



# A strategy for refining post-LGM slip rates of fault systems in the Central Apennines, Italy

S. Pucci

R. Civico, C.A. Brunori, P.M. De Martini, M.Caciagli, T. Ricci

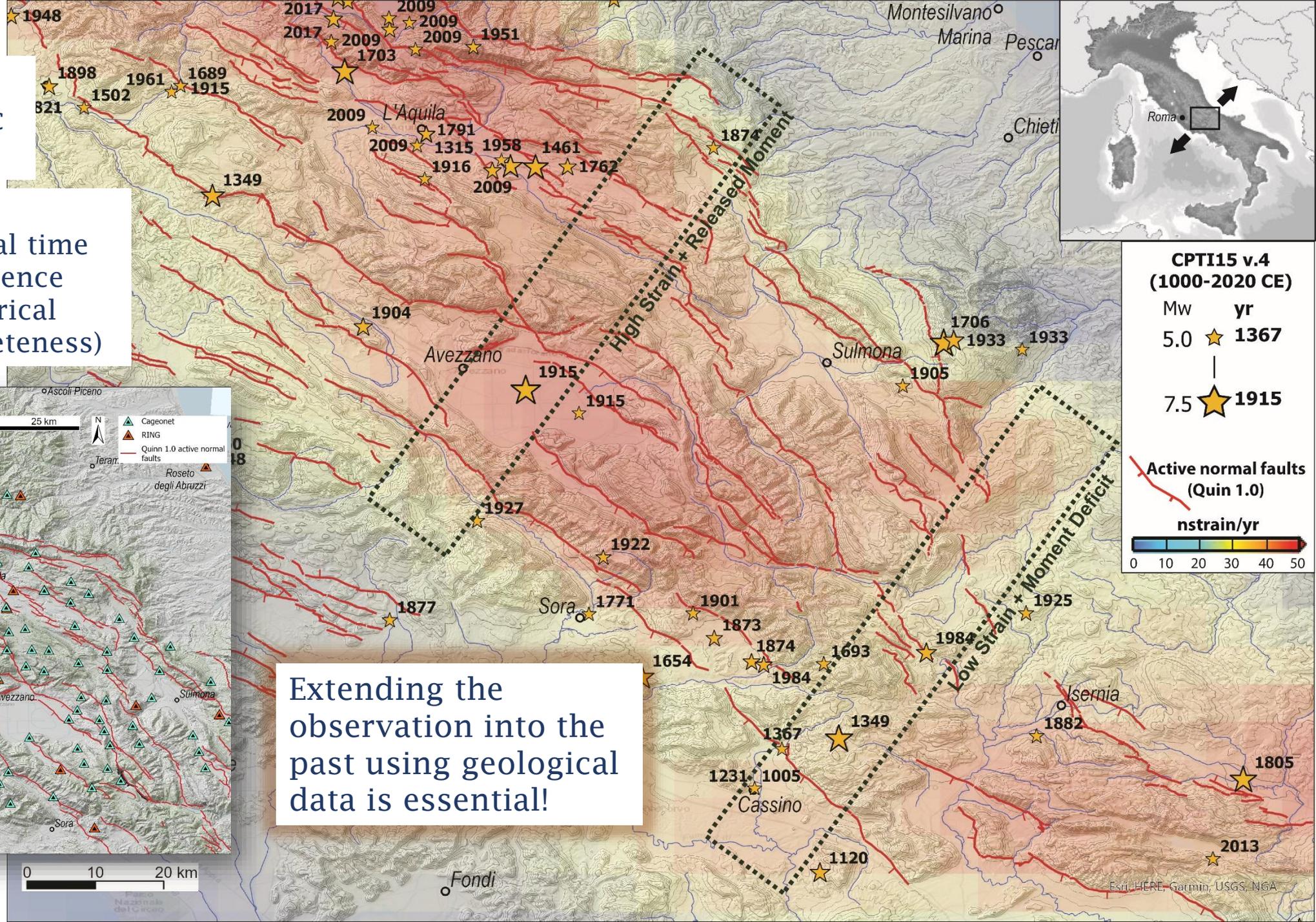
Istituto Nazionale di Geofisica e Vulcanologia (INGV-Italy); stefano.pucci@ingv.it



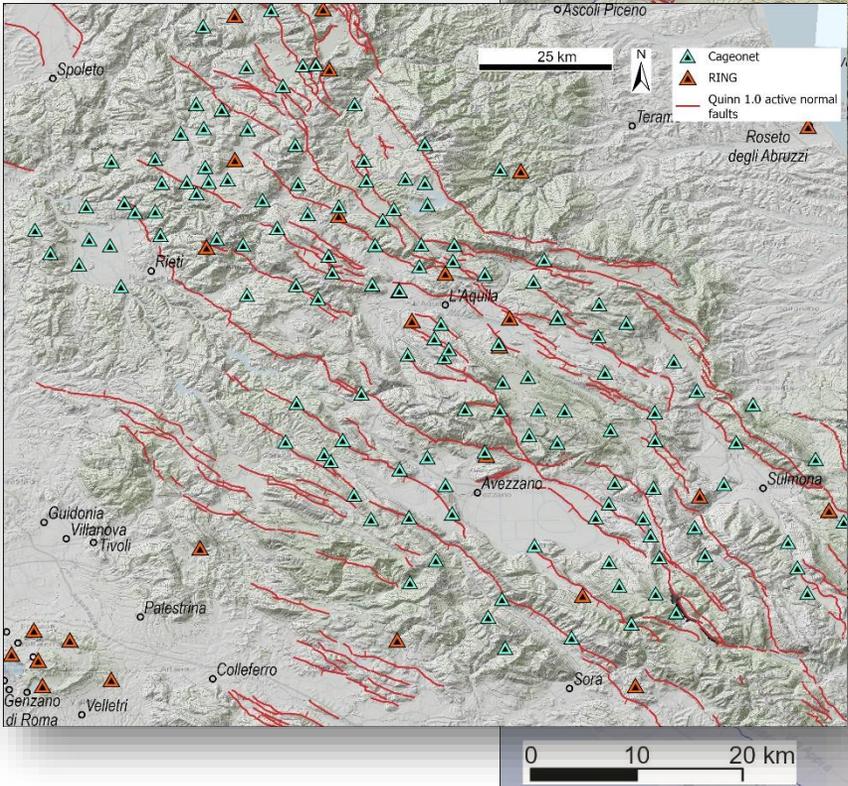
# Motivation

Imbalance in the geodetic-to-seismic budget

- aseismic release
- short observational time window (Eq recurrence intervals vs. historical catalogues completeness)



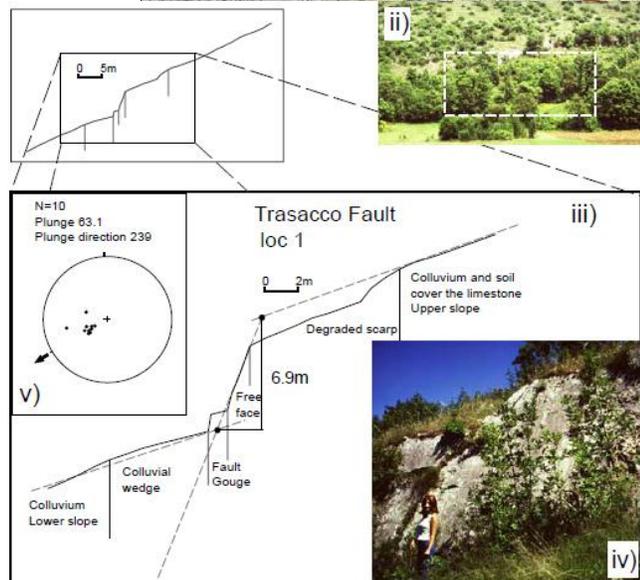
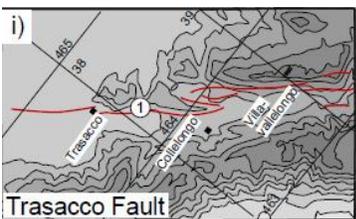
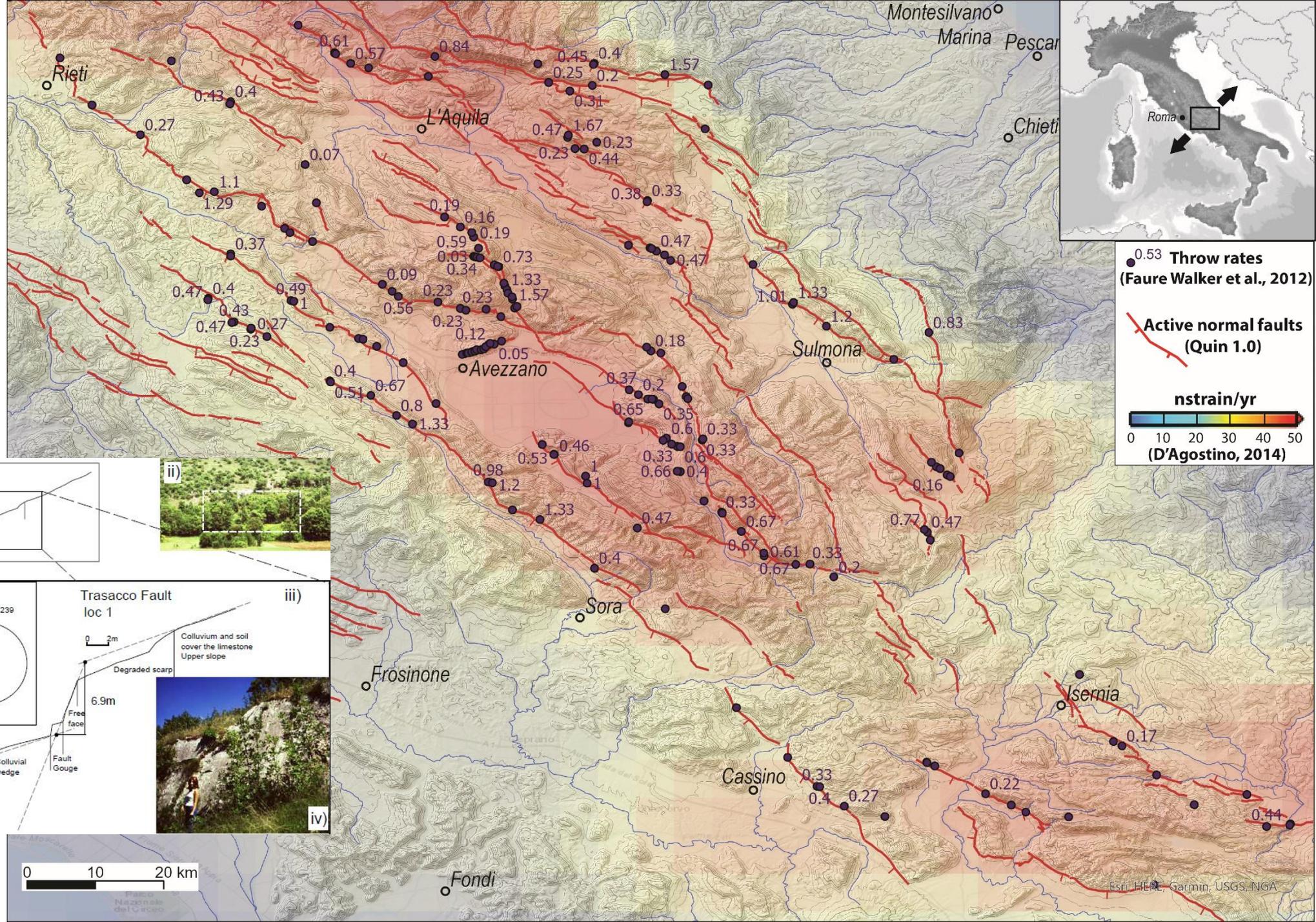
Extending the observation into the past using geological data is essential!



# Motivation

Quaternary fault slip rates do not account for geodetic extension rates

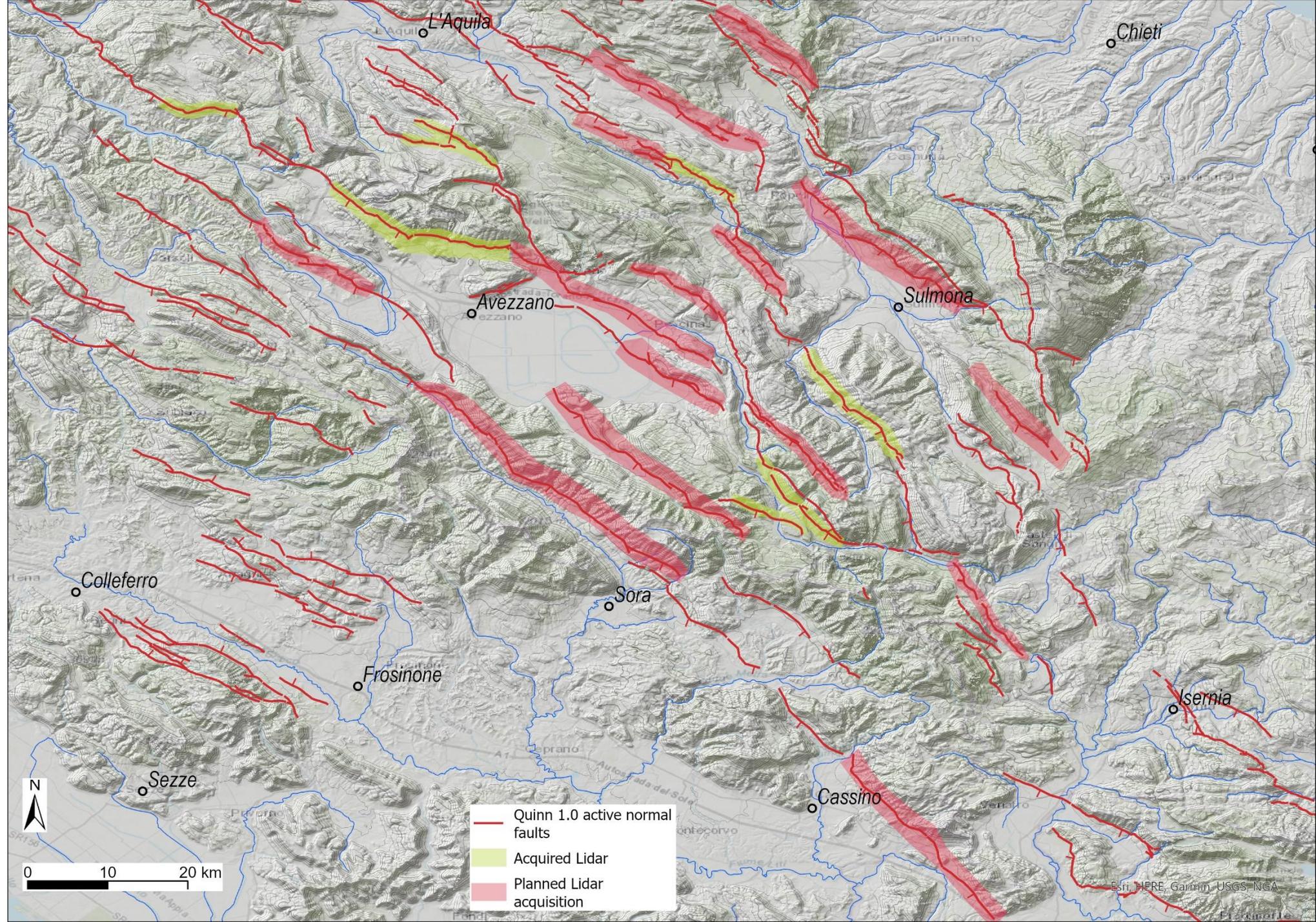
lack and/or inaccuracy in geological slip rate estimates?



From post-LGM scarps

# Approach: Step 1

Systematic acquisition of micro-topographic data using **Airborne LiDAR** along major normal faults

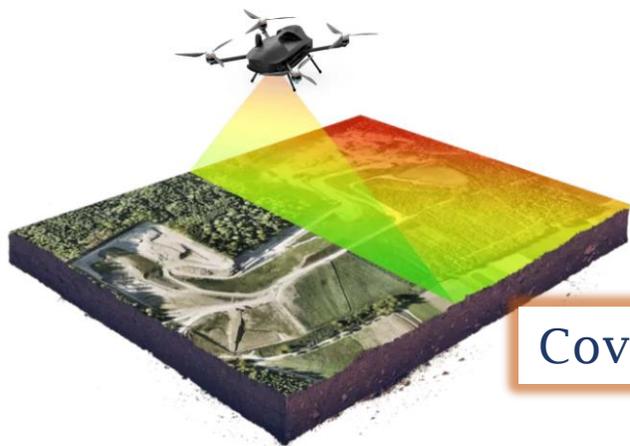




# Step1: Method

## Instrumental setting: Hardware

- Drone: DJI Matrice 400A    Vx: 7 m/s; h ground: 80 m
- Autogyro: Pagotto RAD    Vx: 15-18 m/s; h ground: 100 m



Coverage: ~4 km<sup>2</sup>/day



On-site battery recharging with additional battery set

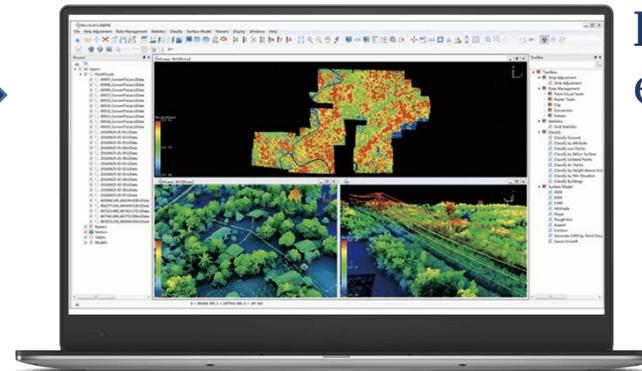
	DJI L3	Riegl Mini VUX
Laser Wavelength	1535nm	905nm
Laser Power (W)	64	18
Weight (g)	1600	1600
Beam divergence horizontal (mrad, FHWM)	0.15	0.5
Beam divergence vertical (mrad, FHWM)	0.15	1.6
Range at 10/20% refl	950m	170m
Max Return Rate	2,000 kHz	300 kHz
Max Returns	16	5
Horizontal System Accuracy (cm)	4	3-5*
Vertical System Accuracy (cm)	3	3-5*
Stated Accuracy Range (m)	120	
Lidar Field of View	80°	120°
IMU Accuracy (Yaw, post-processed)	0.02°	N/A
IMU Accuracy (Roll/pitch, post-processed)	0.01°	N/A
Camera Resolution	2x 100 MP	N/A
Sensor Size	4/3"	N/A
Camera FOV	107°	N/A
Price	~\$17,000	~\$100,000+

# Step1: Method

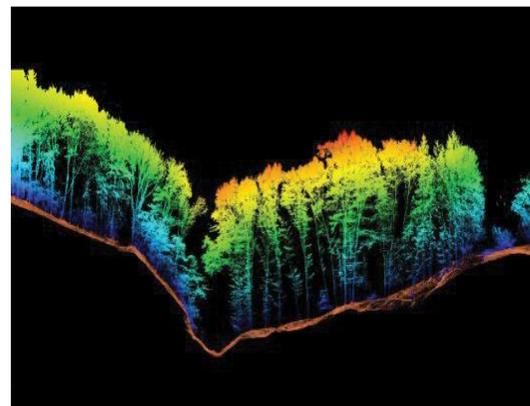
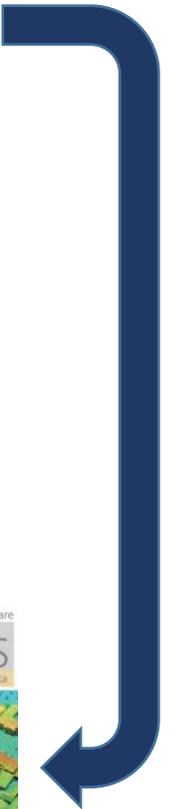
## Instrumental setting: Software



