Monitoring of Active Faults in Taiwan by Geodetic Measurements

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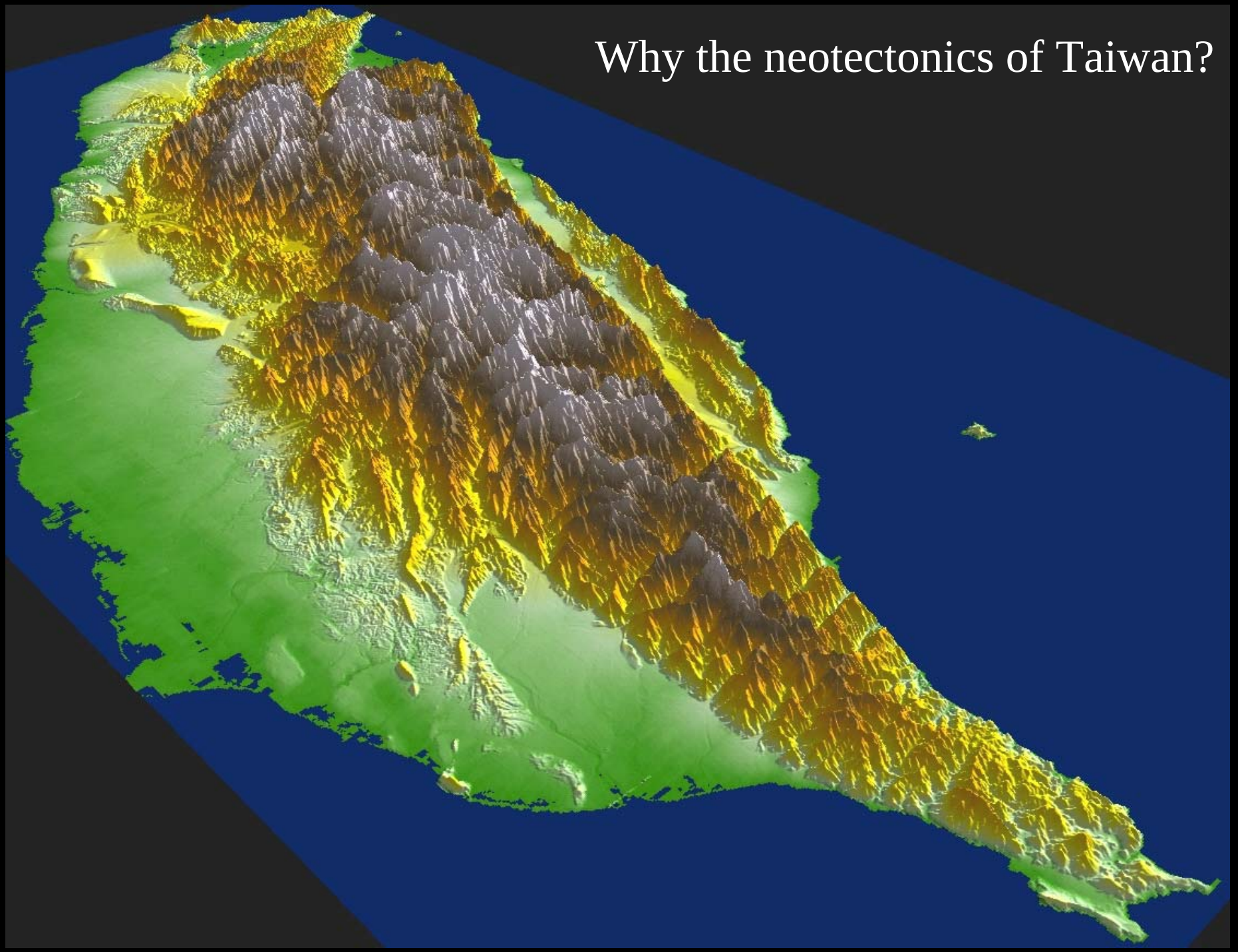
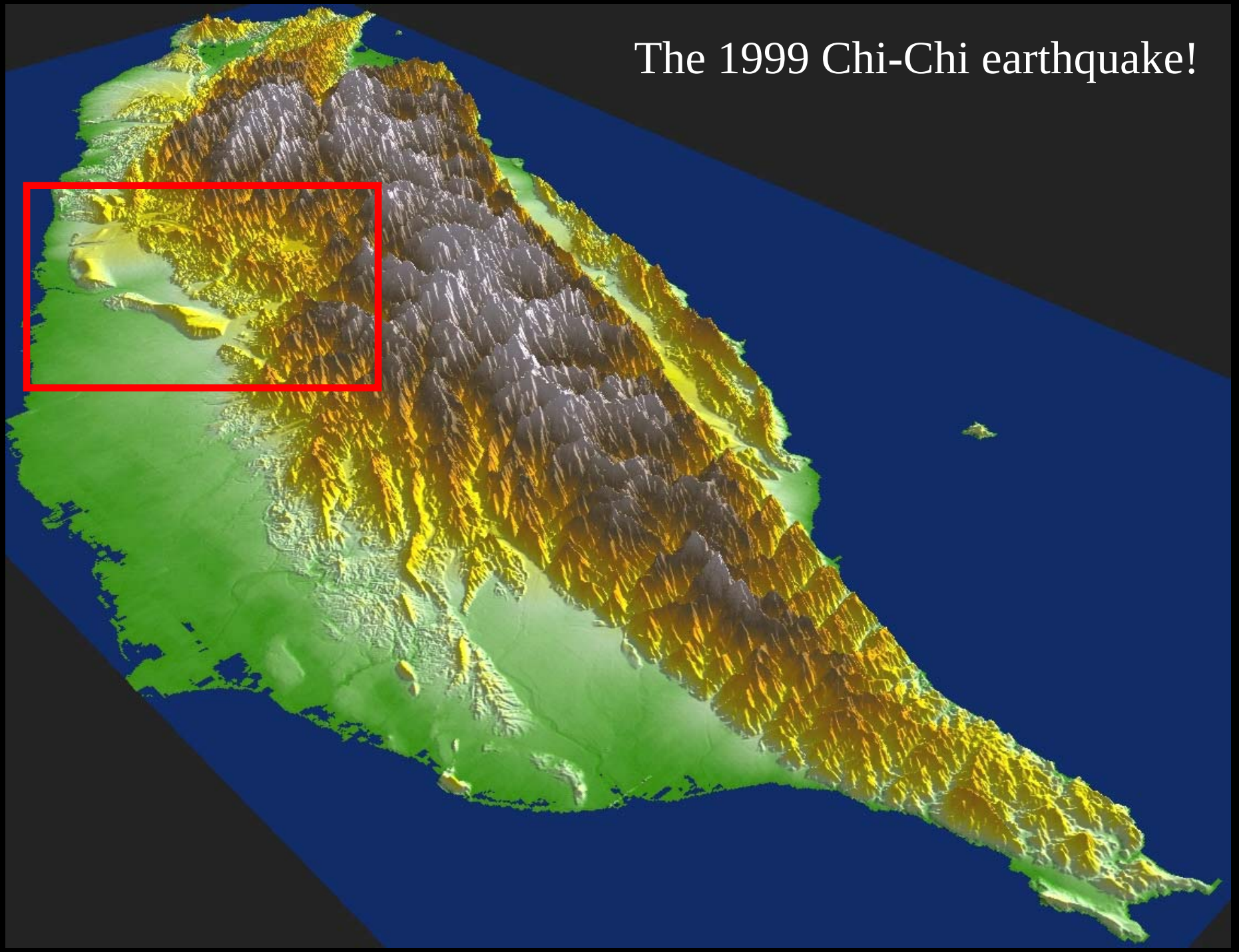
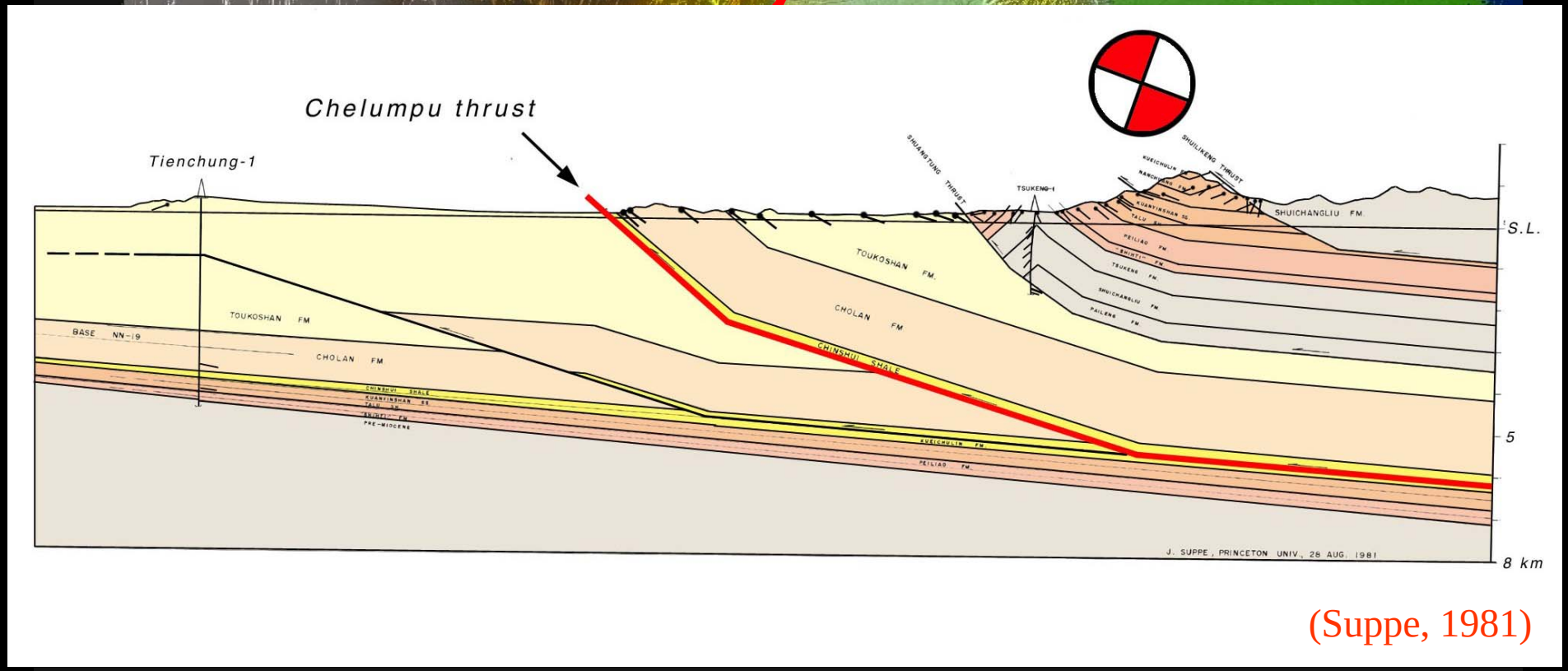
[2]Department of Earth Sciences, National Cheng Kung University, Tainan, Taiwan

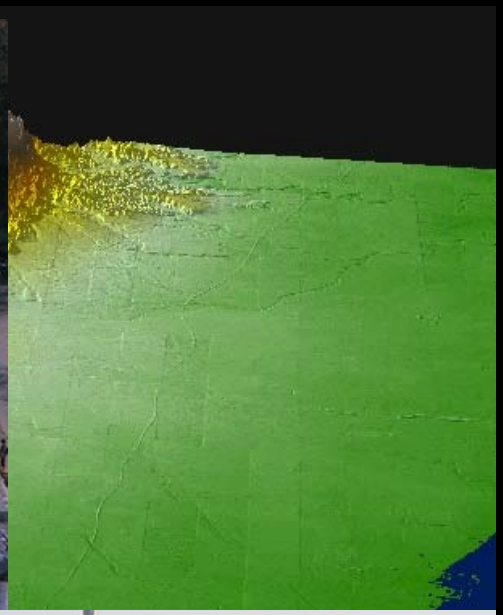
[3]Central Geological Survey, MOEA, Taipei, Taiwan

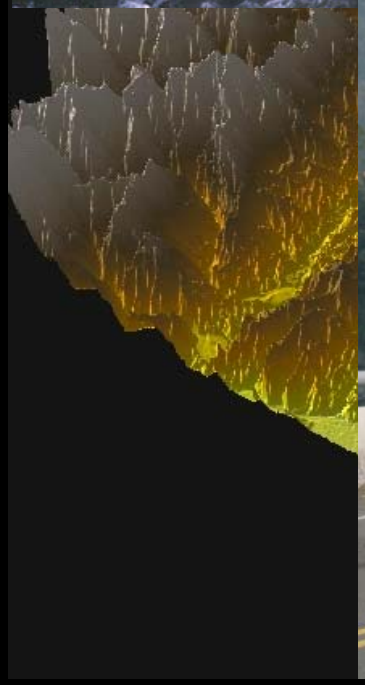

Why the neotectonics of Taiwan?

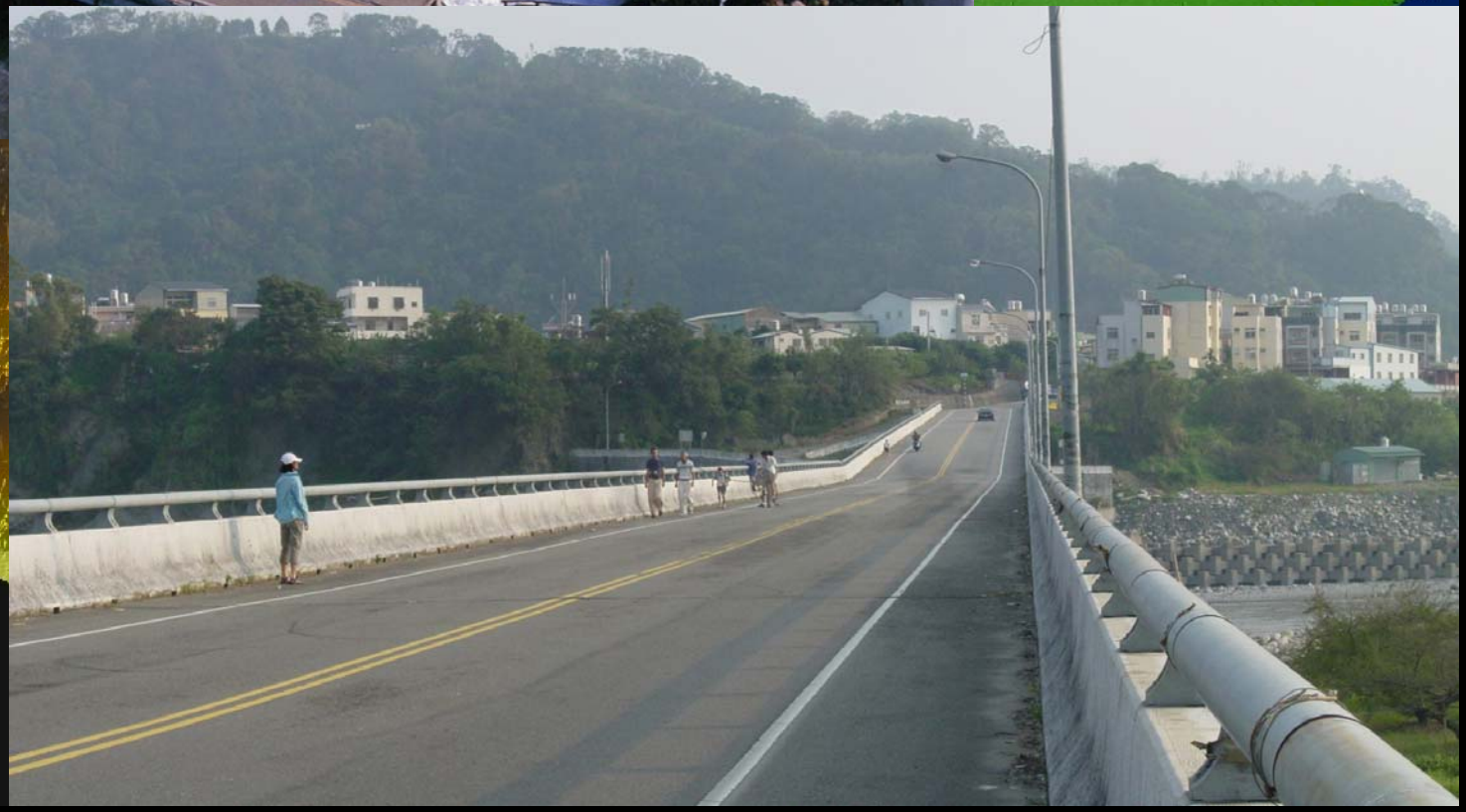

The 1999 Chi-Chi earthquake!


Chelumpu thrust
Tienchung-1
TSUKENG-1
SHUANGTUNG THRUST
SHUILIKENG THRUST
TOUKOSHAN FM.
CHOLAN FM
CHINSHUI SHALE
SHUICHANGLIU FM.
BASE NN-19
J. SUPPE, PRINCETON UNIV., 28 AUG. 1981
S.L.
5
8 km

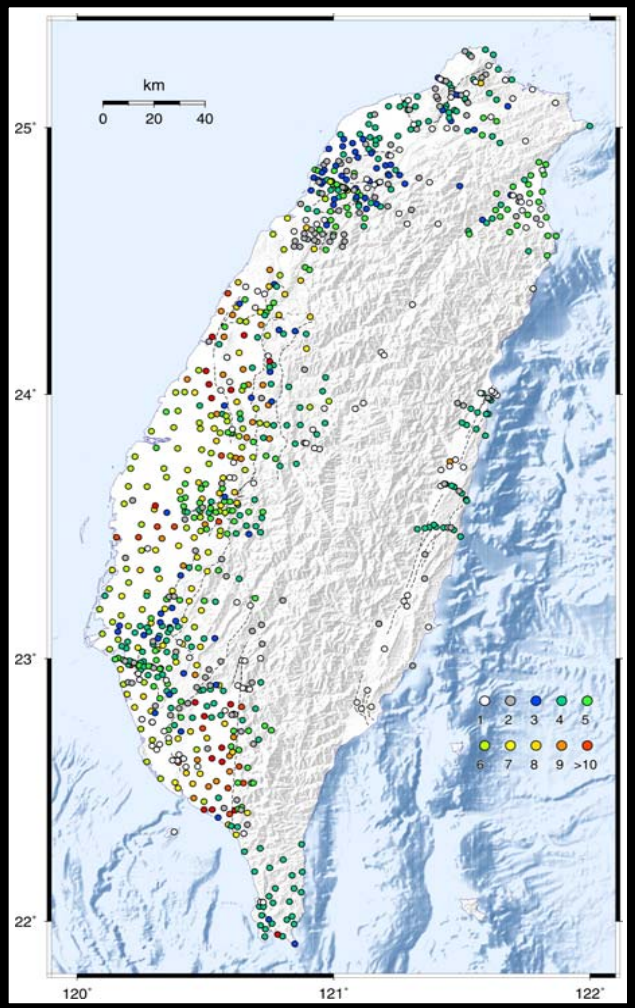
(Suppe, 1981)

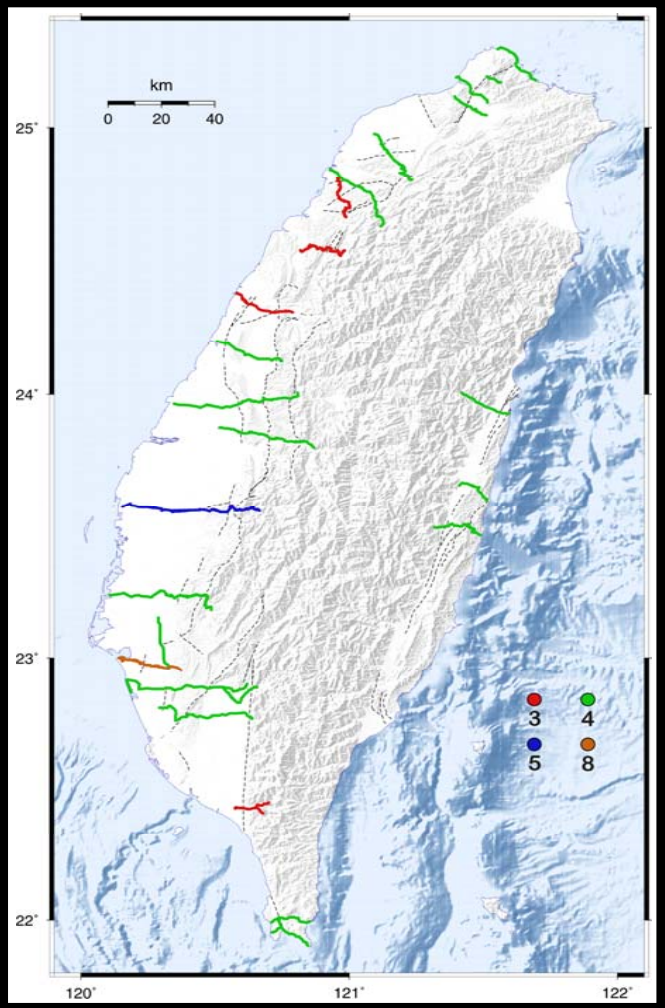






TAIGA: Taiwan Geodetic Array





Central Geological Survey, MOEA
經濟部中央地質調查所

Taiwan Geodetic Array
TAIGA

TAIGA First Phase 2002-2006

TAIGA Second Phase 2007-2011

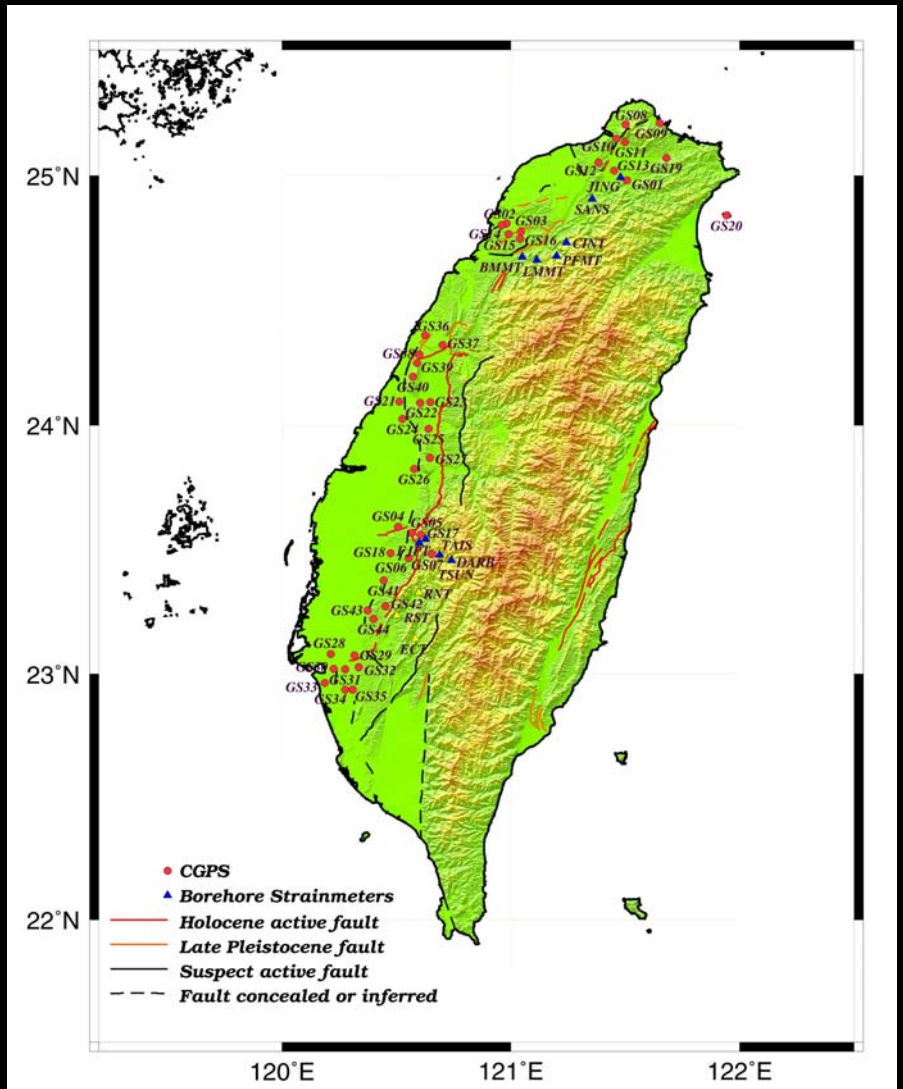
813 GPS stations

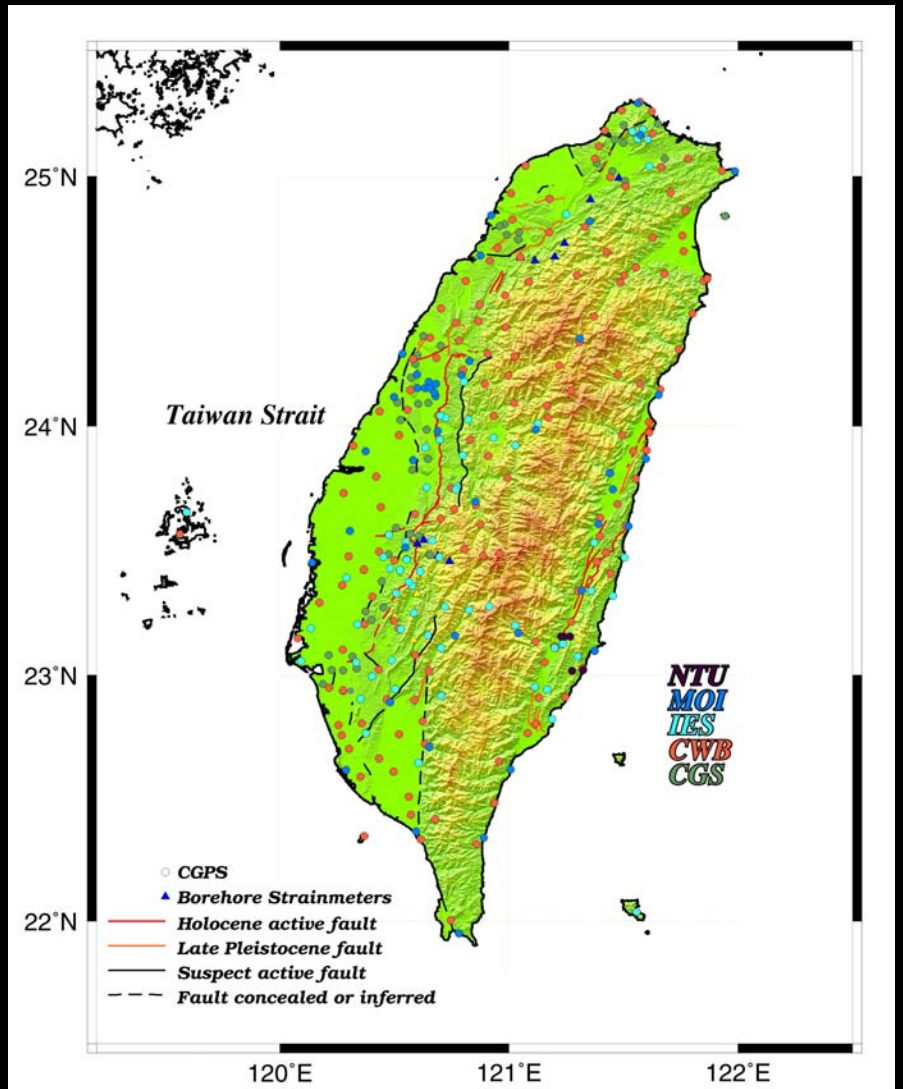
23 Leveling Lines

Borehole Strain Measurement and CGPS Network

13 Gladwin Tensor Strain Monitors from Oct. 2003

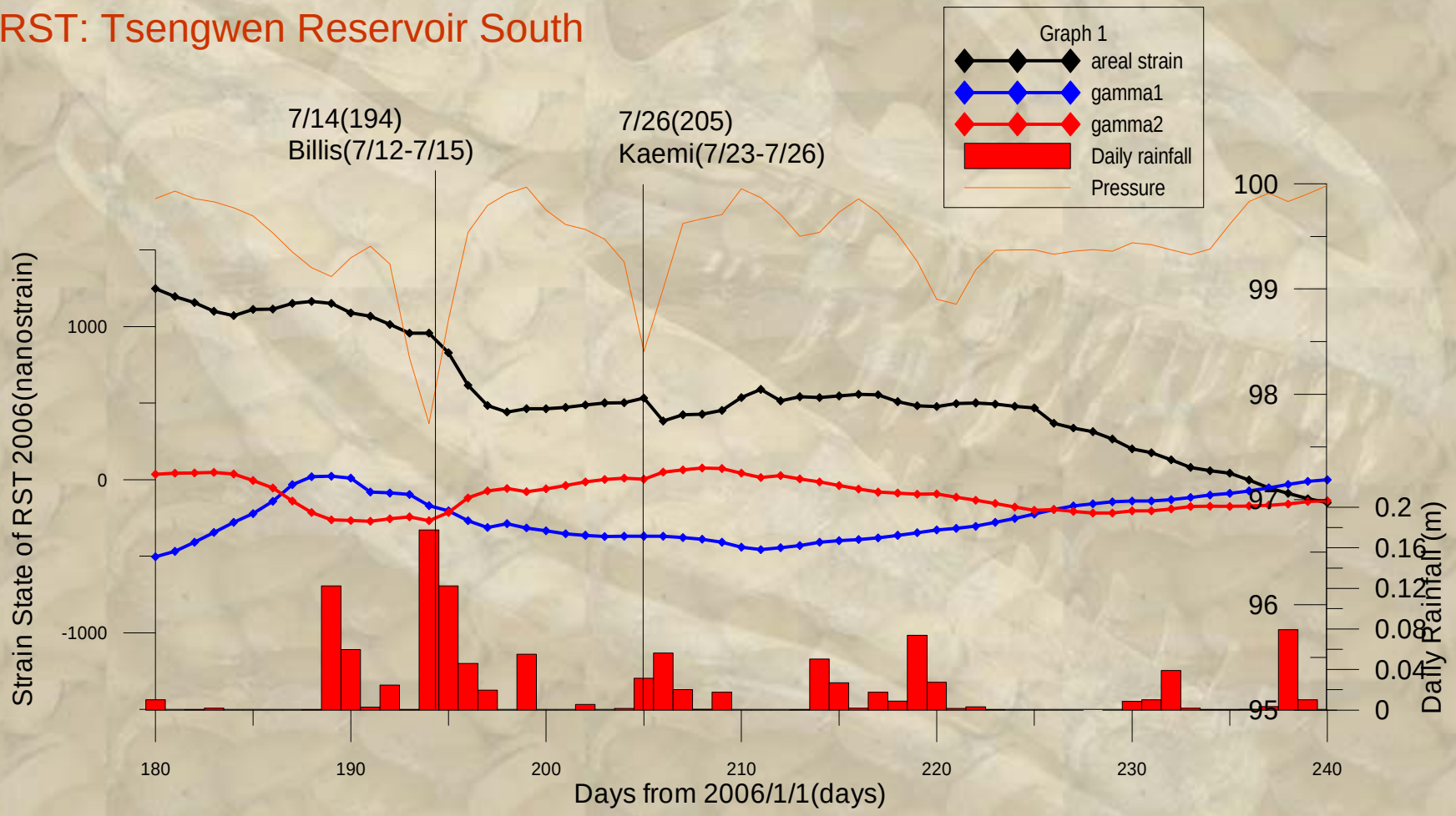
44 Continuous GPS stations





GTSM Data: Atmosphere pressure and rainfall

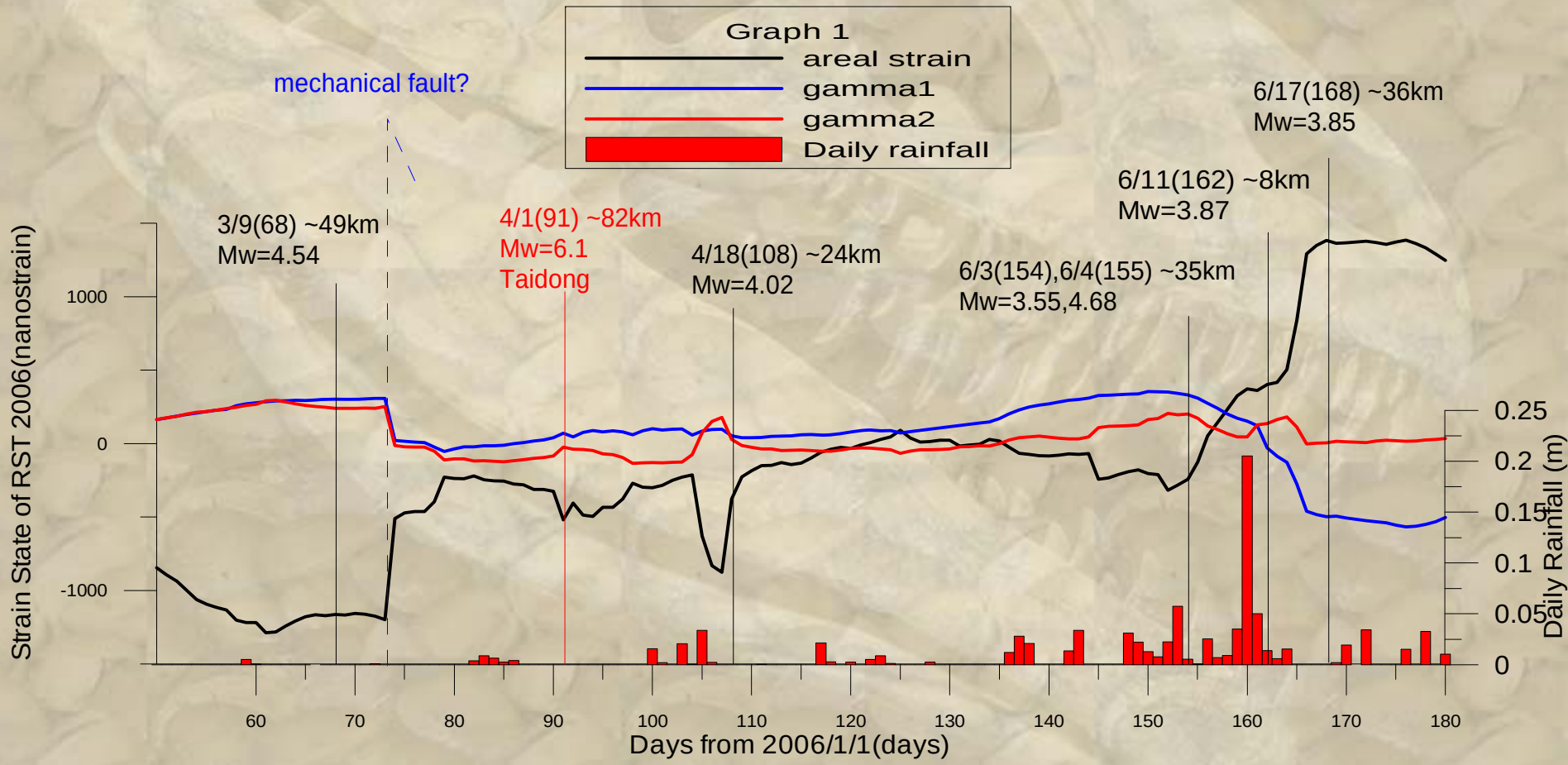
RST: Tsengwen Reservoir South



Data: CGS, MOEA

GTSM Data: Earthquakes

RST: Tsengwen Reservoir South



Data: CGS, MOEA

Objectives

- Application of GPS measurement, precise leveling, conventional SAR interferometry and persistent scatterers InSAR for crustal deformation in Taiwan.

