Integrating Seismological and Geophysical Observations for Earthquake Precursors Studies in Taiwan

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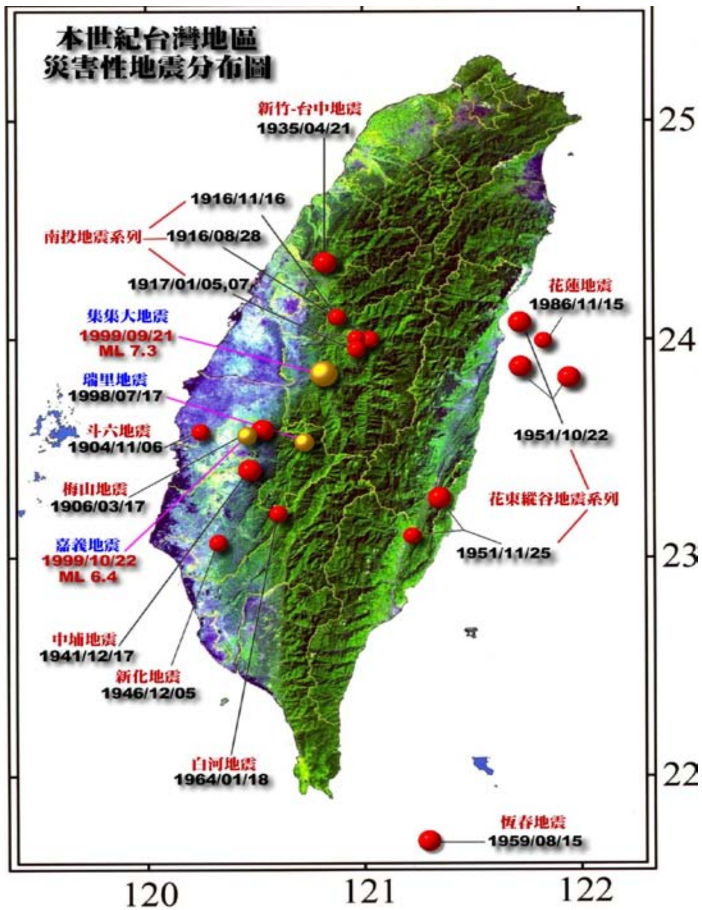
Outlines

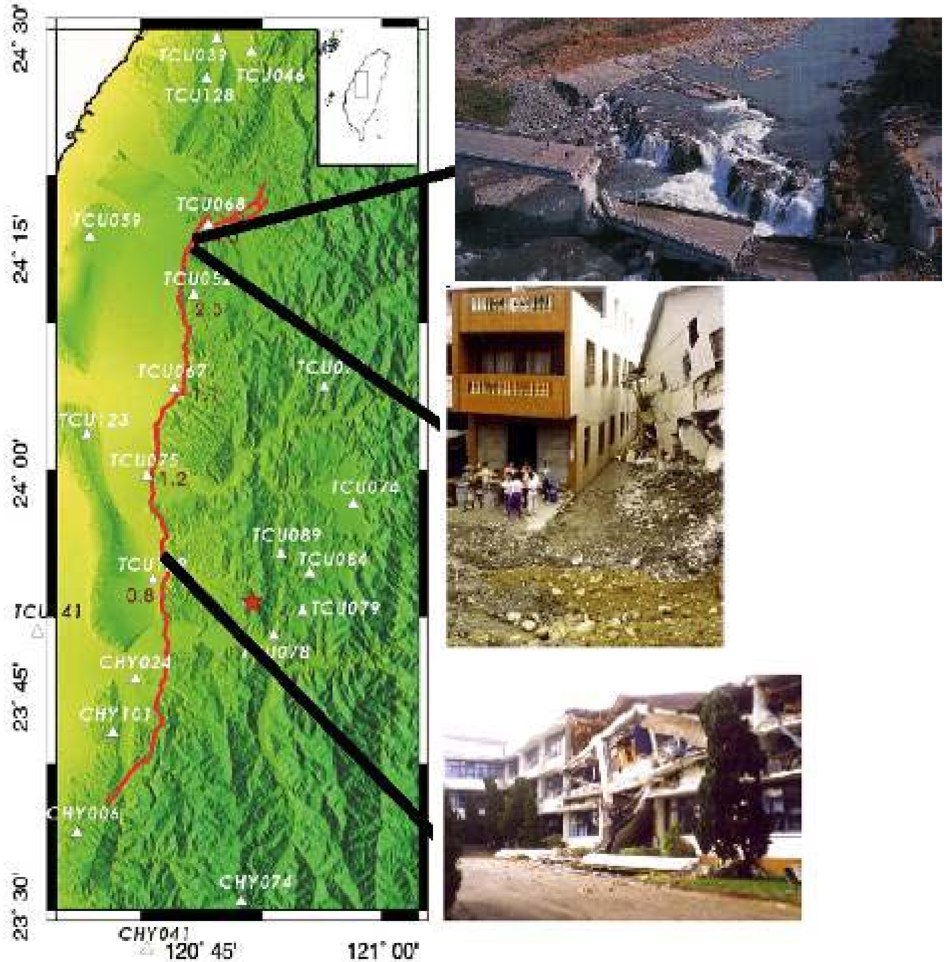
- Motivation

  Pre-seismic anomalies in seismicity and crustal deformation
- Seismological and Geophysical Network
- Seismological precursors studies

  The analyses of the 1999 Mw7.6 Chi-Chi, Taiwan, earthquake
- Geophysical precursors studies
- Conclusions

Earthquake hazard mitigation



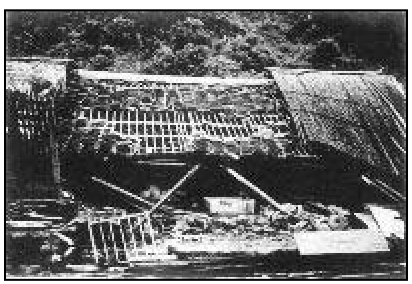


- Earthquake hazard is one of the major natural disasters in Taiwan.
- The case study of the 1999 Chi-Chi eartuquake.

Examples of earthquake hazards in Taiwan

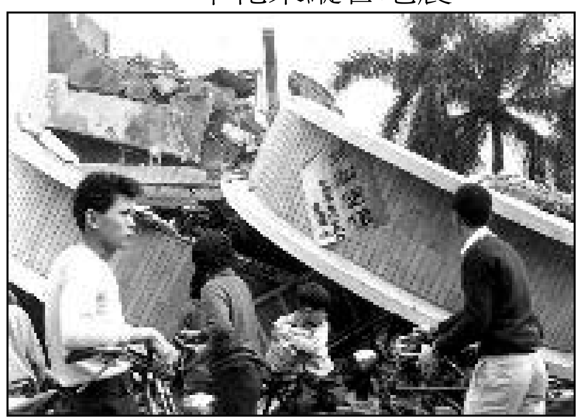
1906年梅山地震

1935年新竹－台中地震



1941年中埔地震

1951年花東縱谷地震



1964年白河地震

1986年花蓮地震

1999年集集地震

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Earthquake precursor

The seismic quiescence before 2011 Mw 9.0 Tohoku, Japan, earthquake

Tsunami (Kyodo news)

Tsunami in Sendai Airport (Kaneda, 2011)

LETTER — *Earth Planets Space*, 63, 709–712, 2011

A long-term seismic quiescence started 23 years before the 2011 off the Pacific coast of Tohoku Earthquake ($M = 9.0$)

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I find that a long-term seismic quiescence started 23.4 years before the 2011 off the Pacific coast of Tohoku Earthquake ($M = 9.0$). An earthquake catalog compiled by the Japan Meteorological Agency (JMA) is analyzed. The catalog includes 5770 earthquakes shallower than 60 km with $M \geq 4.5$. A detailed analysis of the earthquake catalog between 1965 and 2010 using the gridding technique ZMAP shows that the 2011 Tohoku earthquake is preceded by a seismic quiescence anomaly that began in November 1987. The quiescence-anomaly area is located around the deeper edge of the asperity ruptured by the main shock, and the Z-value is +4.9 for a time window of $T_w = 15$ years, using a sample size of $N = 150$ earthquakes. It is suggested that a seismic quiescence which starts more than 20 years before the main shock is common to giant earthquakes ($M \sim 9.0$) in subduction zones.

Key words: Seismic quiescence, the 2011 Tohoku earthquake, JMA earthquake catalog, ZMAP, Z-value.

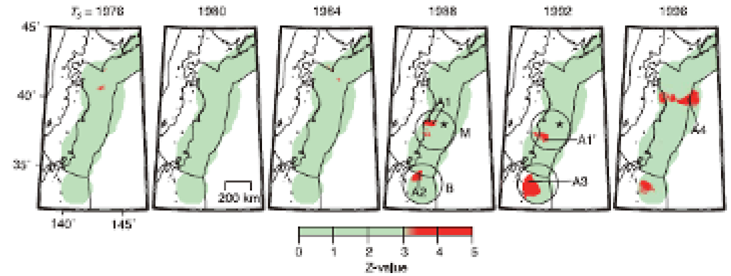

Fig. 3. Time slices of Z-value distribution using the JMA non-declustered catalog. A time window starts at T_s and ends at $T_s + T_w$, here $T_w = 15$ years. A red color (positive Z-value) represents a decrease in the seismicity rate. Circles labeled by M and B indicate Miyagi and Boso quiescence areas, respectively. A1 and A1' are nodes in the Miyagi quiescence area. A2 and A3 are nodes in the Boso quiescence area. A4 is a node in the Sanriku-haruka-oki quiescence area.

Z value

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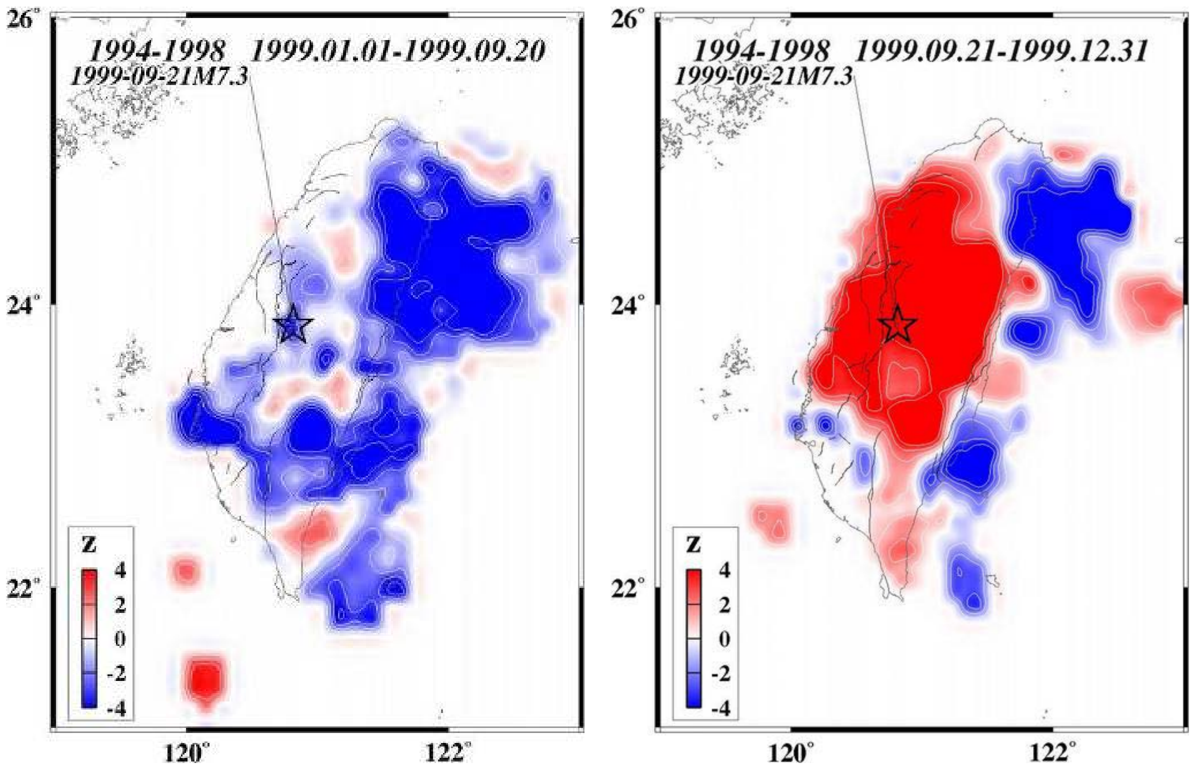
Earthquake precursor

The seismic quiescence before 1999 Mw 7.6 Chi-Chi, Taiwan, earthquake



$$z = \frac{(R - R_b)}{\sqrt{\sigma^2 / n + \sigma_b^2 / n_b}}$$

R : mean seismicity rate

R_b *: background mean seismicity rate*

σ *: standard deviation of seismicity rate*

n : number of samples

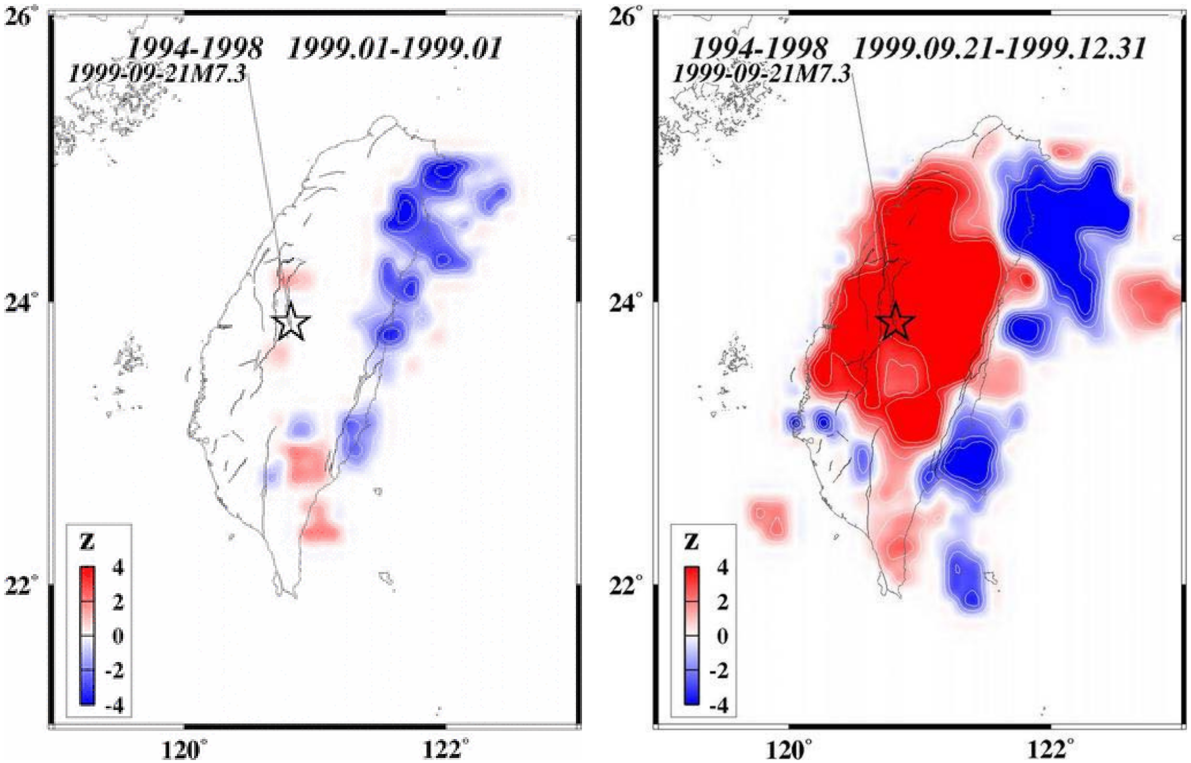
M ≧ 2,

grid 0.3°, interval 0.1°

- The Z value contour before (left) and after (right) the 1999 Chi-Chi, Taiwan, earthquake.
- The red color denotes high seismicity rate, and blue color represents low seismicity rate (seismic quiescence).

