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

Evaluation of the dynamic and static effects on earthquake-induced groundwater level changes in Taiwan

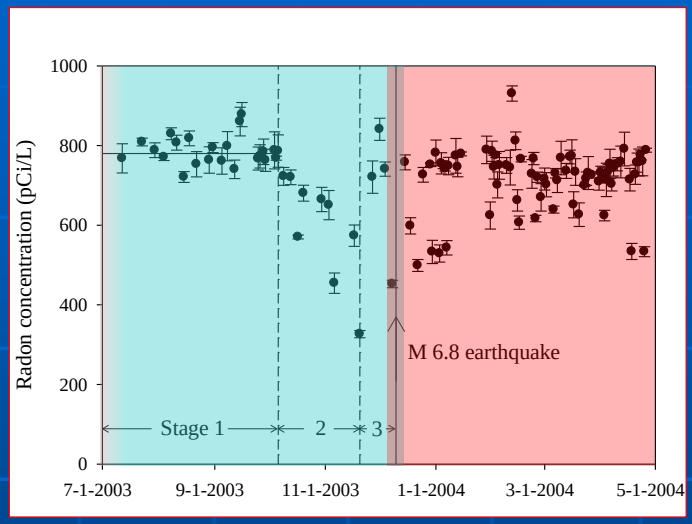
Wen-Chi Lai[1,2], Chjeng-Lun Shieh[1,3], Kuo-Chin Hsu[2],

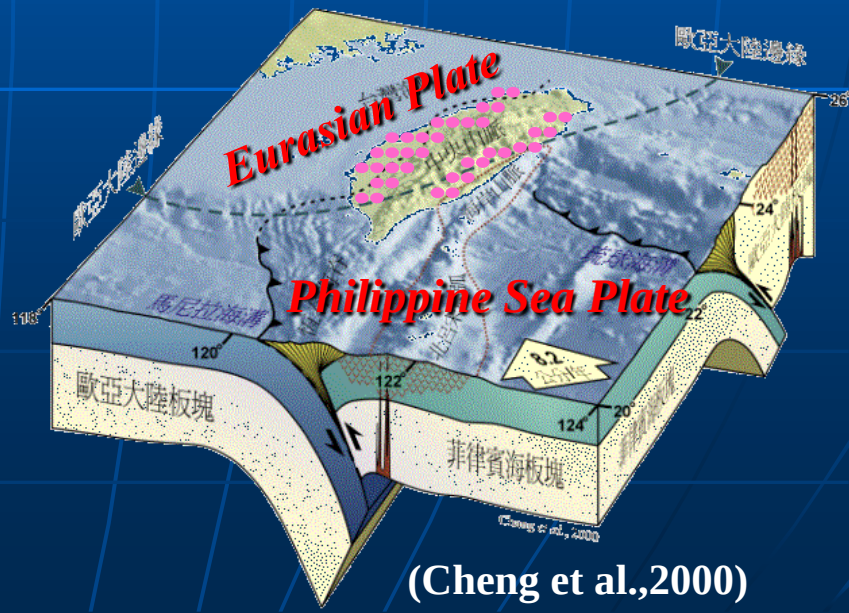
Norio Matsumoto [4], Naoji Koizumi [4]

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.
  - On-land plate boundary
  - Highly deformation rate
  - Active fault in thick alluvial layers
- 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





(Cheng et al.,2000)

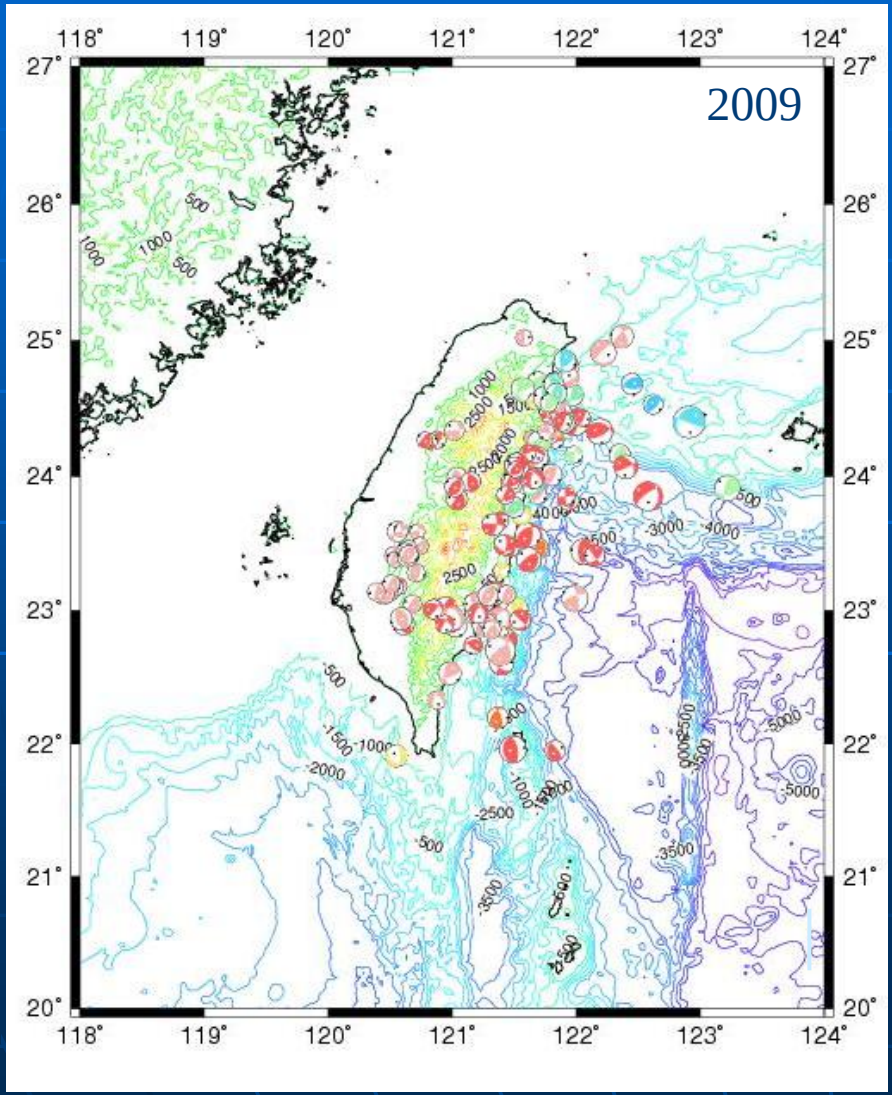
Observation wells

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



Events of the earthquake M_L >3 in Taiwan 03'~09'

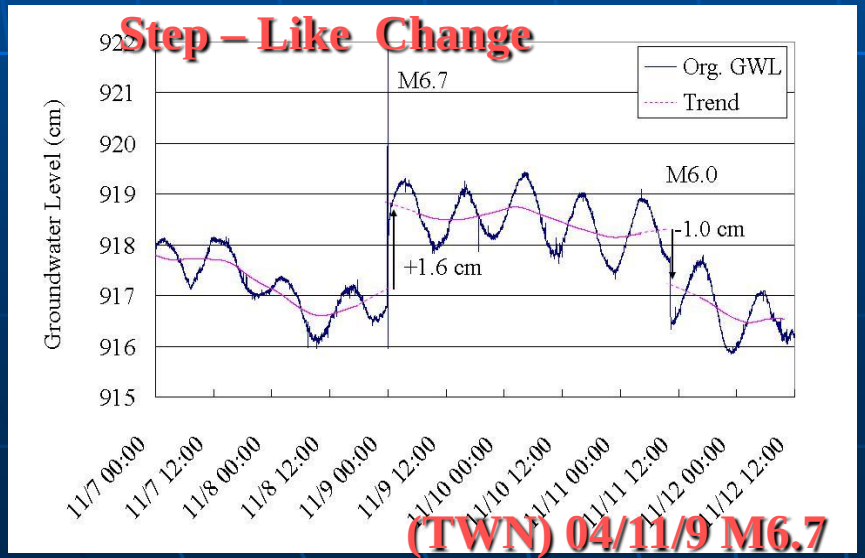
Year	3≦<4	4≦<5	5≦<6	6≦
2003	118	181	43	3
2004	186	125	25	5
2005	277	140	24	3
2006	231	117	21	8
2007	206	176	28	3
2008	248	143	29	2
2009	375	161	29	4
Avg. /yr.	234	149	28	4

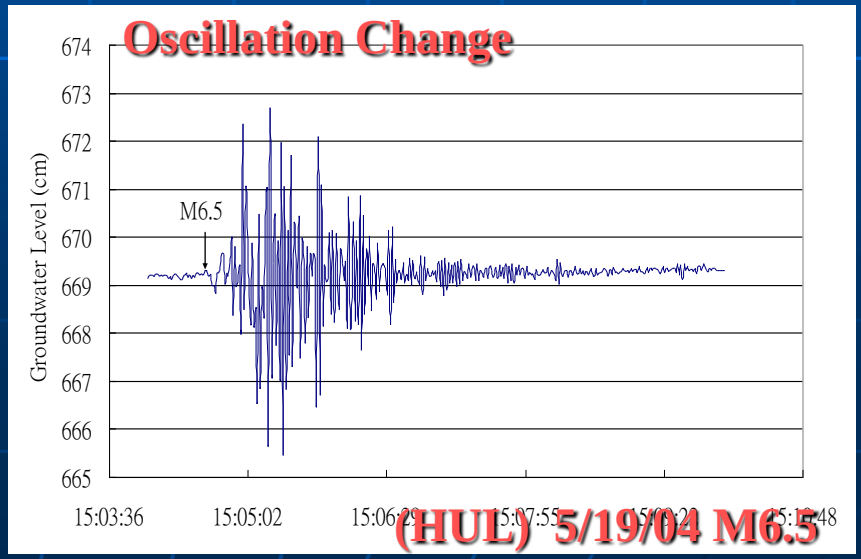
 CMT solution and distribution of events

Observed coseismic events (03'~09')

