ANALOGUE AND NUMERICAL MODELS ON THE INTERACTION BETWEEN TECTONICS AND SURFACE PROCESS

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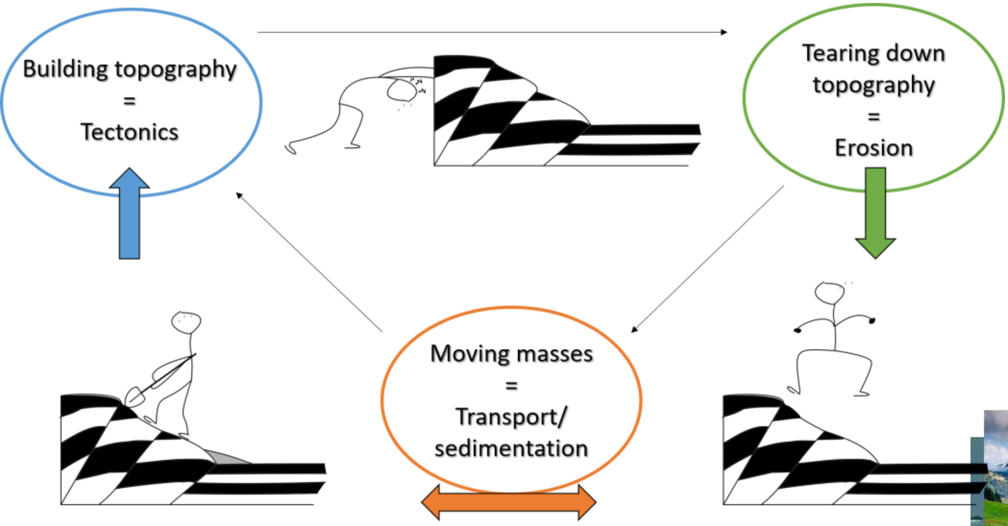
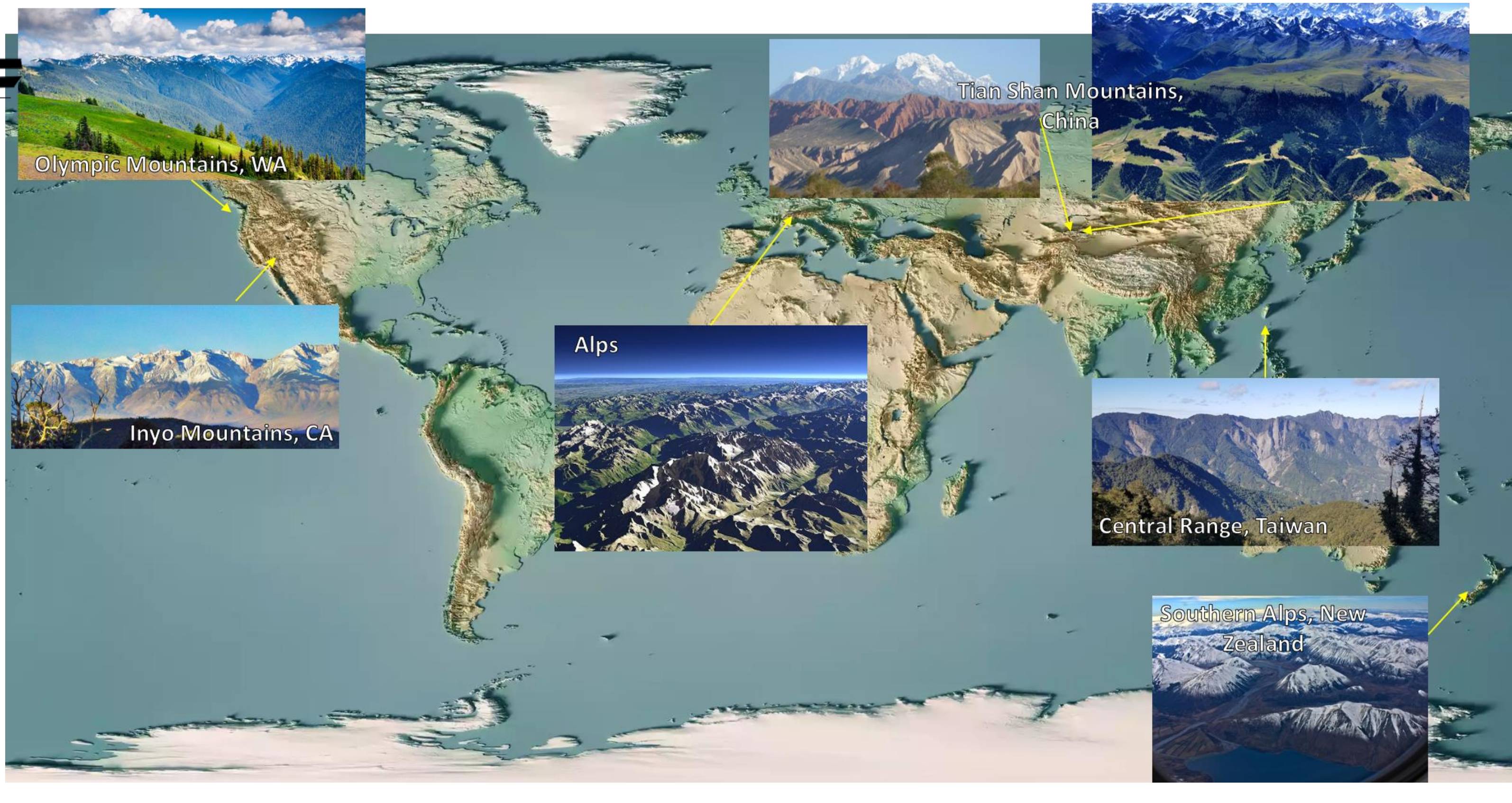
SCIENTIFIC PROBLEM



What we see today in the field is a snapshot of a geological process that works through thousands-millions of years

These processes concur in creating the **present-day landscapes** (not including biological and anthropological factors)



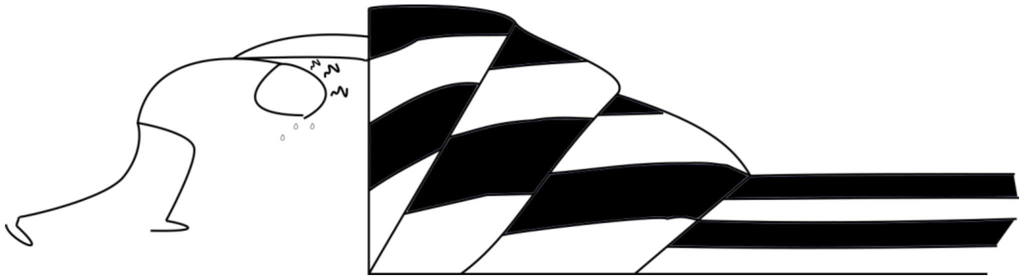
SCIENTIFIC PROBLEM

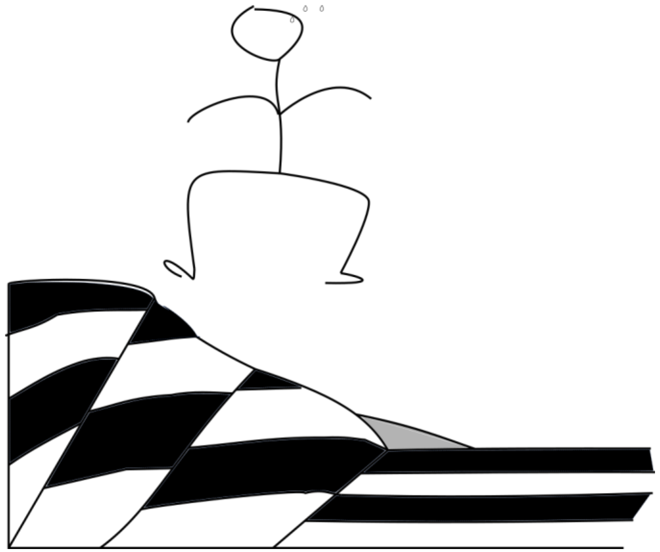
Which is the **nature** of the **interaction** between **tectonic deformation** and **surface processes**?

Physical and quantitative understanding limited by:

- Impossibility to direct observe through evolution
- Different time-scales
- Influence of a lot of parameters

MASS BALANCE FOR DESCRIBING INTERACTION





How do parameters control the interaction between tectonics and erosion?