Earthquake precursor

The seismic quiescence before 1999 Mw 7.6 Chi-Chi, Taiwan, earthquake



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R : mean seismicity rate
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- The Z value contour before (left) and after (right) the 1999 Chi-Chi, Taiwan, earthquake.
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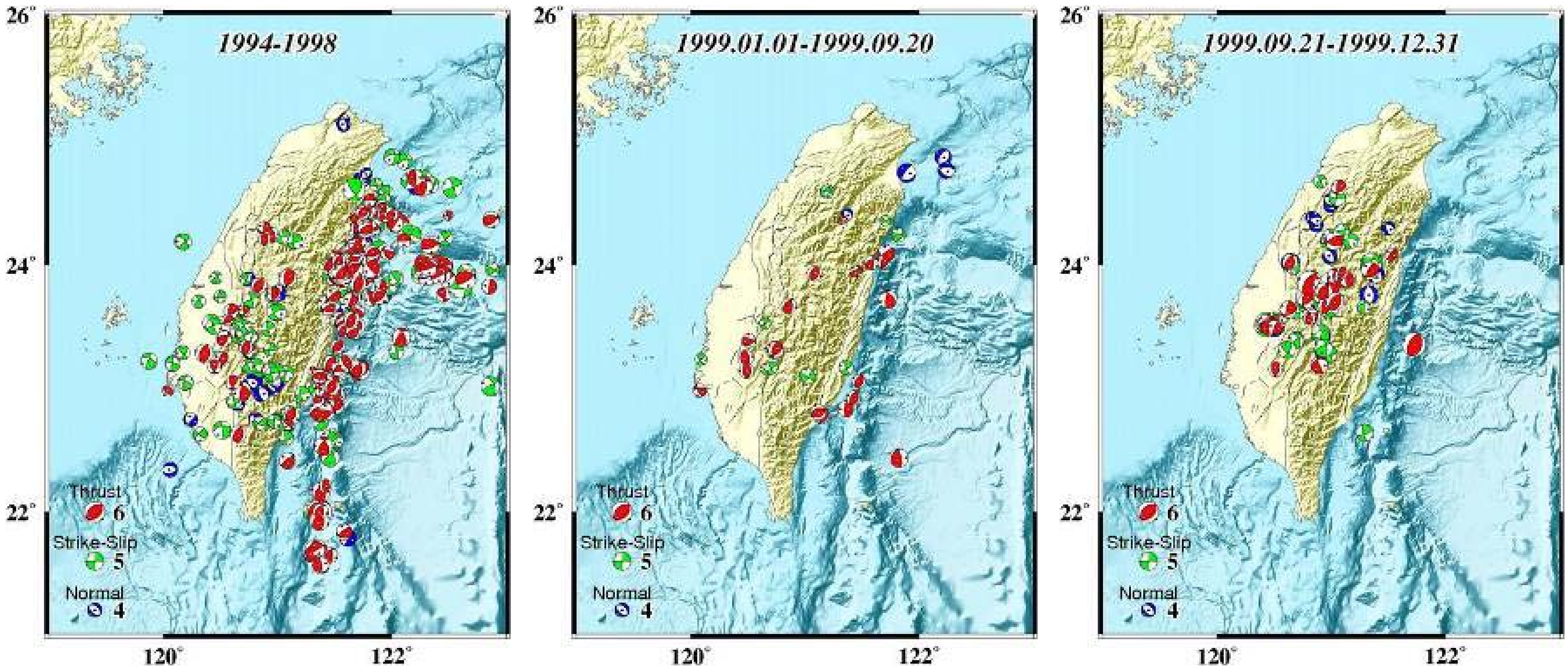
Pre-seismic anomalies in seismicity and crustal deformation before 1999 Mw 7.6 Chi-Chi, Taiwan, earthquake



$$\dot{\varepsilon}_{ij} = \frac{1}{2\mu VT}\sum_{k} M_{ij}^{k}$$

(Kostrov, 1974)

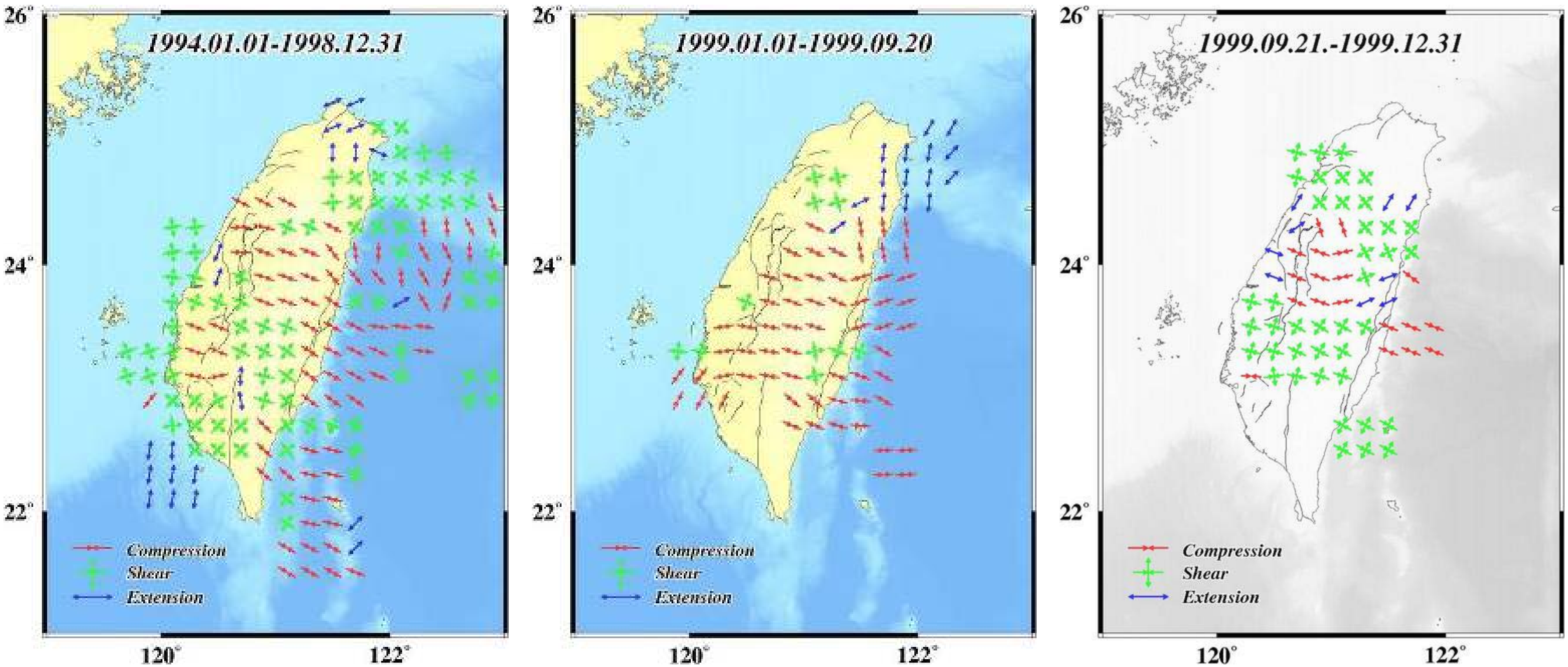
Thrust 6 — Compression Stress

Strike-Slip 5 — Shear Stress

Normal 4 — Extension Stress

$Z \leqq 40$ km

Pre-seismic anomalies in seismicity and crustal deformation before 1999 Mw 7.6 Chi-Chi, Taiwan, earthquake



$$\dot{\varepsilon}_{ij} = \frac{1}{2\mu VT}\sum_k M_{ij}^k$$

(Kostrov, 1974)

Compression

Shear

Extension

Z ≦ 40 km

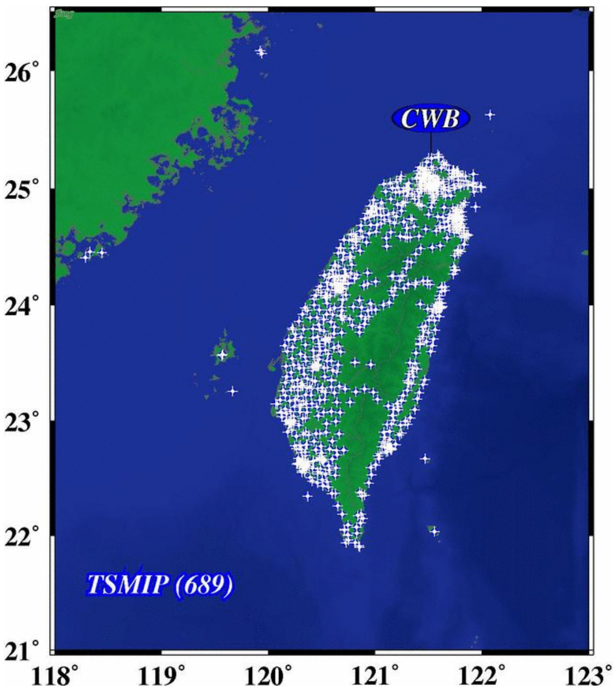
中央氣象局 Central Weather Bureau

The primary missions of the Seismological Center of Central Weather Bureau (**CWB**) are as follows:

- Monitoring seismic activities in and around Taiwan.
- Releasing reports of felt earthquakes and issuing tsunami warnings.
- Implementing Taiwan Strong-motion Instrumentation Program.
- Studying various phenomena that are possible earthquake precursors.
- Providing seismic information and educating the public on earthquake precautionary measures.

Seismological and Geophysical Network

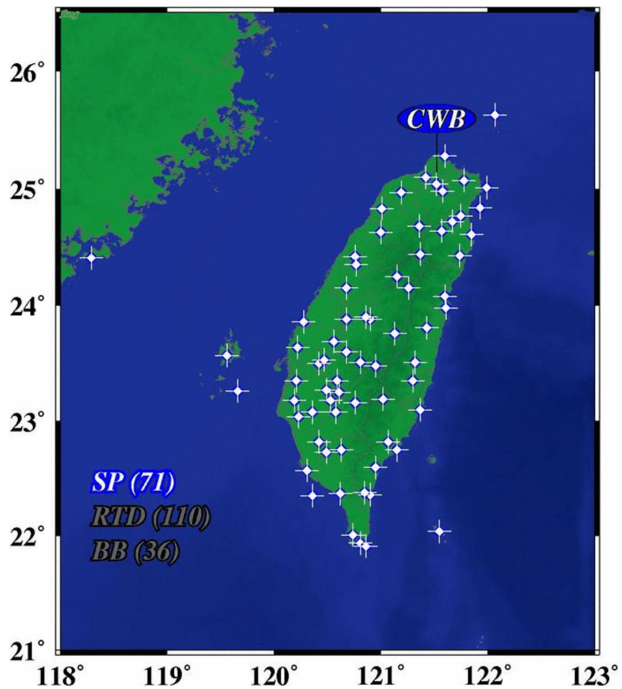
Seismological Center, Central Weather Bureau (**CWB**), Taiwan.



Taiwan Strong Motion Instrumentation Program Network

TSMIP

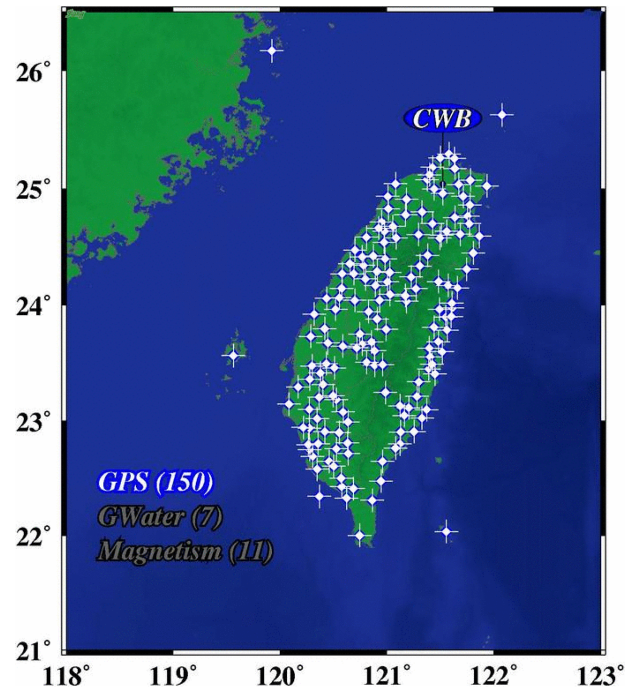
臺灣強地動觀測網



Central Weather Bureau Seismographic Network

CWBSN

中央氣象局地震觀測網



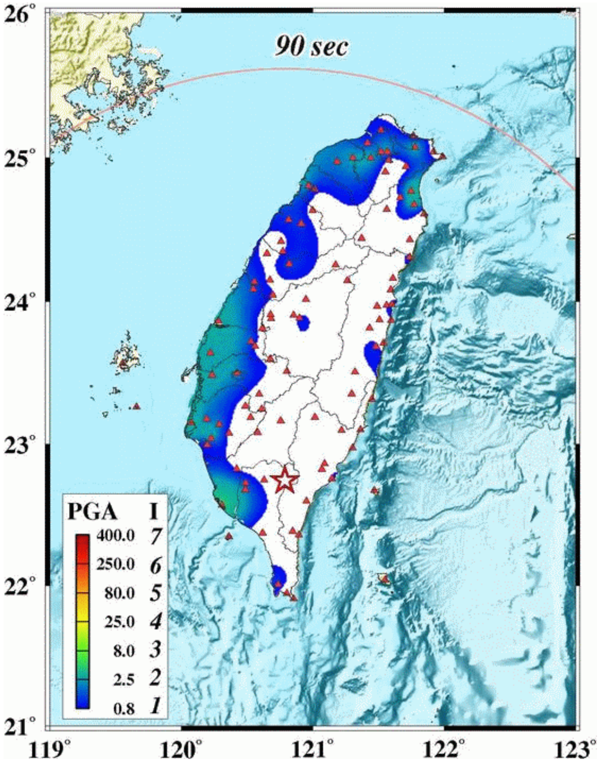
Taiwan Geophysical Network for Seismology

TGNS

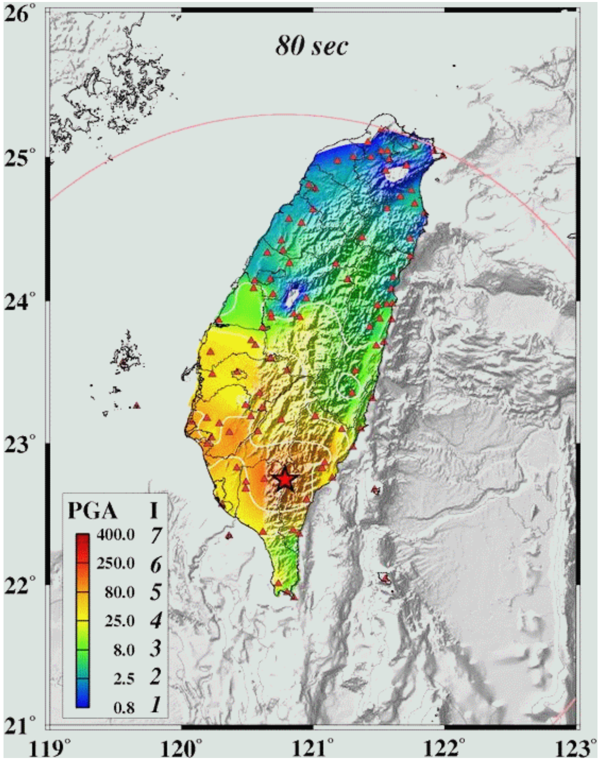
臺灣地球物理觀測網

中央氣象局 Central Weather Bureau

The 2012-02-26 ML6.4 Pingtung, Taiwan, earthquake



(at the each moment)



Horizontal PGA Contour (cumulative)

- The horizontal PGA (Peak Ground Acceleration, gal) contour and intensity at the each moment (left) and cumulative (right).
- Blue circle denotes P-wave and red circle represents S-wave propagation.

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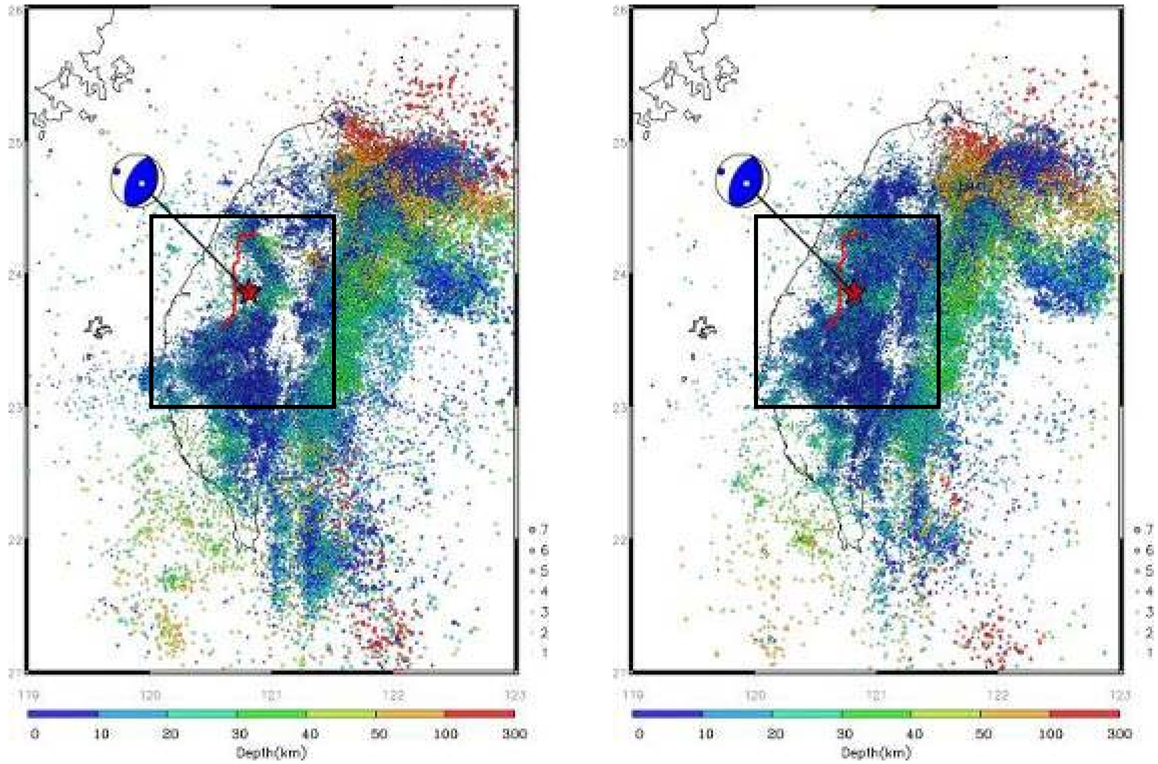
- Conclusions

The following slides will show you how we study possible earthquake precursors.

