Deciphering long-term fault slip vectors from fold scarps on alluvial terraces:

Relationships between long-term and coseismic slip on the Chelungpu fault, central western Taiwan

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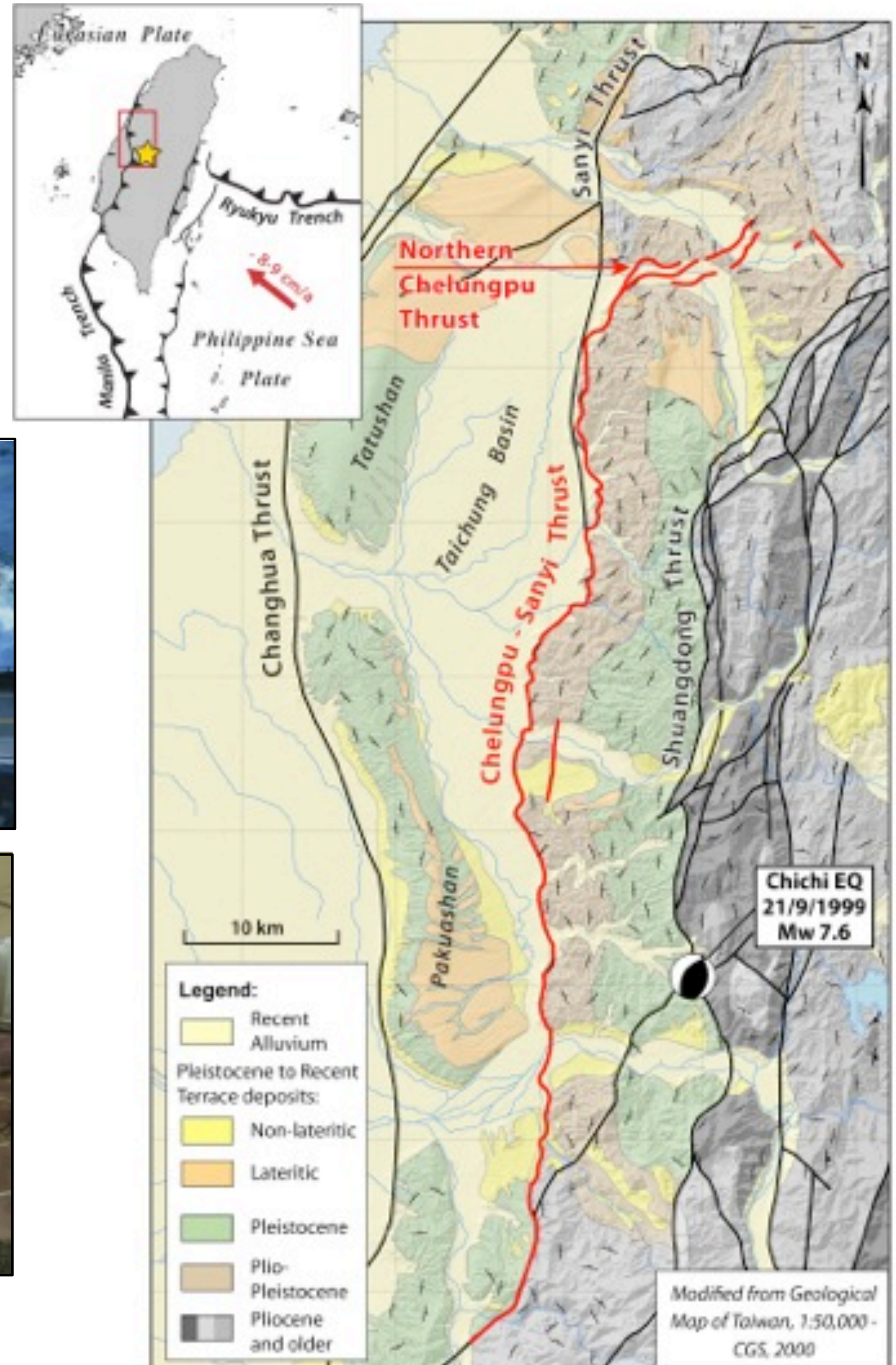
NCU seminar
January 10th 2014

Tectonic setting

Chi-Chi earthquake rupture:

921 earthquake museum, Taichung



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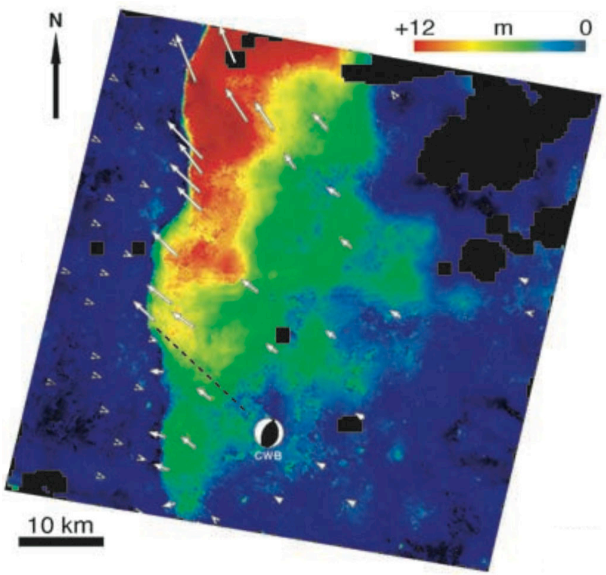
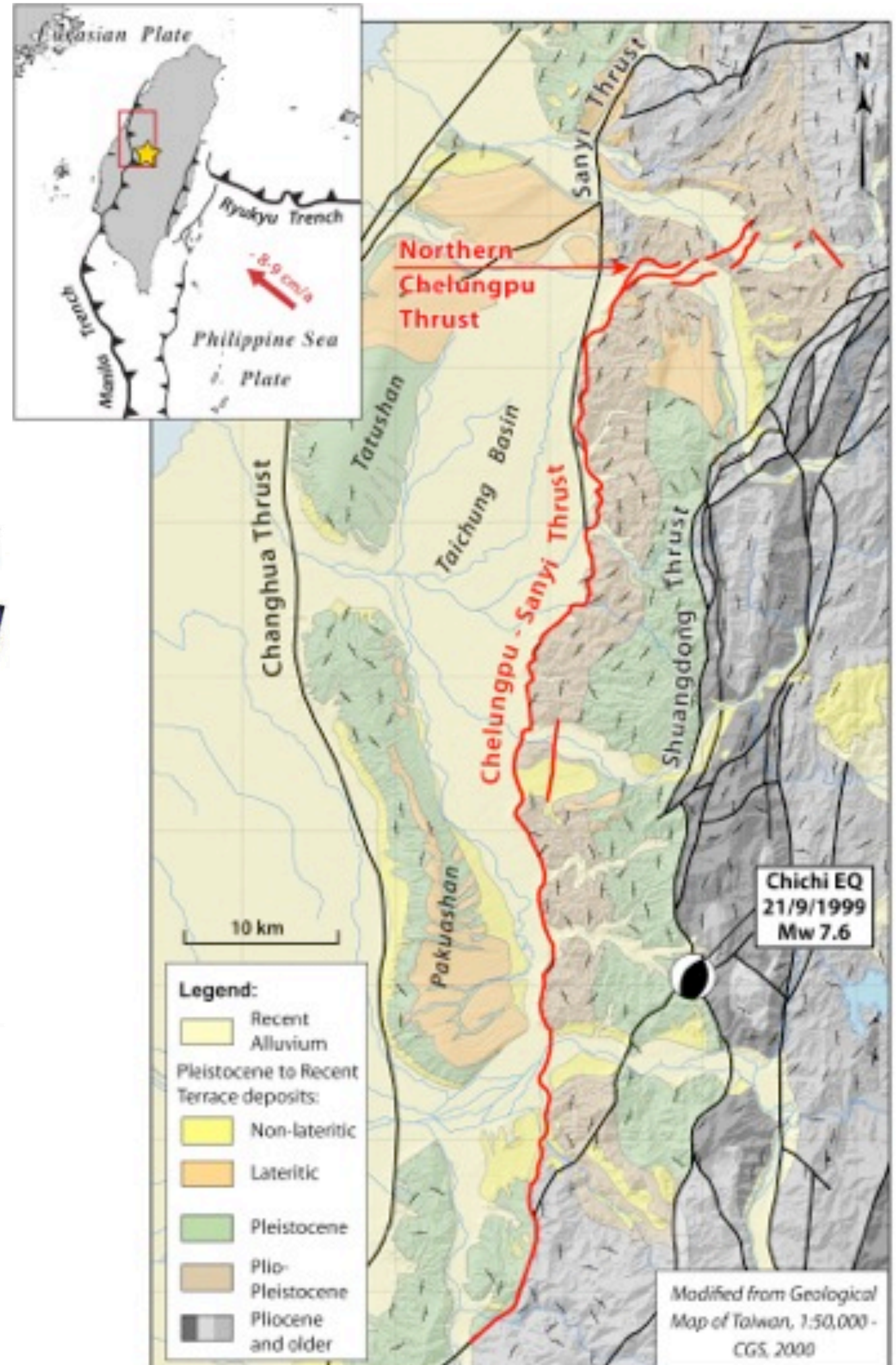


Horizontal coseismic displacements

(Dominguez et al, 2003)



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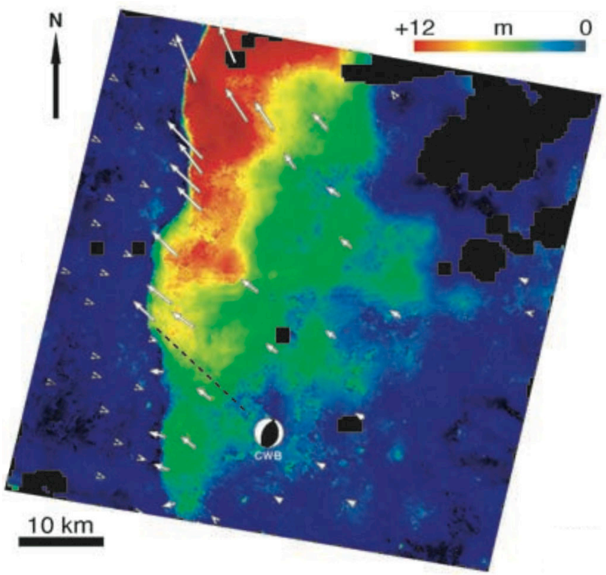

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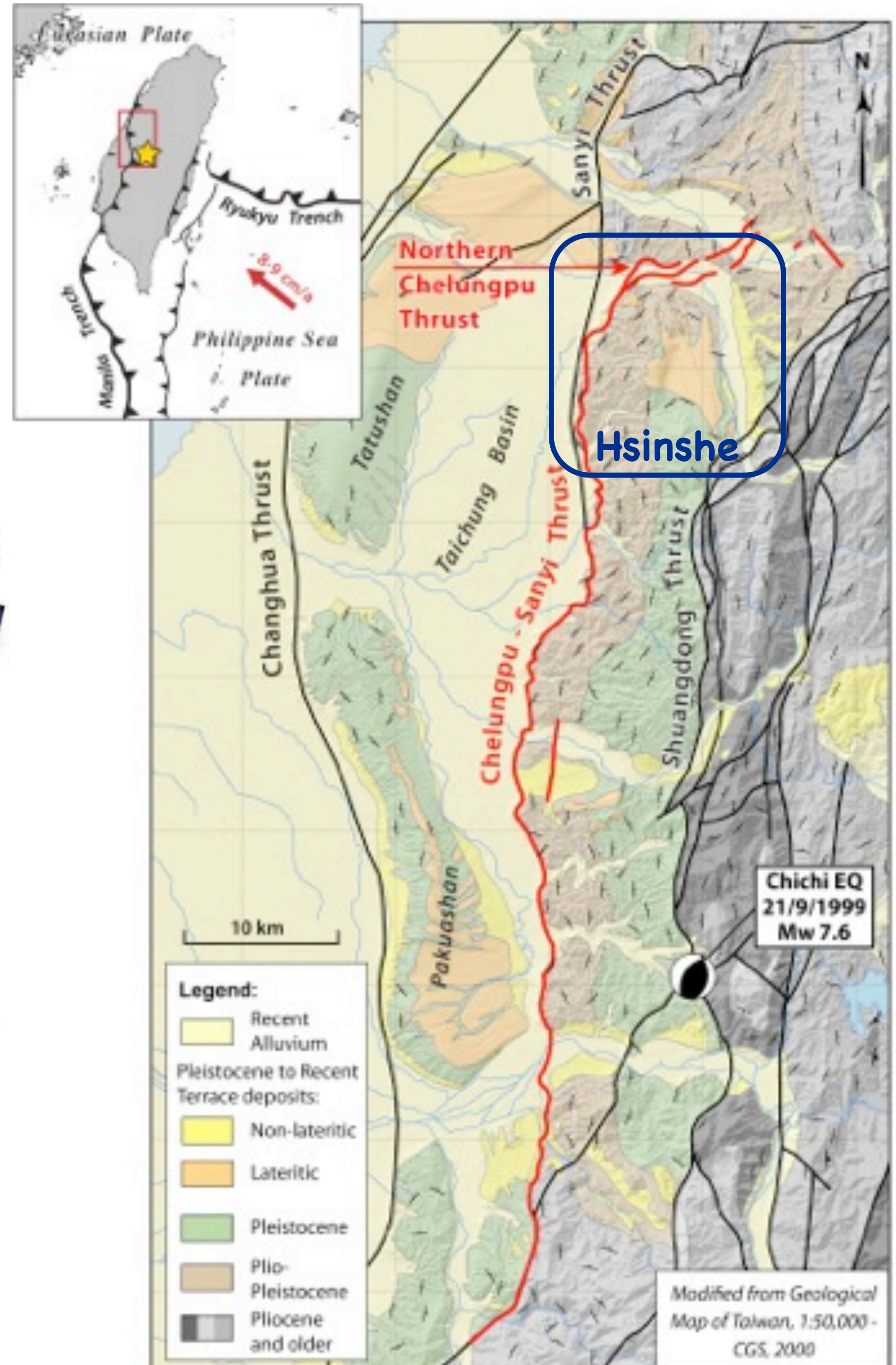
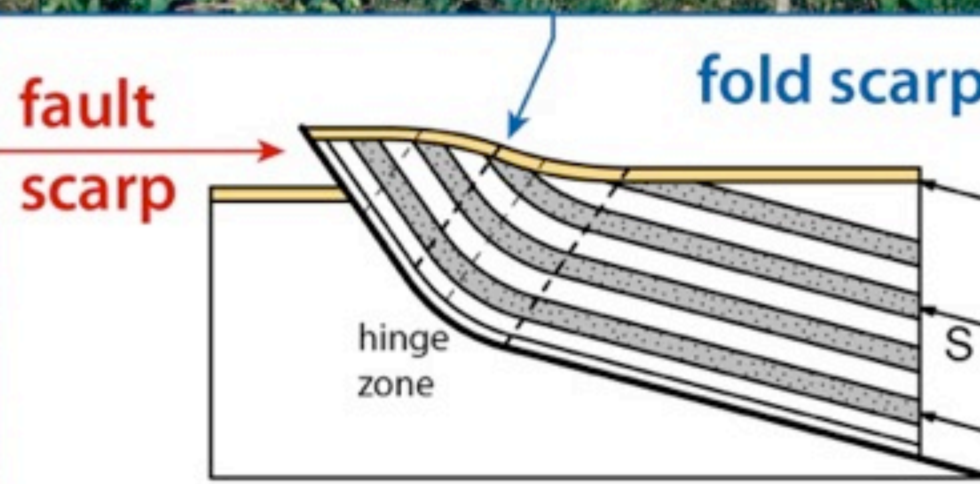


Coseismic fold growth during Chi-Chi earthquake



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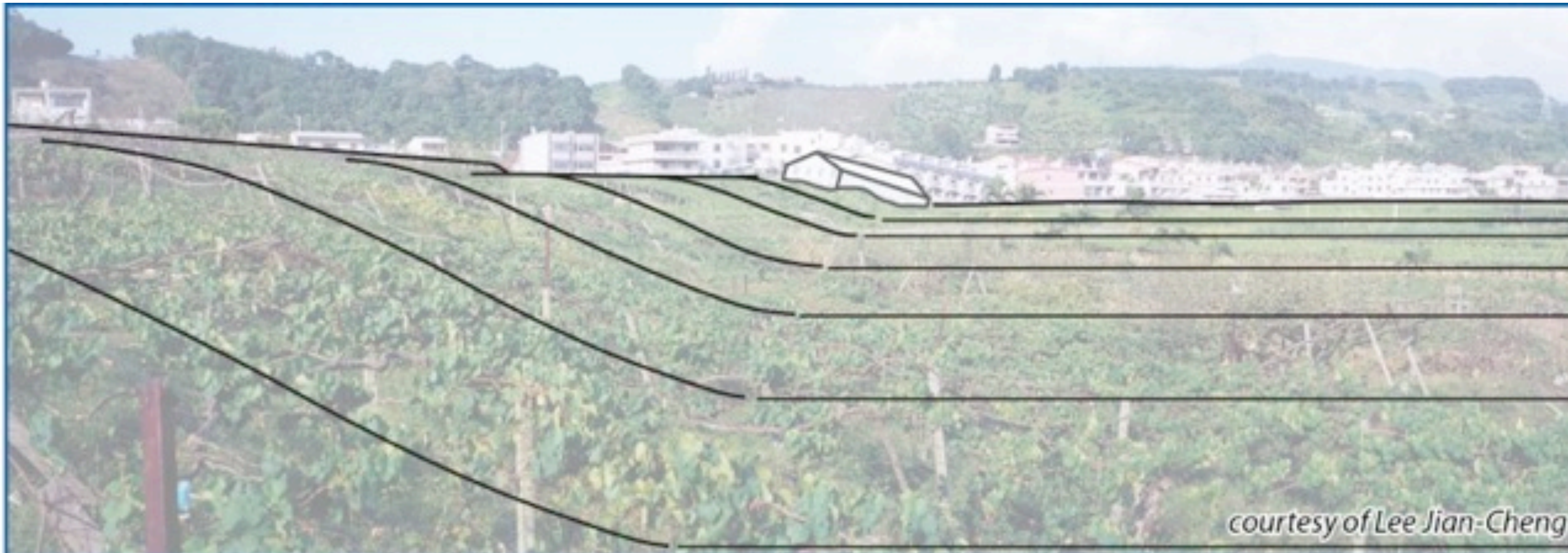
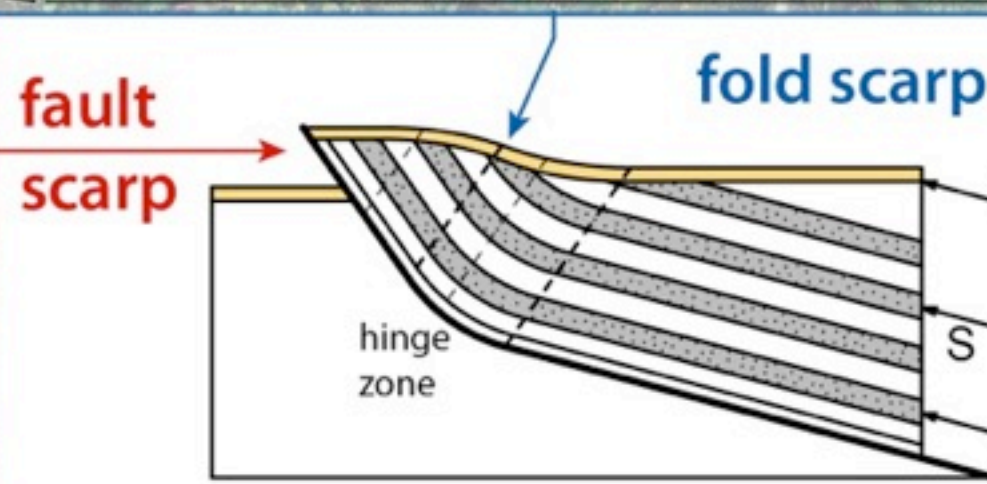
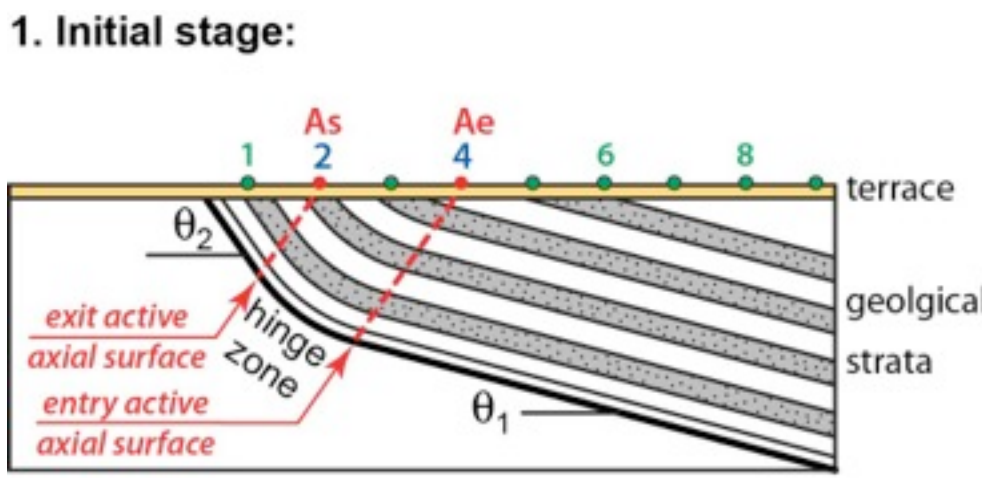




Fault-bend folding over earthquake cycles

Assumptions : Fault-parallel displacement with conservation of bed length

=> Coseismic uplift: $u_i = S \cdot \sin \theta_i$



Modified from
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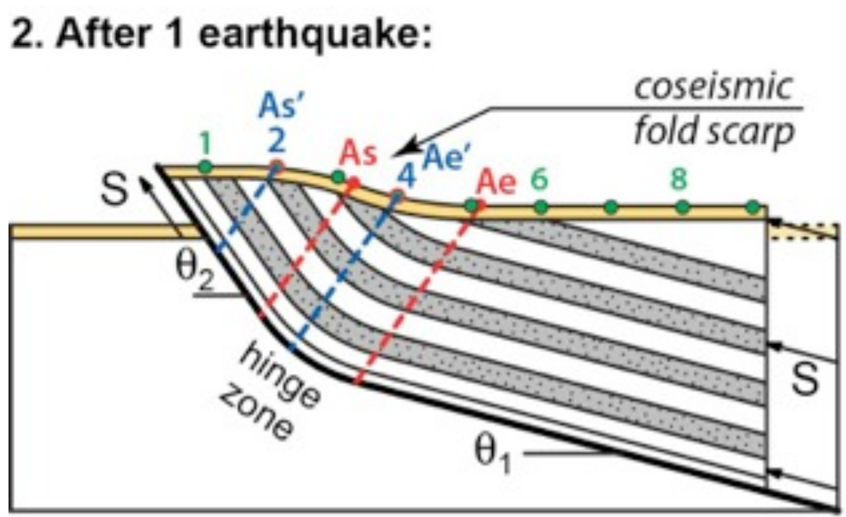

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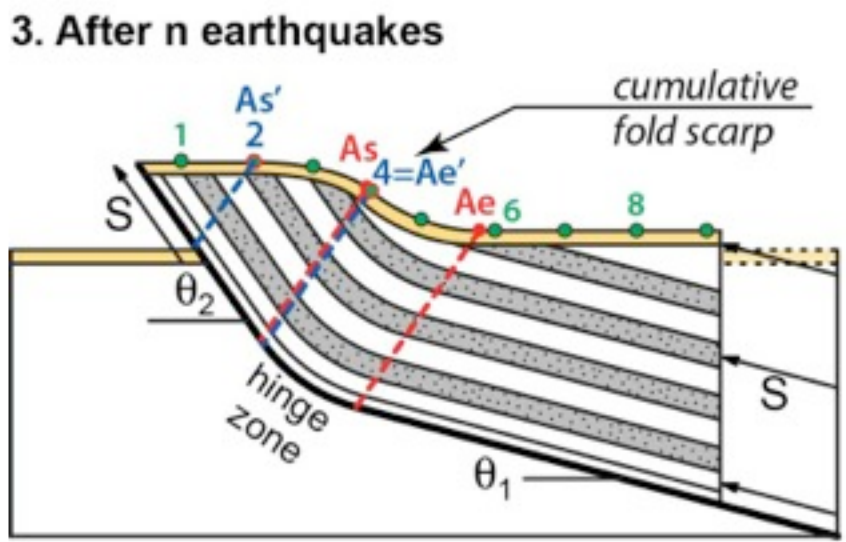

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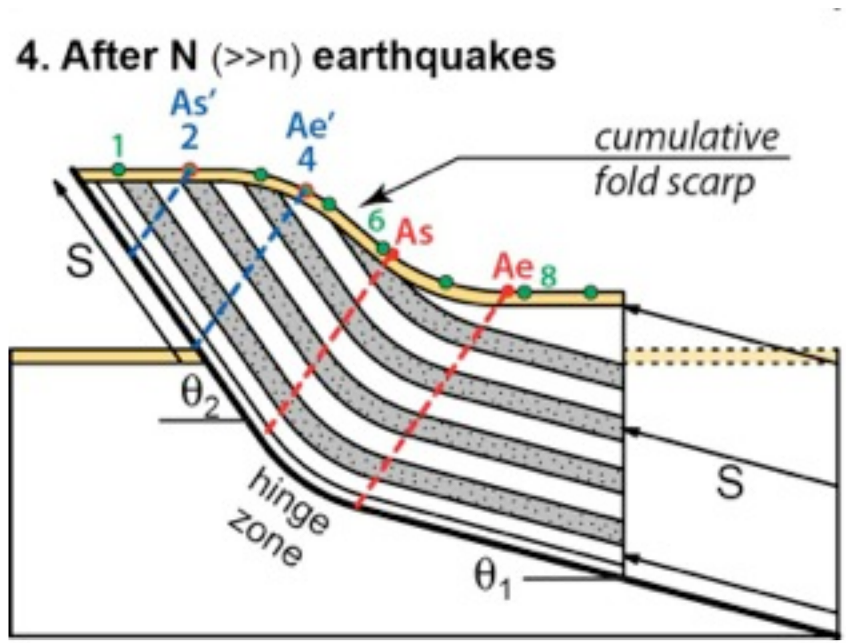

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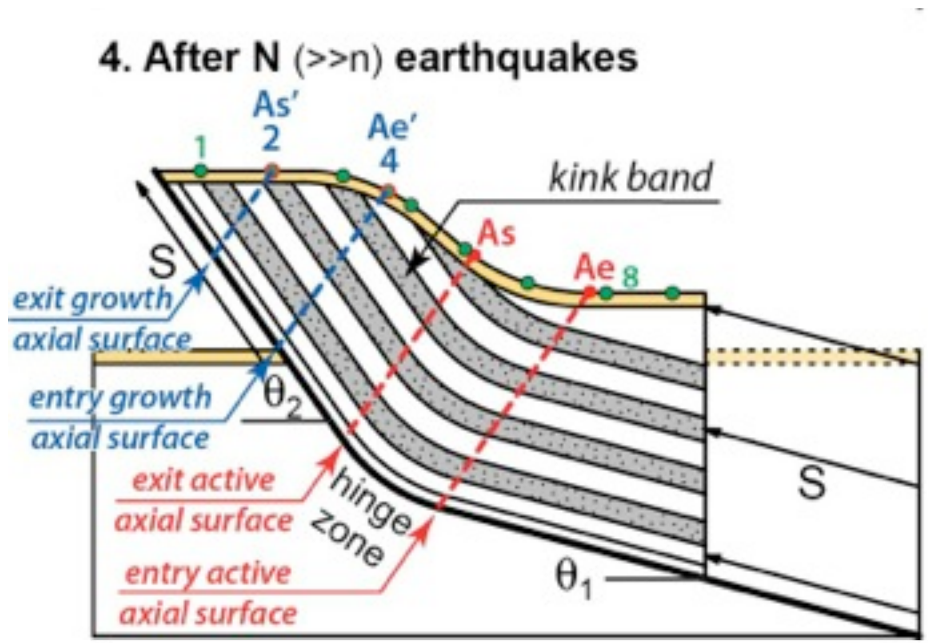

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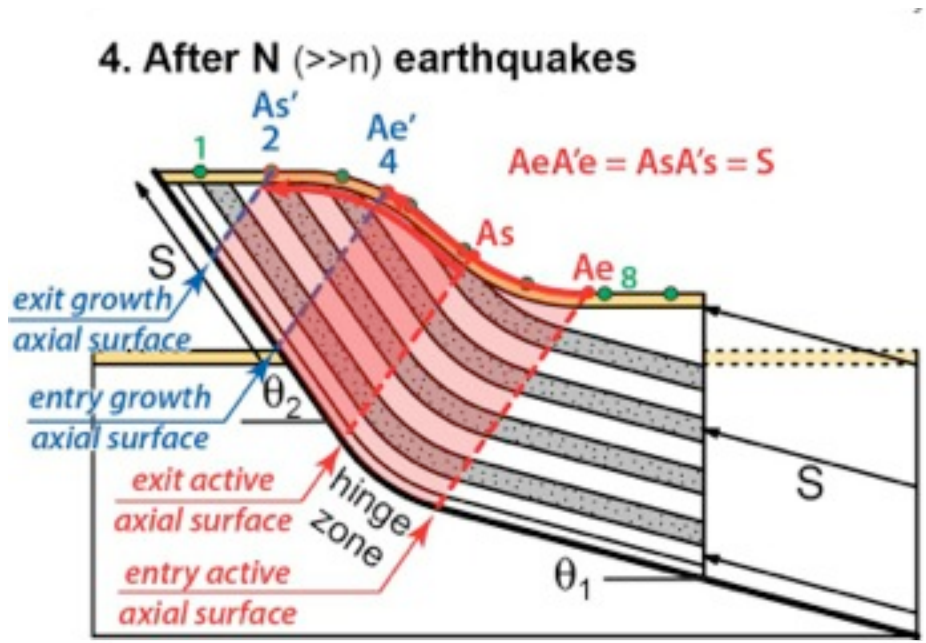

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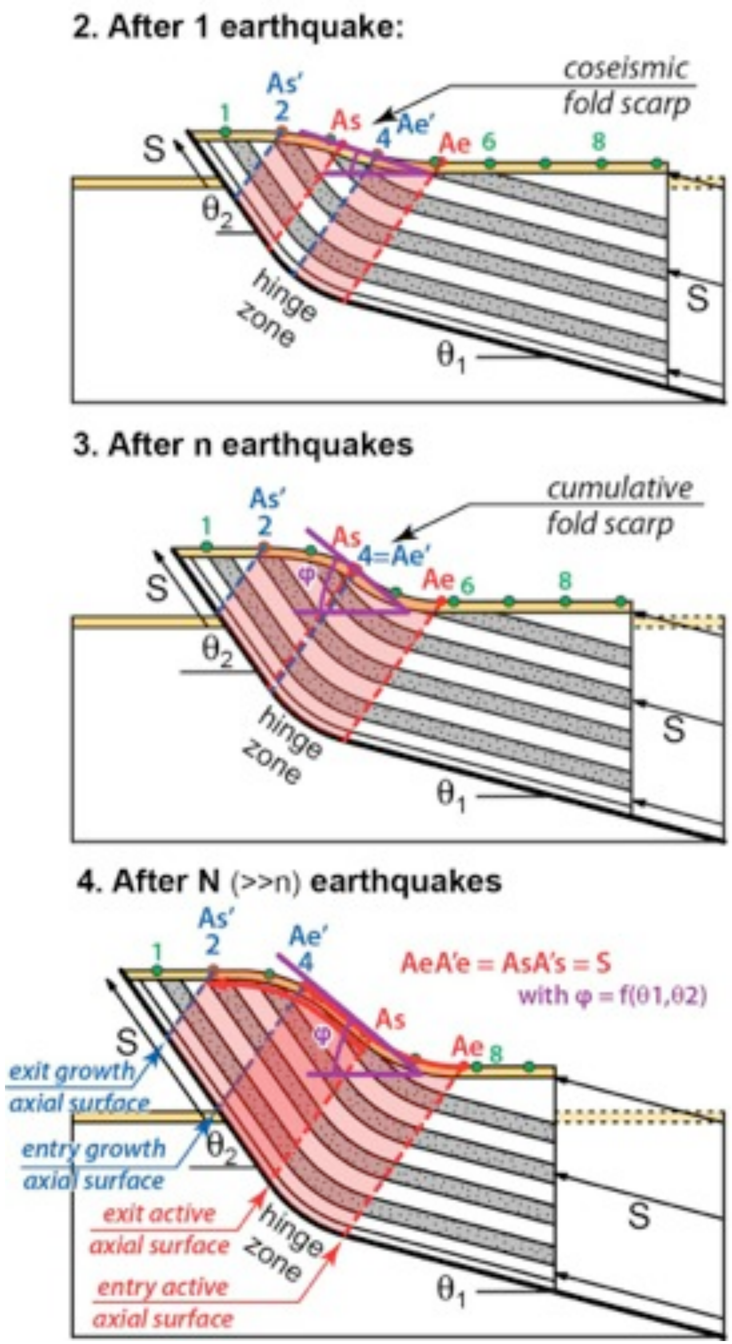


Back limb steepens

and widens.

Misleading morphology for axial surface mapping

=> overestimation of S

Back limb reaches a maximum

and only widens

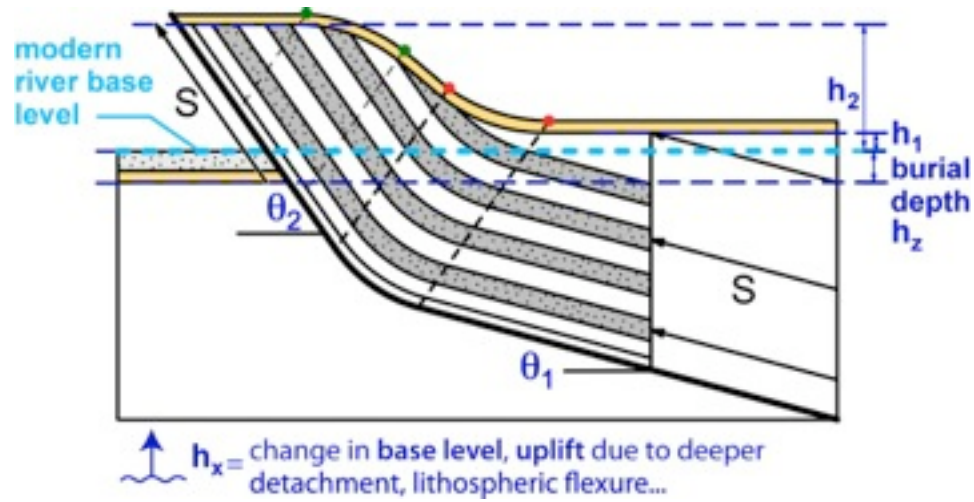
Modified from Suppe et al (1997)

Fault-bend folding theory

Assumption :

Fault-parallel displacement

with conservation of bed length



Modified from Suppe et al (1997)

sensitive to local **base level changes**

depend on **subsurface geometry**

- Recipe 1: **terrace height** relative to footwall:

$$S = (h_1+h_z+h_x) / \sin \theta_1$$

$$S = (h_2+h_z+h_x) / \sin \theta_2$$

Fault-bend folding theory

Assumption :

Fault-parallel displacement

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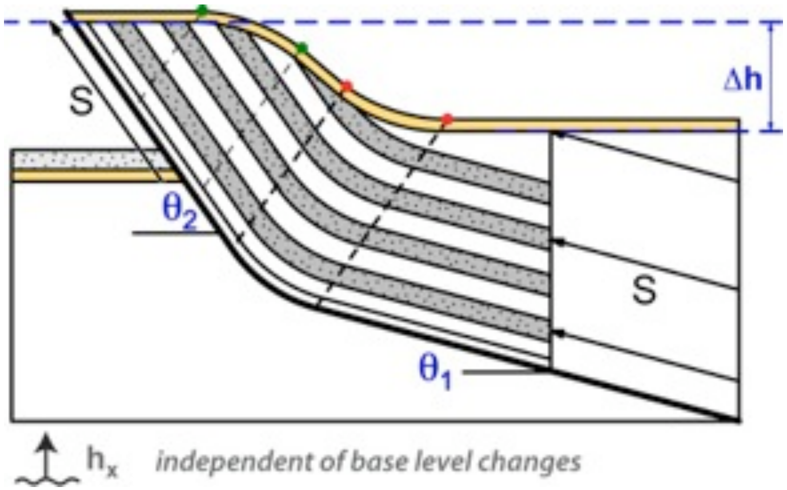

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- Recipe 2: **height of fold scarp**:

$$S = \Delta h / (\sin \theta_2 - \sin \theta_1)$$

Fault-bend folding theory

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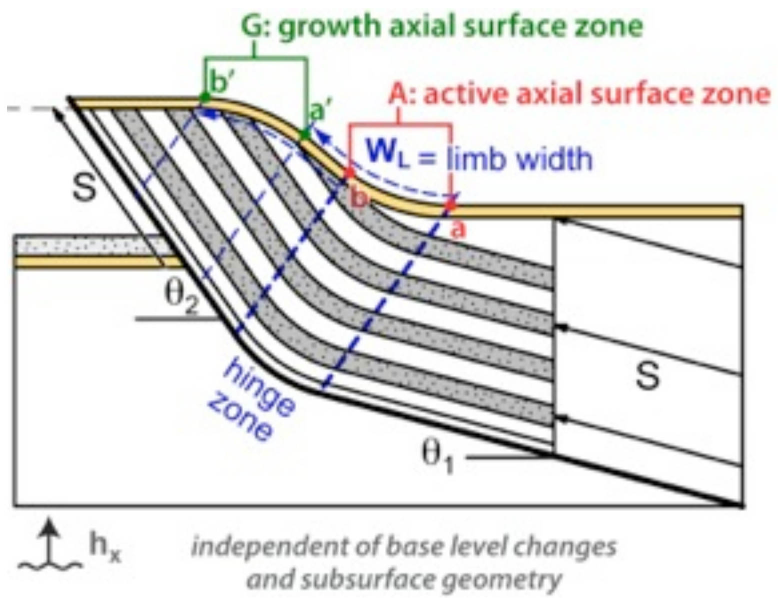

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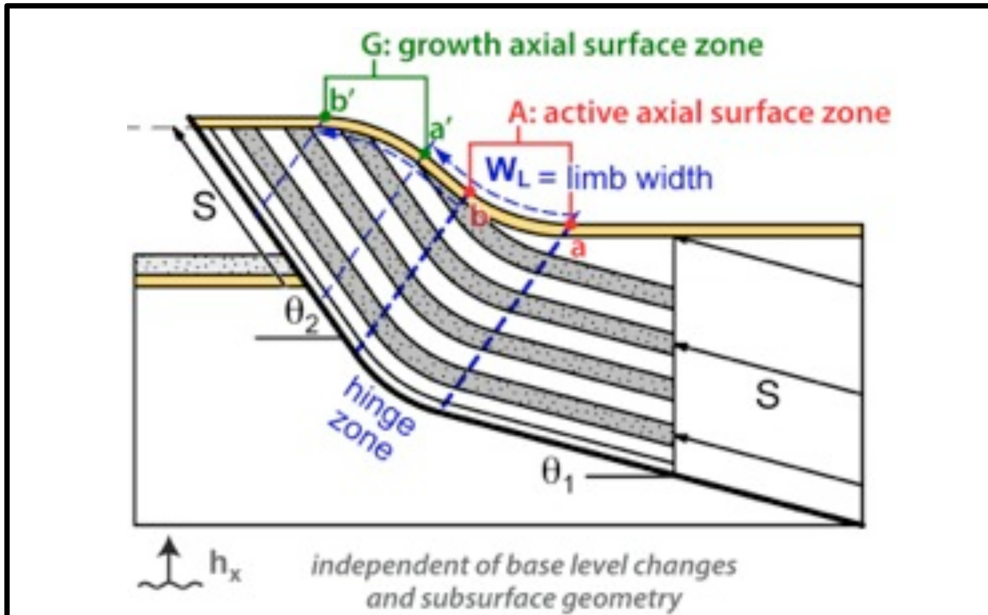

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sensitive to local **base level changes**

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- Recipe 2: **height of fold scarp**:

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- Recipe 3: **width of fold limb**:

$$S = W_L / \cos \alpha$$

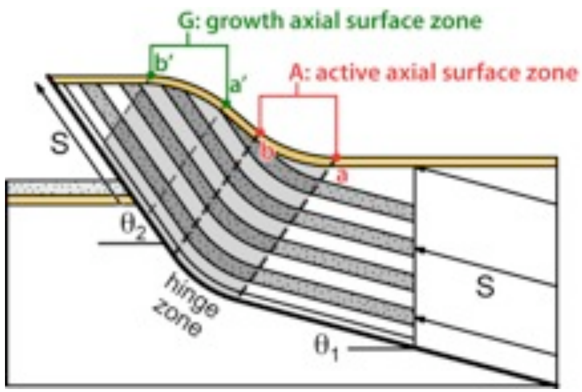
Oblique faulting :

