The role of the ice in shaping landscape morphology

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GM2.6

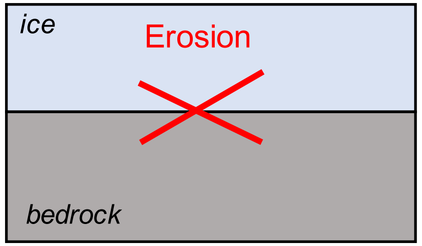
Spatial and temporal distribution of glacial erosion ~~as recorded by apatite (U-Th)/He and ^{4}He/^{3}He thermochronometry~~

Selective linear erosion

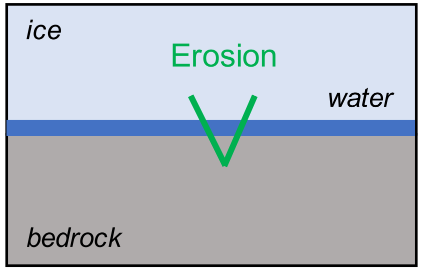
- The ice progressively left the interfluves to focus in valleys
- Glacial erosion incised pre-existing fluvial valleys
- Interfluves are let untouched

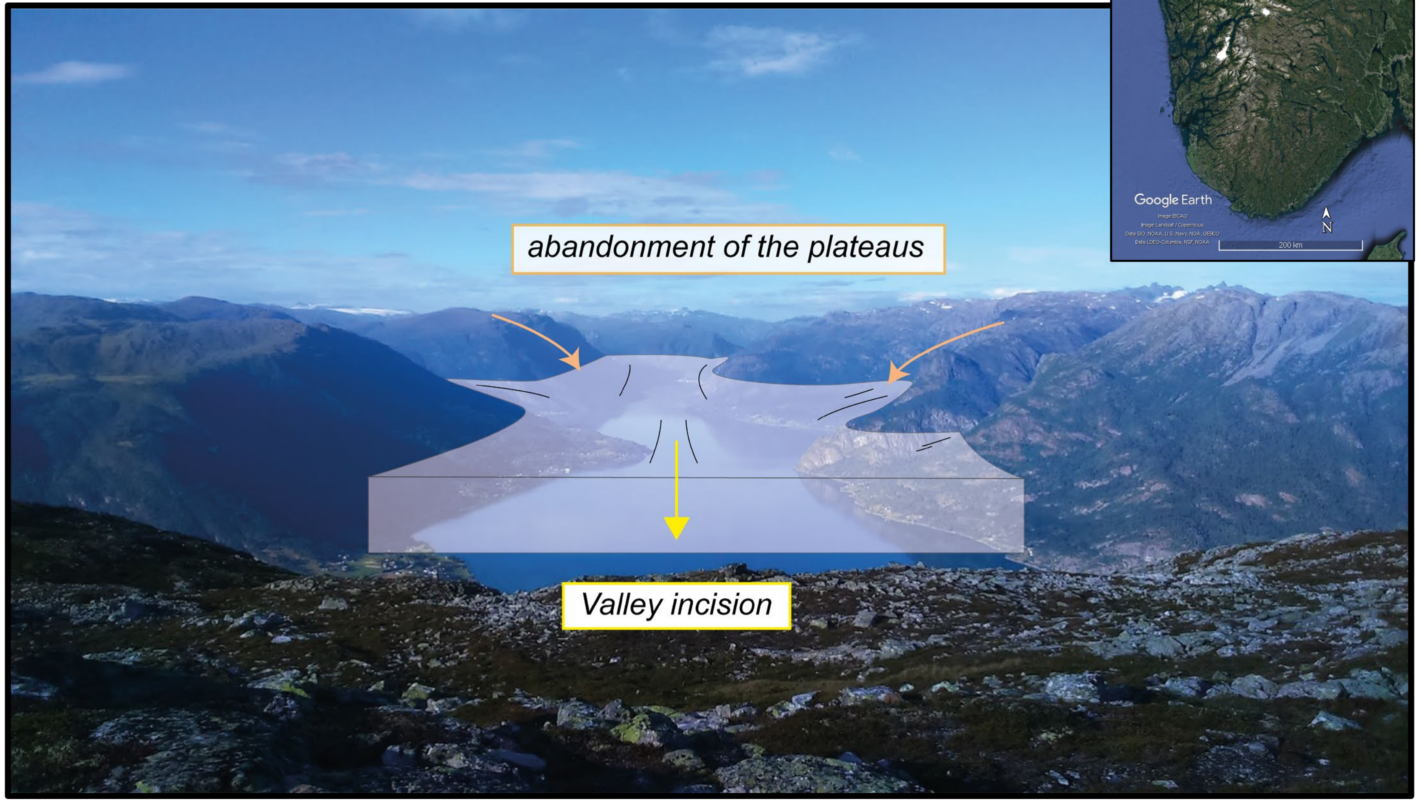
Glacial erosion limited to valleys !

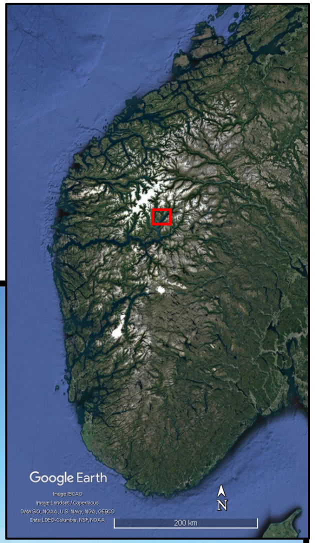
Cold-based ice



Warm-based ice





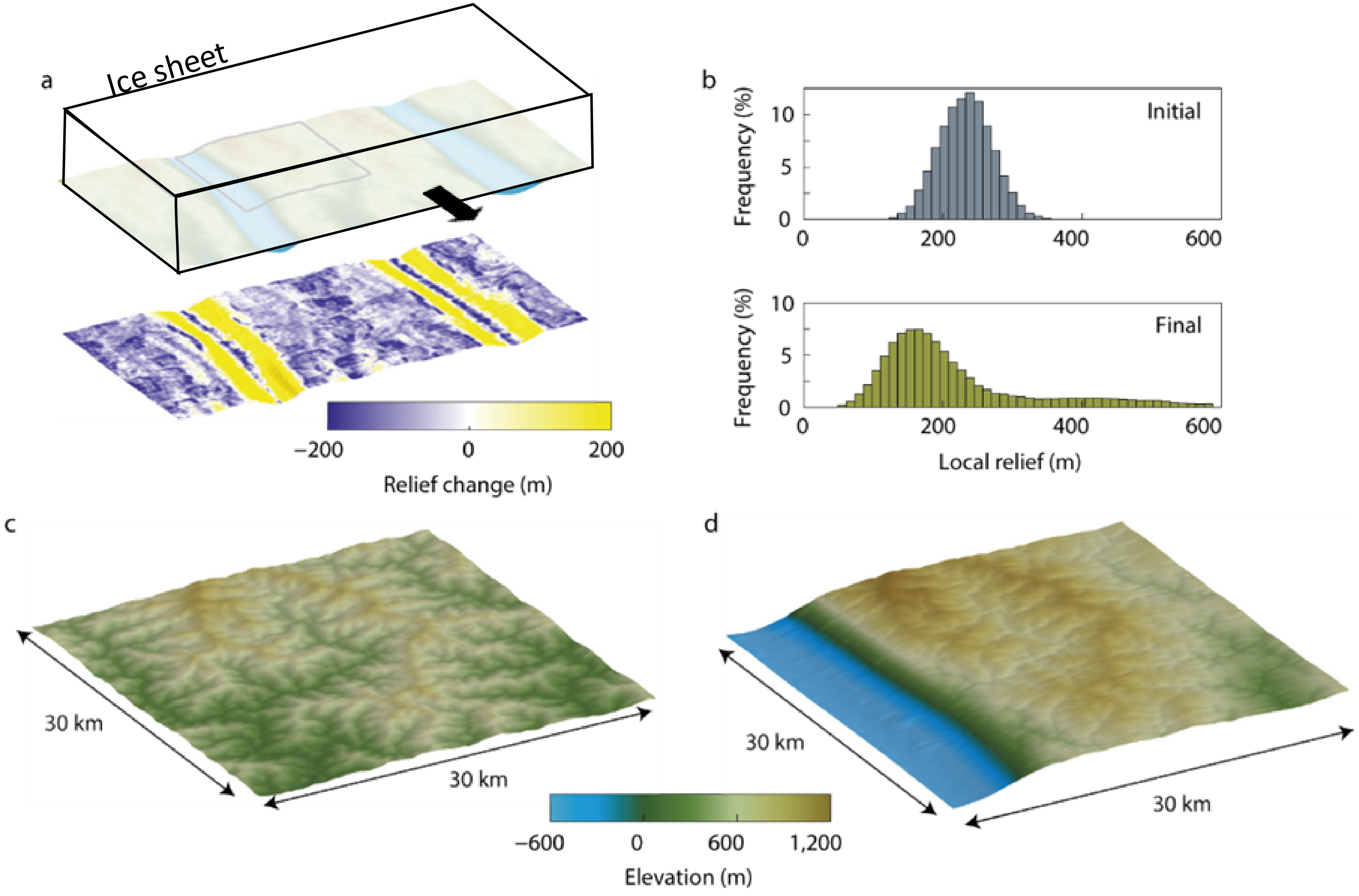


Credit: Maxime Bernard

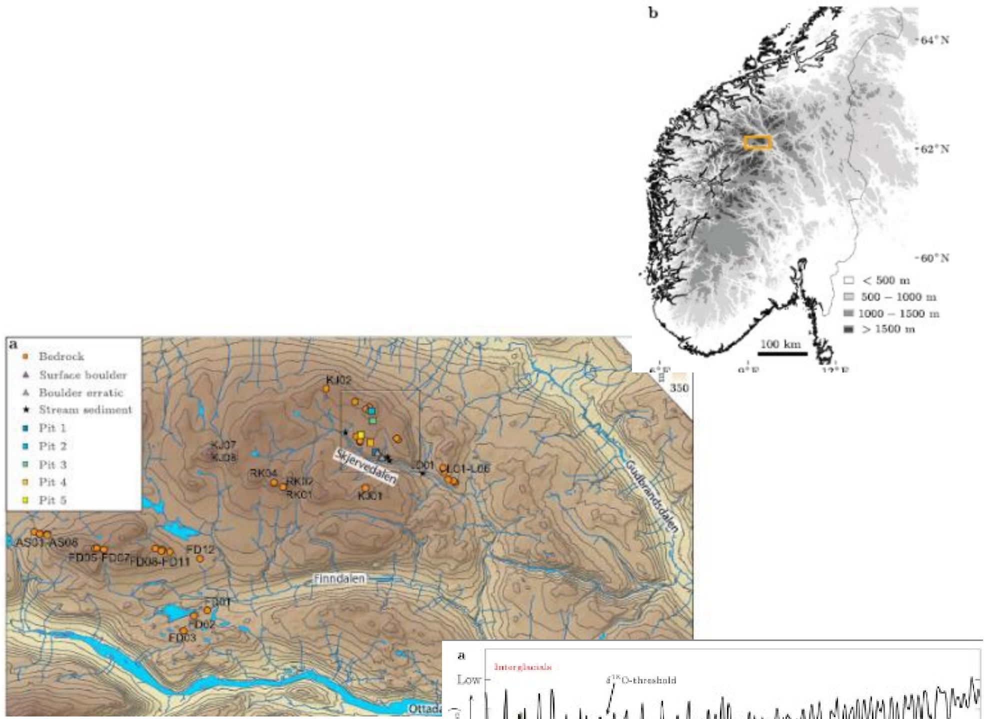
Glacial erosion dependency on basal sliding speed:

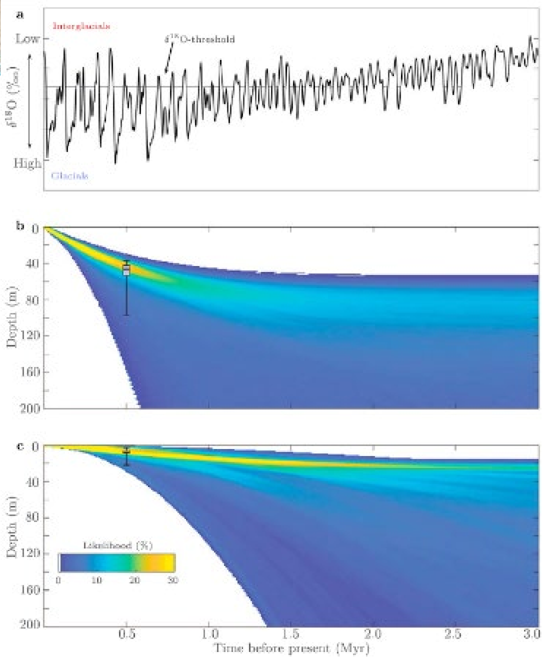
$E_g = k.U^b$

Can glacial erosion and periglacial processes produce low-relief surfaces?



