Parameterizing Surface Processes and their Response to Tectonic and Climatic Forcings

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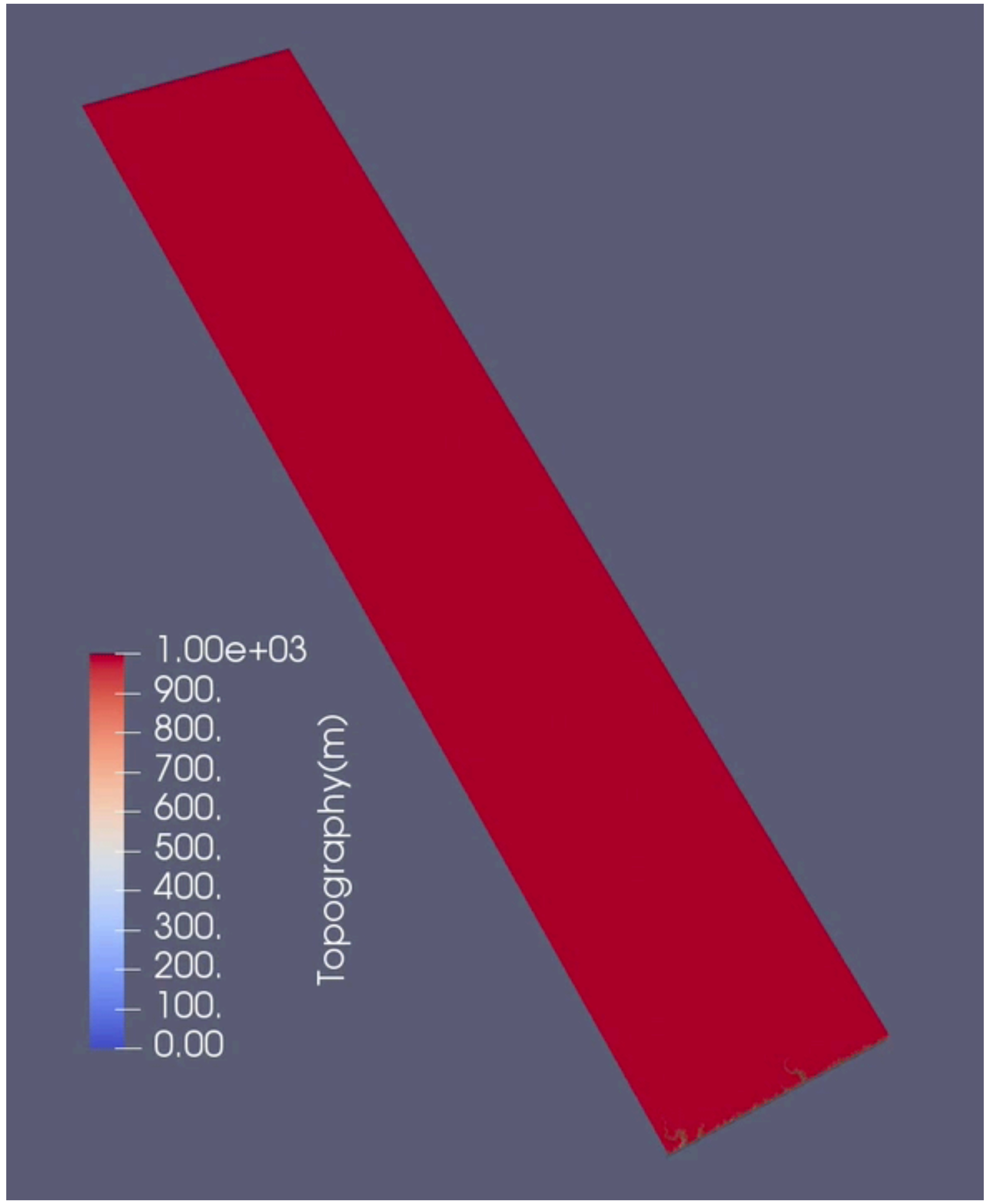
Introduction

- Coupling surface processes (models) to geodynamics (models)
- Present basic parameterization of surface processes
- Assuming that they are a fair/usable representation of the natural world, derive consequences/behaviour that are relevant to coupling between tectonics, erosion and climate (and life?)