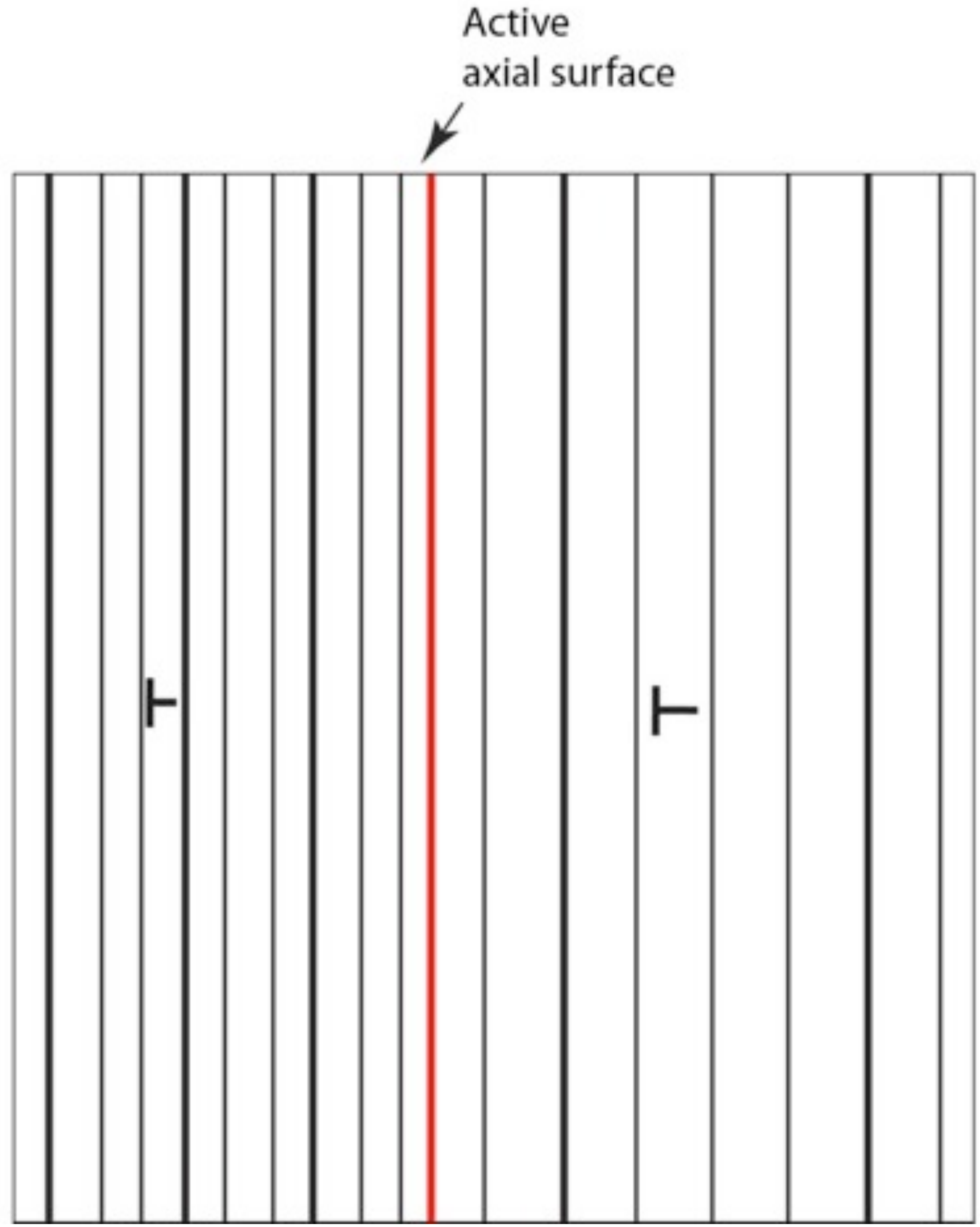
Azimuth of slip vector

Kink-band growth above a 2D pure thrust

Map view

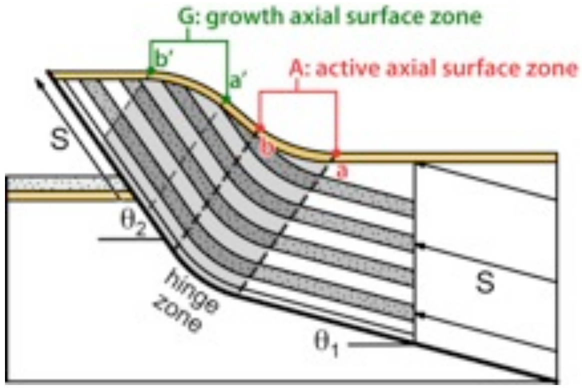
Cross-section



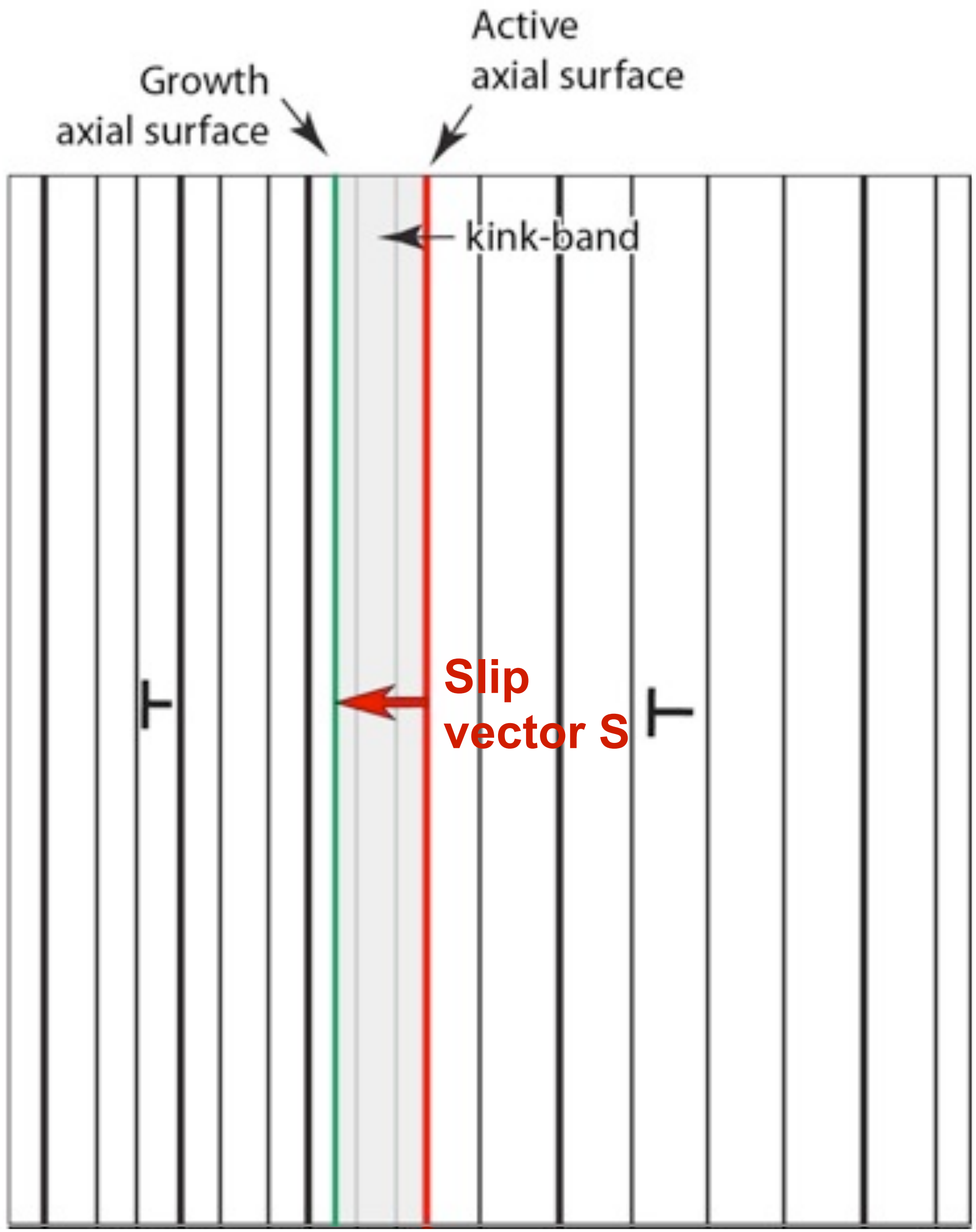


Kink-band growth above a 2D pure thrust

Cross-section



Map view



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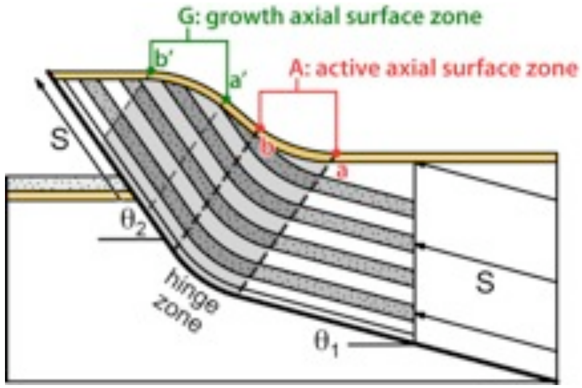

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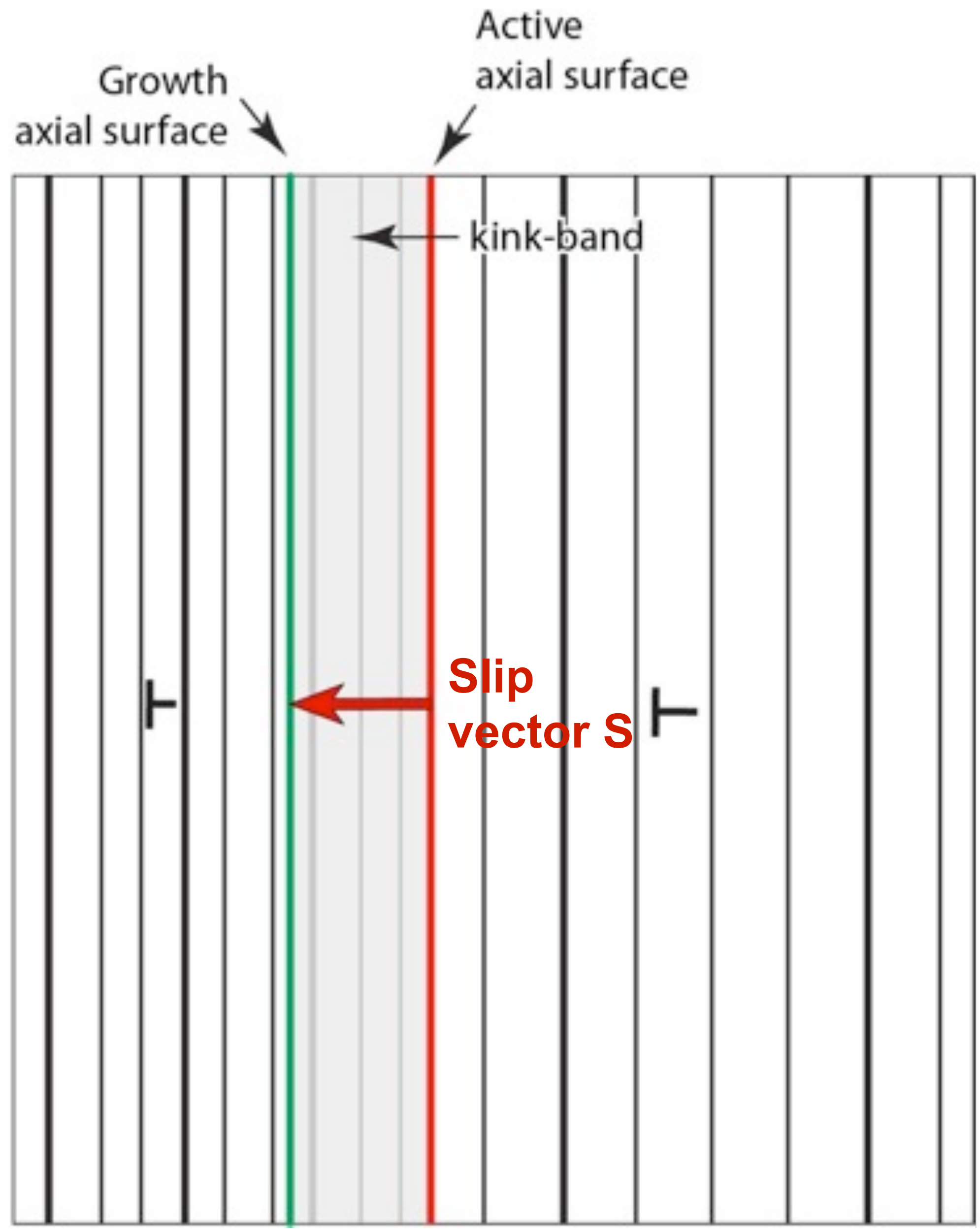

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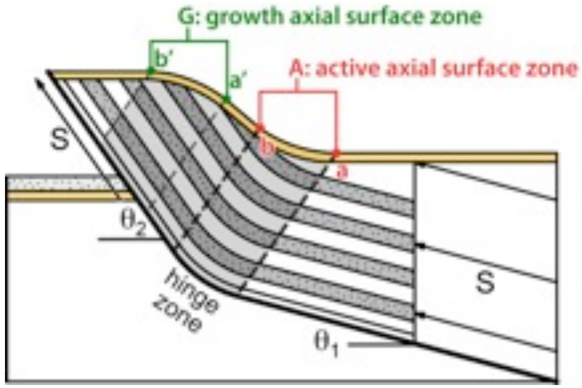

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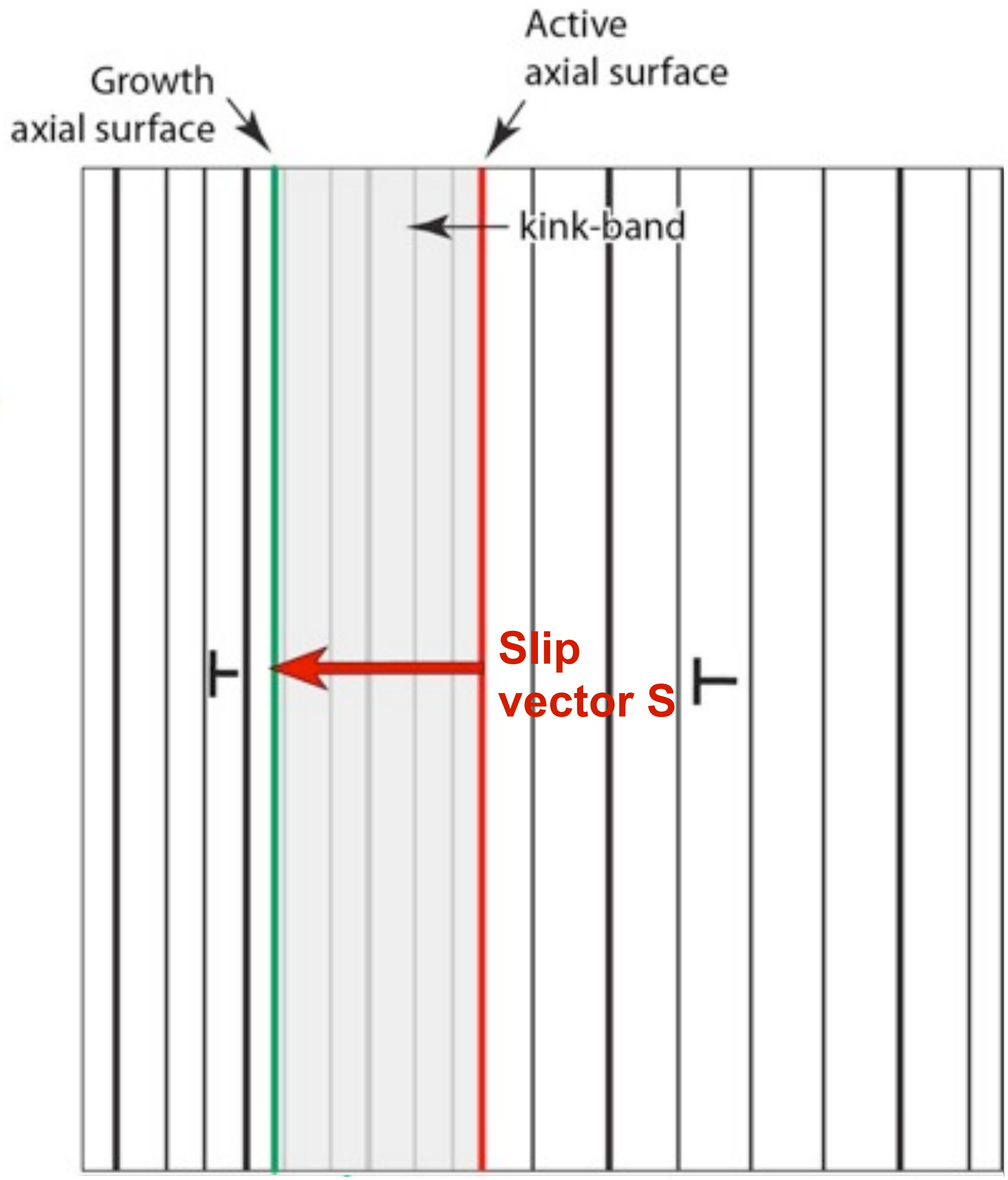
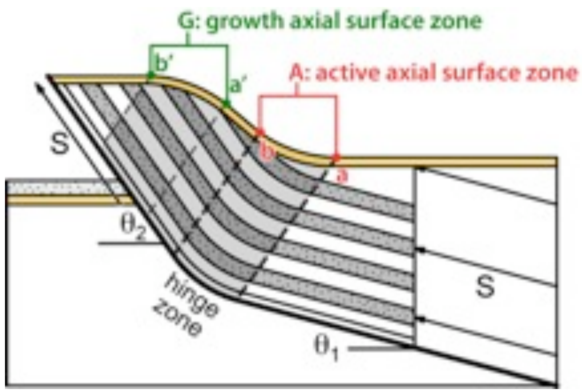
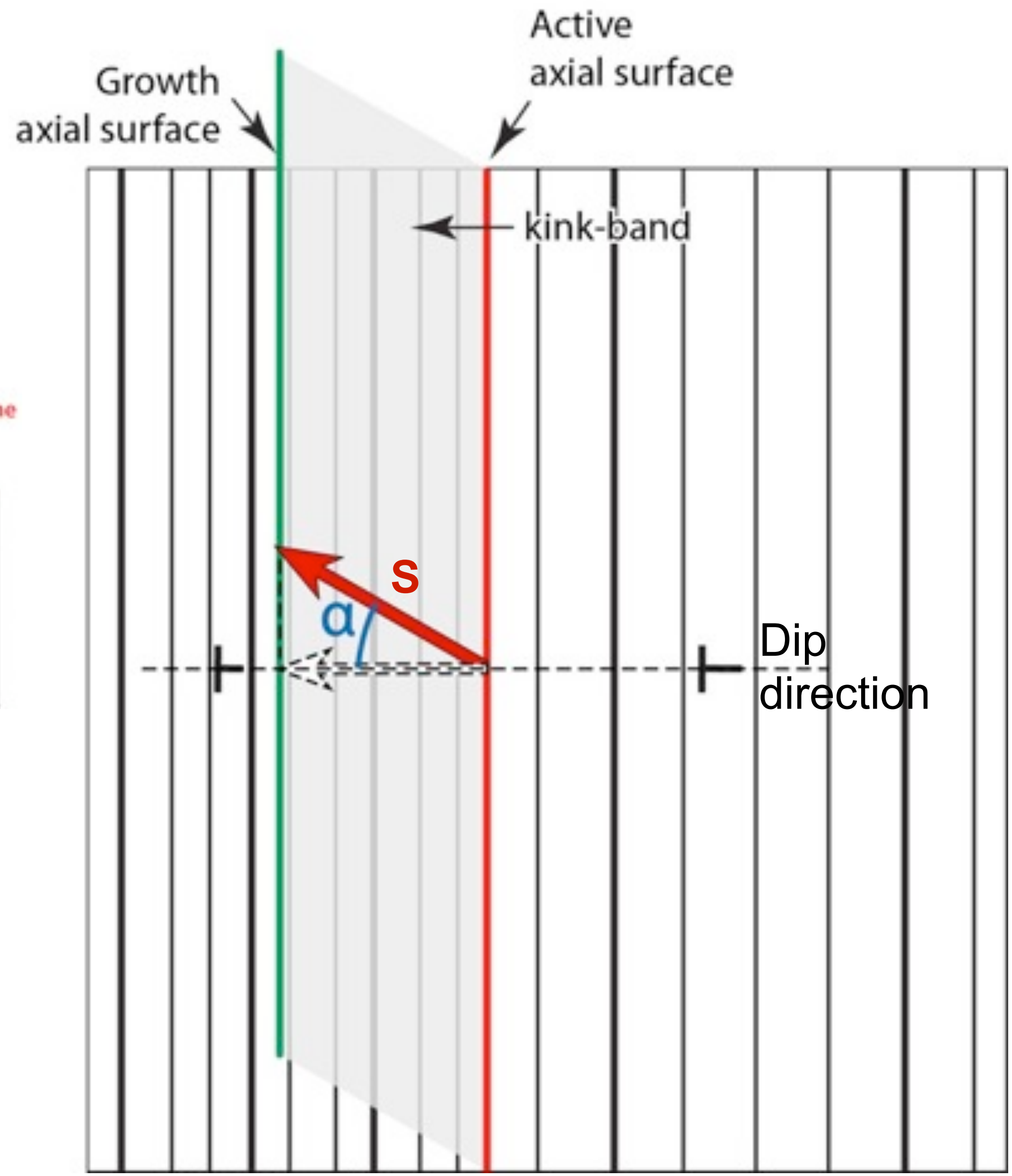


Kink-band growth above a 2D oblique thrust

Cross-section

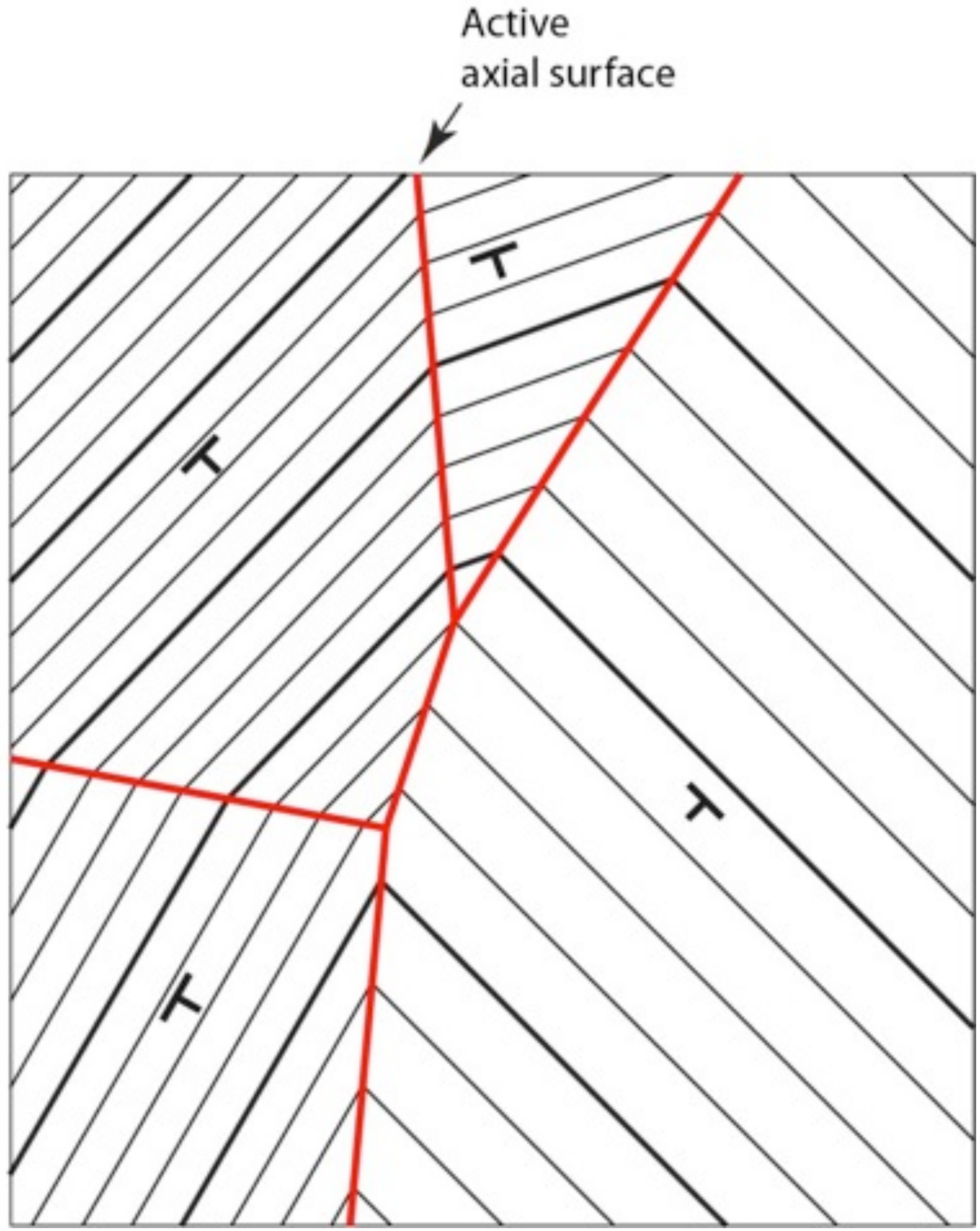


Map view



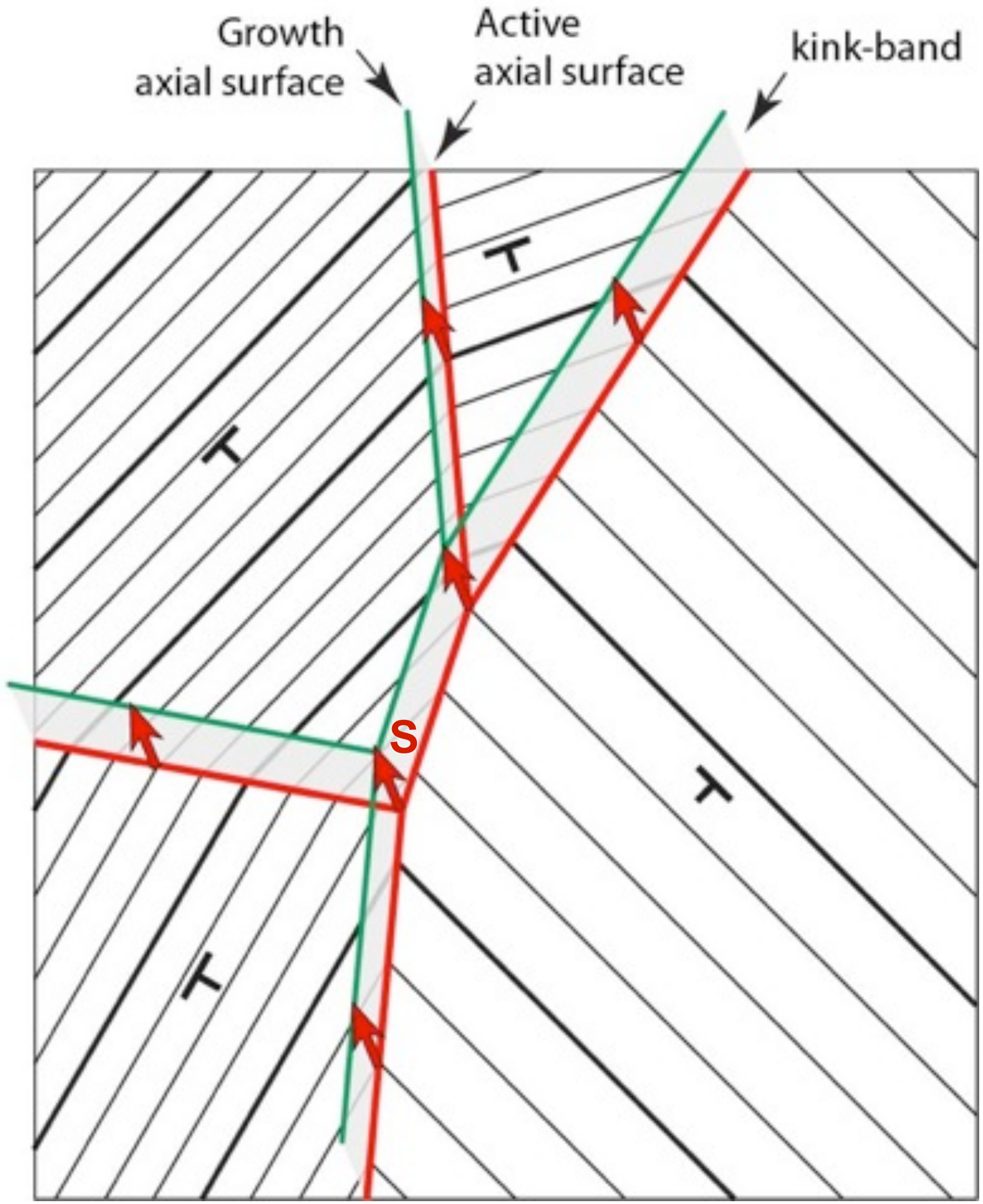
Kink-band growth above a 3D oblique thrust

Map view



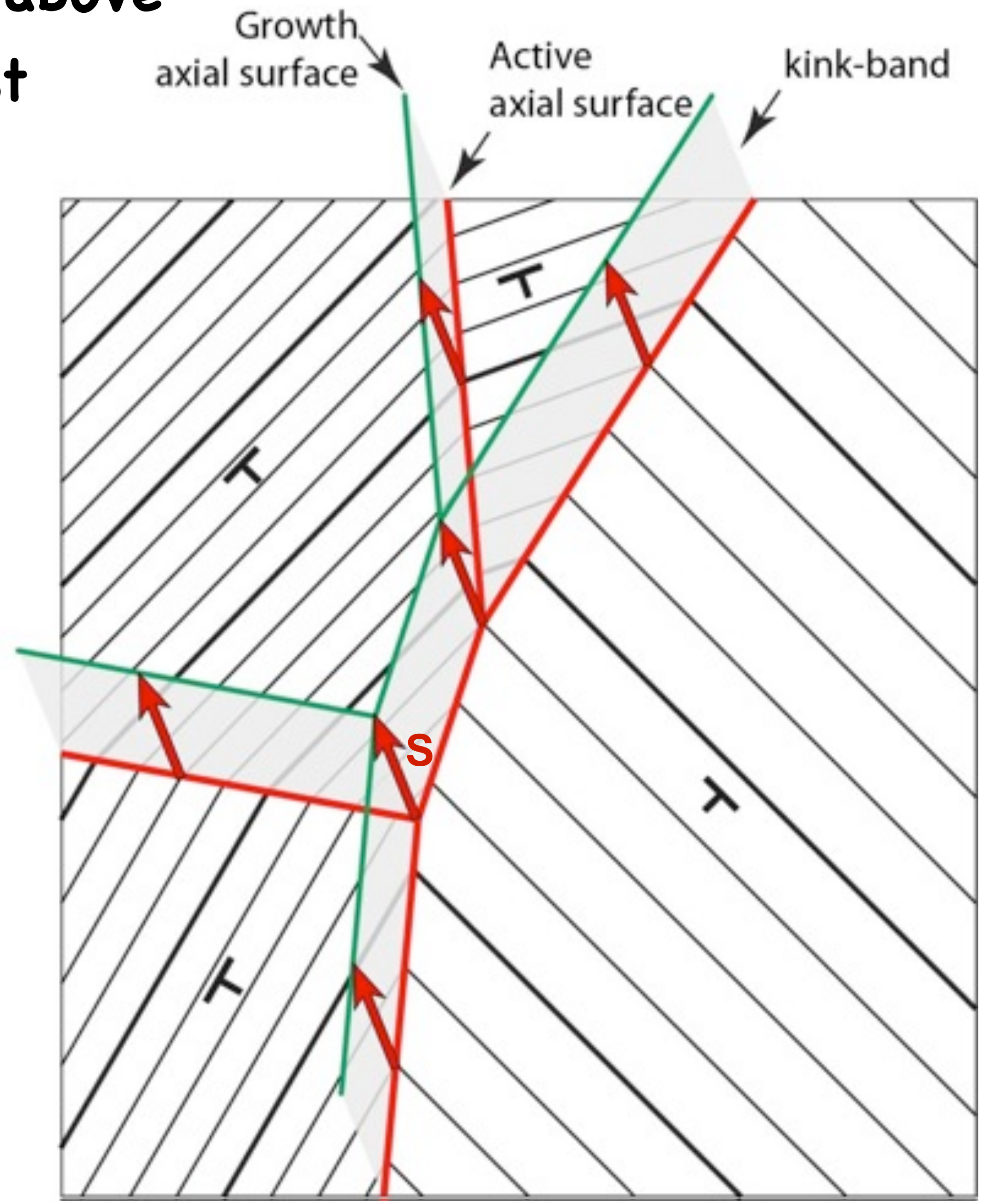
Kink-band growth above a 3D oblique thrust

Map view



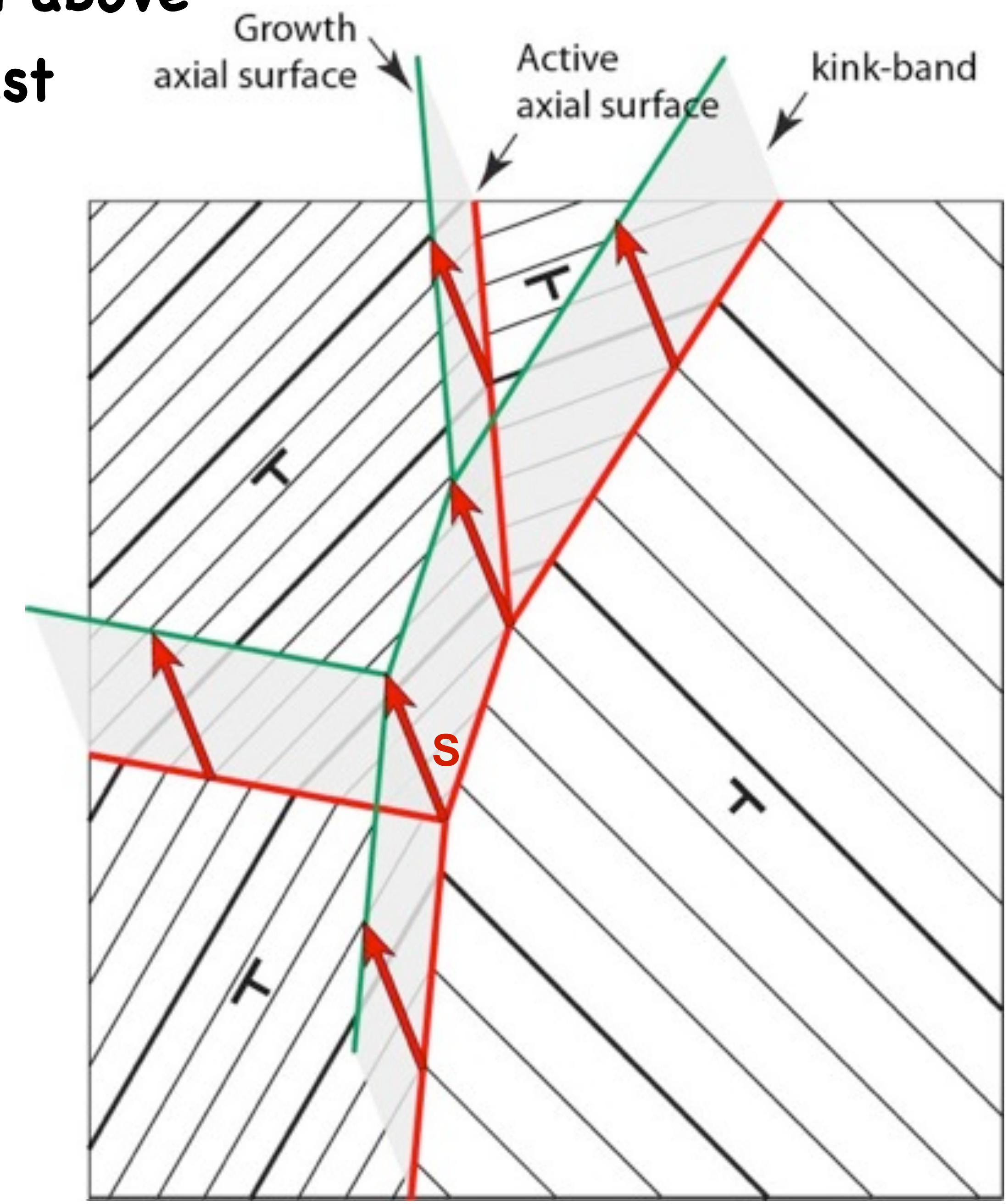
Kink-band growth above a 3D oblique thrust

Map view

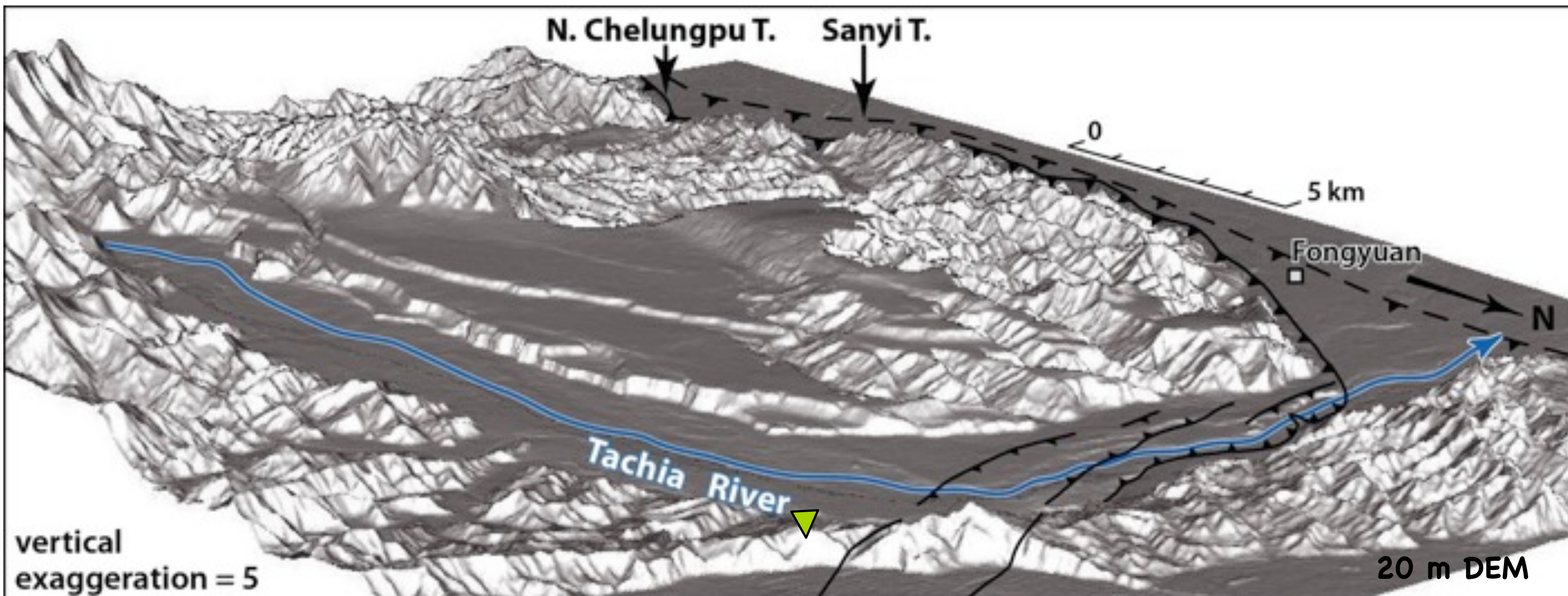


Kink-band growth above a 3D oblique thrust

Map view



Morphology of the Hsinshe terraces



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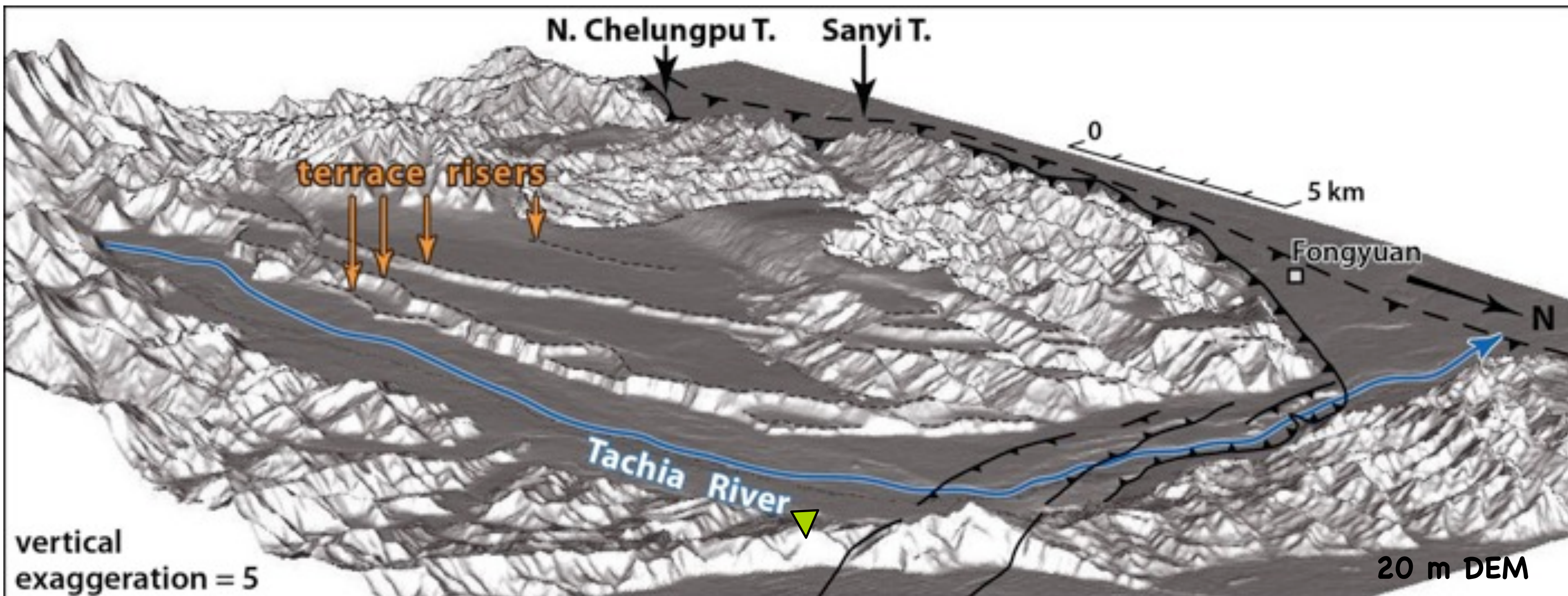

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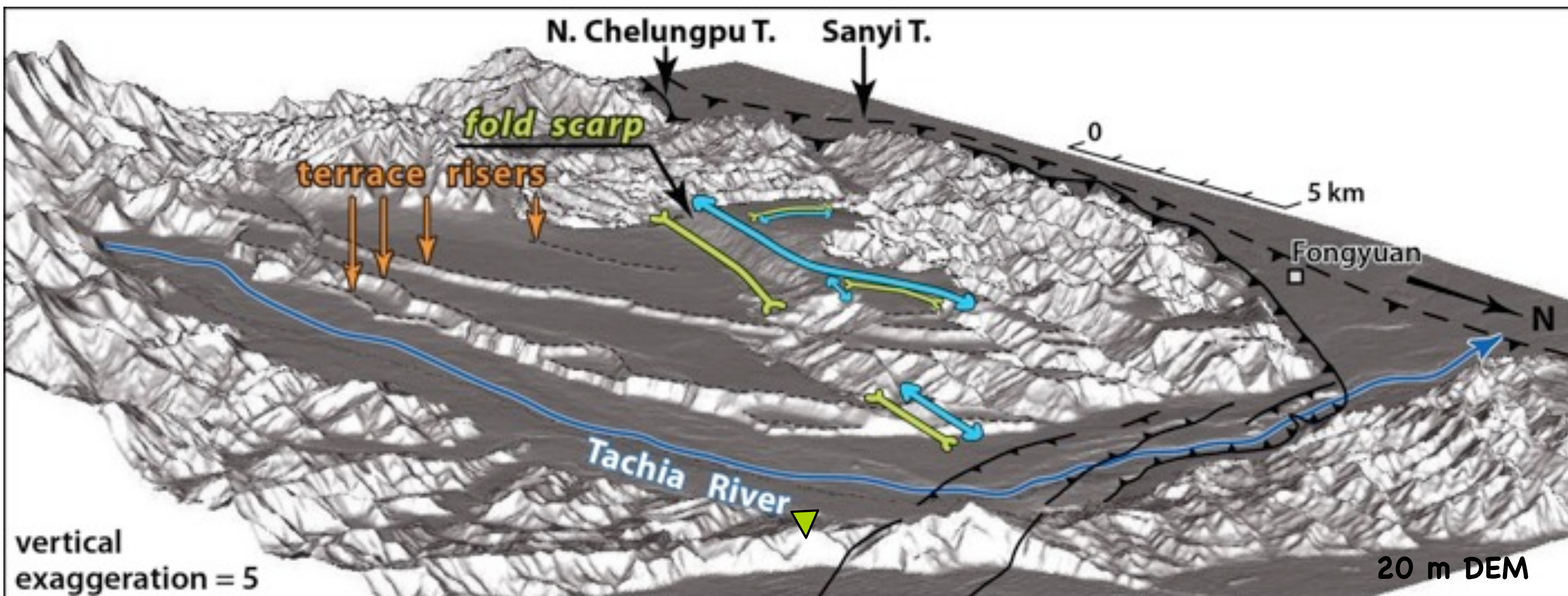
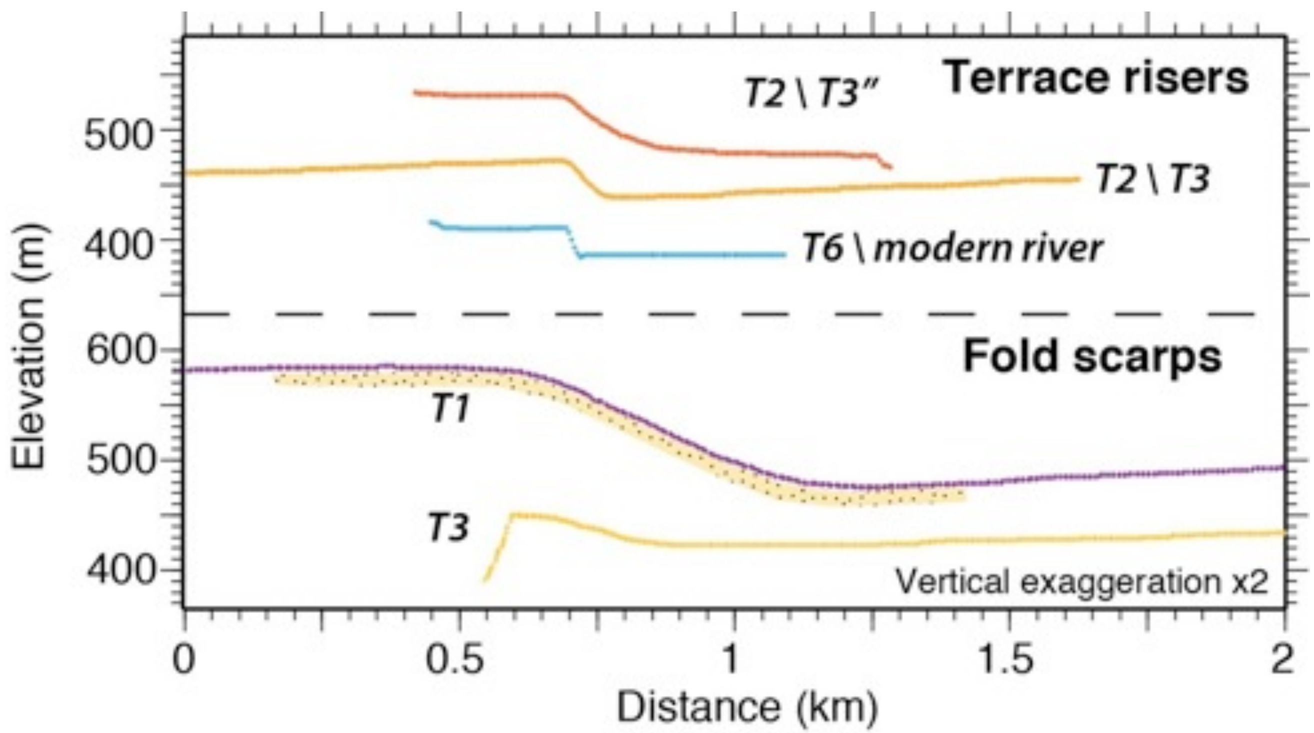


