# Co-Seismic Groundwater Level Changes Induced by the May 12, 2008 Wenchuan Earthquake in the Near Field

Shi, Zheming, Guangcai Wang, and Chenglong Liu. *Pure and Applied Geophysics* 170 (2013): 1773-1783.

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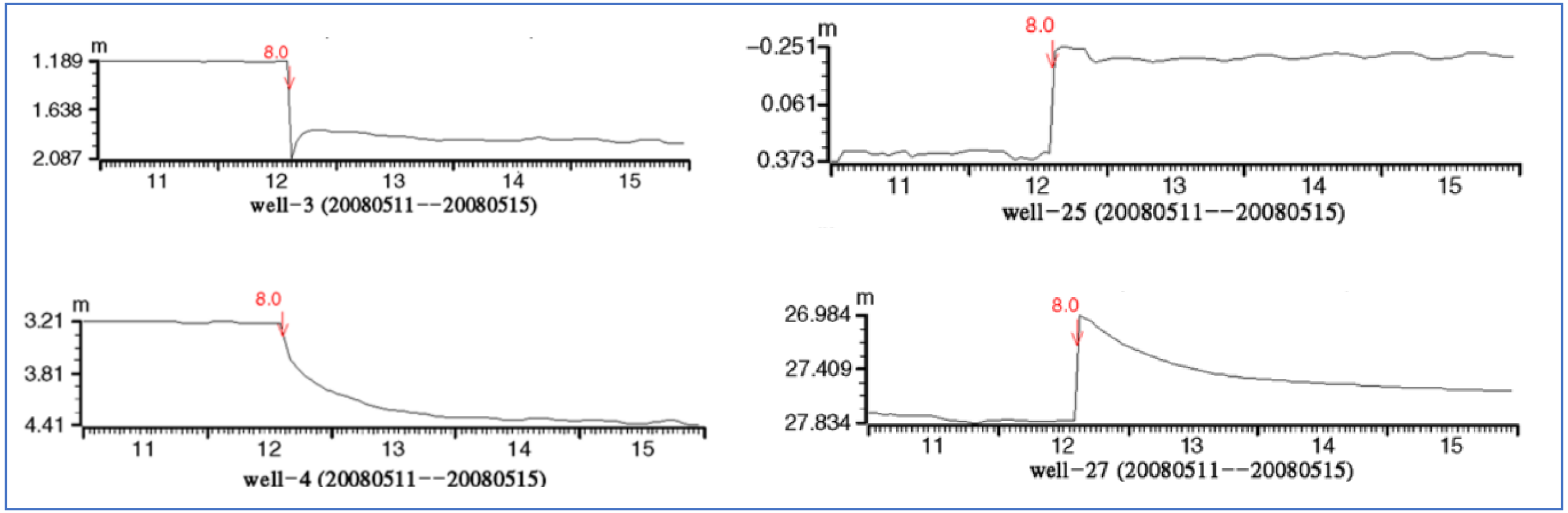
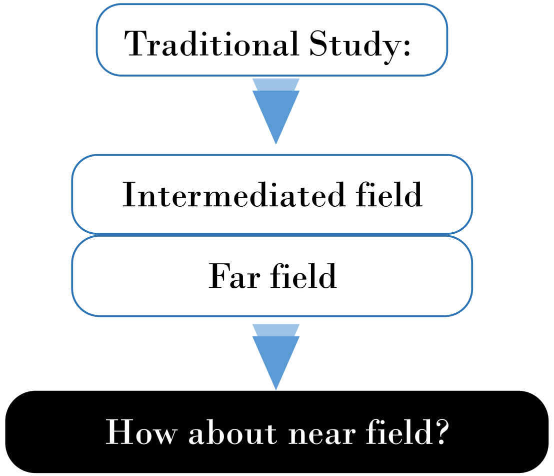
# Introduction

# Co-seismic Groundwater Level Changes

- Many hydrogeological phenomena occur following an earthquake. One of the most interesting phenomena is the change in groundwater level induced by the earthquake.
- The large scales of co-seismic water level changes in mainland China were observed in response to the 2008 Wenchuan earthquake (Ms 8.0 ).
- Many scholars have investigated the co-seismic groundwater level changes induced by the Wenchuan earthquake.

Example (Zhang and Huang,2011):





Traditional Study:

Intermediated field

Far field

How about near field?

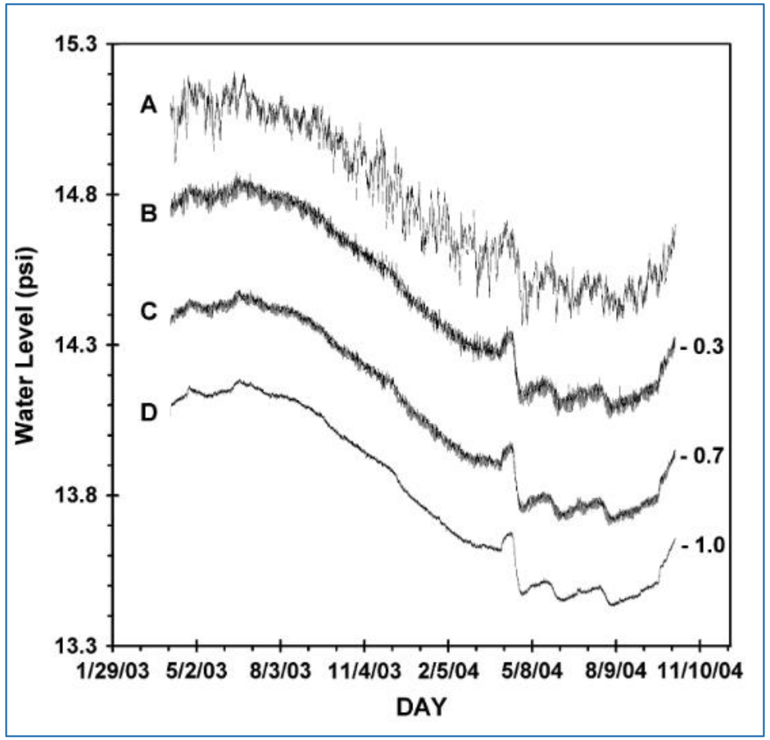
# Stimuli of the Head Variations of Groundwater

- The groundwater level could be affected by the environmental factor that can trigger a response or called as stimuli.

- The natural stimuli such as rainfall, sea tide, earth tide, barometric pressure and earthquake usually contribute more to the head variations of a groundwater system than does artificial stimuli such as pumping.

- The head variations of groundwater which include the stimuli well known as mixed signal which is leading to difficulty in extracting the head variations contributed by a single stimulus (Tsai & Hsiao, 2020).

# Example of Groundwater Level Extraction



- Toll & Rasmussen (2007) try to remove the barometric pressure effect and earth tides from observed water level using regression deconvolution method.
- Regression deconvolution was used to estimate the barometric response function using paired water level–barometric pressure observations. The residual—or corrected—head can be calculated once the response function is known.
- (A) Observed multiyear water levels for a well, (B) water levels corrected using a constant barometric efficiency, (C) water levels corrected using barometric response function only, and (D) water levels once the barometric pressure and earth tides have been removed using regression deconvolution.

# Objective

Understand the mechanism of the co-seismic groundwater level change induced by the Wenchuan earthquake in the near field.

# Hypothesis

There are two main hypothesis on the mechanism of the co-seismic groundwater level change in the near field:

1

The static strain hypothesis states that both the sign and magnitude of the co-seismic water level changes can be compared with those predicted from dislocation theory and poroelastic theory.

▼

The water level rises in the zones of contraction and falls in regions of dilation.

2

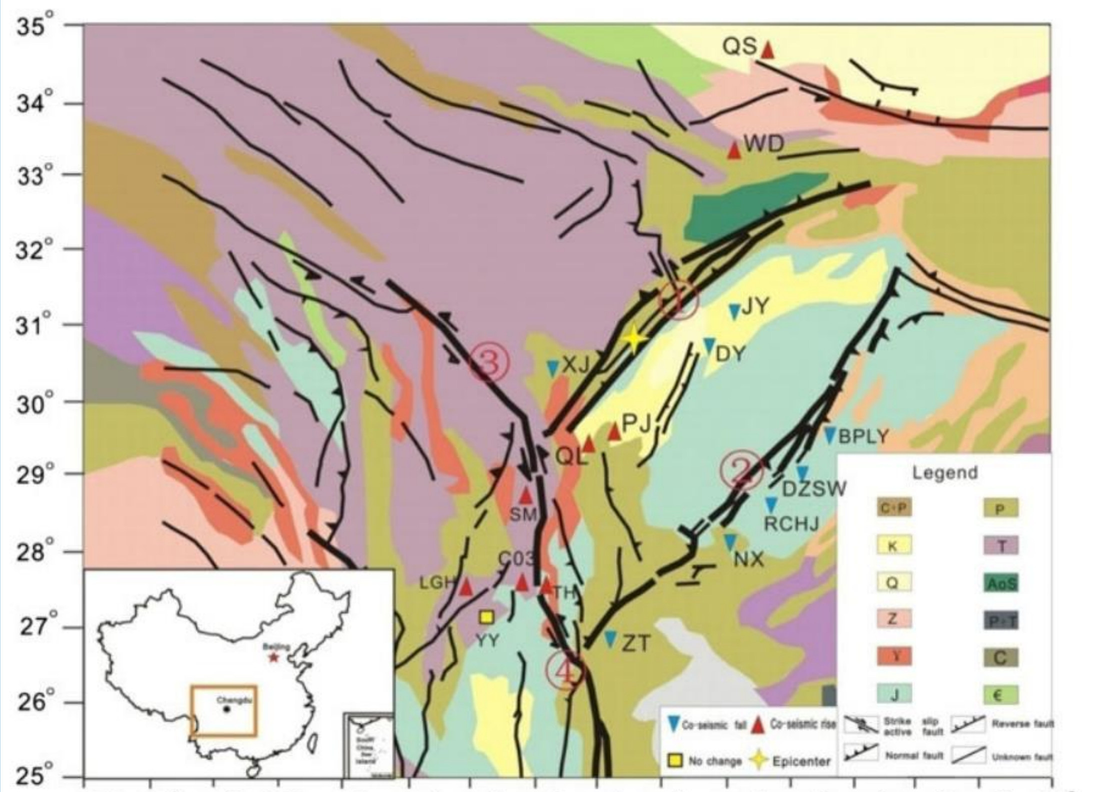
The undrained consolidate hypothesis states that the ground shaking causes sediments around a well to consolidate or dilate, leading to step-like changes in the pores and changes in the groundwater level in the well.

