DPRC

Disaster Prevention Research Center,
National Cheng Kung University, Taiwan

Tectono-Hydrology Research Group

AIST The National Institute of Advanced Industrial Science and Technology
Geological Survey of Japan

Dynamic effects on coseismic groundwater level changes : Cases study of 2003~2006 M_L 6 earthquakes in Taiwan

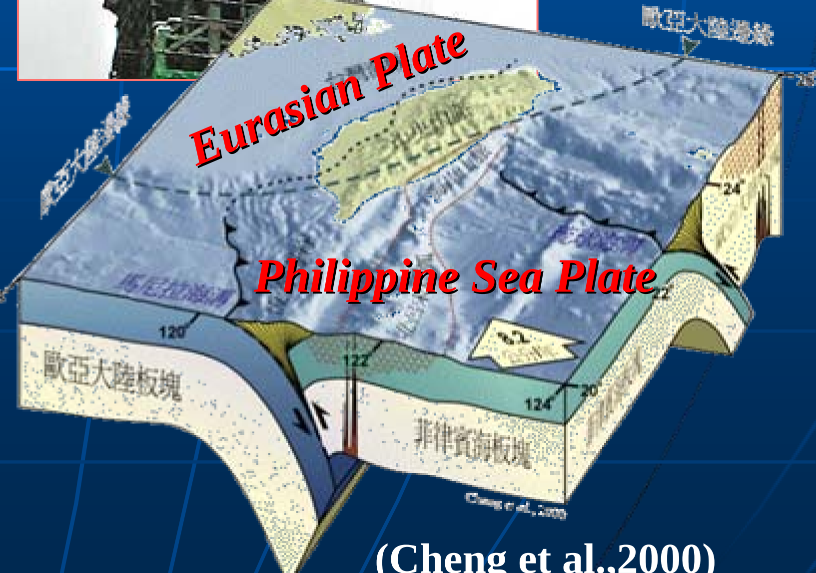
Wen-Chi Lai[1,2], Chjeng-Lun Shieh[1,3], Kuo-Chin Hsu[2], Norio Matsumoto [4], Naoji Koizumi [4]

1. Disaster Prevention Research Center, NCKU, Taiwan
2. Department of Resources Engineering, NCKU, Taiwan
3. Department of Hydraulic and Ocean Engineering, NCKU, Taiwan
4. Geological Survey of Japan, AIST, Japan

I. Introduction

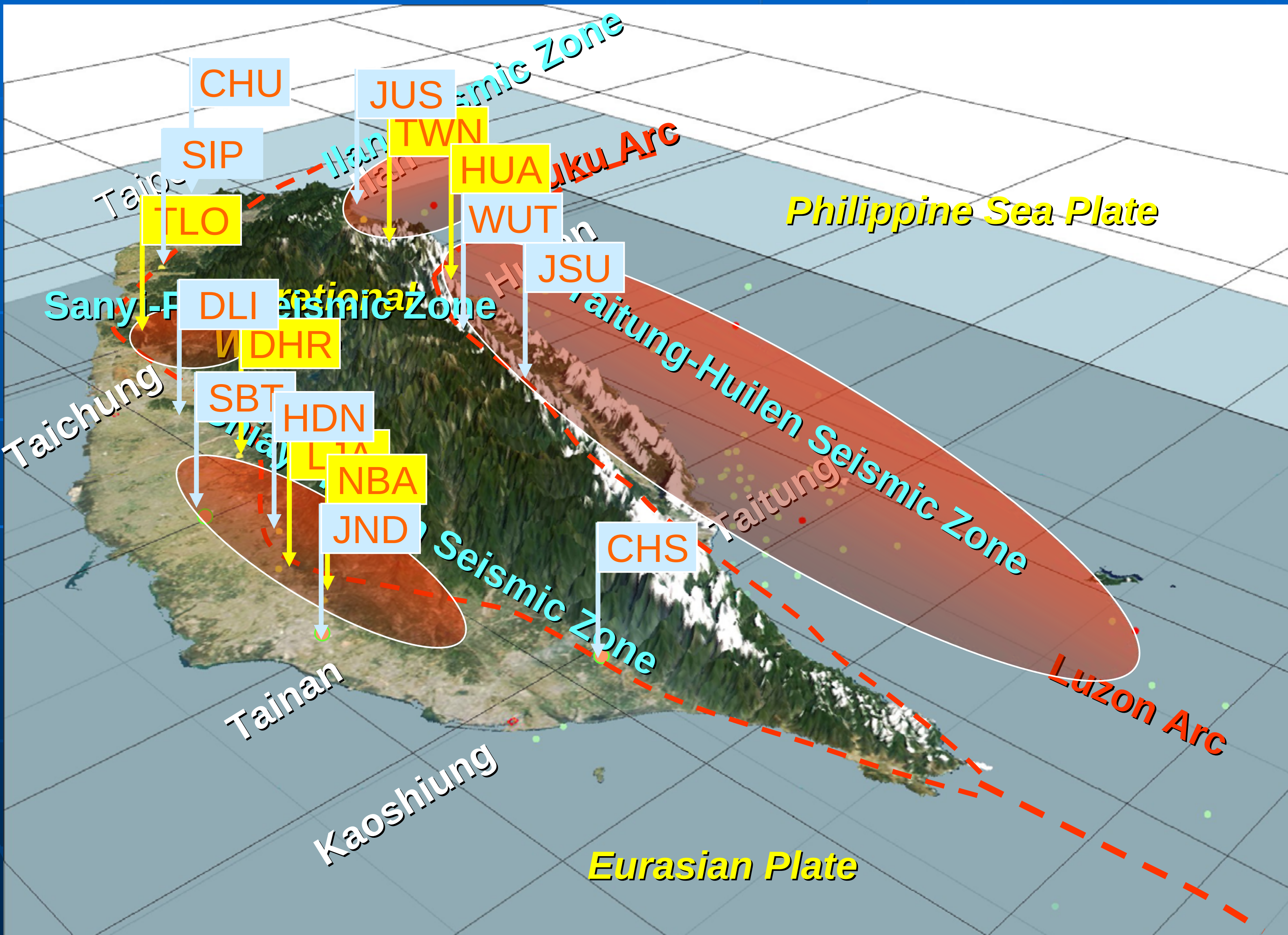
- Tectonic Setting of Taiwan.
- Highly Seismic hazard risk.
- Advantage of the research
  - High density monitoring network for water resources Groundwater Monitoring Networks of Taiwan
  - High density seismic monitoring network.
  - High seismic activity
- Good quality observation

→ ***Waiting for good news…***



(Cheng et al.,2000)

Observation Wells



Well Location

XXX Before 2004

XXX After 2004

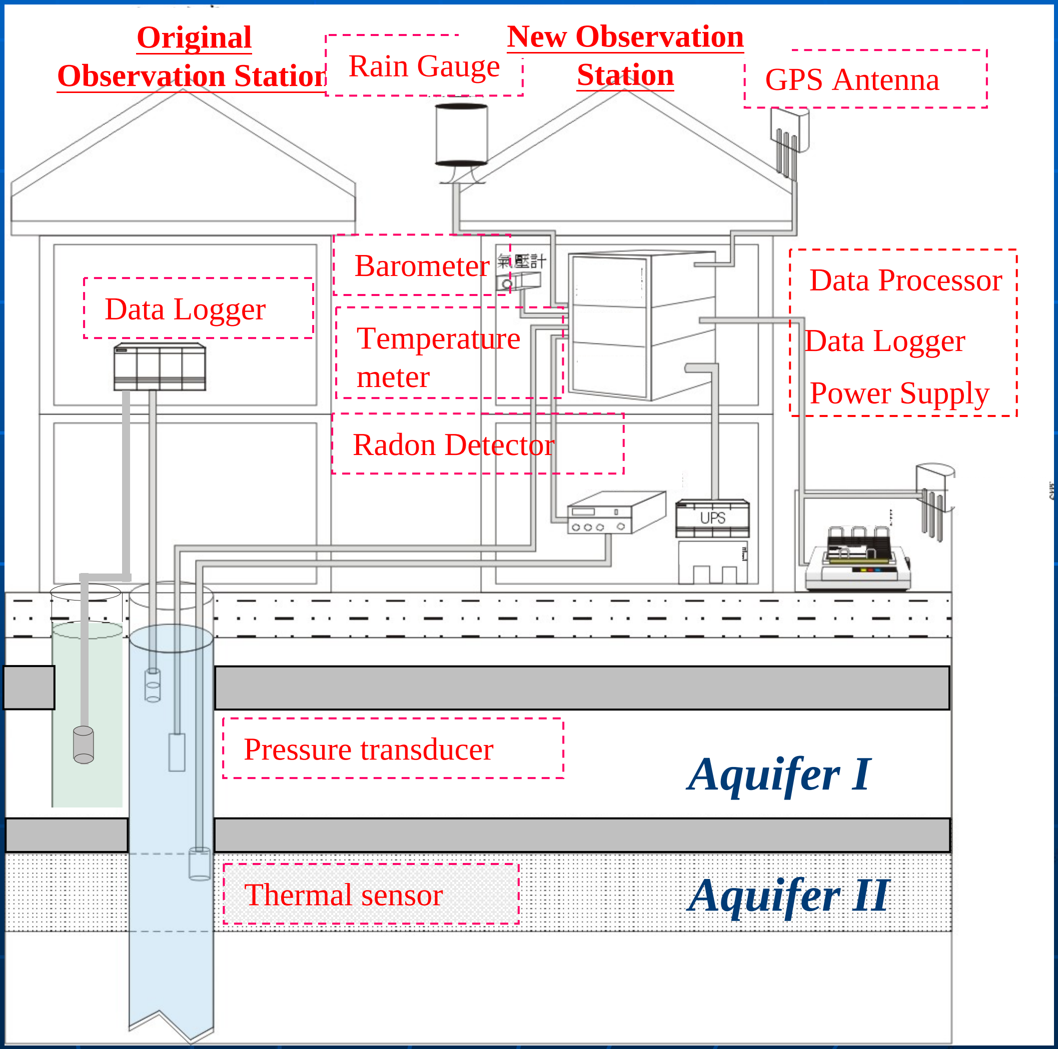
Observation wells

Well	Location		Depth (m)	Screened Depth (m)	Geology	Hydrological Conductivity (m/min)
	Lon.	Lat.				
TWN	121.782	24.746	130	112-124	Qs, Qm	2.22E-04
HUL	121.605	23.977	205	140-160	Qc	
TLO	120.784	24.491	99	84-93	Qs	8.00E-04
DHR	120.561	23.688	258	222-252	Qg	4.15E-03
LUJ	120.342	23.227	228	204-222	Qs, Qm	2.67E-03
NBA	120.340	23.071	153	135-147	Qs, Qm	1.84E-03

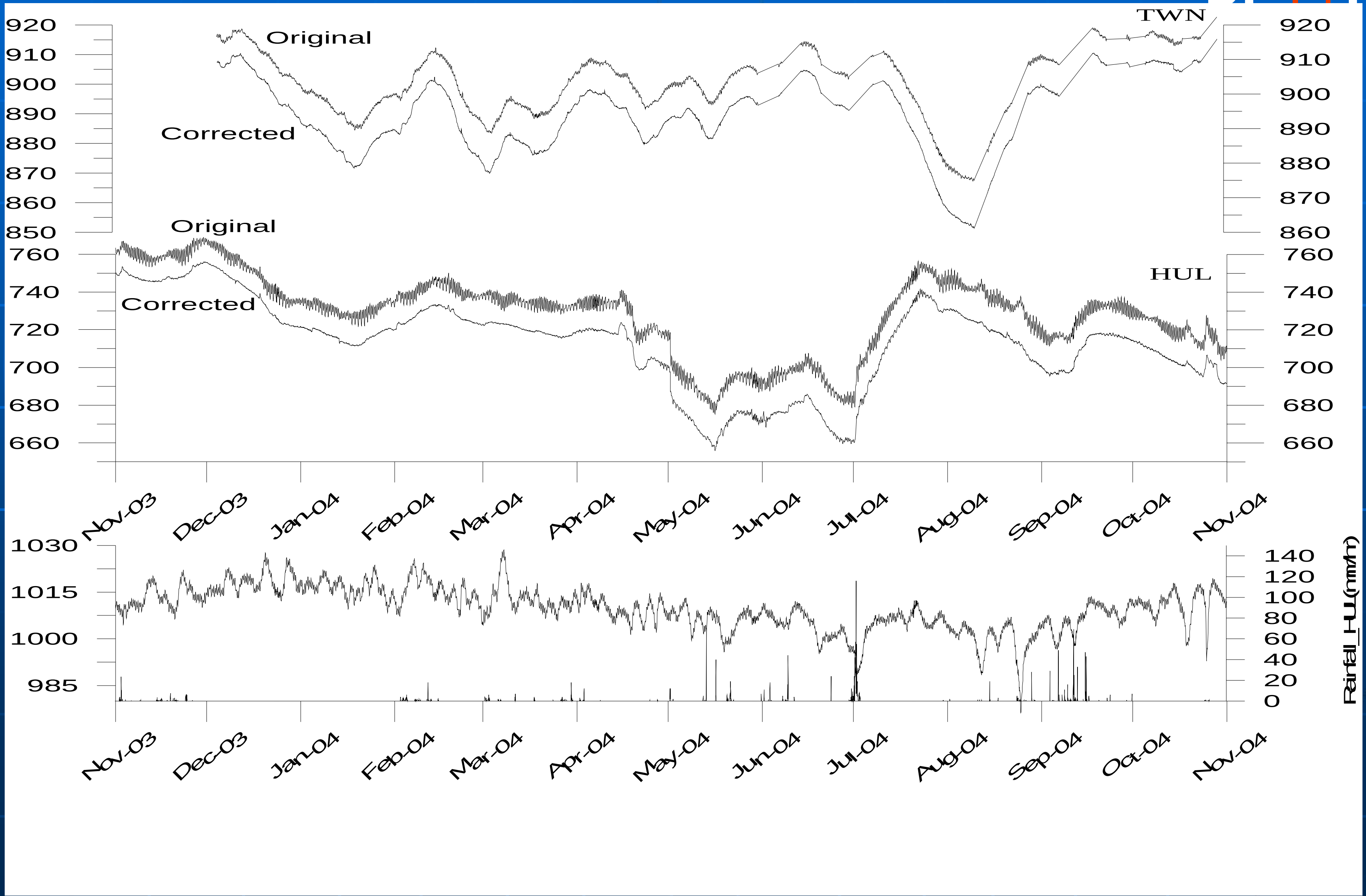
* The monitoring well instrumented in the project

Qc: Quaternary conglomerate, Qg: Quaternary gravel, Qs: Quaternary sandstone, Qm: Quaternary shale and mudstone

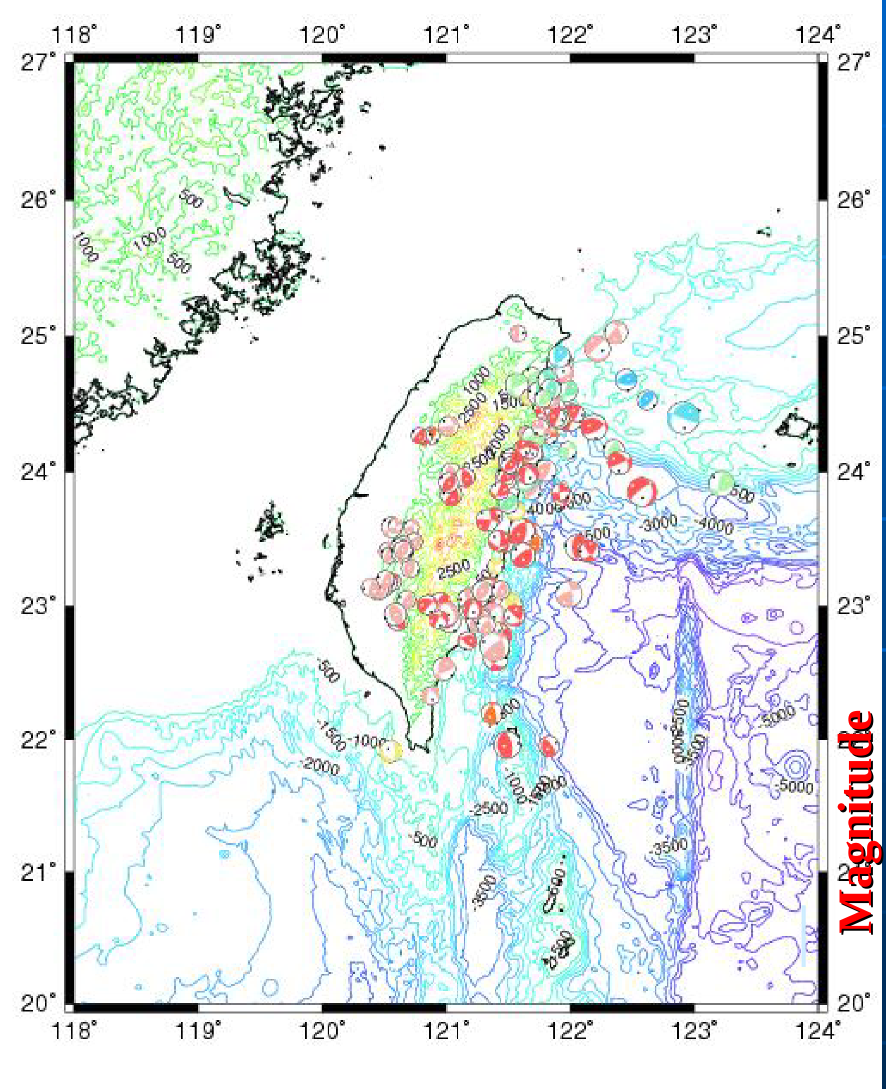
Observation and Instruments setting



Observation hydrograph



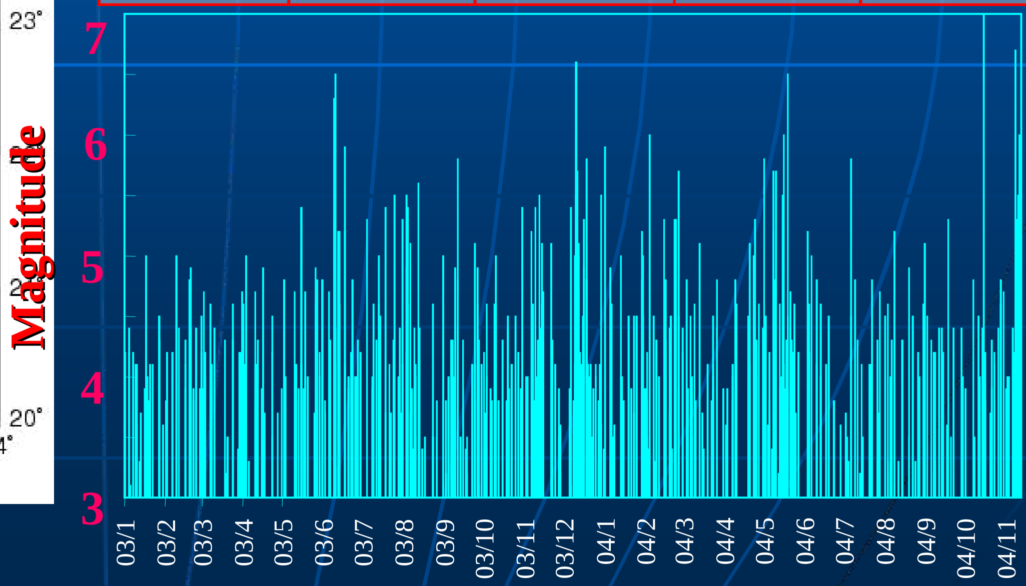
Observation



7 CMT solution and distribution of events

Events of the earthquake M_L >3 in Taiwan 03'~06'