Terrace risers versus fold scarps



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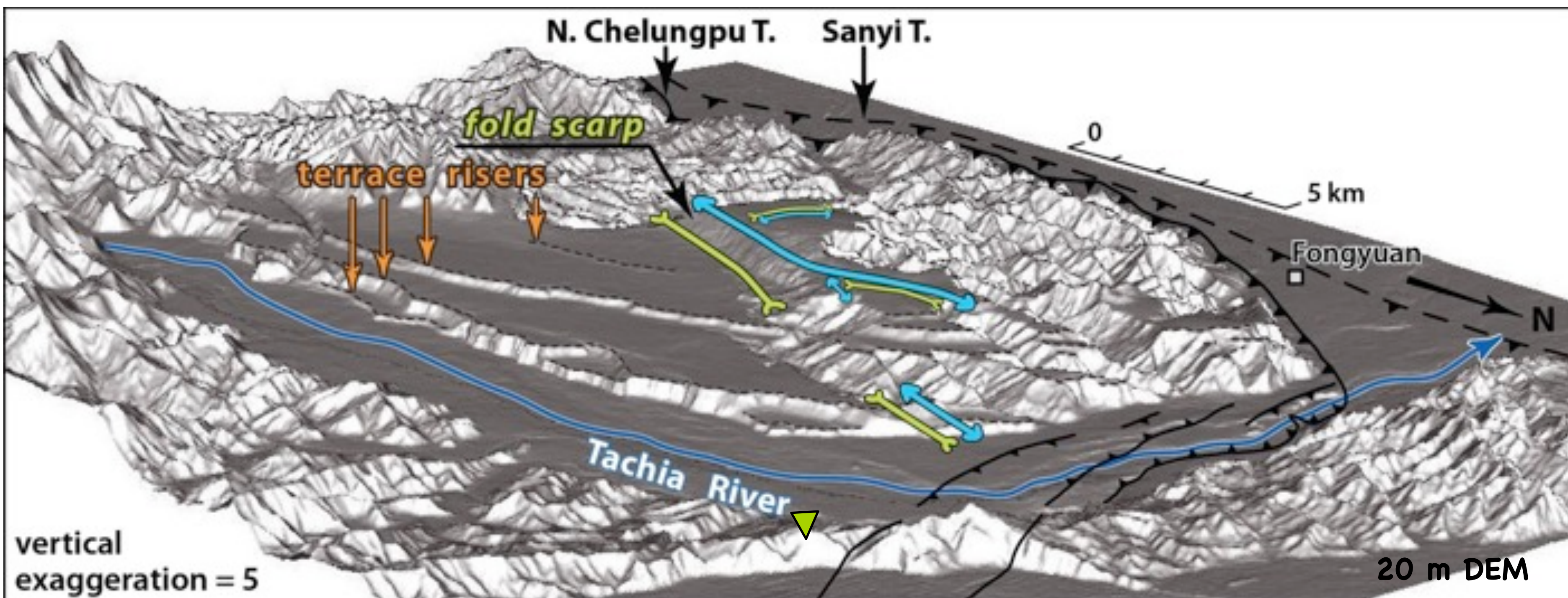

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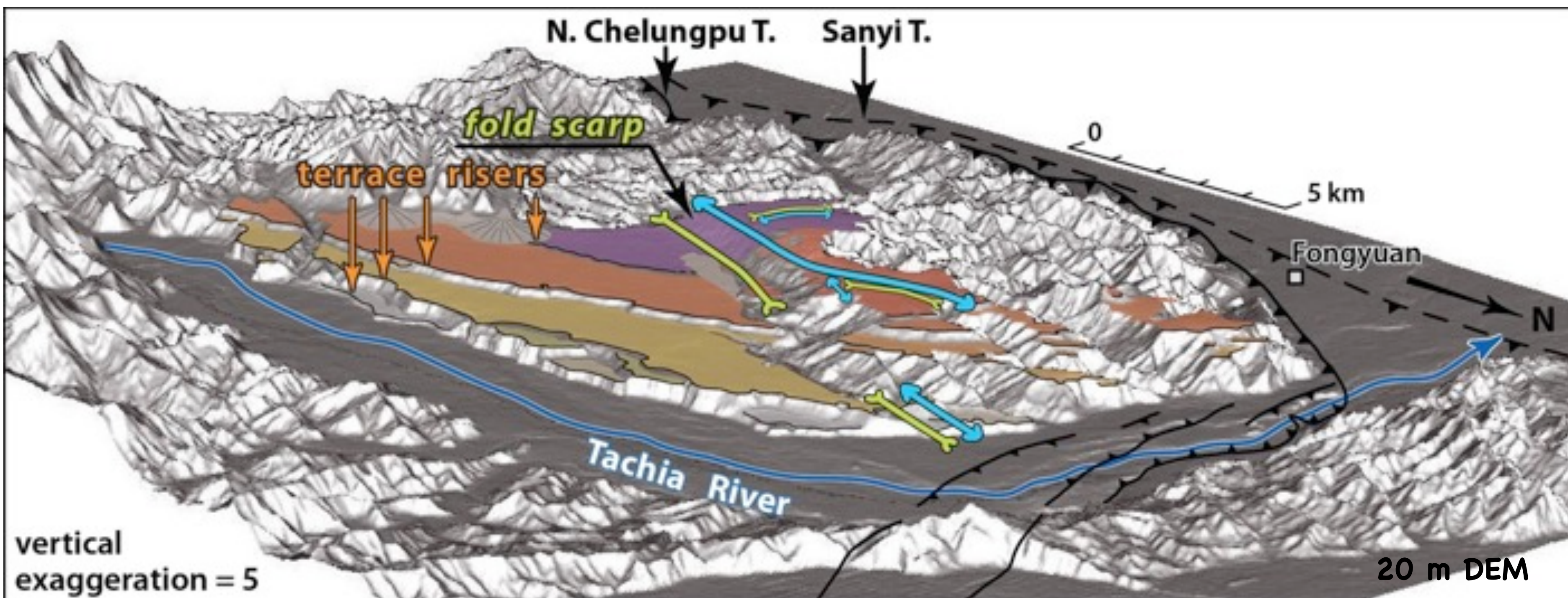
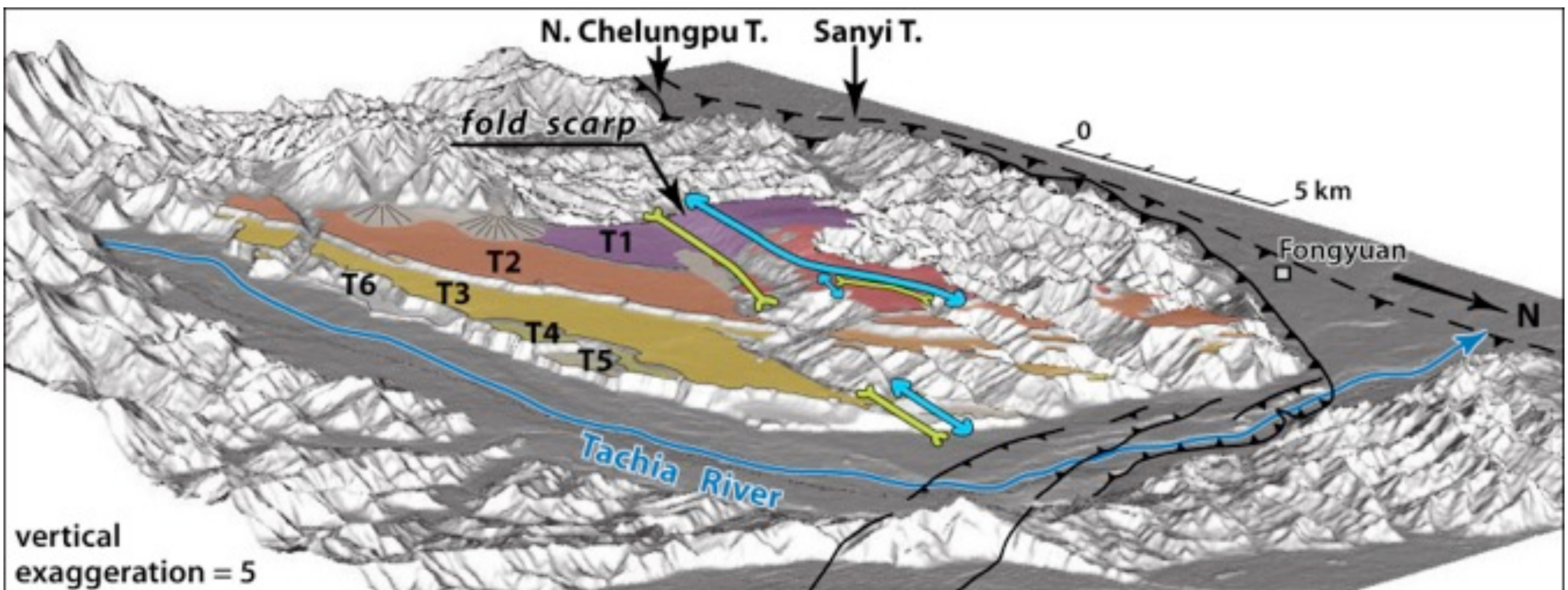


20 m DEM

Morphology of the Hsinshe terraces

3 main terrace levels ; many more on top the scarp

(Tsai & Sung, 2003; Lai et al 2006)



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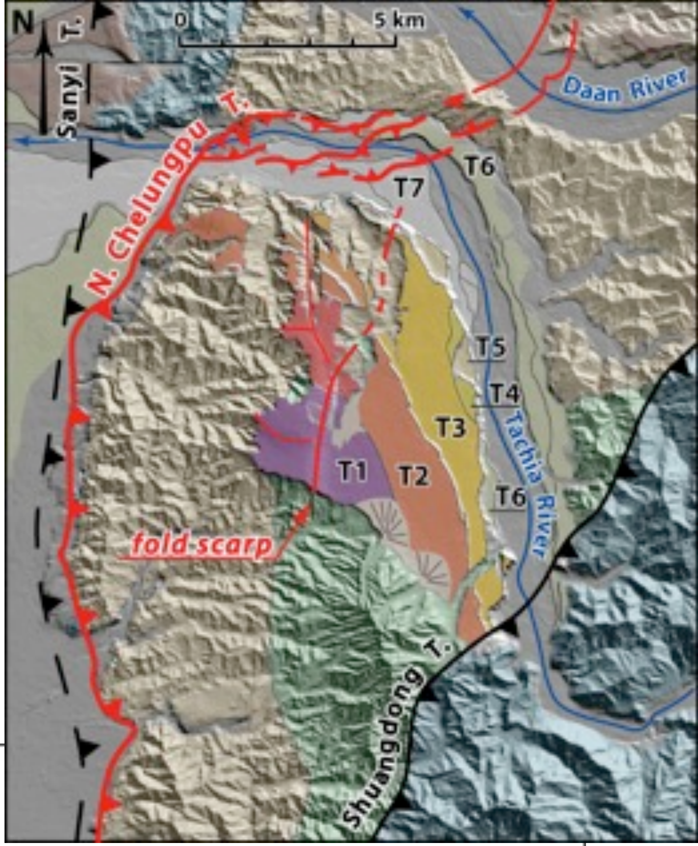
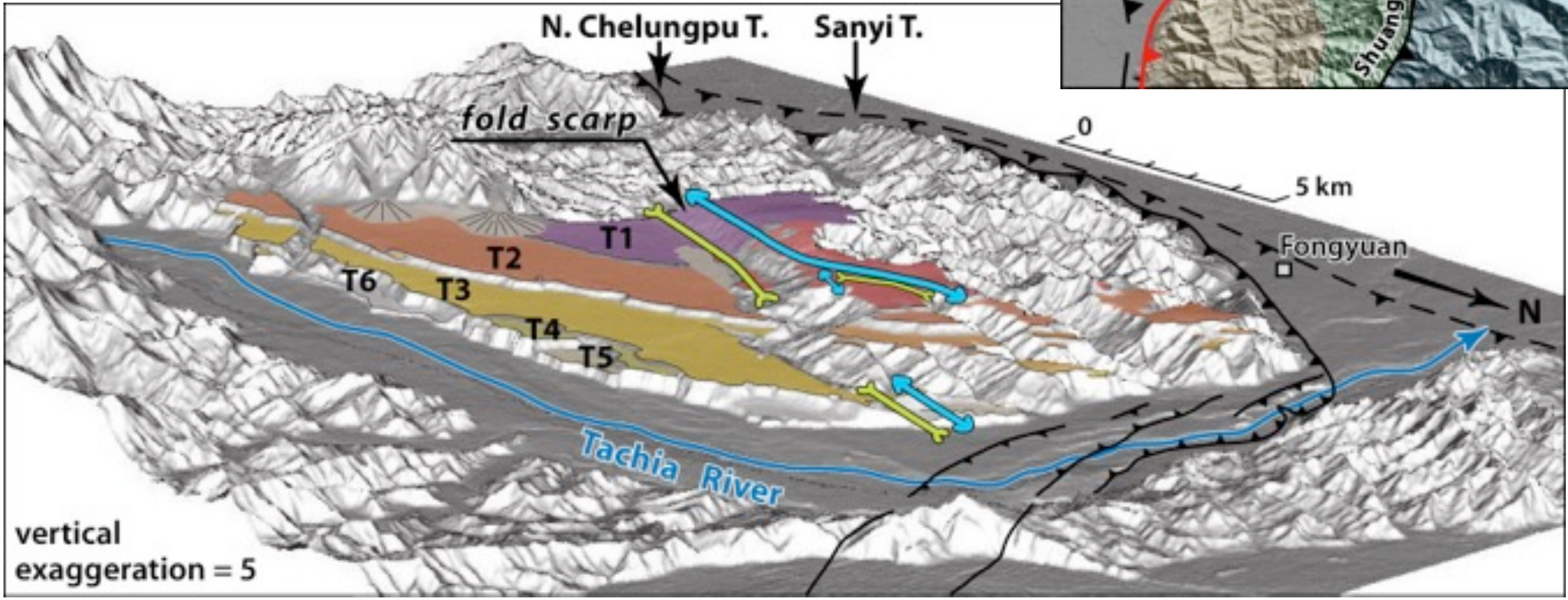




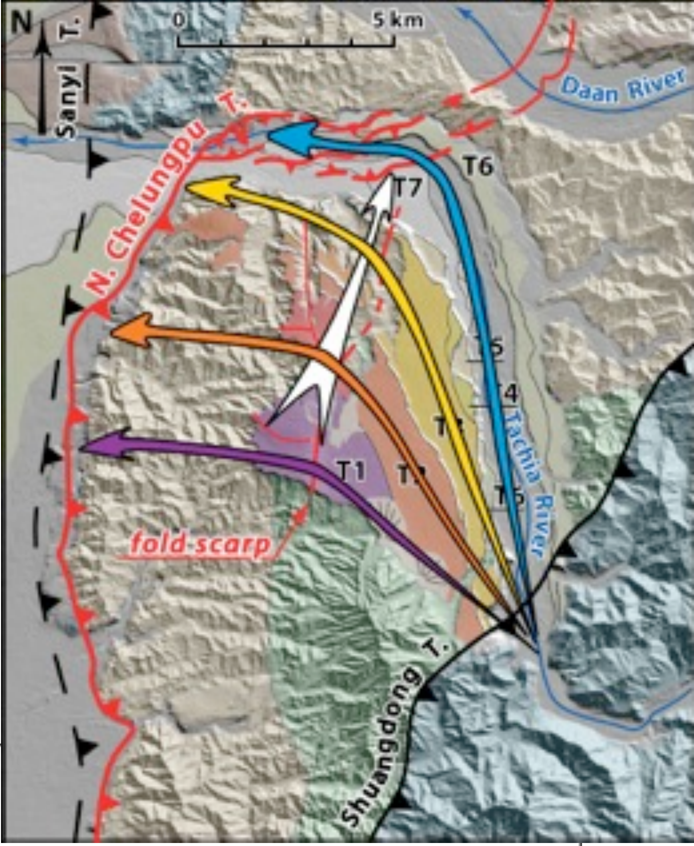
Overview of the Hsinshe terraces

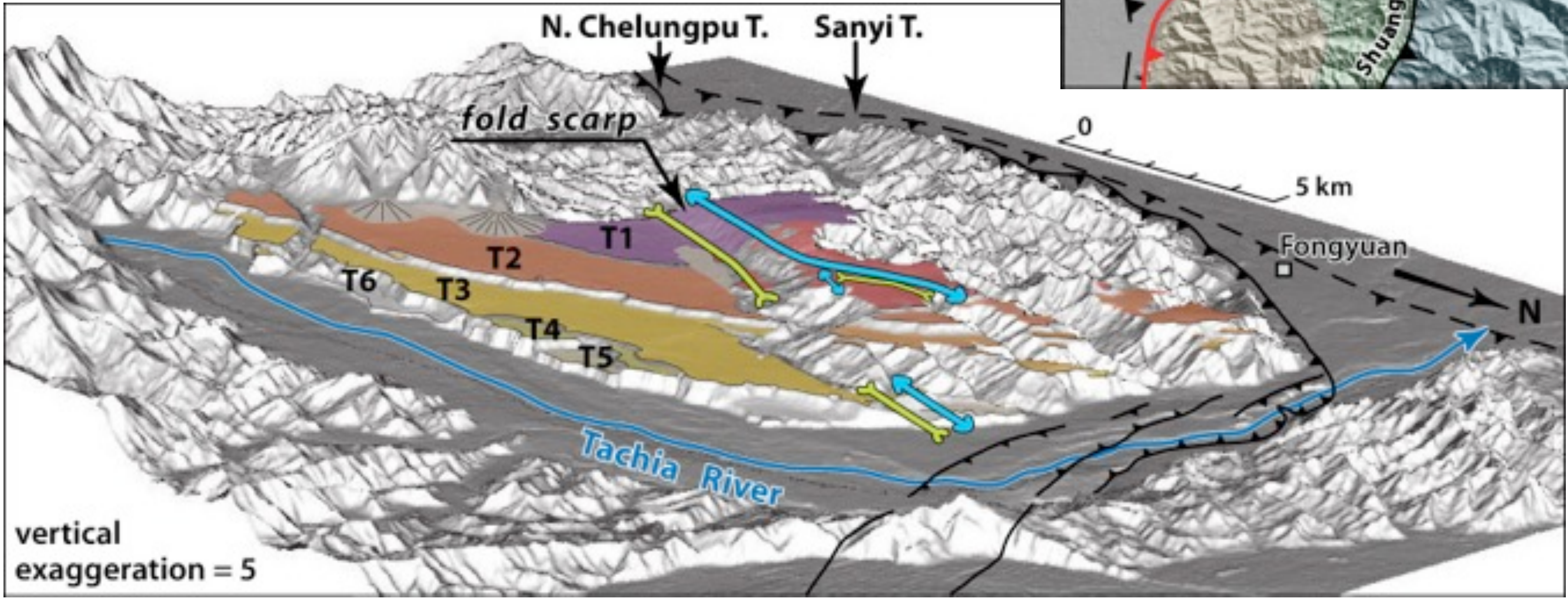
3 main terrace levels ; many more on top the scarp

(Tsai & Sung, 2003; Lai et al 2006)

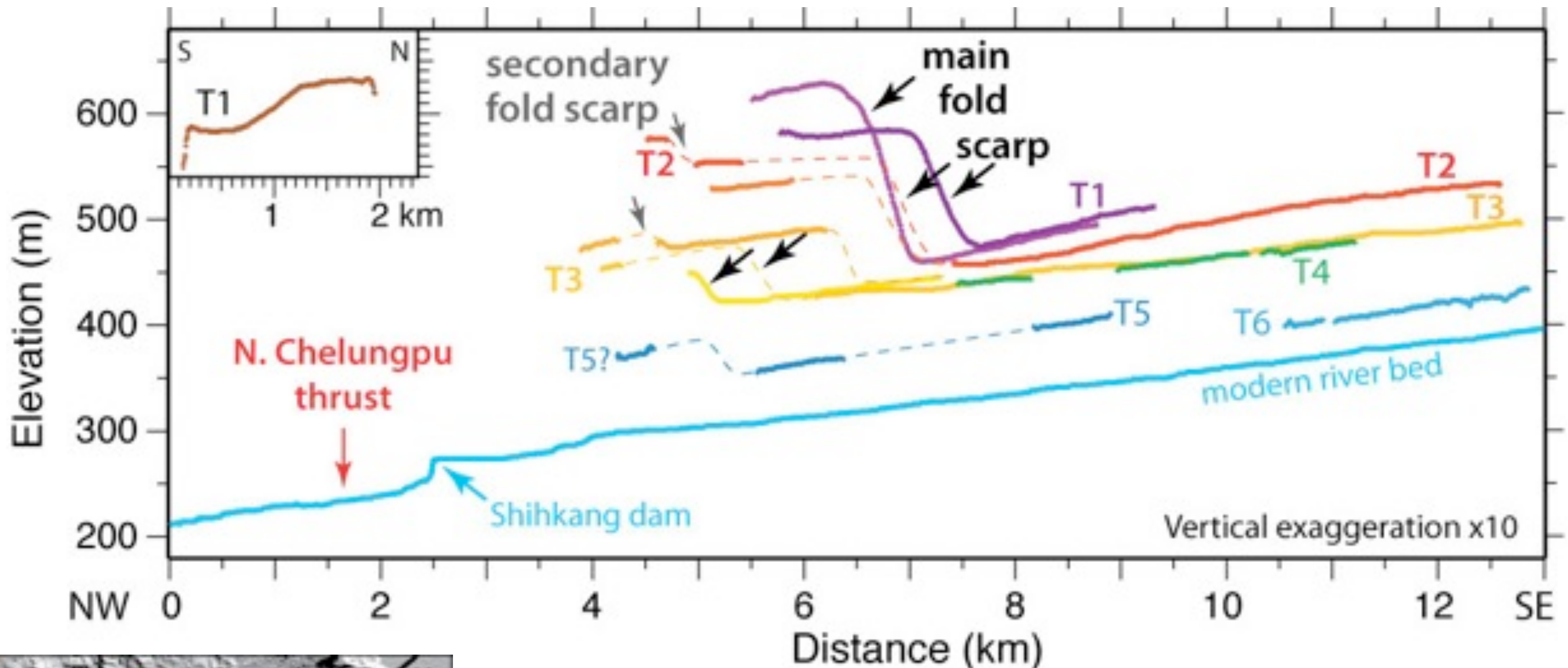
Northward migration of the riverbed

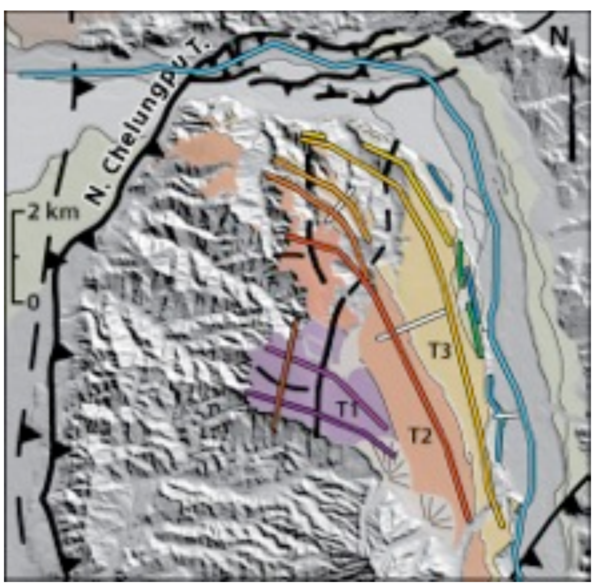
Dramatic **river incision** post-T4





Deformation of the terraces

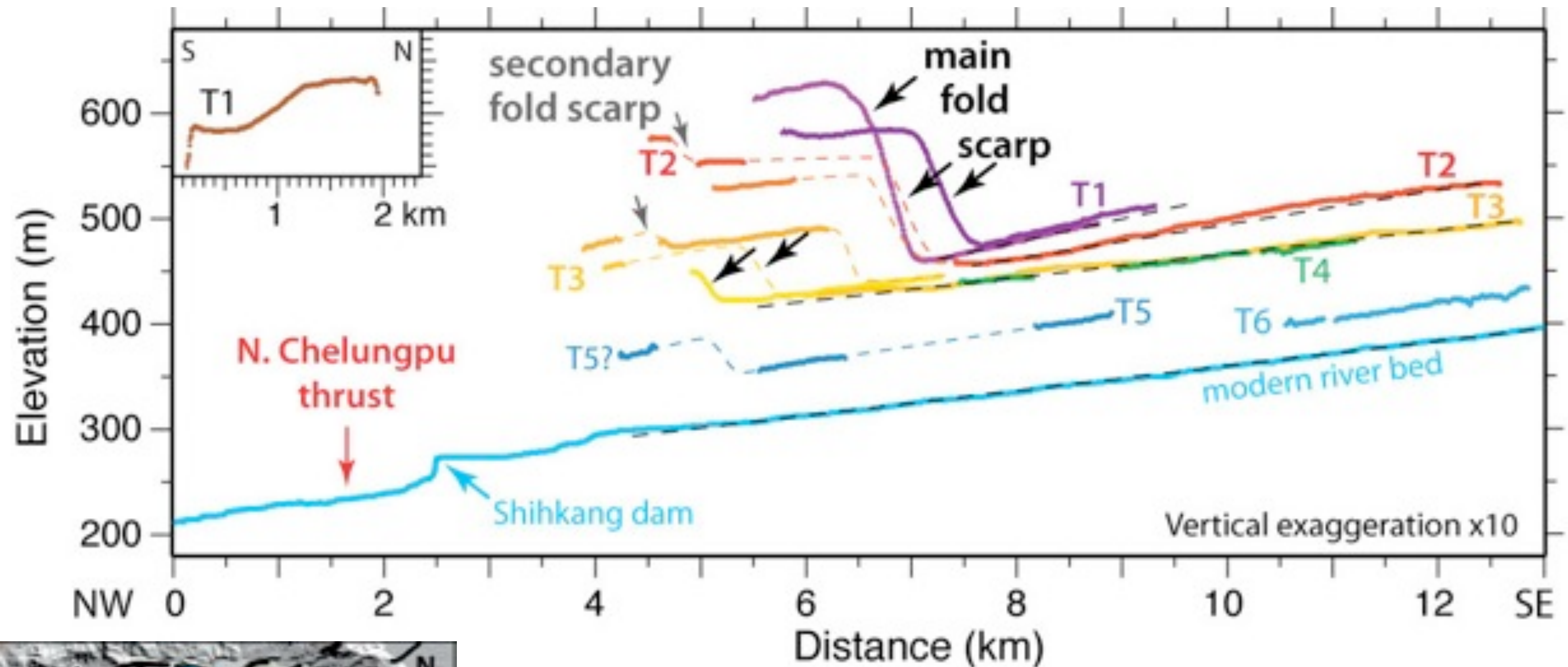


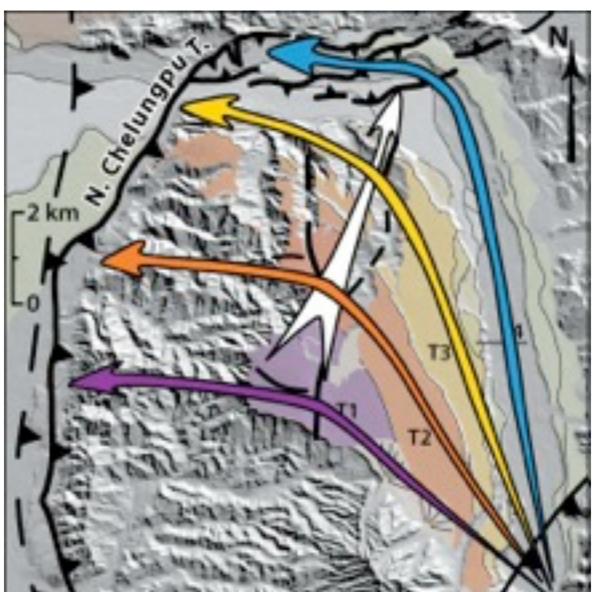


From younger to older terraces :

- Increase in **terrace heights h**
- Increase in **relief across the fold scarp** Δh
- Increase in the **length of the fold limb** W_L

Deformation of the terraces





From younger to older terraces :

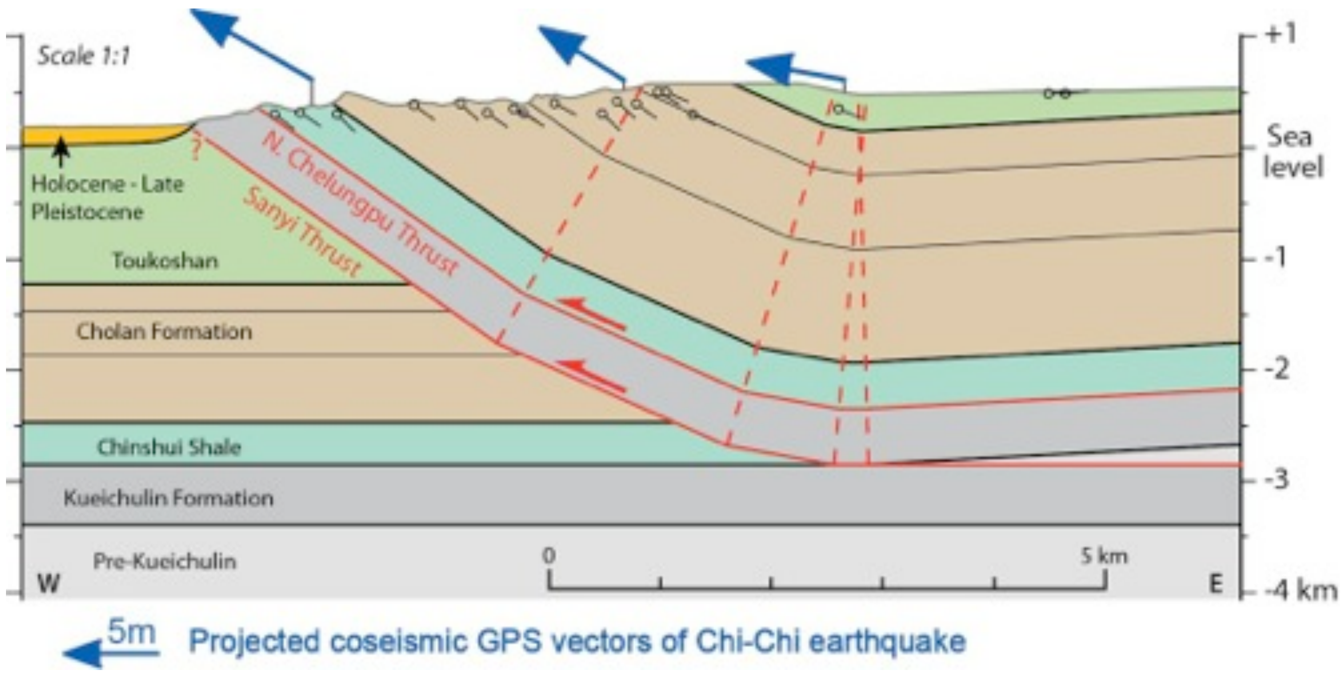
- Increase in **terrace heights h**
- Increase in **relief across the fold scarp Δh**
- Increase in the **width of the fold limb W_L**
- **Decrease in the slope of the riverbed**

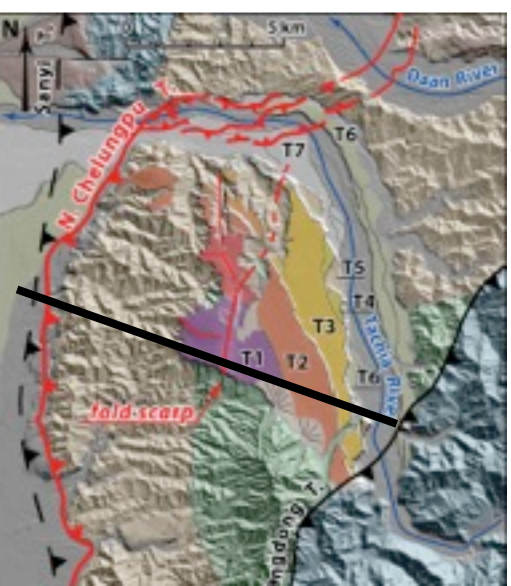
=> Partly due to changes in sinuosity

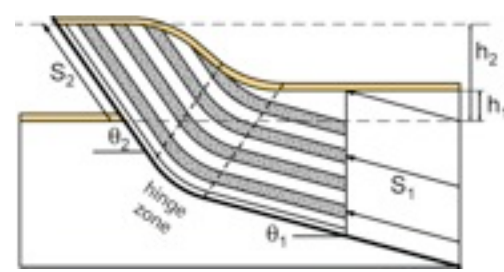
Subsurface structure of the Chelungpu Thrust

Bedding-parallel
thrust ramp with
varying dip

Chi-Chi GPS slip vectors parallel to the ramp dip



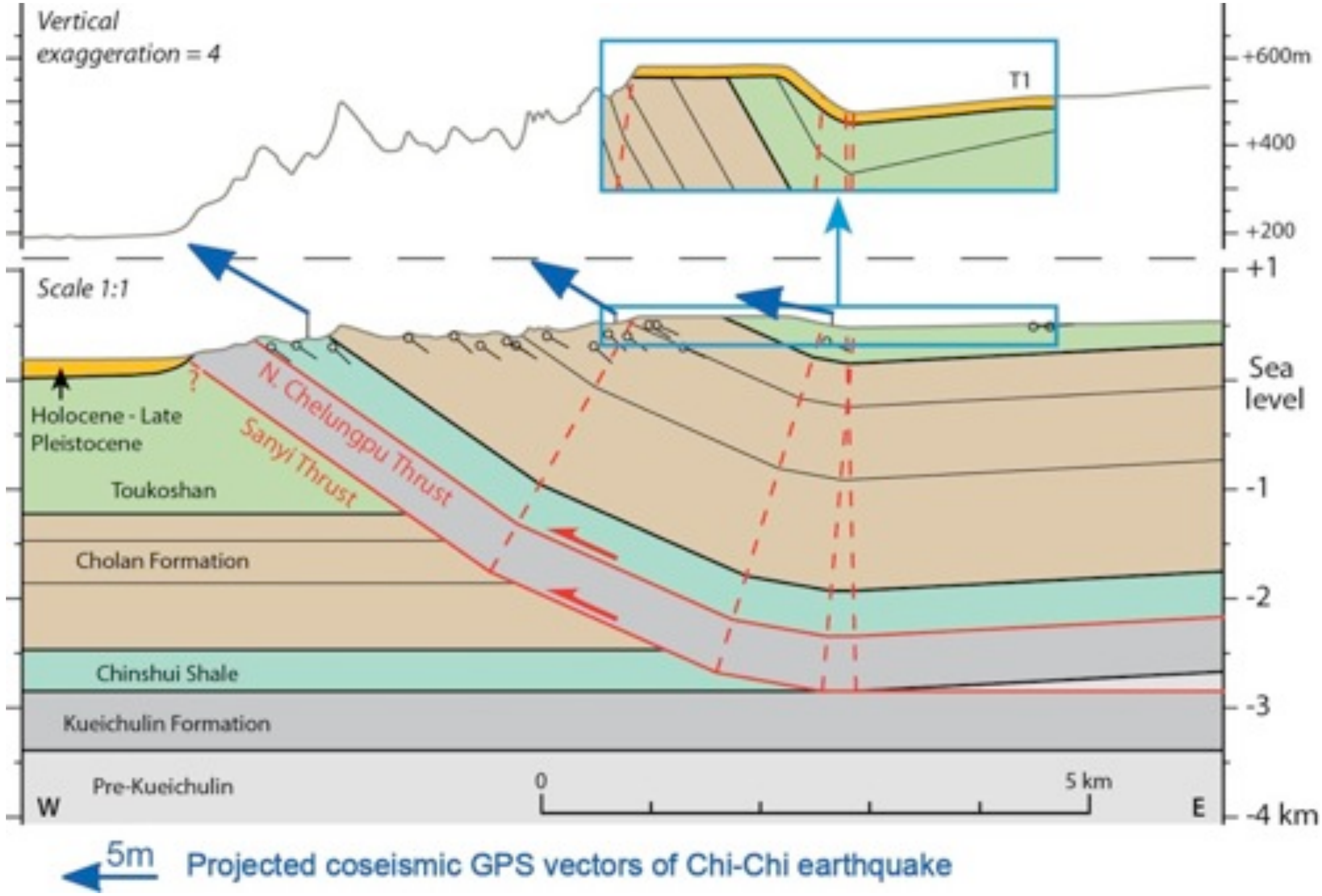


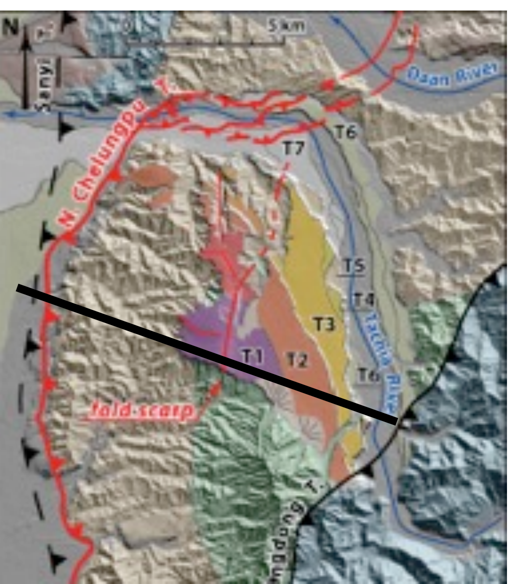


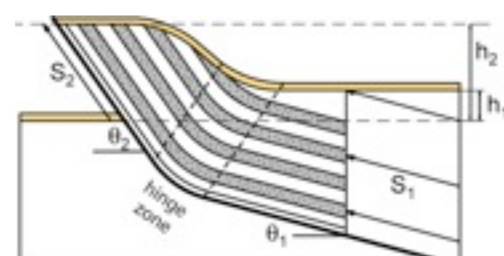
Subsurface structure of the Chelungpu Thrust

Bedding-parallel thrust ramp with **varying dip**

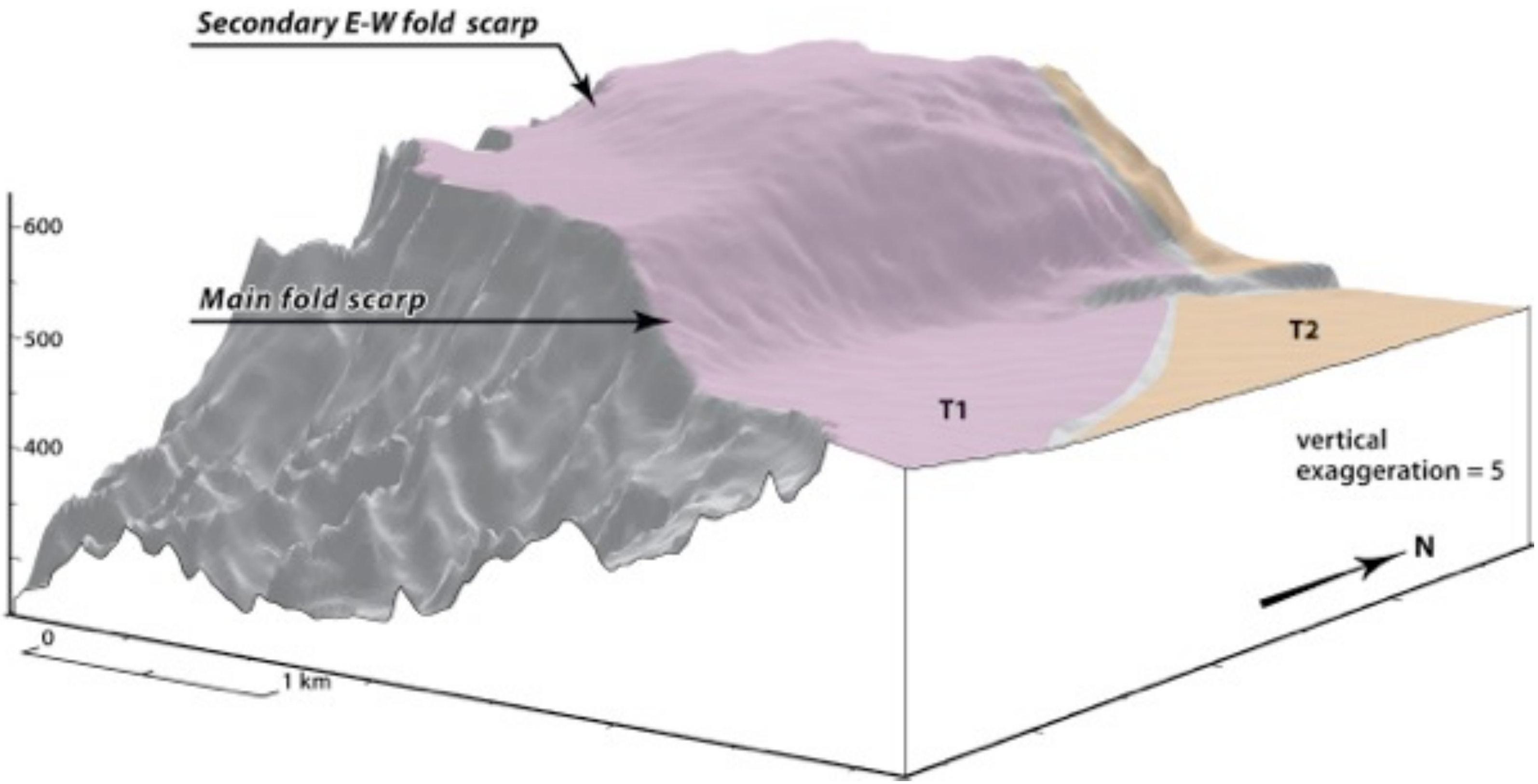
Chi-Chi GPS slip vectors parallel to the ramp dip