$$F_{in} = v_c h$$

Convergence velocity

Characteristic thickness

$$F_{out} = 4KL^2$$

Erodibility constant

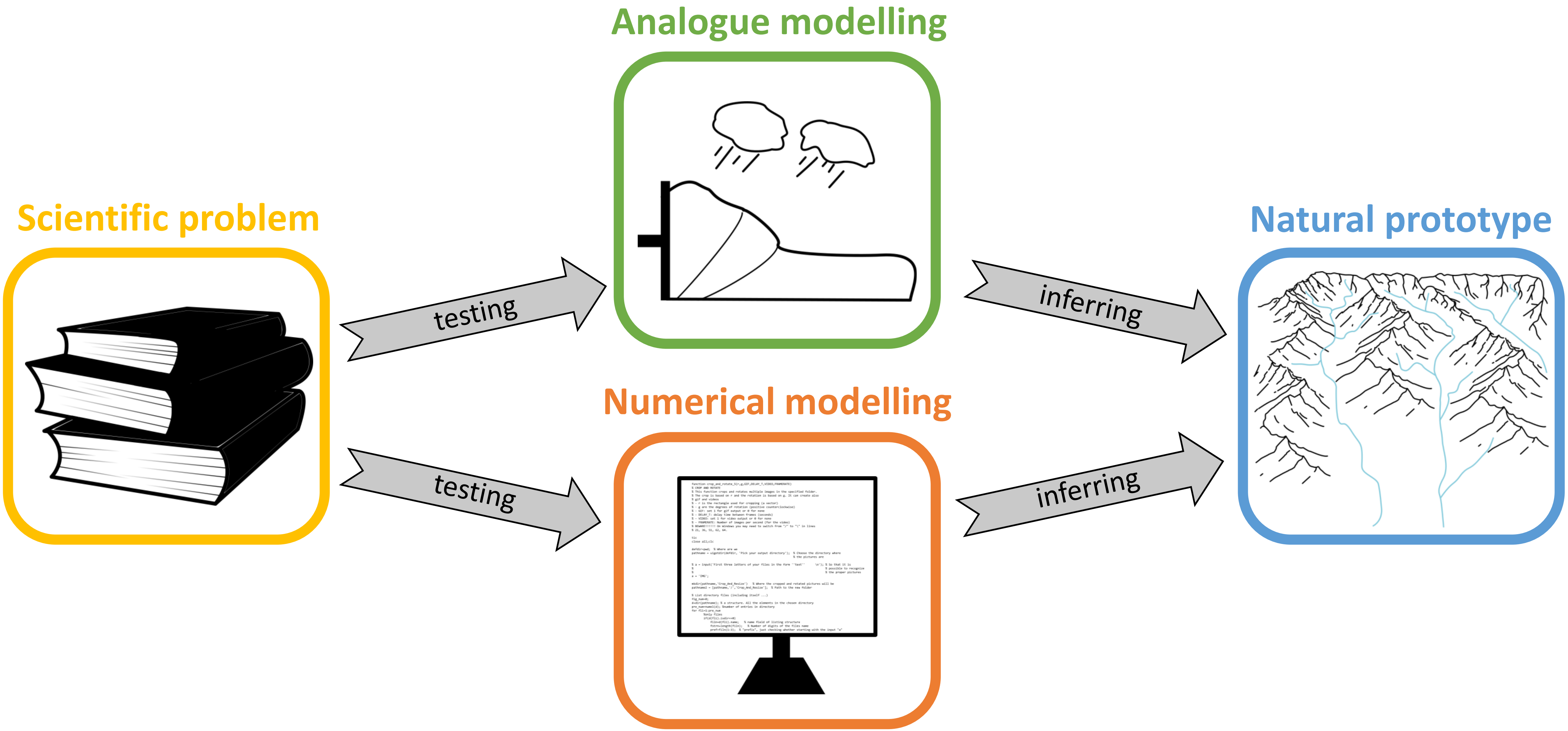
Characteristic length

$$B_{u-e} = \frac{4KL^2}{v_c h}$$

MASS BALANCE

(Willett, 1999)

METHODS


Analogue modelling
Scientific problem
testing
testing
Numerical modelling
inferring
inferring
Natural prototype

WHY BOTH?

Numerical modelling

- Straight forward quantitative approach
- Precise boundary conditions
- Easiness to explore parameters

- ☒ Resolution
- ☒ Numerical diffusion
- ☒ Computational time (3D)
- ☒ Sedimentation

Analogue modelling

- Real physical modelling
- Naturally 3D
- Simplified approach

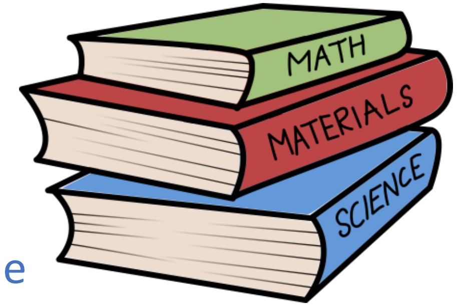
- ☒ Materials
- ☒ Reproducibility
- ☒ Visualization 3D

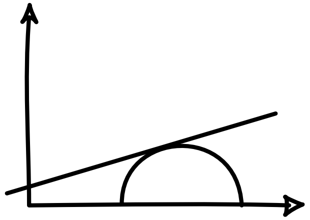
Combined approach!

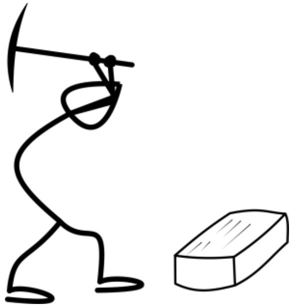
ANALOGUE MATERIAL

Which material?

- Available
- Cheap
- Recyclable
- Manageable

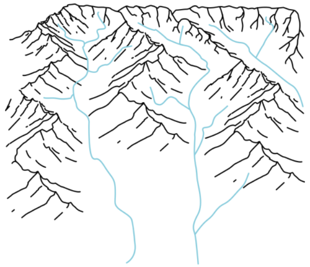


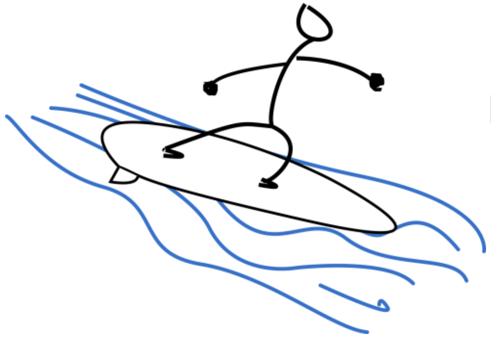




Physical properties

- Satisfy Mohr-Coulomb failure criterion
  - Discrete planes where deformation occurs
- Build wedges

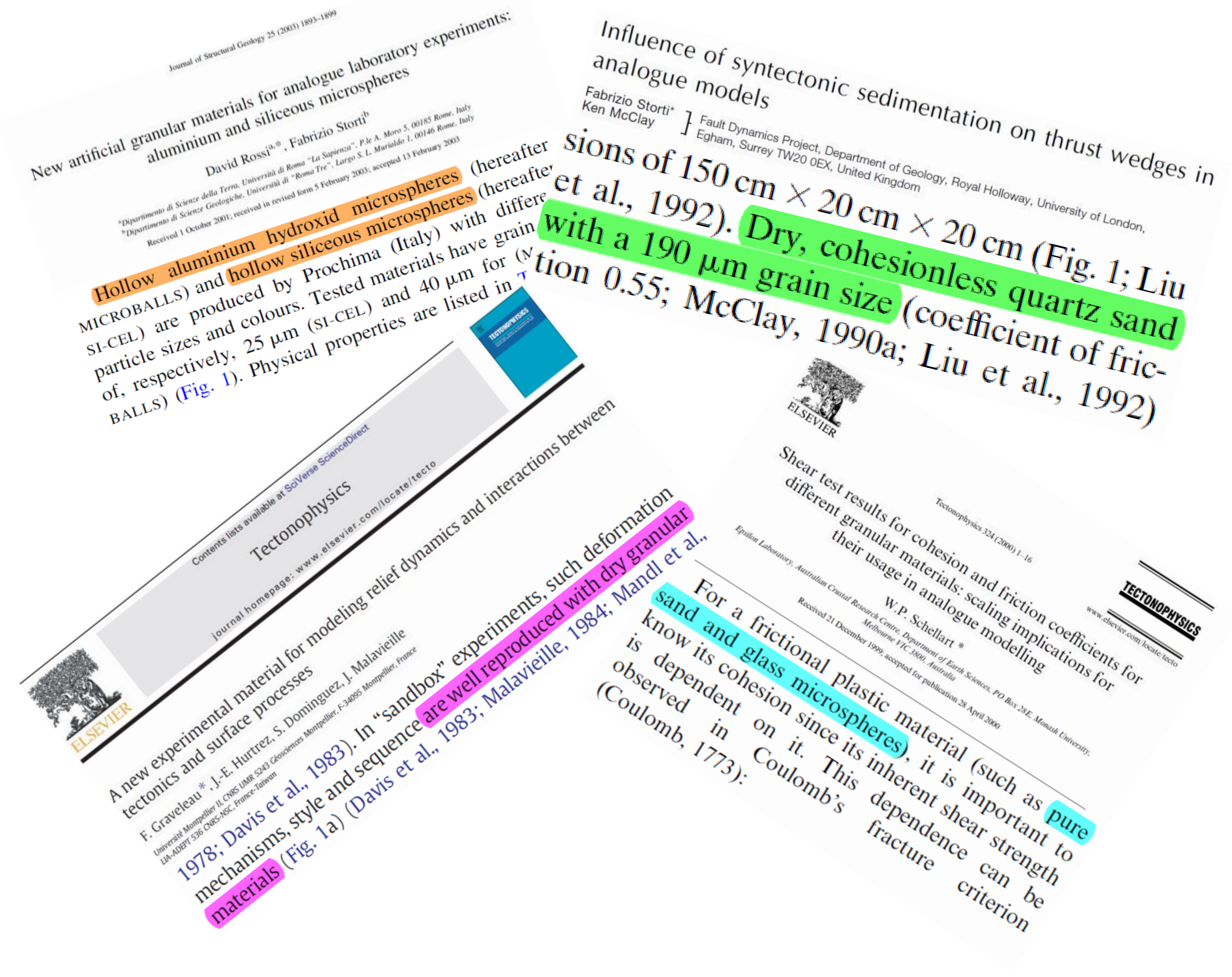




Erosion-transport-sedimentation properties

- Erode trough
  - Diffusive processes on hillslopes
  - Advection in valleys
- Erosion rate well scaled with tectonic rate

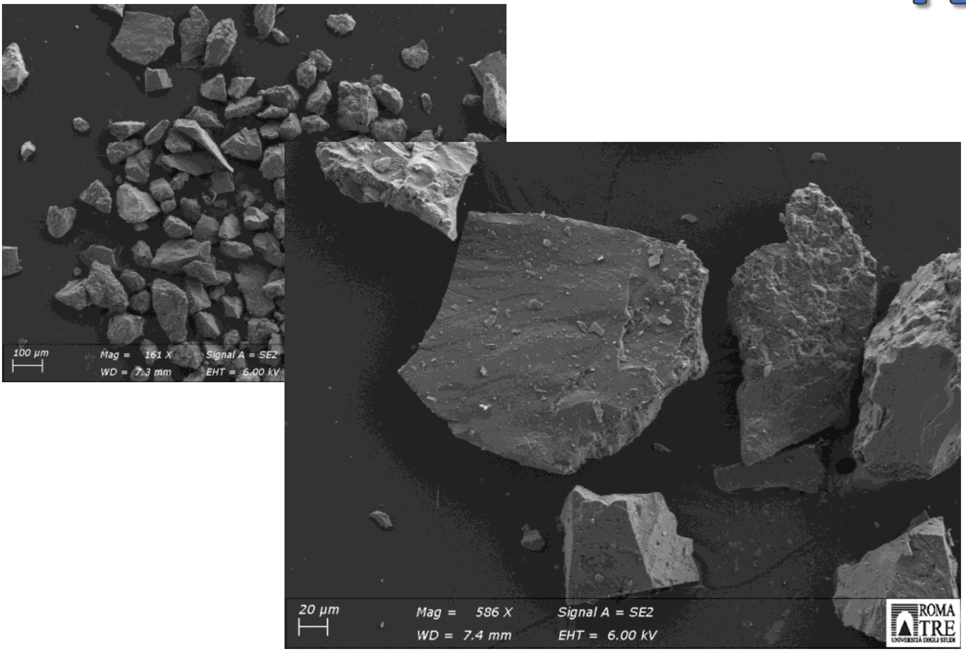
Granular materials are widely used in literature



- Mohr-Coulomb failure criterion
- Good match for internal friction coefficient (φ) and cohesion (C)
- Scaling for density and stress

