Monitoring of active deformation along the collisional plate boundary in eastern Taiwan by PS-InSAR and continuous GPS measurements

Jyr-Ching Hu[1], Johann Champenois[2] , Kuan-Chuan Lin[1],
Benedicte Fruneau[2], Erwan Pathier[3],

1. Department of Geosciences, National Taiwan University, Taiwan
2. University Paris-Est Marne-la-Vallée, France
3. University Grenoble 1, France

Acknowledgements: NSC, CGS, CWB, IES, JAXA

Motivation: PS-InSAR from ALOS

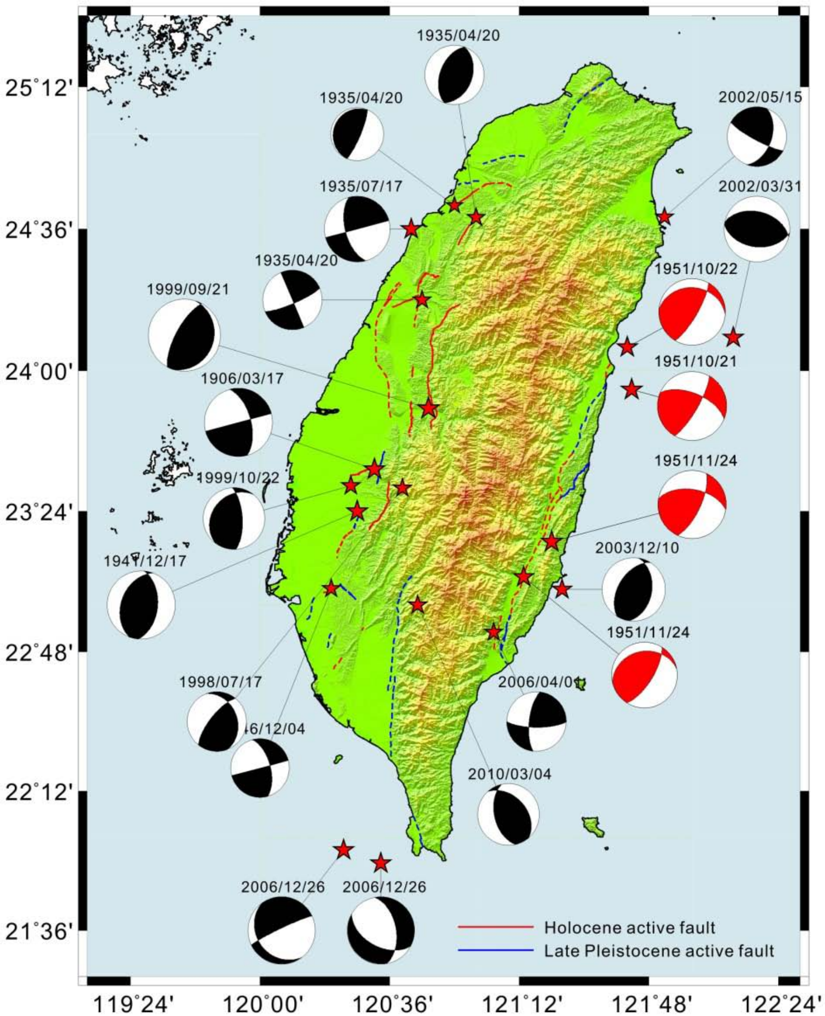
1. How creep is changing along the fault?
- Dense GPS network provides only loose geographical constraints.

2. Could PS-InSAR provide the precise location of faults and the idea for fault segmentation?
- Until now, precise mapping based on geological and geomorphological observations with a few locations of trenching and geodetic observation (GPS, creepmeter, levelling, InSAR)

3. Are other active structures between the Central range and the eastern coast accommodating the crustal deformation?
- The west-dipping Central Range fault? Others faults within the Coastal Range?

4. Is the aseismic creep affected by transient deformations?
- GPS and creepmeters show strong seasonal fluctuations and effects of the 2003 Chengkung earthquake (co- and post-seismic).

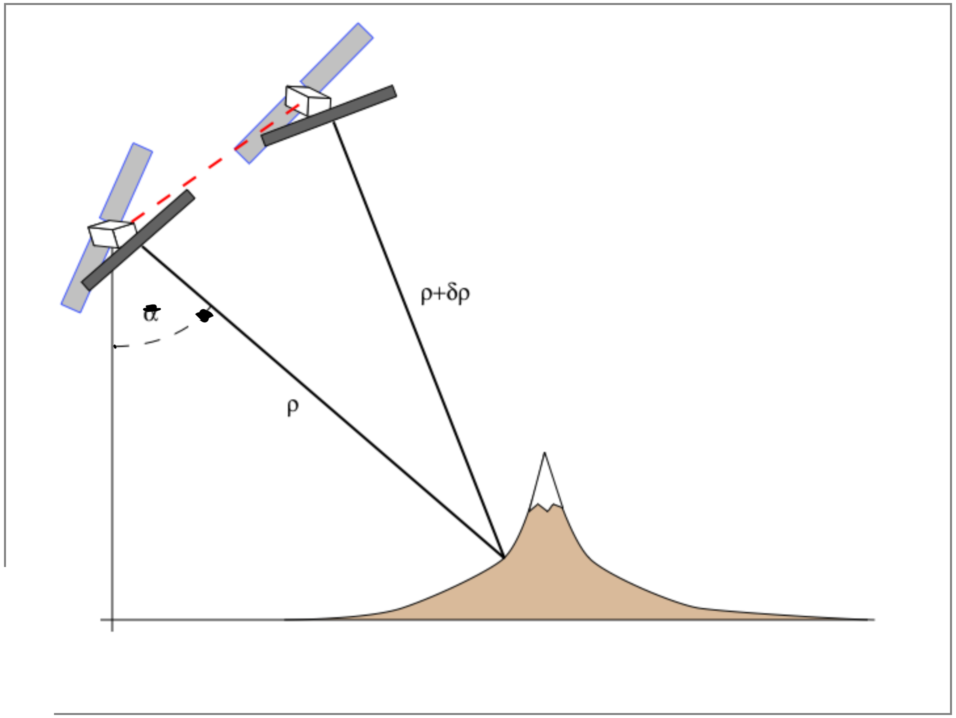
Interseismic strain accumulation and segmentation of the LVF



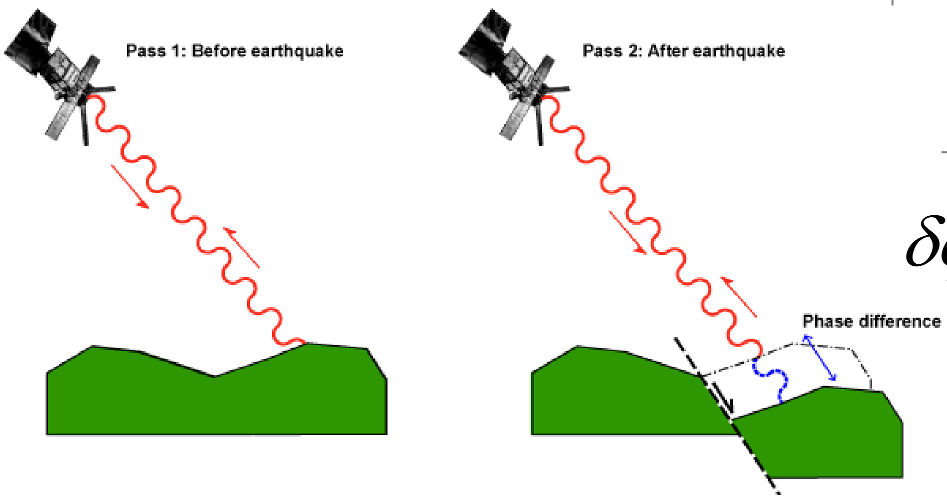
- 1951 Hualien-Taitung EQ sequences (Chen et al., JGR, 2009)
- High interseismic deformation rate (eg., Angelier et al., 2000; Lee et al., JGR, 2003)
- Significant fraction of aseimic slip in shallow depth and seimogenic zone in deeper portion: 2003 Chengkung EQ (Hu et al. GJI, 2007)
- 2006 Peinan earthquake: Central Range fault?

Intro to InSAR: How does it work?

- Two Radar images from space:
  Data is complex: amplitude and phase
- Phase change between images depends on several factors that must be removed before measuring deformation



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

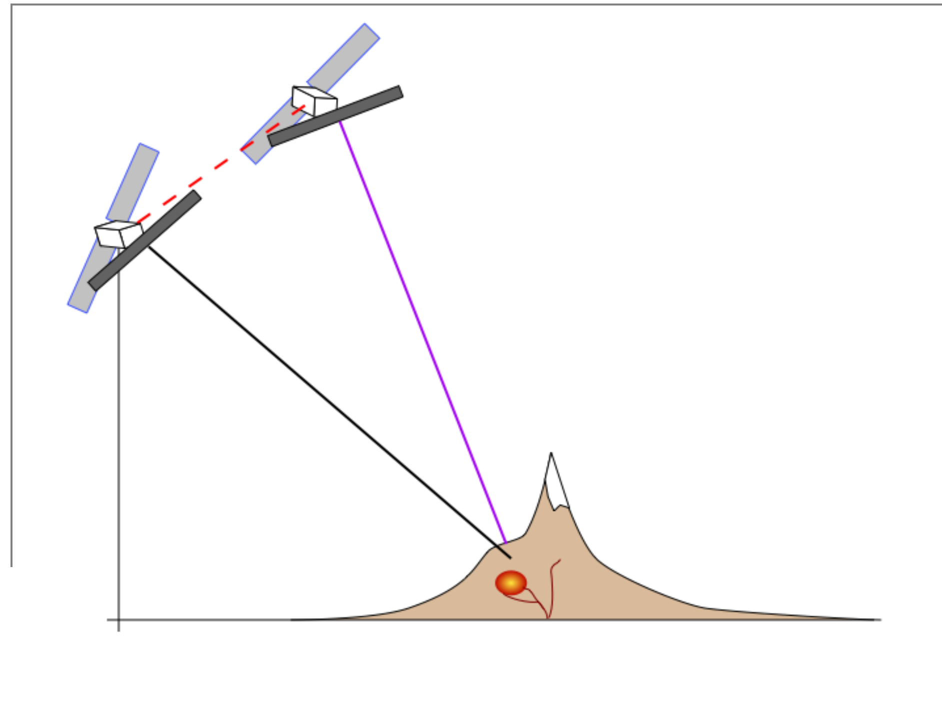


Wright, 2002

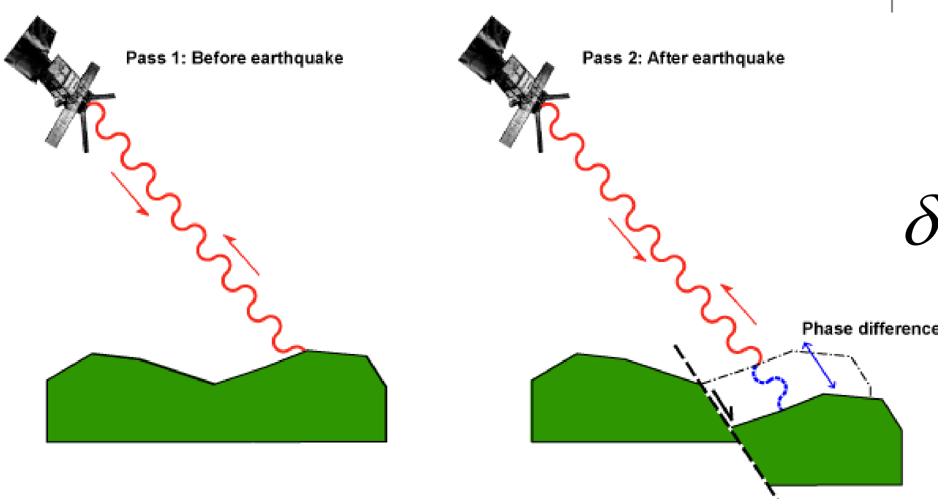
Intro to InSAR: How does it work?

• Two Radar images from space:
Data is complex: has amplitude and phase

• Phase change between images depends on several factors that must be removed before measuring deformation

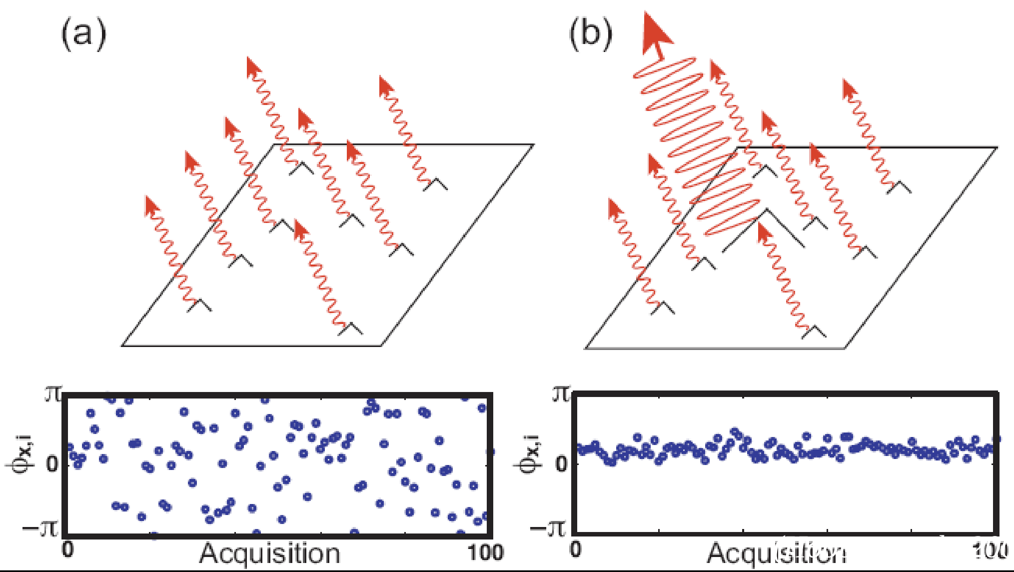


$$\delta\phi_{diff} = \delta\phi_{\varepsilon} + \delta\phi_{mov} + \delta\phi_{atm} + \delta\phi_{noise}$$

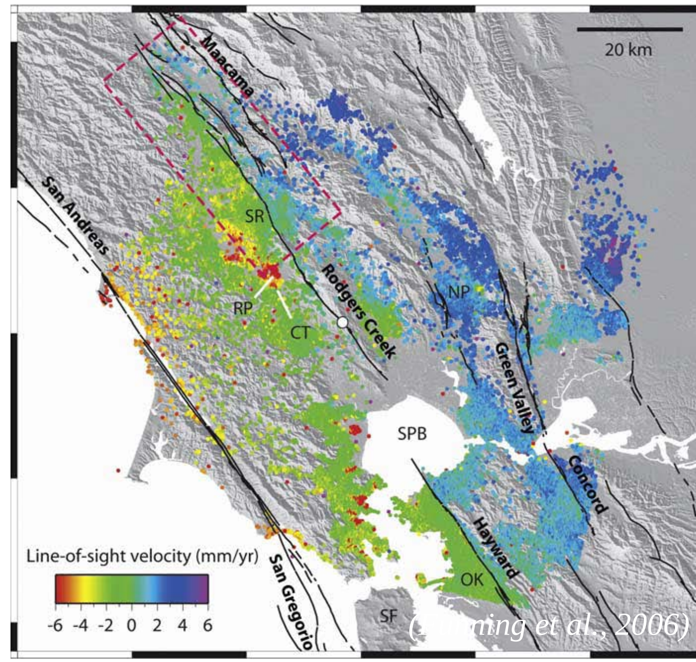


Wright, 2002

What is PS-InSAR ?