Pre-seismic anomalies in seismicity and focal mechanisms

The analyses of the 1999 Mw7.6 Chi-Chi, Taiwan, earthquake



The seismicity before (left, 102581 events) and after (right , 158506 events) the 1999 ML7.3 (Mw7.6) Chi-Chi earthquake from 1991 to 2004. The main shock was followed by a large number of strong aftershocks. Pre- and post-main shock focal mechanisms of this earthquake are analyzed to characterize spatial and temporal variations of stress patterns around the Chelungpu fault, which ruptured during the main shock.

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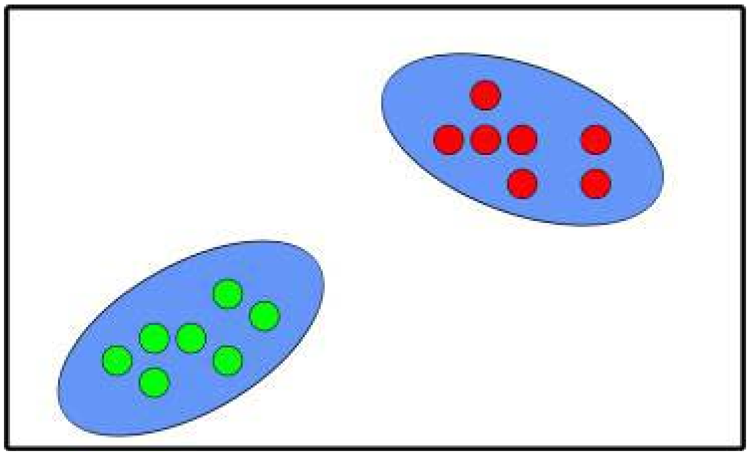
Seismicity Analysis

Earthquake Clustering based on Similar time and space



Clustering method 群集法

Seismicity Clustering(Reasenberg,1985)

Correlation time interval:

$$\tau = \frac{-\ln(1-P)t}{10^{2(\Delta M-1)/3}} = \frac{3t}{10^{2(\Delta M-1)/3}}$$

Correlation distance:

Kanamori and Anderson(1975)

log r = 0.4*M - (log(stress drop))/3 - 1.45

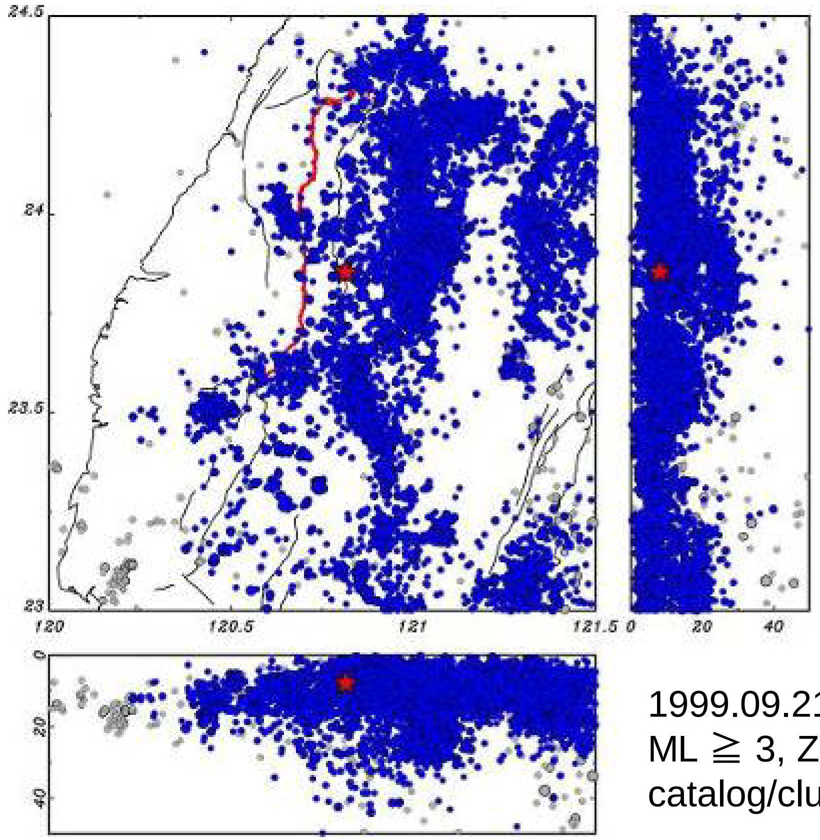
r: radius of a circular crack (km)

stress drop=30 bars.

- In the study of seismicity, we first define the aftershocks of the Chi-Chi earthquake by the earthquake clustering method.

Seismicity Analysis

Earthquake Clustering based on Similar time and space



1999.09.21-2004.12.31,
ML ≧ 3, Z≦50 km
catalog/clustered: 6905 / 6684

- In the study of seismicity, we first define the aftershocks of the Chi-Chi earthquake by the earthquake clustering method.

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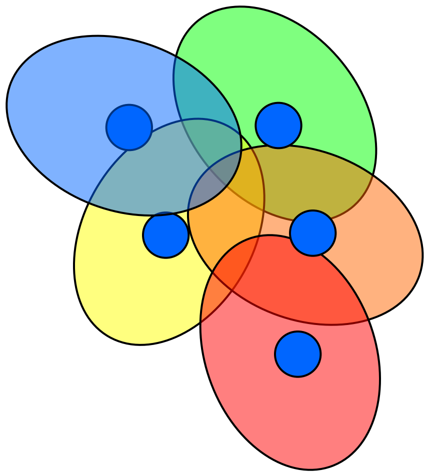
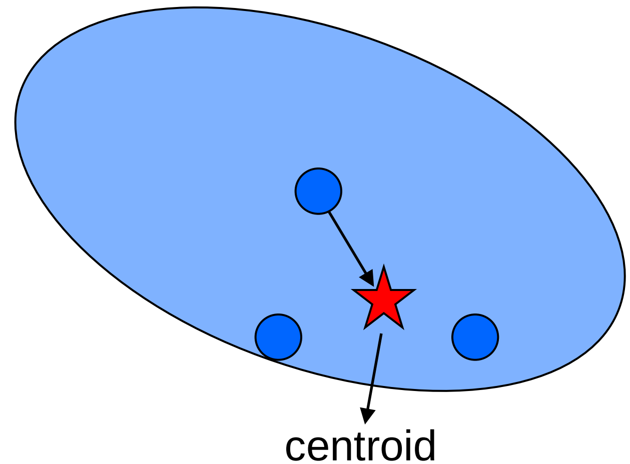
Seismicity Analysis
Earthquake Collapsing



uncertainty ellipsoid
- arrival time picking
- velocity model

Collapsing Seismicity Patterns
(Jones and Stewart,1997; Asanuma et al.,2001)

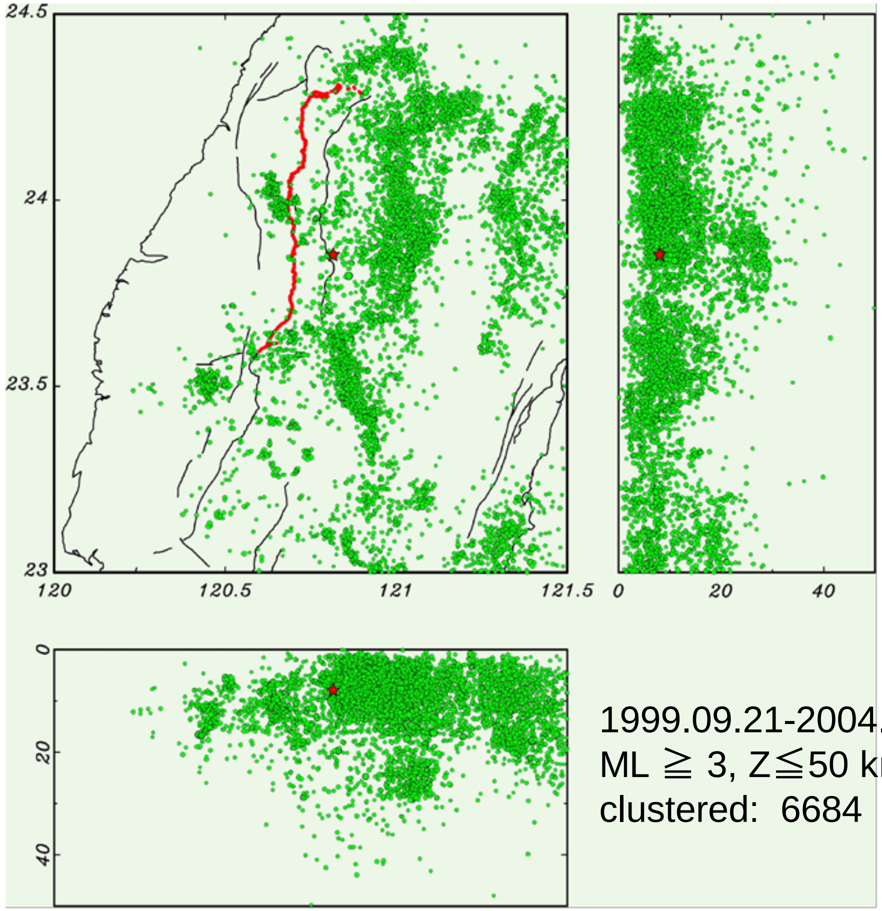


Location adjustment
- chi-square distribution
- degree of freedom
  - plane: one degree of freedom
  - line: two degrees of freedom
  - point: three degrees of freedom

- The locations of aftershocks are then adjusted by the hypocenter collapsing method.

Seismicity Analysis

Earthquake Collapsing



1999.09.21-2004.12.31,
ML ≧ 3, Z≦50 km
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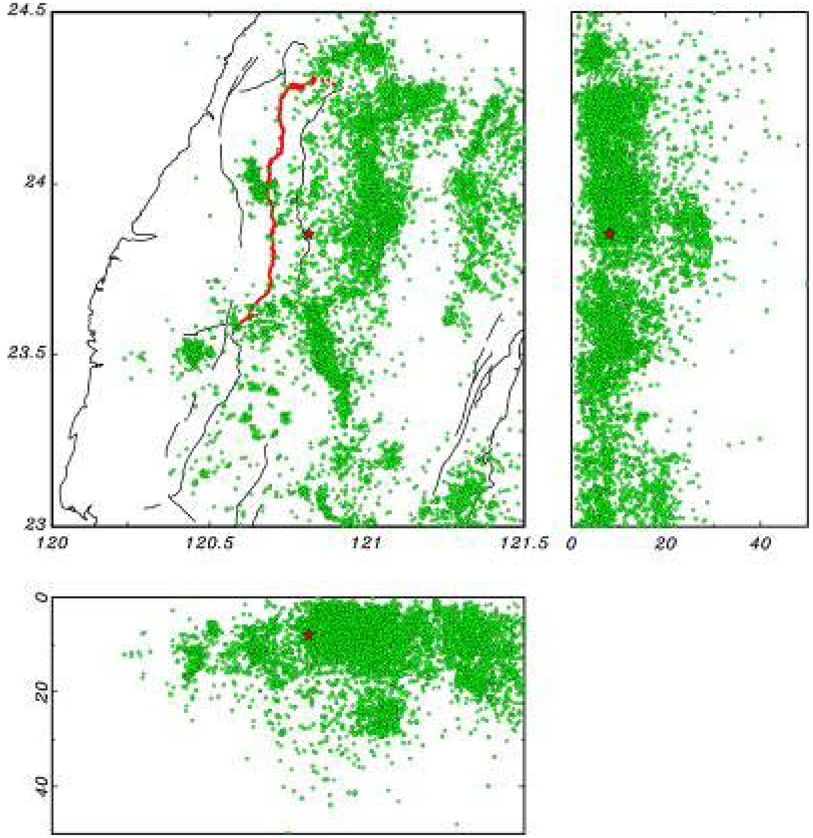
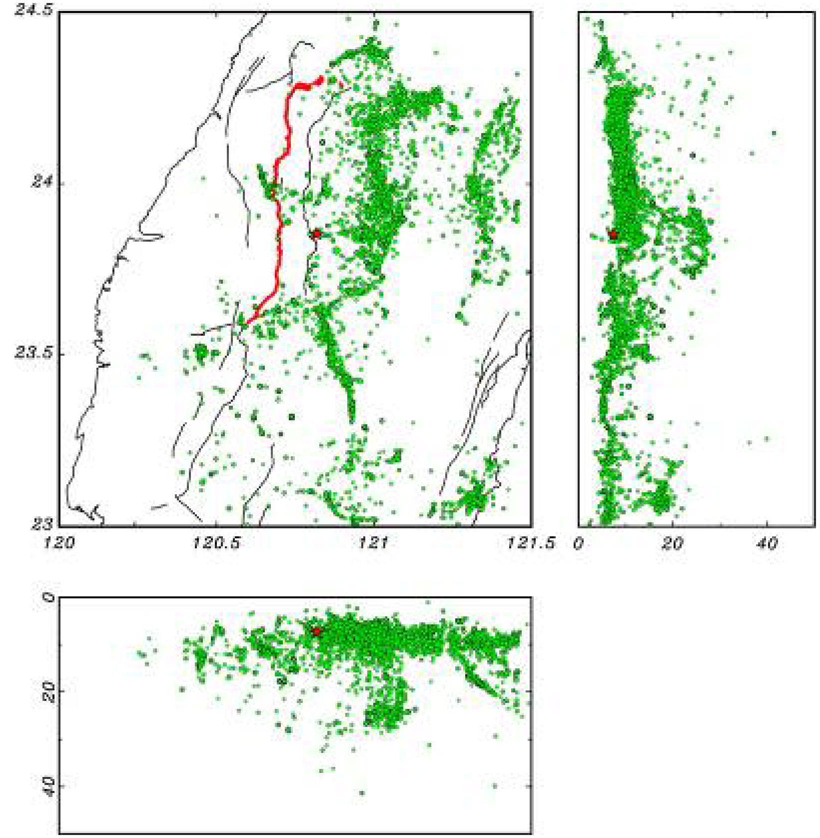
Seismicity Analysis
Earthquake Collapsing