▼

The deformation is undrained: the pore-pressure increases when the shear strain exceeds approximately $10^{-4}$.

The process become drained: the pore-pressure decrease (happen when the shaking is so strong it exceeds some critical threshold which lead to the new fractures)

# Tectonic Setting



Four major faults:

1. Longmenshan fault
2. Huangyingshan fault
3. Xianshuihe fault
4. Anninghe fault

- Four main faults in Longmengshan fault: The Longmenshan Qianshan fault, the Longmenshan Houshan fault, the Longmenshan Central fault, and the Concealed fault at the mountain front.

- Select a study area with an epicenter distance <500 km (considered as a near field). Calculated by the length of the Longmenshan Central fault.

# Data

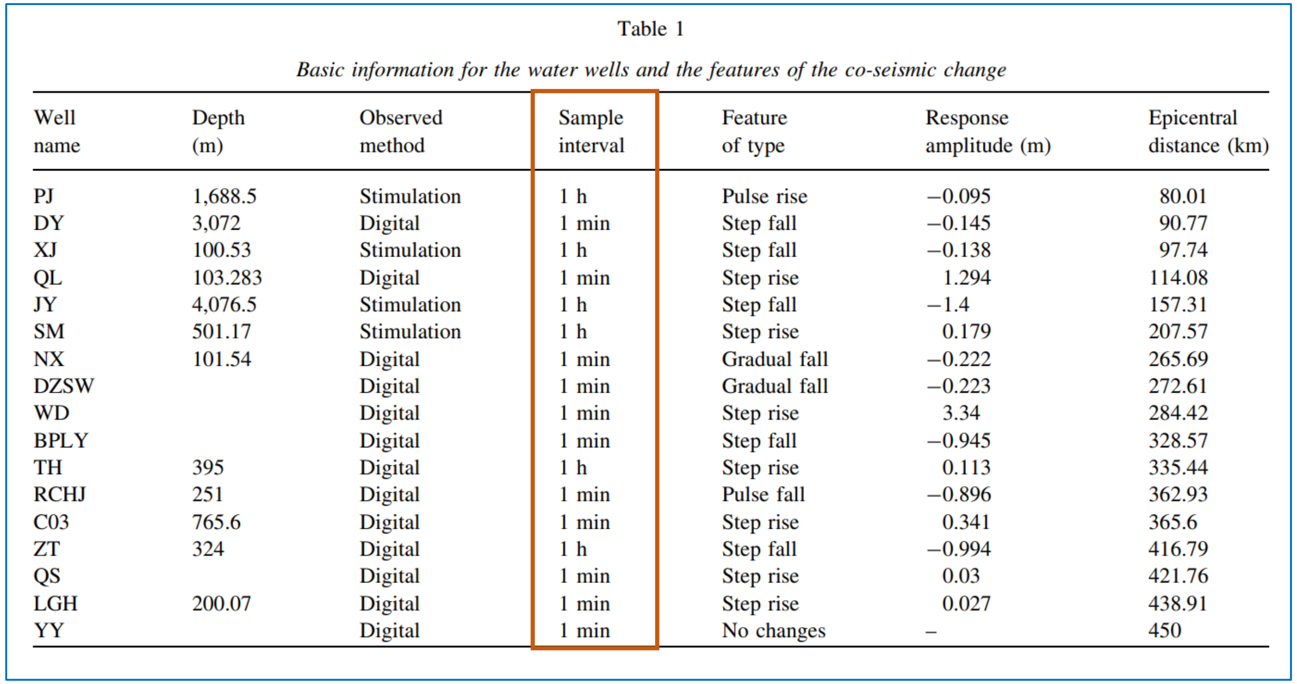


Table 1

*Basic information for the water wells and the features of the co-seismic change*

| Well name | Depth (m) | Observed method | Sample interval | Feature of type | Response amplitude (m) | Epicentral distance (km) |
|---|---|---|---|---|---|---|
| PJ | 1,688.5 | Stimulation | 1 h | Pulse rise | −0.095 | 80.01 |
| DY | 3,072 | Digital | 1 min | Step fall | −0.145 | 90.77 |
| XJ | 100.53 | Stimulation | 1 h | Step fall | −0.138 | 97.74 |
| QL | 103.283 | Digital | 1 min | Step rise | 1.294 | 114.08 |
| JY | 4,076.5 | Stimulation | 1 h | Step fall | −1.4 | 157.31 |
| SM | 501.17 | Stimulation | 1 h | Step rise | 0.179 | 207.57 |
| NX | 101.54 | Digital | 1 min | Gradual fall | −0.222 | 265.69 |
| DZSW |  | Digital | 1 min | Gradual fall | −0.223 | 272.61 |
| WD |  | Digital | 1 min | Step rise | 3.34 | 284.42 |
| BPLY |  | Digital | 1 min | Step fall | −0.945 | 328.57 |
| TH | 395 | Digital | 1 h | Step rise | 0.113 | 335.44 |
| RCHJ | 251 | Digital | 1 min | Pulse fall | −0.896 | 362.93 |
| C03 | 765.6 | Digital | 1 min | Step rise | 0.341 | 365.6 |
| ZT | 324 | Digital | 1 h | Step fall | −0.994 | 416.79 |
| QS |  | Digital | 1 min | Step rise | 0.03 | 421.76 |
| LGH | 200.07 | Digital | 1 min | Step rise | 0.027 | 438.91 |
| YY |  | Digital | 1 min | No changes | – | 450 |

- There are 17 wells were used for the study which primarily located along the fault zones and penetrated with a depth ranging from 100-4,076 m. The well with the largest epicentral distance was called the YY well, which was 450 km away.

- The water level data from 16 wells that underwent co-seismic water level changes were collected from 1 January to 30 April 2008.

# Several typical co-seismic groundwater level changes

The major co-seismic groundwater level changes of the wells in the study area were step-like changes, with some showing a pulse rise or a gradual change. Several typical co-seismic groundwater level changes in some wells in the study area:

a. Pulse fall (RCHJ)