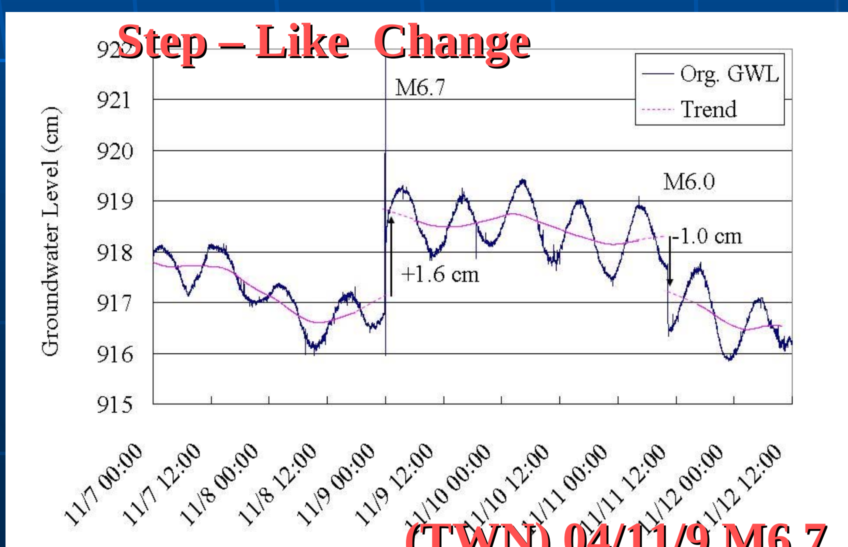
M_L	3~3.9	4~4.9	5~5.9	6.0
2003	118	181	43	2
2004	86	125	25	5
2005	277	140	24	3
2006	231	117	21	8

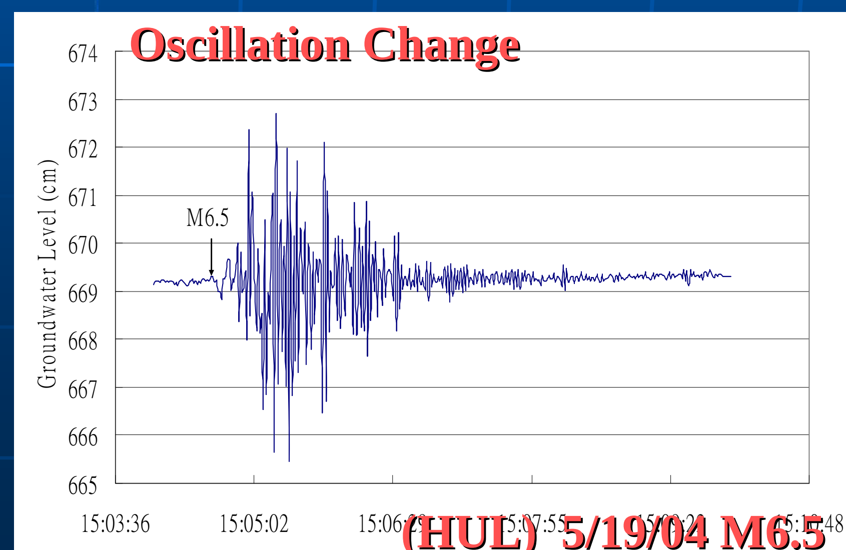


Observed coseismic events (03'~06')

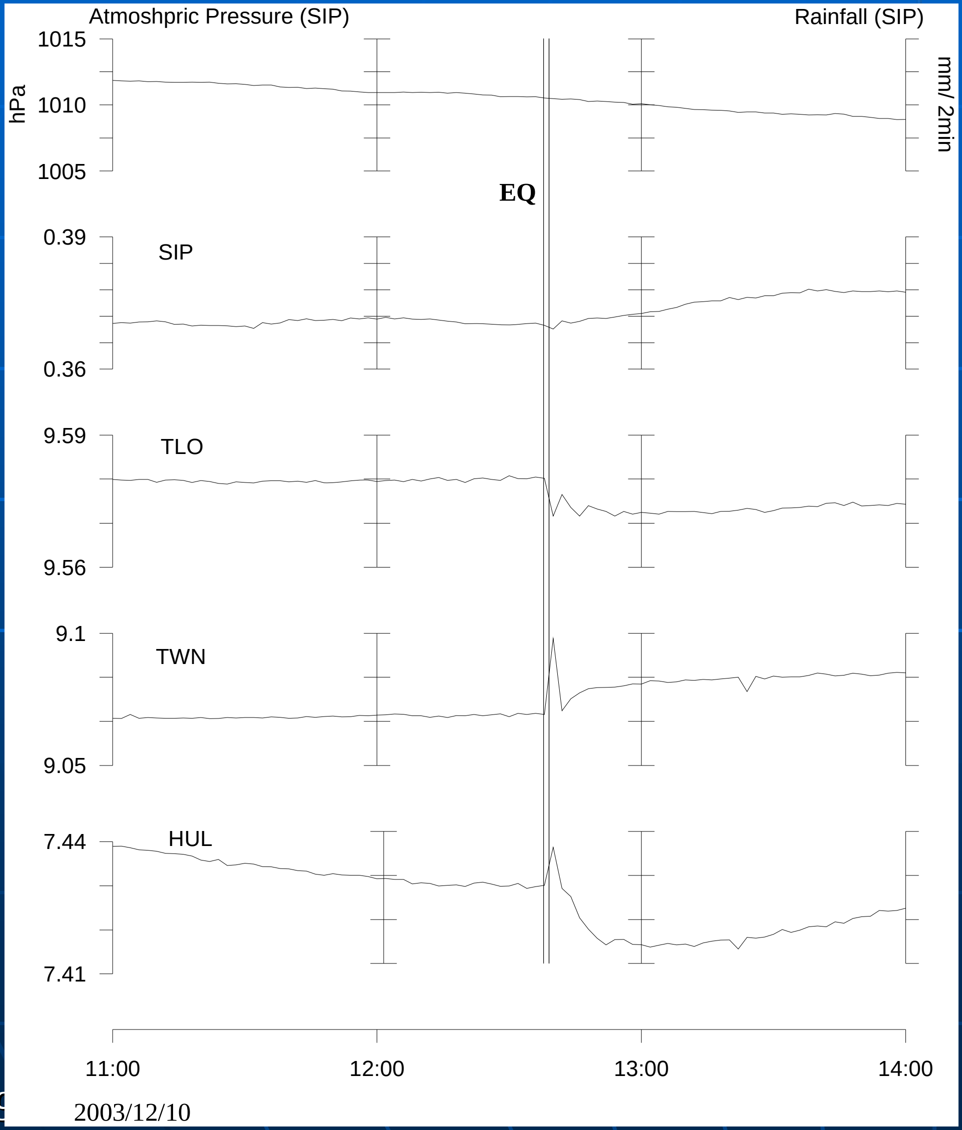
- Total 125 Observation, step changes (S) 26 events, oscillation (O) 76 events, O+S 23 events

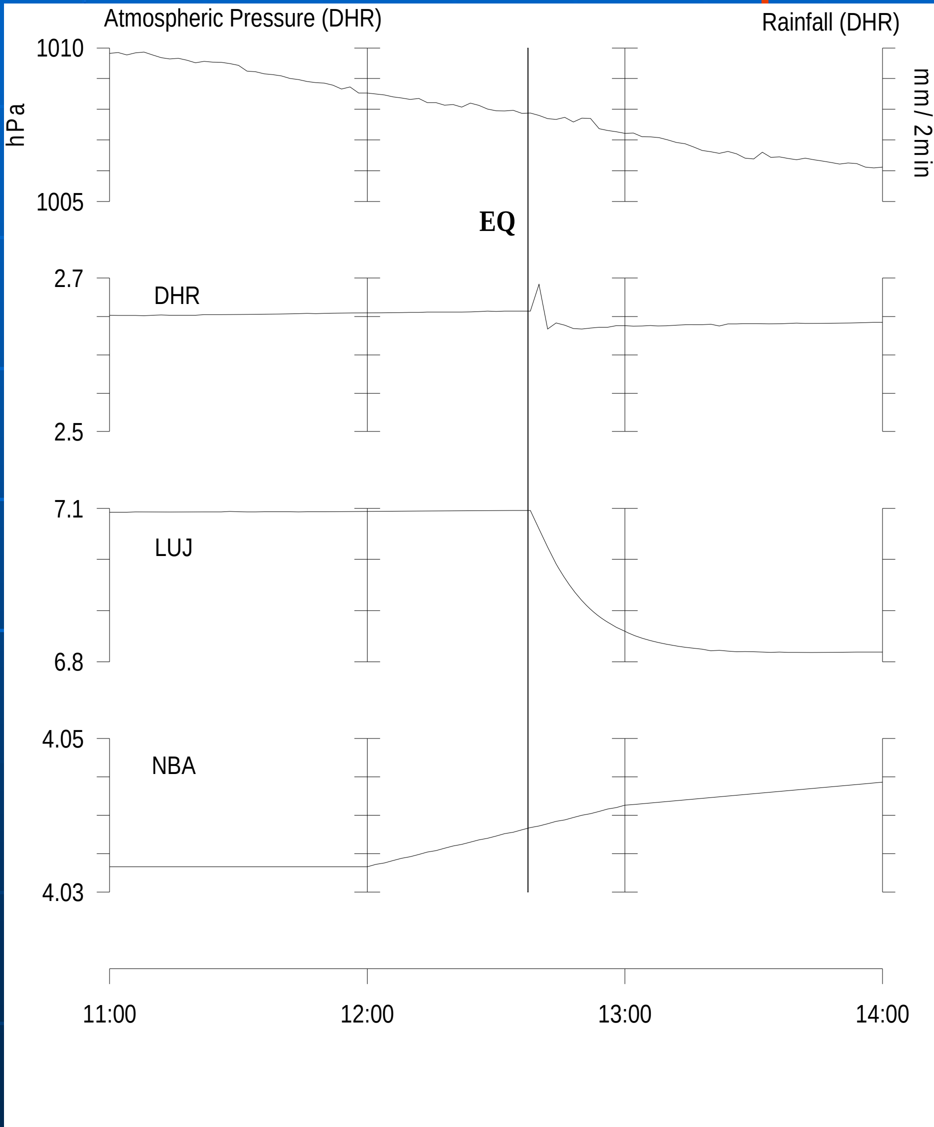
Catalog	Events	HUL	TWN	LUJ	NAB	HRD	DHR	TLO	SIP
2003/4/3 Tainan, M=4.9	2	@	@	S	S	@	@	@	@
2003/6/10 Taitung, M=6.5	4	@	@	S	O	@	O+S	@	O
2003/6/17 Taitung , M=5.9	2	@	@	@	O	@	@	@	O
2003/12/10 Taitung , M=6.6	7	O+S	O+S	S	@	S	O+S	O+S	O
2003/12/11 Taitung, M=5.7	1	@	@	@	S	@	@	@	@
2003/12/18 Taitung, M=5.8	1	O	@	@	@	@	@	@	@





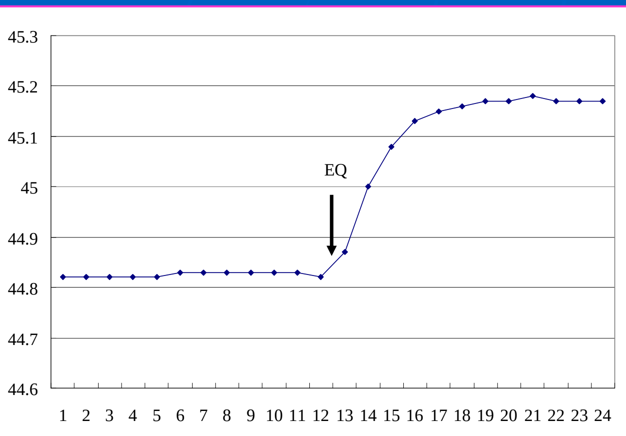
The coseismic groundwater level changes records, eastern Taiwan, Dec. 10, 2003



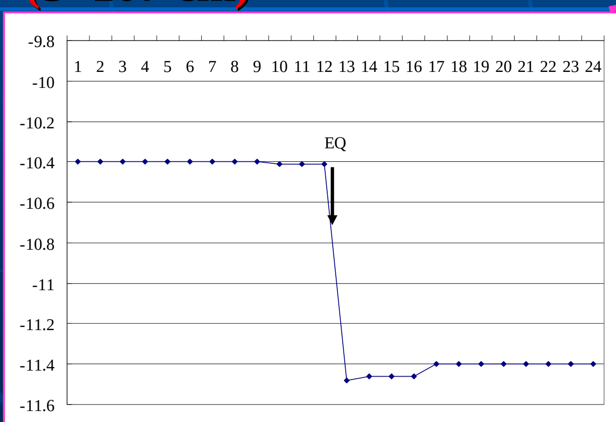


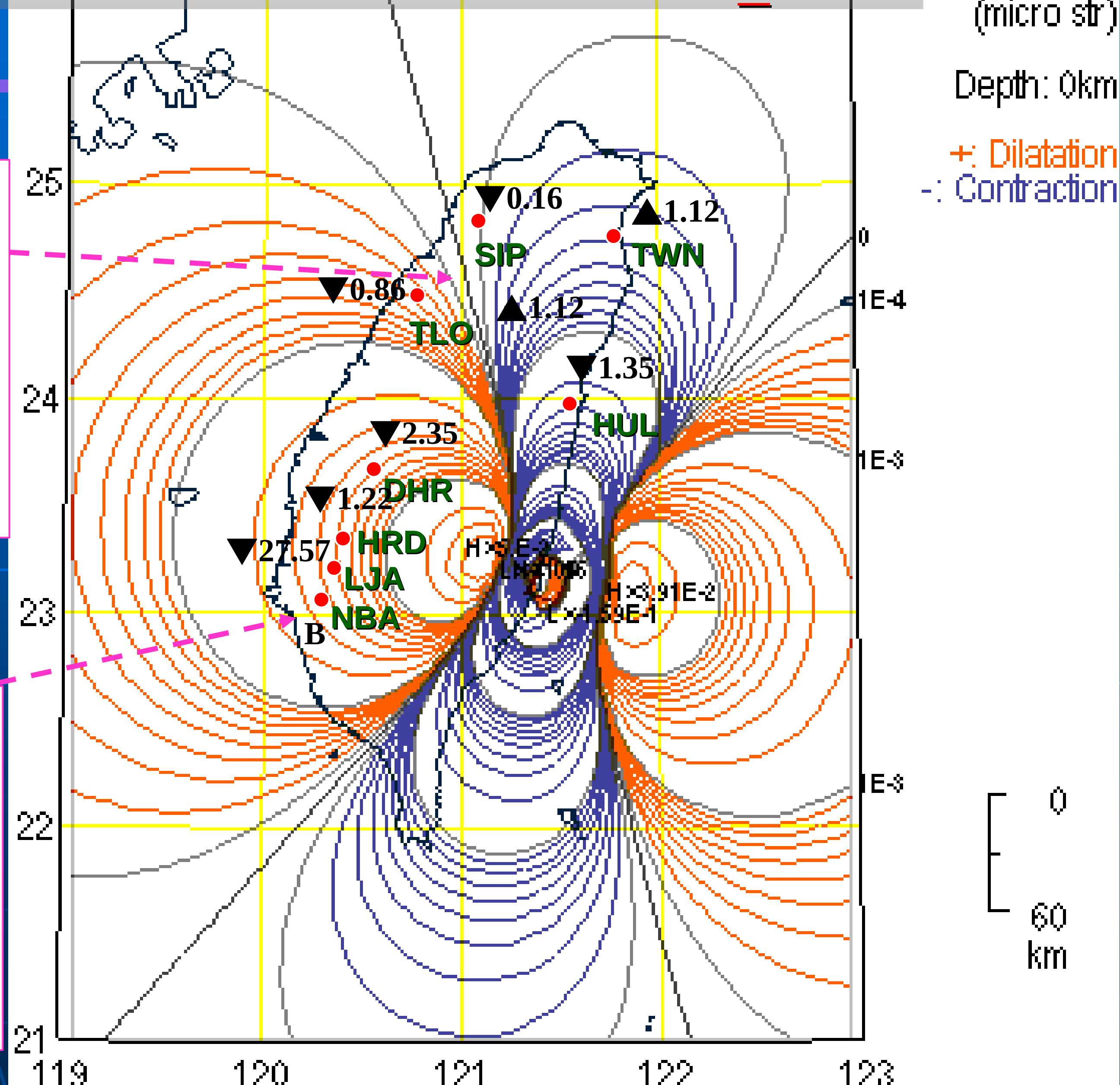
EQ 2003/12/10 Taitung M_L 6.6

2 wells increase in Miaoli area (6cm~35 cm)