Deformation of terrace T1



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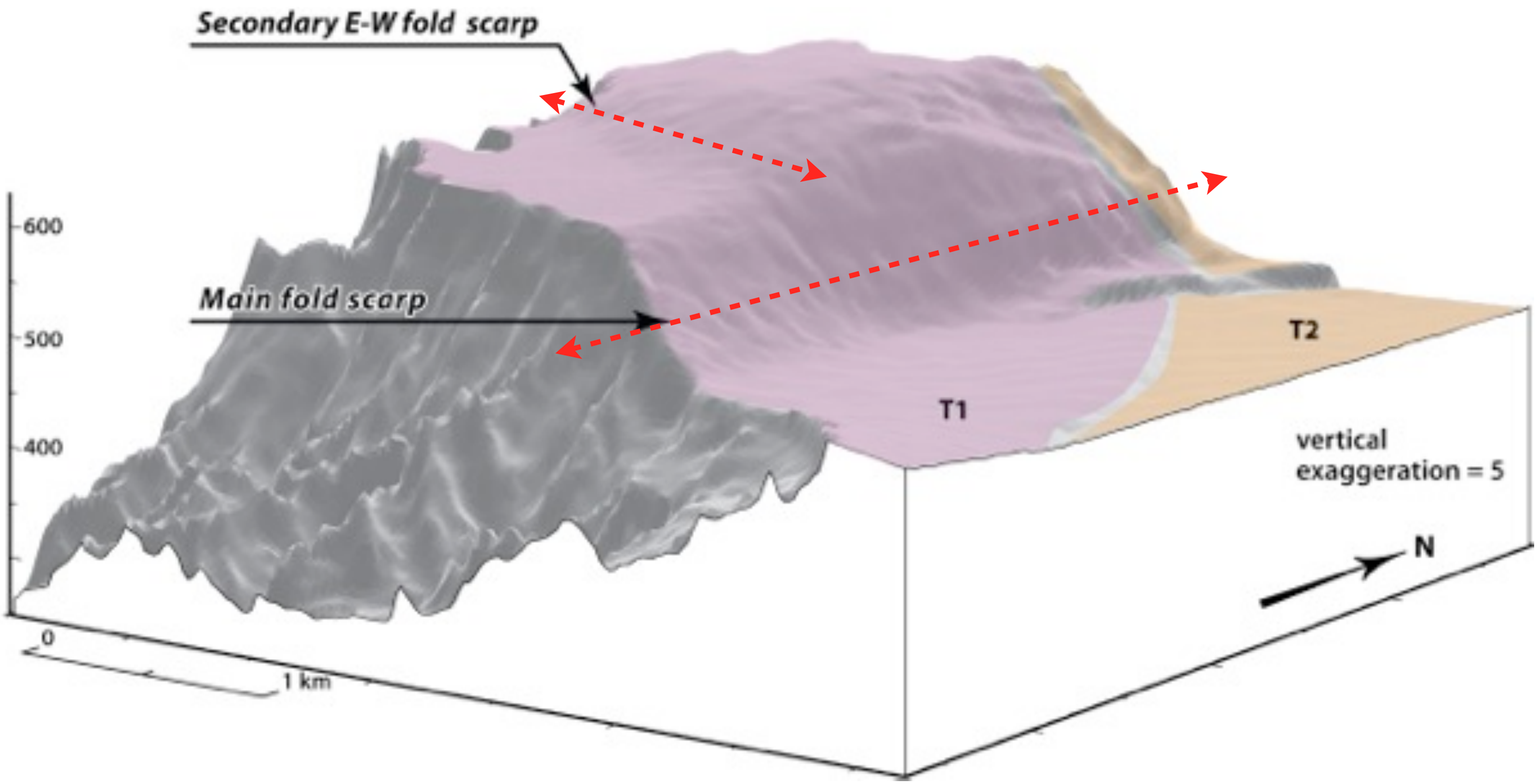

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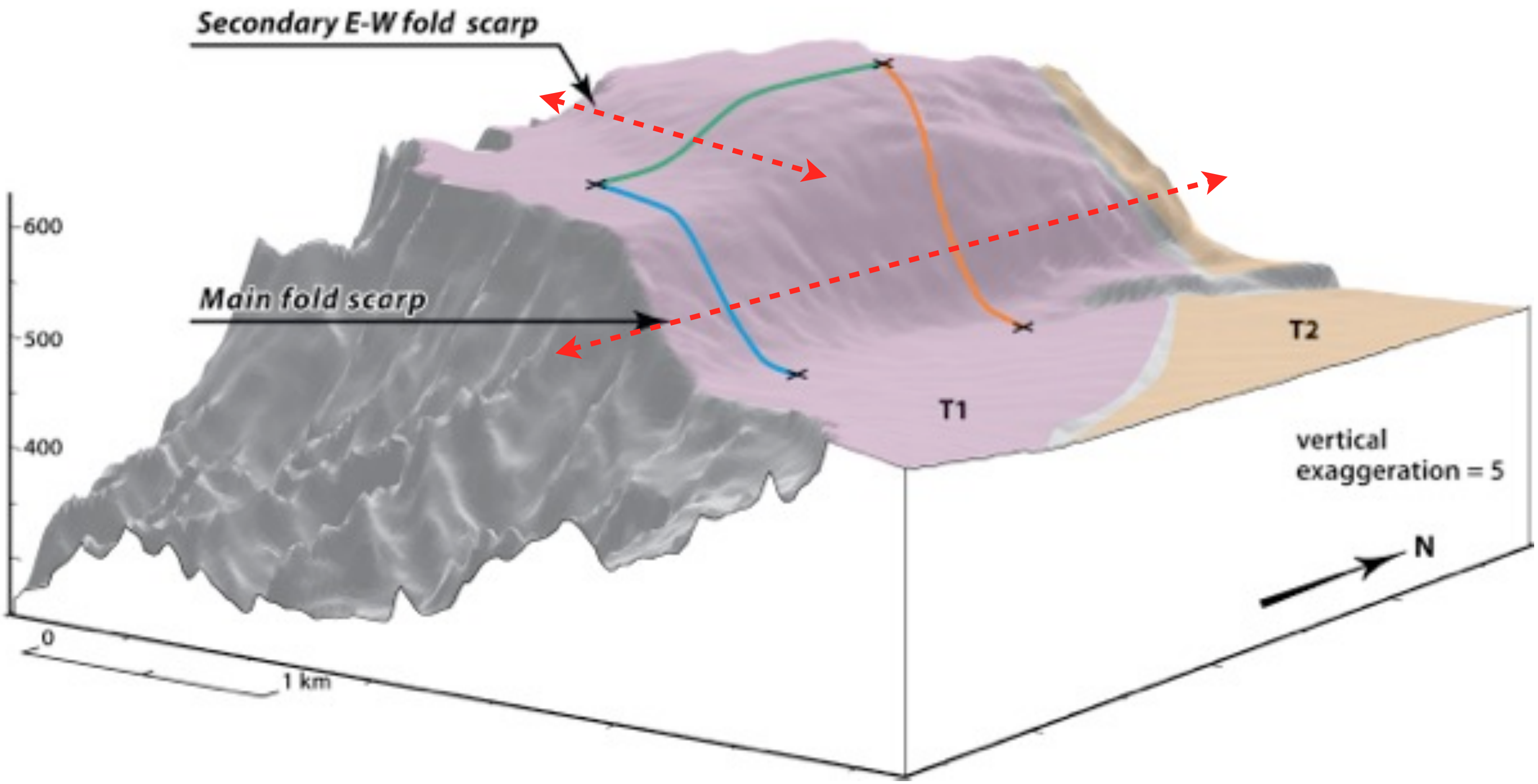

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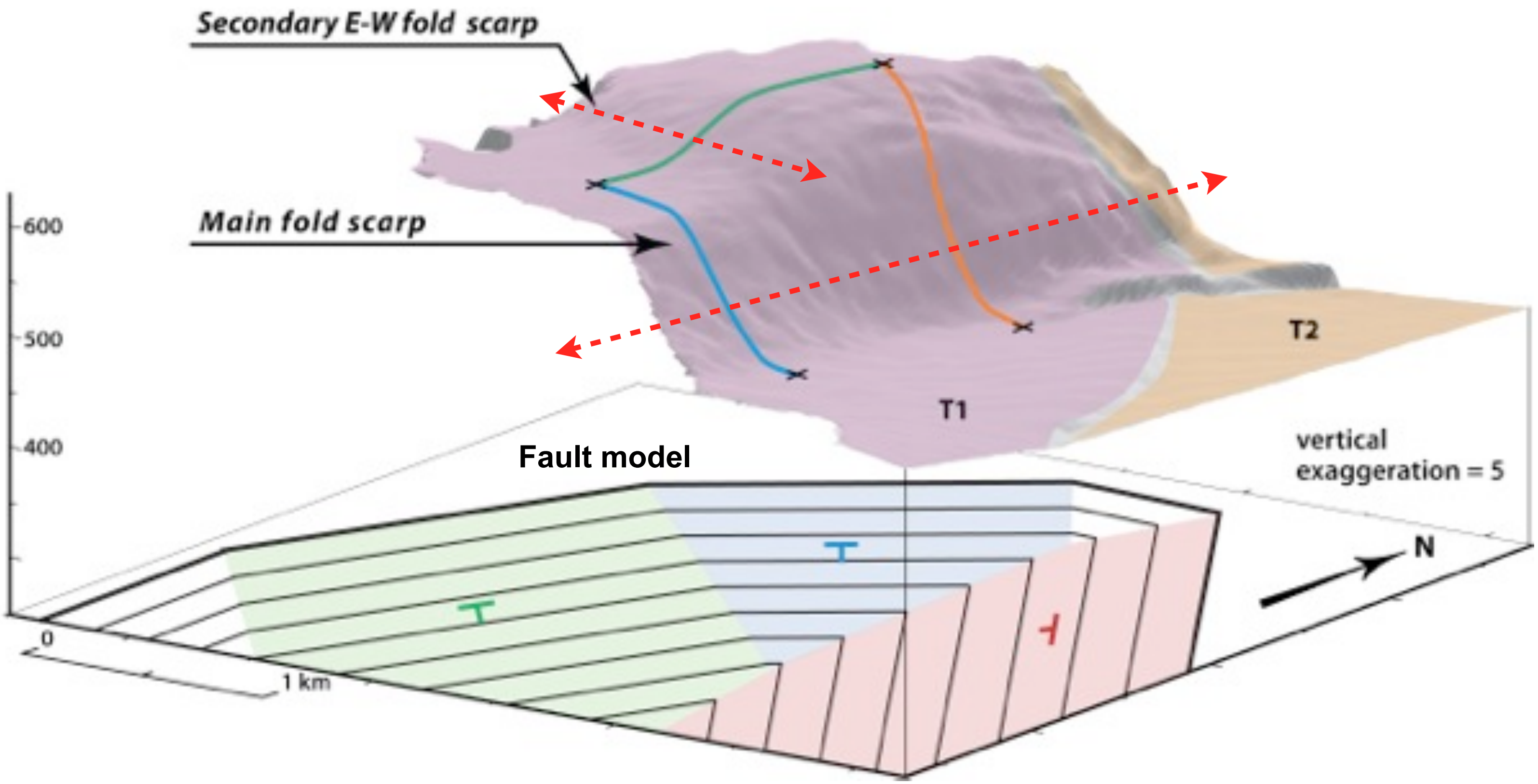


- Recipe 2: **height of fold scarp:**

  $$S = \Delta h \,/\, (\sin \theta_2 . \cos \alpha_2 - \sin \theta_1 . \cos \alpha_1)$$

- Recipe 3: **width of fold back limb:**

  $$S = W_L \,/\, \cos \alpha$$

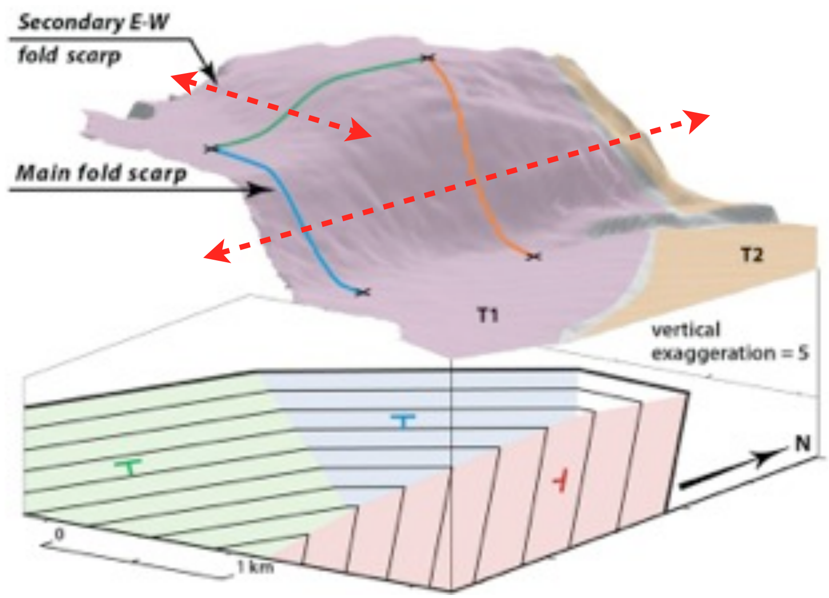
=> 3D : determine simultaneously amplitude and azimuth of long-term slip vector

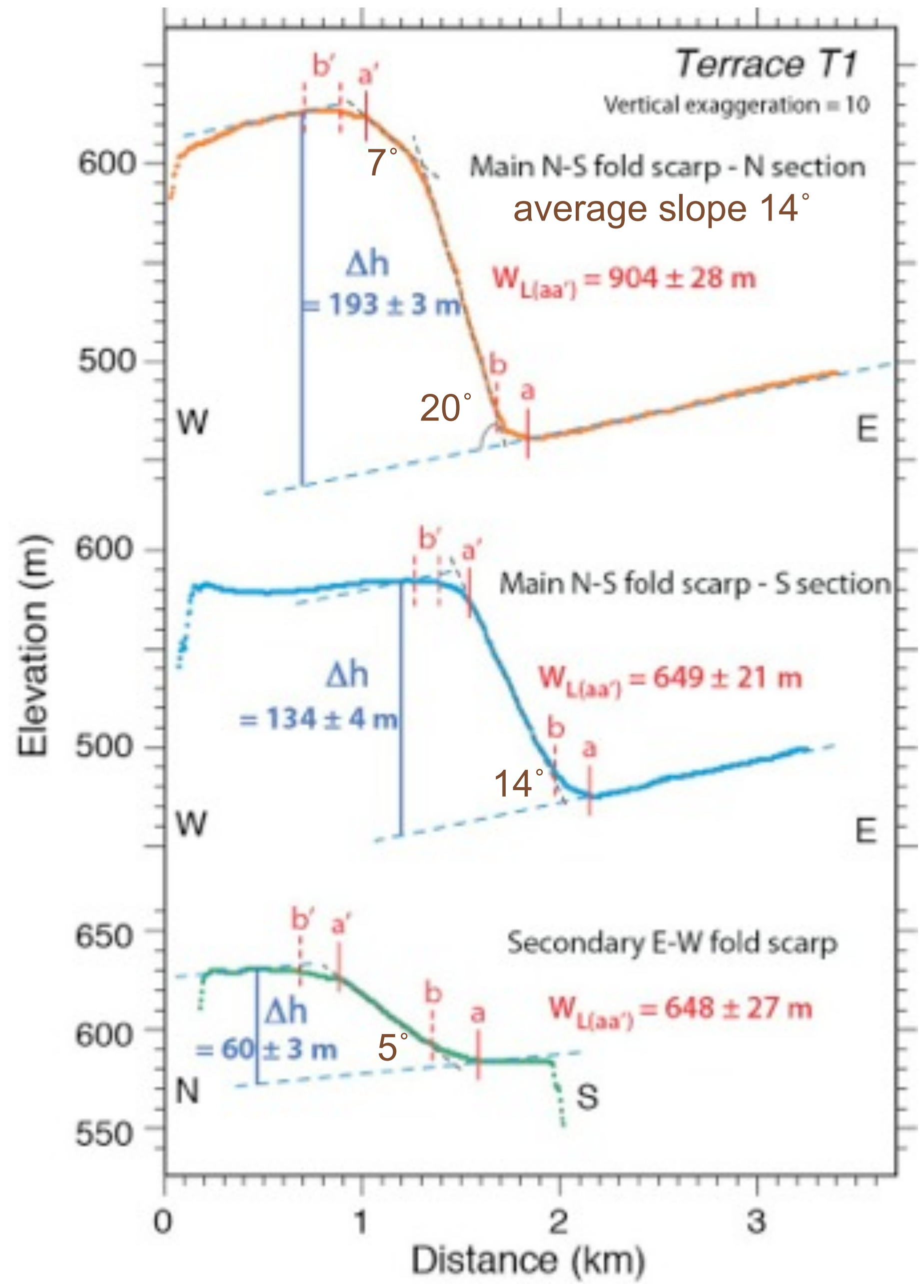
Deformation of the terraces

Measurements of **scarp relief Δh**

and fold **back limb width W_L**

for each of the 3 fold scarps.

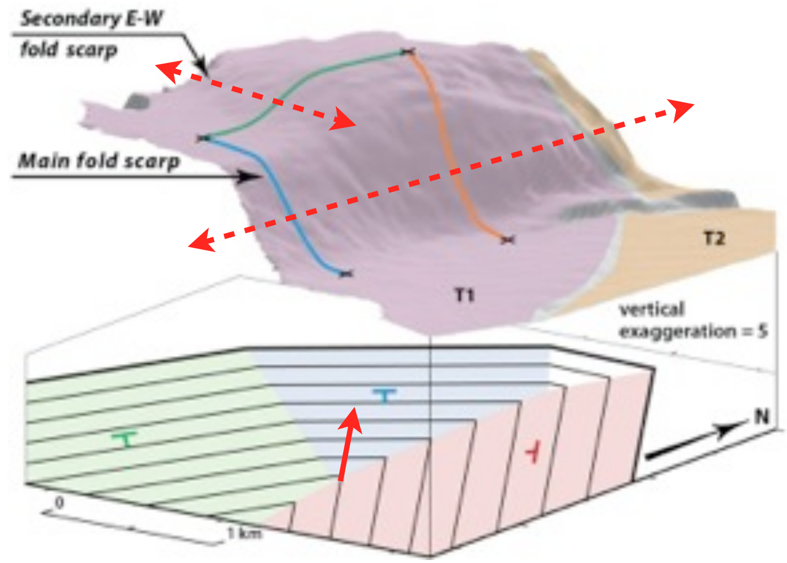


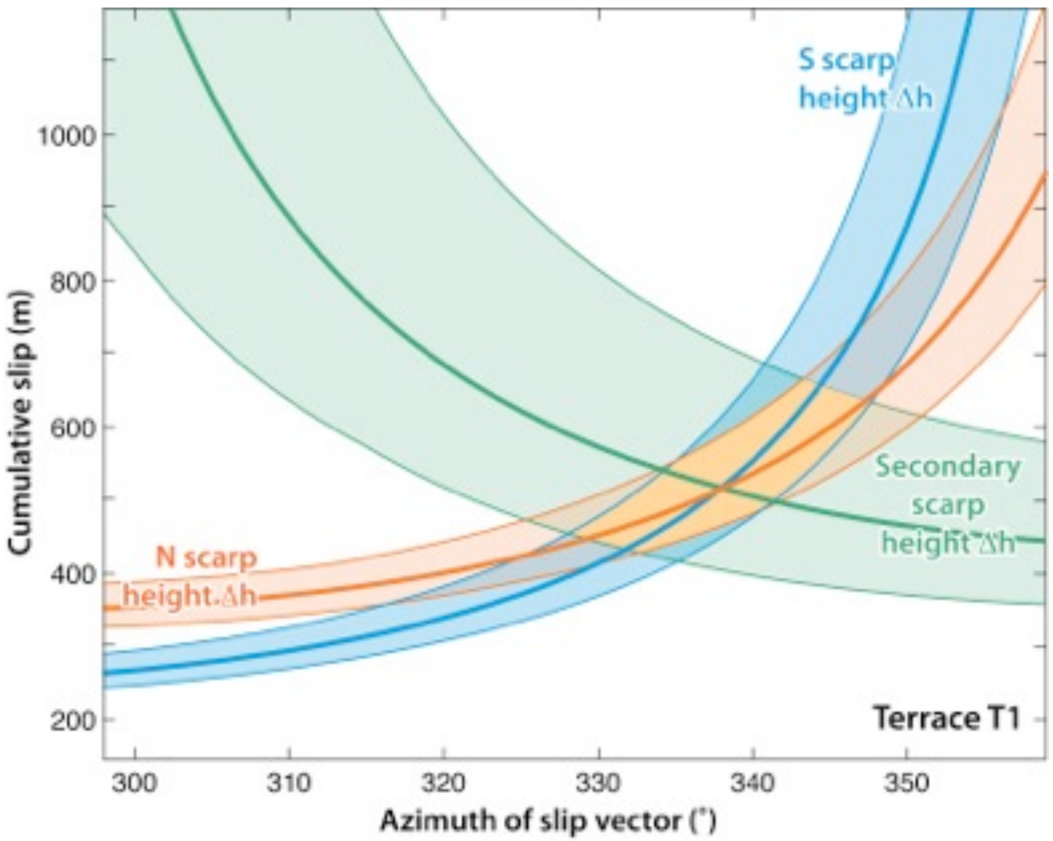


From terrace deformation to cumulative slip: T1

Results from scarp heights:

$$S = \Delta h / (\sin \theta_2 . \cos \alpha_2 - \sin \theta_1 . \cos \alpha_1)$$





From terrace deformation to cumulative slip: T1

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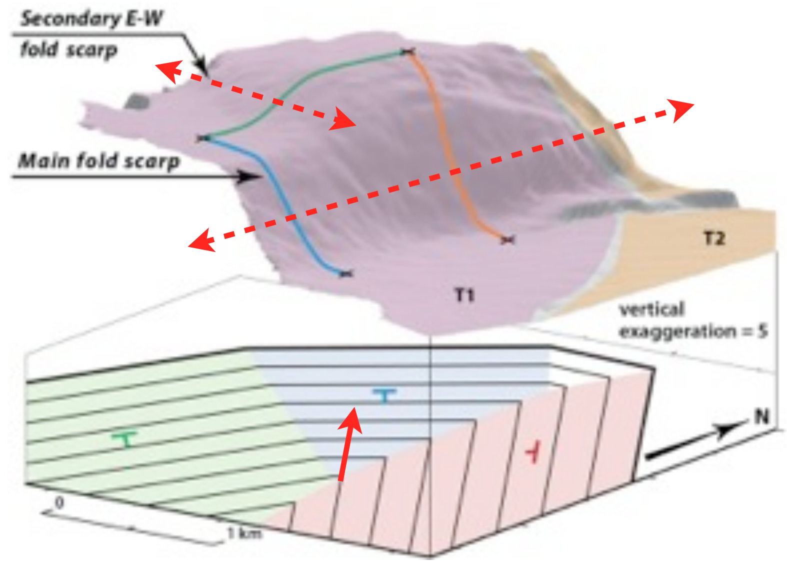
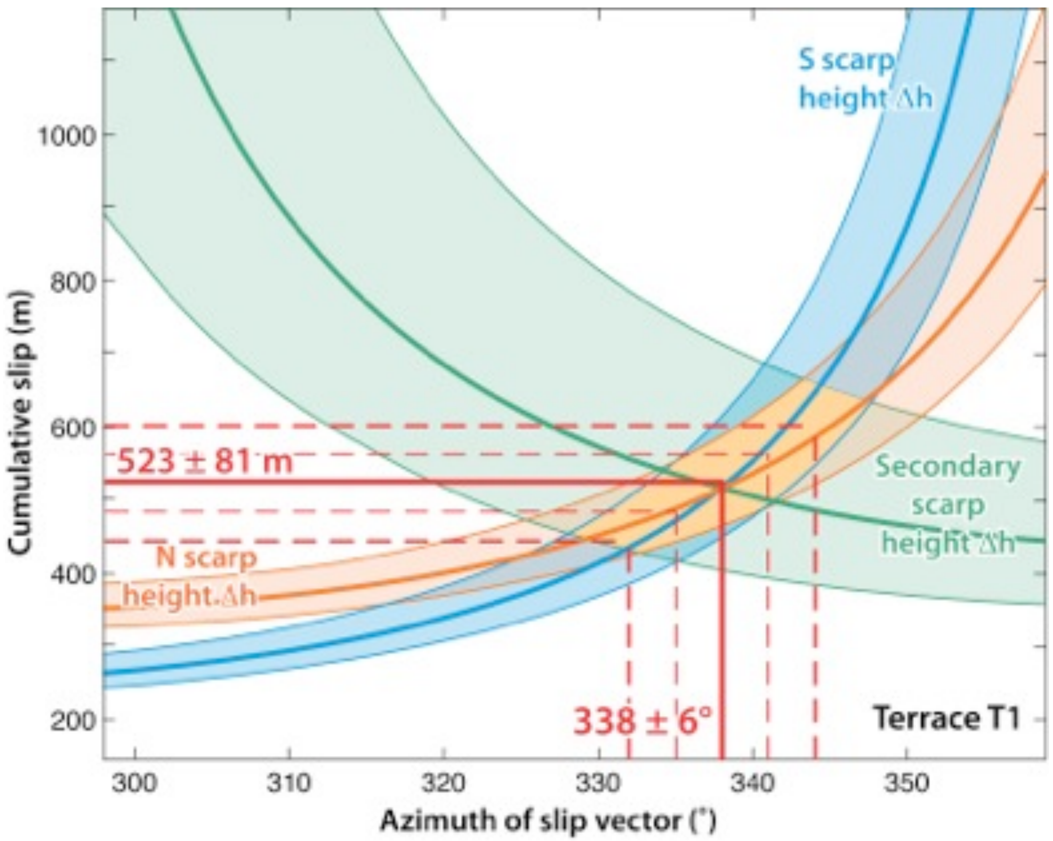
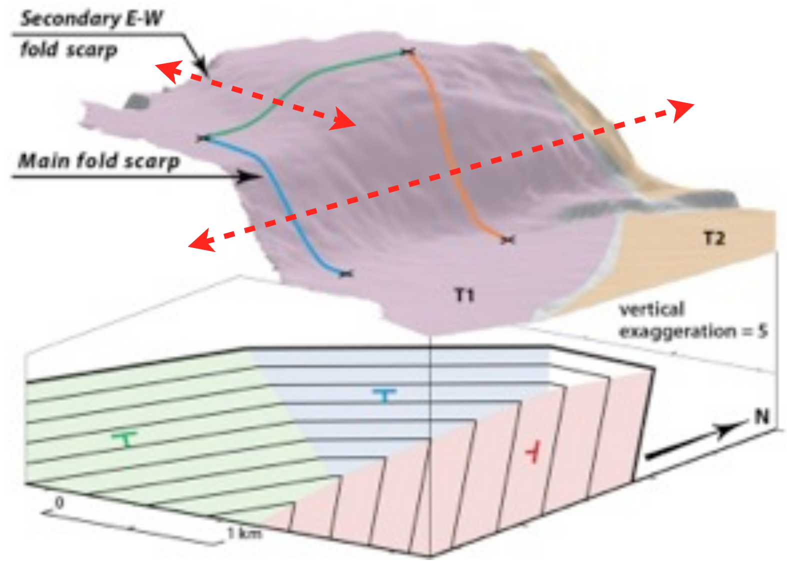


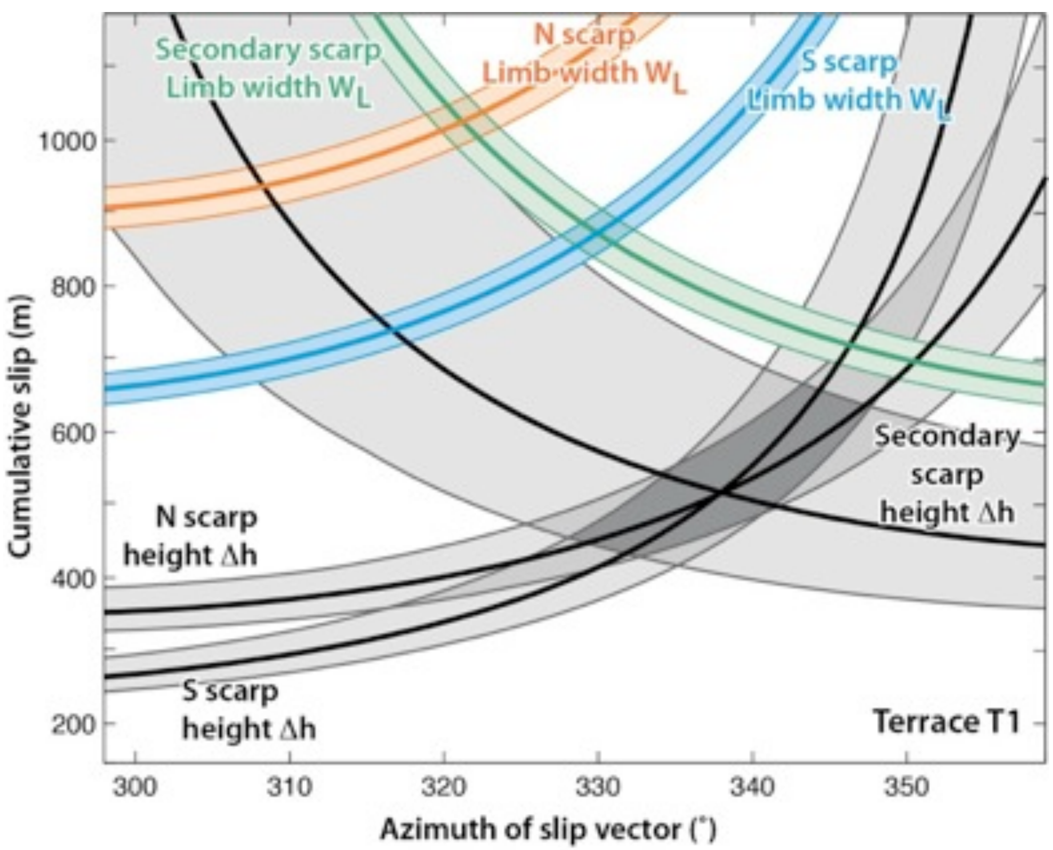


From terrace deformation to cumulative slip: T1

What about fold back limb width?

$S = W_L \,/\, \cos\alpha$



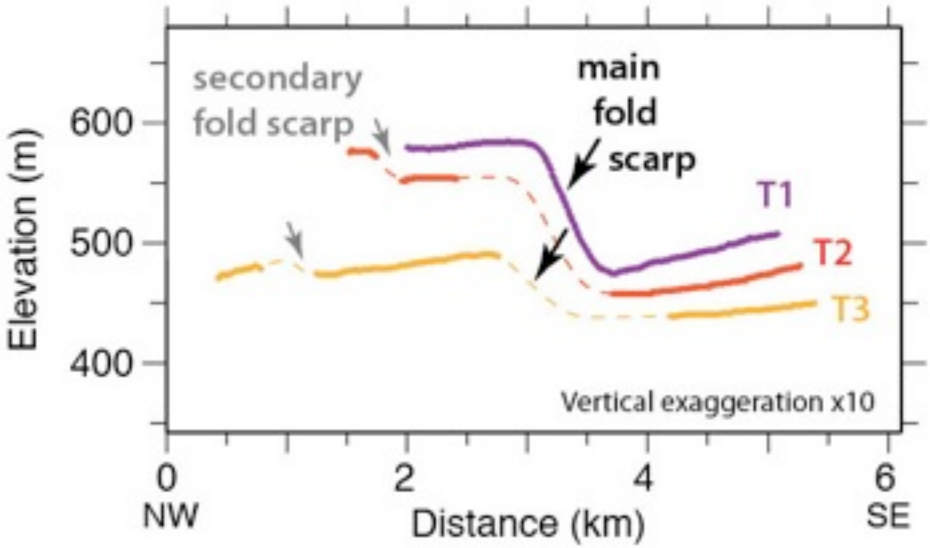


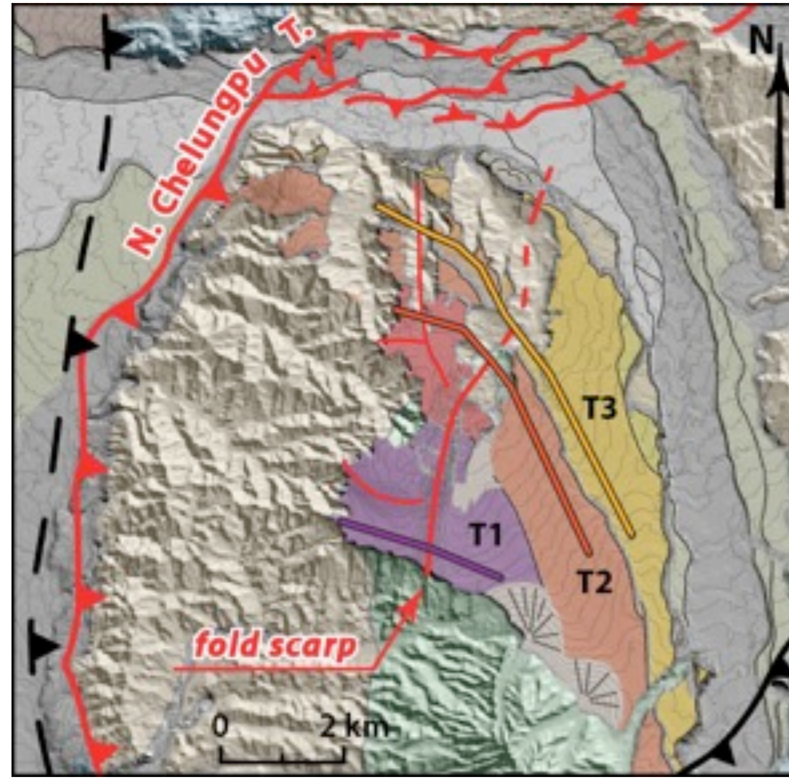
=> W_L models largely overestimate ΔH solution

+ expected slope angle = 30° while observed slope angle = 14°

How to explain this ?

Fold scarp geometry in map view

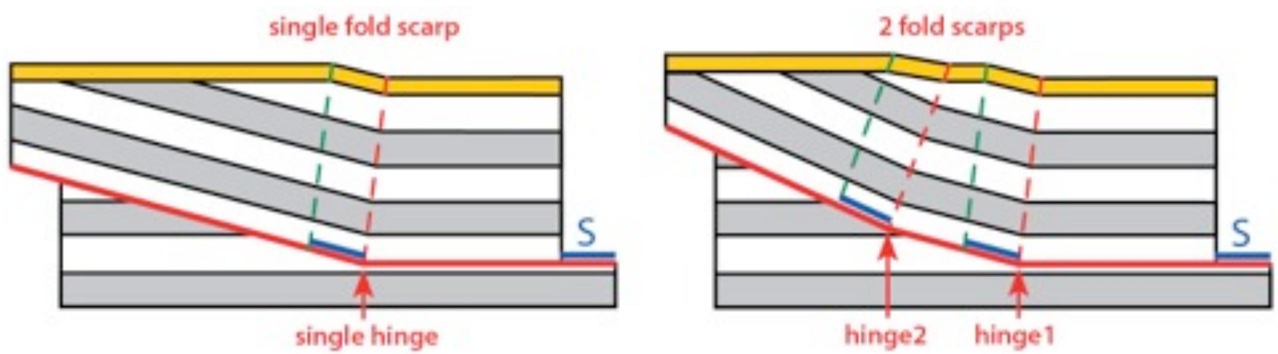




Evidence for **2 fold scarps** across T2 and T3

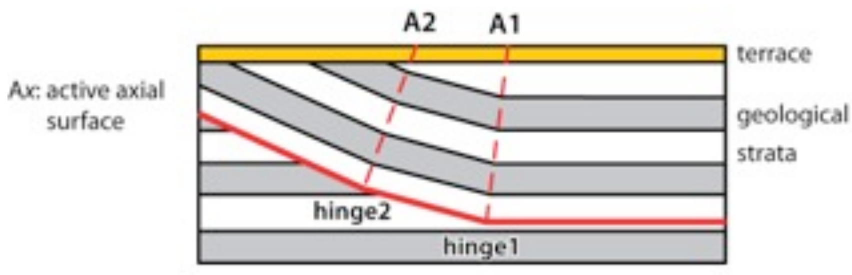
=> Existence of a **double fault bend**

=> This double bend may also exist under T1...