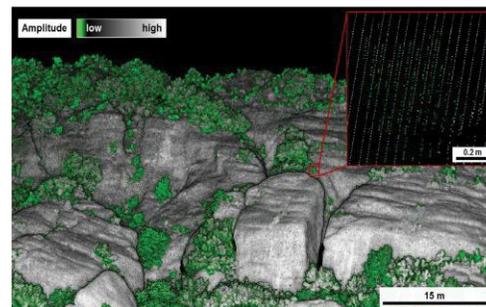
Mission planning & automatic flight



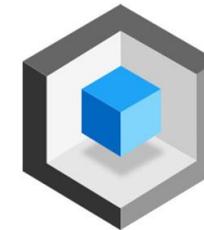
Post-processing elaboration



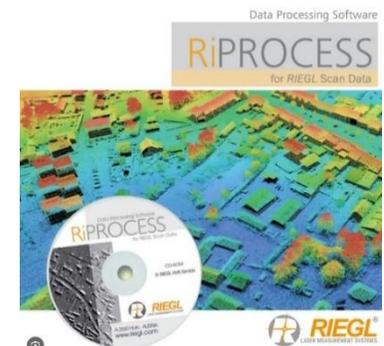
AI for points  
cloud classification



Return intensity data  
DGPS spatial correction



DJI TERRA

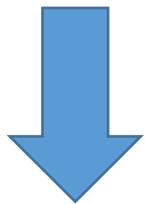


RIEGL  
Light Measurement Systems

# Step1: Method

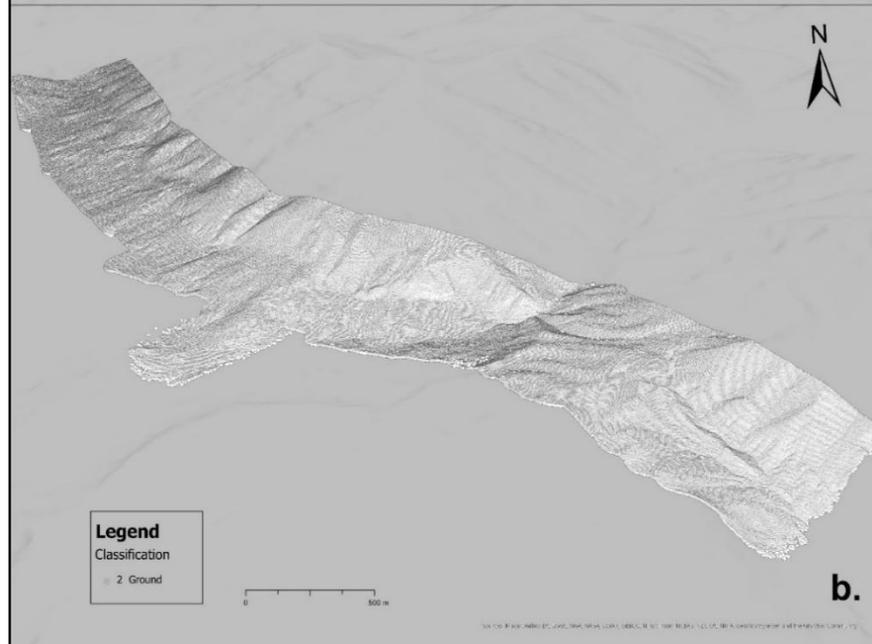
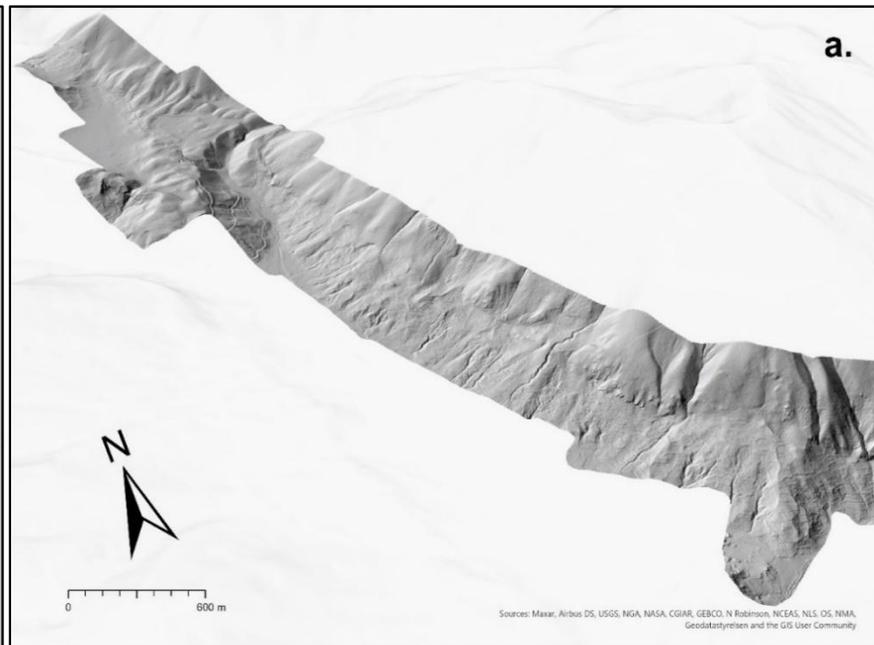
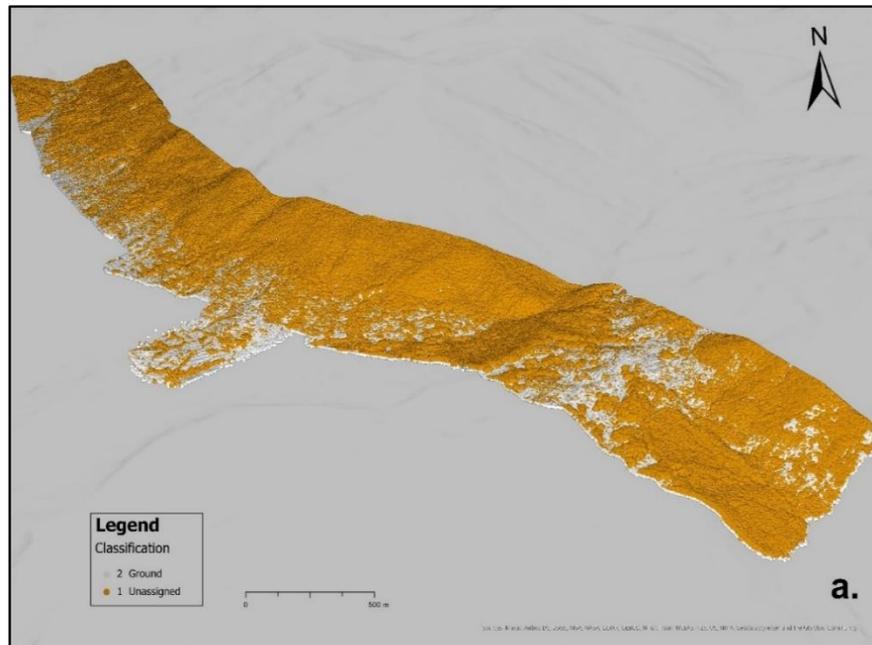
## Output

- Point precision:  $\sim 0.02$  m
- Point accuracy:  $\sim 0.03$  m
- Points density:  $\sim 350$  pts/m<sup>2</sup>



High-resolution bare  
Digital Terrain Models  
(HR-DTMs):  $< 0.3$  m

width along  
the fault trace: 400-600 m



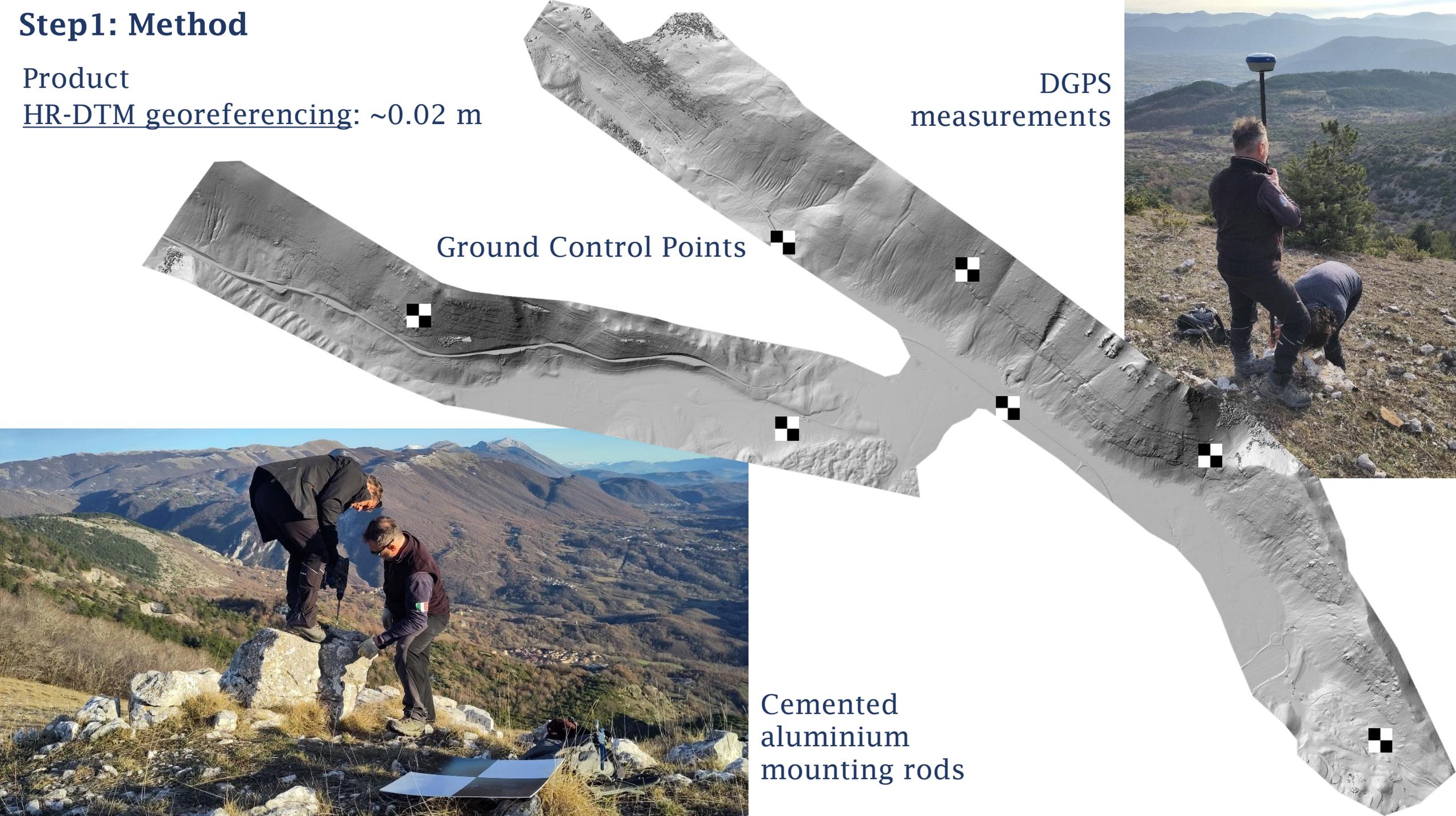
# Step1: Method

Product  
HR-DTM georeferencing: ~0.02 m

DGPS  
measurements

Ground Control Points

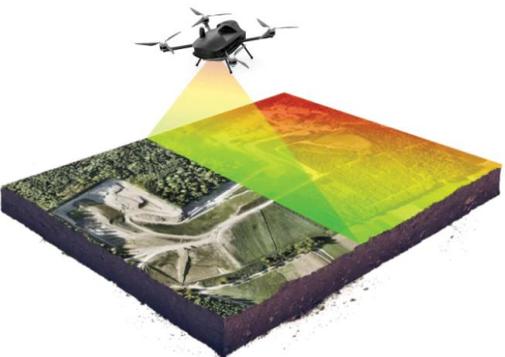
Cemented  
aluminium  
mounting rods



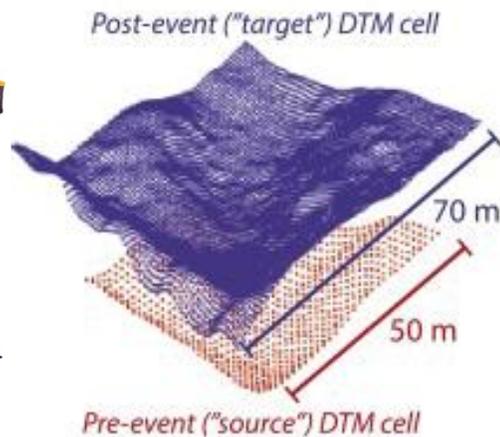
# Step2: Applications

## HR-DTM as baseline

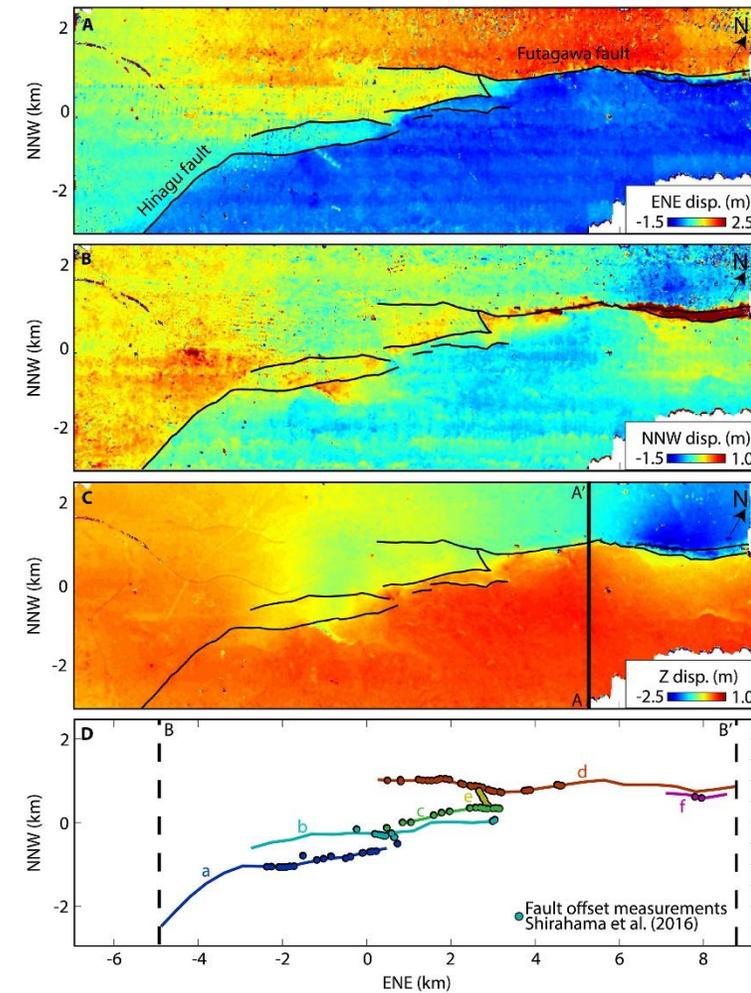
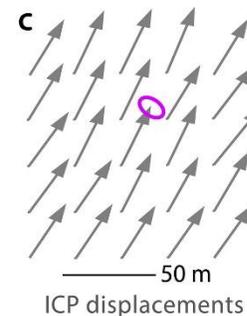
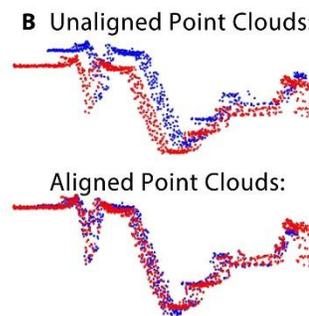
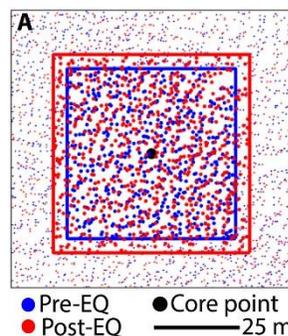
- monitor interseismic morphological evolution of fault scarps
- Post-surface faulting differential Lidar topography



Multi-temporal data



Iterative Closest Point (ICP) algorithm



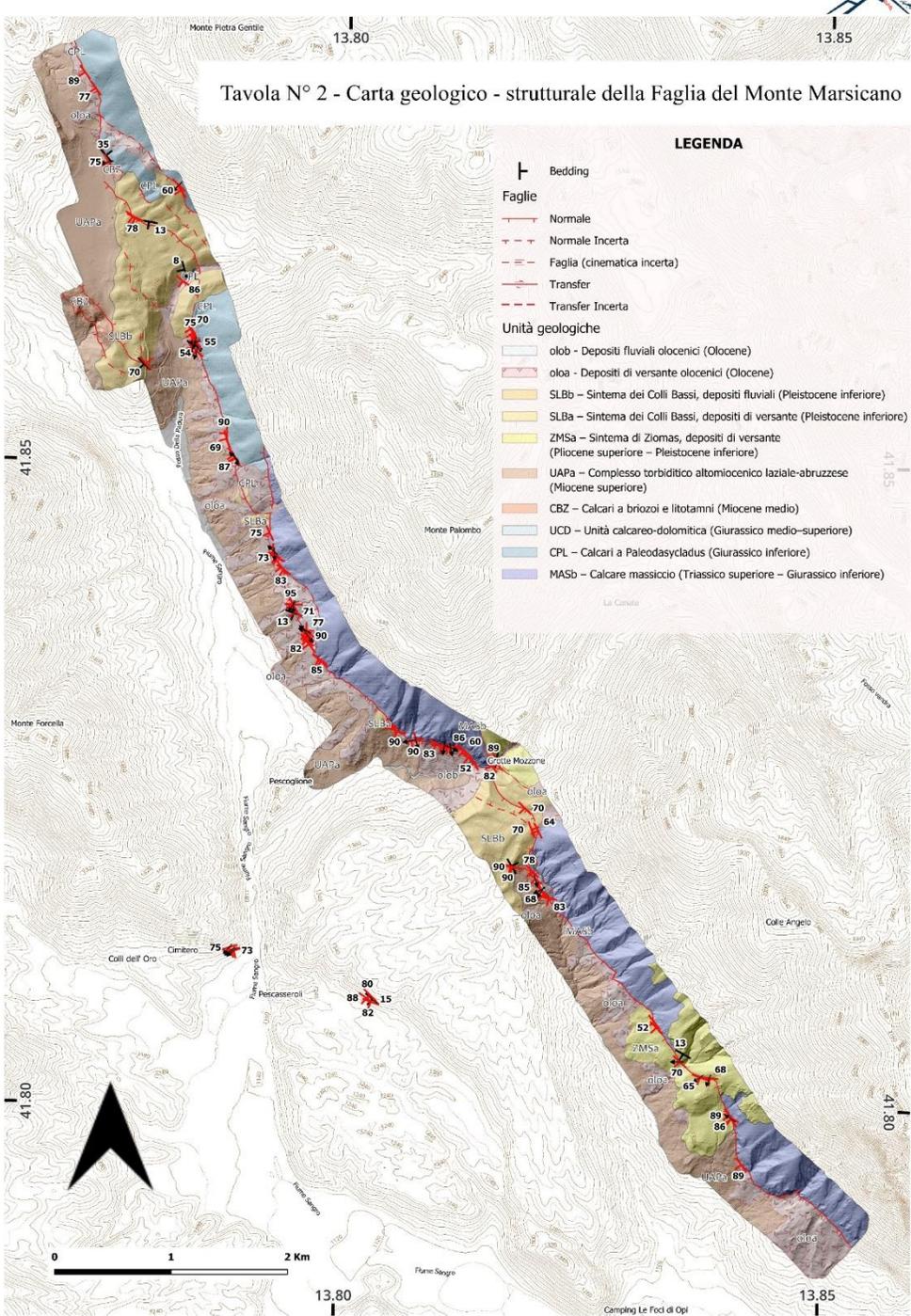
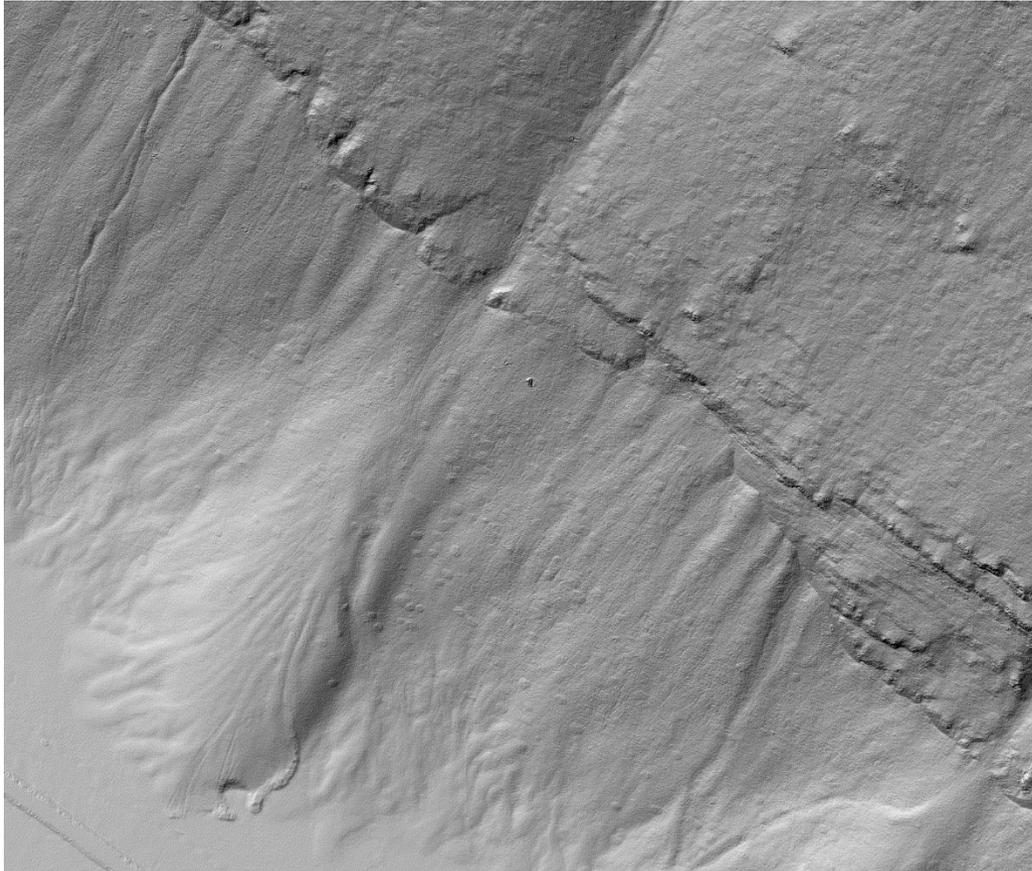
Scott et al., 2018

