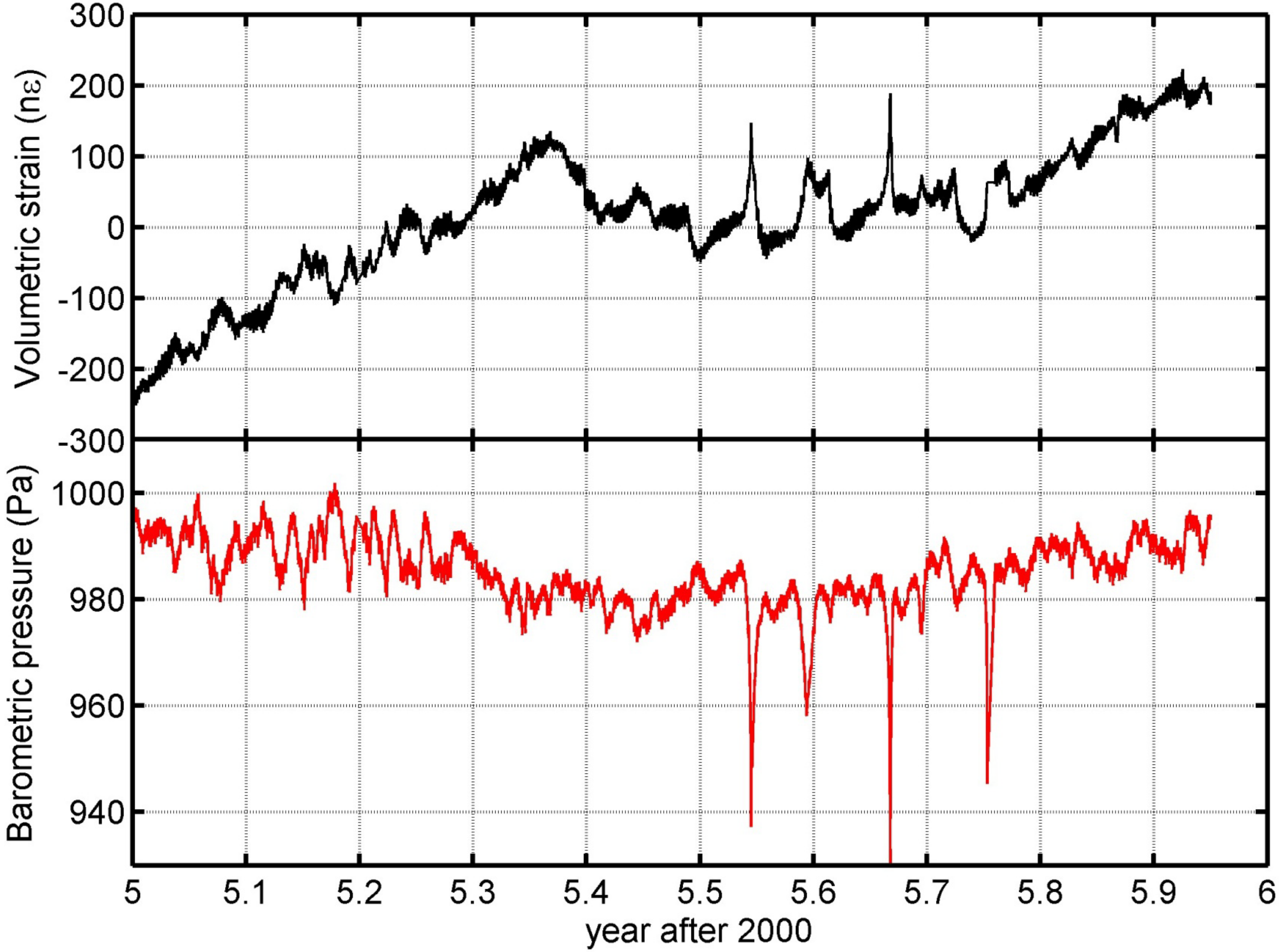


Peak-to-peak Counts : 11975:11835:14879:105420

Waveform admittance : **1.00 : 1.01 : 0.80 : 0.11**

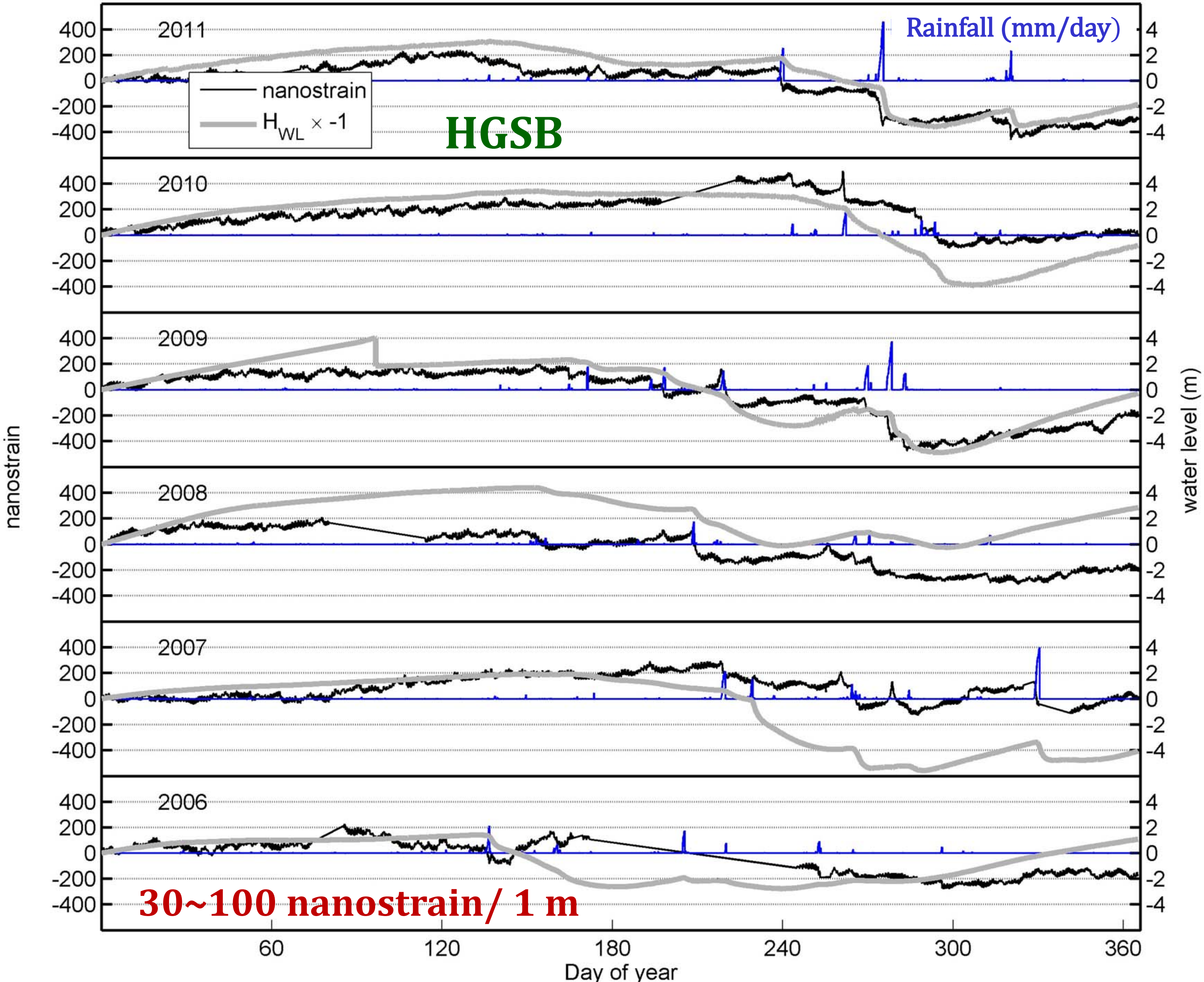
Tidal admittance : **1.00 : 1.18 : 0.61 : 0.13**

The strainmeter response to barometric pressure



-1~-4 (nanostrain/hPa=nε/hPa)