Original pattern



Collapsed pattern

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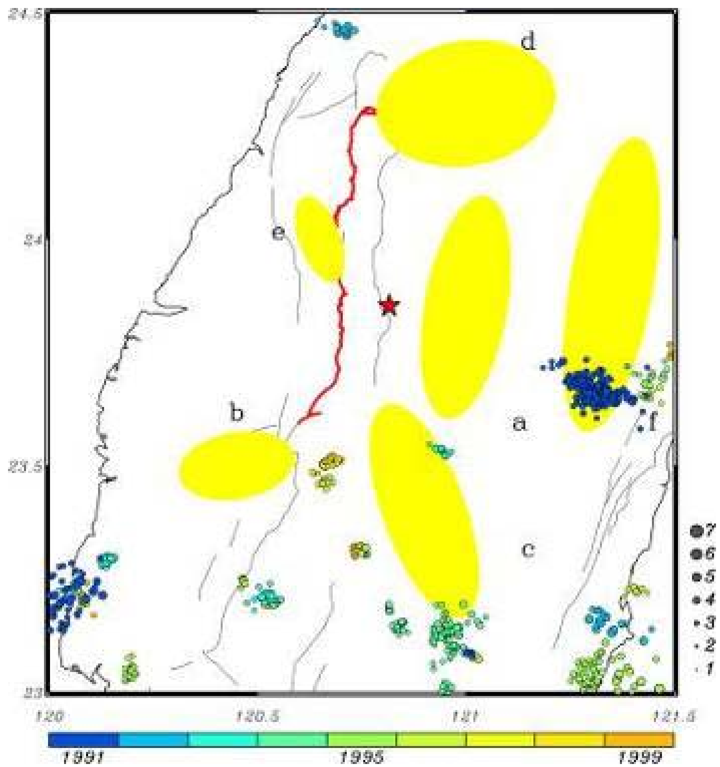
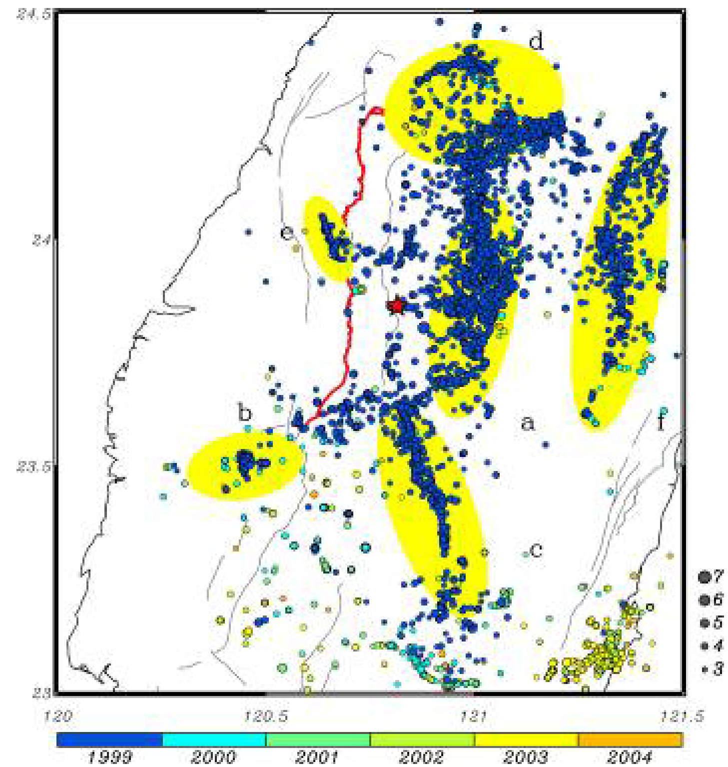
Seismicity patterns before and after the 1999 Chi-Chi earthquake



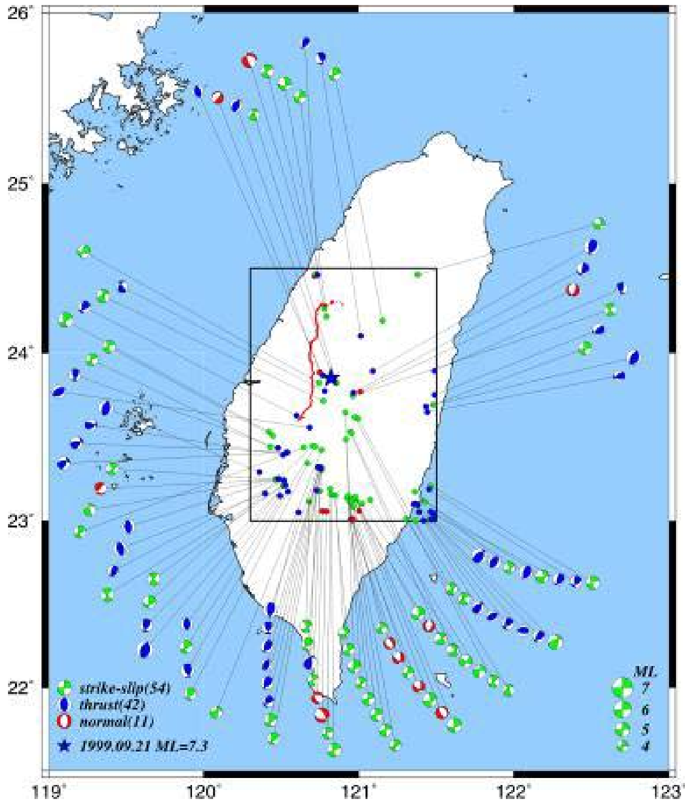
clustered : 684



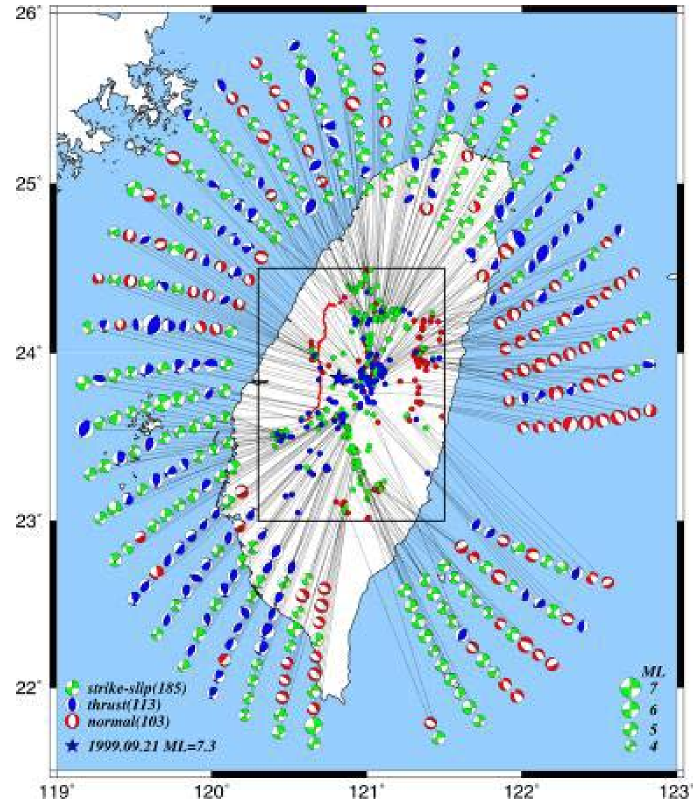
clustered and collapsed:6684

- The patterns of clustered earthquakes before (left) and after (right) the 1999 Chi-Chi earthquake.
- The results show 6 distinct groups of aftershocks.

Earthquake Focal Mechanisms



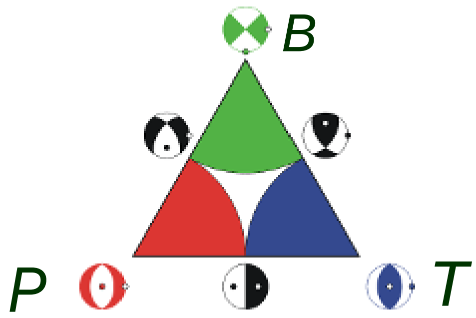
Pre-events：107



After- events：401

- Pre (left)- and post (right)- main shock of the 1999 Chi-Chi earthquake.
- Clearly, each type of aftershock focal mechanism occurred in clusters and formed dominant trends.

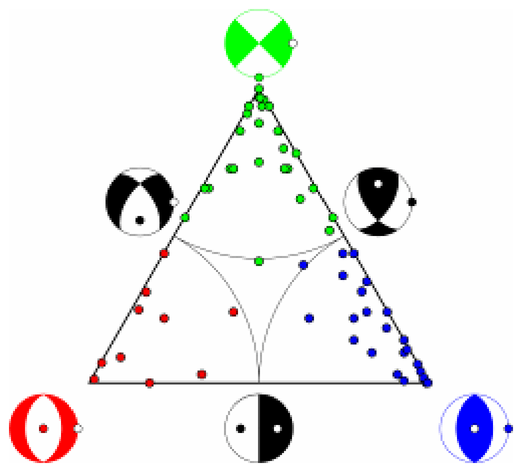
Classification of Earthquake Focal Mechanisms



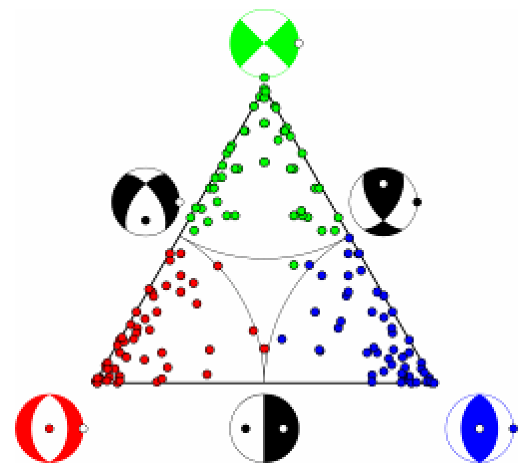
Frohlich's Triangle Diagram(1992)

$\sin^2\theta_P + \sin^2\theta_B + \sin^2\theta_T = 1$

θ_P, θ_B, θ_T are plunge angles of P,B,T axes



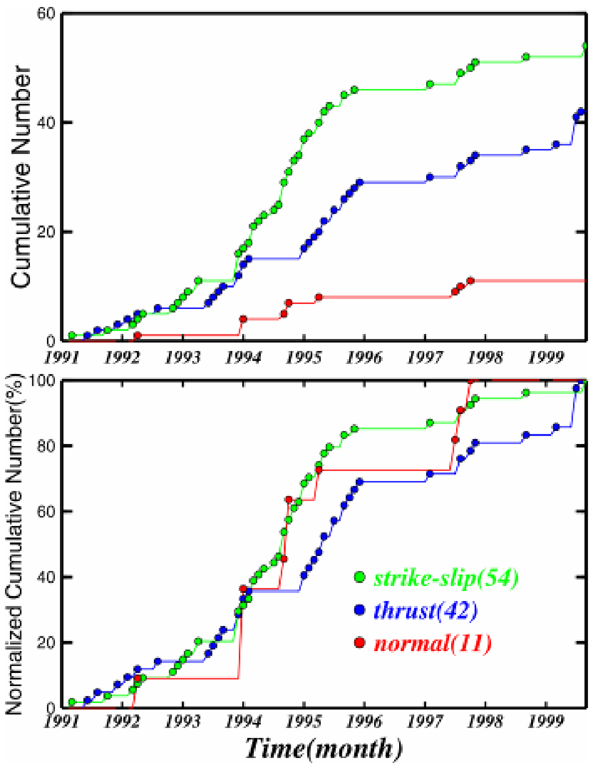
Pre-events：107



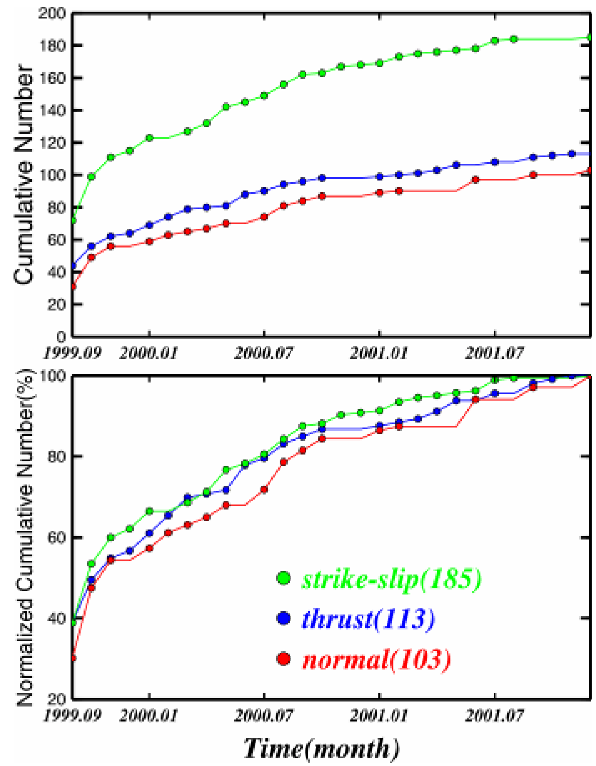
After- events：401

- The Frohlich's triangle diagram of pre (left)- and post (right)- main shock focal mechanisms of the 1999 Chi-Chi earthquake.

Characteristics of Temporal Patterns



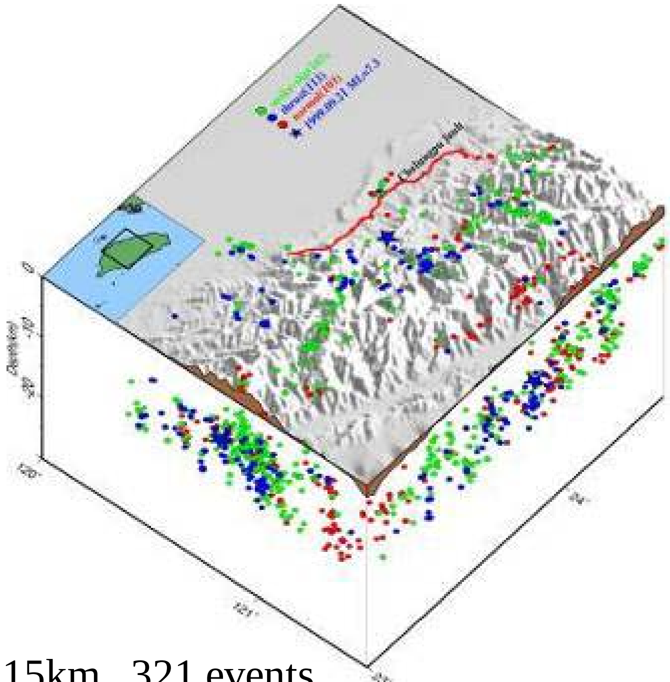
Pre-events：107



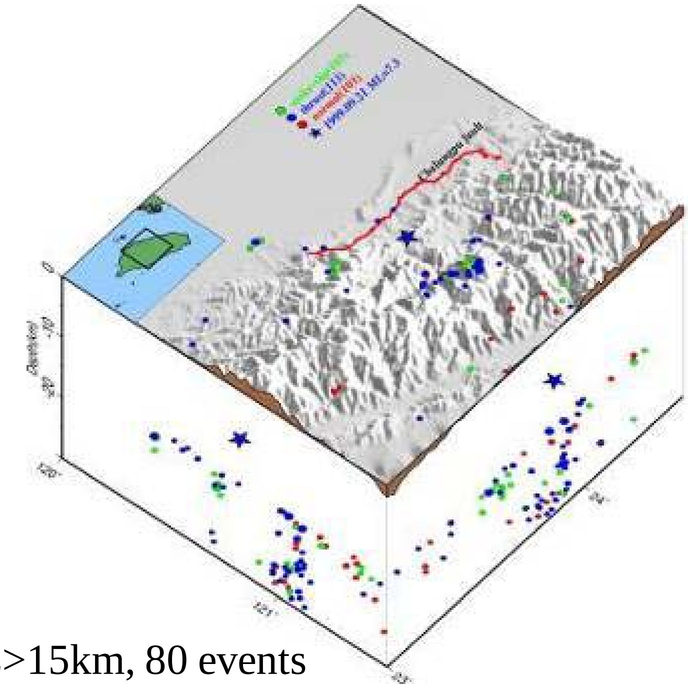
After- events：401

- It is worth noting that the relative ratios of the numbers of the three types of focal mechanism are almost constant throughout the three-year period after the Chi-Chi.

Characteristics of Spatial Patterns



Z ≦15km , 321 events
Strike-slip fault (green), 162 events (51%)
thrust fault (blue), 72 events (22%)
normal fault (red), 87 events (27%)



Z>15km, 80 events
Strike-slip fault (green), 23 events (29%)
thrust fault (blue), 41 events (51%)
normal fault (red), 16 events (20%)

- In the study of focal mechanisms, we found the larger and deeper earthquakes often exhibit thrust faulting whereas smaller and shallower earthquakes exhibit strike-slip type.