[redacted]



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

The goal of PS-InSAR

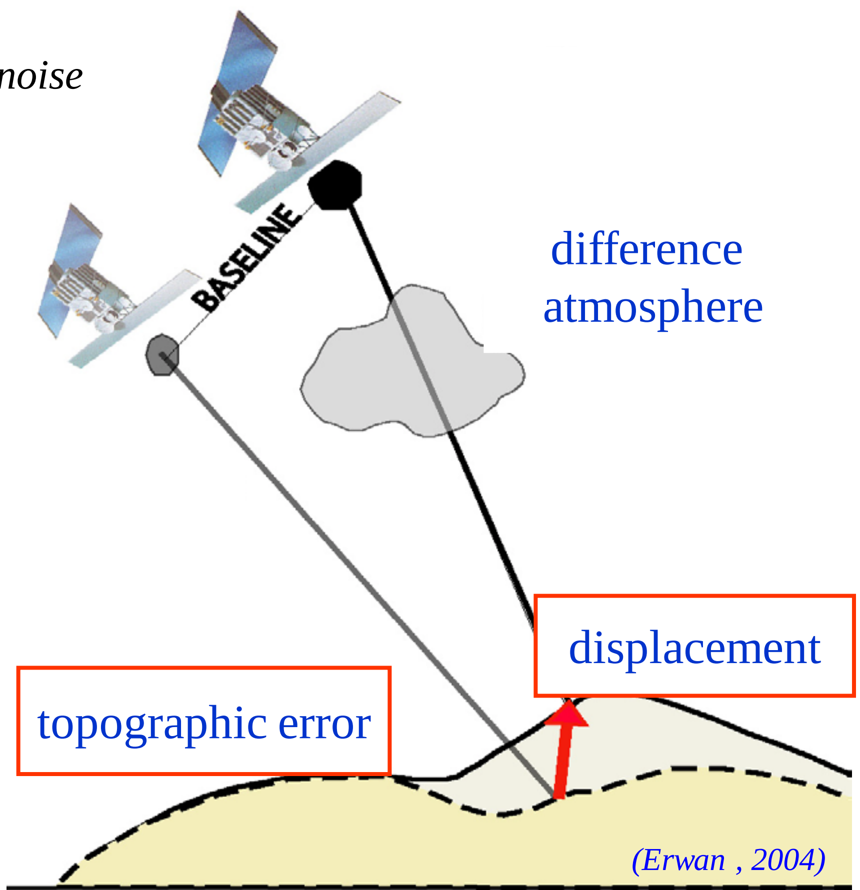
When generating an interferogram by combining two SAR images, by removing the flat earth and topographic terms its DInSAR phase variation between neighboring pixels can be expressed as:

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

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

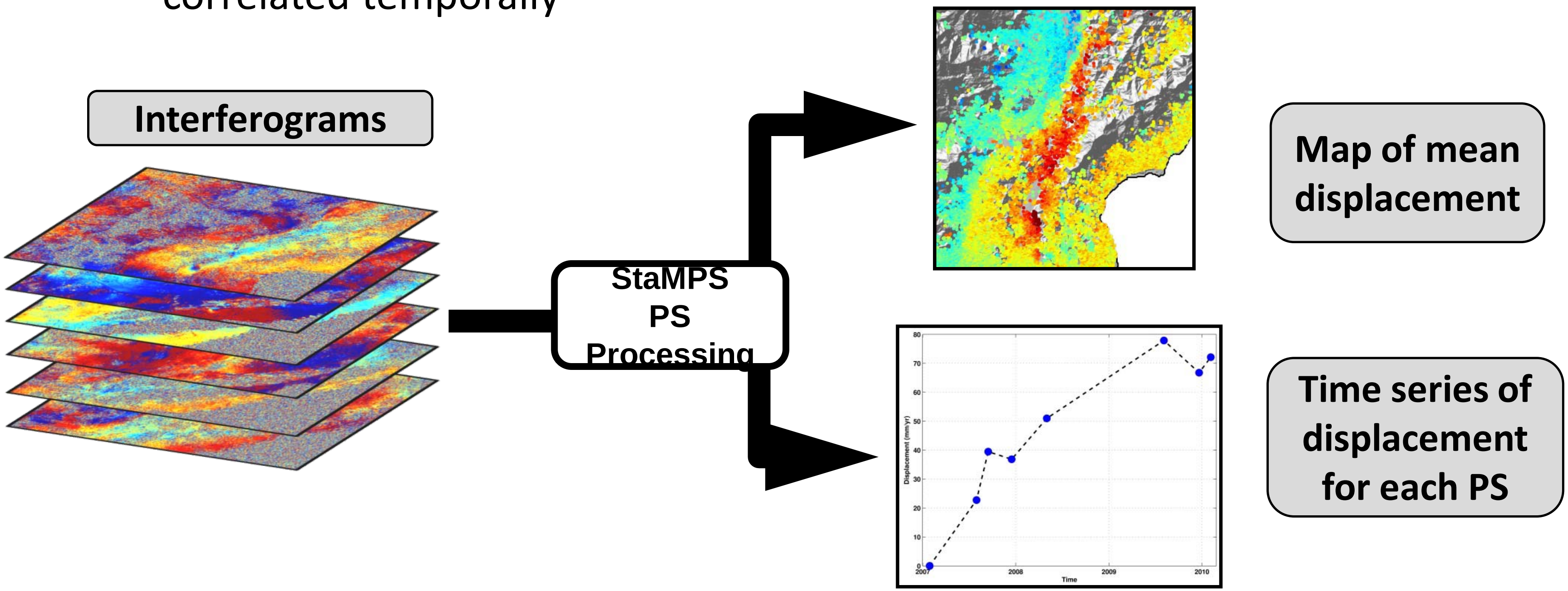
$$\delta\phi_{mov} = \delta\phi_{linear} + \delta\phi_{nonlinear}$$

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

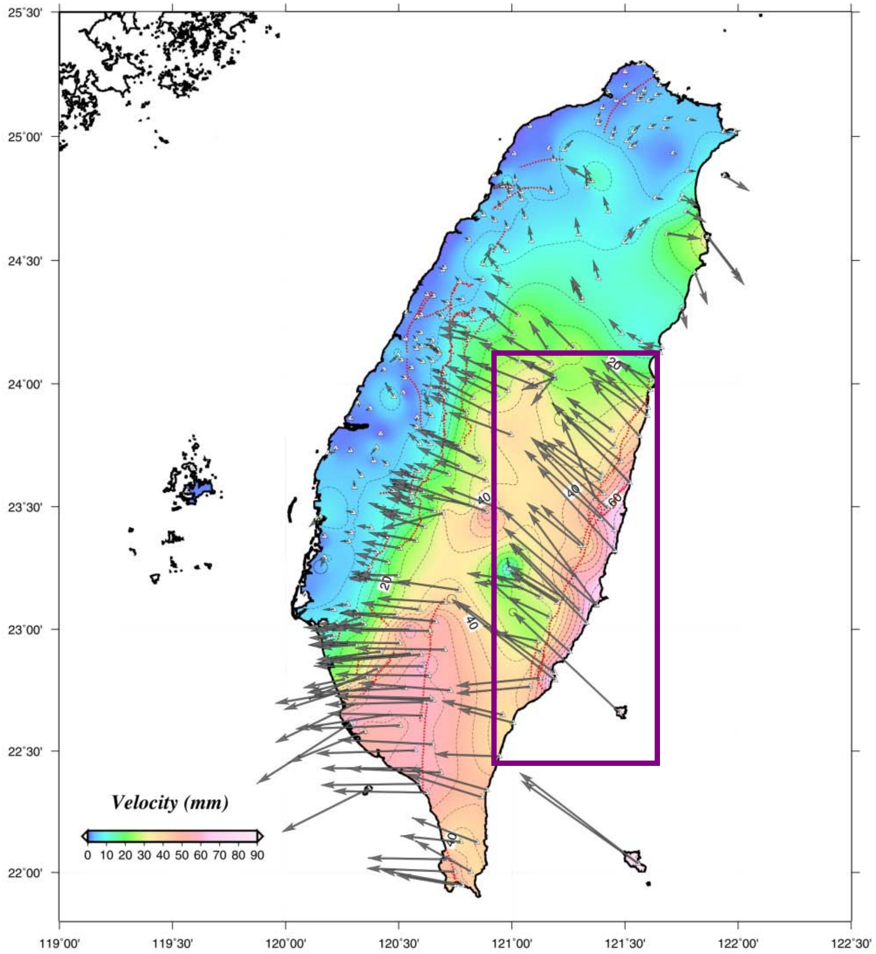


Interferograms analysis

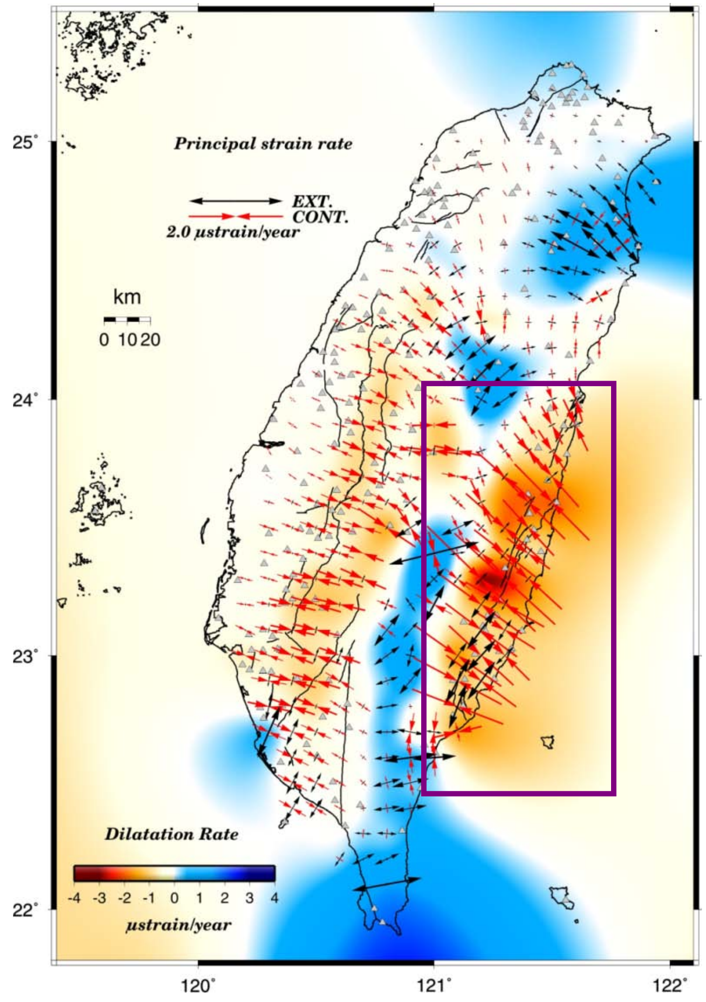
- Time Series analysis using Persistent Scatterer approach
  - Processing chains used : **ROI_Pac** and **StaMPS (Hooper et al., 2007)**
  - PS algorithm involves estimating phase contributions from deformation, DEM, atmospheric and orbital errors terms
  - deformation and atmosphere terms are supposed to be correlated spatially, while the atmosphere term is supposed to be not correlated temporally