# Step2: Applications

## Near-fault fine-scale geological mapping



- Detailed **structural pattern** of the fault trace
- Particularized and accurate **Quaternary deposits** arrangement



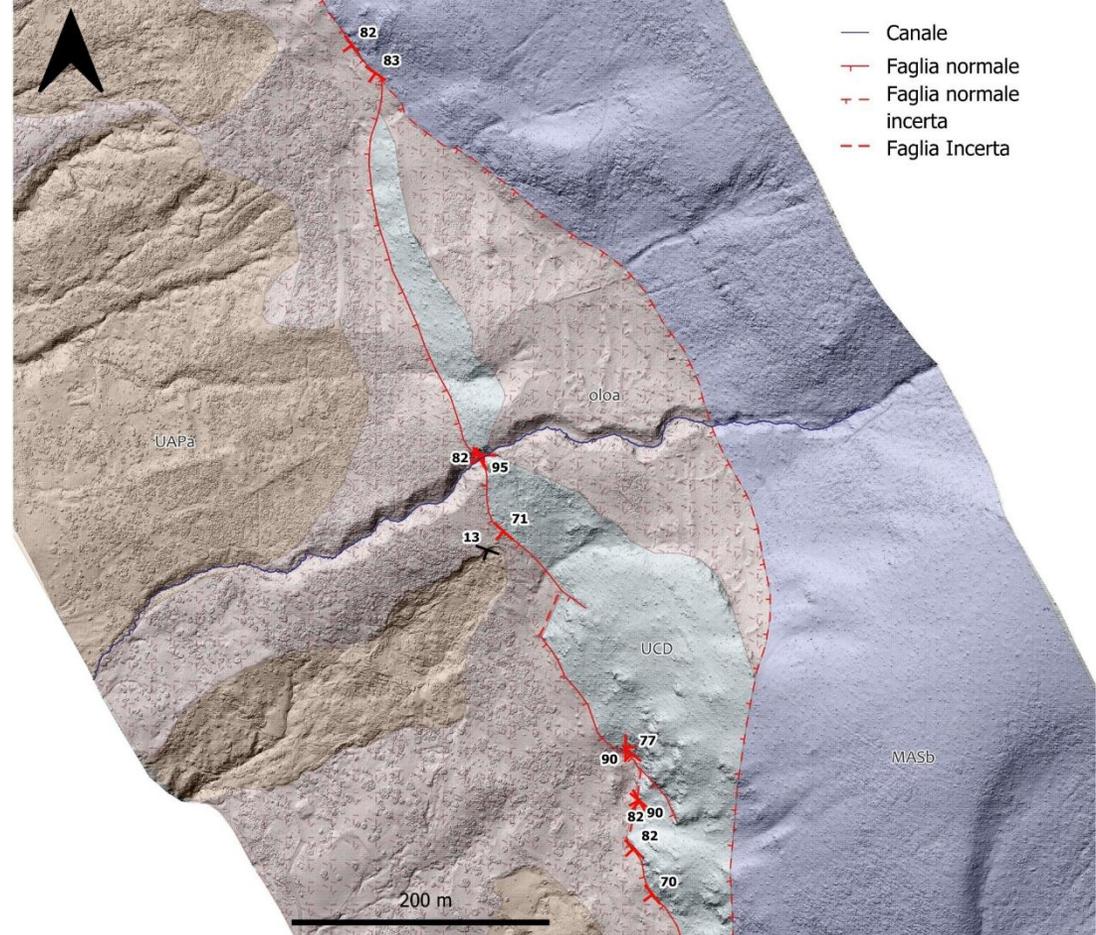
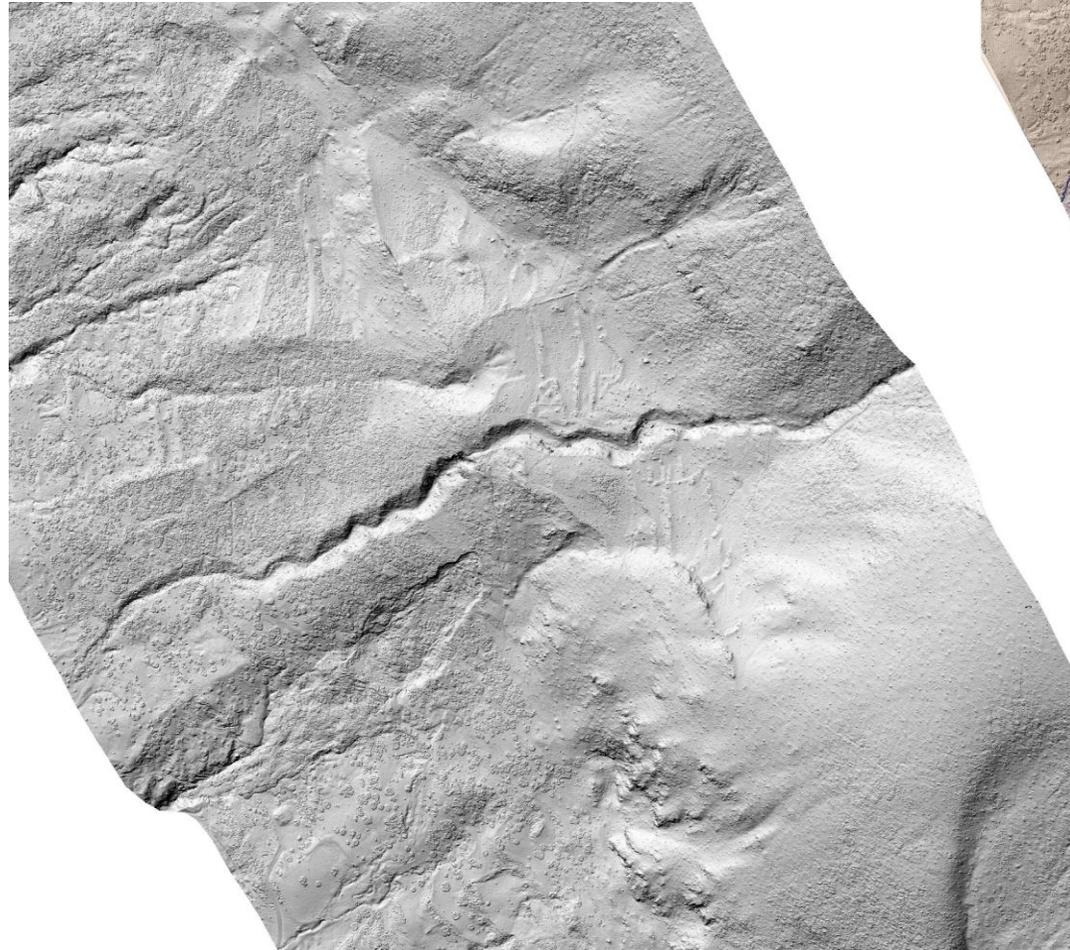
Gigante, 2025

# Step2: Applications

## Near-fault fine-scale geological mapping



- identification **displaced geomorphological markers** for slip rates estimate



## Step2: Applications

### Fault scarp morphometry



- Document **post-Last Glacial Maximum** fault scarps and along-strike throw distributions for **slip rate estimates**

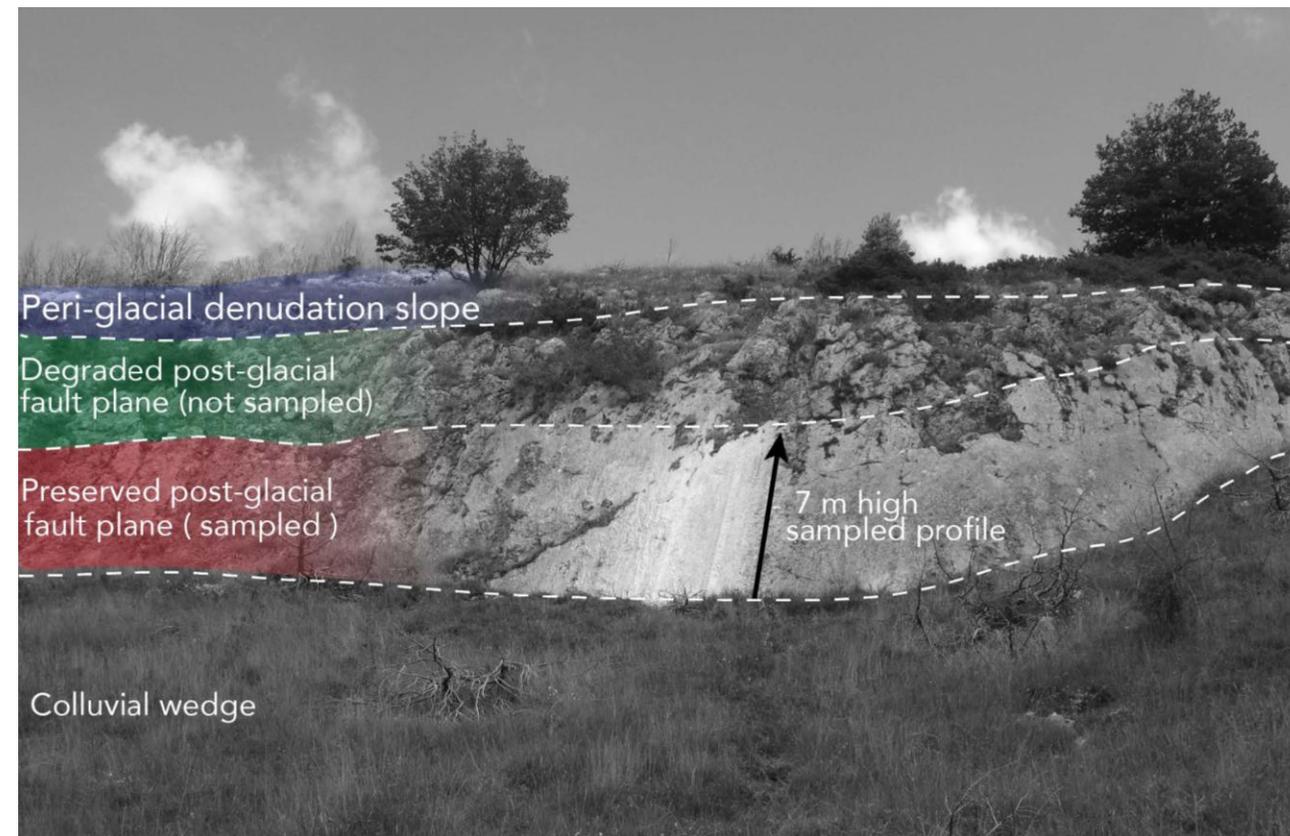
### S.C.A.R.P.S.

(Scarp Analysis and Reconstruction Profile System)

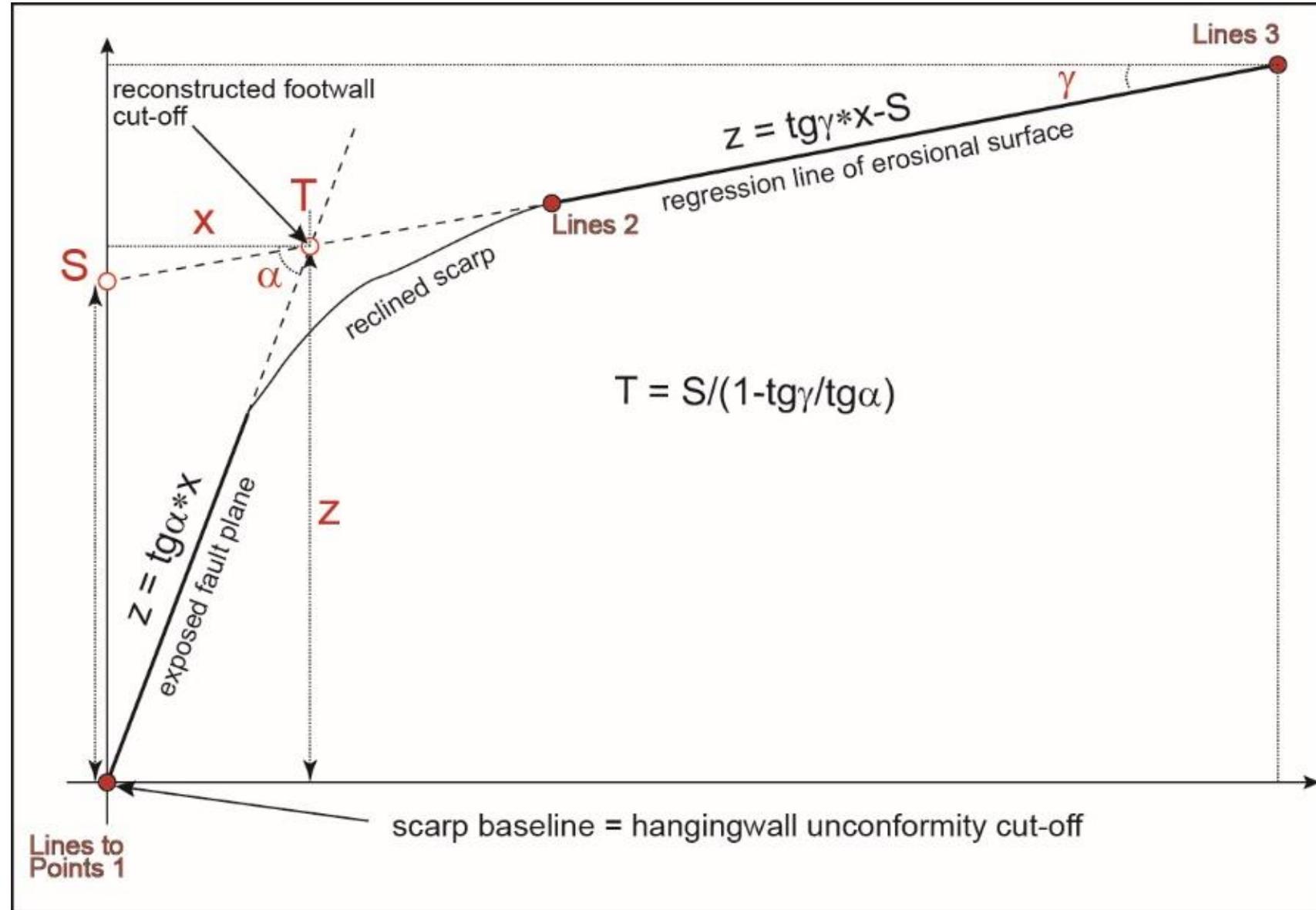
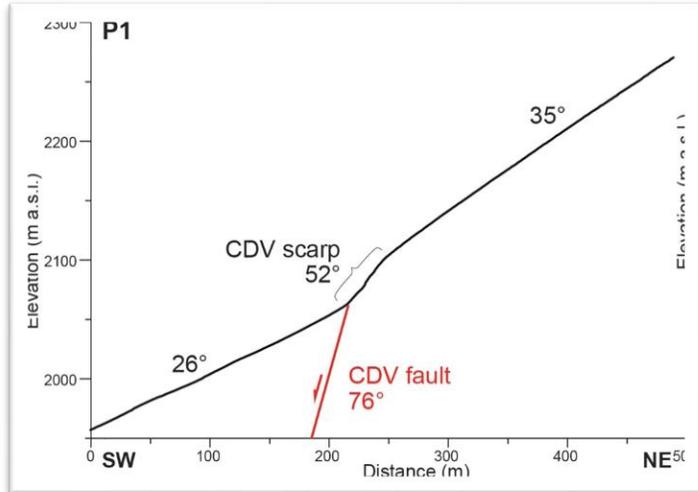
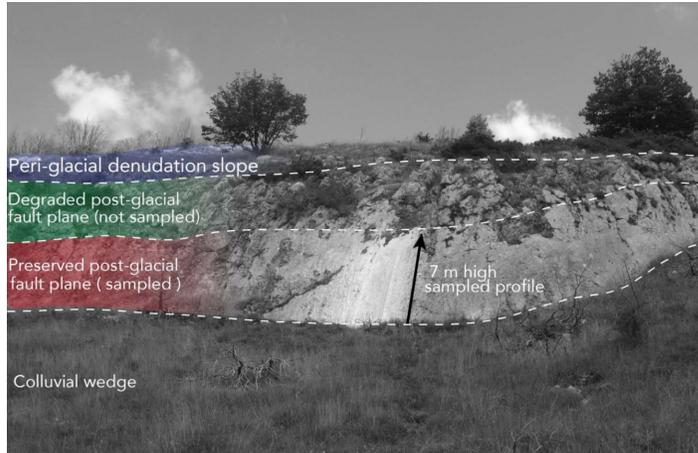
### Python software tool:

semi-automatic analysis of fault scarps from HR-DTMs

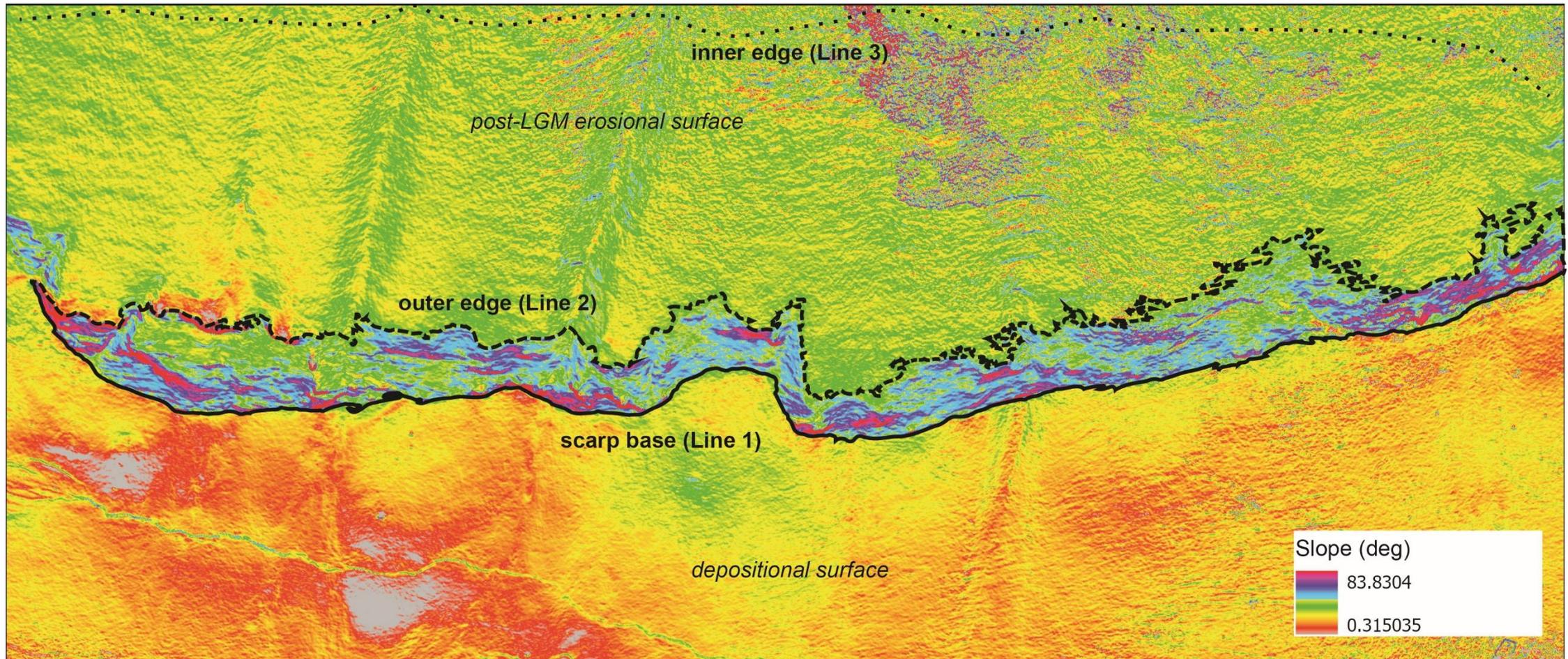
Graphical User Interface (GUI): ease of use and cross-platform (macOS, Windows, Linux)



