Measuring ground deformation across the Chegualin and Chishan faults, Southwestern Taiwan using aerial image correlation and DSM time series

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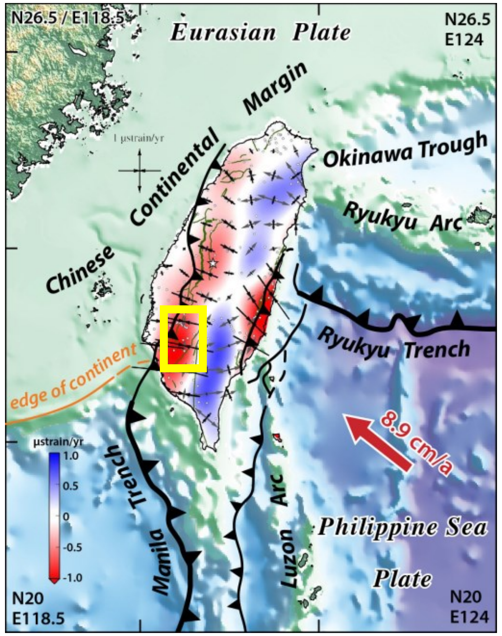
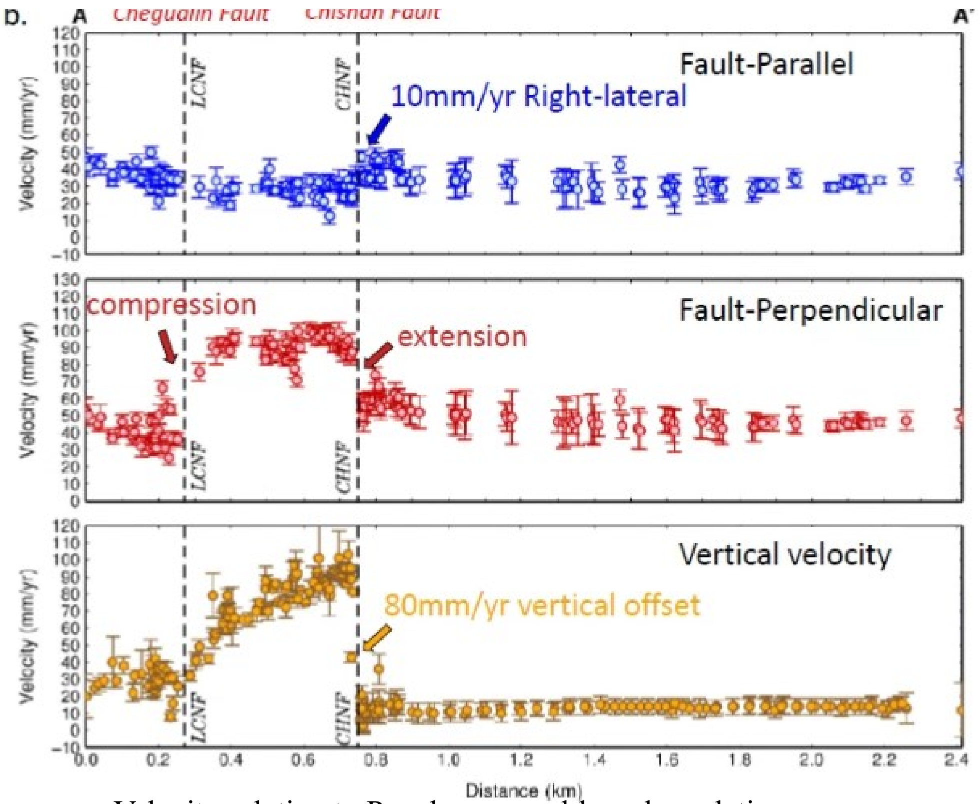
Date: **2024/3/15**

Introduction



Tectonic setting of Taiwan (Strain rate map from Hsu et al., 2009)

Geological map (Lin CW, 2013, complemented with our observations along the Chishan fault).

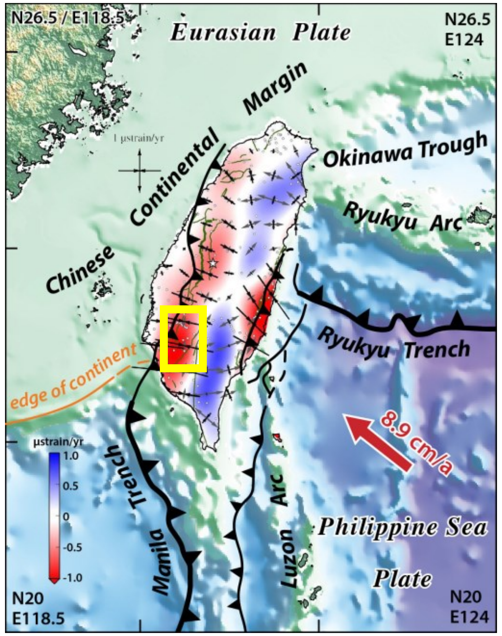


Velocity relative to Penghu, ground-based geodetic measurements, projected on AA' line (Chang-Lee, 2014).

Introduction:

- The Chishan fault is located in the foothills of southwestern Taiwan, where rapid shortening is occurring.
- The present deformation at the Zhongliao tunnel is caused by normal faulting according to geodetic measurements and results in a severe damage of the tunnel.

Introduction



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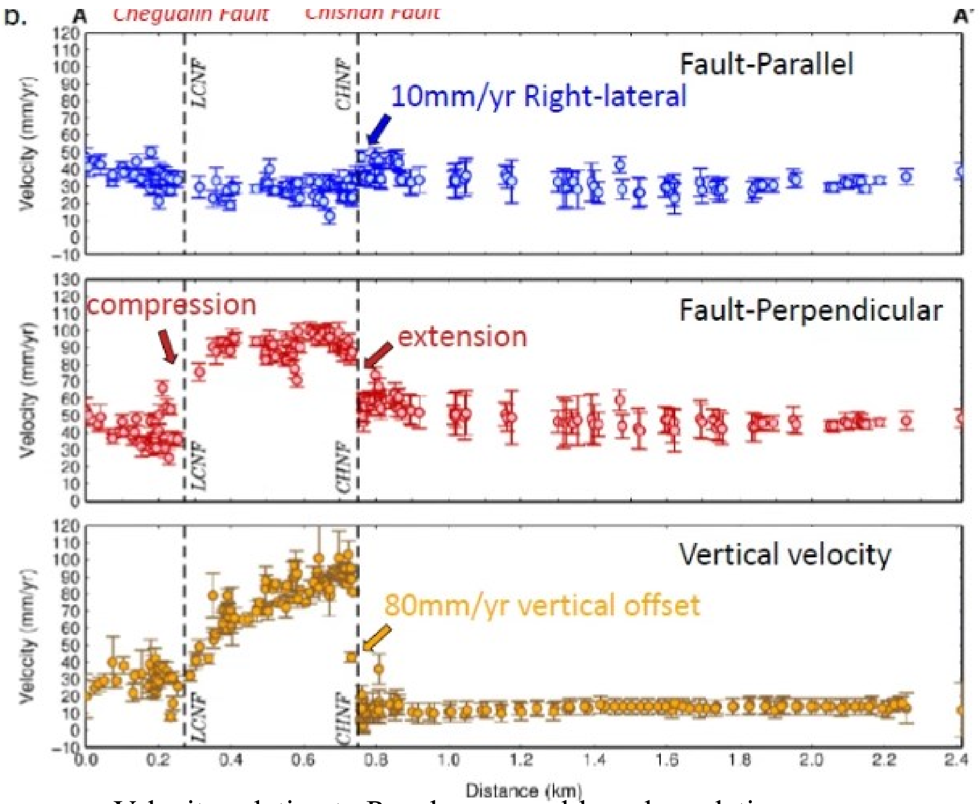


Velocity relative to Penghu, ground-based geodetic measurements, projected on AA' line (Chang-Lee, 2014).

Our Goals:

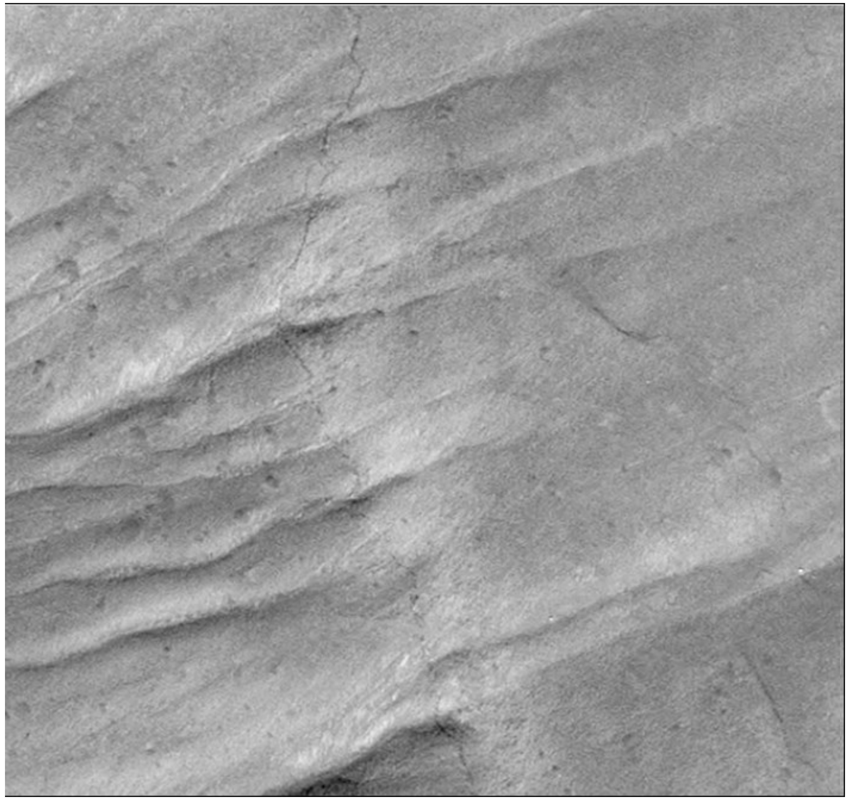
- This study uses aerial image correlation to complement existing geodetic data with moderate spatial resolution but higher spatial coverage.
- To understand the regional tectonics and the mechanism behind these phenomena.

Principle of image correlation

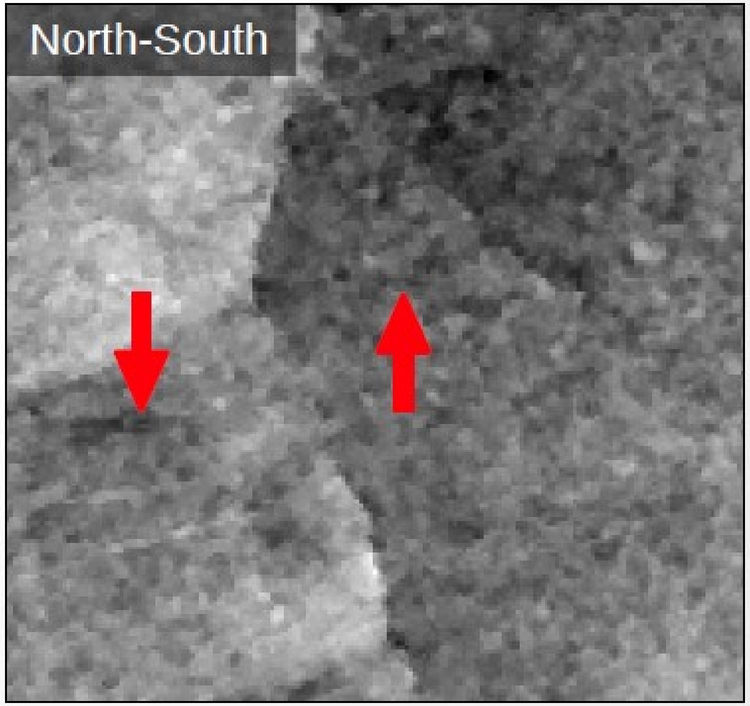
How to measure the surface deformation that results from tectonics?

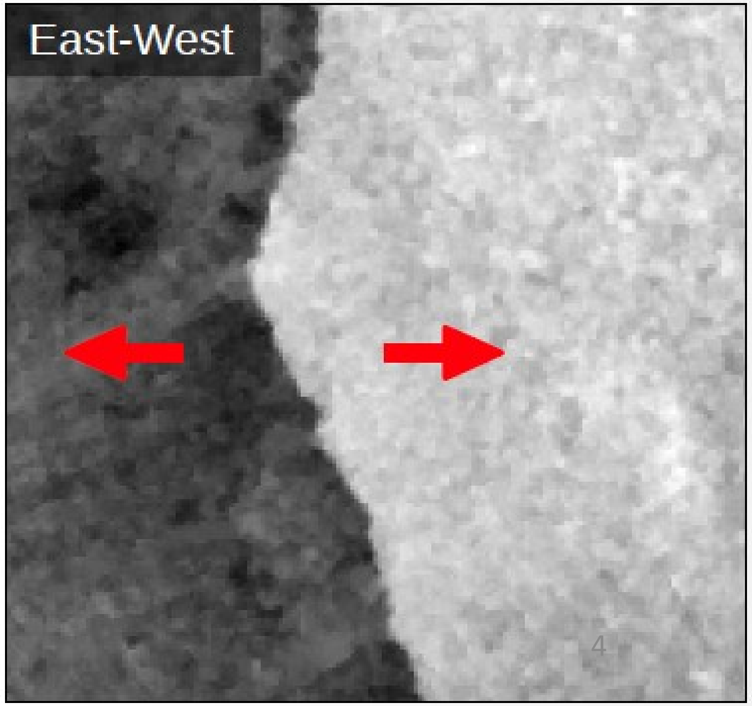
GPS, leveling, InSAR … **Satellite/Aerial Image correlation!**

To detect the displacement of pixels in the images shot before and after tectonic activity.