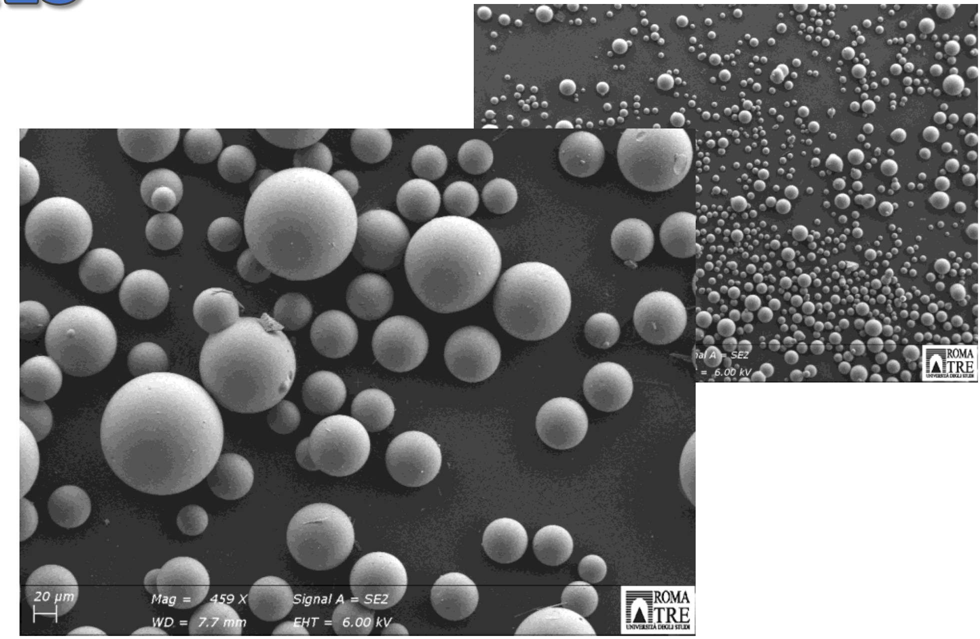
We start from what is known in literature (e.g. *Lague et al., 2003*; *Graveleau et al., 2011*; *Viaplana-Muzas et al., 2015*; *Tejedor et al., 2017*)

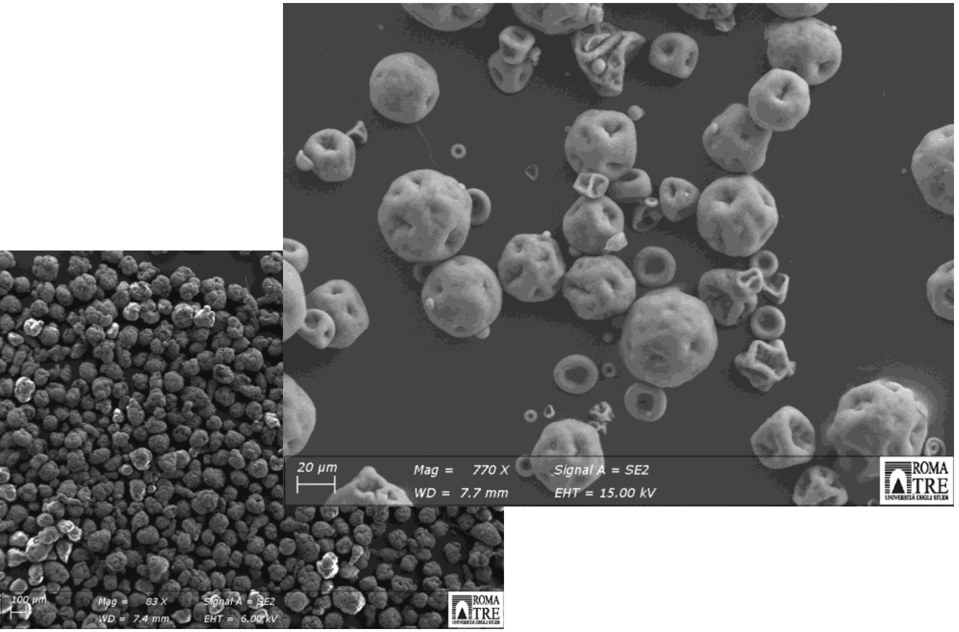
TESTED MATERIALS



Crushed quartz (CQ)
D_{50} = 87 µm
ρ = 2588 ± 1 kg/m^3

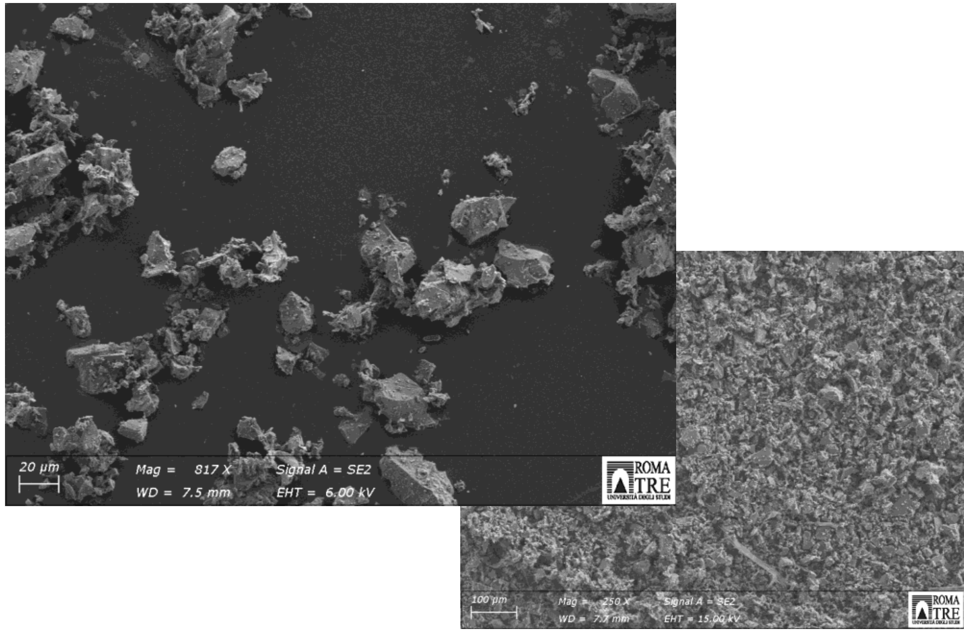
Glass microbeads (GM)
D_{50} = 98 µm
ρ = 2452 ± 1 kg/m^3





PVC powder (PVC)
D_{50} = 181 µm
ρ = 1402 ± 1 kg/m^3

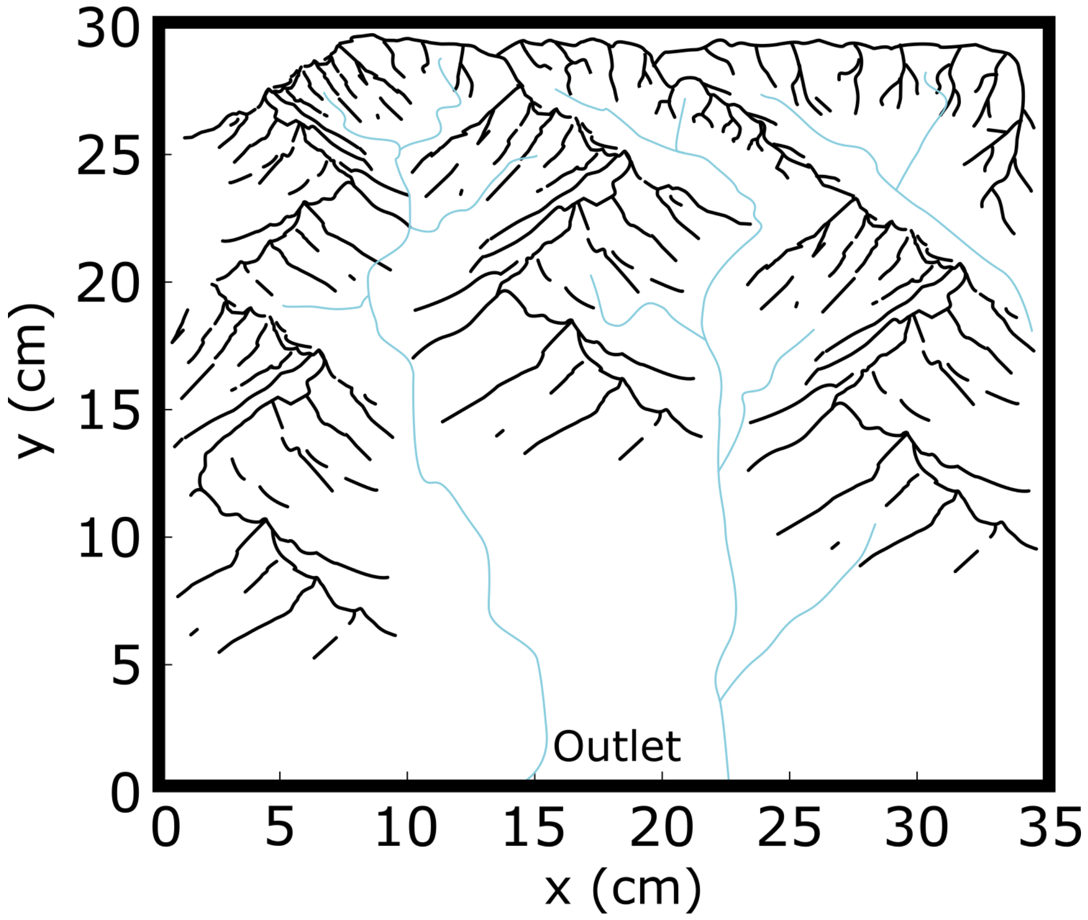
Silica powder (SP)
D_{50} = 20 µm
ρ = 2661 ± 1 kg/m^3

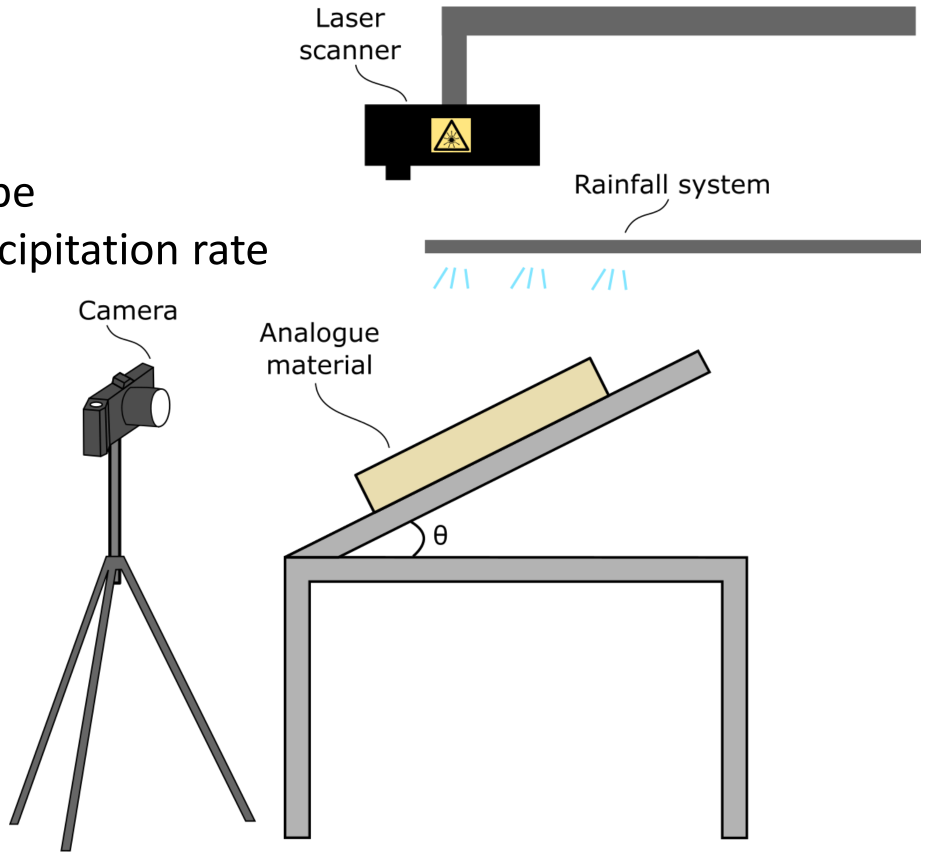


TESTED MATERIALS

How do different composite materials respond to imposed boundary conditions?