# Conceptual model

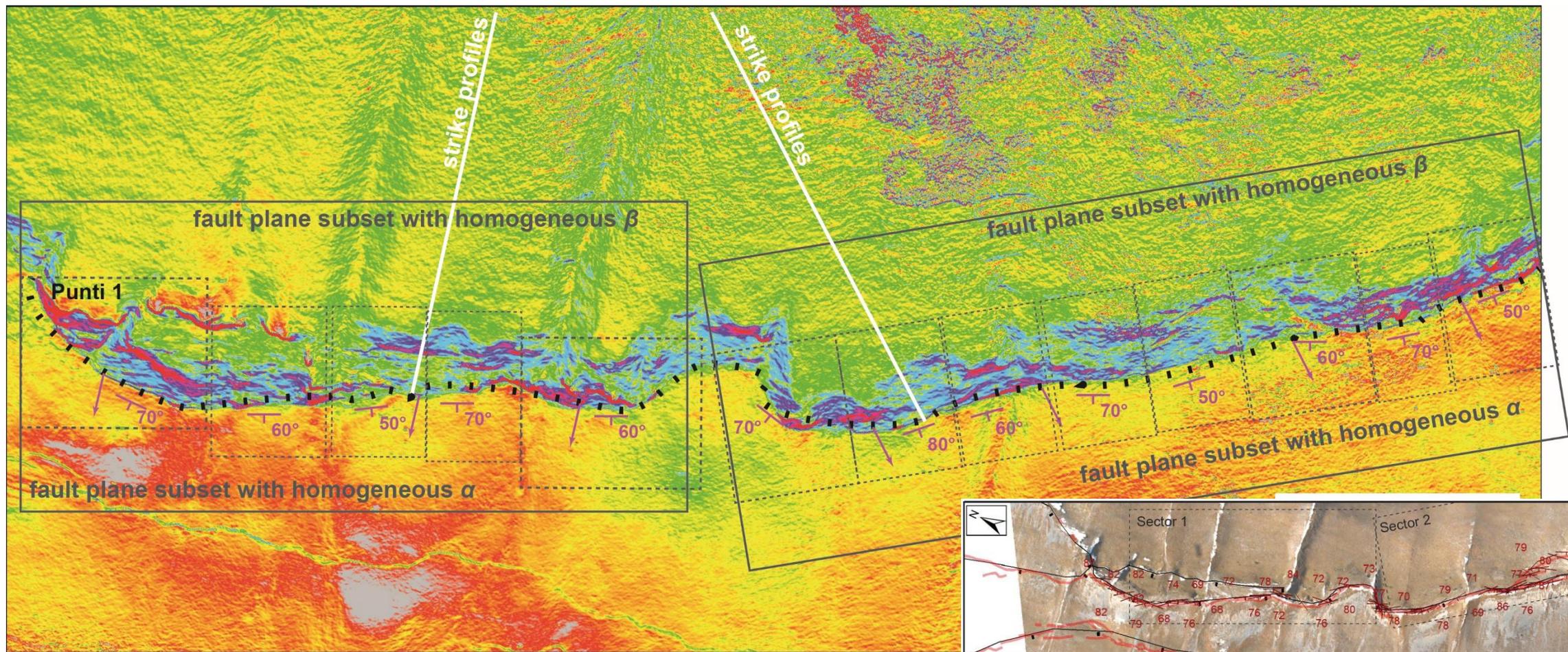


Input (by the operator): from HR-DEM visual interpretation



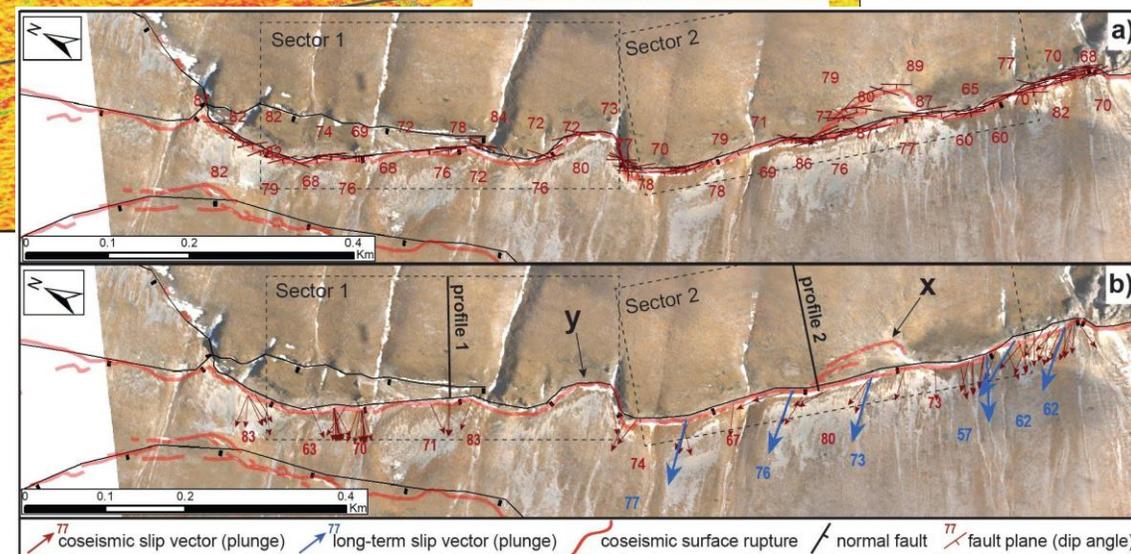
- **HR-DEM** (GeoTIFF)
- **Scarp Base Points** (shp): The point shapefile for the scarp base (Line 1 to Points 1)
- **Scarp Top Line** (shp): The line shapefile for the **outer edge of the erosional surface** (Line 2)
- **Profile End Line** (shp): The line shapefile for the **inner edge of the erosional surface** (Line 3)

Input (by the operator): from fieldwork



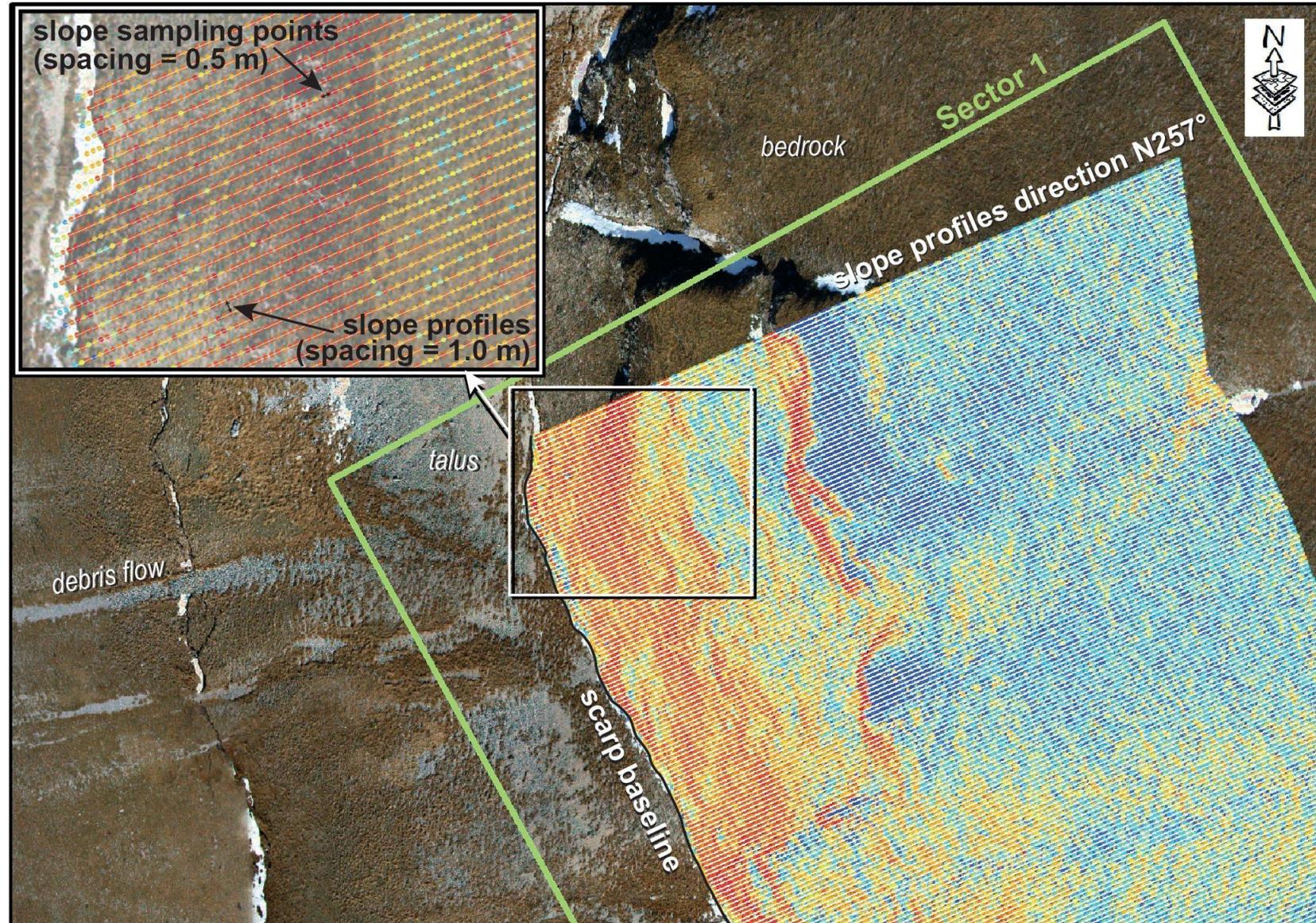
Data attribute for points subset of the scarp base (Points 1):

- $\alpha$ : fault dip angle
- $\beta$ : azimuth of the slip vector (for profile orientation)



**Input (by the operator):** sampling density

- **Sampling Step (m):**  
spacing between the profiles
- **Sampling points (m):**  
spacing of data points along the profile



## Output (by the code):

\*.CSV file format for each analyzed profile:

- p1\_id: Profile **ID**
- x1, y1, z1: **Coordinates** of the **scarp base point** (Point 1)
- xT, yT, zT: **Coordinates** of the reconstructed **throw point** (Point T)
- T\_throw: **total vertical throw** ( $z_T - z_1$ )
- S\_offset: **vertical surface offset** ( $z_S - z_1$ )
- gamma\_deg: **angle** of the **footwall surface**
- baseline\_dist: progressive **distance** along the scarp

## Plots:

- plot\_throw\_vs\_distance.pdf
- plot\_reconstructed\_profiles.pdf
- plot\_representative\_profile.pdf

Synthetic **HR-DTM** of the **non-reclined scarp**

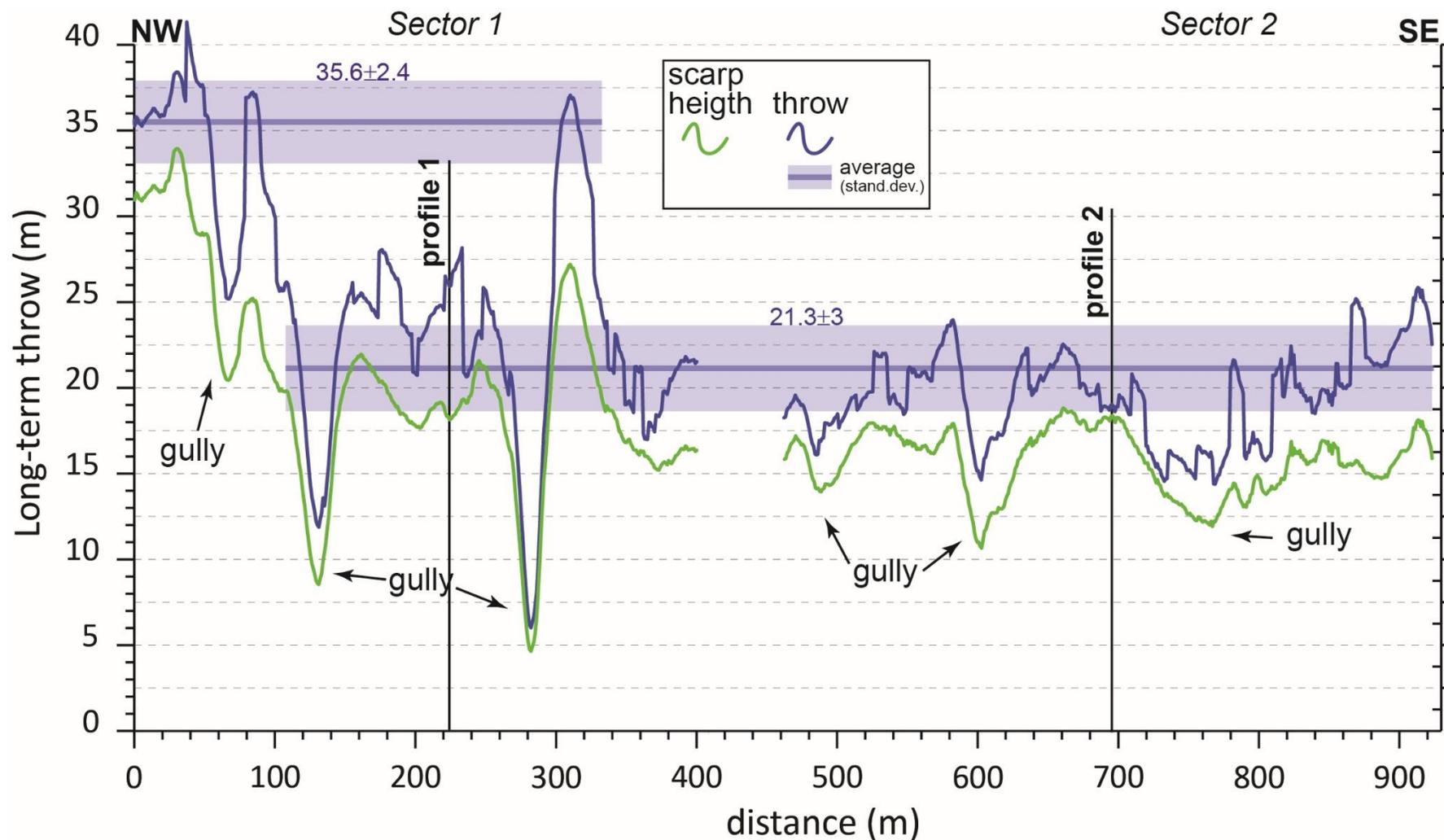
The screenshot shows the SCARPS - Fault Scarp Analysis Tool v1.0 by cab-gemini supported interface. The window is divided into several sections:

- Input Files:** Four input fields with 'Browse...' buttons: DEM (GeoTIFF), Scarp Base Points (Point1.shp), Scarp Top Line (Line2.shp), and Profile End Line (Line3.shp).
- Analysis Parameters:** Three input fields: Alpha (dip) field name (alpha), Beta (azimuth) field name (beta), and Sampling Step (m) (1.0).
- Output:** Four input fields with 'Browse...' buttons: Output Folder, CSV Filename (throw\_analysis\_results.csv), Throw Plot Filename (plot\_throw\_vs\_distance.pdf), Profiles Plot Filename (plot\_reconstructed\_profiles.pdf), and Rep. Profile Plot Filename (plot\_representative\_profile.pdf).
- Generate Plots after Analysis:** A checked checkbox.
- Start Analysis:** A button.
- Exit:** A button.
- Process Log:** A large empty text area at the bottom.

Output (by the code): Plots

plot\_throw\_vs\_distance.pdf

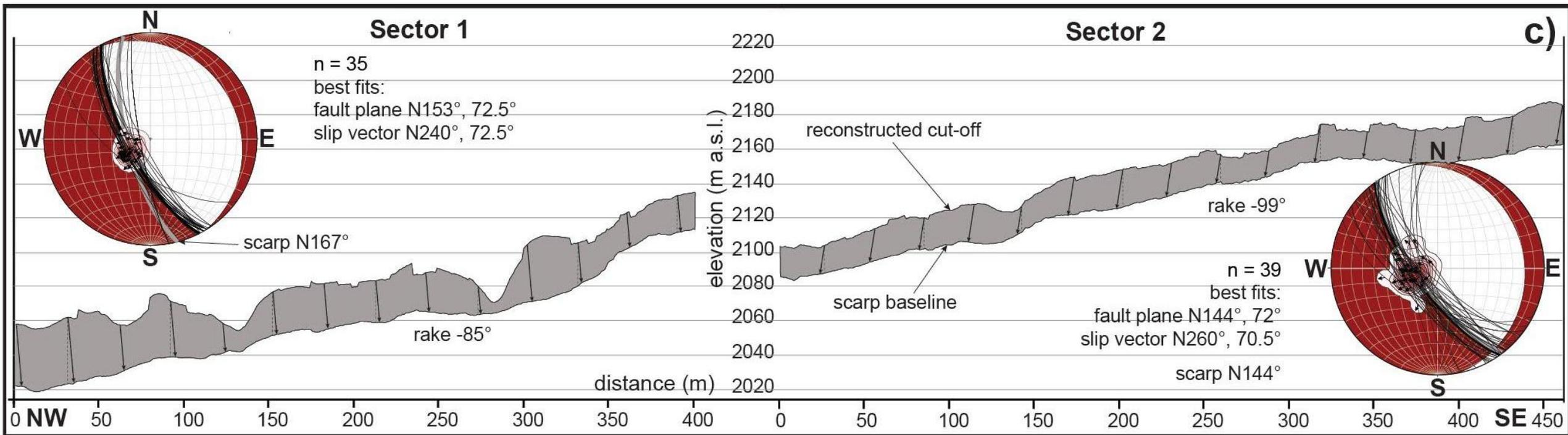
distribution of throw/slip  
along the scarp



Output (by the code): Plots

plot\_reconstructed\_profiles.pdf

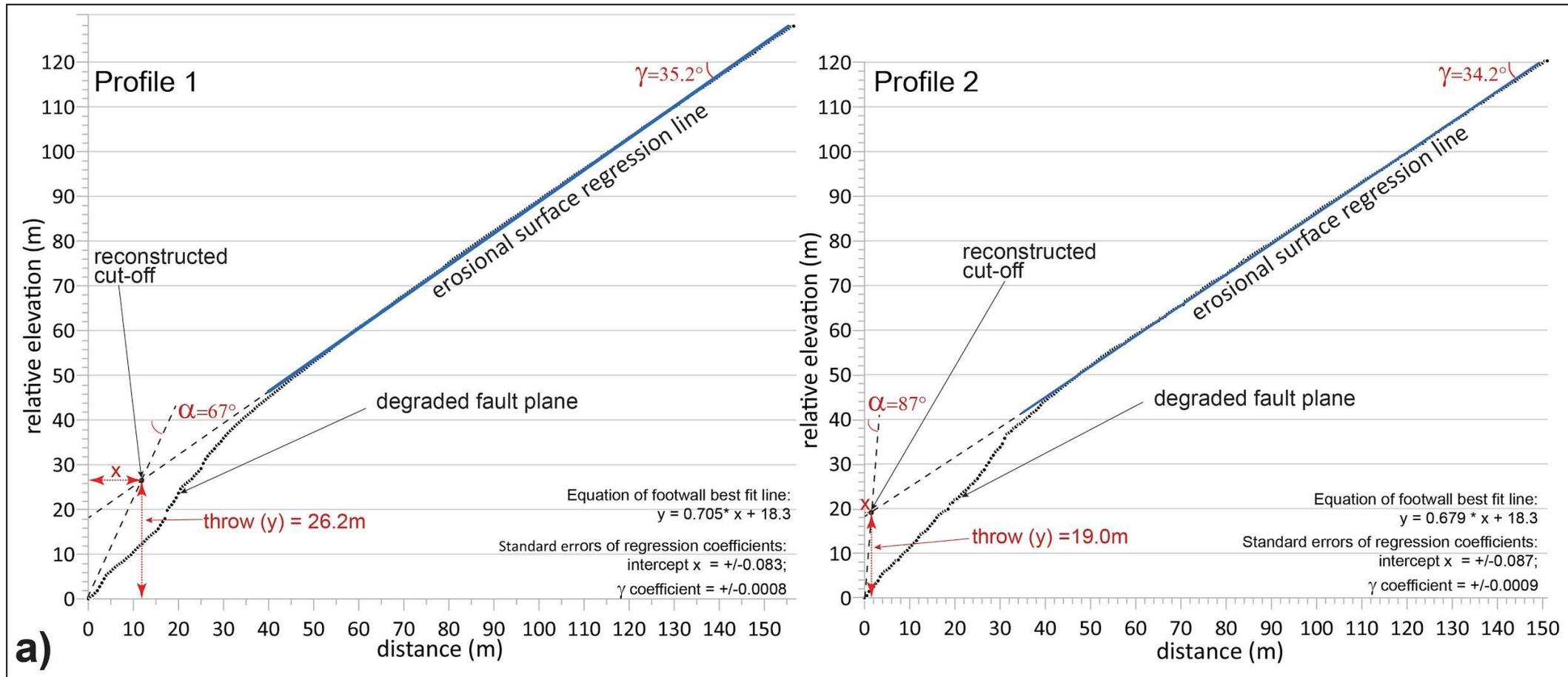
reconstructed scarp morphology, showing the along-strike elevation distribution of the base and top