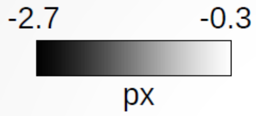
Pleiades satellite image





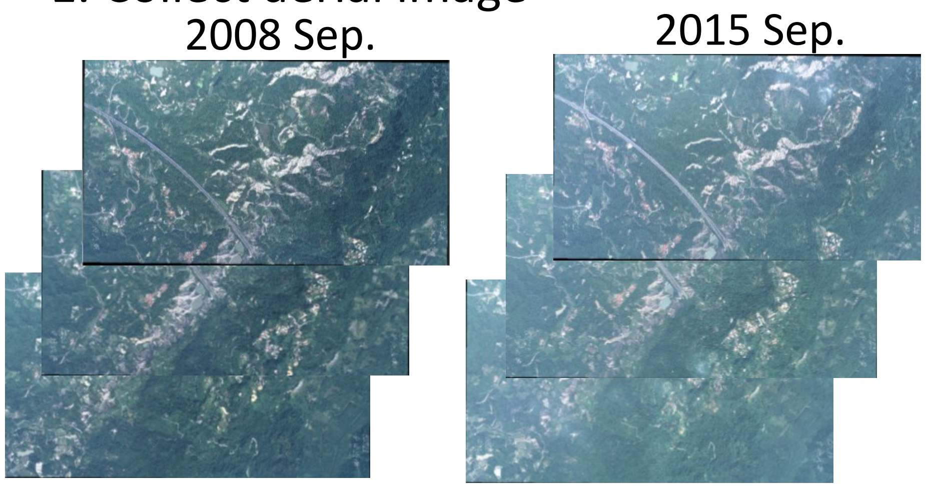
~2 px (1 m) of relative horizontal displacement between the two blocks

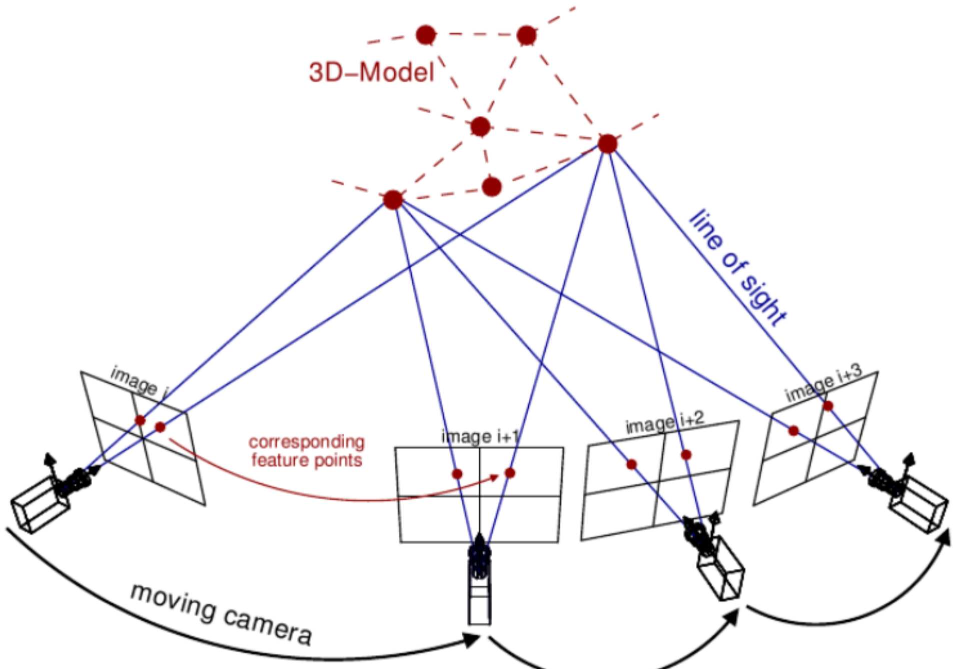
Images are provided by Arthur Delorme (Norcia earthquake, Italy, 2016)