21 Wells decrease in Tainan-Kaoshiung Area (3~107 cm)

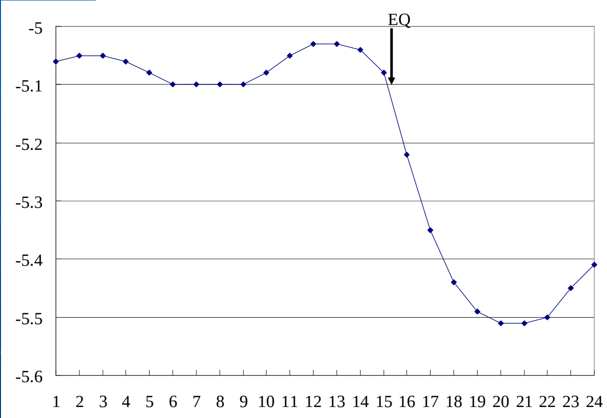


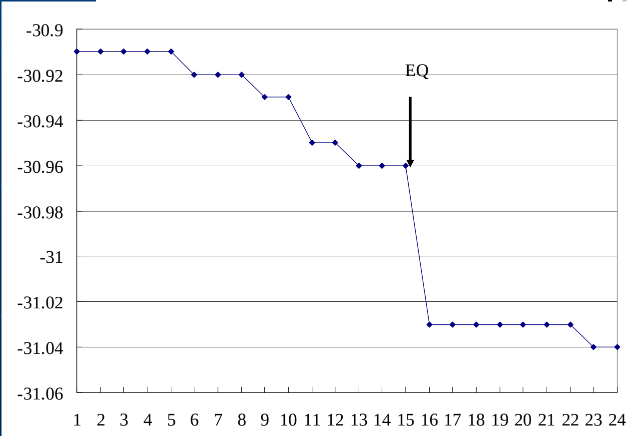


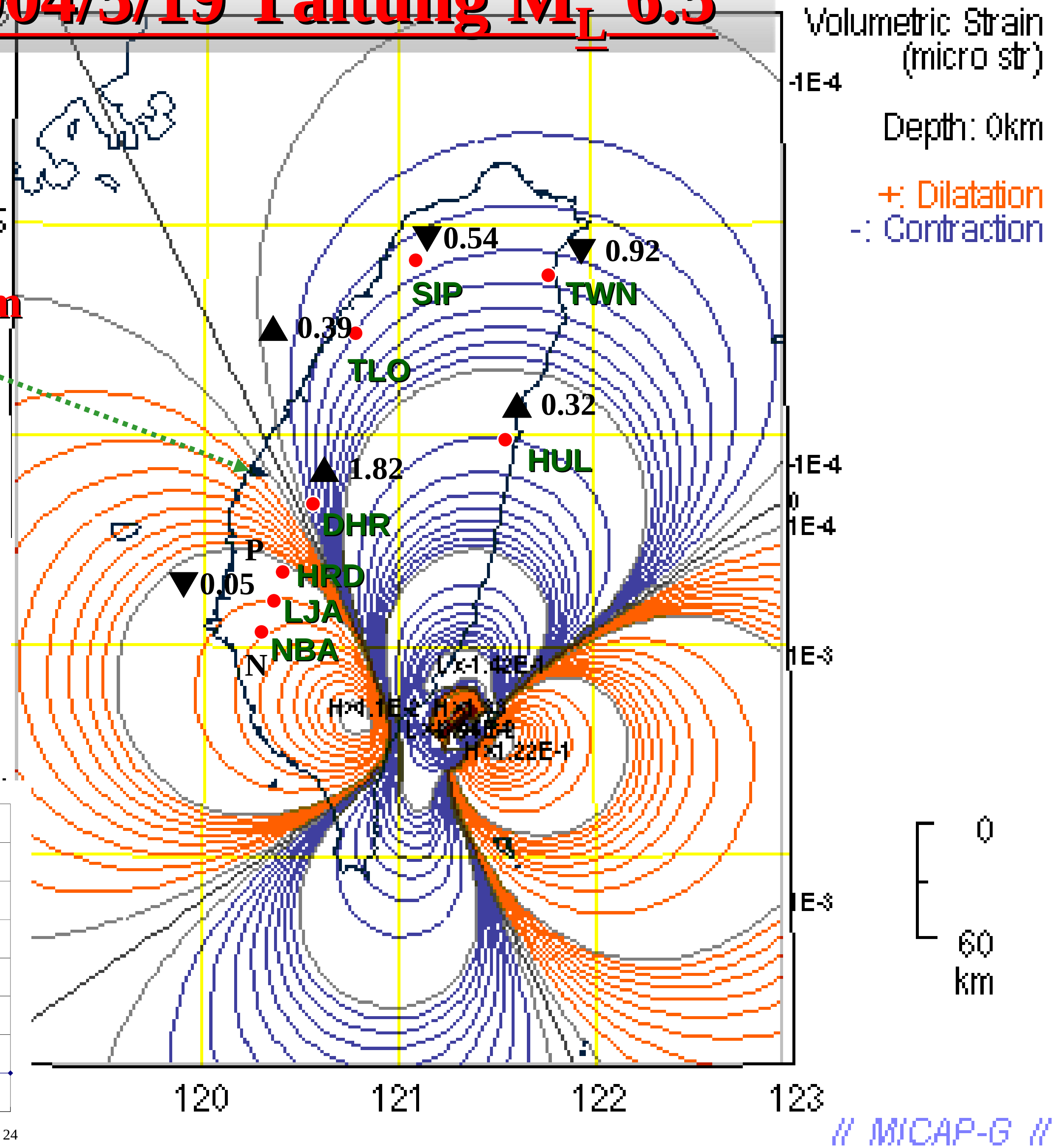
MICAP-G (Naito & Yoshikawa, 1999)

EQ 2004/5/19 Taitung M_L 6.5

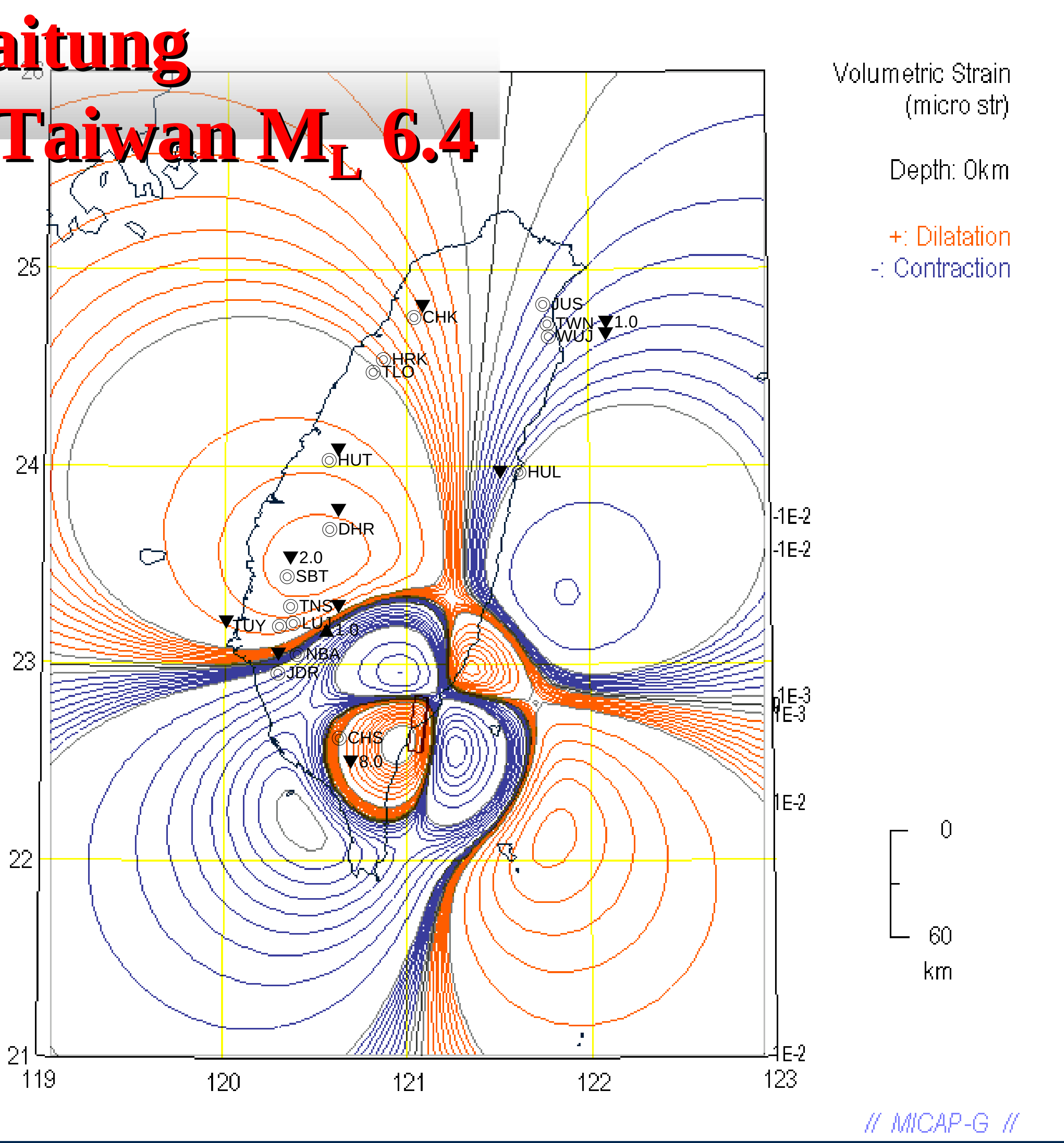
6 Wells decrease 2~40 cm in Yunlin-Chiayi Area







2006/04/01 Taitung Earthquake, Taiwan M_L 6.4



Estimation of the theoretical responses

DPRC

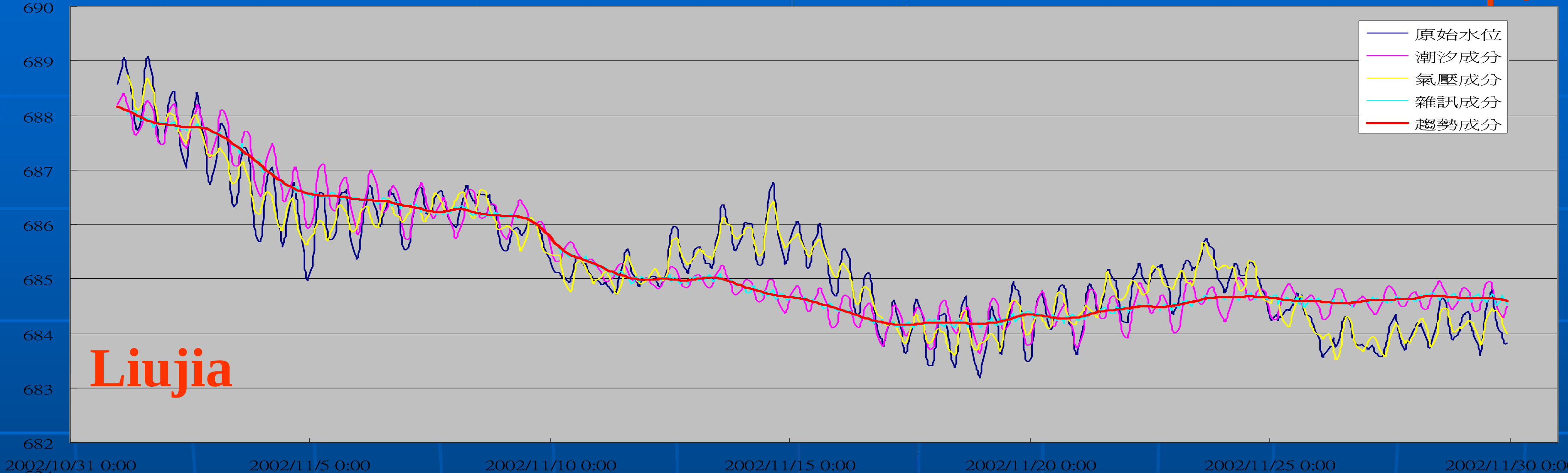
- Using Baytap-G Program to estimate the Tidal component of observed groundwater level
- Calculate the theoretic tidal potential from GOTIC II Program
- Derived the static strain volumetric sensitivity by

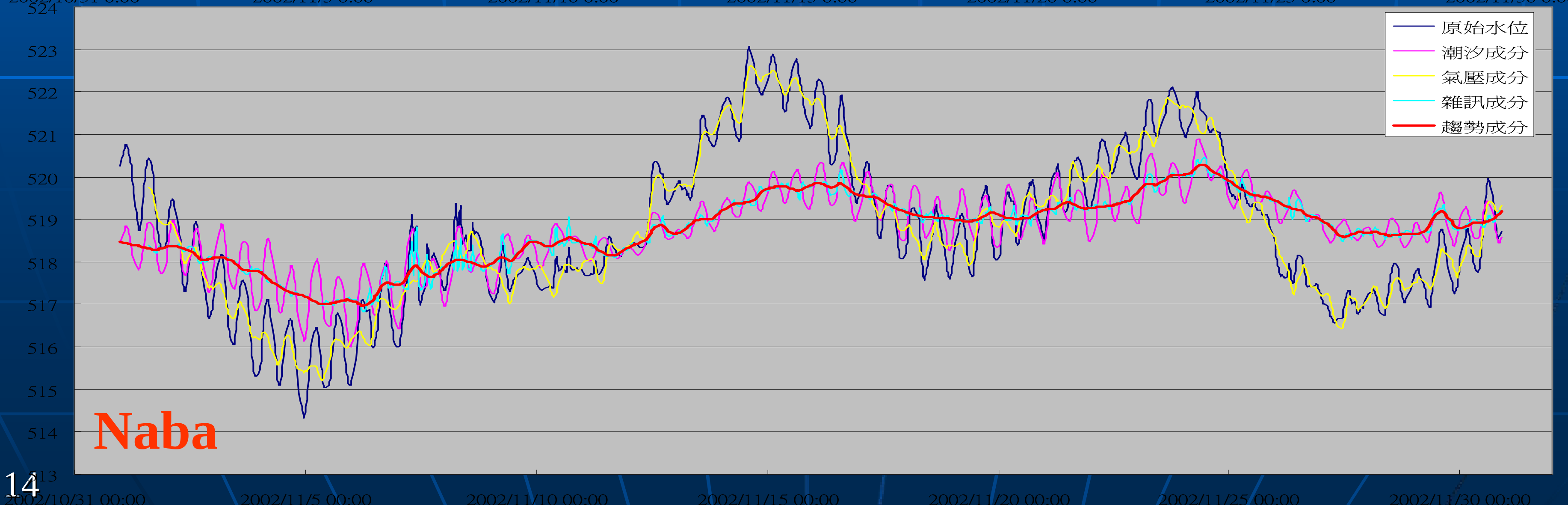
static volumetric strain sensitivity = (tidal responses   tidal potential)

- Calculate the coseismic static volumetric strain using MICAP-G program.
- Derived the predicted amplitude estimated from tidal response by

Amp. Of Chg.= (calculated volumetric strain   strain sensitivity)