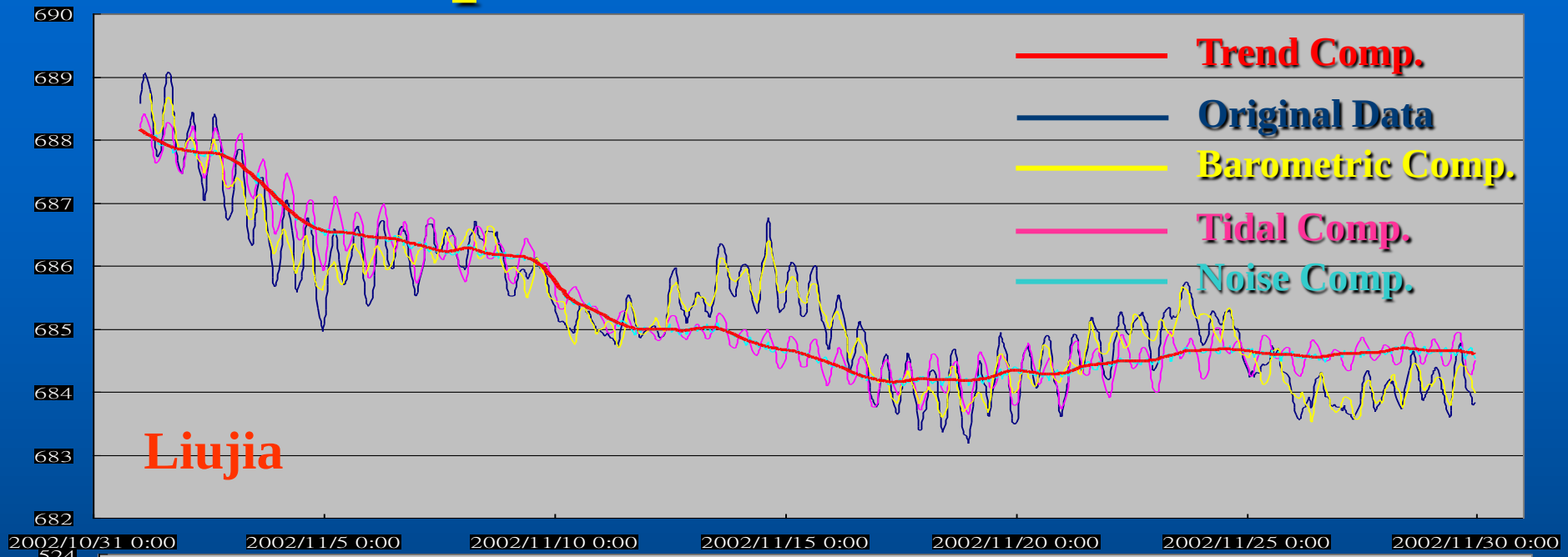
- Total 196 Observation, step changes (S) 36 events, oscillation (O) 129 events, O+S 31 events

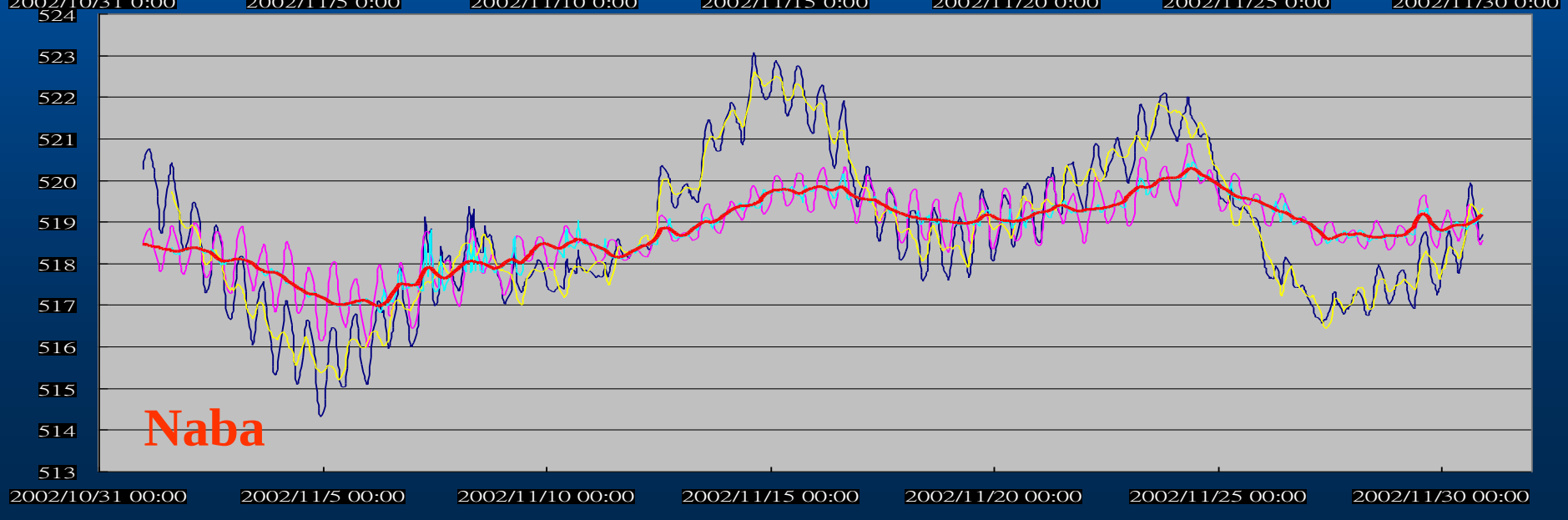
Catalog	Events	HUL	TWN	LUJ	NAB	HRD	DHR	TLO	SIP
2003/4/3 Tainan, M=4.9	2			S	S				
2003/6/10 Taitung, M=6.5	4			S	O		O+S		O
2003/6/17 Taitung , M=5.9	2				O				O
2003/12/10 Taitung , M=6.6	7	O+S	O+S	S		S	O+S	O+S	O
2003/12/11 Taitung, M=5.7	1				S				
2003/12/18 Taitung, M=5.8	1	O							





Decomposition and Extraction

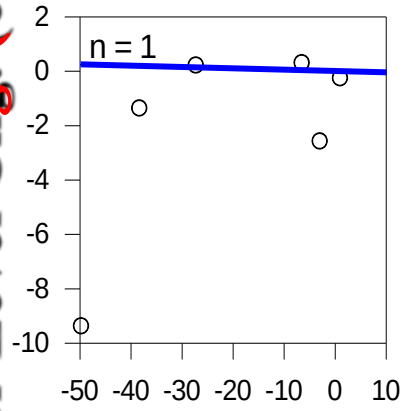




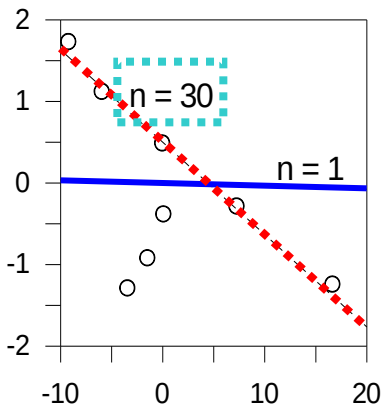
Static Volumetric Strain Sensitivity

	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

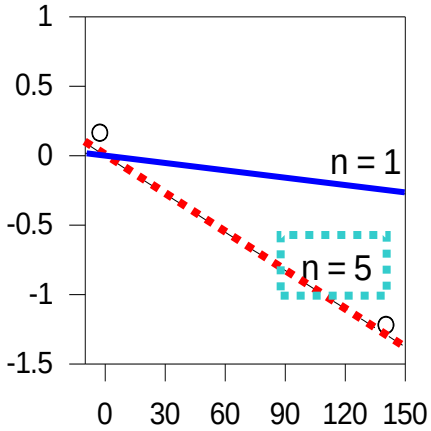
Comparison of the theoretic and observed responses



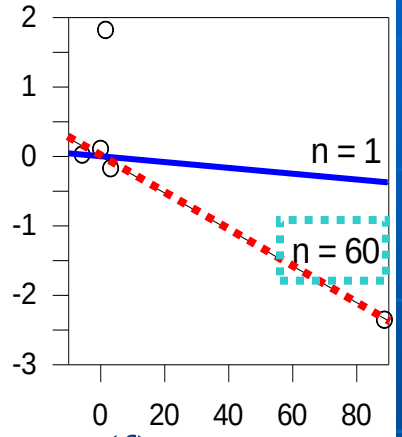
(a) HUL



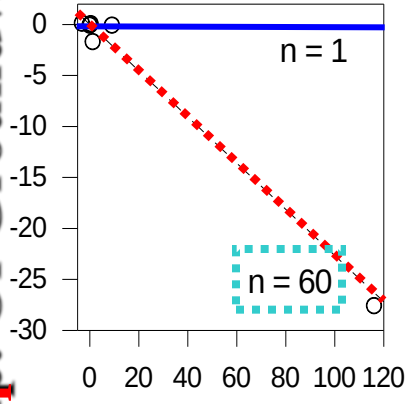
(b) TWN



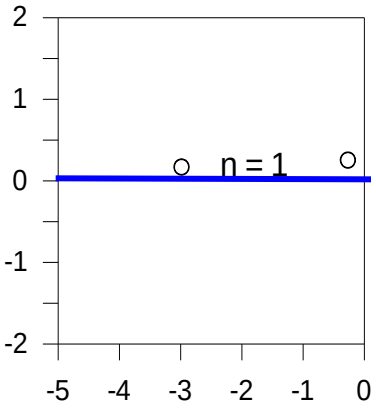
(e) HRD



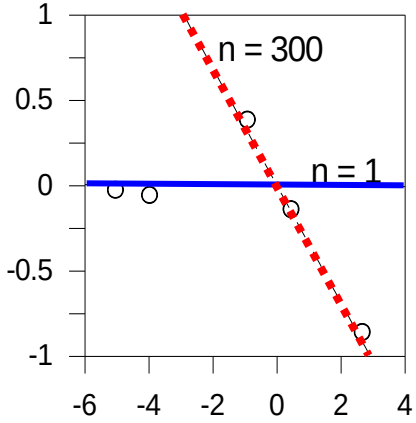
(f) DHR



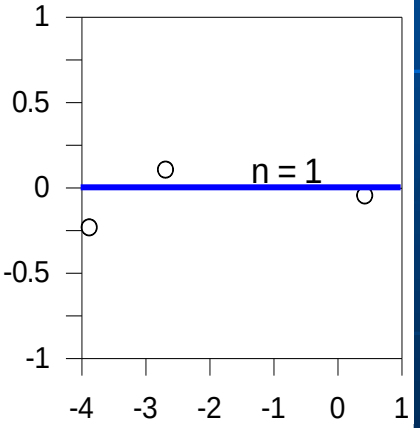
(c) LUJ



(d) NAB



(g) TLO



(h) SIP

Amp. Of Groundwater Level Chg. (cm)