(a) SW Taiwan: Tectonic extrusion?

(b) Active folding of Tainan Tableland near Deformation Front

- Seismic hazards assessment: subsurface fault geometry and short-term slip rate

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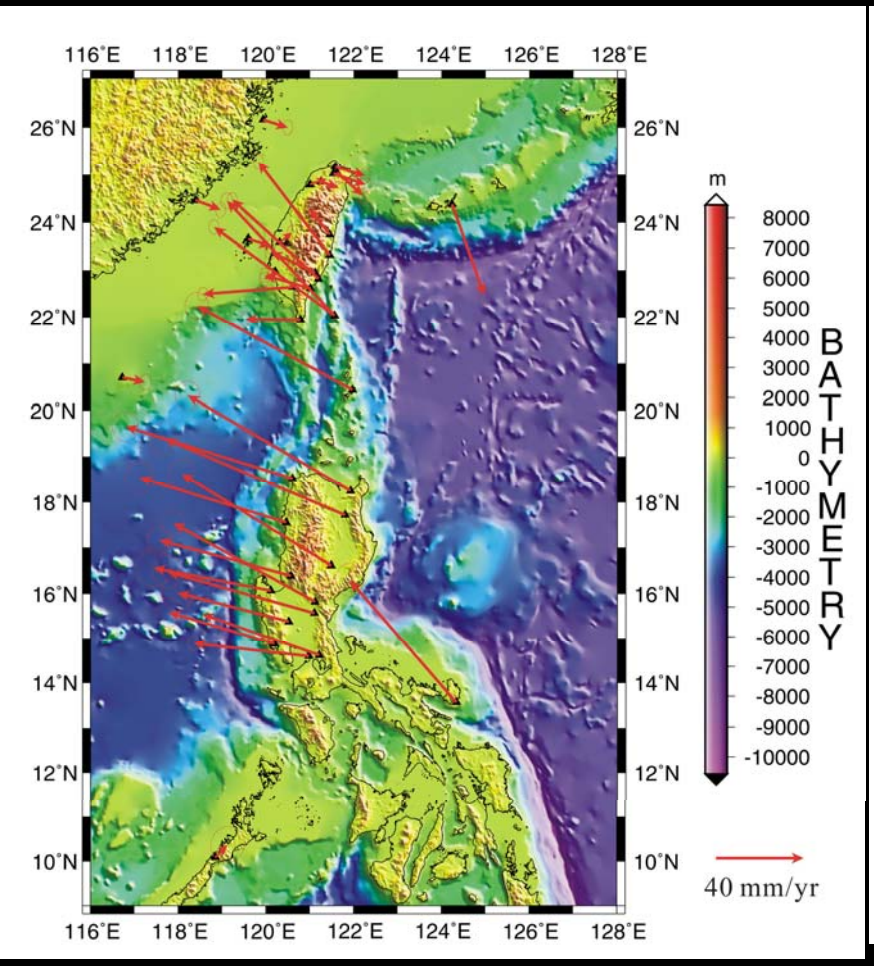
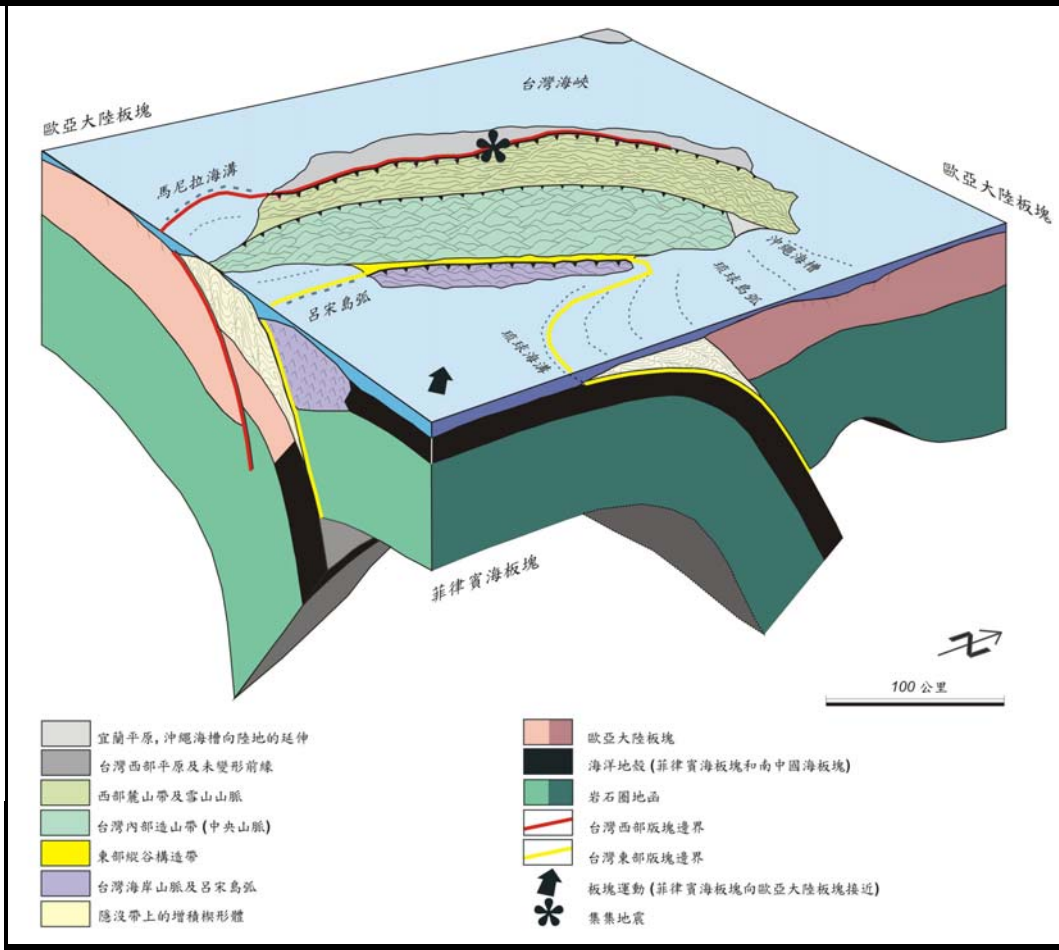
Geodynamic Framework



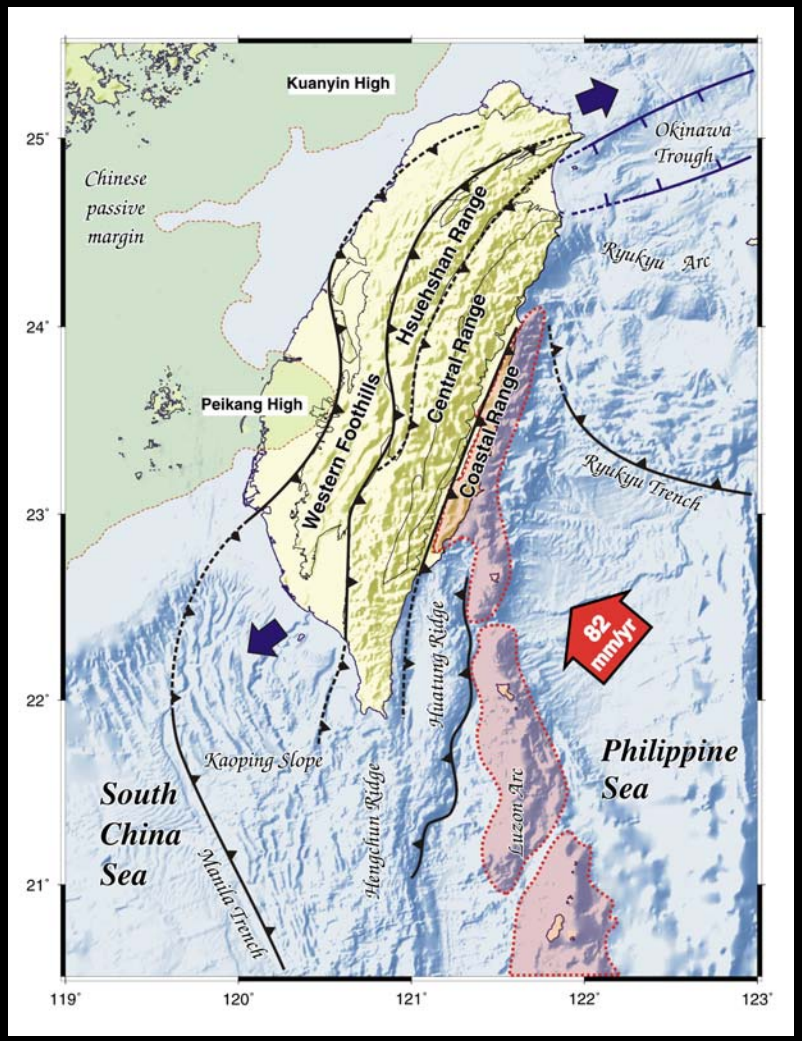


Reference: VLBI station in Shanghai

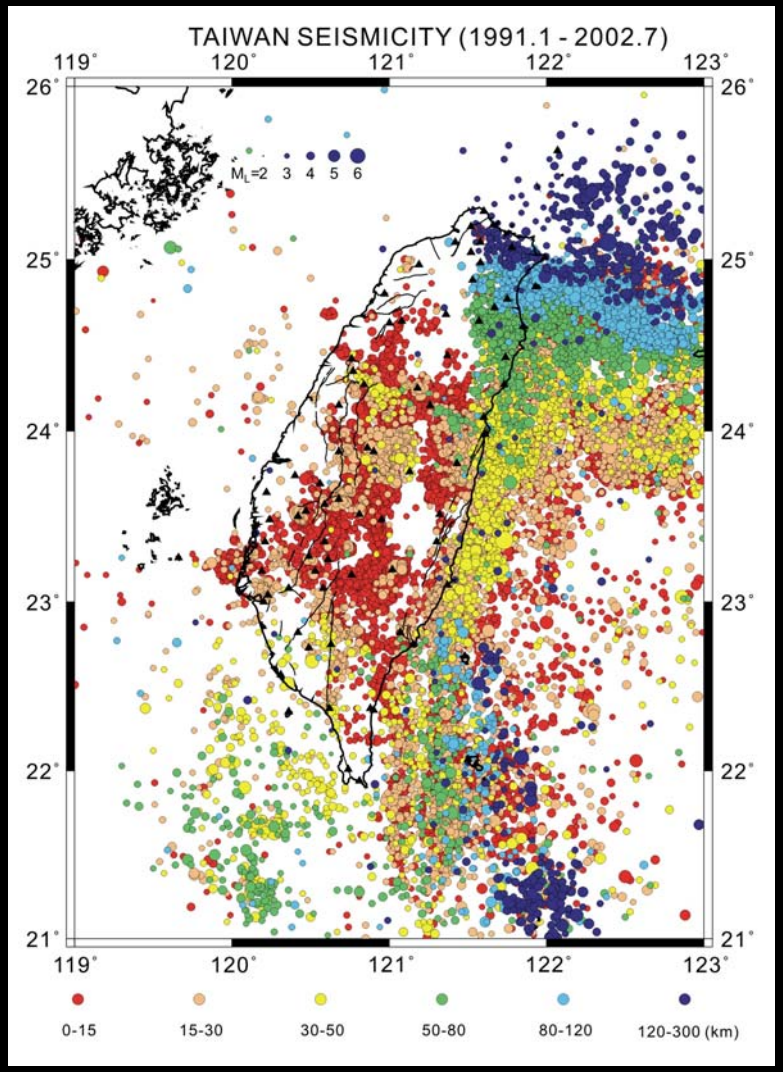
(Yu et al., GRL 1999)

Courtesy of Professor Jacques Angelier

Geodynamic Framework and Seismicity

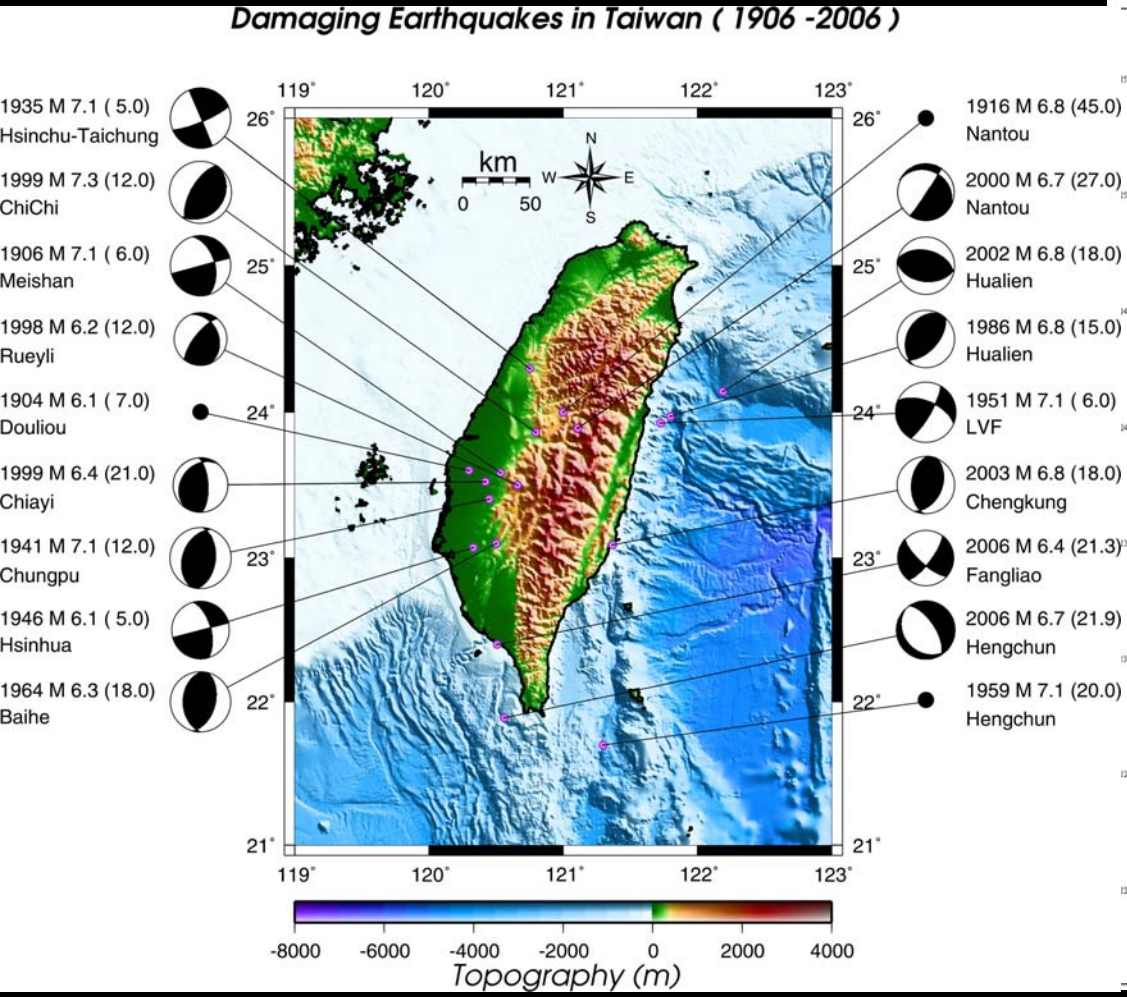


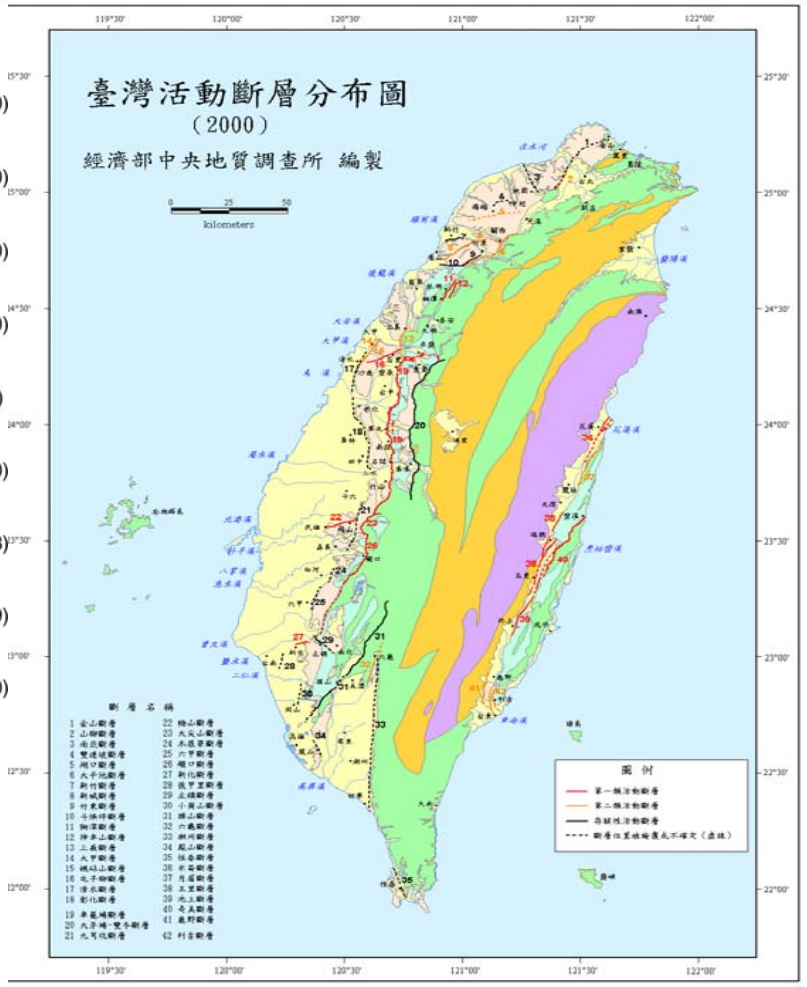
(Courtesy of Kuo-En Ching)



(Courtesy of CWB)

Historical Earthquakes and Active Faults

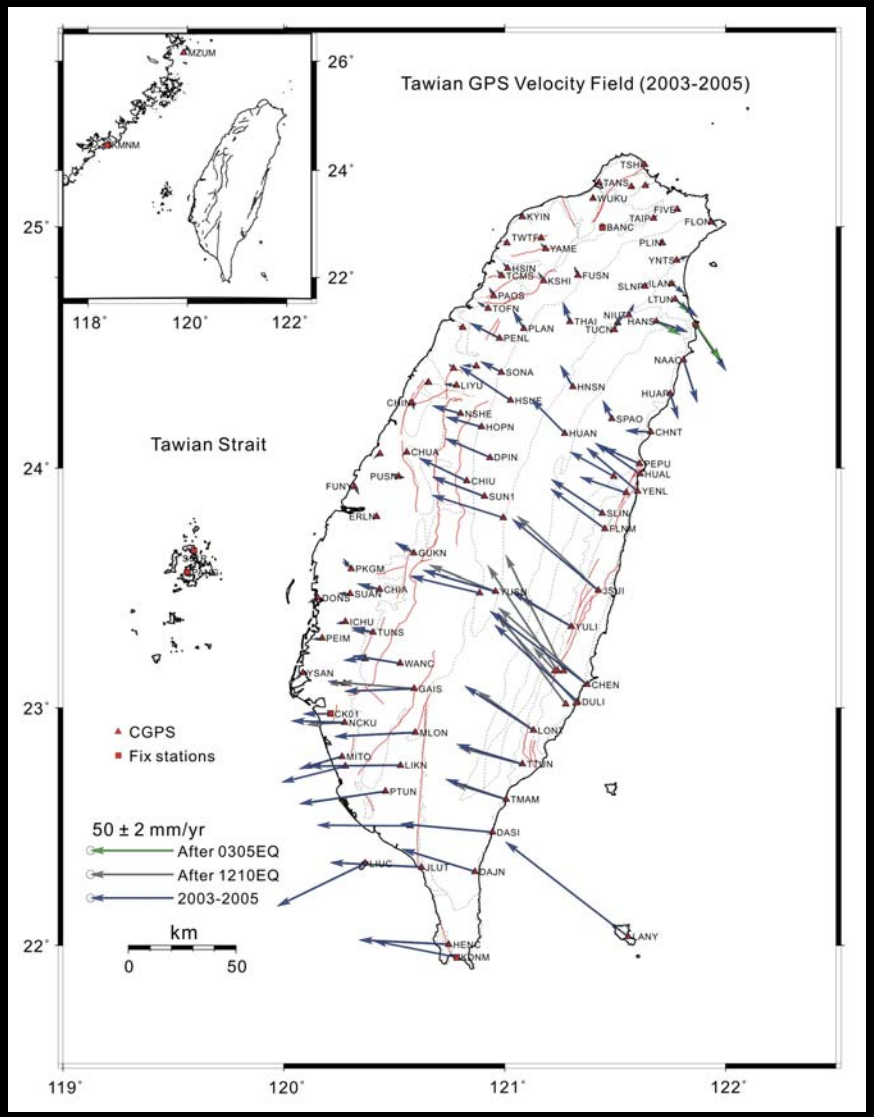




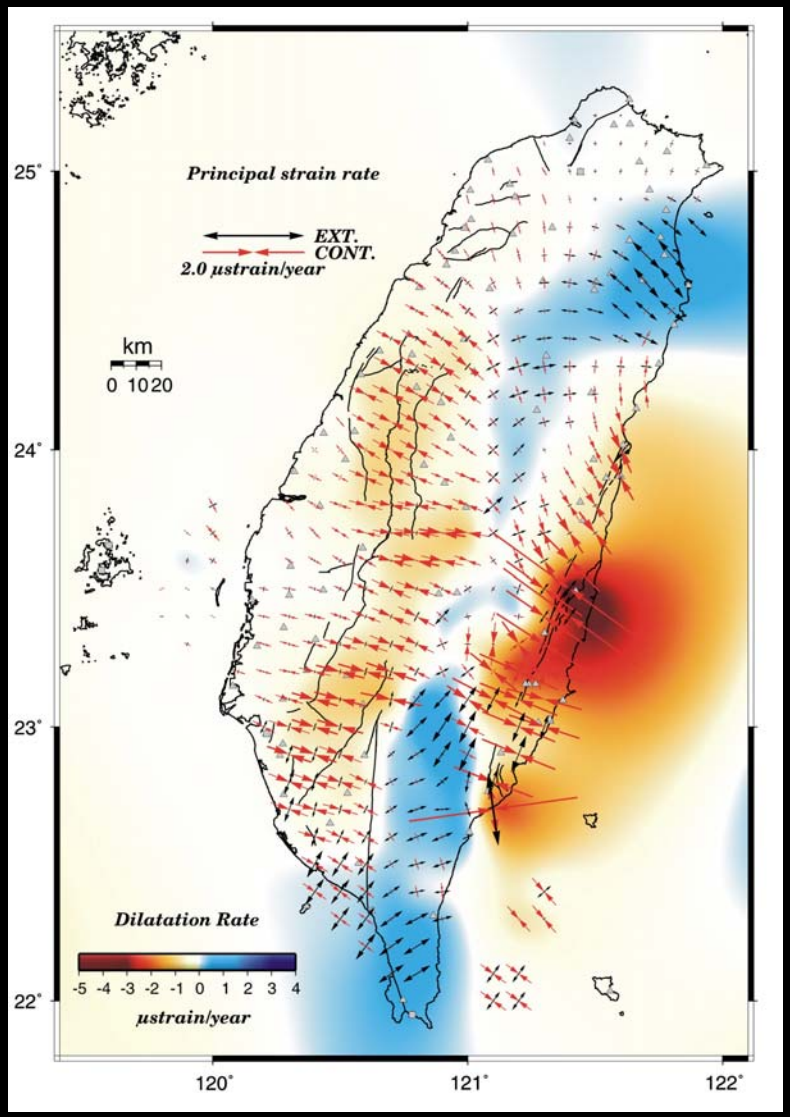
Data: Cheng (1995) and CWB

Data: Central Geological Survey

Continuous GPS Network in Taiwan



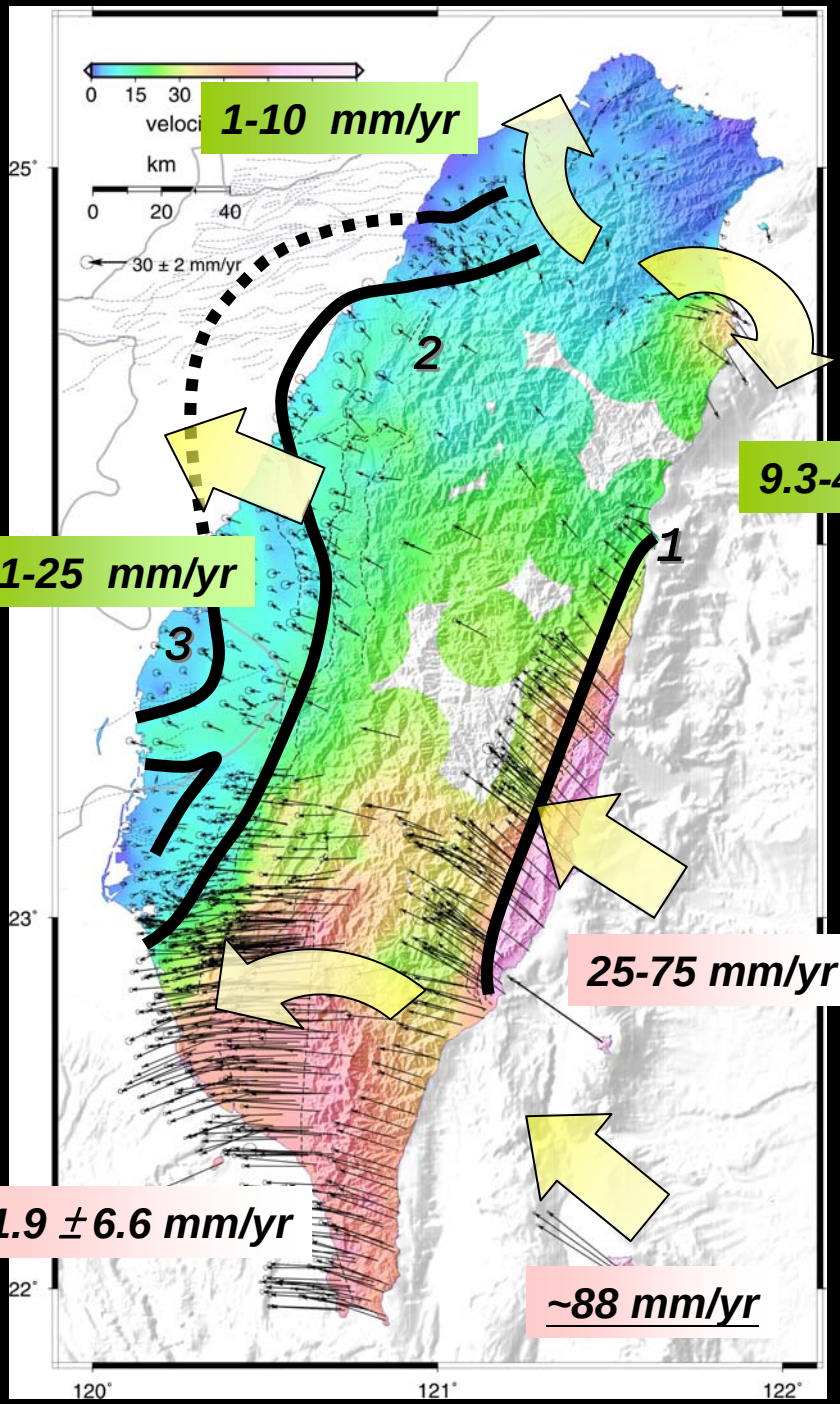
Data: CWB, MOEA and NTU

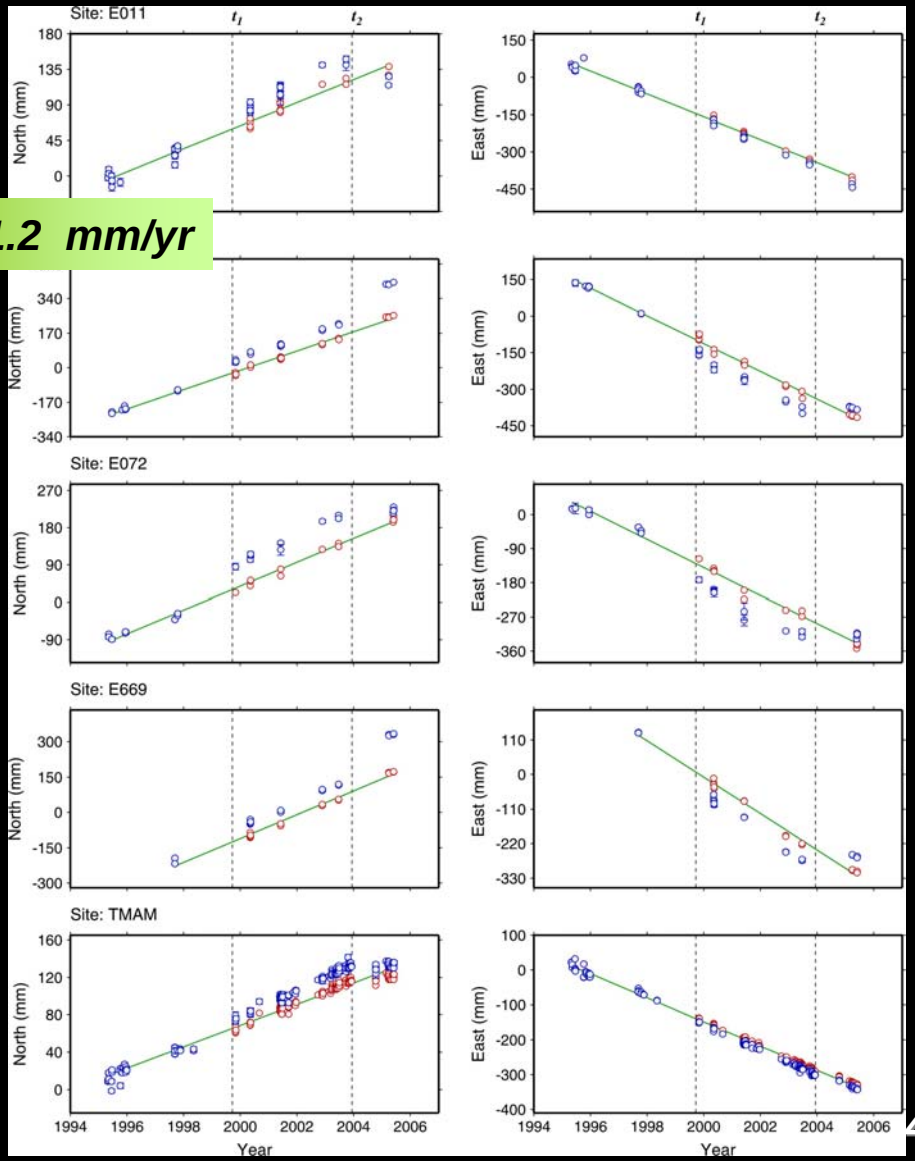


(Lin et al., 2008, EPSL, submitted)