Decomposition and Extraction



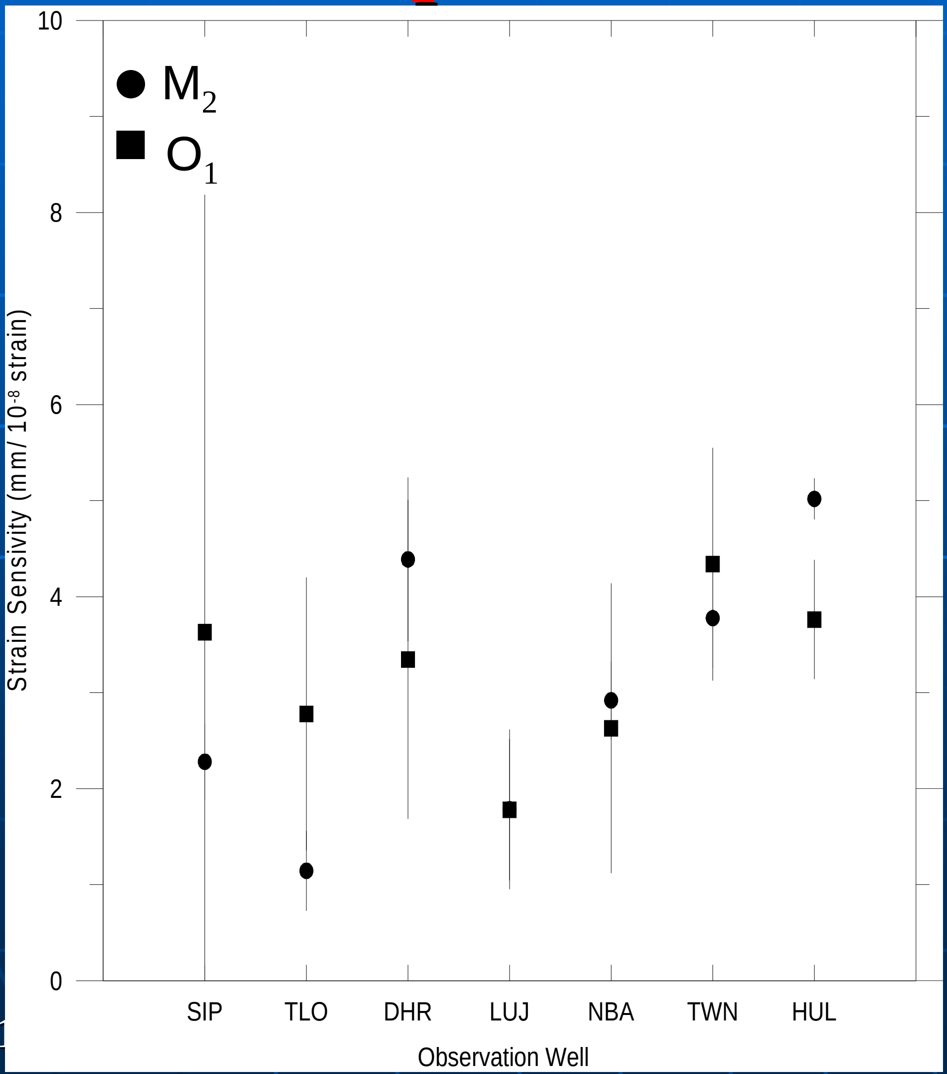


Static Volumetric Strain Sensitivity

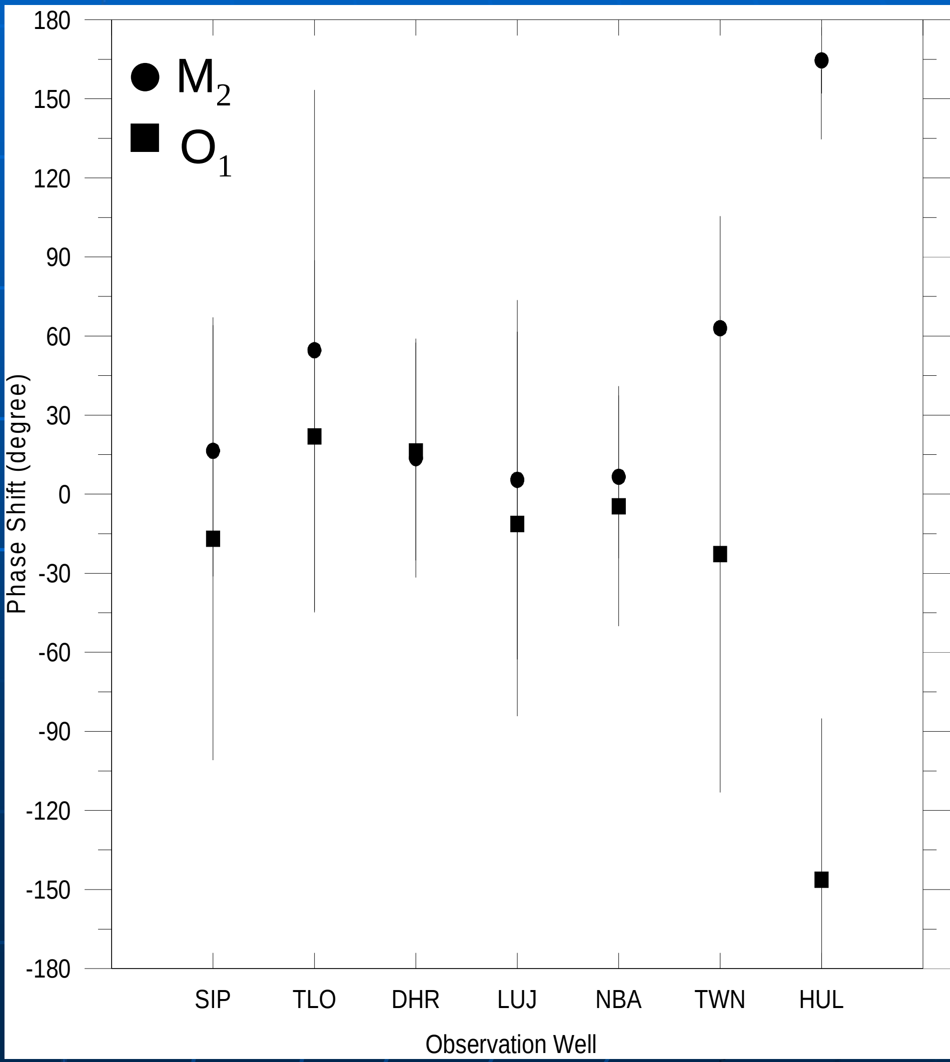
	TLO	DHR	LUJ	NBA	TWN	HUL
	Amplitude (10^{-8}) [Phase Shift (degree)]					
Vol. strain by M_2 earth tide, t_e	**1.35 [0]**	**1.37 [0]**	**1.38 [0]**	**1.38 [0]**	**1.35 [0]**	**1.37 [0]**
Vol. strain by M_2 oceanic tidal loading, t_o	**2.08 [-321]**	**0.18 [-276]**	**0.11 [-290]**	**0.11 [-301]**	**0.60 [-227]**	**6.10 [-184]**
Vol. strain by earth + oceanic tide, $t_t = t_e + t_o$	**3.25 [-336]**	**1.40 [-352]**	**1.42 [-356]**	**1.45 [-356]**	**1.04 [-335]**	**4.73 [-185]**
M_2 amplitude(water level, t_w)	**3.72±0.67 [-282±49]**	**6.17±0.60 [-339±23]**	**2.54±0.59 [-350±34]**	**4.24±0.29 [-349±15]**	**3.93±0.27 [-272±21]**	**23.77±0.50 [-21±6]**
Strain sens. by **Water Level** M_2 tide, **Ws** = t_w/t_t (mm/10^{-8})	**1.14**	**4.39**	**1.78**	**2.92**	**3.78**	**5.02**

Verify of the Static Volumetric Strain Sensitivity

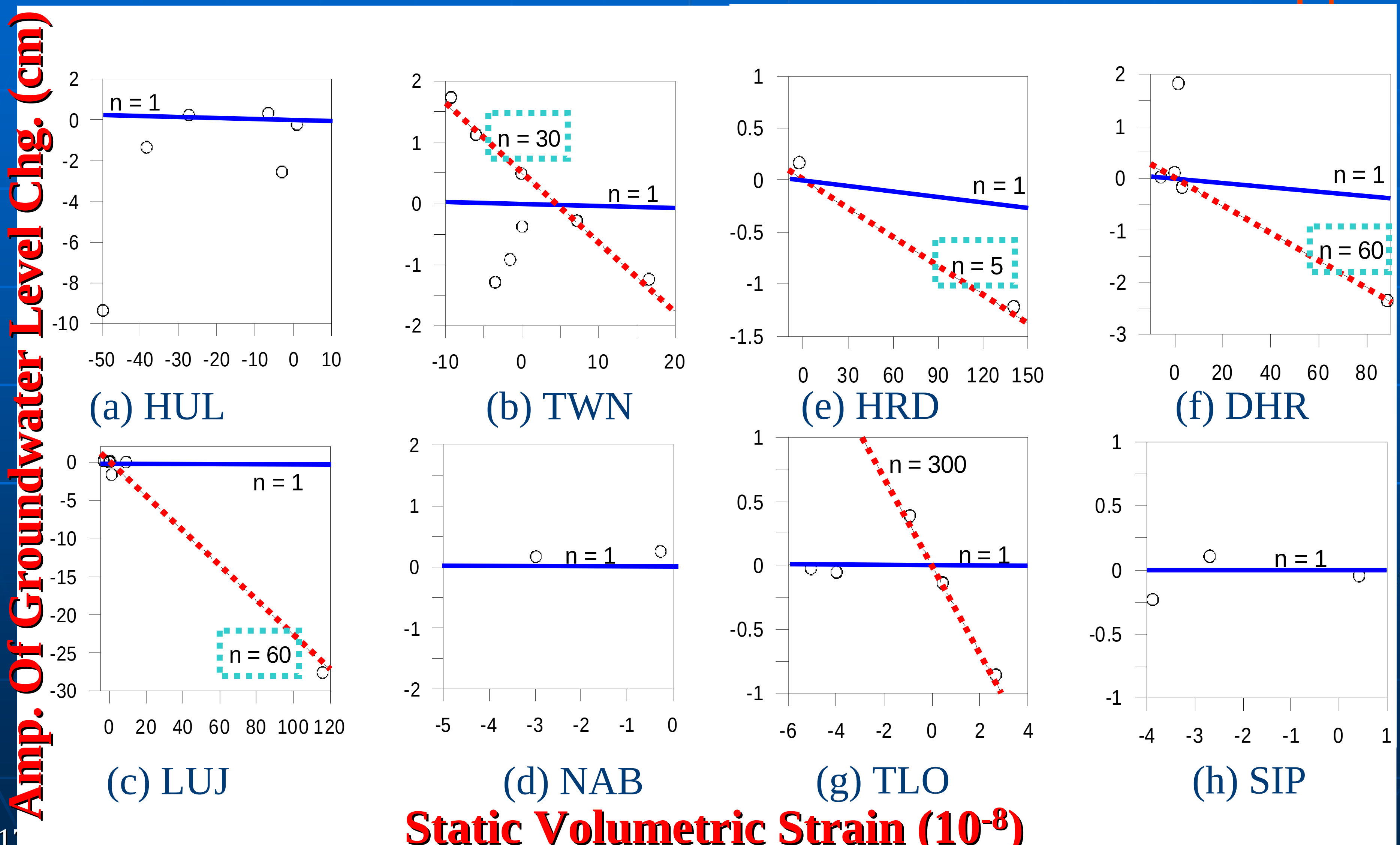
Amplitude



Phase Angle



Comparison of the theoretic and observed responses



Static Volumetric Strain Sensitivity

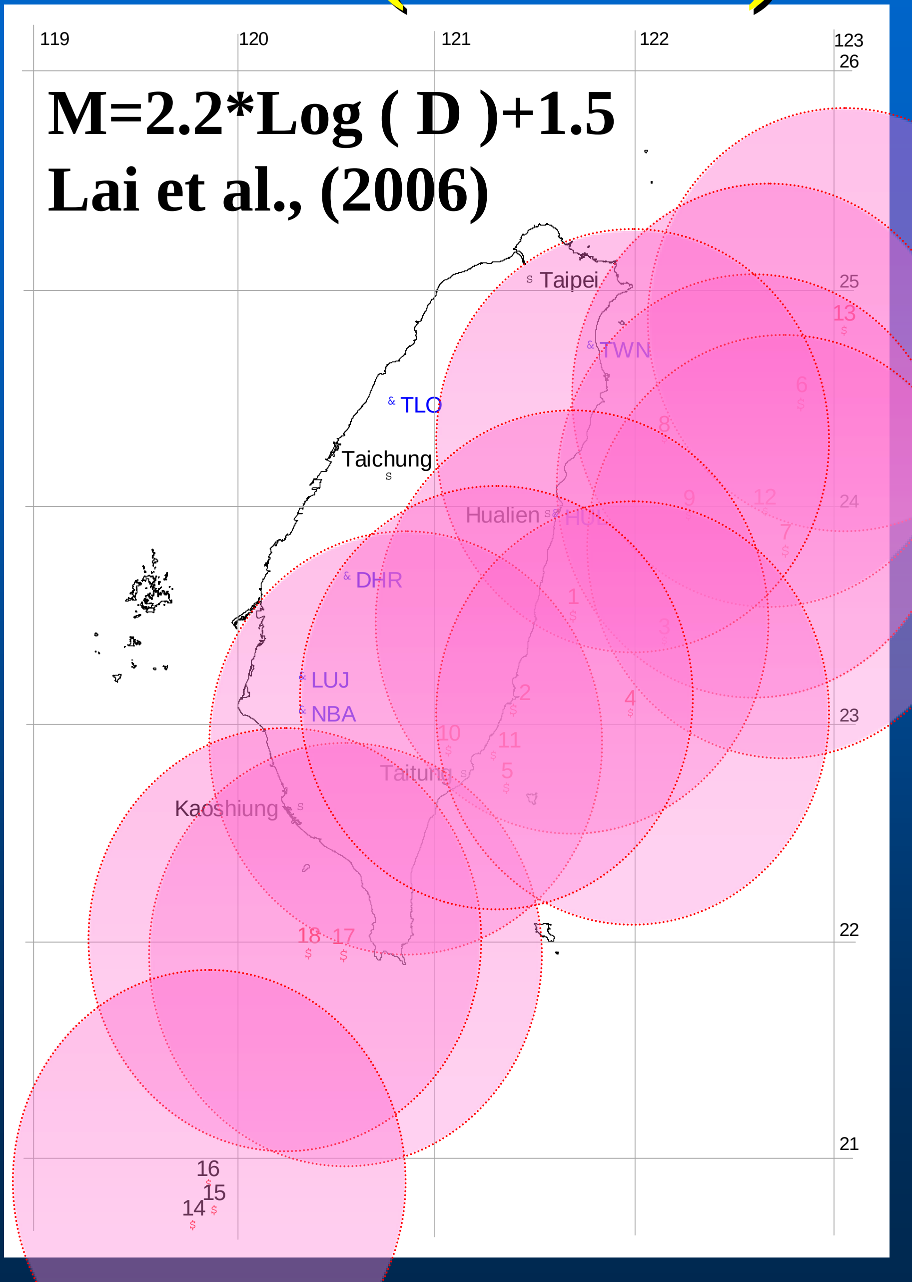
	TLO	DHR	LUJ	NBA	TWN	HUL
	Amplitude (10^{-8}) [Phase Shift (degree)]					
Vol. strain by M_2 earth tide, t_e	**1.35 [0]**	**1.37 [0]**	**1.38 [0]**	**1.38 [0]**	**1.35 [0]**	**1.37 [0]**
Vol. strain by M_2 oceanic tidal loading, t_o	**2.08 [-321]**	**0.18 [-276]**	**0.11 [-290]**	**0.11 [-301]**	**0.60 [-227]**	**6.10 [-184]**
Vol. strain by earth + oceanic tide, $t_t = t_e + t_o$	**3.25 [-336]**	**1.40 [-352]**	**1.42 [-356]**	**1.45 [-356]**	**1.04 [-335]**	**4.73 [-185]**
M_2 amplitude(water level, t_w)	**3.72±0.67 [-282±49]**	**6.17±0.60 [-339±23]**	**2.54±0.59 [-350±34]**	**4.24±0.29 [-349±15]**	**3.93±0.27 [-272±21]**	**23.77±0.50 [-21±6]**
Strain sens. by **Water Level** M_2 tide, $Ws = t_w/t_t$ (mm/10^{-8})	**1.14**	**4.39**	**1.78**	**2.92**	**3.78**	**5.02**
Strain sens. by **Coseismic Responses** (mm/10^{-8})	**18.42**	**42.22**	**76.15**	**56.93**	**43.85**	**25.82**

Problem statement

- Observed coseismic patterns can fit to strain model , but the amplitudes are amplify tens~hundreds times compare to the static strain sensitivity estimated from tidal response.
- Some wells seems always coseismic roses or coseismic lowering, them were not expected by the fault-dislocation volumetric strain .
- The mechanism of the coseismic groundwater level changes remains unknown.