Active Crustal Deformation in Taiwan



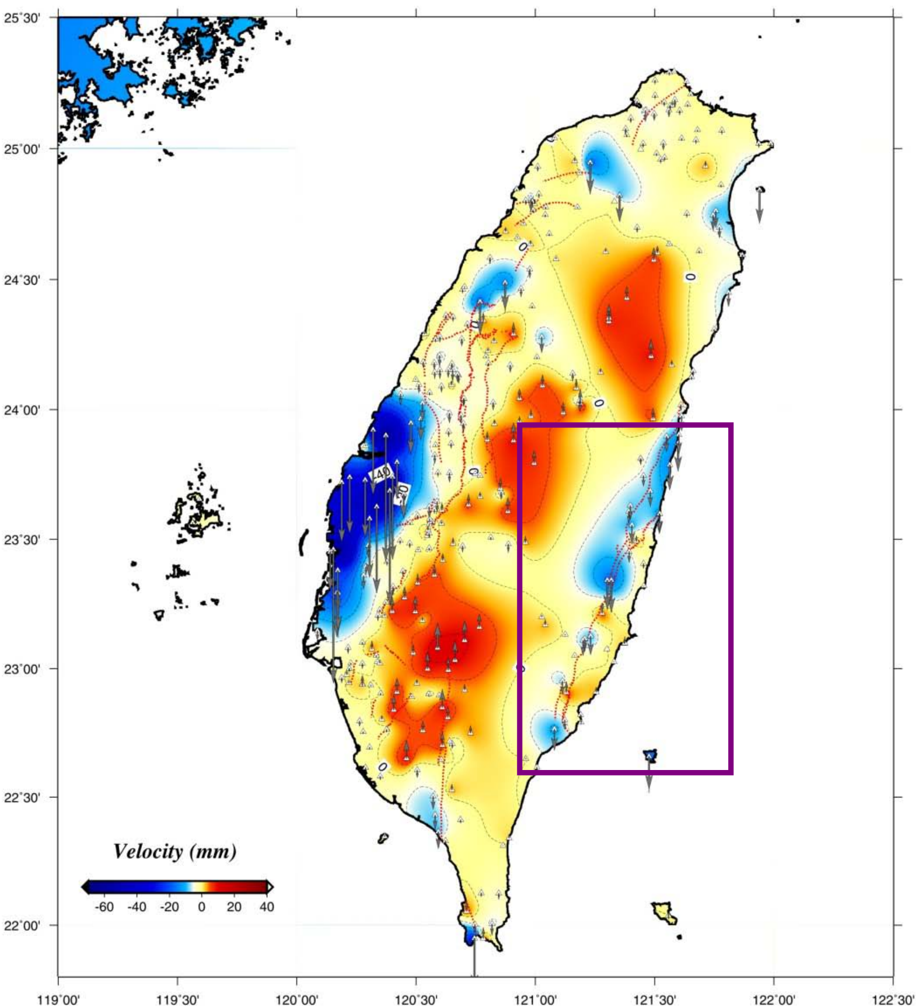
Continuous GPS: 2003-2007

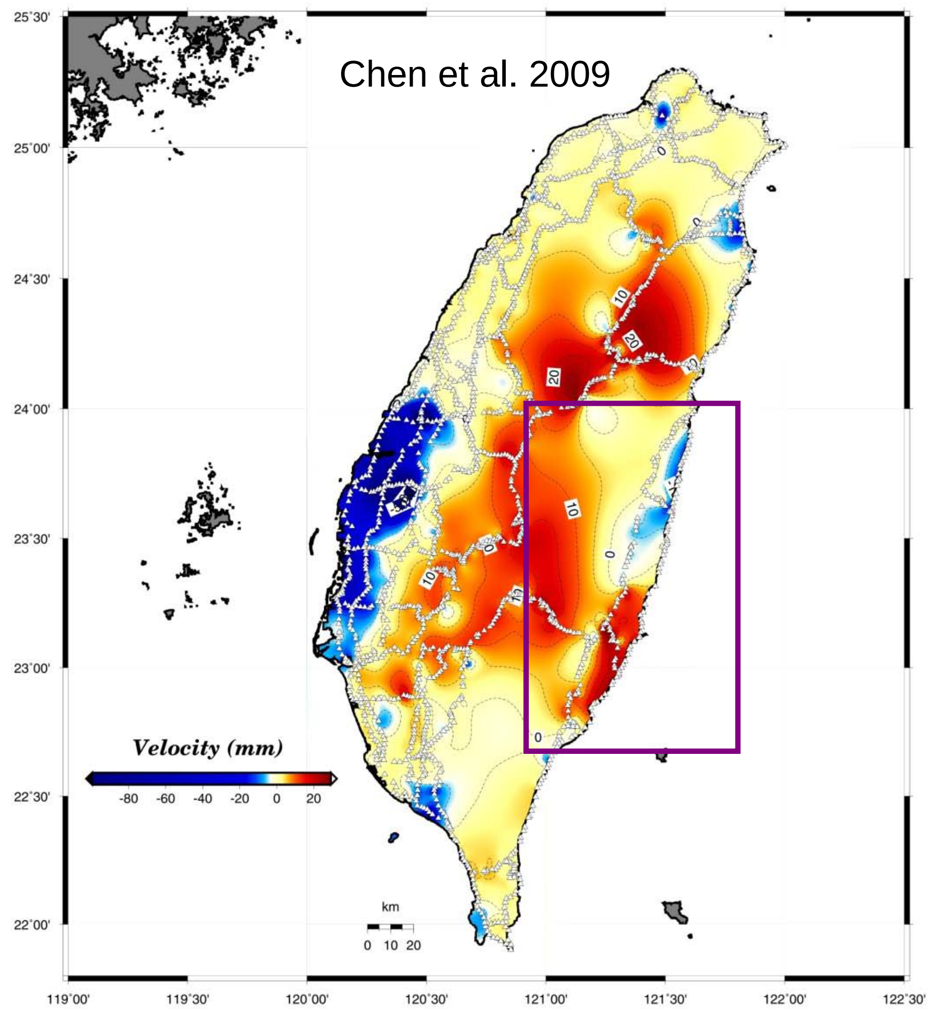


Lin et al., JGR, 2010

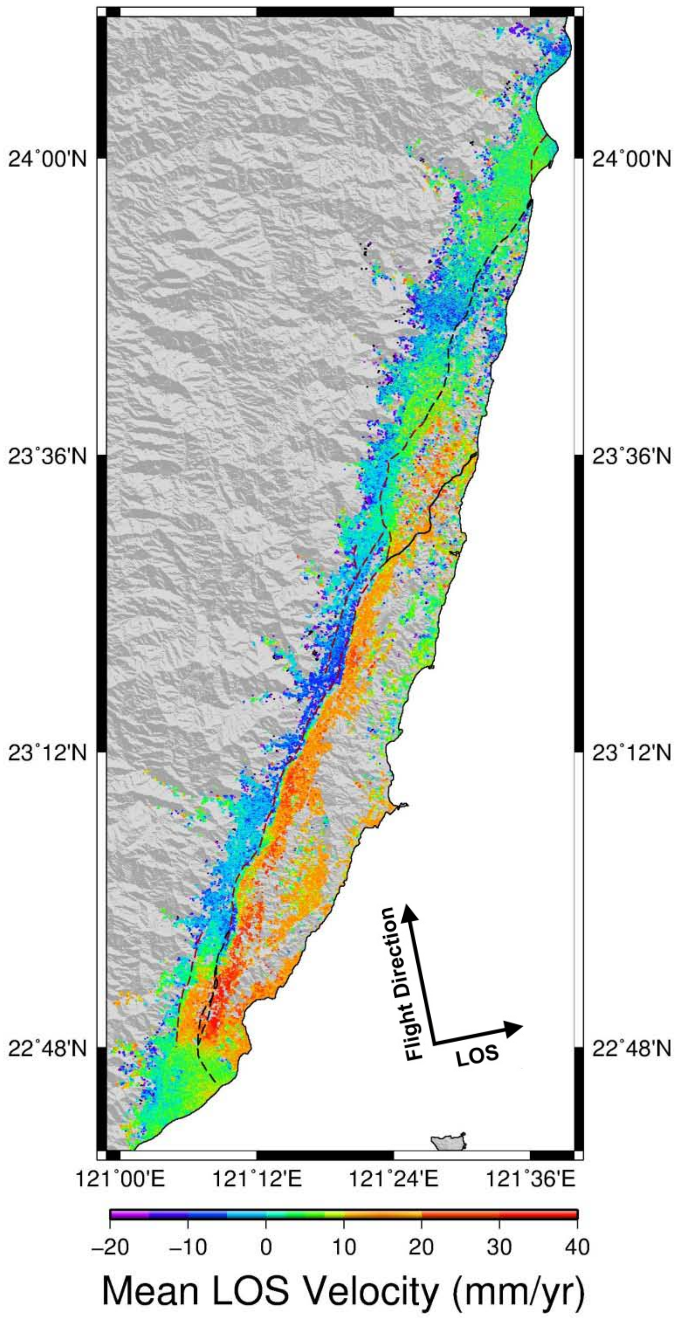
Vertical Deformation: CGPS and precise leveling

Four precise leveling campaigns from 2000 to 2008: > 4000 km in leveling lines

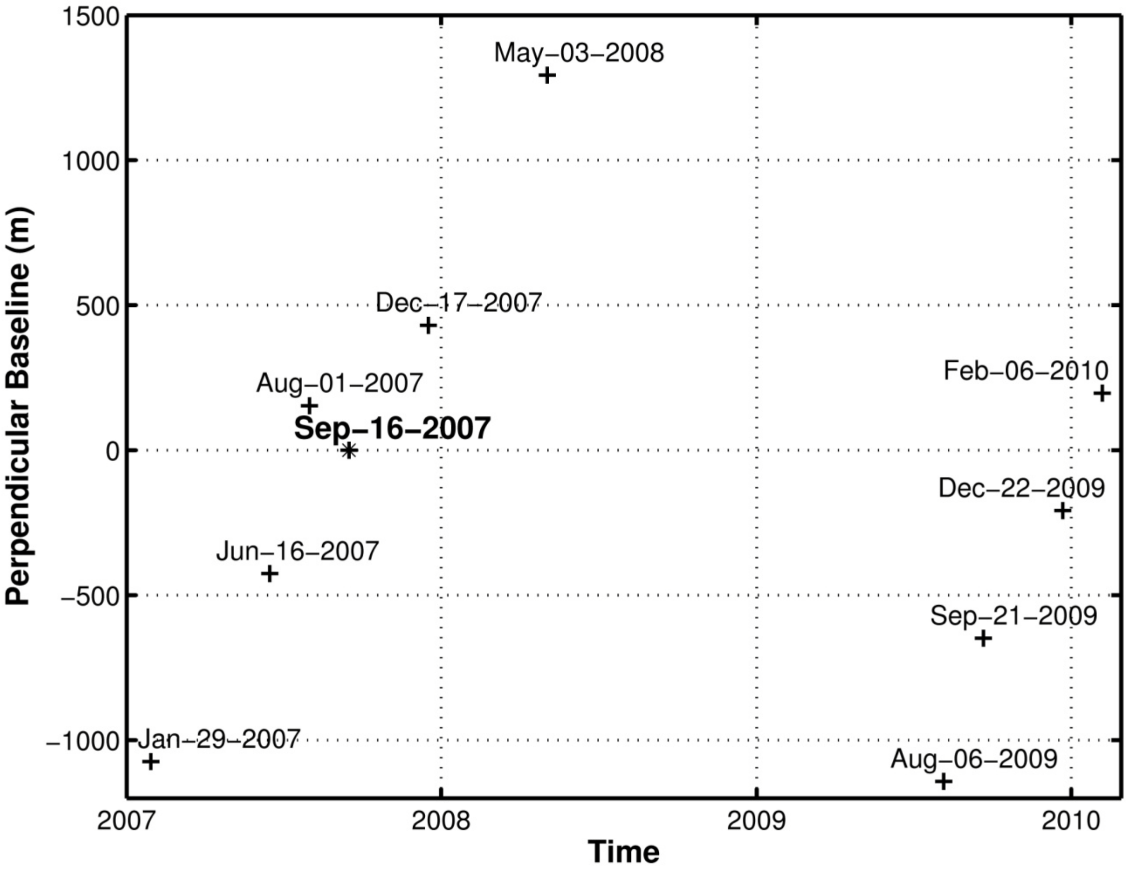




ALOS data and Mean LOS velocity from PS analysis



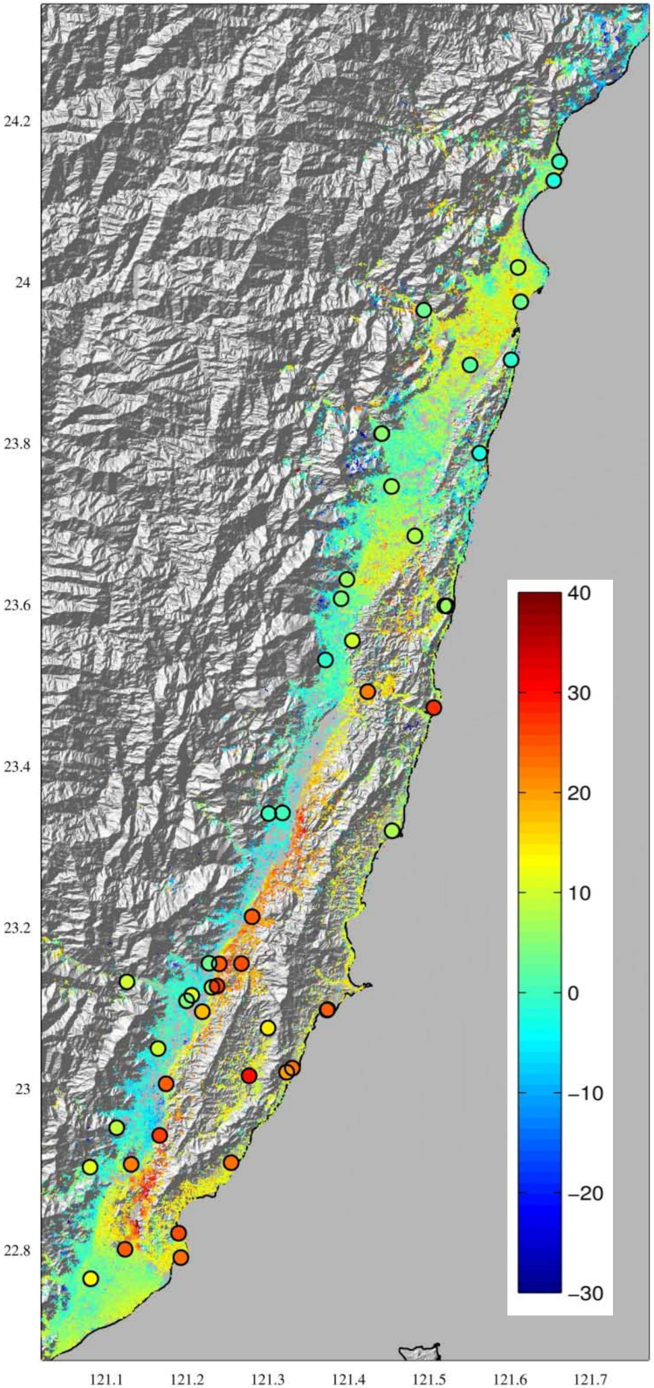
10 ALOS PALSAR images, ascending path, mode FBS + FBD, 34.3°, from 2007 to 2010.

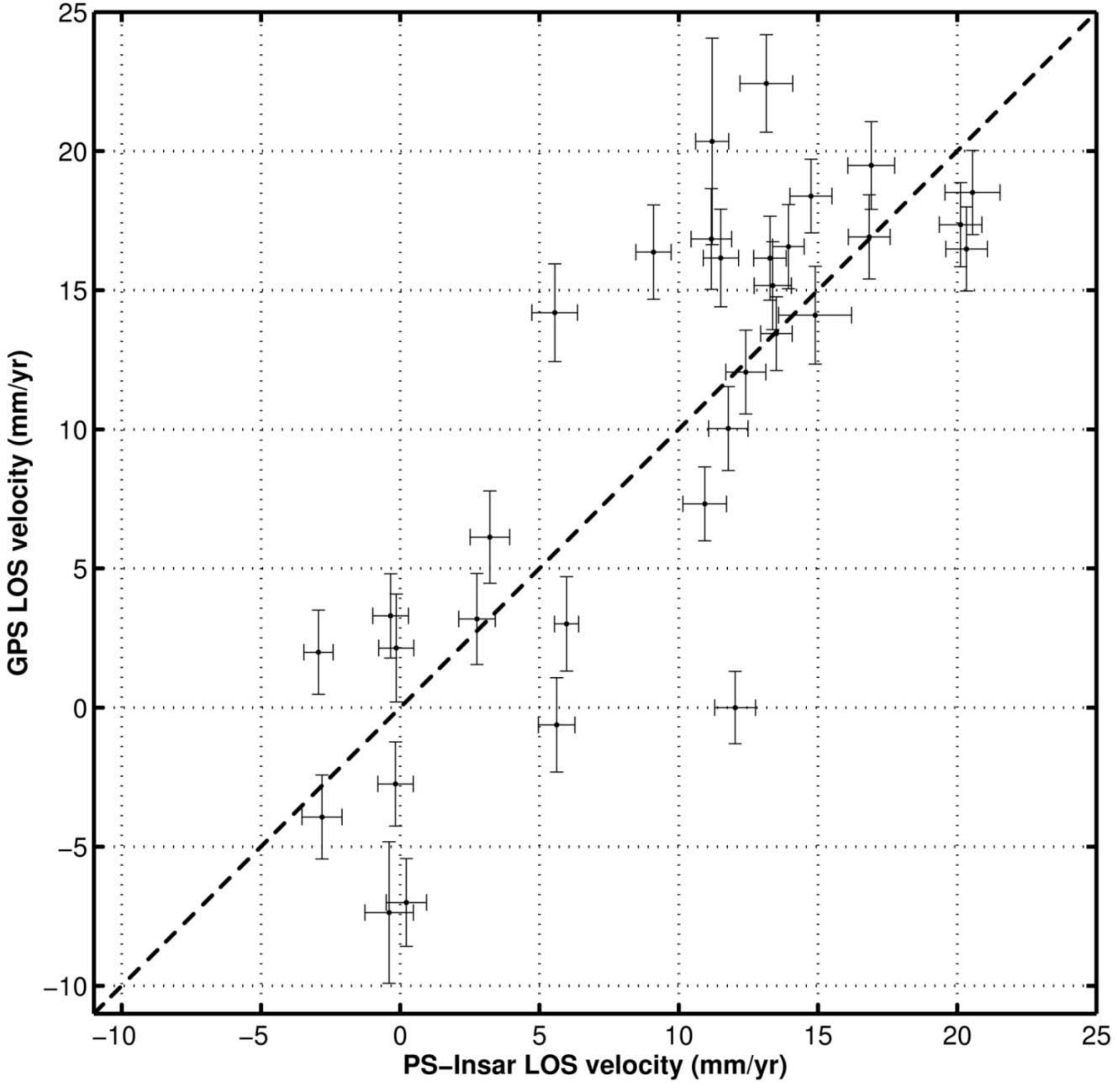


PS density: ~42 PSs/km²

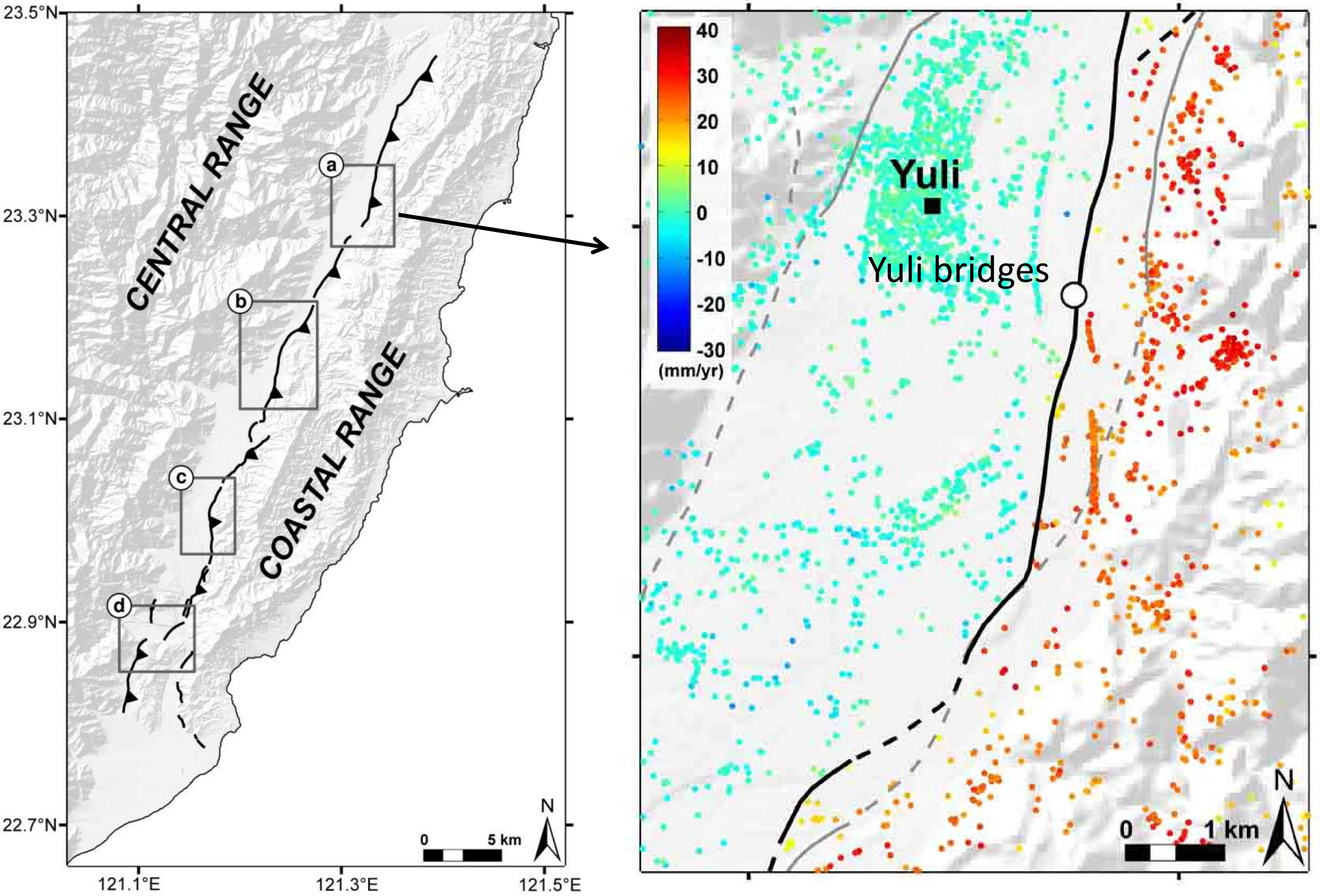
Comparison with continuoud GPS data

Residual regional trend : Orbital or atmospheric/ionospheric effects ?