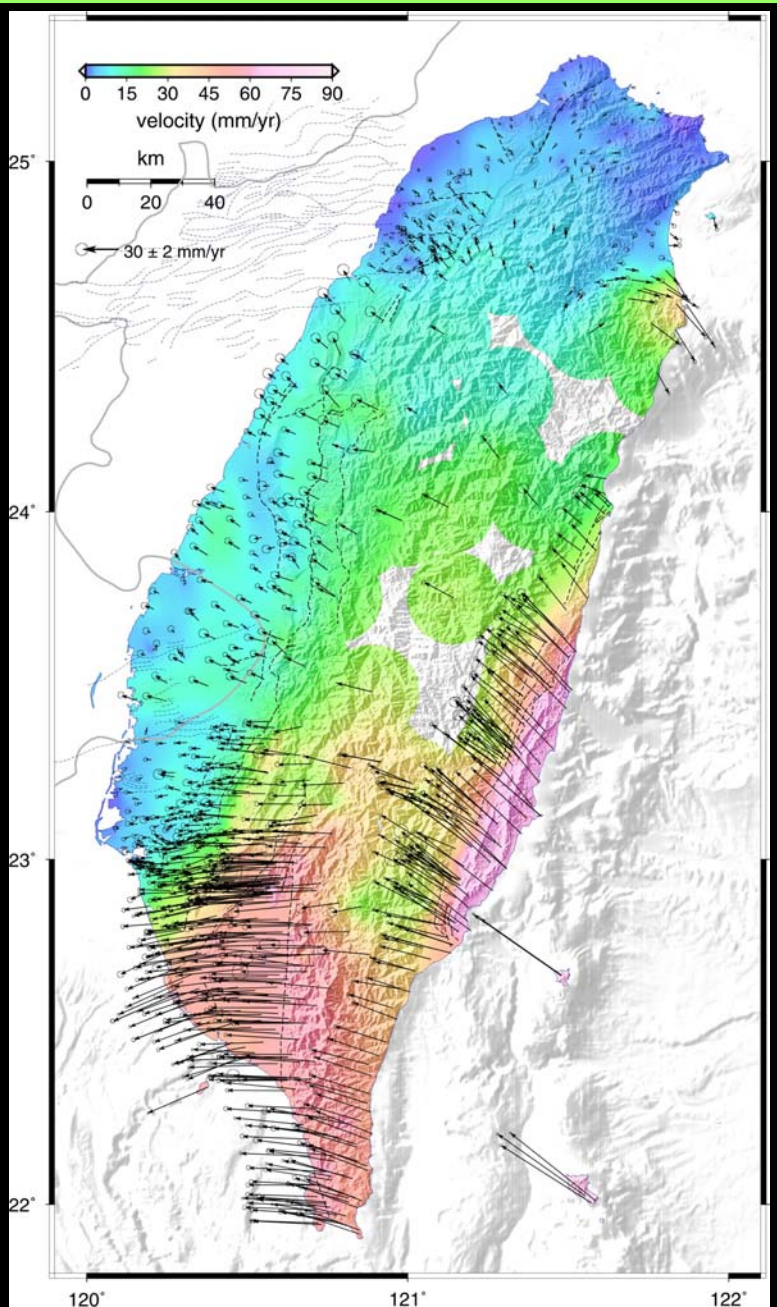
GPS Velocity Field

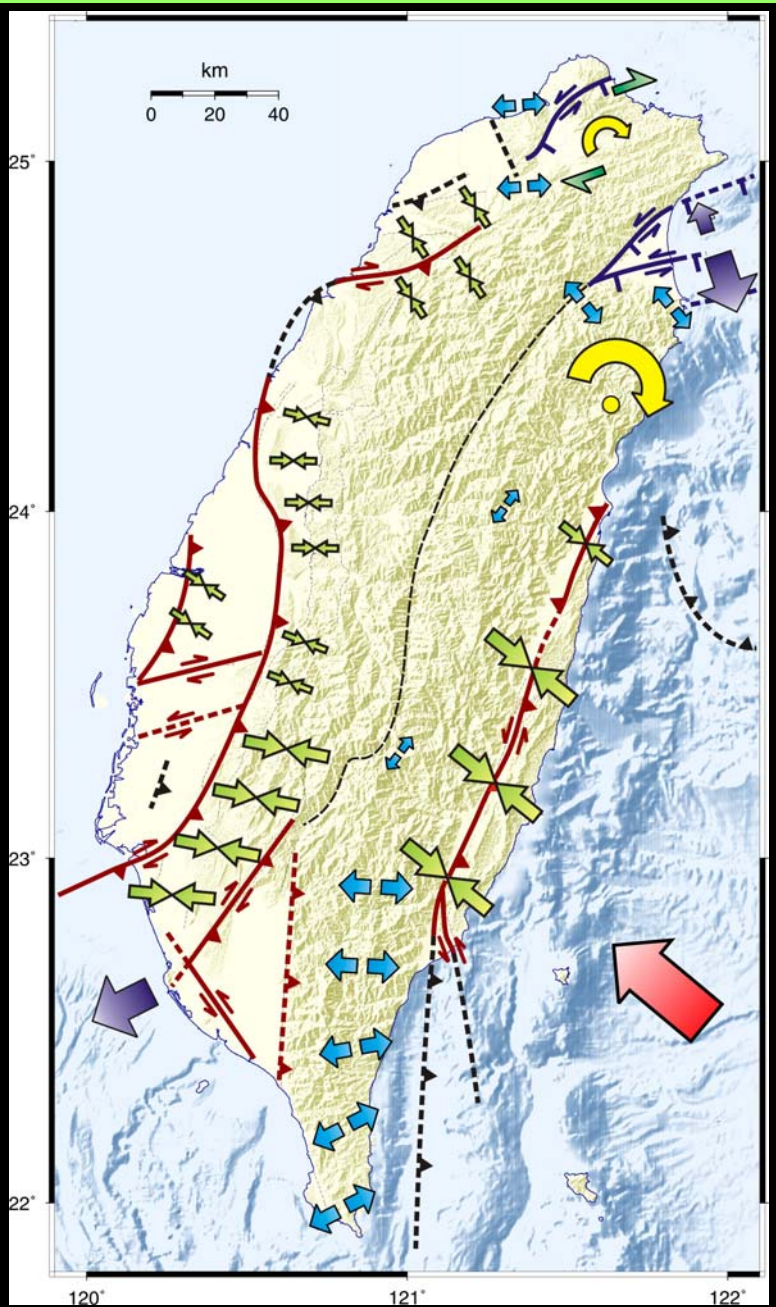
1995-2005

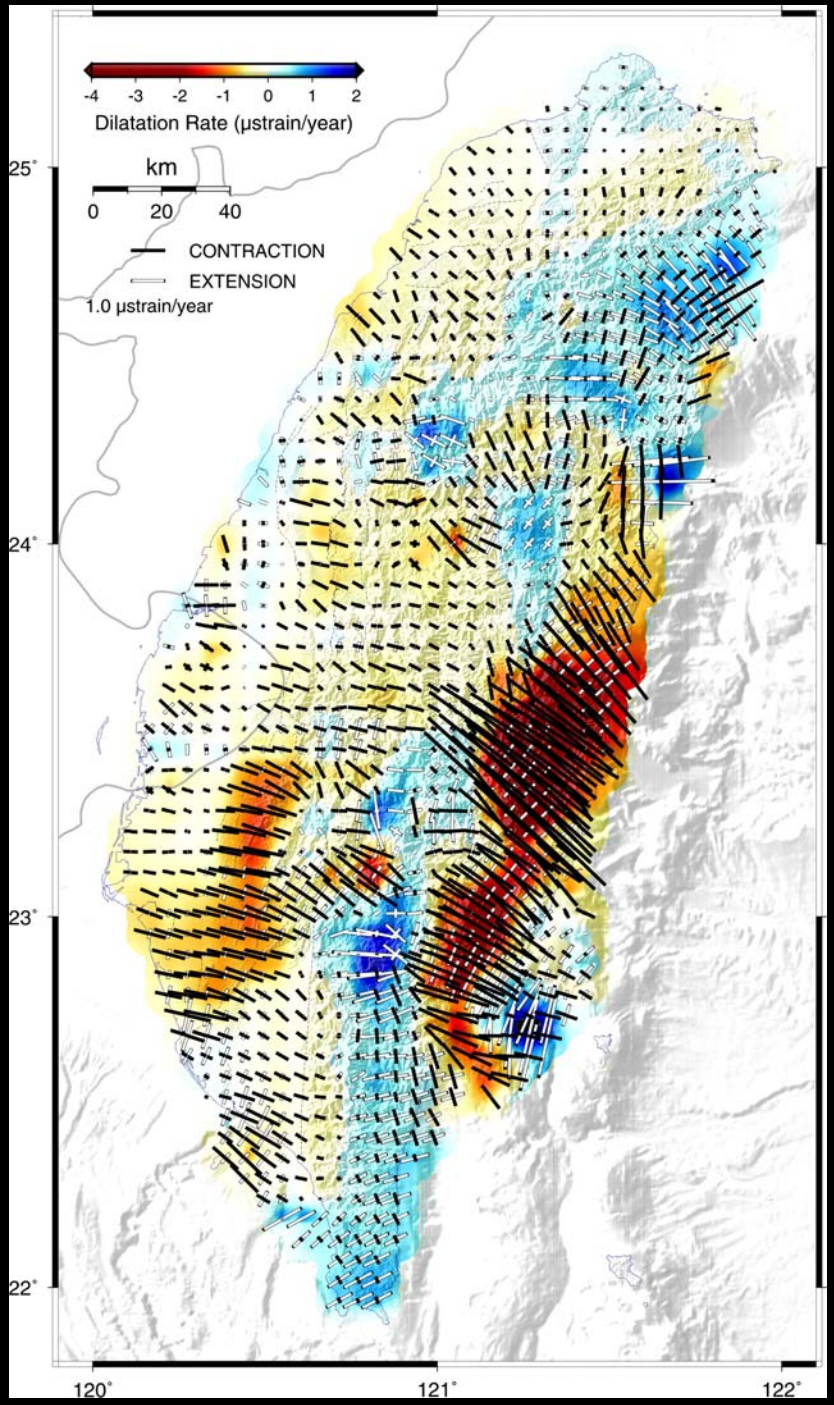


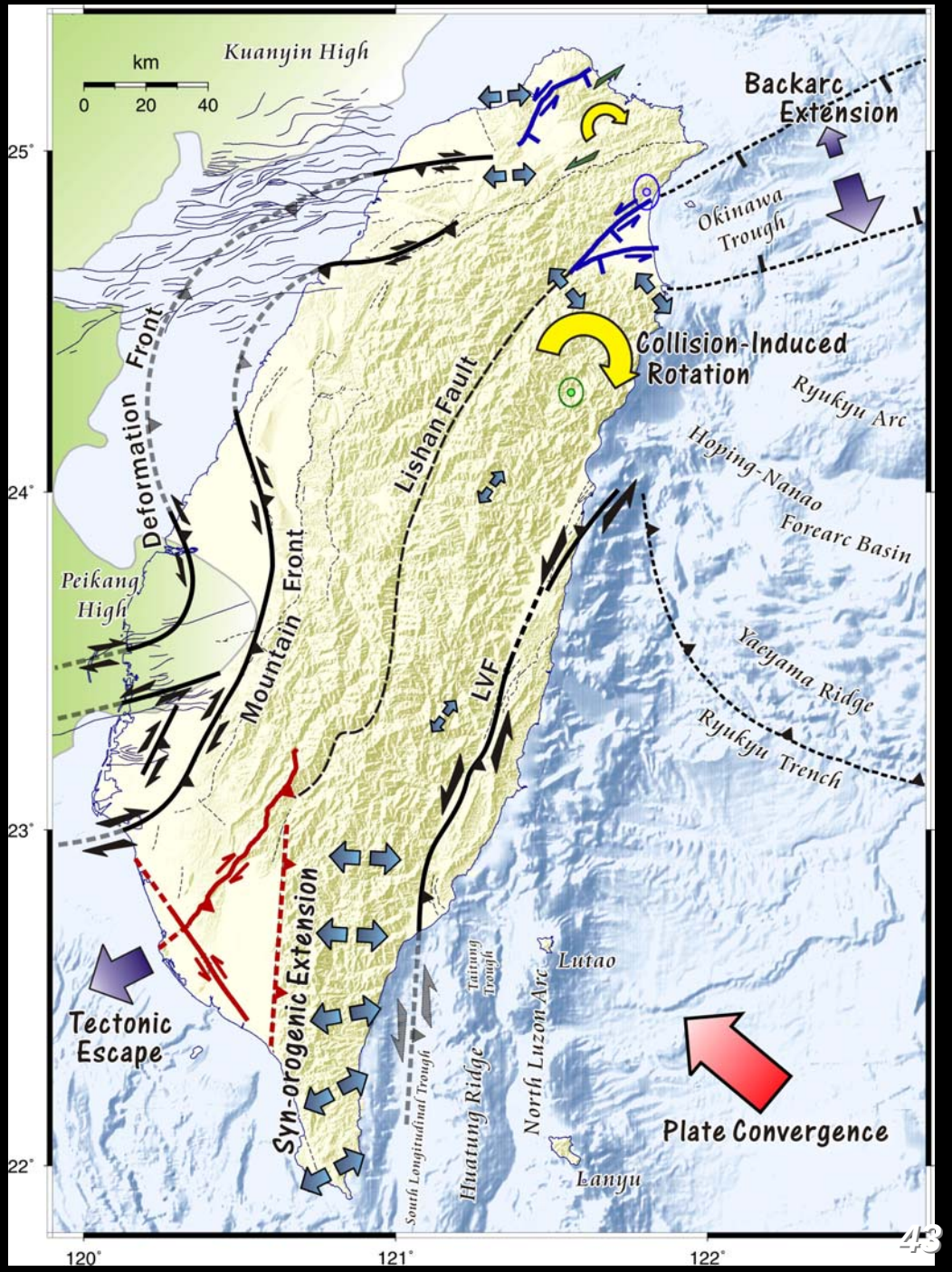


GPS Measurements and Modern Tectonic Model of Taiwan

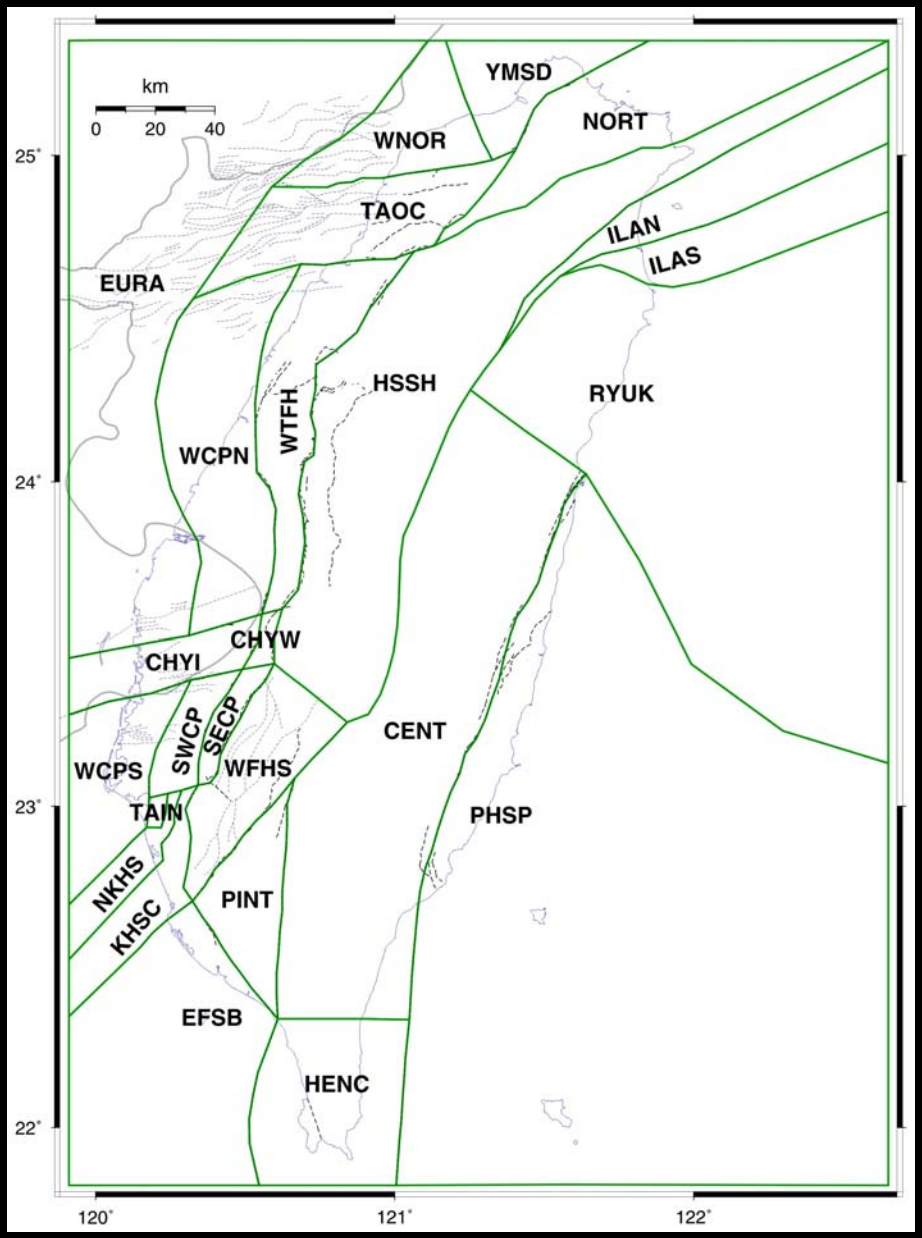




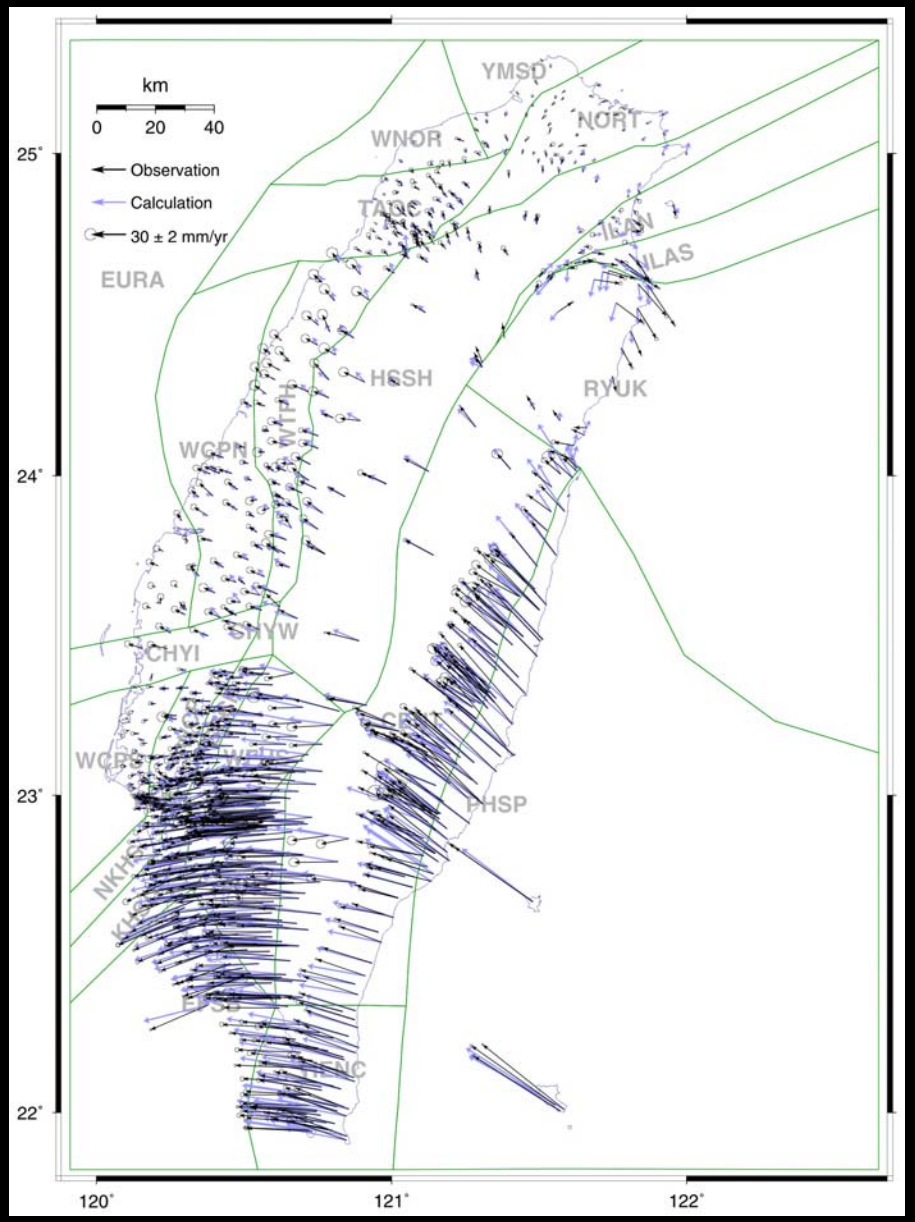

-4 -3 -2 -1 0 1 2
Dilatation Rate (μstrain/year)
km
0 20 40
CONTRACTION
EXTENSION
1.0 μstrain/year
25°
24°
23°
22°
120°
121°
122°

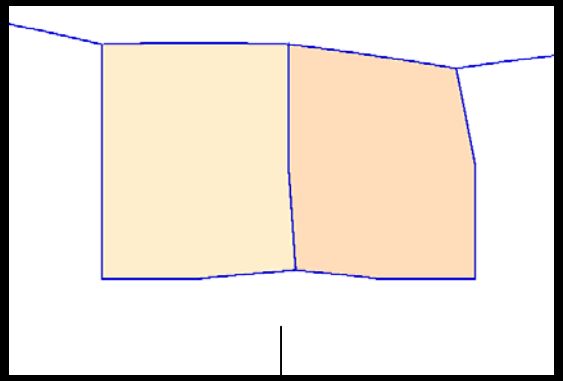

km
0 20 40
Kuanyin High
Backarc Extension
Okinawa Trough
Collision-Induced Rotation
Ryukyu Arc
Hoping-Nanao Forearc Basin
Yaeyama Ridge
Ryukyu Trench
Deformation Front
Lishan Fault
Mountain Front
LVF
Peikang High
Syn-orogenic Extension
Tectonic Escape
Plate Convergence
Taitung Trough
South Longitudinal Trough
Huatung Ridge
North Luzon Arc
Lutao
Lanyu
25°
24°
23°
22°
120°
121°
122°

Block Models

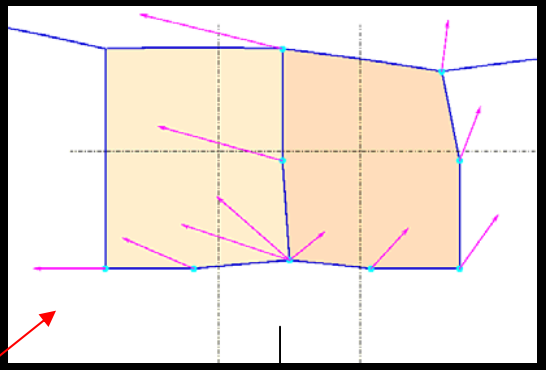


Predicted and Observed Velocity Field

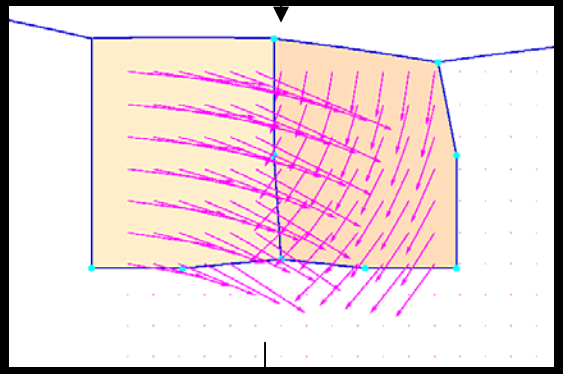




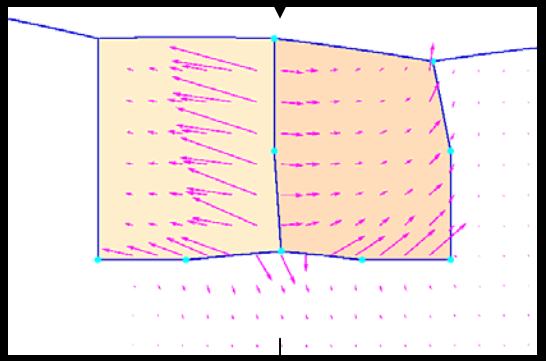
Region is divided into ‘blocks’, contiguous areas that are thought to rotate rigidly.



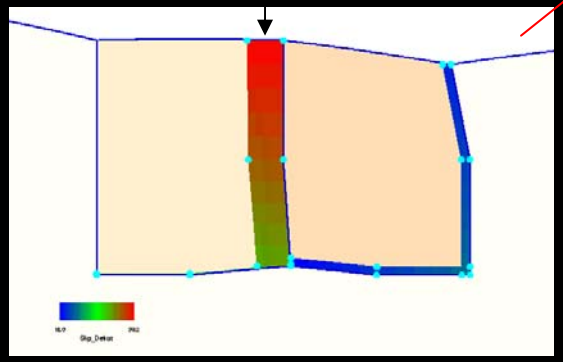
The relative long-term slip vectors on the faults are determined from rotation poles.



Each block rotates about a pole.

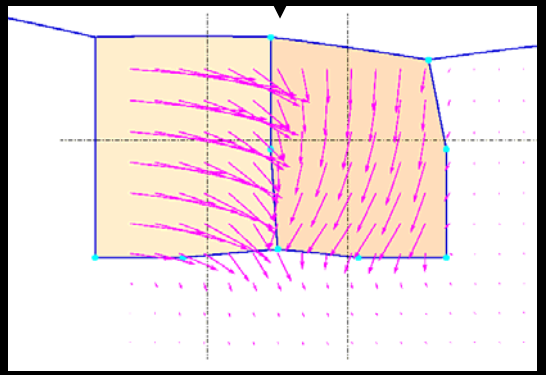


Back-slip is applied at each fault to get surface velocities due to locking.



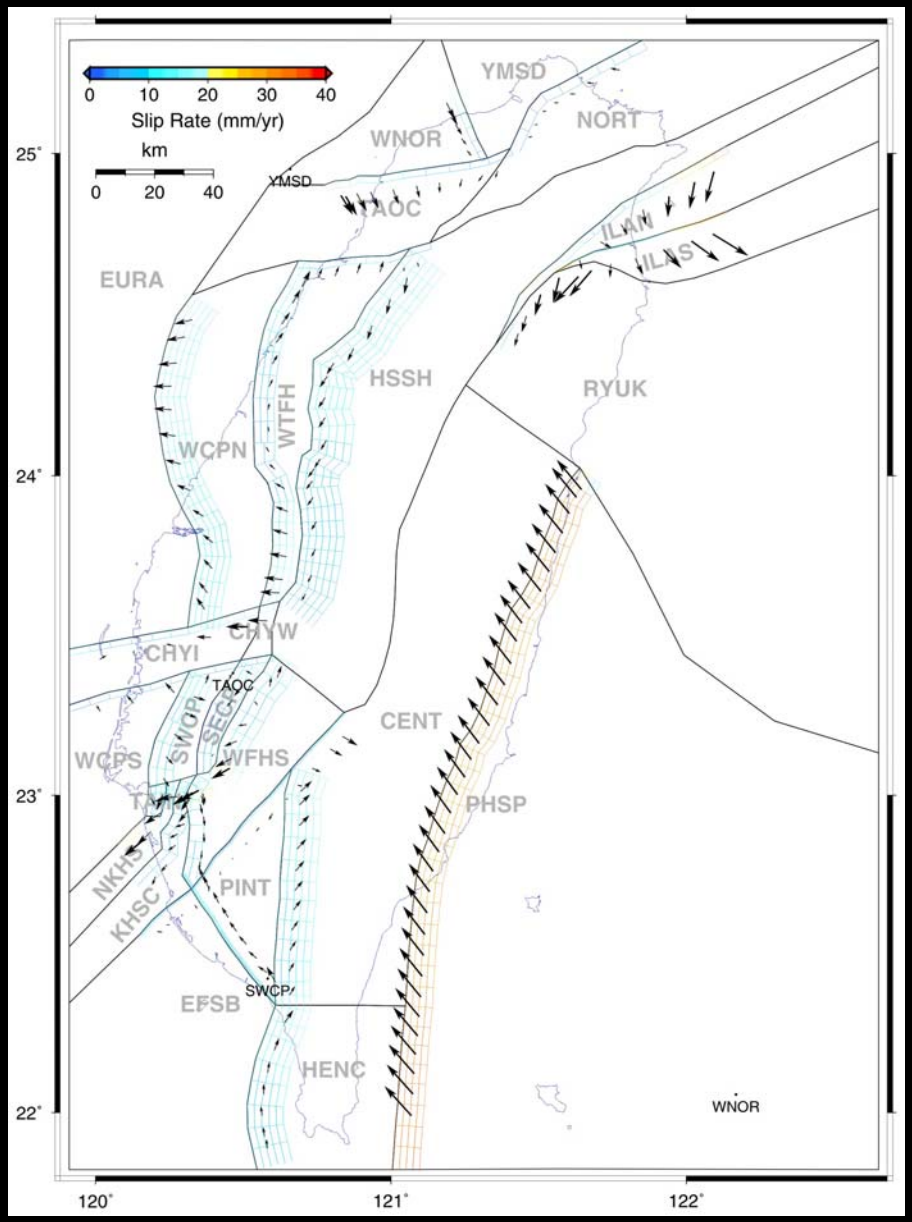
Velocities due to fault locking are added to rotations to get full velocity field.

The rotating blocks are separated by dipping faults.