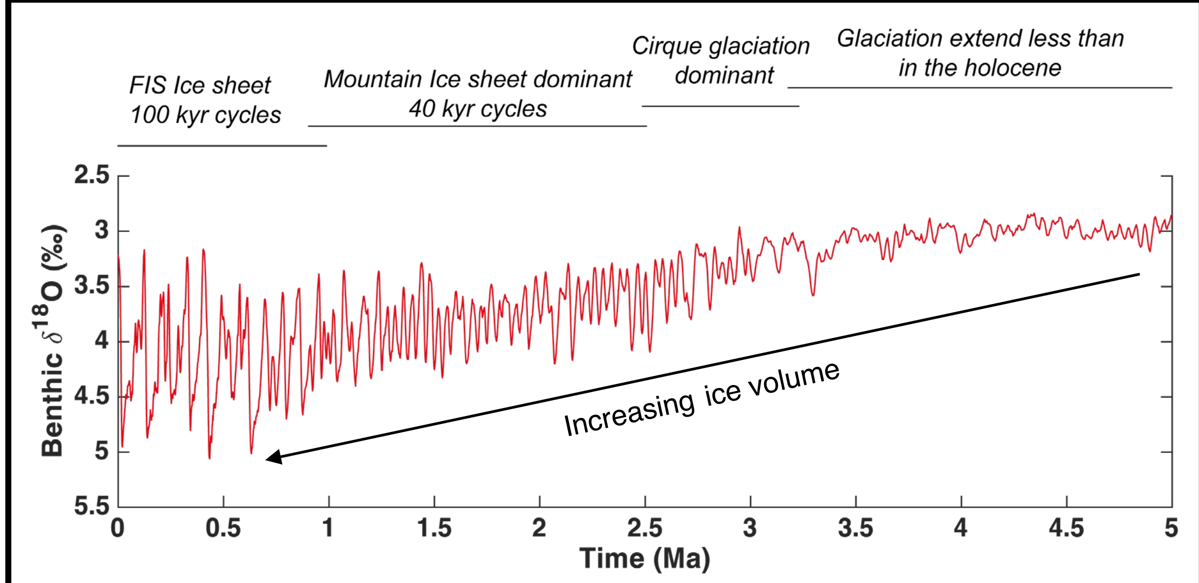
Egholm et al. (2017)



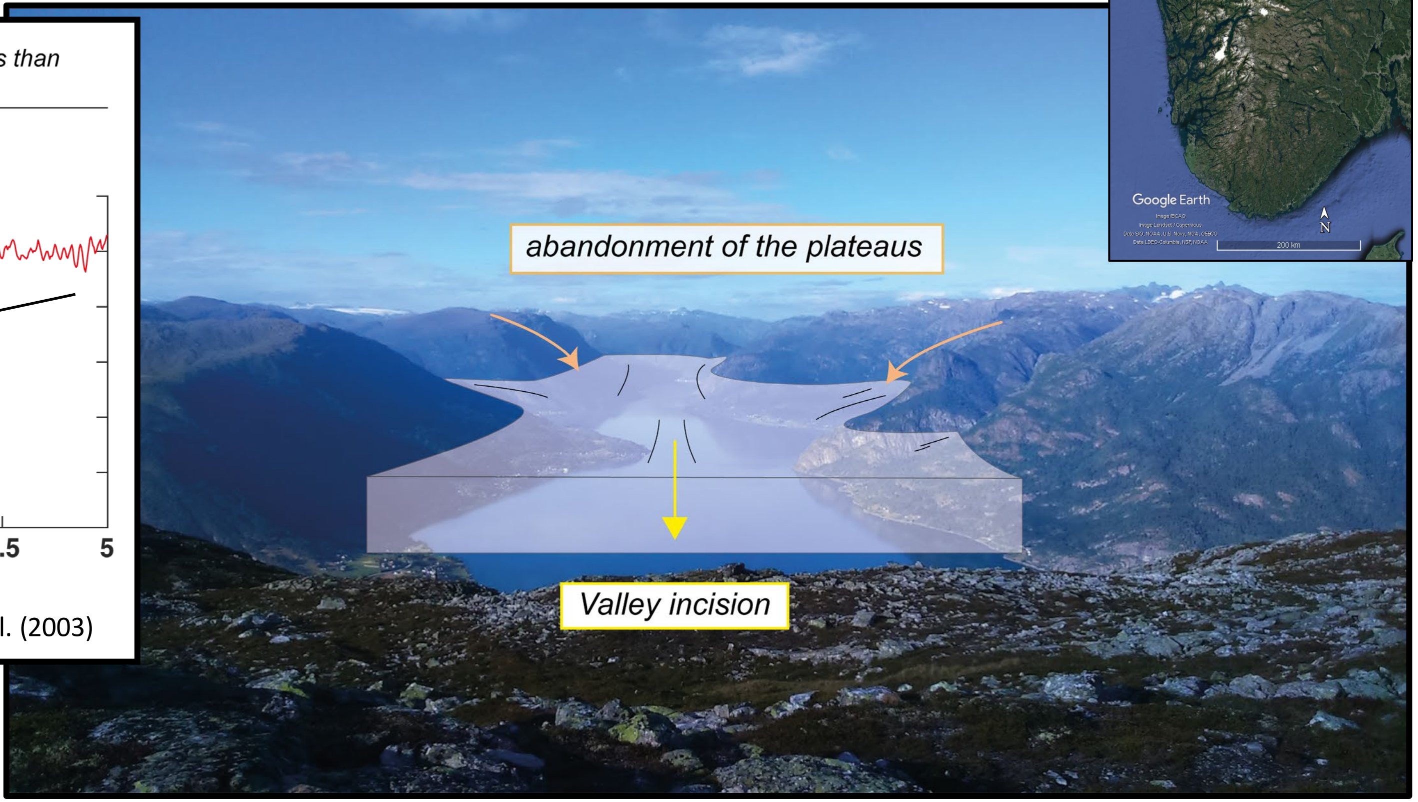


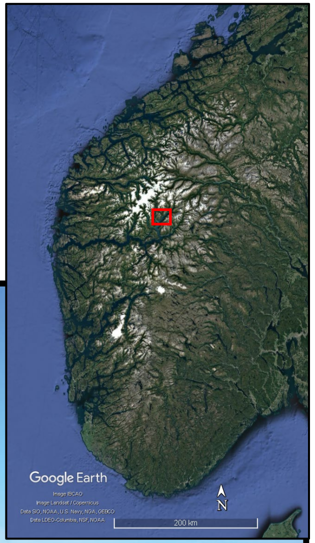
Andersen et al. (2018)

Selective linear erosion



Redrawn from Hall et al. (2003)





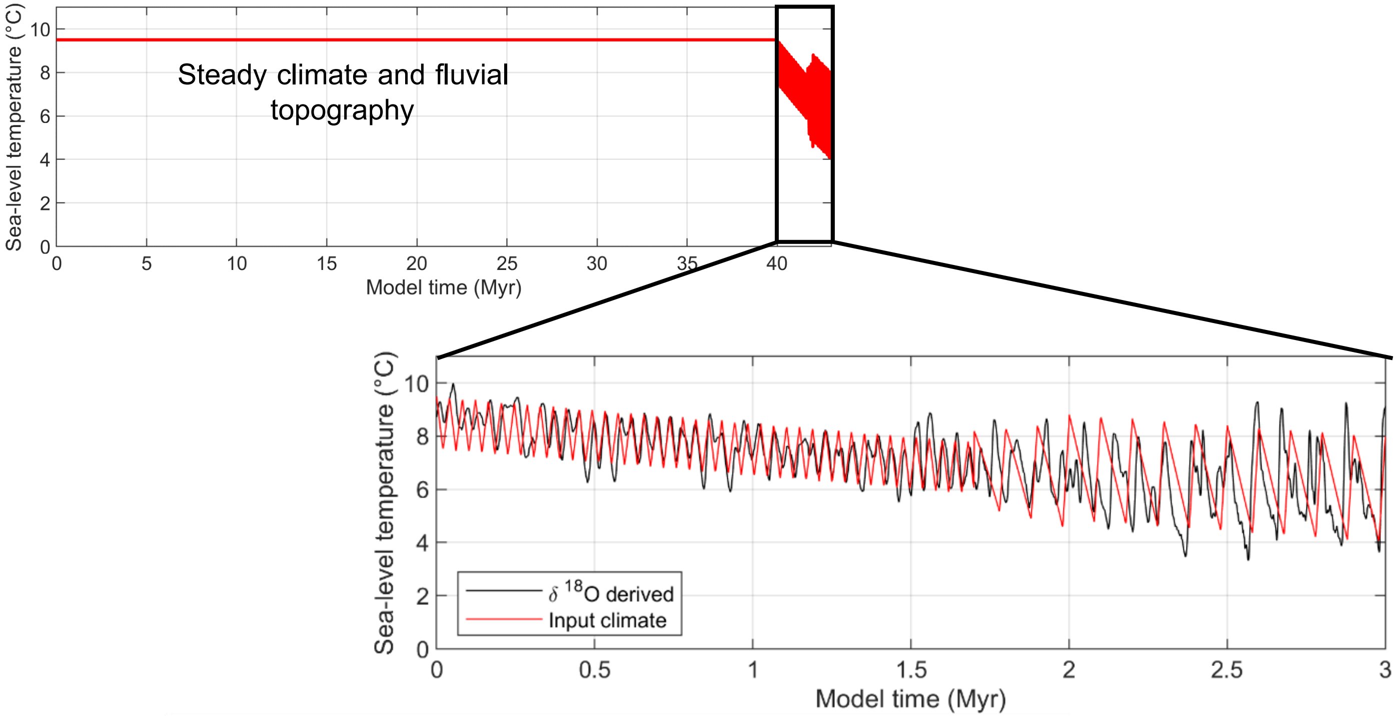
Credit: Maxime Bernard

How transitioning from surface processes impacts the landscape morphology ?

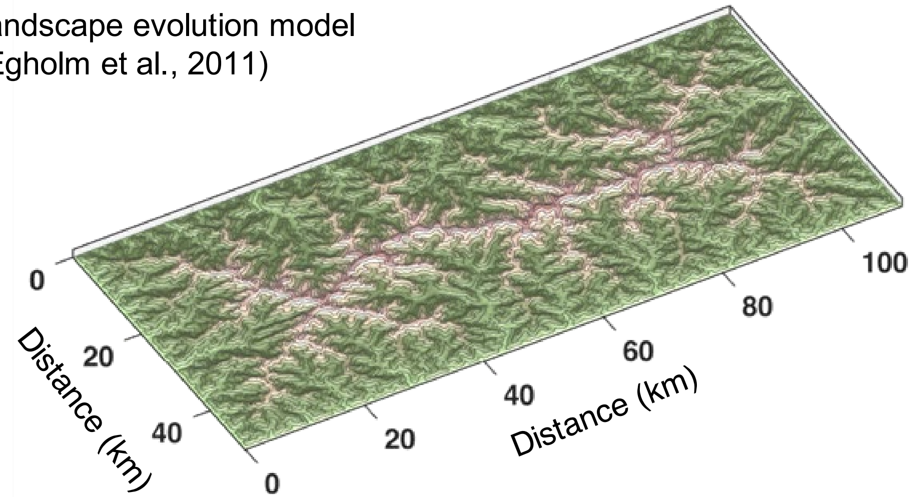
Can low-relief surfaces be the result of the Quaternary climate cooling ?

Simulate Quaternary glaciations

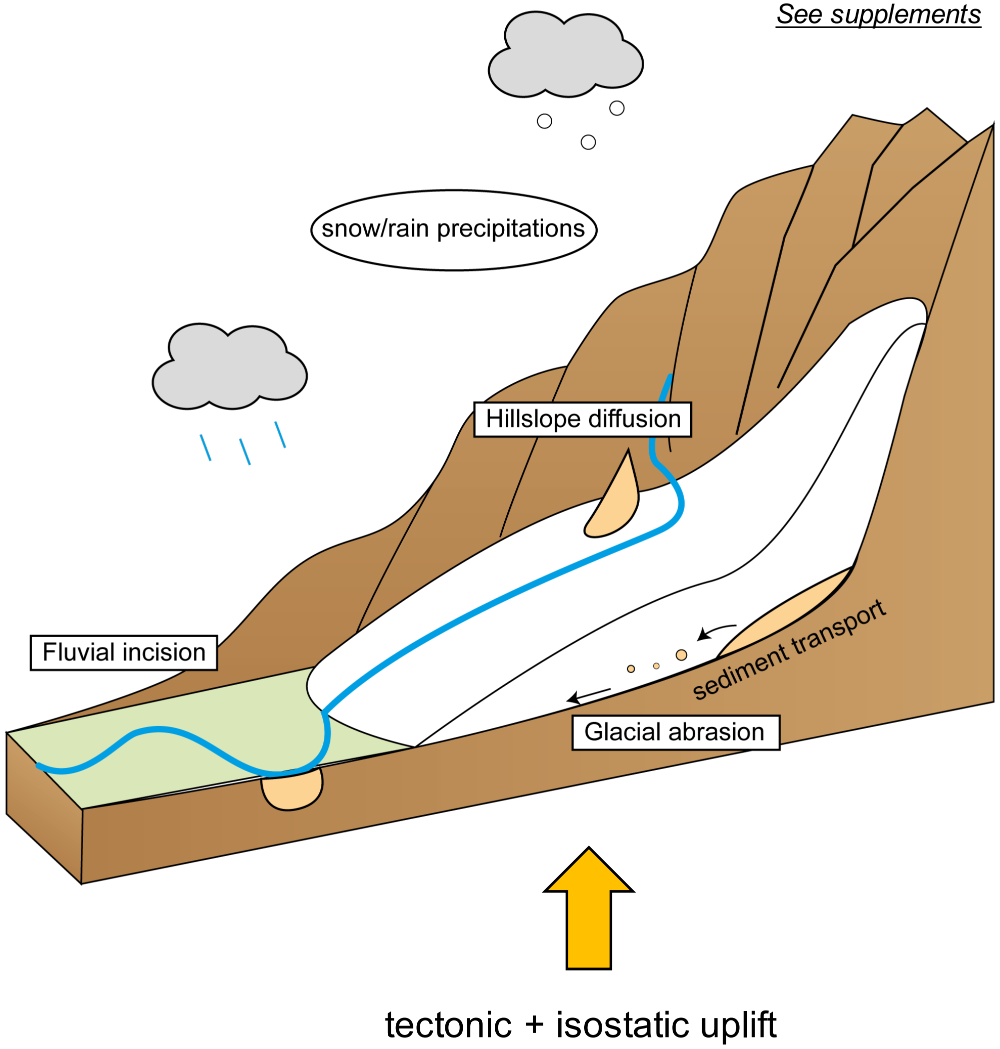
A coupled fluvial, hillslope, glacial erosion and sediment transport model