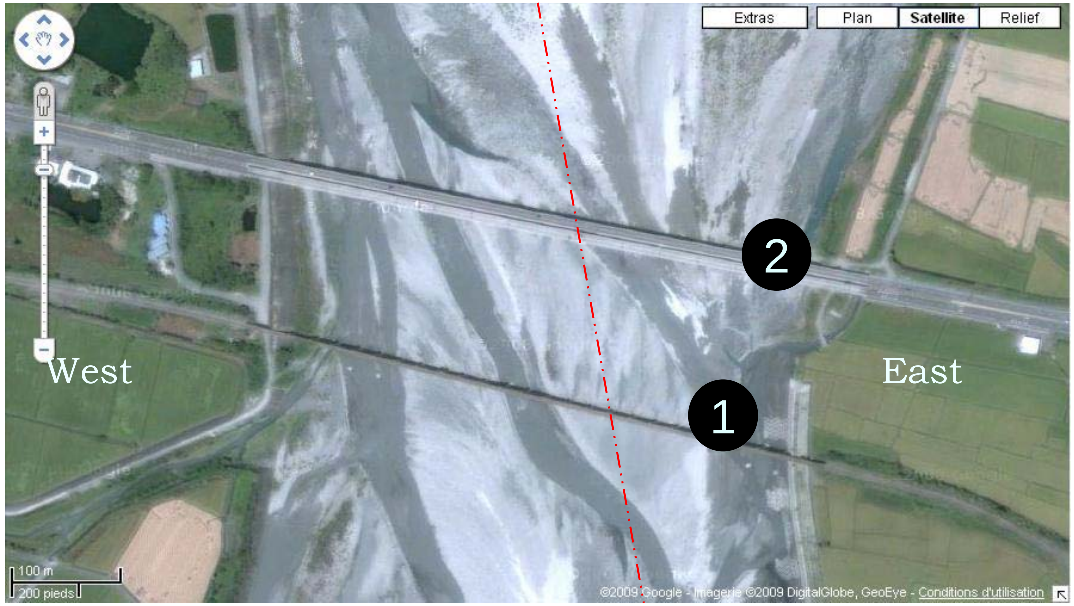




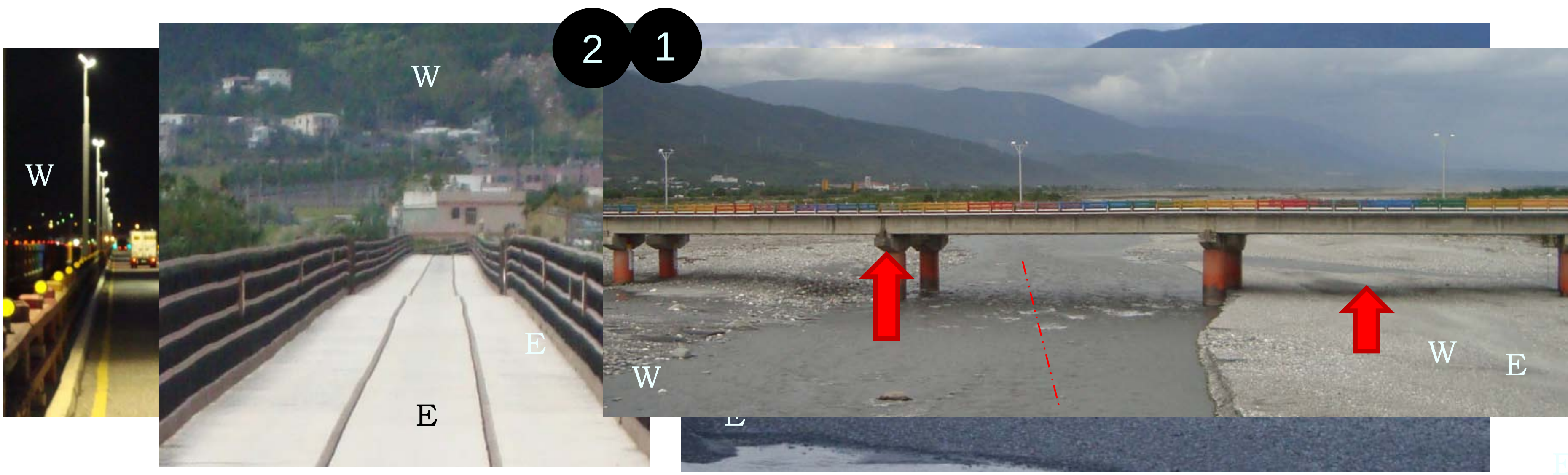
Improved Fault trace mapping: Ground truth validation



Yuli Bridge

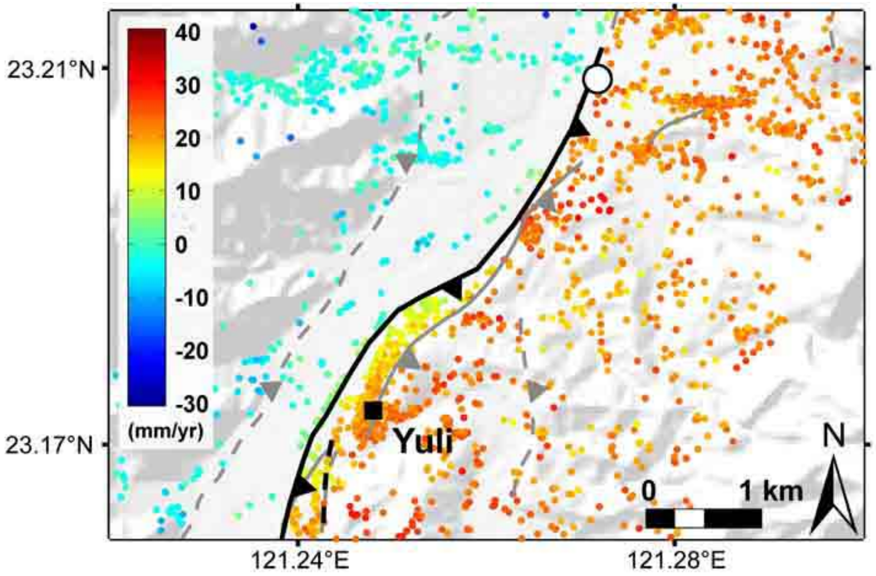


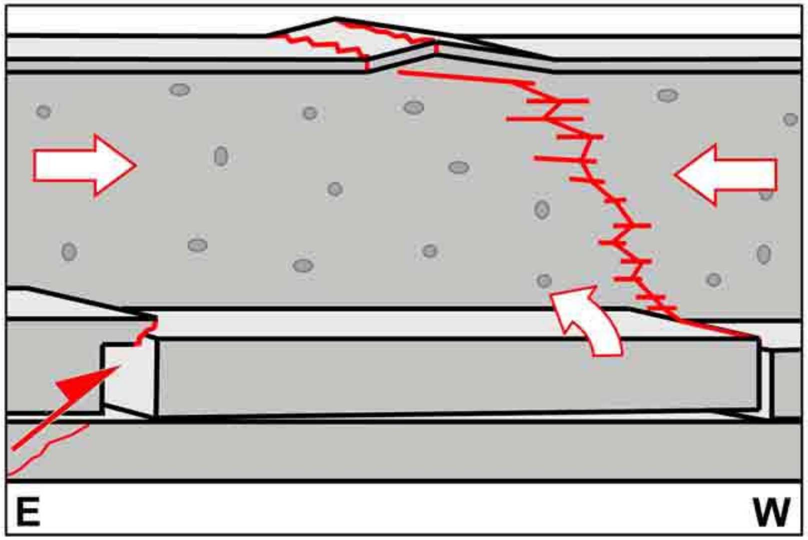
Extras
Plan
Satellite
Relief
2
West
East
1
100 m
200 pieds
©2009 Google - Imagerie ©2009 DigitalGlobe, GeoEye - Conditions d'utilisation



2
1
W
W
E
E
W
W
E

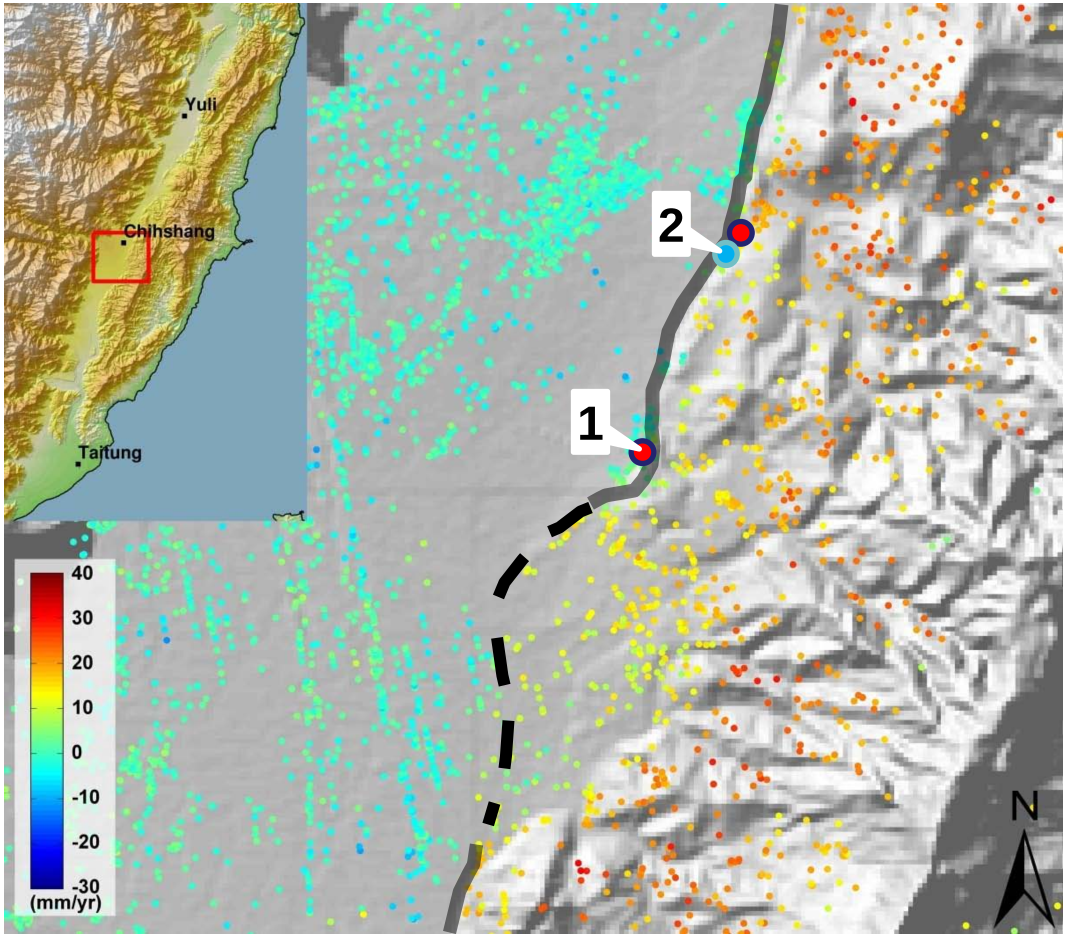
Localized deformation in the field using InSAR map





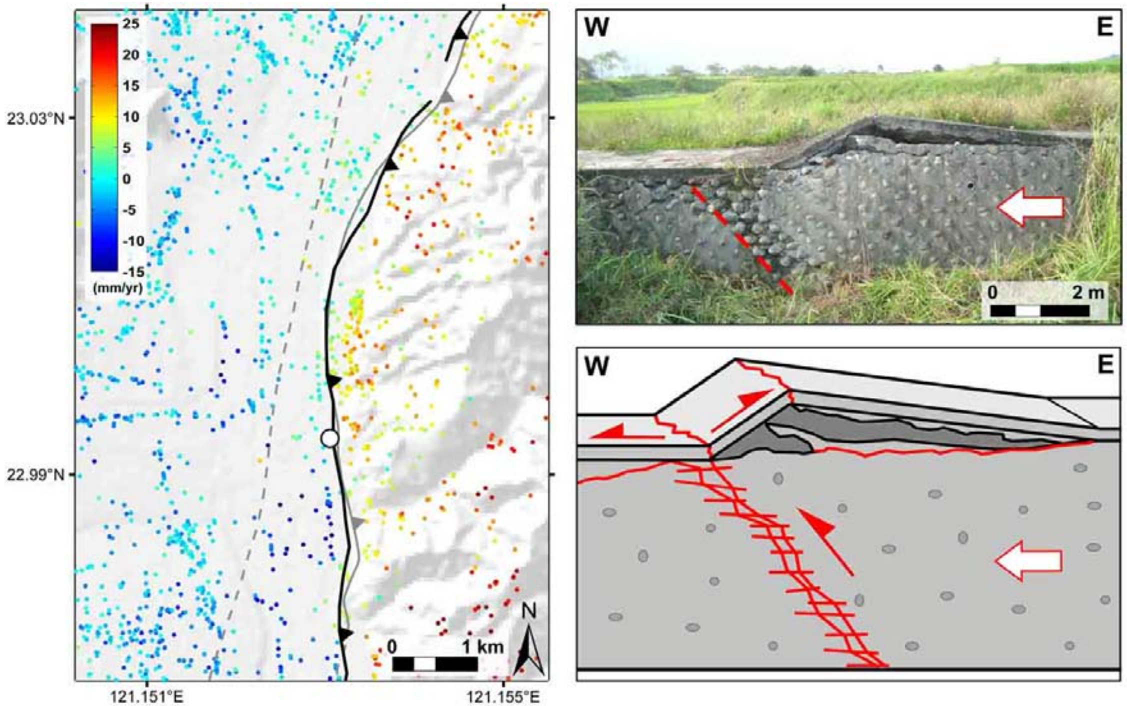
- # Tapo – Chihshang area

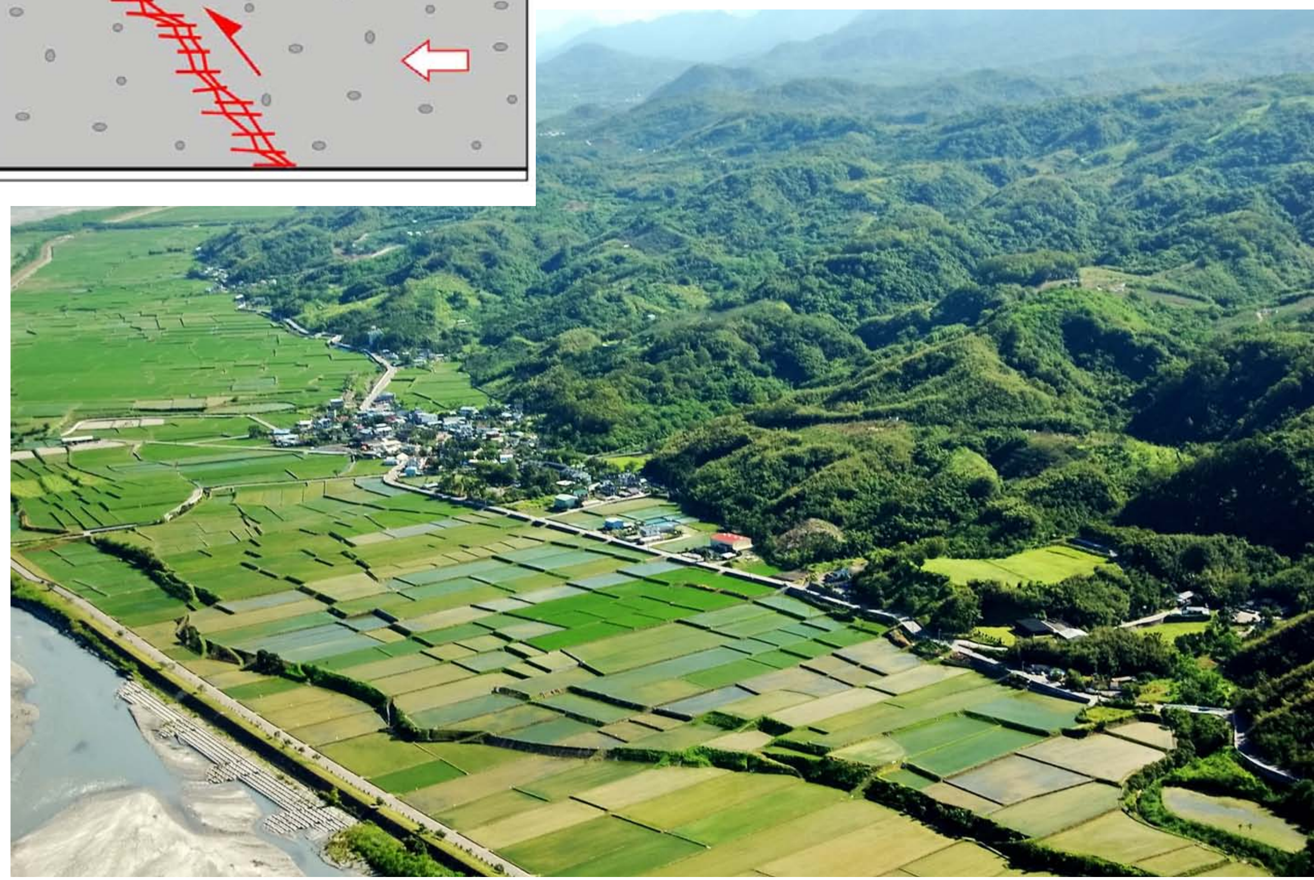
- Area monitored with two creepmeters (red circles) [Lee et al., 2003]