Observed coseismic events (03'~06')

No.	Time	Lat.	Long.	Depth (km)	M_W
1	2003/6/10 8:40	23.50	121.70	27.59	**6.54**
2	2003/12/10 4:38	23.07	121.40	10	**6.6**
3	2004/2/4 3:24	23.38	122.15	4.07	**6.03**
4	2004/5/16 6:04	23.05	121.98	12.52	**6**
5	2004/5/19 7:04	22.71	121.37	8.68	**6.49**
6	2004/10/15 4:08	24.46	122.85	58.84	**7.03**
7	2004/11/8 15:54	23.79	122.76	10	**6.6**
8	2004/11/11 2:16	24.31	122.16	27.3	**6.04**
9	2005/9/6 9:16	23.96	122.28	16.8	**6.12**
10	2006/4/1 18:02	22.88	121.08	7.2	**6.35**
11	2006/4/16 6:40	22.86	121.3	17.9	**6.2**
12	2006/7/28 15:40	23.97	122.66	28	**6.06**
13	2006/8/28 1:11	24.8	123.07	135.3	**6.1**
14	2006/10/9 18:01	20.7	119.83	28	**6.1**
15	2006/10/9 19:08	20.77	119.93	8	**6.1**
16	2006/10/11 14:43	20.89	119.9	10	**6**
18	2006/12/26 20:34	21.95	120.39	47.03	**6.4**

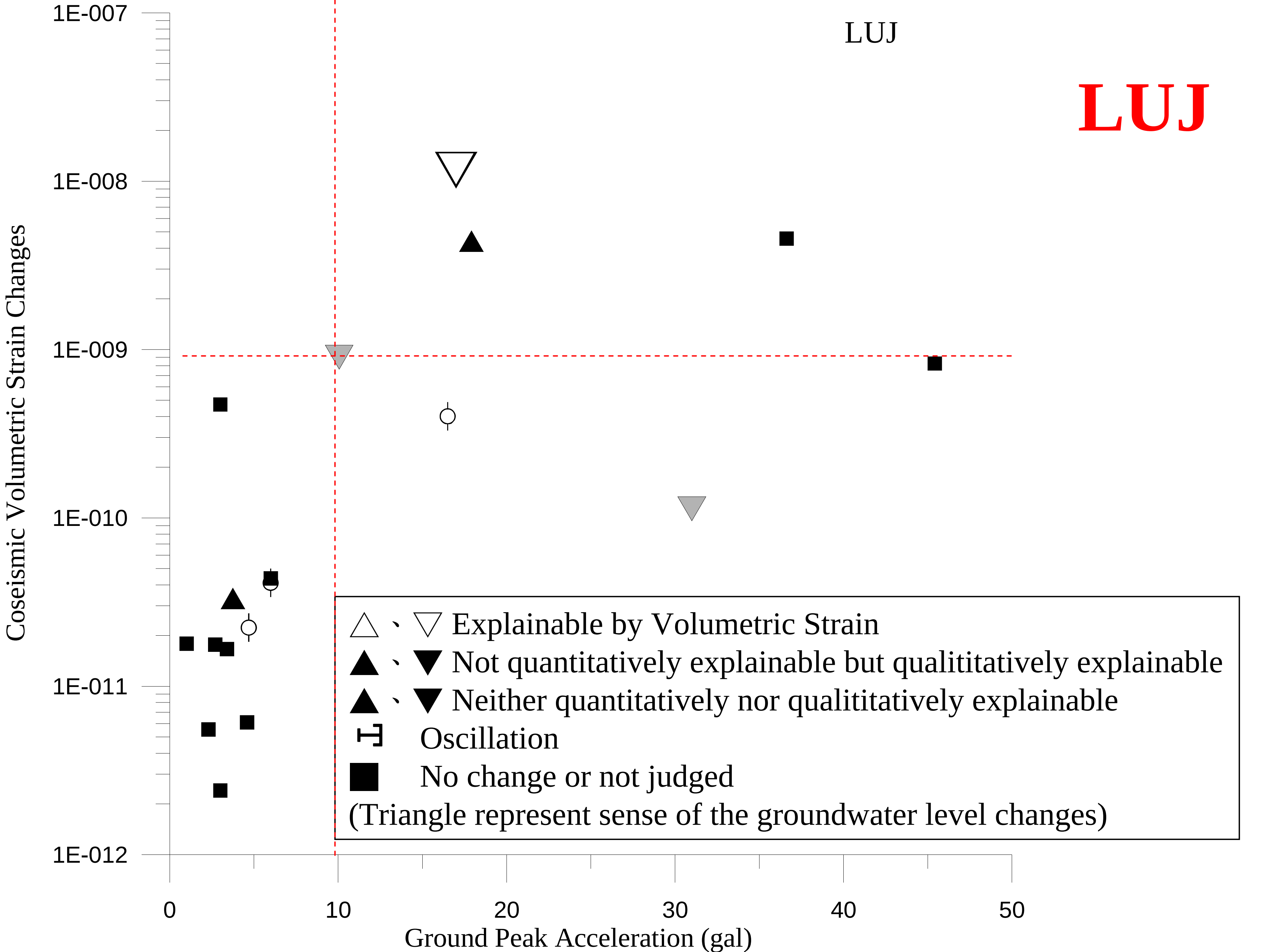


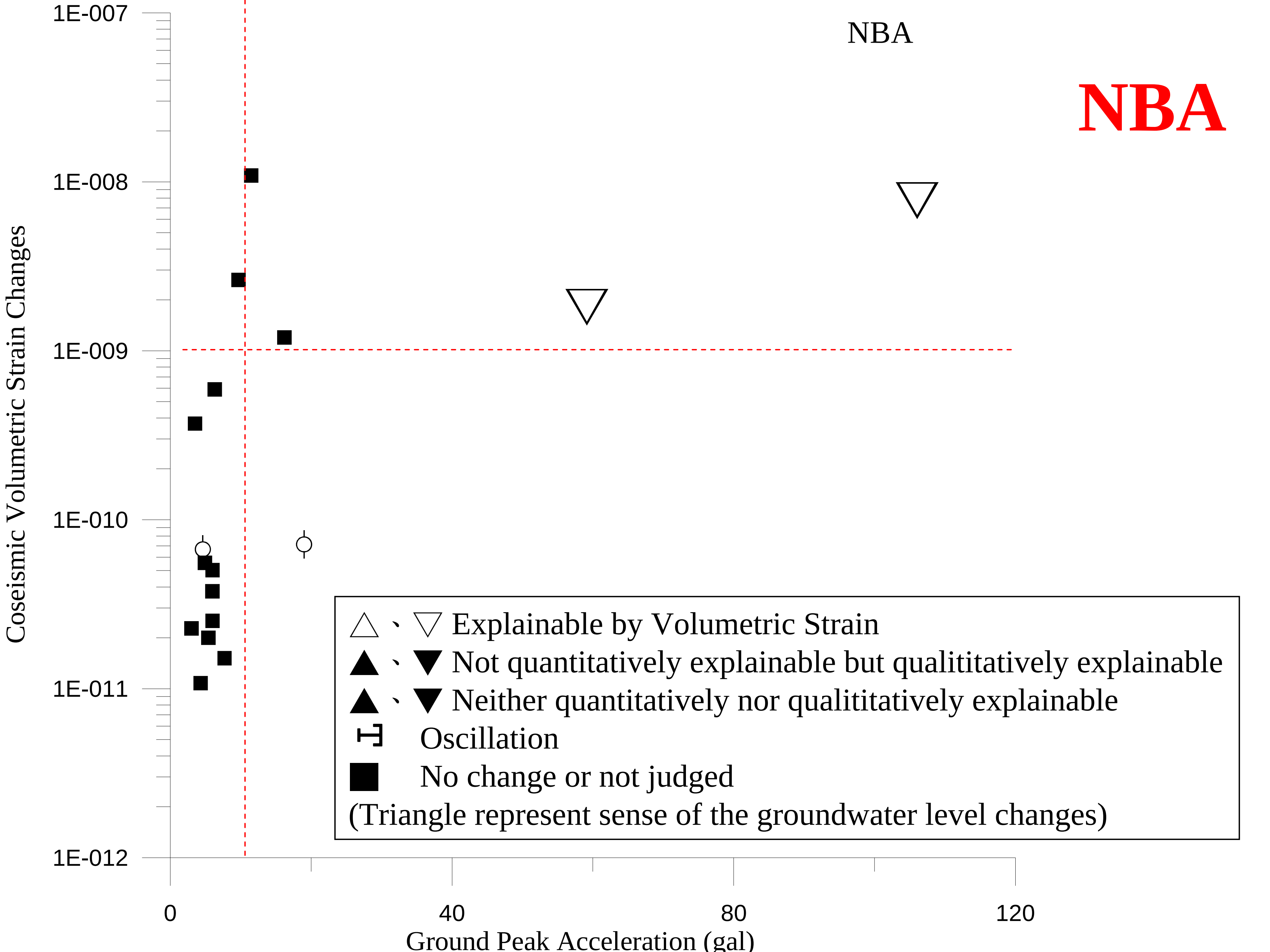
Observed coseismic events (03'~06')

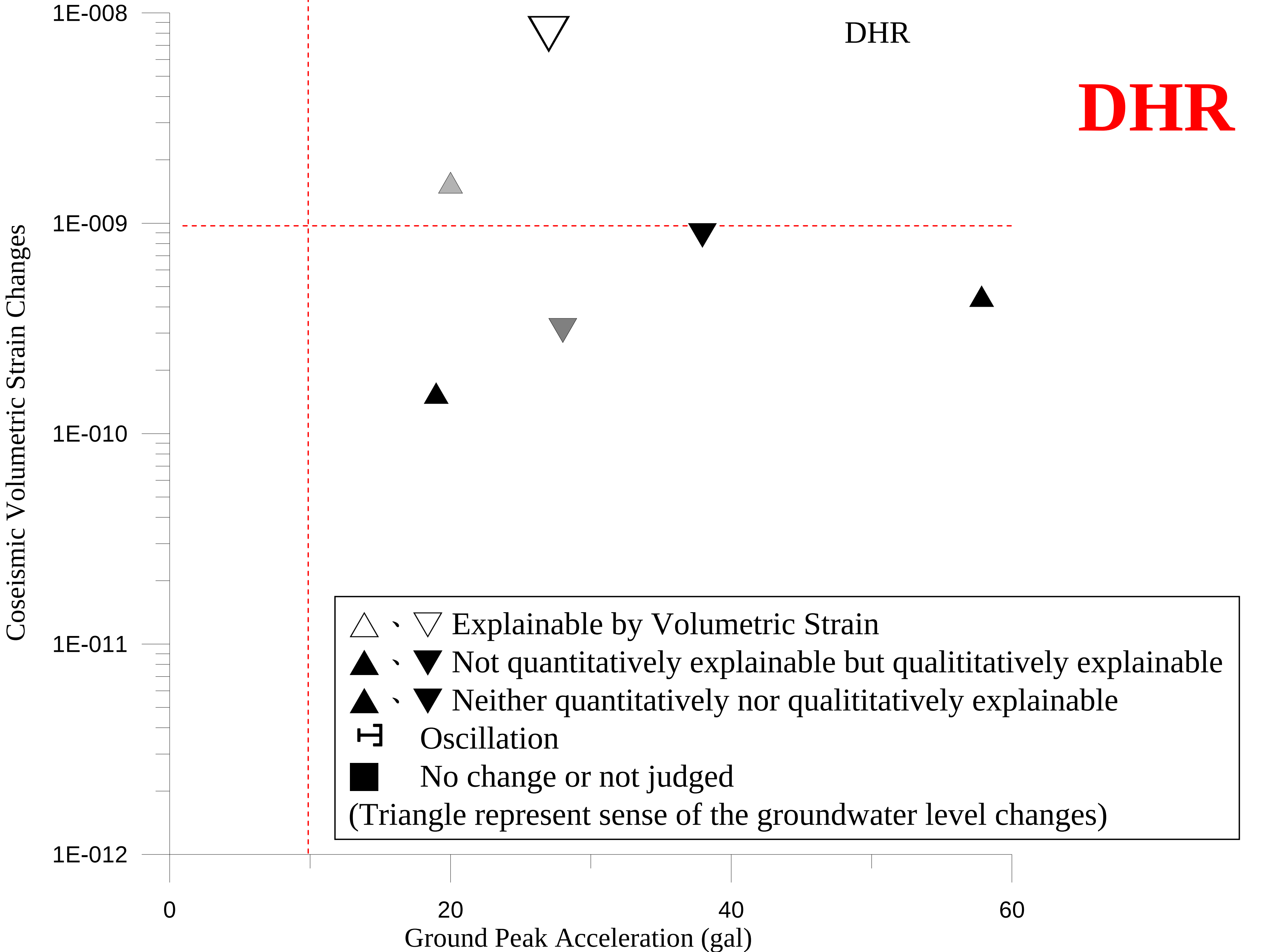
No.	LUJ					NBA					DHR				
	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)
1	-16.70	S	1.13E-10	-0.64	31	±3.51	O	7.15E-11	-0.24	20	-1.69	O+S	3.09E-10	-0.70	28
2	-275.66	S	1.16E-08	-65.32	17		N	1.09E-08	-37.32	11	-23.51	O+S	7.91E-09	-18.02	27
3		N	1.77E-11	-0.10	3		N	1.52E-11	-0.05	8		N	-2.77E-15	0.00	2
4	0.93	S	3.16E-11	-0.18	4		N	2.51E-11	-0.09	6		N	-1.02E-14	0.00	2
5	-0.51	S	9.01E-10	-5.06	10		N	1.20E-09	-4.11	16	18.23	S	1.50E-10	-0.34	19
6		O	-4.01E-10	2.25	17		N	-3.71E-10	1.27	4	0.28	S	-1.50E-09	3.42	20
7	±1.20	O	2.23E-11	-0.13	5	±1.50	O	6.68E-11	-0.23	5		N	5.54E-10	-1.26	10
8	±2.40	O	-4.11E-11	0.02	6		N	3.77E-11	-0.13	6		N	-3.36E-11	0.08	5
9		N	6.11E-12	-0.03	5		N	1.08E-11	-0.04	4		N	-1.78E-11	0.04	5
10	7.76	S+O	4.19E-09	-23.54	18		N	2.63E-09	-9.00	10		N	3.20E-09	-7.28	5
11		N	4.71E-10	-2.65	3		N	5.91E-10	-2.02	6		N	7.79E-11	-0.18	7
12		N	-2.40E-12	0.01	3		N	-7.51E-13	0.00	2		N	-9.82E-12	0.02	5
13		N	5.54E-12	-0.03	2		N	5.56E-11	-0.20	5		N	-9.12E-12	0.02	4
14		N	4.38E-11	-0.25	6		N	5.04E-11	-0.17	7		N	2.12E-11	-0.05	4
15		N	-1.66E-11	0.09	3		N	-2.00E-11	0.07	5		N	-8.93E-12	0.02	2
16		N	-1.79E-11	0.10	2		N	-2.27E-11	0.08	4		N	-1.12E-11	0.03	2
17		N	8.25E-10	-4.64	45	-12.23	O+S	1.81E-09	-6.21	59	±27.13	O	-8.75E-10	1.99	38
18		N	4.55E-09	-25.56	37	-25.75	O+S	7.74E-09	-26.52	106	±15.29	O	4.33E-10	-0.99	58

Observed coseismic events (03'~06')

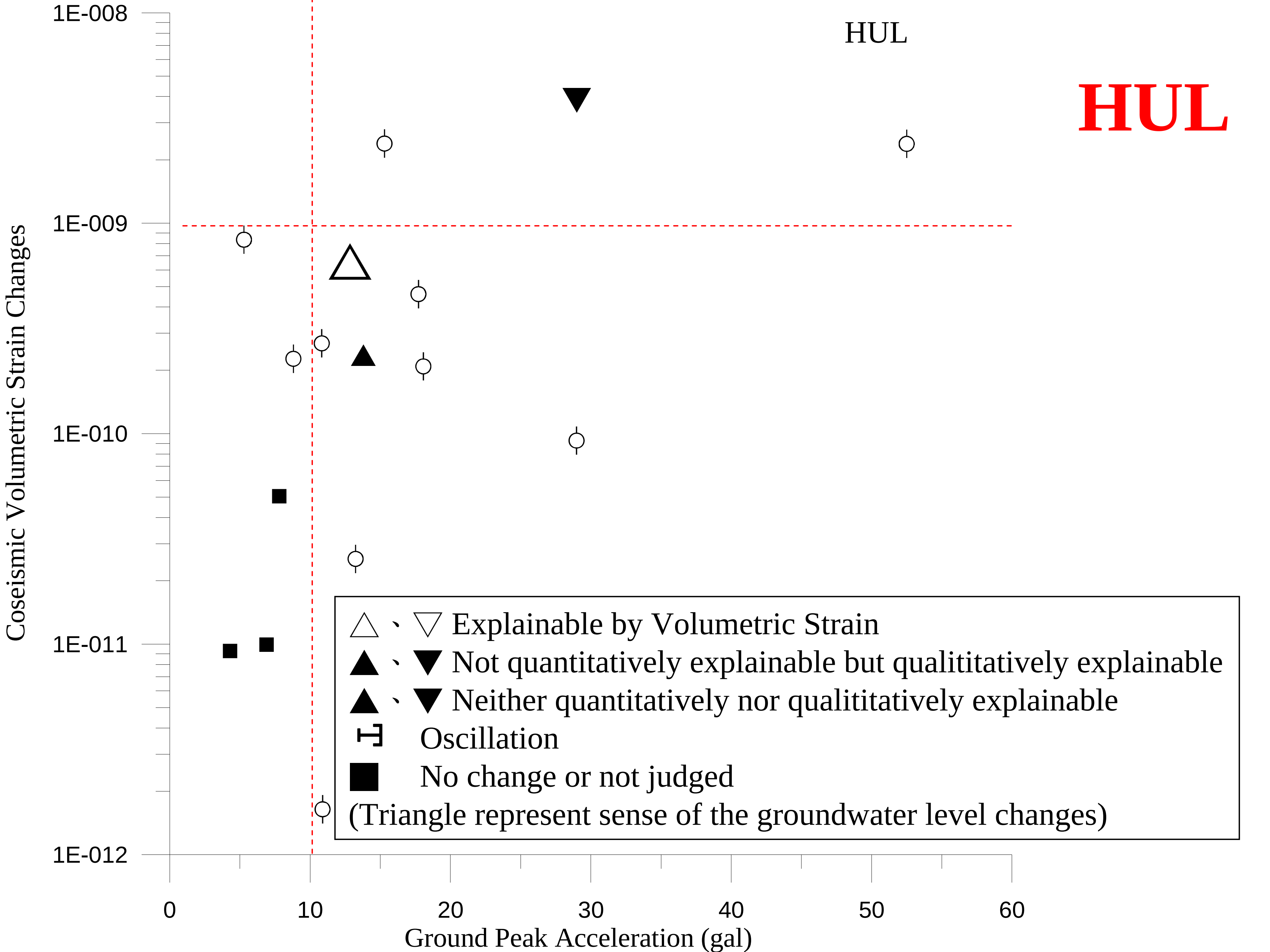
No.	HUL					TWN					TLO				
	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)
1	-					-					-				
2	-13.47	O+S	-3.84E-09	7.65	29	11.24	O+S	-5.98E-10	1.58	6	-8.57	O+S	2.66E-10	-2.33	11
3	±2.36	O	9.28E-11	-0.18	29	4.92	O	-5.41E-12	0.01	6	±4.794	O	1.26E-11	-0.11	4
4	±3.60	O	2.54E-11	-0.05	13		N	-1.06E-11	0.03	8		N	1.92E-11	-0.17	3
5	3.20	S	-6.58E-10	1.31	13	-9.16	O+S	-1.51E-10	0.40	4	3.88	S	-9.30E-11	0.82	7
6	±0.04	O	-2.38E-09	4.75	53	-12.86	O+S	-3.47E-10	0.92	70	-0.23	O+S	-5.05E-10	4.43	23
7	2.39	S	2.27E-10	-0.45	14	15.92	O+S	-9.76E-10	2.58	38	±1.38	O	-2.04E-11	0.18	9
8	±2.21	O	-2.27E-10	0.45	9	-12.28	S	4.76E-10	-1.26	14		N	-7.04E-12	0.06	3
9	±16.03	O	2.09E-10	-0.42	18	-5.73	S	2.09E-10	-0.55	12		N	-6.67E-11	0.58	7
10	±11.88	O	-8.35E-10	1.66	5	-6.96	S	-1.46E-10	0.39	5		N	3.34E-10	-2.92	9
11	±18.57	O	-2.69E-10	0.54	11	-5.77	S+O	-5.09E-11	0.13	4		N	-3.88E-11	0.34	8
12		N	-5.05E-11	0.10	8	-19.56	S	1.72E-11	-0.05	31		N	-1.90E-11	0.17	3
13	±8.1	O	-1.64E-12	0.00	11		N	-6.71E-12	0.02	4		N	-2.14E-11	0.18	8
14		N	9.29E-12	-0.02	4		N	-2.68E-12	0.01	2		N	-3.19E-12	0.03	6
15		N	-1.30E-12	0.00	4		N	-1.15E-12	0.00	2		N	-4.11E-12	0.04	9
16		N	-9.94E-12	0.02	7		N	-5.06E-12	0.01	4		N	-5.21E-12	0.05	6
17	±15.76	O	-2.39E-09	4.76	15	-2.14	S	-9.60E-10	2.54	6		N	-5.61E-10	4.92	12
18	±5.3	O	-4.61E-10	0.92	18	-6.86	S	-3.13E-10	0.83	7		N	-2.84E-10	2.49	9