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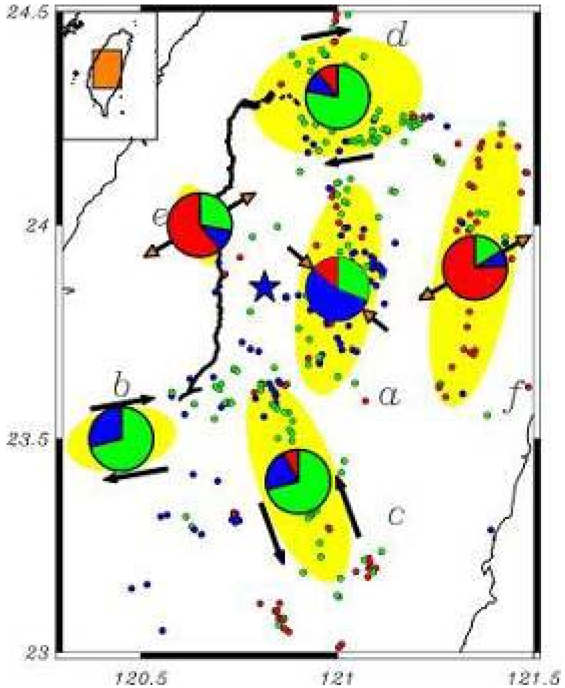
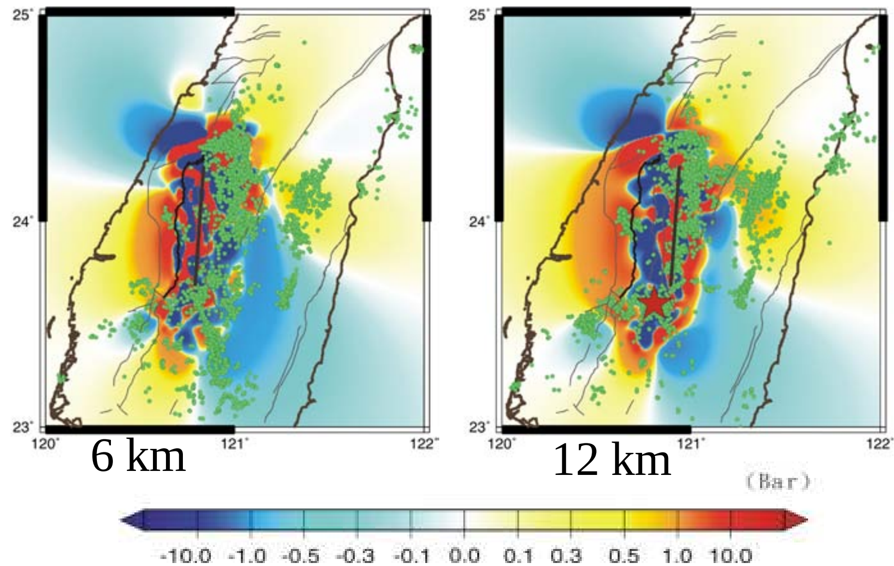
Dominant Stress Patterns

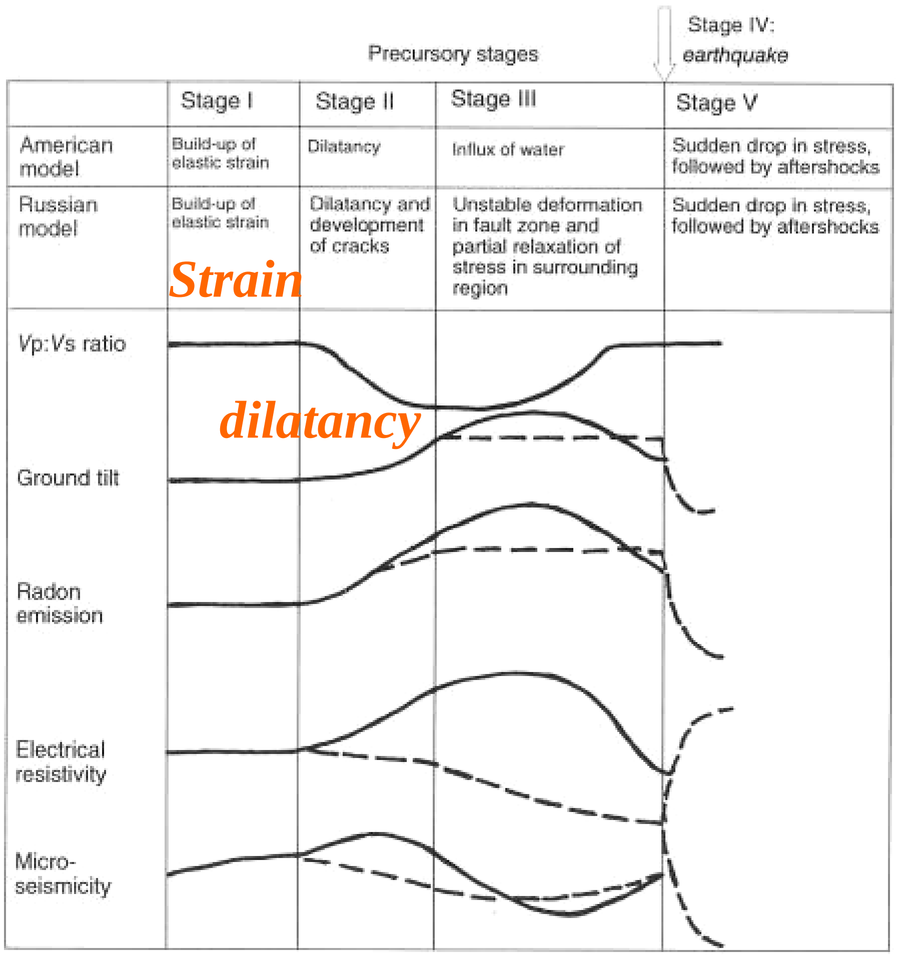




Stress Transfer (Ma et al., 2004)

- The fact that larger earthquakes are dominantly thrust faulting is a reflection of the regional crustal stress regimes in the Chi-Chi source.
- With respect to the Chelungpu fault, thrust faulting dominates the hanging wall areas to the east, strike-slip faulting near its southern and northern ends, and southeastern side, whereas normal faulting in its central part and to the eastern side of the Central Mountain Range.

Earthquake precursors studies



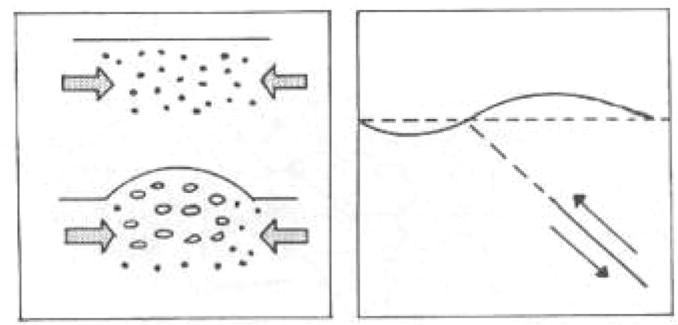
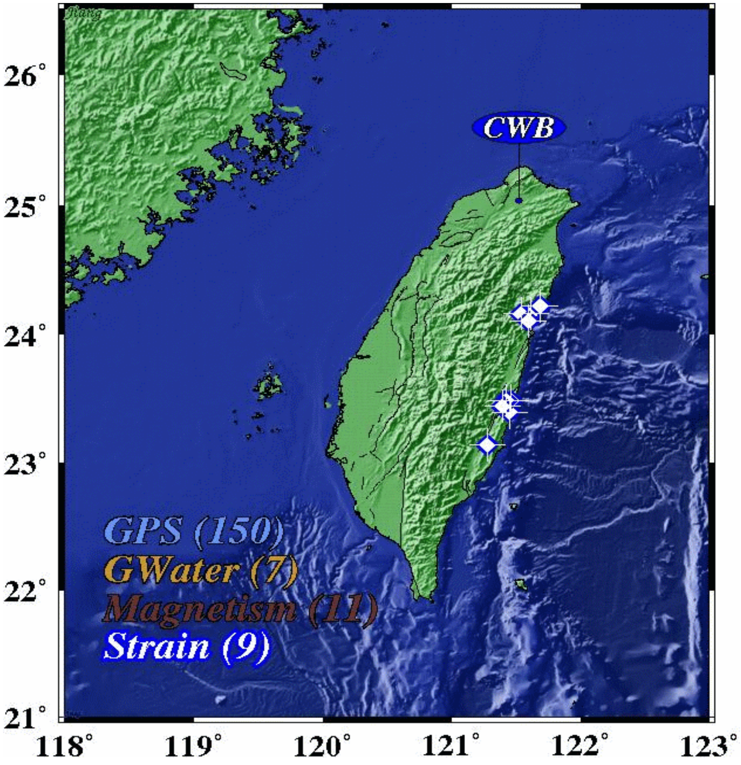


Figure 2.8 Expected changes in physical variables before an earthquake (Scholz et al. 1973: 806). Copyright 1976 by the AAAS.

The Geophysical Observations for Earthquake Precursors Studies in Taiwan



Taiwan Geophysical Network for Seismology (TGNS)

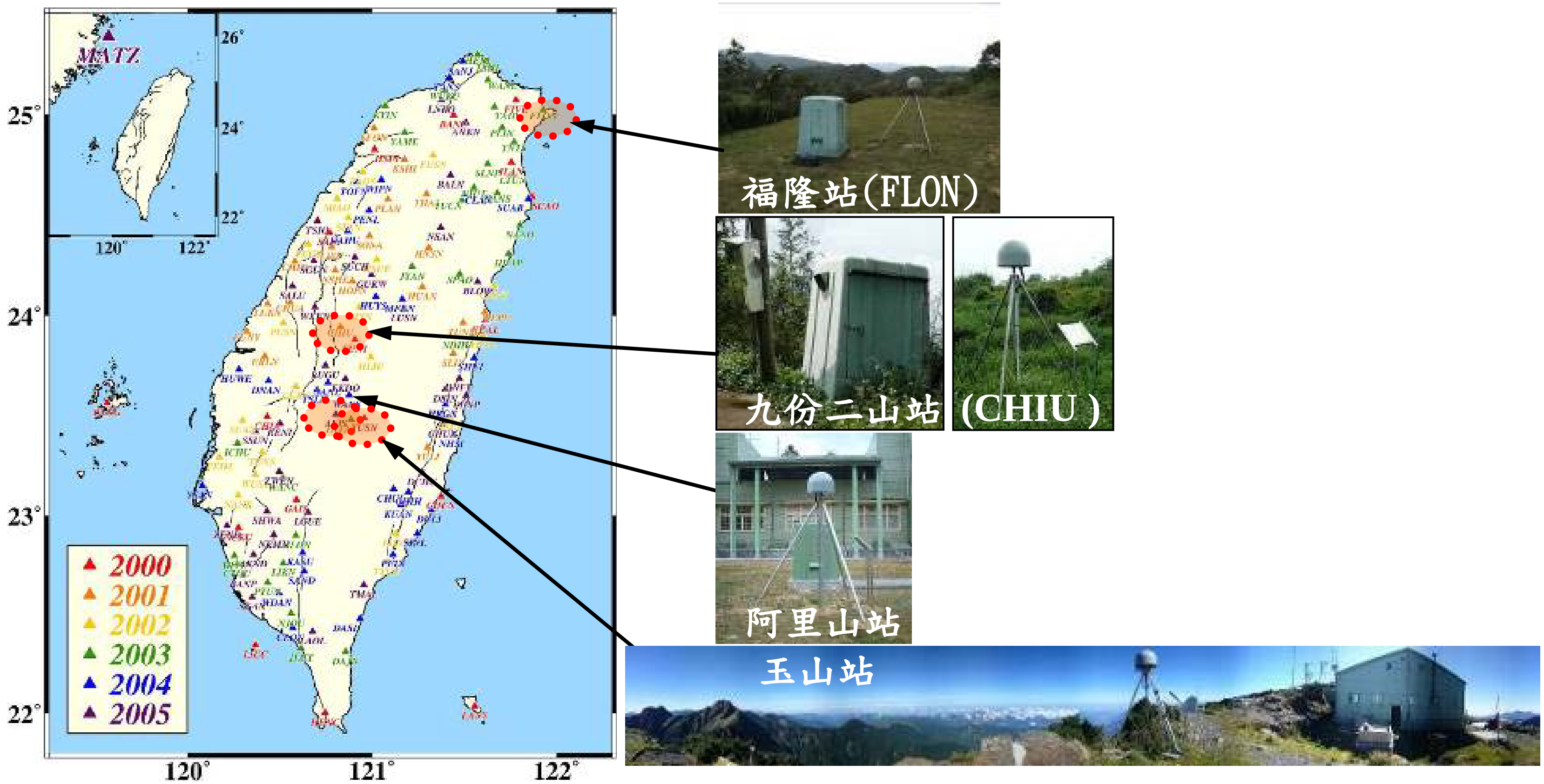
- GPS (150 stations)
- GPS-TEC
- Groundwater Level (7 stations)
- Magnetism (11 stations)
- Borehole Strain (9 stations)

- In the following slides, I am going to introduce the geophysical study of earthquake precursors by the CWB.

The CWB TGNS (Taiwan Geophysical Network for Seismology) consisits of:

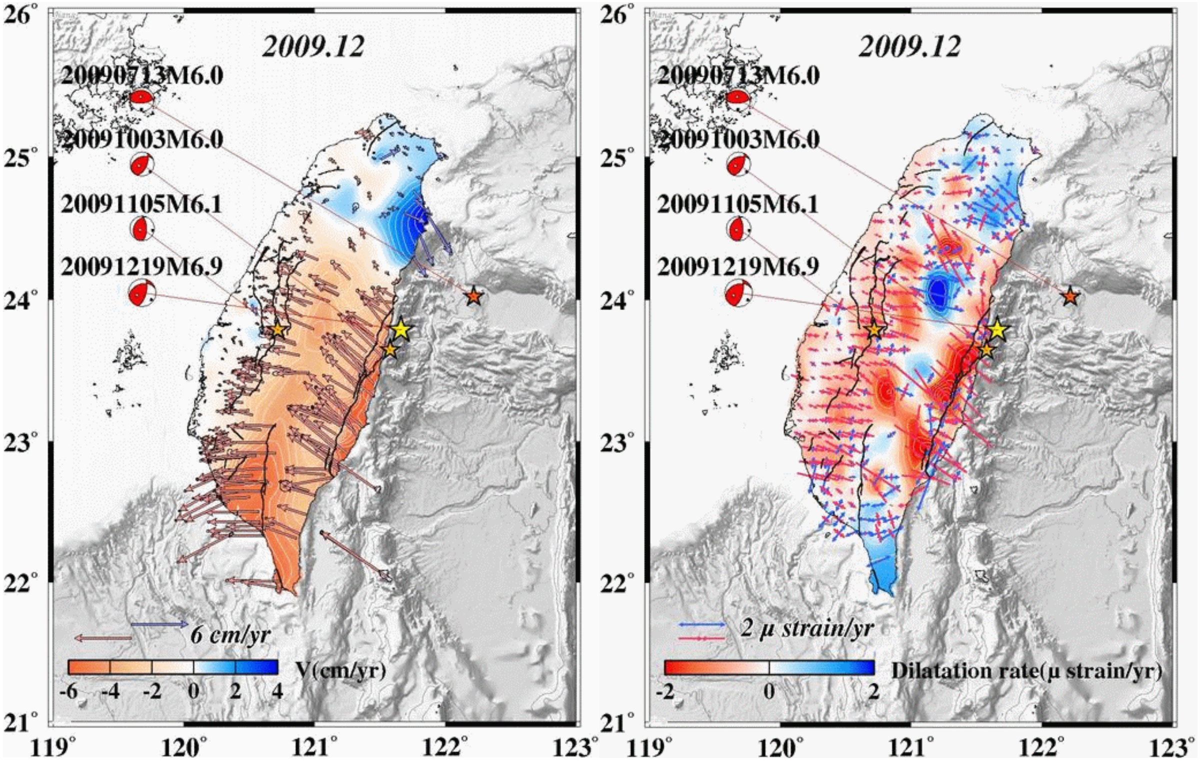
- 150 stations of the Global Positioning System (GPS) network.
- The variation of ionospheric total electron content (TEC) monitoring, by utilizing the GPS data.
- 7 stations of the groundwater seismic observation network.
- 11 stations of the geomagnetic network.
- 9 stations of the borehole strainmeter network (real-time data transmission in association with the Acdemia Sinica.)

Continuous CWB GPS array in Taiwan



- 150 stations of the Global Positioning System (GPS) network.

The GPS horizontal velocity field and crustal strain rate



Velocity $v_i = (1/T)u_i$ Strain $\varepsilon_{ij} = \dfrac{\partial u_i}{\partial x_j}$

- The GPS horizontal velocity field (left) and crustal strain rate (right).
- The principal strain rates are shown by arrows and color scale. Red color denotes contraction and blue color represents extension.