Static Volumetric Strain (10^{-8})

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]
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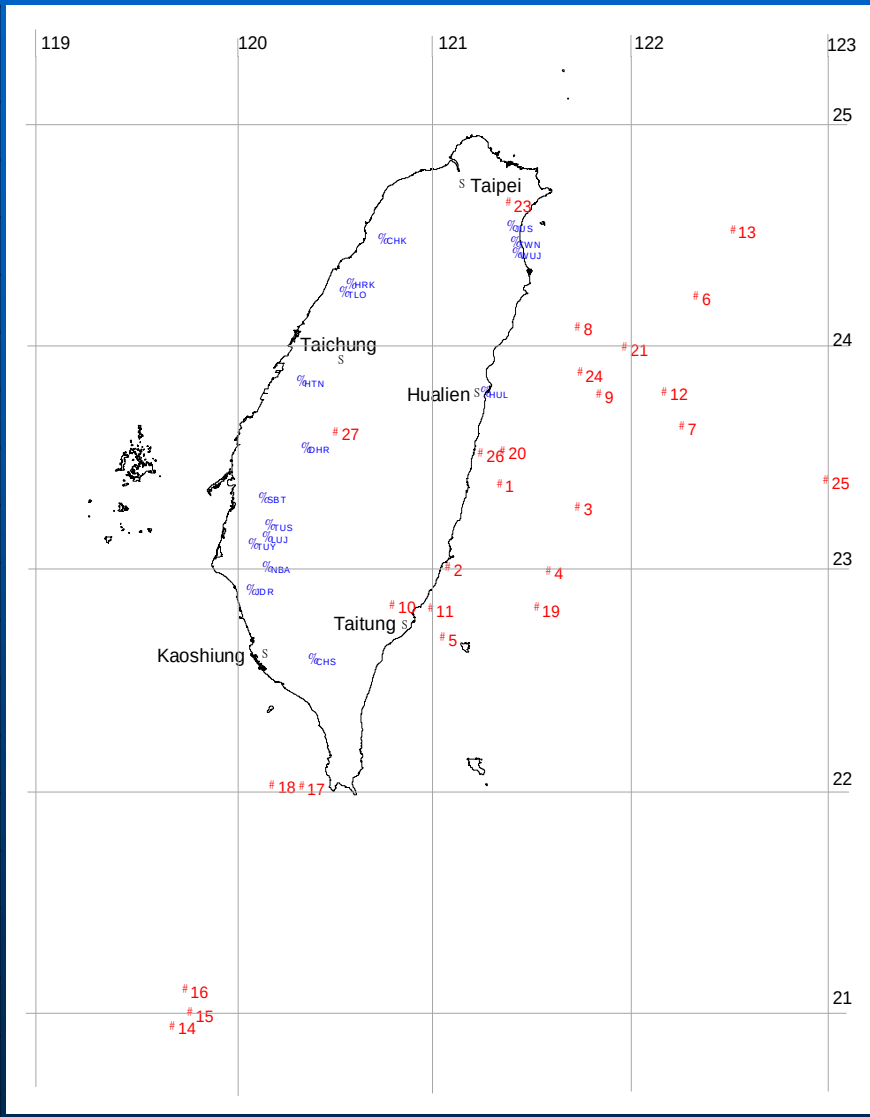
Vol. strain by earth + oceanic tide, $t_t=t_e+t_o$	3.25 [-336]	1.40 [-352]	1.42 [-356]	1.45 [-356]	1.04 [-335]	4.73 [-185]
M_2 amplitude(water level, t_w)	3.72±0.67 [-282±49]	6.17±0.60 [-339±23]	2.54±0.59 [-350±34]	4.24±0.29 [-349±15]	3.93±0.27 [-272±21]	23.77±0.50 [-21±6]
Strain sens. by **Water Level** 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 always have unusual amplification or site effects, them were not expected by the fault-dislocation volumetric strain .
- The mechanism of the coseismic groundwater level changes remains unknown.

Observed coseismic events (03'~09')

No.	Time	Lat.	Long.	Depth (km)	M_L
1	2003/6/10 8:40	23.50	121.70	27.59	6.54
2	2003/12/10 4:38	23.07	121.40	10.00	6.60
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	6.00
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	10.00	6.60
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	6.20
12	2006/7/28 15:40	23.97	122.66	28.00	6.06
13	2006/8/28 1:11	24.80	123.07	135.3	6.10
14	2006/10/9 18:01	20.70	119.83	28.00	6.10
15	2006/10/9 19:08	20.77	119.93	8.00	6.10
16	2006/10/11 14:43	20.89	119.9	10.00	6.00
18	2006/12/26 20:34	21.95	120.39	47.03	6.40
19	2007/1/25 18:59	22.65	122.02	20.00	6.20



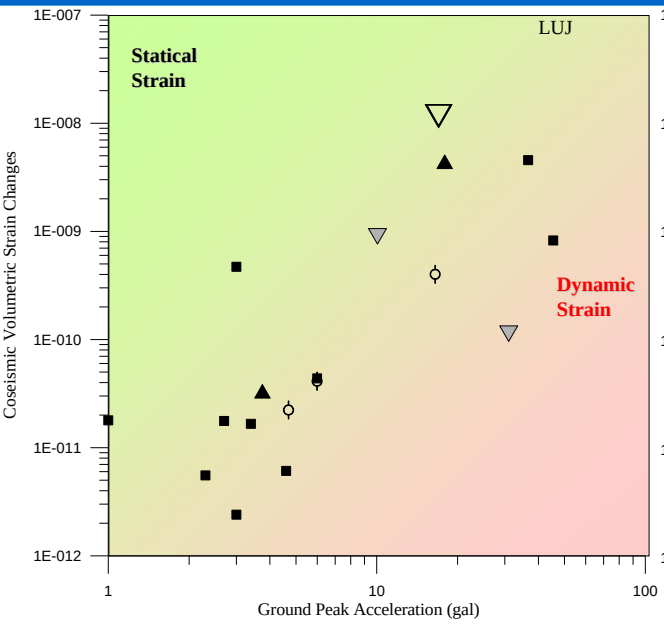
Observed coseismic events (03'~06')

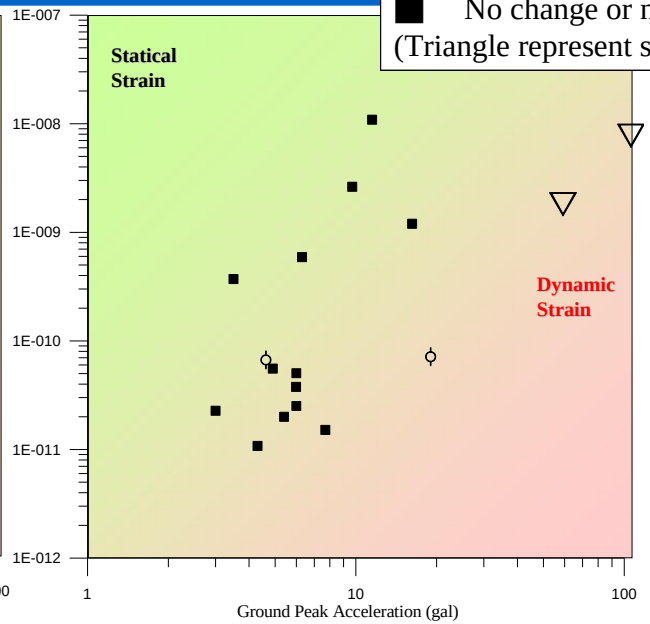
No.	LUJ					NBA					DHR				
	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)
1	-16.70	S	1.13E-10	-0.64	31	±3.51	O	7.15E-11	-0.24	20	-1.69	O+S	3.09E-10	-0.70	28
2	-275.66	S	1.16E-08	-65.32	17		N	1.09E-08	-37.32	11	-23.51	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

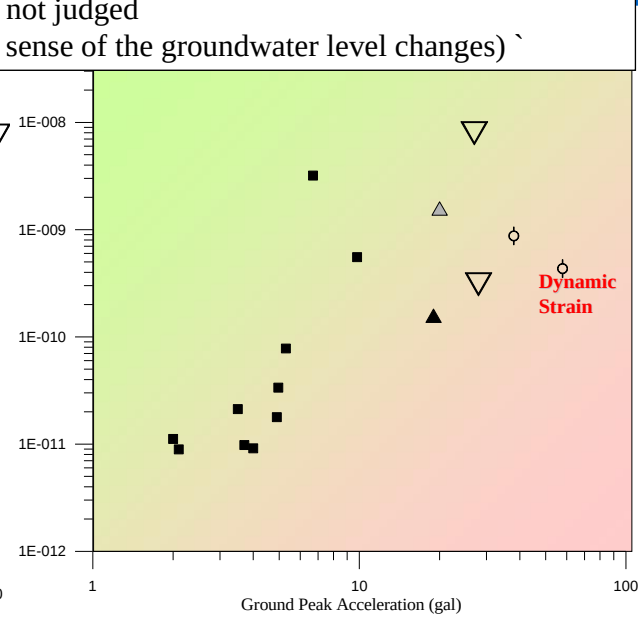
Observed coseismic events (03'~06')

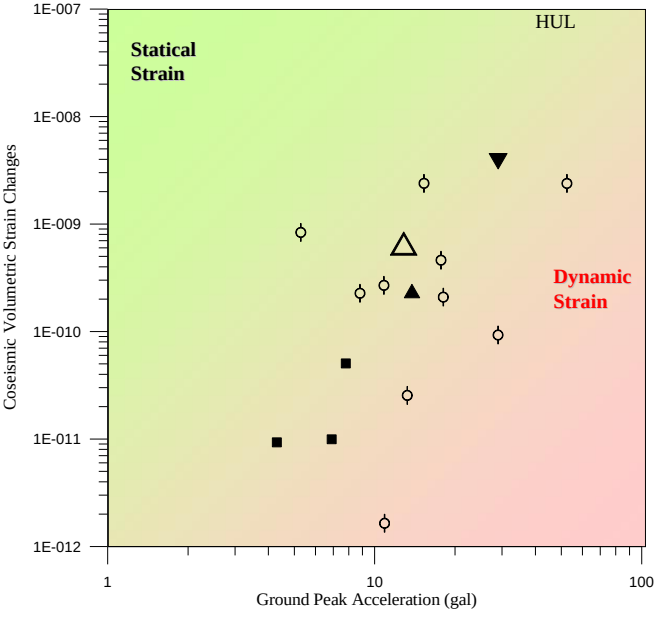
No.	HUL					TWN					TLO				
	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)
1	-					-					-				
2	-13.47	O+S	-3.84E-09	7.65	29	11.24	O+S	-5.98E-10	1.58	6	-8.57	O+S	2.66E-10	-2.33	11
3	±2.36	O	9.28E-11	-0.18	29	4.92	O	-5.41E-12	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