➢ A glacial landscape evolution model (iSOSIA, Egholm et al., 2011)

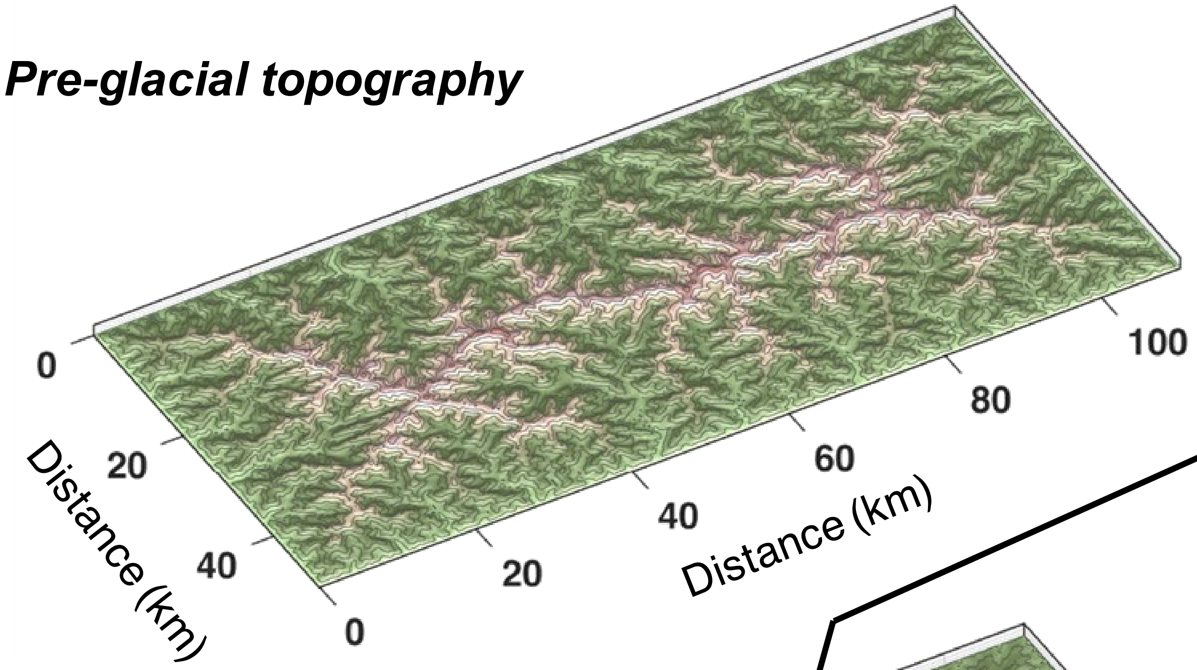


See supplements

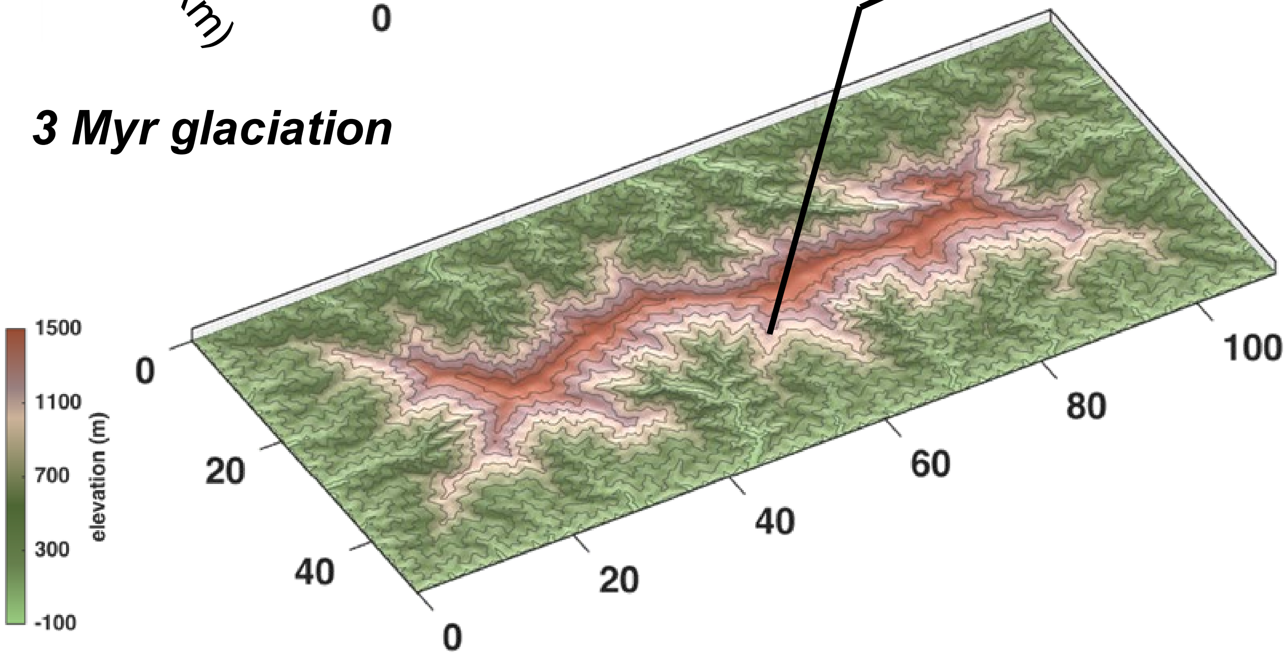


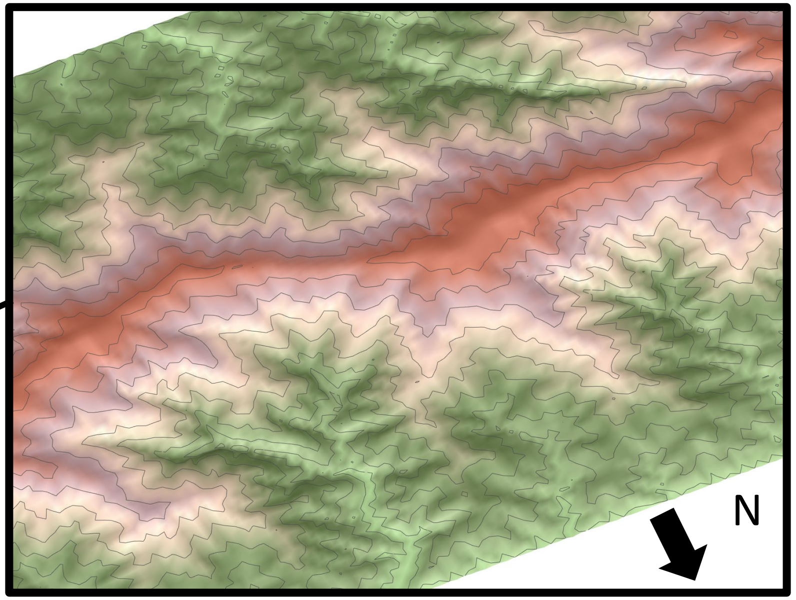
Model results – production of low-relief surfaces