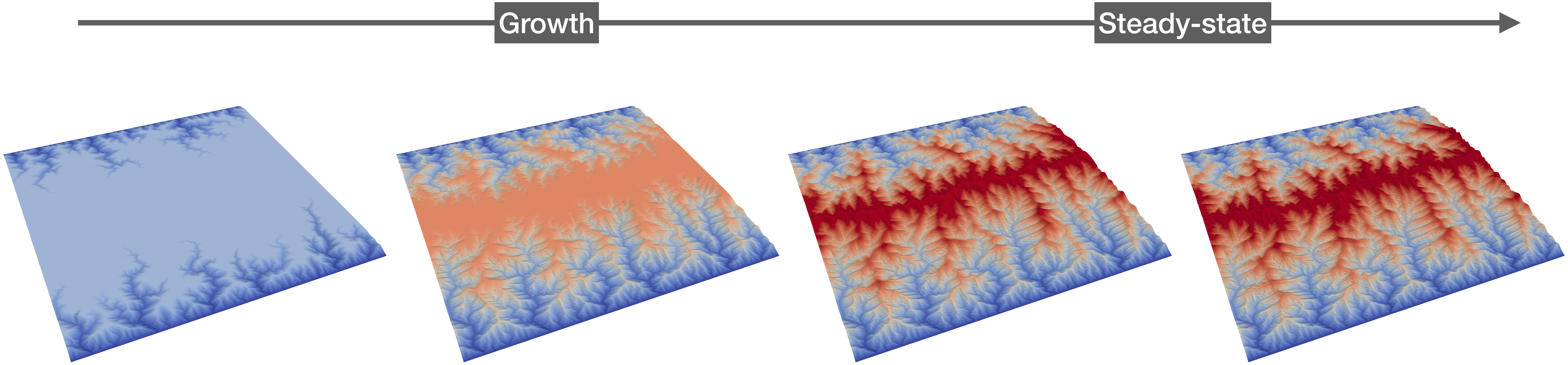


1. Response of surface processes to tectonic forcing