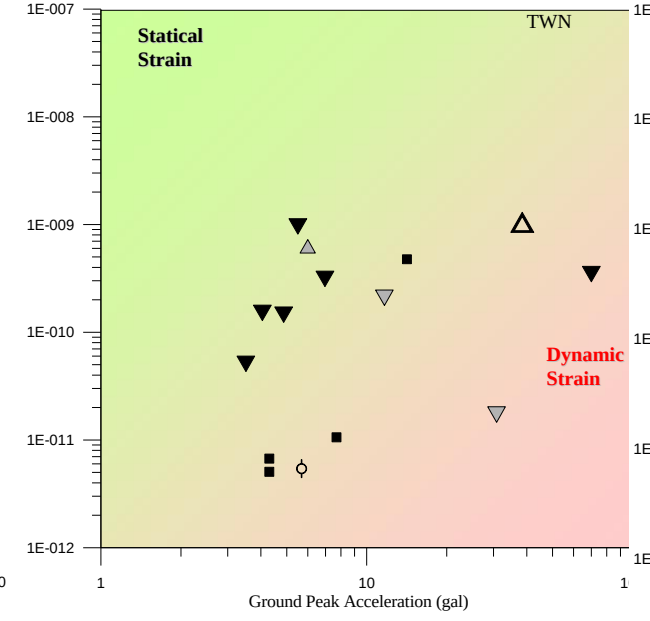
△、▽ Explainable by Volumetric Strain
▲、▼ Not quantitatively explainable but qualititatively explainable
▲、▼ Neither quantitatively nor qualititatively explainable
S Oscillation
■ No change or not judged
(Triangle represent sense of the groundwater level changes) `

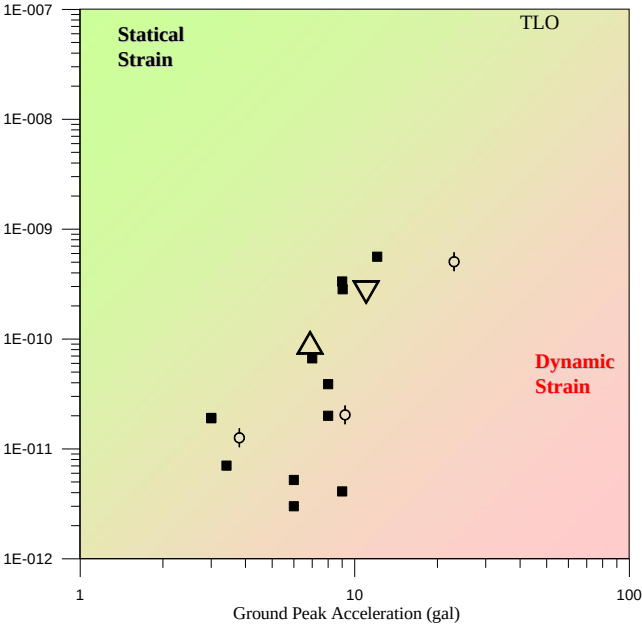




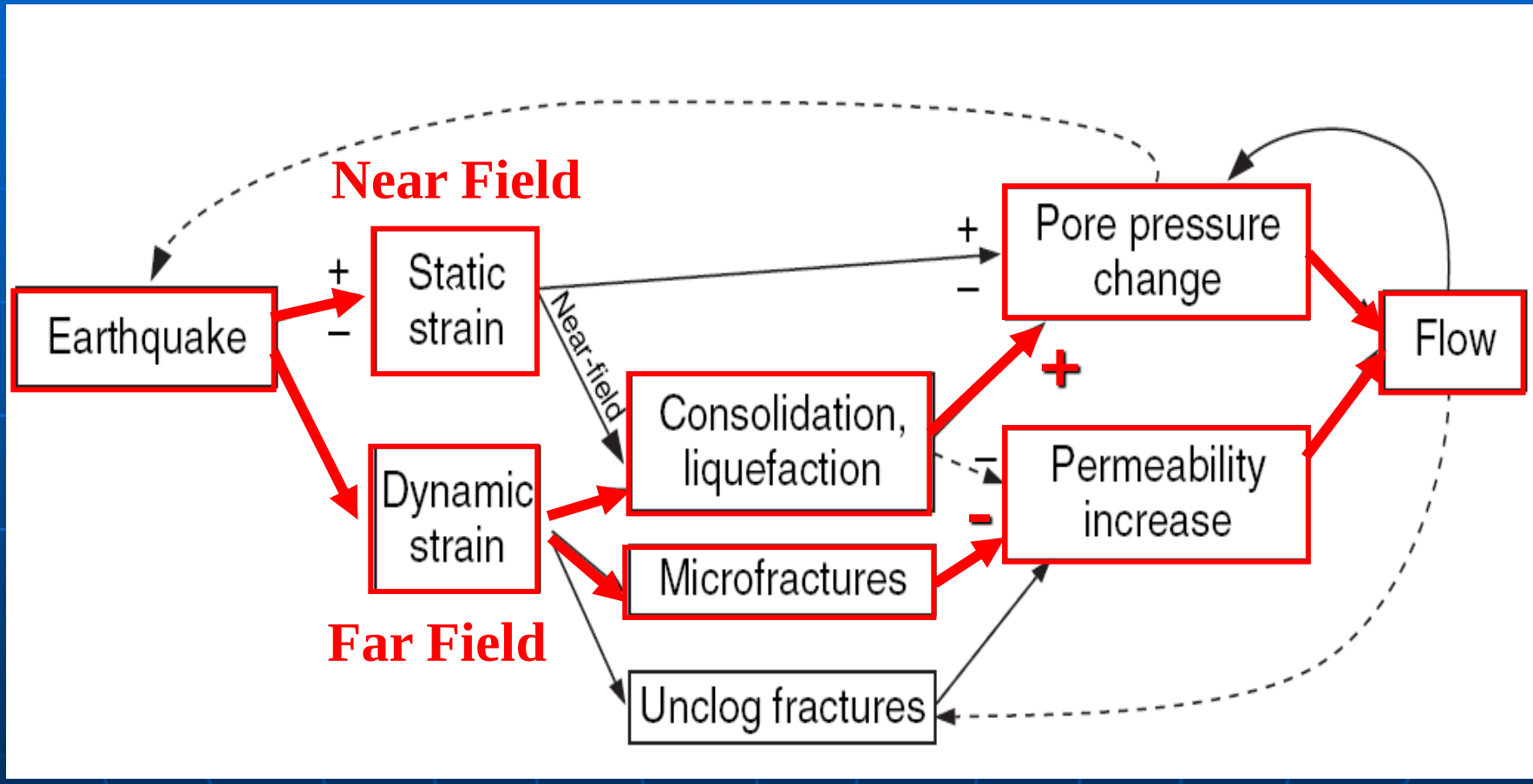








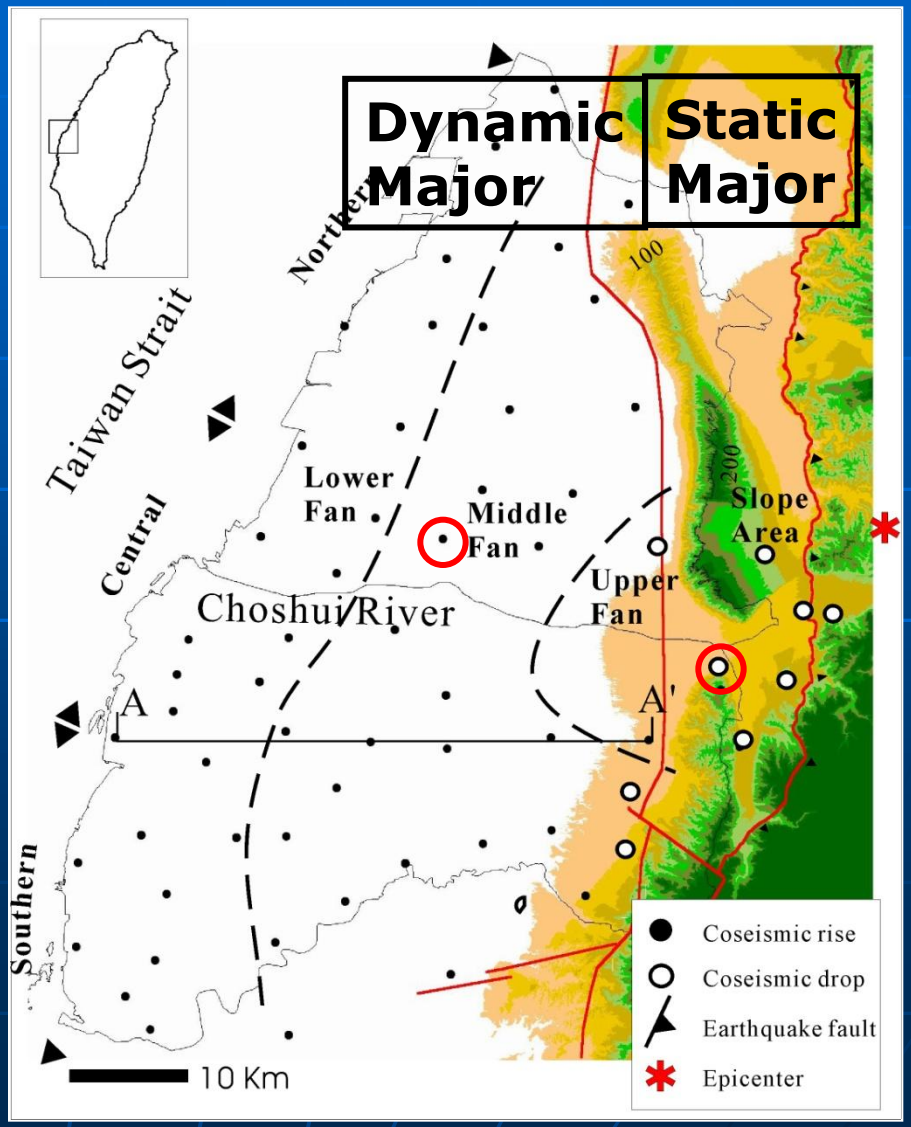
Mechanism of coseismic groundwater level changes