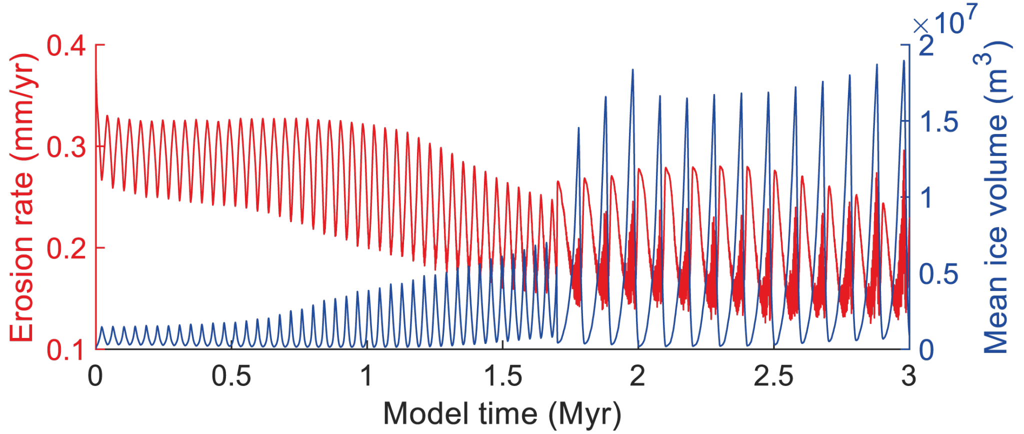
Pre-glacial topography



3 Myr glaciation

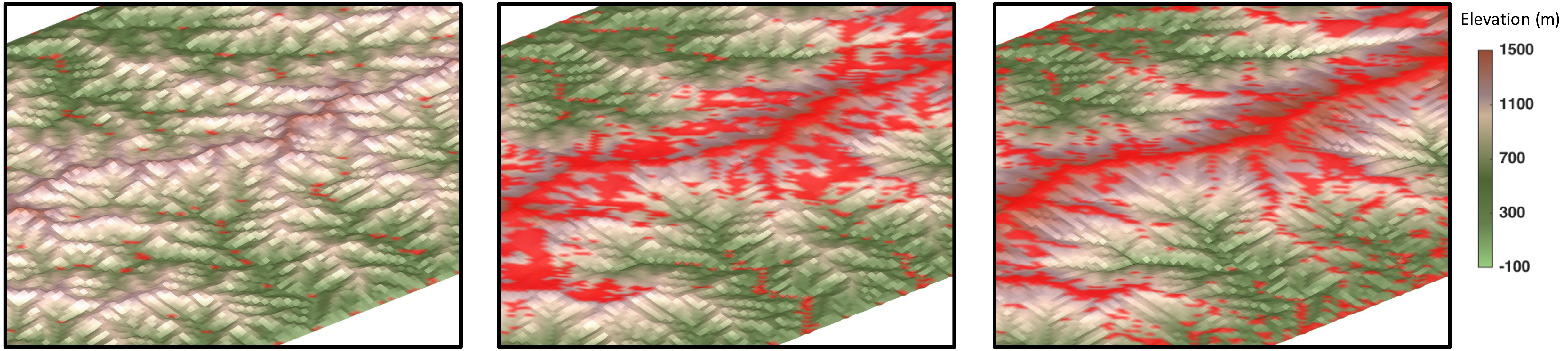




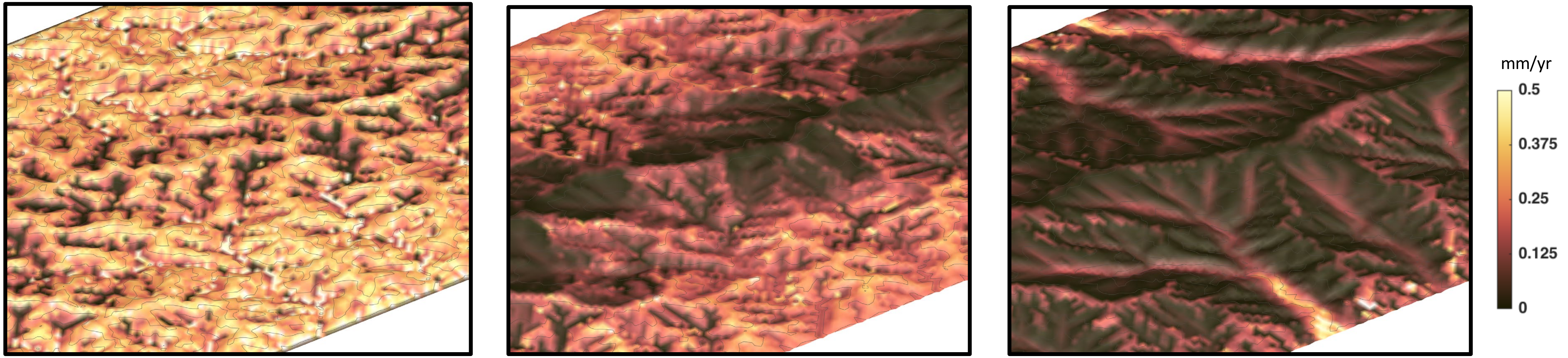


Time evolution of low-relief surfaces

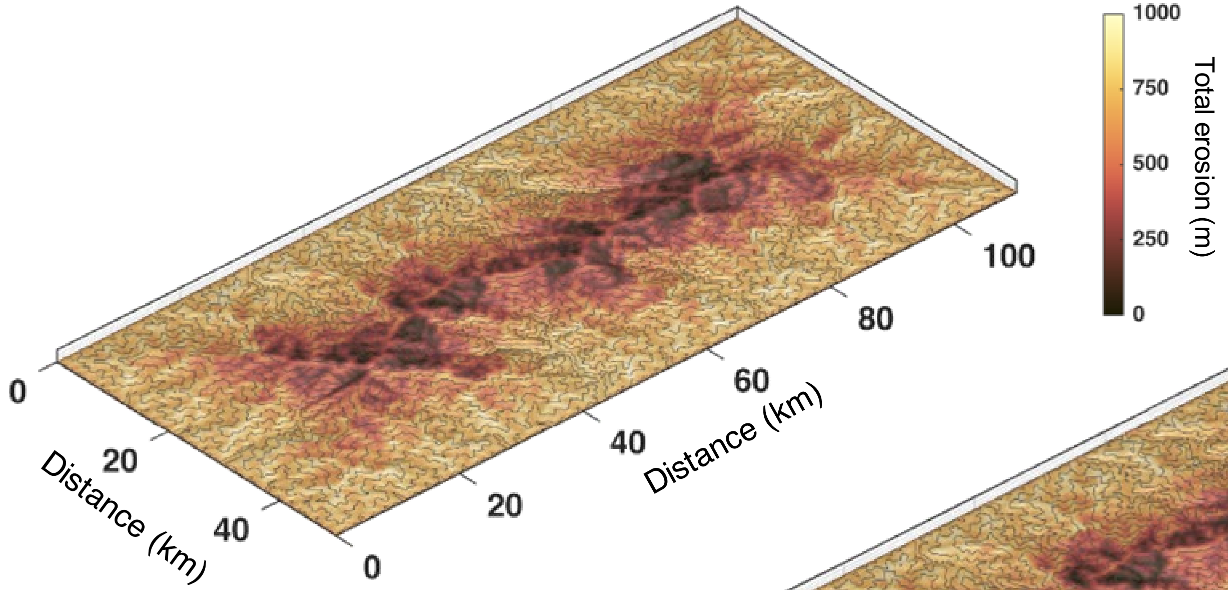
Time = 0.04 Myr | Time = 1.7 Myr | Time = 3 Myr

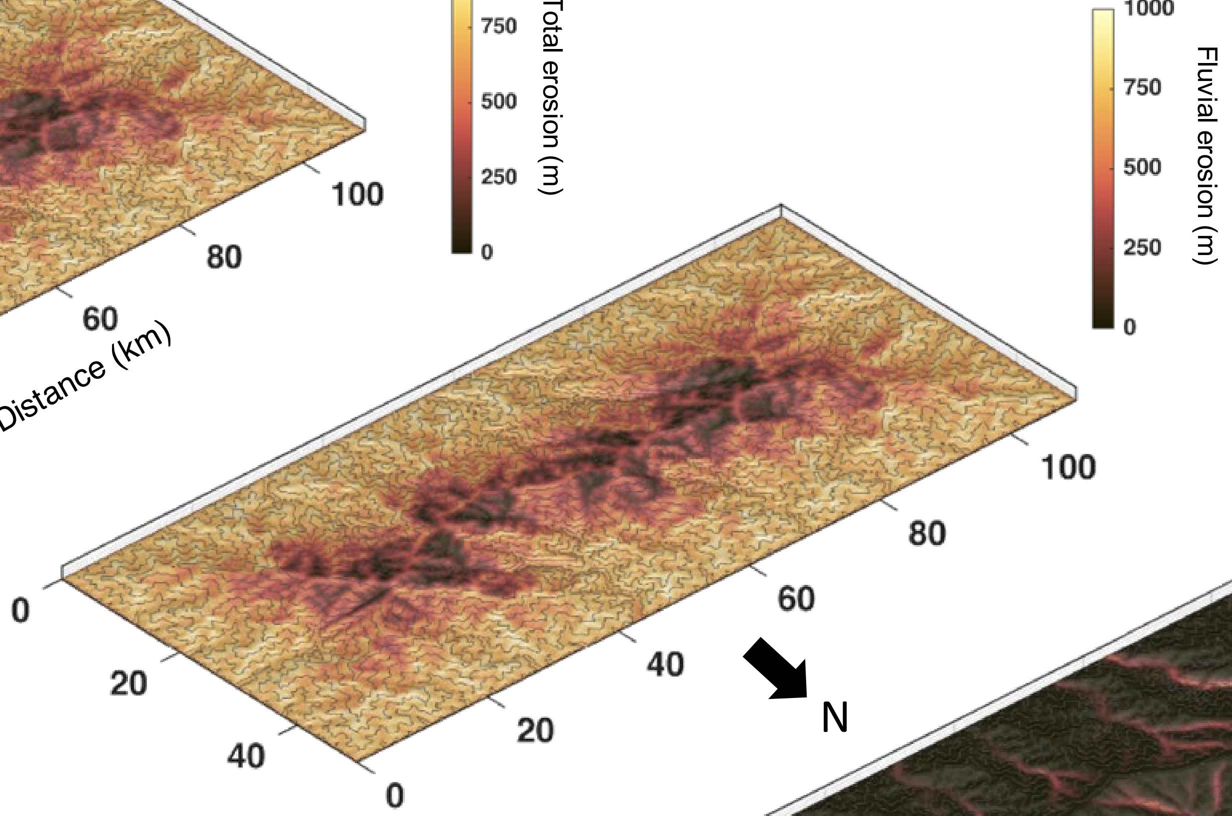


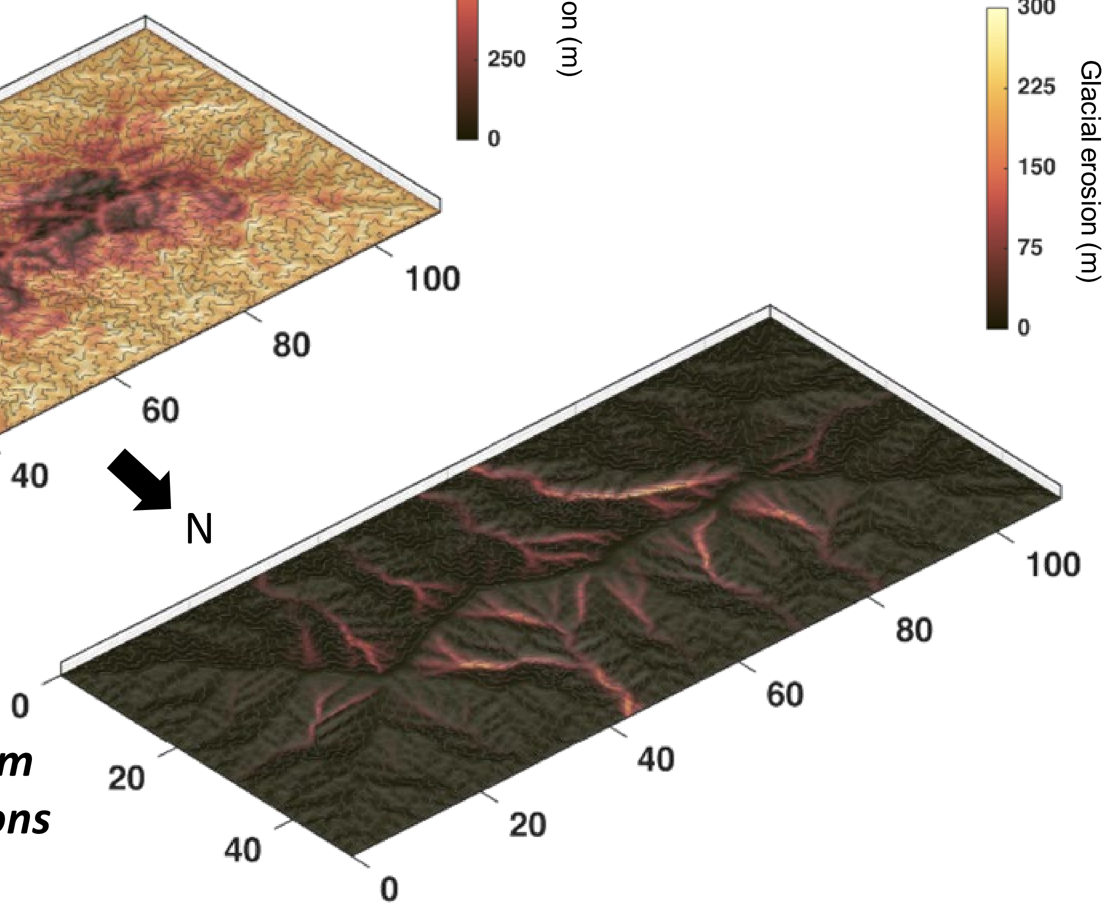
Instantaneous erosion rates

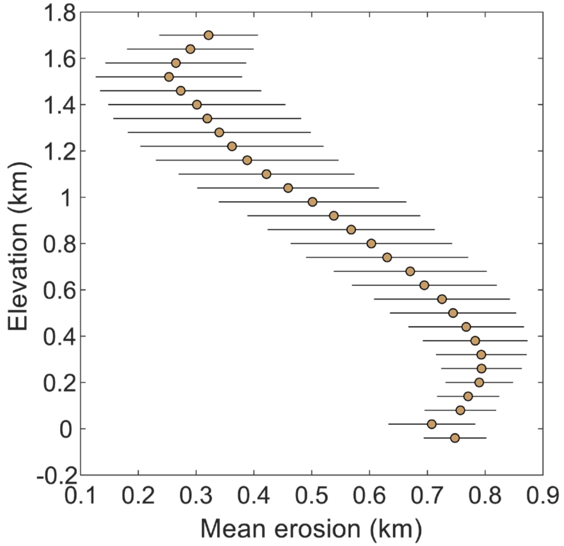


The ice contribution to low-relief surfaces production



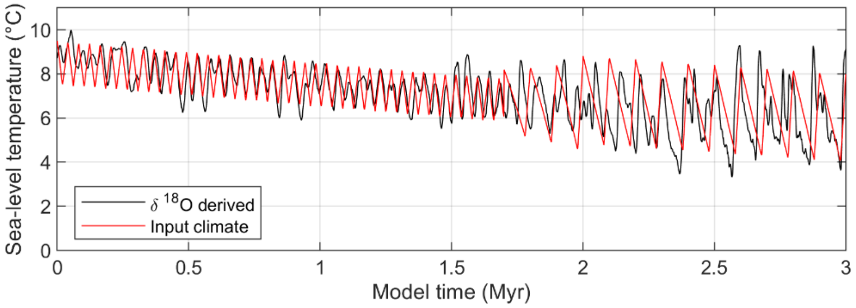




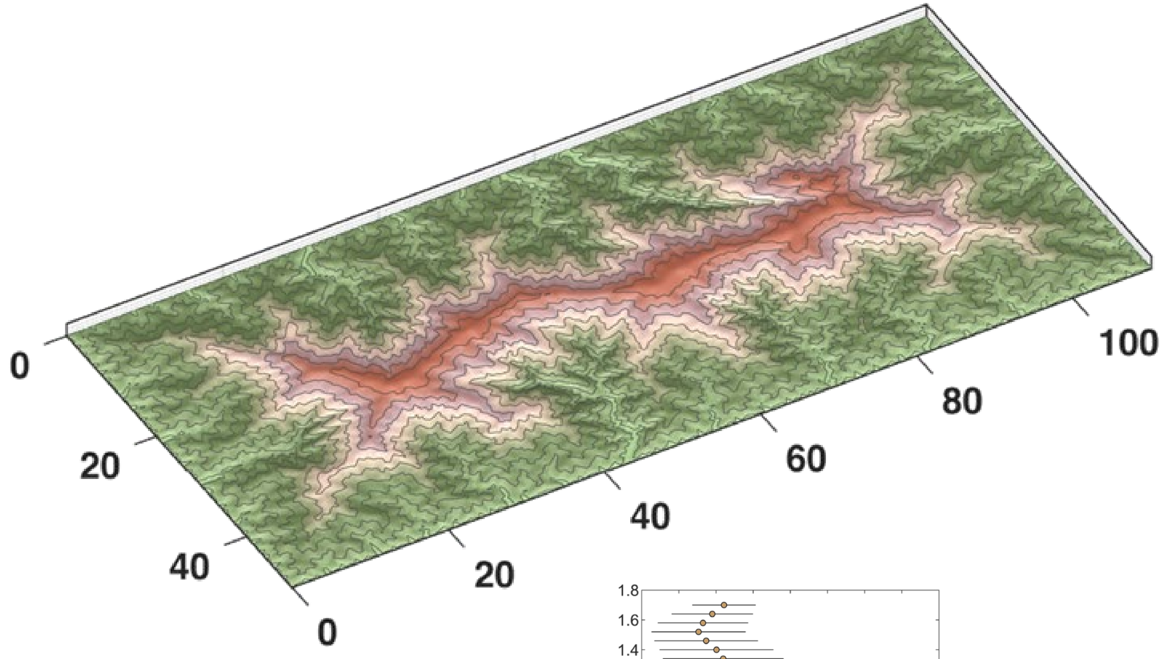


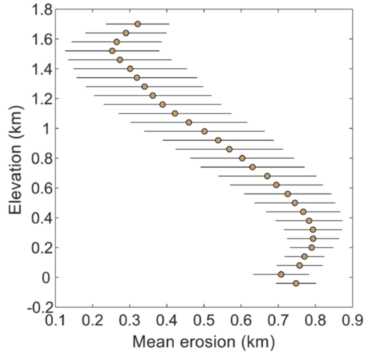
The ice protects the bedrock from erosion at intermediate elevations