Processing steps

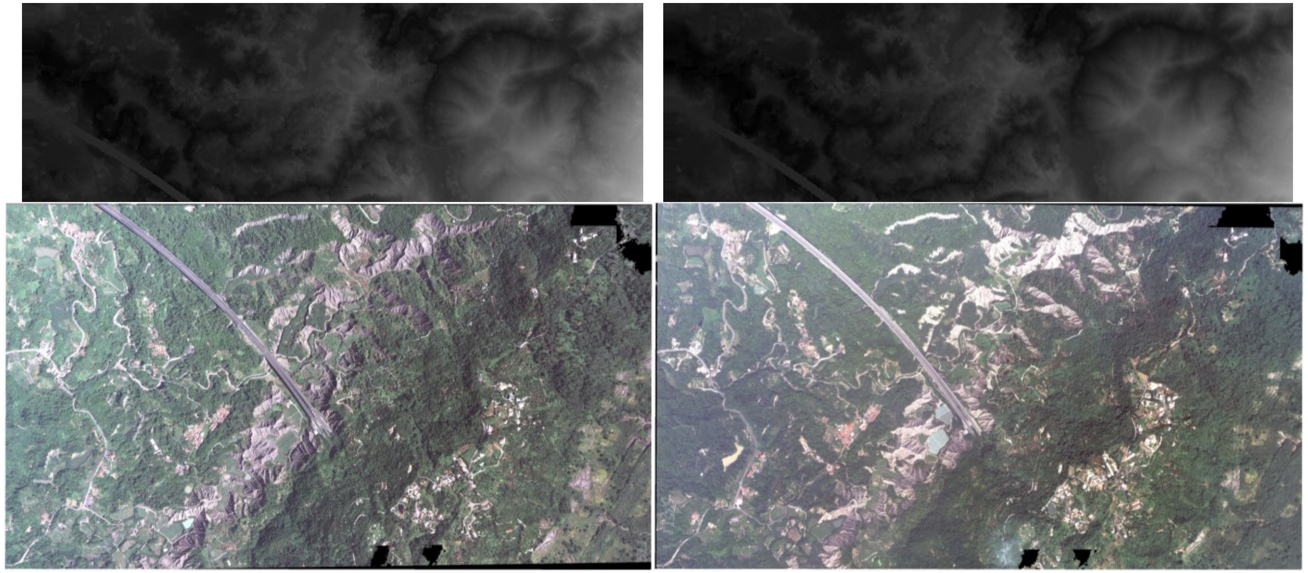
1. Collect aerial image

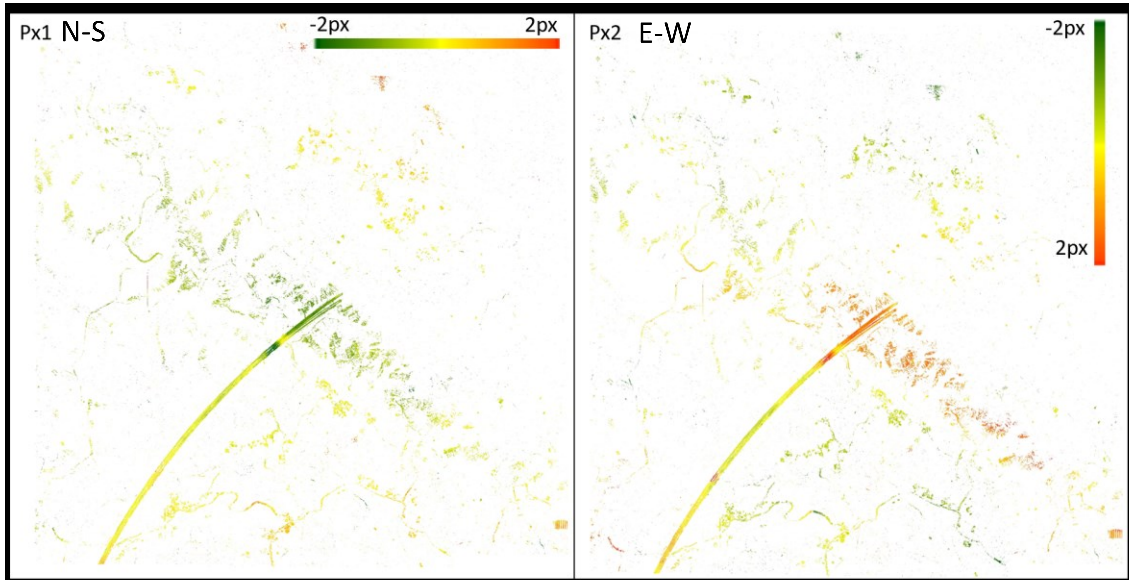




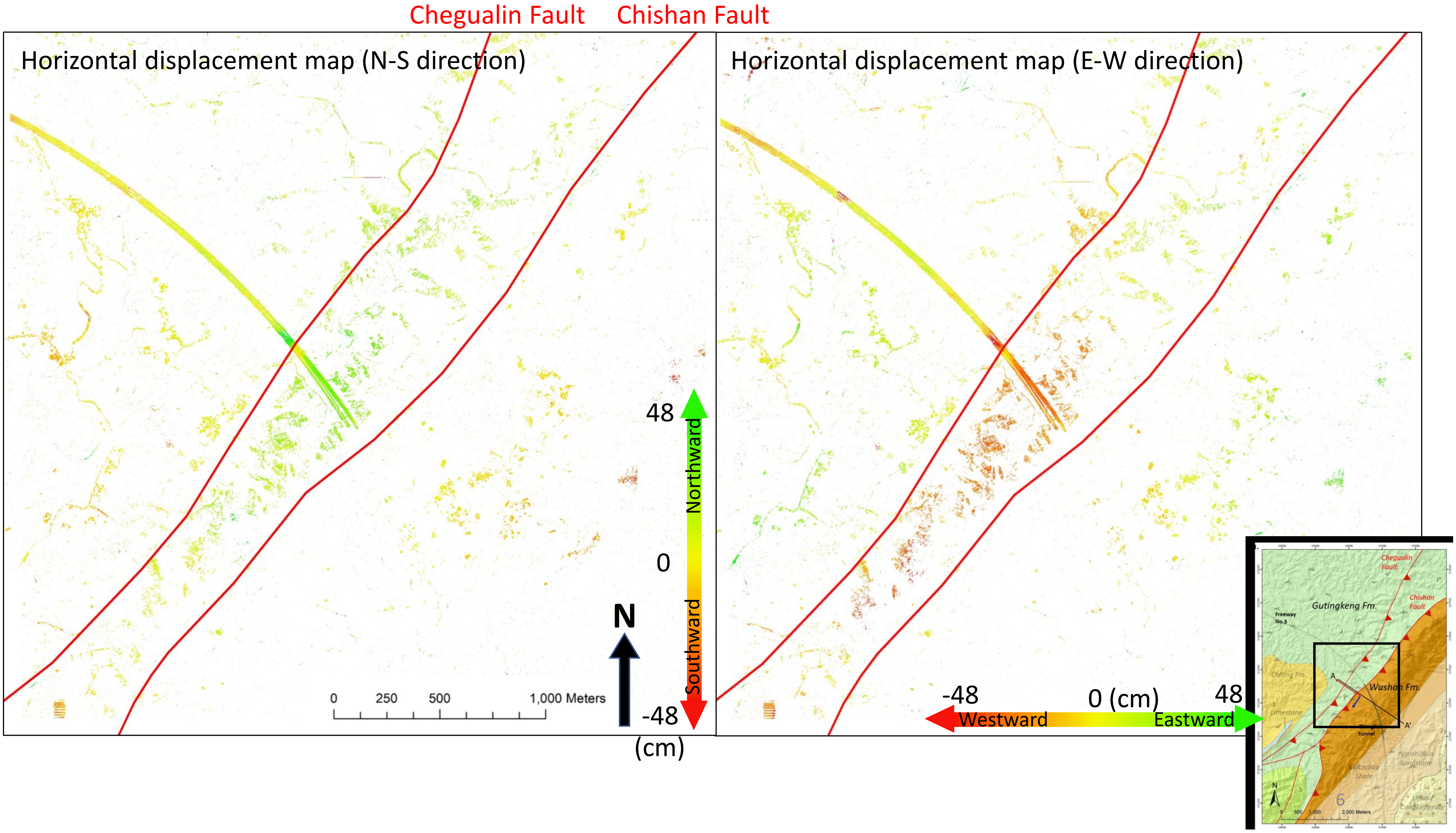
2.Reconstruct 3D-model by SfM

3. Extract DSM and orthorectify the aerial images





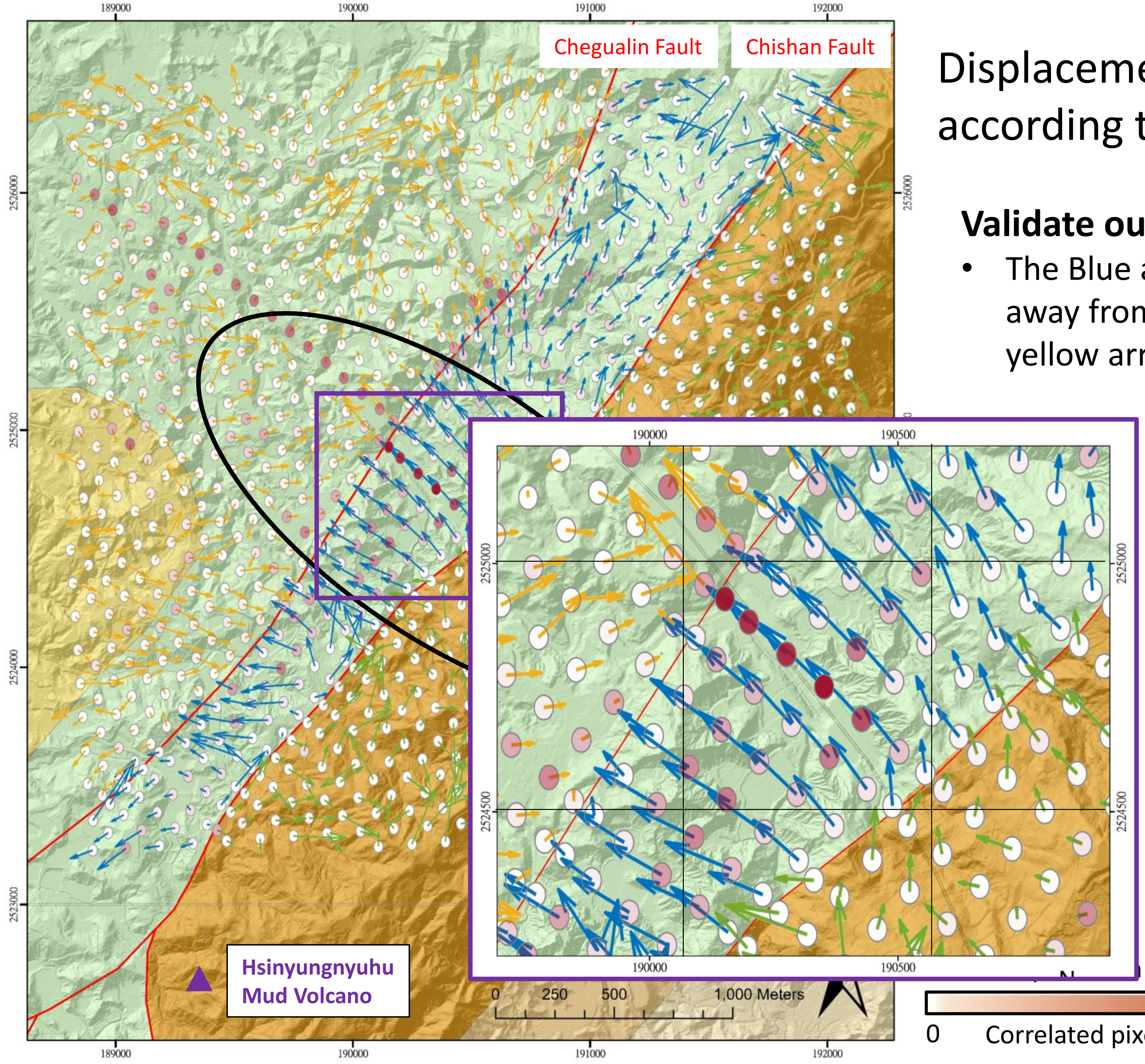
4. Measure 2D horizontal displacement


Chegualin Fault
Chishan Fault
Horizontal displacement map (N-S direction)
Horizontal displacement map (E-W direction)
48
Northward
0
Southward
-48
(cm)
N
0
250
500
1,000 Meters
-48
0 (cm)
48
Westward
Eastward
Cheguelin Fault
Chishan Fault
Gutingkeng Fm.
Freeway No.3
Chiting Fm.
Wushan Fm.
Limestone
A
A'
tunnel
Nanshihlun Sandstone
Kaitzuliao Shale
N
2,000 Meters

Displacement field of the Zhongliao tunnel area, according to aerial image correlation results.

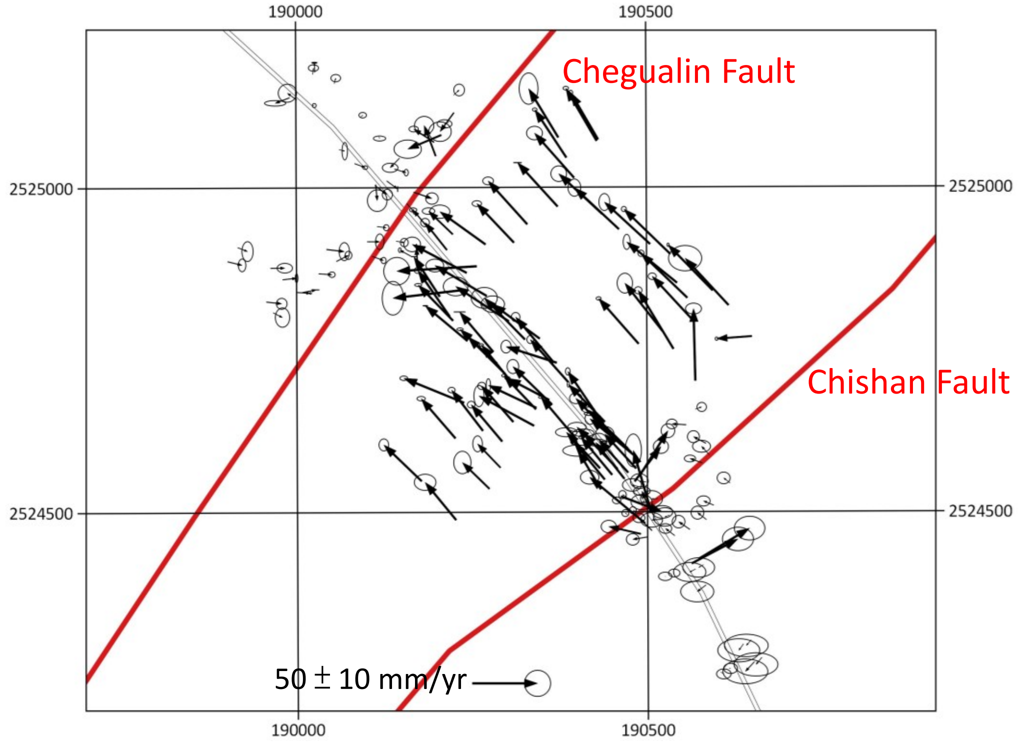
Validate our measurement with GNSS network:

- The Blue arrows (the middle block) are generally moving away from green arrows (SE block), but moving toward to yellow arrows (NW block).



0 Correlated pixels per m^2 6.5

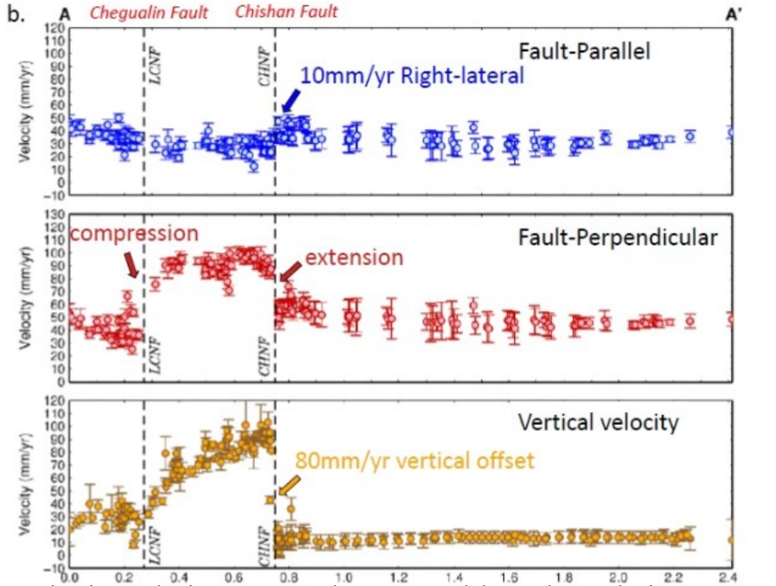
Horizontal velocity measured by GNSS network



Data provided by Prof. Jing Kuo-En

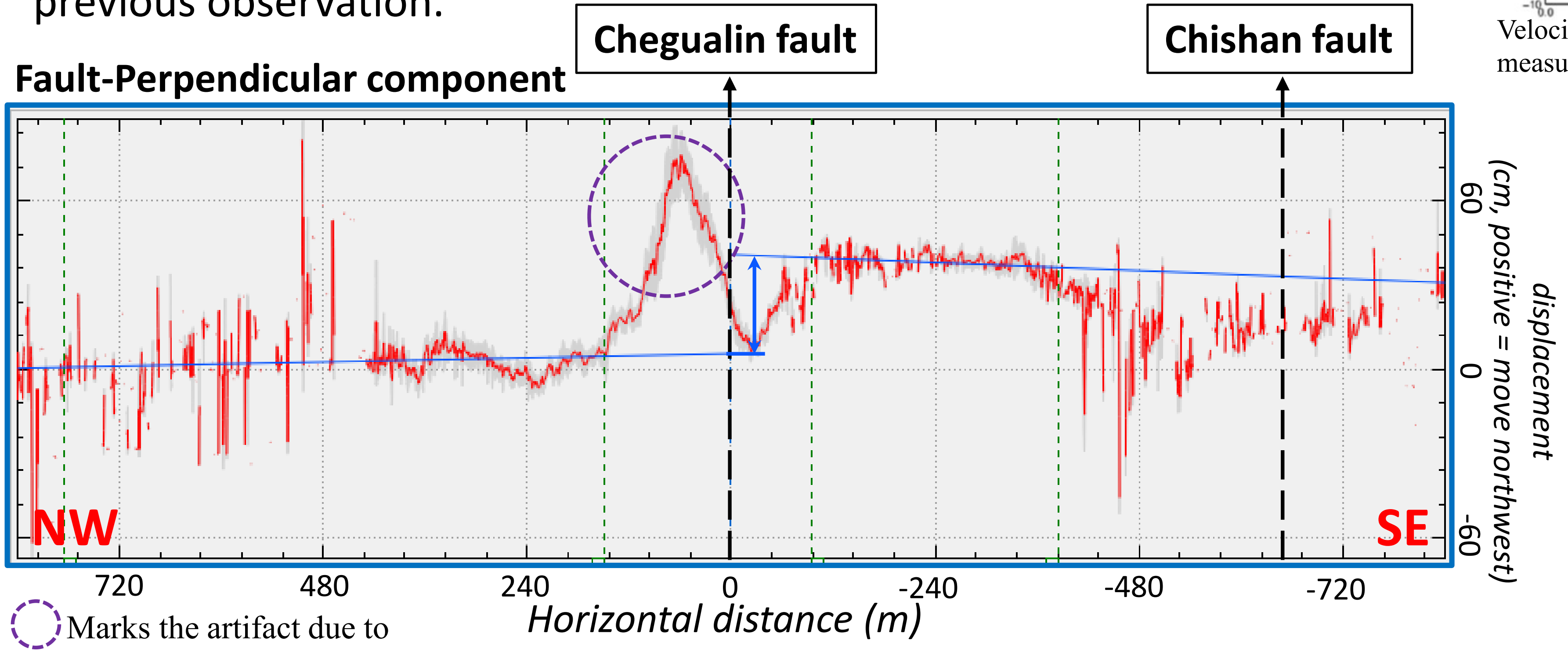
Ground displacement nearby Zhongliao tunnel

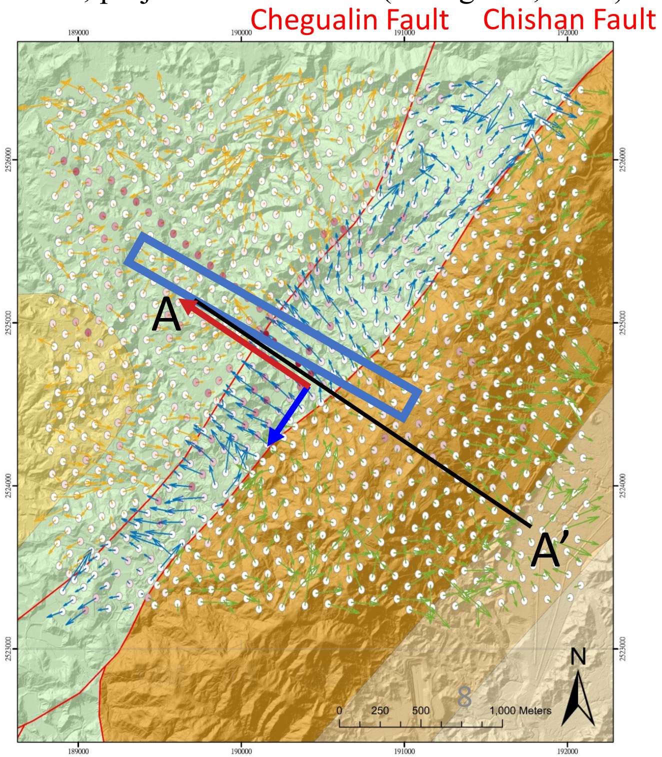
- Ground-based geodetic measurements along the freeway, the displacement at fault-perpendicular direction: **50 mm/yr compression across the Chegualin fault**.
- We expect a **total displacement of 35 cm during 2008-2015**.
- The displacement across Chegualin fault measured from the **aerial images (2008-2015) correlation** is about **35.2 cm,** which is quite consistent with previous observation.



Velocity relative to Penghu, ground-based geodetic measurements, projected on AA' line (Chang-Lee, 2014).

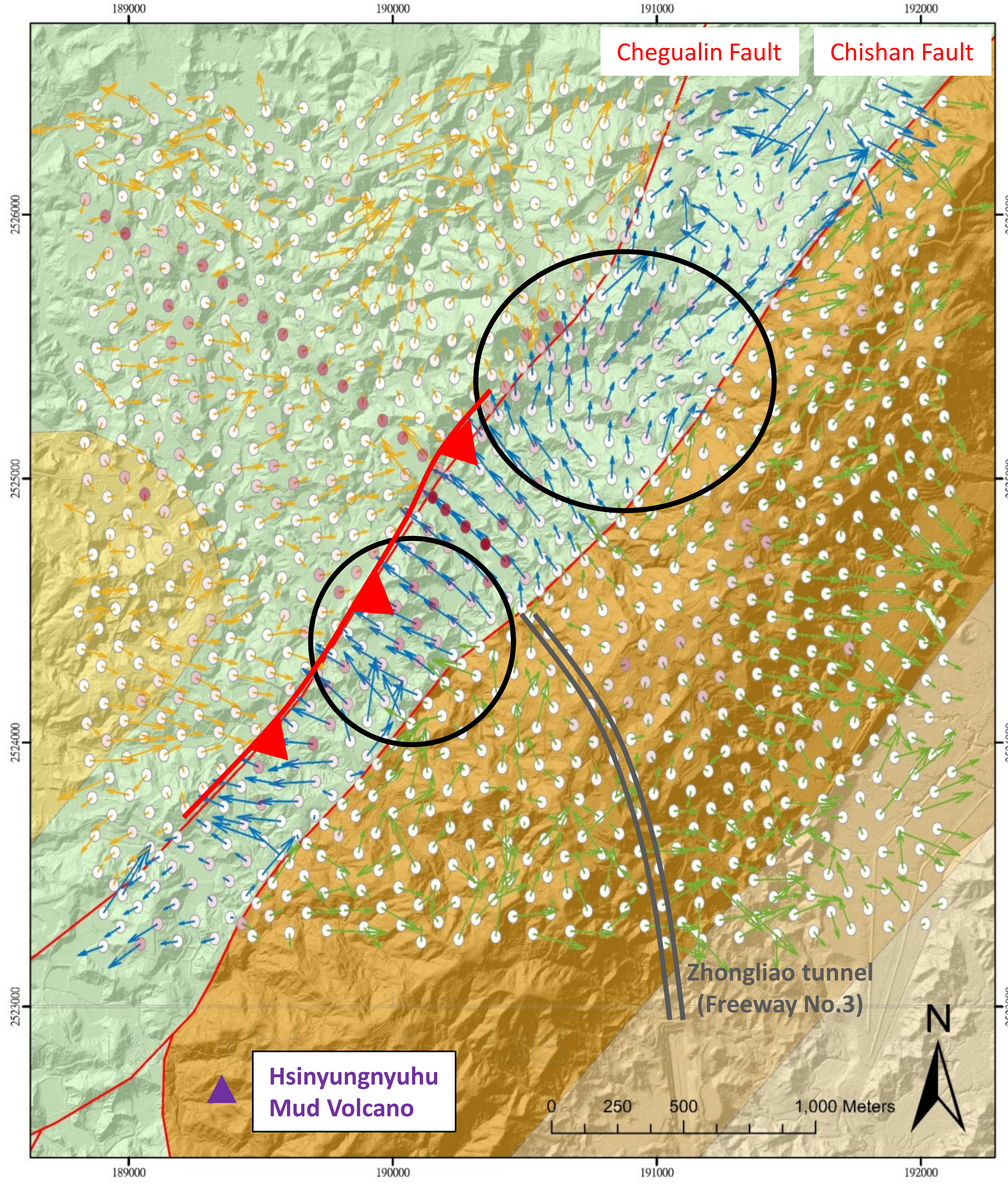
Fault-Perpendicular component





Marks the artifact due to repavement of the highway (non-tectonic related signal)