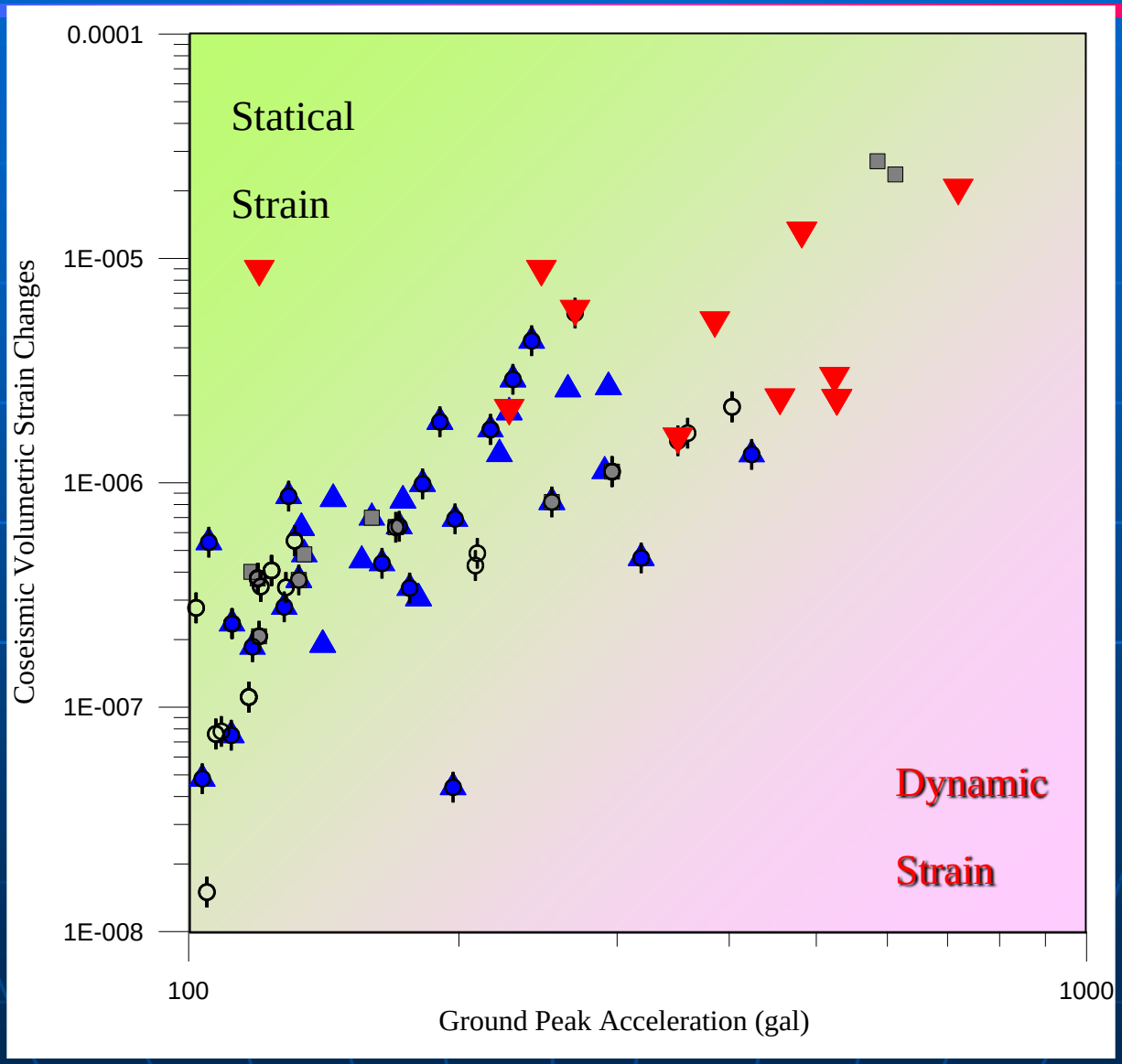
M. Manga and C.-Y. Wang (2007)

1999/9/21 Chi-Chi Eq.

- **Location:** Choushui River Alluvial Fan, Central Taiwan
- **Area:** Show in fan shape, Width **90** Km, Length **40** Km, Area around **1,800** Km^2.
- **Observation wells: 70** sites, **177** wells.



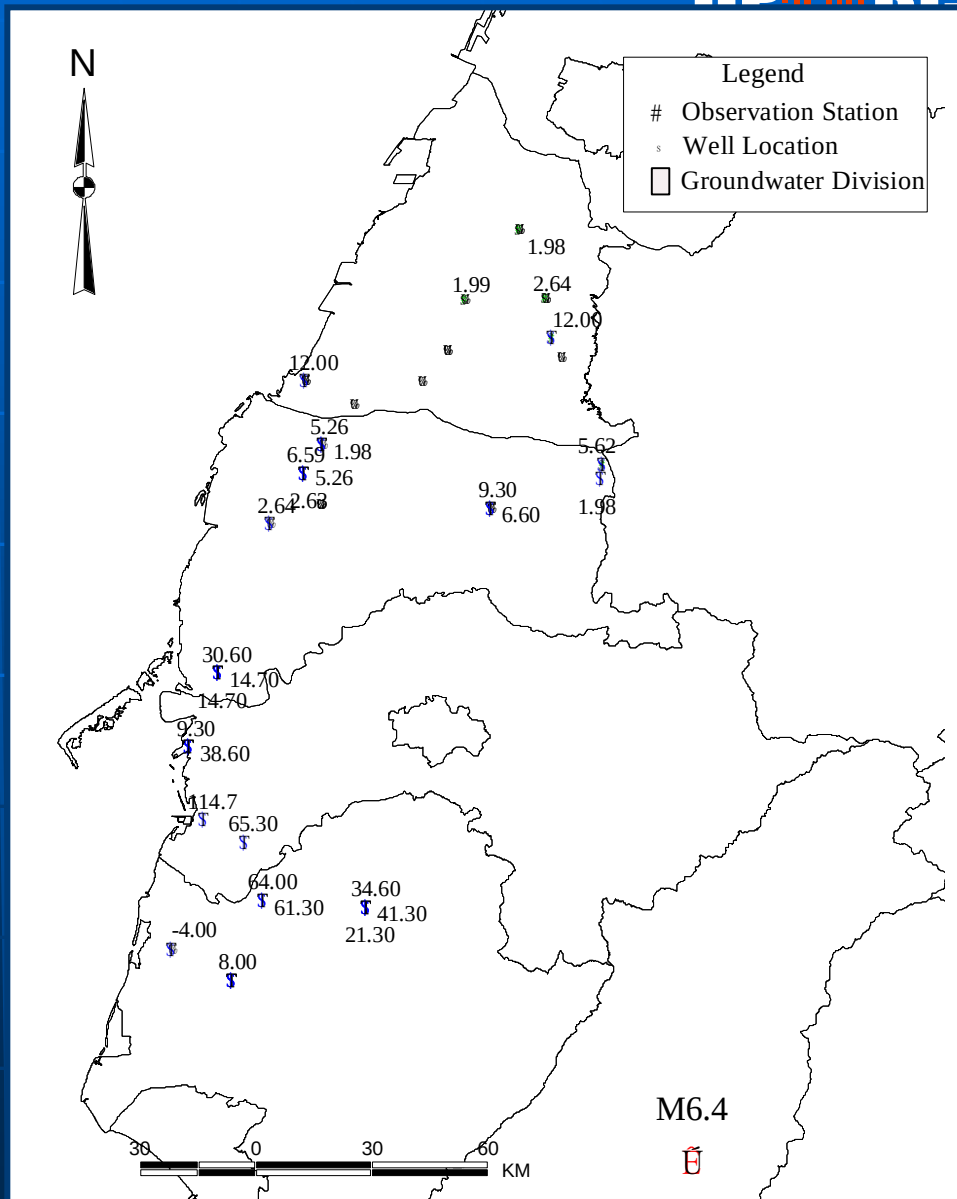
Near Field：1999/9/21 Chi-Chi Eq.



▲: Step-Rise、▼：Step-Drop，Φ：Oscillation、■：Non-detactable)