The strainmeter response to ground water variations



State-Space Model

$$S_n^o = S_n^c + P_n + E_n + R_n + \varepsilon_n$$

raw **de-trend**

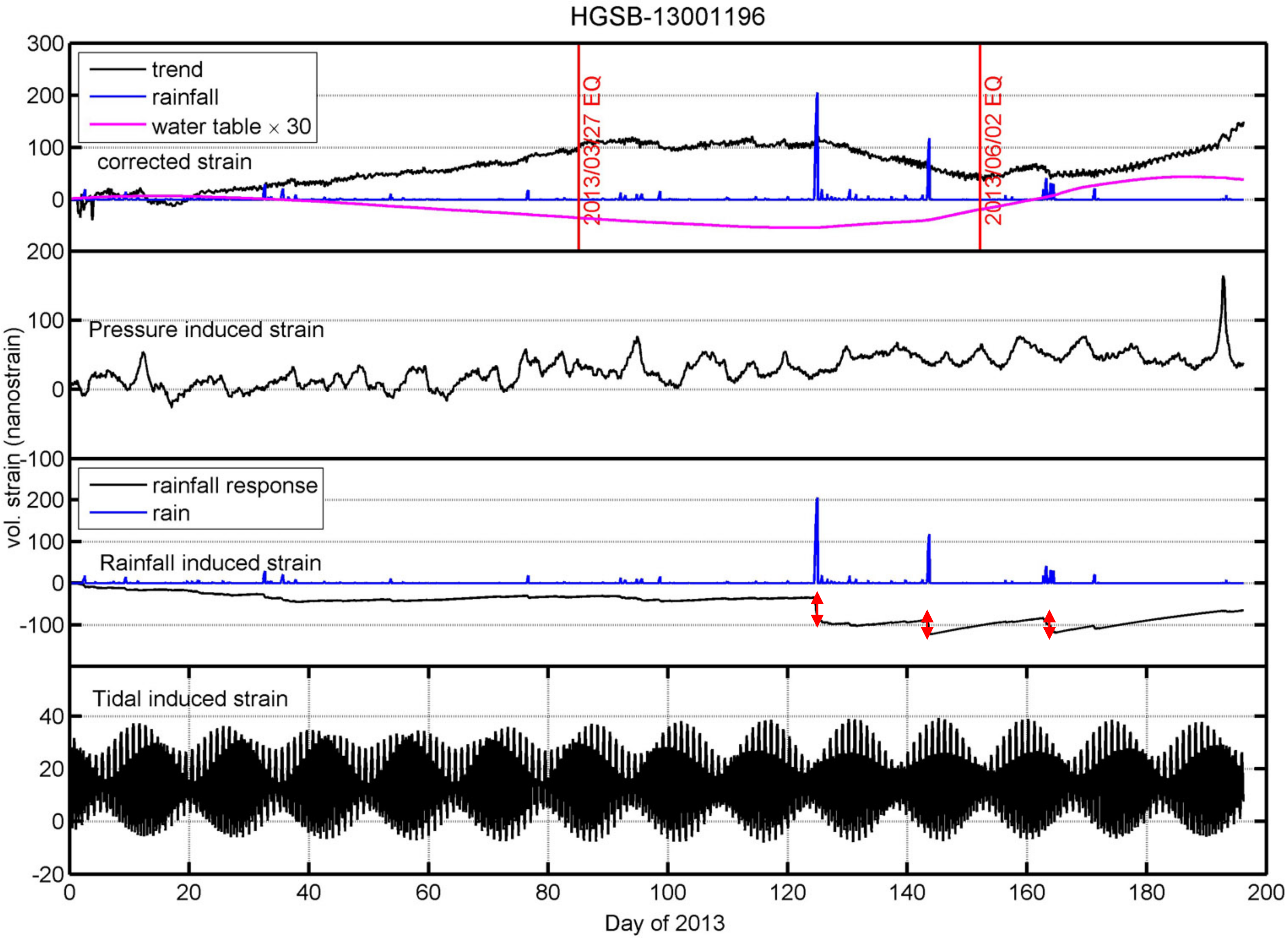
$$\varepsilon_n \sim N(0, \sigma^2), \qquad n = 1, \dots, N$$

$$P_n = \sum_{i=o}^{m} a_i P_{n-1}$$ **Response of barometric pressure**

$$E_n = \sum_{i=o}^{l} b_i et_{n-i}$$ **Response of the Earth tides**

$$R_n = \sum_{i=1}^{k} C_i R_{n-i} + \sum_{i=1}^{k} d_i r_{n-i}$$ **Response of rainfall**

Decompose data with a state-space model



Barometric pressure: -1~-3 nε/hPa; GW: -0.3~-1.0 nε/hPa; Rainfall: -5.1 nε/hPa

Effect of pore-fluid flow on a dilatometer response

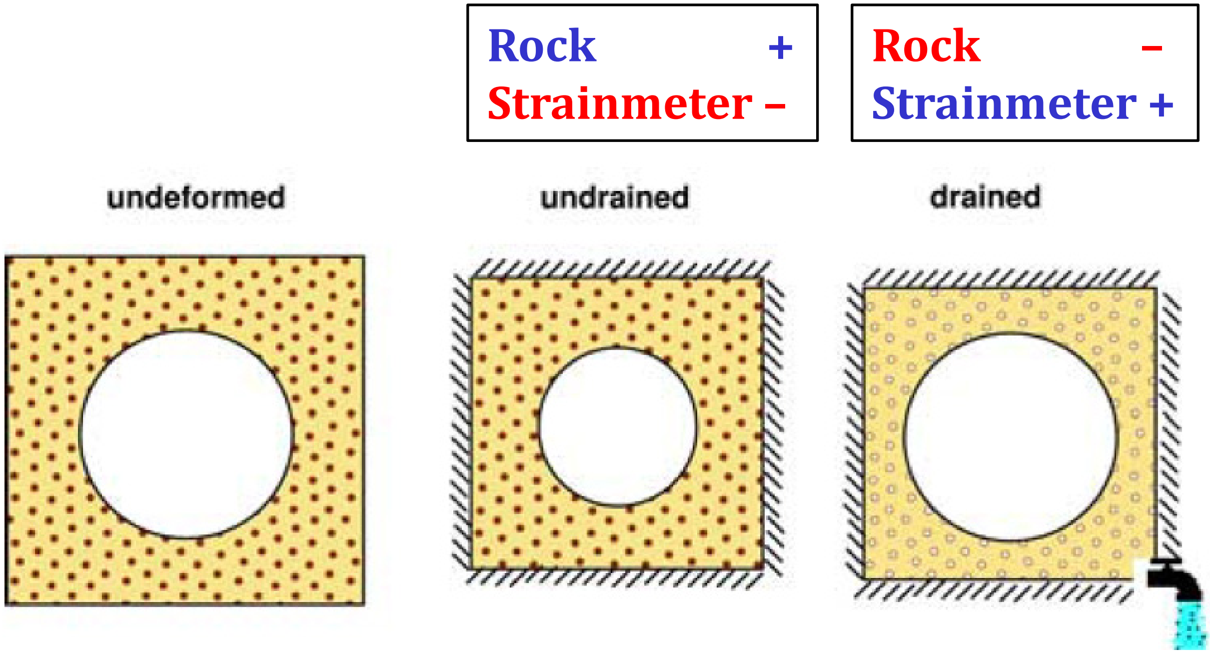


Figure 1. Thought experiment to illustrate the effect of pore-fluid flow on a dilatometer response. A block of fluid saturated rock with a cylindrical hole is compressed. With the external displacements fixed the fluid is allowed to drain. As the fluid drains the rock contracts and the hole expands.

(Segall et al, 2003)

Uniaxial-stress

$$\varepsilon_{zz} = \frac{1}{E}(\sigma_{zz} - \nu(\sigma_{xx} + \sigma_{yy}))$$

$$\varepsilon_{zz} = \frac{1}{E}\sigma_{zz} = \frac{\sigma_{zz}}{2G(1+\nu)}$$

E and *G* are Young's modulus and shear modulus, ν is Poisson's ratio

ν=0.25 and *G*=30 GPa, the resulting vertical strain is $\varepsilon_{zz} = 1.3\times10^{-11}$ Pa^{-1}

$$\varepsilon_a = -2\nu\ \varepsilon_{zz} \quad ; \ \varepsilon_{vol} = (1-2\nu)\ \varepsilon_{zz}$$

-0.7 *nε*/hPa

Volumetric strain resulted from per meter of water level change ($=9.8\times10^3$Pa) ν=0.25, porosity (φ) =0.2, and *G*=30 GPa

-13 *nε*/1-m water level change

Uniaxial strain

$$\sigma_{zz} = \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_{zz} + (\varepsilon_{xx} + \varepsilon_{yy})\right]$$