- Fixed slope
- Fixed precipitation rate



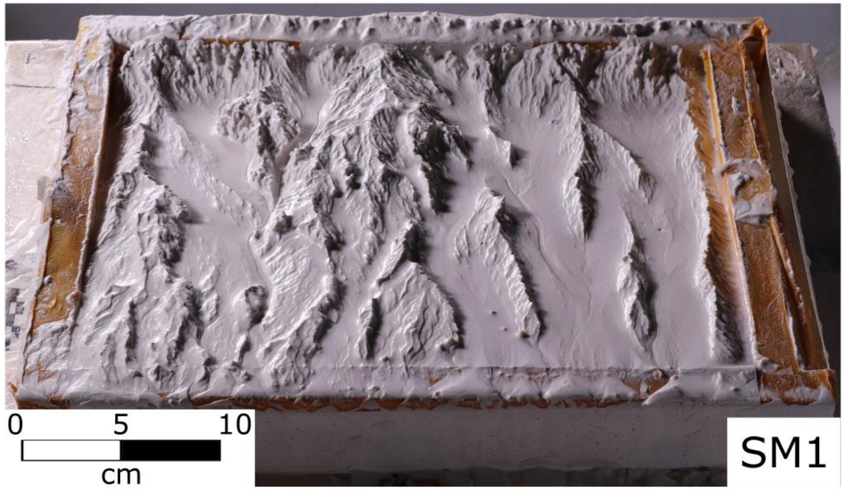


- Granular material on **15° slope** box
- Rainfall system for precipitation rate
- 1 camera for evolution recording
- Laser for high resolution topography measurement
- MATLAB codes for topography evolution, erosion rate and mass discharge calculations

EROSIONAL LANDSCAPES

Exp. name	Composition (wt. %)			
	CQ	SP	GM	PVC
SM1	0	100	0	0
CM1	40		40	20
CM2		40	40	20
CM3		50	35	15
CM4		60	30	10
CM5		70	25	5

We added 25 wt. % of water for every sample



SP only

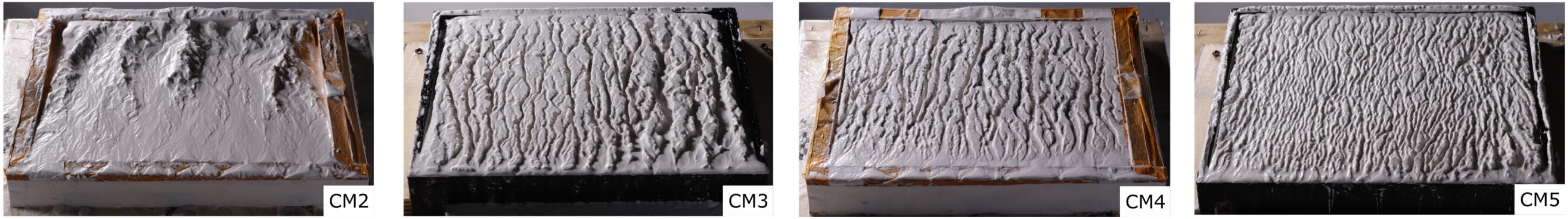
CQ, GM, PVC

- **SP** is widely used for landscape evolution analogue models (e.g. Bonnet, 2009; Graveleau et al., 2011; *Singh et al., 2017*). We tested this material as well.
- Due to the high mechanical strength of SP, this can be mixed with other materials (e.g. *Graveleau et al., 2011*)
- **SP** and **CQ** have the same chemical composition, but the resultant landscape (exp. **CM1 and CM2**, p. 12) is very different
- From 87 to 20 µm (**CQ and SP, respectively**) the importance of grain size and grain shape is strongly highlighted.

EROSIONAL LANDSCAPES

Increasing the concentration of SP and decreasing the concentration of GM and PVC produces:

- Reduction of basin morphology
- Straighter and narrower channel
- Less incision
- Anastomose channels



SP, GM, PVC

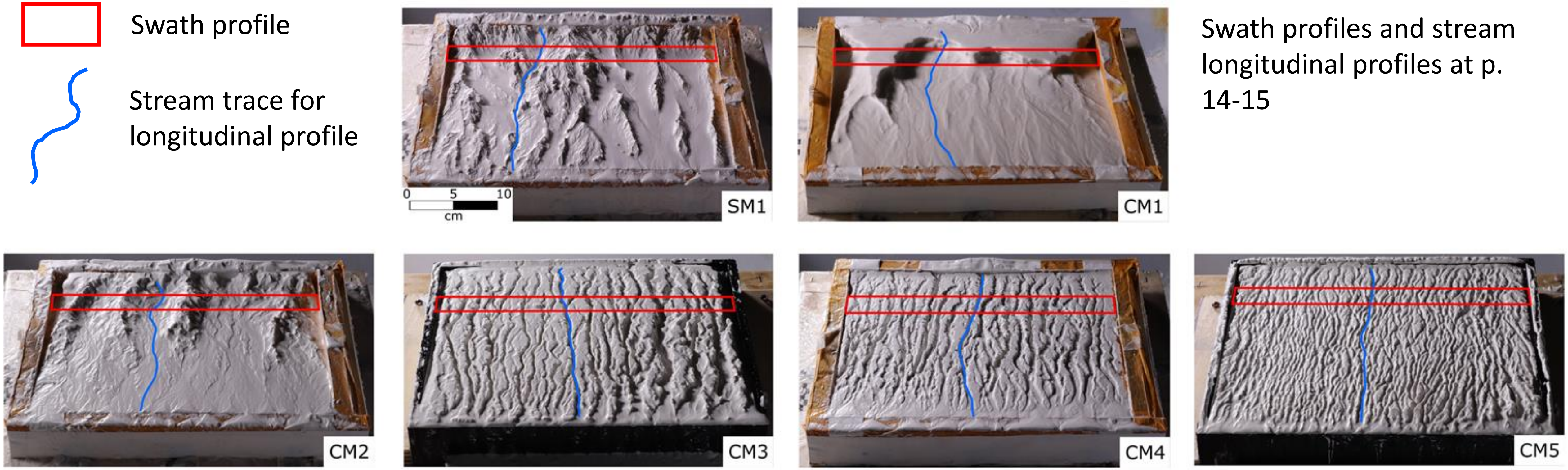
Less SP
More GM, PVC

More SP
Less GM, PVC

EROSIONAL LANDSCAPES

Swath profile

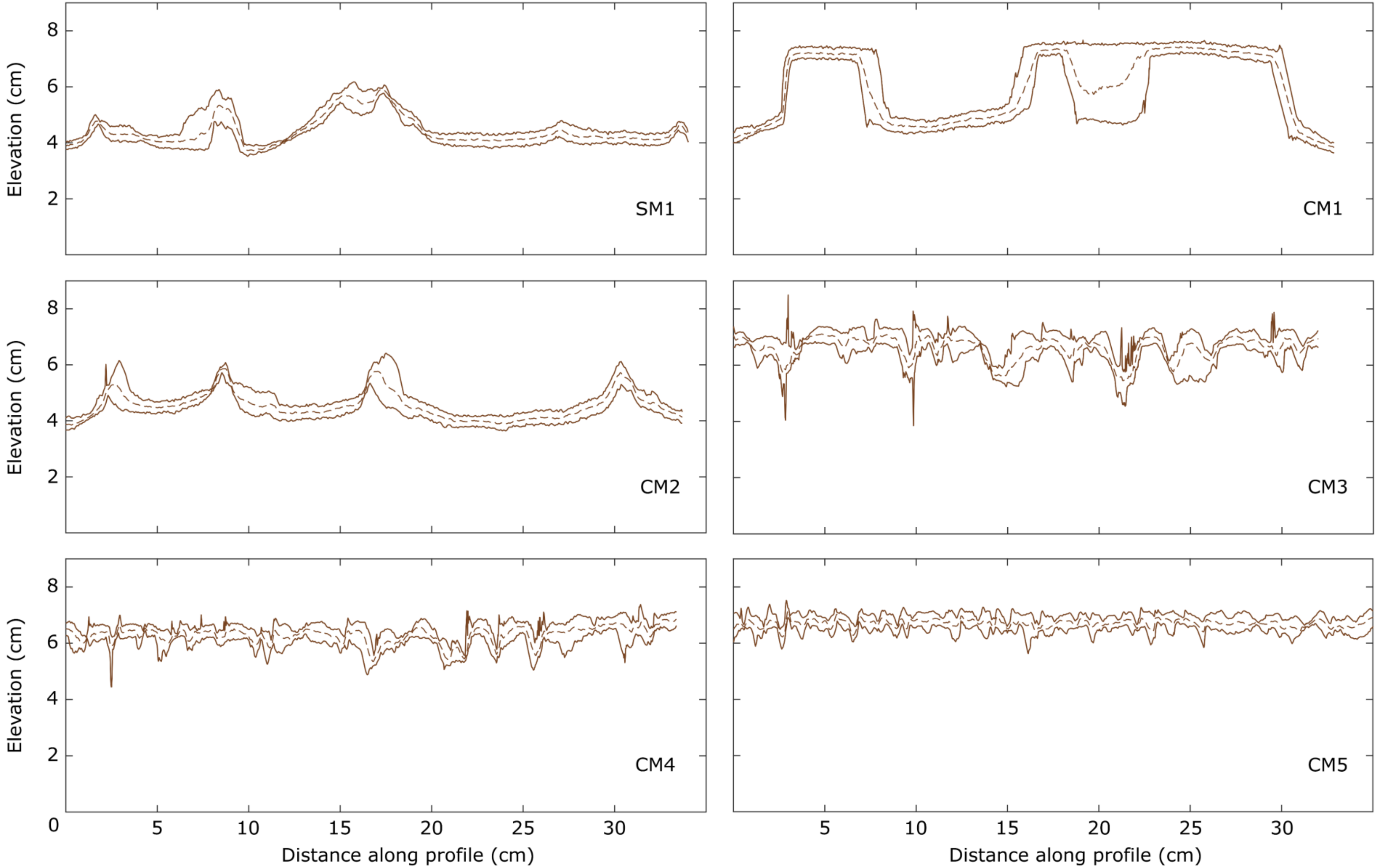
Stream trace for longitudinal profile



Swath profiles and stream longitudinal profiles at p. 14-15

Using a laser scanner, and converting the scans in DEMs using MATLAB, is it possible to analyze the analogue landscapes using the same tools implemented for natural landscapes (e.g. GIS, TopoToolbox (*Schwanghart and Scherler, 2014*))