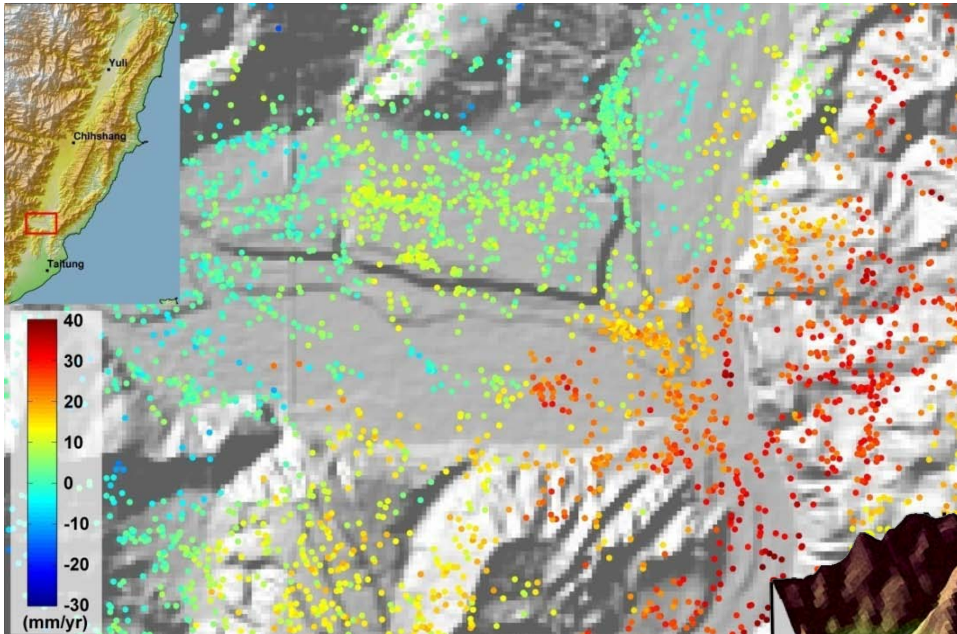
Mean LOS velocity for the period 29/01/2007 to 06/02/2010

Tiengwan area

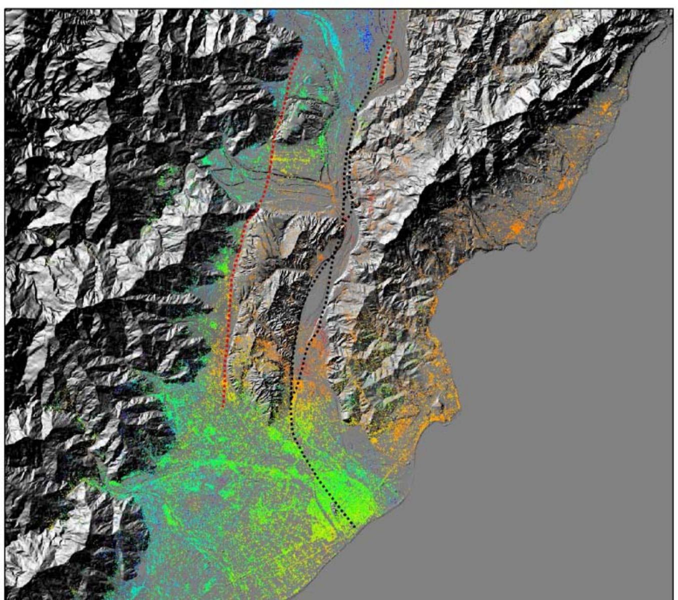


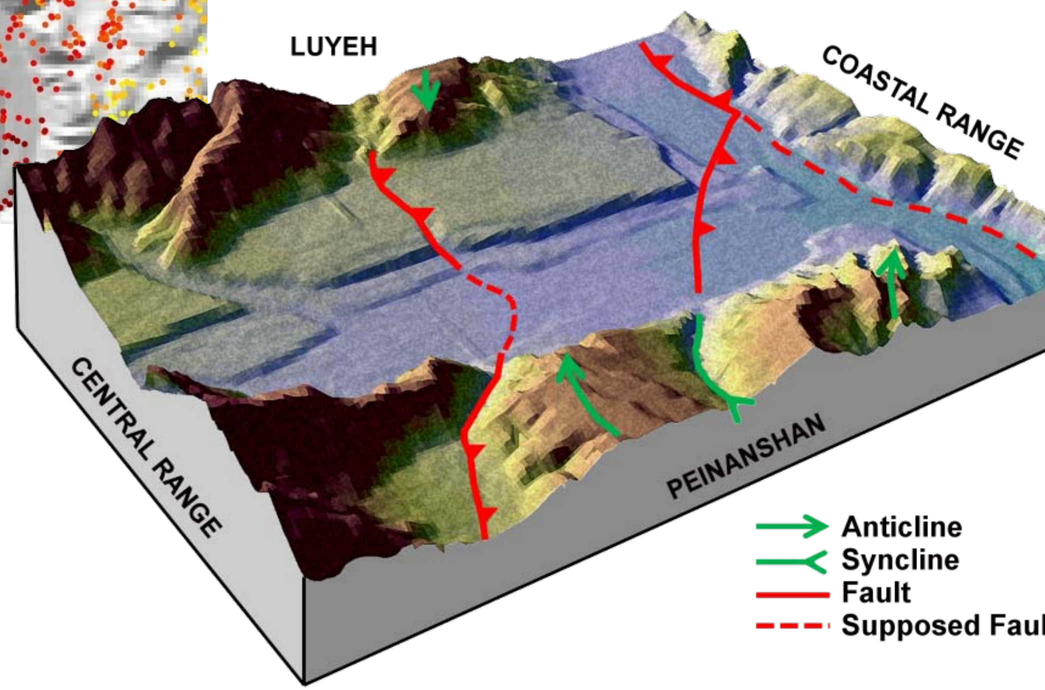


- # Peinanshan – Luyeh area



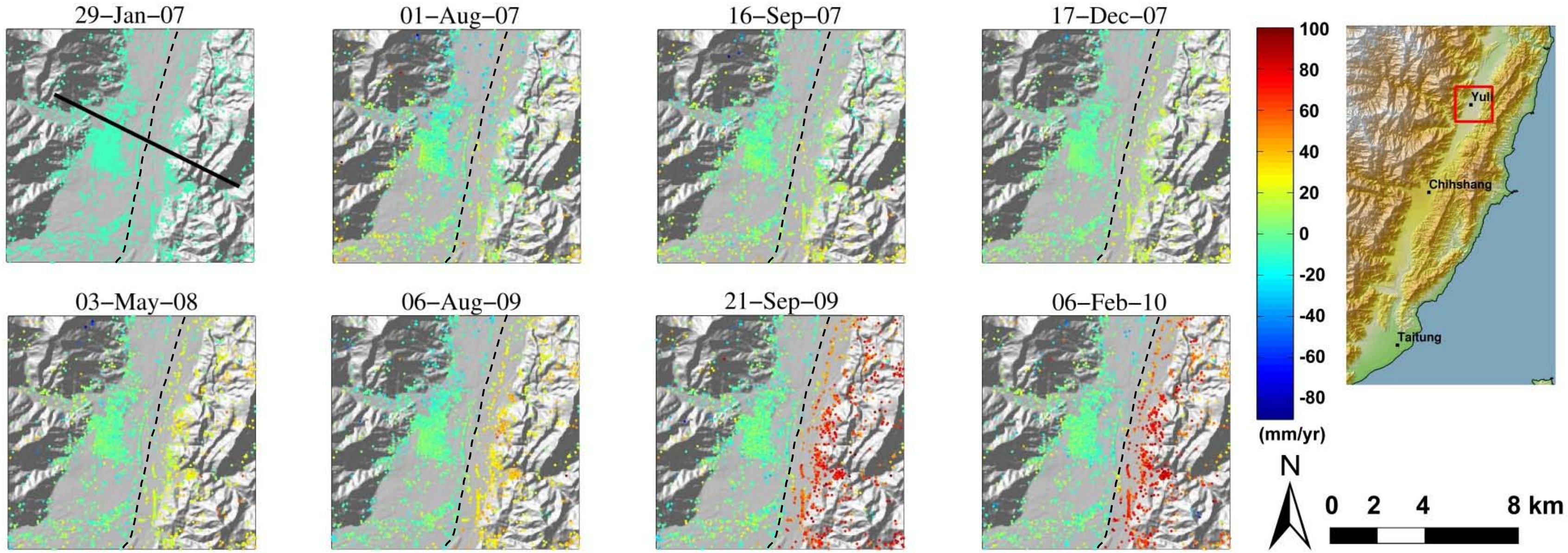
1. Slip partitioning of the strike-slip Lichi fault and the pure Luyeh thrust fault? (Lee et al., Tectonics, 1998)
2. South of longitudinal Valley deformation is more distributed



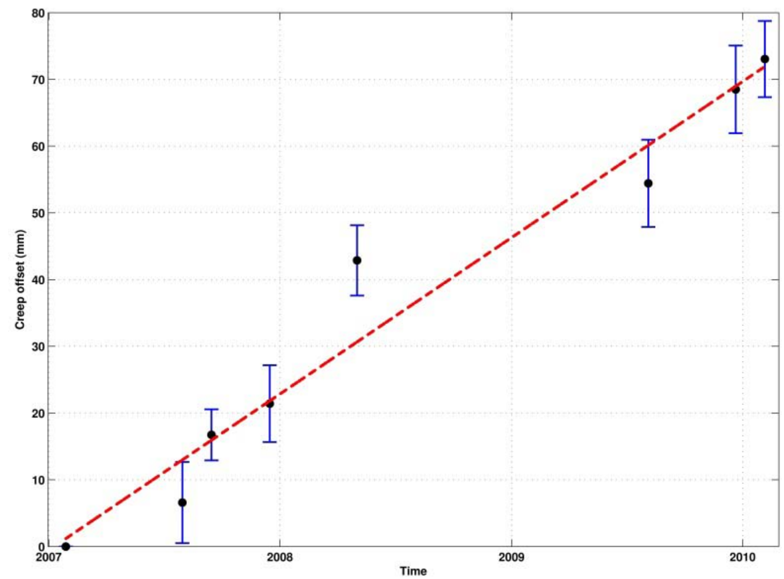


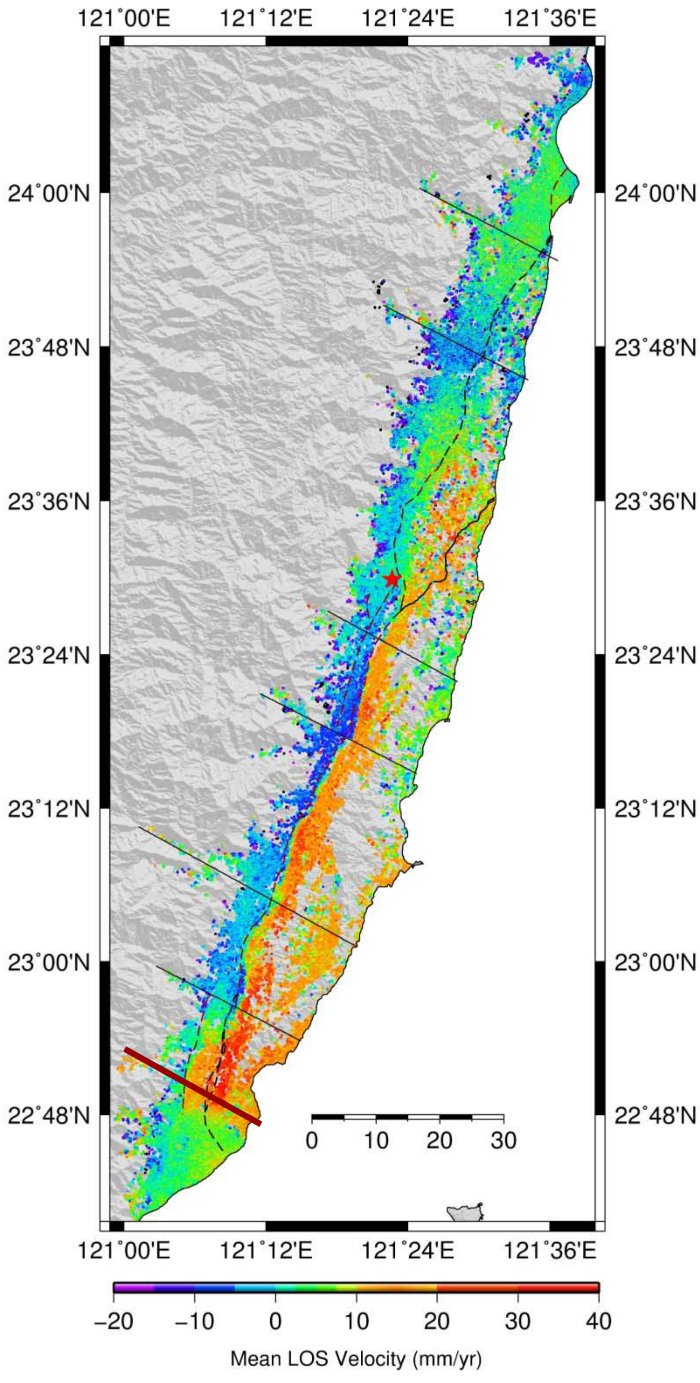
Mean LOS velocity for the period 29/01/2007 to 06/02/2010

Example of PS-INSAR Time series at Yuli bridges

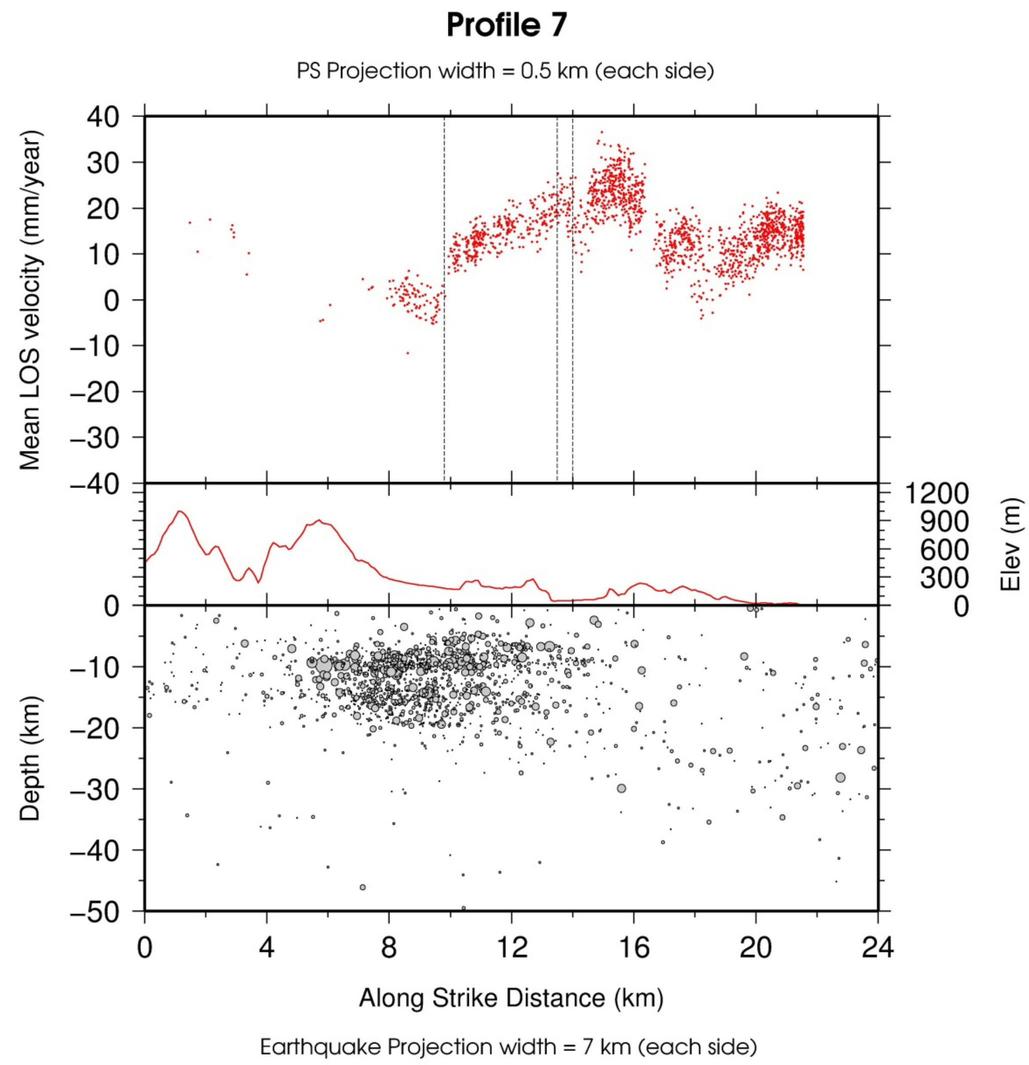


- Temporal series of displacement with measurement at each acquisition dates
- Creep offset estimation across the fault (~24 mm/yr along line of sight)
- Temporal Sampling does allow to discriminate seasonal effect or significant transient deformation. At first order, the creep seems to be steady state.