Offset = 35.2cm



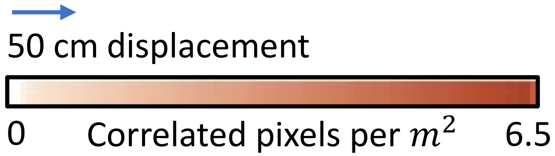
Horizontal displacement field of the Zhongliao tunnel area, according to aerial image correlation results.

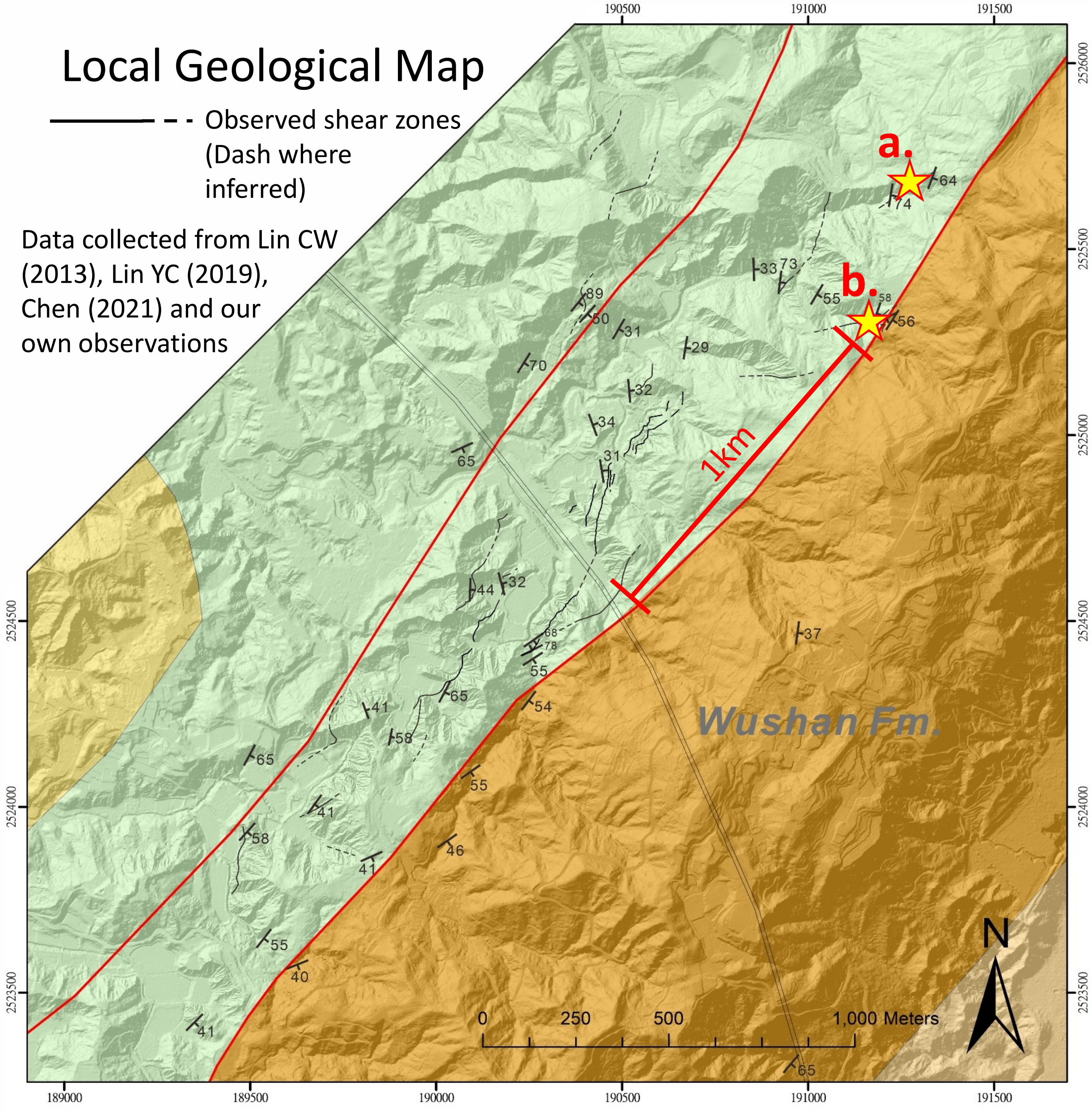
Validate our measurement with GNSS network:

- The Blue arrows (the middle block) are generally moving away from green arrows (SE block), but moving toward to yellow arrows (NW block).
- The **total displacement** across the **Chegualin fault** is about **35 cm over 7 years**, which is quite comparable with geodetic observation.
- **Image correlation results have good consistency with existing data!**

What else is happening?

- The **compression** of the Chegualin fault **can extrapolate about 2km along** the fault strike.
- Northeast of the freeway, there is a clear **clockwise rotation** pattern on the blue vectors.
- Southwest of the freeway, there is a **counter-clockwise rotation** pattern on the blue vectors.





Field geological survey: North of the tunnel

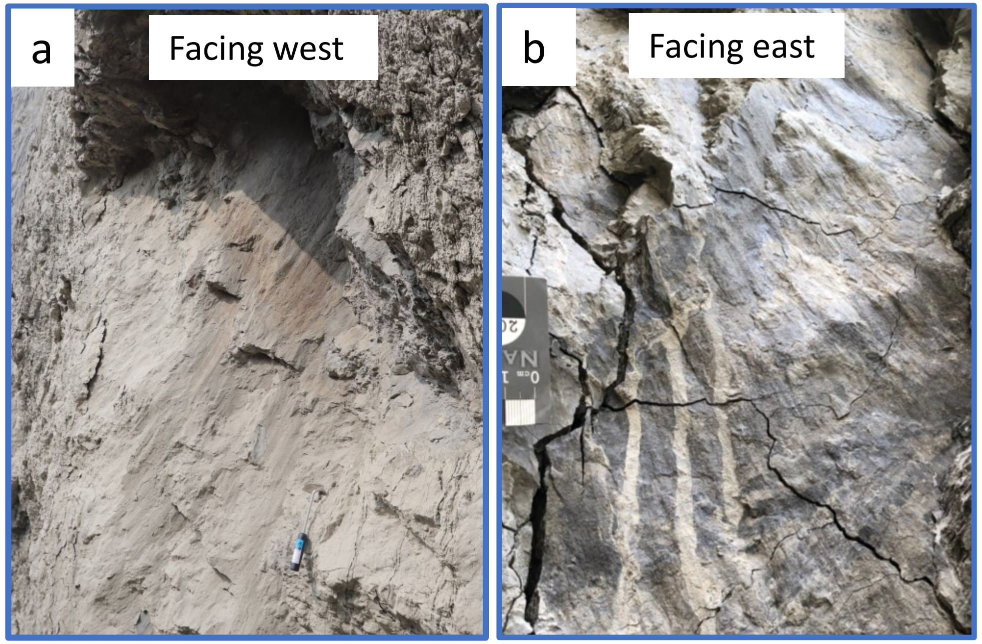
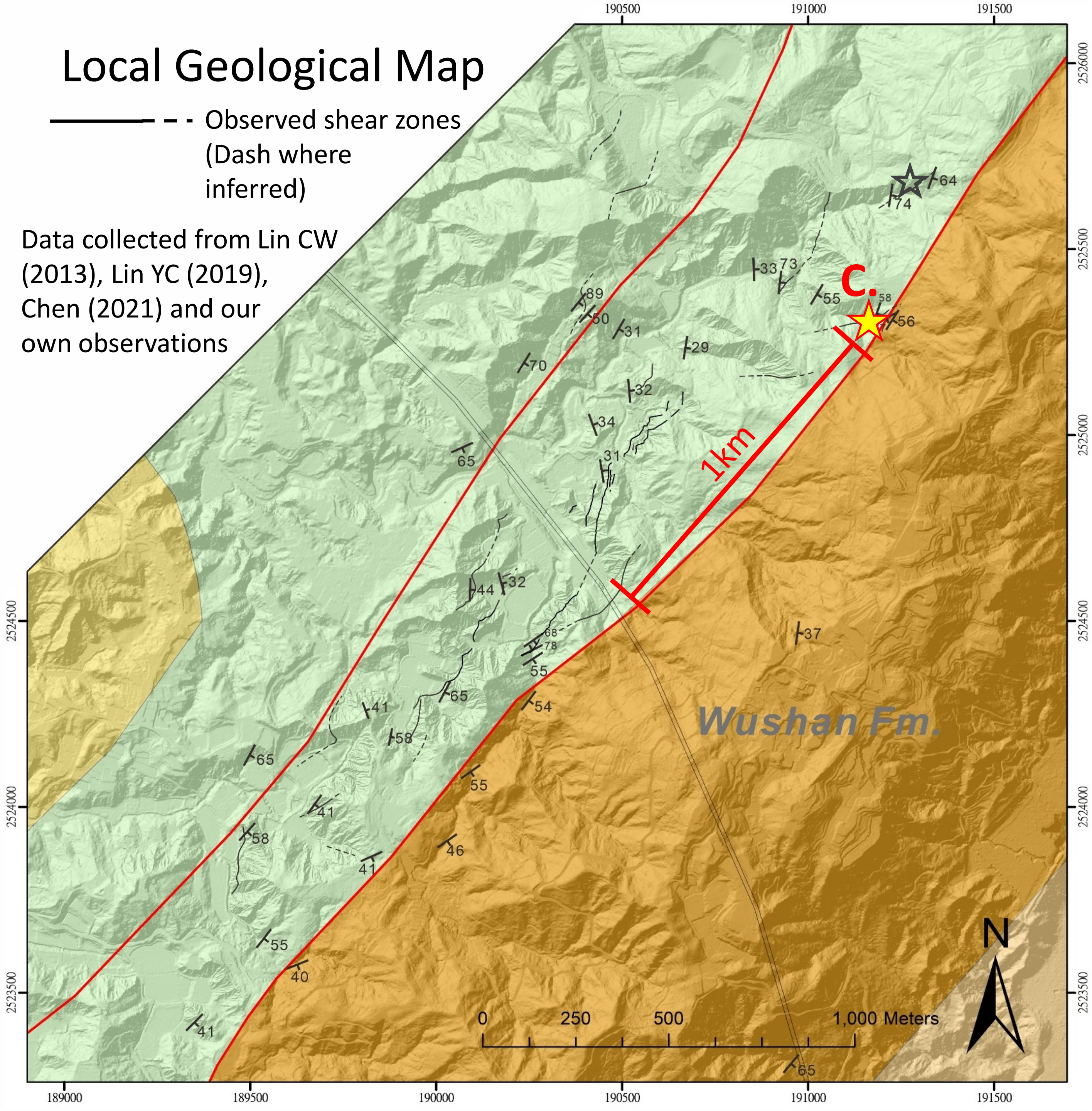


Fig. (a) and (b): SE-dipping shear planes with slickenlines, these slickenlines are results from normal faulting with right-lateral component.