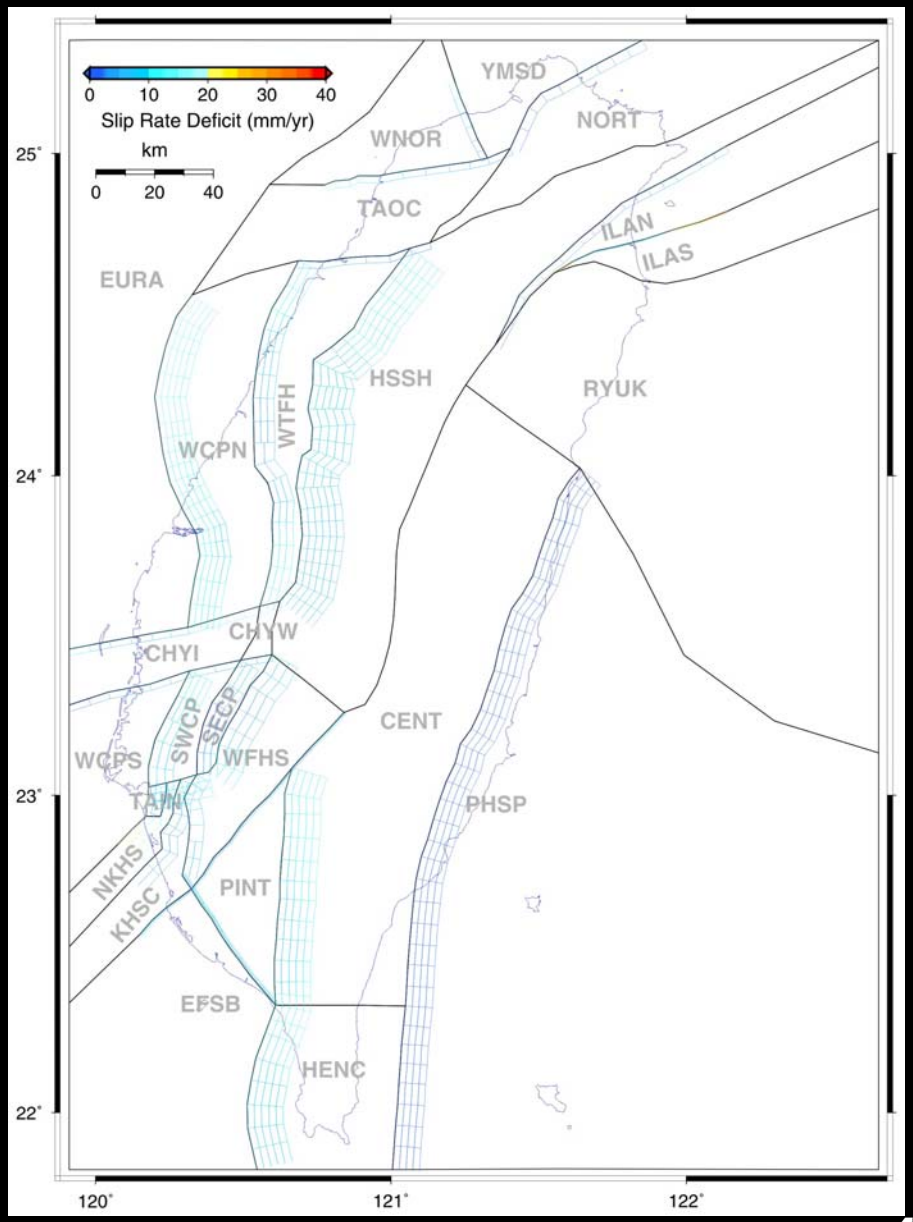


Bob McCaffrey

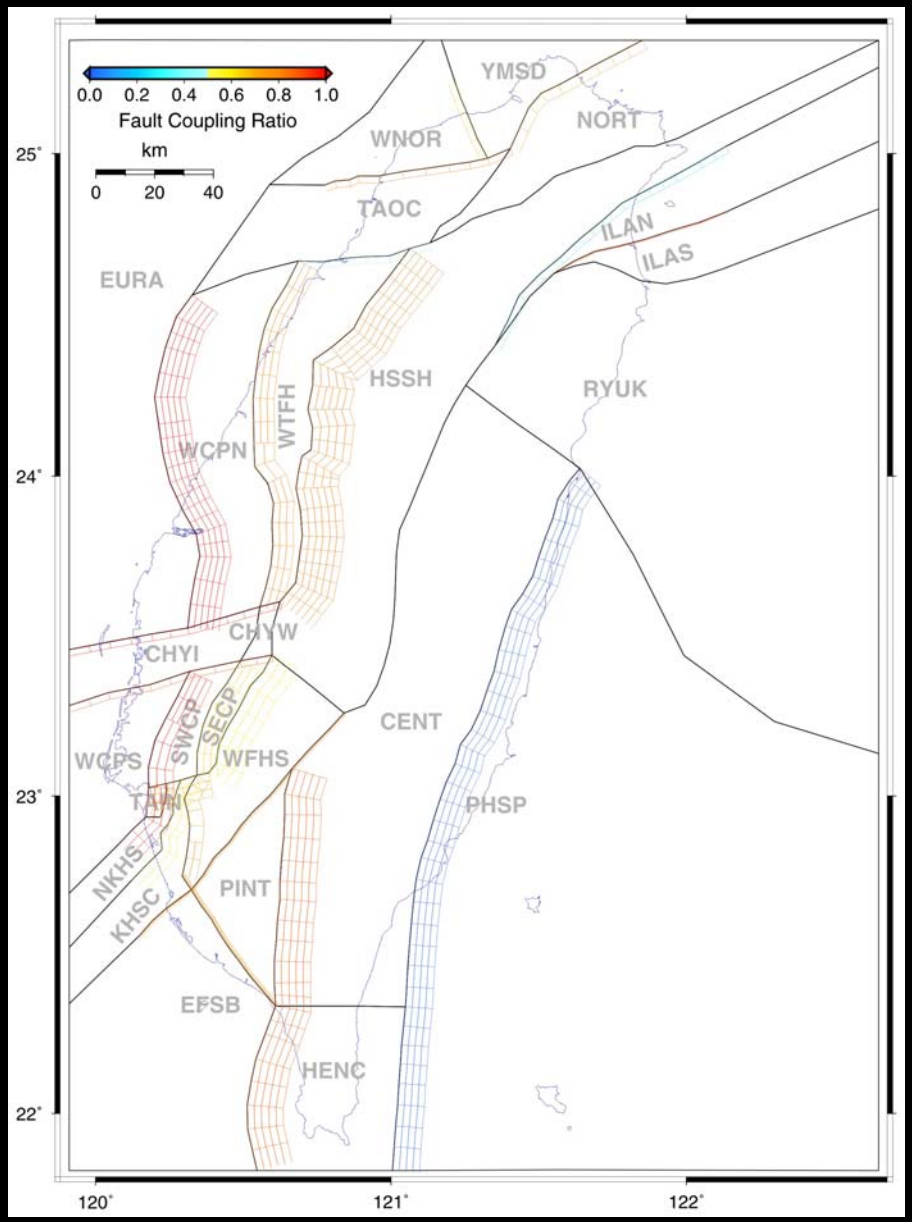
Slip Rate



Slip Rate Deficit



Fault Coupling Ratio



Earthquake Potential

Chaochou fault

1.11E+18 N-m/yr (Mw = 7.3)

Fontshan fault

2.54E+17 N-m/yr (Mw = 6.9)

Chishan fault

2.23E+17 N-m/yr (Mw = 6.8)

Hsinhua fault

1.23E+17 N-m/yr (Mw = 6.7)

Chukou fault

1.75E+17 N-m/yr (Mw = 6.8)

Meishan fault

1.81E+17 N-m/yr (Mw = 6.8)

Houchiali fault

8.23E+16 N-m/yr (Mw = 6.5)

Does Tectonic Extrusion Occur in SW Taiwan ?

Plate motion parallel components

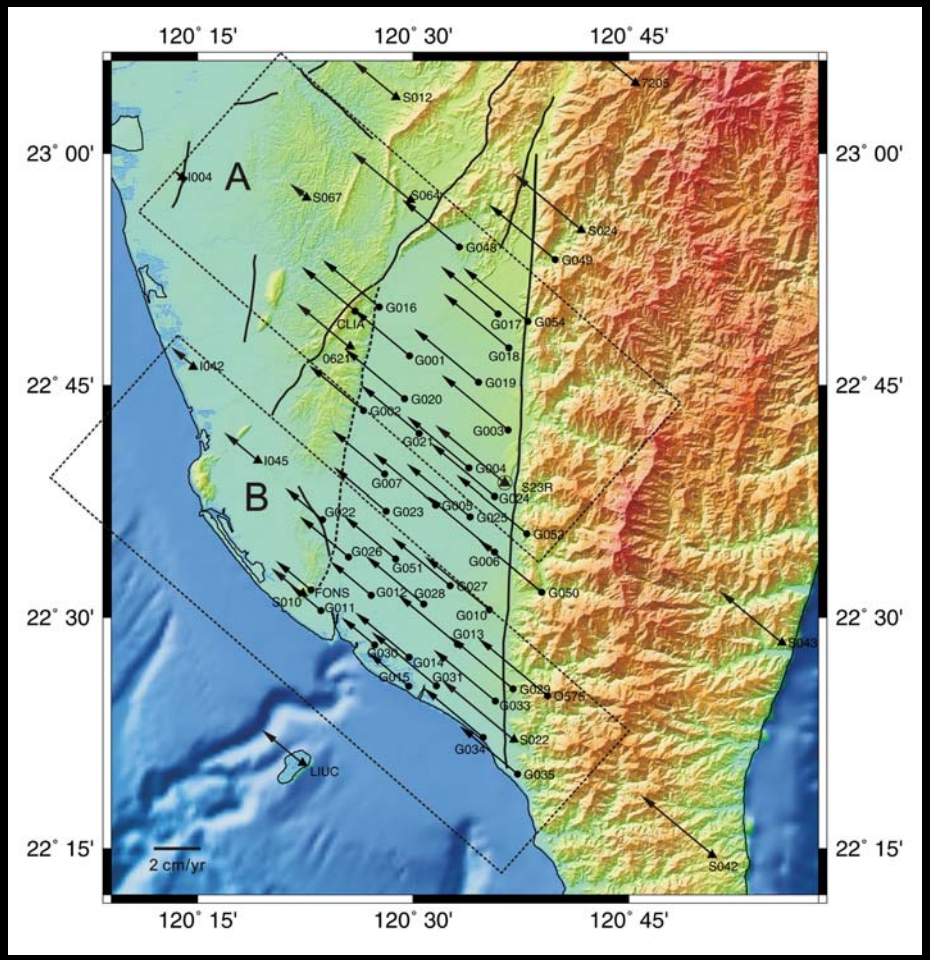
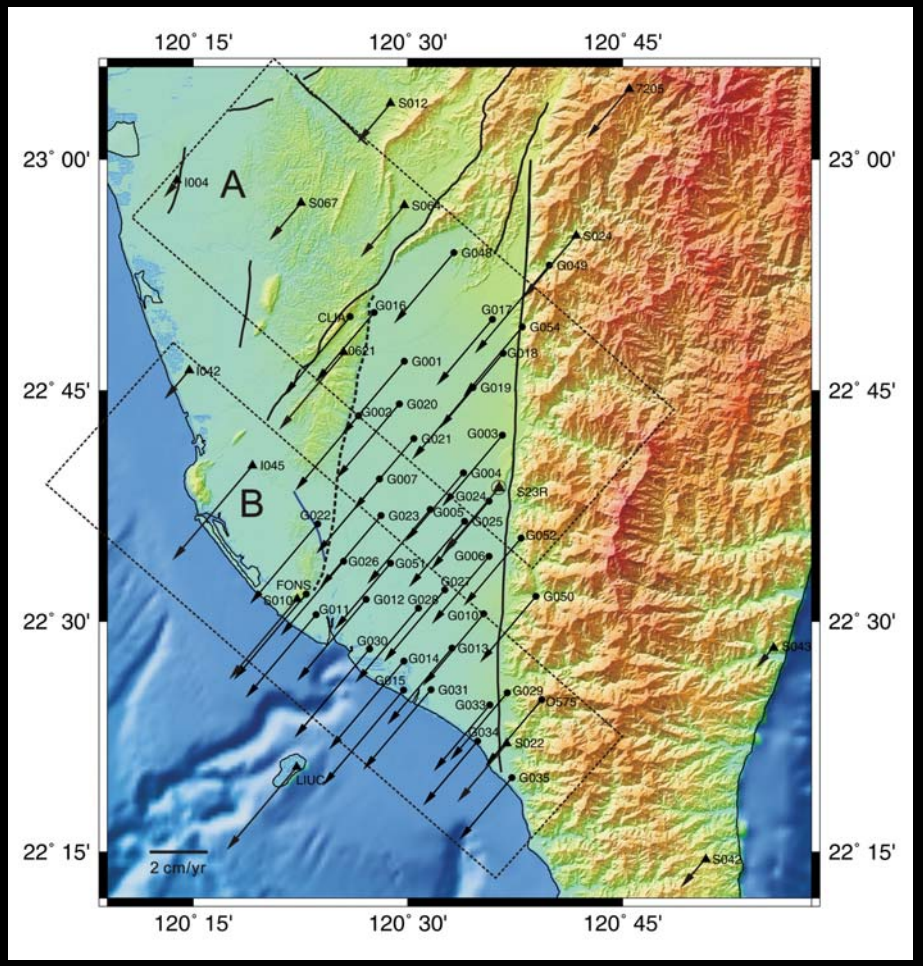


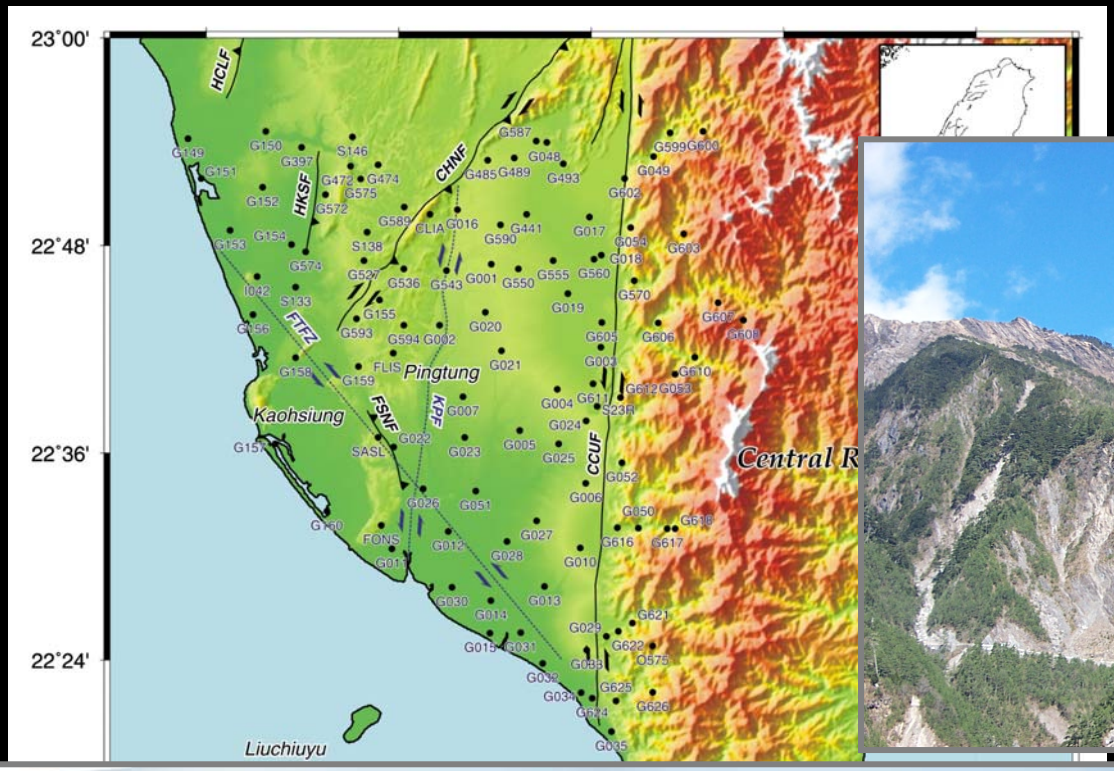
Plate motion normal components



GPS data: 1995-1999

(Hu et al., JAES, 2007)

South Taiwan



South Taiwan GPS Network

Pingtung Plain
Hengchun Peninsula

Station-spacing: ~ 5 km

132 GPS sites
July 1995 ~ August 2005.

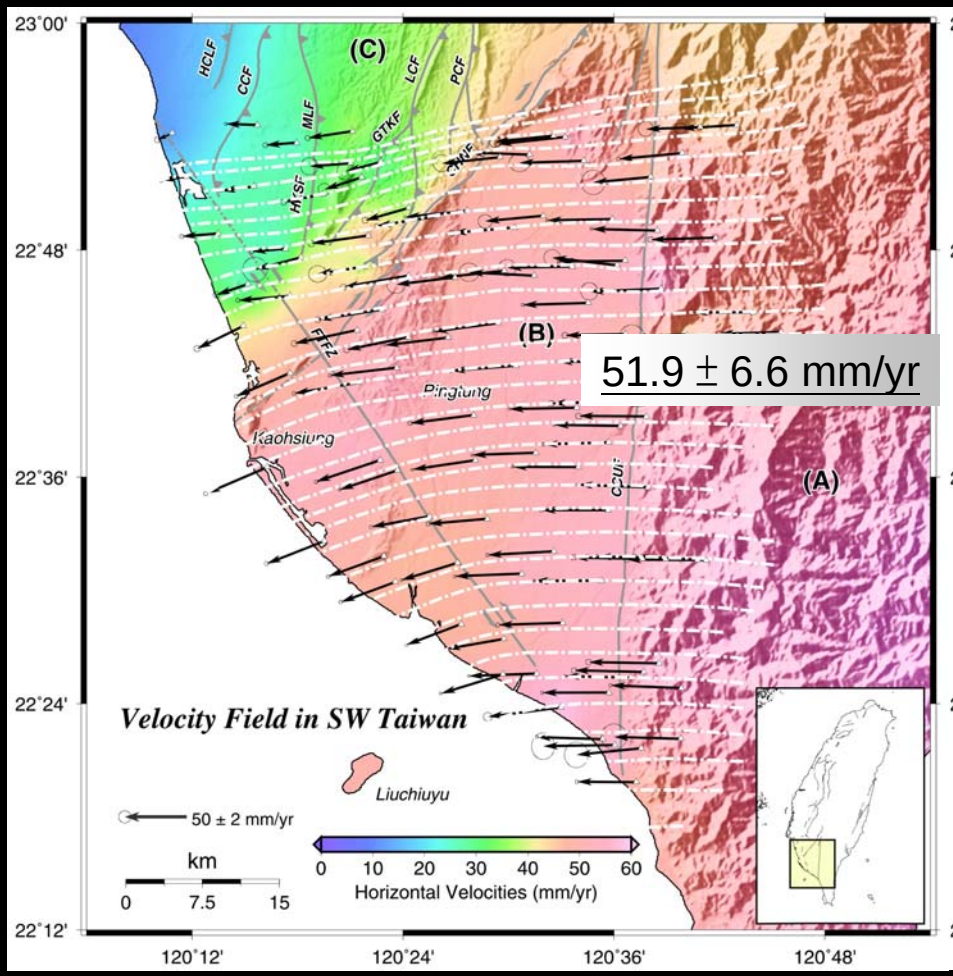
Aim:

1. Comprehending surface defo
   transition from subduction t

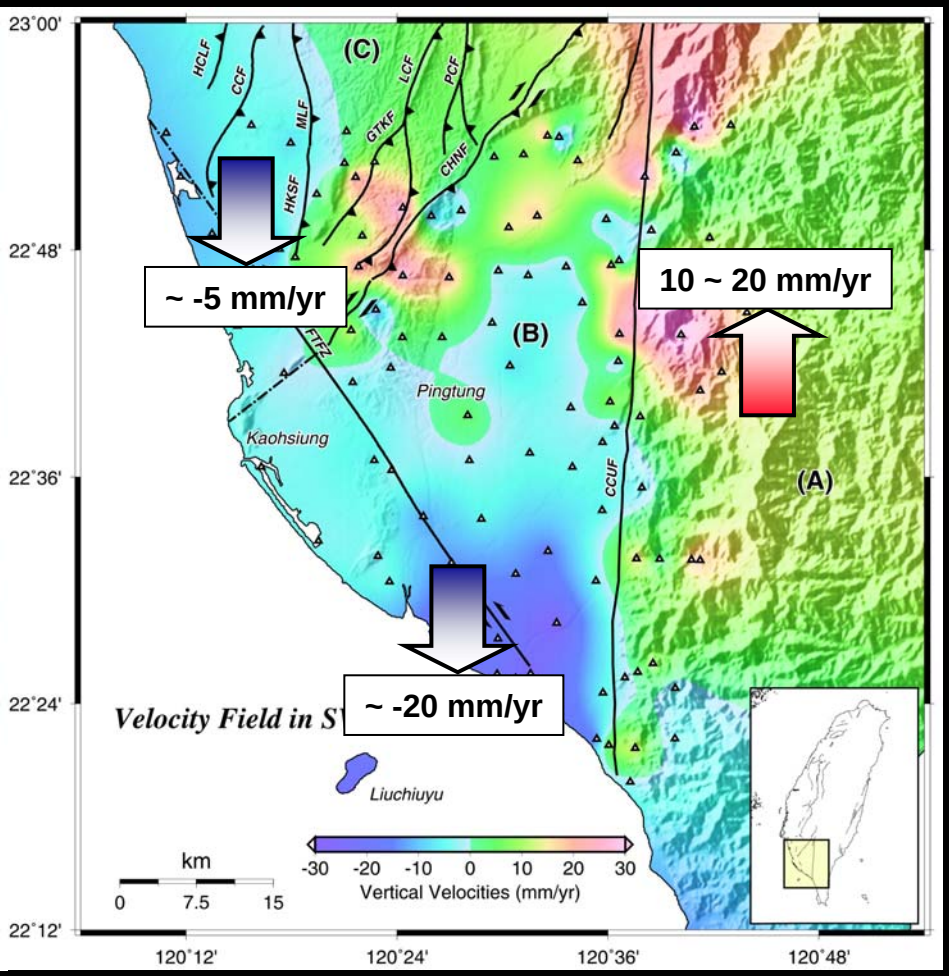
2. Investigating possible mech
   rotation hypothesis in south
   collision transition zone

GPS Velocity Field in SW Taiwan

Horizontal Component

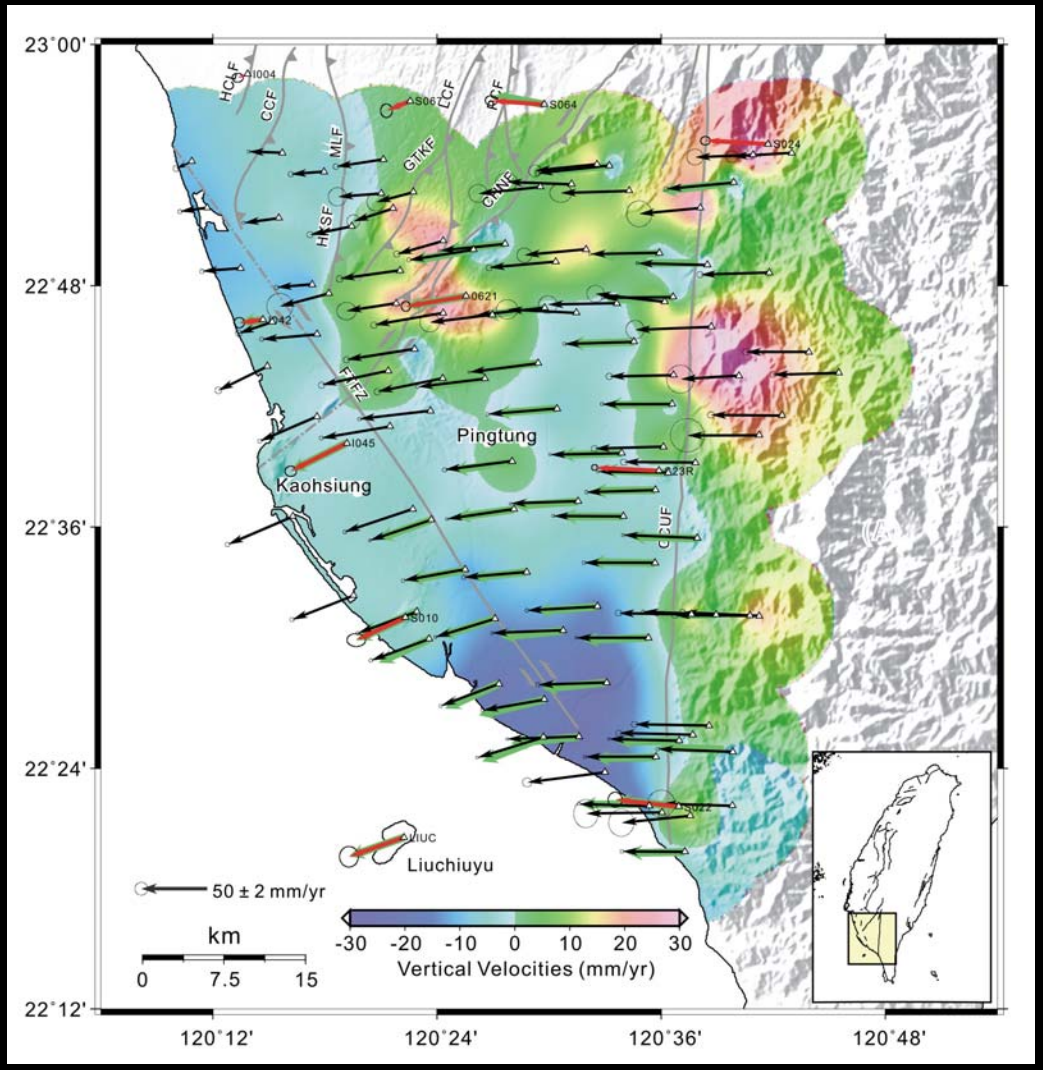


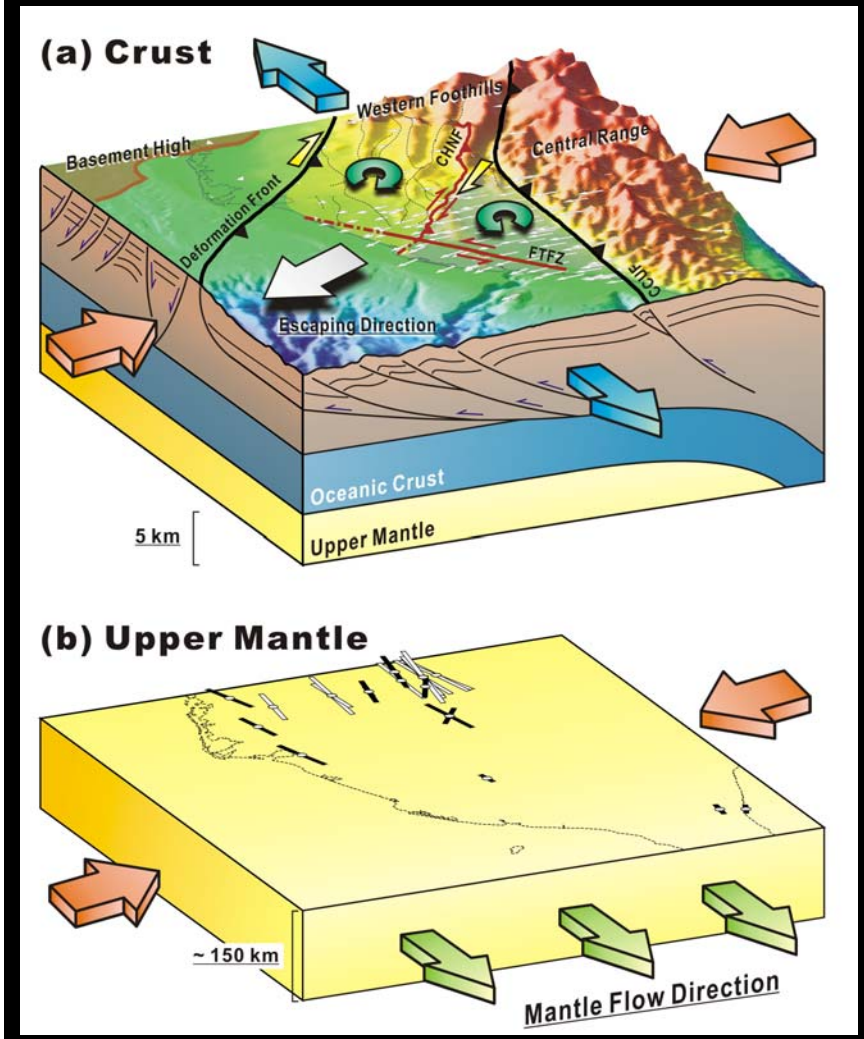
Vertical Component



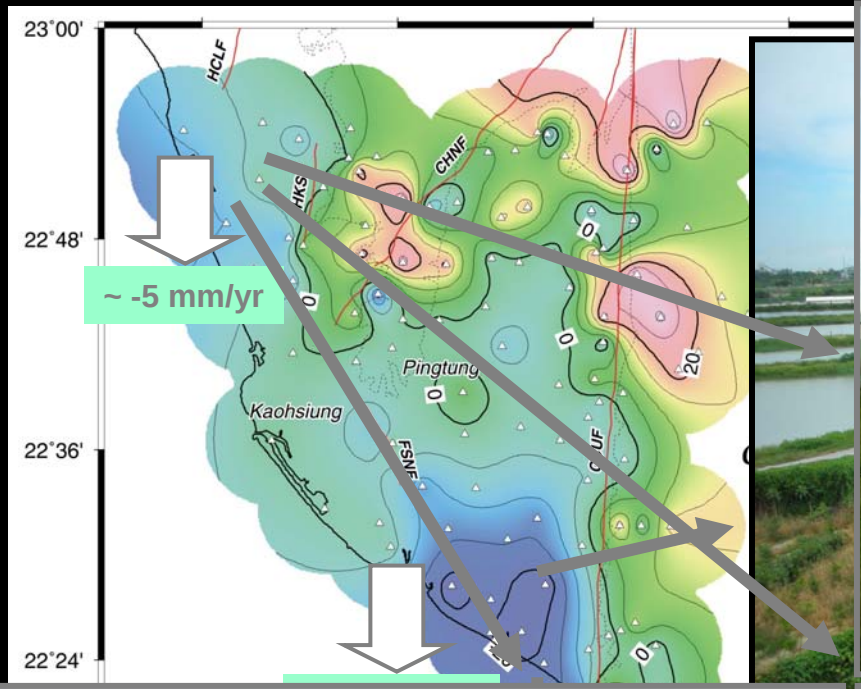
Ching, Rau, Lee & Hu, EPSL, 2007

GPS Velocity Field in SW Taiwan

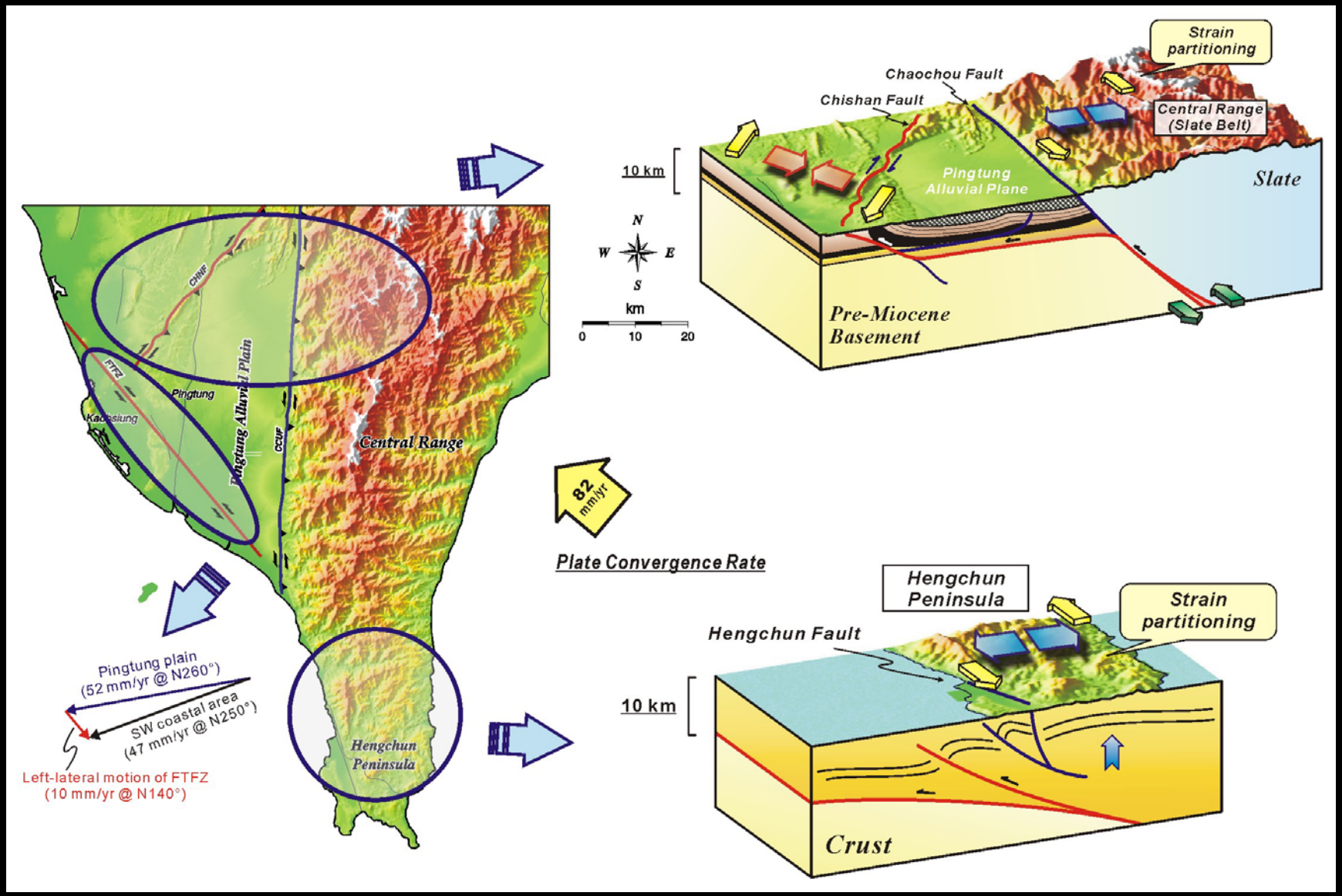


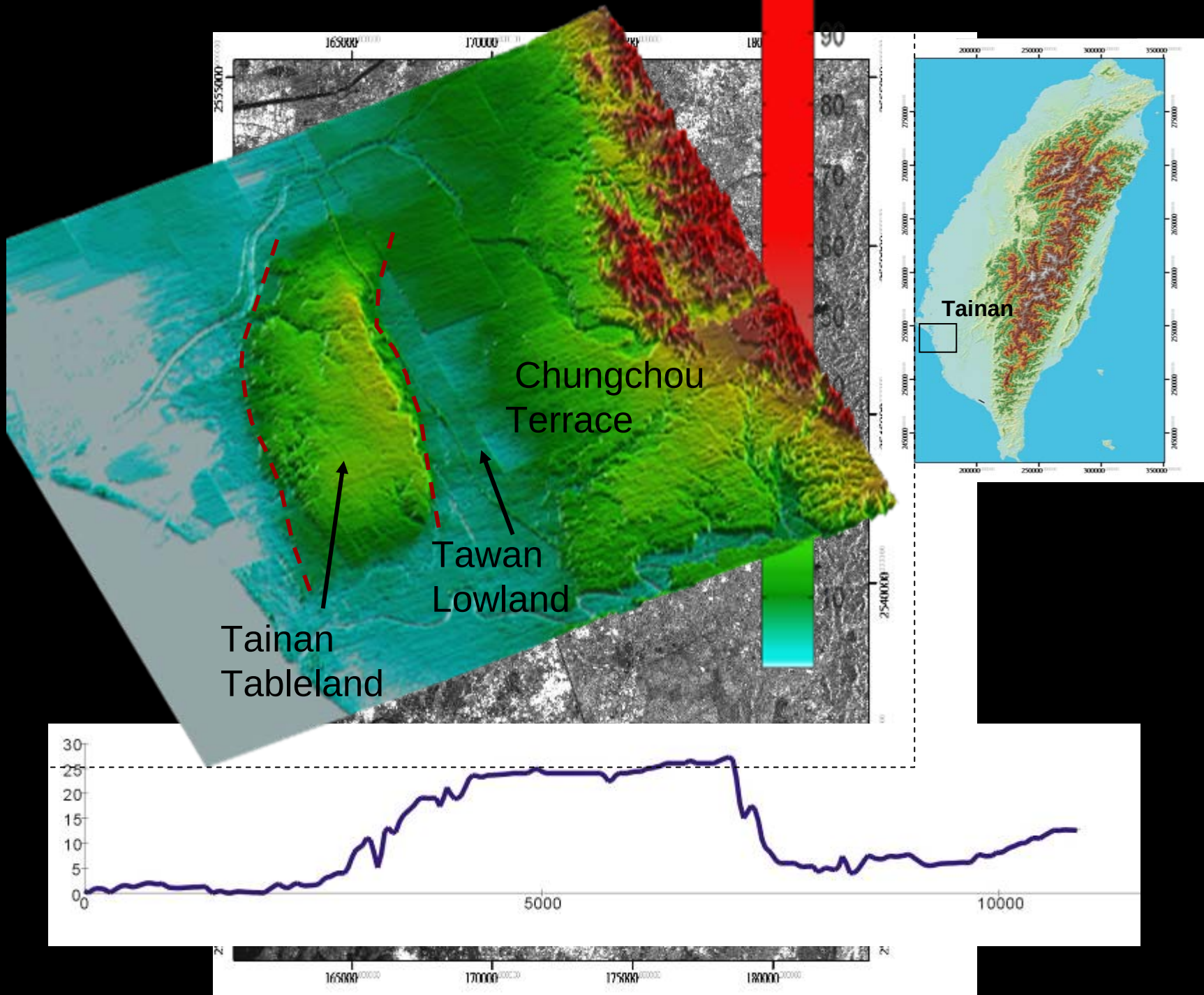


(Ching et al., J. Geophys. Res., 2007)