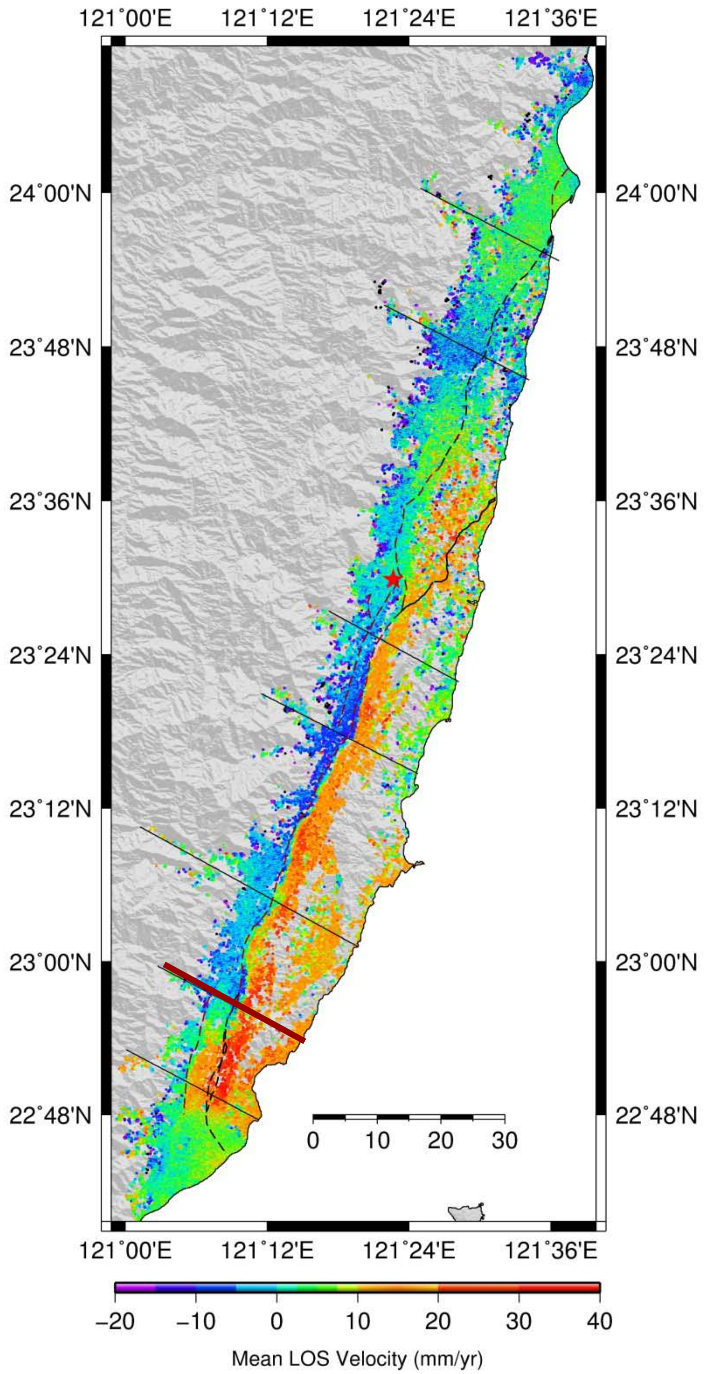




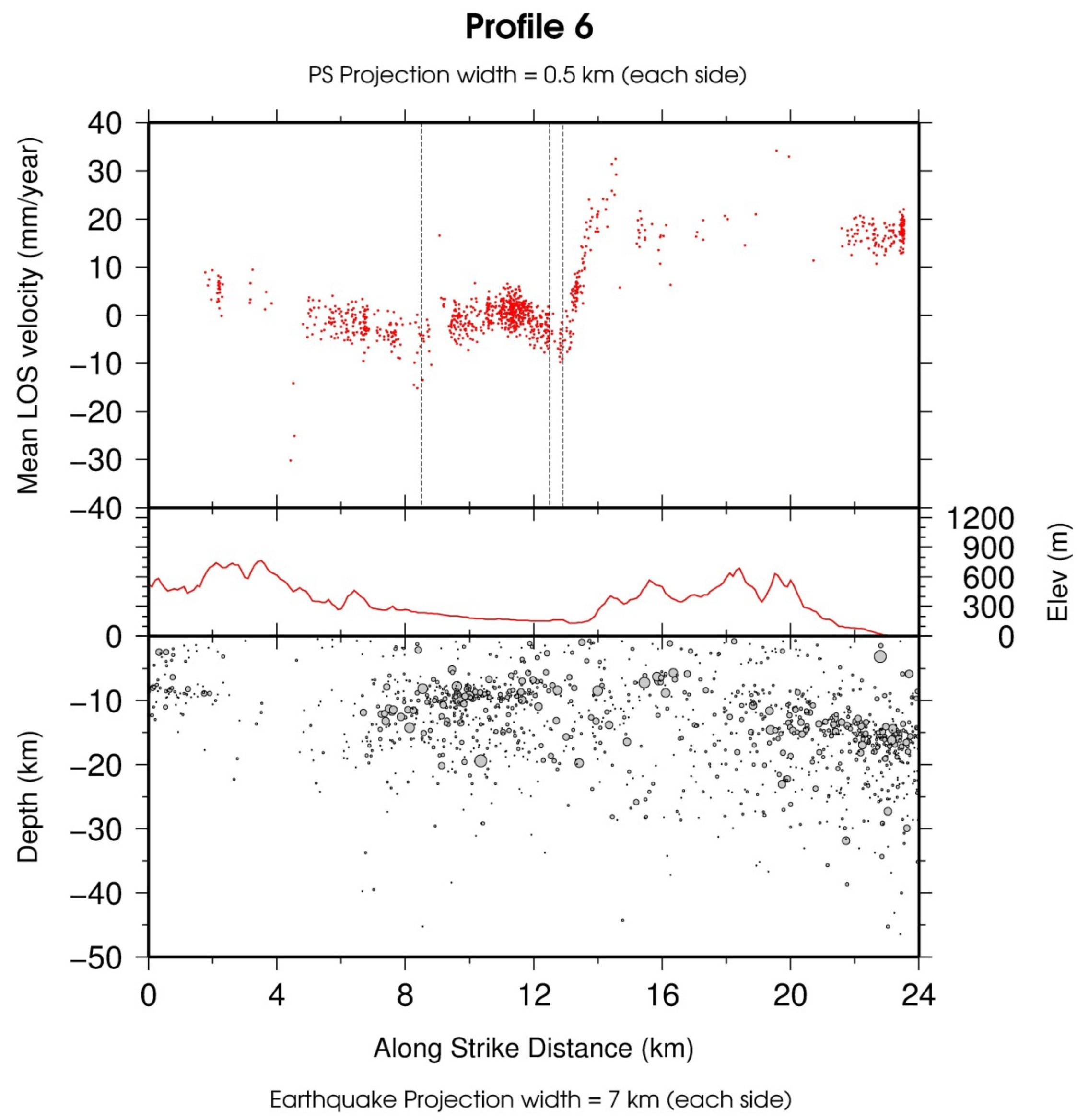
121°00'E
121°12'E
121°24'E
121°36'E
24°00'N
23°48'N
23°36'N
23°24'N
23°12'N
23°00'N
22°48'N
0
10
20
30
−20
−10
0
10
20
30
40
Mean LOS Velocity (mm/yr)



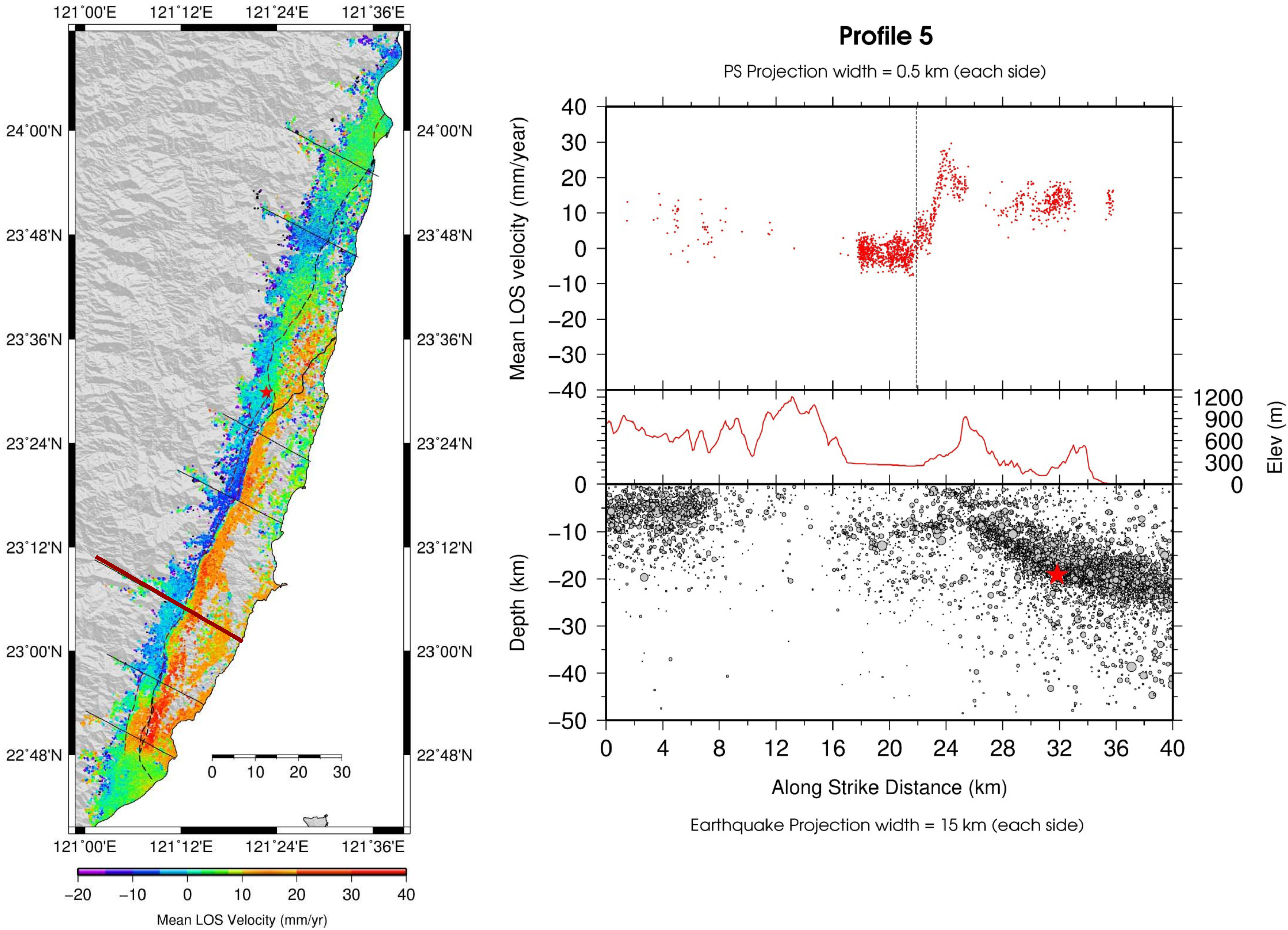
Profile 7
PS Projection width = 0.5 km (each side)
Mean LOS velocity (mm/year)
Elev (m)
Depth (km)
Along Strike Distance (km)
Earthquake Projection width = 7 km (each side)



121˚00'E
121˚12'E
121˚24'E
121˚36'E
24˚00'N
23˚48'N
23˚36'N
23˚24'N
23˚12'N
23˚00'N
22˚48'N
0
10
20
30
−20
−10
0
10
20
30
40
Mean LOS Velocity (mm/yr)

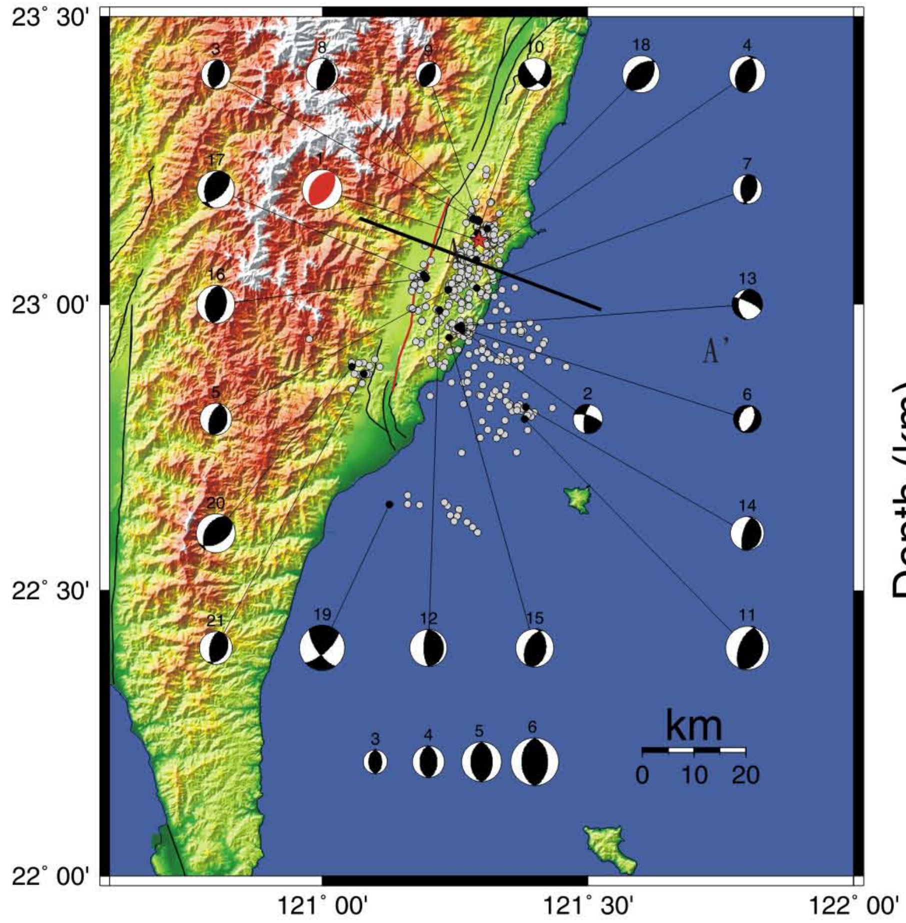


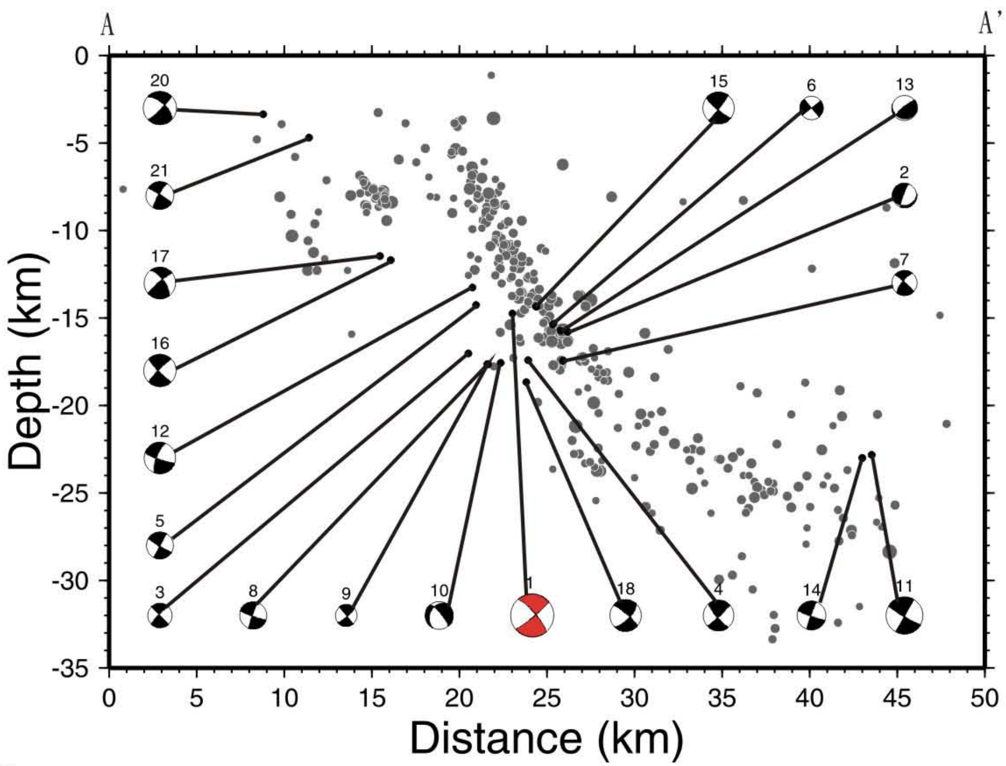
Profile 6
PS Projection width = 0.5 km (each side)
Mean LOS velocity (mm/year)
40
30
20
10
0
−10
−20
−30
−40
1200
900
600
300
0
Elev (m)
Depth (km)
−10
−20
−30
−40
−50
0
4
8
12
16
20
24
Along Strike Distance (km)
Earthquake Projection width = 7 km (each side)