Local Geological Map



Field geological survey: North of the tunnel

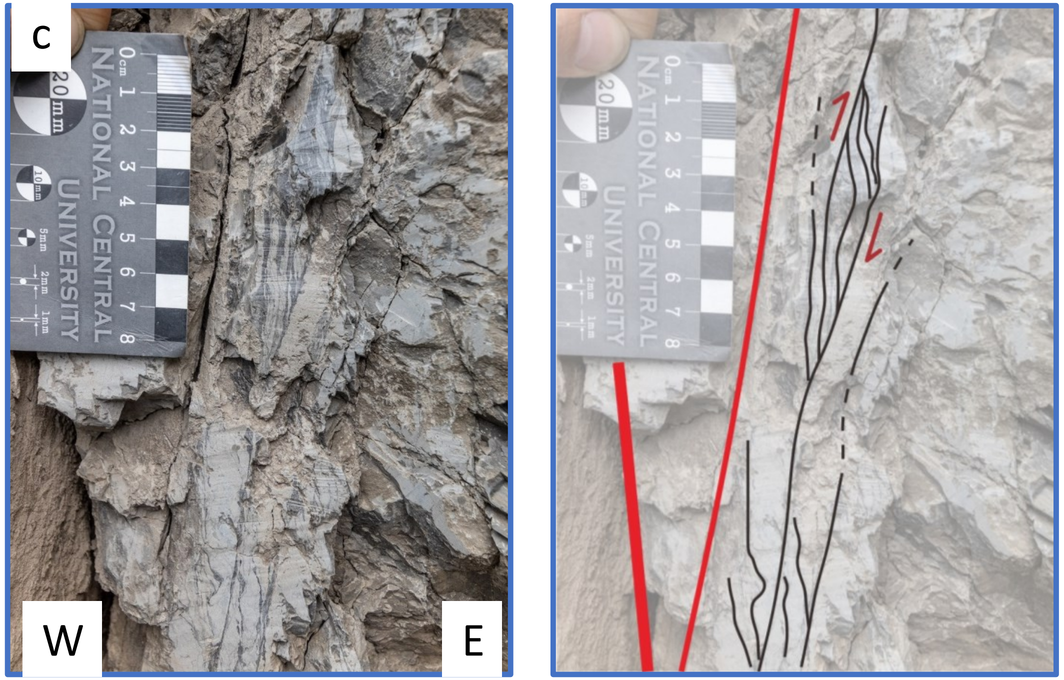
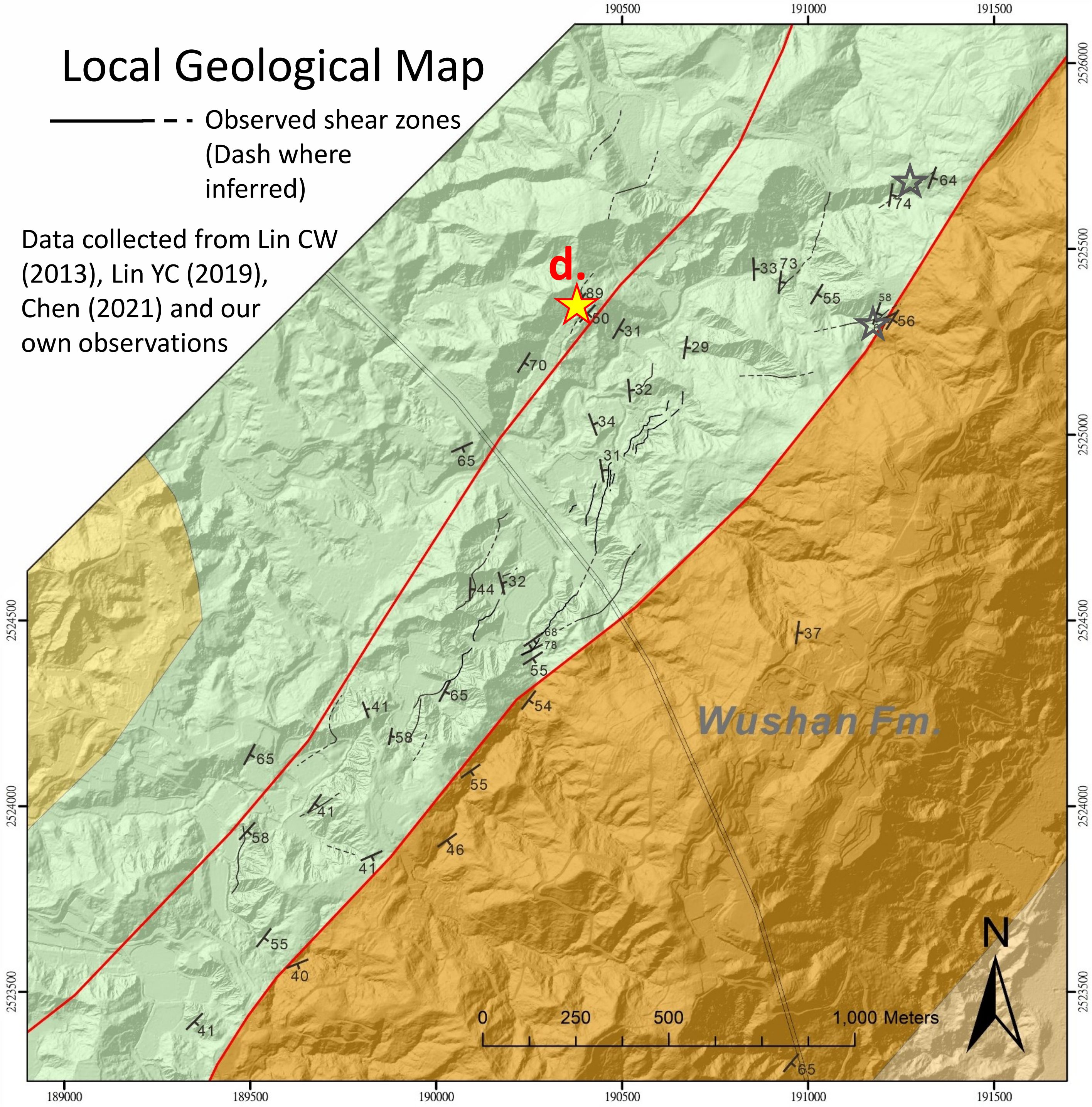


Fig. (c): Besides brittle fractures, theses black shear bands (results from ductile deformation) with clear C-S fabric also indicate normal faulting.

Local Geological Map

Observed shear zones (Dash where inferred)

Data collected from Lin CW (2013), Lin YC (2019), Chen (2021) and our own observations



Field geological survey: North of the tunnel

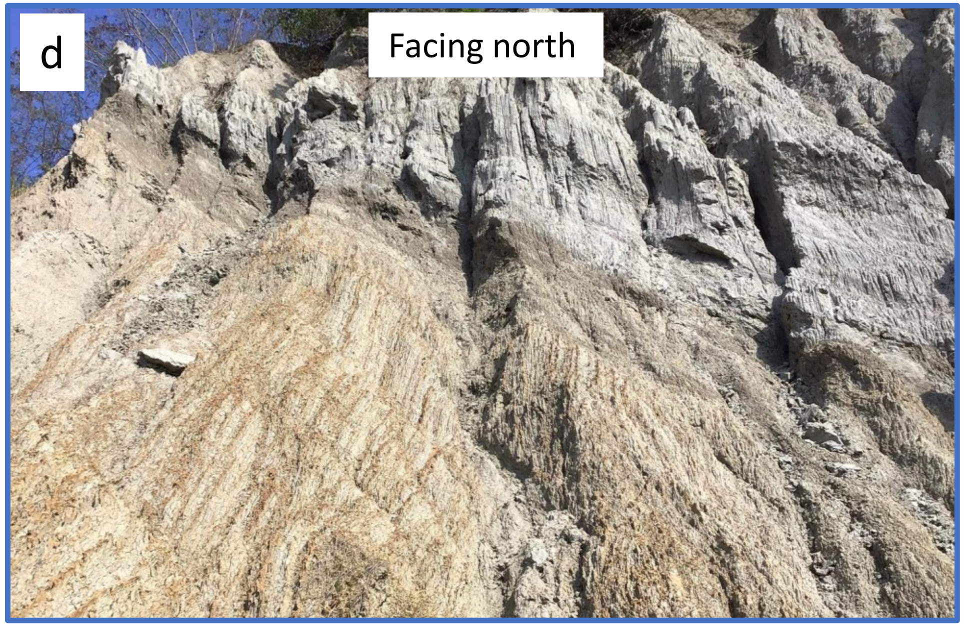
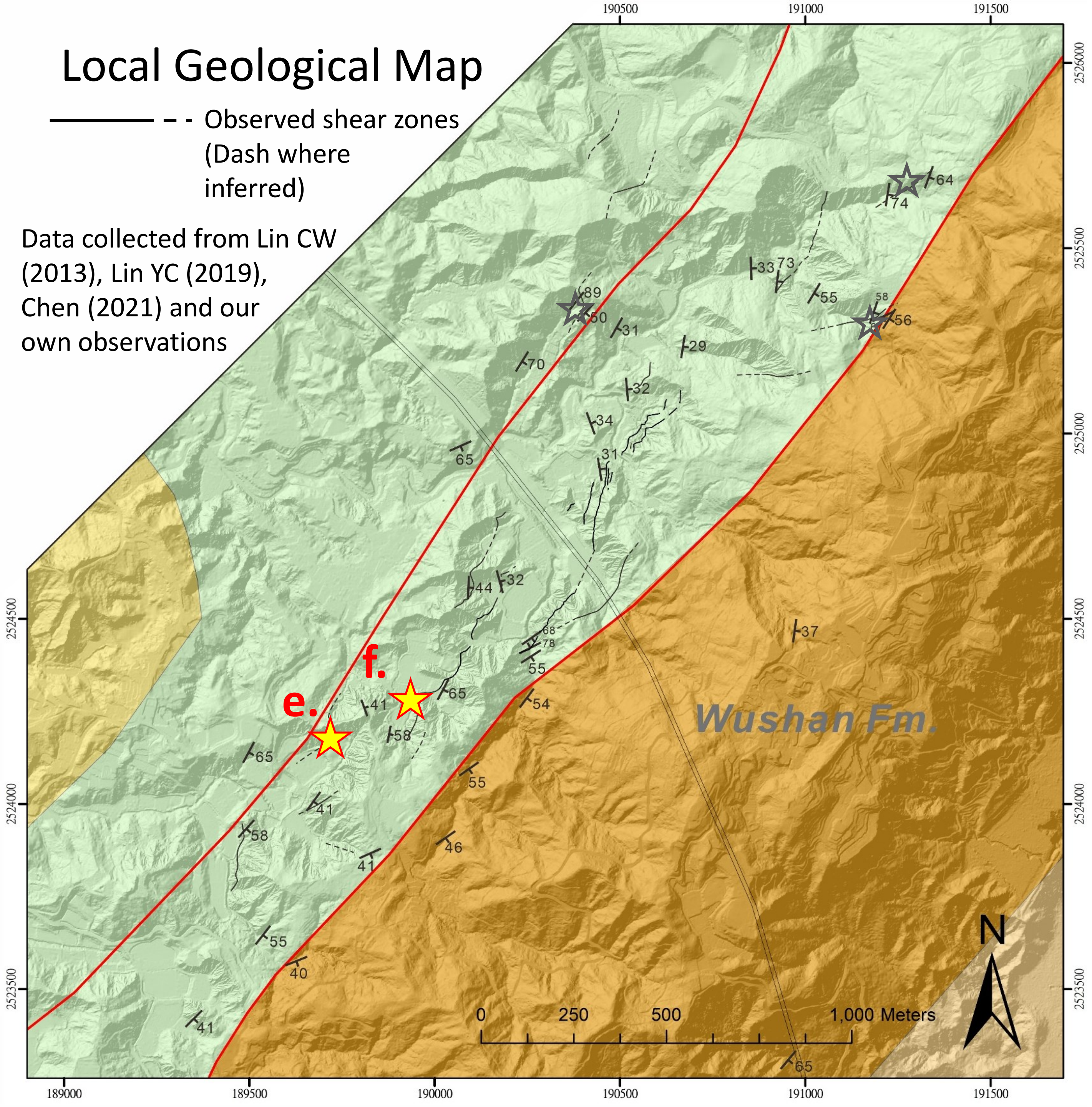
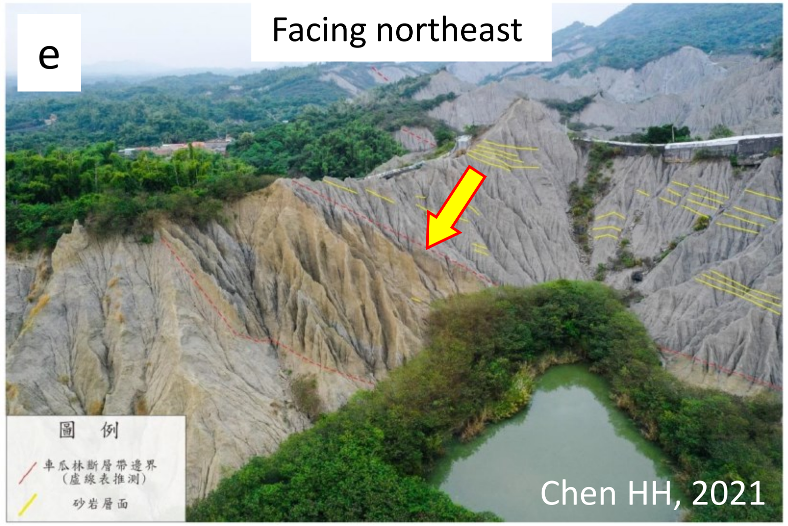


Fig. (d): Shear zone at the Chegualin fault. The slip sense is reverse fault.