Output (by the code): Plots

plot\_representative\_profile.pdf

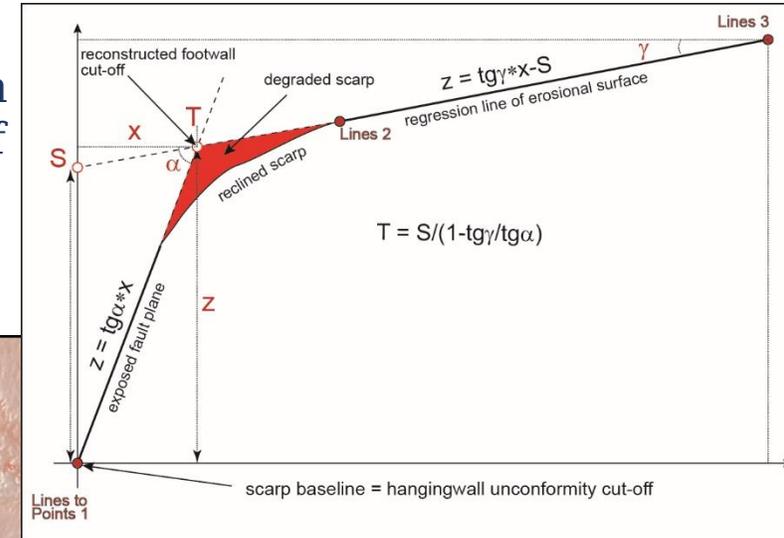
individual cross-sectional  
profile results



Output (by the code): Synthetic HR-DTM of the non-reclined scarp

Reconstructed from  
footwall cut-off

to quantify and imaging degradation  
through topographic differencing

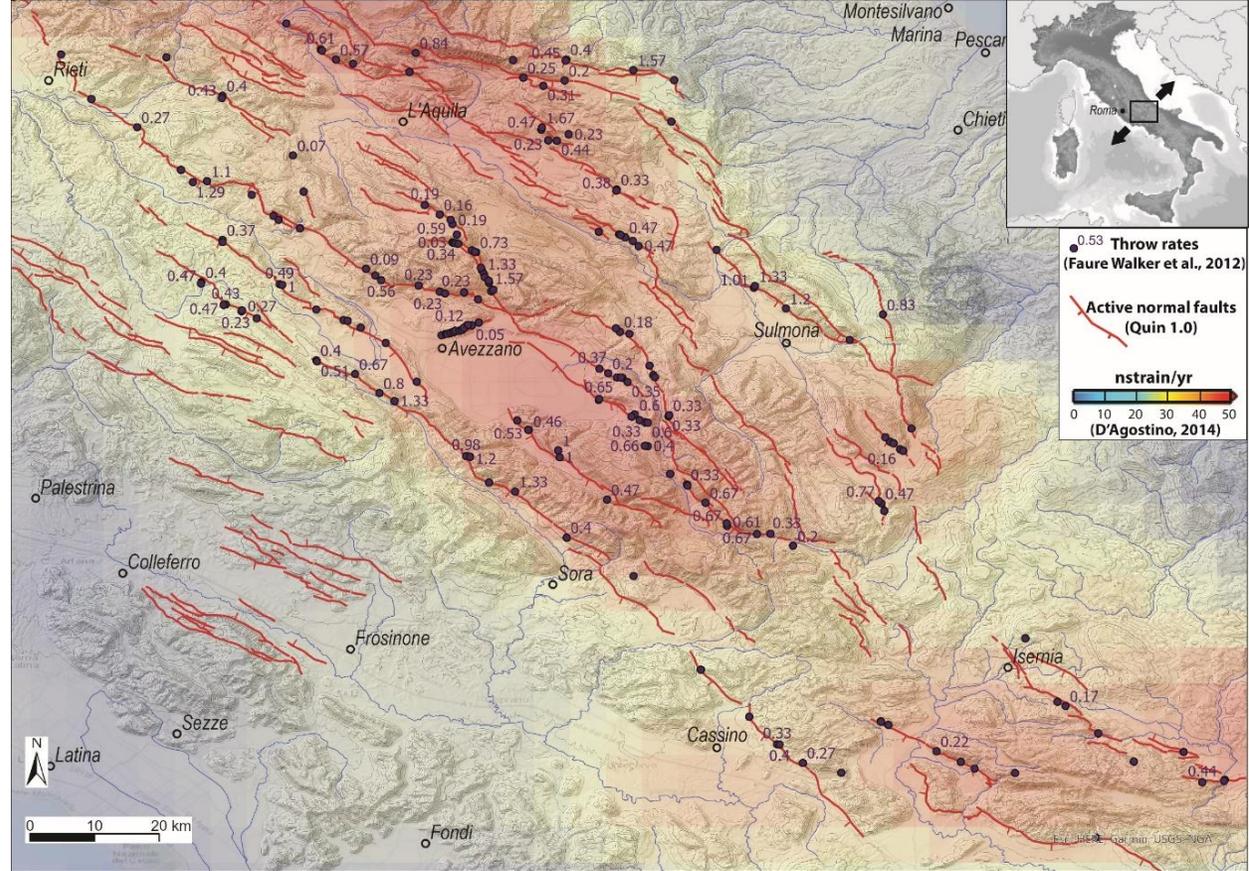
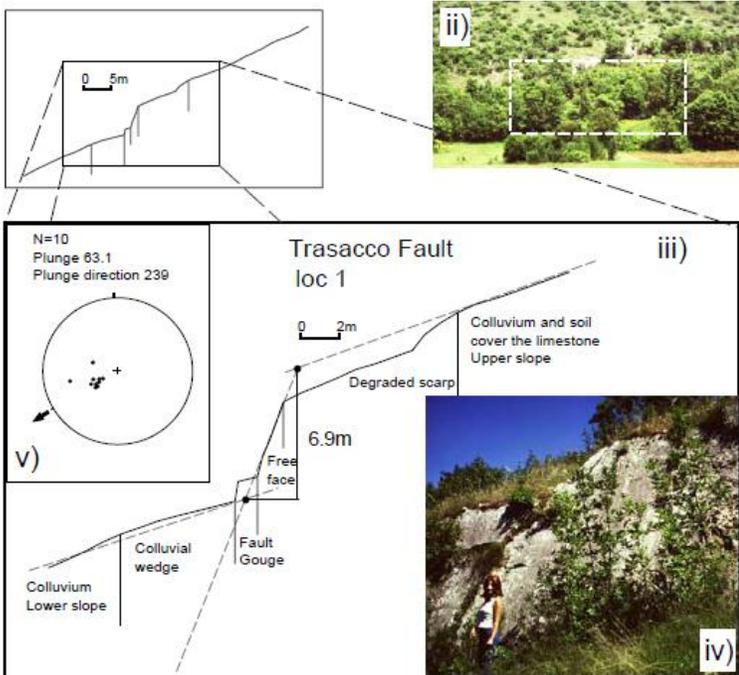
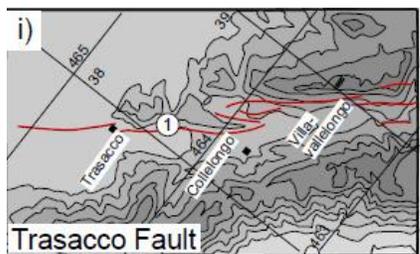


# Step2: Applications



**S.C.A.R.P.S.** Outcomes to refine post-LGM slip rate estimates

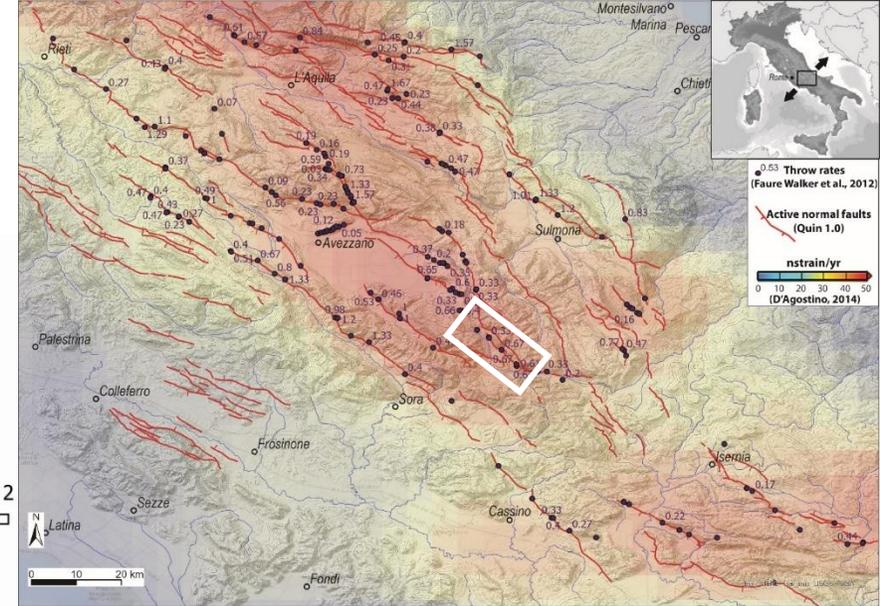
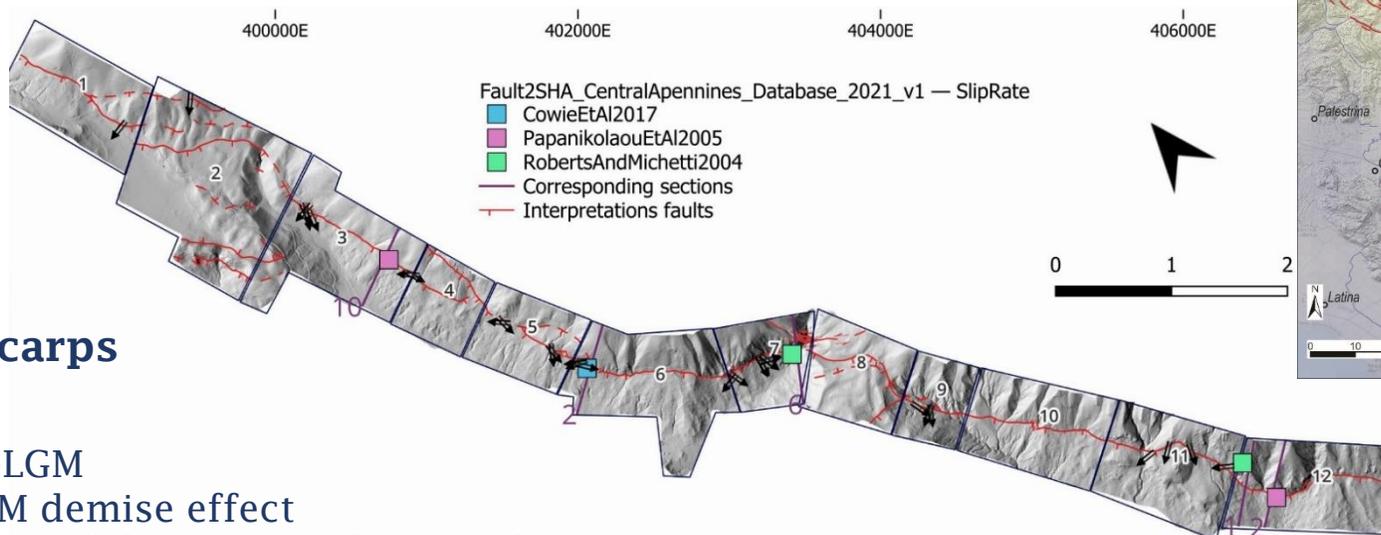
**Question:** are the bedrock fault scarps used properly?



# Step2: Applications



## S.C.A.R.P.S. Outcomes to review post-LGM slip rate estimates



..about fault scarps

### Debatable:

- entirely post-LGM
- age of the LGM demise effect
- correct location of the topographic profile
- single-profile throw data as indicative of the fault slip distribution

Sector-Section	Authors	slipPreferredM	slipMinimumM	slipMaximumM	throwPreferredM	throwMinimumM	throwMaximumM	olderAgePreferredKA	olderAgeMinimumKA	olderAgeMaximumKA
3-10	PapanikolaouEtAl2005	4.99	3.94	6.12	4.9	3.92	5.88	15	12	18
6-2	CowieEtAl2017	6.07	4.68	7.62	5.5	4.4	6.6	15	12	18
7-6	RobertsAndMichetti2004	12.87	9.65	16.68	10	8	12	15	12	18
12-1	RobertsAndMichetti2004	11.13	8.57	14	10	8	12	15	12	18
12-2	PapanikolaouEtAl2005	10.12	7.8	12.74	9.1	7.28	10.92	15	12	18

Sector-Section	Authors	slipRatePreferredMmYr	slipRateMinimumMmYr	slipRateMaximumMmYr	throwRatePreferredMmYr	throwRateMinimumMmYr	throwRateMaximumMmYr
3-10	PapanikolaouEtAl2005	0.33	0.22	0.51	0.33	0.22	0.49
6-2	CowieEtAl2017	0.4	0.26	0.64	0.37	0.24	0.55
7-6	RobertsAndMichetti2004	0.86	0.54	1.39	0.67	0.44	1
12-1	RobertsAndMichetti2004	0.74	0.48	1.17	0.67	0.44	1
12-2	PapanikolaouEtAl2005	0.67	0.43	1.06	0.61	0.4	0.91

# Step2: Applications

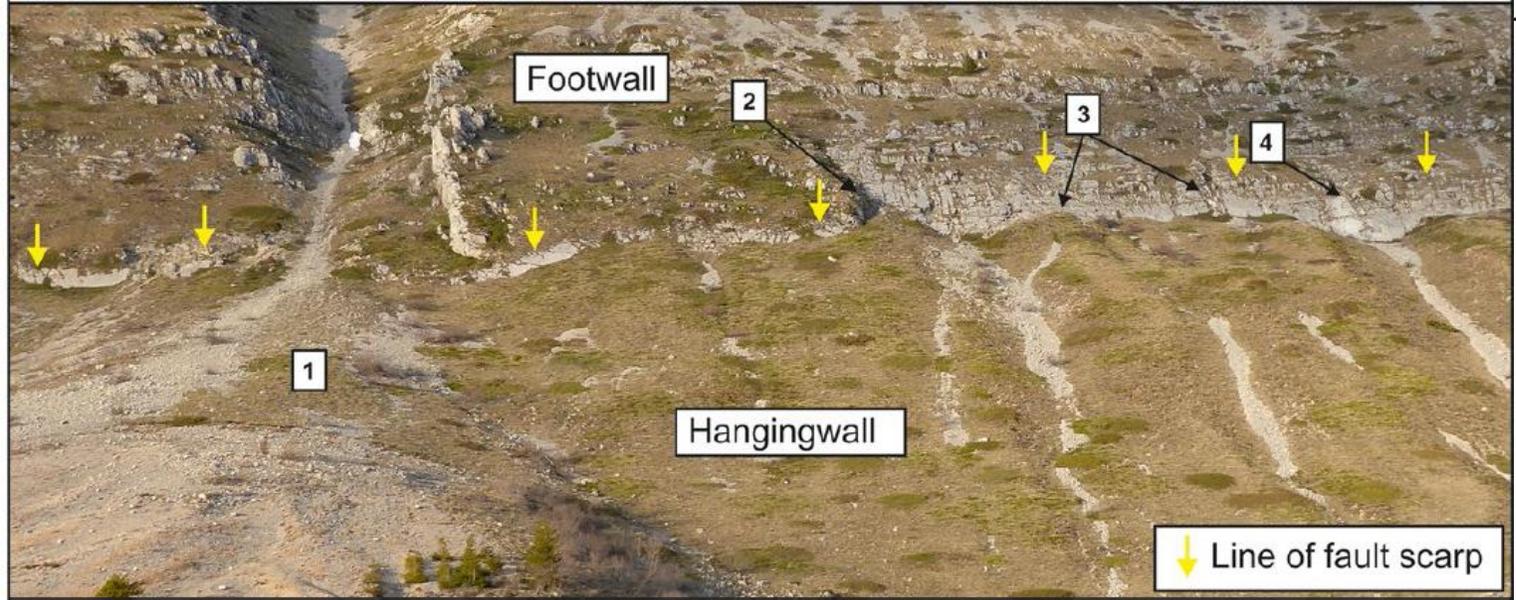
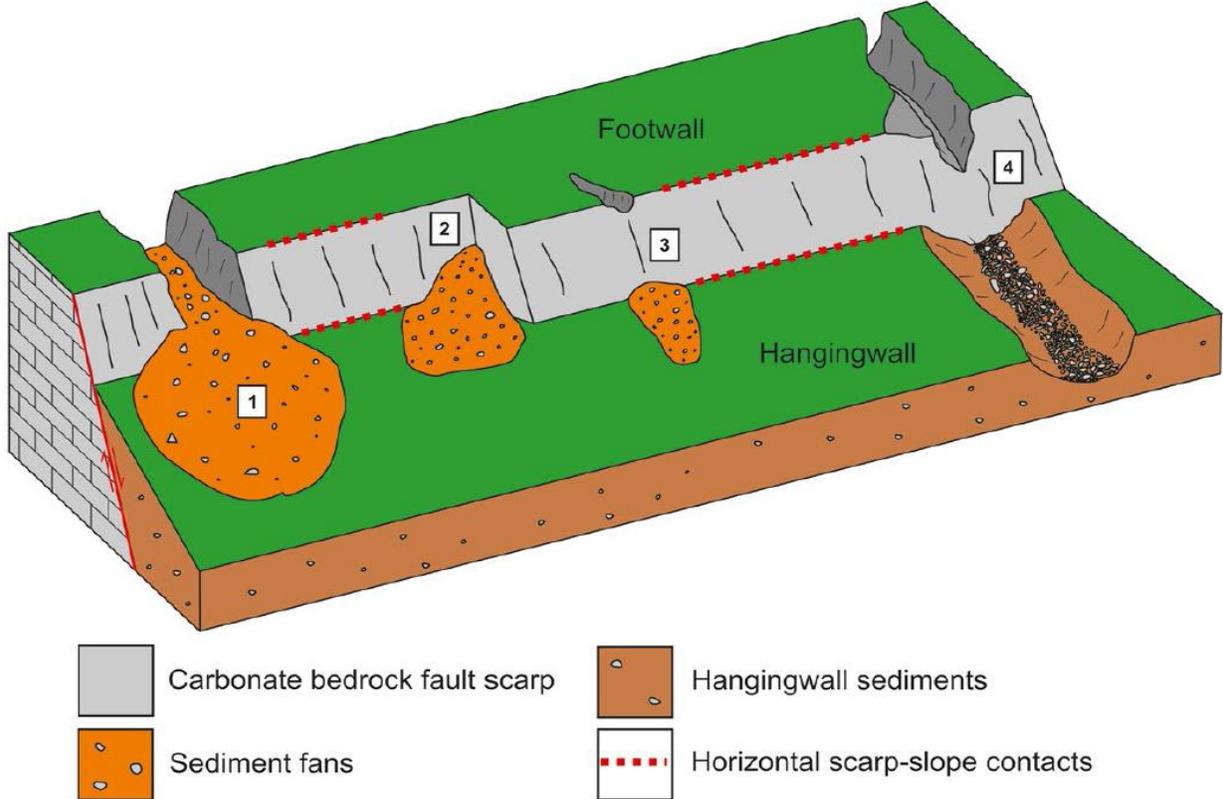


**S.C.A.R.P.S.** Outcomes to review post-LGM slip rate estimates

..about fault scarps

Debatable:

- correct location of the topographic profile



fine-scale **morpho-structural mapping:**

Detect **influence** of post-LGM **surface processes** in the throw measure

# Step2: Applications



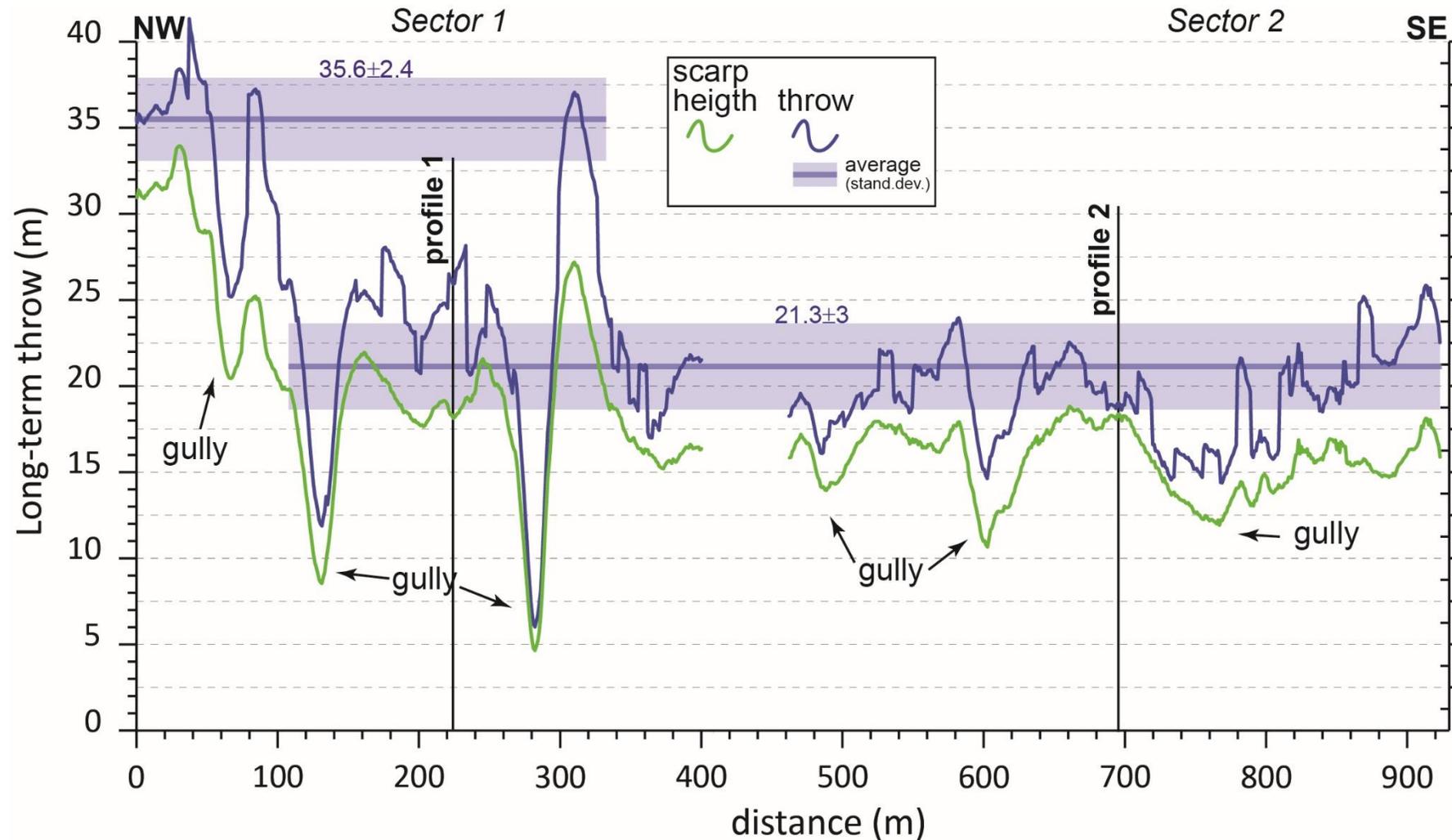
**S.C.A.R.P.S.** Outcomes  
to review post-LGM slip rate estimates