Folding above a double fault bend

a. Initial stage:



Modified from

Medwedeff & Suppe (1997)

Folding above a double fault bend

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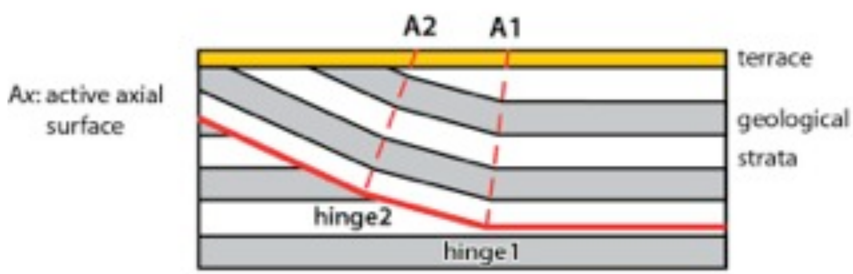
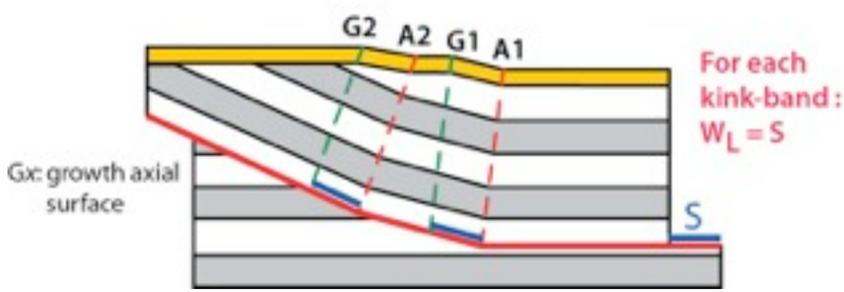


b. Fault slip S < distance A1-A2:



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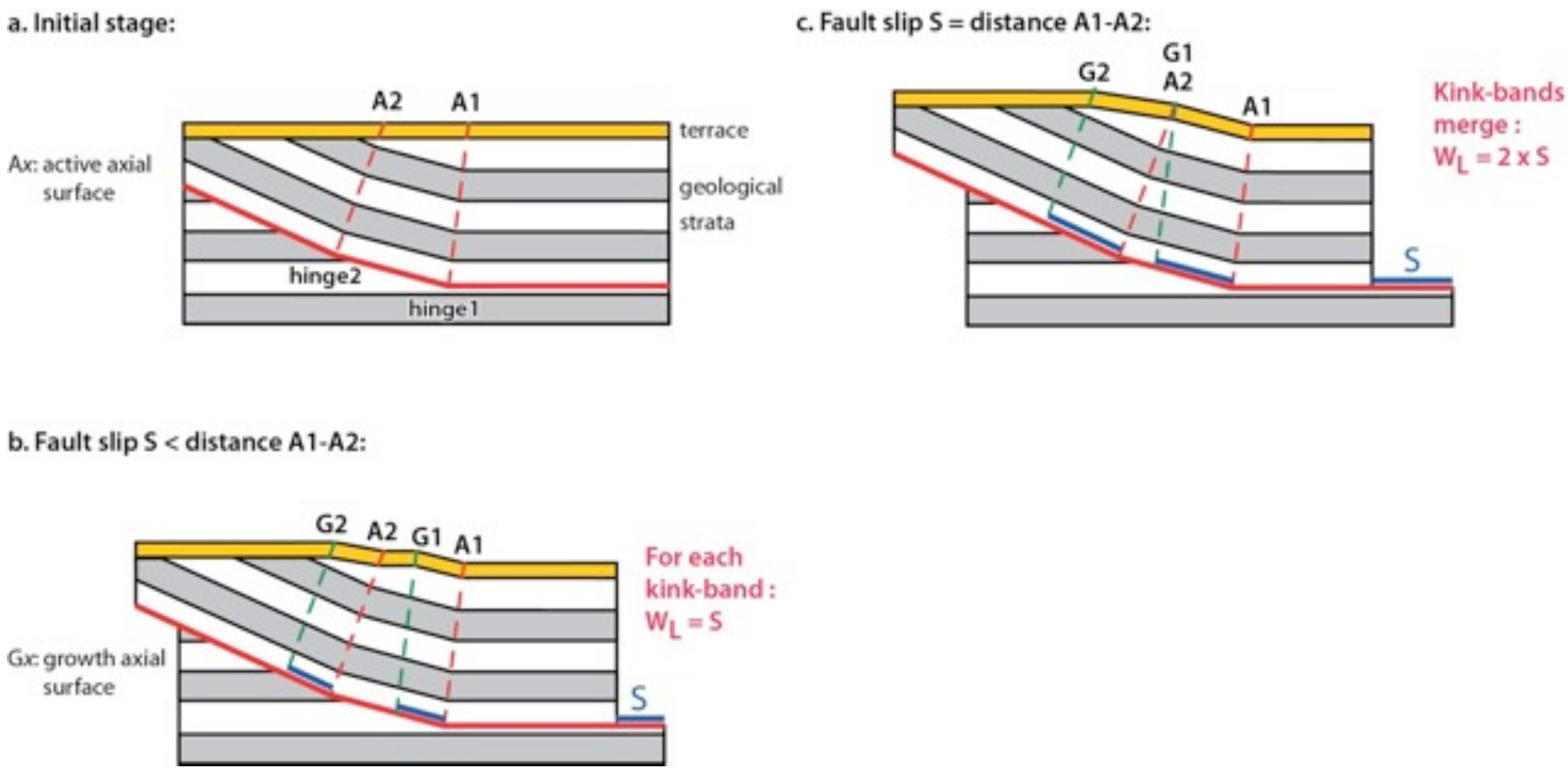

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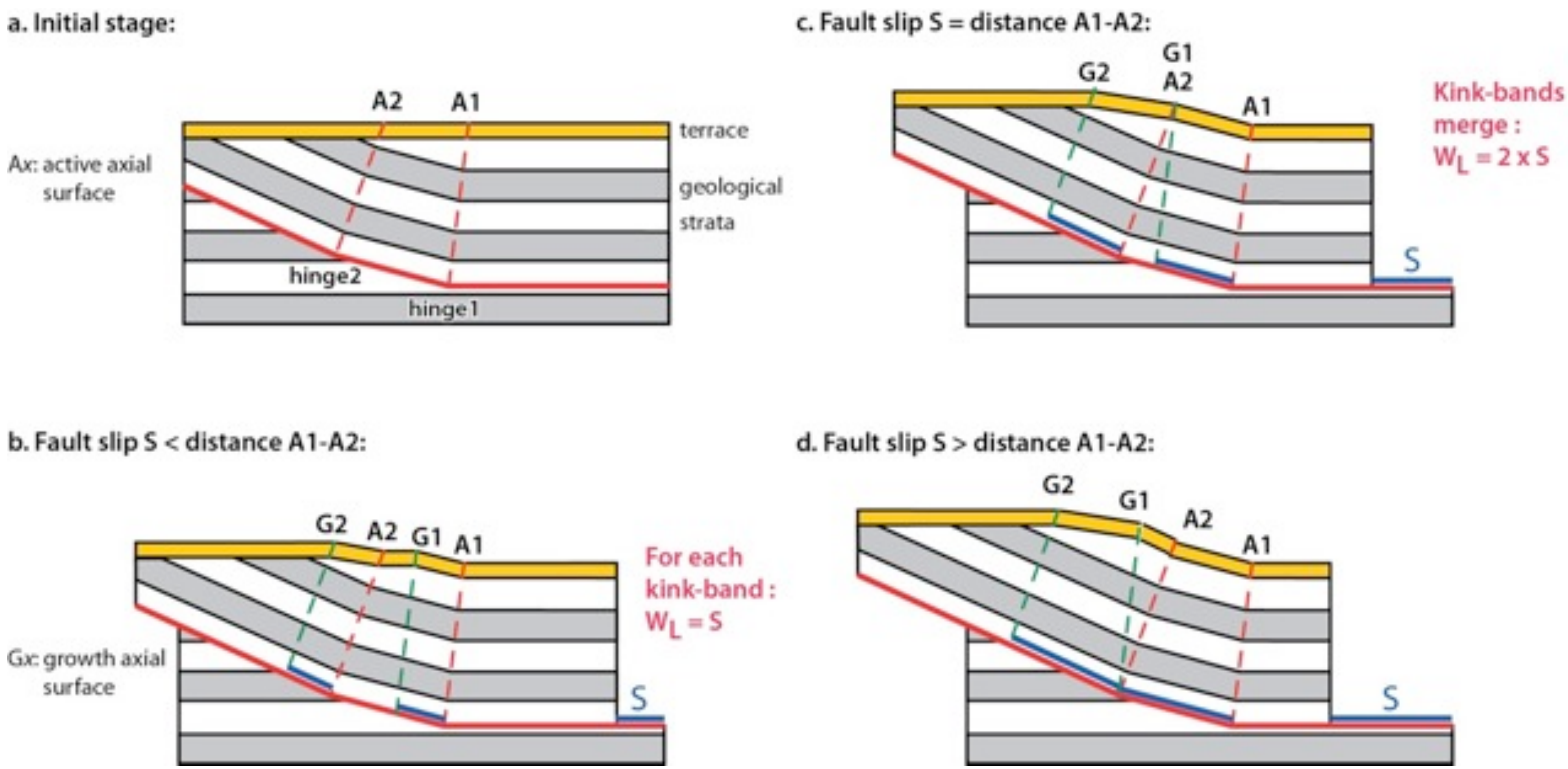

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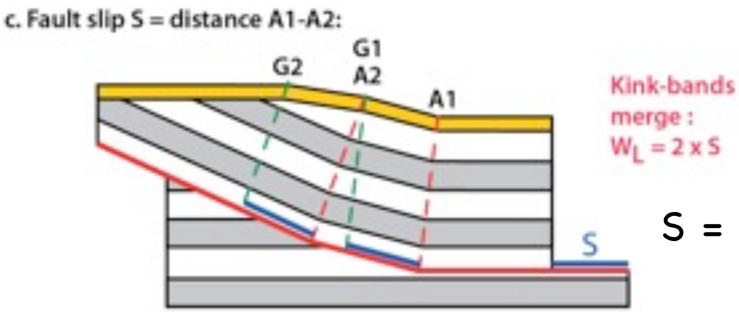
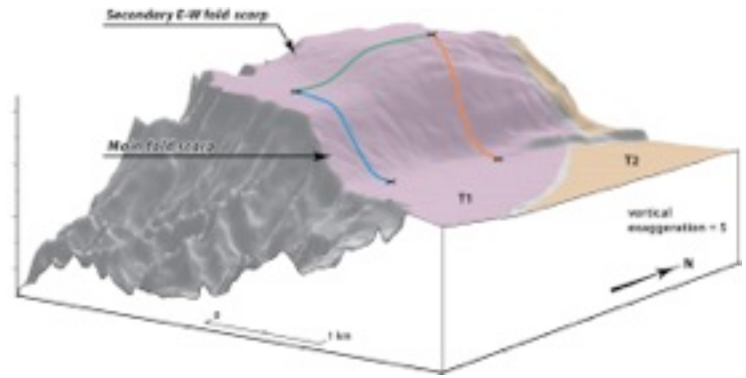
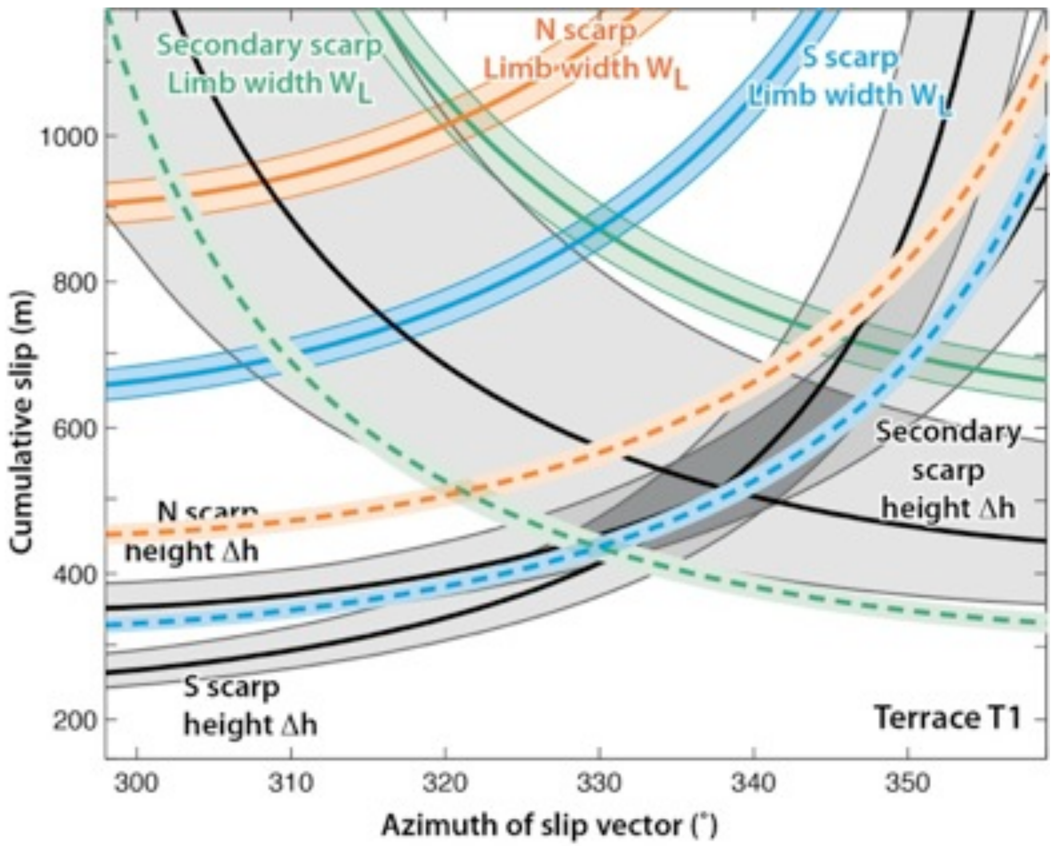
From terrace deformation to cumulative slip: T1



$S = 1/2 * W_L / \cos \alpha$





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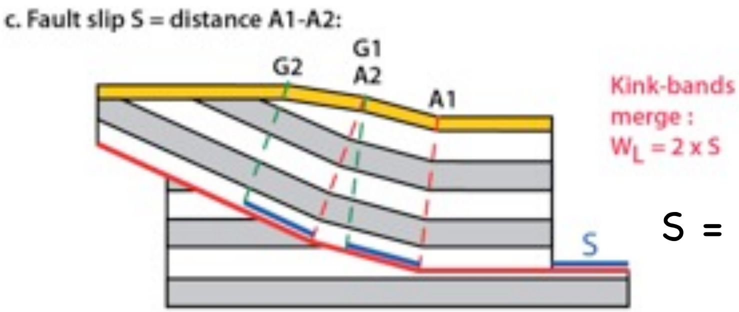

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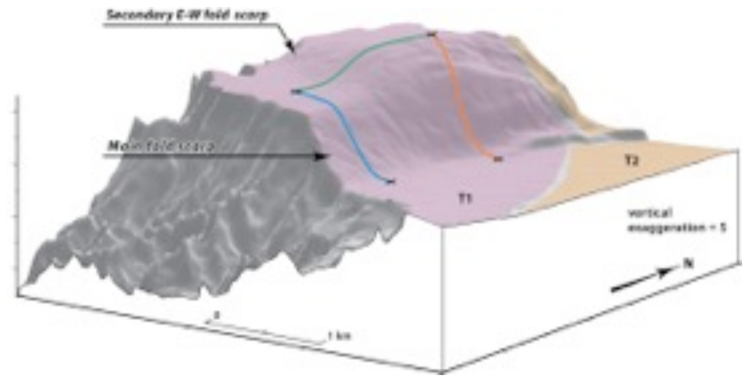
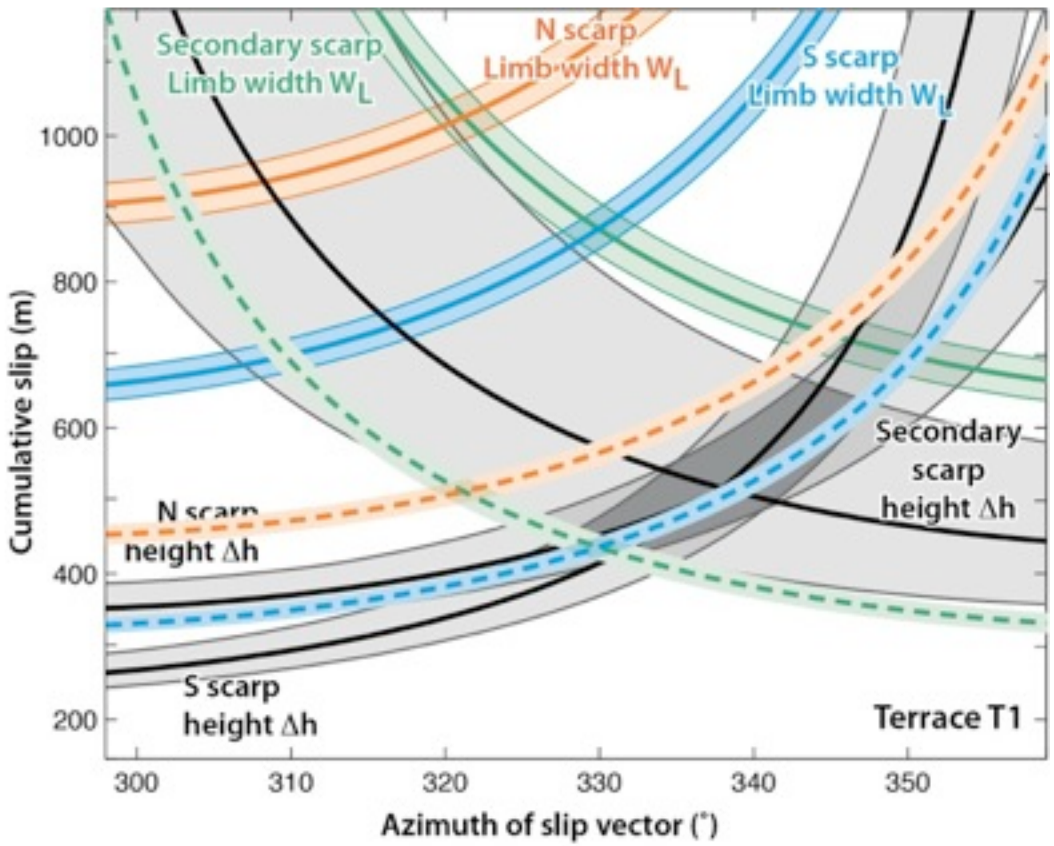




=> W_L models are biased due to merged kink-bands

$W_L = 2 \times S$

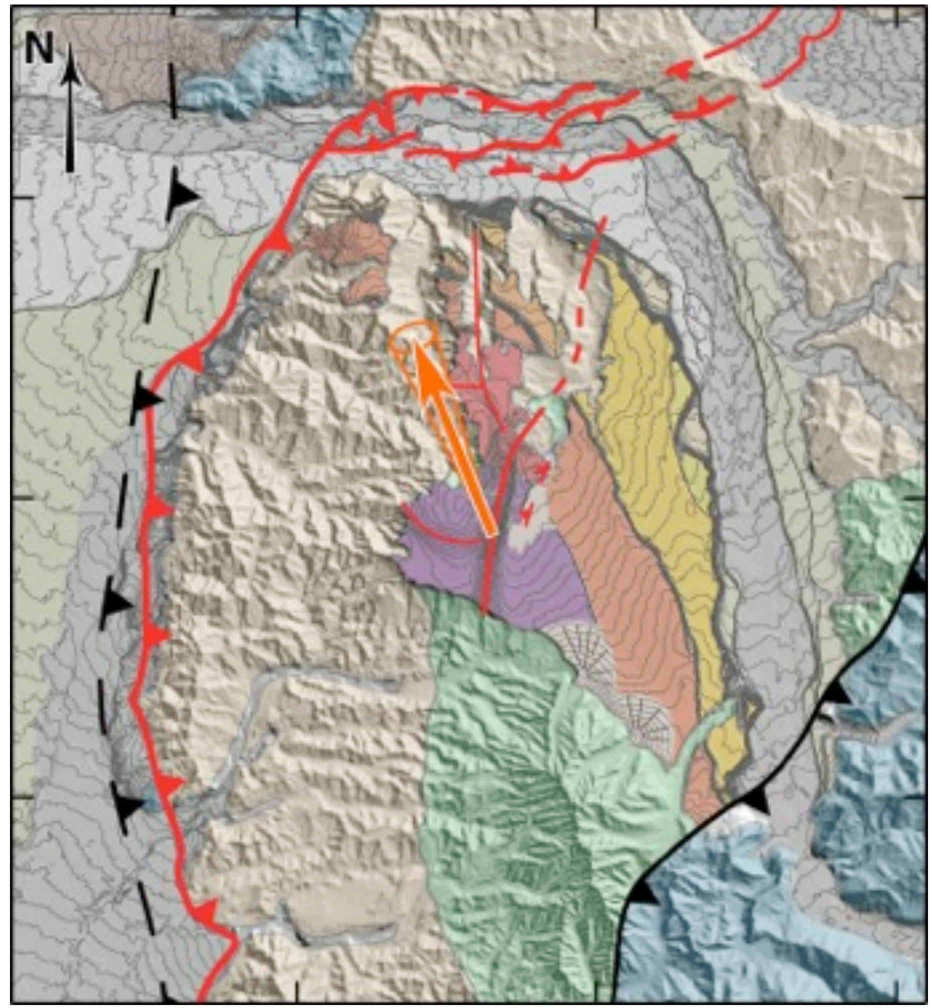
=> Long-term slip vector based on scarp relief:

523 ± 81 m oriented N338° ± 6°

Long-term slip vector versus Chi-Chi coseismic displacements

Long-term slip vector =

523 ± 81 m oriented N338° ± 6°



Cumulative fold scarp

Coseismic displacements from Yang et al (2000), Yu et al (2001), Dominguez et al (2003)

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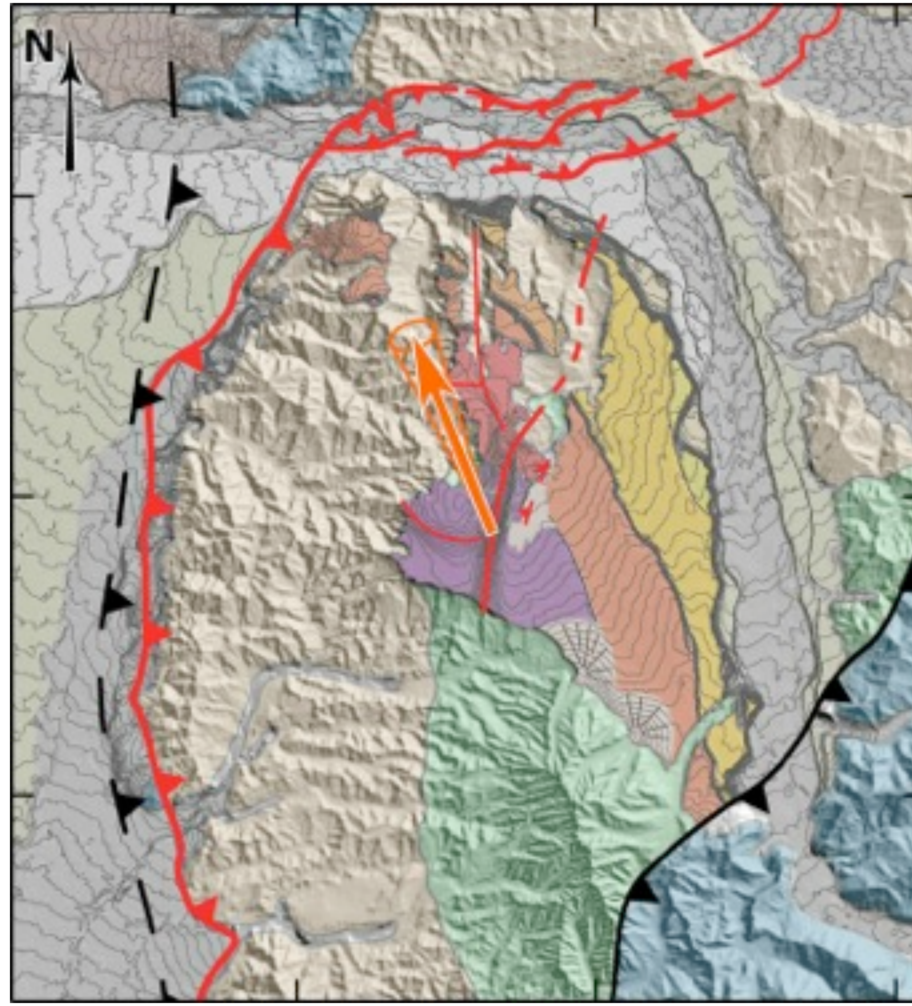
=> Long-term slip vector parallels

Chi-Chi coseismic displacements !



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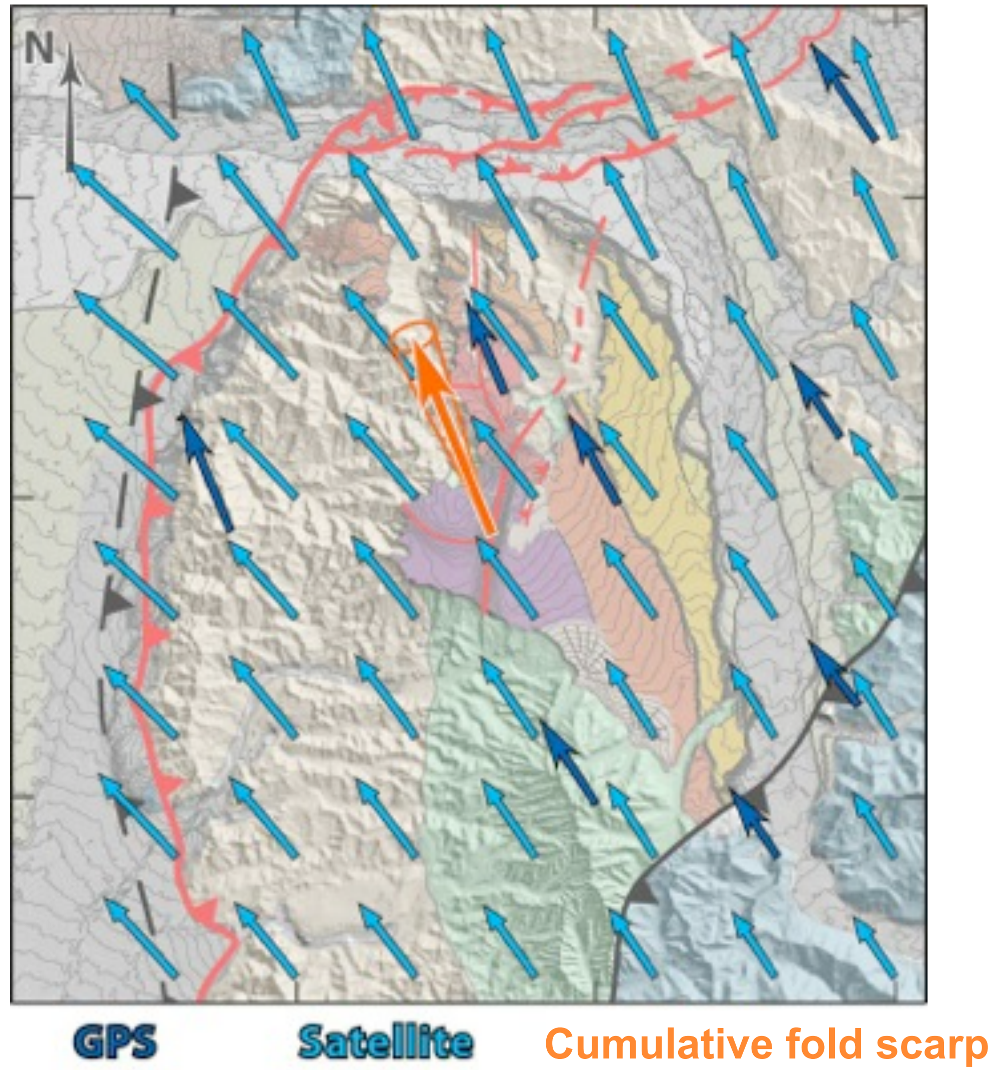
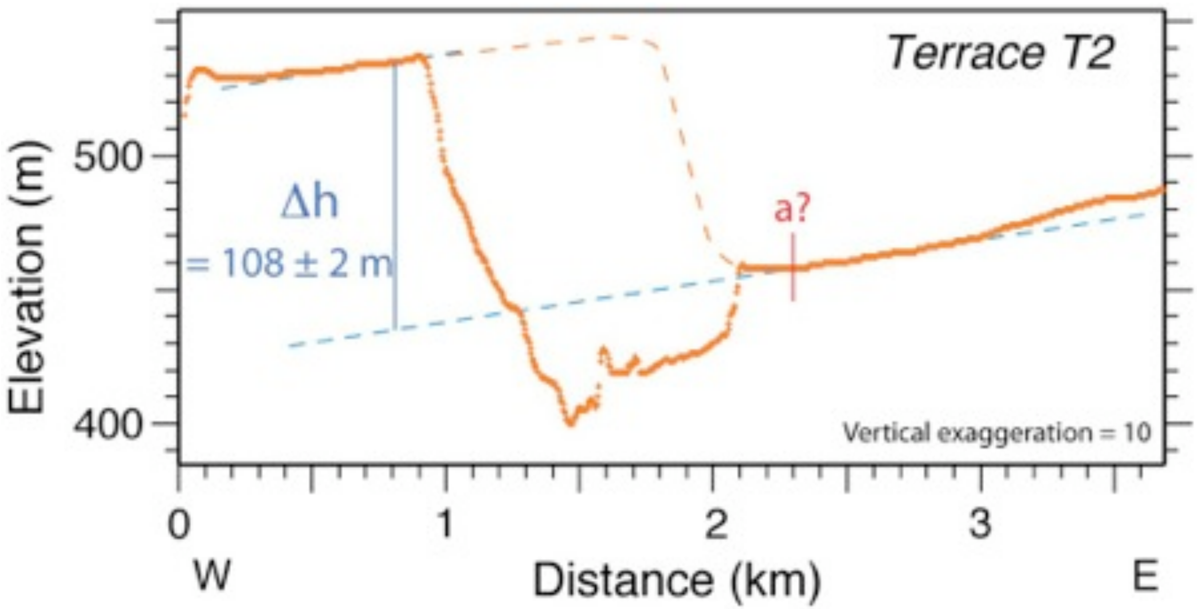


Coseismic displacements from Yang et al (2000),
Yu et al (2001), Dominguez et al (2003)

From terrace deformation to cumulative slip: T2

Fold back limb eroded away:



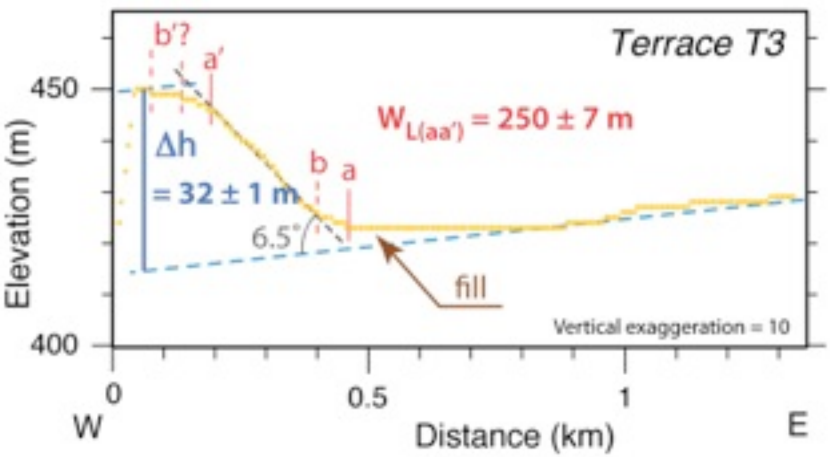
Using scarp relief ΔH + azimuth N338°±6°

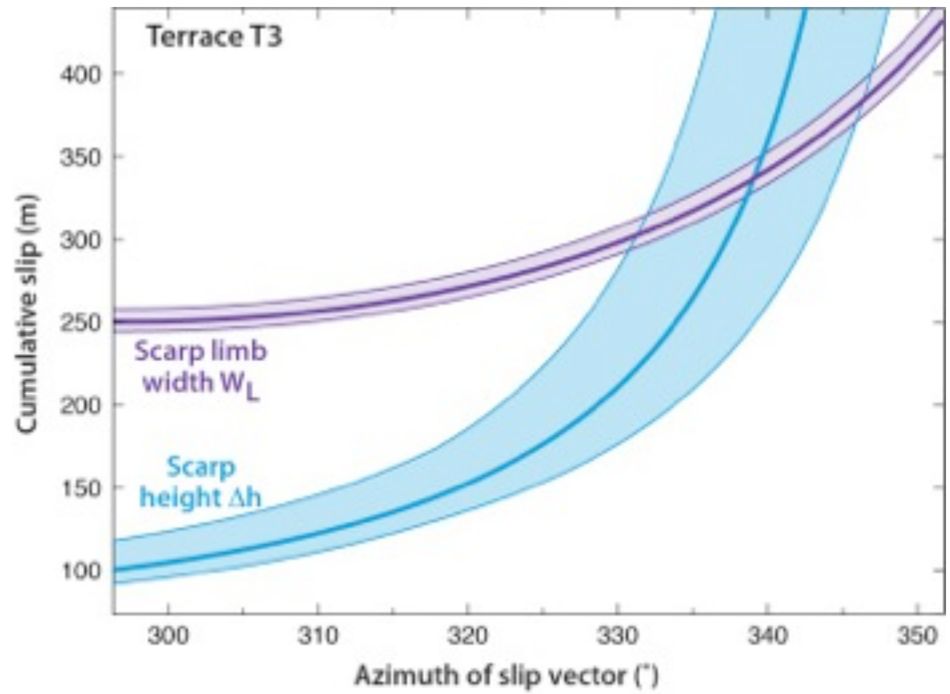
=> Slip = 432 ± 78 m

From terrace deformation to cumulative slip: T3

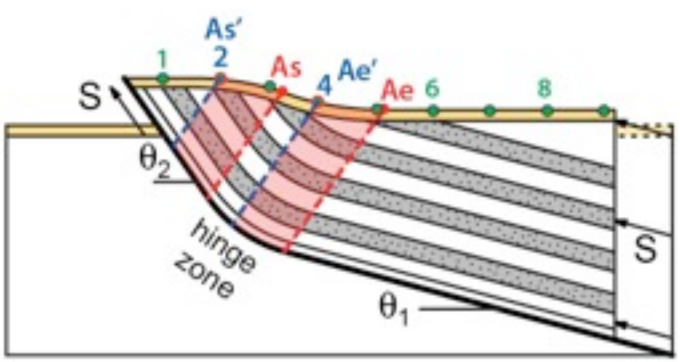
Back limb slope angle << predicted slope (21°)

=> immature fold scarp





Fault slip S < hinge width => $W_L > S$



From terrace deformation to cumulative slip: T3

Back limb slope angle << predicted slope (21°)

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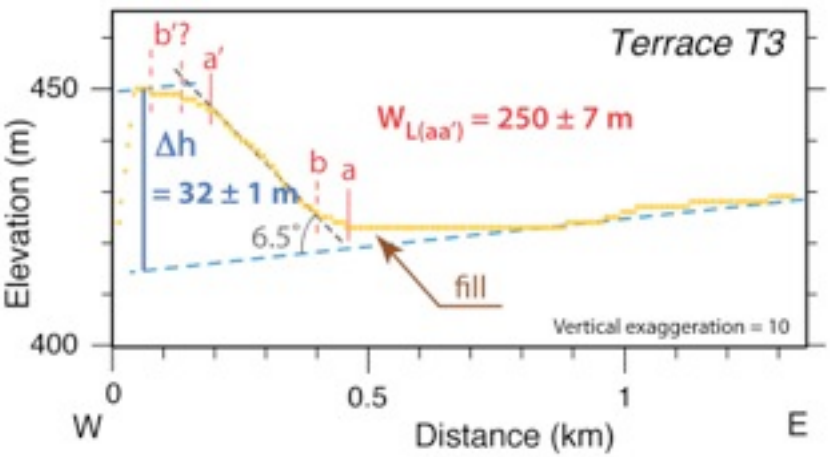

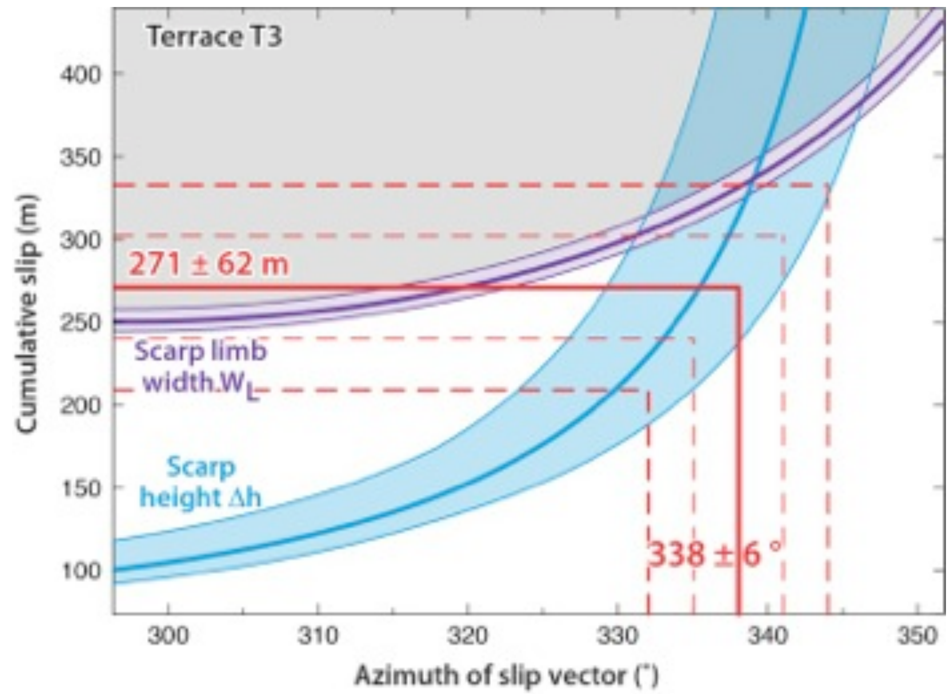

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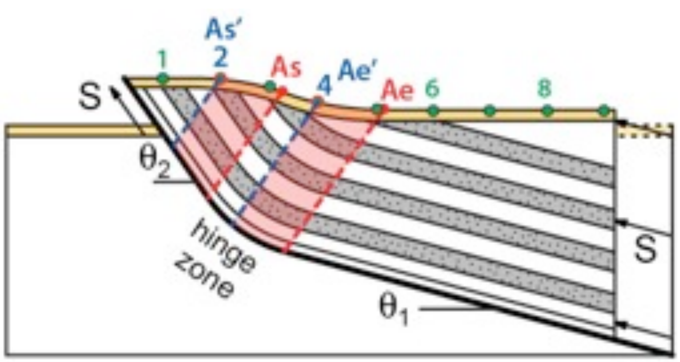
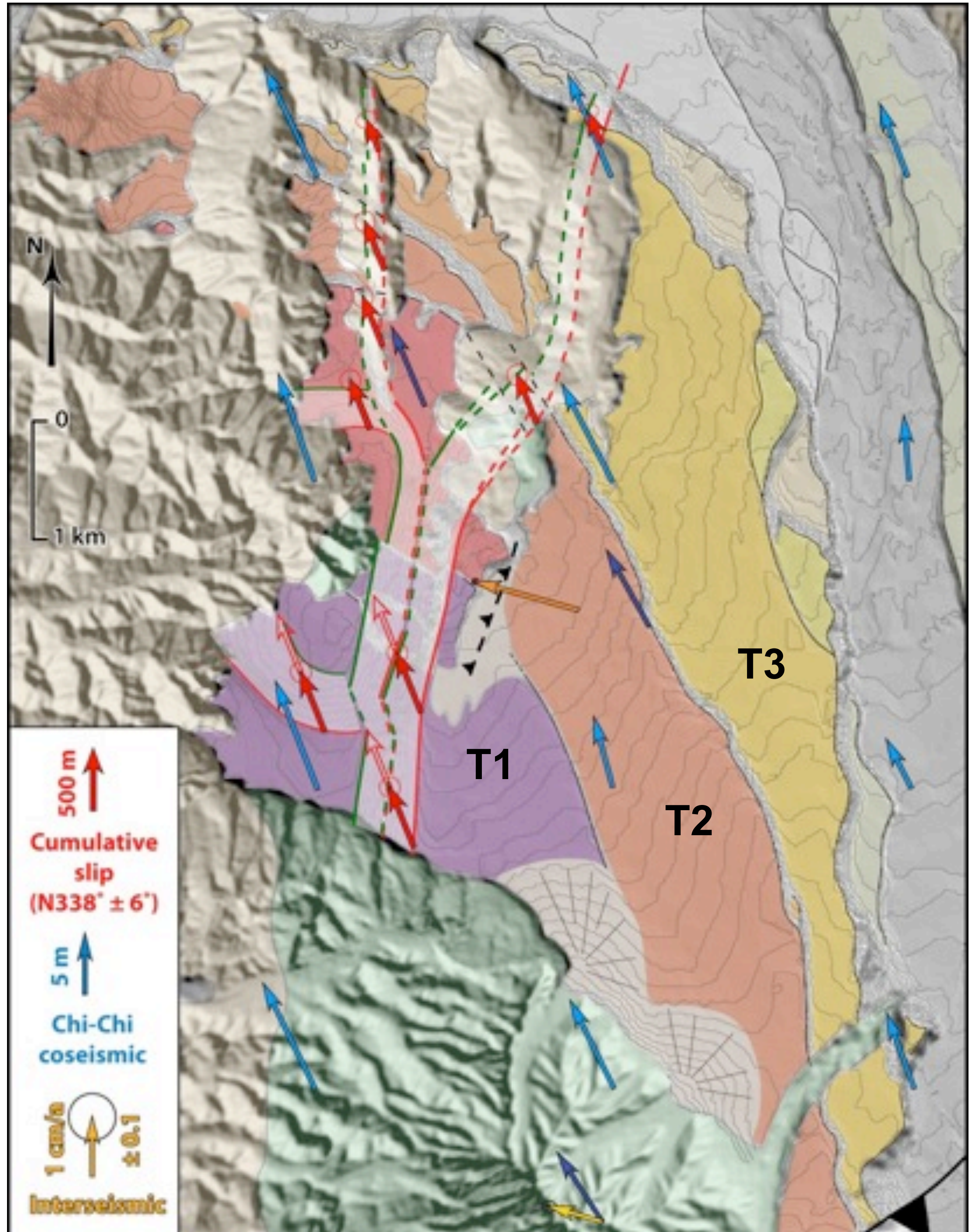


Cumulative slip results

- T1 : 3D-deformation ΔH:
=> Long-term slip vector
523 ± 81 m along N338° ± 6°

- Using N338° ± 6° and ΔH :
=> T2: 432 ± 78 m
=> T3: 271 ± 62 m

Long-term slip vector:
- Similar to Chi-Chi
- 45° away from interseismic



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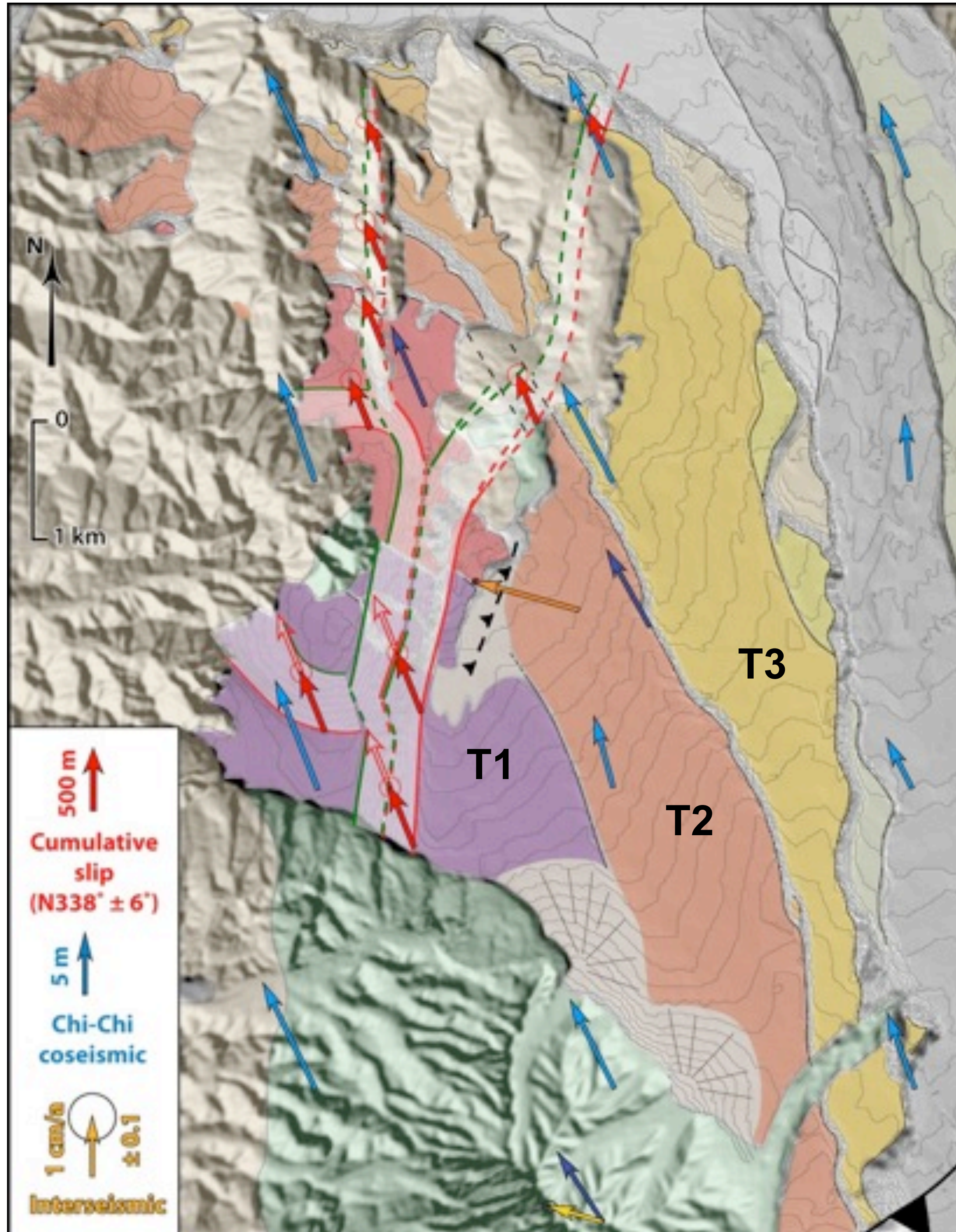
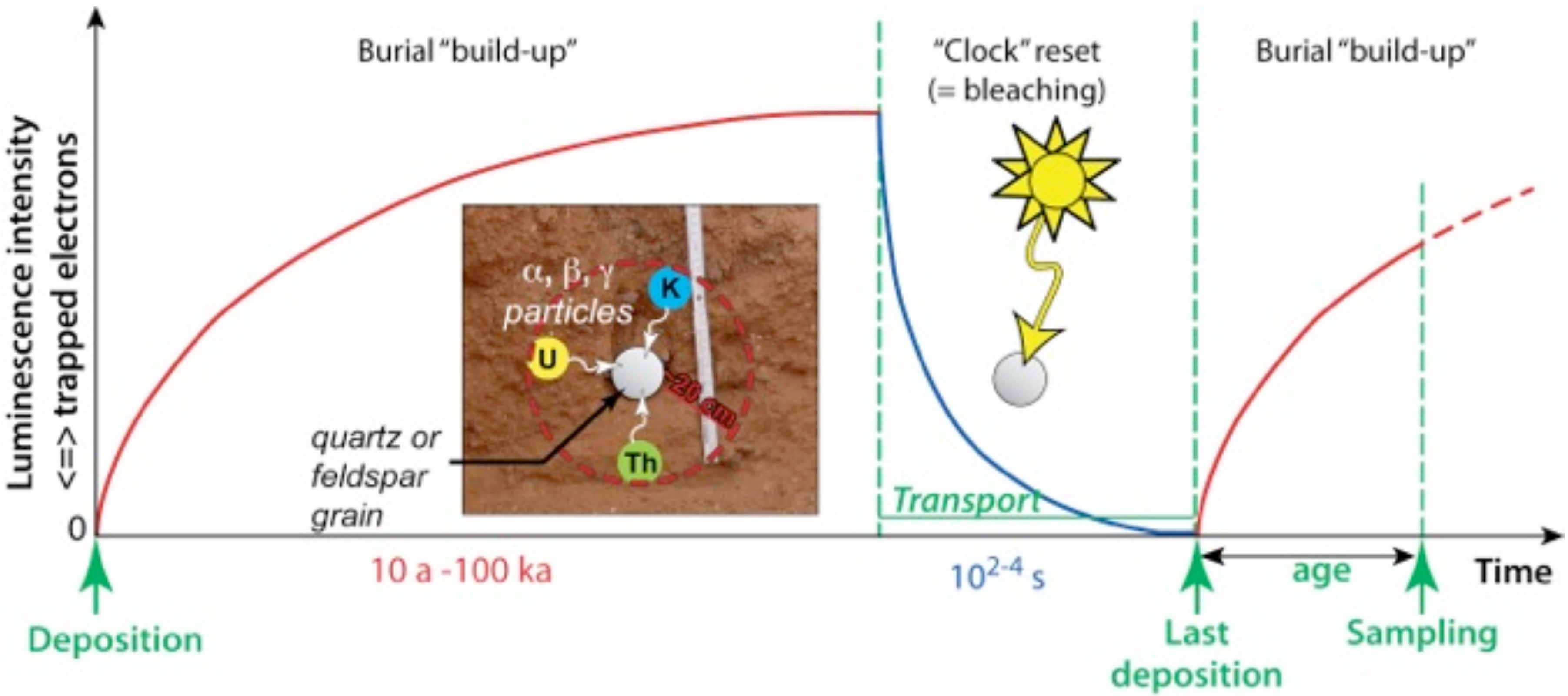
We now need a fault slip rate !