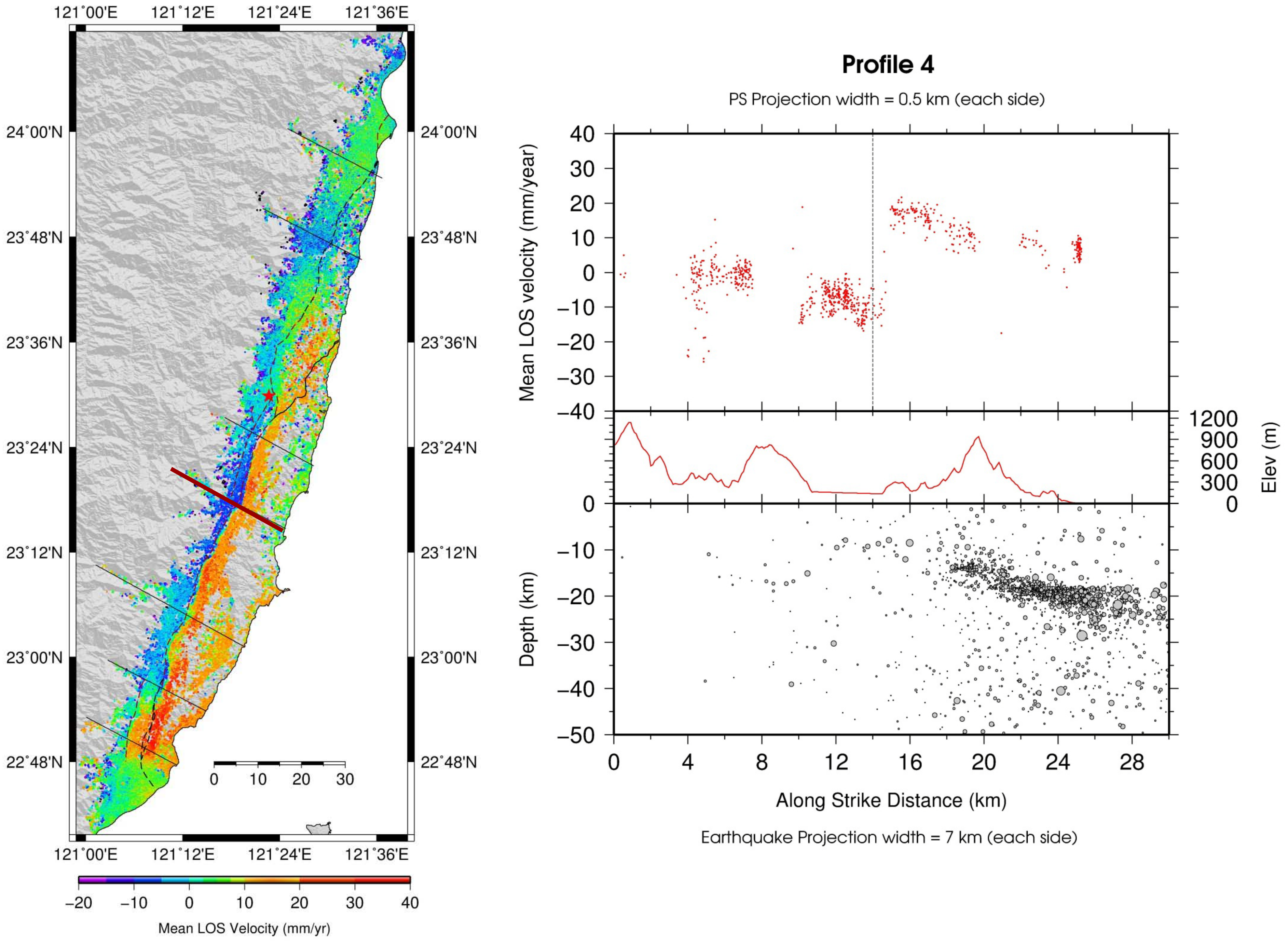


121˚00'E
121˚12'E
121˚24'E
121˚36'E
24˚00'N
23˚48'N
23˚36'N
23˚24'N
23˚12'N
23˚00'N
22˚48'N
0
10
20
30
−20
−10
0
10
20
30
40
Mean LOS Velocity (mm/yr)
Profile 5
PS Projection width = 0.5 km (each side)
Mean LOS velocity (mm/year)
40
30
20
10
0
−10
−20
−30
−40
1200
900
600
300
0
Elev (m)
Depth (km)
−10
−20
−30
−40
−50
0
4
8
12
16
20
24
28
32
36
40
Along Strike Distance (km)
Earthquake Projection width = 15 km (each side)

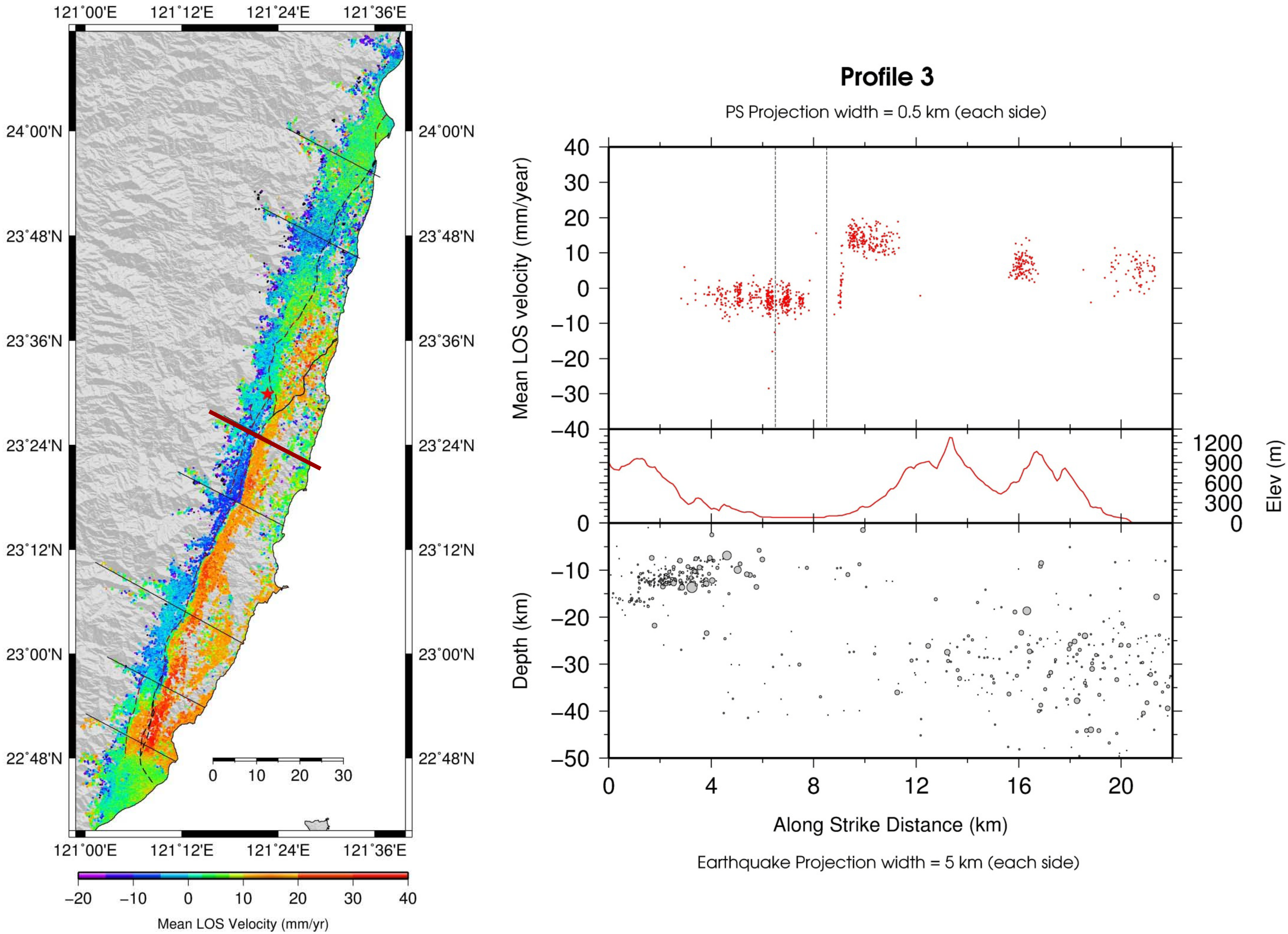
2003 Mw 6.8 Chengkung Earthquake



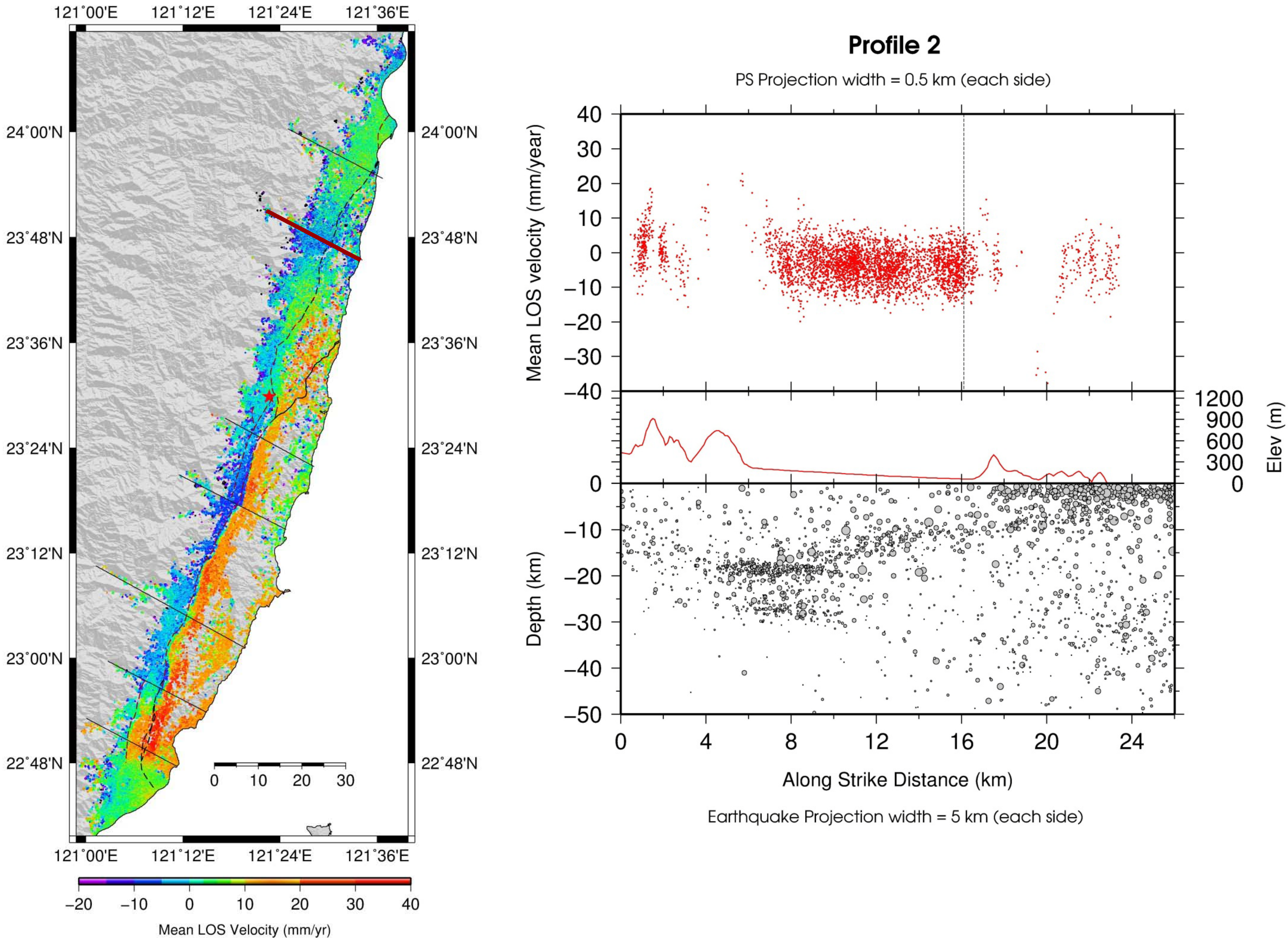




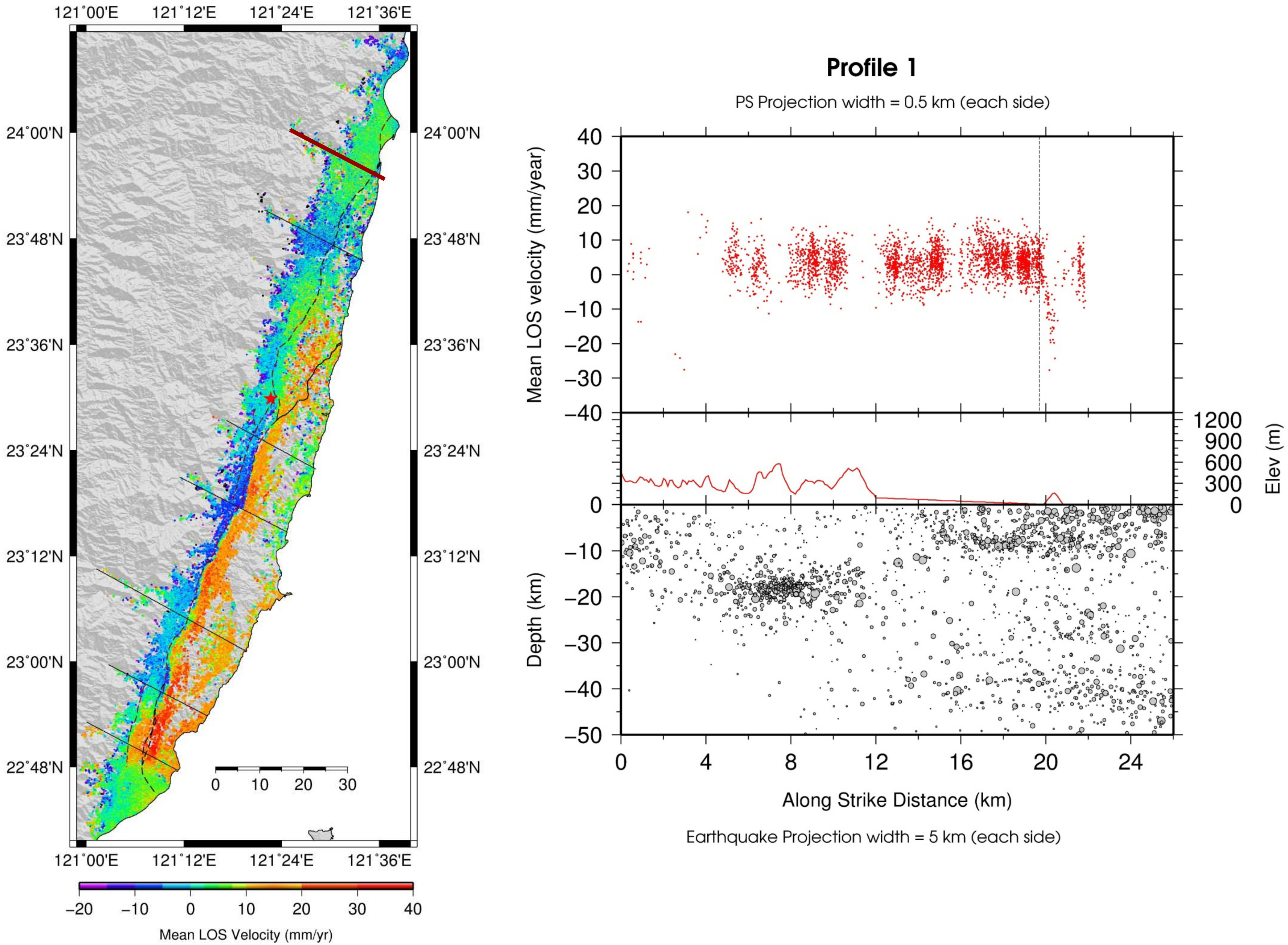
121°00'E
121°12'E
121°24'E
121°36'E
24°00'N
23°48'N
23°36'N
23°24'N
23°12'N
23°00'N
22°48'N
0 10 20 30
−20 −10 0 10 20 30 40
Mean LOS Velocity (mm/yr)
Profile 4
PS Projection width = 0.5 km (each side)
Mean LOS velocity (mm/year)
Elev (m)
Depth (km)
Along Strike Distance (km)
Earthquake Projection width = 7 km (each side)