Orogenic cycle

Howard, 1984

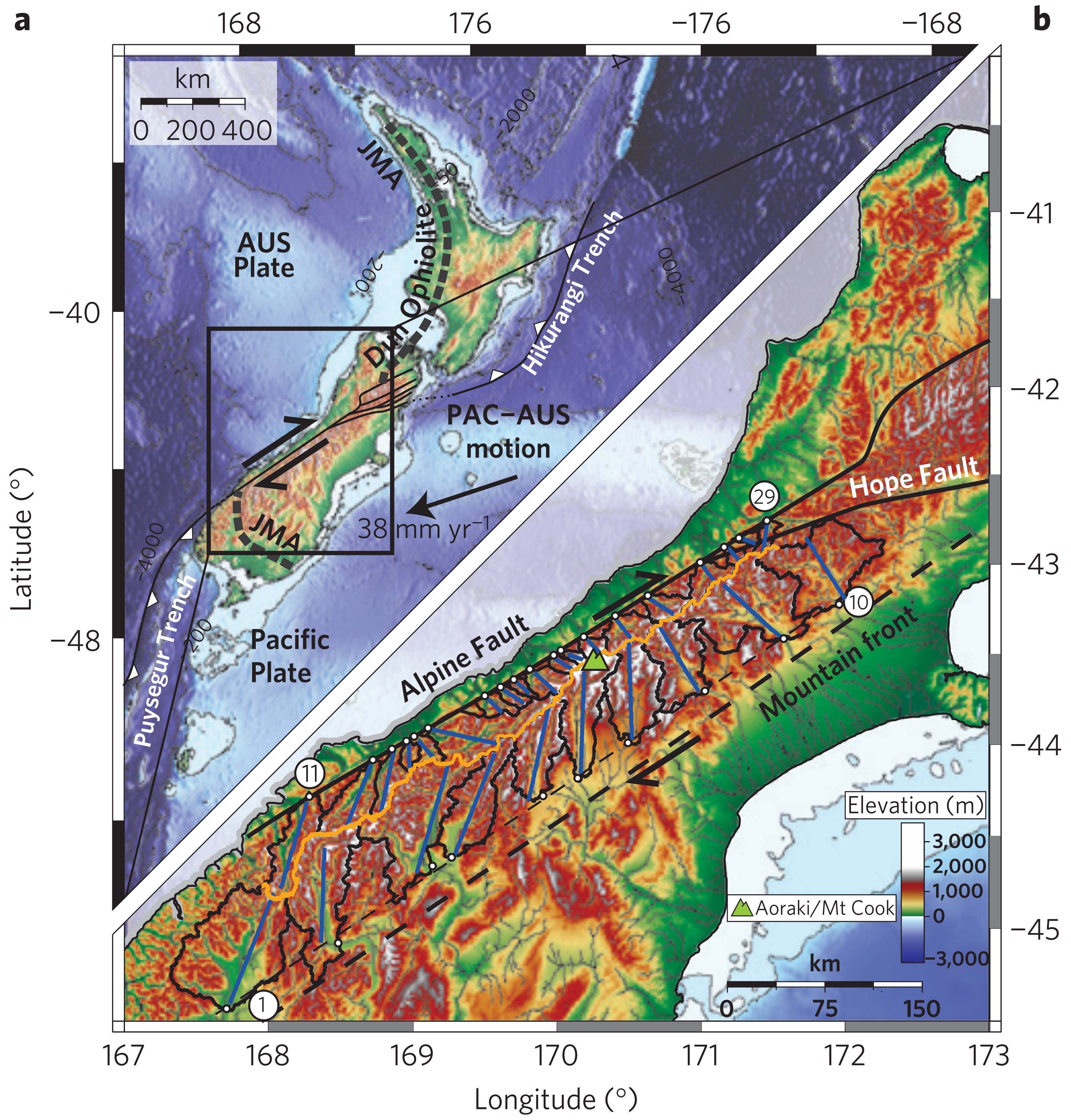
Jamieson and Beaumont, 1988