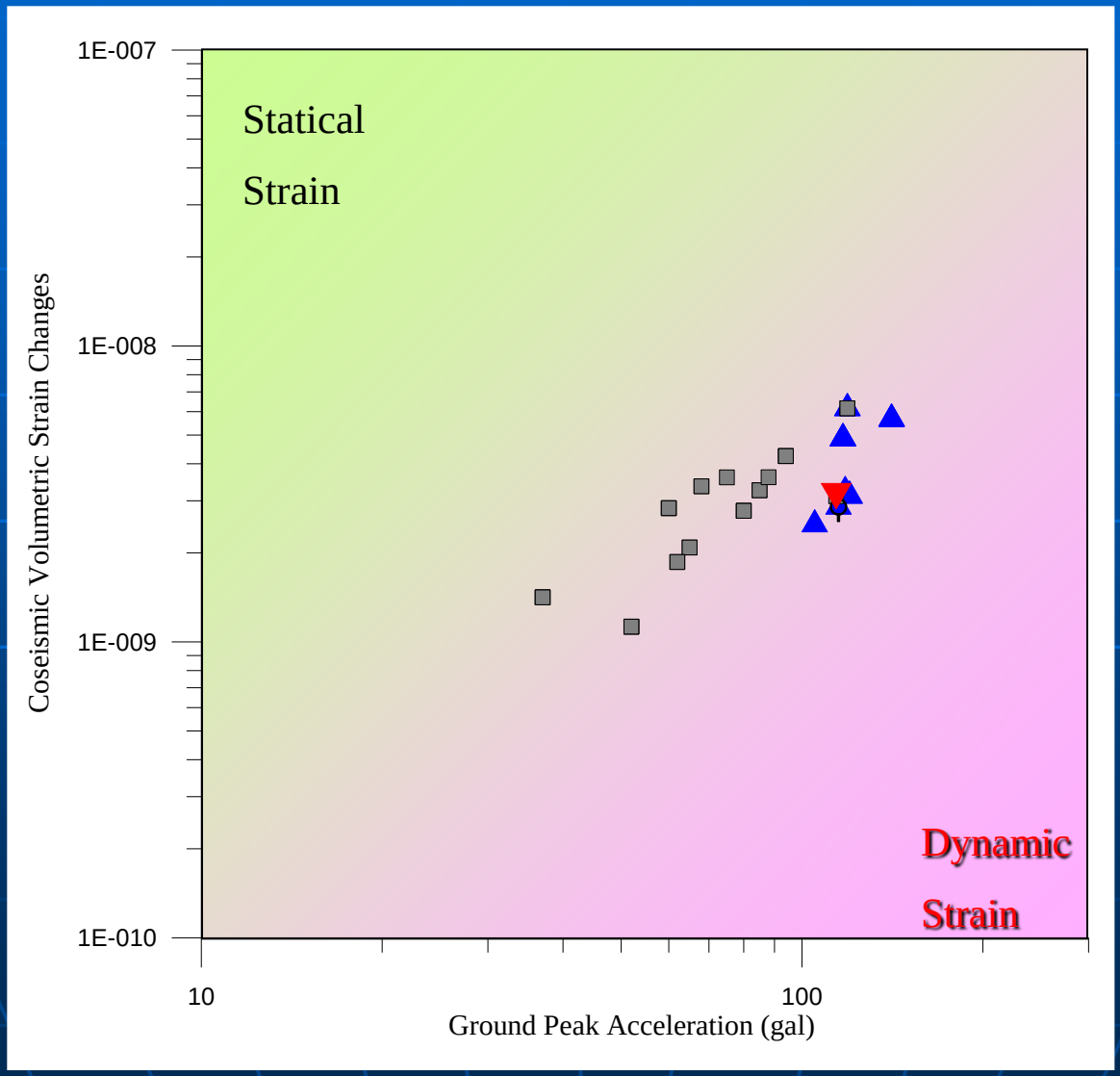
2010/3/4 Chiashian Eq. M_L6.4

- Large step-roses
- Amplication in the coastal area
- Shallow well >> Deeper well in the same sites.
- Oscillation mainly in the hill, slope area.
- Amplitudes of the step proportion to PGA



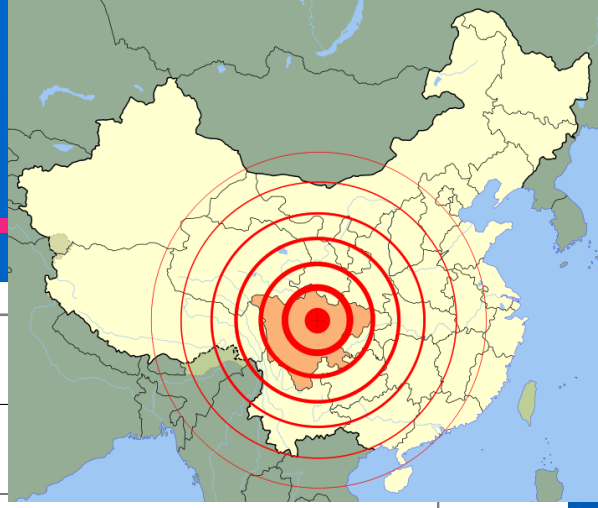
Well	PGA (gal)	Vol. Strain	Oscillation (cm)	Step-offset (cm)	G_{exp}(cm)
花壇(2)	52	-1.13E-09	±1.98	—	0.49
員林(1)	37	-1.41E-09	±2.64	—	0.62
文山(1)	50	-1.75E-09	—	12.00	0.77
文山(2)	50	-1.75E-09	±4.00	—	0.77
溪湖(1)	65	-2.09E-09	±1.99	—	0.92
西港(1)	60	-2.83E-09	—	12.00	1.24
虎溪(1)	119	-6.16E-09	—	9.30	2.70
虎溪(2)	119	-6.16E-09	—	6.60	2.70
觸口(1)	115	-2.86E-09	—	5.62	1.26
觸口(2)	115	-2.86E-09	±85.80	—	1.26
坪頂(1)	118	-3.24E-09	—	1.98	1.42
豐榮(2)	75	-3.60E-09	—	5.26	0.64
豐榮(3)	75	-3.60E-09	—	1.98	0.64
興化(1)	85	-3.67E-09	—	6.59	0.65
興化(2)	85	-3.67E-09	—	5.26	0.65
興化(3)	85	-3.67E-09	—	2.63	0.65
安南(2)	88	-3.60E-09	—	2.64	0.64

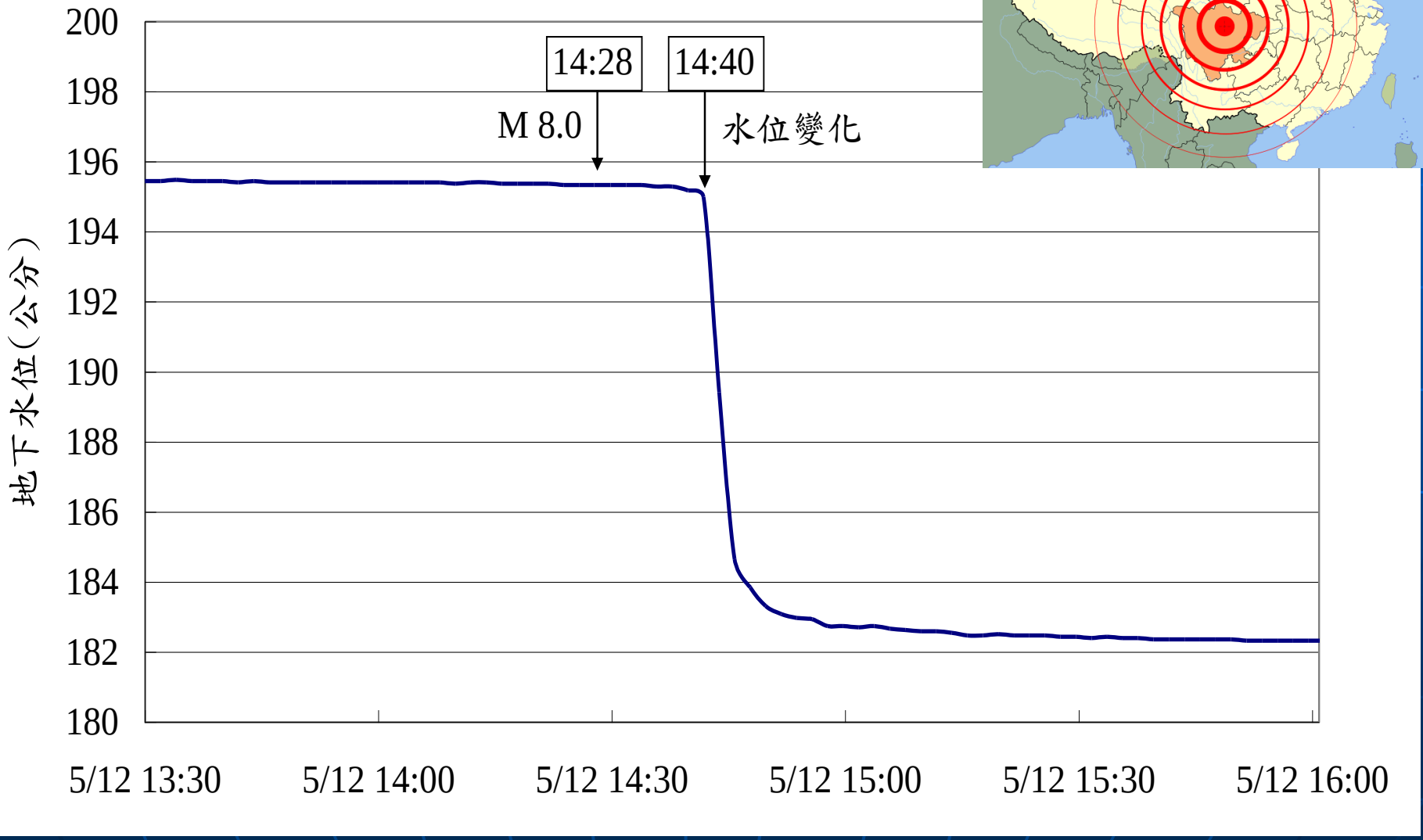
2010/3/4 Chiashian Eq. M_L6.4



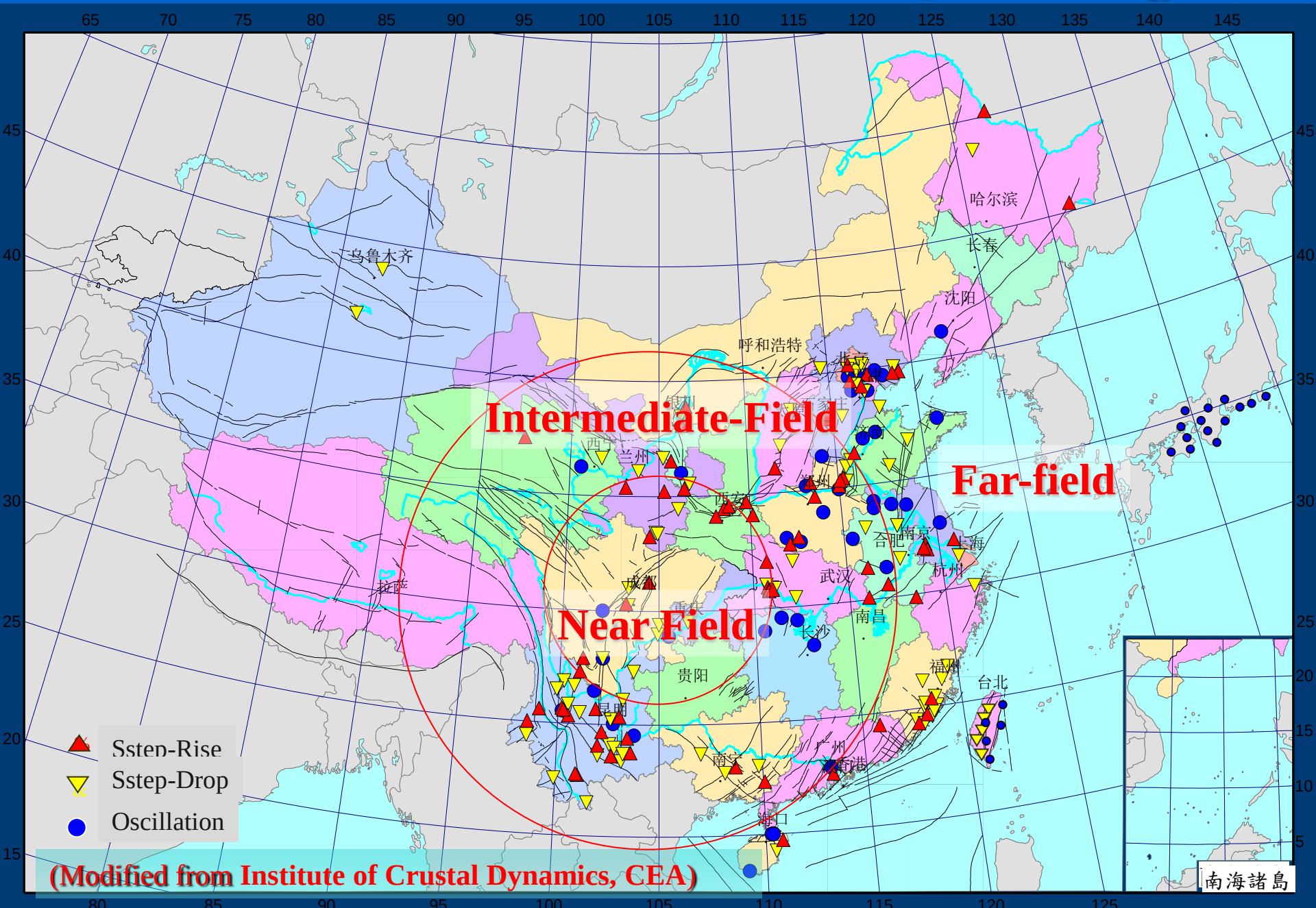
▲: Step-Rise、▼：Step-Drop，Φ：Oscillation、■：Non-detactable)