23°00'
22°48'
22°36'
22°24'
HCLF
HKS
CHNF
FSNF
~ -5 mm/yr
Pingtung
Kaohsiung
0
20

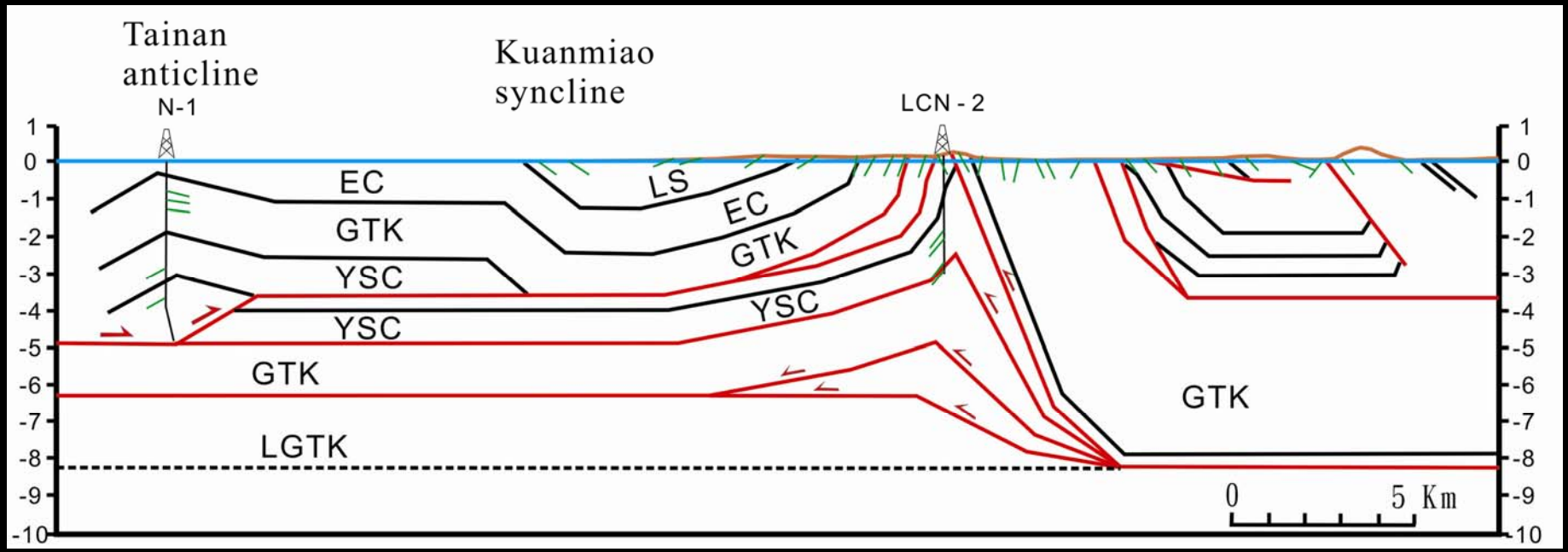
Tectonic Model of South Taiwan




Chungchou
Terrace
Tawan
Lowland
Tainan
Tableland
Tainan
30
25
20
15
10
5
0
0
5000
10000

Geological Profile

Tainan Anticline is probably associated with back thrusting mechanism at about 5 km.

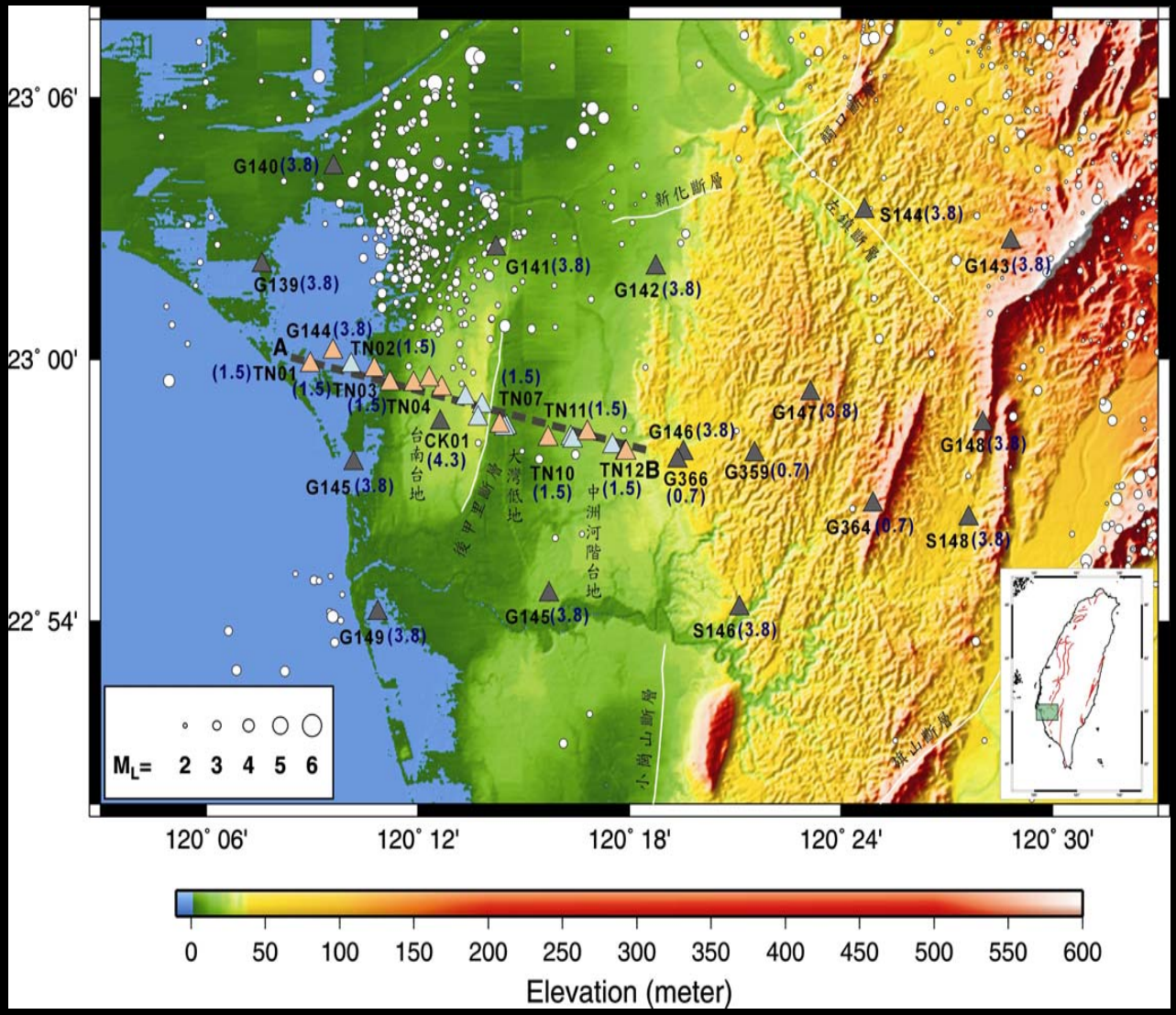


Huang et al., 2004

LS: Liushuang Fm.
EC: Erhchuangchi Fm.
YSC: Yunshuichi Fm.
GTK: Gutingkeng Fm.

GPS and Leveling Network in Study Area

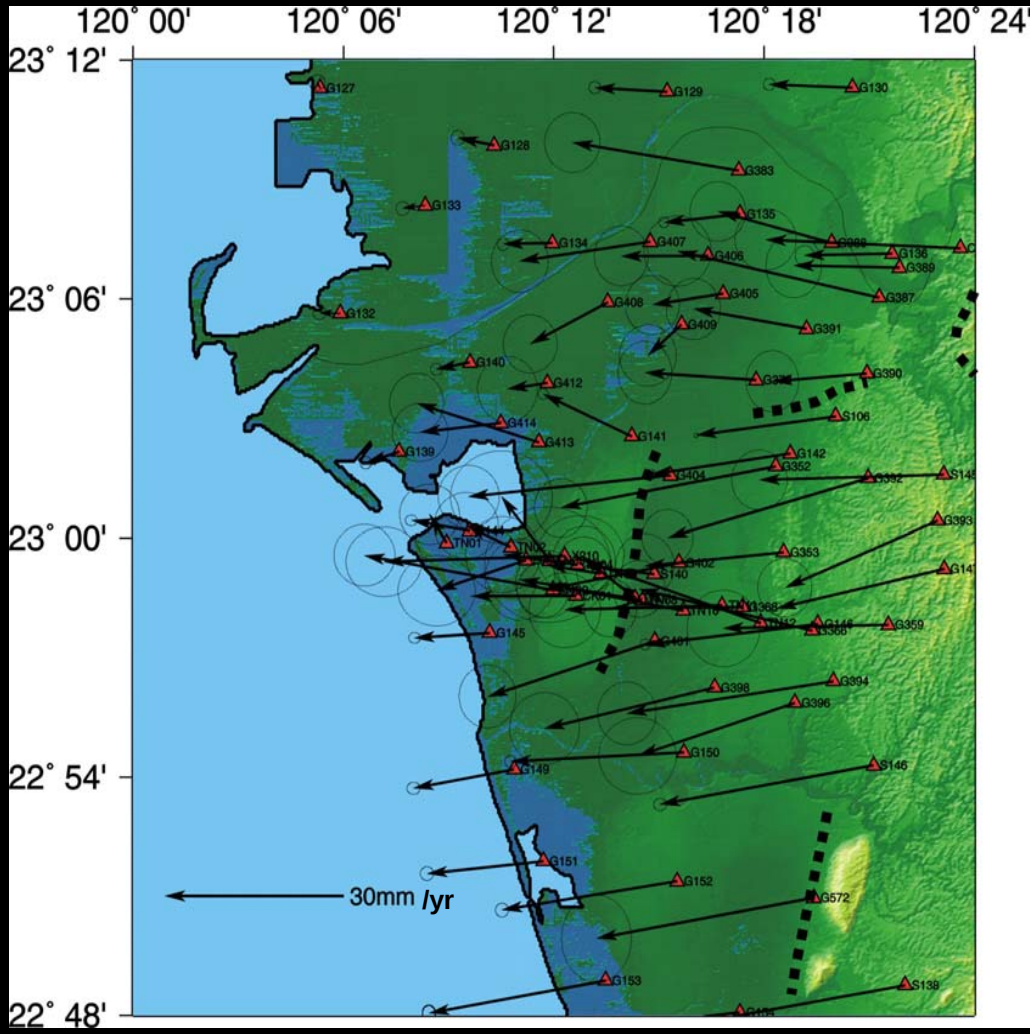
19 leveling benchmarks,
11 co-sited with GPS measurements.



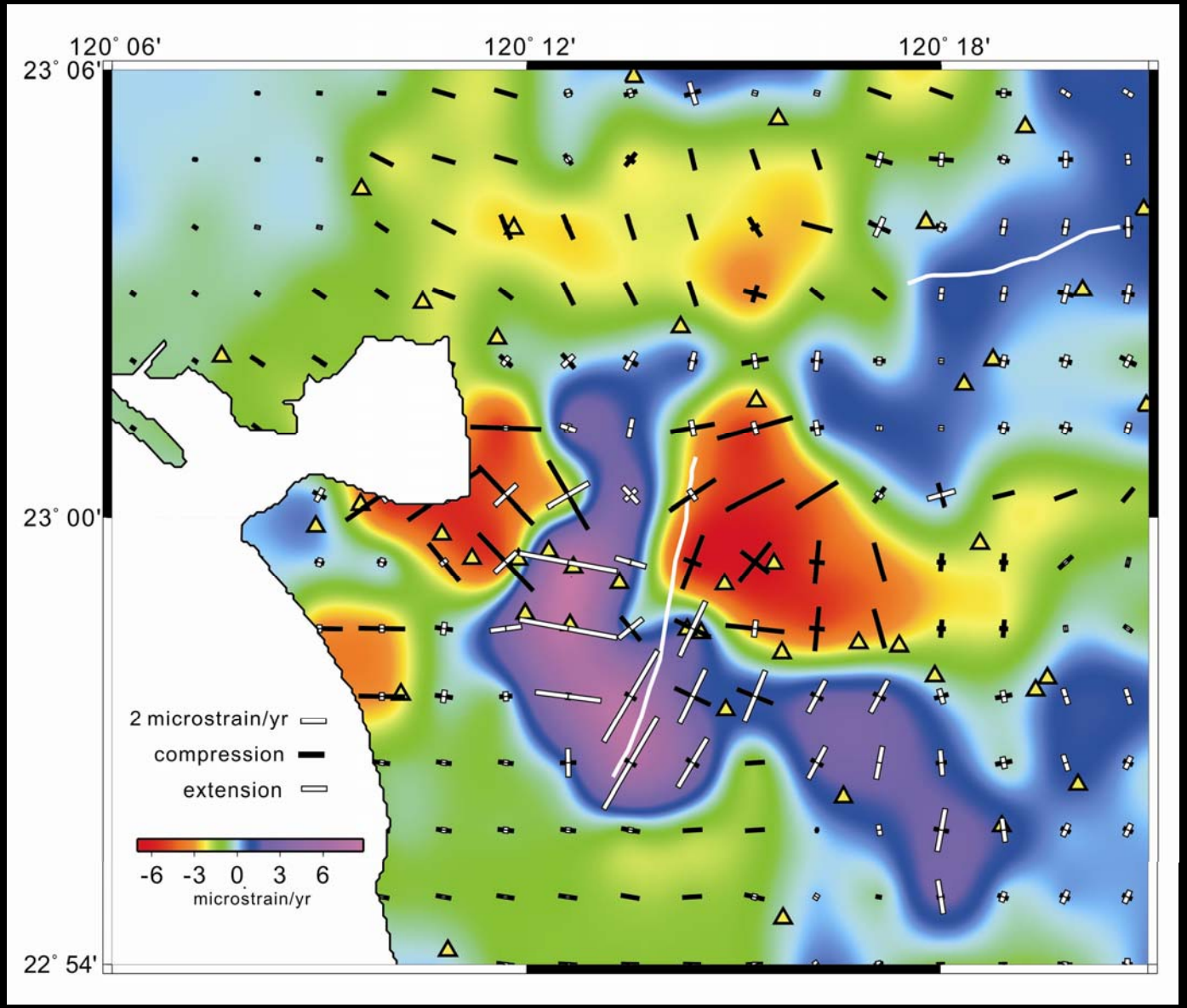
GPS Velocity Field

Reference station: S01R in Penghu Island

Horizontal velocity on the Tainan tableland is increasing from west to east with the rate 17-40 mm/yr in a direction of 260°, almost perpendicular to the direction of long axis of the Tainan tableland (N20°E).



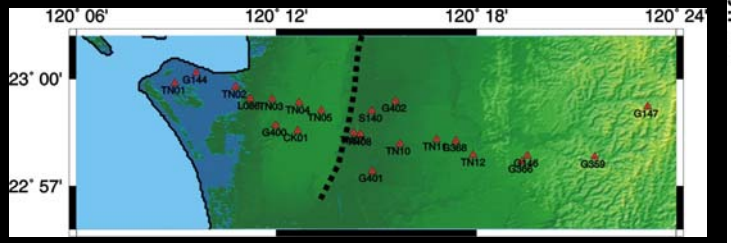
Strain rate

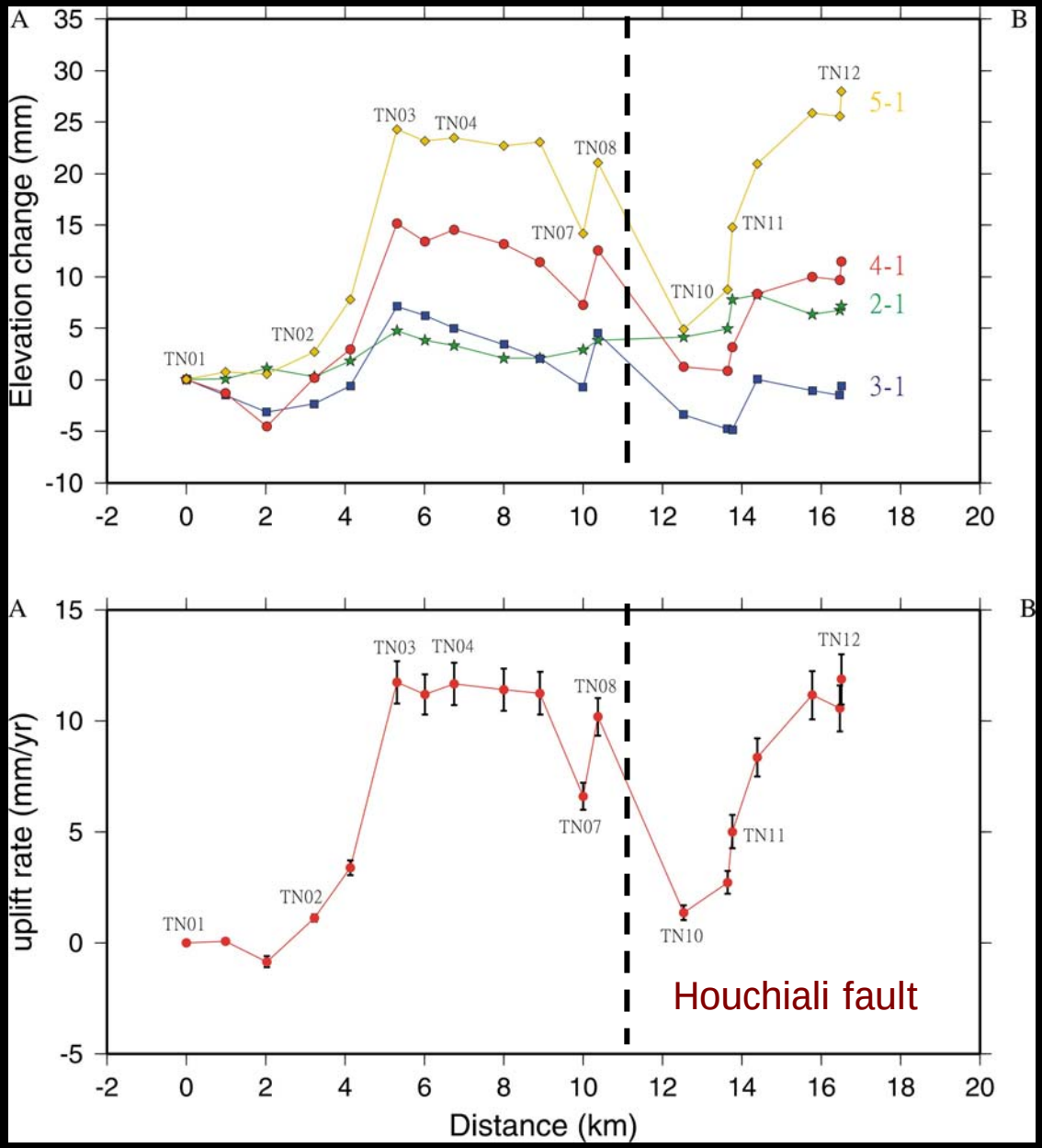

120° 06'
120° 12'
120° 18'
23° 06'
23° 00'
22° 54'
2 microstrain/yr
compression
extension
-6 -3 0 3 6
microstrain/yr

Precise Leveling

- 1st: 2001/07
- 2nd: 2001/10
- 3rd: 2002/05
- 4th: 2002/11
- 5th: 2002/06

An uplift rate of ~10-12 mm/yr for the benchmarks on the Tableland.
~2.5 mm/yr on the Tawan lowland.



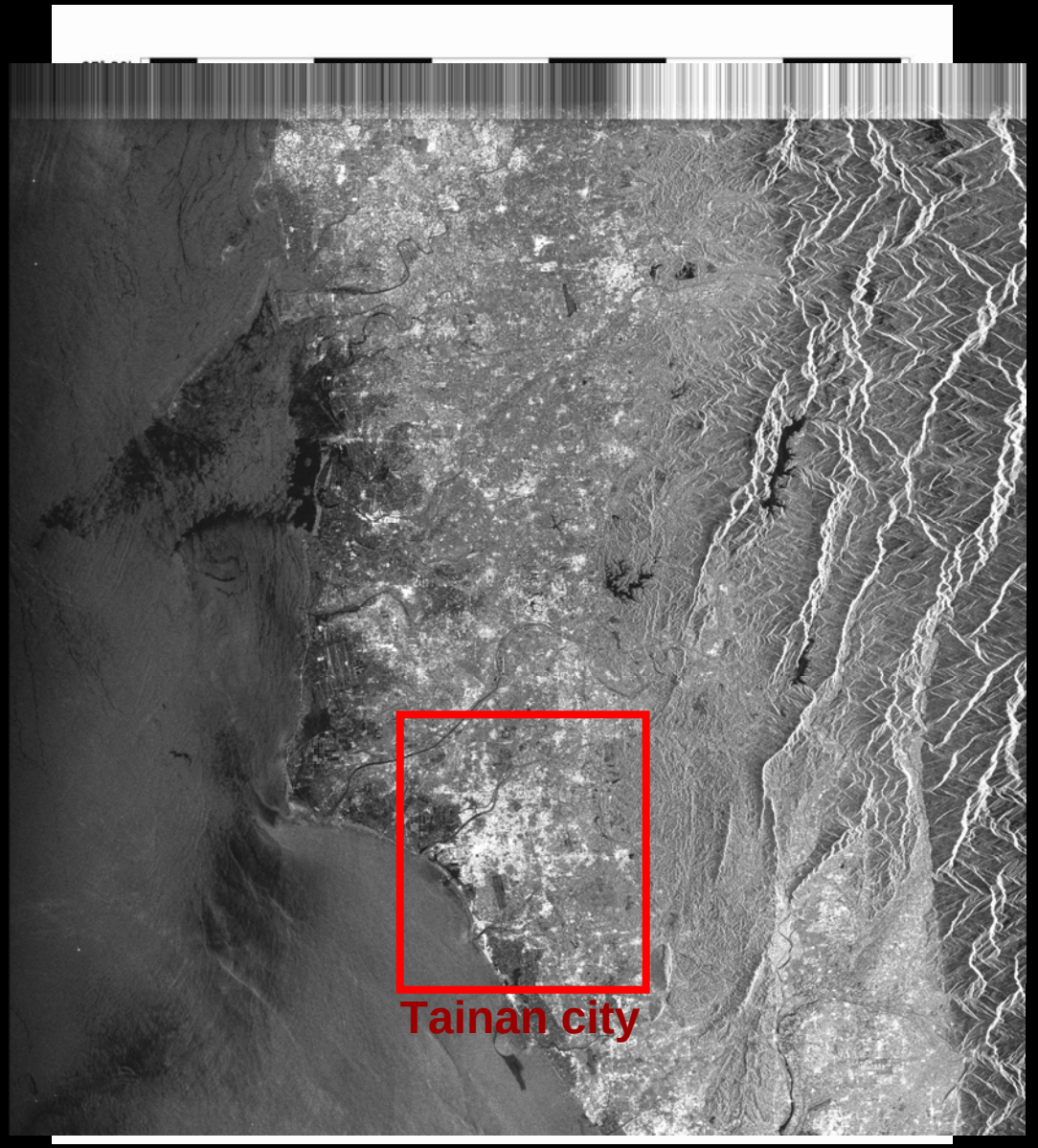


ERS1/2 SAR images

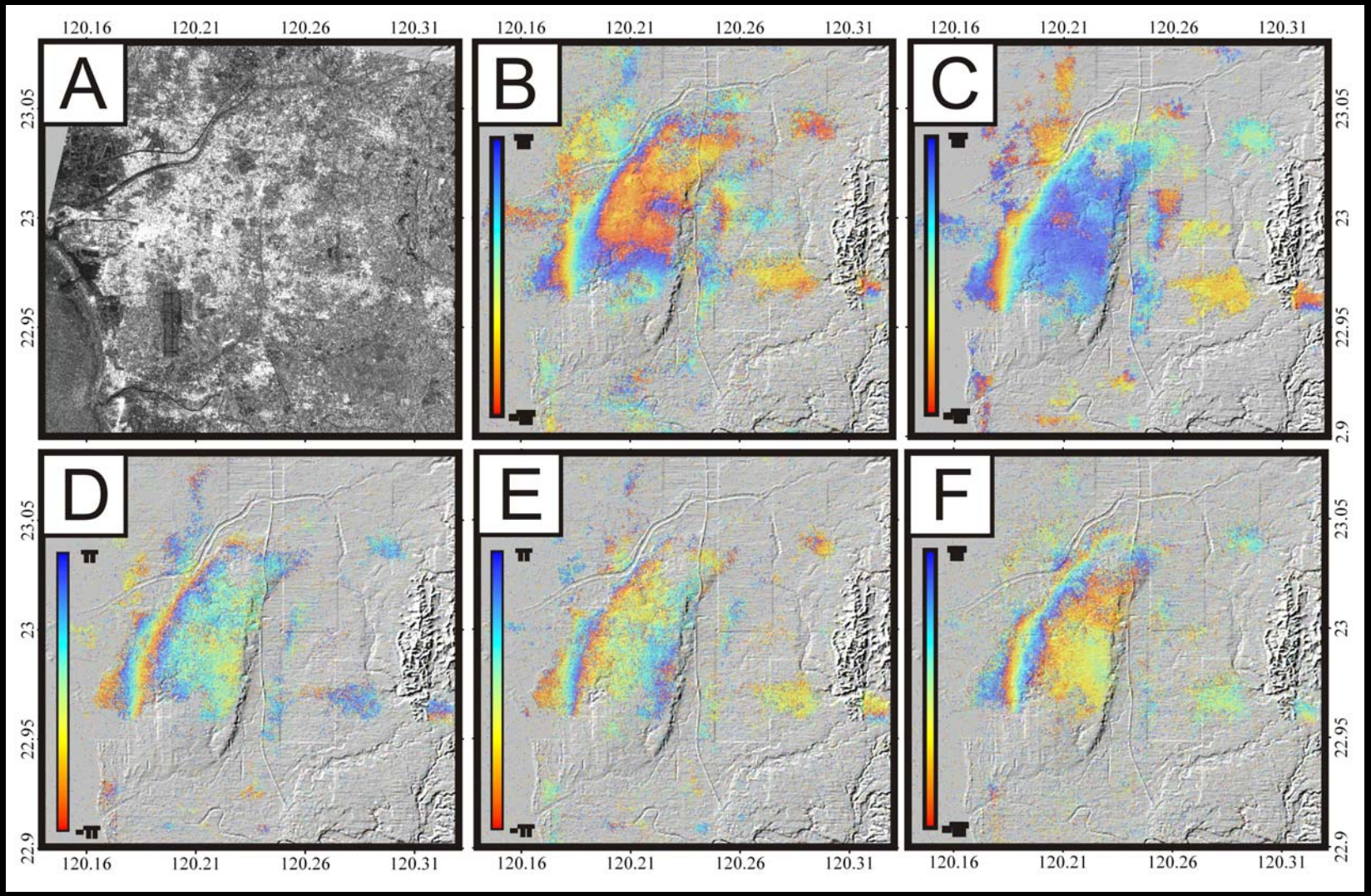
Master Image
1996/05/16

Slave images
1998/11/12
1999/01/21
1999/10/28
2000/10/12

(track: 232, frame: 3135)