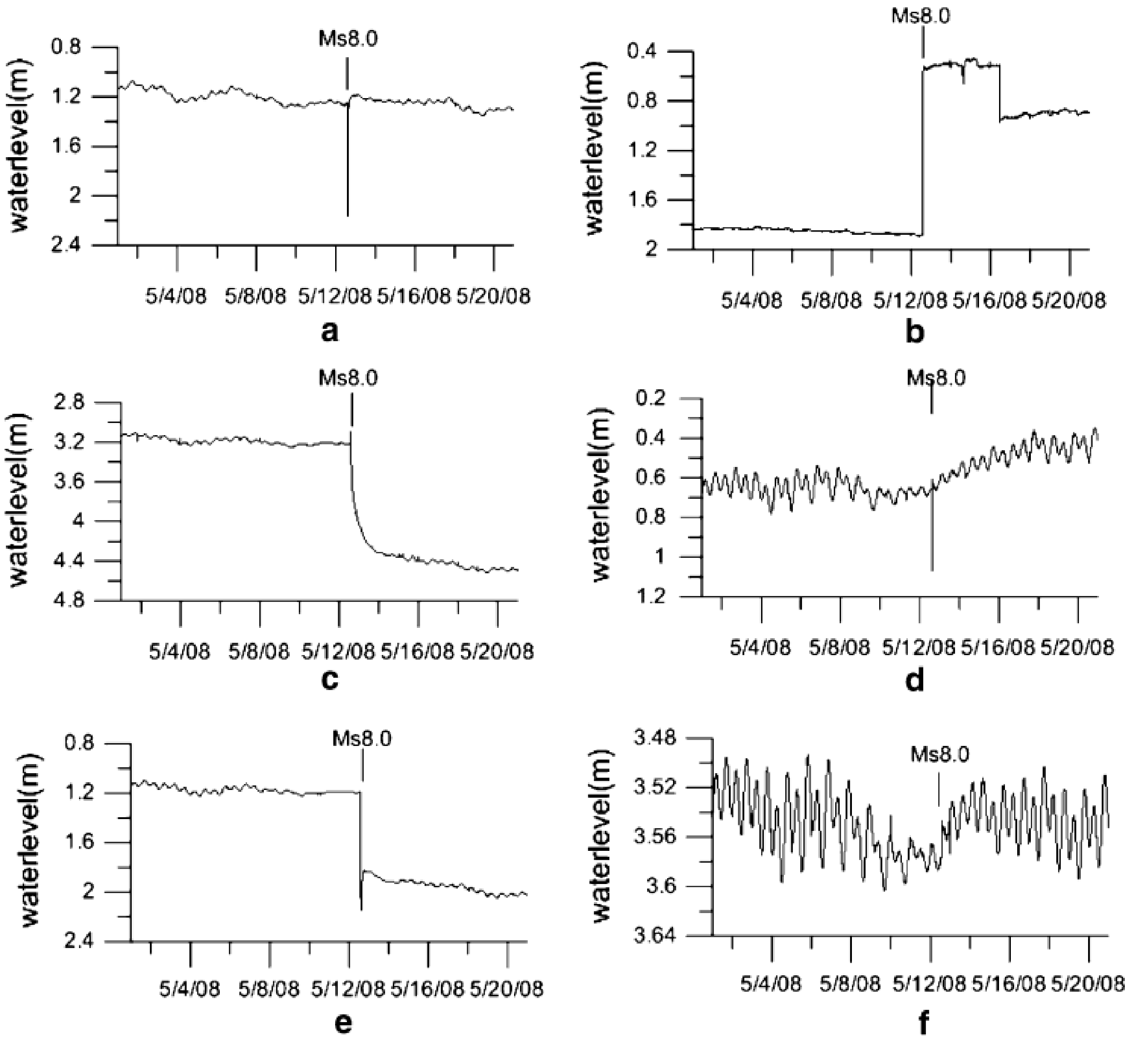
b. Step rise (QL)

c. Gradual fall (NX)

d. Step rise (C03)

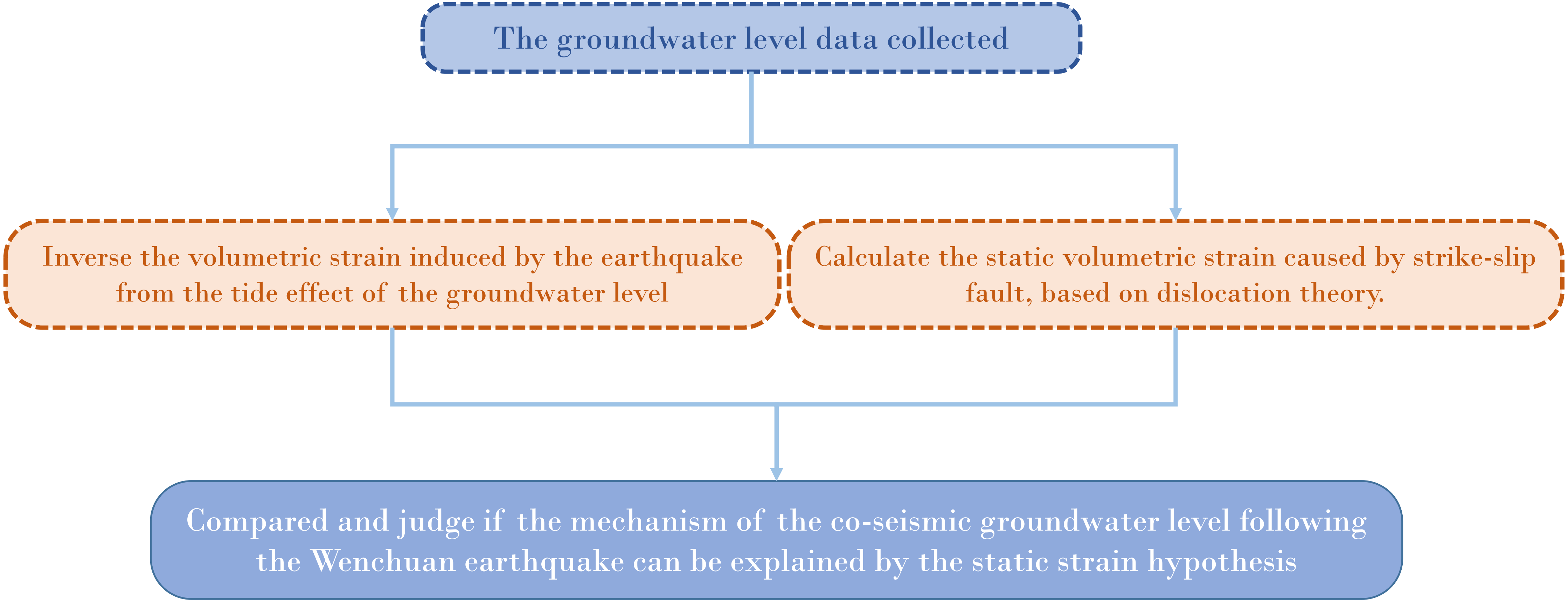
e. Step fall (DZSW)

f. Step rise (LGH)



# Methodology

# Static Strain Hypothesis



The groundwater level data collected

Inverse the volumetric strain induced by the earthquake from the tide effect of the groundwater level

Calculate the static volumetric strain caused by strike-slip fault, based on dislocation theory.

Compared and judge if the mechanism of the co-seismic groundwater level following the Wenchuan earthquake can be explained by the static strain hypothesis

# Estimating the Change in the Co-Seismic Volumetric Strain by the Tide Effect of Groundwater

The changes in the pore pressure that related to the strain:

$$\Delta P = BK_u\left[-\Delta_{\varepsilon_{kk}} + \frac{1}{1-K/K_s}\,\frac{m-m_0}{\rho}\right]$$

Undrained condition(there are no water flows in or out of the well aquifer system): $\Delta P = -BK_u\Delta_{\varepsilon_{kk}}$

The water level change in the well is proportional to the change in the volumetric strain when the well aquifer system is undrained.

▶

Strain Sensitivity

$$\Delta h = \boxed{\frac{-BK_u}{\rho g}}\,\Delta_{\varepsilon_{kk}}$$

▶

$$\Delta h = -A_s\Delta_{\varepsilon_{kk}}$$

Where:

$\Delta P$ : pore water pressure changes

$B$ : Skempton's coefficient

$K_u$ : bulk modulus of the saturated rock under undrained conditions

$\Delta_{\varepsilon_{kk}}$ : volumetric strains changes

$K$ : bulk modulus of the saturated rock under drained conditions

$K_s$ : bulk modulus of the solid grains in the rock

$m - m_0$ : water mass changes

$\rho$ : density of the water

$\Delta h$ : height of the water column changes

$g$ : gravity acceleration

# Estimating the Change in the Co-Seismic Volumetric Strain by the Tide Effect of Groundwater

- When examining the change in water level induced by the volumetric tide strain, $A_s$ can be obtained from the tidal analysis.
- The strain sensitivity of the water wells, which is based on the response to earth tides, can be applied to the tectonic strain.

The change in the co-seismic volumetric strain estimation:

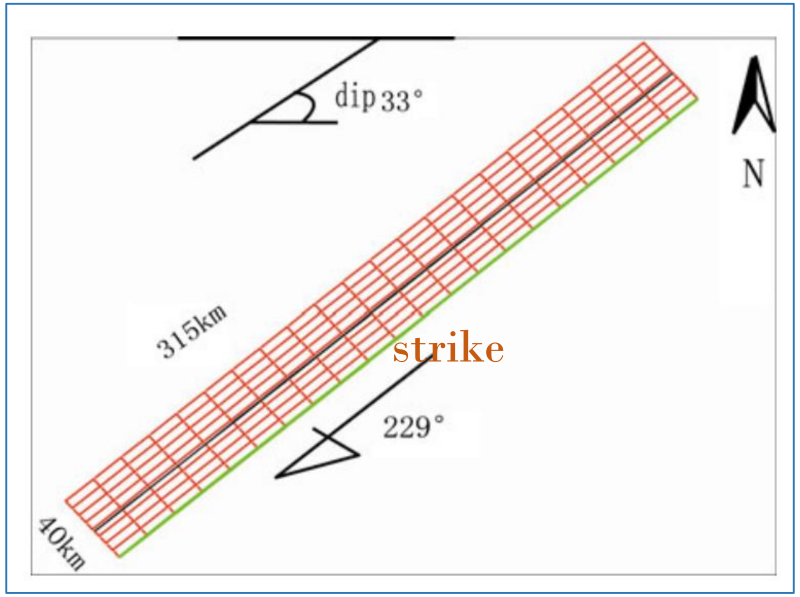
The co-seismic volumetric strain changes