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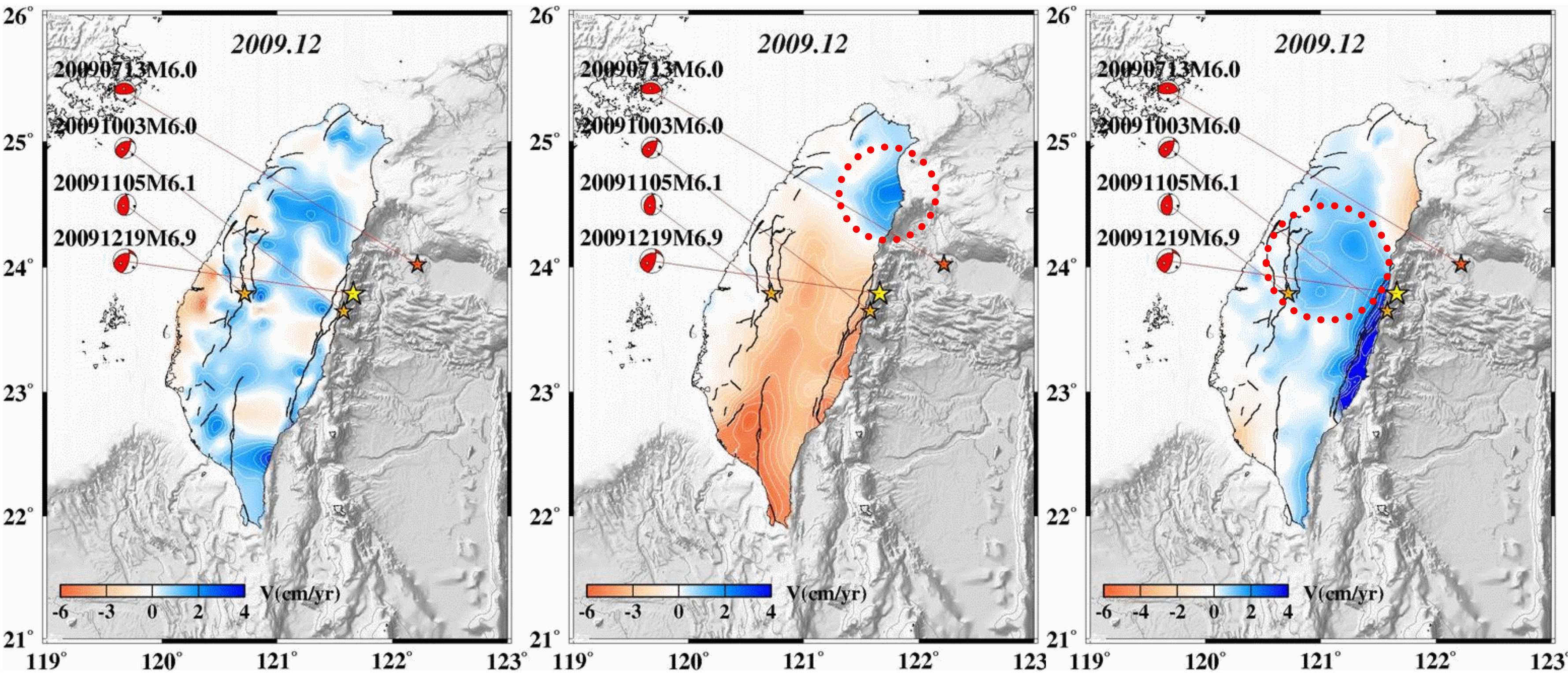
The 2009 GPS velocity field in Taiwan



Vertical-component *East-component* *North-component*

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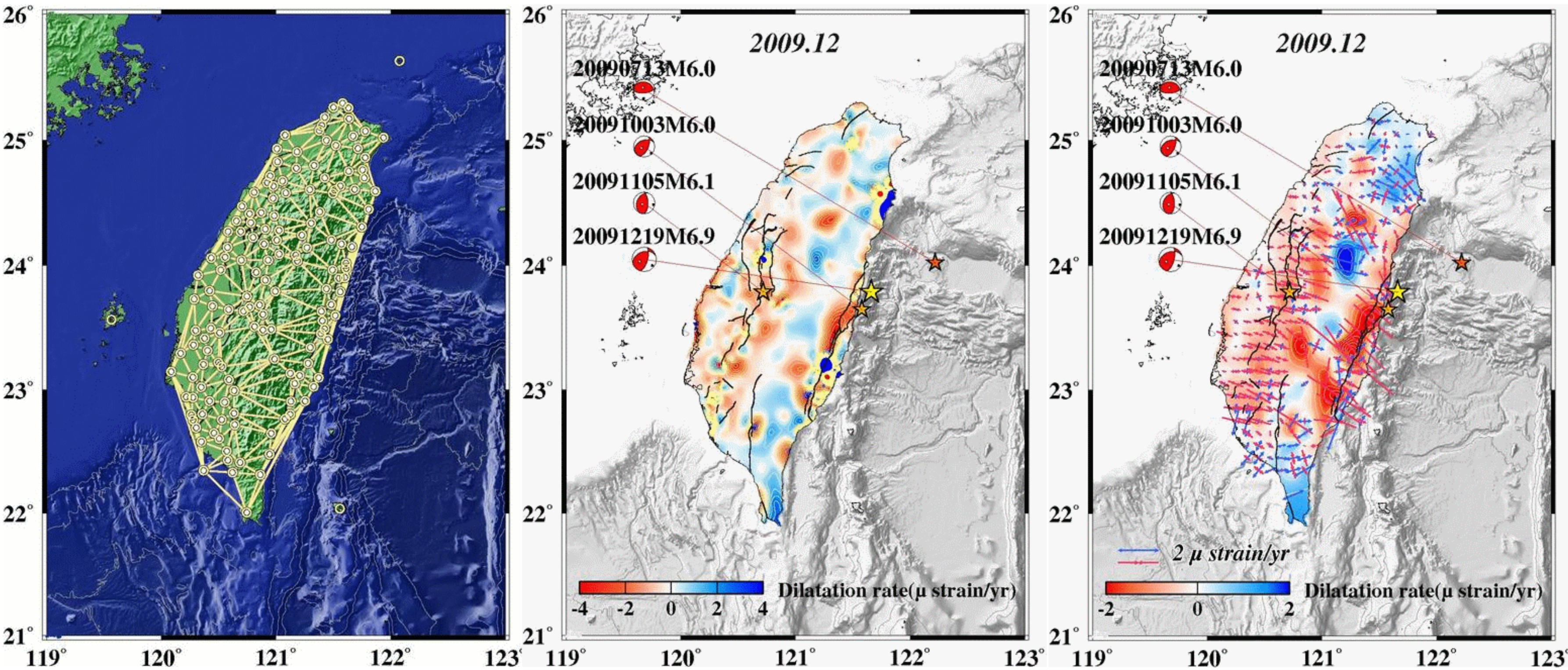
The GPS crustal strain rate



Delaunay triangulation

grid 0.5°×0.5°, moving 0.1

- The GPS crustal strain rate based on grid (right) and Delaunay triangulation (left).
- Red color denotes contraction and blue color represents extension.

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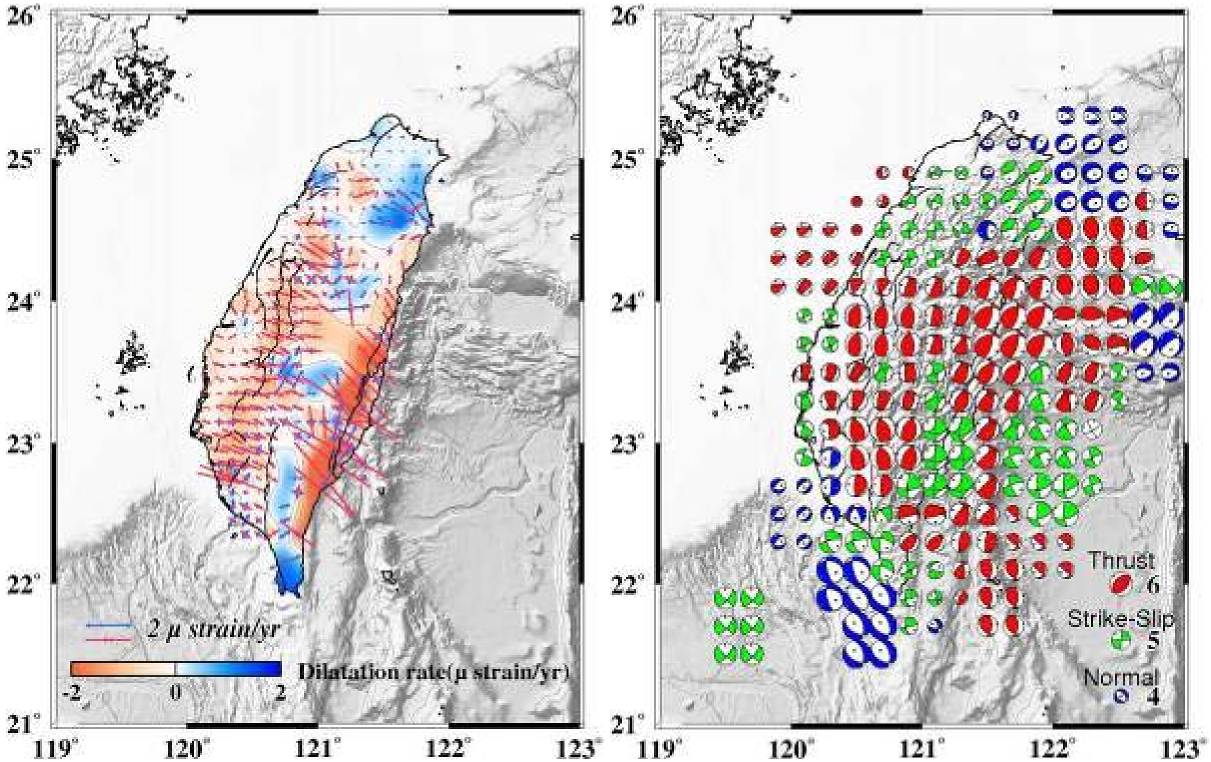
The GPS and Seismic Strain Rate in 2004-2010



GPS Strain Rate *Seismic Strain Rate*

- The results of composite analyses of seismic and GPS data can be summed up to the application of earthquake potential analyses.
- It indicates that the pattern of GPS strain and seismic strain are very consistent.

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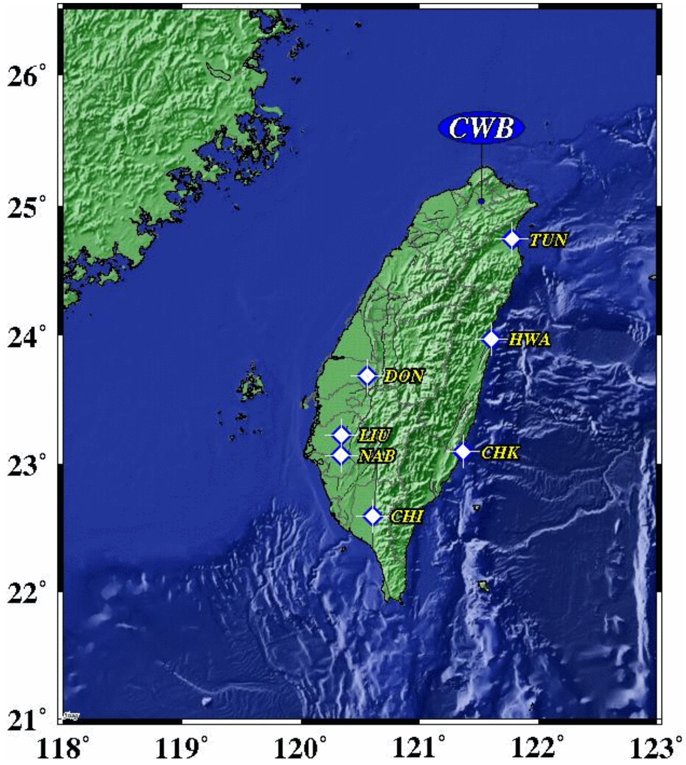
The Geophysical (groundwater level) Observations for Earthquake Precursors Studies in Taiwan



- HWA：2004/03~
  花蓮氣象站(含水層深度：140-160m)
- TUN：2005/01~
  宜蘭縣壯圍國小(130-150m)
- LIU：2005/01~
  台南縣六甲國小(204-222m)
- NAB：2005/01 ~
  台南縣那菝國小(135-147m)
- DON：2006/01 ~
  雲林縣東和國小(222-252m)
- CHI：2006/01 ~
  屏東縣赤山國小(199.6m)
- CHK：2007/07 ~
  成功氣象站

- The 7 stations of the groundwater seismic observation network. This figure shows the layout of the groundwater station.
- Monitoring changes of the groundwater level may help us learn of about earthquake precursors.

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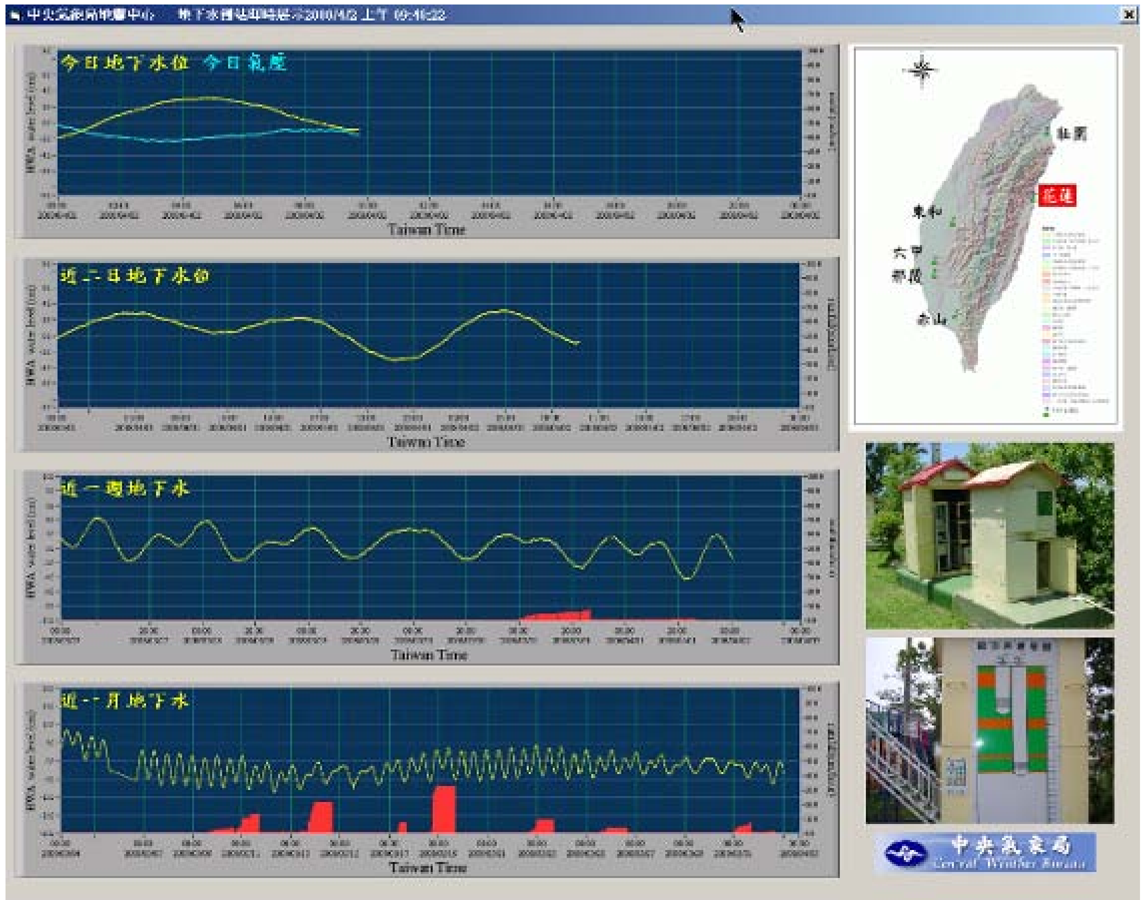
Monitoring of groundwater level in Taiwan