Orogenic cycle

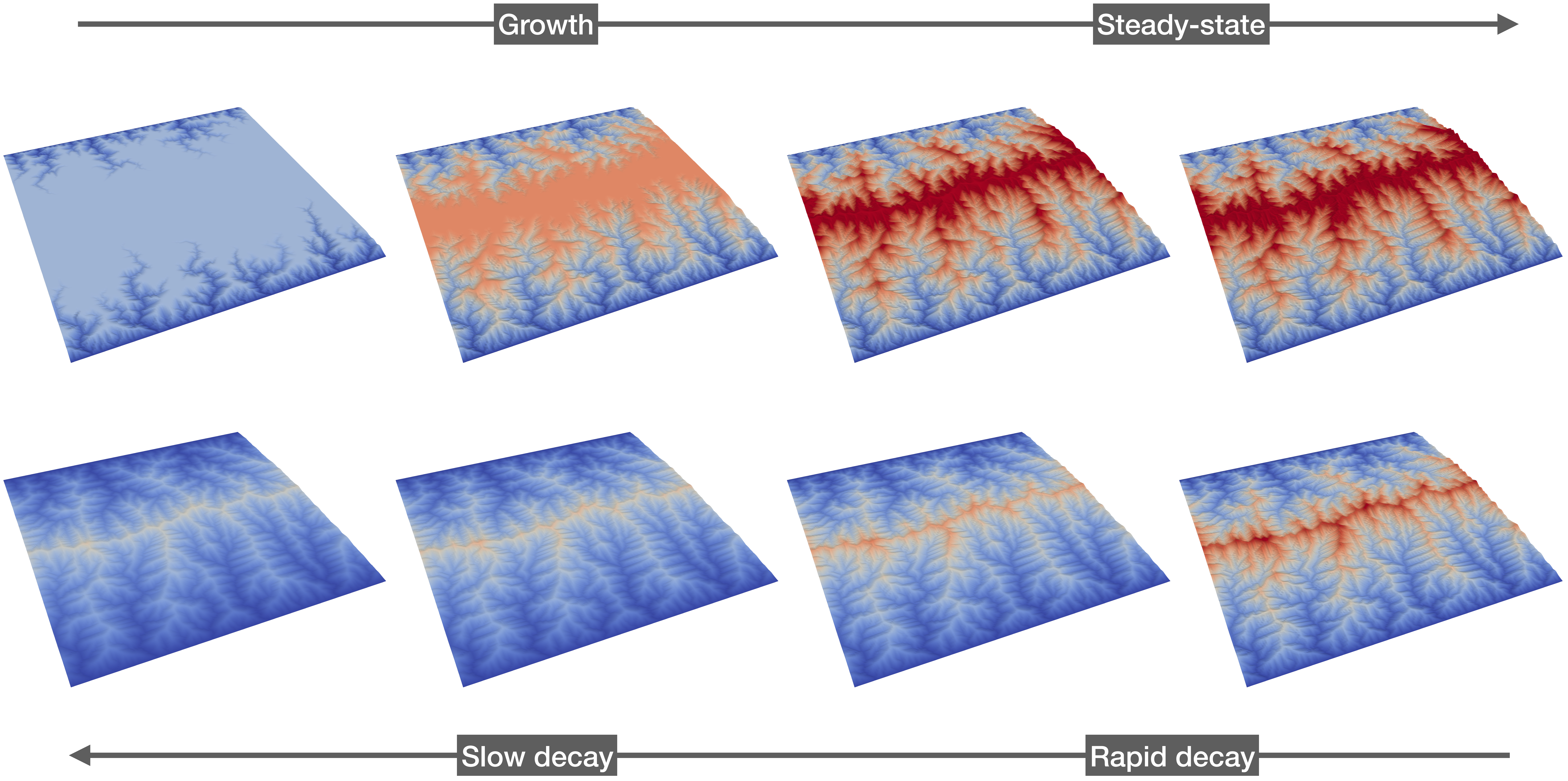
An orogen in "steady-state"