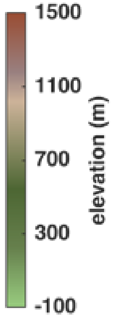
The ice contribution to low-relief surfaces production



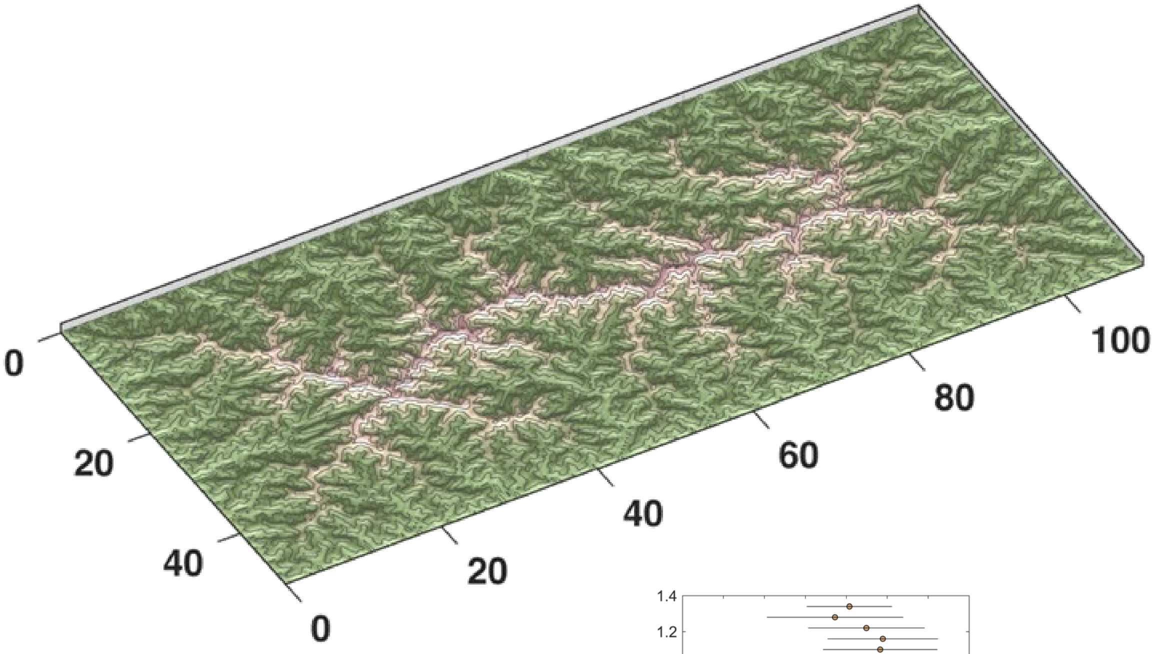
Ice allowed

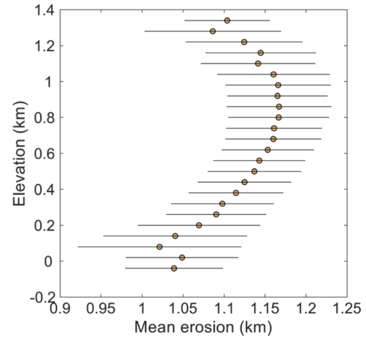






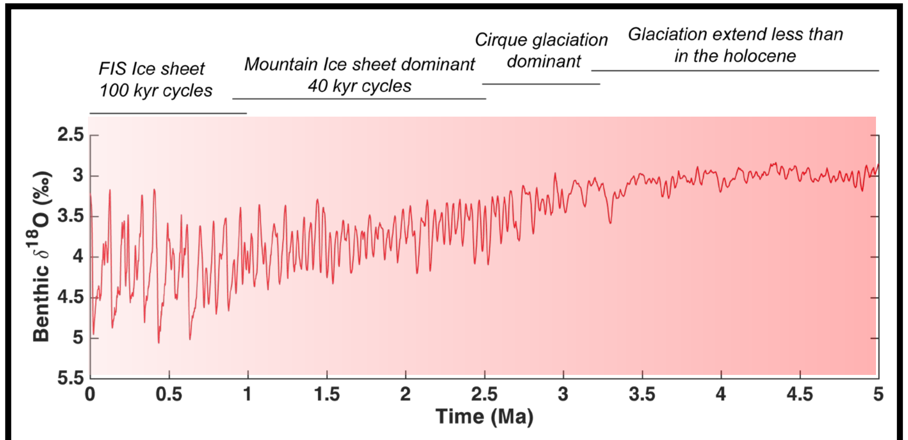
No ice allowed



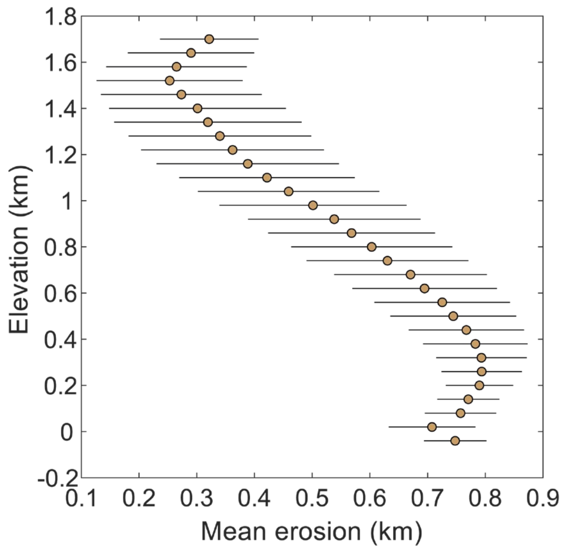


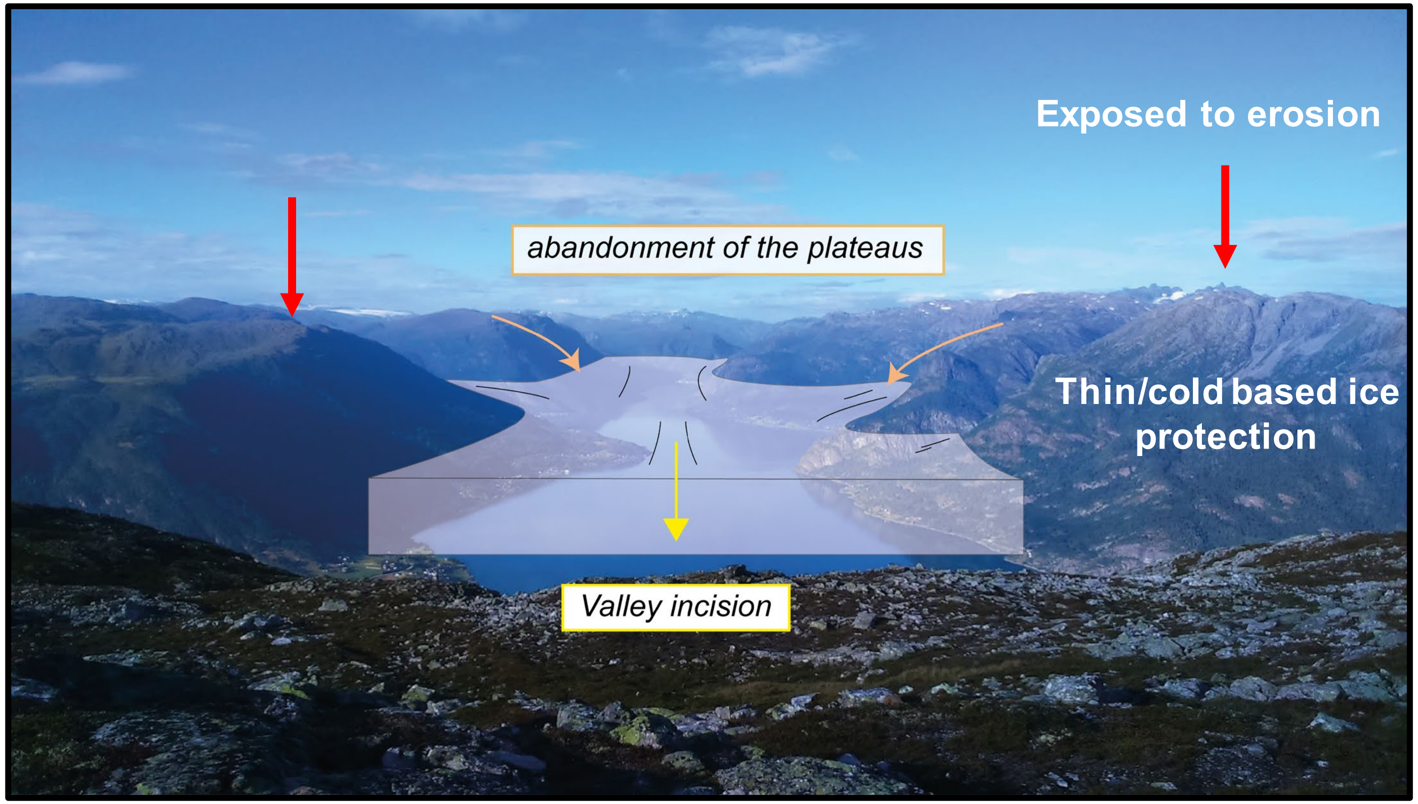
Insights on selective linear erosion

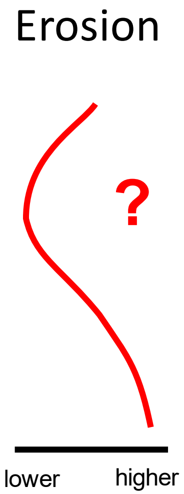
- The thin cold-based ice can protect intermediate elevations from erosion
- The summit elevations above the ice are eroded, then producing low-relief surfaces



Redrawn from Hall et al. (2003)







Credit: Maxime Bernard

Model framework: erosion functions

- Glacial erosion: $\dot{E}_g = k_g U$

  U : basal sliding speed, kg = 10^{-5}

- Fluvial erosion: $\dot{E}_f = k_f f(Q_s) {q_w}^m S^n$, $f(Q_s) = 4\left[\frac{Q_s}{Q_c} - \left(\frac{Q_s}{Q_c}\right)^2\right]$ (Whipple and Tucker, 2002)

  Qs : sediment discharge, Qc: transport capacity, qw: water discharge, S: bed slope, kf = $0.6.10^{-4} m^{-0.5}$

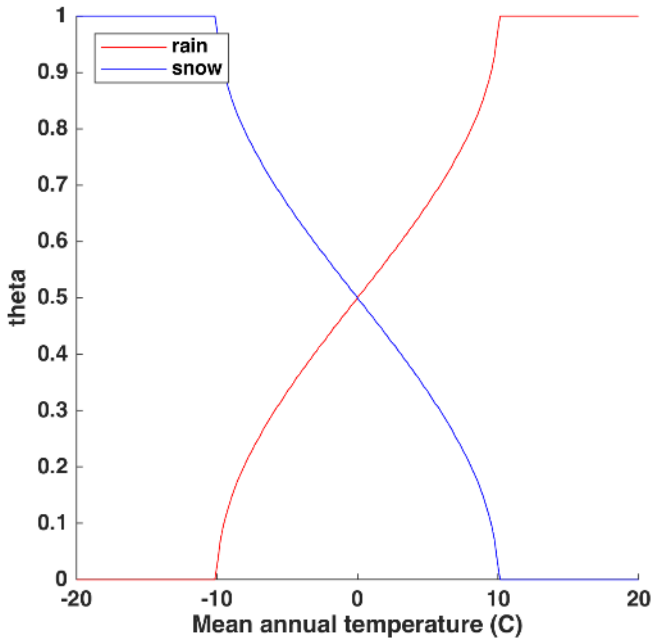
- Hillslope erosion: $\dot{E}_h = \frac{k_h S}{1 - (\frac{S}{S_c})^2}$ (Roering et al, 1999)