$$\boxed{\Delta_{EQ}} = -\boxed{dh_{EQ}} \;/\; \boxed{A_s}$$

Strain Sensitivity

The co-seismic water level changes

# Estimating the Change in the Co-Seismic Static Strain using a Fault Dislocation Model



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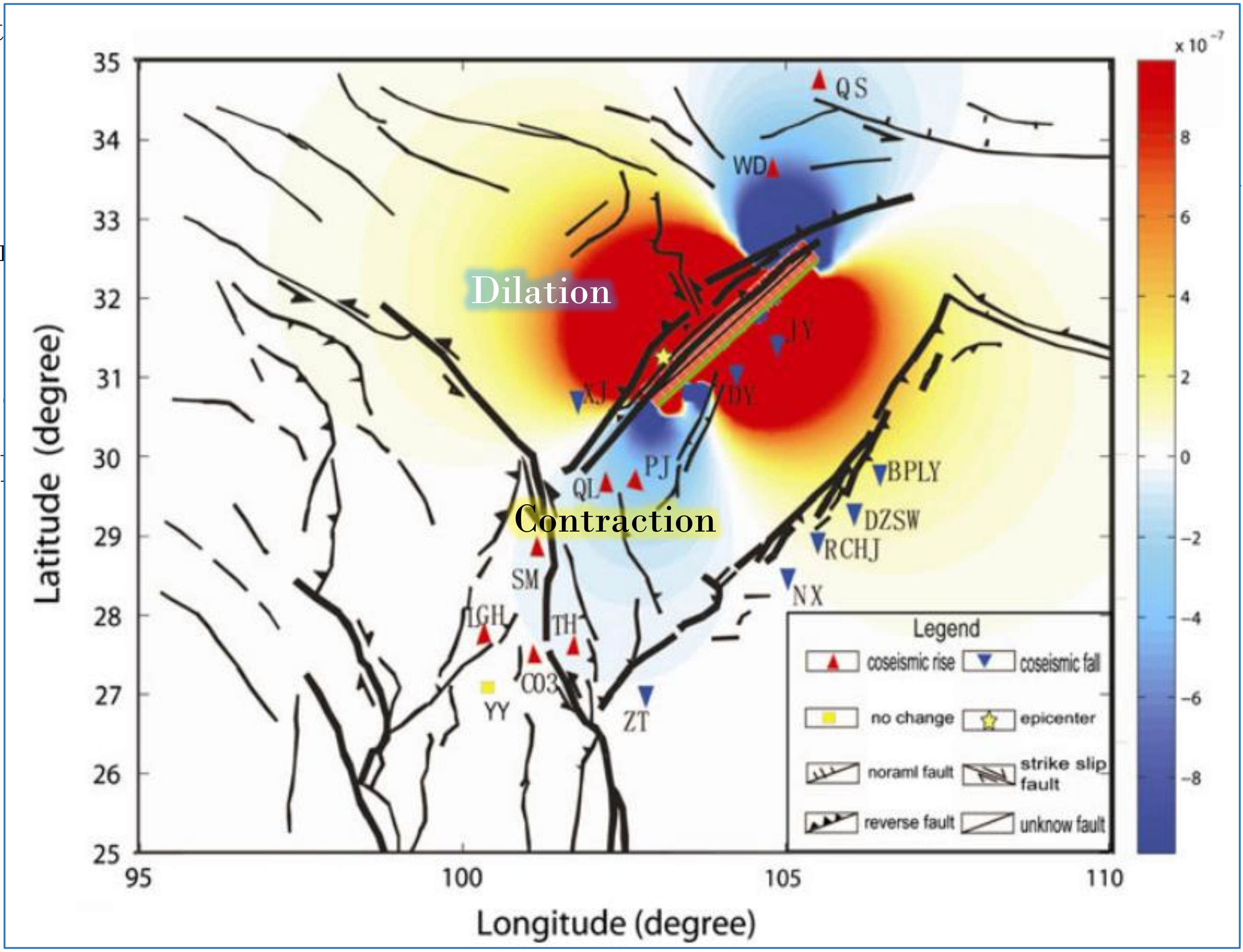
Co-seismic strain distribution calculated from the fault dislocation model



# Results and Discussion

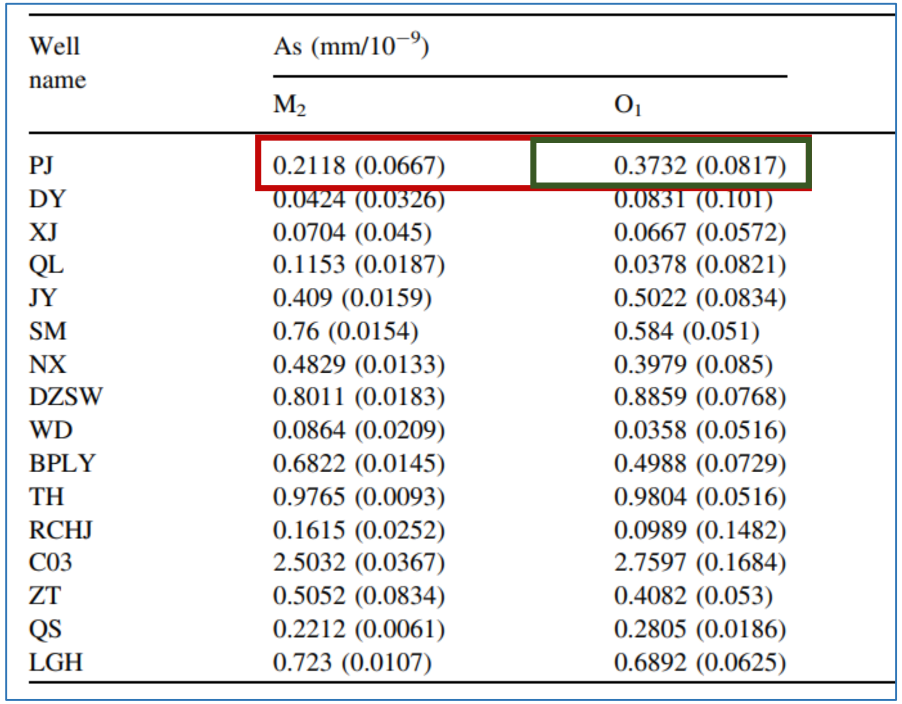
# Strain sensitivities of $M_2$ and $O_1$ for the 16 wells

- The effect of barometric pressure was removed using regression deconvolution.
- A band pass filter was then designed and the window function was used to extract the groundwater level tide component.
- Venedikov harmonic analysis was used to process the data.
- $M_2$ and $O_1$ are seldom effected by the barometric pressure and have the largest amplitude, the study focused on these two tide constituents.

$$\Delta_{EQ} = -dh_{EQ} / \boxed{A_s}$$

The largest strain sensitivities between $M_2$ and $O_1$ was chosen

The result of the $A_s$ calculation



| Well name | As (mm/$10^{-9}$) | |
|---|---|---|
| | $M_2$ | $O_1$ |
| PJ | 0.2118 (0.0667) | 0.3732 (0.0817) |
| DY | 0.0424 (0.0326) | 0.0831 (0.101) |
| XJ | 0.0704 (0.045) | 0.0667 (0.0572) |
| QL | 0.1153 (0.0187) | 0.0378 (0.0821) |
| JY | 0.409 (0.0159) | 0.5022 (0.0834) |
| SM | 0.76 (0.0154) | 0.584 (0.051) |
| NX | 0.4829 (0.0133) | 0.3979 (0.085) |
| DZSW | 0.8011 (0.0183) | 0.8859 (0.0768) |
| WD | 0.0864 (0.0209) | 0.0358 (0.0516) |
| BPLY | 0.6822 (0.0145) | 0.4988 (0.0729) |
| TH | 0.9765 (0.0093) | 0.9804 (0.0516) |
| RCHJ | 0.1615 (0.0252) | 0.0989 (0.1482) |
| C03 | 2.5032 (0.0367) | 2.7597 (0.1684) |
| ZT | 0.5052 (0.0834) | 0.4082 (0.053) |
| QS | 0.2212 (0.0061) | 0.2805 (0.0186) |
| LGH | 0.723 (0.0107) | 0.6892 (0.0625) |