Southern Alps, New Zealand

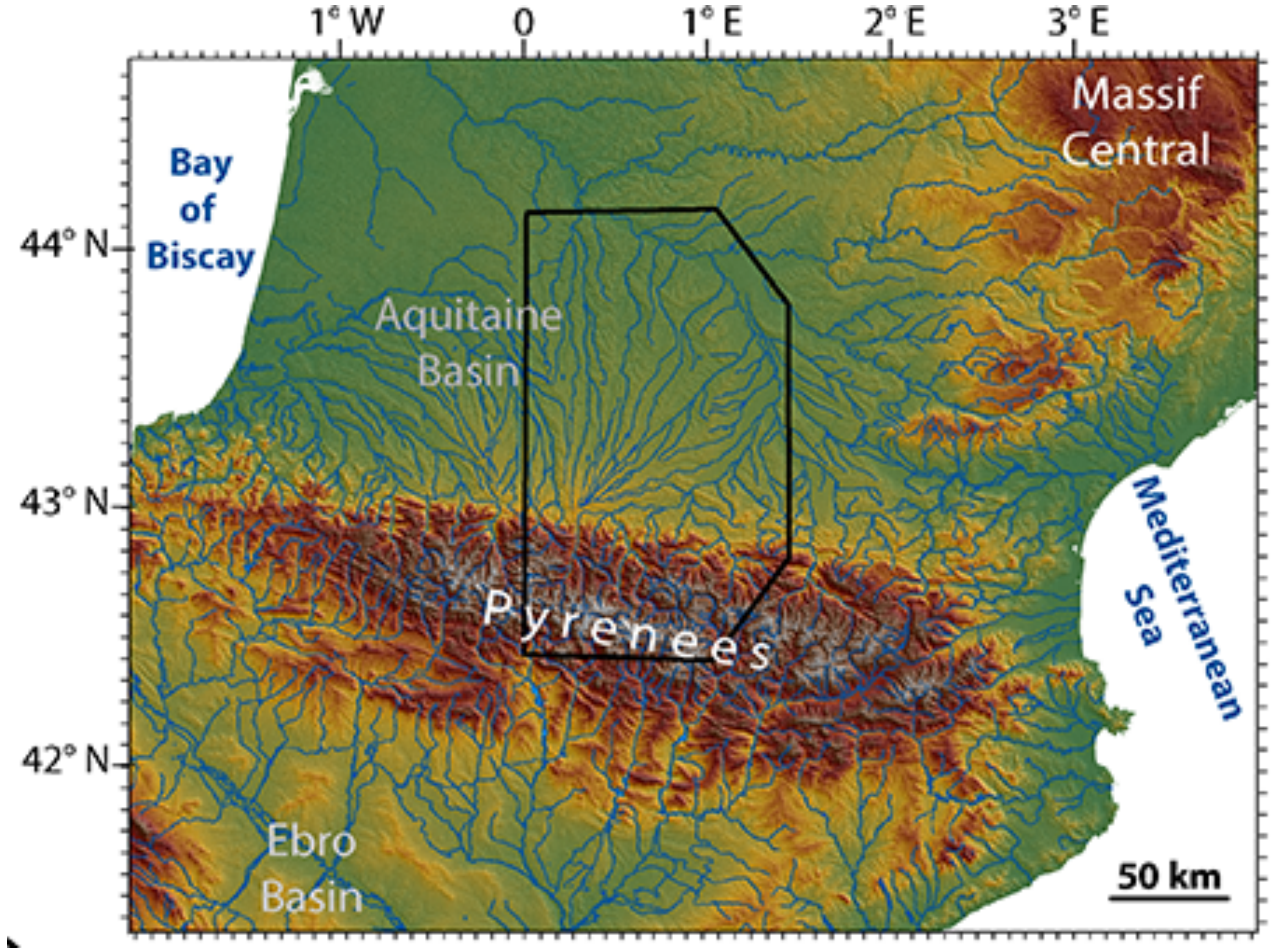


Castelltort et al, 2012

Orogenic cycle



Orogenic cycle



Mouchene et al, 2017

A decaying orogen

The Pyrenees

Orogenic cycle

An orogen in “steady-state”