LUJ
LUJ
Coseismic Volumetric Strain Changes
1E-007
1E-008
1E-009
1E-010
1E-011
1E-012
0
10
20
30
40
50
Ground Peak Acceleration (gal)
△ 、▽ Explainable by Volumetric Strain
▲ 、▼ Not quantitatively explainable but qualititatively explainable
▲ 、▼ Neither quantitatively nor qualititatively explainable
Oscillation
No change or not judged
(Triangle represent sense of the groundwater level changes)

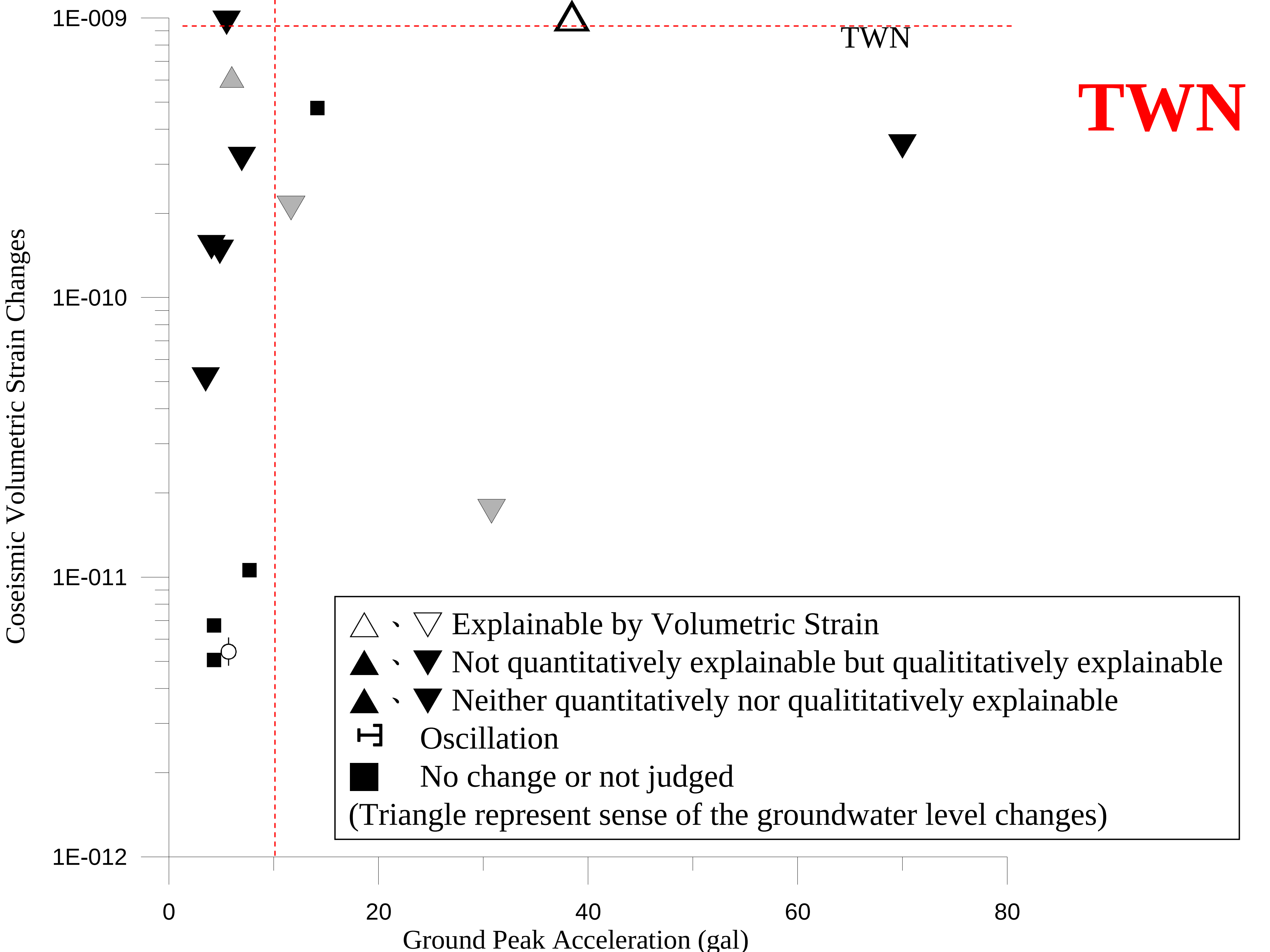

NBA
NBA
1E-007
1E-008
1E-009
1E-010
1E-011
1E-012
Coseismic Volumetric Strain Changes
0
40
80
120
Ground Peak Acceleration (gal)
△ 、▽ Explainable by Volumetric Strain
▲ 、▼ Not quantitatively explainable but qualititatively explainable
▲ 、▼ Neither quantitatively nor qualititatively explainable
Oscillation
No change or not judged
(Triangle represent sense of the groundwater level changes)



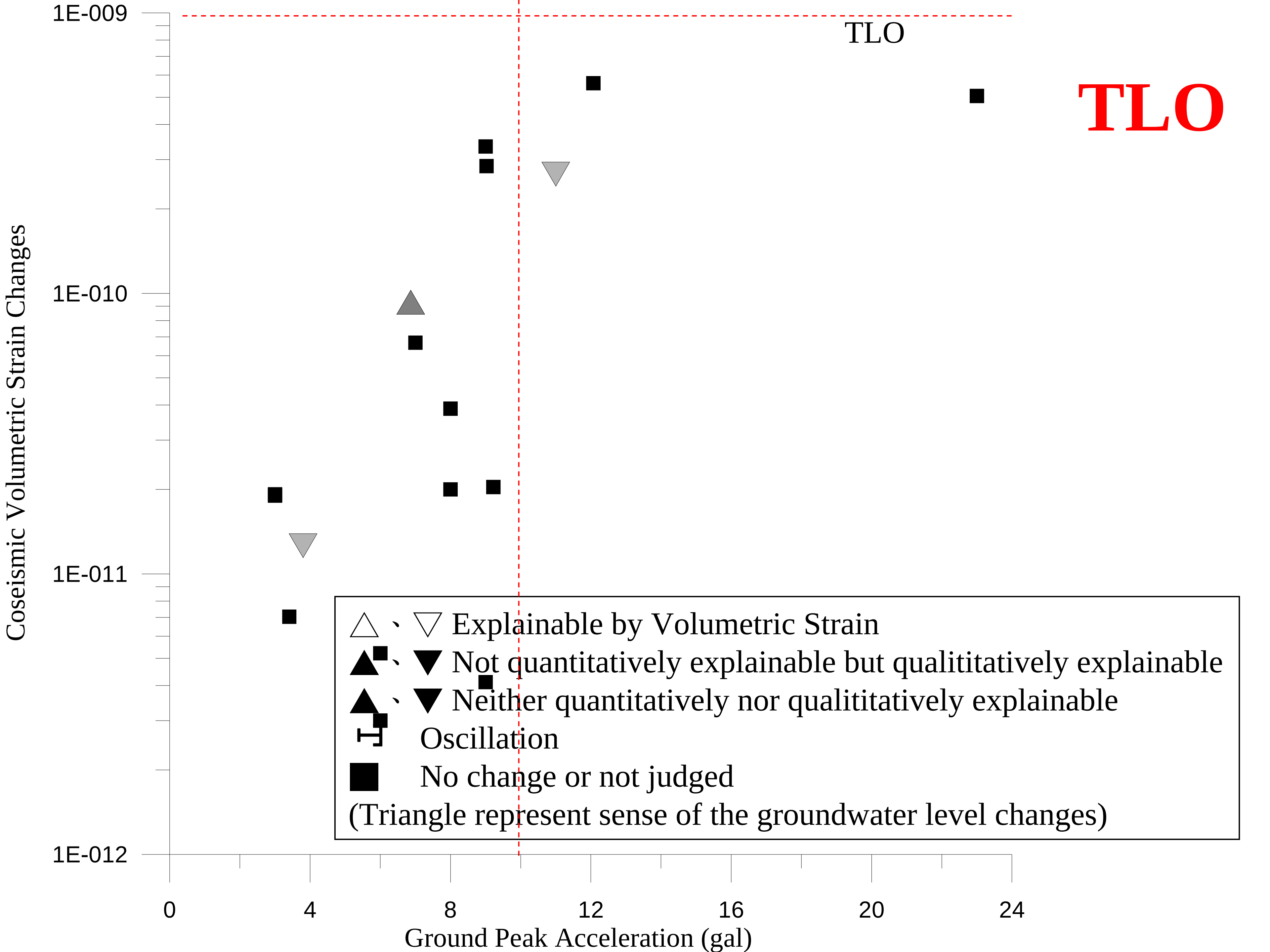
DHR
DHR
1E-008
1E-009
1E-010
1E-011
1E-012
0
20
40
60
Coseismic Volumetric Strain Changes
Ground Peak Acceleration (gal)
△ 、▽ Explainable by Volumetric Strain
▲ 、▼ Not quantitatively explainable but qualititatively explainable
▲ 、▼ Neither quantitatively nor qualititatively explainable
Oscillation
No change or not judged
(Triangle represent sense of the groundwater level changes)



HUL
HUL
1E-008
1E-009
1E-010
1E-011
1E-012
Coseismic Volumetric Strain Changes
0
10
20
30
40
50
60
Ground Peak Acceleration (gal)
△ 、▽ Explainable by Volumetric Strain
▲ 、▼ Not quantitatively explainable but qualititatively explainable
▲ 、▼ Neither quantitatively nor qualititatively explainable
Oscillation
No change or not judged
(Triangle represent sense of the groundwater level changes)

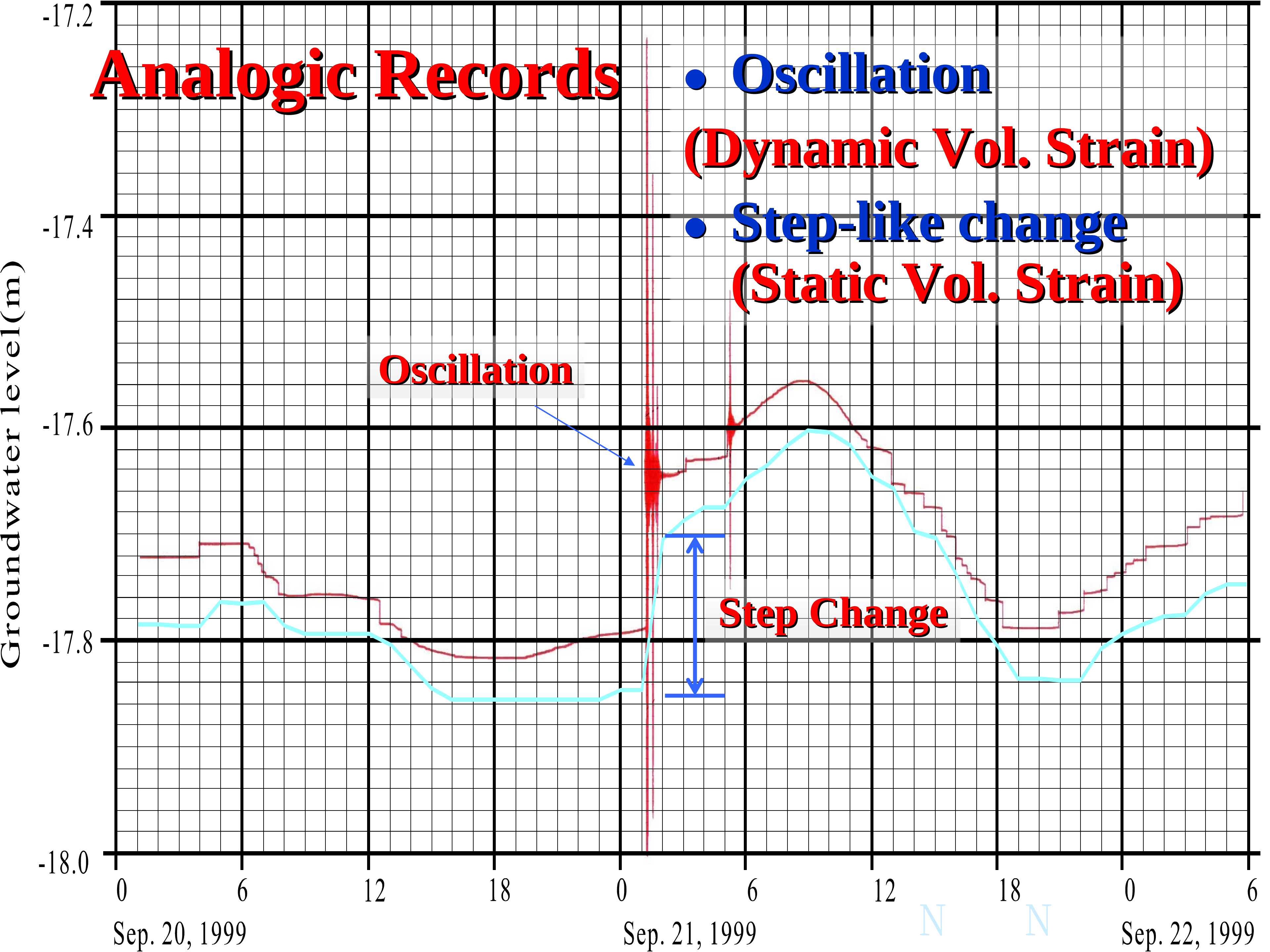


1E-009
1E-010
1E-011
1E-012
Coseismic Volumetric Strain Changes
0
20
40
60
80
Ground Peak Acceleration (gal)
TWN
TWN
△ 、▽ Explainable by Volumetric Strain
▲ 、▼ Not quantitatively explainable but qualititatively explainable
▲ 、▼ Neither quantitatively nor qualititatively explainable
Oscillation
No change or not judged
(Triangle represent sense of the groundwater level changes)


1E-009
1E-010
1E-011
1E-012
Coseismic Volumetric Strain Changes
0
4
8
12
16
20
24
Ground Peak Acceleration (gal)
TLO
TLO
△ 、▽ Explainable by Volumetric Strain
▲ 、▼ Not quantitatively explainable but qualititatively explainable
▲ 、▼ Neither quantitatively nor qualititatively explainable
Oscillation
No change or not judged
(Triangle represent sense of the groundwater level changes)