## ..about fault scarps

### Debatable:

- correct location of the topographic profile
- single-profile throw data as indicative of the fault slip distribution

## Statistical analysis of throw distribution along the scarp



# Step2: Applications

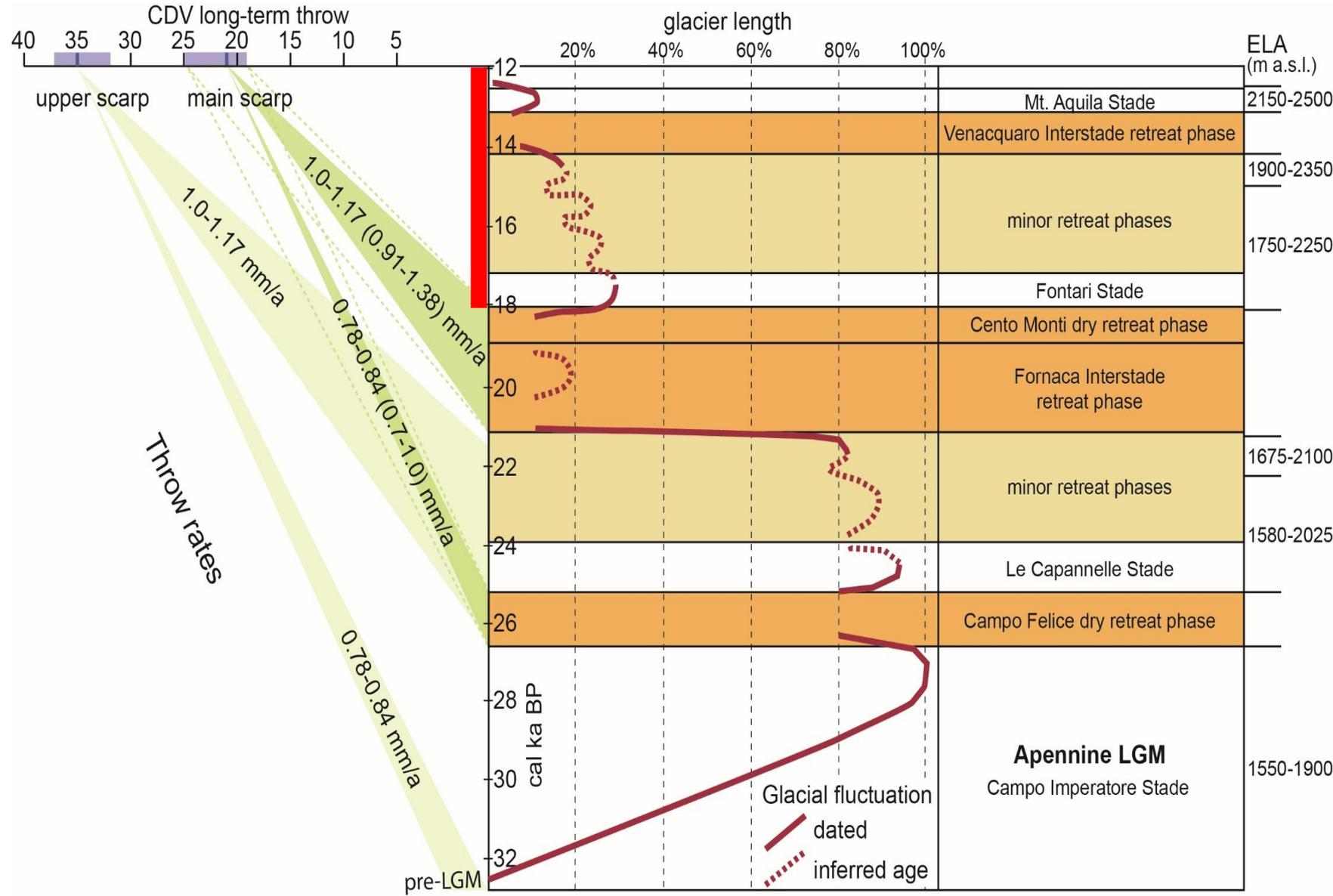


## S.C.A.R.P.S. Outcomes to review post-LGM slip rate estimates

### ..about fault scarps

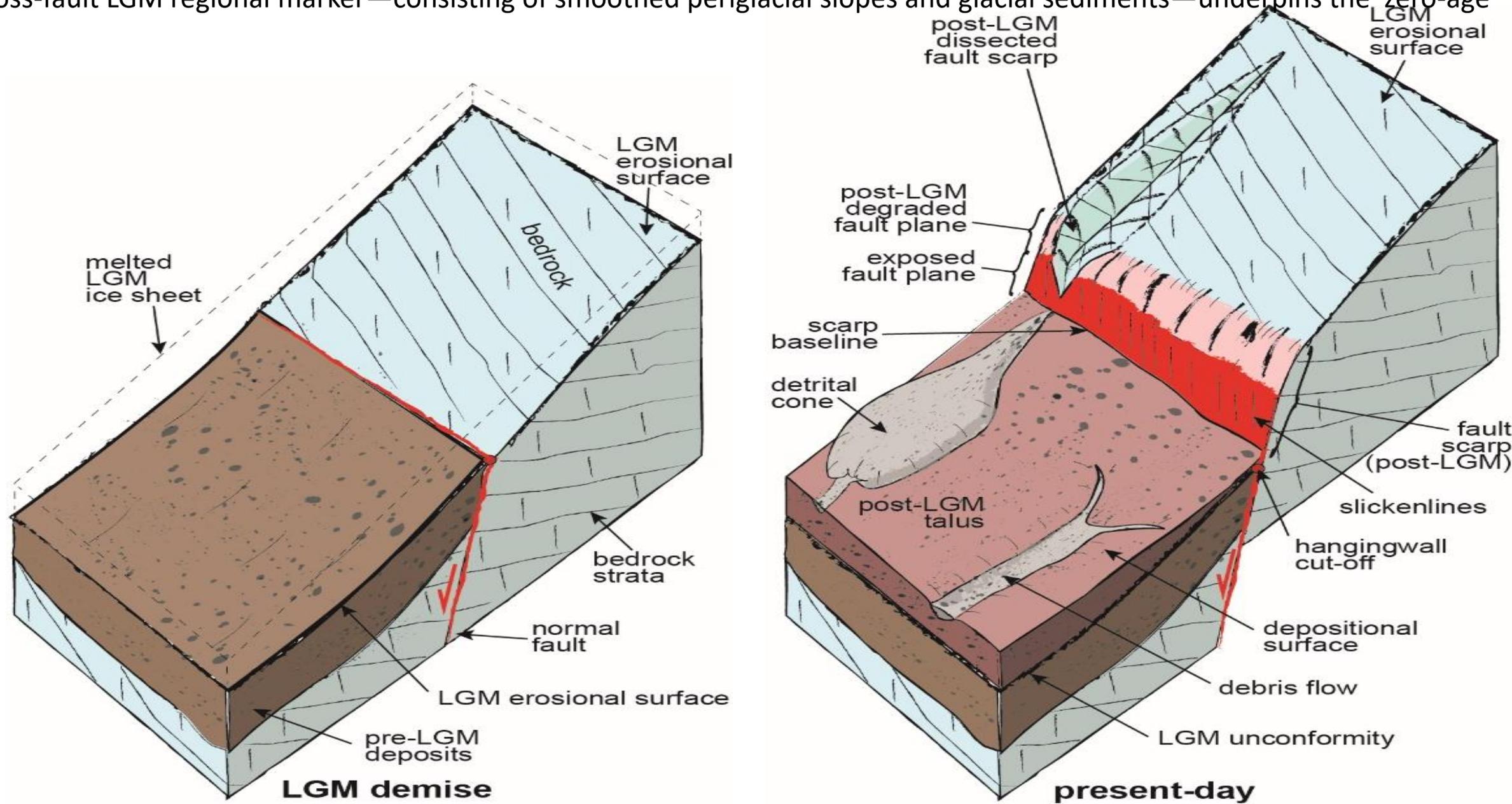
#### Debatable:

- entirely post-LGM
- age of the LGM demise effect



# post-LGM fault scarps: assumptions

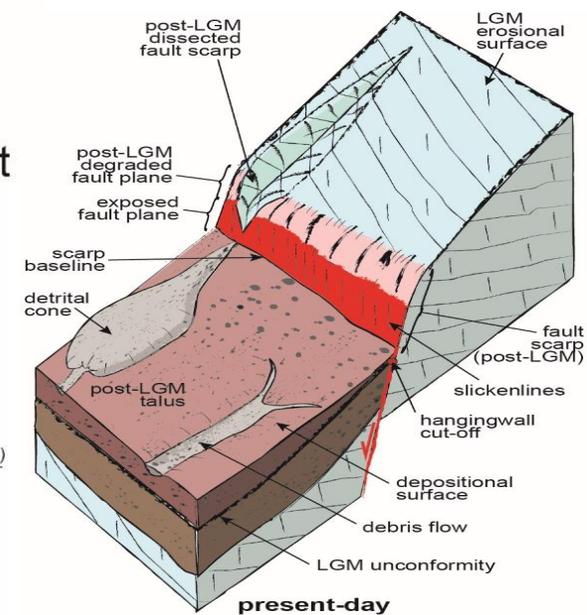
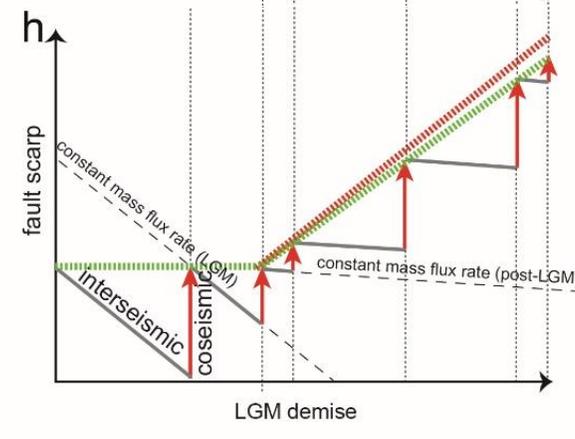
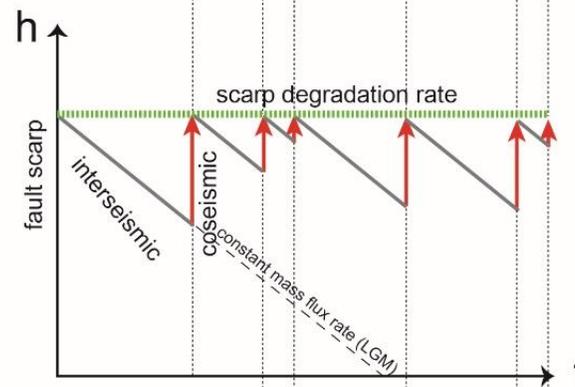
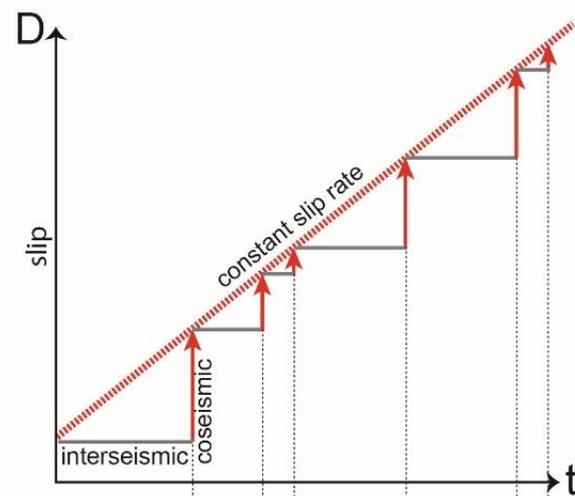
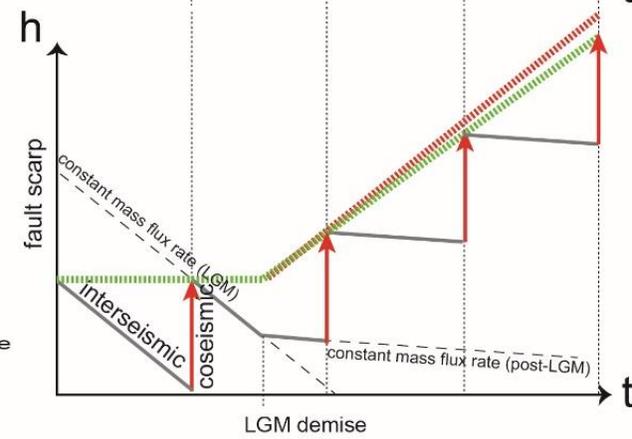
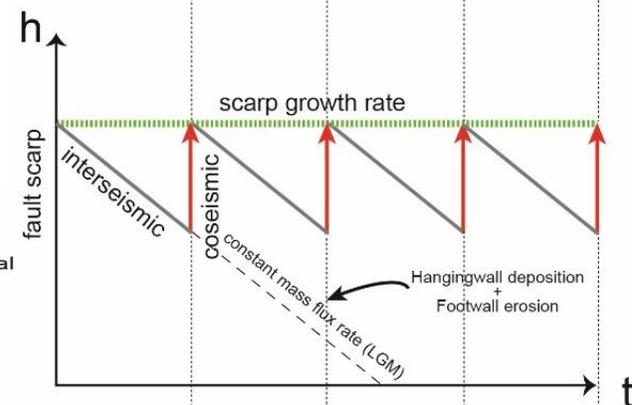
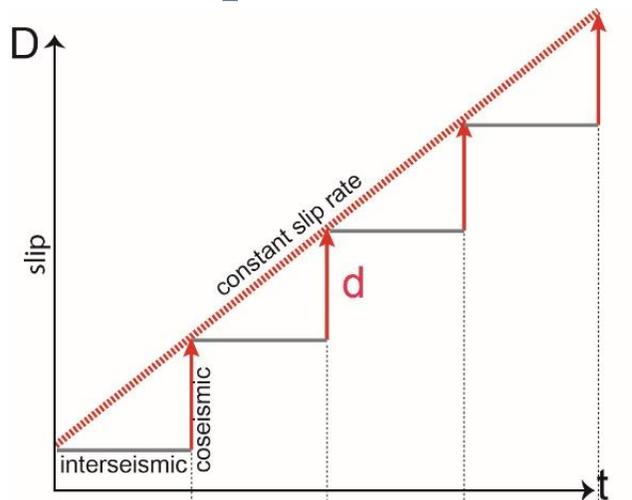
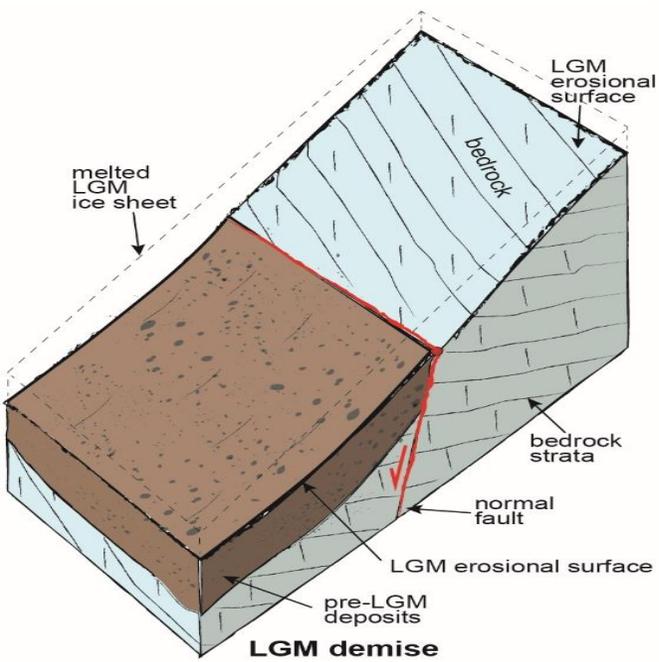
The cross-fault LGM regional marker—consisting of smoothed periglacial slopes and glacial sediments—underpins the 'zero-age'





# post-LGM fault scarps: assumptions

Balance between:  
coseismic slip  
&  
interseismic remodeling  
processes



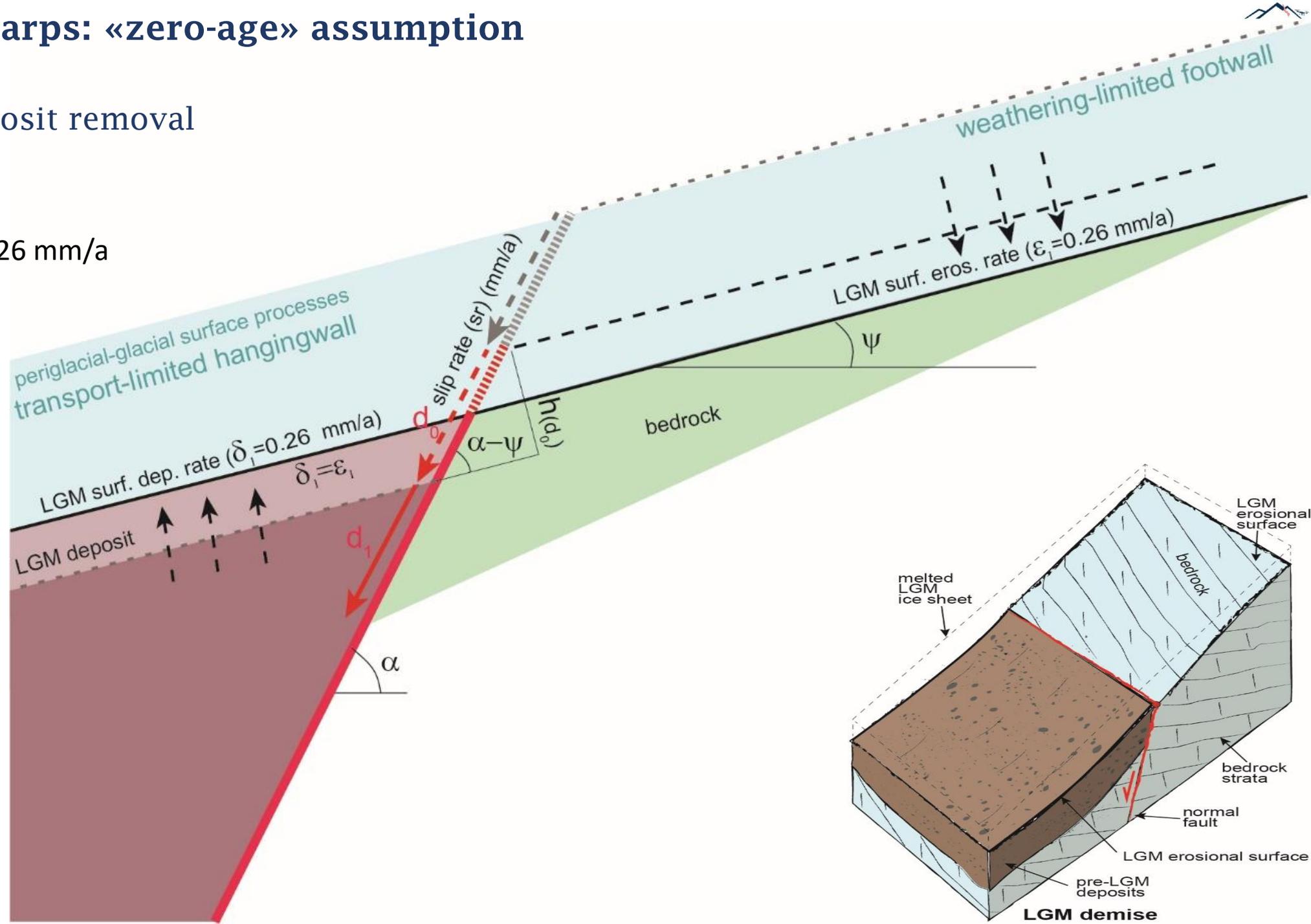
# post-LGM fault scarps: «zero-age» assumption