  Sc : critical slope

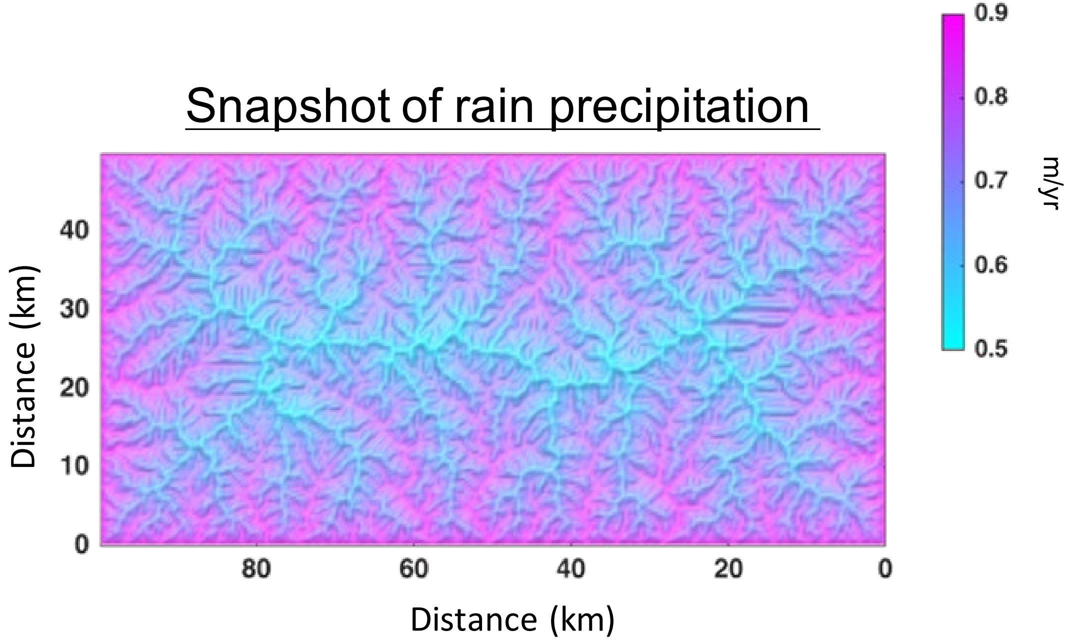
Model framework: Precipitation function

- Precipitation phase f(T°)
- PDD algorithm: $T = T_0 + dT_a * \sin(\frac{2\pi t}{365})$
- Rain fraction: $\theta = \frac{N_{T>0}}{365}$

  $N_{T>0}$: number of days > 0 °C
- Snow fraction = $1 - \theta$

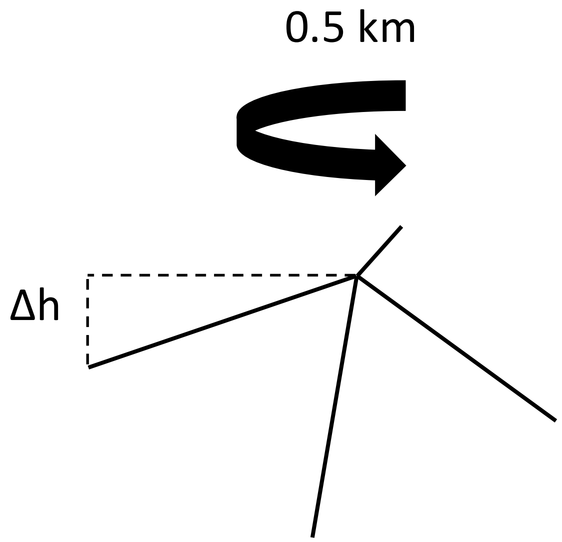


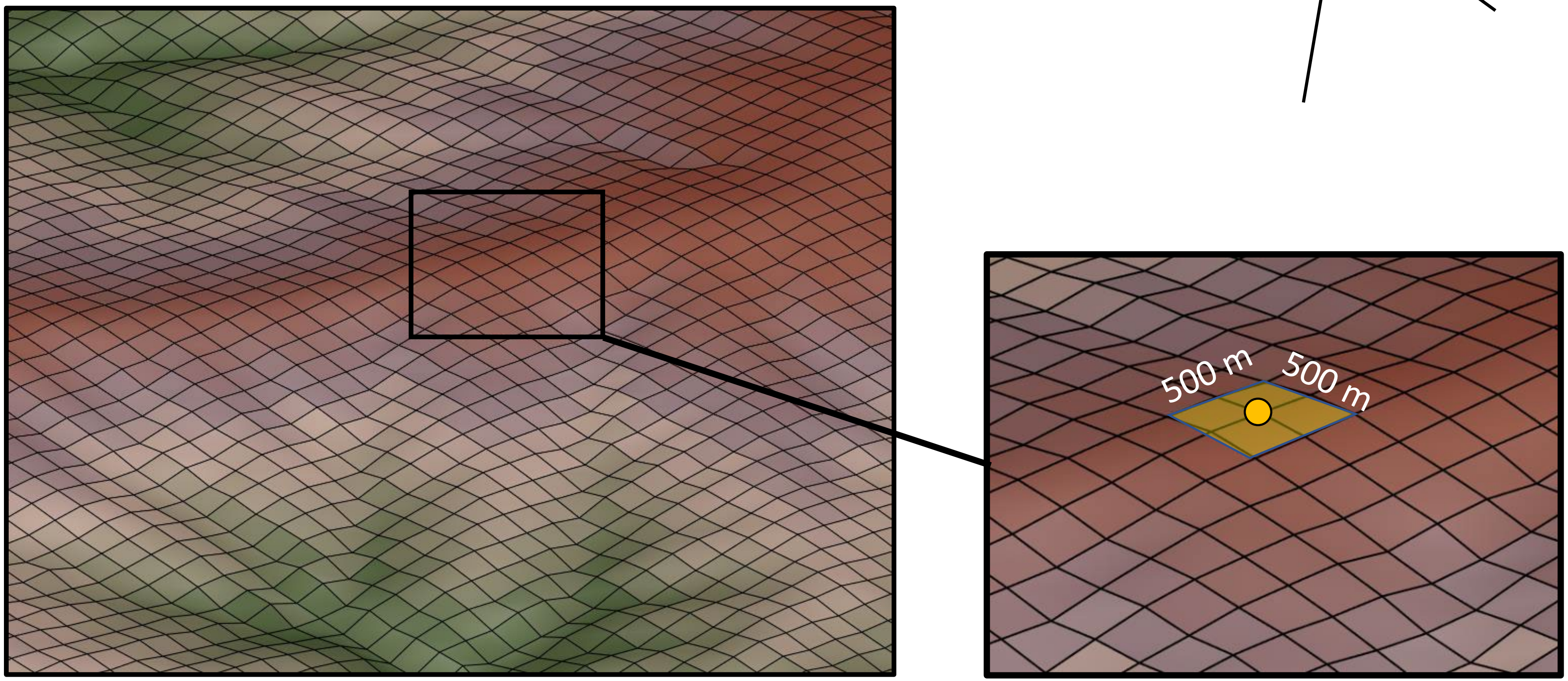
Snapshot of rain precipitation



Low-relief surfaces

Model definition: $bed\ slope < 10° \ and\ \Delta h < 200\ m$

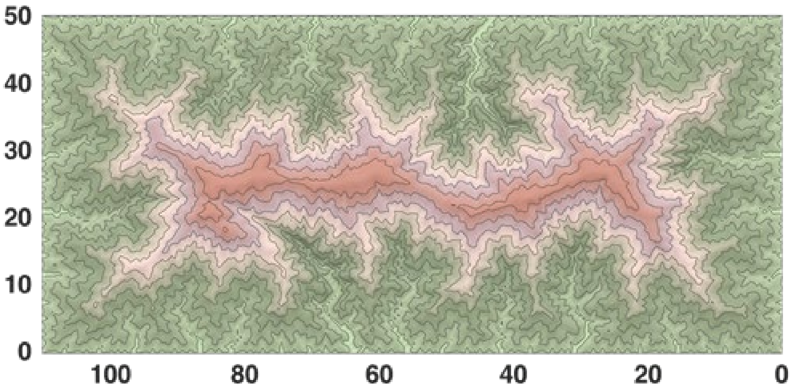


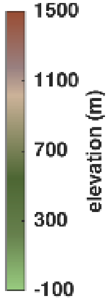


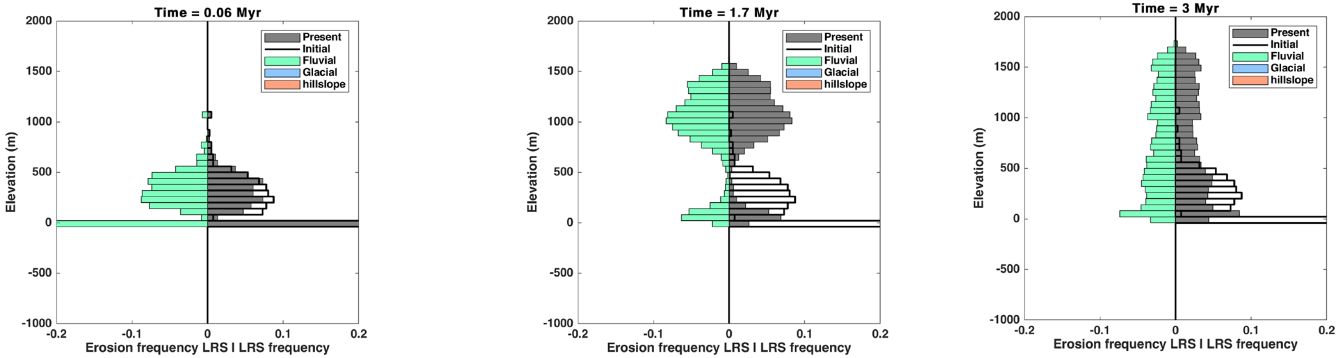
The ice contribution to low-relief surfaces production