Differential InSAR of Tainan Area

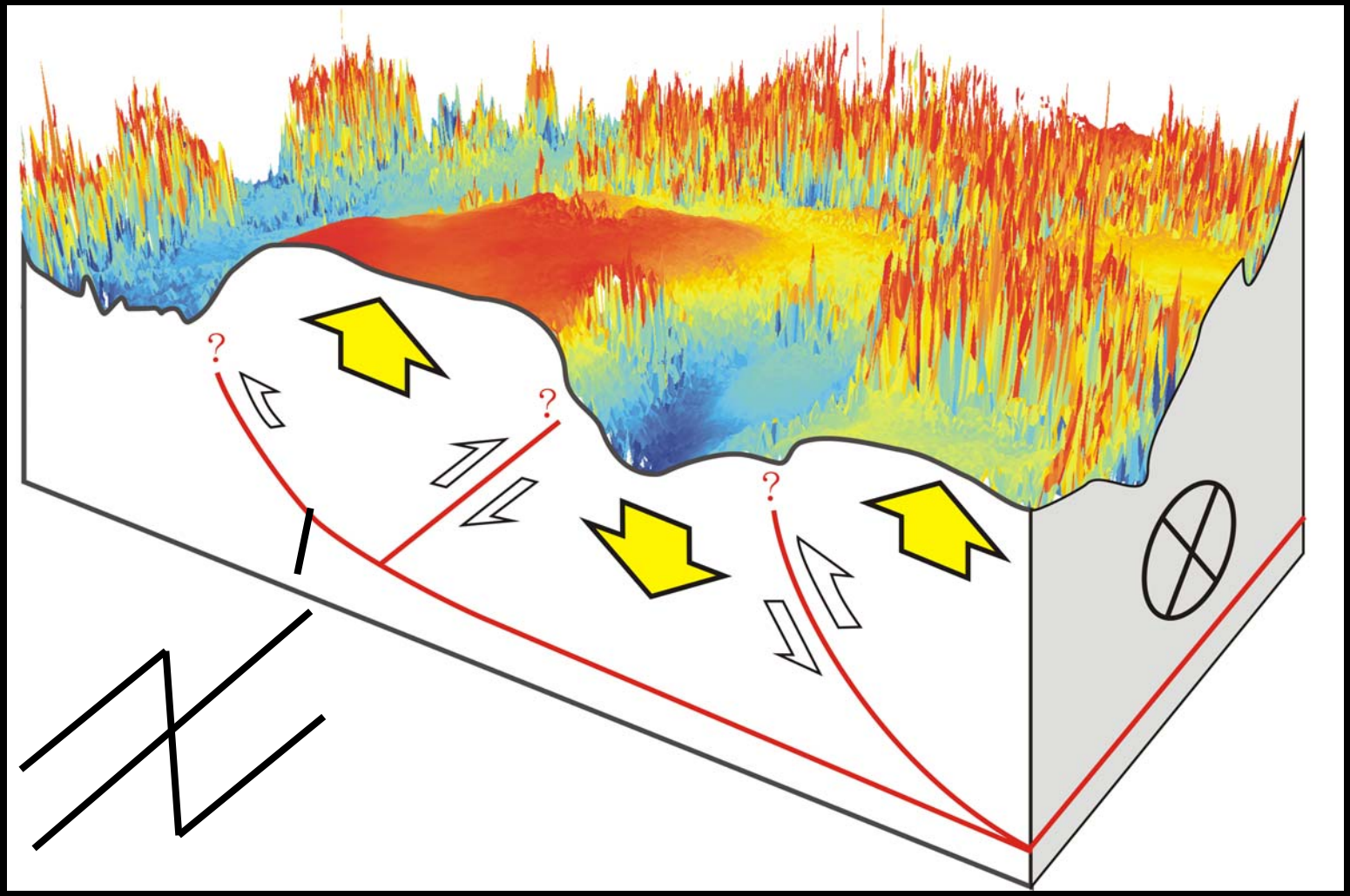


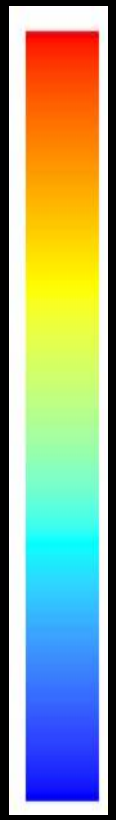
B: 960516-981112 (910 days); C: 960516-990121 (980 days)
D: 960516-990506 (1085 days); E: 960516-991028 (1260 days)
F: 960516-001012 (1610 days)

(Huang et al., GRL, 2006)

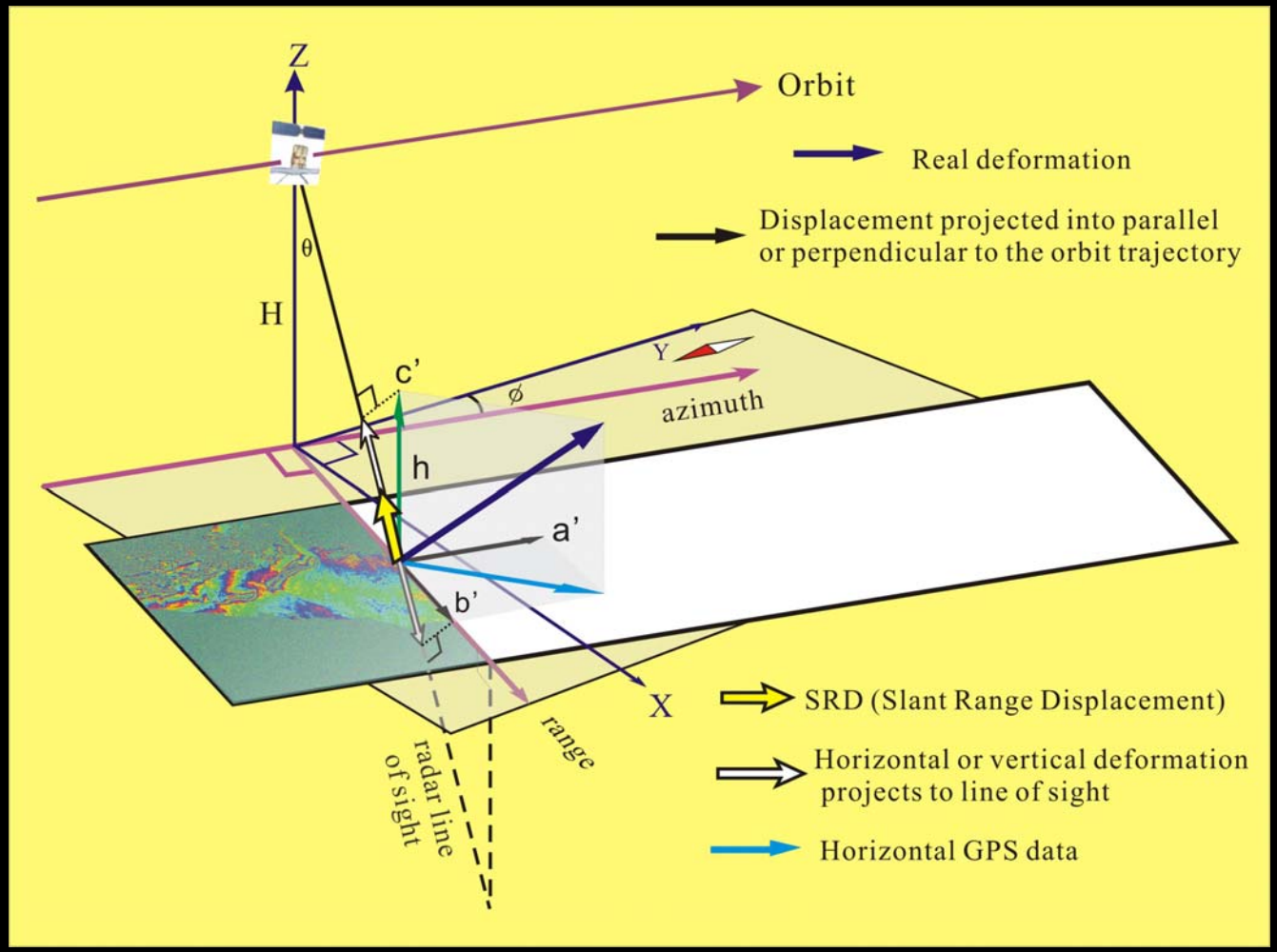
The interpretation of the result of SRD

A pop-up model of a shallow decollement underlying the Tainan anticline



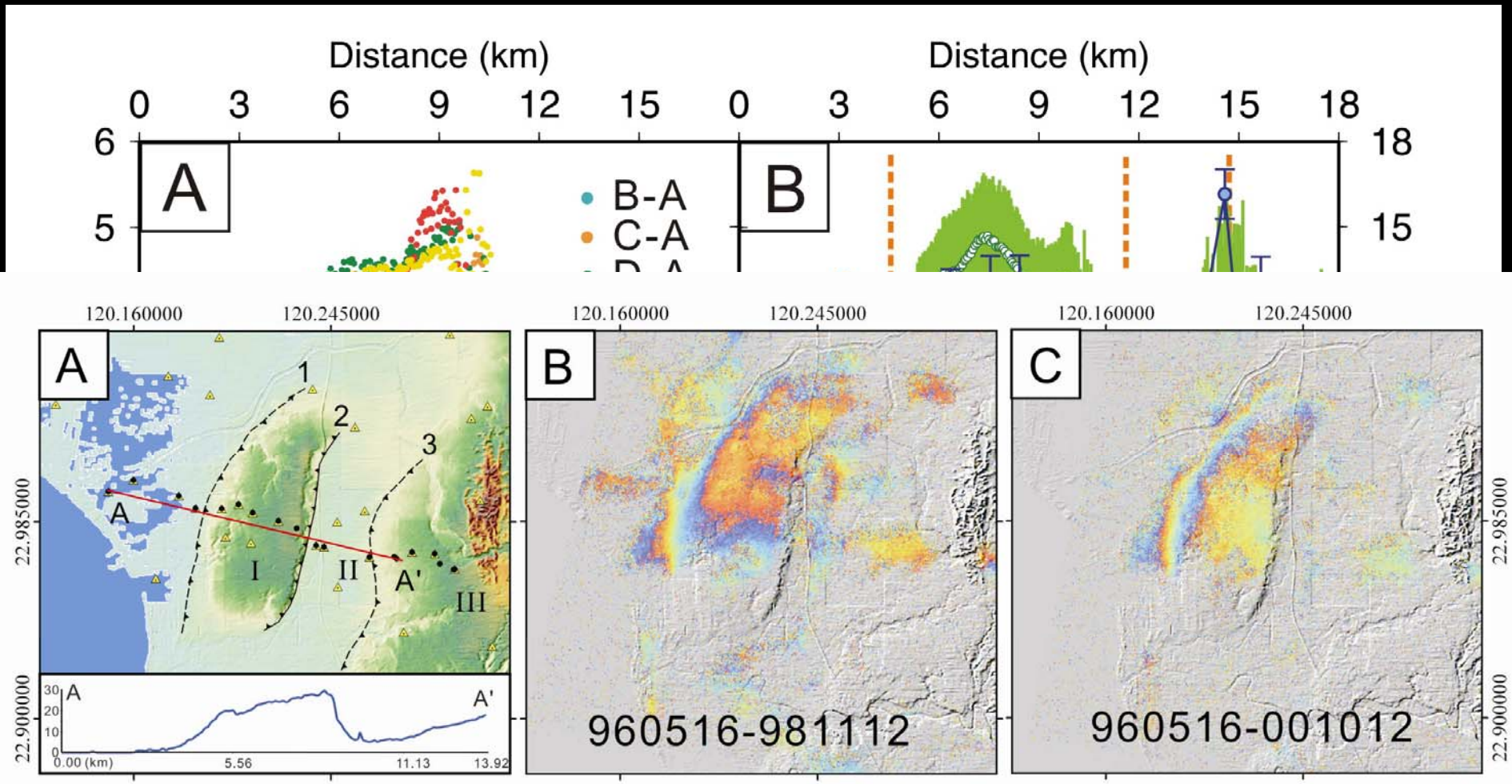


Transformation from SRD to Vertical Deformation



$$\mathbf{V} = \begin{bmatrix} a' \\ b' \\ c' \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} a\cos\phi + b\sin\phi \\ -a\sin\phi + b\cos\phi \\ c \end{bmatrix}$$

$$h = \Delta r \sec\theta - (a\cos\phi + b\sin\phi)\tan\theta$$



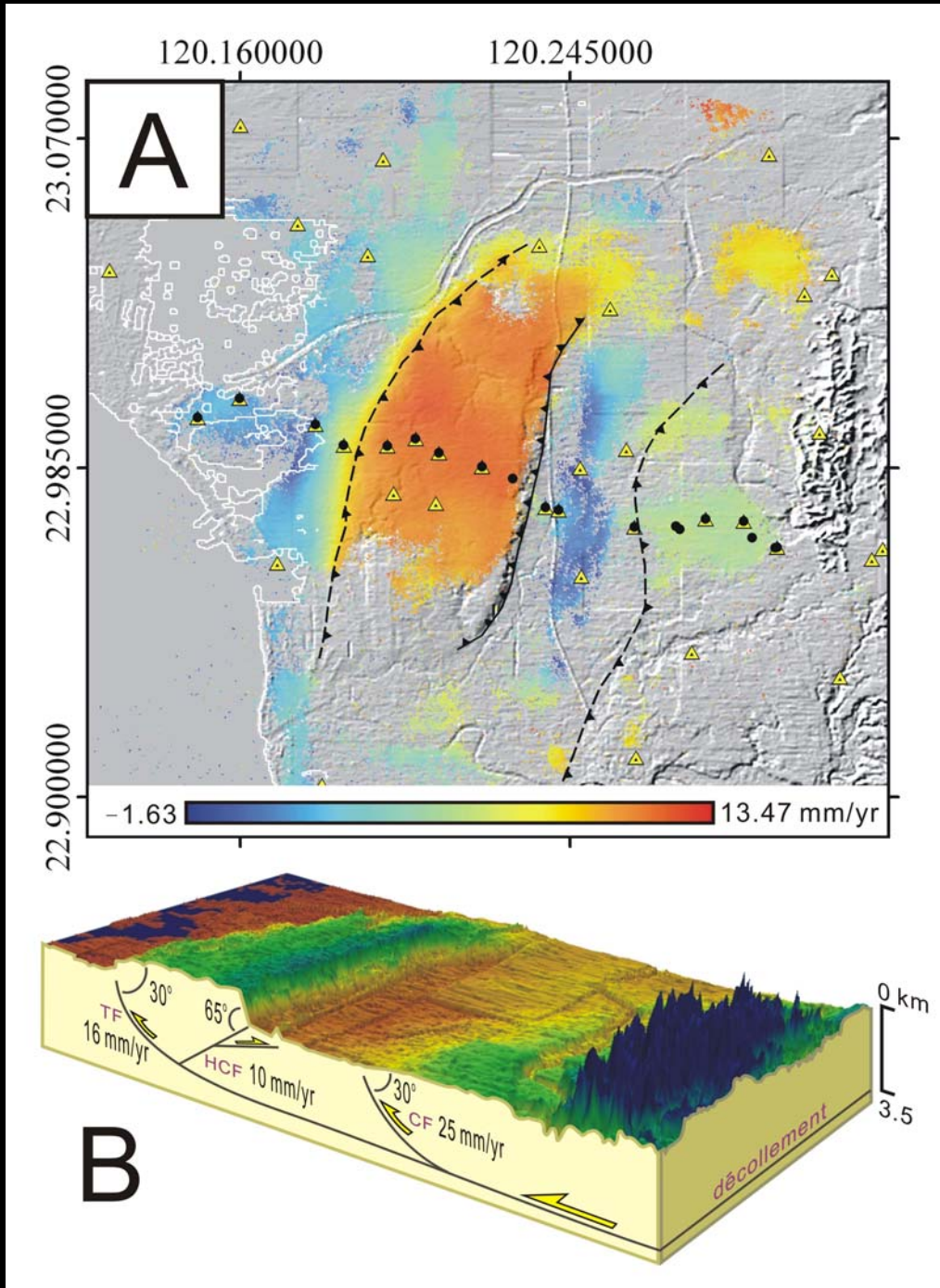
B-A: 960516-981112 (910 days); C-A: 960516-990121 (980 days)
D-A: 960516-990506 (1085 days); E-A: 960516-991028 (1260 days)
F-A: 960516-001012 (1610 days)

Huang et al., Geophys. Res. Lett., 2006

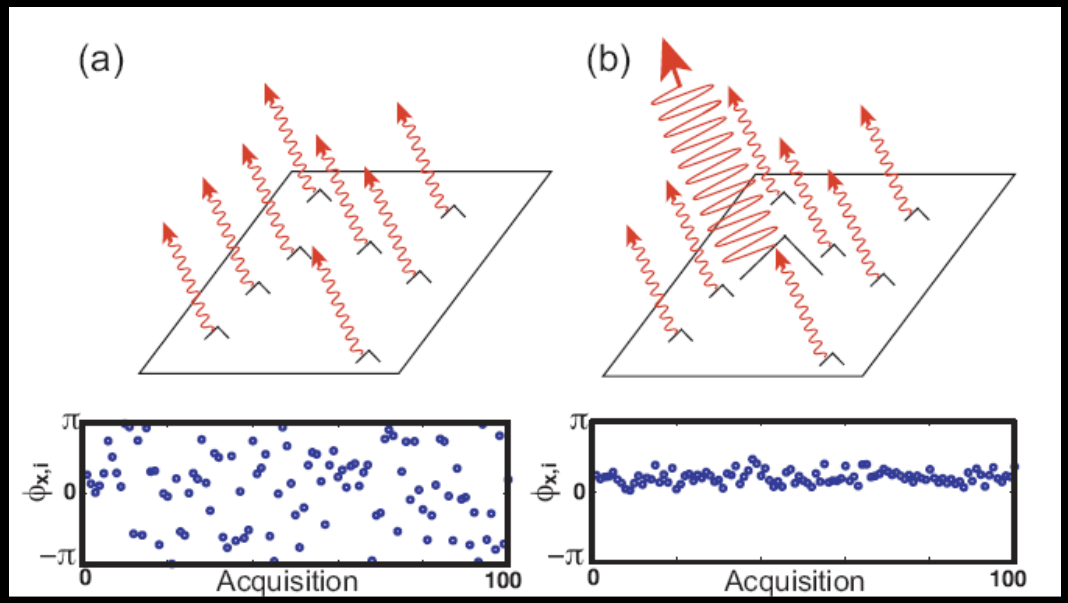
Dislocation Model

Slip rate along the inferred Tainan fault is ~16 mm/yr, ~10 mm/yr along the Houchiali fault, and ~25 mm/yr along the inferred Chungchou fault.

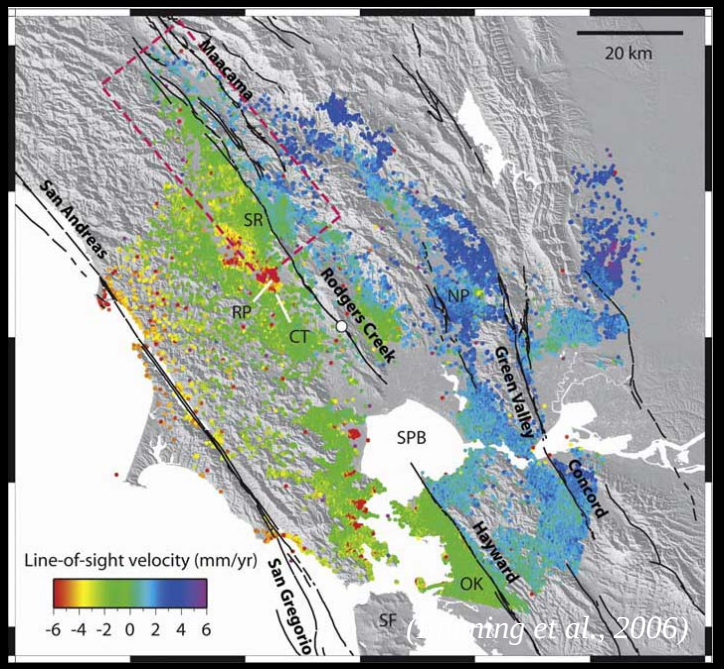
Huang et al., Geophys. Res. Lett., 2006



What is PS ?



(Hooper et al., 2004)



(Ferretti et al., 2006)

- Permanent Scatterers™
- Persisitent Scatterers
- Stable Point-wise Target

The goal of PS-InSAR

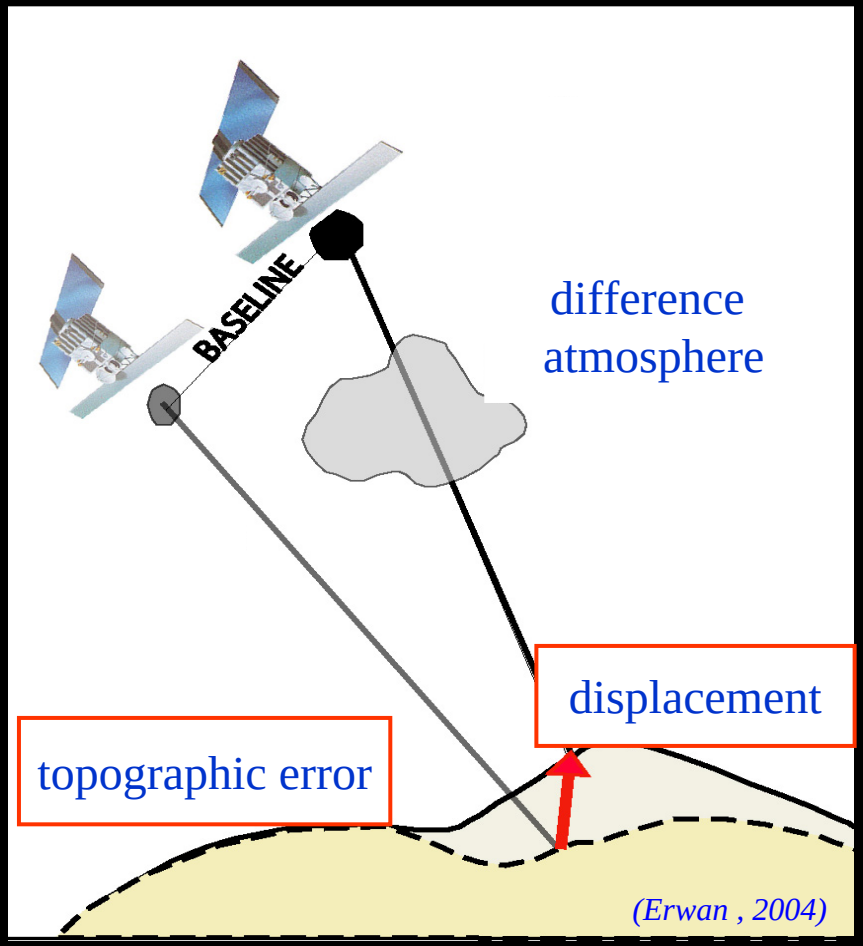
When generating an interferogram by combining two SAR images, by removing the flat earth and topographic terms its DInSAR phase variation between neighboring pixels can be expressed as:

$$\delta\phi_{diff} = \delta\phi_{\varepsilon} + \delta\phi_{mov} + \delta\phi_{atm} + \delta\phi_{noise}$$

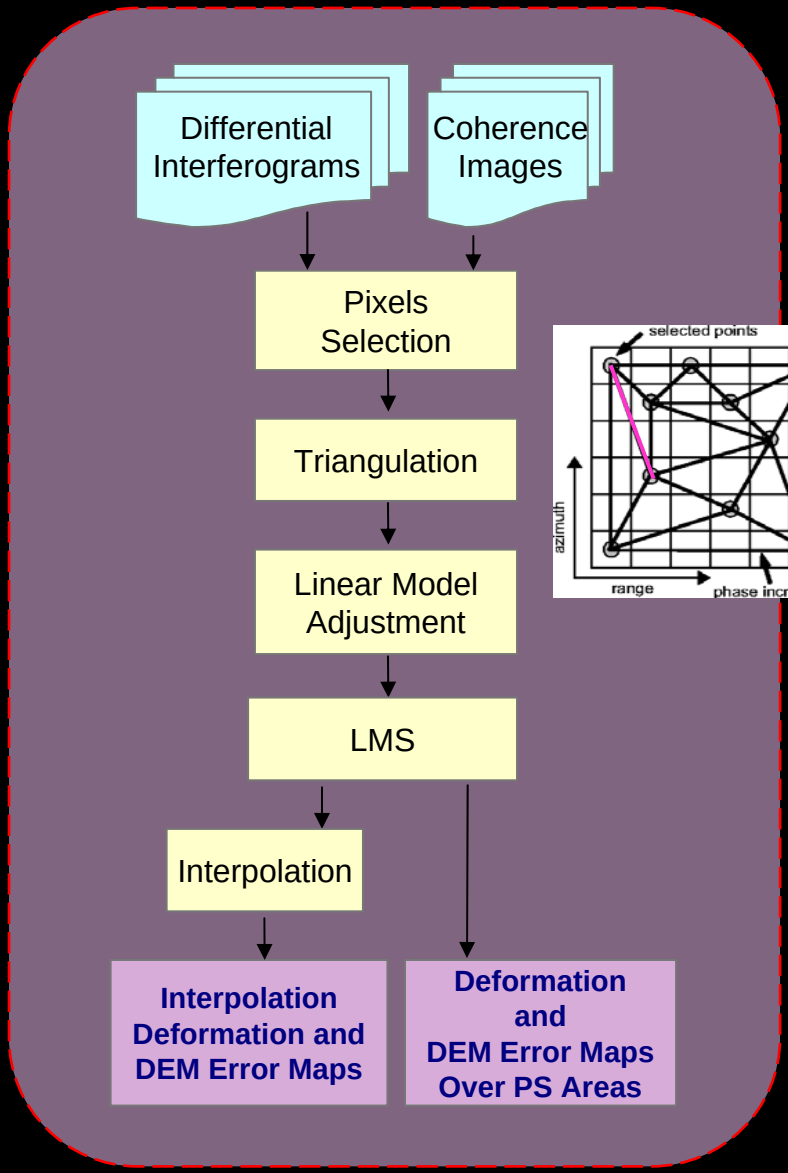
$$\delta\phi_{\varepsilon} = \frac{4\pi}{\lambda} \cdot \frac{B \cdot \Delta\varepsilon}{r \cdot \sin\theta}$$

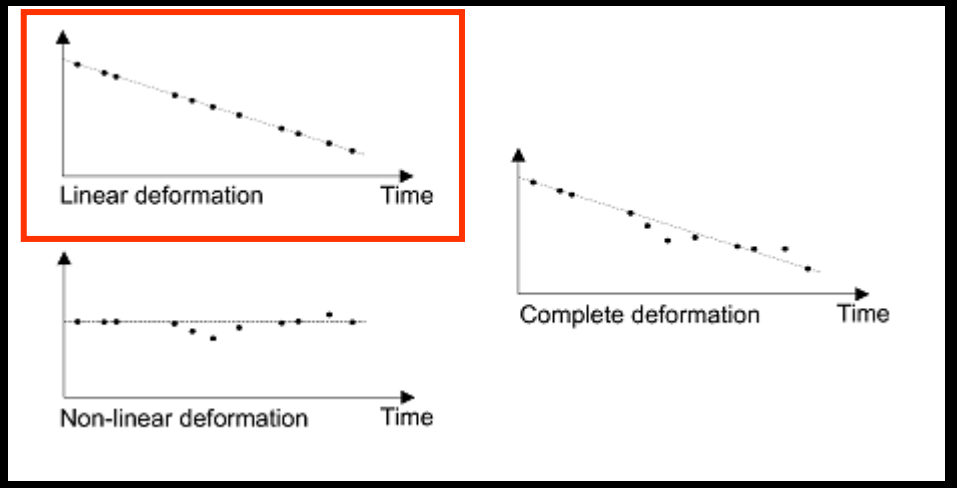
$$\delta\phi_{mov} = \delta\phi_{linear} + \delta\phi_{nonlinear}$$

$$= \frac{4\pi}{\lambda} \cdot \Delta v \cdot T + \delta\phi_{nonlinear}$$



Process of PS-InSAR (Linear)

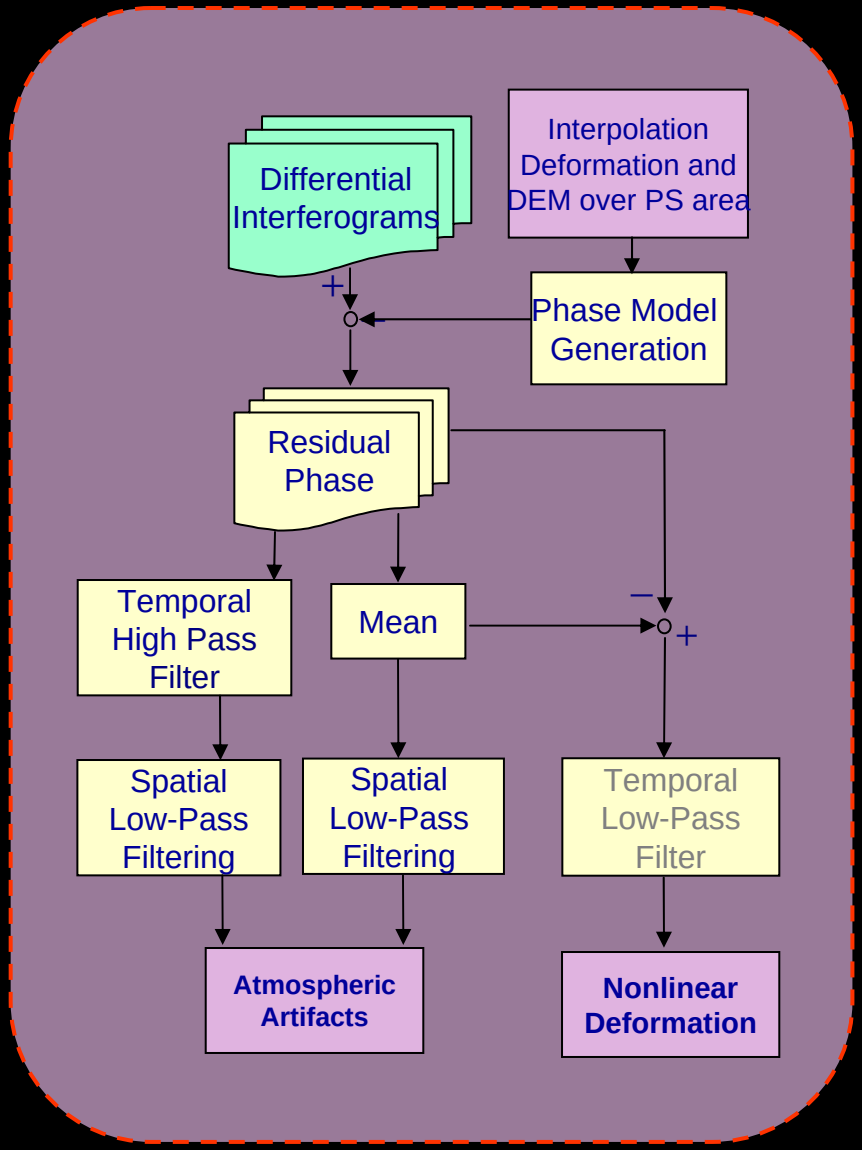


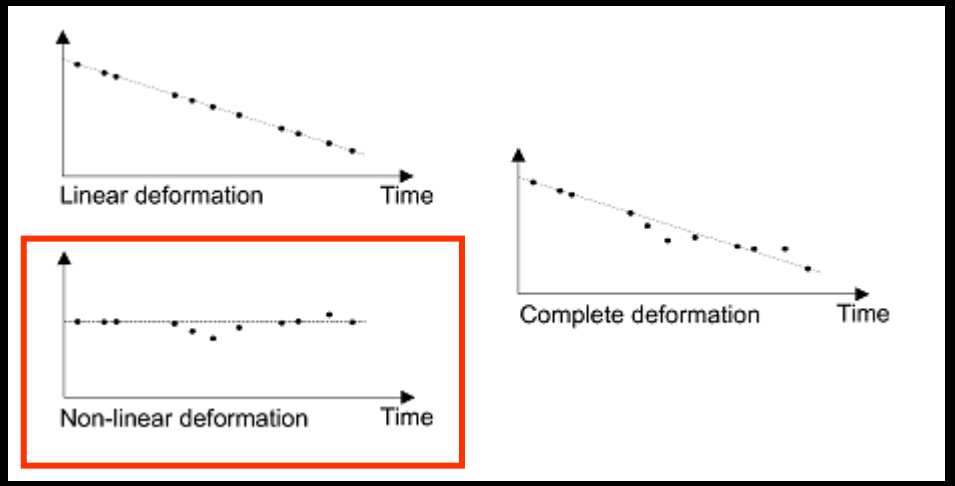


$$\delta\phi_{diff}(x_a, y_a, x_b, y_b, T_i) = \frac{4\pi}{\lambda} \cdot \frac{B(T_i)}{r(T_i) \cdot \sin(\theta_i)} \cdot \Delta\varepsilon + \frac{4\pi}{\lambda} \cdot T_i \cdot \Delta v + \Delta\beta + \Delta\alpha + \Delta n$$

$$\gamma = \frac{1}{N} \left| \sum_{i=0}^{N} \exp\left[j \cdot (\delta\phi_{diff} - \delta\phi_{model}) \right] \right|$$

Process of PS-InSAR (Nonlinear)





$$\delta\phi_{residual}(x_a, x_b, T_i) = \delta\phi_{nonlinear} + \delta\phi_{atmos} + \delta\phi_n$$