GEOMORPHIC ANALYSIS – SWATH PROFILES



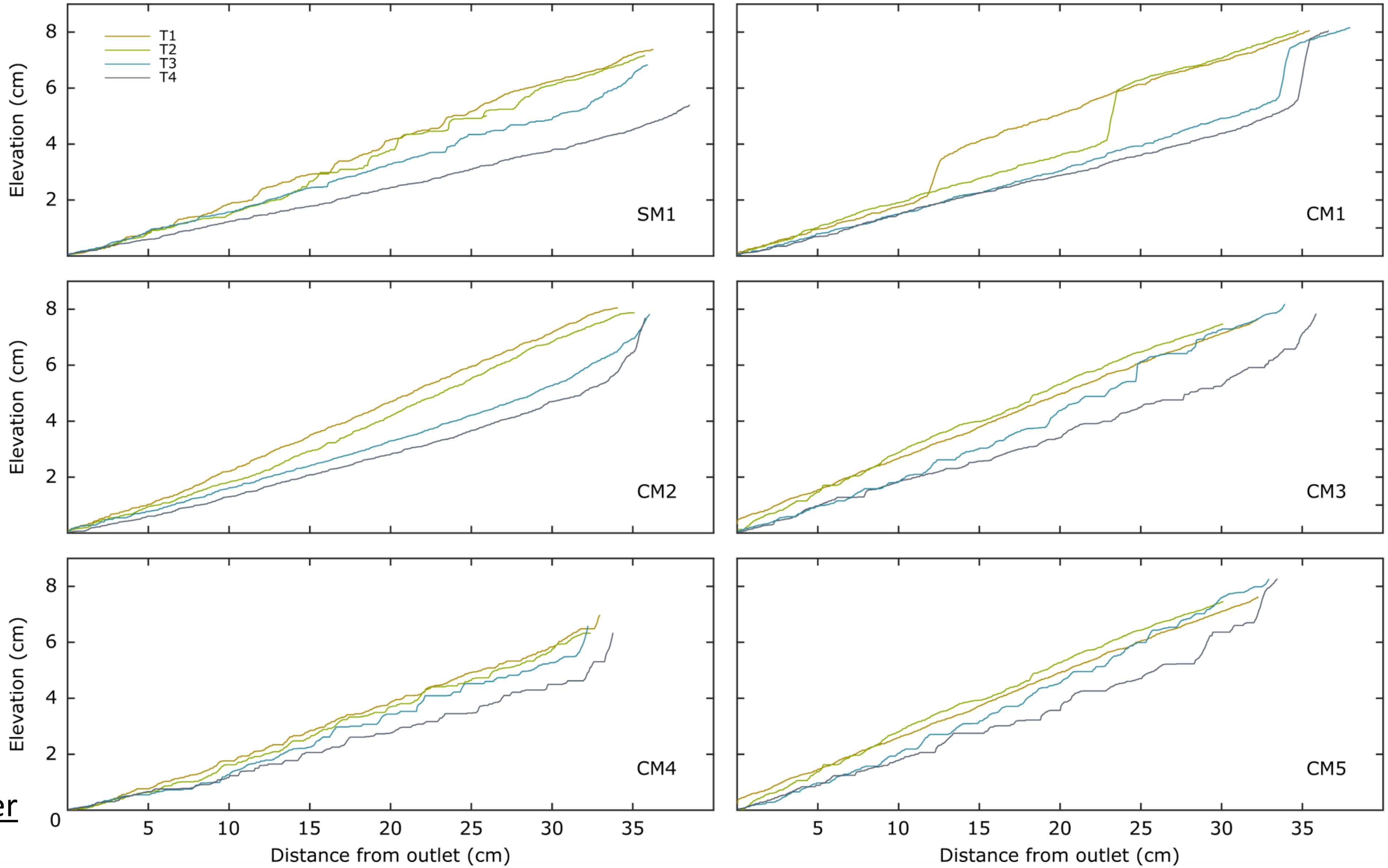
- **SM1:** incised valleys with ridges between them.
- **CM1:** planar surfaces (12° slope) standing at two different elevation. Very sharp scarps.
- **CM2:** incised valleys with sharp ridges between them.
- **CM3, CM4, CM5:** high frequency reliefs. Very low incision in the valleys.

<u>SM1 and CM2 well reproduce the morphology of natural landscapes</u>

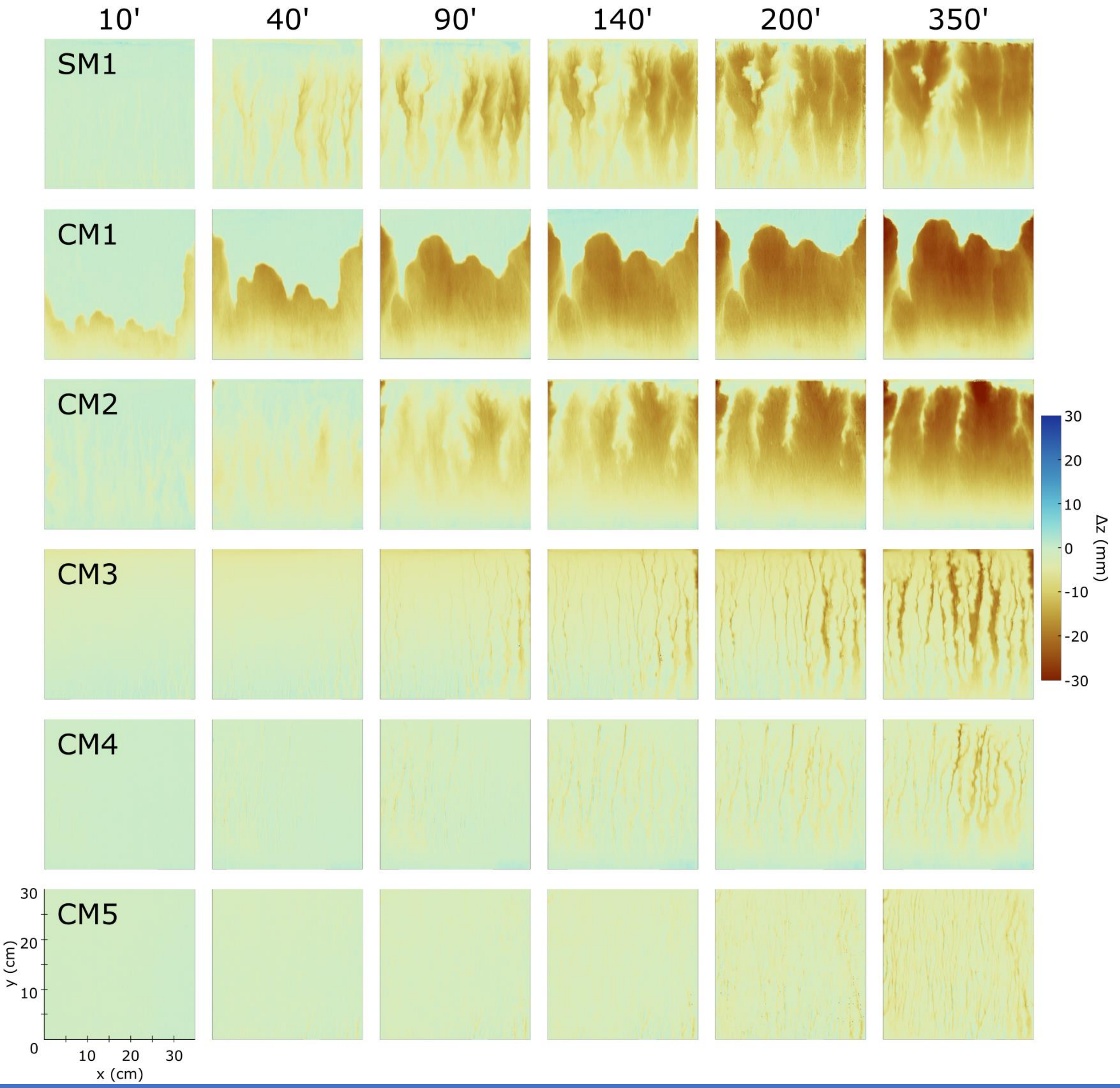
GEOMORPHIC ANALYSIS – STREAM LONGITUDINAL PROFILE

- **SM1:** the stream evolves to a new equilibrium profile with a concave-upward shape.
- **CM1:** no proper rivers develop. The longitudinal profile follows the topography.
- **CM2:** evolution of longitudinal profile towards concave-upward shape.
- **CM3:** evolution similar to CM2.
- **CM4, CM5:** straight channels with a very low evolution in morphology. The "flickering" in the longitudinal profile is linked to laser resolution.