$$\varepsilon_{zz} = \frac{\sigma_{zz}(1-2\nu)}{2G(1-\nu)}$$

ν=0.25 and *G*=30 GPa

$$\varepsilon_{zz} = \varepsilon_{vol} = 1.1\times 10^{-11}\ \text{Pa}^{-1}$$

-1.1 *nε*/hPa

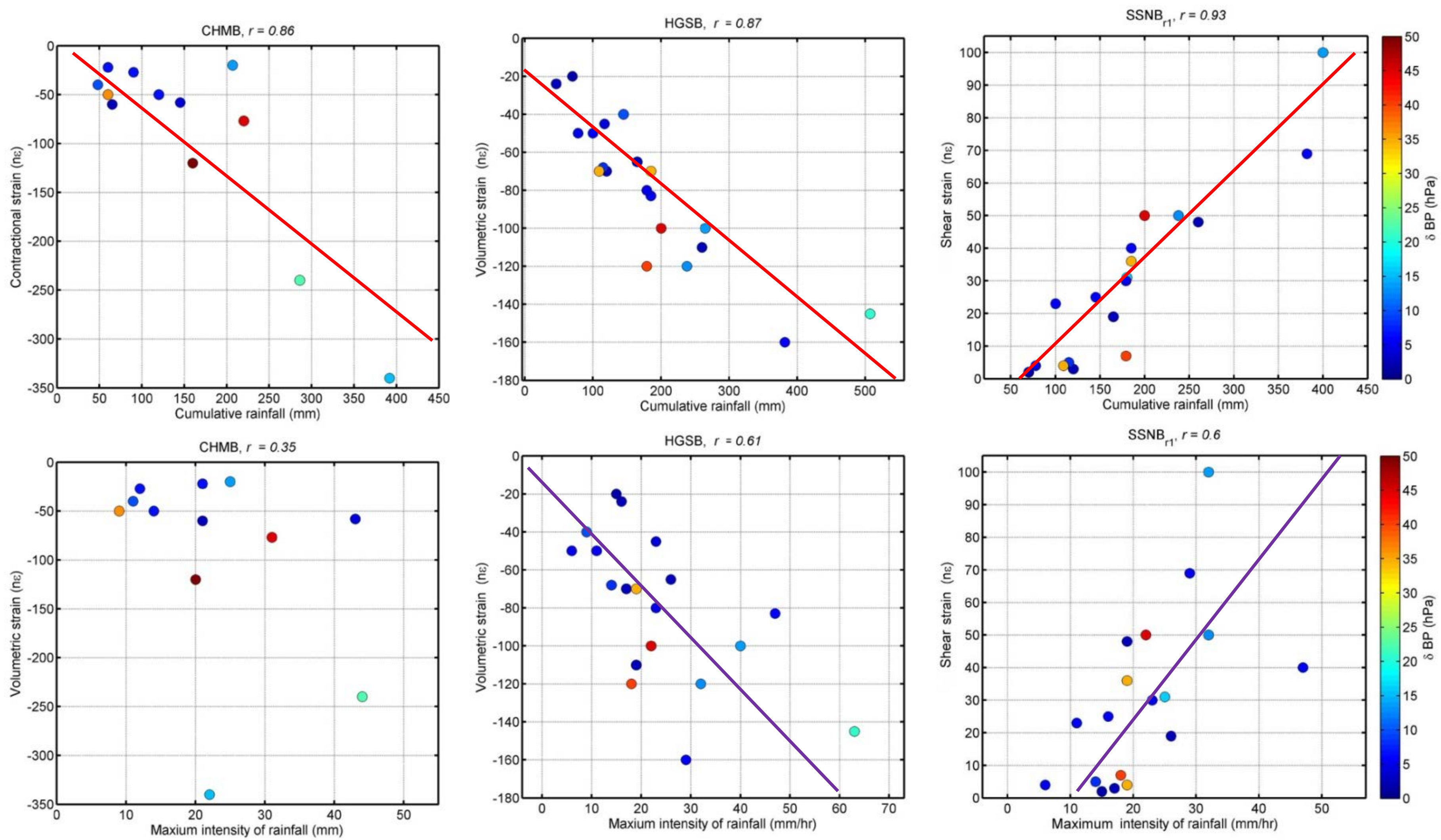
ν=0.25, porosity (*φ*) =0.2, and *G*=30 GPa

-22 *nε*/1-m water level change

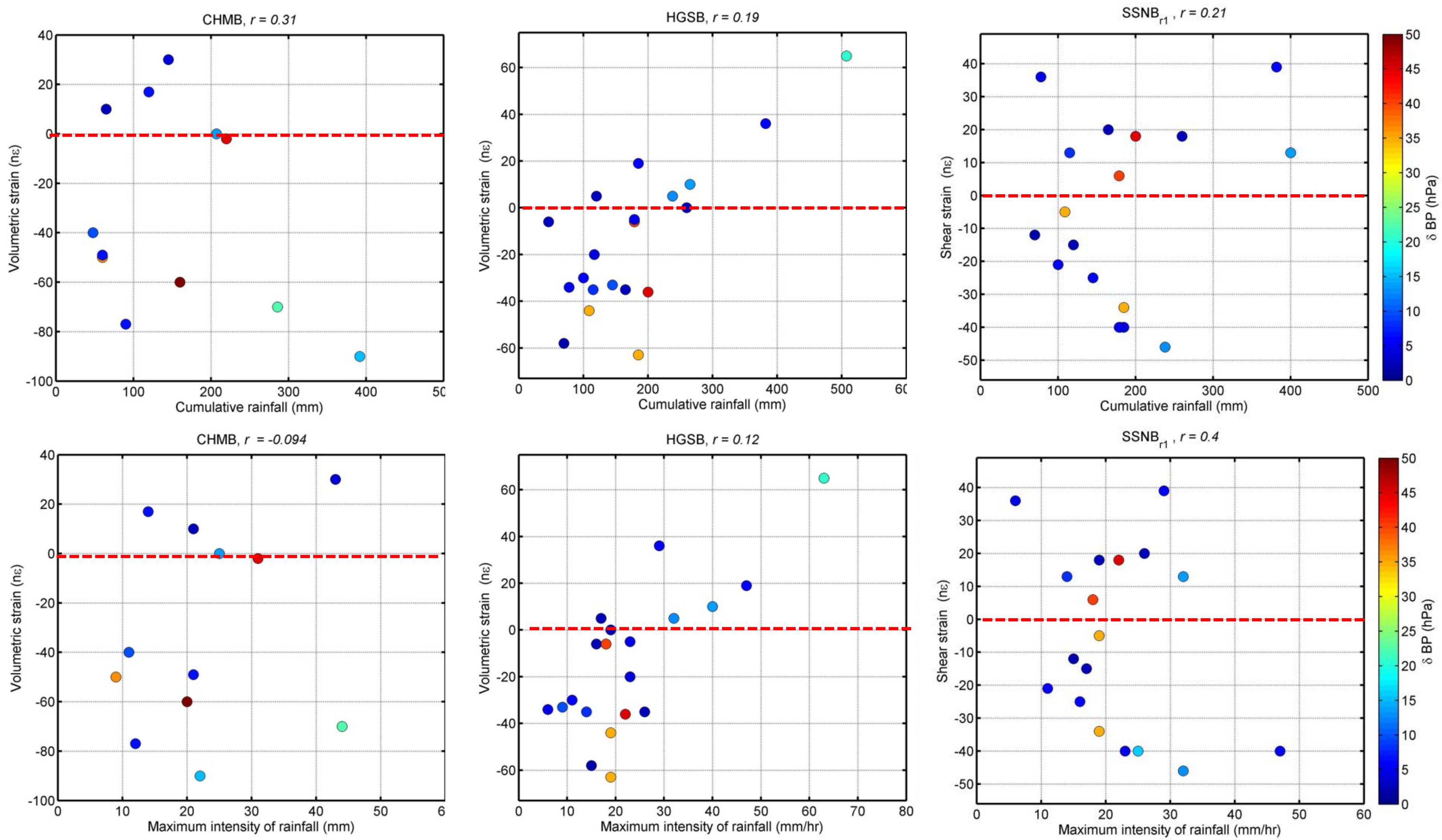
Strain responses to environmental factors

	Observed	Theoretical
Barometric pressure	-1~-3 $n\varepsilon$/hPa	-0.7~ -1.1 $n\varepsilon$/hPa (ν=0.25,G=30 GPa)
Ground water table	-30~-100 $n\varepsilon$/1m -0.3~-1.0 $n\varepsilon$/hPa	-13~-22 $n\varepsilon$/1m (ν=0.25, G=30 GPa, Φ=0.2)
Precipitation	-50 $n\varepsilon$/100 mm (-5.1 $n\varepsilon$/hPa)	