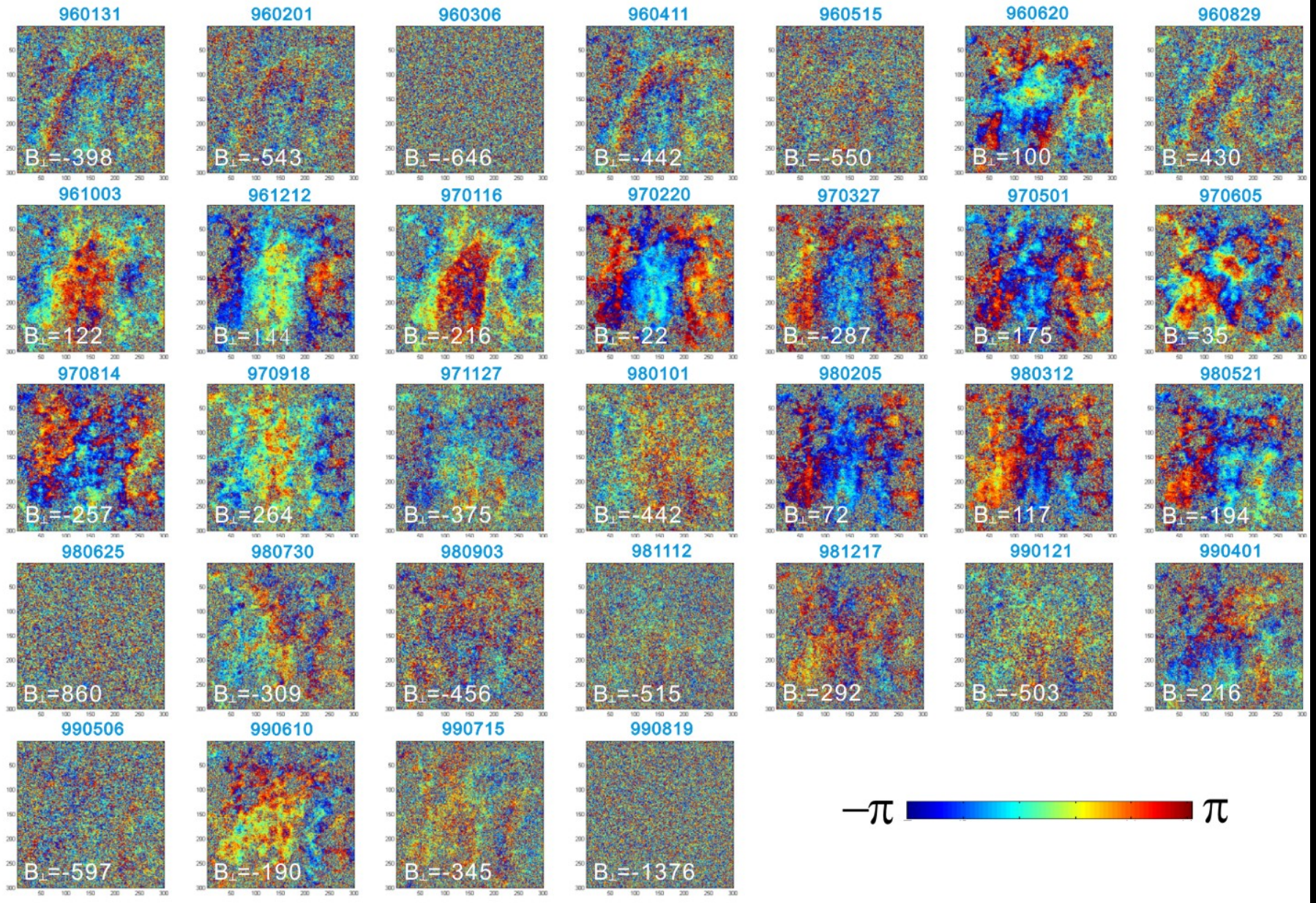
$$\phi_{atmos} = \left[\left[\phi_{res}\right]_{HP\_Time}\right]_{LP\_Space} + \left[\overline{\phi}_{res}\right]_{LP\_Space}$$

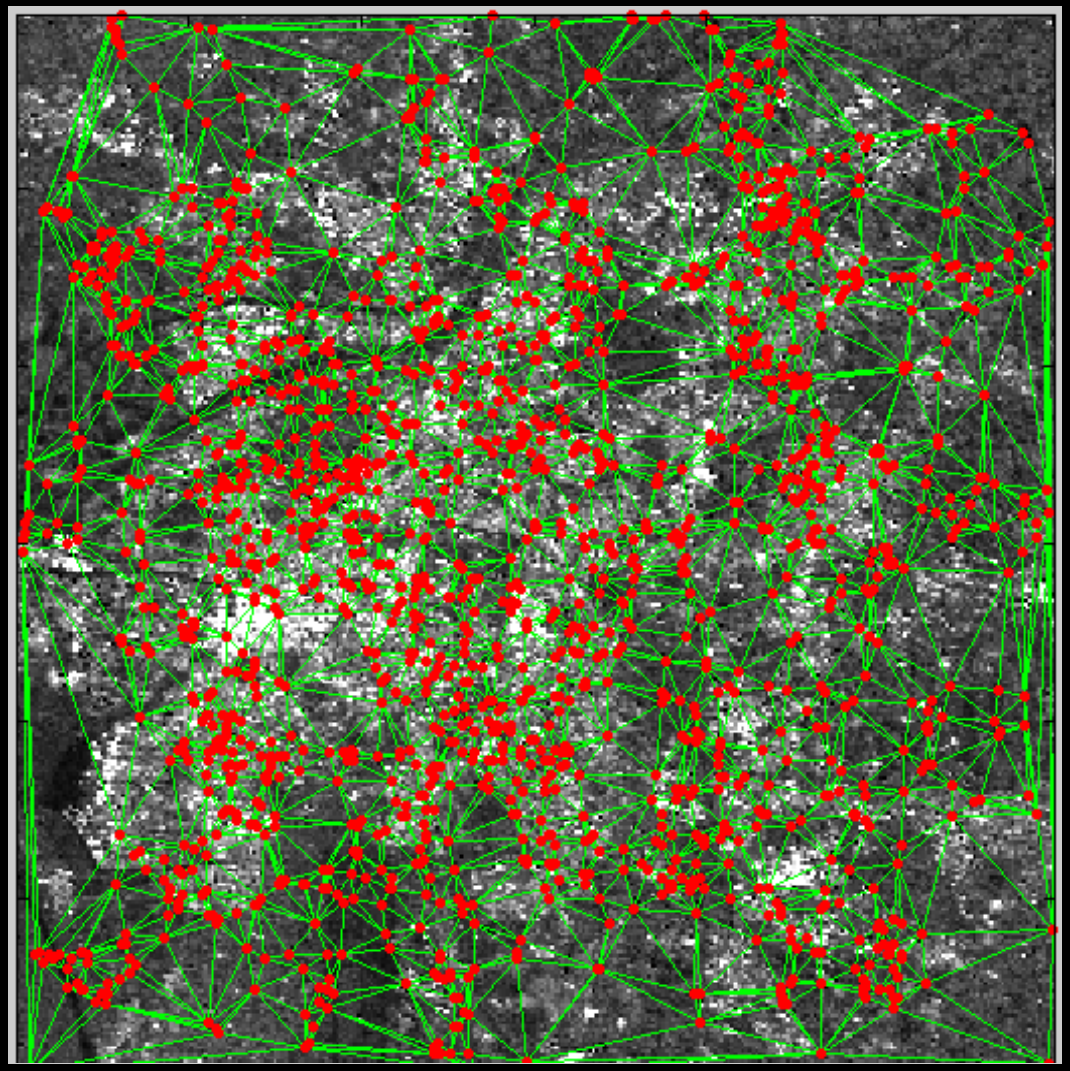
$$\phi_{nonlinear} = \left[\delta\phi_{residual}(T_i) - \overline{\delta\phi}_{residual}\right]_{LP\_Time}$$

Choice of Master Image

Date	Baseline	F_{DC}	Date	Baseline	F_{DC}
19960131	923	25.68	19971127	900	-21.07
19960201	1068	-10.31	19980101	967	-19.51
19960306	1171	26.99	19980205	453	-32.12
19960411	967	-14.18	19980312	408	-16.82
19960515	1075	32.03	19980521	719	0.34
19960620	425	-13.15	19980625	-335	-1.37
19960829	95	-21.16	19980730	834	-4.96
19961003	403	-18.31	19980903	981	-3.79
19961212	381	-14.24	19981112	1040	-10.10
19970116	741	-18.53	19981217	233	-15.55
19970220	547	-8.23	19990121	1028	-12.89
19970327	812	-7.61	19990401	309	-10.88
19970501	350	-15.88	19990506	1122	-5.42
19970605	490	-11.31	19990610	715	-6.10
19970710	525	-10.84	19990715	870	-6.22
19970814	782	-18.73	19990819	1091	-10.21
19970918	261	-17.14			

$$\rho_{total} = \rho_{temporal}\rho_{spatial}\rho_{doppler}\rho_{thermal} \approx \left[1 - f\left(\frac{T}{T^c}\right)\right]\left[1 - f\left(\frac{B_\perp}{B^c_\perp}\right)\right]\left[1 - f\left(\frac{F_{DC}}{F^c_{DC}}\right)\right]\rho_{thermal}$$


960131
B⊥=-398
960201
B⊥=-543
960306
B⊥=-646
960411
B⊥=-442
960515
B⊥=-550
960620
B⊥=100
960829
B⊥=430
961003
B⊥=122
961212
B⊥=144
970116
B⊥=-216
970220
B⊥=-22
970327
B⊥=-287
970501
B⊥=175
970605
B⊥=35
970814
B⊥=-257
970918
B⊥=264
971127
B⊥=-375
980101
B⊥=-442
980205
B⊥=72
980312
B⊥=117
980521
B⊥=-194
980625
B⊥=860
980730
B⊥=-309
980903
B⊥=-456
981112
B⊥=-515
981217
B⊥=292
990121
B⊥=-503
990401
B⊥=216
990506
B⊥=-597
990610
B⊥=-190
990715
B⊥=-345
990819
B⊥=-1376
−π
π

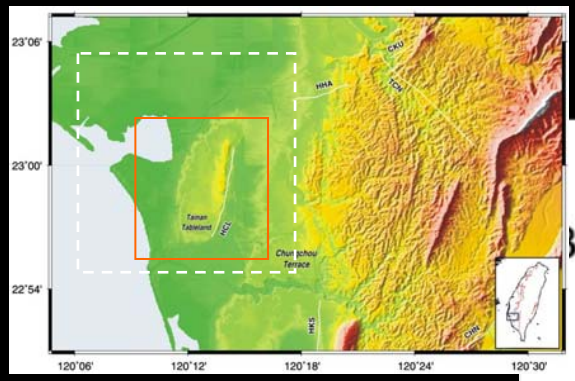


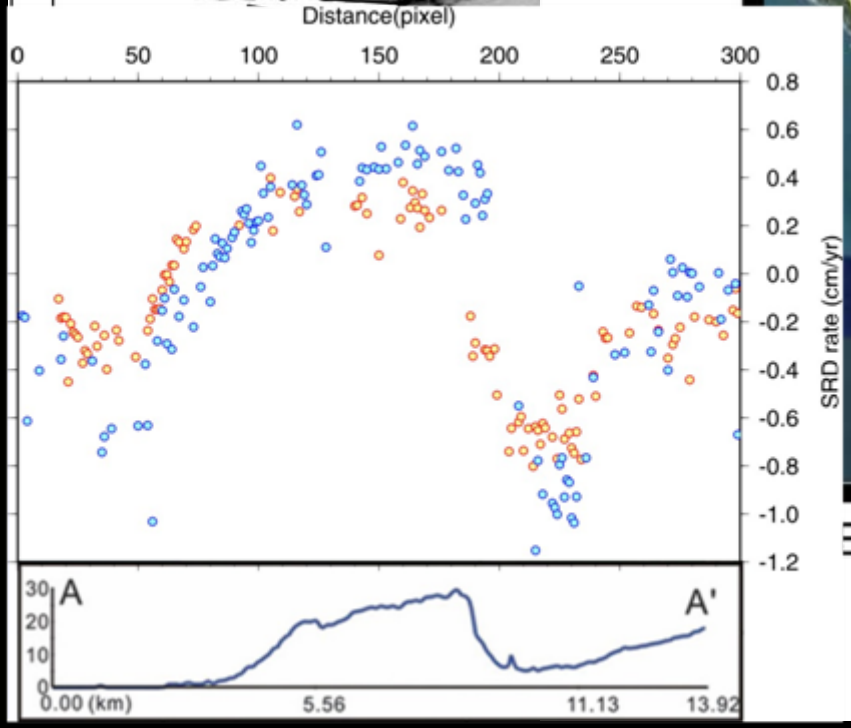
- Area : 144 (km^2)
- PSC number : 1649 (pixel)
- PSC density : 11.45 (pixel/km^2)

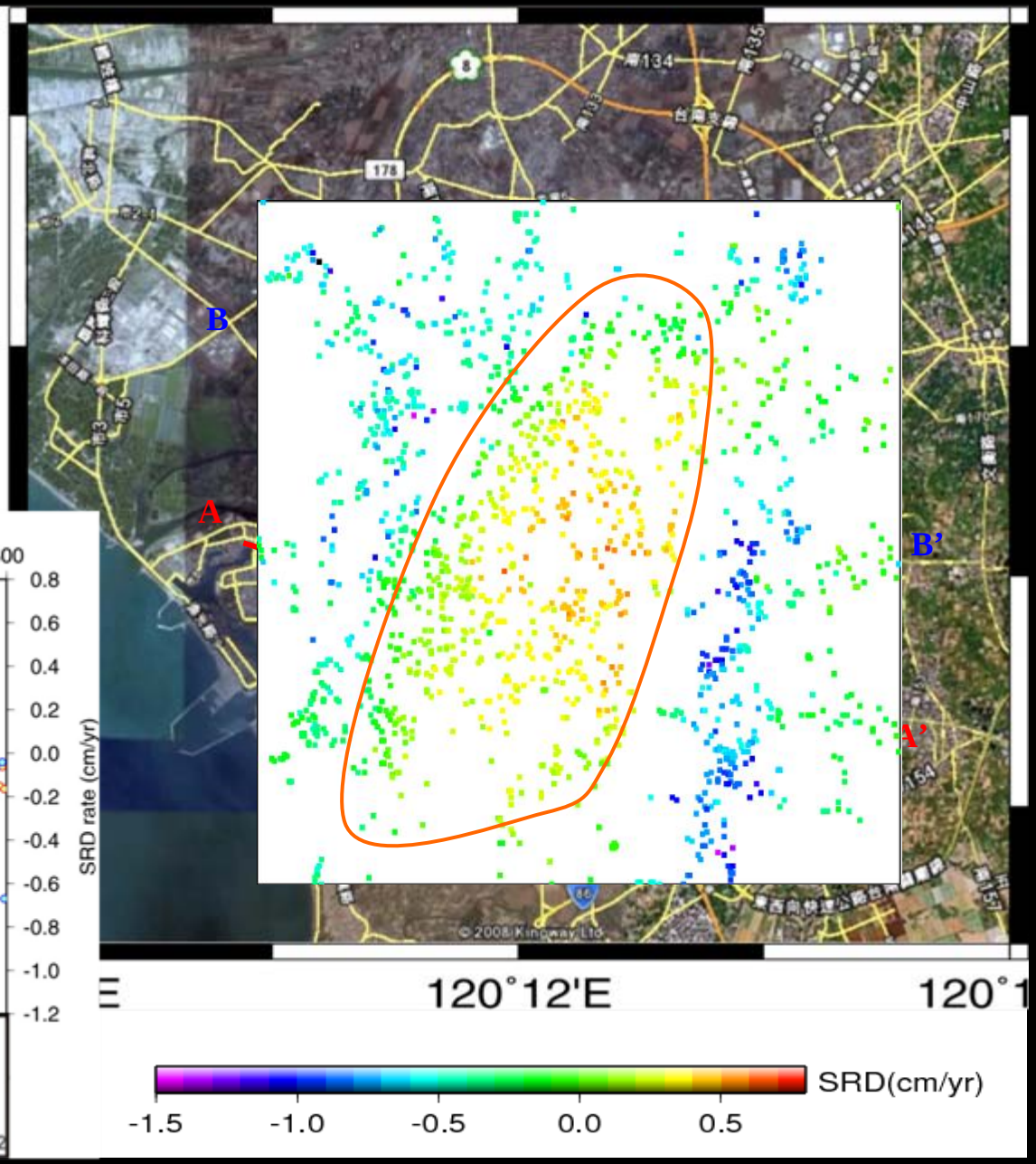
Software:

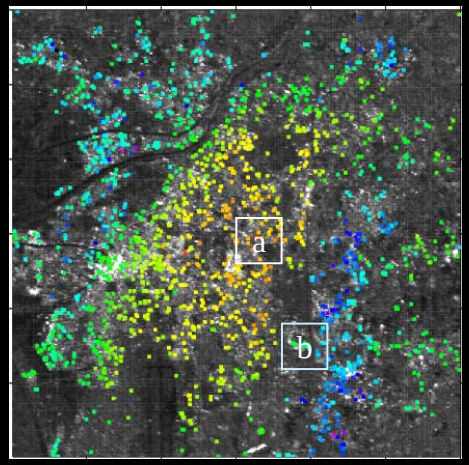
DInSAR : DIAPASON V4.0

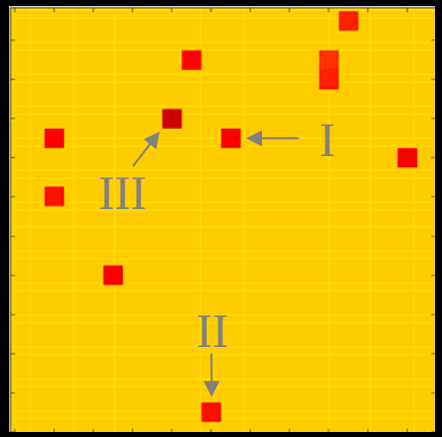
PSInSAR : MATLAB

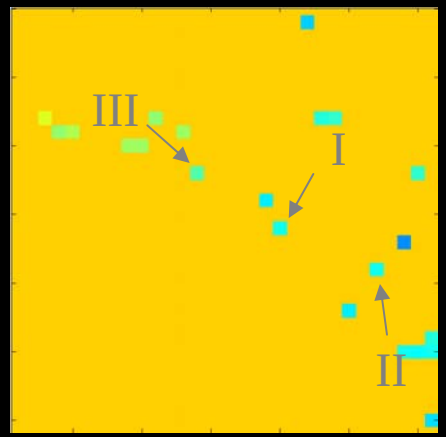

23°06'
23°00'
22°54'
120°06'
120°12'
120°18'
120°24'
120°30'
Taiwan Tablerand
Chun tzhou Terrace
HHA
CKU
TCH
HKS
CHY

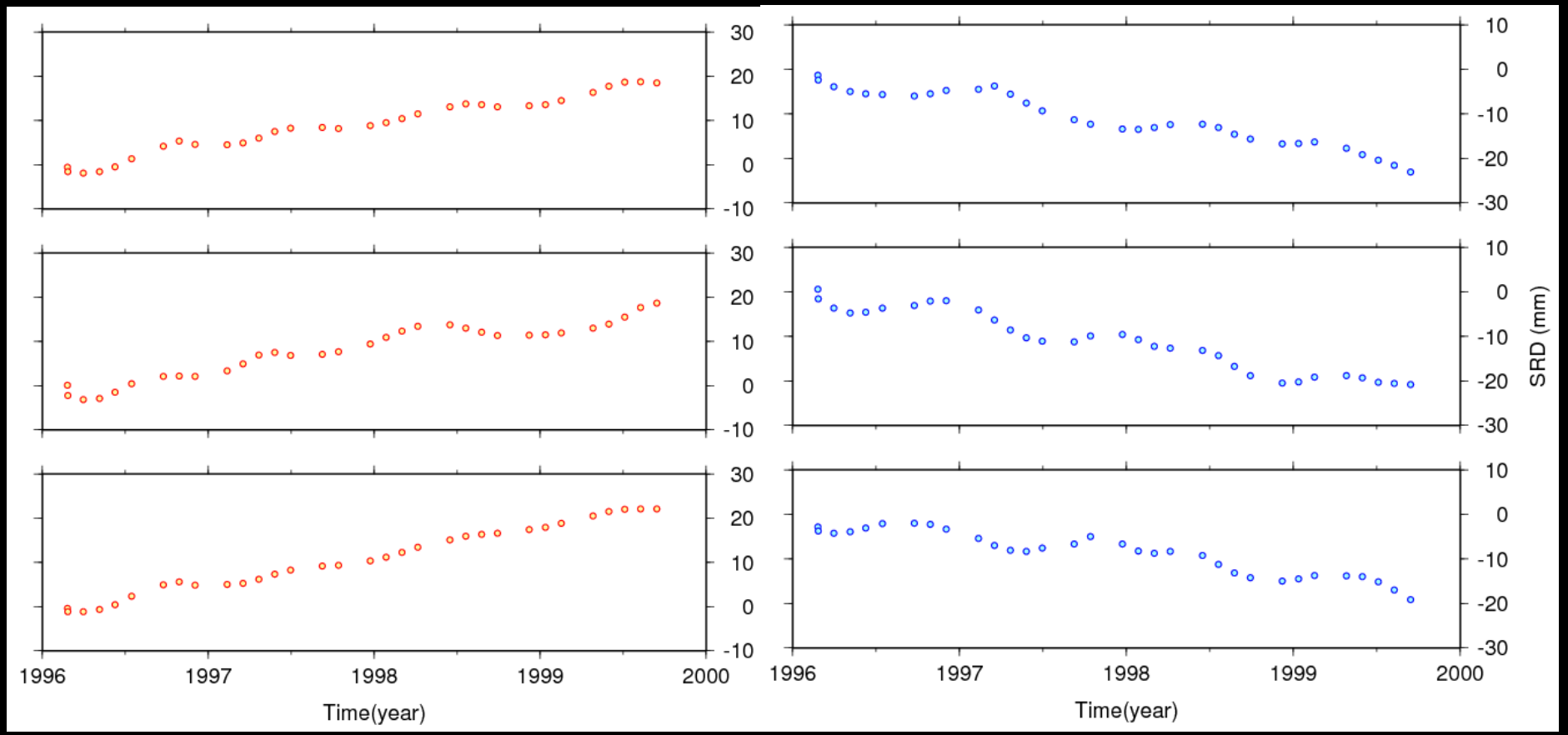

Distance(pixel)
0
50
100
150
200
250
300
SRD rate (cm/yr)
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
A
A'
30
20
10
0
0.00 (km)
5.56
11.13
13.92


B
A
B'
A'
120°12'E
SRD(cm/yr)
-1.5
-1.0
-0.5
0.0
0.5

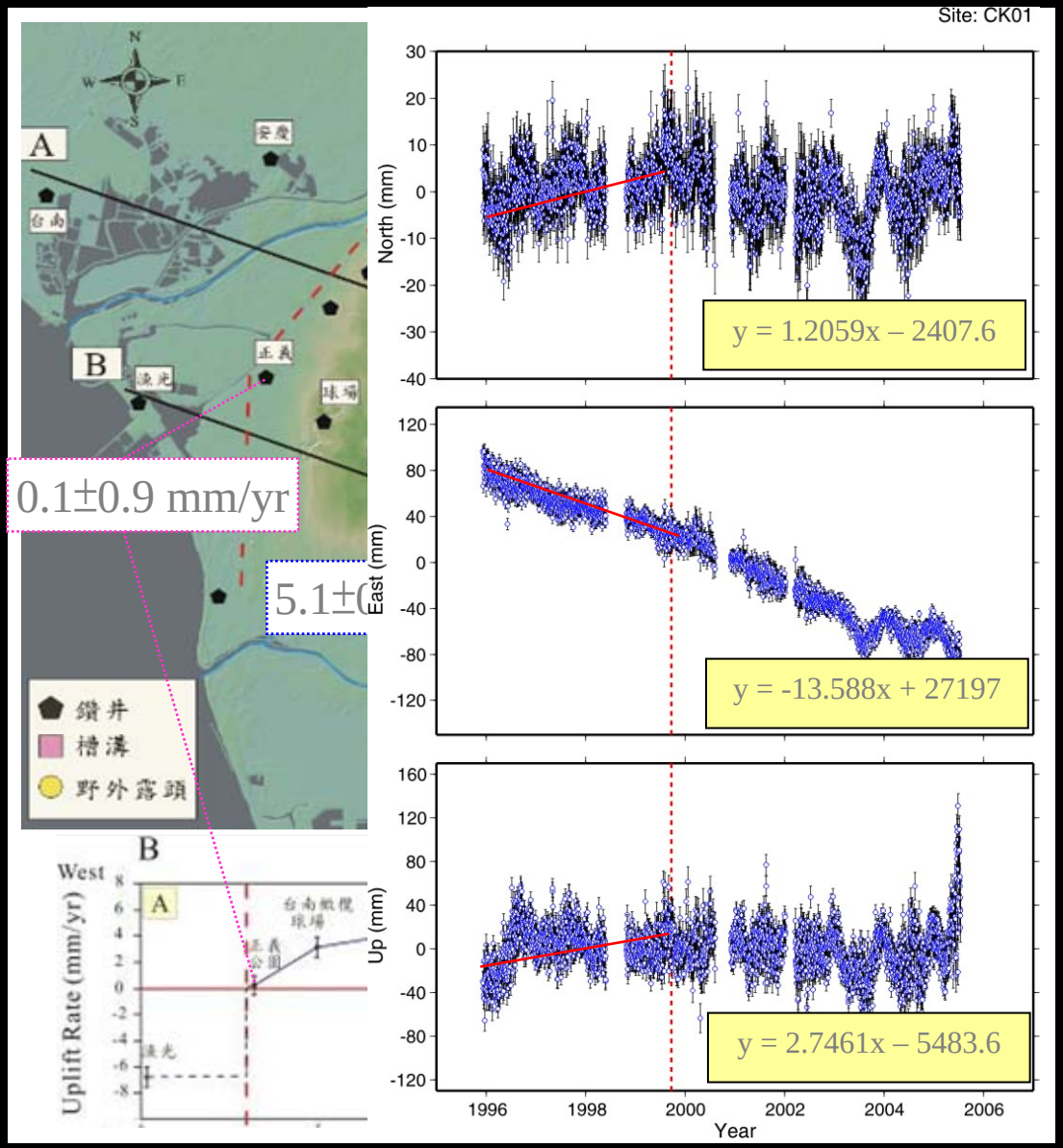

a
b

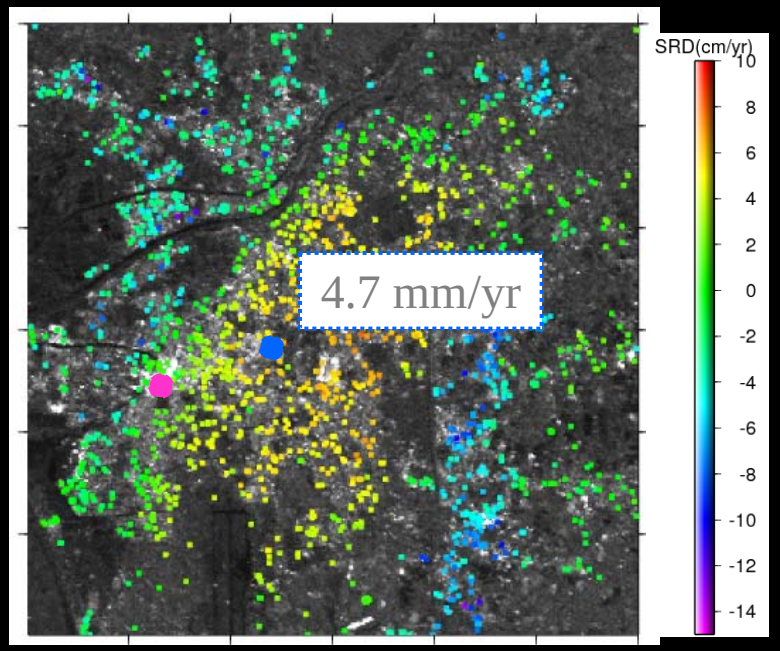

I
II
III

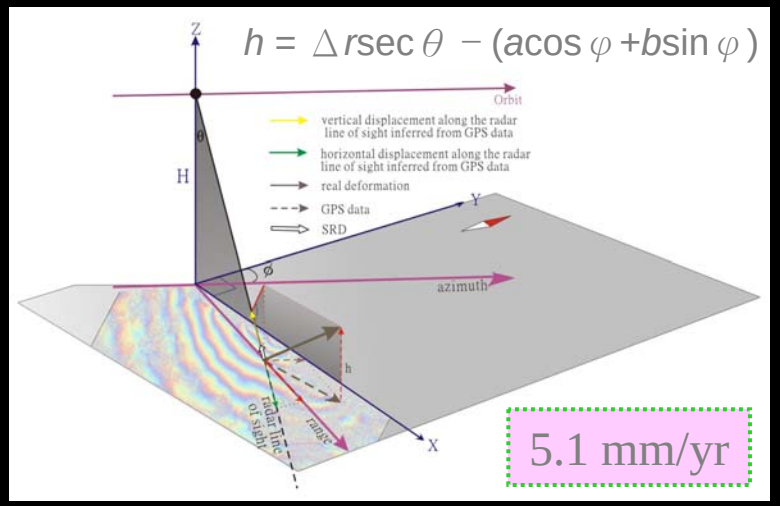

I
II
III

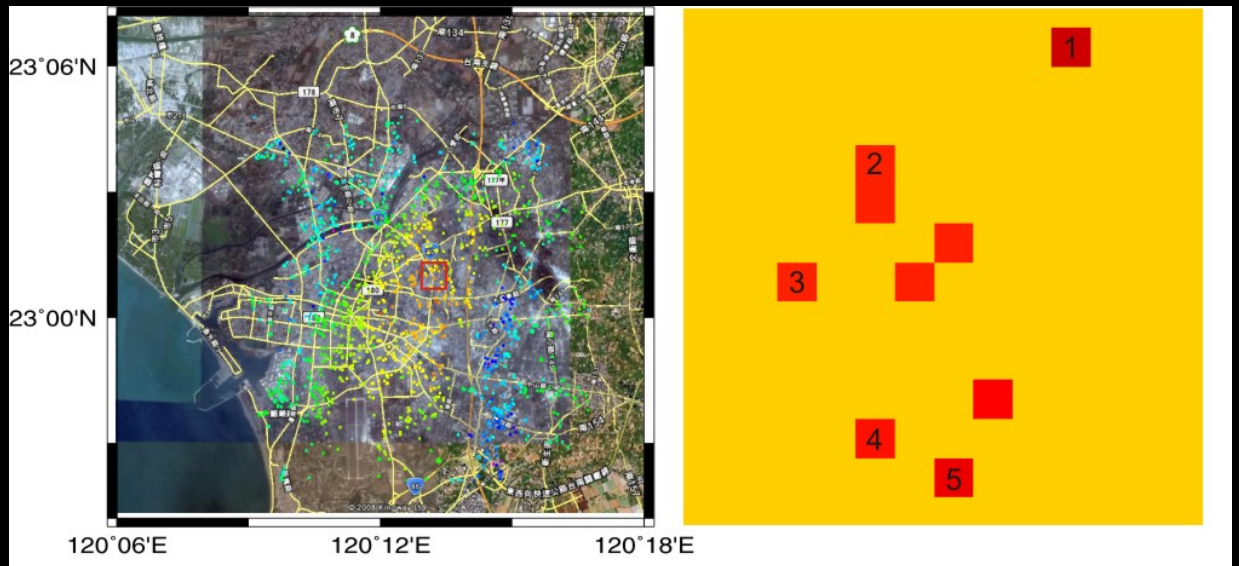

30
20
10
0
-10
10
0
-10
-20
-30
1996
1997
1998
1999
2000
Time(year)
SRD (mm)