Local Geological Map



Field geological survey: South of the tunnel



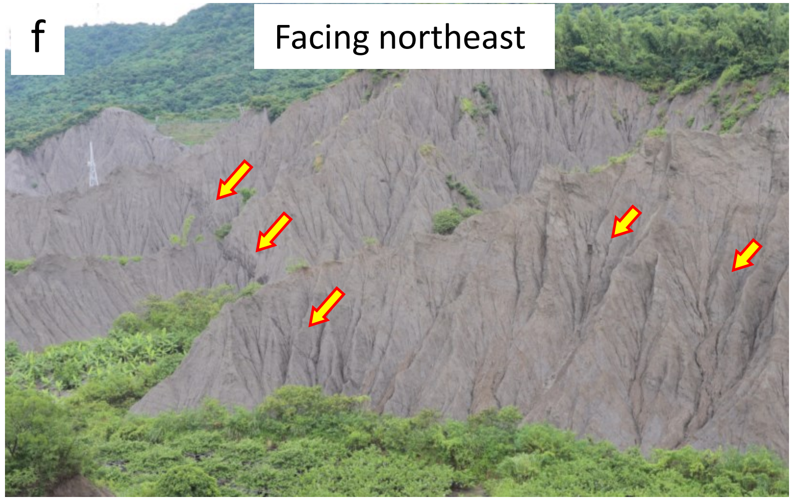
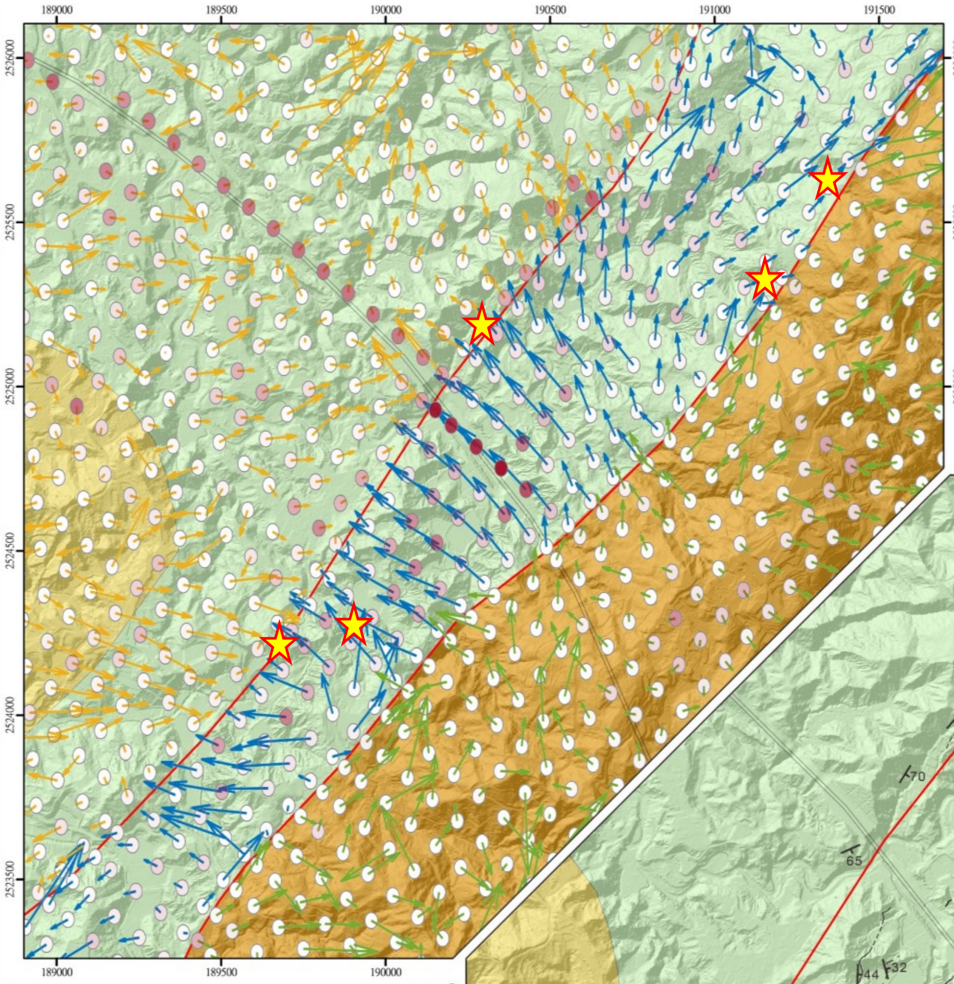


Fig. (e): Shear zones south of the Freeway. The slip sense is reverse fault.



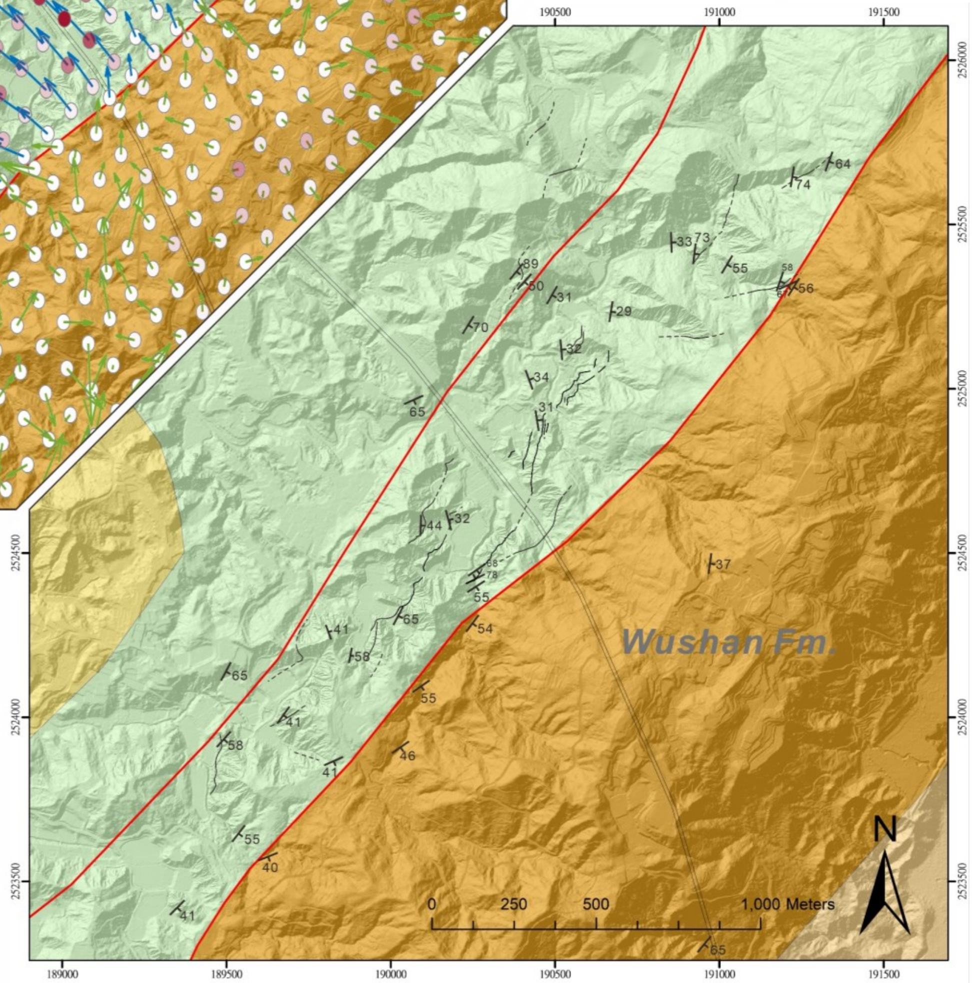
Displacement field

50 cm displacement

Correlated pixels per m^2

0 6.5

Chegualin Fault Chishan Fault



Local Geological Map

Observed shear zones (Dash where inferred)

Data collected from Lin CW (2013), Lin YC (2019), Chen (2021) and our own observations

Summary:

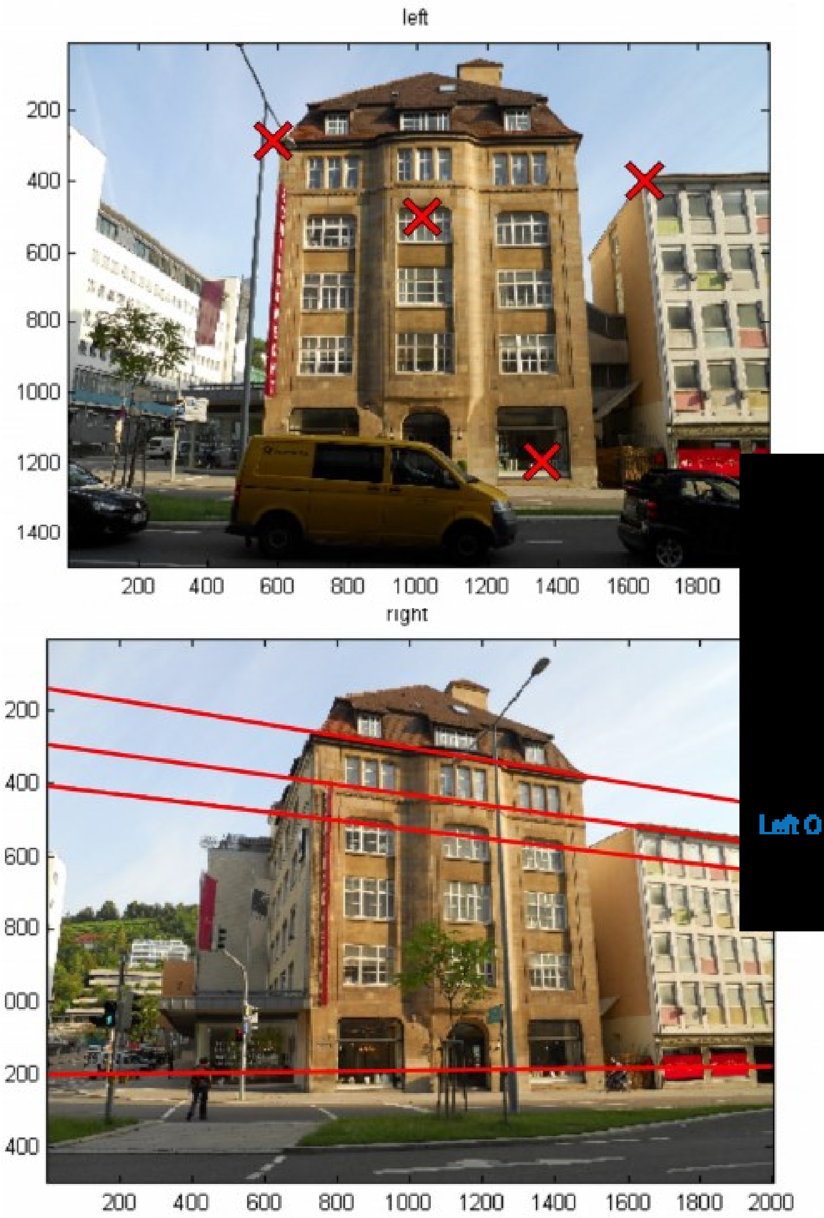
- Image correlation suggested the horizontal shortening across the Chegualin fault is about 5 cm/yr, the compression can extrapolate 2 km along the fault strike.
- It is very challenging to quantify the displacement across the Chishan fault, due to high density of vegetation.

Questions to solve:

- What is the connection between geological structures and ground deformation?
- What is the mechanism leading to the observed deformation and the regional tectonics?

Thank you :)

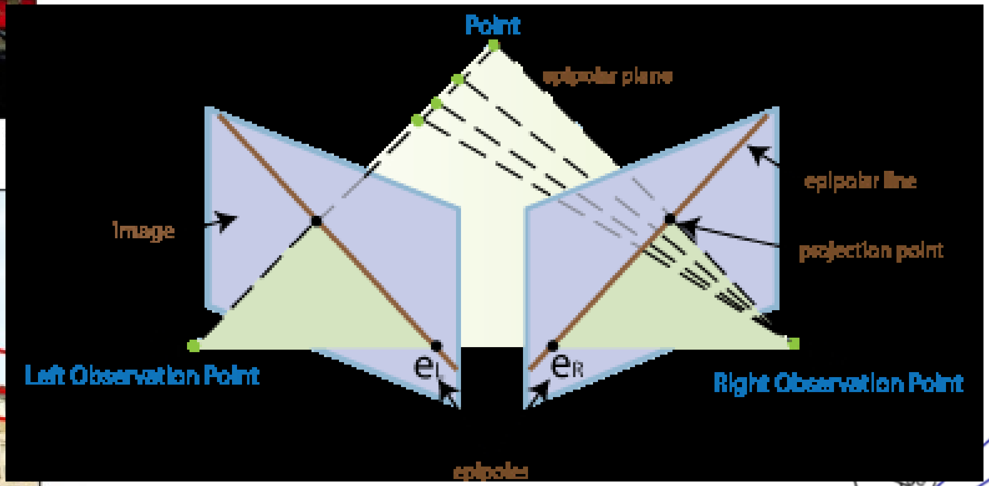
Structure from Motion (SfM)



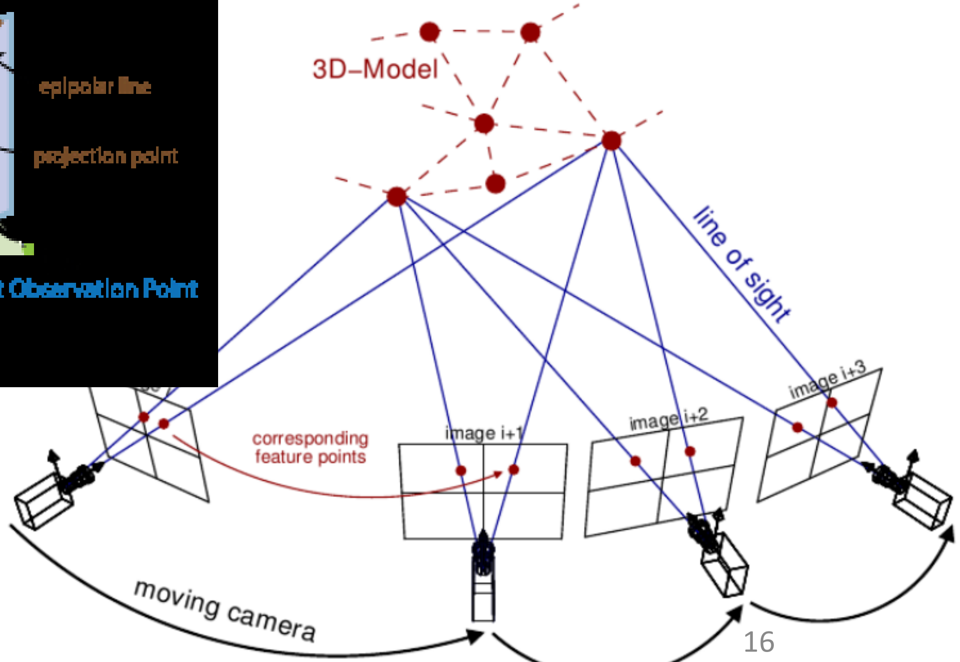
Structure from motion (SfM): the process to estimate the 3-D structure from a set of 2-D images

Structures: Topography, buildings, any 3D objects

Software for SfM processing : Pix4D, MetaShape, MicMac, etc.