Relations between rainfall-induced strain, rainfall, and air pressure

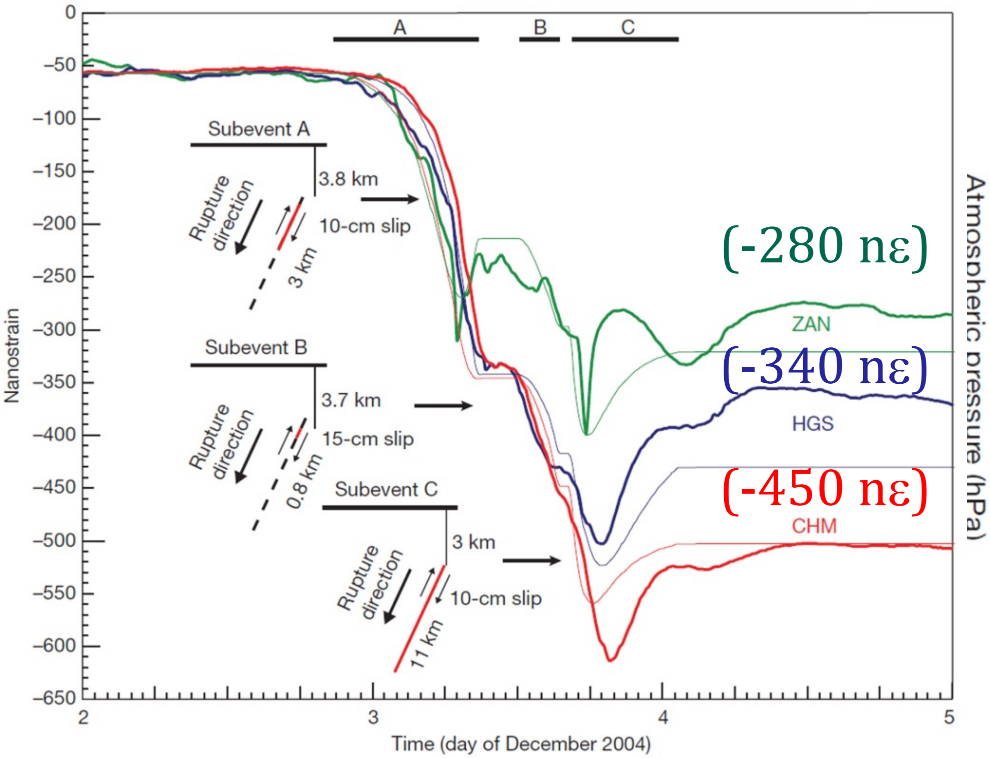


Relations between residual strain, rainfall, and air pressure

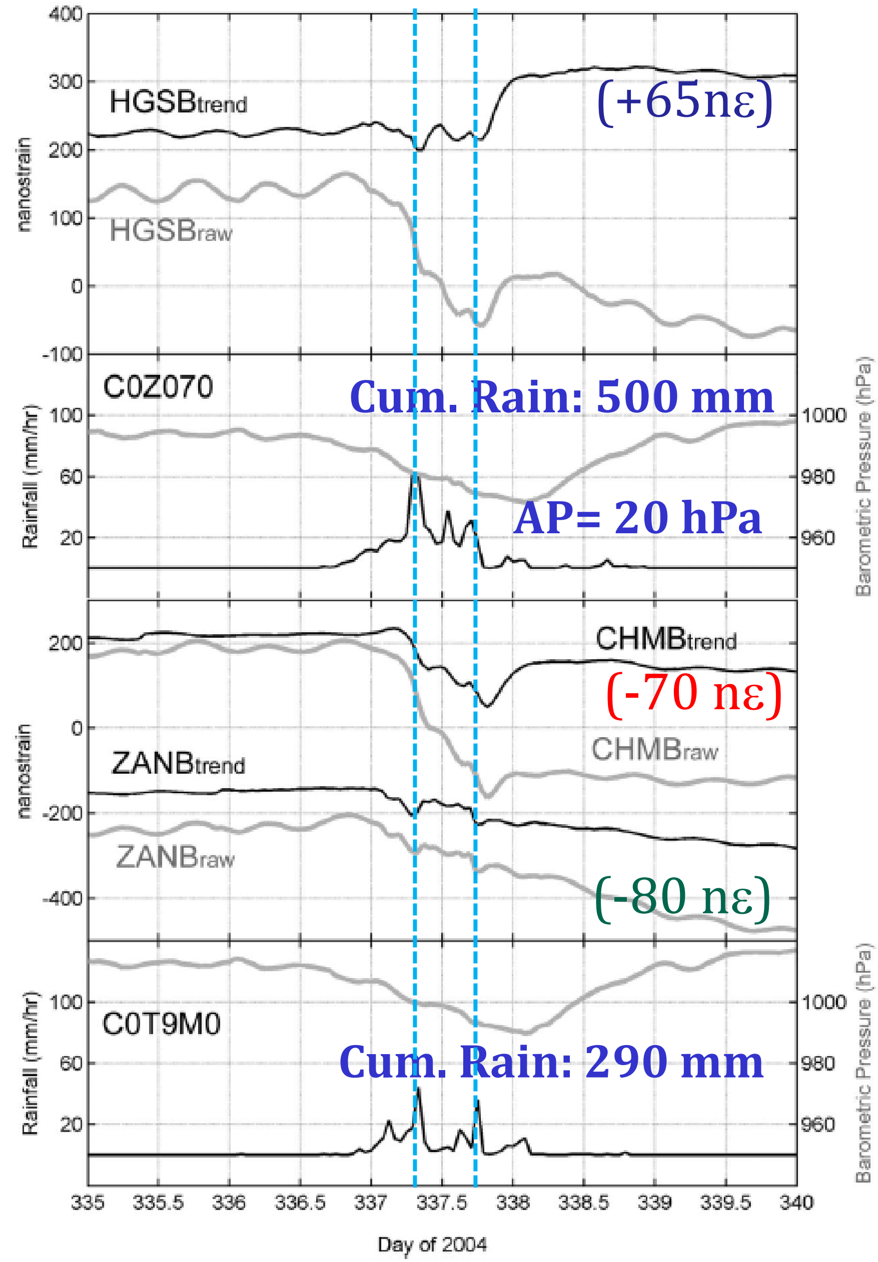


2004 Namadol Typhoon

(Liu et al., 2009)

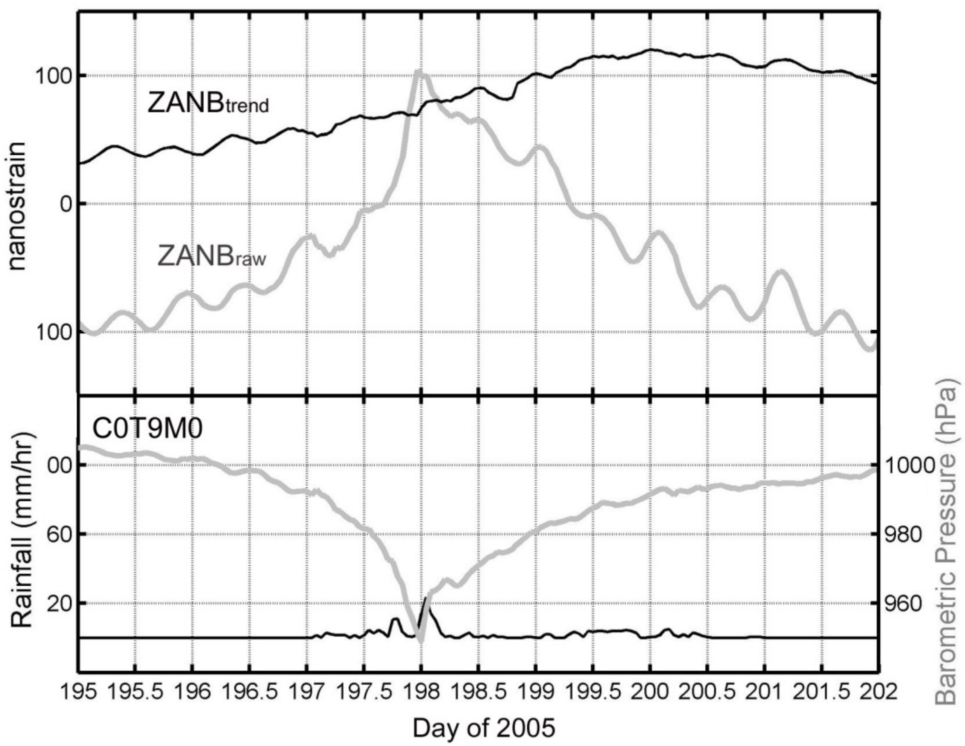


(Hsu et al., 2015)