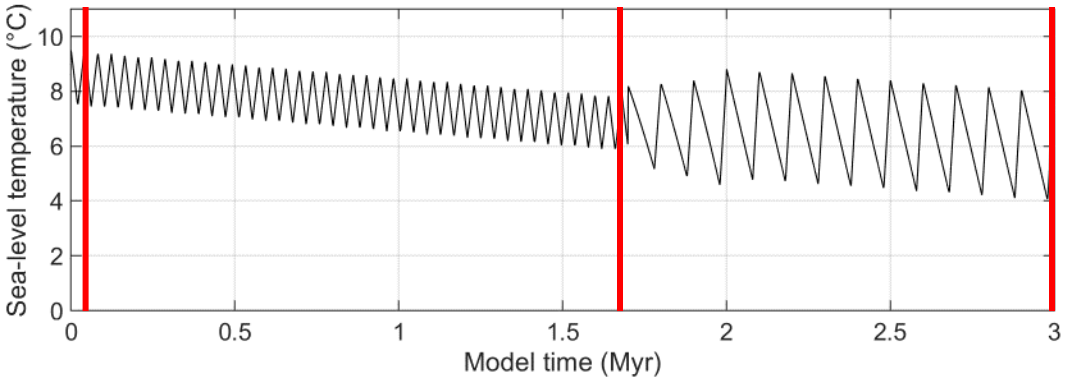
3 Myrs glaciations

With ice

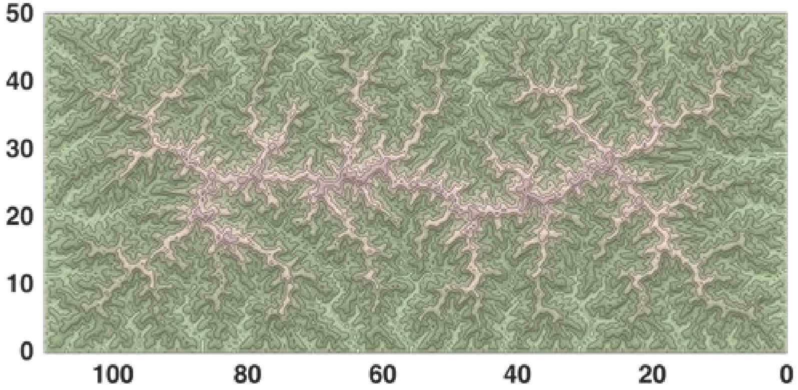


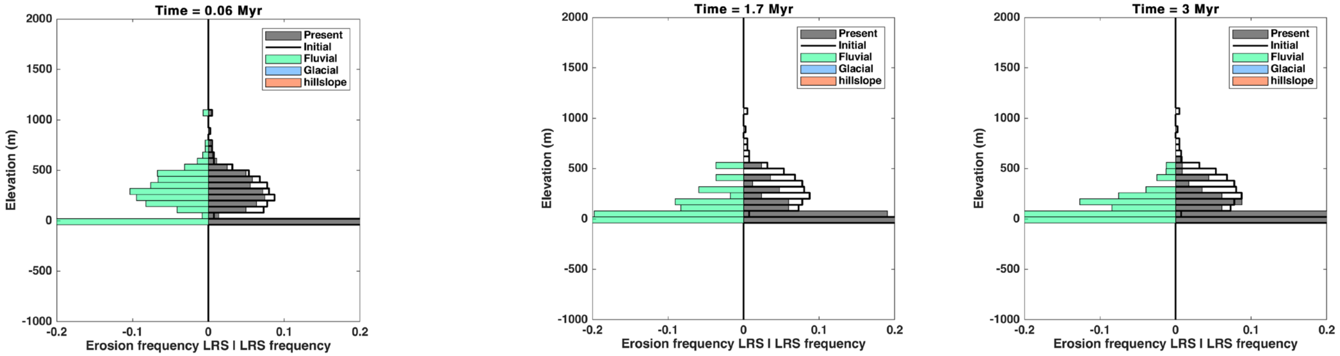






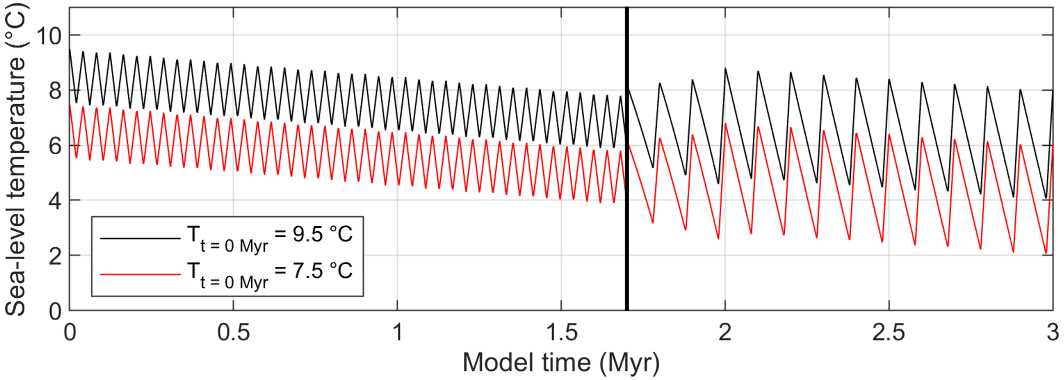
No ice allowed

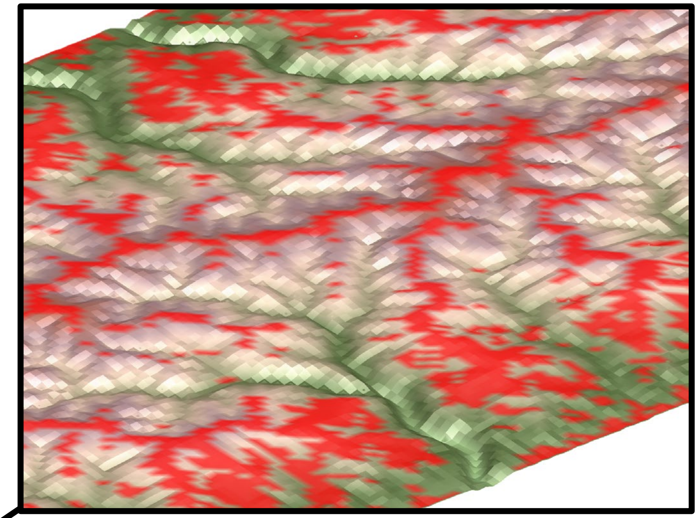


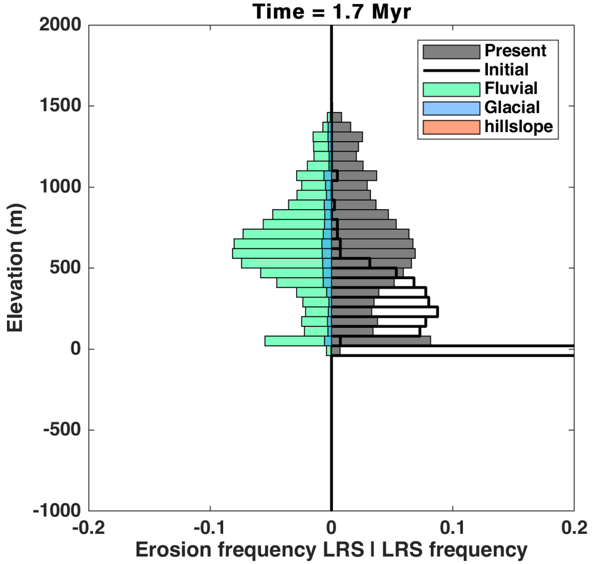


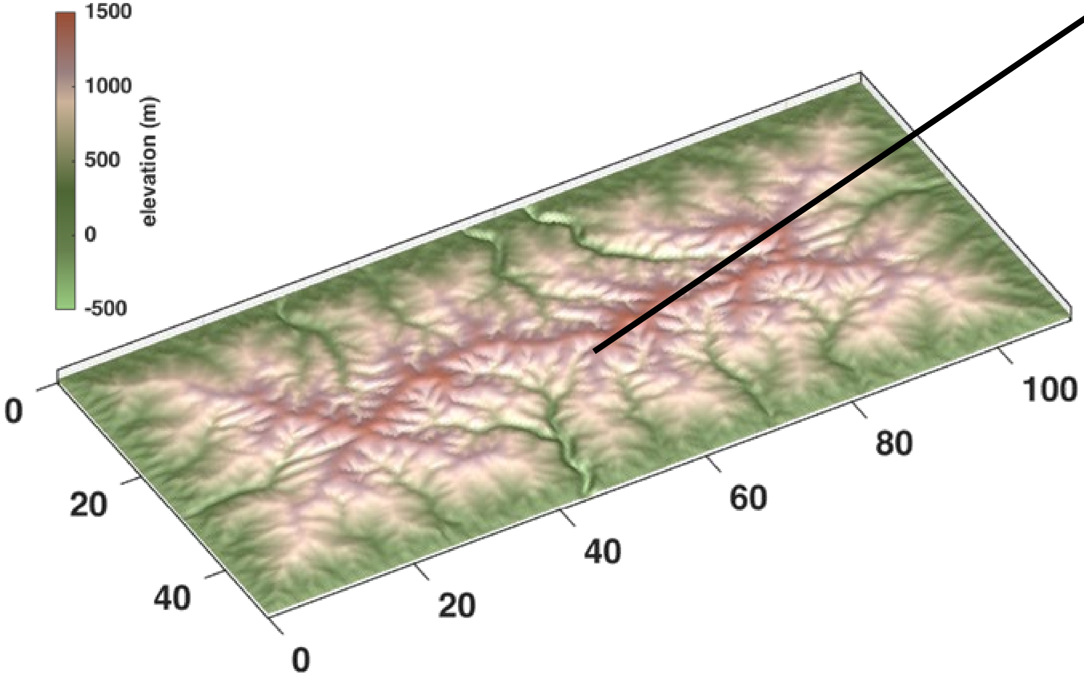
Cooler climate scenario

Glacial erosion law: $E_g = kU$



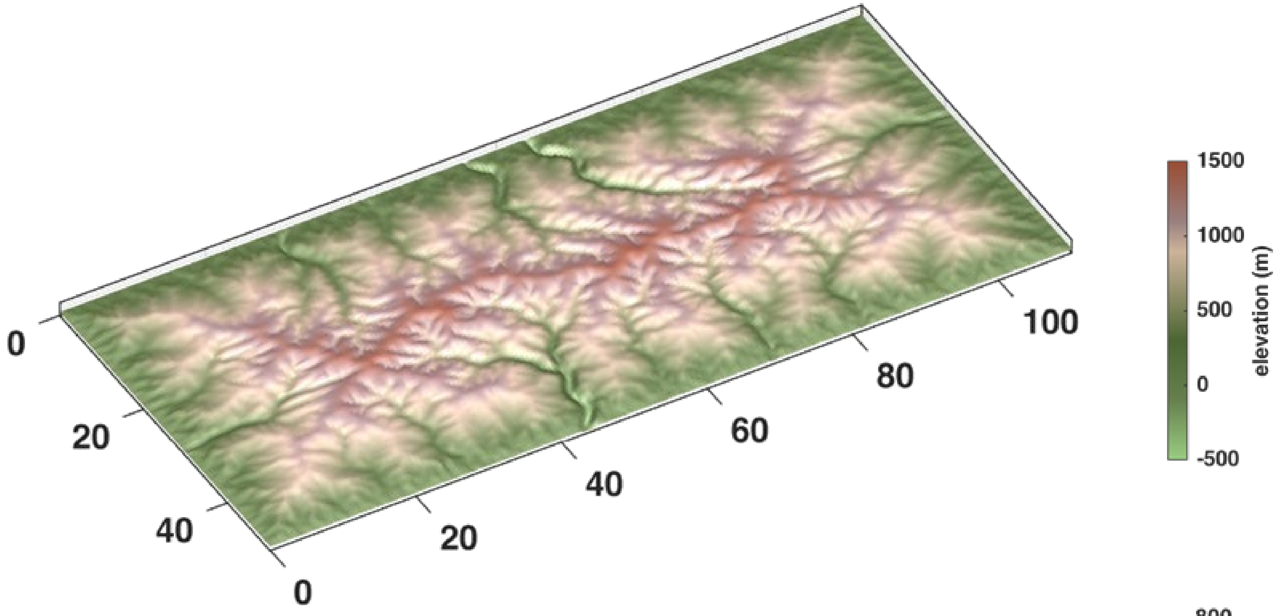


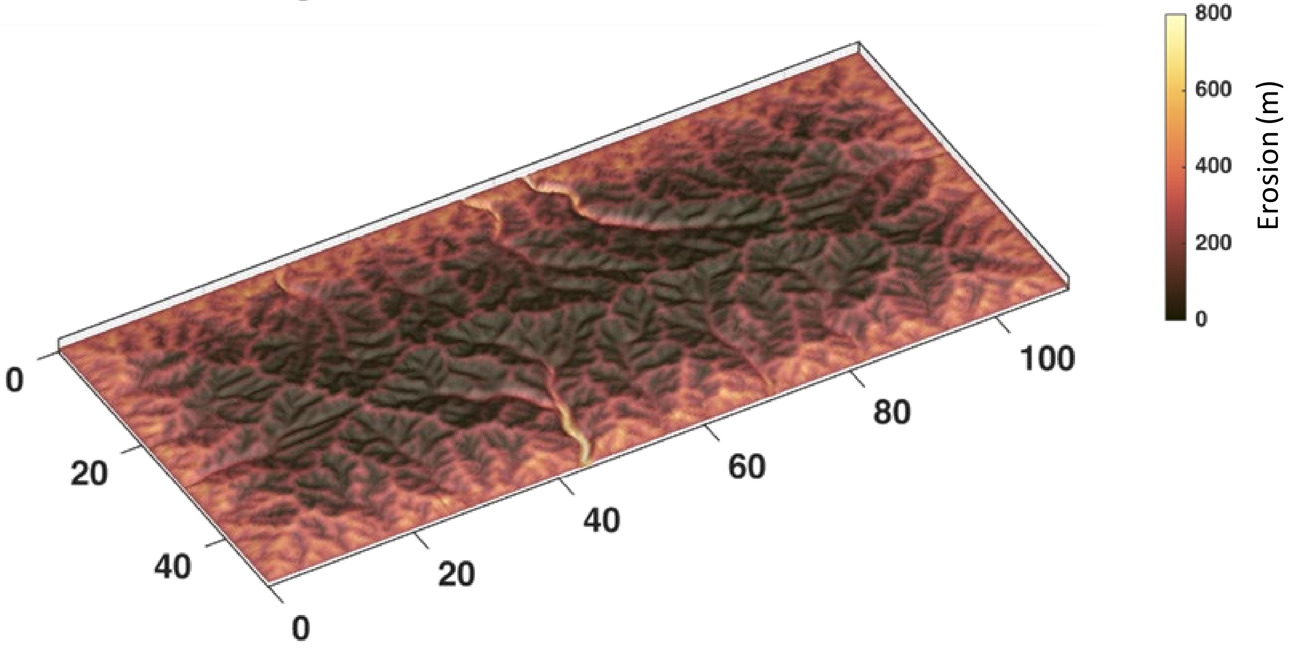


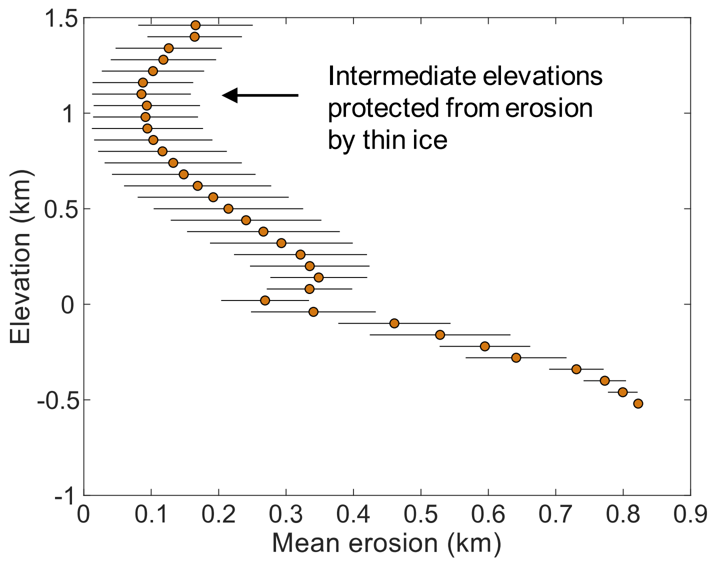


- Formation of low-relief surfaces + deeply incised glacial valleys similar to fjords
- Glacial erosion participates more significantly to produce low-relief surfaces because of significant ice volume