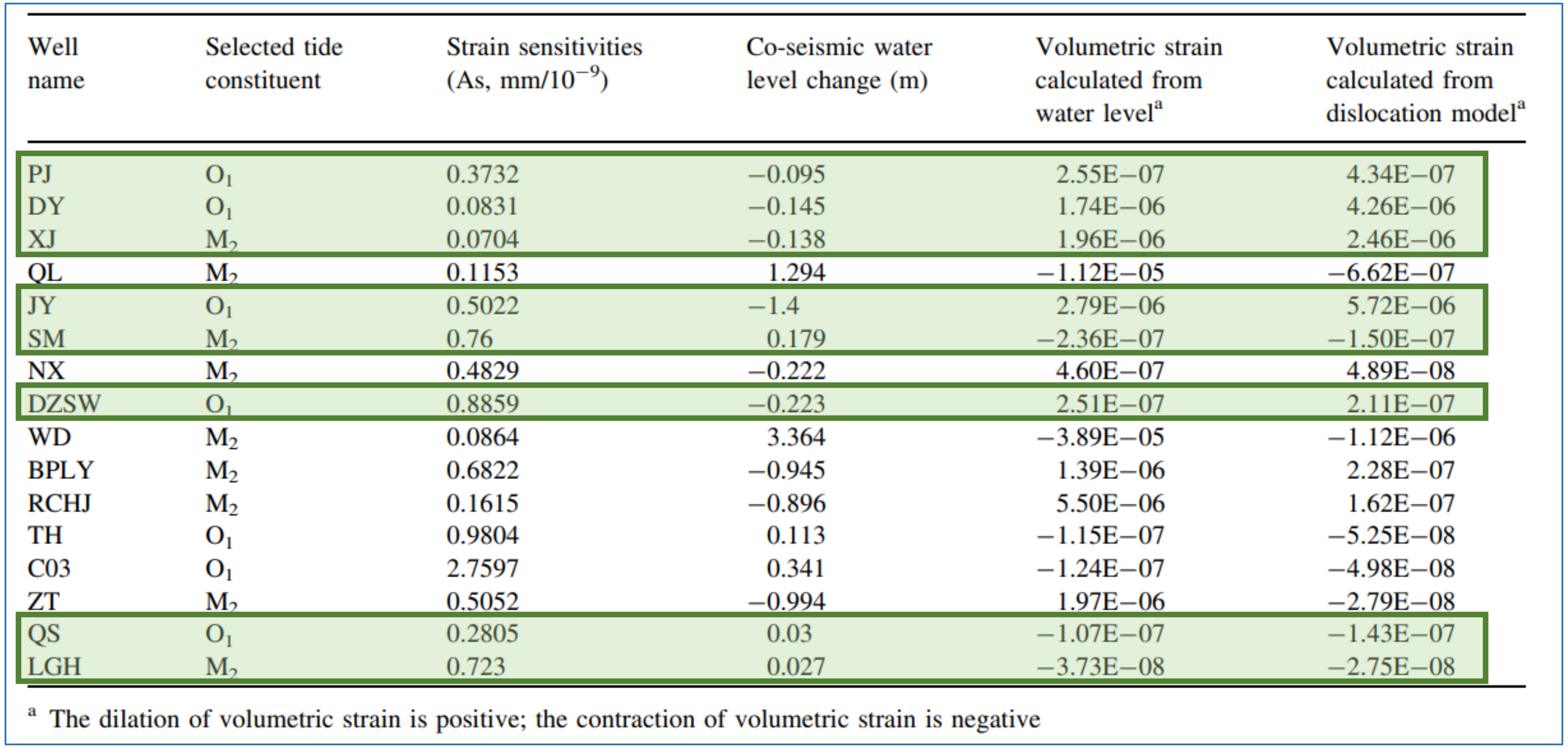
# Comparison of co-seismic volumetric strains deduced from two different method

- The volumetric strain is obtained from the co-seismic groundwater level change ($\Delta_{EQ} = -dh_{EQ} / A_s$).
- The co-seismic volumetric strain change in two ways was obtained (first method used the inversing of the groundwater and the second method used fault dislocation theory).

The volumetric strain computed from the co-seismic change in groundwater level in 8 wells were the same order of magnitude as the co-seismic static strain determined using dislocation theory.

The co-seismic water level changes in these wells are explained by the static strain hypothesis.

The comparison results

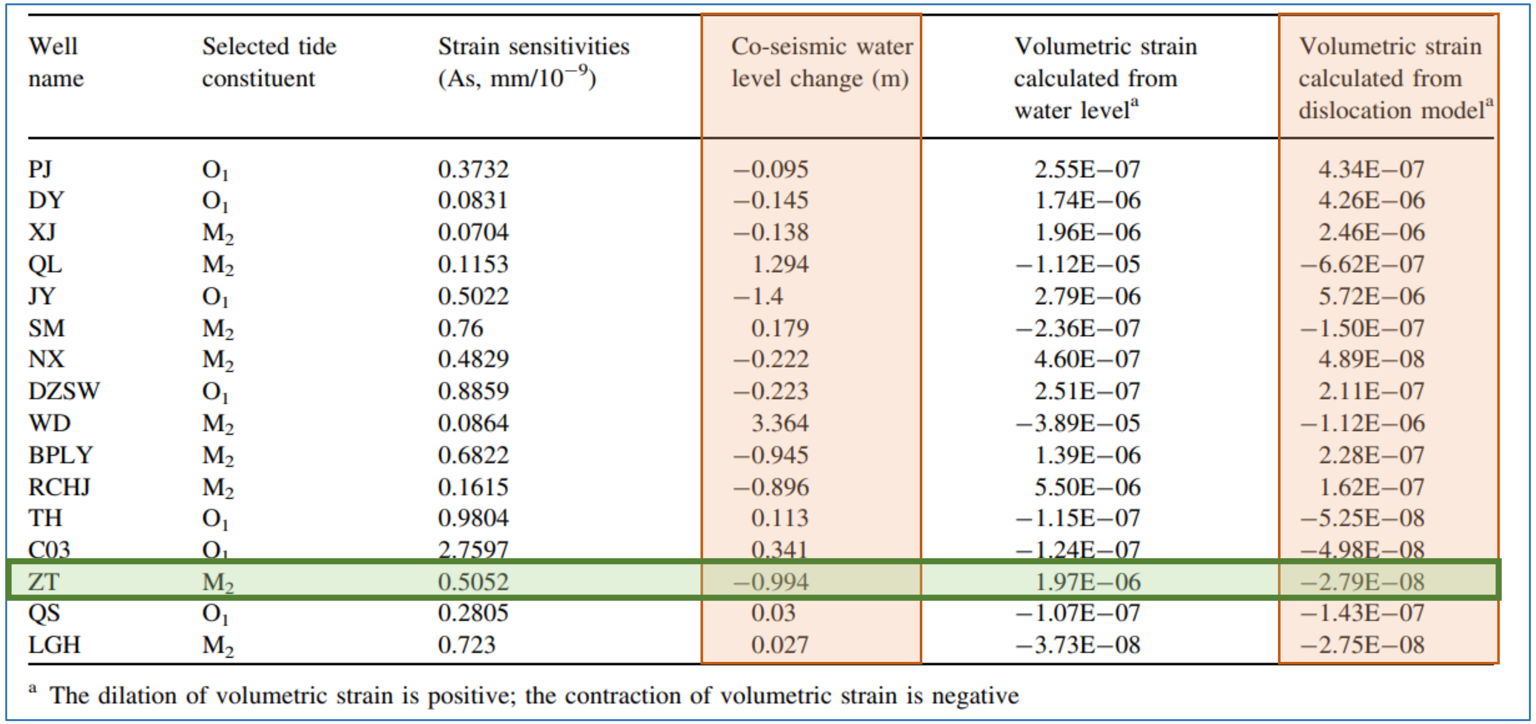


| Well name | Selected tide constituent | Strain sensitivities (As, mm/10$^{-9}$) | Co-seismic water level change (m) | Volumetric strain calculated from water level[a] | Volumetric strain calculated from dislocation model[a] |
|---|---|---|---|---|---|
| PJ | $O_1$ | 0.3732 | −0.095 | 2.55E−07 | 4.34E−07 |
| DY | $O_1$ | 0.0831 | −0.145 | 1.74E−06 | 4.26E−06 |
| XJ | $M_2$ | 0.0704 | −0.138 | 1.96E−06 | 2.46E−06 |
| QL | $M_2$ | 0.1153 | 1.294 | −1.12E−05 | −6.62E−07 |
| JY | $O_1$ | 0.5022 | −1.4 | 2.79E−06 | 5.72E−06 |
| SM | $M_2$ | 0.76 | 0.179 | −2.36E−07 | −1.50E−07 |
| NX | $M_2$ | 0.4829 | −0.222 | 4.60E−07 | 4.89E−08 |
| DZSW | $O_1$ | 0.8859 | −0.223 | 2.51E−07 | 2.11E−07 |
| WD | $M_2$ | 0.0864 | 3.364 | −3.89E−05 | −1.12E−06 |
| BPLY | $M_2$ | 0.6822 | −0.945 | 1.39E−06 | 2.28E−07 |
| RCHJ | $M_2$ | 0.1615 | −0.896 | 5.50E−06 | 1.62E−07 |
| TH | $O_1$ | 0.9804 | 0.113 | −1.15E−07 | −5.25E−08 |
| C03 | $O_1$ | 2.7597 | 0.341 | −1.24E−07 | −4.98E−08 |
| ZT | $M_2$ | 0.5052 | −0.994 | 1.97E−06 | −2.79E−08 |
| QS | $O_1$ | 0.2805 | 0.03 | −1.07E−07 | −1.43E−07 |
| LGH | $M_2$ | 0.723 | 0.027 | −3.73E−08 | −2.75E−08 |

[a] The dilation of volumetric strain is positive; the contraction of volumetric strain is negative

# Comparison of co-seismic volumetric strains and water level changes

The comparison results:



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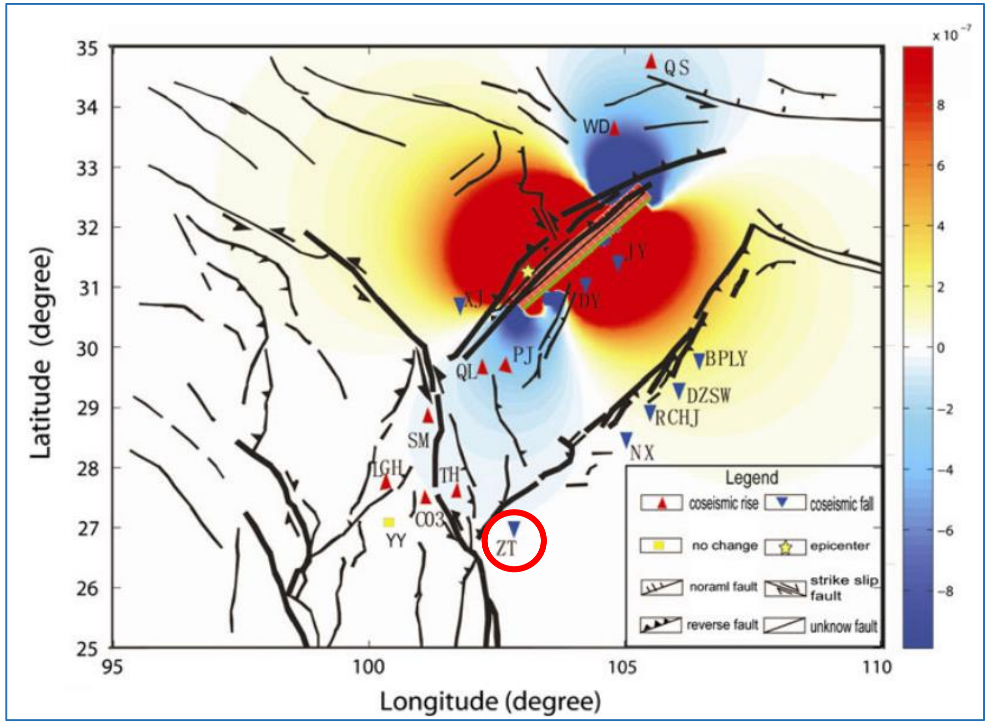
[a] The dilation of volumetric strain is positive; the contraction of volumetric strain is negative

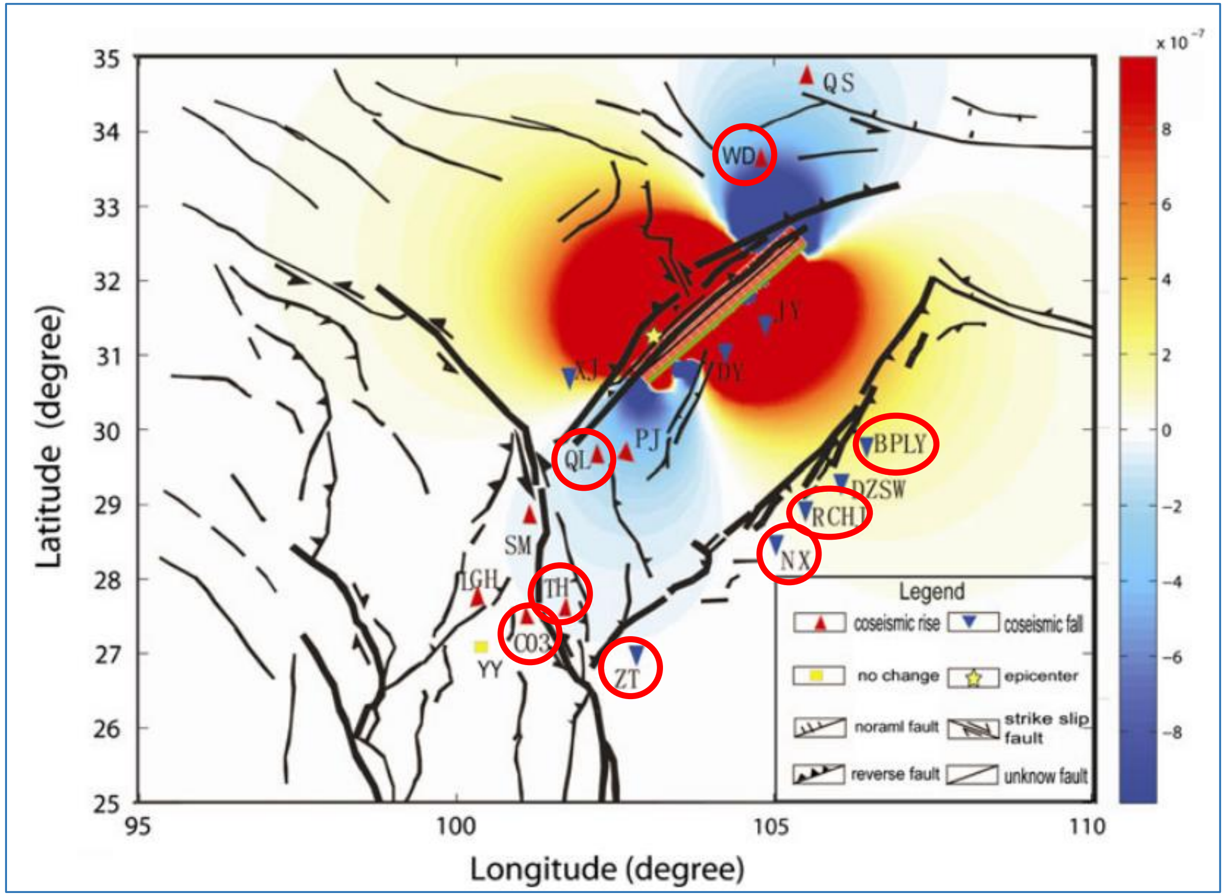


Dilation (volumetric strain positive) ▶ Groundwater level decrease

In the remaining wells, the water level changes had the same sign as the static strain change calculated from dislocation theory (except ZT)

# Static and dynamic strain and the groundwater level changes

- Both static and dynamic stresses can cause changes in the water level.
- Near the epicenter ▶ static stress dominates ▶ decreases more quickly than the dynamic stresses.
- The wells that has inconsistent strain between the two methods mostly had an epicenter distance >300 km.



The changes in water level in wells QL, NX, WD, BPLY, RCHJ, TH, C03, and ZT were dominated by the dynamic strain

# Dynamic strain (seismic wave) and groundwater level changes

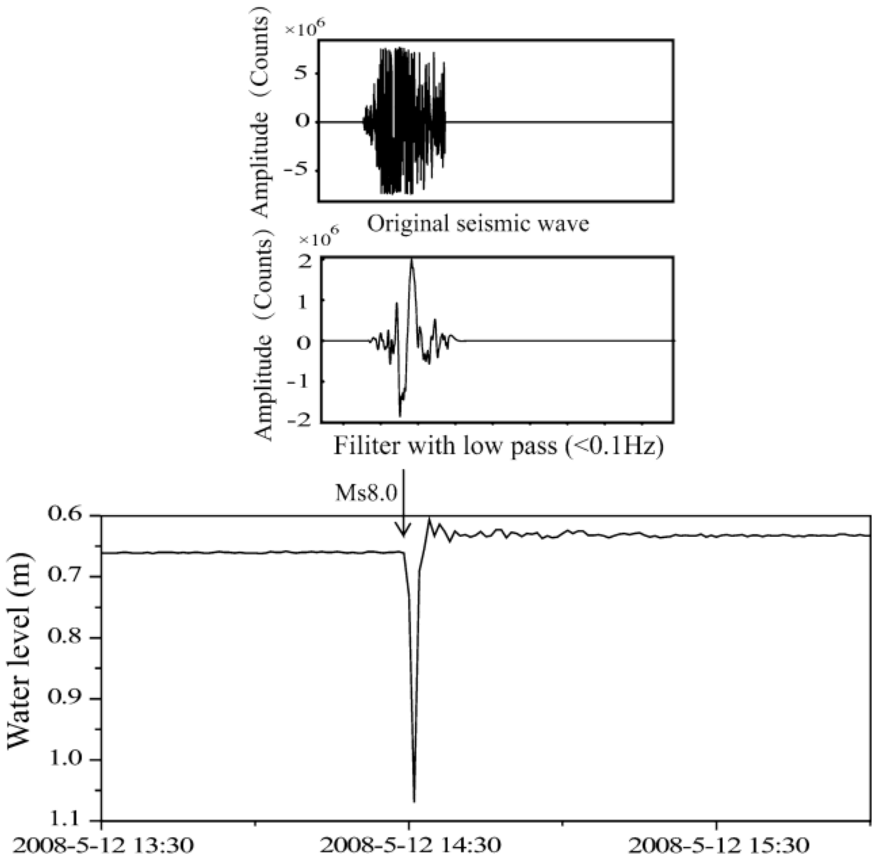


Figure 5
Vertical channel seismogram recorded by broad band seismometer and the water-level change in C03

- The seismic wave record by broadband seismometer at the station near well C03 (30 km away) was filtered with low pass filtering (<0.1 Hz).

- Comparing the seismic wave with the water-level changes caused by the Wenchuan earthquake in well C03, the water-level begins dropped following the oscillation of seismic wave was found.

- The indication of the co-seismic water-level changes in C03 were induced by the seismic wave, or dynamic strain

# Conclusions and Future Work

# Conclusions

- The sign of the co-seismic water level changes was consistent with the static strain change predicted using dislocation theory. Half of the wells could be explained by the poroelasticity theory with the static strain hypothesis.

- The strain calculated from the water level is one or two orders of magnitude larger than the static strain calculated from the fault dislocation model in the remaining wells. It appears because the excess part of the strain may be caused by the dynamic strain (caused by the seismic wave and ground shaking).

- The different calculation results for the strains using two methods provide us with a rough estimate of the effective range for the static stress and the dynamic stress.