<u>SM1, CM2 and CM3 show proper longitudinal profiles</u>



GEOMORPHIC ANALYSIS

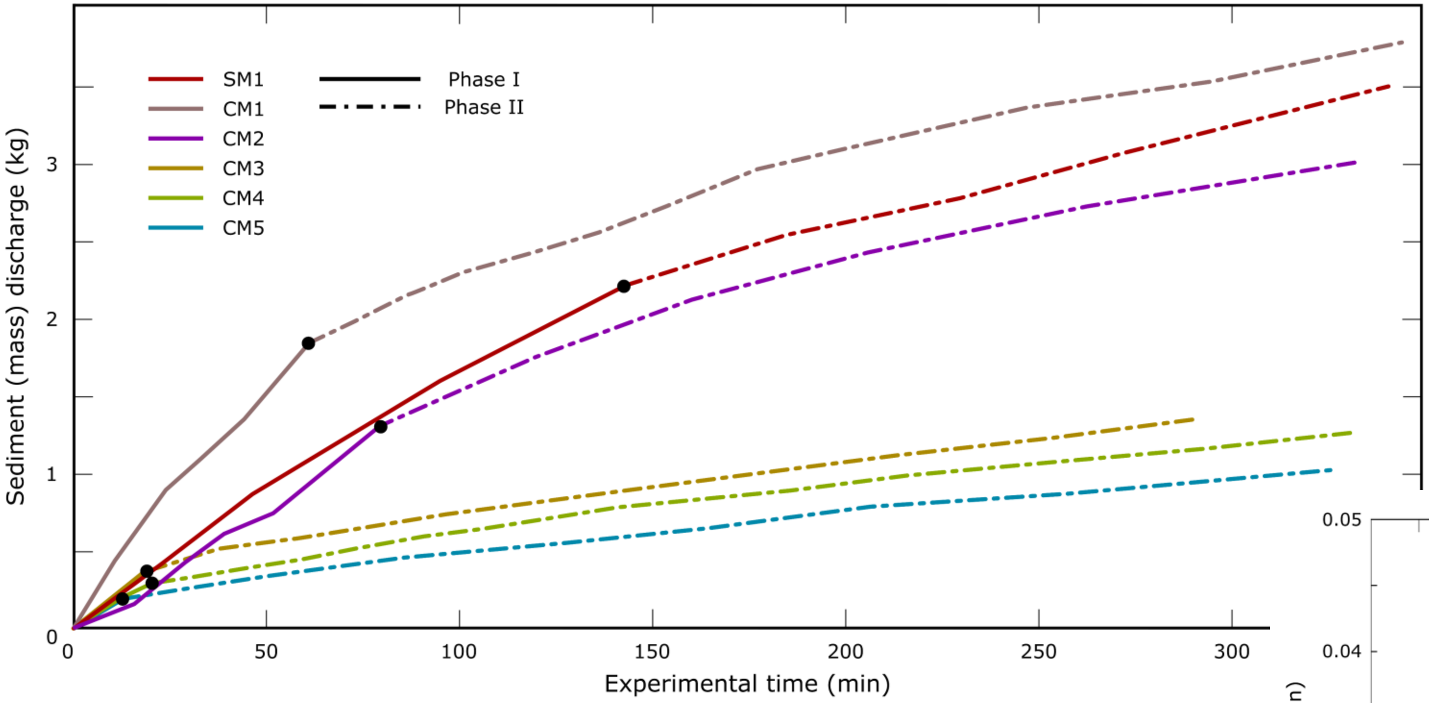


Cumulative difference in elevation between consecutive scans at different time steps(Δz). Negative values (brownish colors) indicate decreasing topography due to **erosion**, while positive values (bluish colors) indicate increasing topography due to **sedimentation**.

- In SM1 and CM2 the erosion is focused in the valleys.
- In CM1 the erosion is diffused on the lower planar surface
- In CM3, CM4 and CM5 the erosion focuses in the straight channels. They are less and less incised moving from CM3 to CM5

<u>SM1, CM2 and CM3 show erosion focused in valleys, and evolve in a reasonable experimental time (6-8 hours)</u>

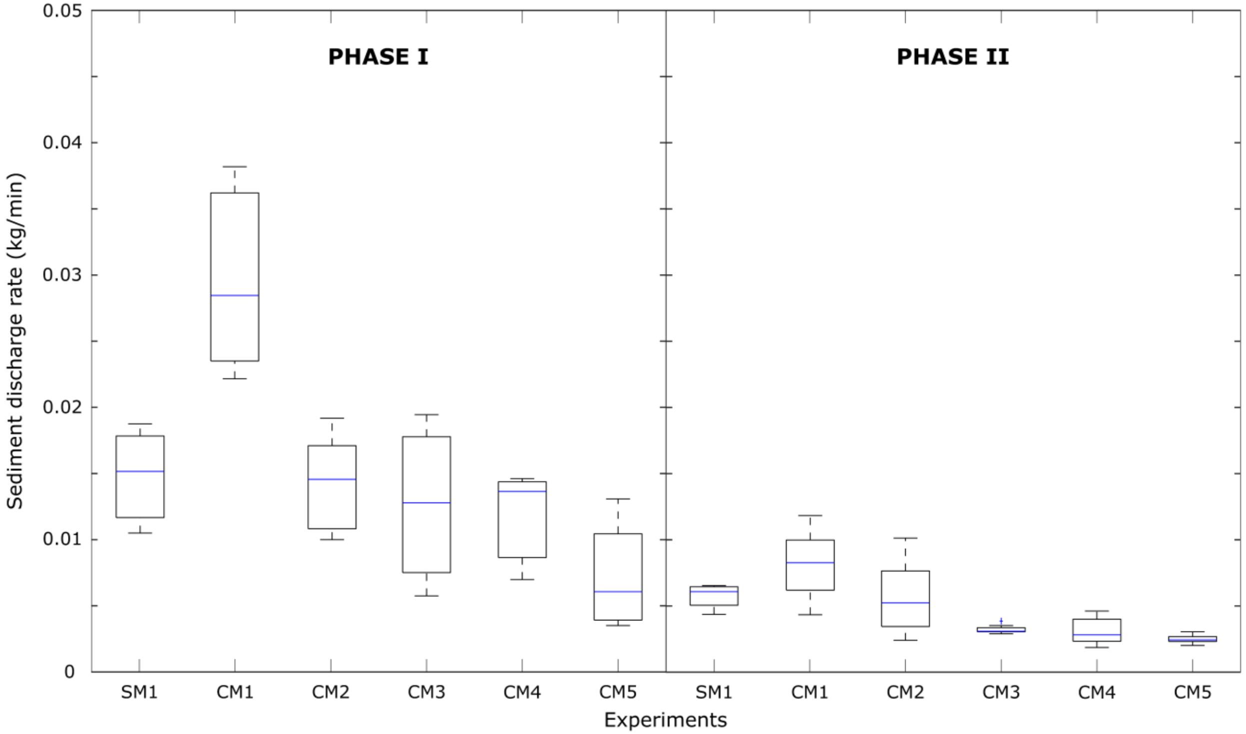
SEDIMENT DISCHARGE



Two phases recognized in the sediment discharge evolution:

- Phase I: fast removal of material from the model
- Phase II: slower removal of material with a lower discharge rate that is kept constant until the end of the experiment

- CM1 shows the highest mean Sediment Discharge Rate (sdr) in both phases.
- SM1 and CM2 show similar values for sdr.
- From CM3 to CM5 the sdr decrease, and it lower than the other models.



THE ROAD SO FAR

$$\frac{Precipitation\ rate\ (P)}{Infiltration\ capacity\ (I)}$$

< 1 = No surface runoff (R)

> 1 = Surface runoff

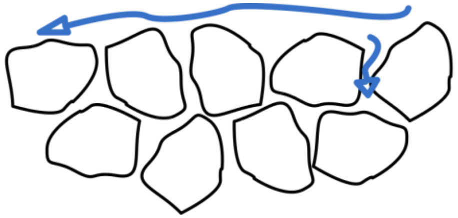
We can work on small ranges of P → **Working on Infiltration capacity (analogue material)**

Small grainsize (µm) with good grain size (shape) distribution reproduce reliable analogue landscapes.

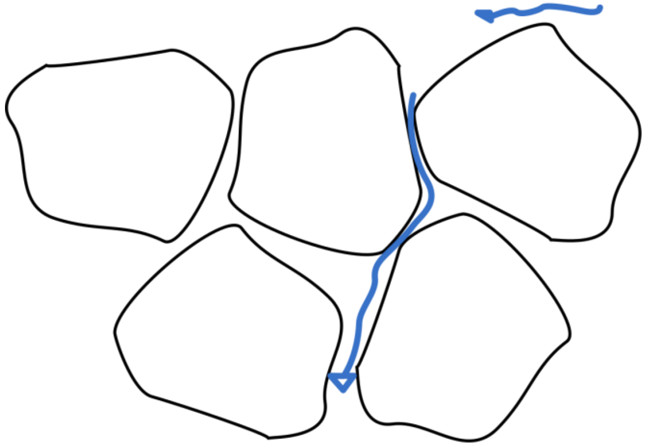
↓

<u>Exp. and samples SM1, CM2 and CM3</u>

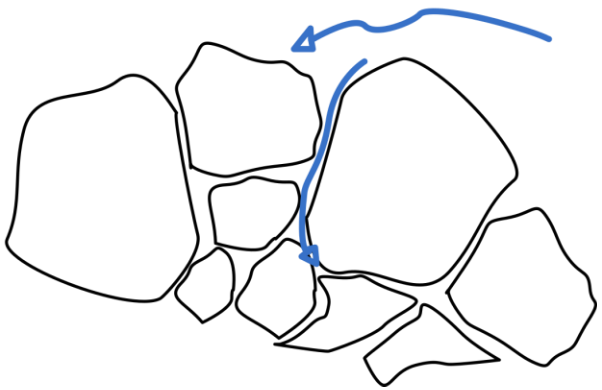
Sample	Permeability (m^2)
SM1	$3.56 \cdot 10^{-14}$
CQ	$2.34 \cdot 10^{-12}$
GM	$2.87 \cdot 10^{-12}$
PVC	$1.06 \cdot 10^{-12}$
CM1	$7.42 \cdot 10^{-13}$
CM2	$2.90 \cdot 10^{-13}$
CM3	$9.25 \cdot 10^{-14}$
CM4	$2.63 \cdot 10^{-13}$
CM5	$4.06 \cdot 10^{-13}$



→ Low I High R



→ High I Low R



→ Both I & R

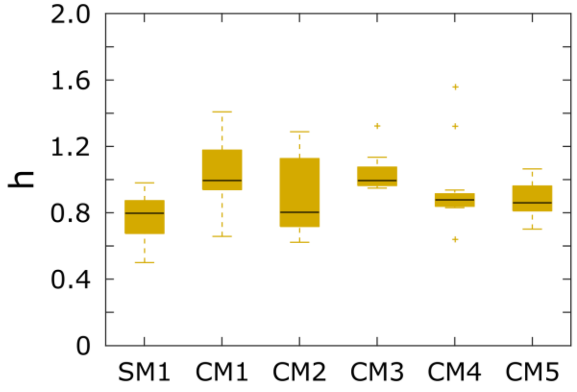
NATURAL LAWS APPLIED TO ANALOGUE MODELLING