2005 Haitang Typhoon

AP= 50 hPa, Cum. Rain: 190 mm

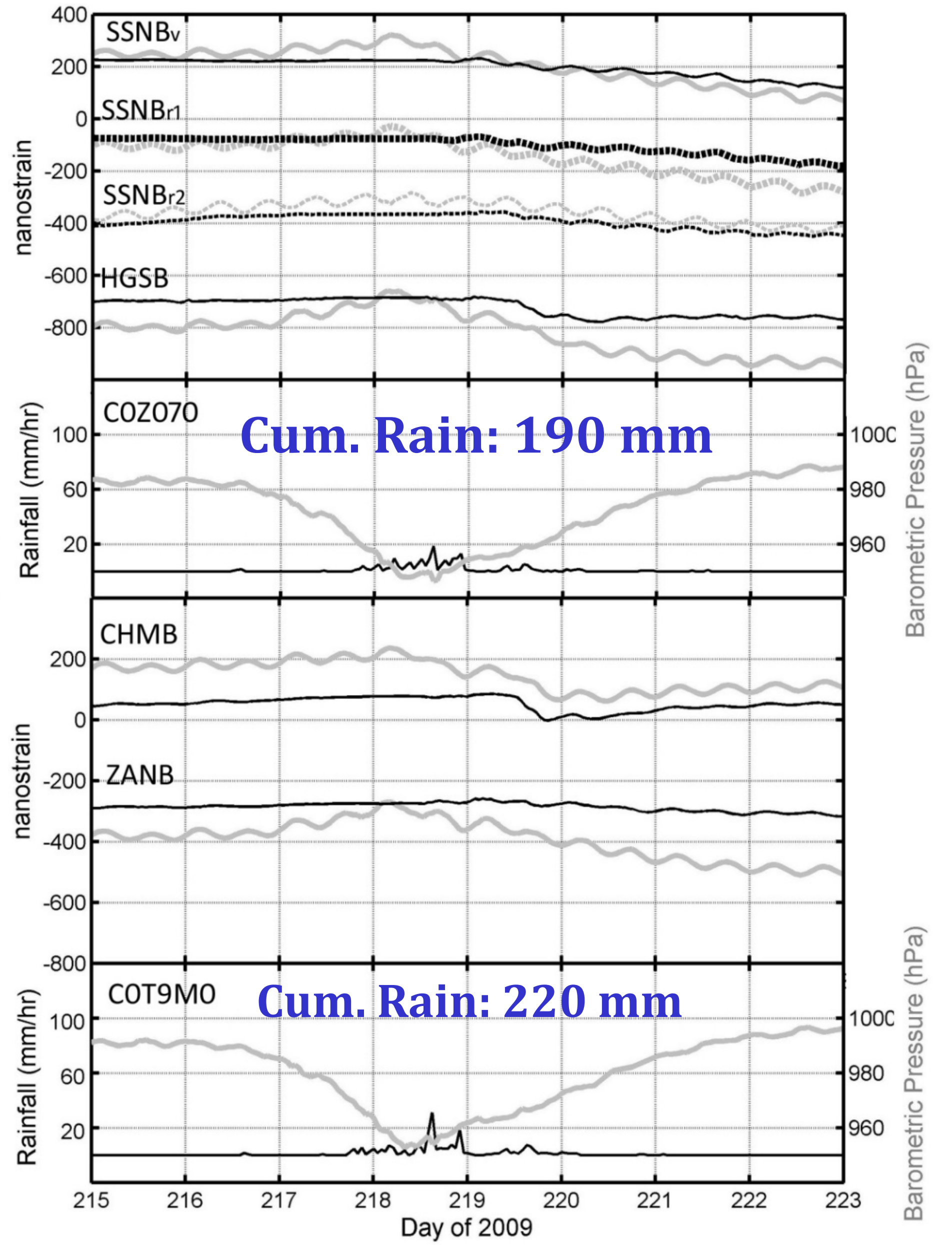


Black (trend) : $S_{raw} - S_{AP} - S_{tide} - S_{rain}$

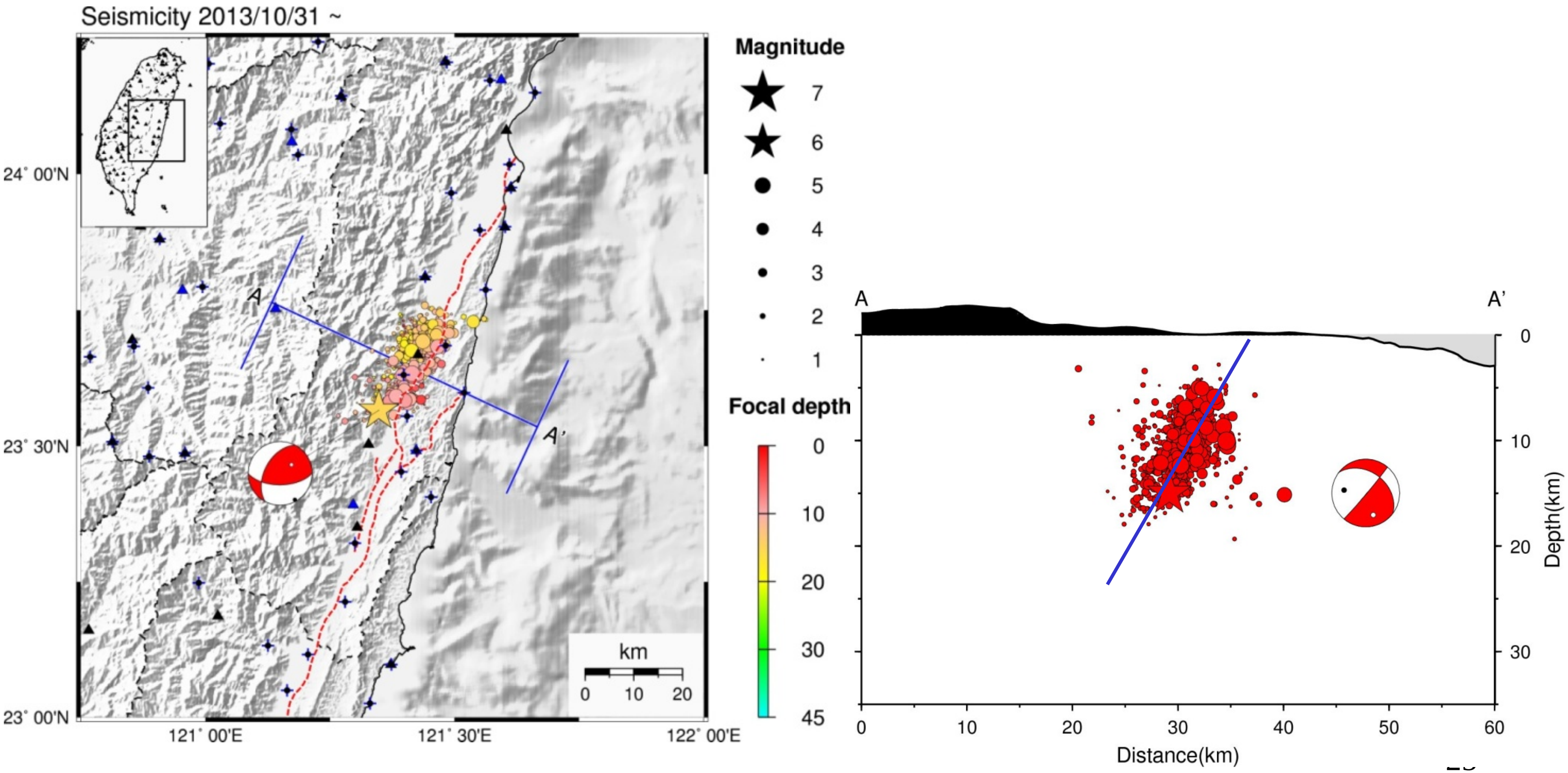
Gray **:** S_{raw}

2009 Morakot Typhoon

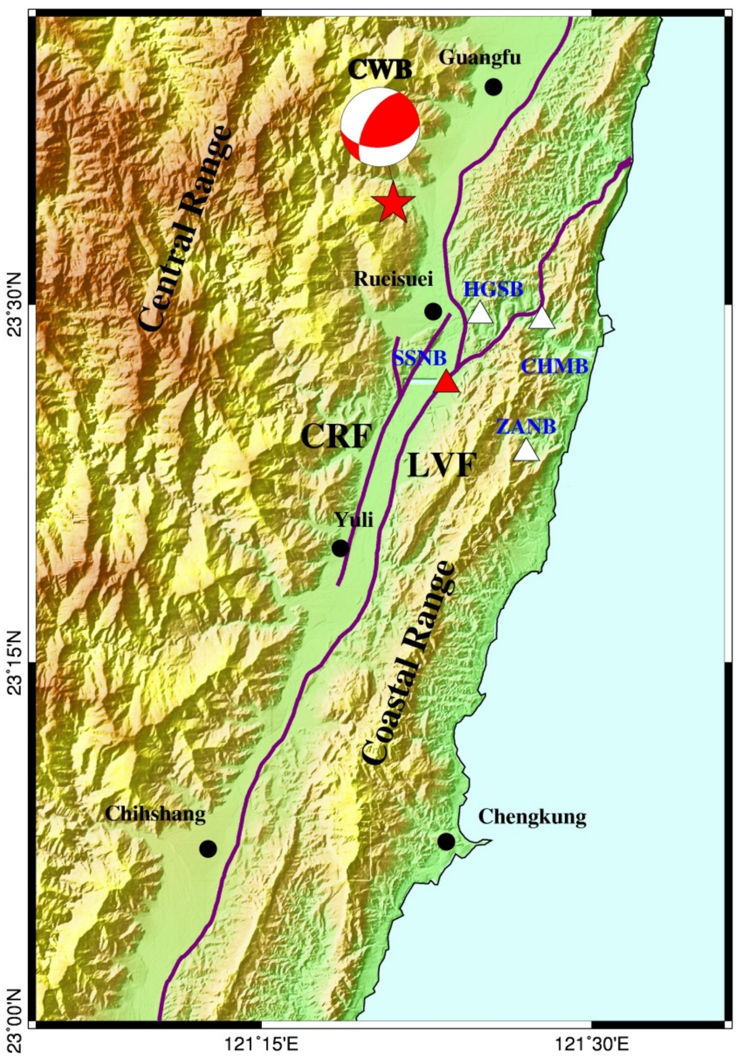
AP= 35 hPa



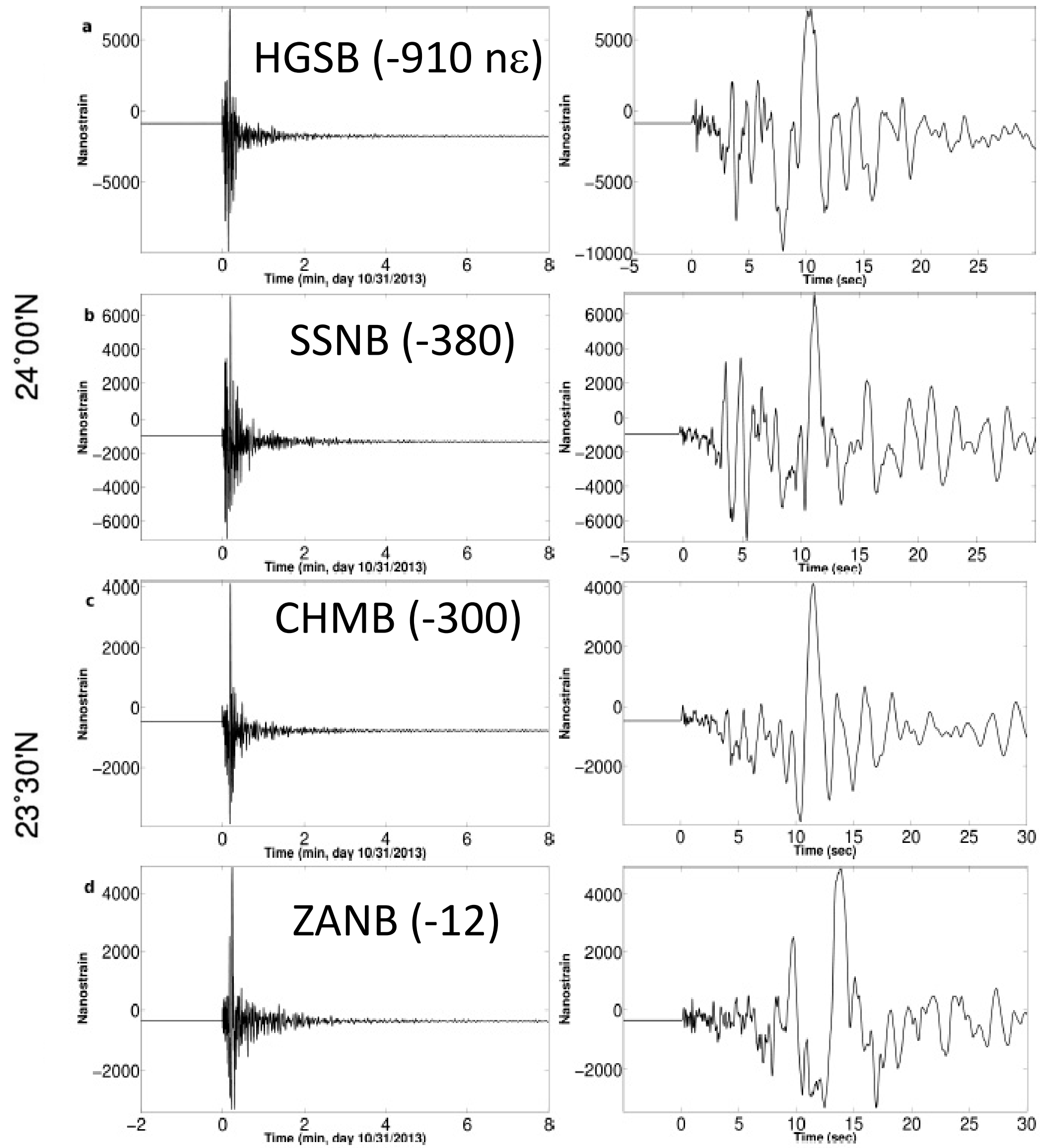