- The static stress dominated at an epicenter distance of <300 km (roughly the length of rupture zones), and the dynamic stress became significant beyond this distance for the. However, different geological conditions and the distribution direction relative to the epicenter may also play an important role in determining the strain.

# Future Work

- Groundwater Level Data Decomposition

  Using the BAYTAP-G model to decompose the groundwater level data.

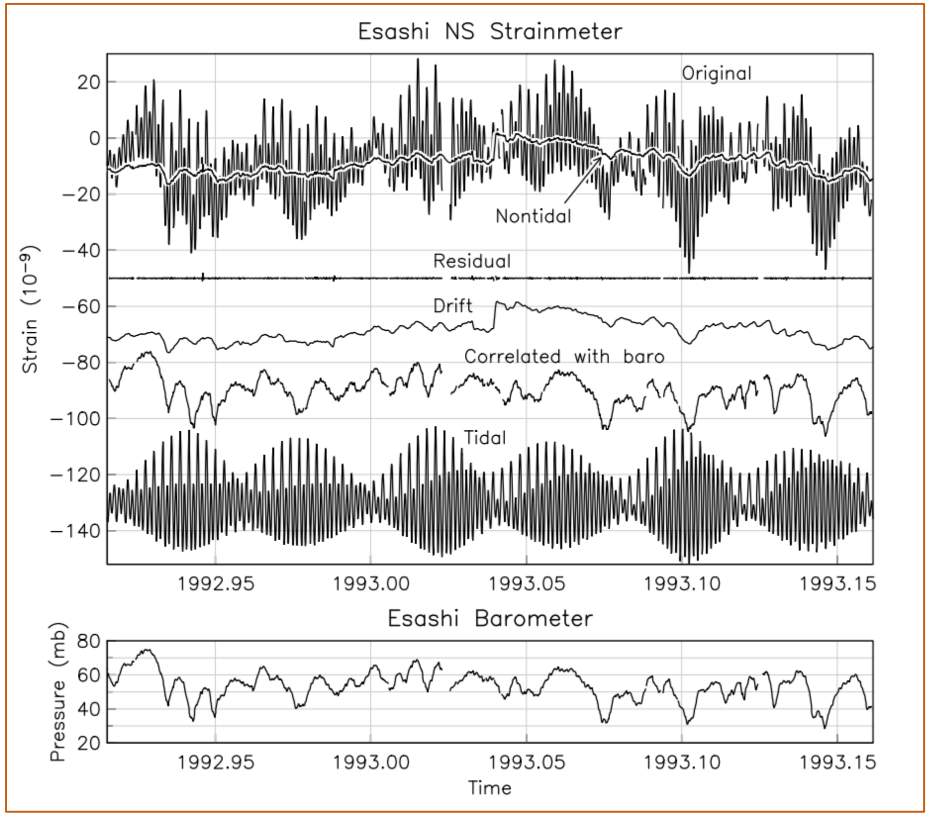
- Pre-seismic Groundwater level changes

  Find and analyze the groundwater level anomalies related to the earthquake events.

# BAYTAP-G Signal Decomposition

BAYTAP-G (Bayesian Tidal Analysis Program-Grouping Model): program uses a Baysian modeling procedure to analyze time series that contain both tidal and other variations (includes tidal gravity, ocean tides, and strain and tilt data).

Example: Strainmeter data from Esashi, Japan, as processed by BAYTAP-G



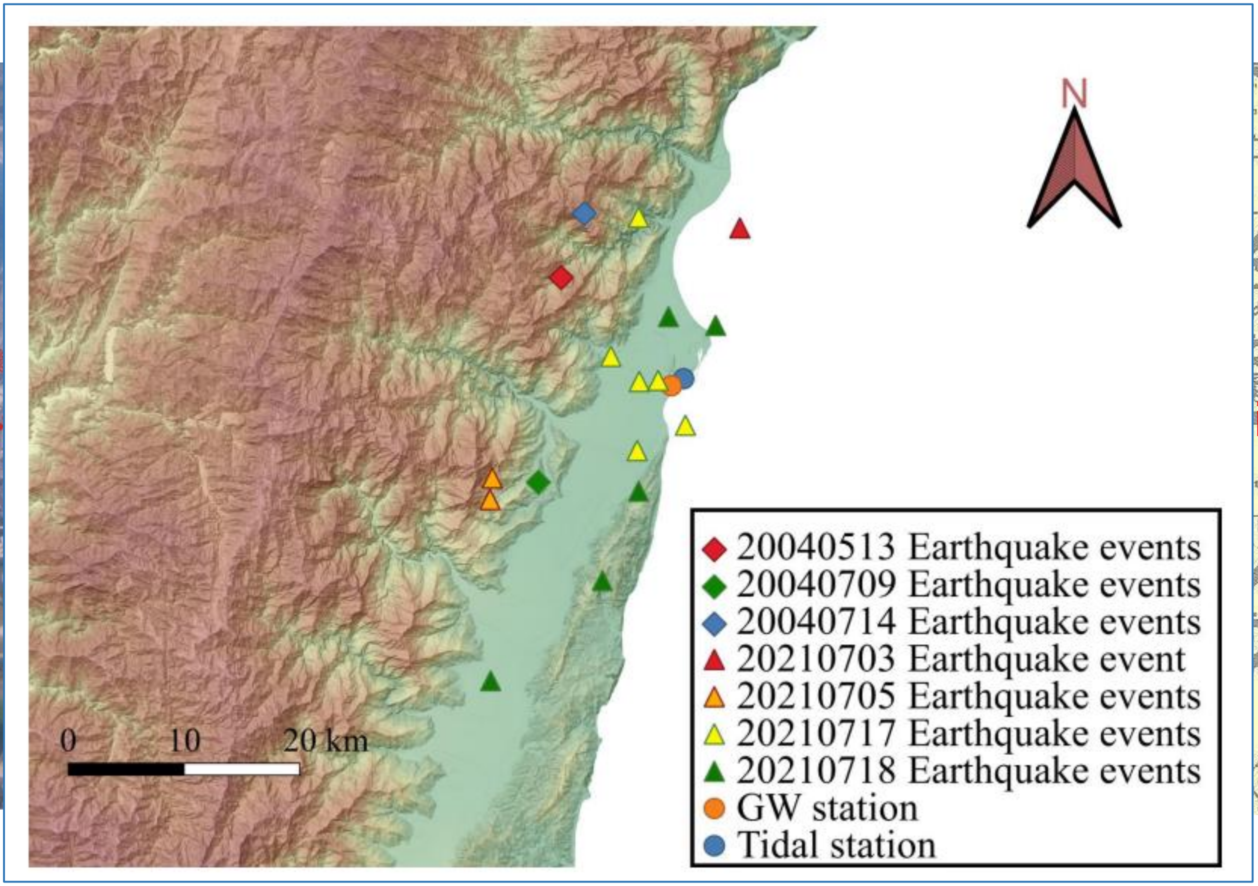
The original data is decomposed into:

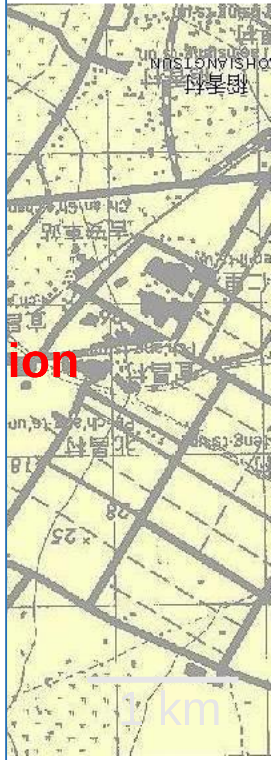
- a white-noise part (the "residual")
- a lower-frequency part (the "drift")
- a part correlated with the local air pressure
- a tidal part