Cooler climate scenario

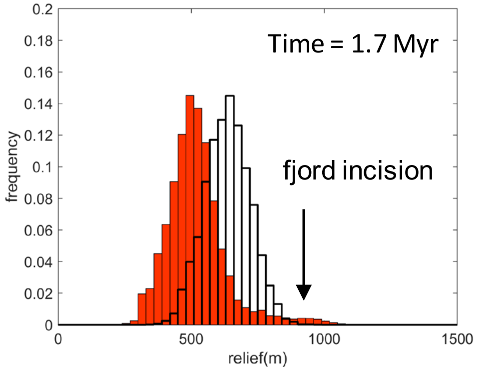




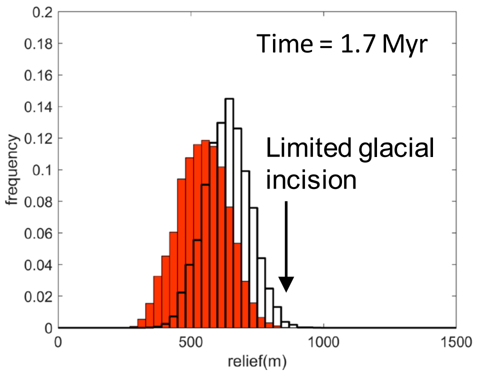


Relief frequency distribution (radius = 2km)

$T_{t = 0\ Myr} = 7.5°C$



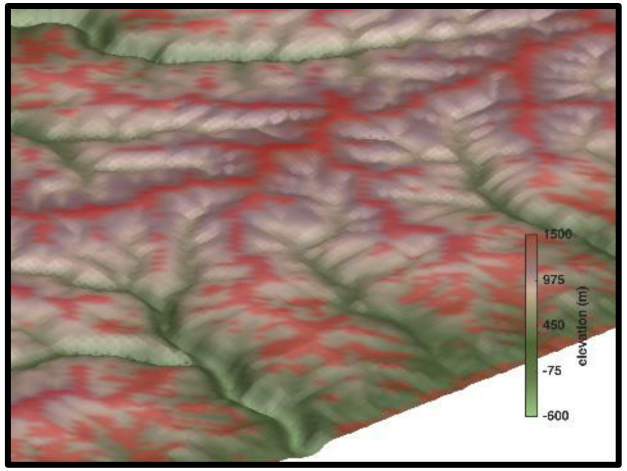
$T_{t = 0\ Myr} = 9.5°C$



Comparison to low-relief surfaces (LRS) Norway

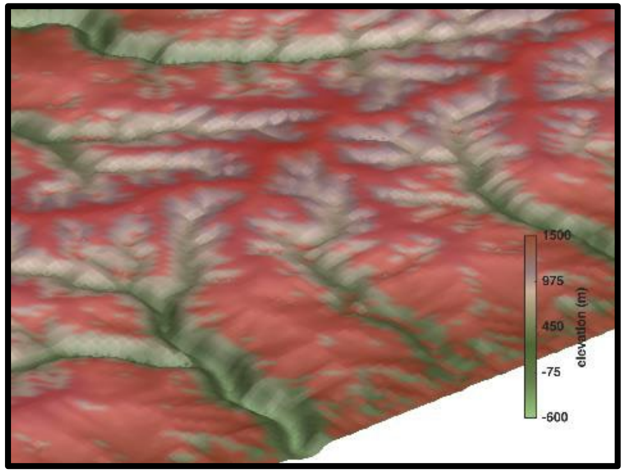
Bed slope < 10 ° and Relief = 200 m

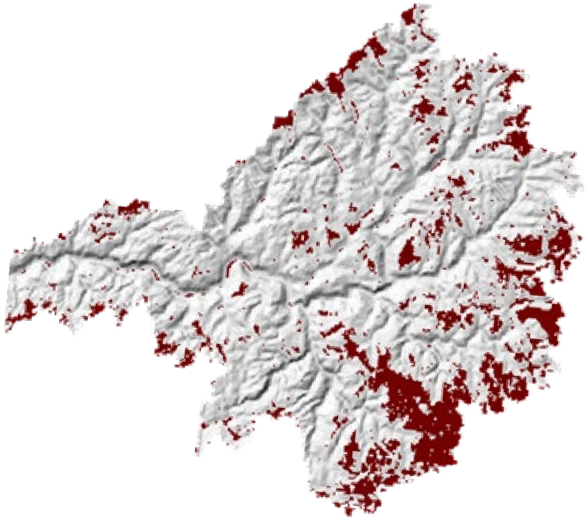
Bed slope < 10 ° and Relief = 300 m

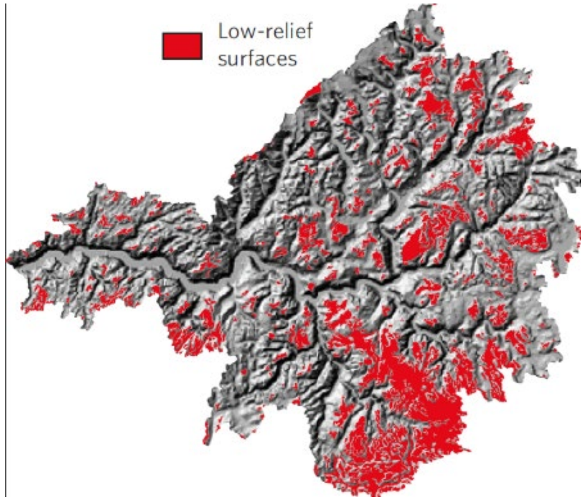


From Steer et al. (2012):

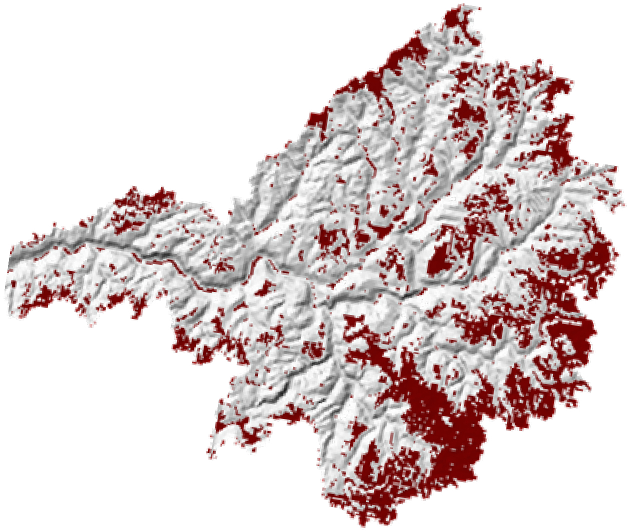
LRS < 10° and 0.2 km²







Steer et al. (2012)



iSOSIA – limitation

- Depth-integrated version of the second-order shallow ice approximation
- Continuity equation: $\frac{\partial H}{\partial t} = -\nabla.(H\bar{u}) + M$

H: ice thickness, M: ice source, $\bar{u}$: depth-averaged ice velocity vector

- $\bar{u}$ approximated by a 10th order polynomials of H (Egholm et al., 2011):

$$\bar{u} = \sum_{p=10}^{10} w_p(\nabla h, \nabla^2 h, \nabla b, u, u_s)H^p + u_b$$

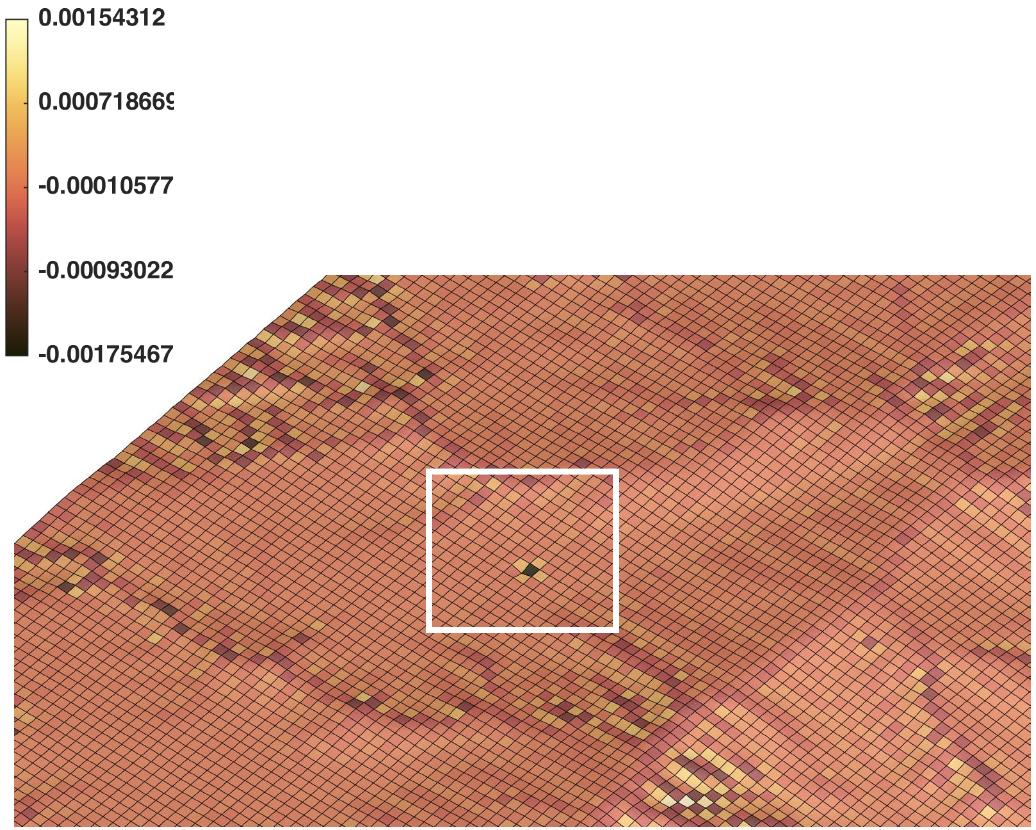
➢ **Sensitive to bed (∇b), ice surface slopes (∇h) and ice surface curvature ($\nabla^2 h$) !**

- Solve the equation by numerical relaxation and nested iteration for stresses and ice deformation velocity (Egholm et al., 2011). Residuals must be below < 10^{-3} to maintain accuracy and to limit divergence.

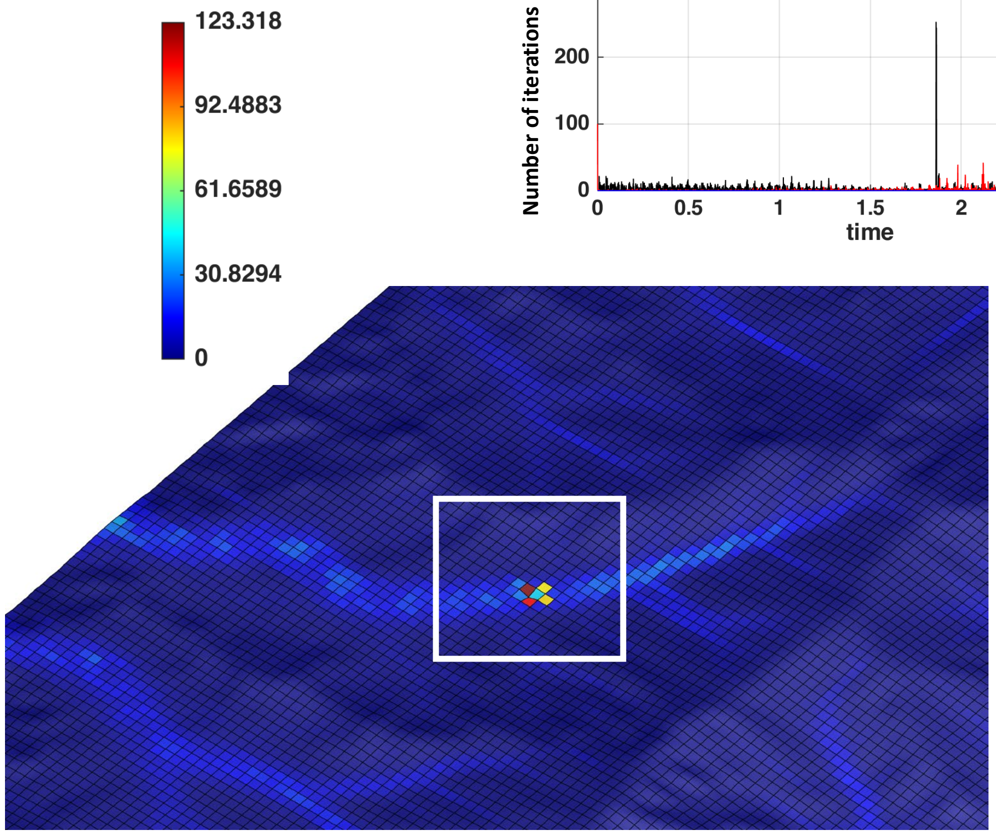
iSOSIA – limitation

- An example: Divergence for locally high ice curvature

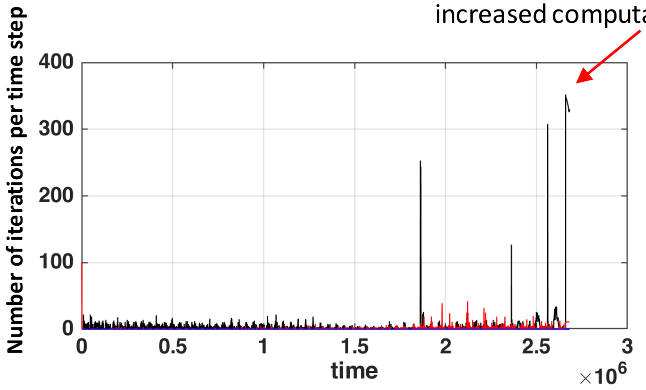
Ice surface curvature



Ice deformation rate (m/yr)



Long convergence = increased computation time



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