Today

Recent two day

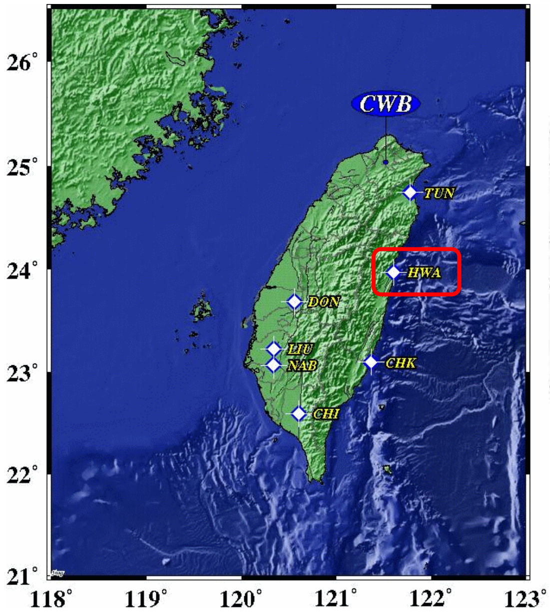
Recent one week

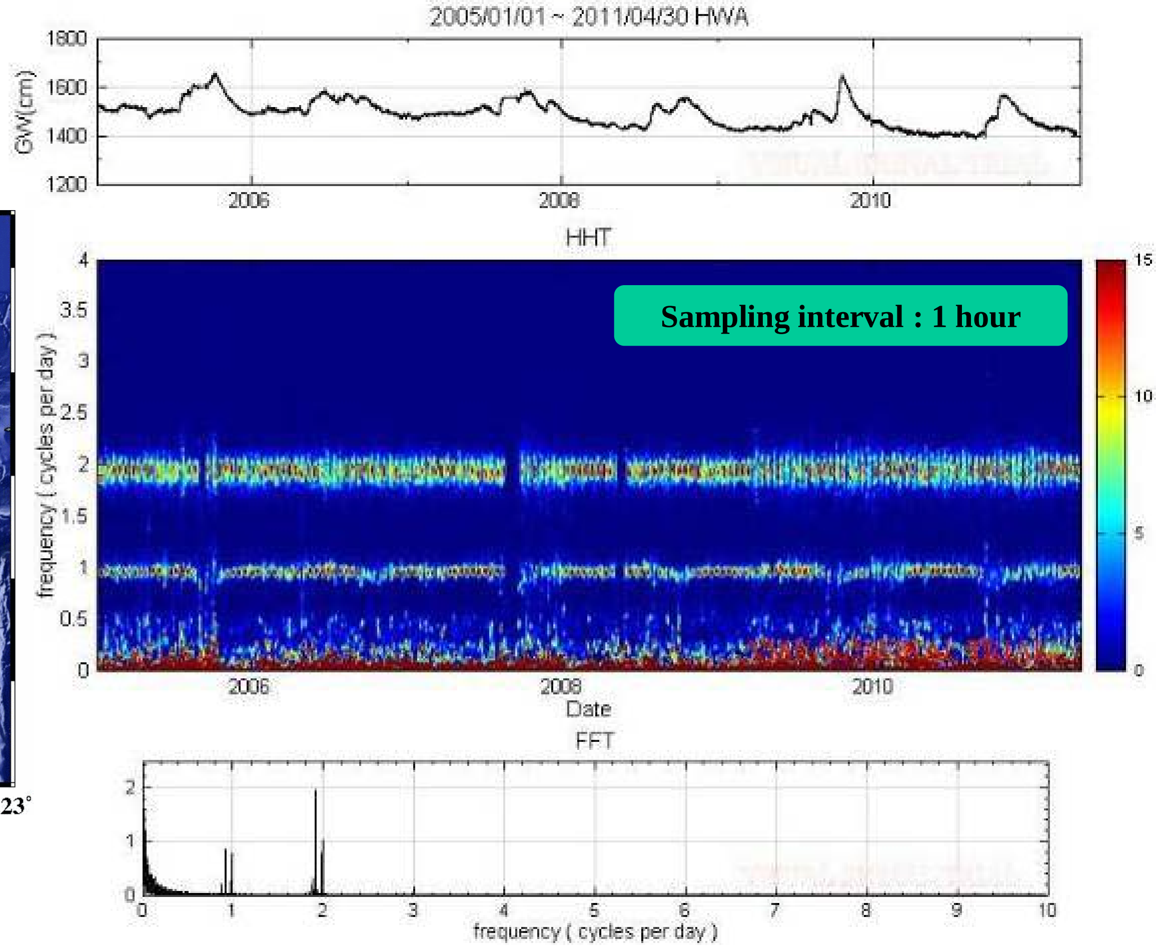
Recent one month



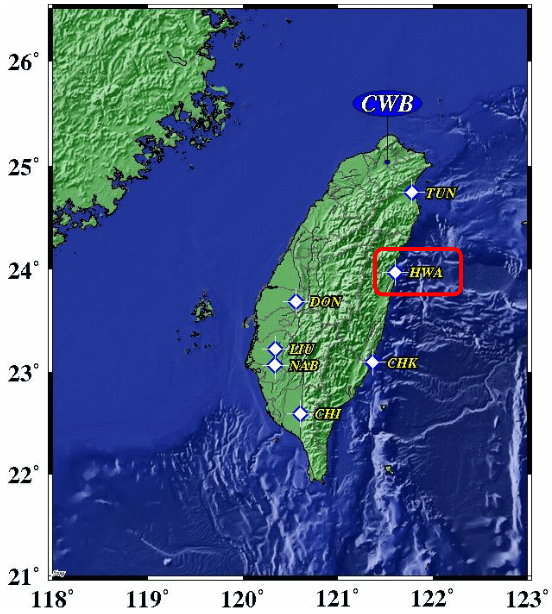
- The real-time data (**1 sample per second)** are transmitted to Taipei headquarters through ADSL or leased line.

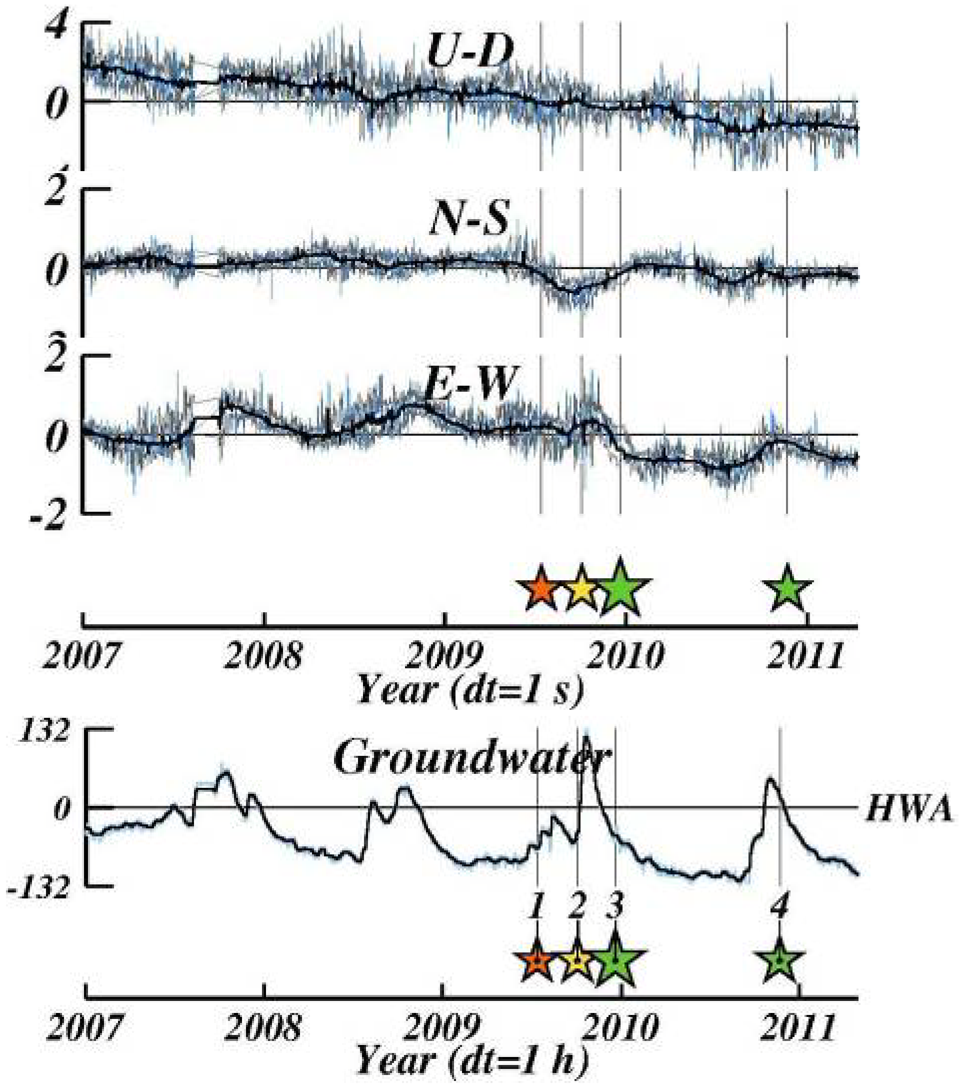
The FFT and HHT of groundwater level data





The correlation of groundwater level and GPS displacement





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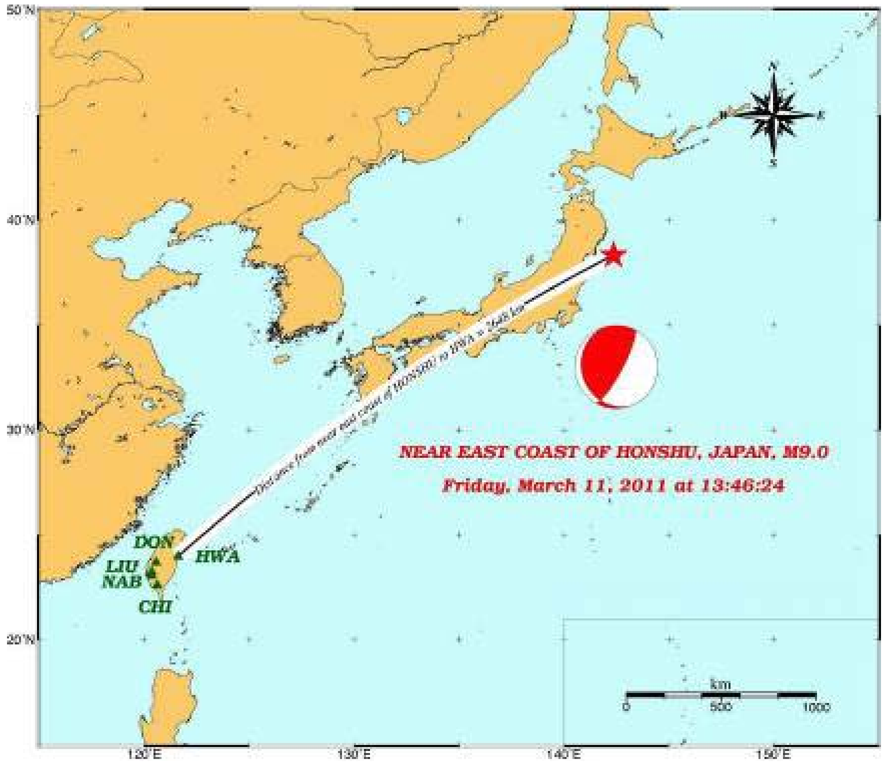
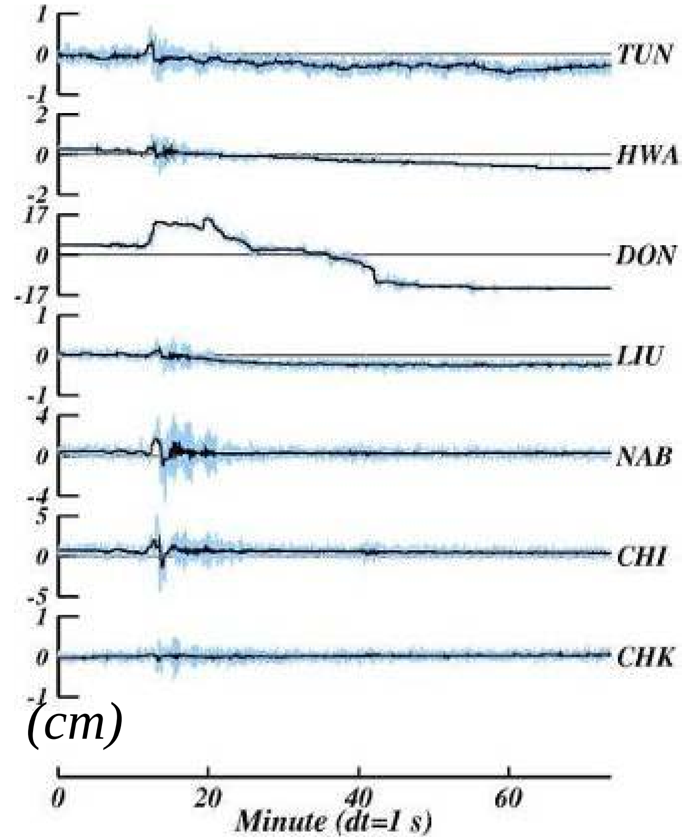
The co-seismic changes of groundwater level of the 2011-03-11 Mw9.0 Japan earthquake





- When the devastating earthquake occurred on March 11, 2011 in Japan, the CWB groundwater stations had observed variations of the groundwater level, the co-seismic changes brought by the seismic wave.

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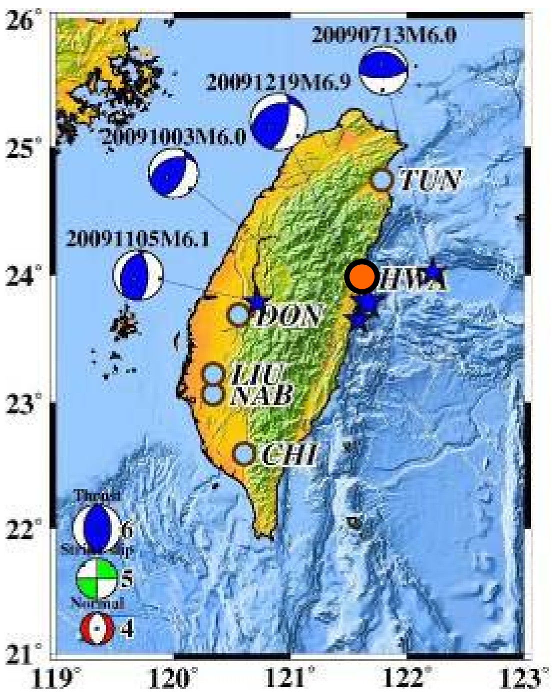
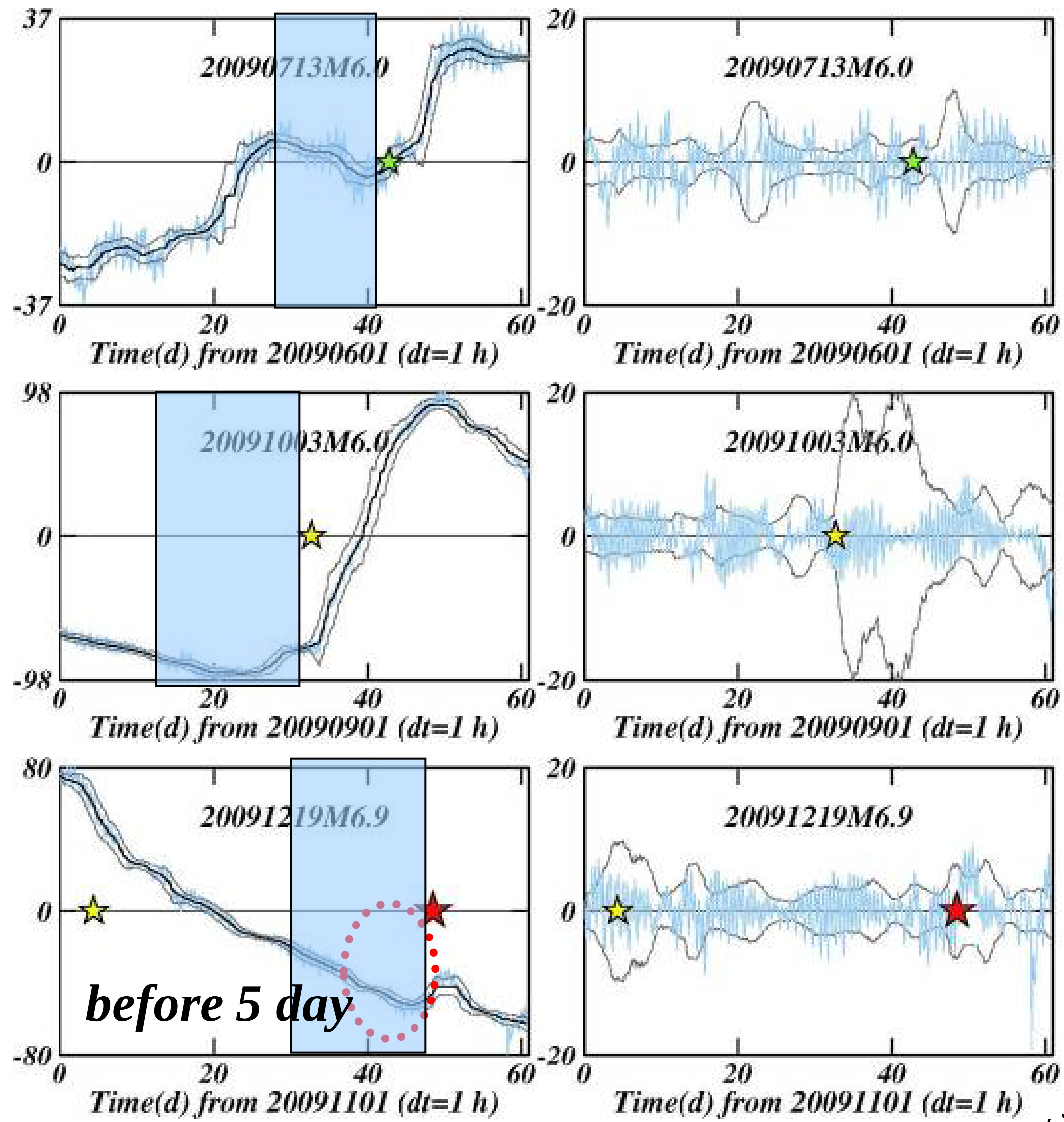
The signal decomposition of groundwater level data