2013/10/31 M_w 6.2 Ruisui, Taiwan earthquake



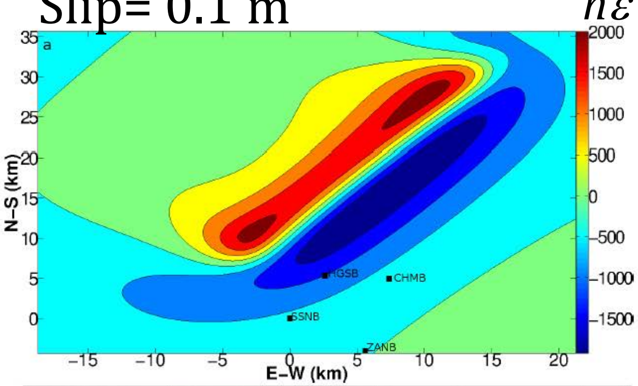
2013/10/31 M_w 6.2 Ruisui earthquake

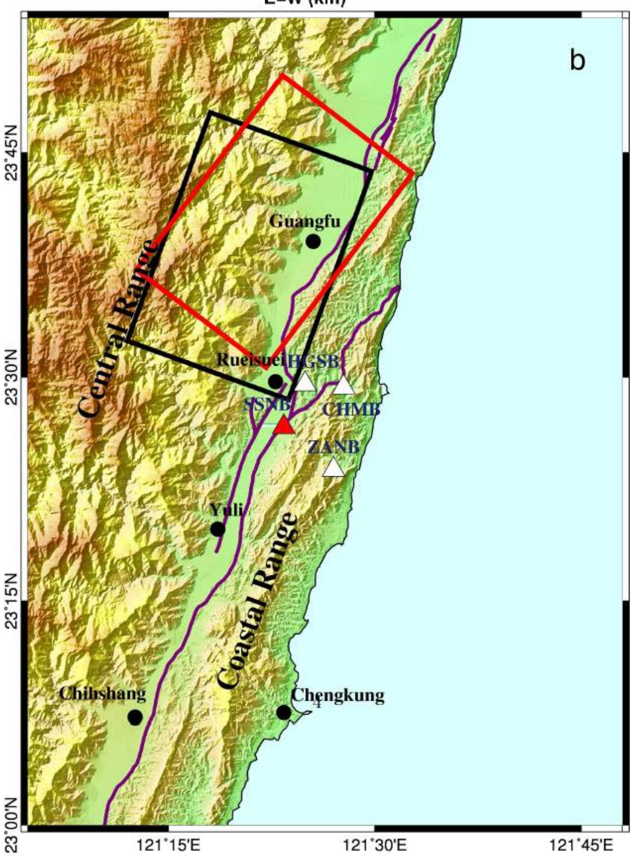


(Canitano et al., 2015)

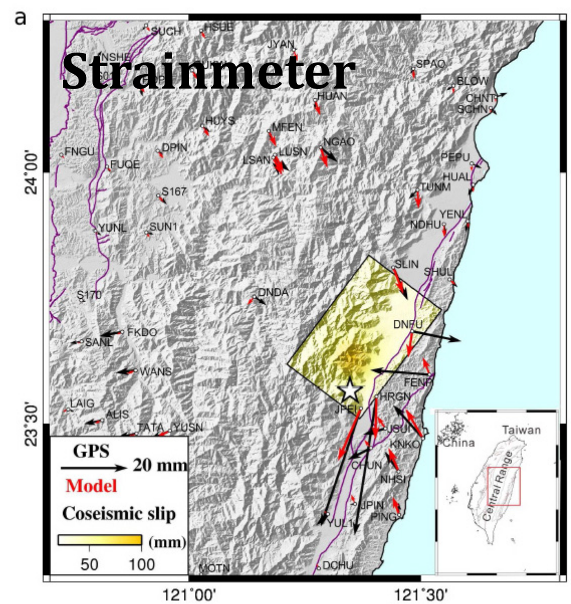


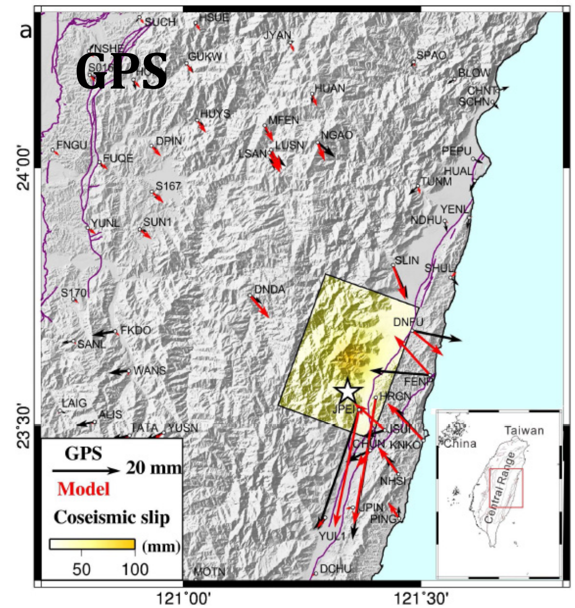
Strike/Dip/Rake=
217° /48° /49°
Slip= 0.1 m