Hack's Law

$$L = cA^h$$

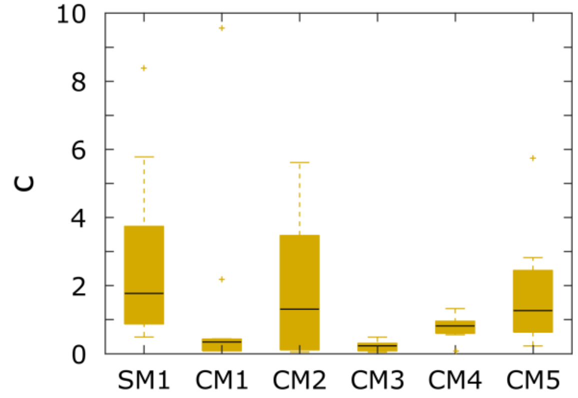
Relationship between channel length (L) and drainage area (A). Allows to analyze the geometry of the drainage network.

h gives information about the basin geometry



h > 0,5 → basin elongation with increasing size

SM1 and CM2 → high values for h, but lower respect to the other models

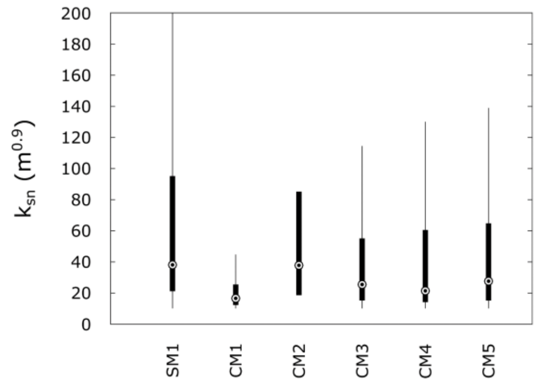


Flint's Law

$$S = k_s A^{-\theta}$$

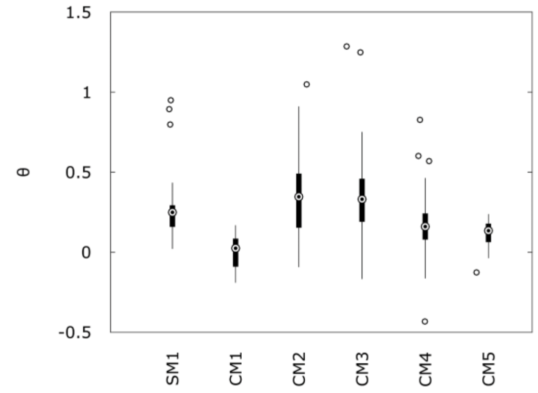
Relationship between channel slope (S) and drainage area (A). θ (concavity index) and k_s (steepness index) are autocorrelate

Channel steepness is normalized (k_{sn}) to a regionally constant reference concavity, typically taken to be 0.45 (θ_{ref} = 0.45)



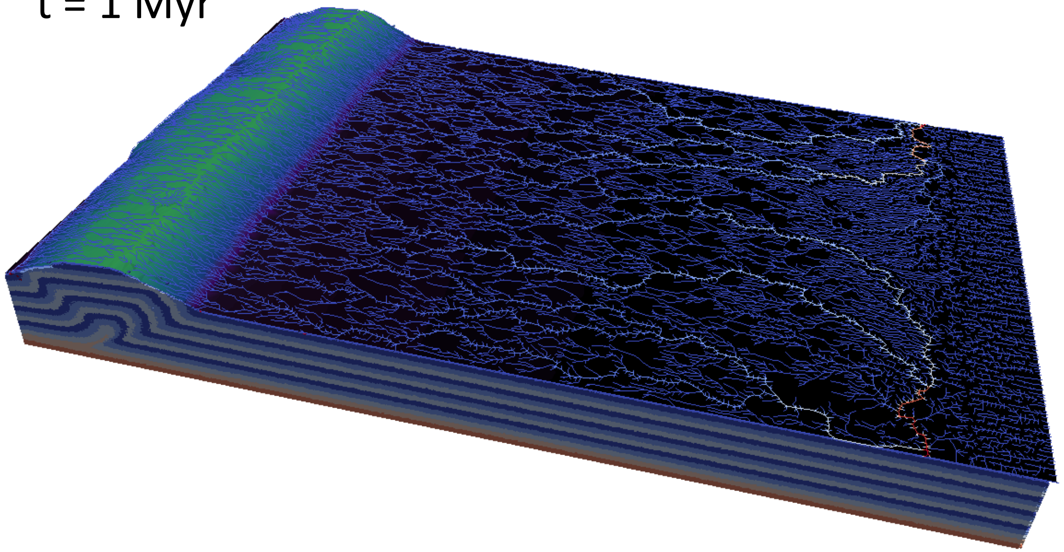
k_{sn} and θ in the range of natural values