https://www.mathworks.com/help/vision/ug/structure-from-motion.html



http://www.theia-sfm.org/sfm.html

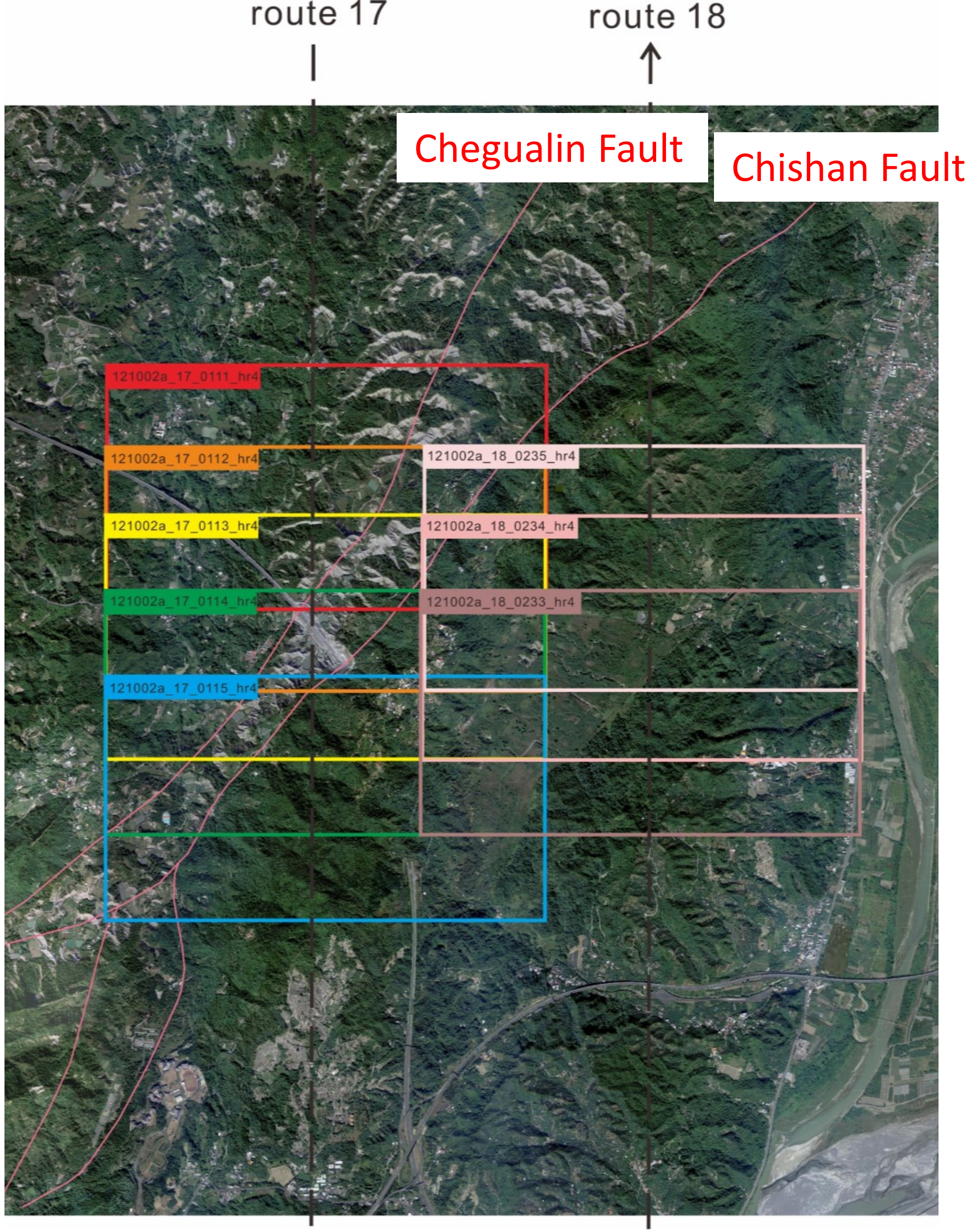


Image acquisition

Aerial images are acquired from Aerial Survey and Remote Sensing Branch, Forestry and Nature Conservation Agency.

We acquired 8 images for 8 epochs, from 2008-09-07 to 2015-09-23: total of 64 images.

The image correlation is processed mainly on 2008-2015, other intermediate epochs will be assistive to the processing.

Image geometry and bundle adjustment

The position and orientation of the sensor (Ex. The camera of UAV)

The physical parameters are divided into two categories:

● The **internal parameters**

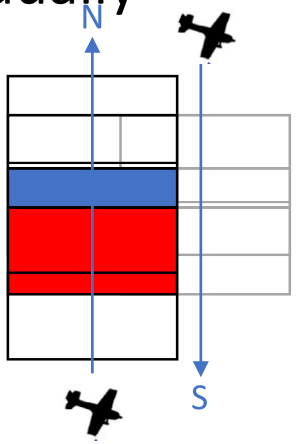
- Camera : focal length, principal point, size of the sensor, distortions of the lens
- Satellite : geometry of the focal plane (line of sight of the detector for each pixel)

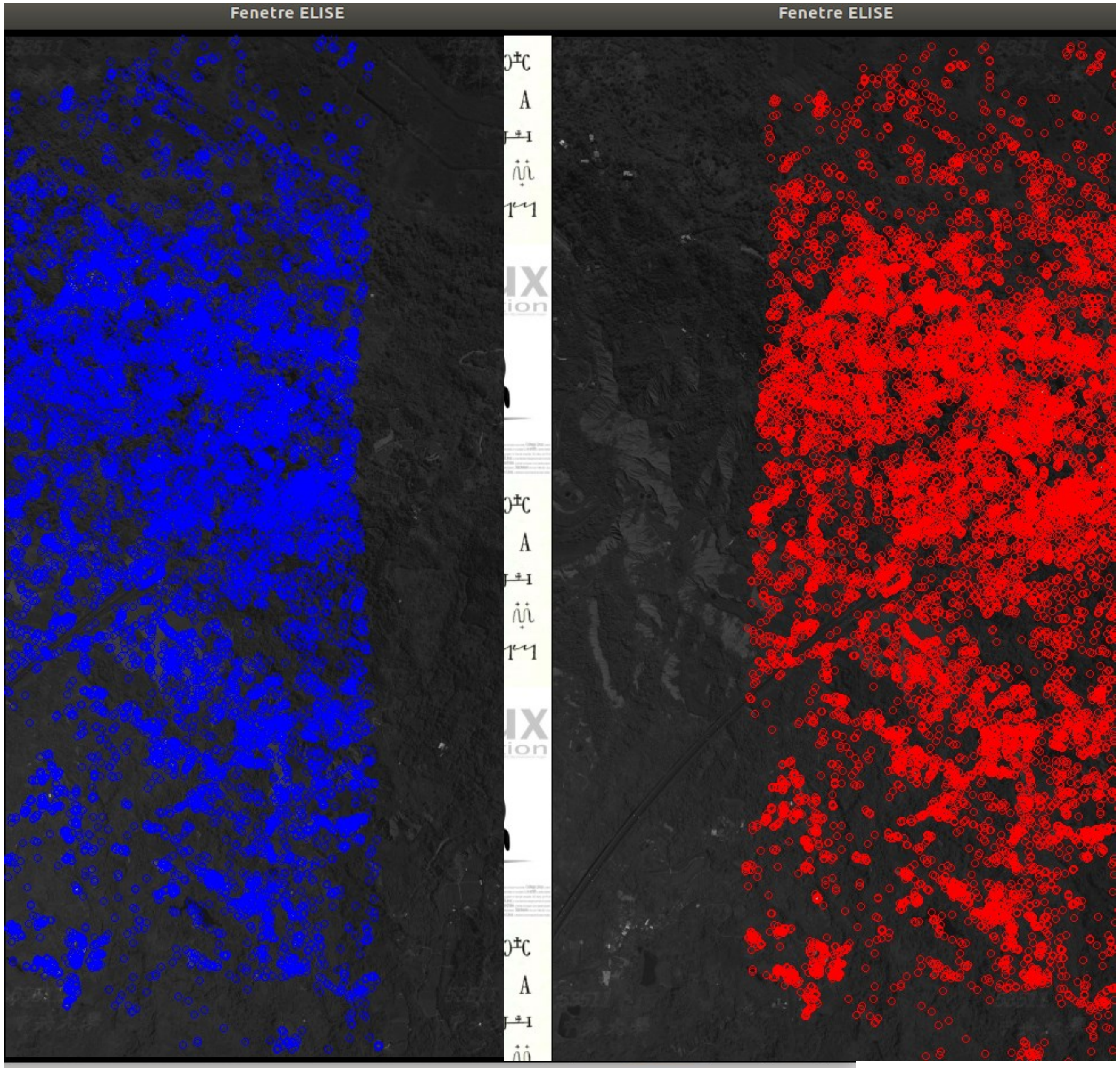
● The **external parameters**

- Camera : position (X, Y, Z) and attitude (R, T, L)
- Satellite : time of acquisition, position (X, Y, Z), attitude (R, T, L) and their derivatives ($\partial X/\partial t$, $\partial Y/\partial t$, …)

Processing steps

- Tapioca for both epochs individually --- result-A
- Tapioca for inter-epoch tie points
- Mask the inter-epoch tie points that are inside of the deformation zone --- result-B
- Tapas with the merged result of A and B
- Malt both epoch individually
- MM2DPosSism





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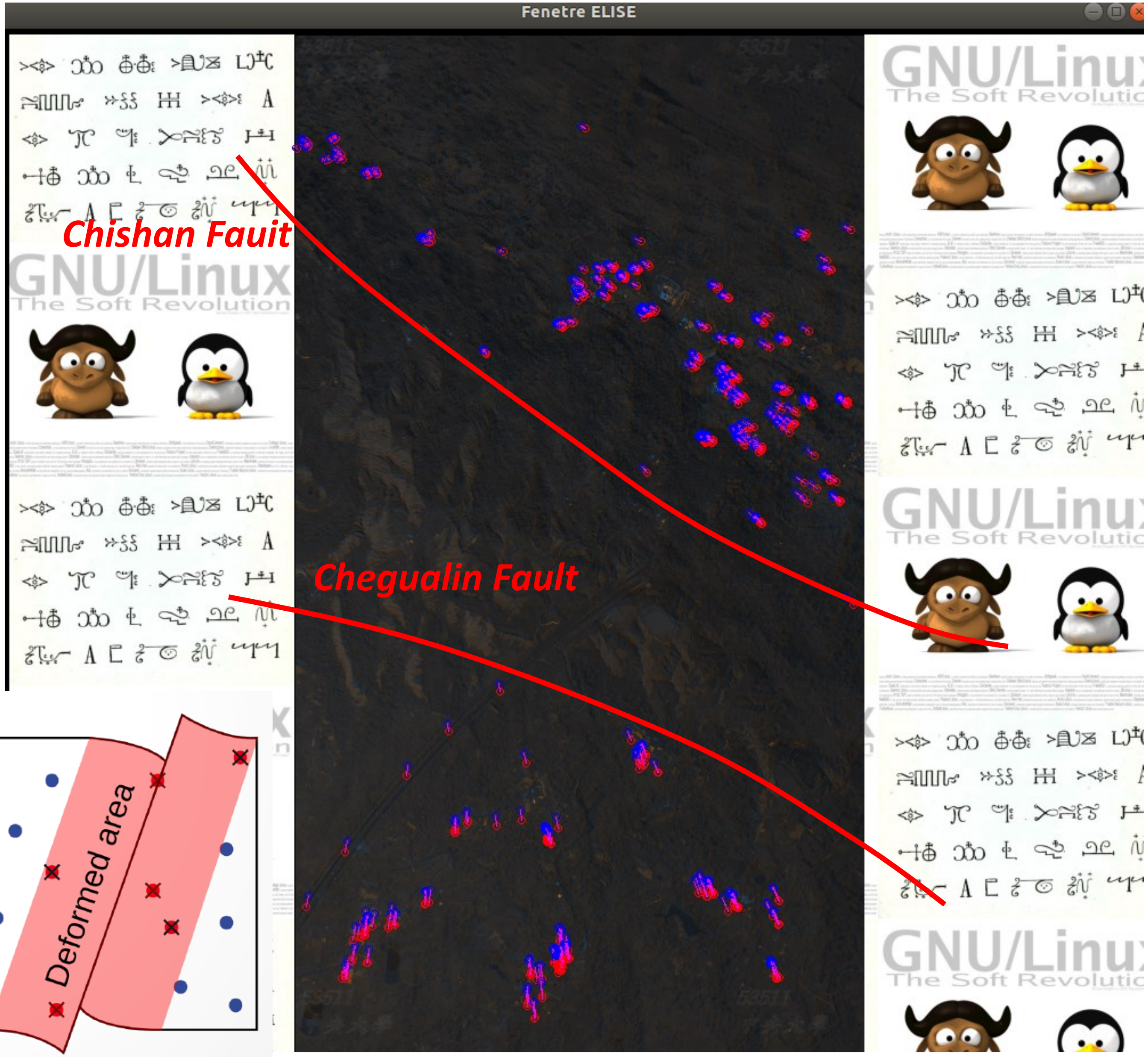


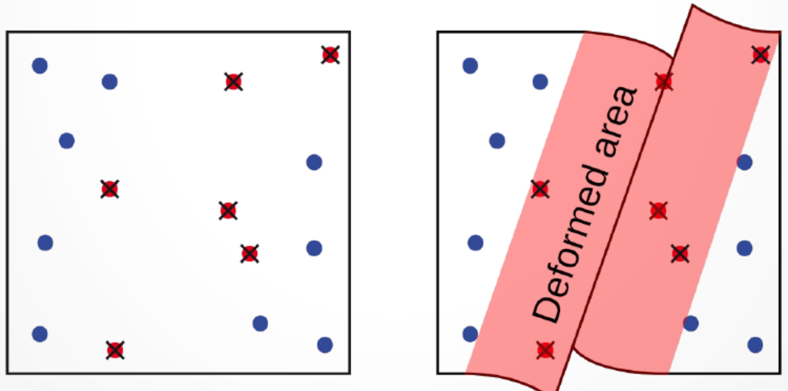
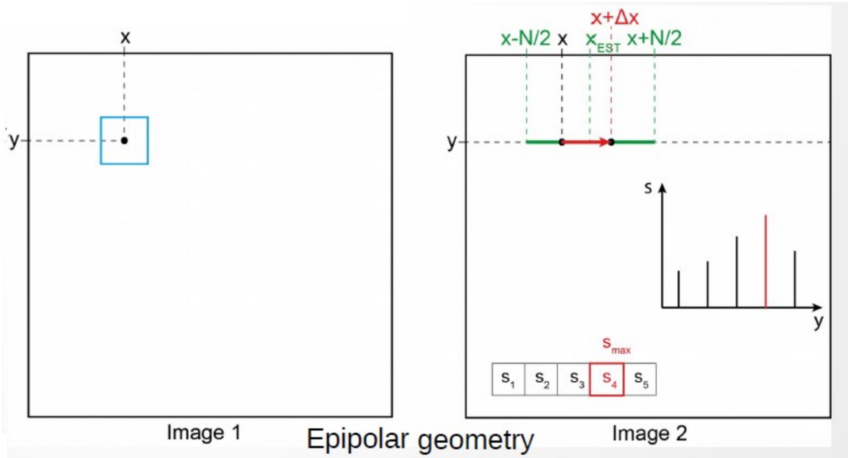
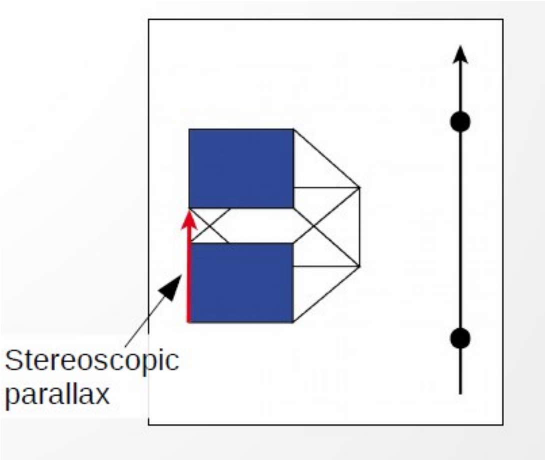


Image before the EQ   Image after the EQ

For each pixel in image 1, we want to estimate the position of the homologous pixel in image 2, to measure the parallax.
Consider the images resampled in **epipolar geometry**. Consider a pixel (x, y) in image 1. In image 2, we define a search space of size N on the epipolar line, centered on the estimated position of the homologous pixel, to save computation time and reduce the risks of confusion.