The moving median and interquartile range

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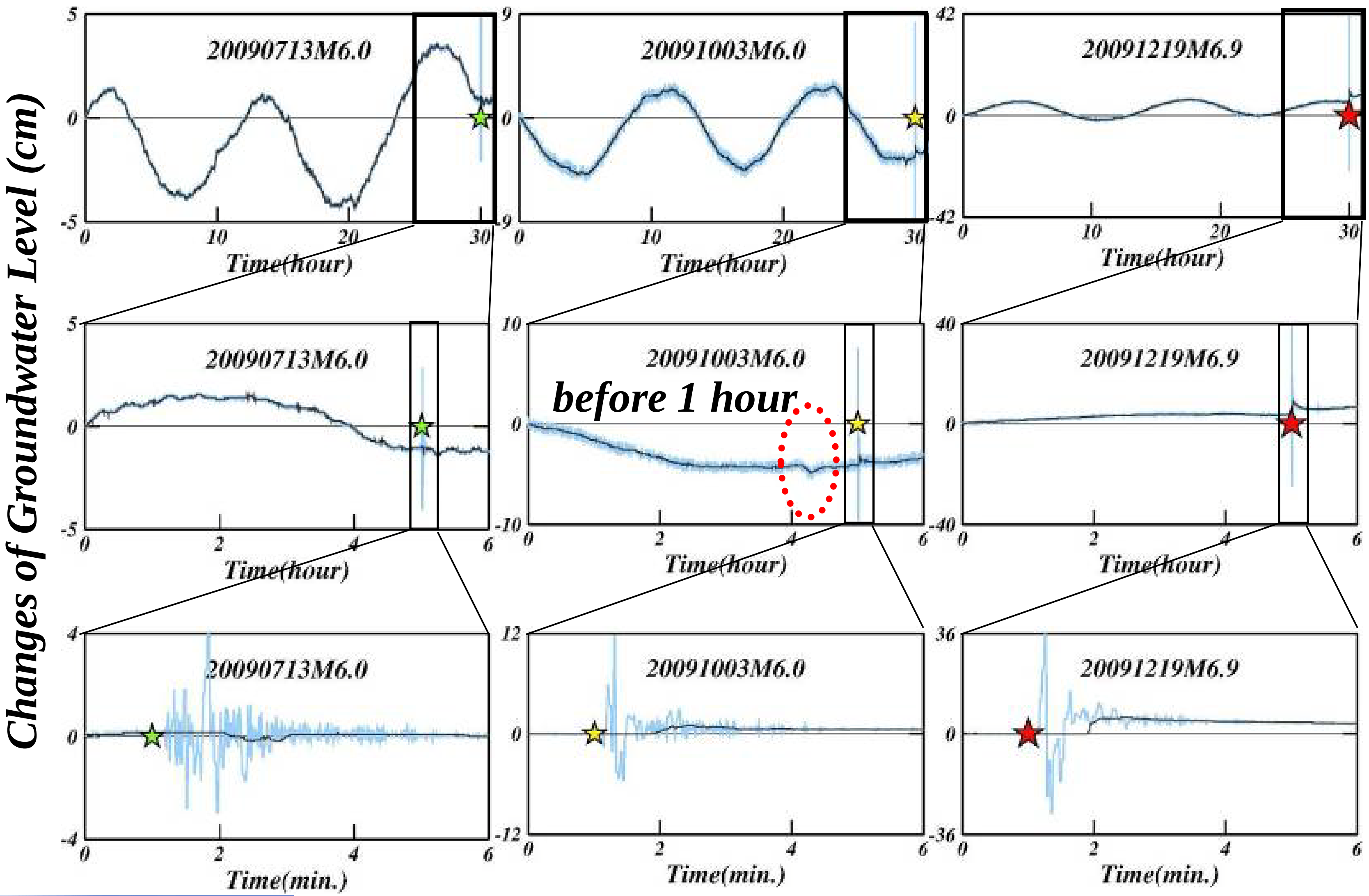
The observations of groundwater level



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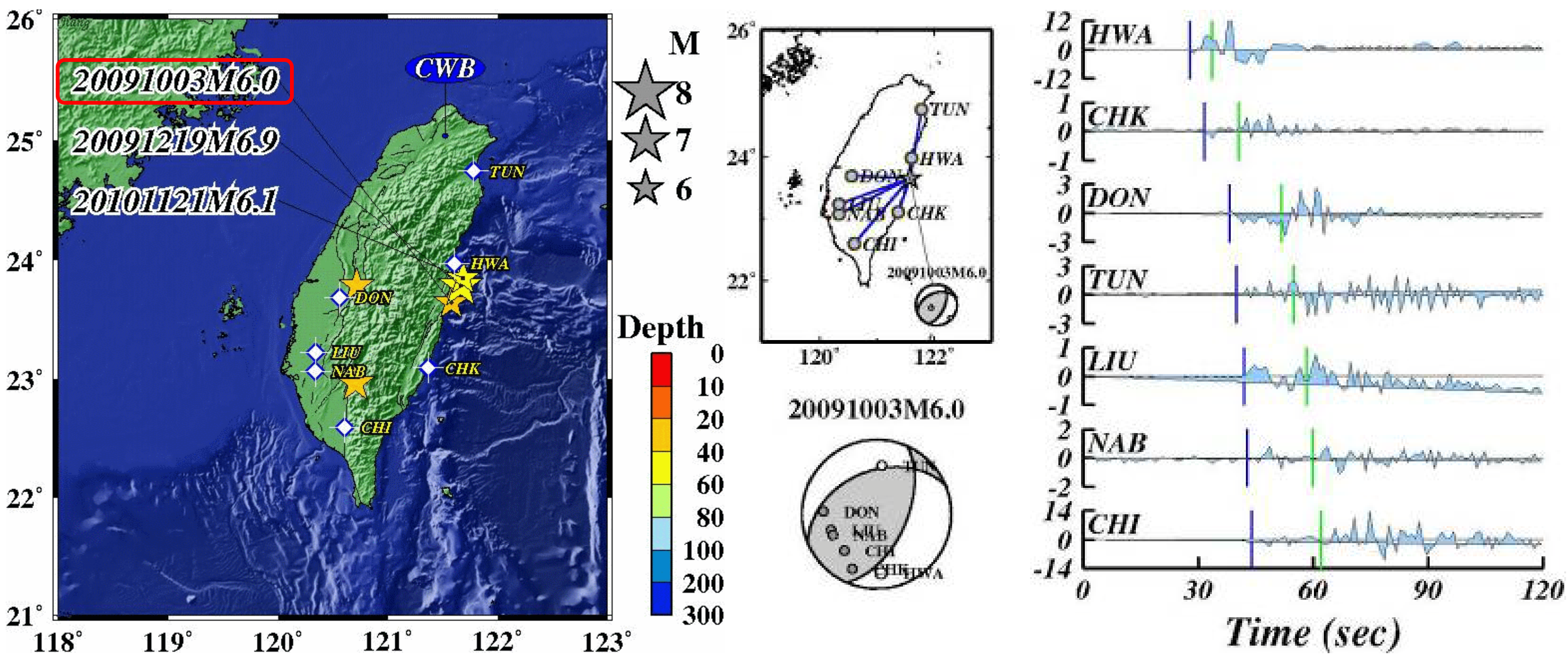
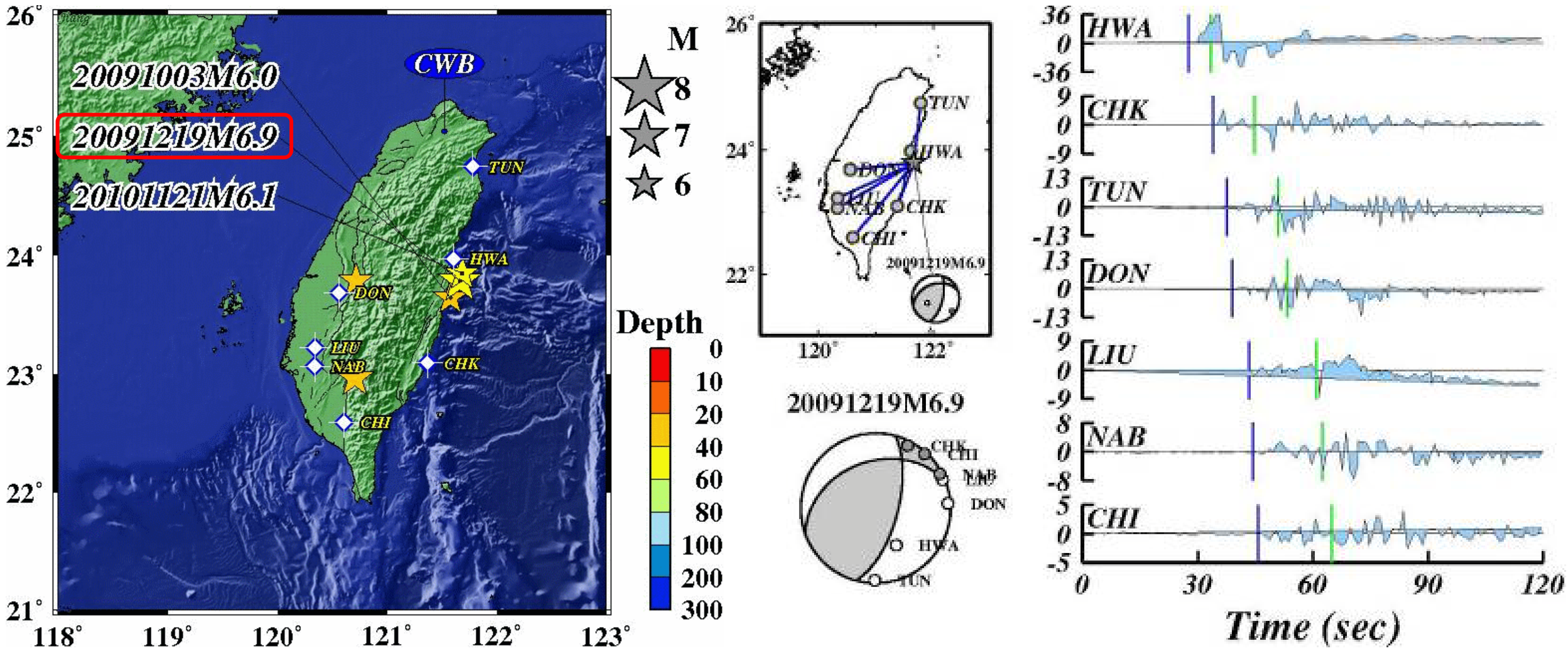
The correlation of co-seismic groundwater level variation and earthquake focal mechanism



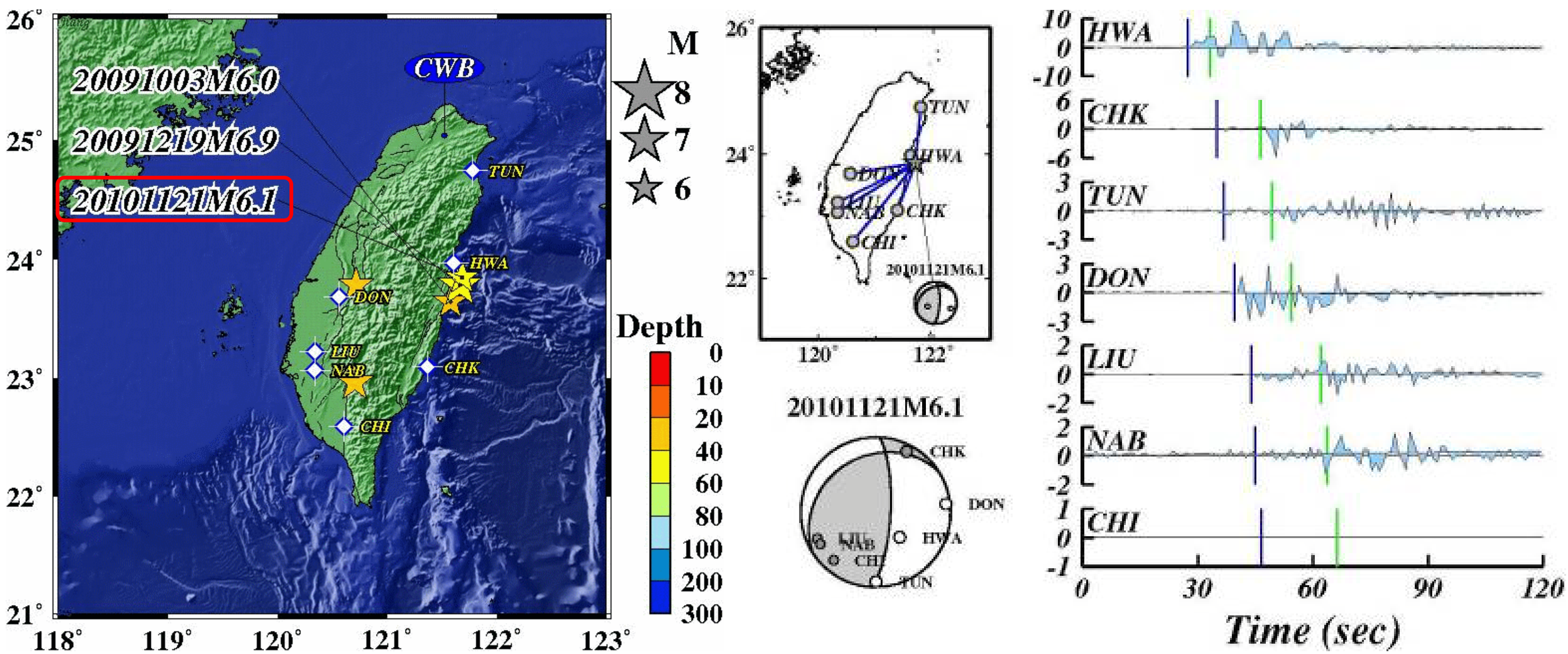
Earthquake sequence - foreshock

The correlation of co-seismic groundwater level variation and earthquake focal mechanism



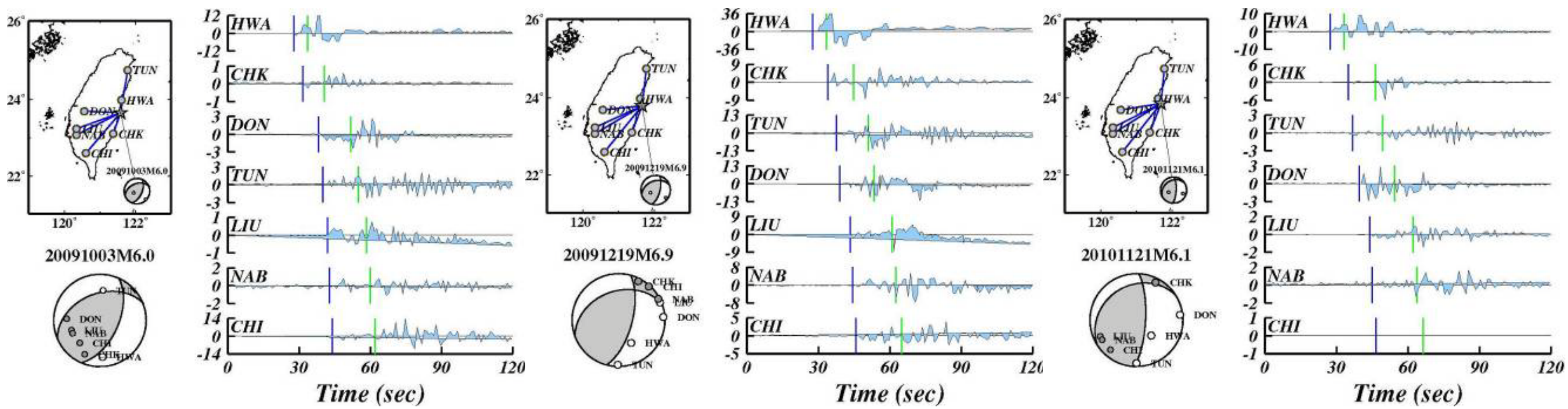
Earthquake sequence - mainshock

The correlation of co-seismic groundwater level variation and earthquake focal mechanism



Earthquake sequence - aftershock

The correlation of co-seismic groundwater level variation and earthquake focal mechanism



foreshock mainshock aftershock

Earthquake sequence

- It is useful that if we can identify the foreshock, mainshock and aftershock of an earthquake sequence based on groundwater level variation and focal mechanism.

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Conclusions

- Up to the present time, it is very hard to predict the time of occurrence, location and magnitude of a strong earthquake. However, studies of seismic precursor are actively underway in Taiwan. We also have been working with seismologists in the world for such studies.
- A long time seismic quiescence is needed for the strain energy to be stored again up to a critical level to generate the next potential strong earthquake over the same seismic zone.
- As a significant precursor to large earthquake, pre-seismic geophysical anomalies can play an important role in earthquake prediction, possibly providing useful information on its location, time and size.

Thank you very much.