SM1, CM2 and CM3 → higher distribution of ksn and higher values of theta

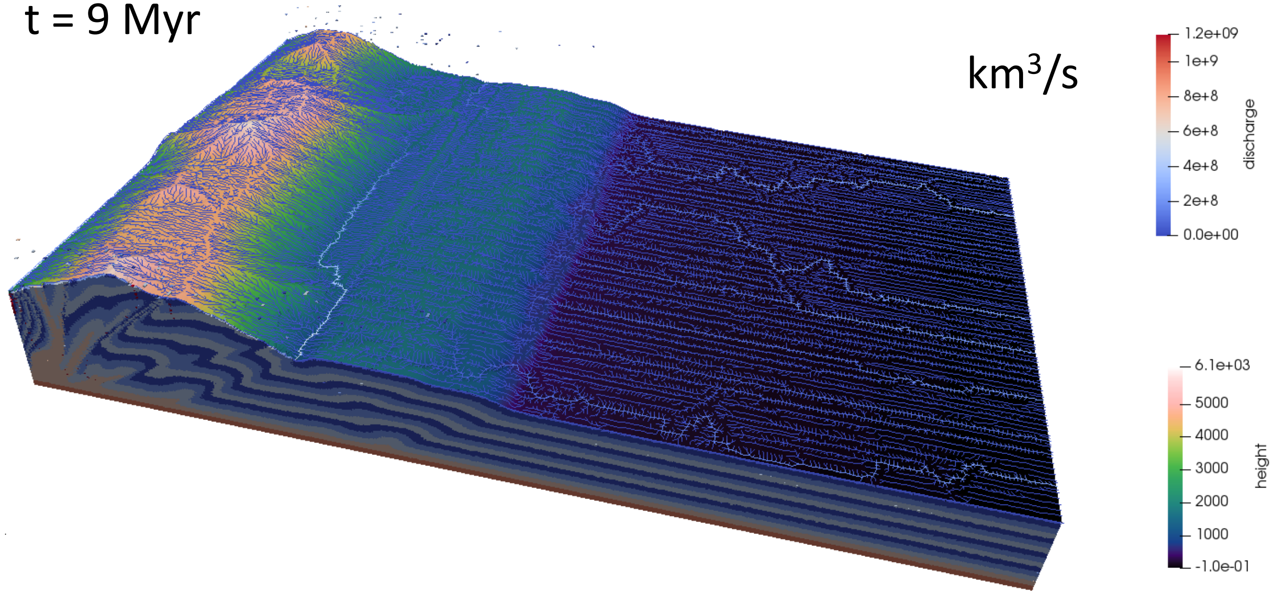


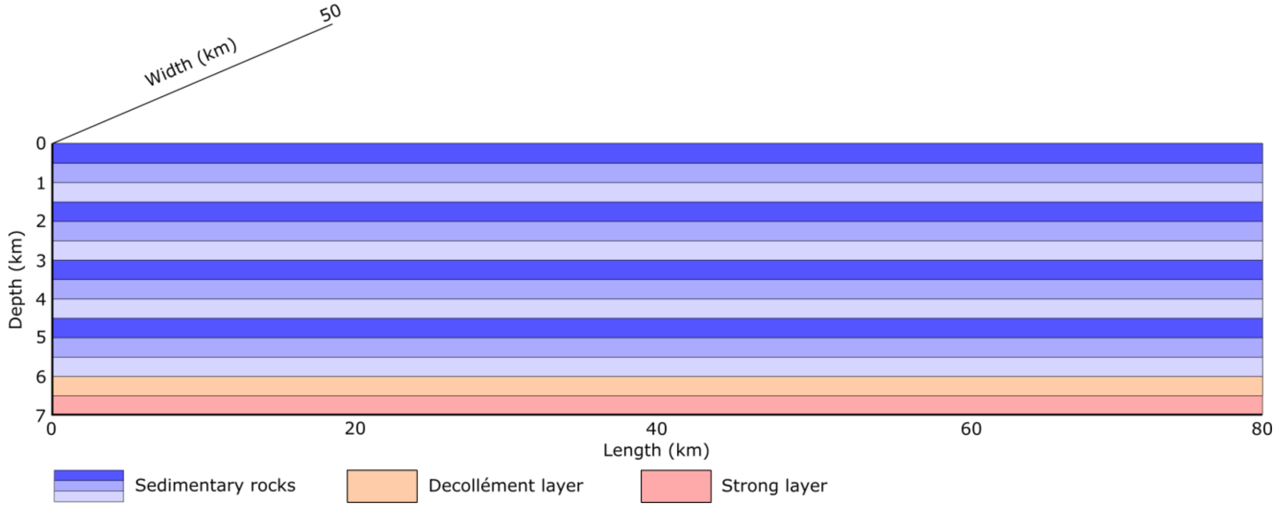
NUMERICAL CODE IMPLEMENTATION

t = 1 Myr



t = 9 Myr

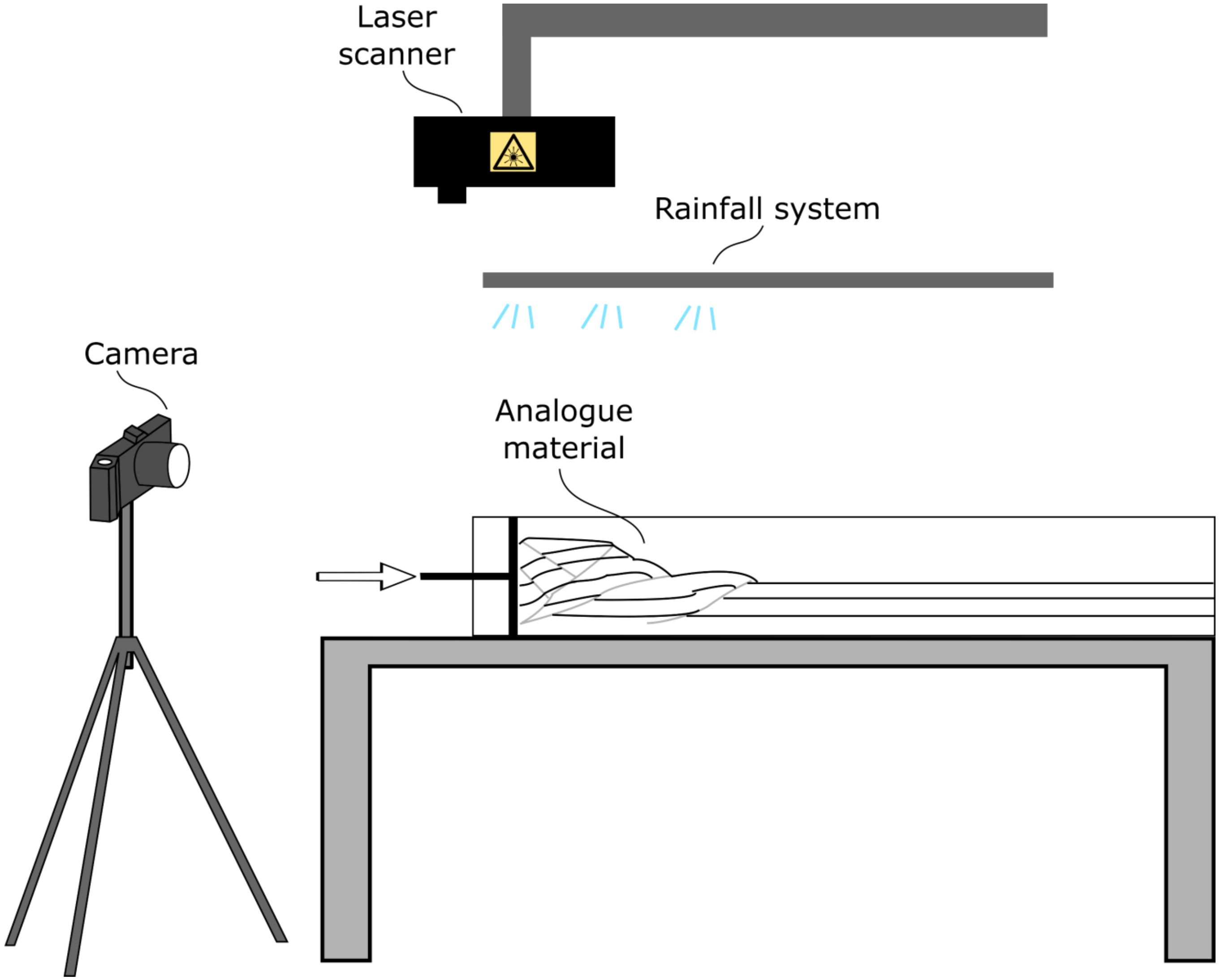


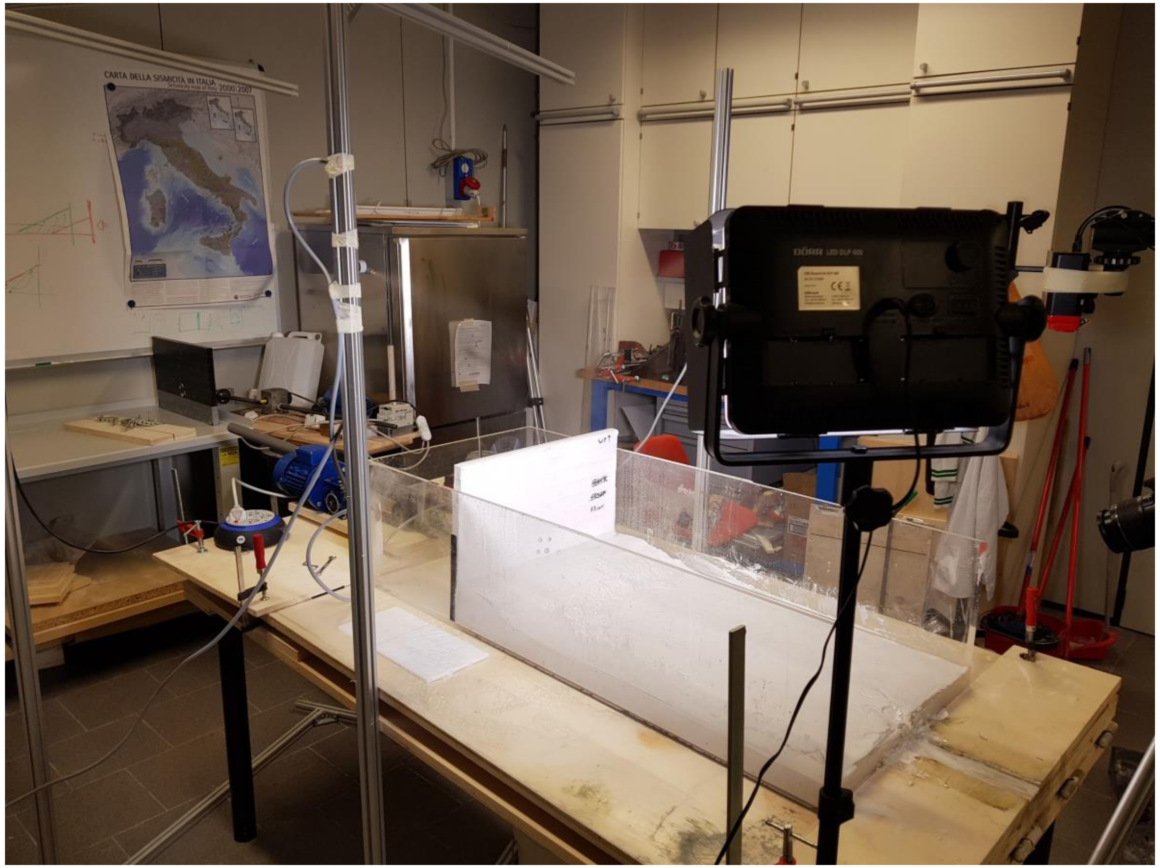


Thermo-Mechanical code for Elasto-Plastic-Viscous rheology I3ELVIS *(Gerya and Yuen, 2007)* **and Landscape Evolution Model DAC** *(Goren et al., 2014)*

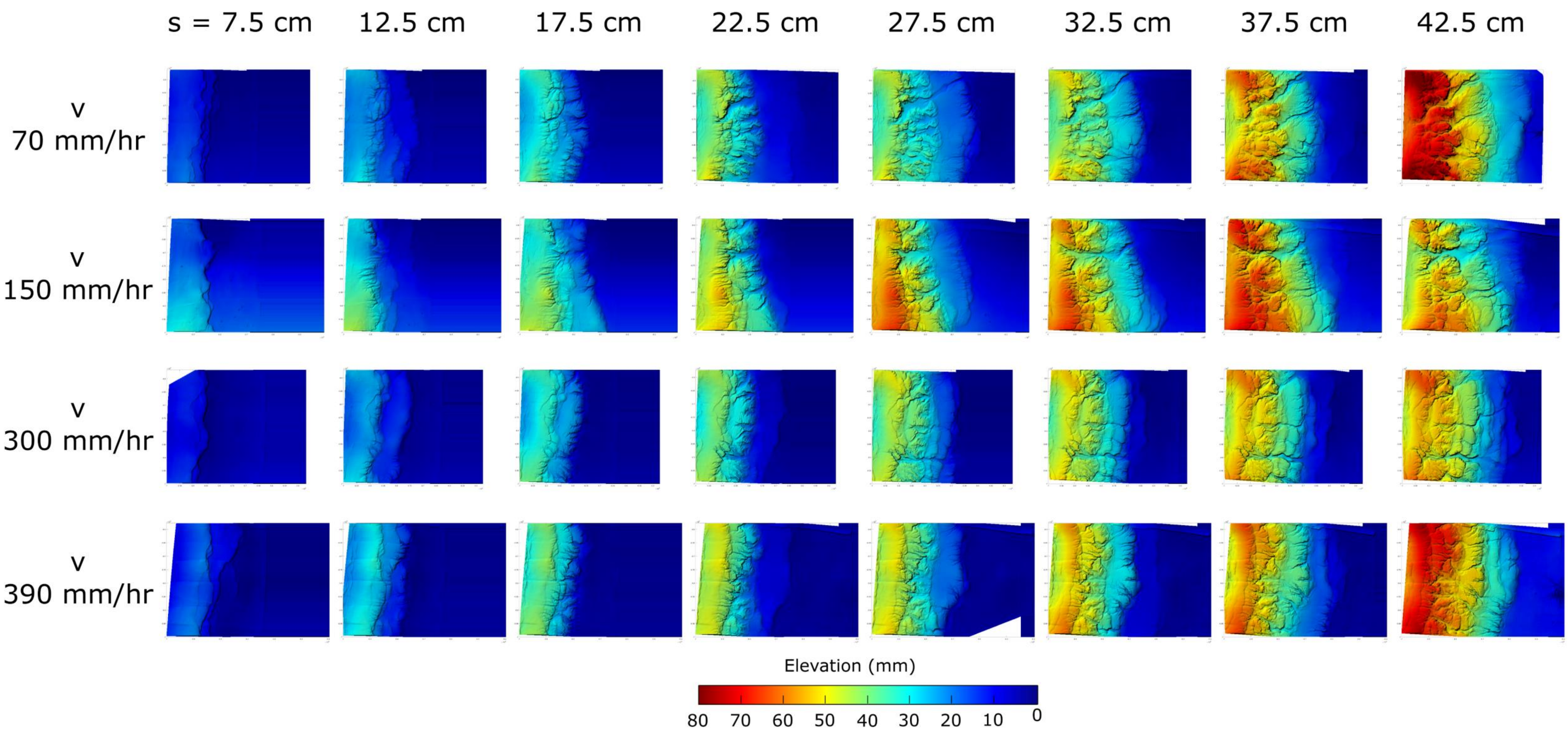
- Staggered, finite-difference scheme, marker-in-cell
- Solve conservation equations for momentum, mass and energy
- Velocity weakening and strengthening
- Simple shear application
- Developing of a river network
- Kinematic component of the surface model replaced by a dynamically calculated surface velocity field
- Two different time scales for a coupled model

WEDGE EROSION/SEDIMENTATION





WEDGE EROSION/SEDIMENTATION



v = convergence velocity   s = shortening

CONCLUSIONS

CONCEPTUAL MODEL

In the building of an orogenic wedge, the **balance** between the flux of **material added** to the wedge by convergence and the flux of **material removed** controls the growth of this one and can be described by a **dimensionless number** ($\boldsymbol{B}_{u\text{-}e}$).

ANALOGUE MODELLING

Tests on materials show how **silica powder** is a **necessary component** of the analogue material, better if **mixed with glass microbeads and PVC powder**, to enhance the development of different geomorphological features and processes and to reduce the mechanical strength of the silica powder. Samples **CM2 and CM3** meet Hack's and Flint's Law and should be implemented in landscape evolution models.

NUMERICAL MODELLING

It is possible to test several different parameters. The effect of different parameters in the **balance** between tectonics and erosion will be investigated.

THANK YOU FOR THE ATTENTION

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