We define a window of size n*n, centered on the pixel in image 1 and a “sliding“ window of the same size in image 2, which is moved step by step (step = p) inside the search space. For each position, we estimate the **similarity** between the two windows. The similarity criteria can be radiometrical, statistical or mathematical. We can use for instance the **normalized cross-correlation coefficient**.
We obtain a **similarity score** for each position of the window in the search space.



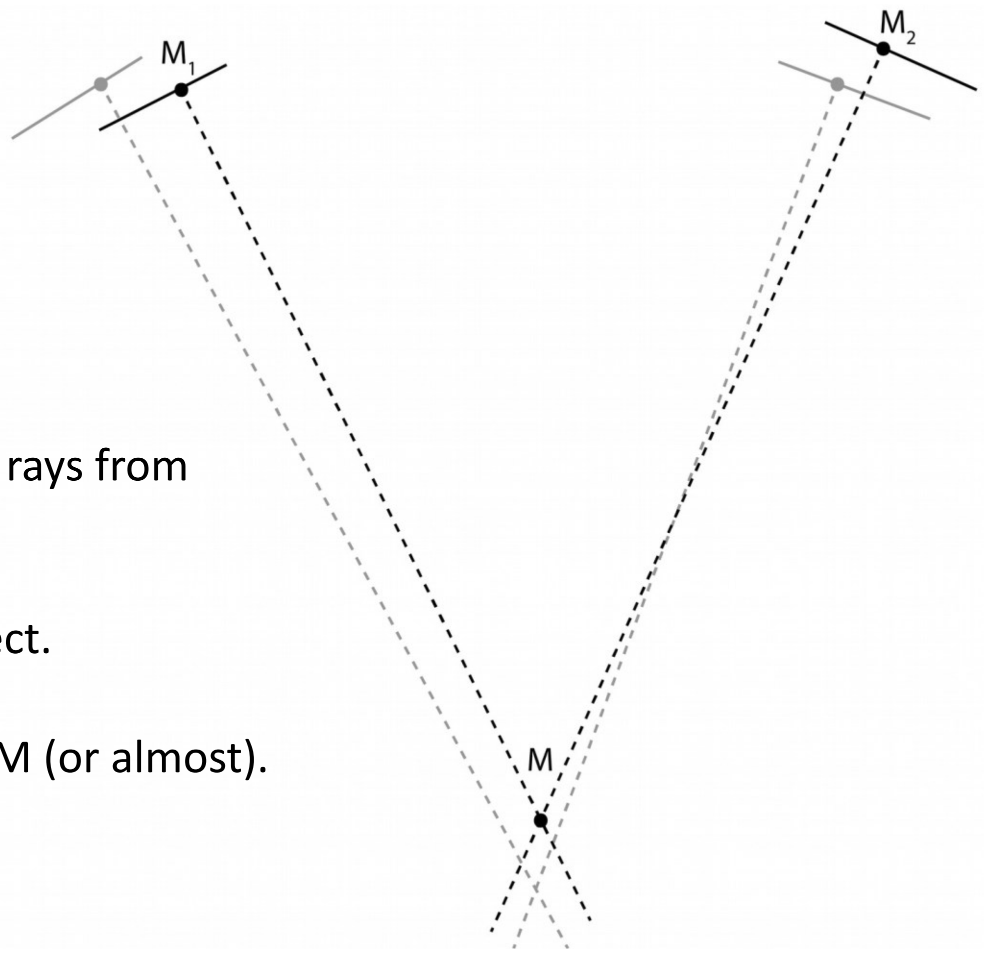


We measure Δx, the parallax at (x, y).
If p < 1 px, the measurement resolution is **sub-pixel**. The detection threshold can reach ~0.05 px in the most favorable cases.

Processing Pipeline:

1. Tapioca for the **intra-epoch** tie points (2008-2015)
2. SuperGlue for **inter-epoch** tie points (2008-2015)
3. Merge all the tie points and perform **bundle adjustment** (Tapas)
4. Select **manual tie points** on designated epochs for Campari (2008 and 2015)
5. Malt with the Image geometry given by Campari
6. Use the orthoimage for **pixal correlation** (MM2DPosSism)

Image geometry and bundle adjustment



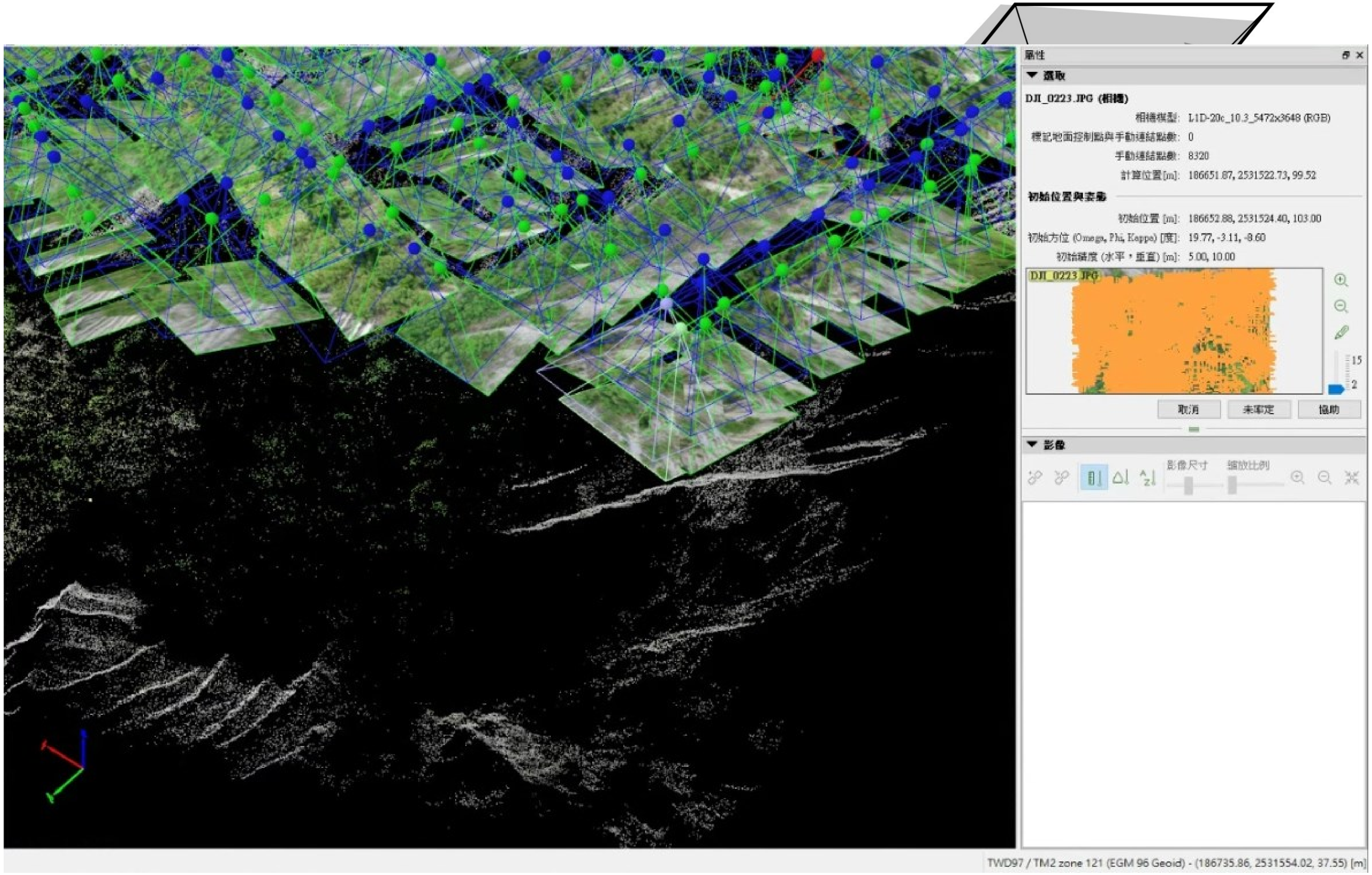
If the geometry were perfectly known, the rays from M1 and M2 should intersect in 3D in M.

Before the refining: the rays do not intersect.

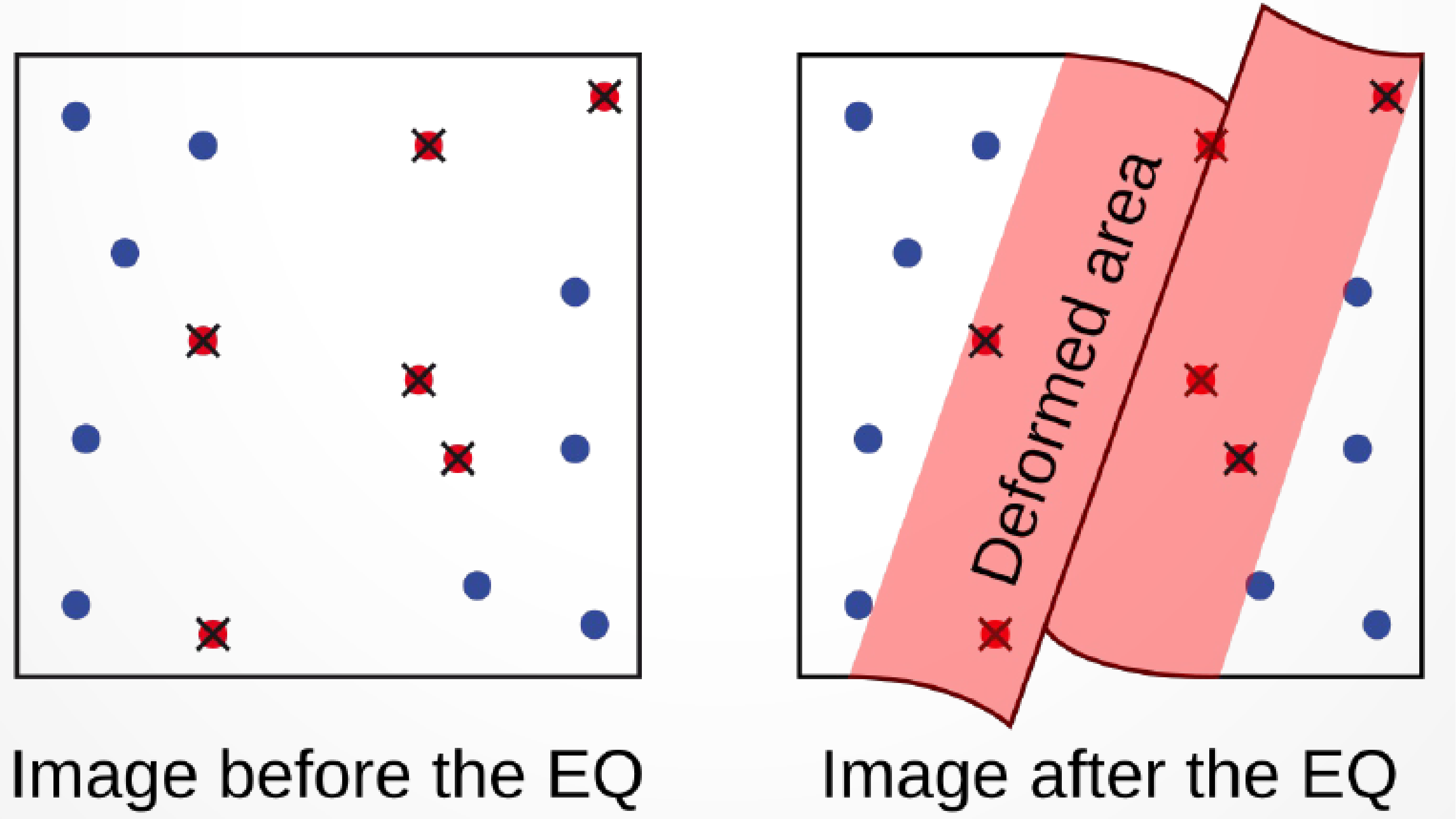
After the refining: the rays do intersect in M (or almost).

The method that consists in refining simultaneously the models of geometry of two or more images is called **bundle block adjustment**.

Image geometry and bundle adjustment



As for 3D restitution, a **bundle block adjustment** is performed to refine the models of geometry.
However, we must be careful not to include the deformation caused by the studied event in this refining. The tie points must therefore be selected **outside** the deformed area.



In the case of the **deformation measurement**, from one ortho-image to the other, the pixel may have moved as well according to the columns as according to the lines.
The search for the homologous pixel must therefore be carried out in these **two dimensions**.