slip rate = slip / **deformation age**



Optically Stimulated Luminescence (OSL) dating: Principle



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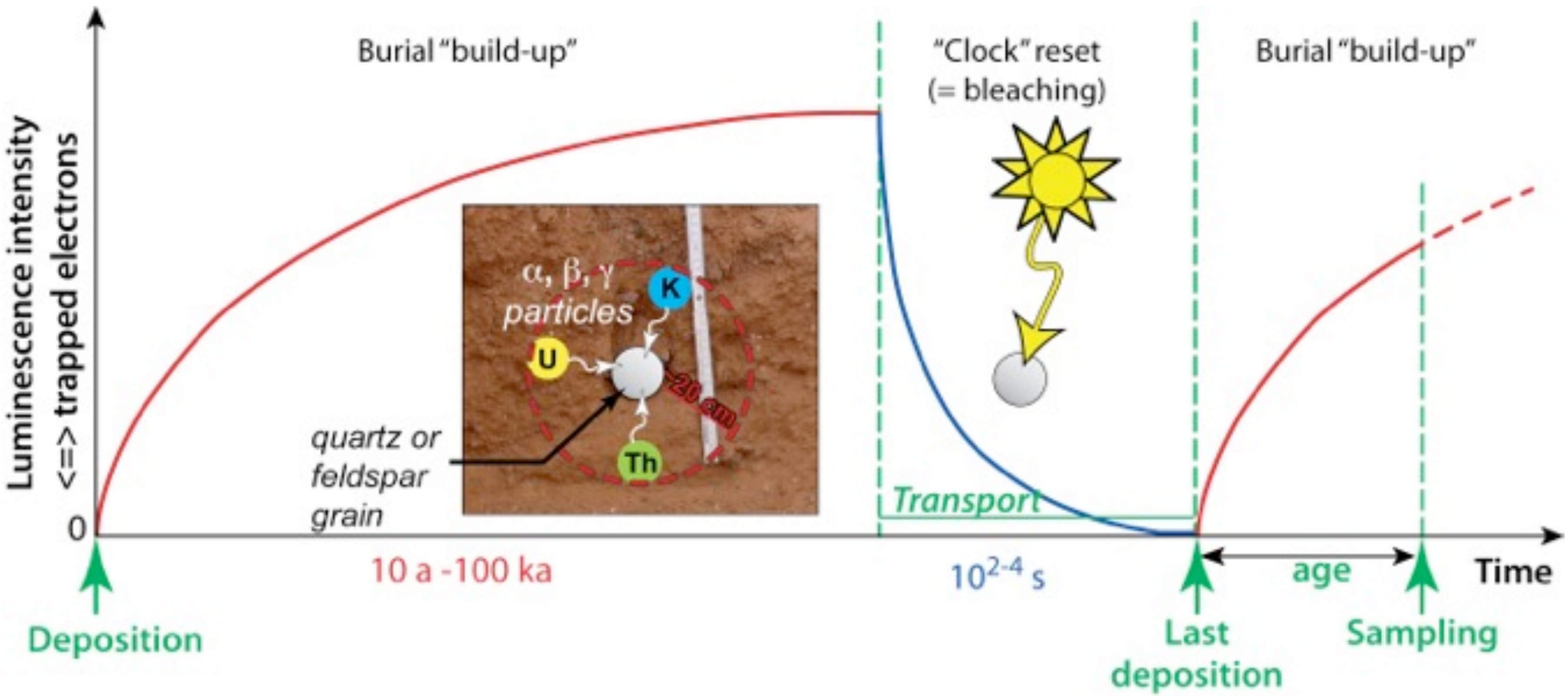
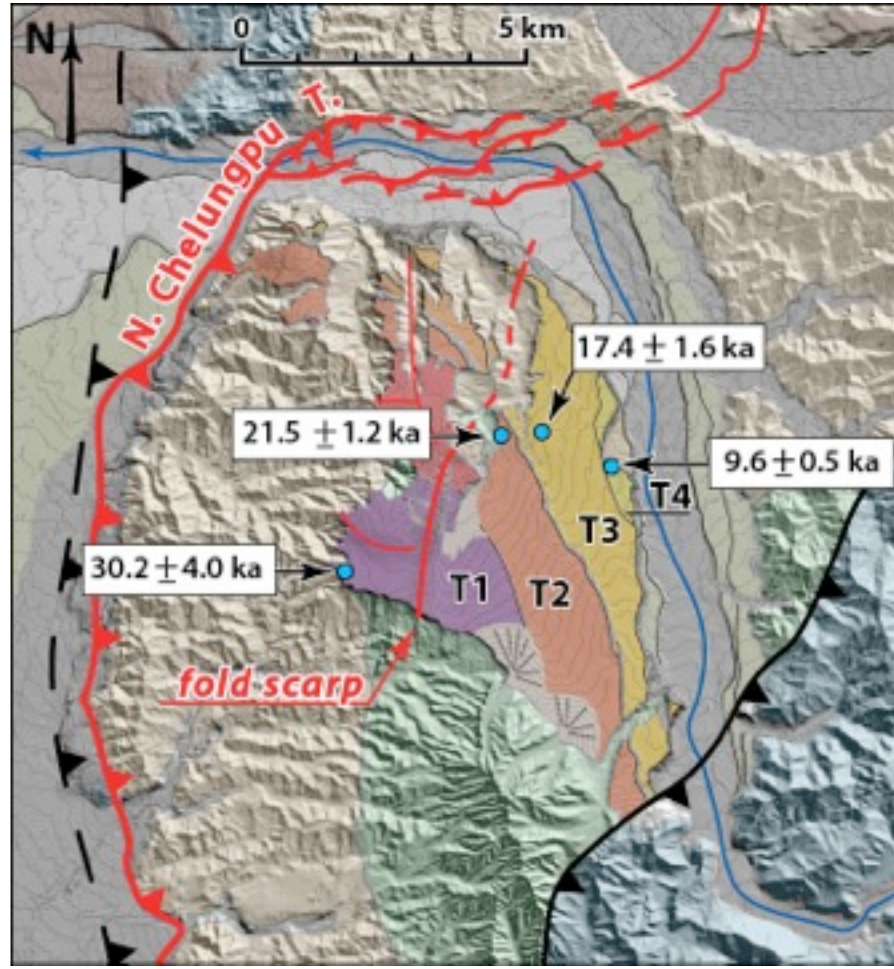


$$\text{Age} = \frac{\text{acquired luminescence (= paleodose)}}{\text{rate of luminescence acquisition (= dose rate)}}$$

acquired luminescence (= paleodose) → laboratory optical stimulation

rate of luminescence acquisition (= dose rate) → geochemistry

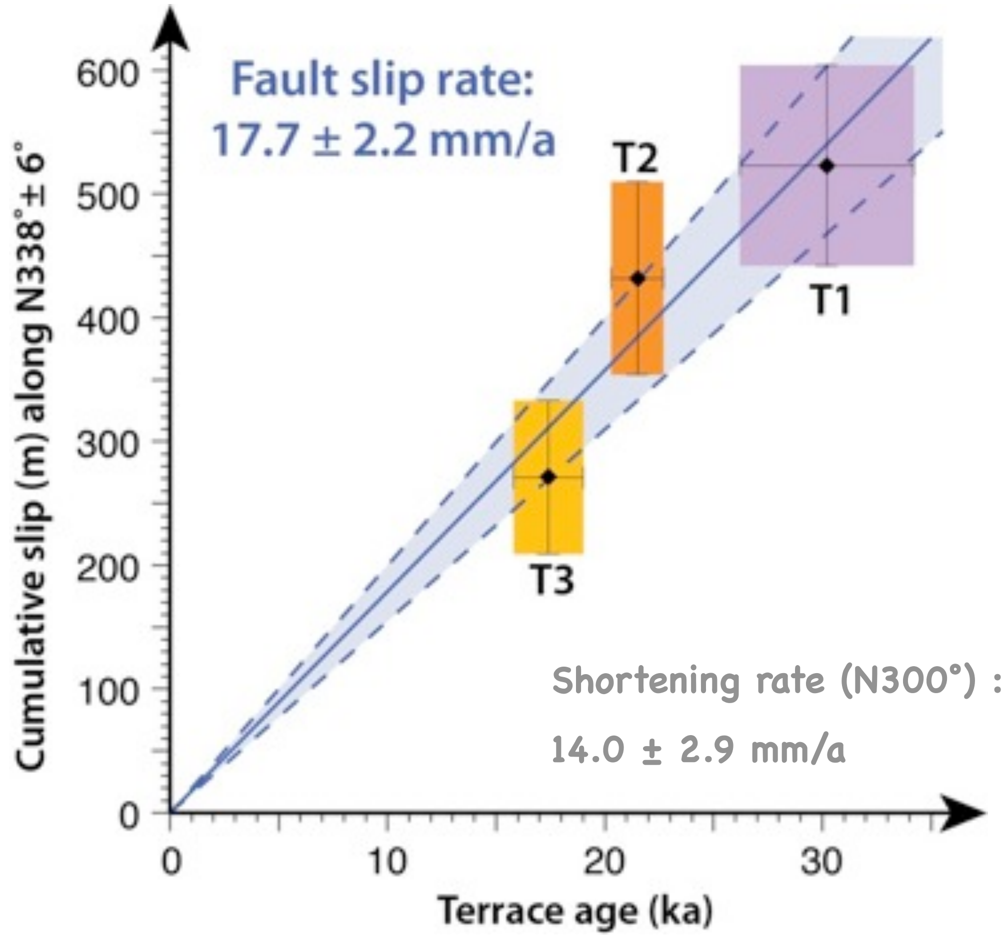
OSL ages



Consistent ages

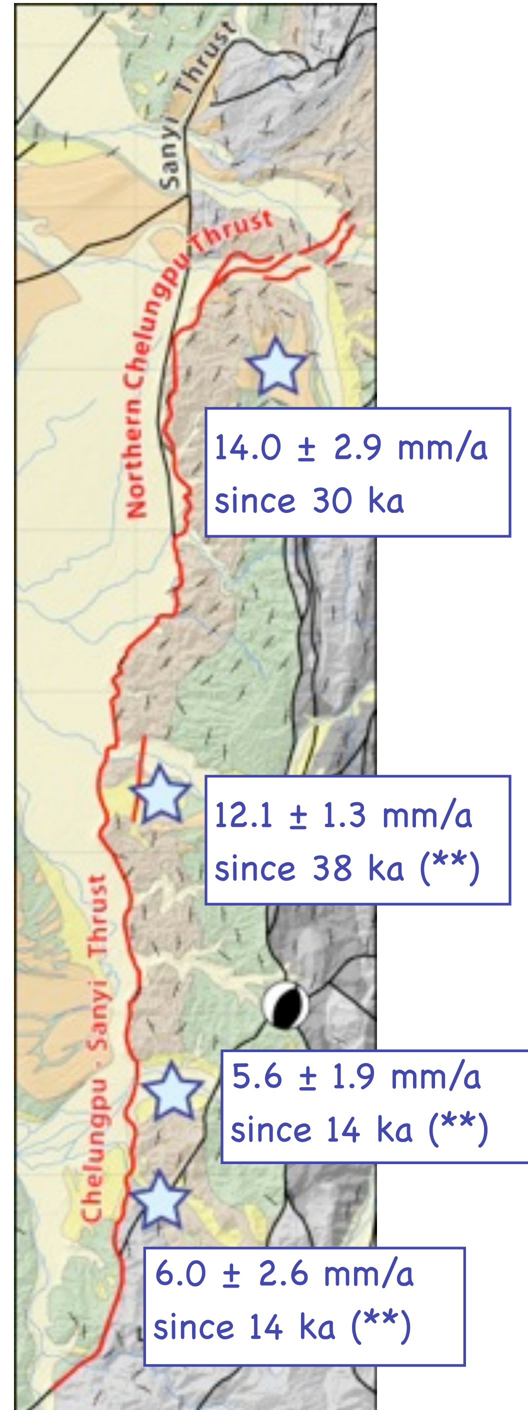
on 4 consecutive terrace levels

Fault slip rate on the Northern Chelungpu Thrust



Shortening rates along strike

- Significant increase from south to north

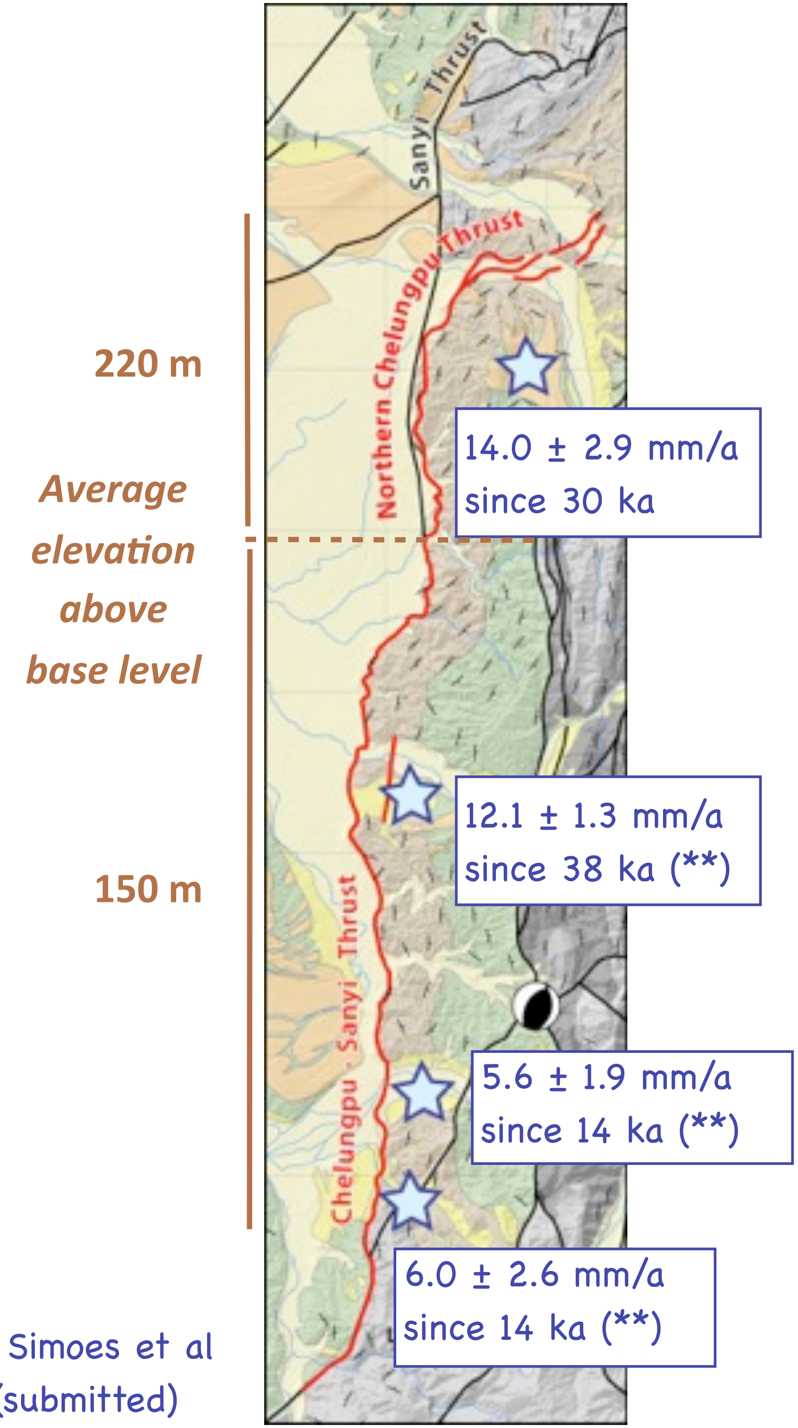


** Simoes et al (submitted)

Shortening rates along strike

- Significant increase from south to north

- Faster rate in the north also supported by higher mean elevation of the hanging-wall topography



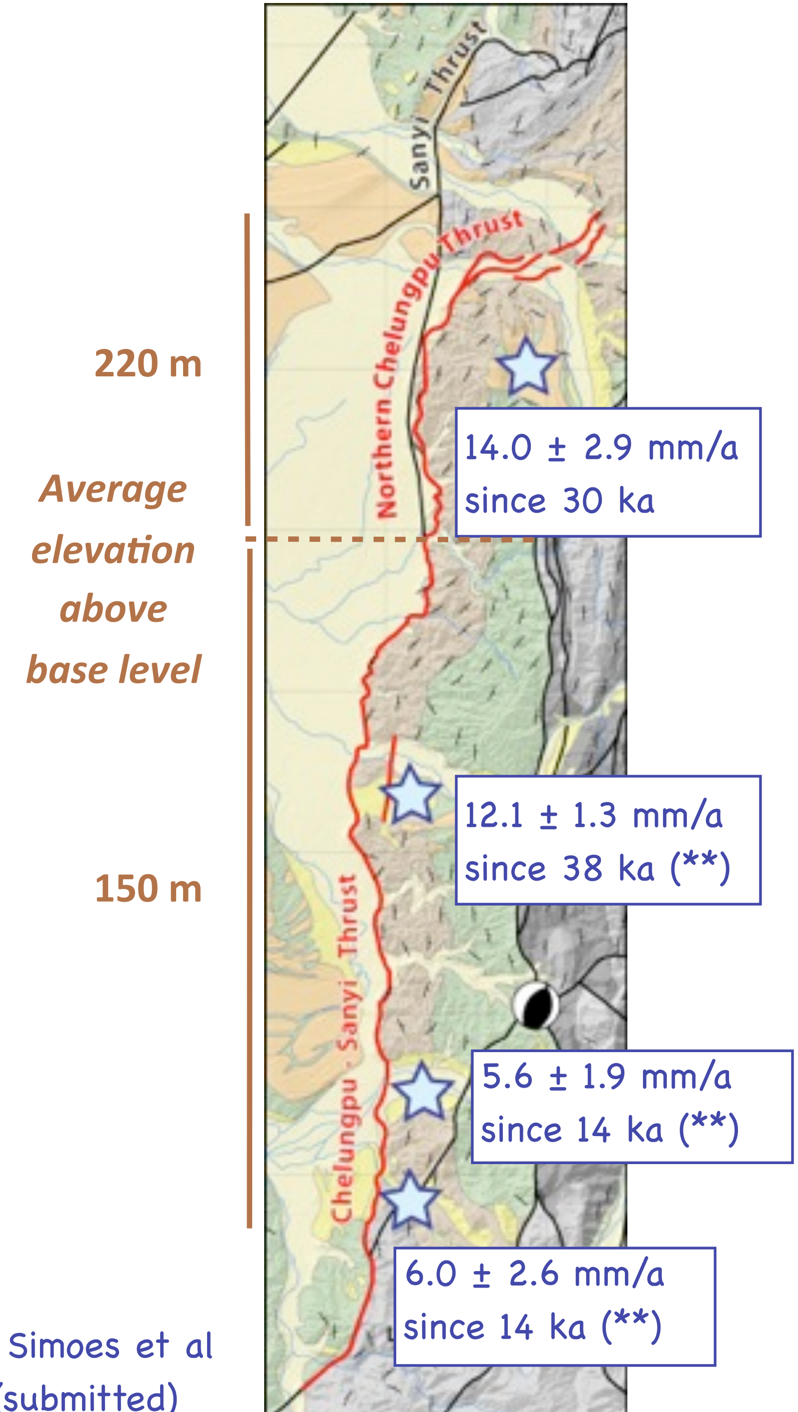
** Simoes et al (submitted)

Shortening rates along strike

- Significant increase from south to north

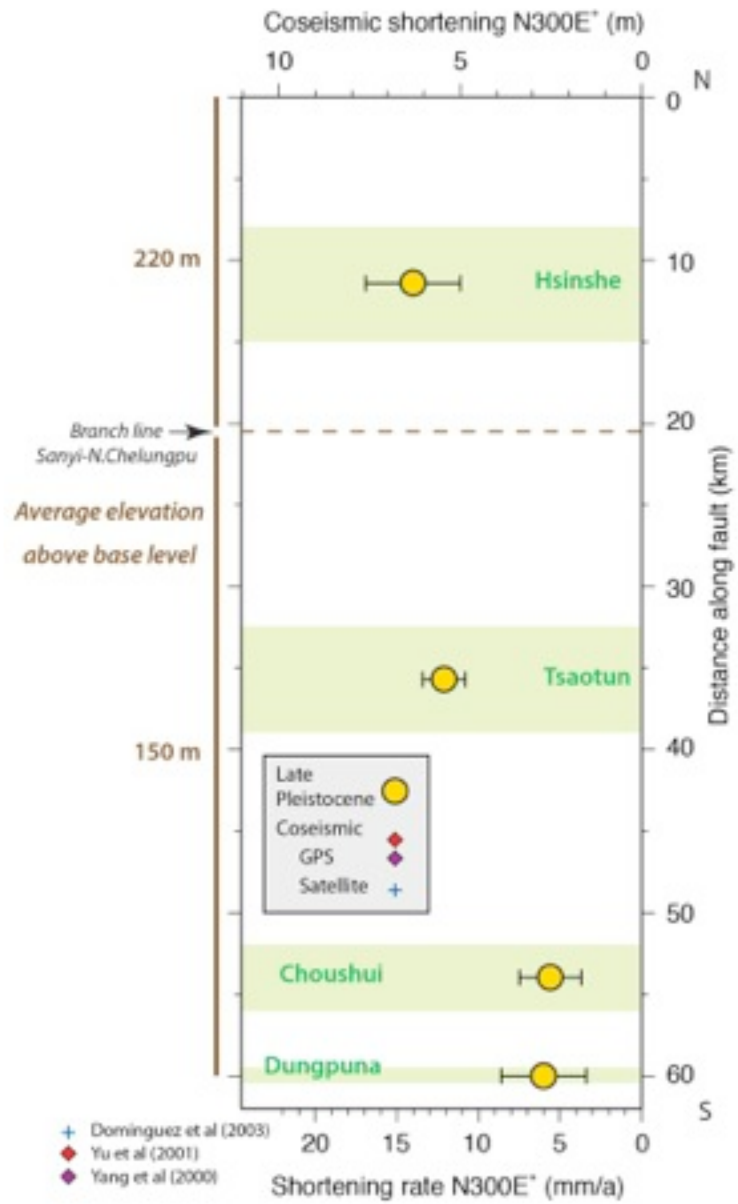
- Faster rate in the north also supported by higher mean elevation of the hanging-wall topography

- Chi-Chi coseismic displacements increased from south to north as well...



** Simoes et al (submitted)

Coseismic versus Long-term shortening along strike



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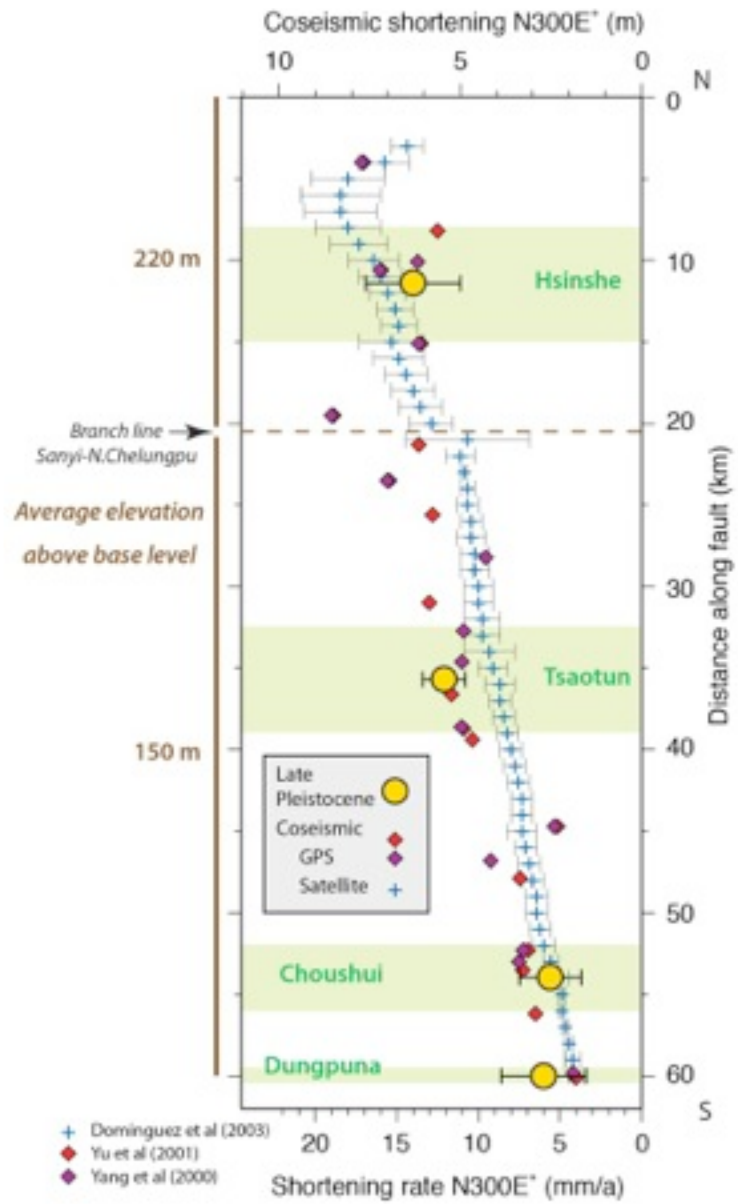
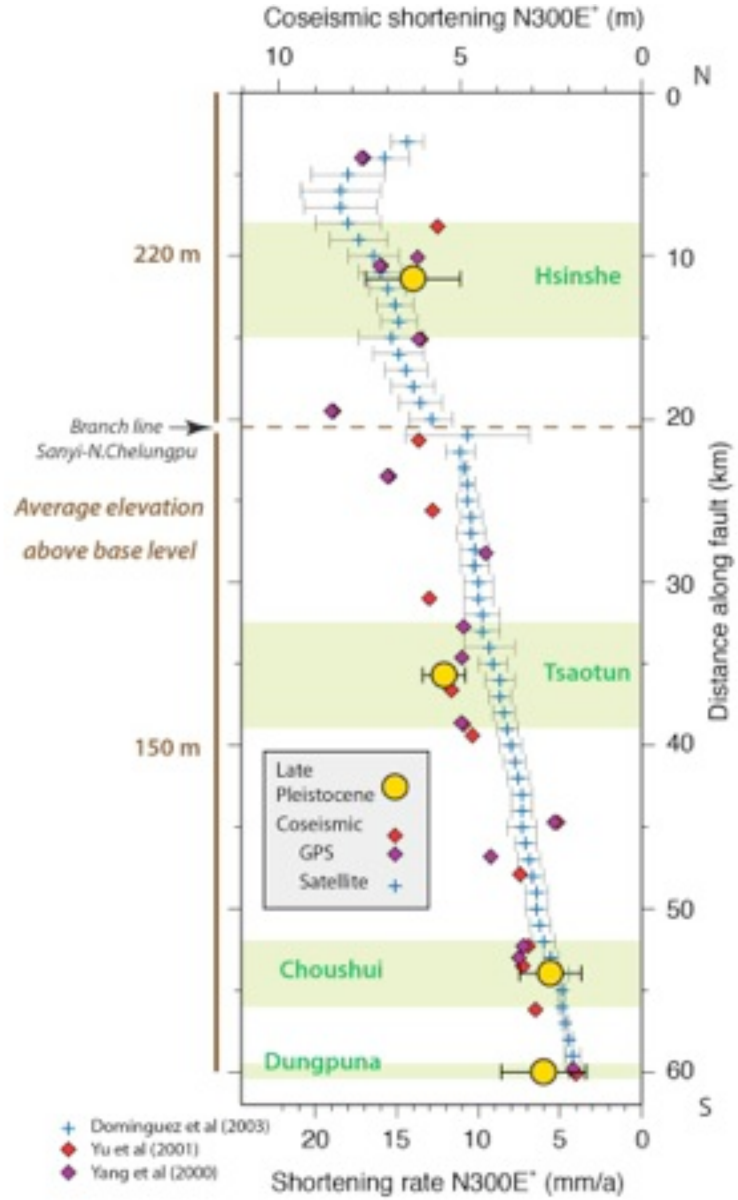


Coseismic versus Long-term shortening along strike

Chi-Chi coseismic displacements and long-term shortening rates vary in similar proportions !



Coseismic versus Long-term deformation

Chi-Chi coseismic displacements
and long-term shortening rates
vary in similar proportions !

+

Long-term slip vector parallels
Chi-Chi coseismic displacements,
at least in Hsinshe !

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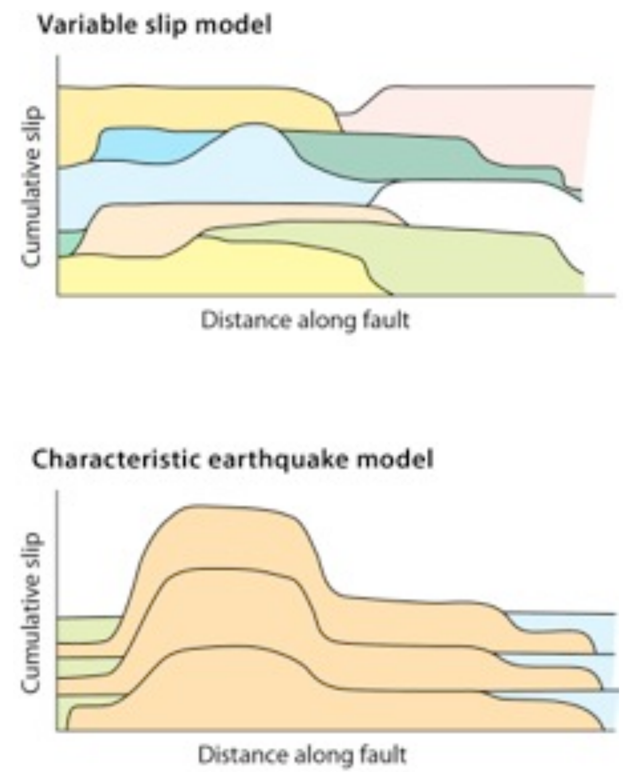
Slip distribution models



Modified from Schwartz and Coppersmith, 1984

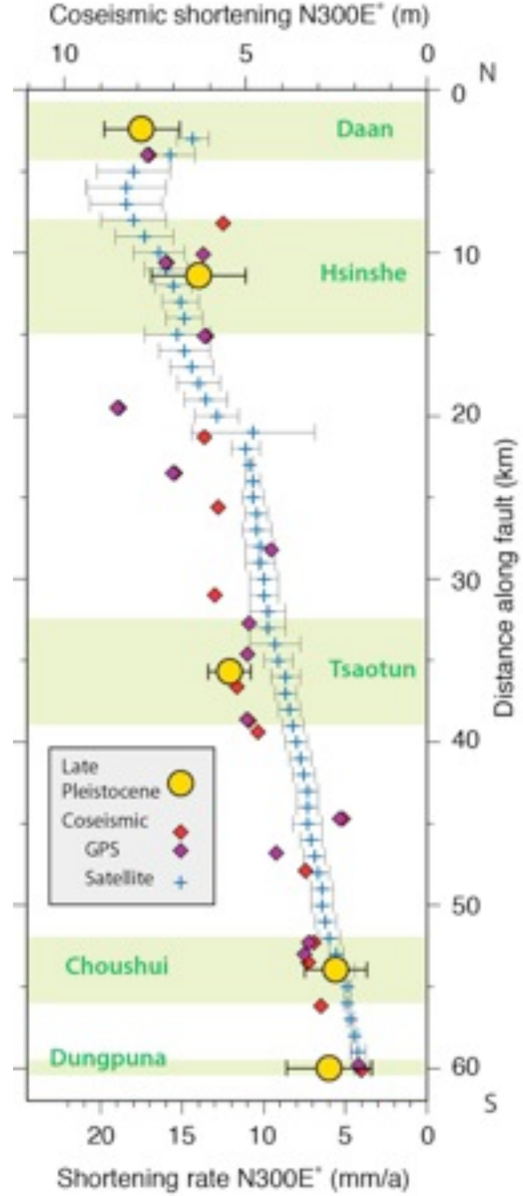
Age of fault inception

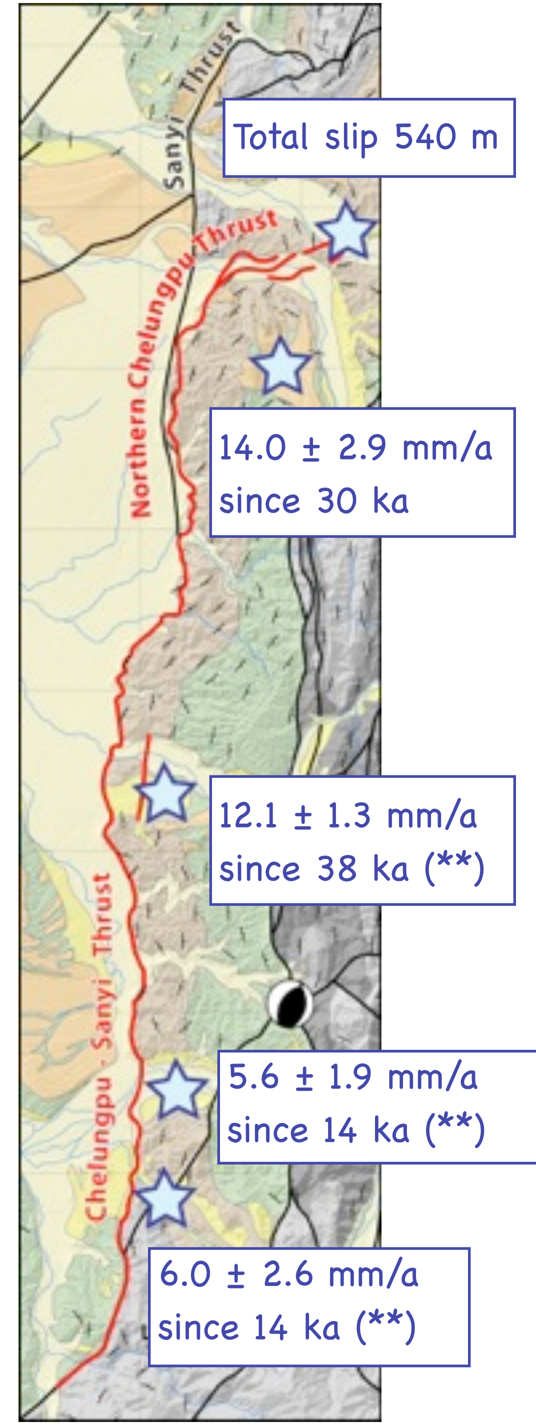
- Neiwan anticline:
  total shortening: ~540 m
  (Graveleau et al, in prep.)
  => Recently propagated fault

- Assuming shortening rate proportional to Chi-Chi coseismic displacements: 16.4 ± 5.5 mm/a

=> **Fault inception 32 ± 11 ka ago**

Similar to T1 (30 ± 4 ka) in Hsinshe

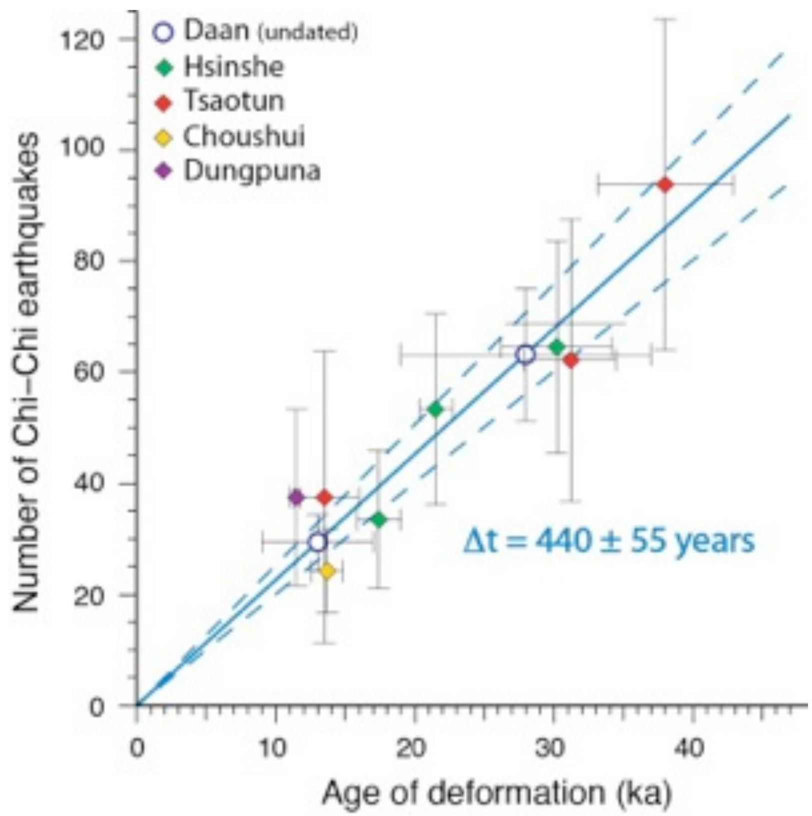




Chi-Chi as a characteristic earthquake

How many Chi-Chi earthquakes are responsible

for the cumulative slip determined at each site ?



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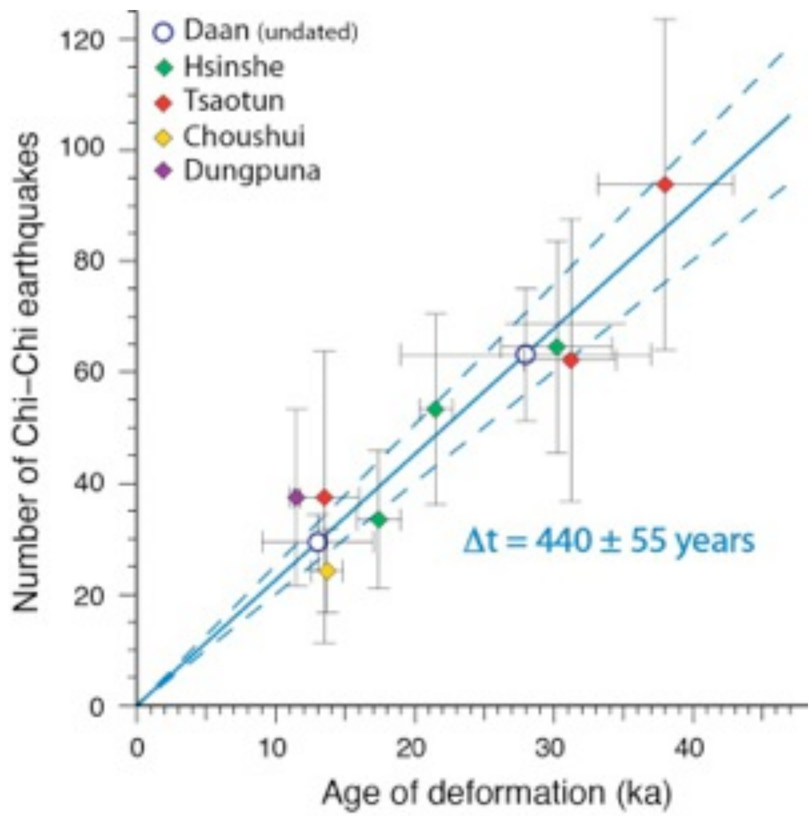

Chi-Chi earthquakes recurrence interval : 440 ± 55 years.

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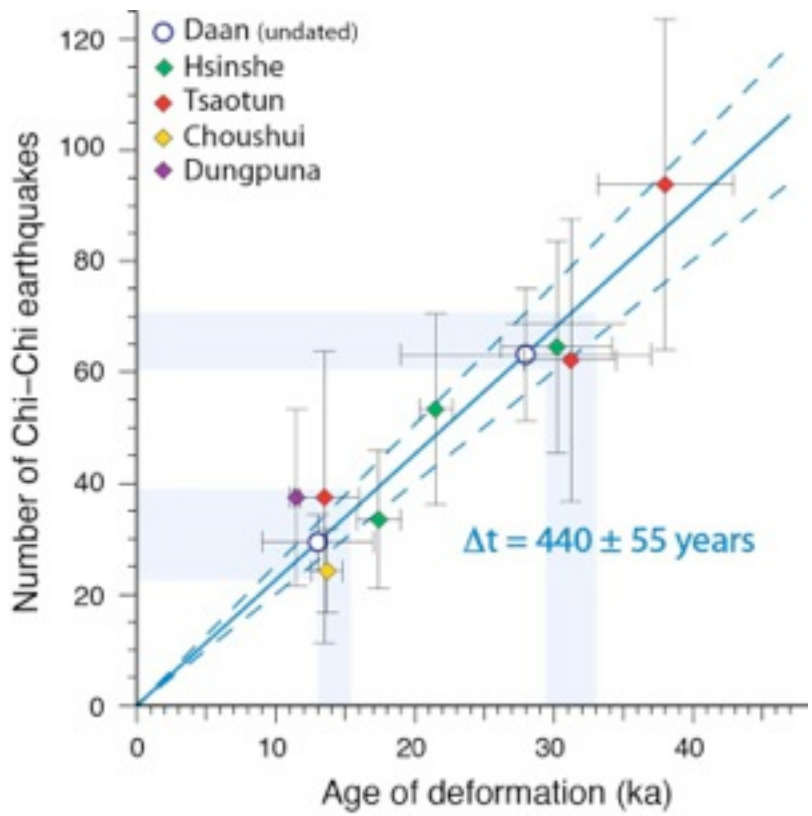
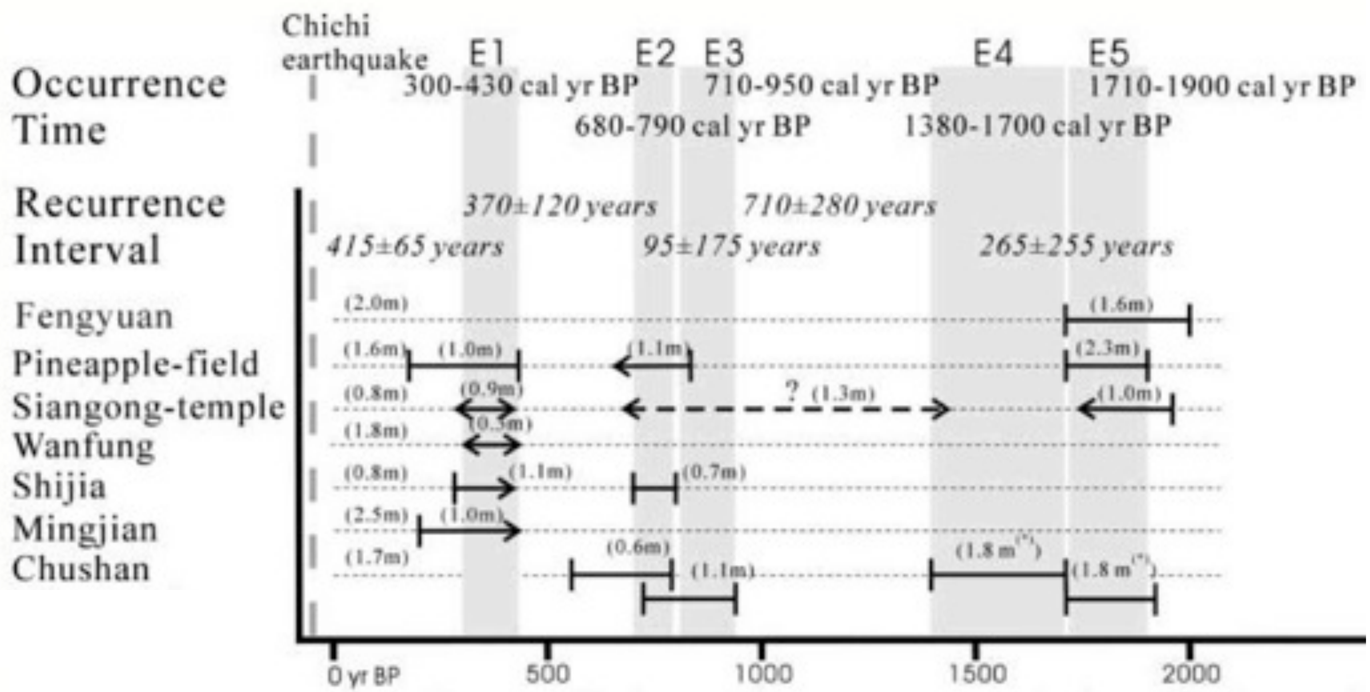


Chi-Chi earthquakes recurrence interval : 440 ± 55 years.