LGM setting: no deposit removal

$$2\varepsilon_1 / \sin(\alpha - \psi) = sr$$

$$\varepsilon_1 = (sr * \sin(\alpha - \psi)) / 2 = 0.26 \text{ mm/a}$$

d=1m  
 $\psi \approx 38^\circ$   
 $\alpha = 70^\circ$   
 sr=1.0 mm/a

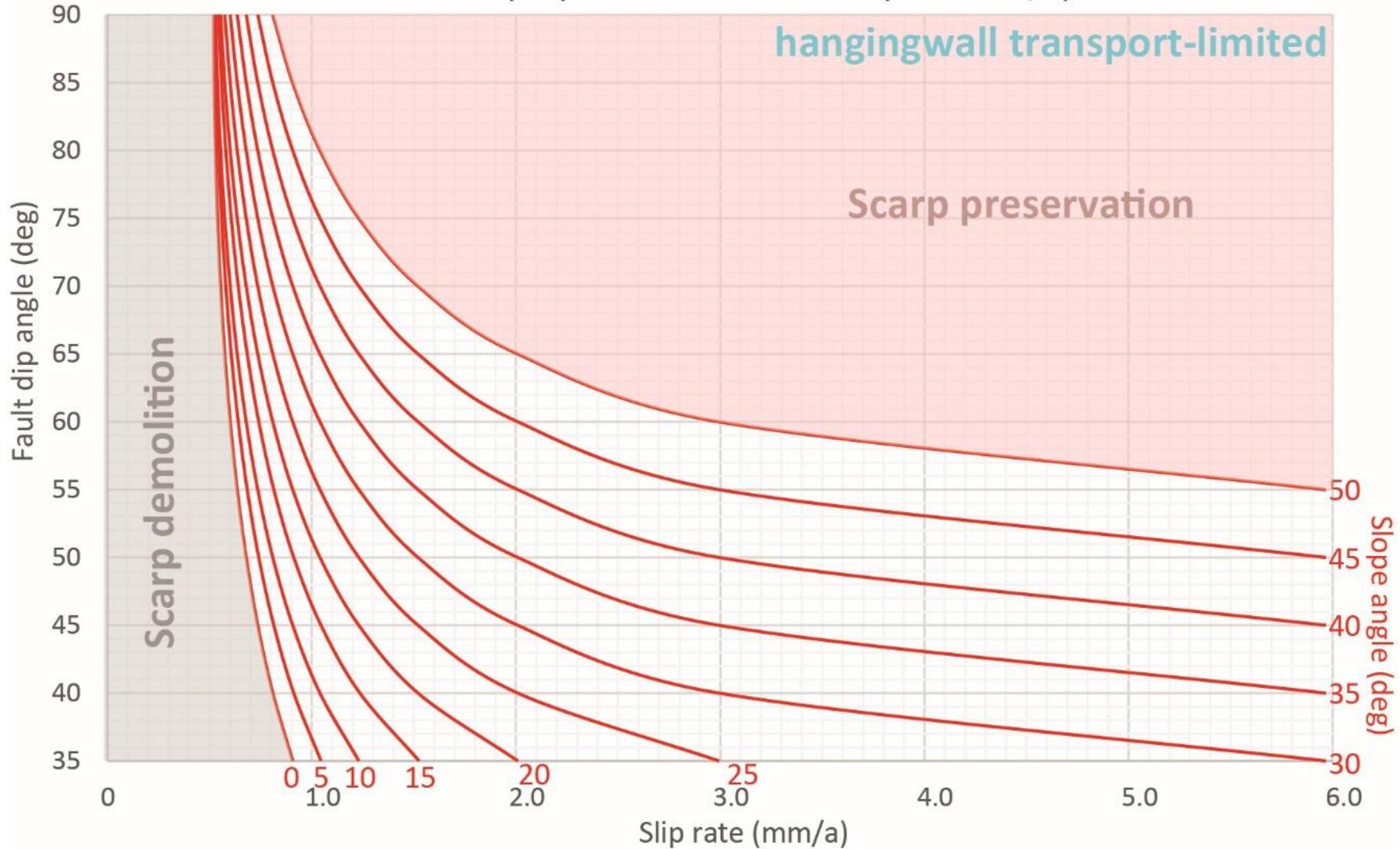


at a fixed erosion/deposition rate and slip rate:

scarp preservation depends on fault/slope angular relationship

# post-LGM fault scarps: «zero-age» assumption

LGM slope-parallel erosion rate (0.26 mm/a)

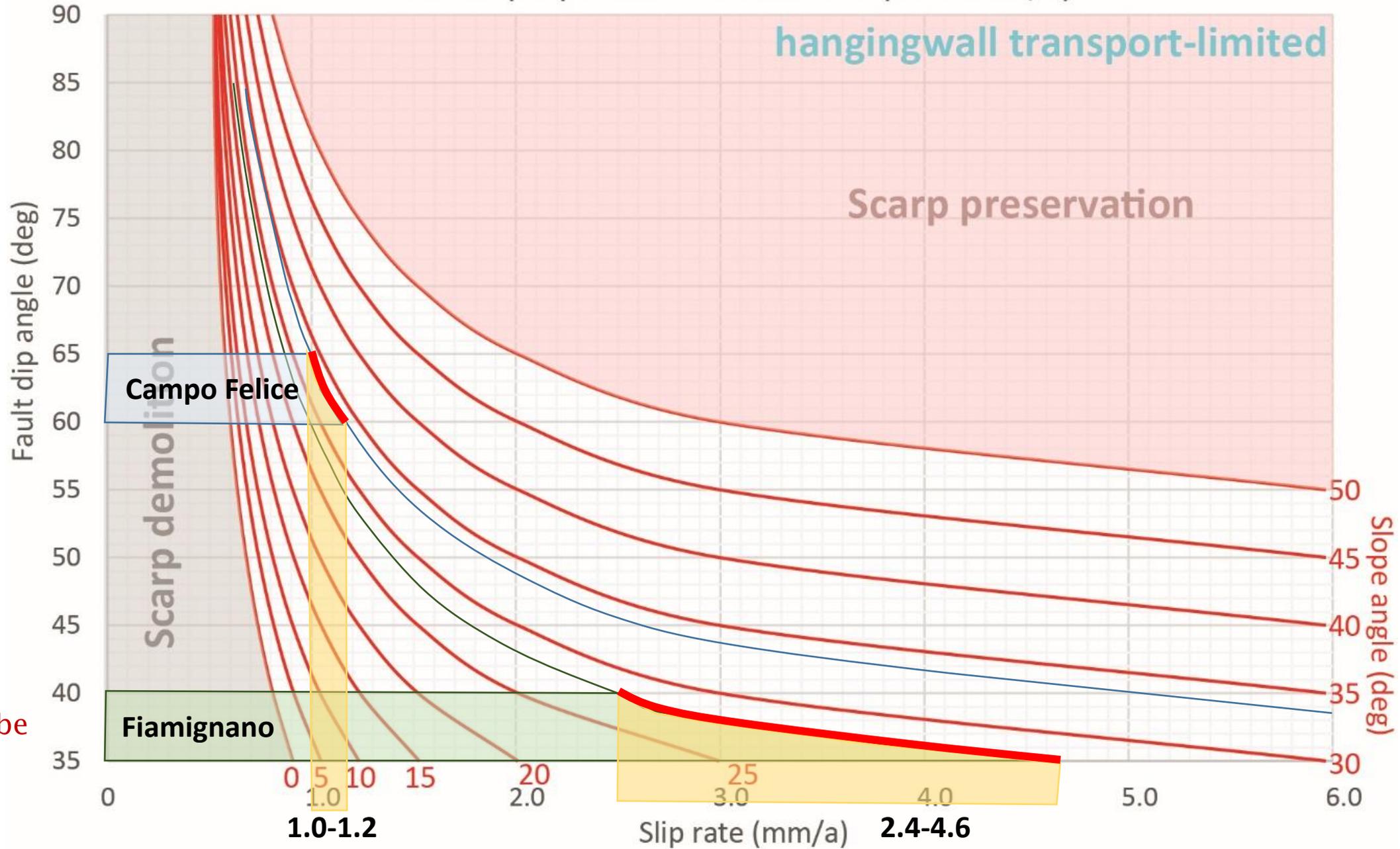


diagrams of function curves between the variables

boundary between scarp preservation and demolition

# post-LGM fault scarps: «zero-age» assumption

LGM slope-parallel erosion rate (0.26 mm/a)



Different fault setting = different maximum slip rate for complete scarp demolition

the zero-age assumption must be validated in geometrical arrangement!

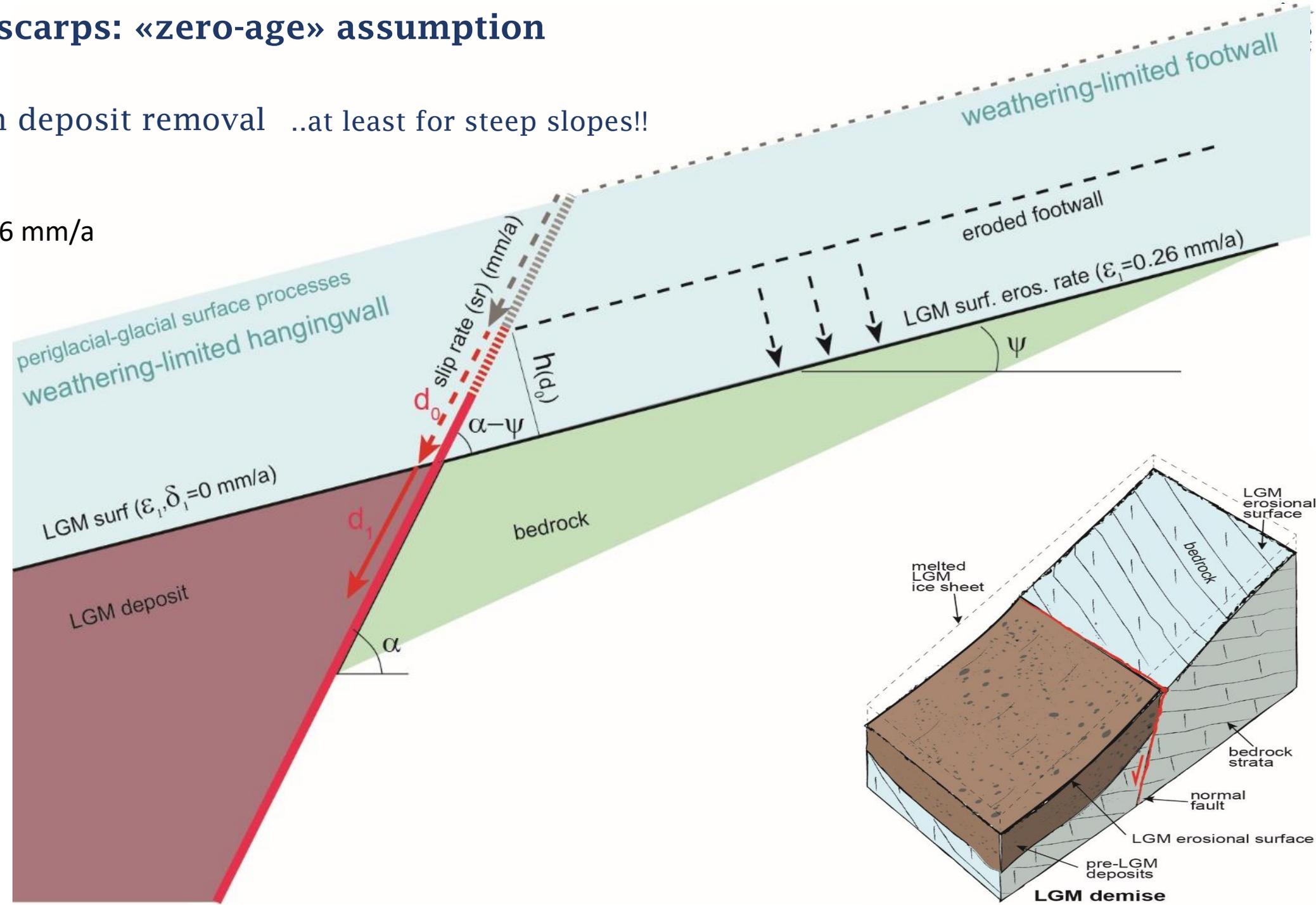
# post-LGM fault scarps: «zero-age» assumption

LGM setting: with deposit removal ..at least for steep slopes!!

$$\varepsilon_1 / \sin(\alpha - \psi) = sr$$

$$\varepsilon_1 = sr * \sin(\alpha - \psi) = 0.26 \text{ mm/a}$$

- d=1m
- $\psi \sim 38^\circ$
- $\alpha = 70^\circ$
- sr  $\sim 0.5 \text{ mm/a}$



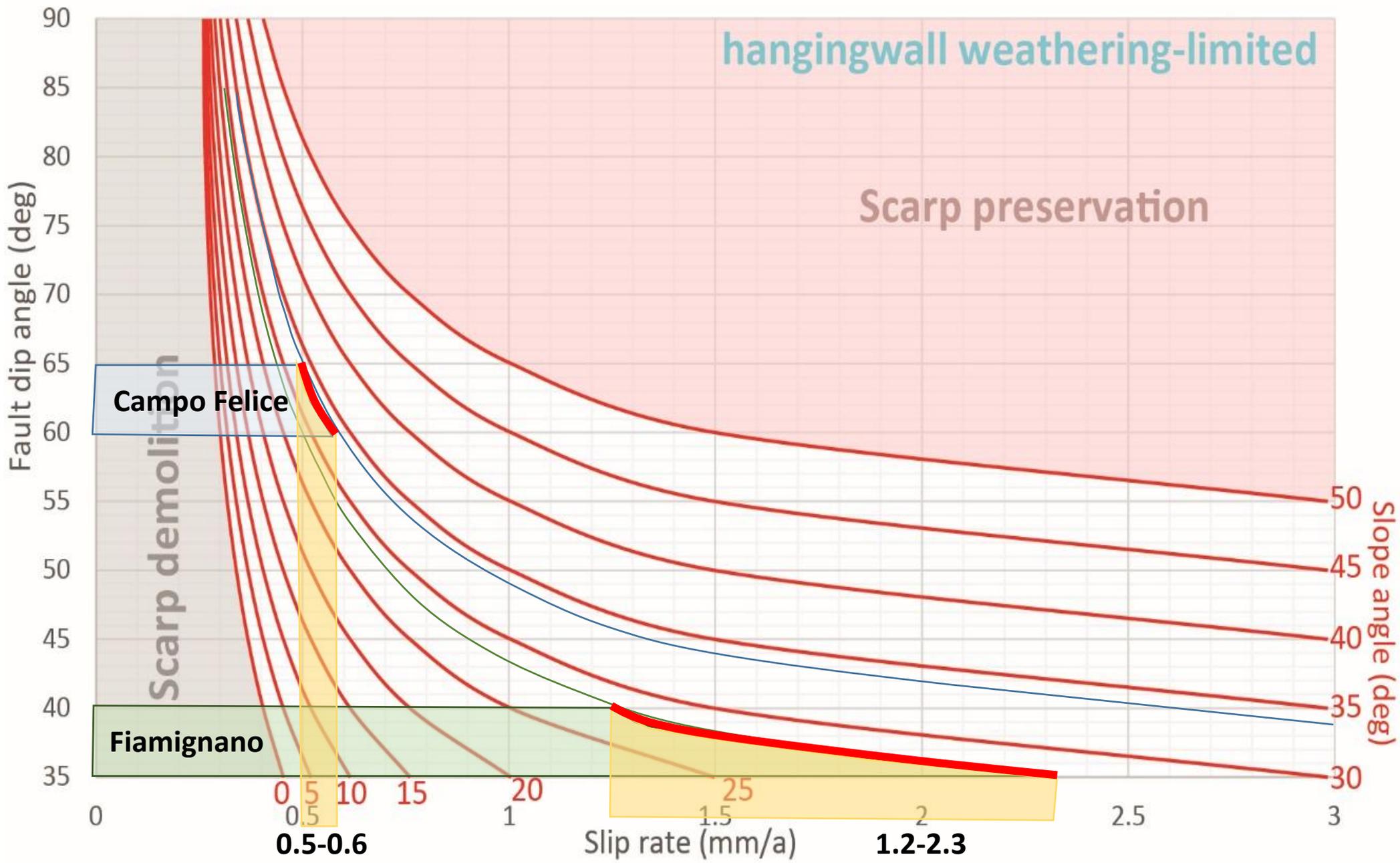
# post-LGM fault scarps: «zero-age» assumption

LGM slope-parallel erosion rate (0.26 mm/a)

Different fault setting  
=  
different maximum slip rate for complete scarp demolition

With **deposit removal** the max slip rate is **halved**

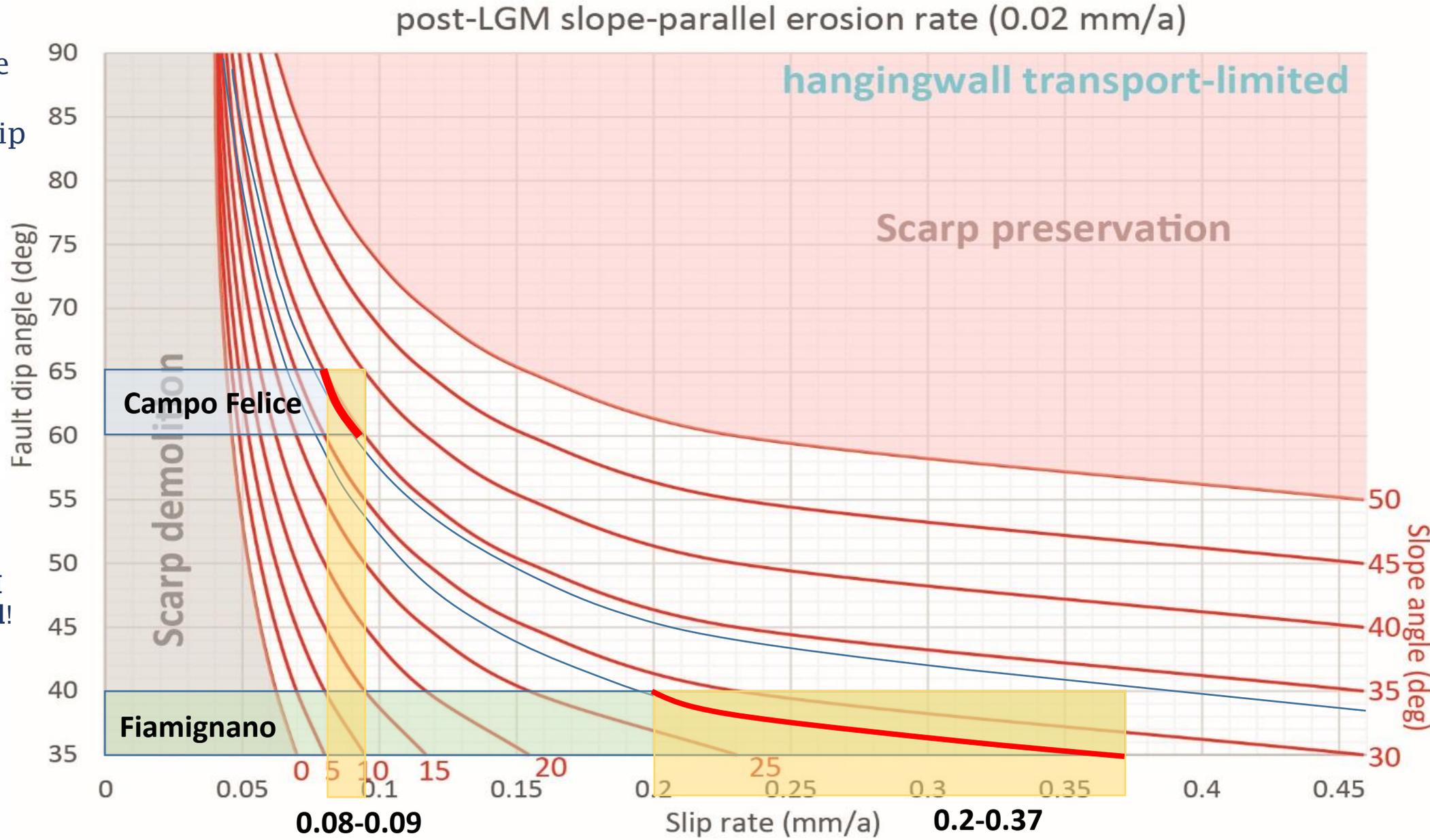
The zero-age assumption must be validated about the surface processes efficiency!