# Pre-seismic groundwater level changes

Location of Hualien observation well and tidal gauge station

Distribution of the Earthquake Events History





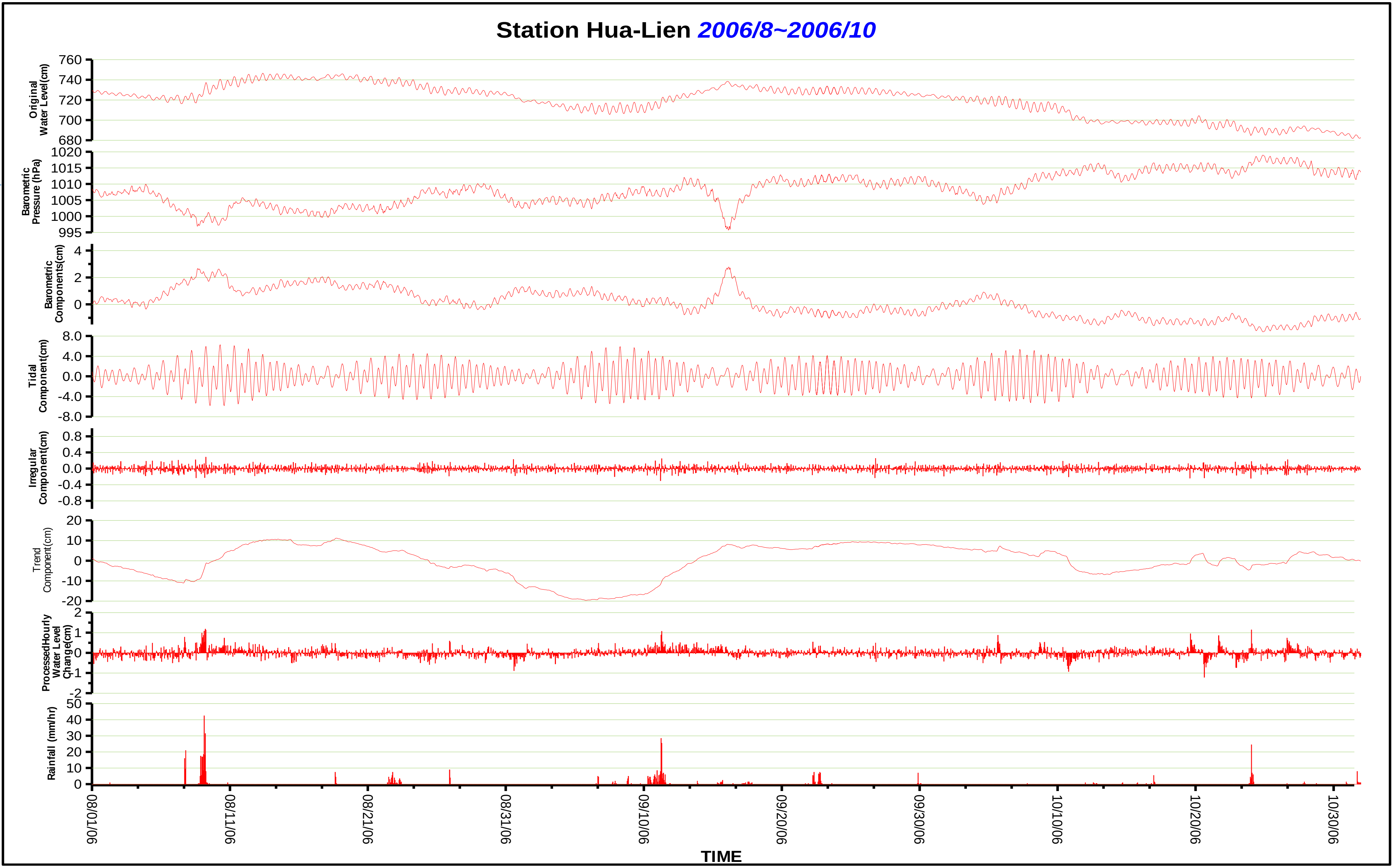
# Typical hydrograph in observation well

Original Water Level

Barometric Pressure

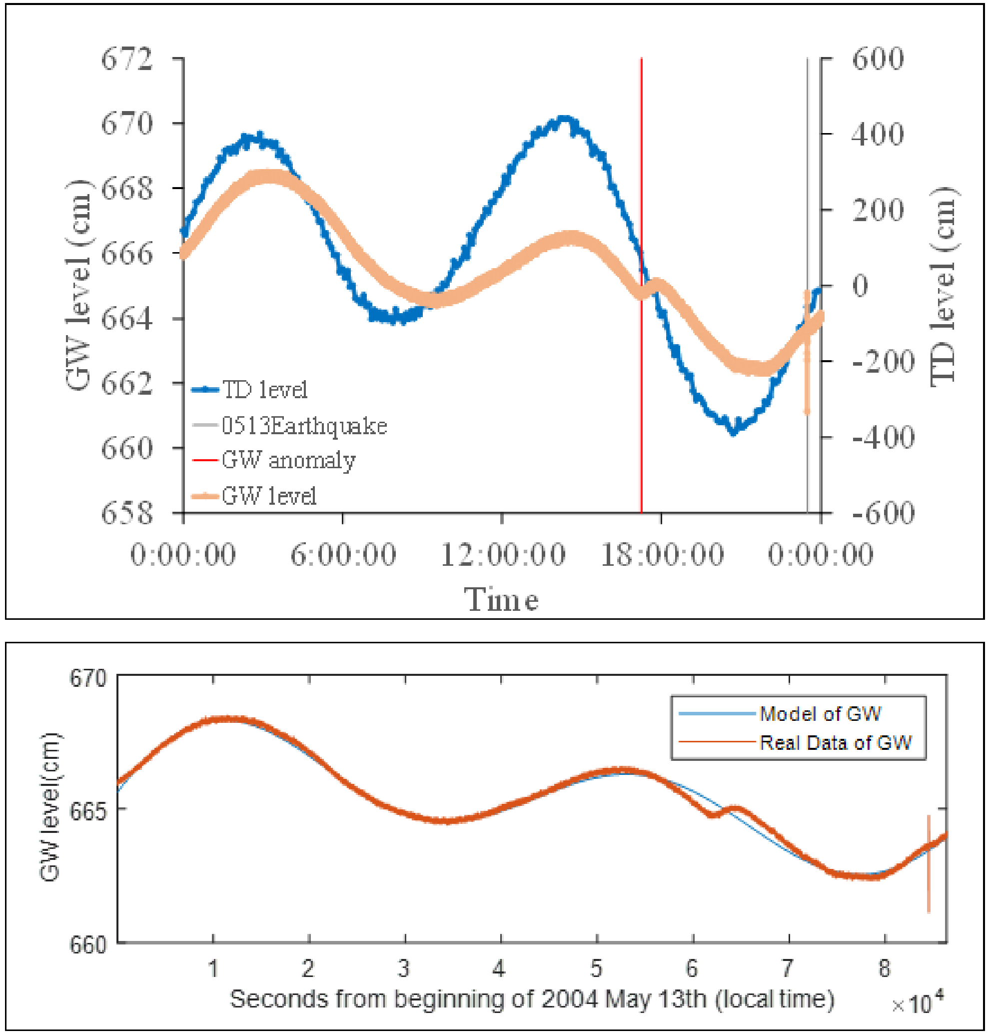
Tidal Component

Rainfall

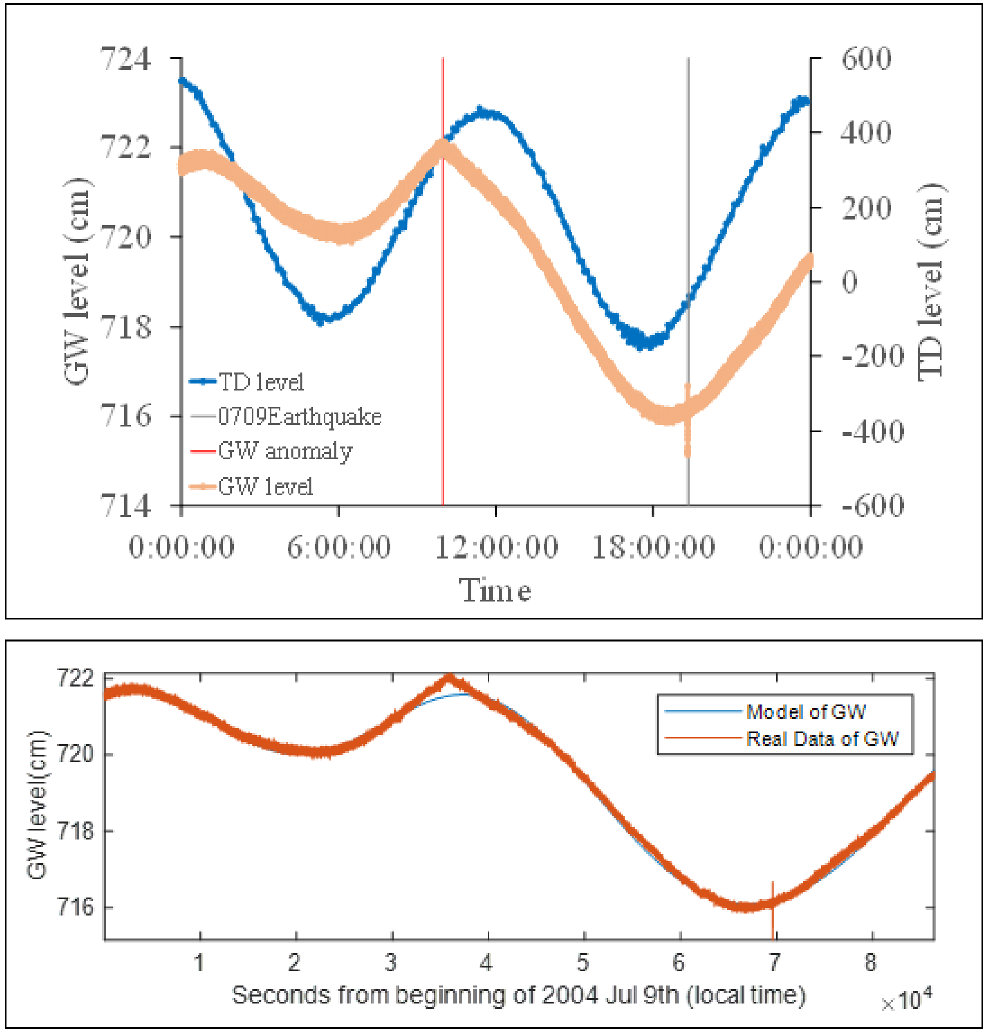


# Groundwater level anomaly

**Case 2004/05/13**



**Case 2004/07/09**



# Thank You