Southern Alps, New Zealand

A decaying orogen

The Pyrenees

The Stream Power Law

Rate of topographic change — Uplift rate — Drainage area

$$\frac{\partial h}{\partial t} = U - K' A^m S^n = U - K P^m A^m S^n$$

Precipitation rate — Slope

Howard and Dietrich, 1994

Response time

$$\tau = \frac{h_0}{\rho' U}$$

Steady-state height

$$h_0 = \frac{U^{1/n} L^{1-mp/n}}{K^{1/n} P^{m/n} k^{m/n} (1 - mp/n)}$$

Isostatic rebound per unit erosion

Ahnert, 1977

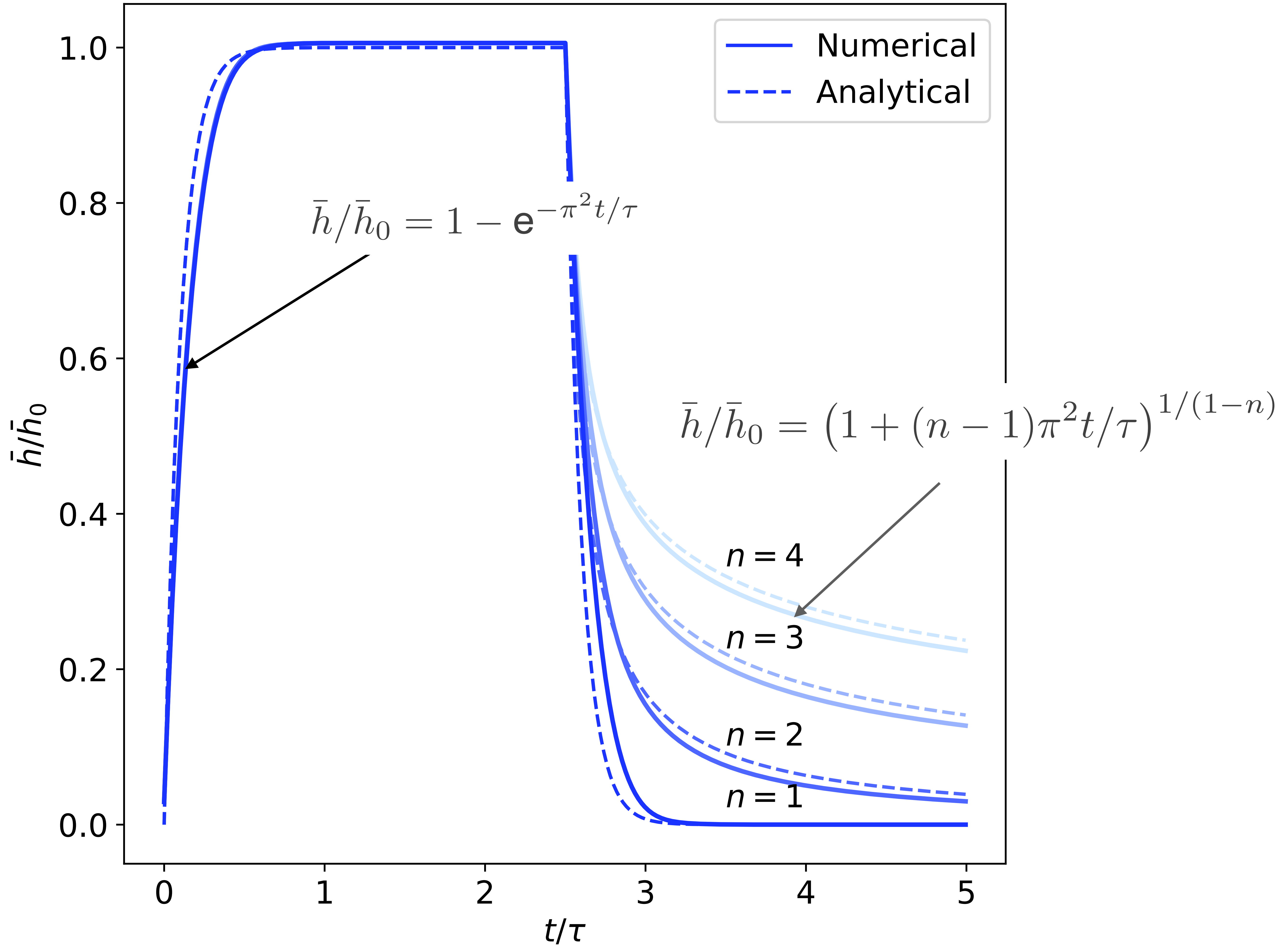
$$\rho' = \frac{\partial h}{\partial e} = 1 - \frac{\rho_s}{\rho_a + \frac{D}{g}\left(\frac{\pi}{2L}\right)^4}$$