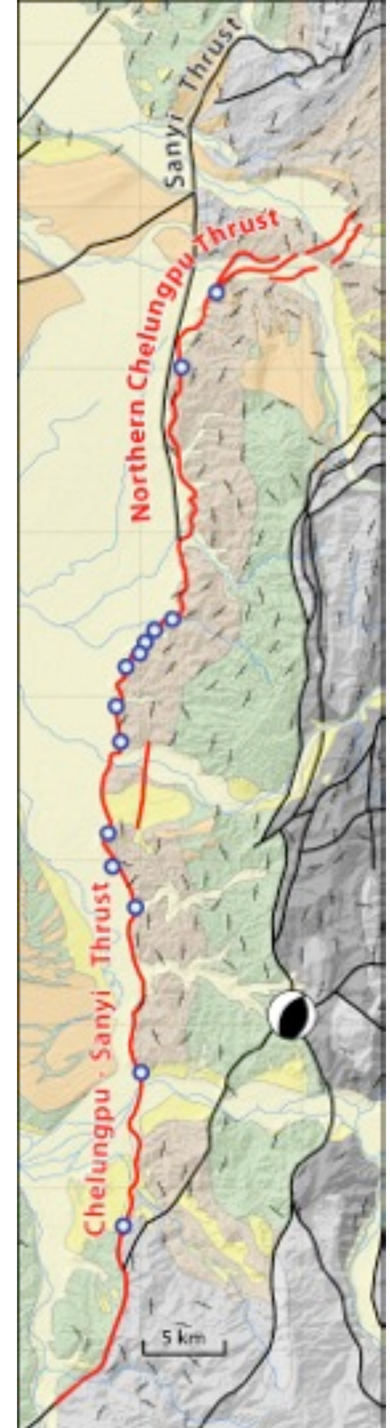
Comparison with paleo-seismology studies

Late Pleistocene record:

Paleo-earthquake record:



Chen et al [2007]



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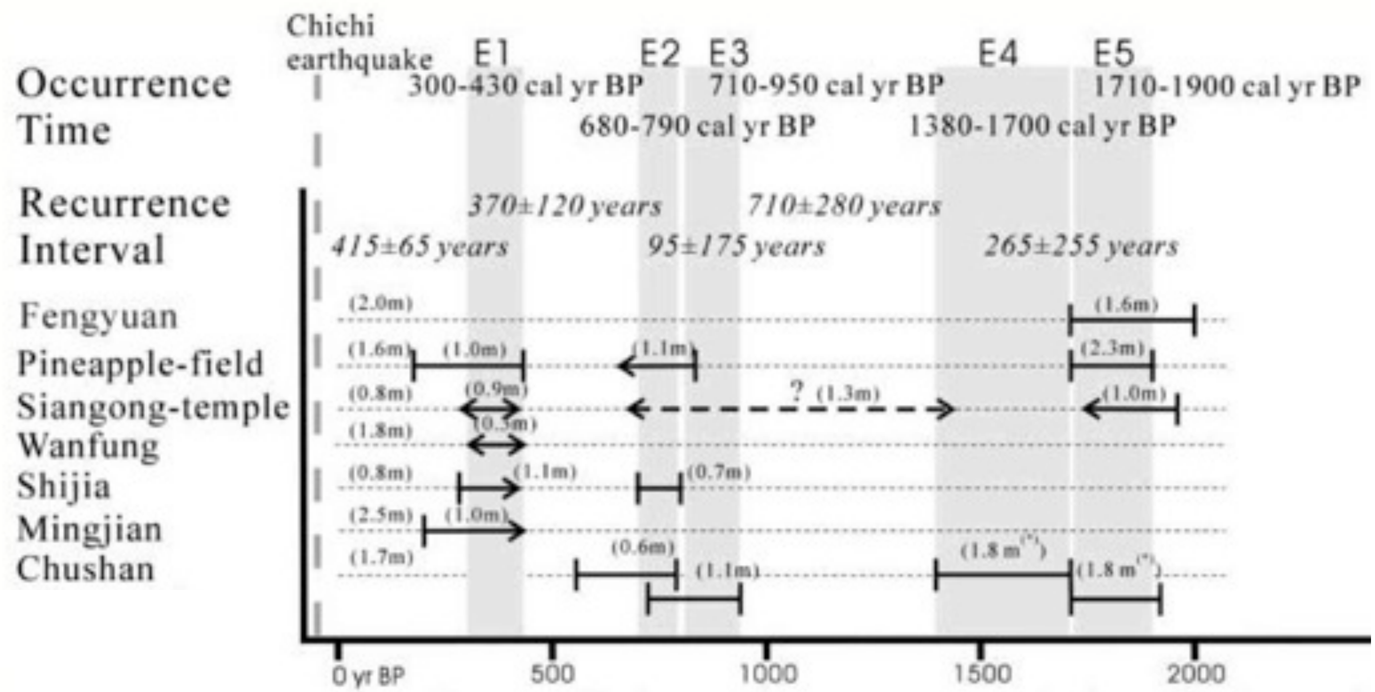

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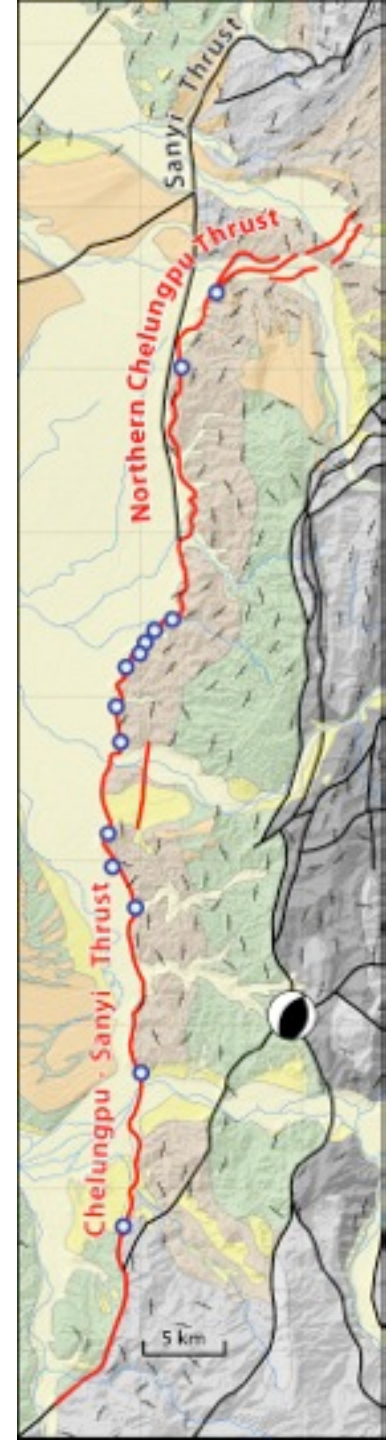

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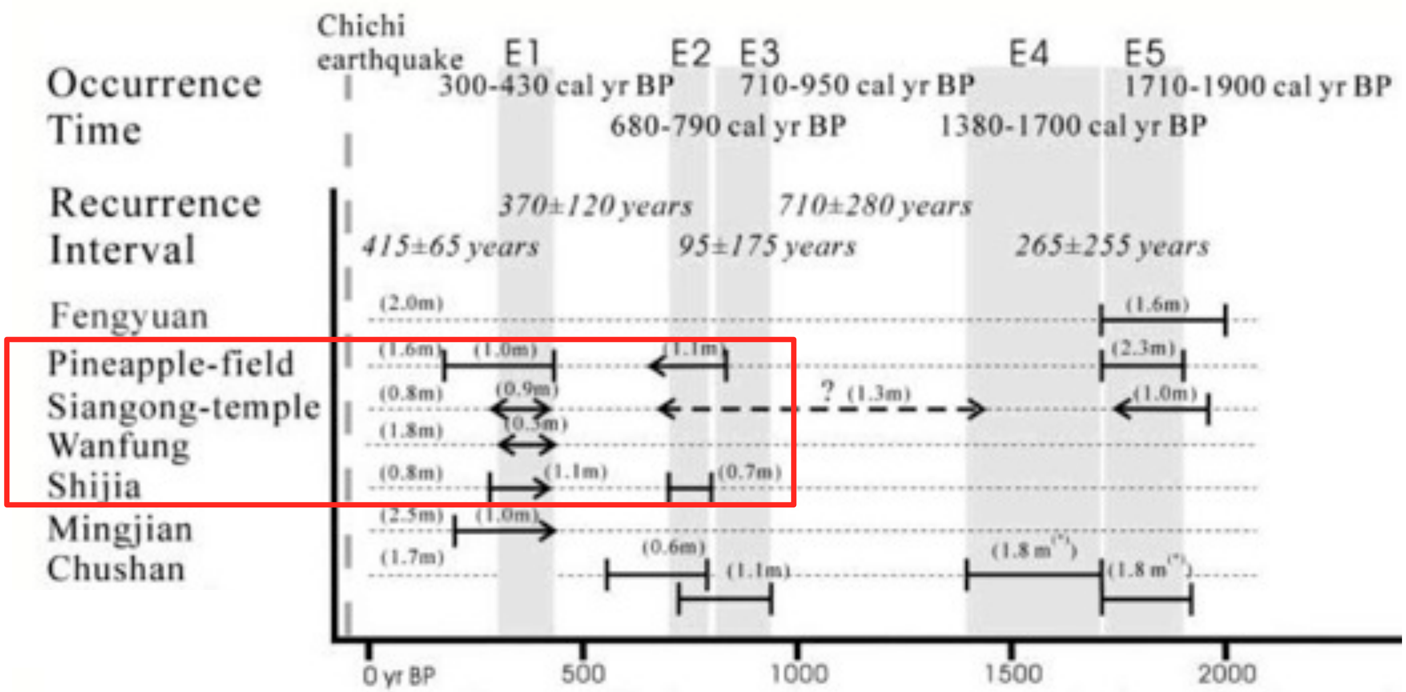

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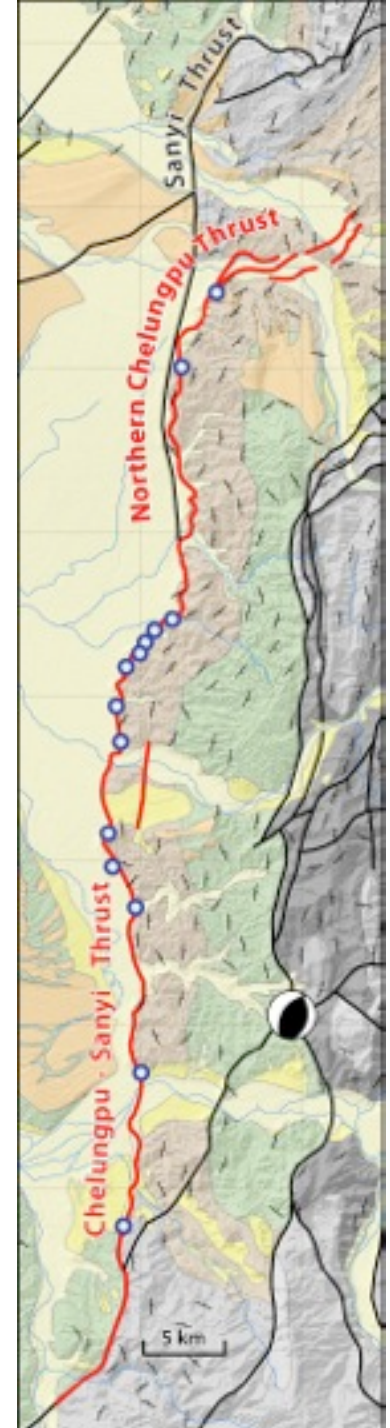
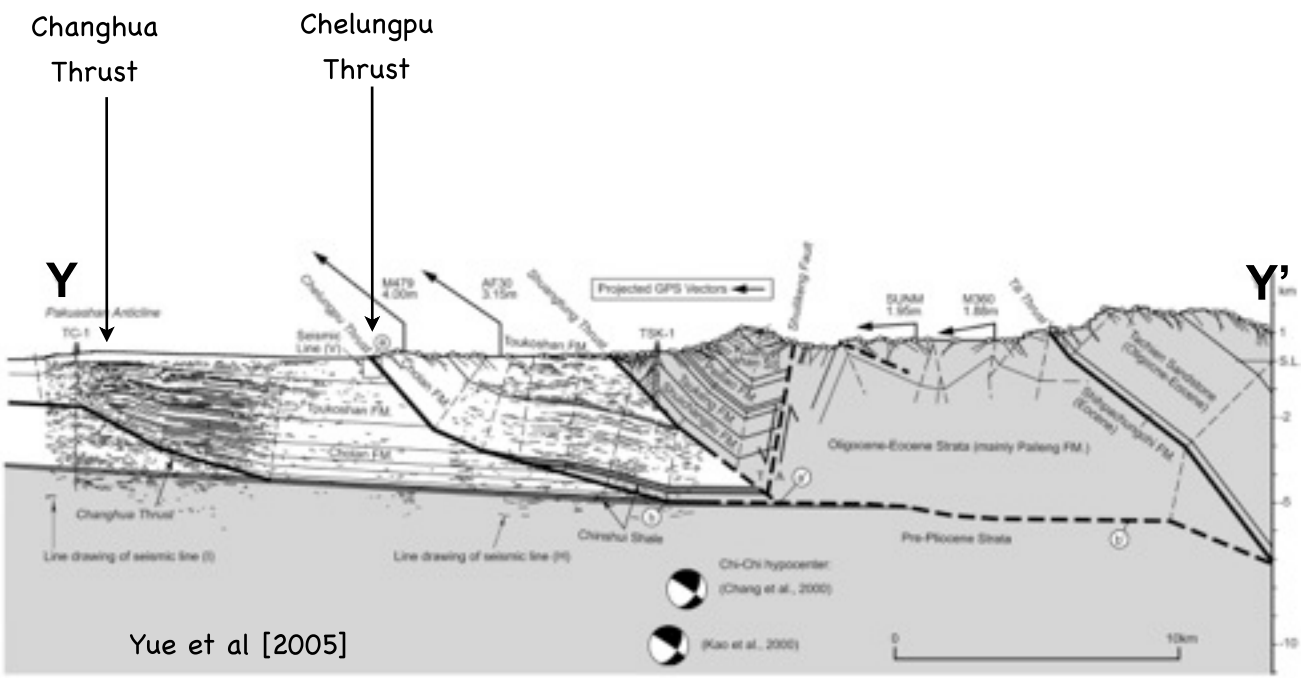
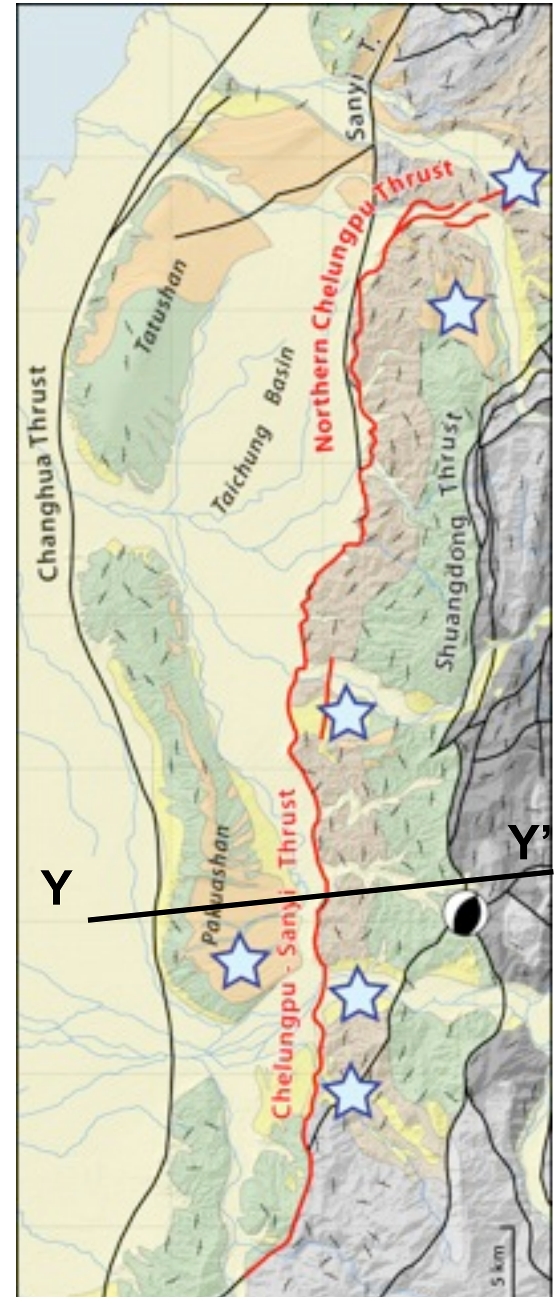


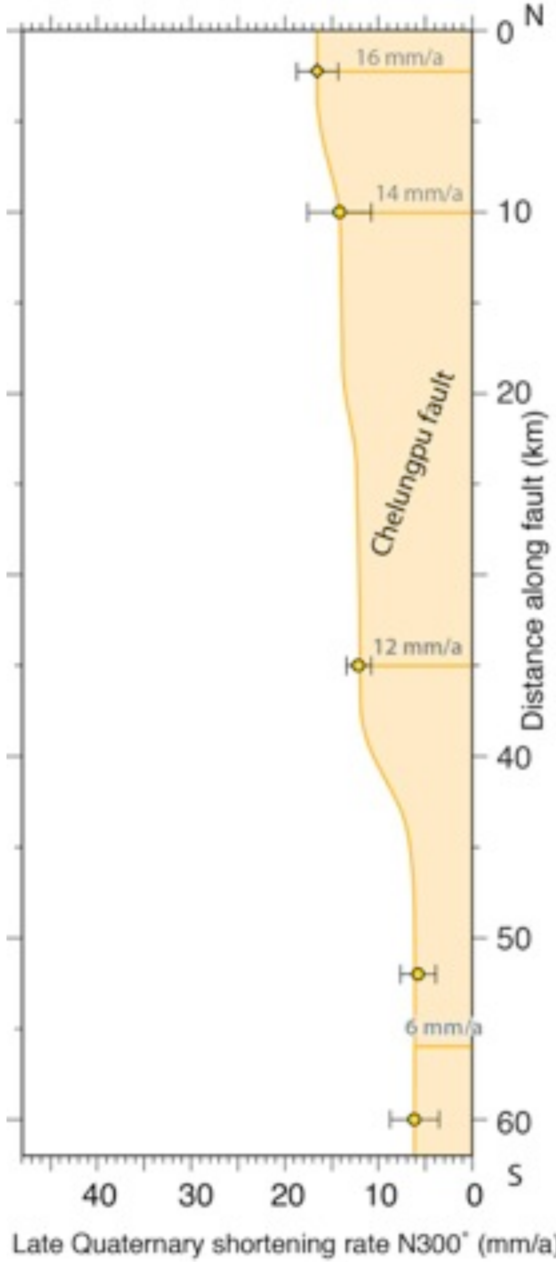
Distribution of shortening in Central Western Taiwan



Yue et al [2005]



Distribution of shortening in Central Western Taiwan



Simoes et al
[2007, a & b, 2013 submitted],
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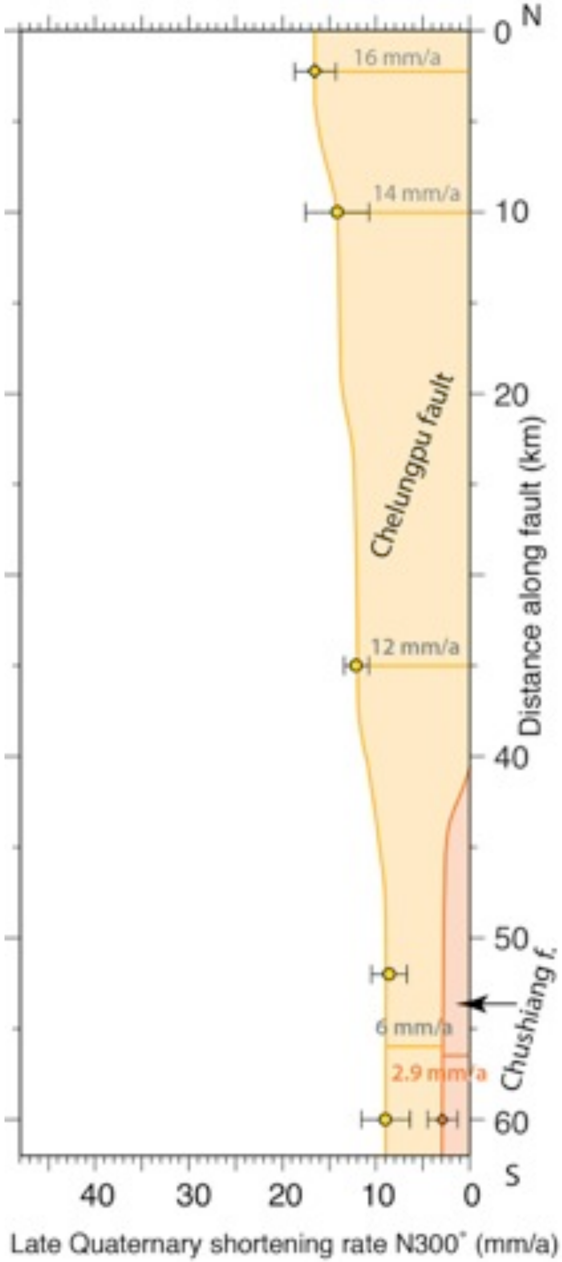

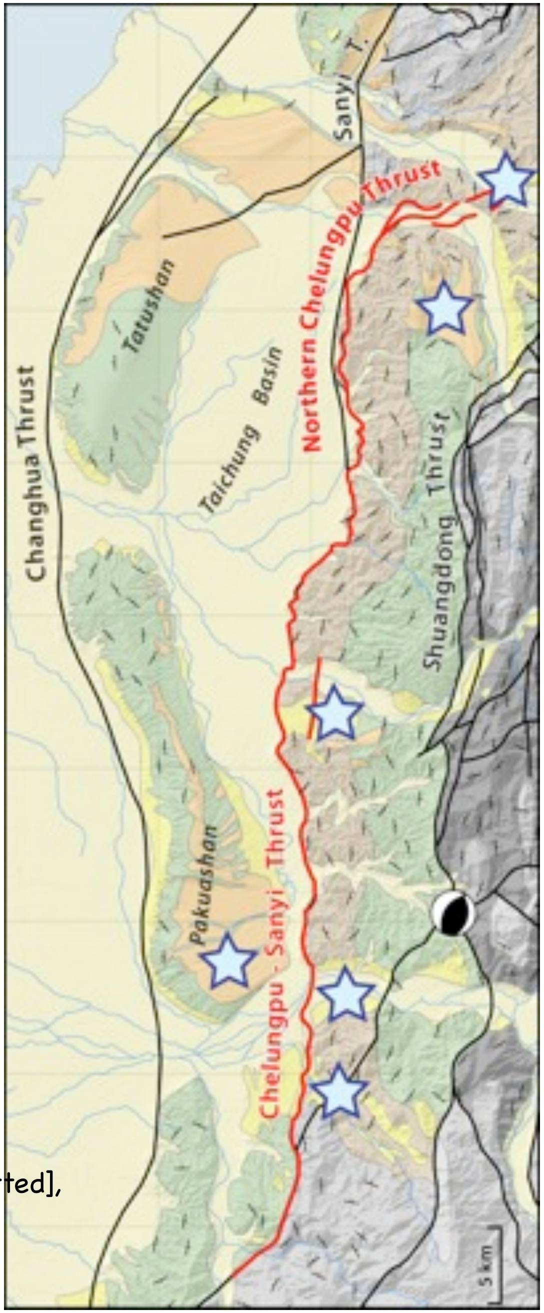

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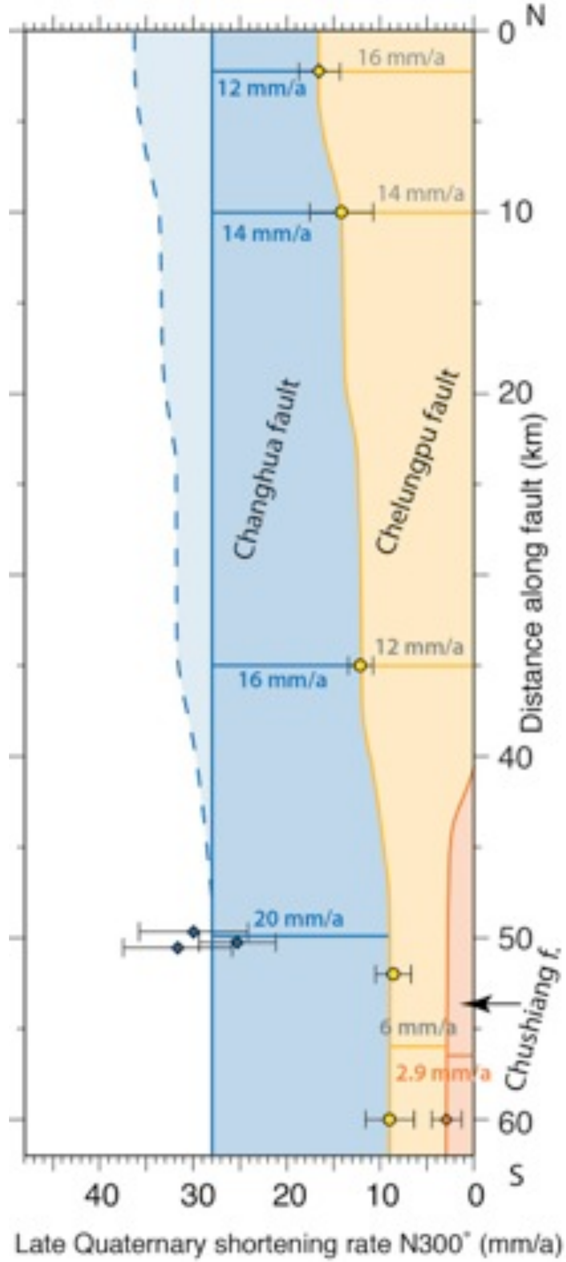

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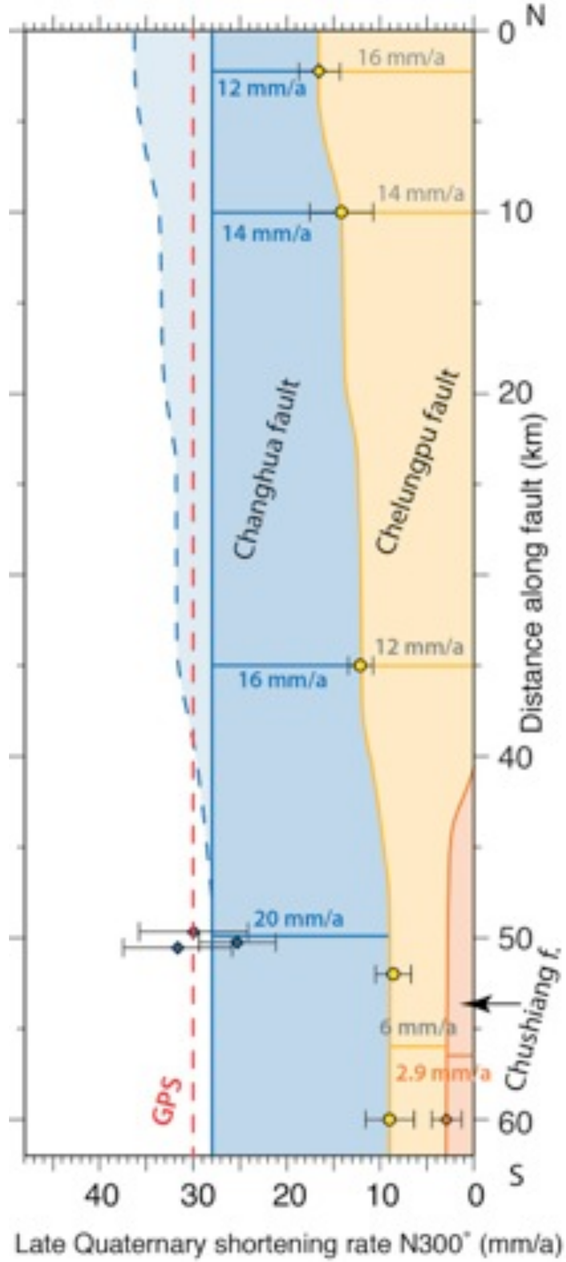

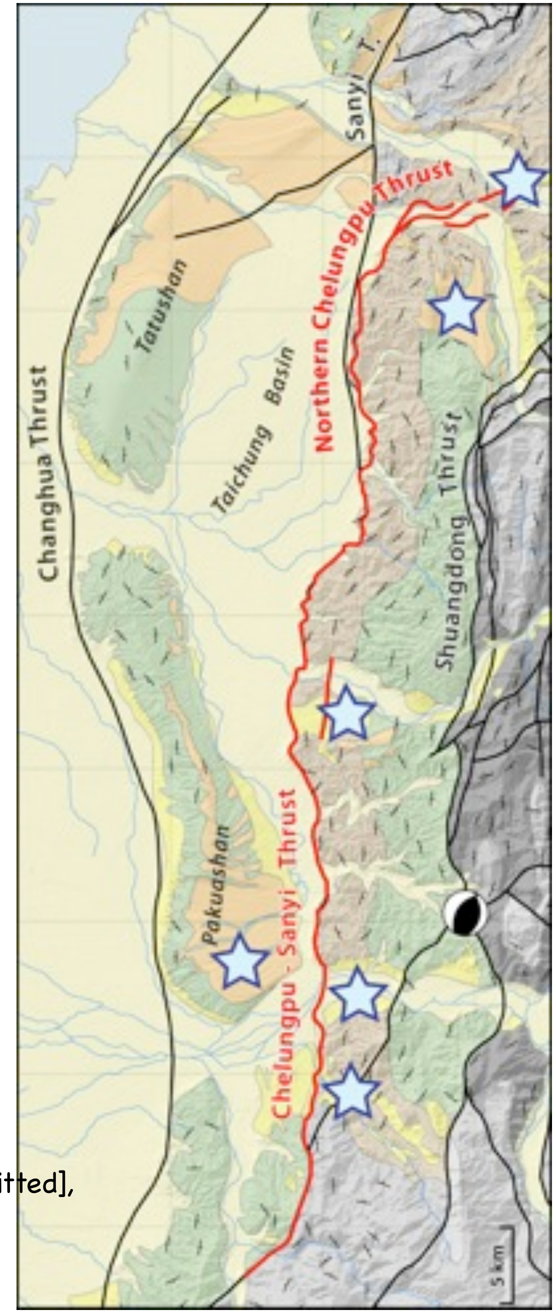

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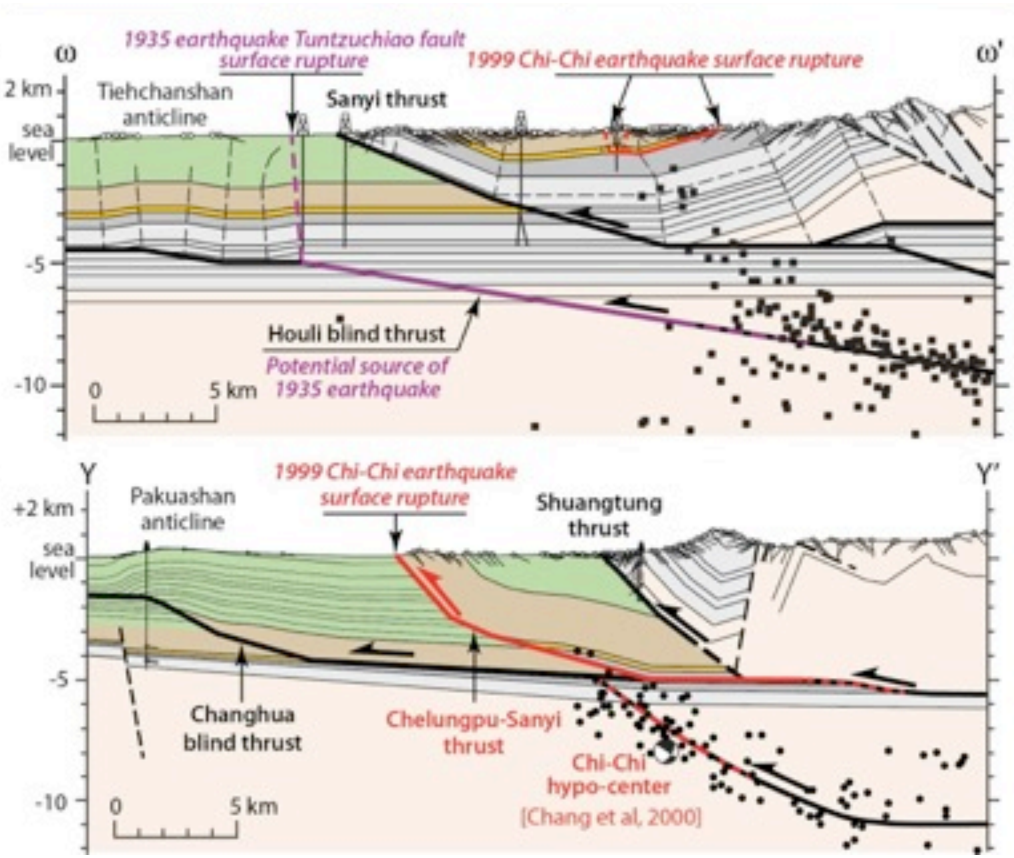
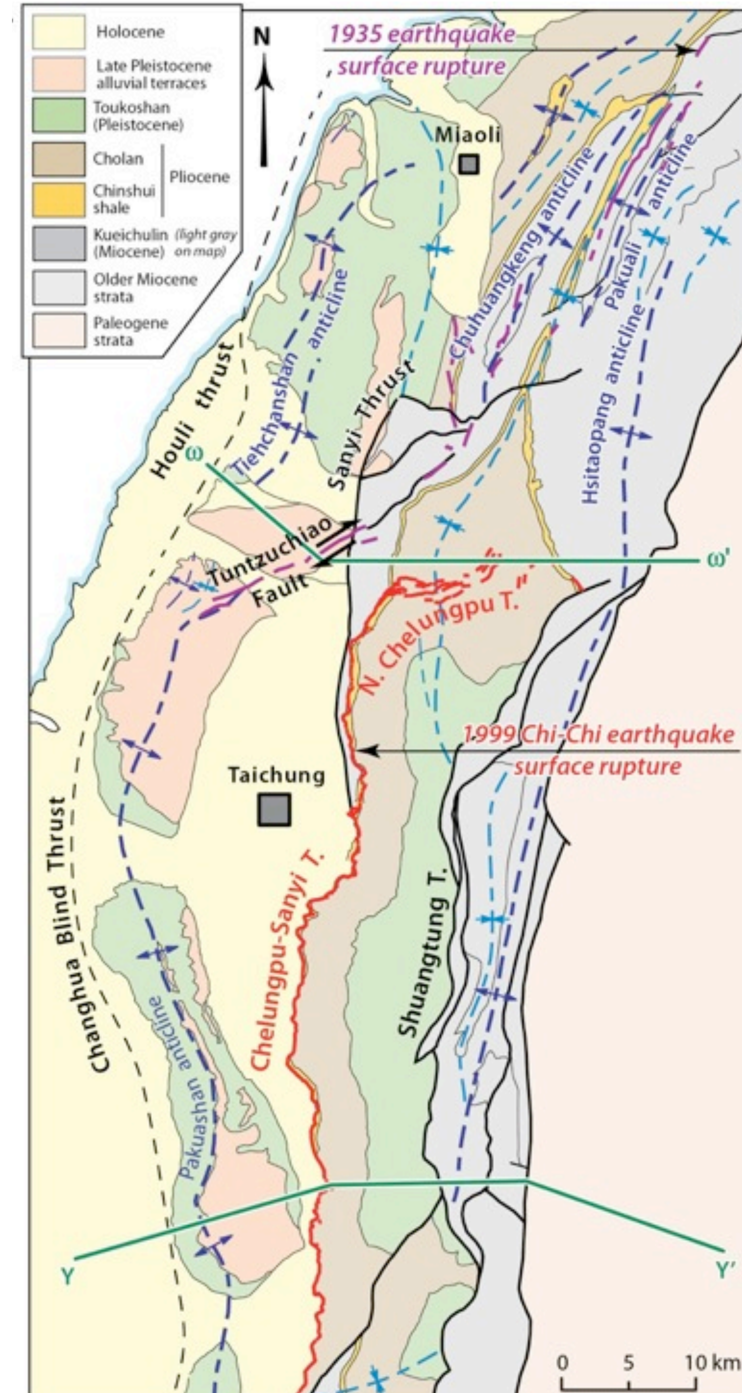
Relationship with N. Changhua fault + 1935 earthquake fault?





Conclusions

- **Methodology**:

Extensive exploration regarding how to use geomorphic criteria from **fold scarps**

Although powerful, fold back limb width can be misleading.

Importance to relate surface deformation and sub-surface structure

Conclusions

- **Methodology**:

Extensive exploration regarding how to use geomorphic criteria from **fold scarps**

Although powerful, fold back limb width can be misleading.

Importance to relate surface deformation and sub-surface structure

- Determination of the **long-term slip vector** thanks to 3D analysis of deformation and sub-surface structure

+ **Collinearity of long-term and coseismic slip vector** at our study site

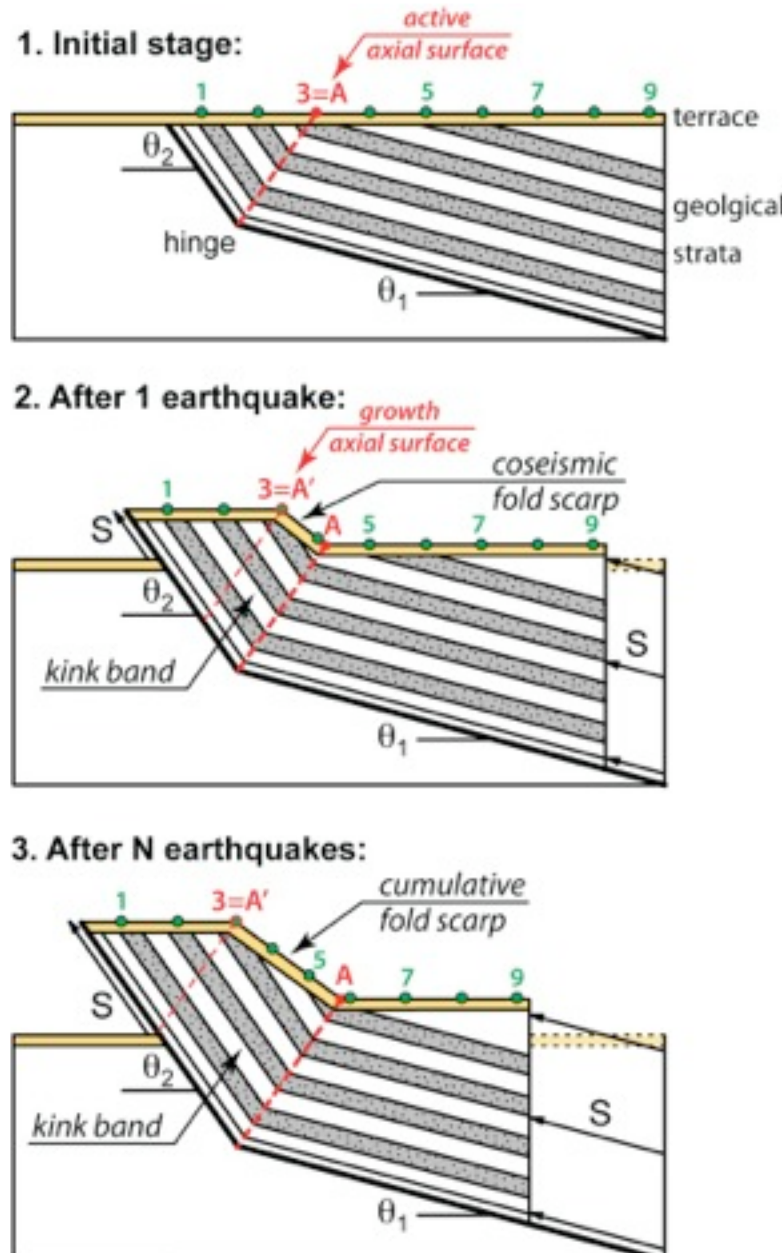
- **Chi-Chi could be a characteristic earthquake** for the Chelungpu fault ramp, probably since about 32 ka.

Recurrence interval = 440 ± 55 years


Thanks for your attention !