# post-LGM fault scarps: «zero-age» assumption

Lower erosion rate  
=  
Lower maximum slip  
rate for complete  
scarp demolition

For **such** values of  
**erosion** rates,  
most of the **pre-LGM**  
**scarps** are **preserved!**



## Hypotesis 1: denudation rate during LGM was one order higher than during Holocene

*In situ* talus production by **frost weathering** and transport by **solifluction** and **gelifluction** (e.g. Anderson, 2002).

**Ice-free slopes** underwent **accelerated denudation** due to the lack of vegetation and frequent **freeze-thaw cycles**, leading to the formation of **smooth cryoplanation surfaces** (e.g. Ballantyne, 2002).

## Hypotesis 2: erosion rate during LGM was one order lower than during Holocene

Due to Holocene warming and increased runoff (meltwater and rain), the system has shifted **from being transport-limited to detachment-limited** with streams incision up to **0.5-0.6 mm/anno** (e.g. Roda-Boluda et al., 2019).

**Detachment-limited:** The water has more than enough energy to move sediment, but it is limited by how fast it can actually erode or "detach" material from the bed (often seen in rocky or icy environments)

**Transport-limited:** The system has plenty of loose material, but not enough water energy to move it

**Upland transmission** of the transient response to the **perturbations** (base levels lowering) **by knickpoints**

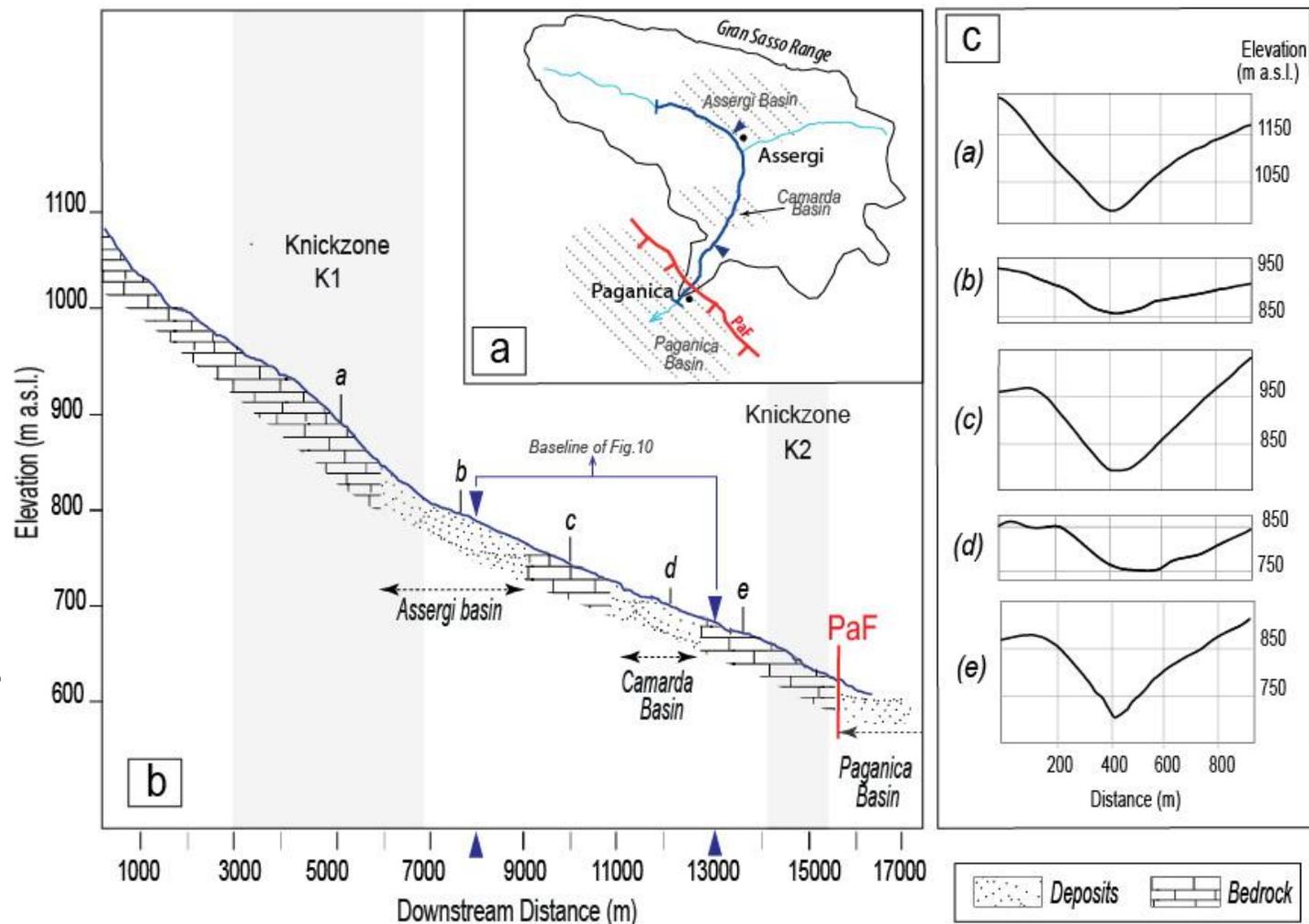
**Upstream Domain (Relict Landscape):** Above the knickpoint, incision rates are low and steady (approx. **0.1 mm/yr**). This landscape is "unaware" of recent climate shifts or fault movements.

**Downstream Domain (Transient Landscape):** Below the knickpoint, incision rates are significantly higher (reaching **0.5-0.6 mm/yr**).

Hillslopes respond through landslides and intense denudation.

## Slope erosion is linked to river incision

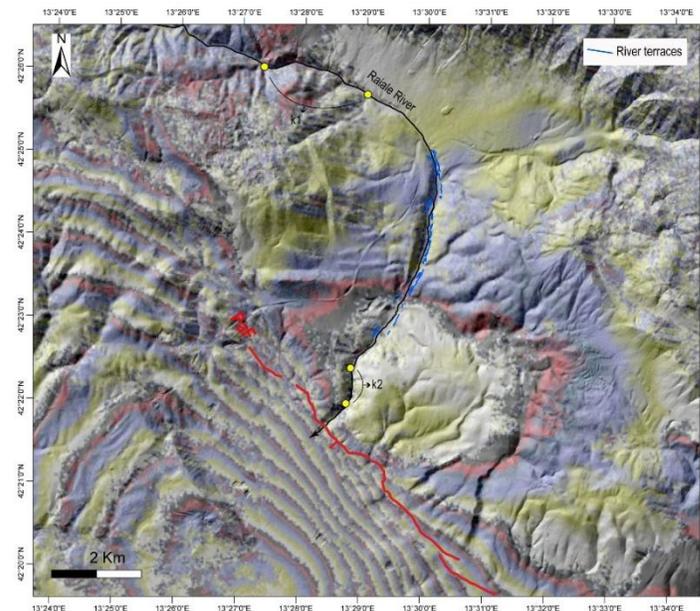
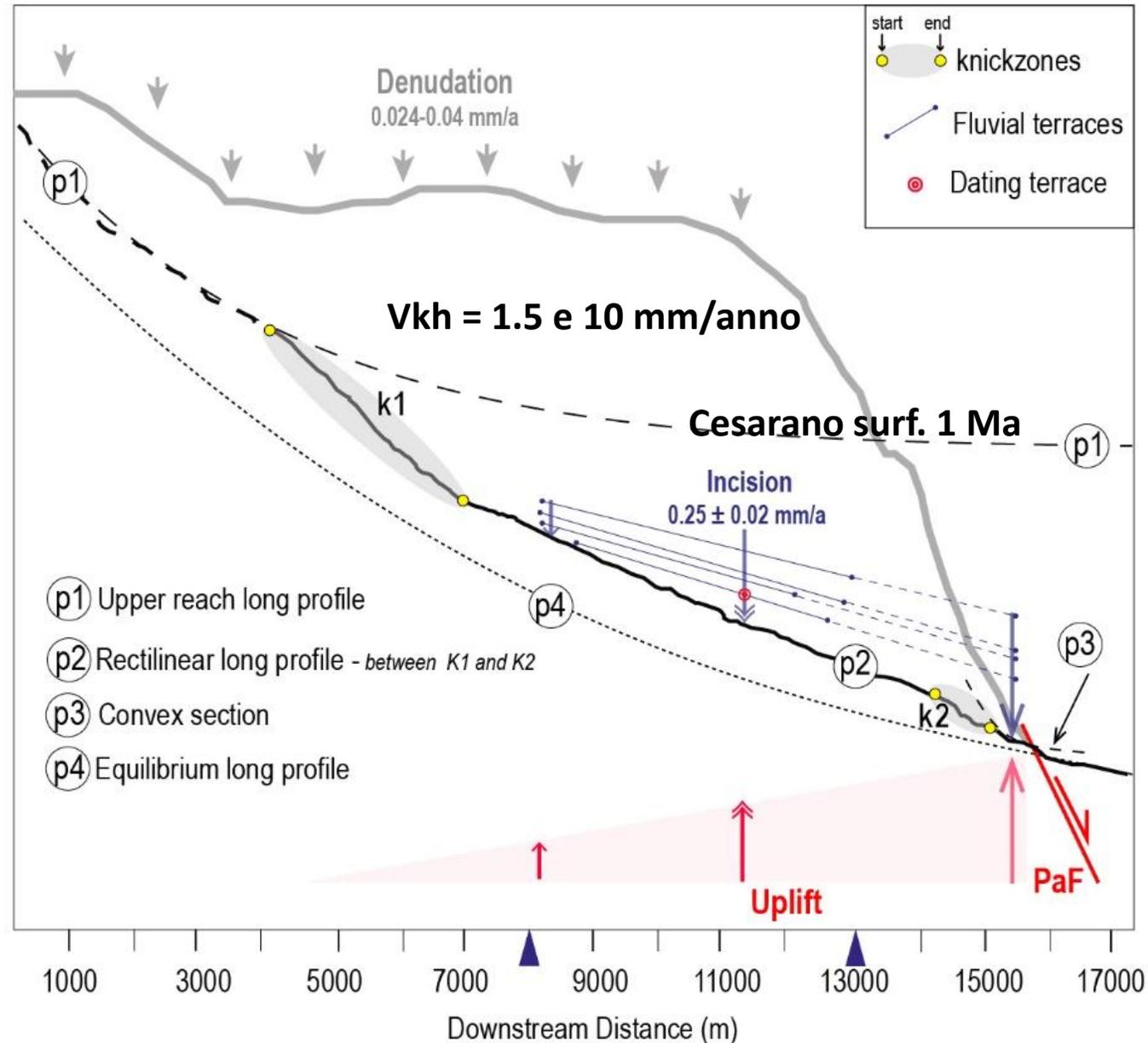
Where river cuts deeper, slopes erode faster to maintain critical steepness.



# post-LGM fault scarps: Erosion-rate observations

**Upstream of the knickpoints** (areas that have not yet "felt" tectonic rejuvenation or major post-glacial changes)

**The landscape is still in an adjustment phase**  
(it will take approximately **1-3 million years** for the accelerated post-LGM erosion to reach the valley headwaters).



# post-LGM fault scarps: Erosion-rate observations

## Linear Correlation

between fault slip-rate and drainage incision rates

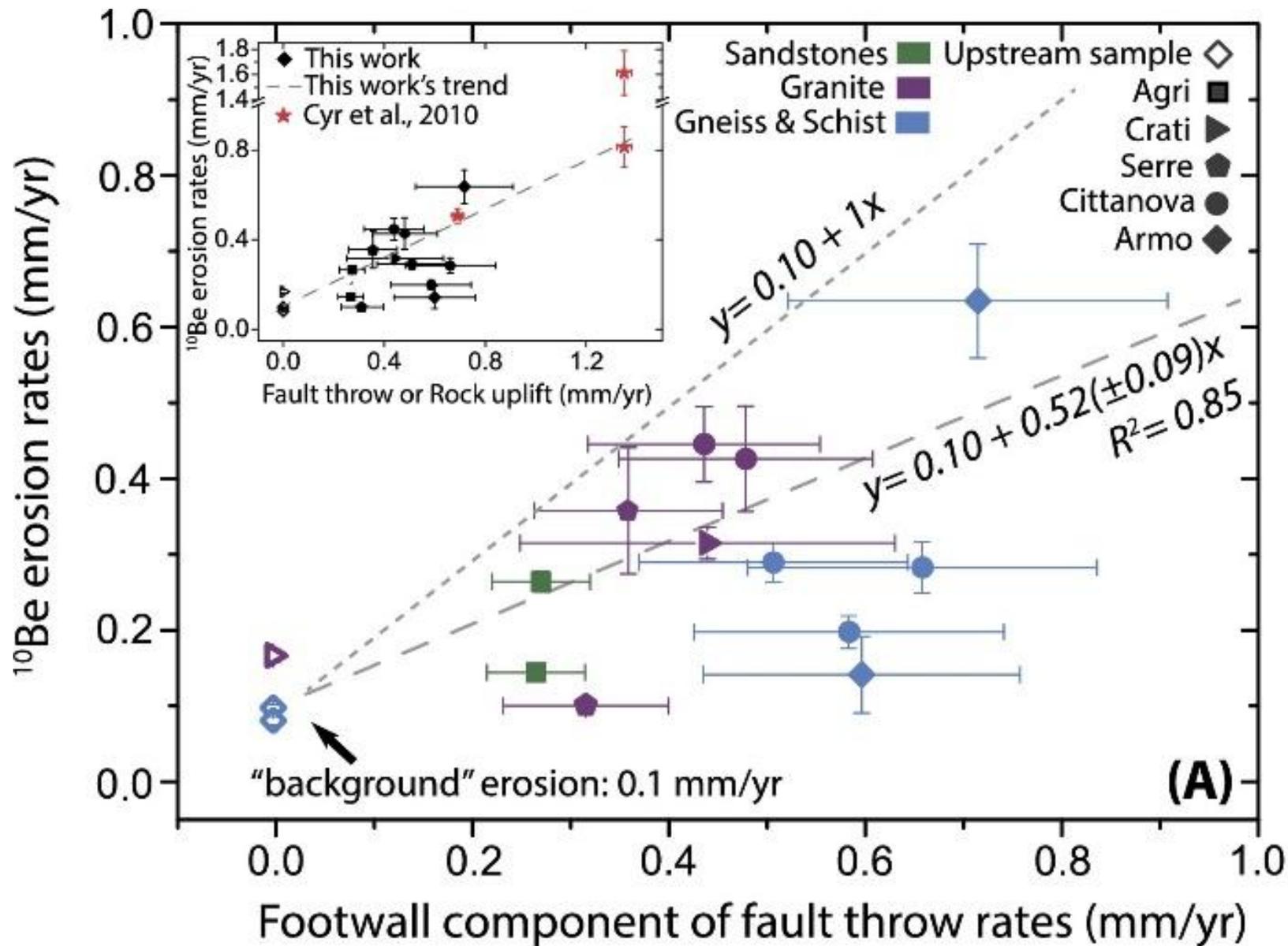
= tectonics is the main driver of erosion over long periods!

1:1 line

=

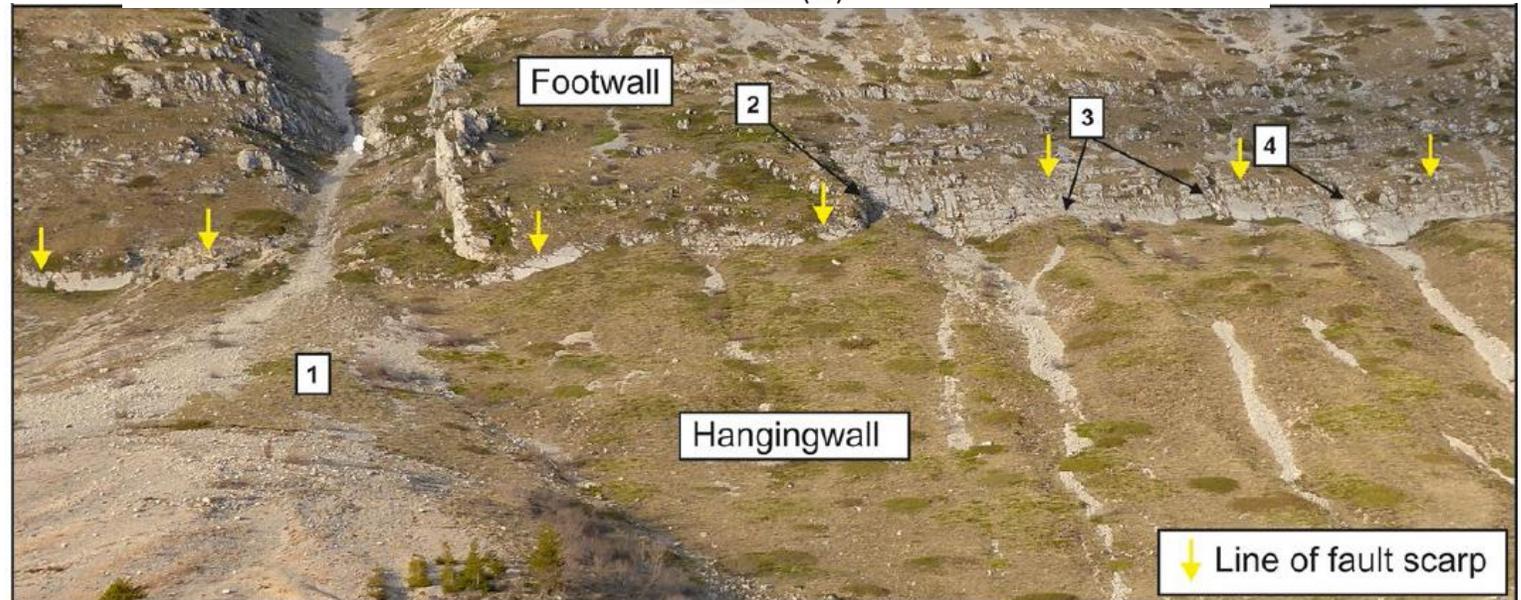
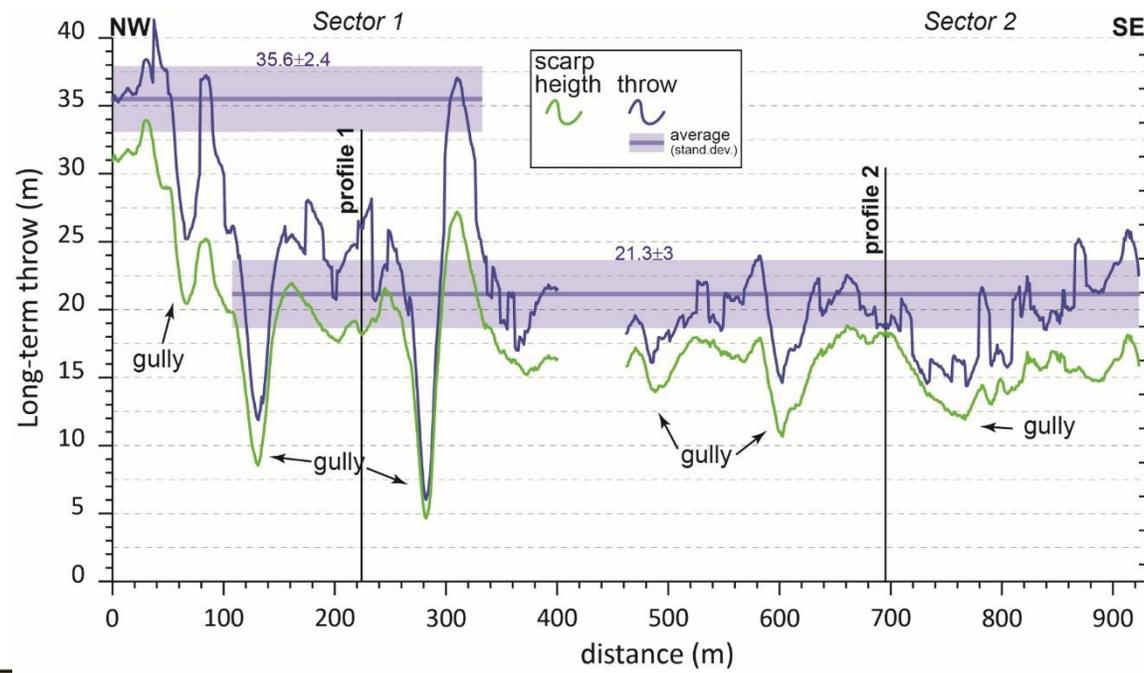
basins still reacting to the Last Glacial Maximum (LGM) or recent tectonic activity.

The "response time" is not yet finished!



# post-LGM fault scarps: Remarks

- Caution in **selecting** the appropriate slopes as **LGM geomorphic markers** at the footwall of fault scarps
- **Reconstruction** and **statistical treatment of throw-rates** distribution from fault scarps
- **Verify the «zero-age» assumption** against occasional absolute dating
- **Evaluate** the different **status** of the local **drainage** basin (with position of knickpoints)
- Estimate the transient transmission to the hangingwall slope denudation rate



# Thanks for your attention!

S. Pucci

R. Civico, C.A. Brunori, P.M. De Martini, M.Caciagli, T. Ricci

Istituto Nazionale di Geofisica e Vulcanologia (INGV-Italy); stefano.pucci@ingv.it