Hack's Law

$$A = k(L - x)^p$$

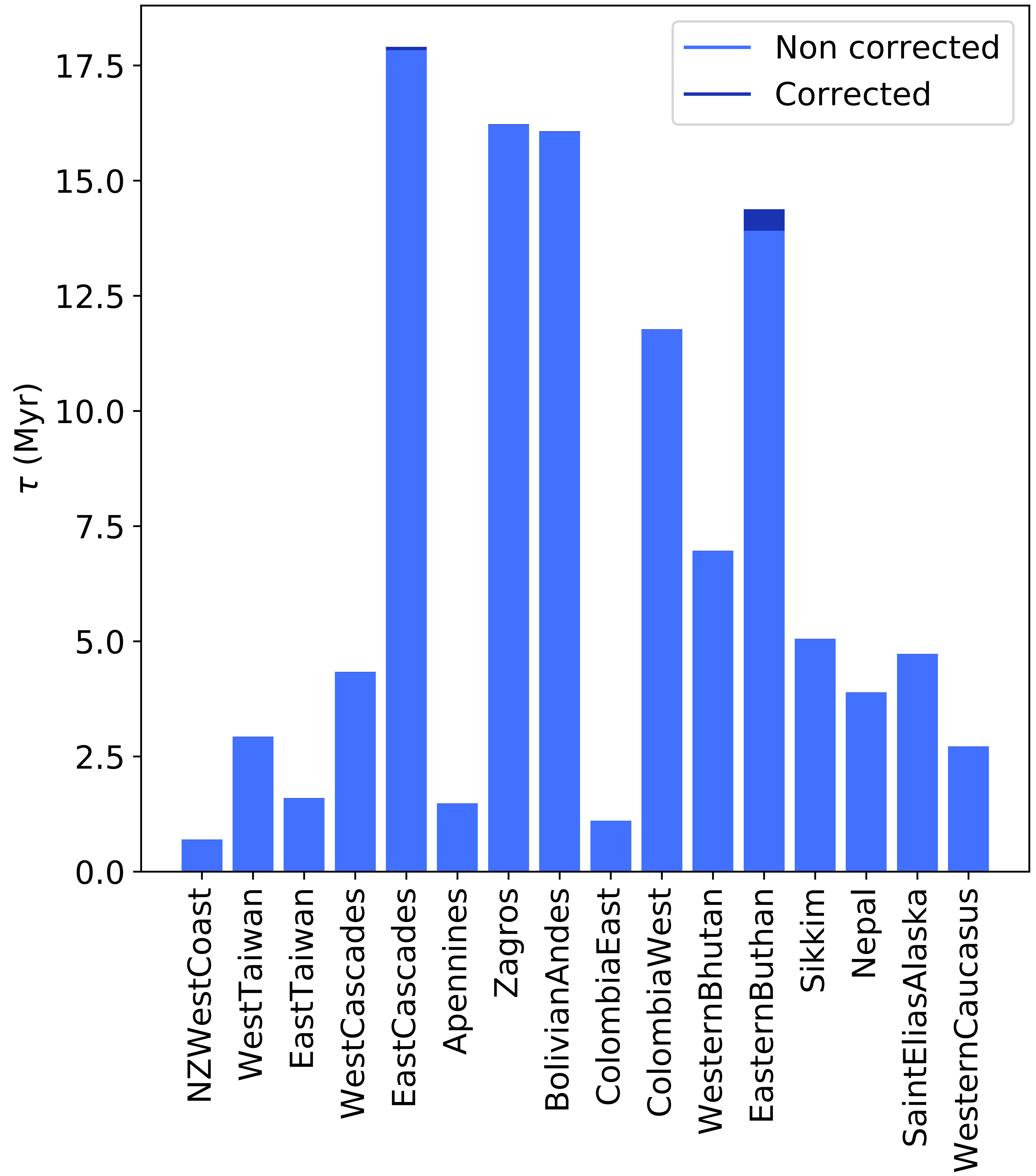
Mean topography