121°00'E
121°12'E
121°24'E
121°36'E
24°00'N
23°48'N
23°36'N
23°24'N
23°12'N
23°00'N
22°48'N
0 10 20 30
−20 −10 0 10 20 30 40
Mean LOS Velocity (mm/yr)
Profile 3
PS Projection width = 0.5 km (each side)
Mean LOS velocity (mm/year)
Elev (m)
Depth (km)
Along Strike Distance (km)
Earthquake Projection width = 5 km (each side)



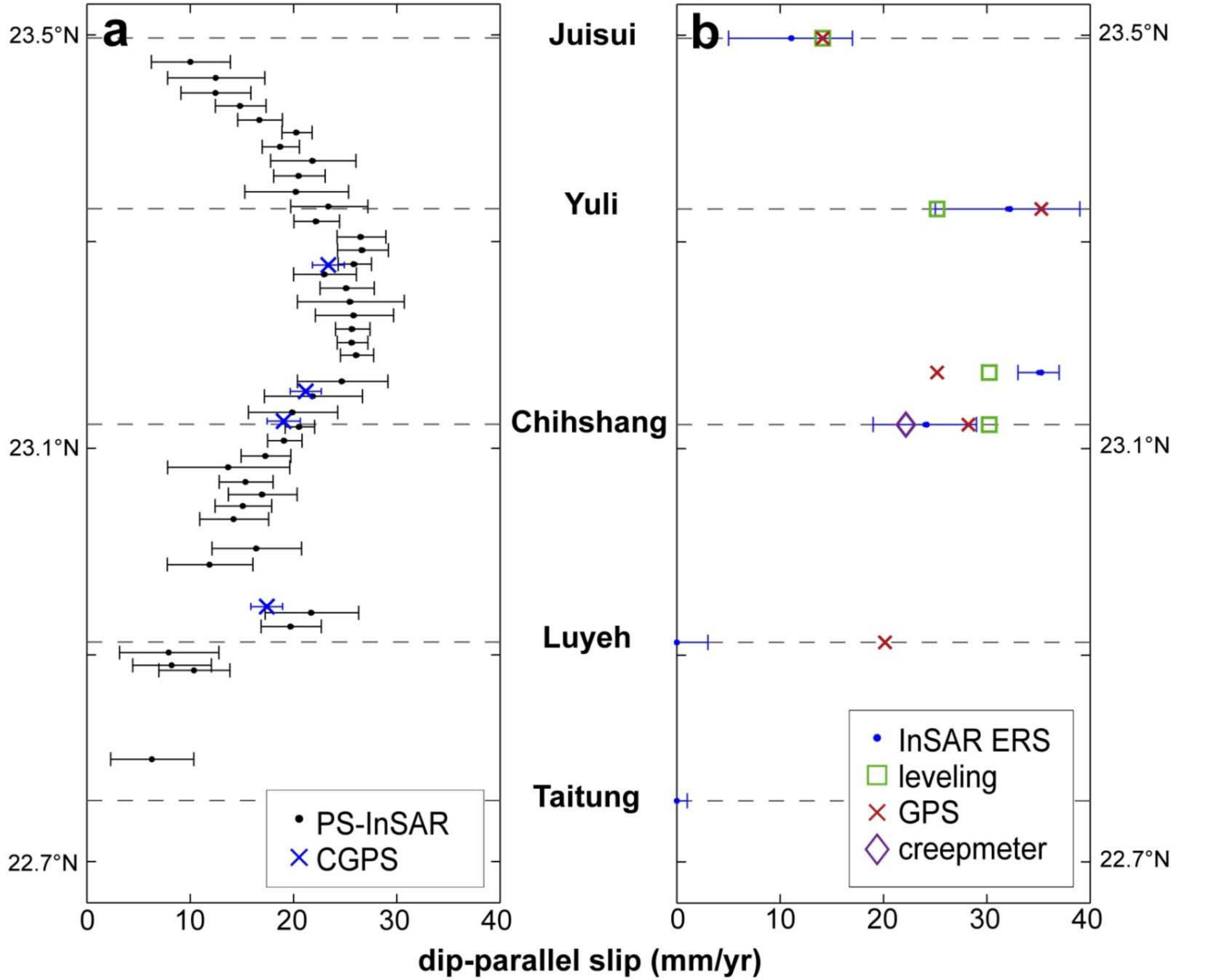
121°00'E
121°12'E
121°24'E
121°36'E
24°00'N
23°48'N
23°36'N
23°24'N
23°12'N
23°00'N
22°48'N
0 10 20 30
Mean LOS Velocity (mm/yr)
−20 −10 0 10 20 30 40
Profile 2
PS Projection width = 0.5 km (each side)
Mean LOS velocity (mm/year)
Elev (m)
Depth (km)
Along Strike Distance (km)
Earthquake Projection width = 5 km (each side)



121°00'E
121°12'E
121°24'E
121°36'E
24°00'N
23°48'N
23°36'N
23°24'N
23°12'N
23°00'N
22°48'N
0 10 20 30
−20 −10 0 10 20 30 40
Mean LOS Velocity (mm/yr)
Profile 1
PS Projection width = 0.5 km (each side)
Mean LOS velocity (mm/year)
Elev (m)
Depth (km)
Along Strike Distance (km)
Earthquake Projection width = 5 km (each side)

Slip distribution along the Longitudinal Valley fault

Our study — Modified from Hsu and Bürgmann, 2006



Summary

- L-band ALOS InSAR in the Longitudinal Valley allows a dramatic improvement with respect to previous C-Band studies.

- We improved the mapping of the fault trace (100 m accuracy) where it creeps.

- Superficial aseismic creep seems to be limited to the eastern Longitudinal Valley fault

- Creep rate change along the fault with two maximums (2.5 cm/cm dip-parallel). It vanishes North of Rueisuei and South of the Pinanshan.

- InSAR temporal sampling does not allow to discriminate seasonal effect or significant transient deformation. At first order, the creep seems to be steady state over the 2007-2010 period.

Future study: Can we remove the atmospheric signal from interferograms?

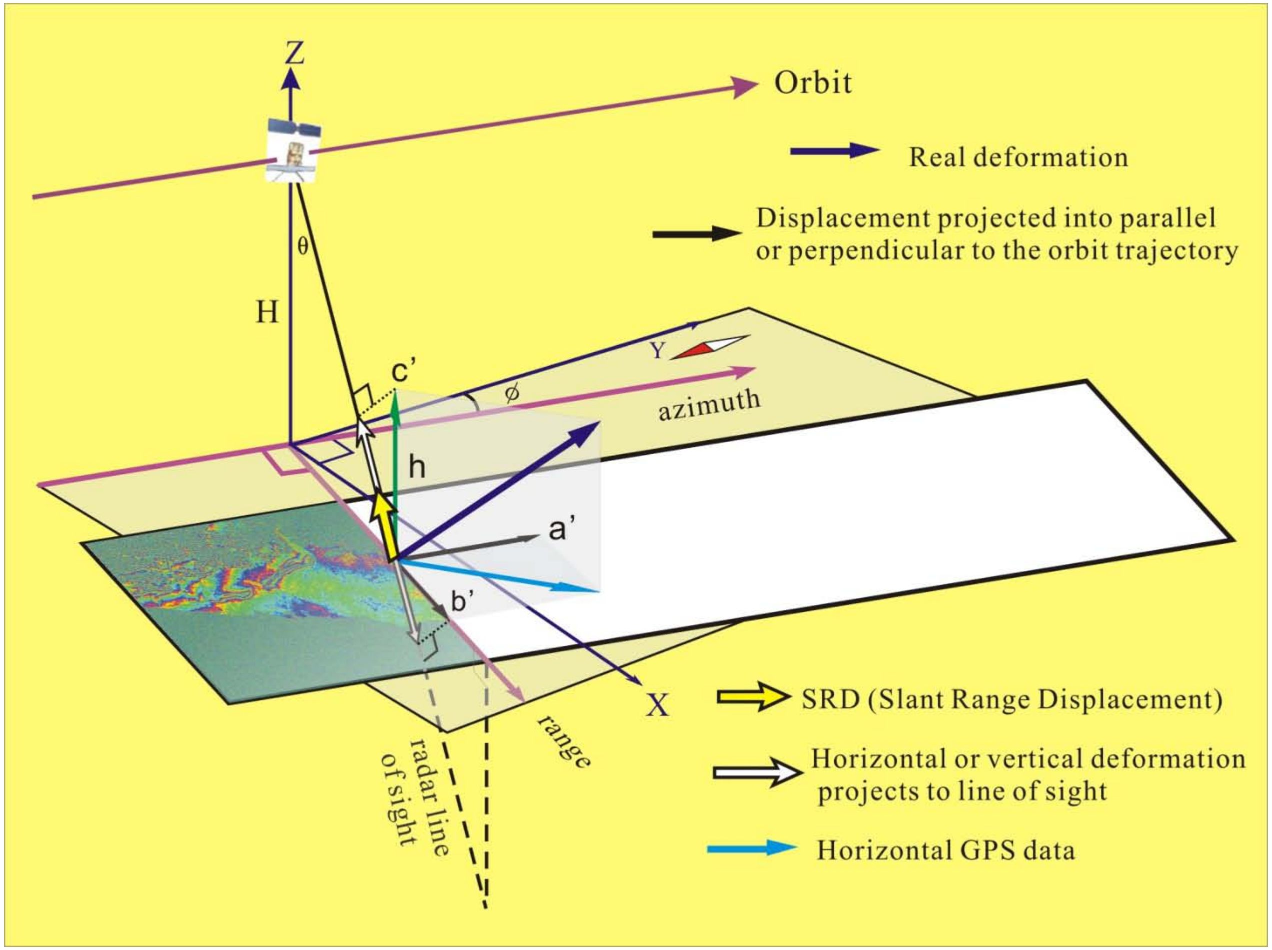
1. Use interferograms themselves to estimate linear or exponential phase with elevation: constant for image or spatially variable
2. Direct water vapor and "dry delay" observations:
(a) From satellite (e.g., Li et al., 2005)
(b) From GPS & other ground sensors (e.g., Webley et al., 2002)
3. Data stacks or APS: Assume atmosphere random in time or low-pass time domain filtering (e.g., Ferretti et al., 2001; Simons and Rosen, 2007)

Based on several studies, we can't remove everything. Will likely always need to account for atmosphere effects

Thank you for your attention!

The Longitudinal Valley at Chihshang area

Transformation from SRD to Vertical Deformation

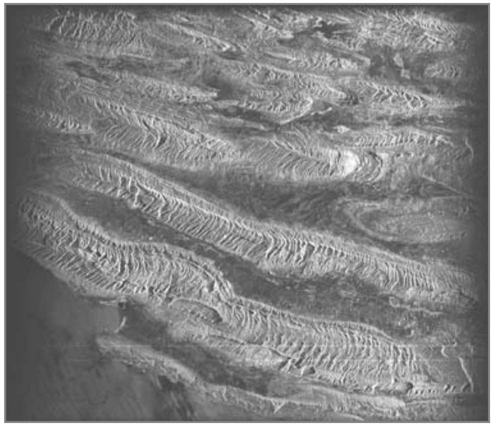


$$\mathbf{V} = \begin{bmatrix} a' \\ b' \\ c' \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} a\cos\phi + b\sin\phi \\ -a\sin\phi + b\cos\phi \\ c \end{bmatrix}$$

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

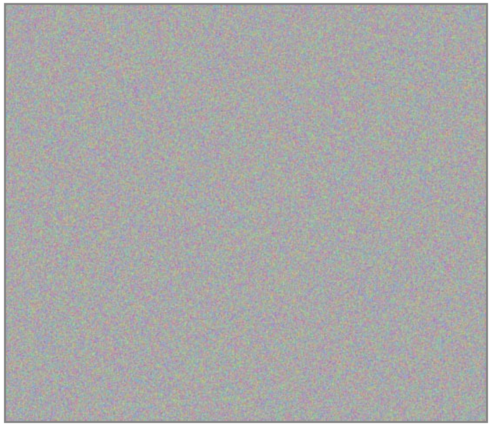
Interferogram Formation

1999/04/21



Amplitude

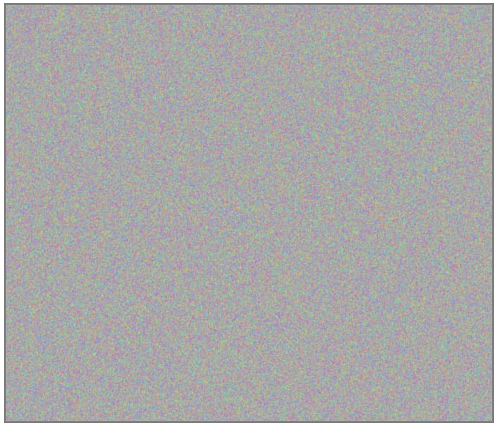
+



Phase

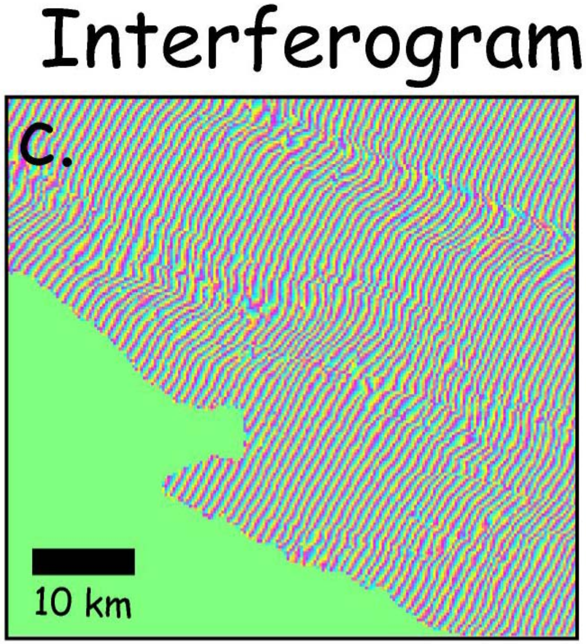
1999/05/26

Amplitude



Phase

=



Modified from Rowena Lohman

What are the sources of error?

How do we evaluate them?

- Unwrapping errors: assess by looking a image with different wrap rates

- Atmospheric/ionospheric errors: use multiple images and pairwise logic (e.g., Feigl & Massonnet, 1995)

- Orbital errors: understand their basic characteristics, try different orbital estimates, process tracks of different lengths, tandem pairs can be useful

- DEM errors: inspect the raw DEM, process interferograms with different baselines and timespans, tandem pairs can be useful