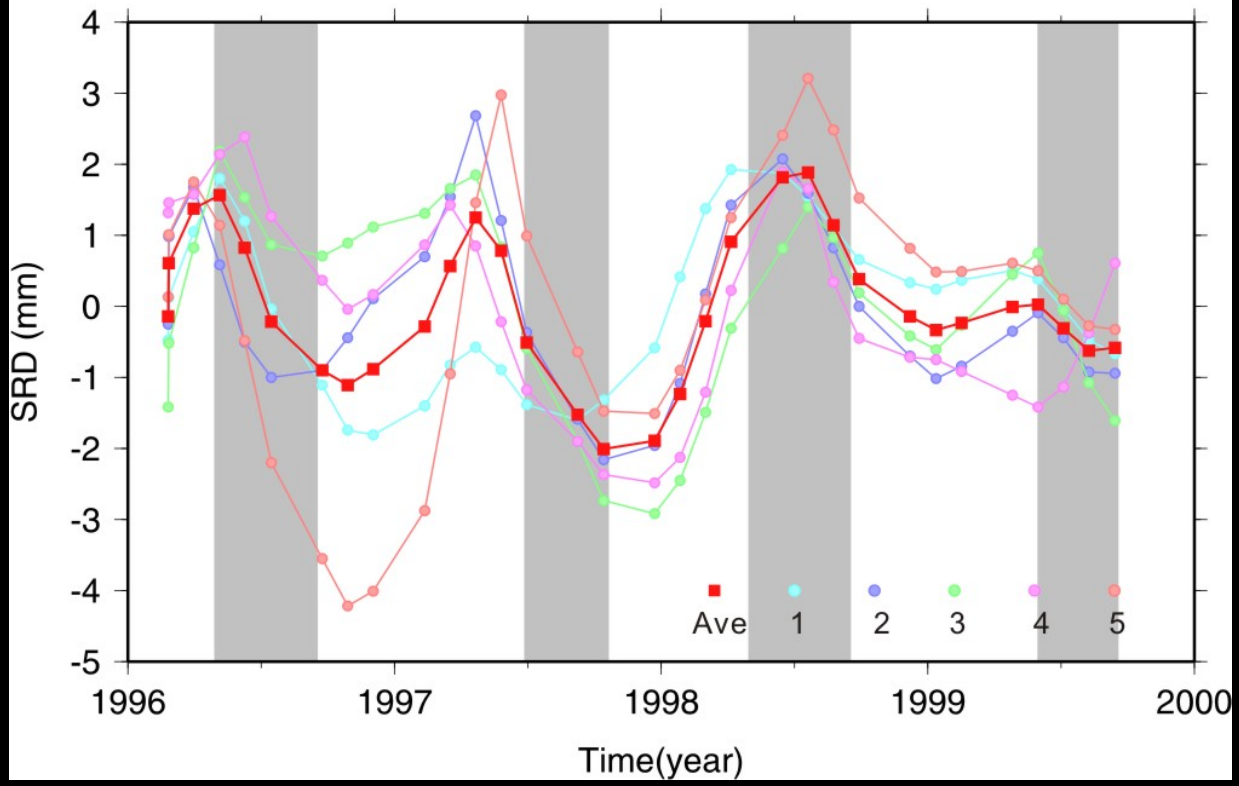
Discussion I





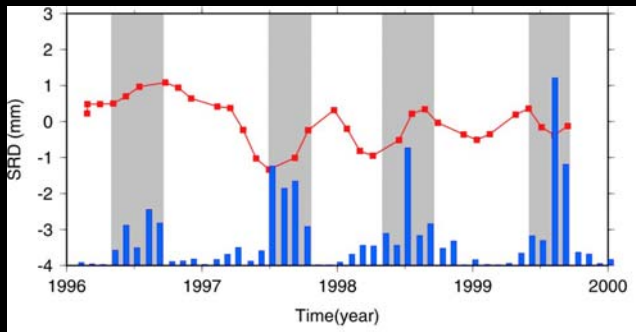


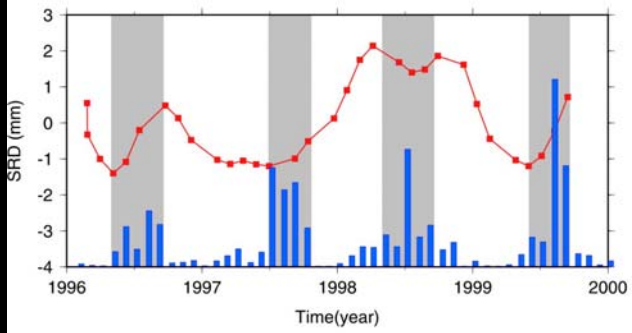


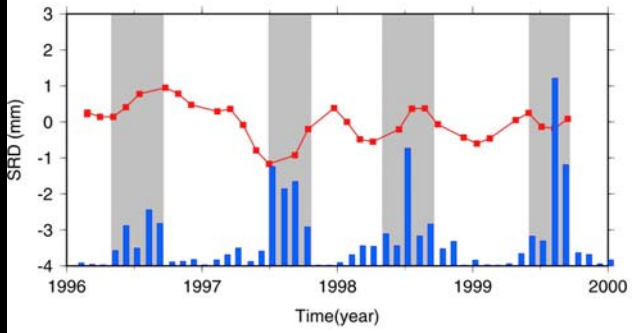


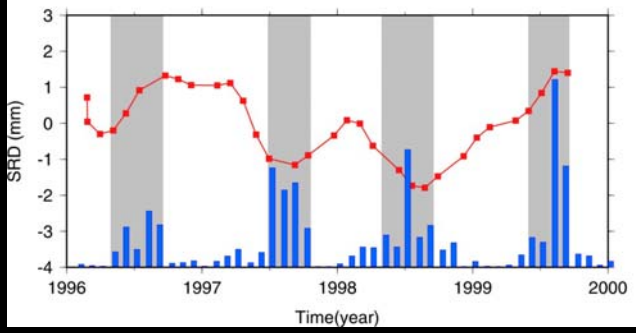
Time series of nonlinear deformation of five PS points :

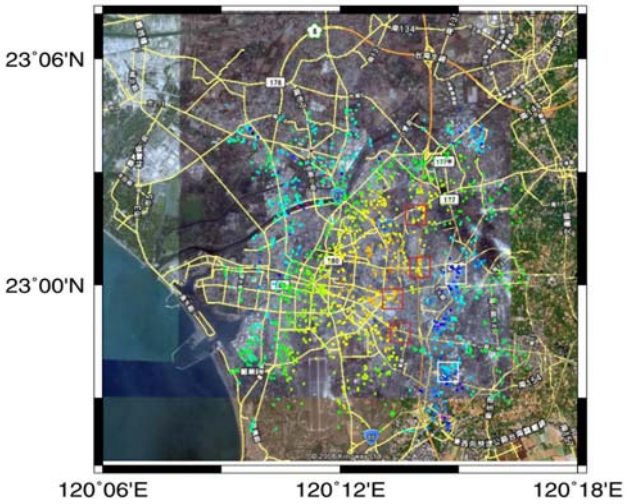
The nonlinear deformation characterizes with high spatial correlation in each pixel within a small area.

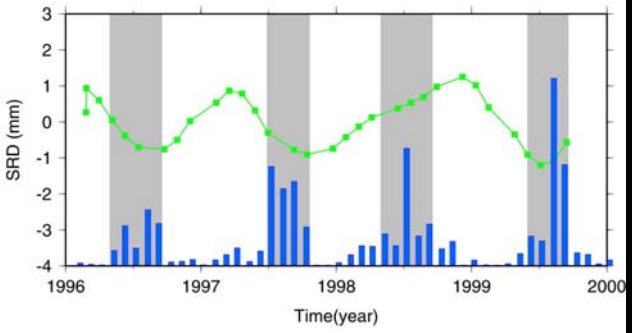


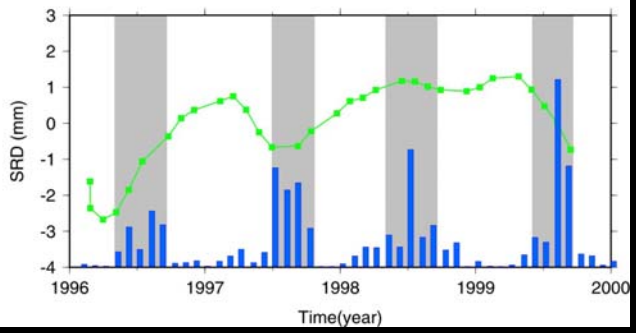












Nonlinear deformation evolution :

Red (Tainan Tableland)
Respectable correlation with seasonal rainfall.

Green (Tawan Lowland)
No correlation with seasonal rainfall.

One of the reasons might be the behaviors of fault creeping during the rainy seasons.

Conclusion

- There are 1649 PS points have been identified by using spatial coherence. The PS density is about 11.45 PS/km^2, which is enough to overcome the atmospheric affections.

- The linear deformation revealed by PSInSAR predicts a maximum of SRD rate of about 8 mm/yr on the central part of the Tainan Tableland; the Tawan Lowland indicates a SRD rate of about -10 mm/yr.

- The PS points close to the continuous GPS station CK01 represent a vertical velocity of 5.1 mm/yr by using Zheng Park as a reference point is quite coincident with the uplift rate of the borehole data.

- The nonlinear deformation evolutions show a respectable correlation with seasonal rainfall on the Tainan Tableland near the Houchiali fault. One of the reasons might be the behaviors of fault creeping during the rainy seasons.

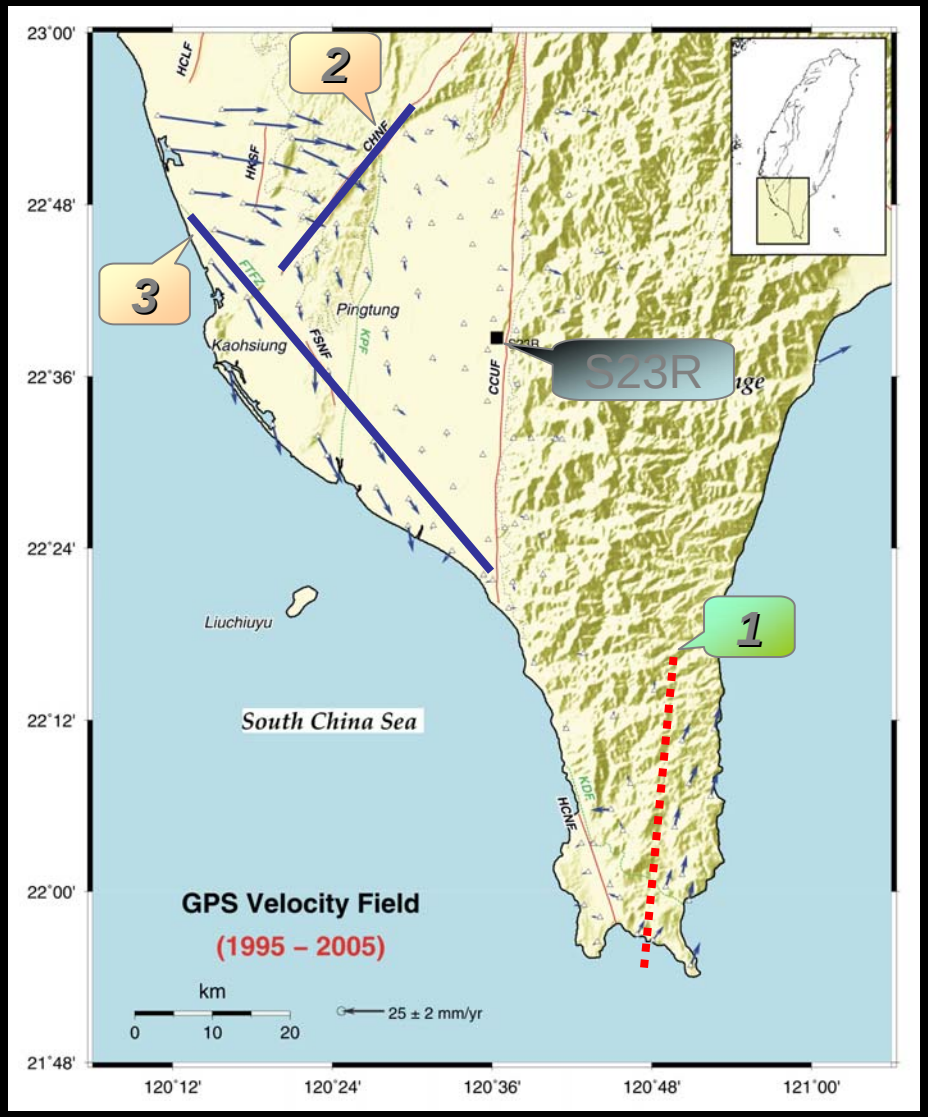
Future Collaboration with GSJ

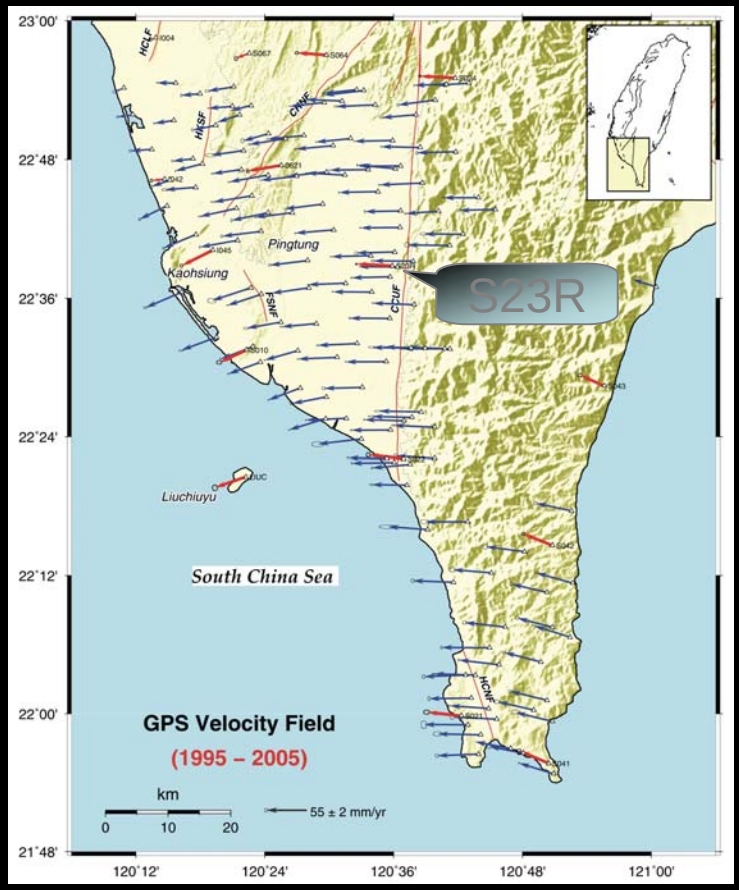
- Seismic hazards assessment based on the TAIGA of Central Geological Survey, MOEA,.
- Analysis of borehole strainmeters data and continuous GPS network by Central Geological Survey.

Thank you for your attention!

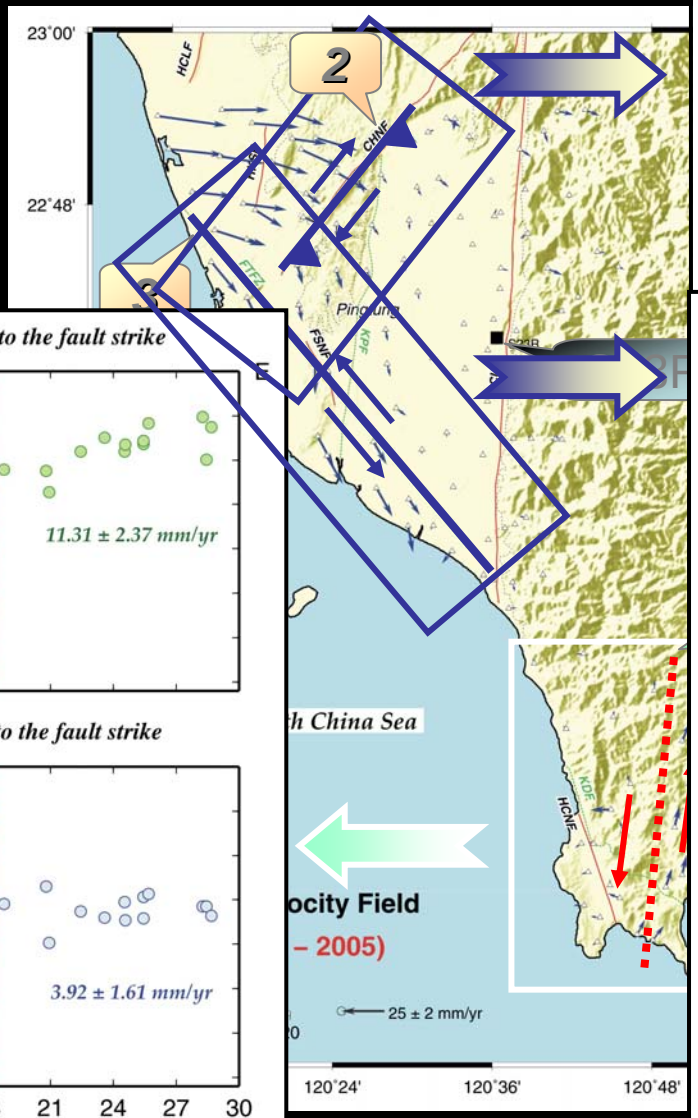
The Longitudinal Valley of the Chihshang area

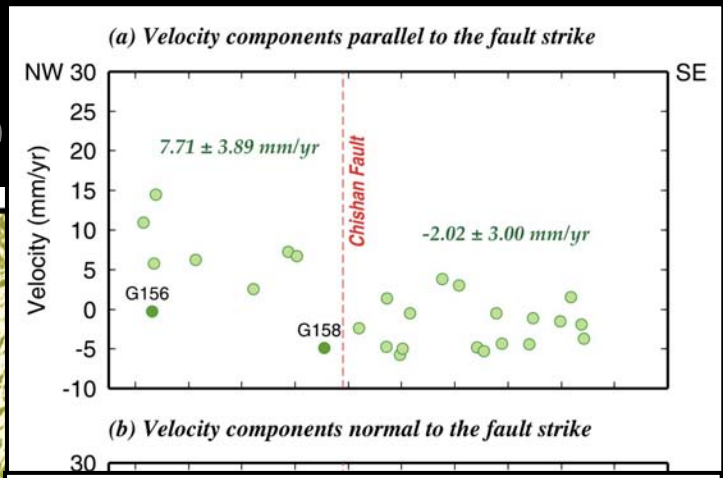
Velocity Field Relative to S23R

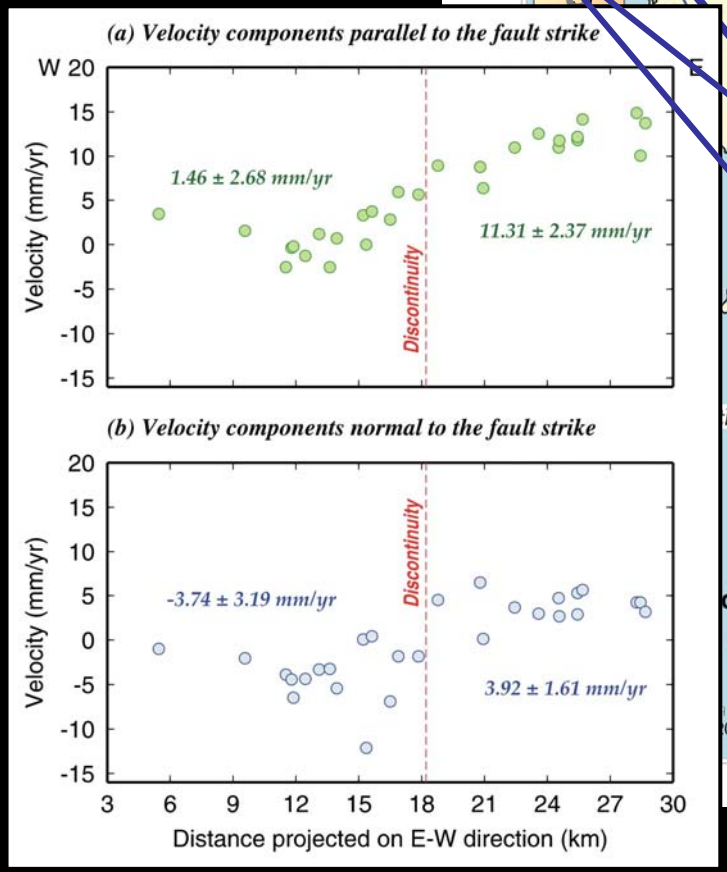


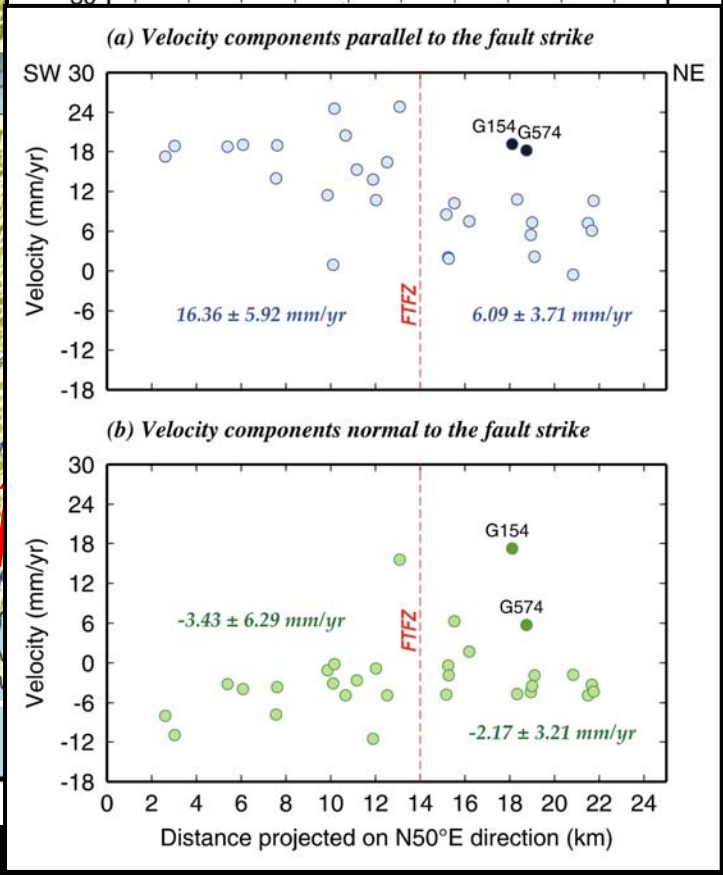


Velocity Field Relative

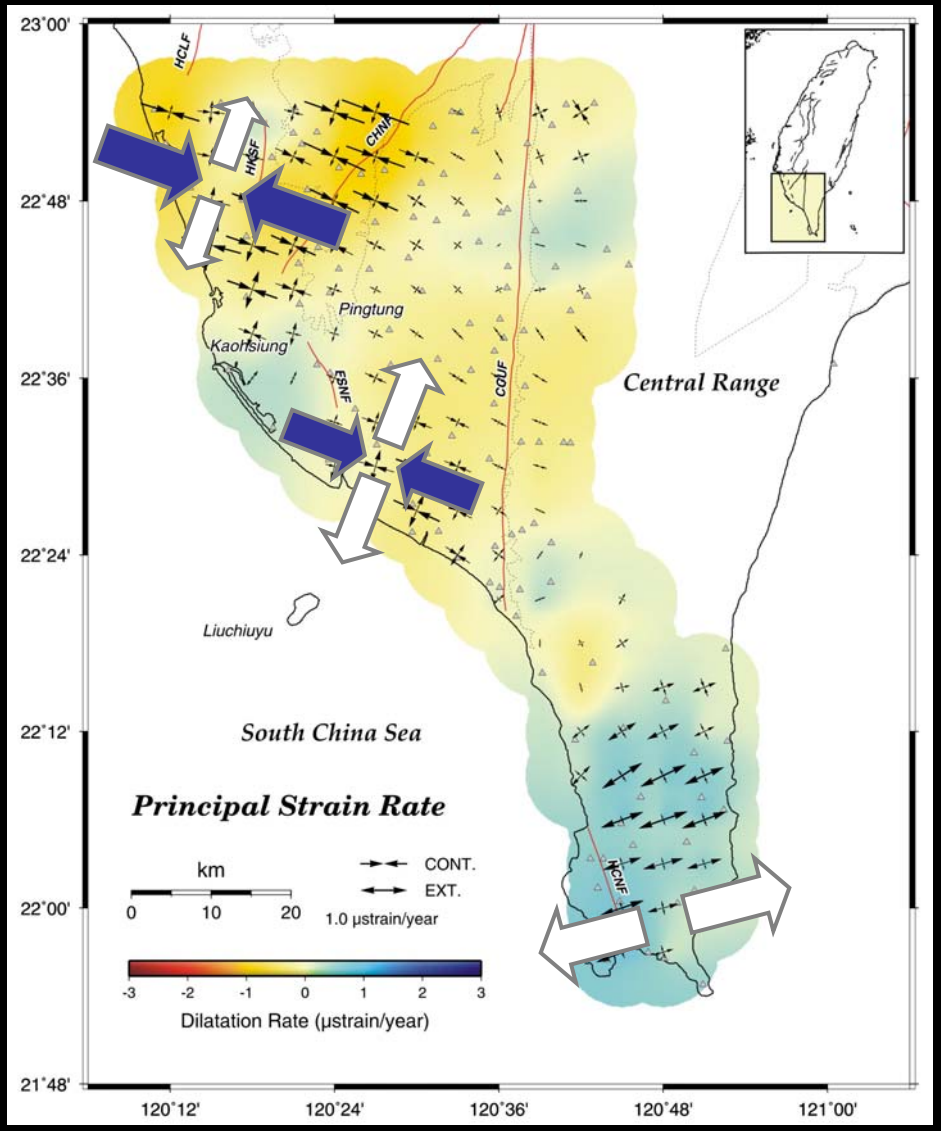




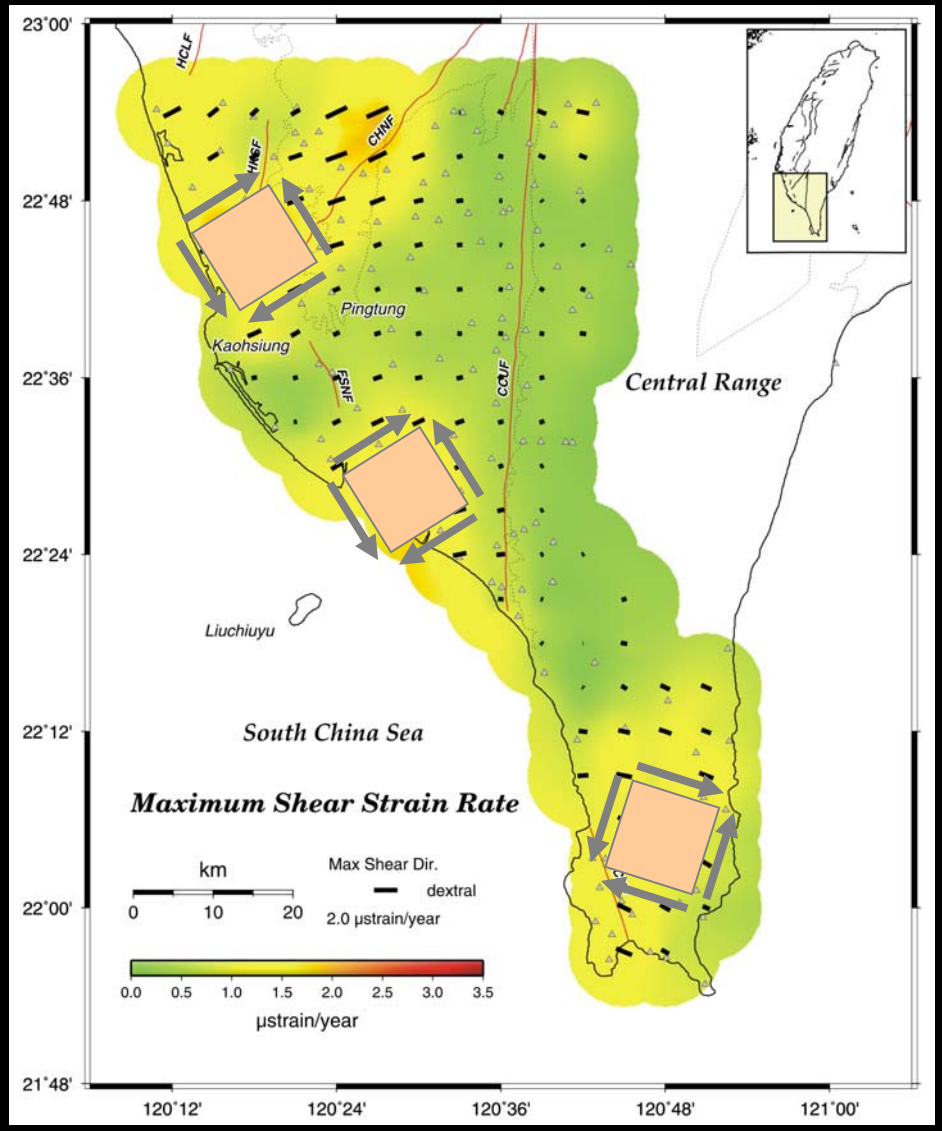




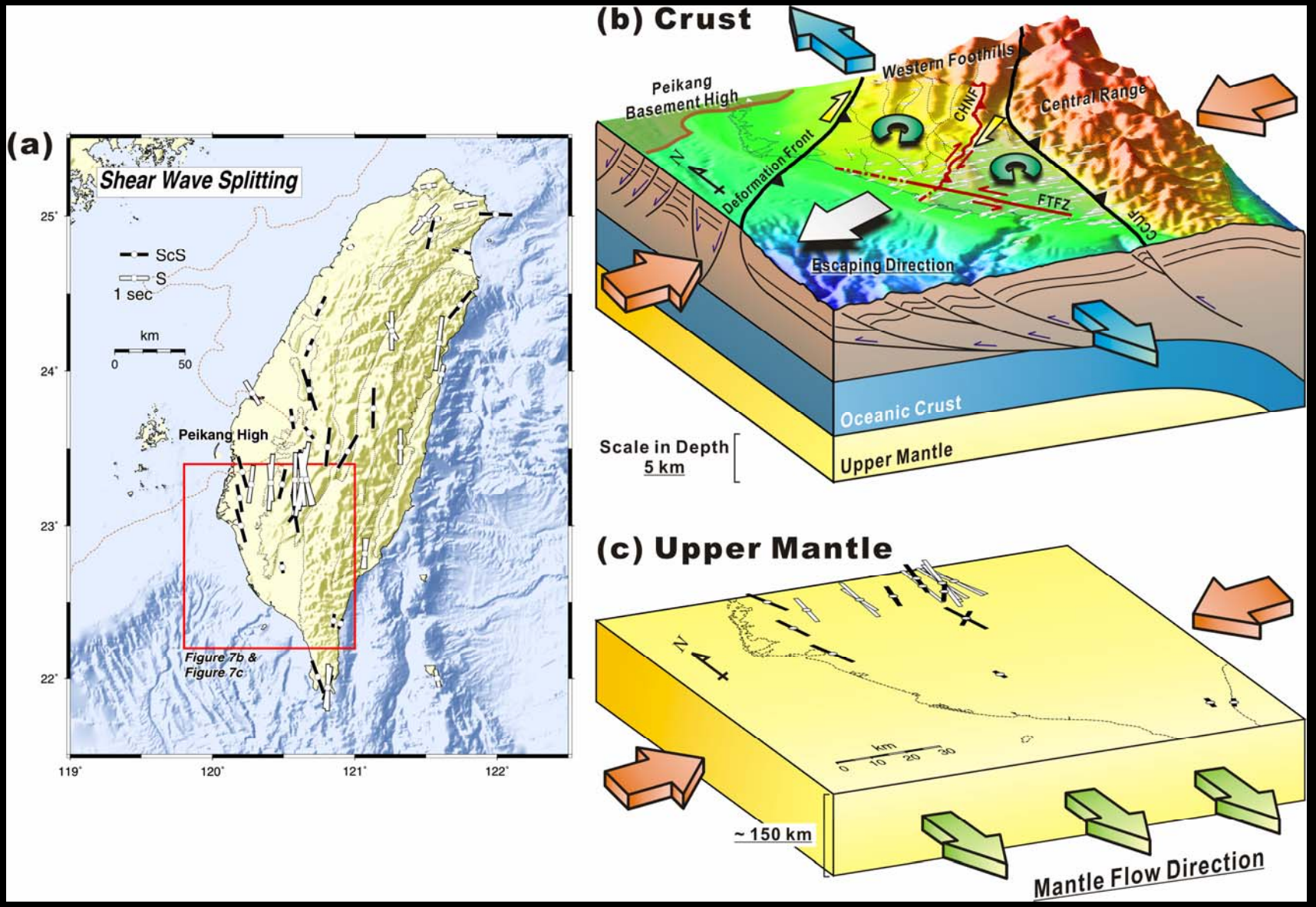
Principal Strain Rate



Maximum Shear Strain Rate



Kinematic model of SW Taiwan



Ching, Rau, Lee & Hu, EPSL, 2007