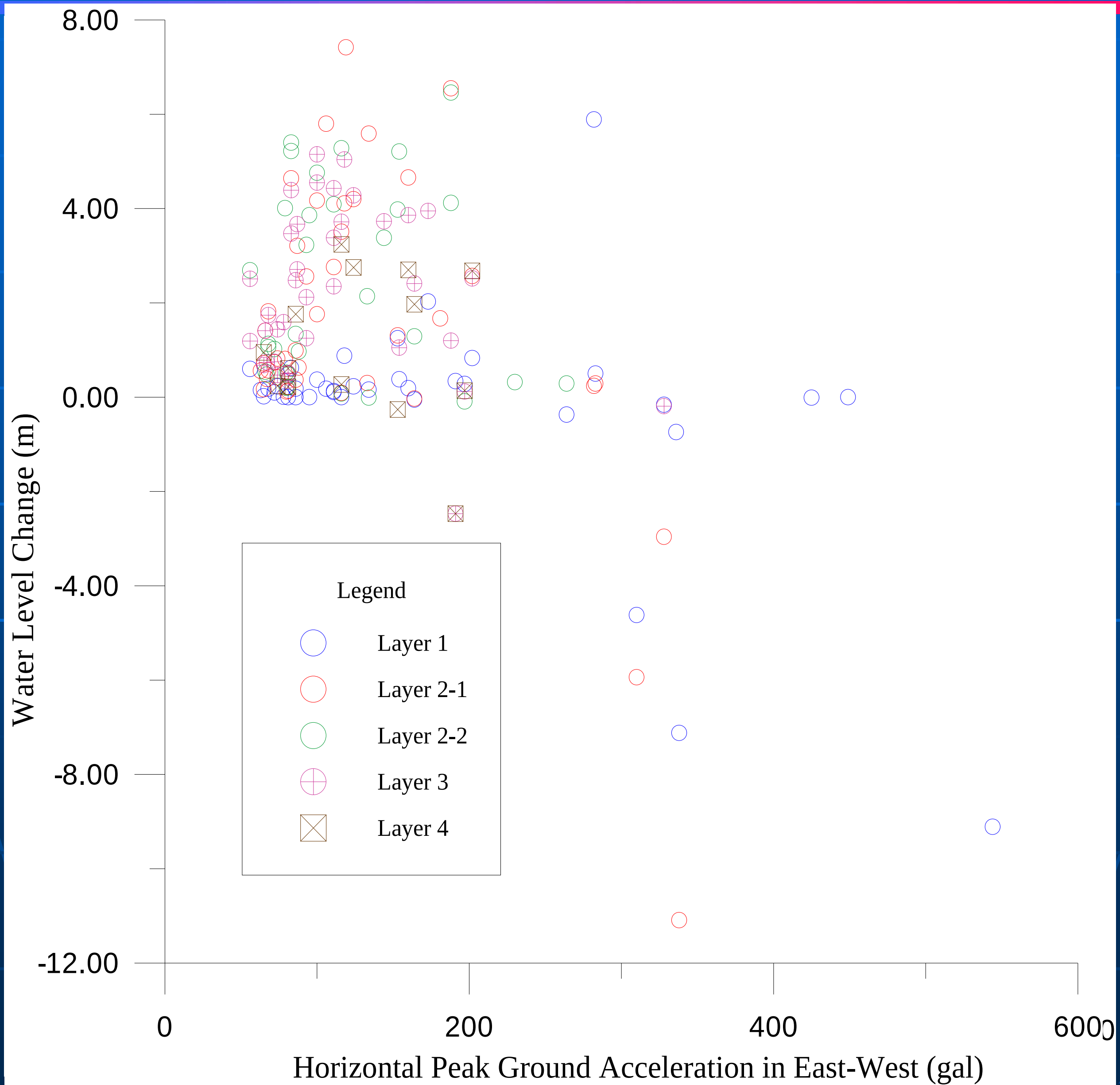
Discussion

- Unusual large increasing of pressure head in deeper (> 100 m) aquifers during 1999 Chi-Chi Earthquake.
- Mechanism of the coseismic groundwater level changes in 1999 Chi-Chi Earthquake.
- Observation of coseismic groundwater level changes in 2008/5/12 Wenchuan, China Earthquake



Analogic Records
• Oscillation
(Dynamic Vol. Strain)
• Step-like change
(Static Vol. Strain)
Oscillation
Step Change
Groundwater level(m)
-17.2
-17.4
-17.6
-17.8
-18.0
0
6
12
18
0
6
12
18
0
6
Sep. 20, 1999
Sep. 21, 1999
Sep. 22, 1999

Peak ground acceleration and coseismic groundwater level changes

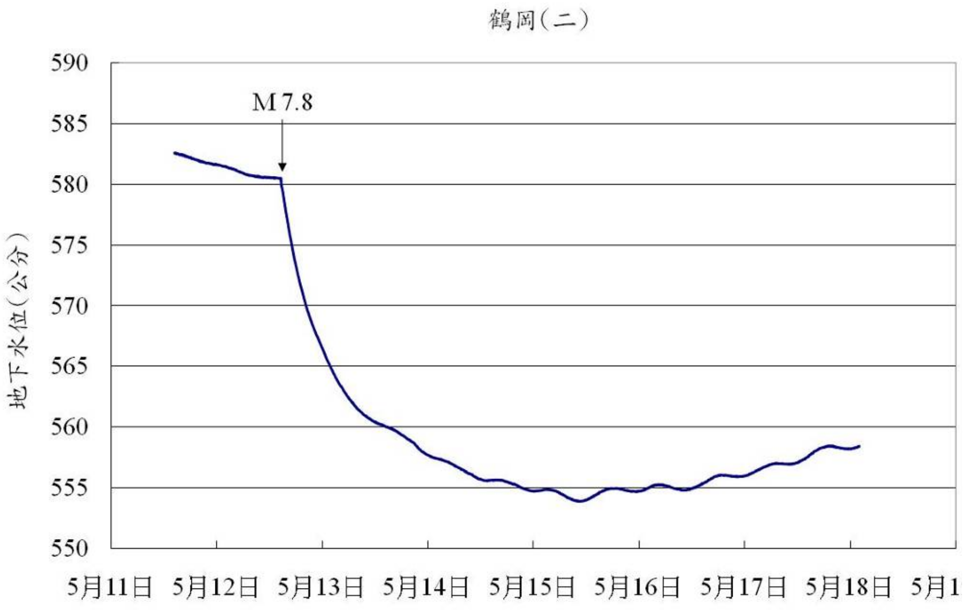


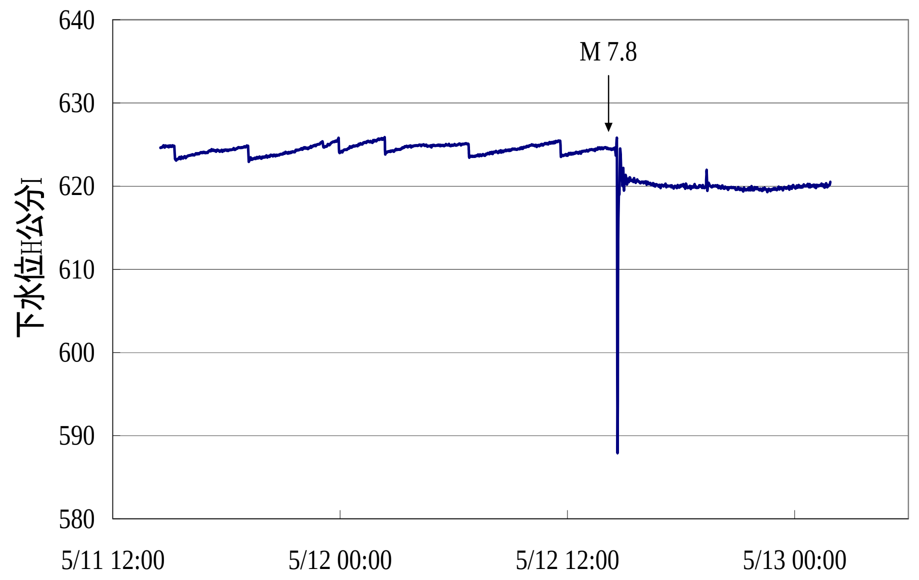
Mechanism of the persistent changes after the dynamic strain

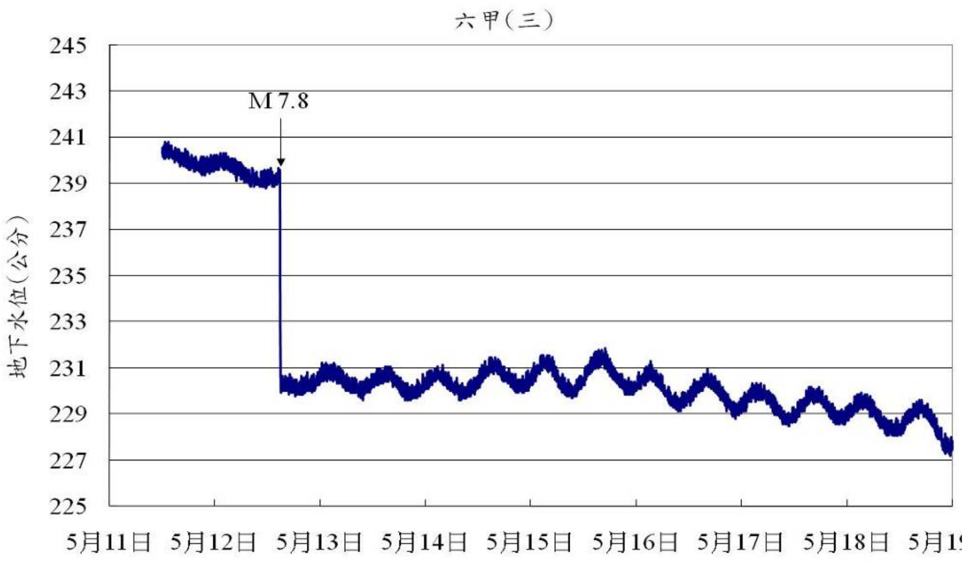
DP RC

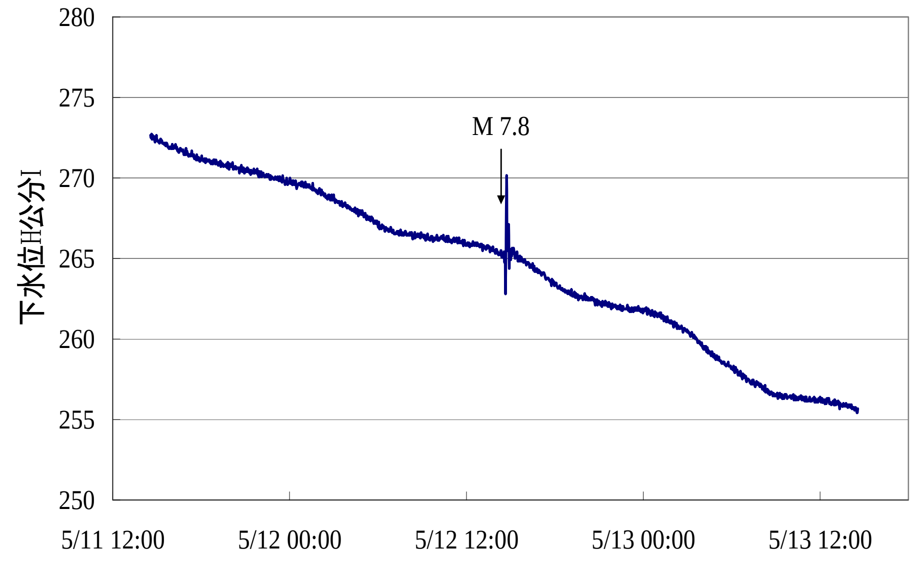
- **Cleaning of fracture-filled** oscillatory flow back and forth in fractures caused by cyclic strain removes “barriers” of fracture-blocking deposits then increases permeability and affects the final distribution of pore pressure (Brodsky et al. 2003).
- **Liquefaction /pore-pressure build up** (Wang et al., 2003 Lai, Koizumi et al., 2004)
- **Shaking-induced dilatency** (Bower and Heaton 1978)
- **Seismically-induced growth /decrease of bubbles** (e.g., Linde et al. 1994 Matsumoto and Roeloff, 2005)

2008/5/12 Wenchuan, China Earthquake (M_L 8.0)