2008/5/12 Wenchuan, China Eq. (M_L 8.0)



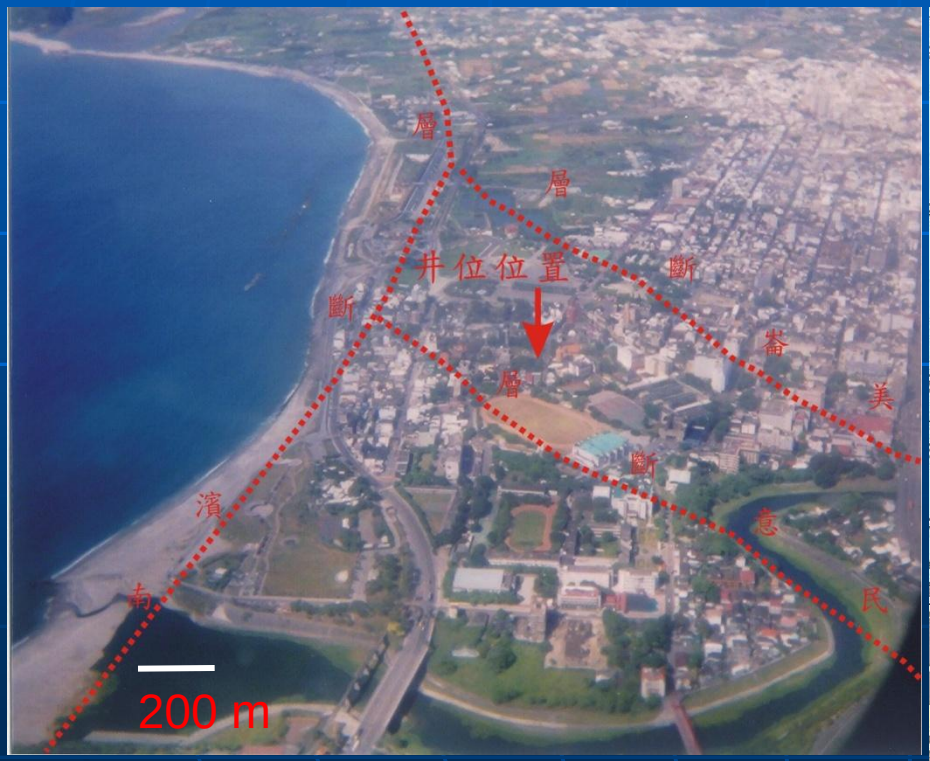


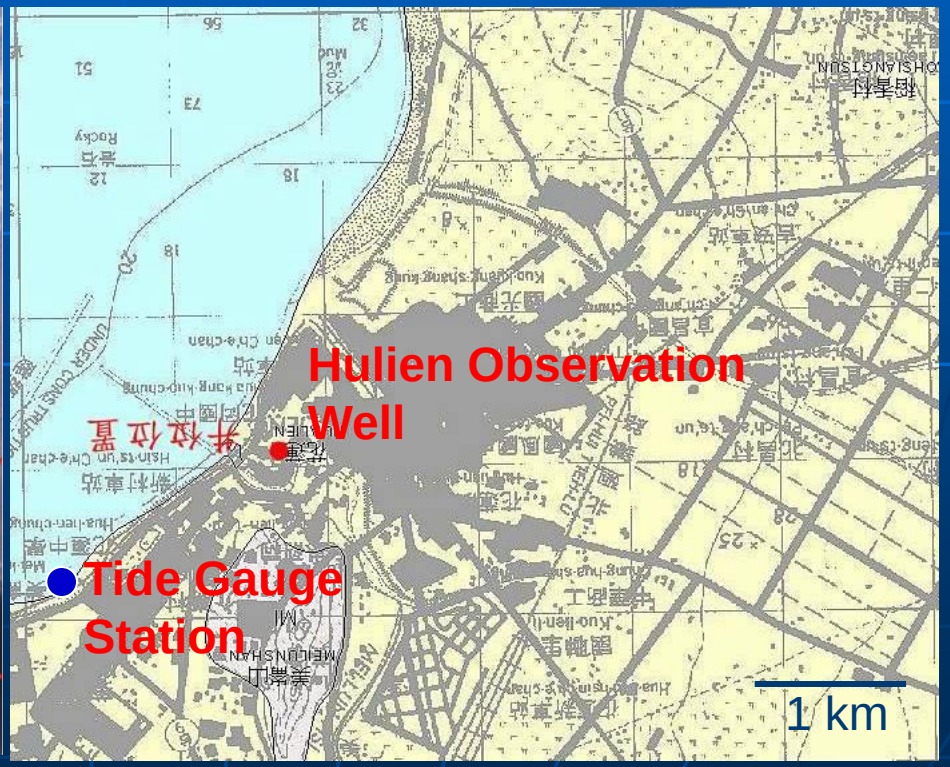
2008/5/12 Wenchuan, China Earthquake (M_L 8.0)



Discussion: *Possible Mechanism of Observation in Hulien Observation Well*

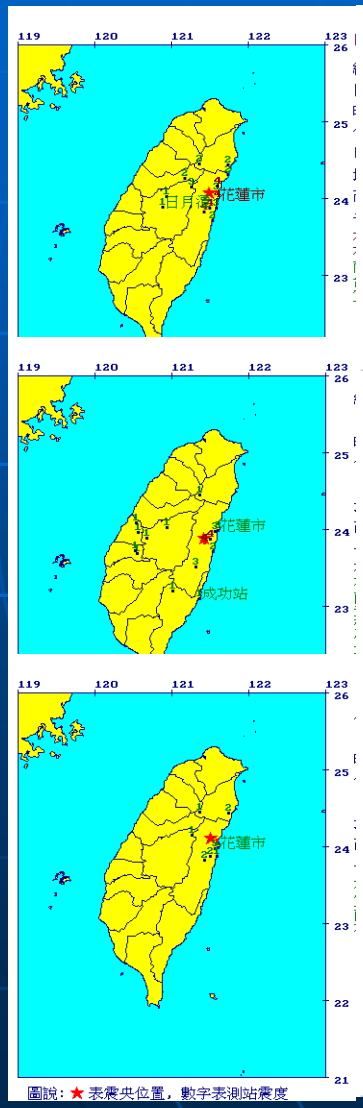
- Effected by ocean tide
- Located on complex fault zone