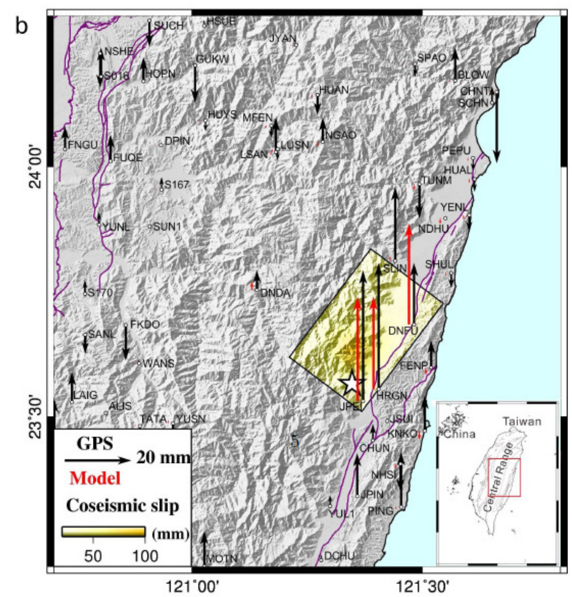


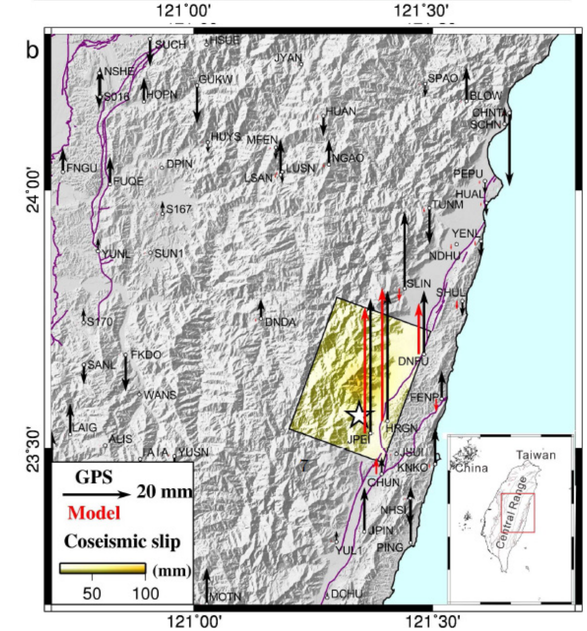


Best source model constrained by the borehole strainmeter and GPS data

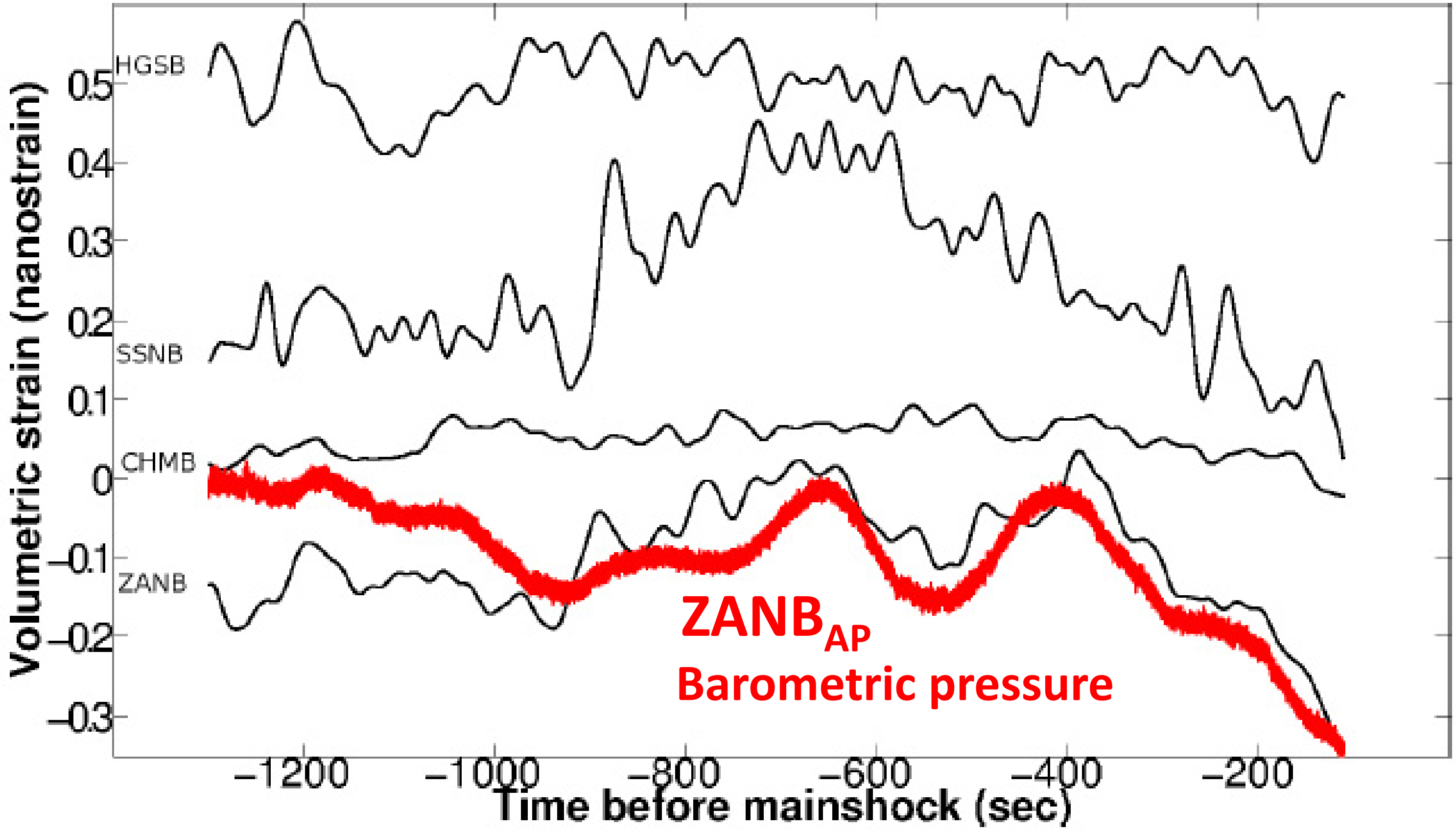






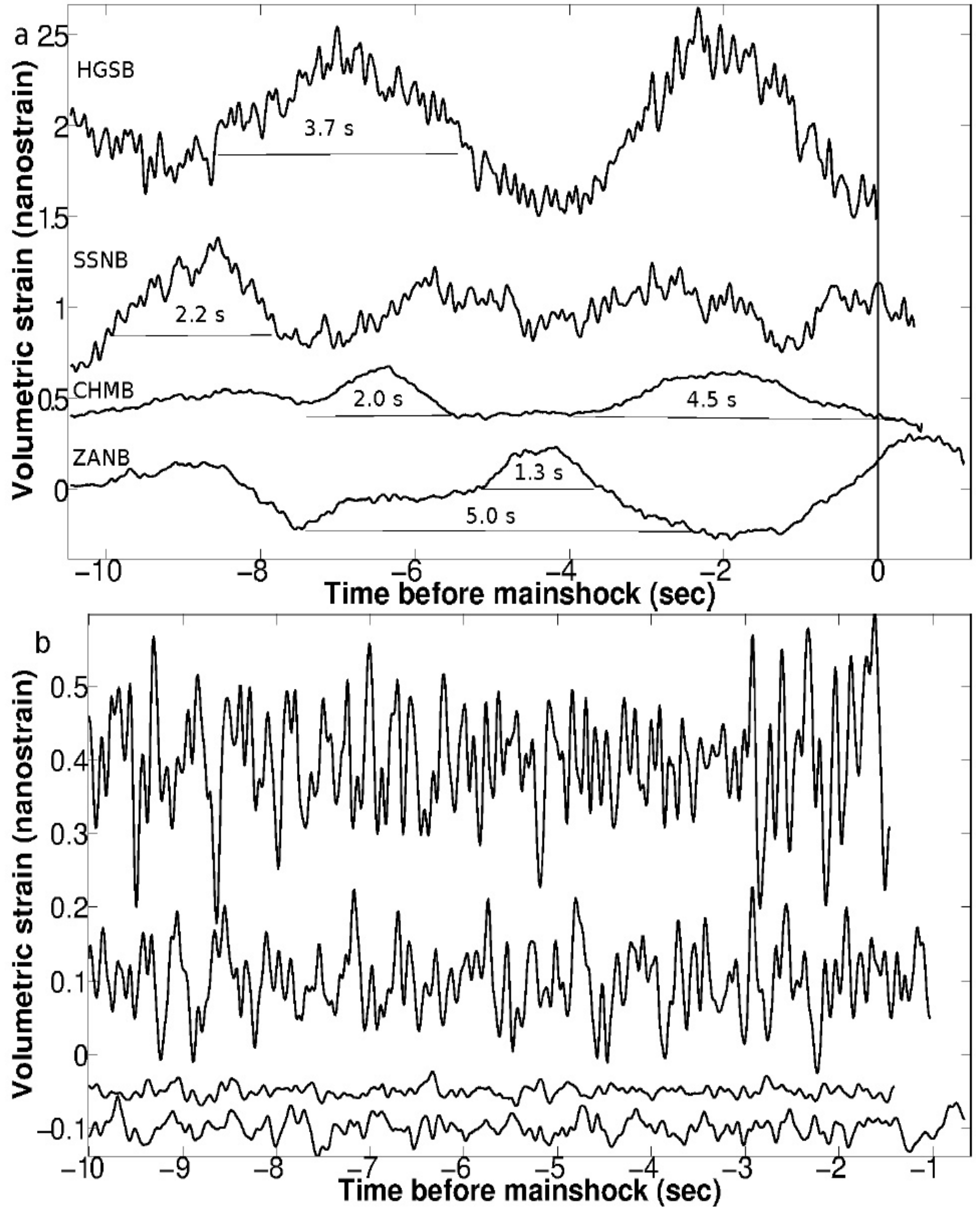


Data prior to the Ruisui earthquake



Strainmeter data prior to the Ruisui earthquake

De-trended
high cut of 10 Hz



Bandpass
(1-10 Hz)
Noise level
0.1-0.01 nε

(Canitano et al., 2015)