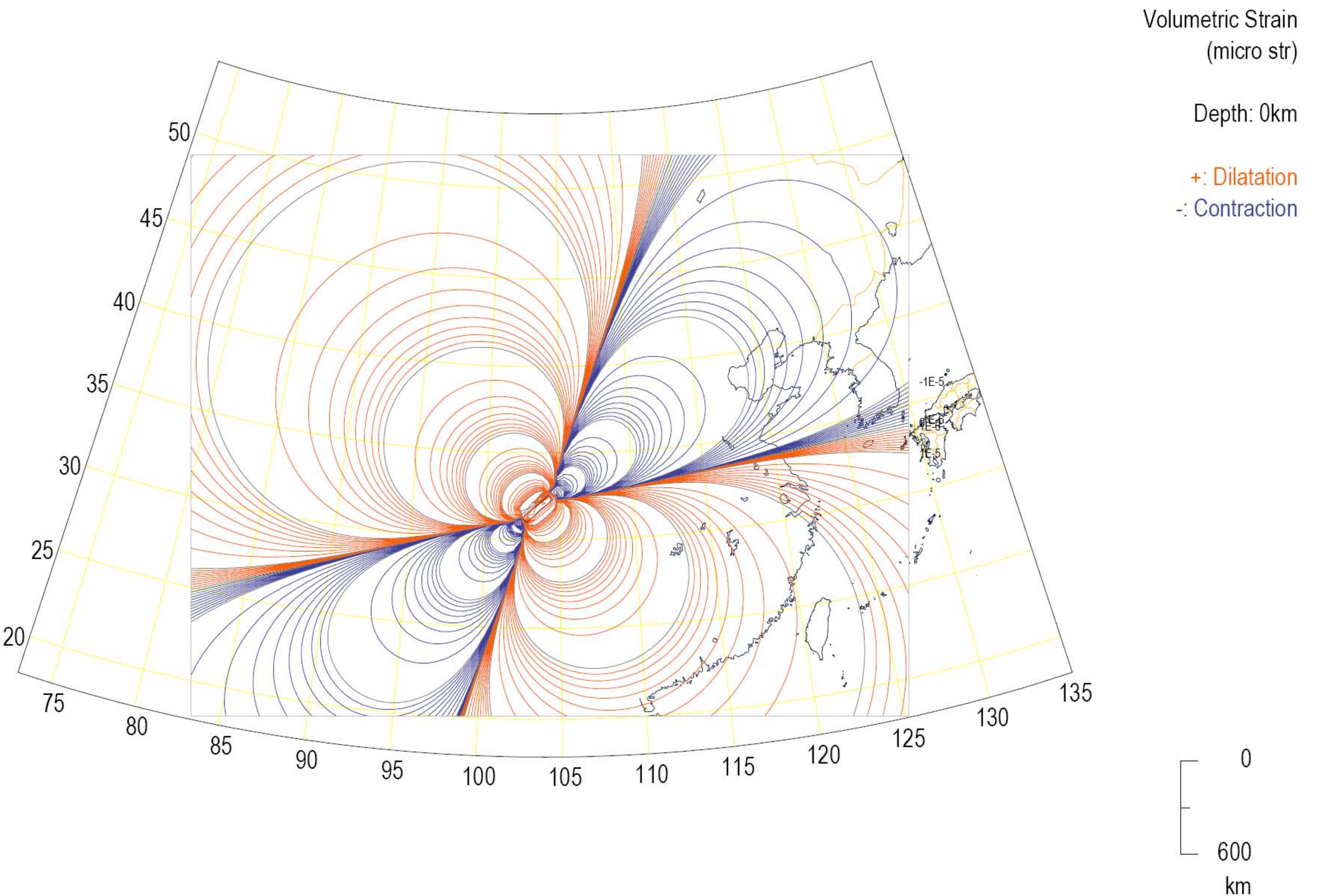




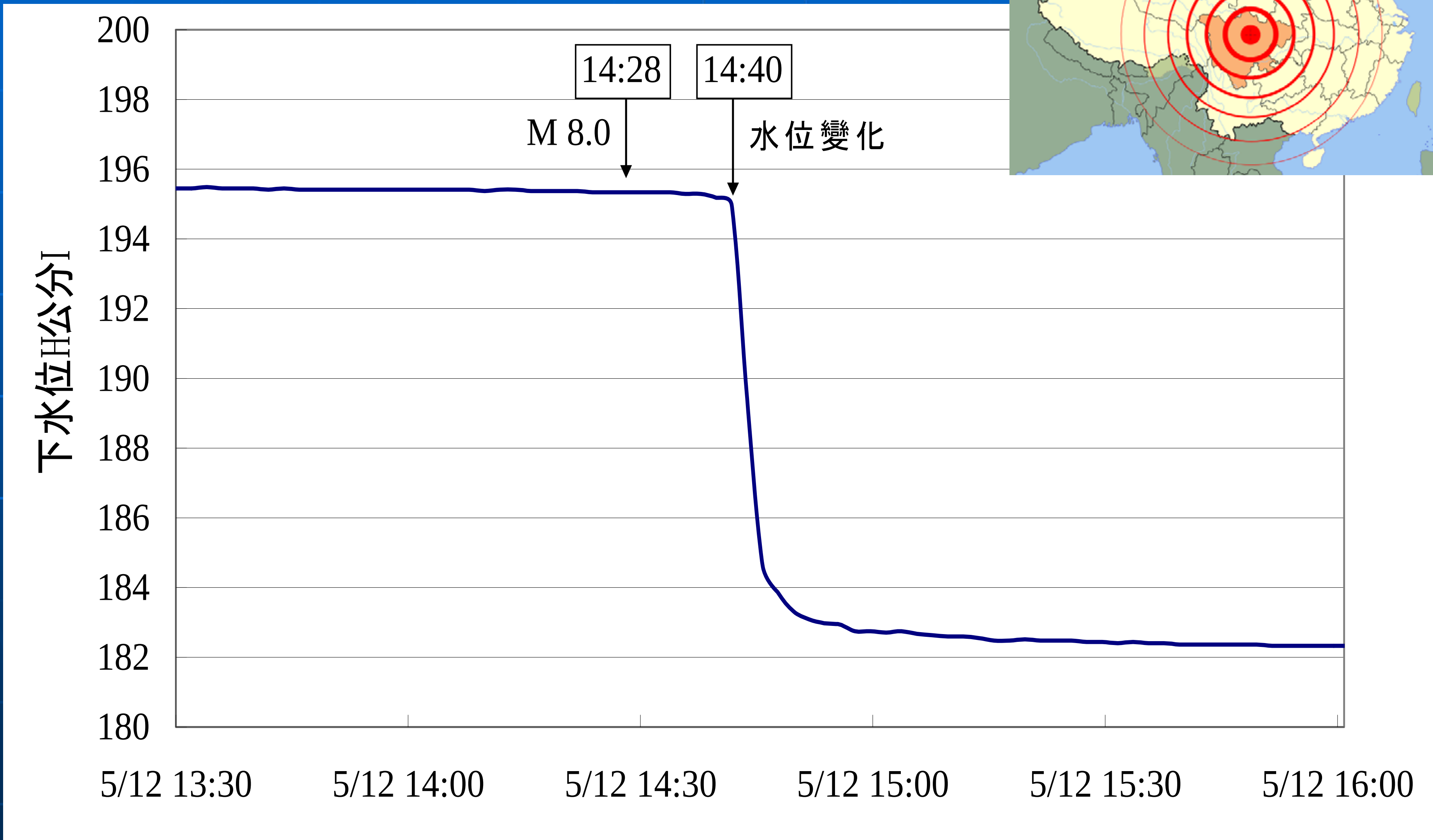


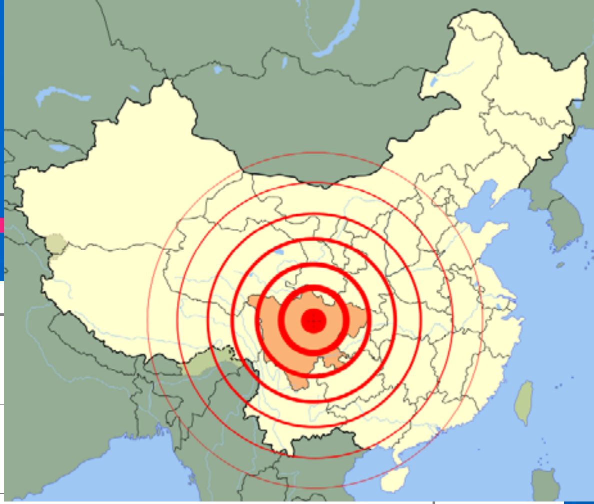


2008/5/12 Wenchuan, China Earthquake (M_L 8.0)

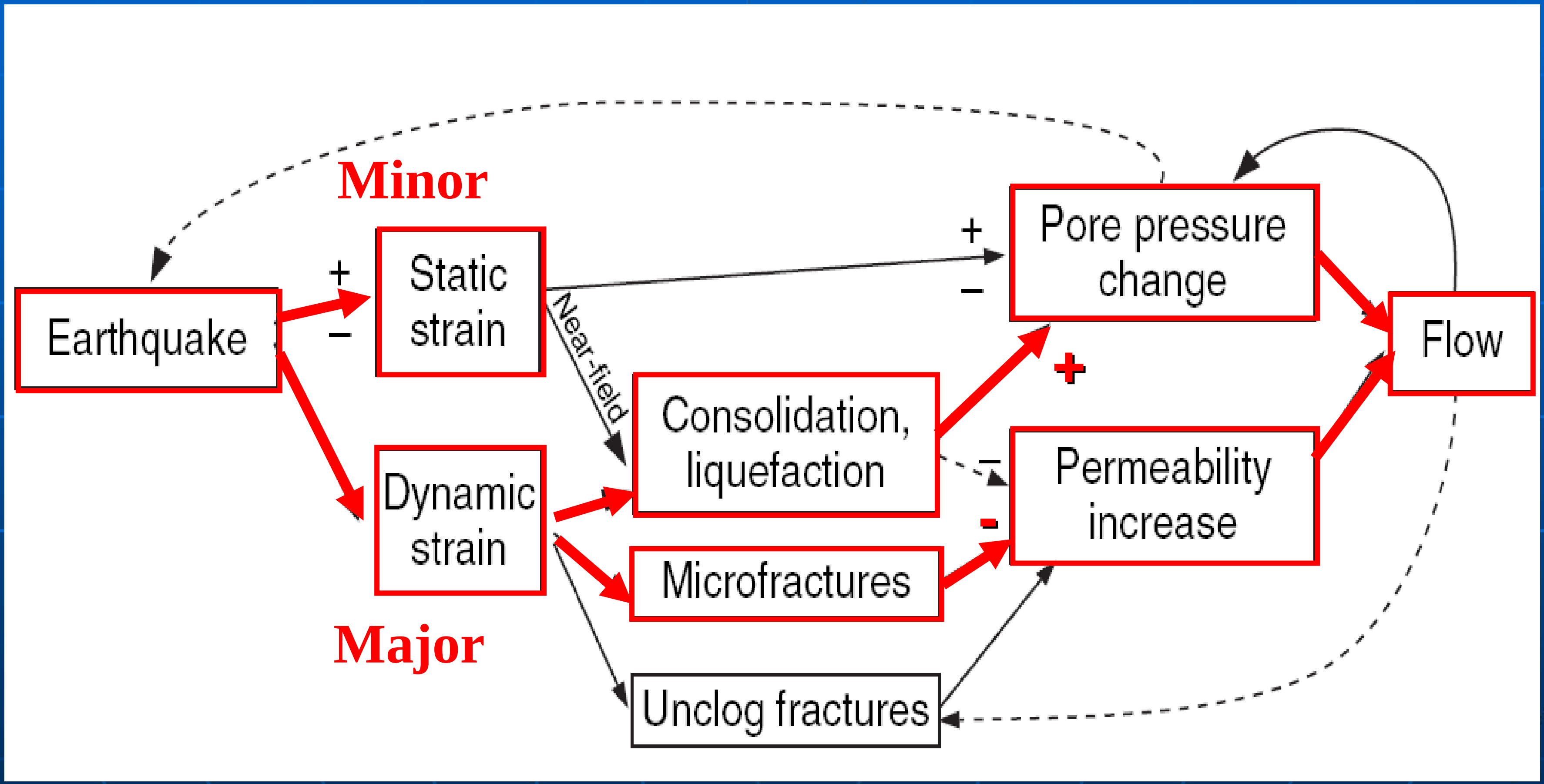


2008/5/12 Wenchuan, China Earthquake (M_L 8.0)





Mechanism of coseismic groundwater level changes



M. Manga and C.-Y. Wang (2007)

Conclusion

DP RC

- The results show that the dynamic strains induced by ground shaking could be another possible factor for the coseismic groundwater level changes.
- It seems to appear especially in shallow aquifers with high hydraulic conductivity in lose-cemented and permeable sedimentary deposits.
- The similar effects can also be recognized in the coseismic groundwater level changes related to the 1999 Chi-Chi earthquake and 2004 Wenchuan earthquake .

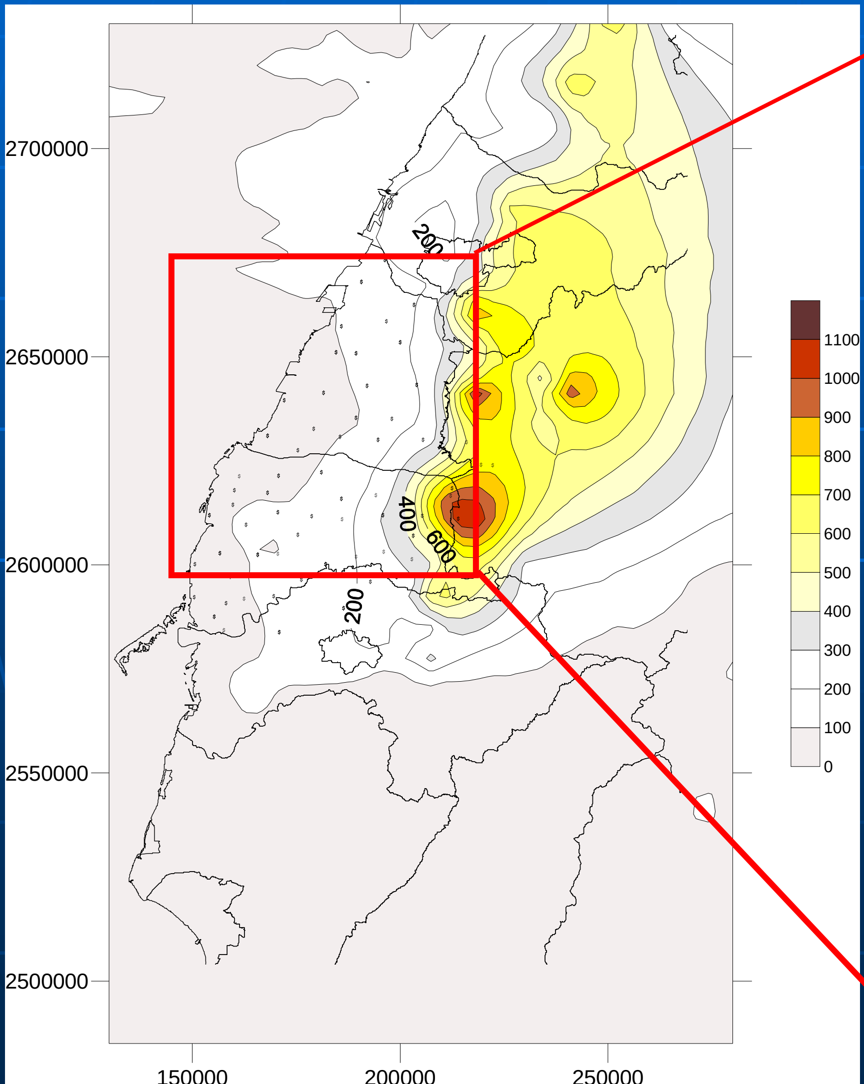
Disaster Prevention Research Center,
National Cheng Kung University, Taiwan

Tectono-Hydrology Research Group
AIST The National Institute of Advanced Industrial Science and Technology
Geological Survey of Japan

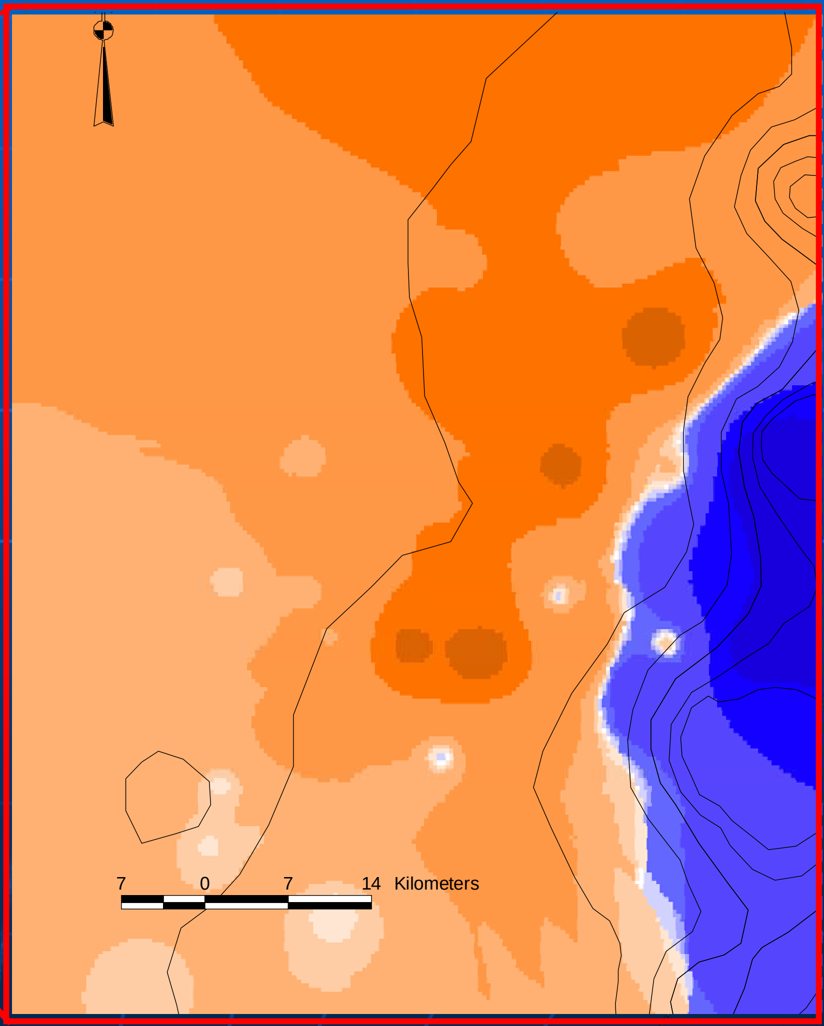
Thank you !

Coseismic groundwater level changes in 1999 Chi-Chi earthquake

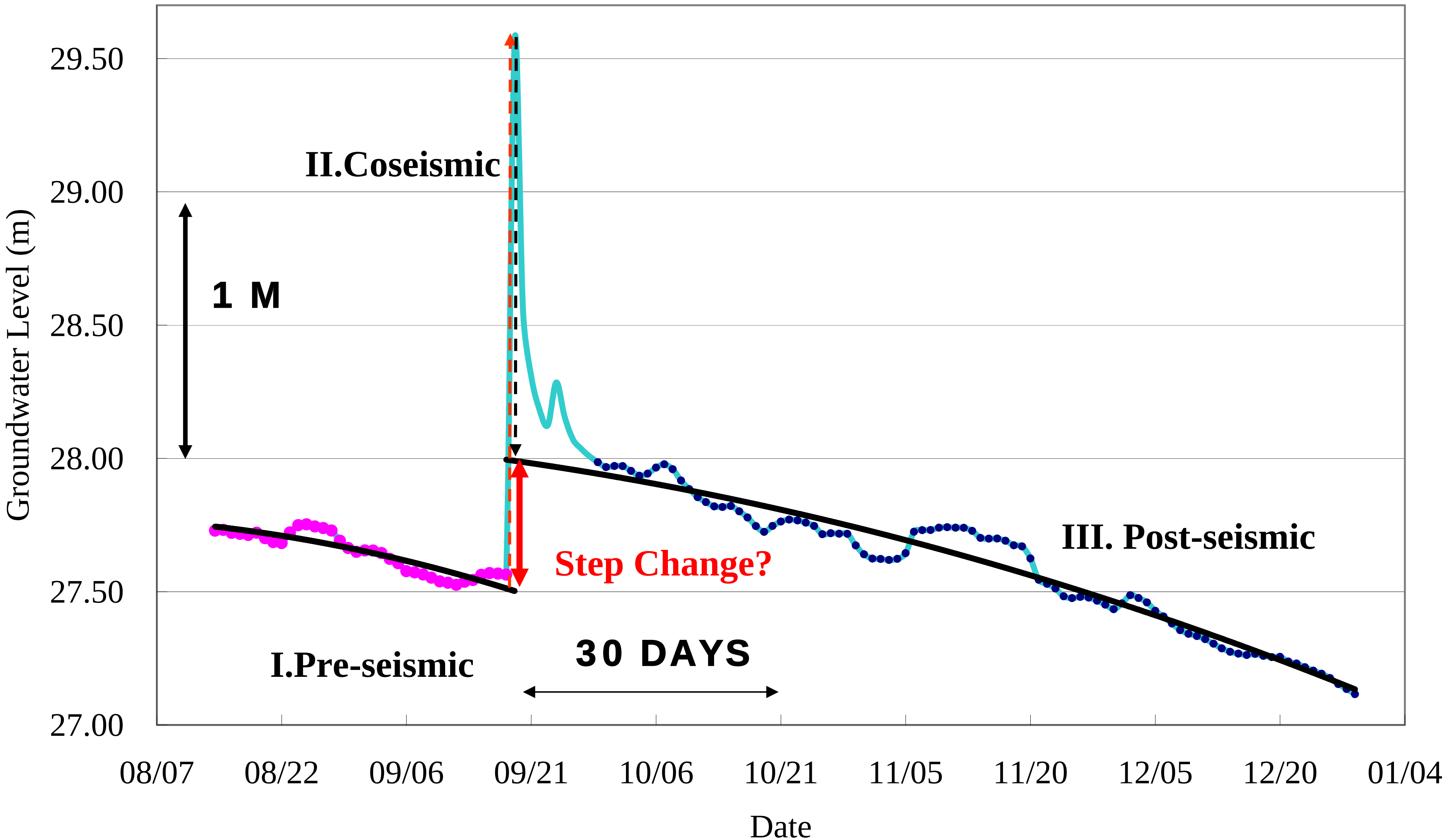
- PGA_H



Coseismic GWL Changes



Groundwater Changes in Fan Area



Groundwater Changes in Slope Area