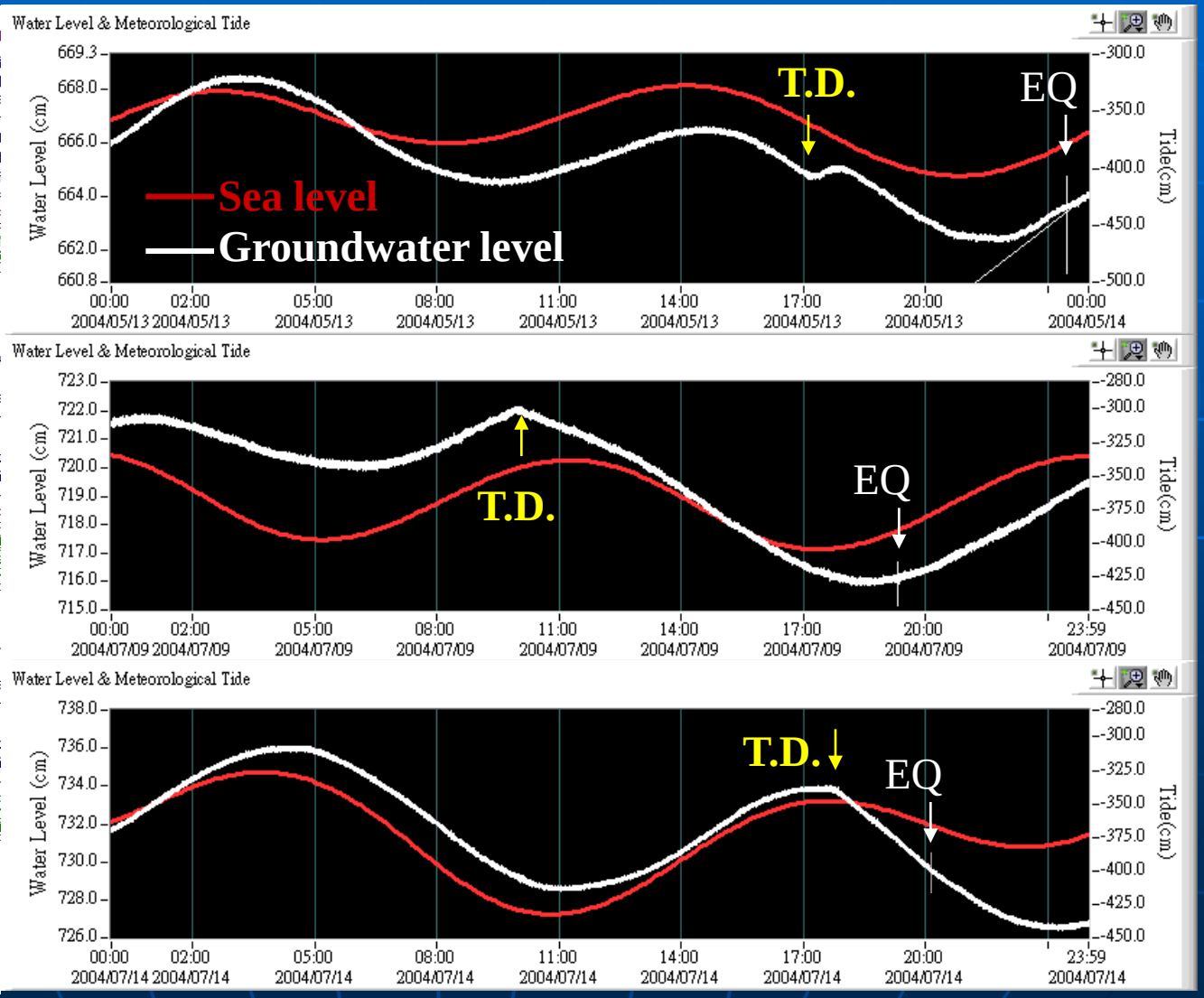


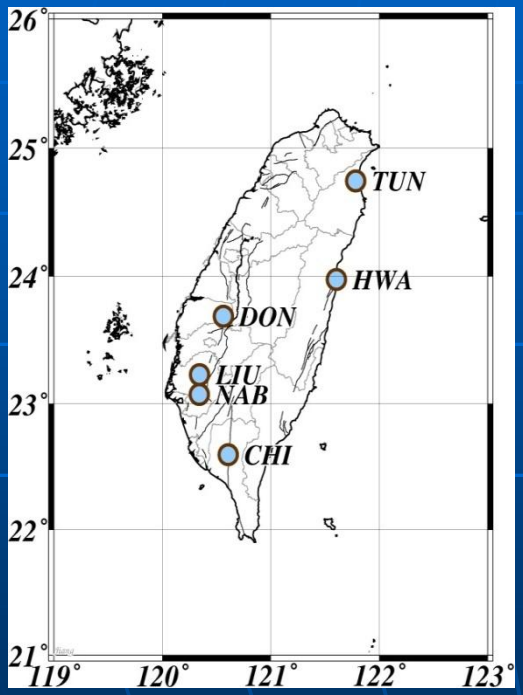


Location of Hulien observation well and tidal gauge station

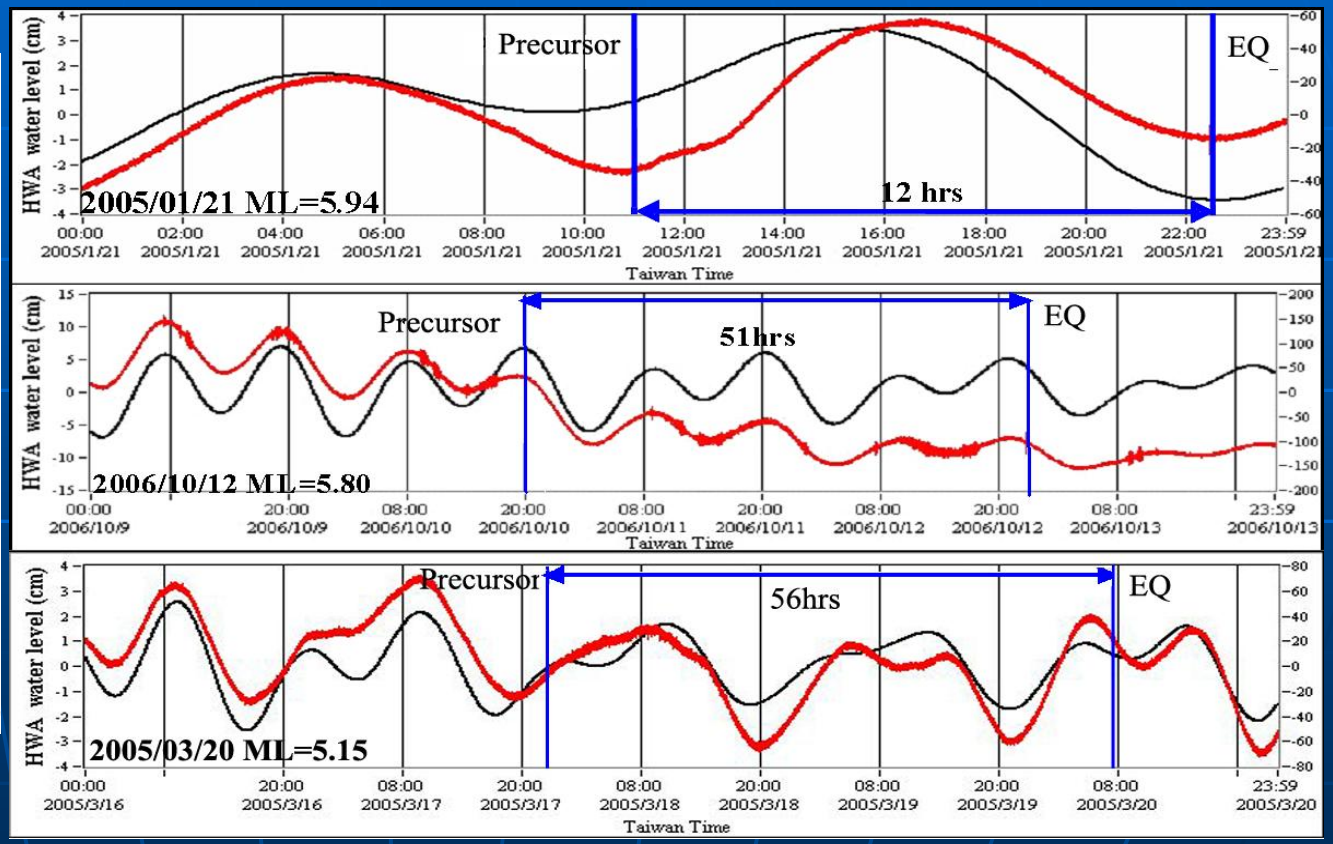
No.	Occ. Time	M_L	Lon.	Lat.	Depth (km)	Distance (km)	Obs. Sta.	Intens.
93053	2004/05/13 23:28:47	4.6	121.51	24.05	18.9	13.3	HUL	4
93069	2004/07/09 19:19:29	4.8	121.43	23.86	19.5	23.3	HUL	3
-	2004/07/14 20:04:30	4.1	121.52	24.09	21.1	15.7	HUL	1

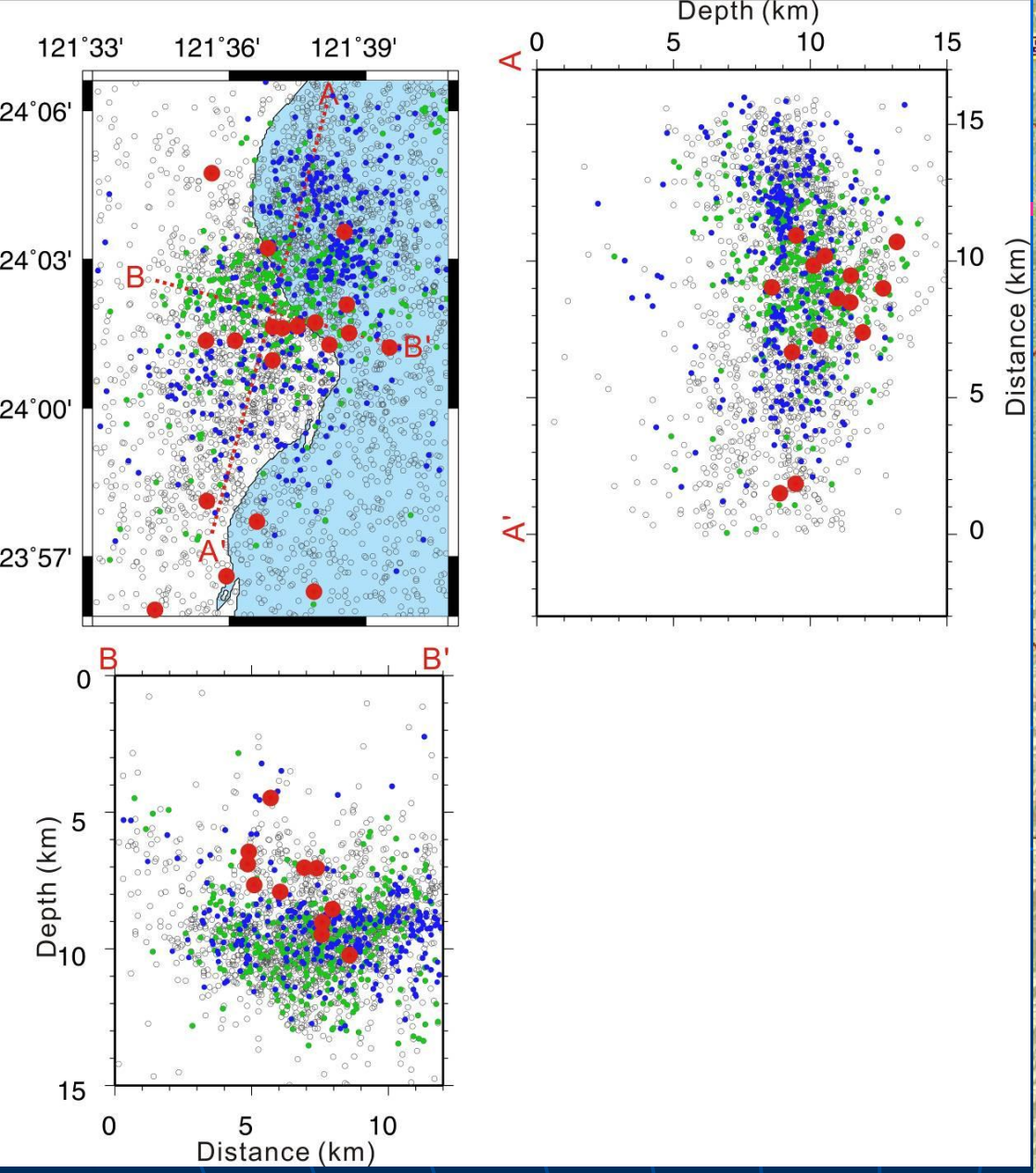






CWB Observation





Precursory swarms of moderate-sized earthquakes in eastern Taiwan, Rau (2009)

Conclusion

- 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 、 2004 Wenchuan earthquake 、2010 Jia-sian earthquake .

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

Thank you !