Fault-bend folding over earthquake cycles

Case of a **sharp** fault bend



Coseismic uplift:

$u_i = S \, . \, \sin \theta_i$

Modified from
Suppe et al (1997)

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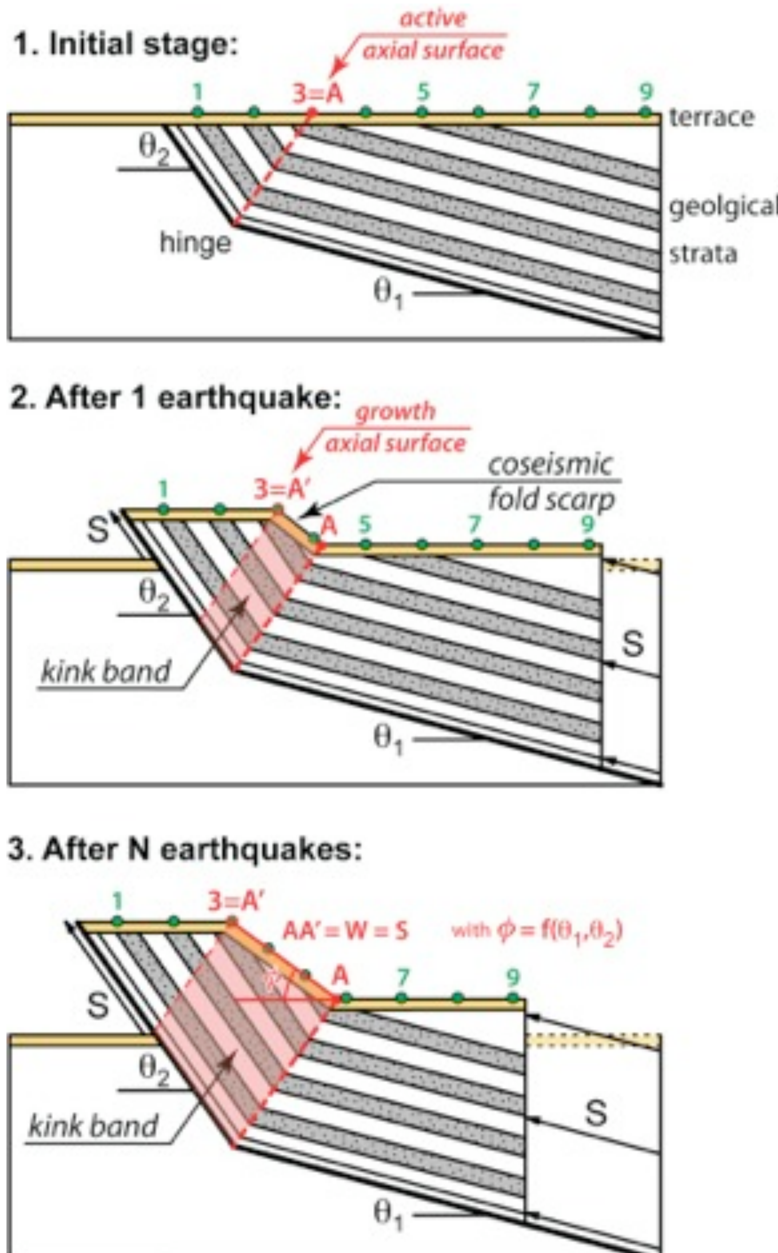

Coseismic uplift:

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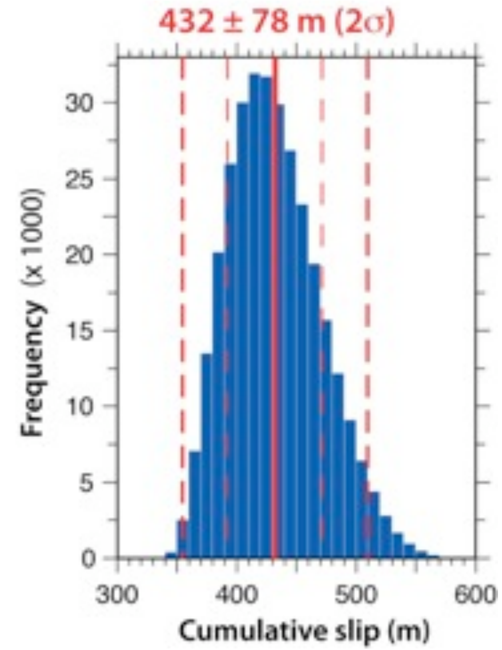
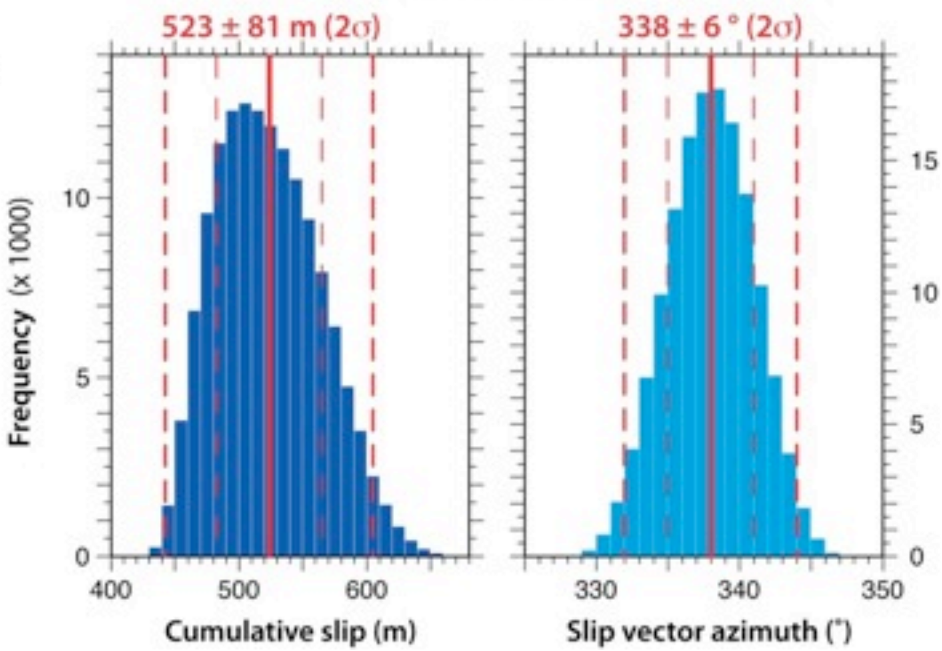
Fault slip and azimuth determination

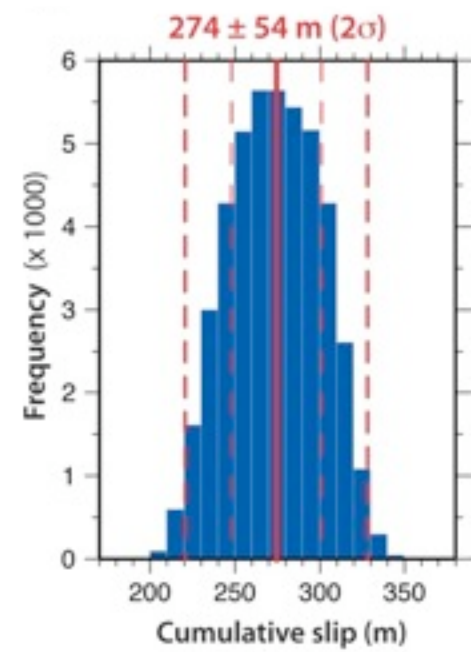
Terrace T2 :



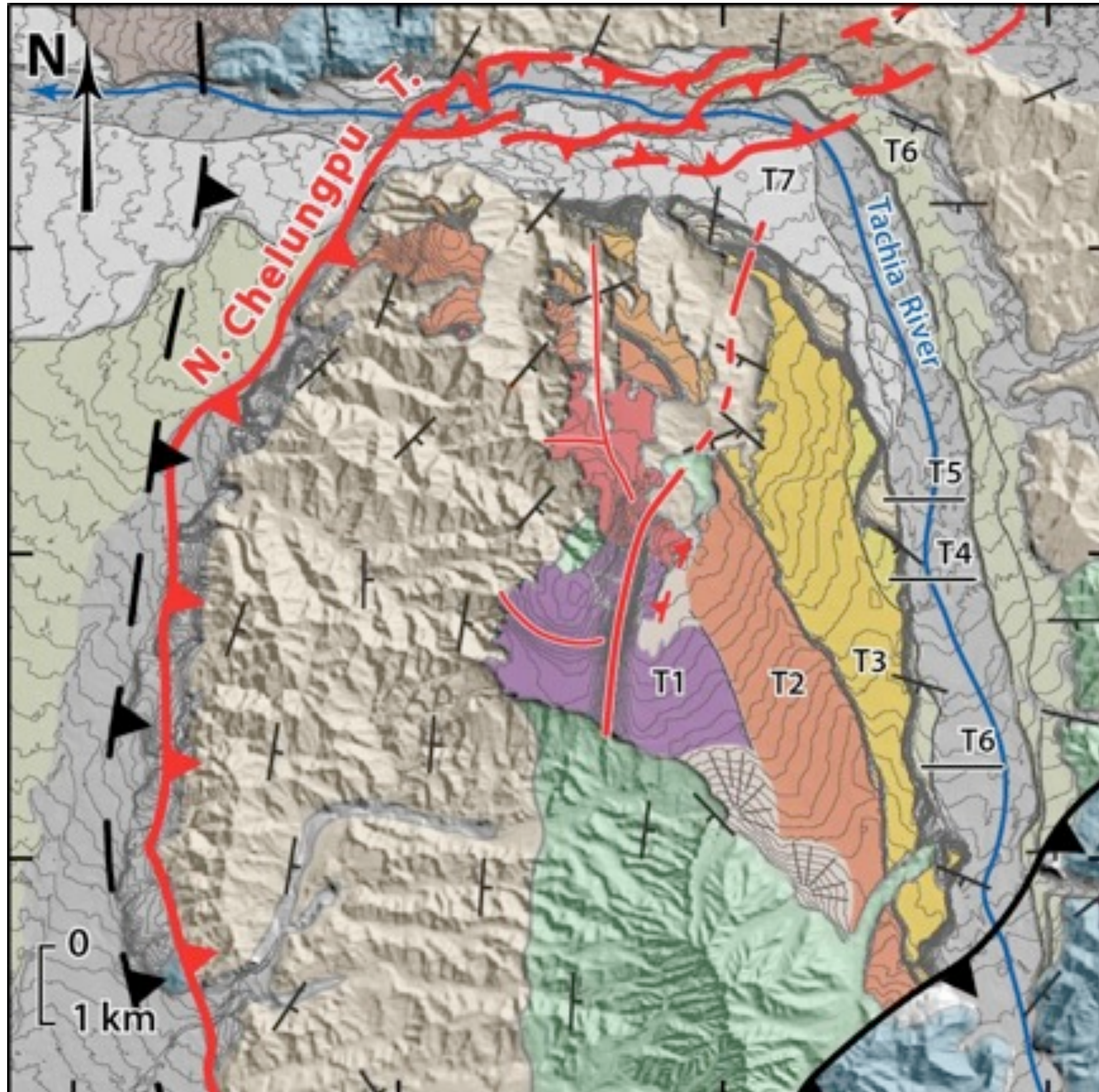
Terrace T1 :



Terrace T3 :



Fold scarp geometry in map view



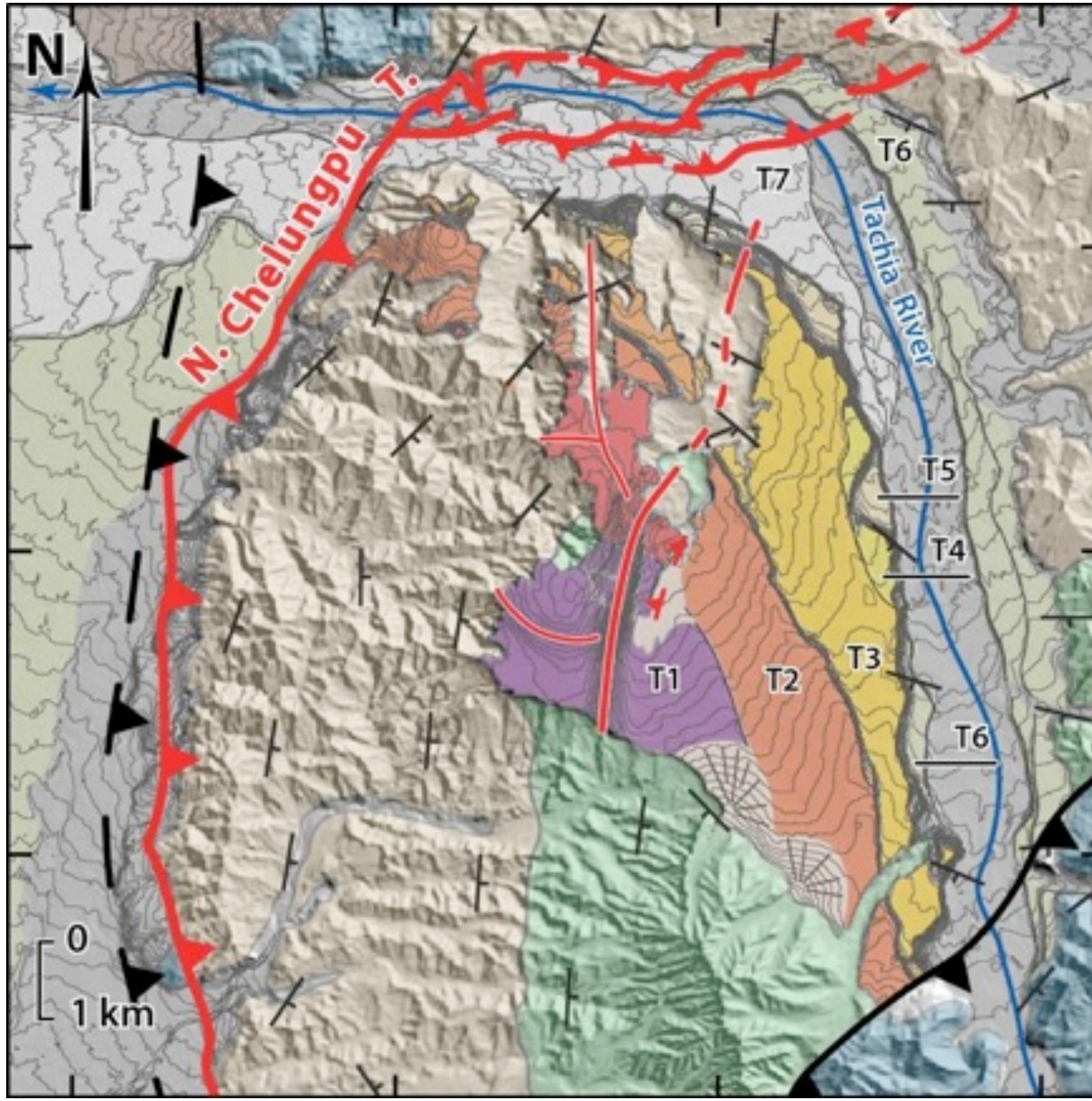
Fold scarp geometry in map view

2 fold scarps in the North

=> 2 fault bends

that likely merge into

a single bend to the South



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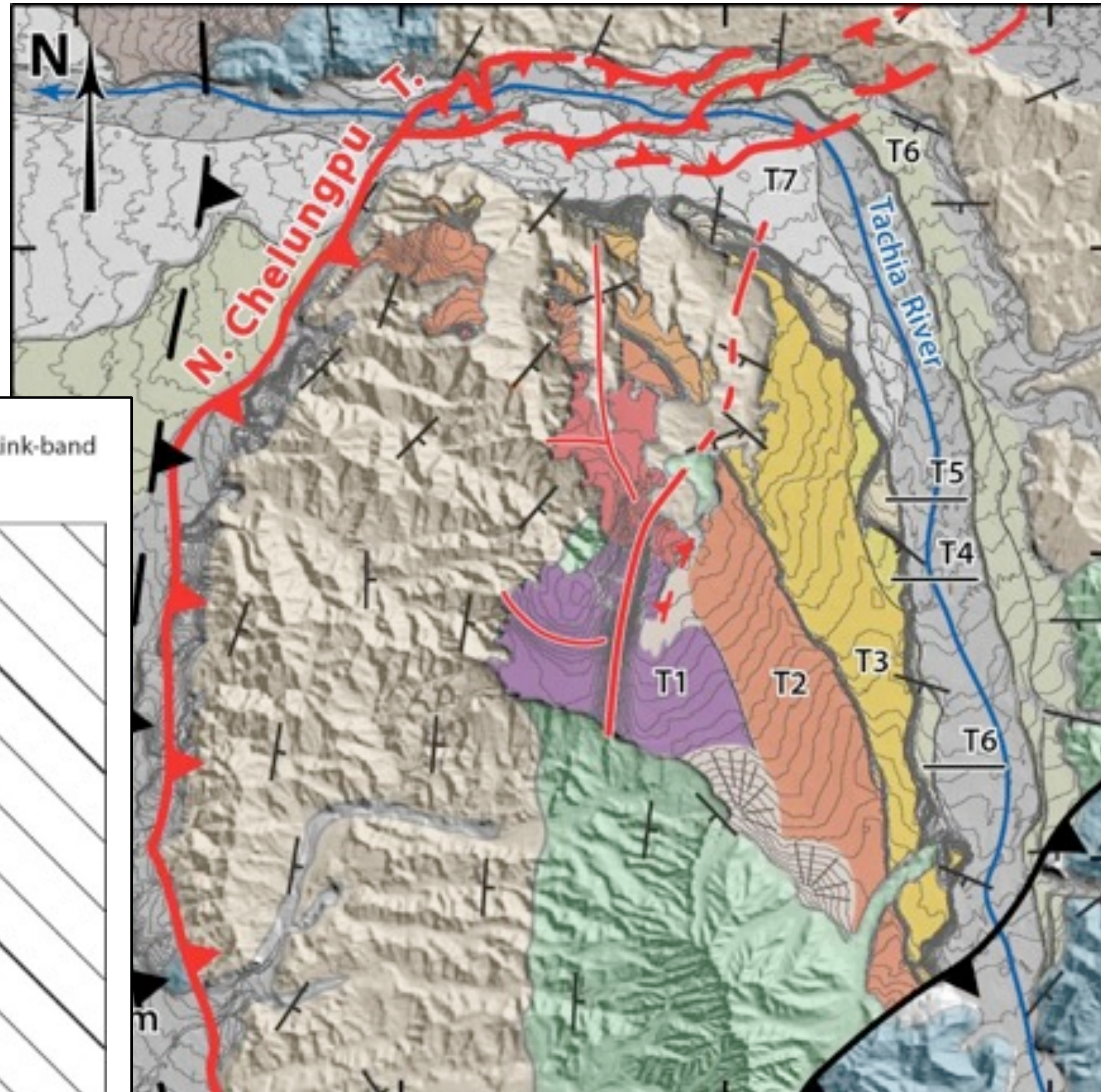
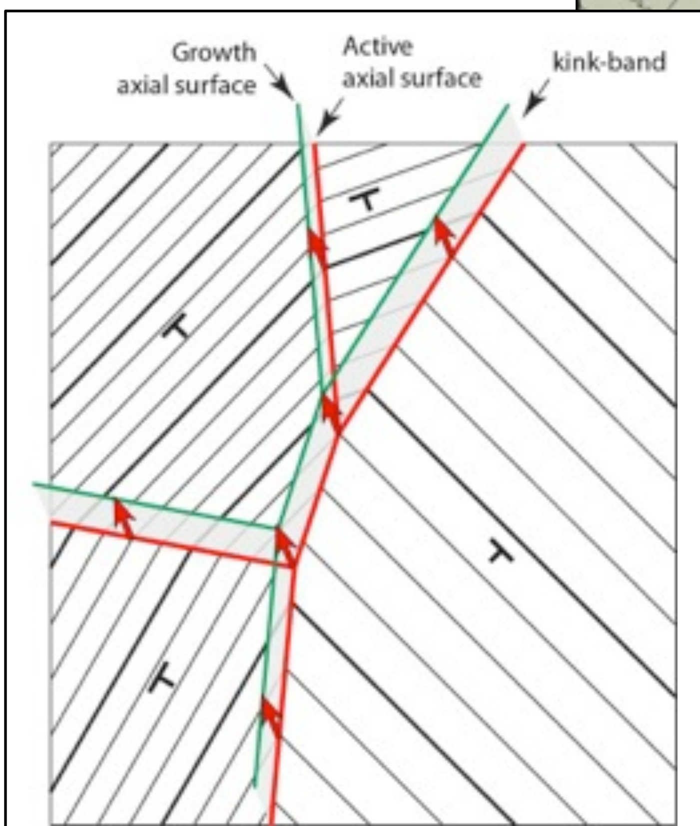
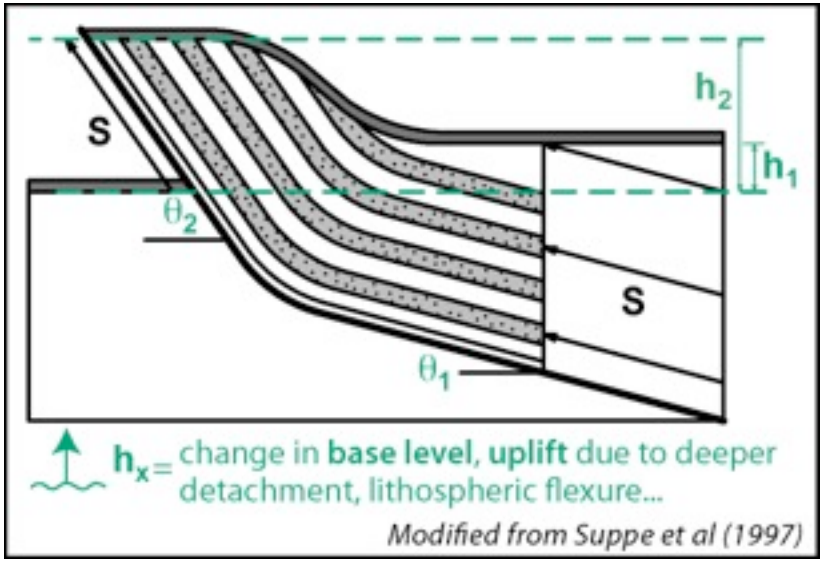




Tectonic uplift versus base level change

Cumulative slip:

Cumulative slip:	T1 :	**523 ± 81 m**
	T2 :	**432 ± 78 m**
	T3 :	**271 ± 62 m**

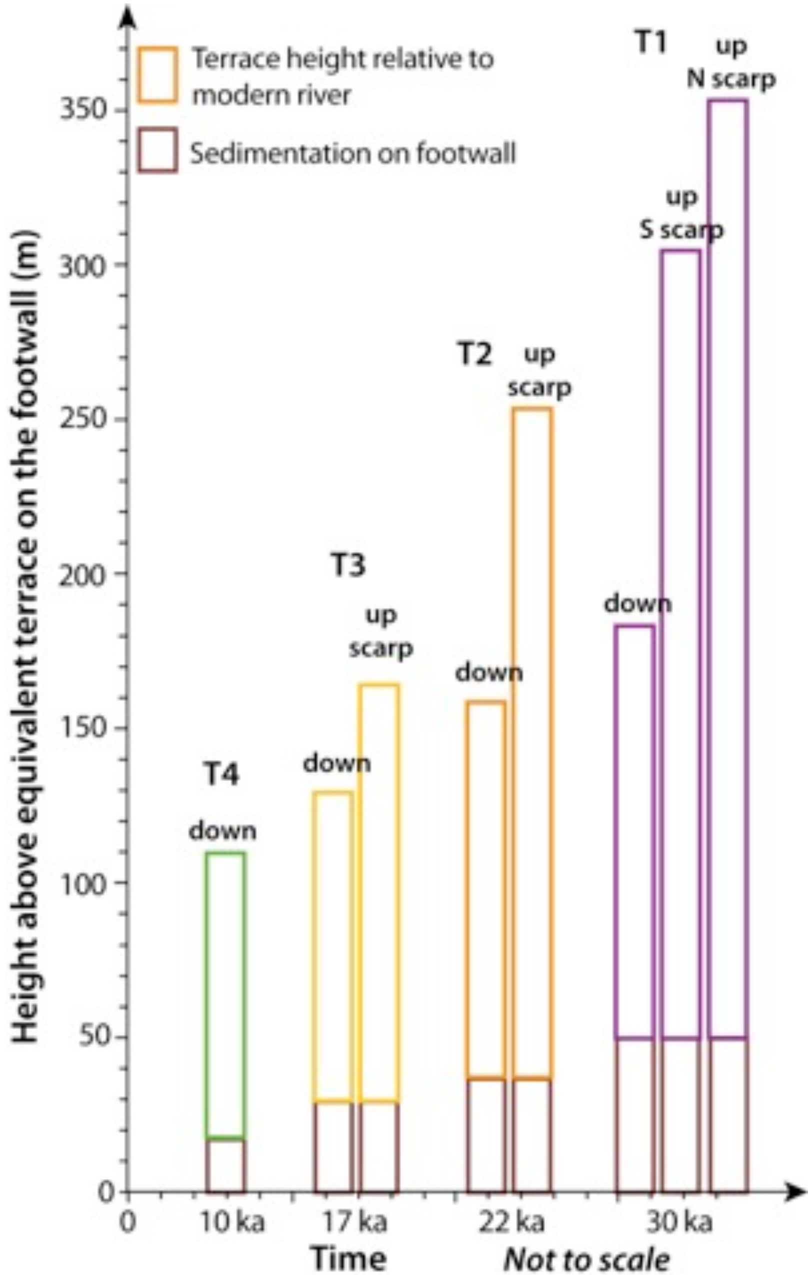


sensitive to local base level changes

- Recipe 1: **terrace height** relative to footwall:

$$S = (h + h_x) / \sin\theta$$

Tectonic uplift versus base level change



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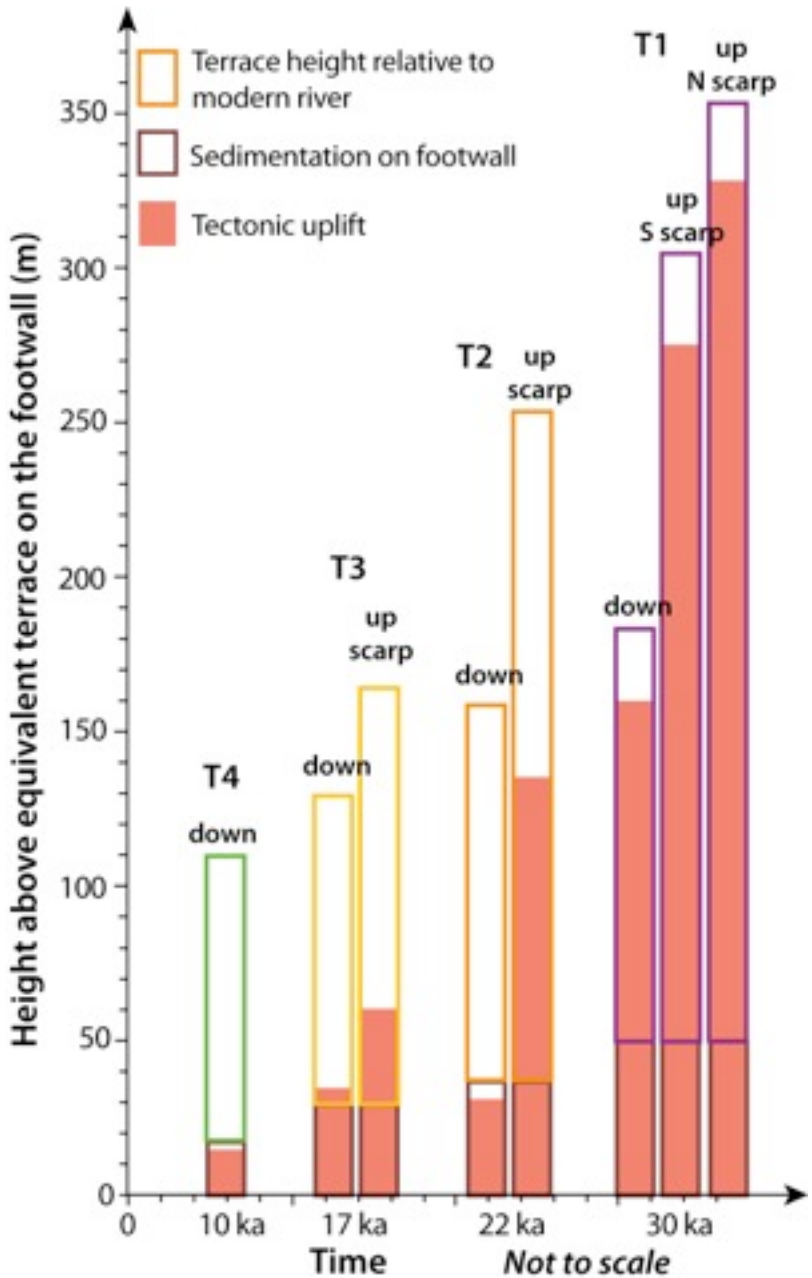

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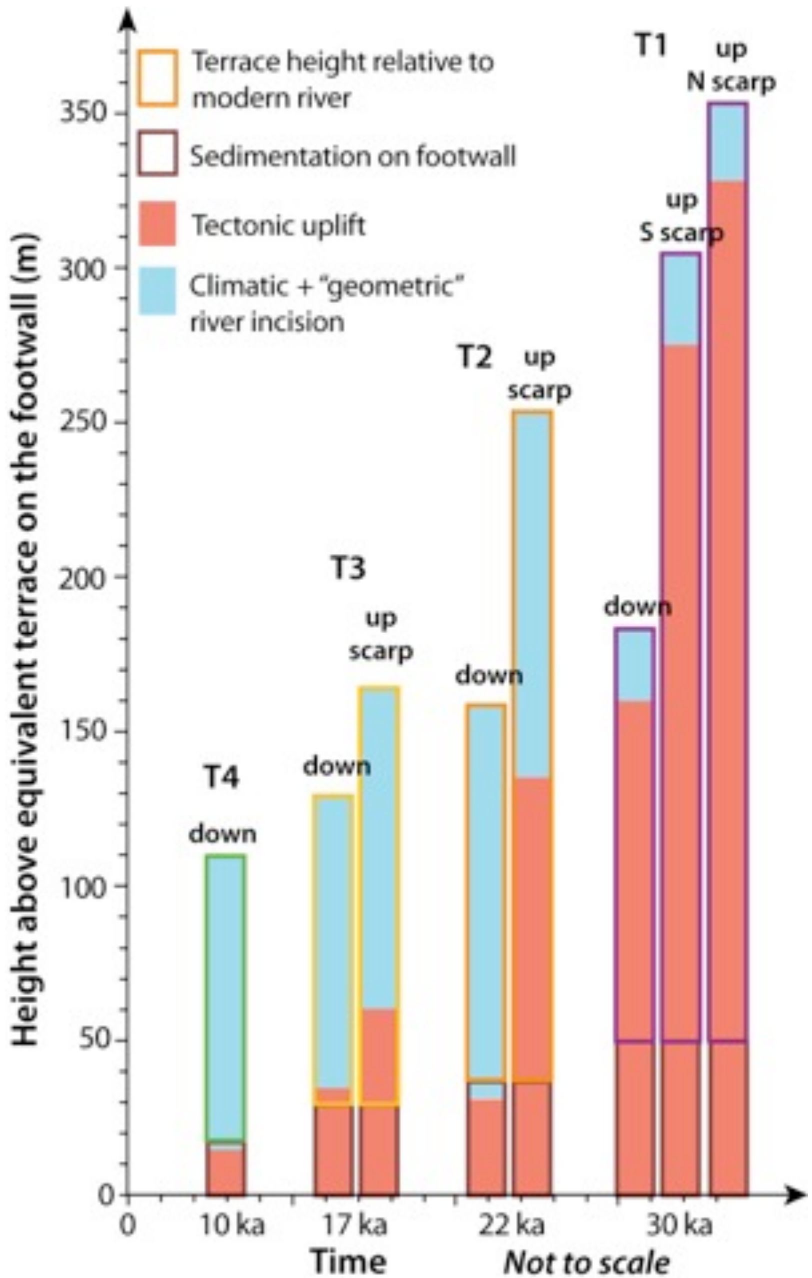
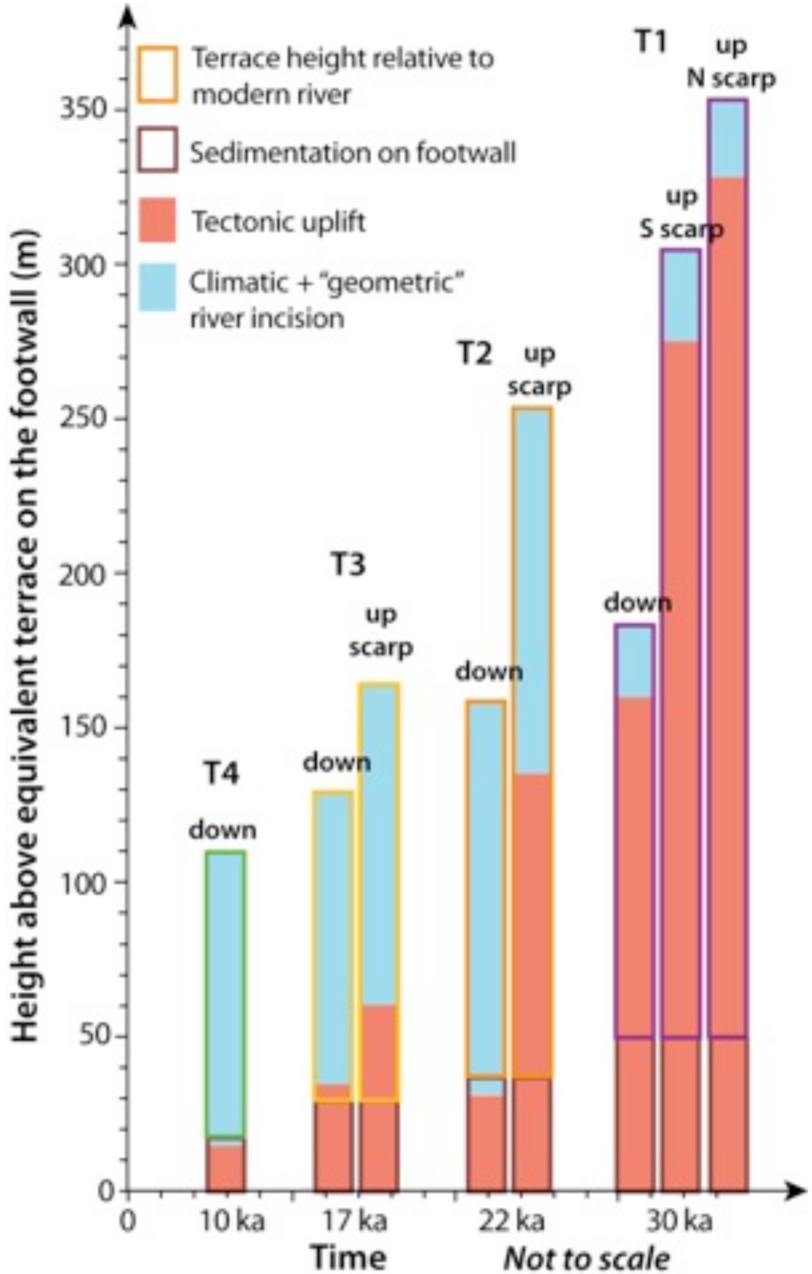
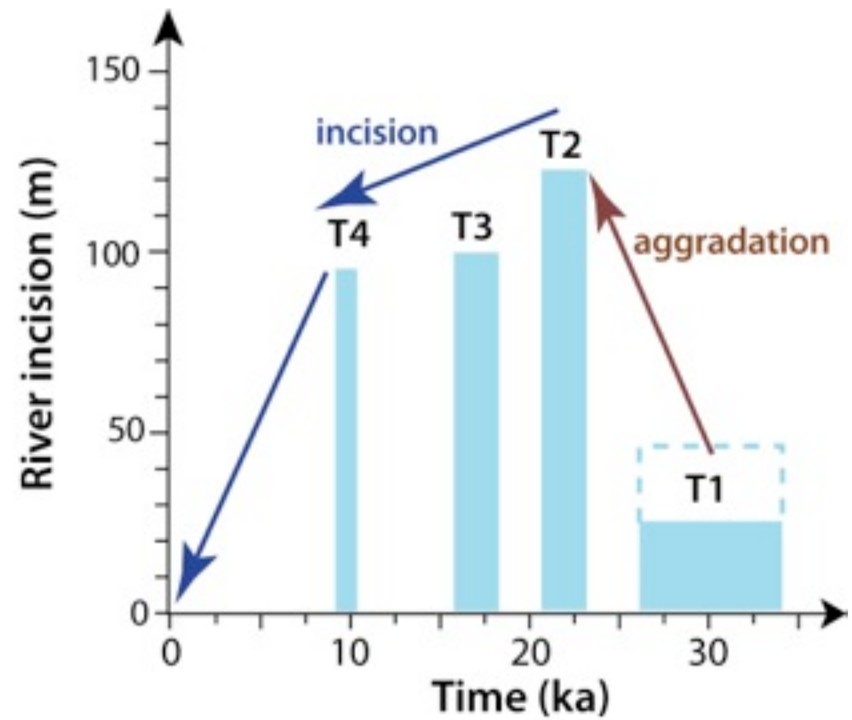


Tectonic uplift versus base level change





Changes in river regime

that coincide with paleo-climatic variations

(Liew et al 2006)

OSL dating the terraces

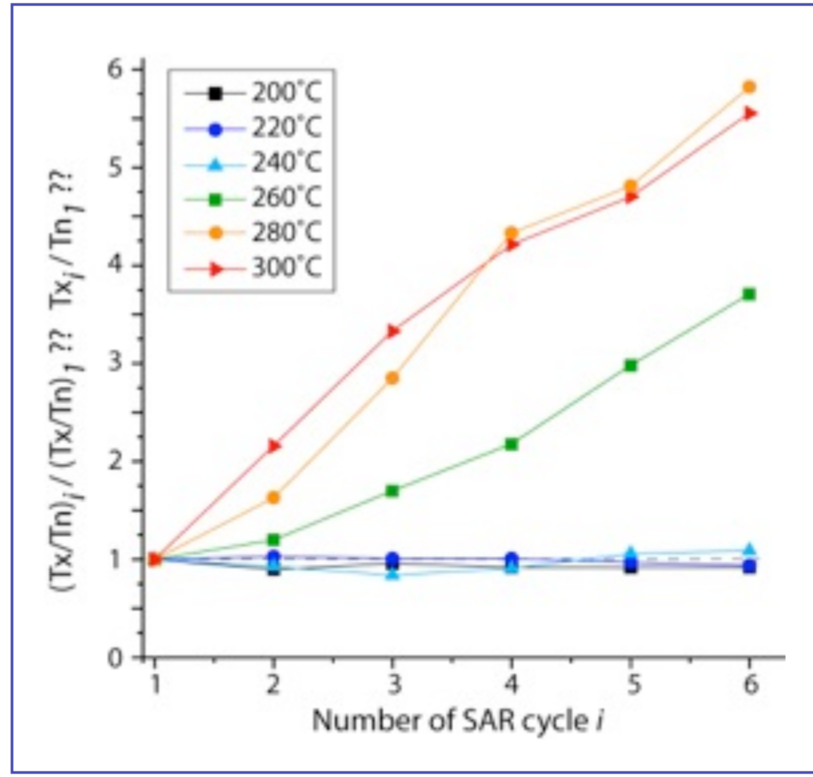
- Sampling -

Sampling

in tube within sand lenses

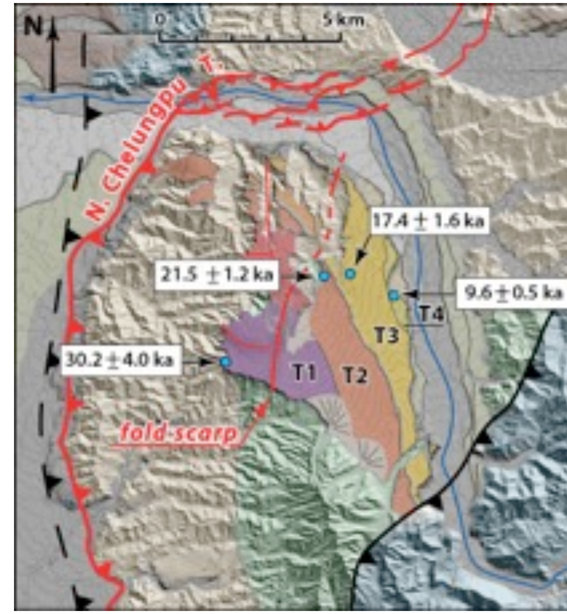
or interstitial sand under black cover

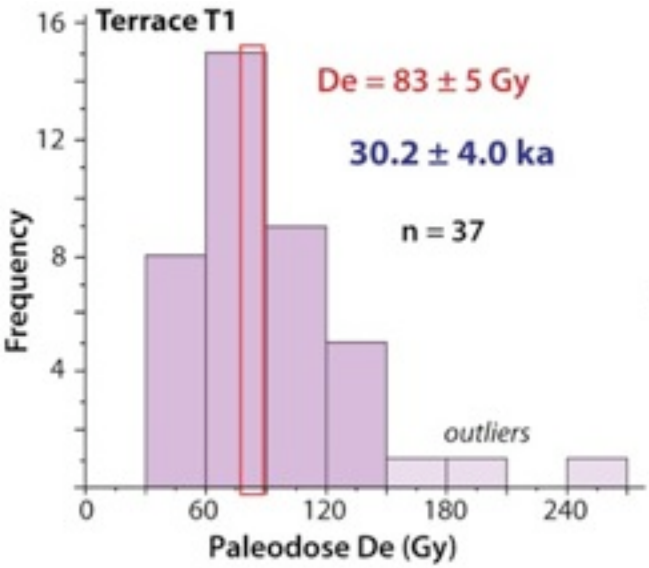
- Pre-heat test -

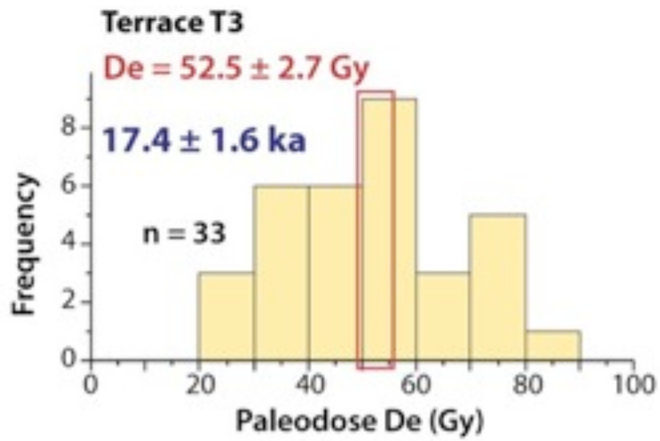


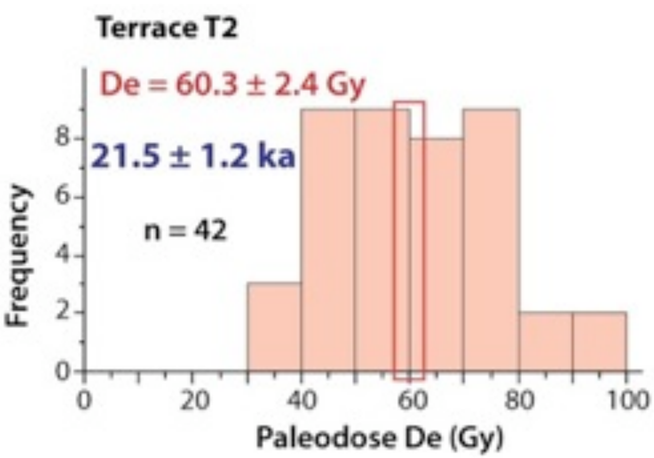
OSL ages

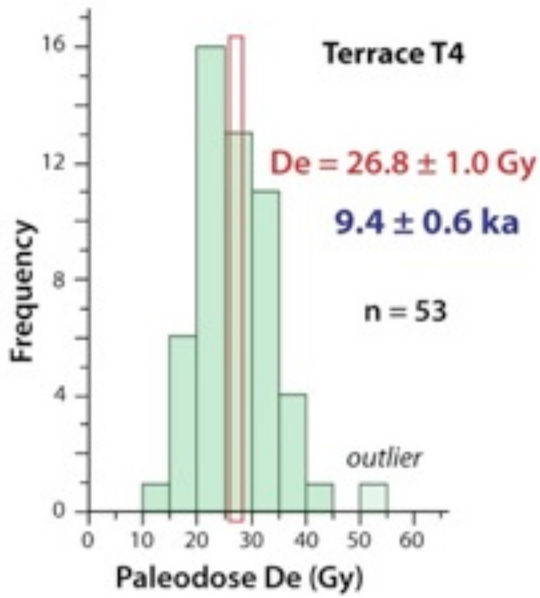
Consistent ages on 4 consecutive terrace levels











De = Paleodose