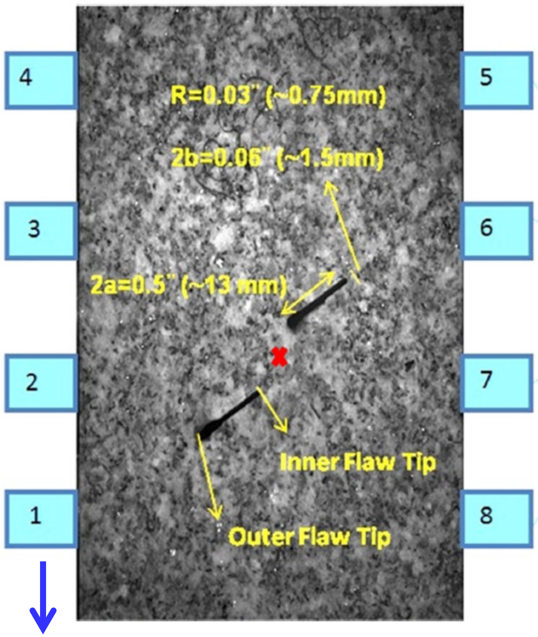
Estimated slip, maximal nucleation moment, and maximal length of nucleation zone

S(1) GPS / S(2) Strainmeter $M=\mu 10^{-4}L^3$ (Johnston and Linde, 2002)

	HGSB	SSNB	CHMB	ZANB
Standard deviation σ_ϵ (nϵ)	10^{-1}	$5\text{x}10^{-2}$	10^{-2}	$2\text{x}10^{-2}$
(S1) Maximal moment (N.m) (Slip, in m)	$3.6\text{x}10^{14}$	$3\text{x}10^{14}$	$4.8\text{x}10^{13}$	$2.4\text{x}10^{14}$
Maximal slip (in m)	$12\text{x}10^{-3}$	$10\text{x}10^{-3}$	$1.6\text{x}10^{-3}$	$8\text{x}10^{-3}$
Maximal nucleation length (m)	490	465	250	430
(S2) Maximal moment (N.m) (Slip, in m)	$4.5\text{x}10^{14}$	$3.3\text{x}10^{14}$	$8.1\text{x}10^{13}$	$3\text{x}10^{14}$
Maximal moment (N.m)	$15\text{x}10^{-3}$	$11\text{x}10^{-3}$	$2.7\text{x}10^{-3}$	$10\text{x}10^{-3}$
Maximal nucleation length (m)	530	480	300	465

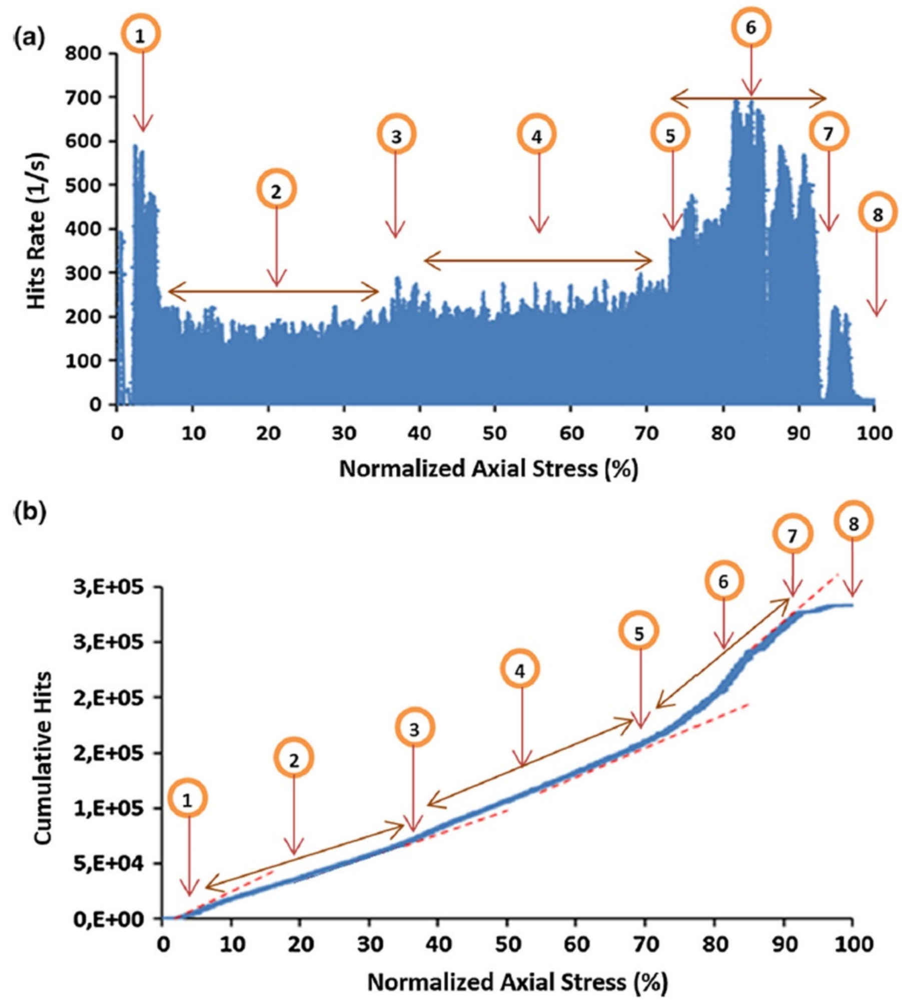
(Canitano et al., 2015)

Detection of cracking levels during the crack propagation



Sensor for acoustic emissions

1. crack closure
2. linear elastic deformation
3. micro-crack initiation
4. micro-crack growth
5. micro-crack coalescence
6. macro-crack growth
7. macro-crack coalescence
8. failure



(Moradian Z et al., 2015)

Summary – (1)

- The rises/drops of barometric pressure and ground water table result in contractional/extensional strain.
- Comparisons between the observed volumetric strain response to barometric pressure and groundwater table variations are in good agreement with theoretical predictions.

	Observed	Theoretical
Barometric pressure	**-1~-3 $n\varepsilon$/hPa**	**-0.7~ -1.1 $n\varepsilon$/hPa (ν=0.25,G=30 GPa)**
Ground water table	**-30~-100 $n\varepsilon$/1m -0.3~-1.0 $n\varepsilon$/hPa**	**-13~-22 $n\varepsilon$/1m (ν=0.25, G=30 GPa, Φ=0.2)**
Precipitation	**-50 $n\varepsilon$/100 mm (-5.1 $n\varepsilon$/hPa)**	

Summary – (2)

- The majority of strain changes attributed to slow earthquakes seem rater to be related to environmental disturbances.
- Strain polarity changes during passages of typhoons and significant residual strain after correcting environmental factors that may suggest influences from tectonic-origin motions.
- Analysis of 10 seconds data prior to the Ruisui mainshock indicates no pre-seismic strain change emergent from the instrumental noise level (from 10^{-2} to 10^{-1} $n\varepsilon$).
- This observation sets limits on any precursory change in a nucleation area, taken to have dimensions of about 250-300 m ($\sim 10^{14}$ N-m), seconds before the mainshock.

Thank you for your attention

Calibration for 3-component strainmeter

$$\begin{bmatrix} \frac{g_1}{C} DT1_a \\ \frac{g_2}{C} DT1_b \\ \frac{g_3}{C} DT1_c \end{bmatrix} = \begin{bmatrix} 0.5 & \frac{D}{C} 0.5\cos(2\theta_a) & \frac{D}{C} 0.5\sin(2\theta_a) \\ 0.5 & \frac{D}{C} 0.5\cos(2\theta_b) & \frac{D}{C} 0.5\sin(2\theta_b) \\ 0.5 & \frac{D}{C} 0.5\cos(2\theta_c) & \frac{D}{C} 0.5\sin(2\theta_c) \end{bmatrix} \begin{bmatrix} \varepsilon_v \\ \gamma_1 \\ \gamma_2 \end{bmatrix}$$

$$\varepsilon_v = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$$
$$\gamma_1 = \varepsilon_{xx} - \varepsilon_{yy}$$
$$\gamma_2 = 2\varepsilon_{xy}$$

The gauge weights ($g_{1\sim3}$) are (-1, -0.9481, -0.9411 measured in Lab)

$$\frac{1}{C} g_i \varepsilon = 0.5\left(1 - \frac{D}{C}\right)\varepsilon_{xx} + 0.5\left(1 - \frac{D}{C}\right)\varepsilon_{yy} + \frac{D}{C}\varepsilon_{xx}\cos^2\theta + 2\frac{D}{C}\varepsilon_{xy}\sin\theta\cos\theta + \frac{D}{C}\varepsilon_{yy}\sin^2\theta$$

1/C, *D/C*, and the azimuth of *DT1* are solved