$$\bar{h}_0 = h_0 \frac{3n - mp}{2n - mp}$$



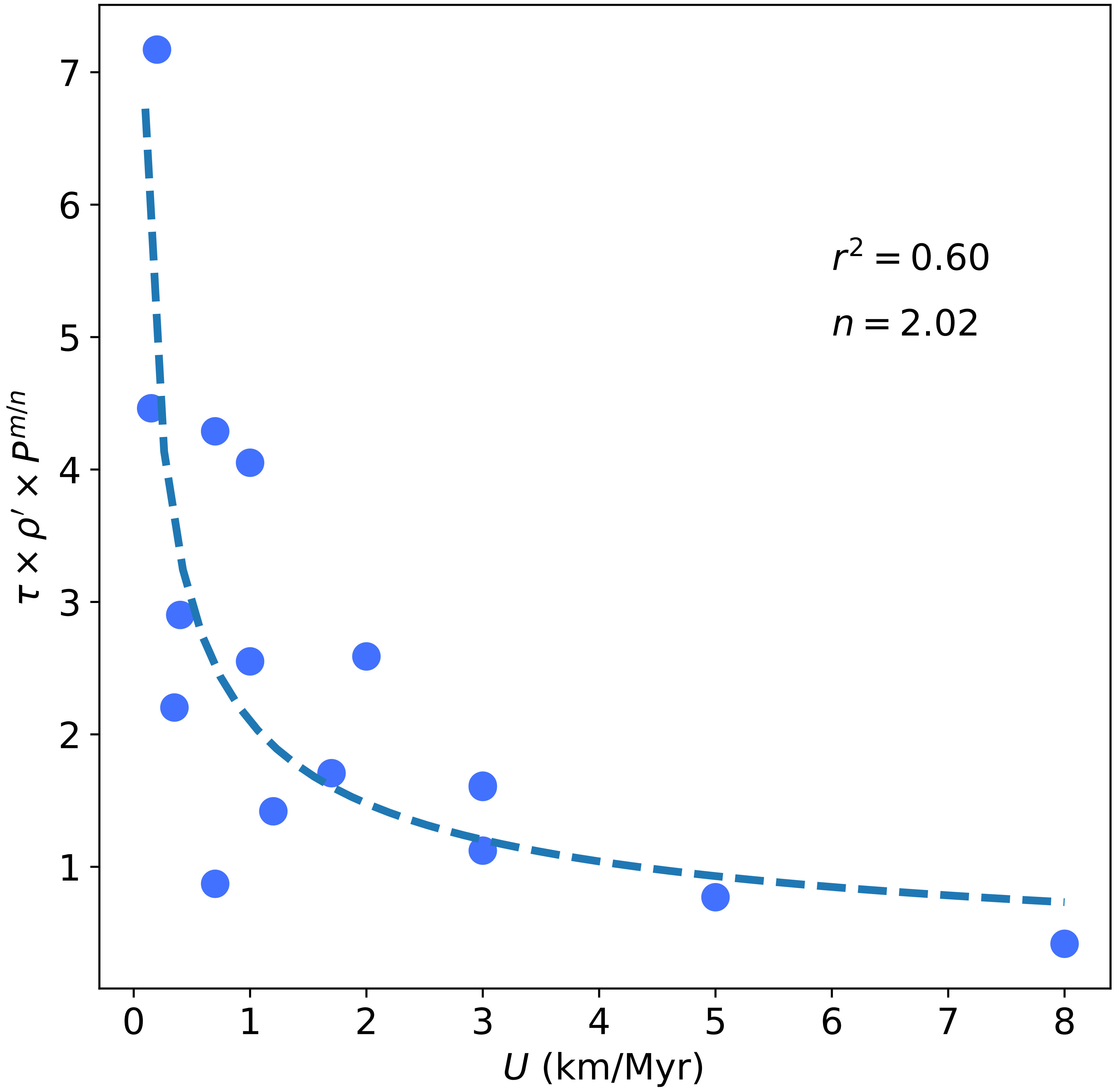
Orogenic response times

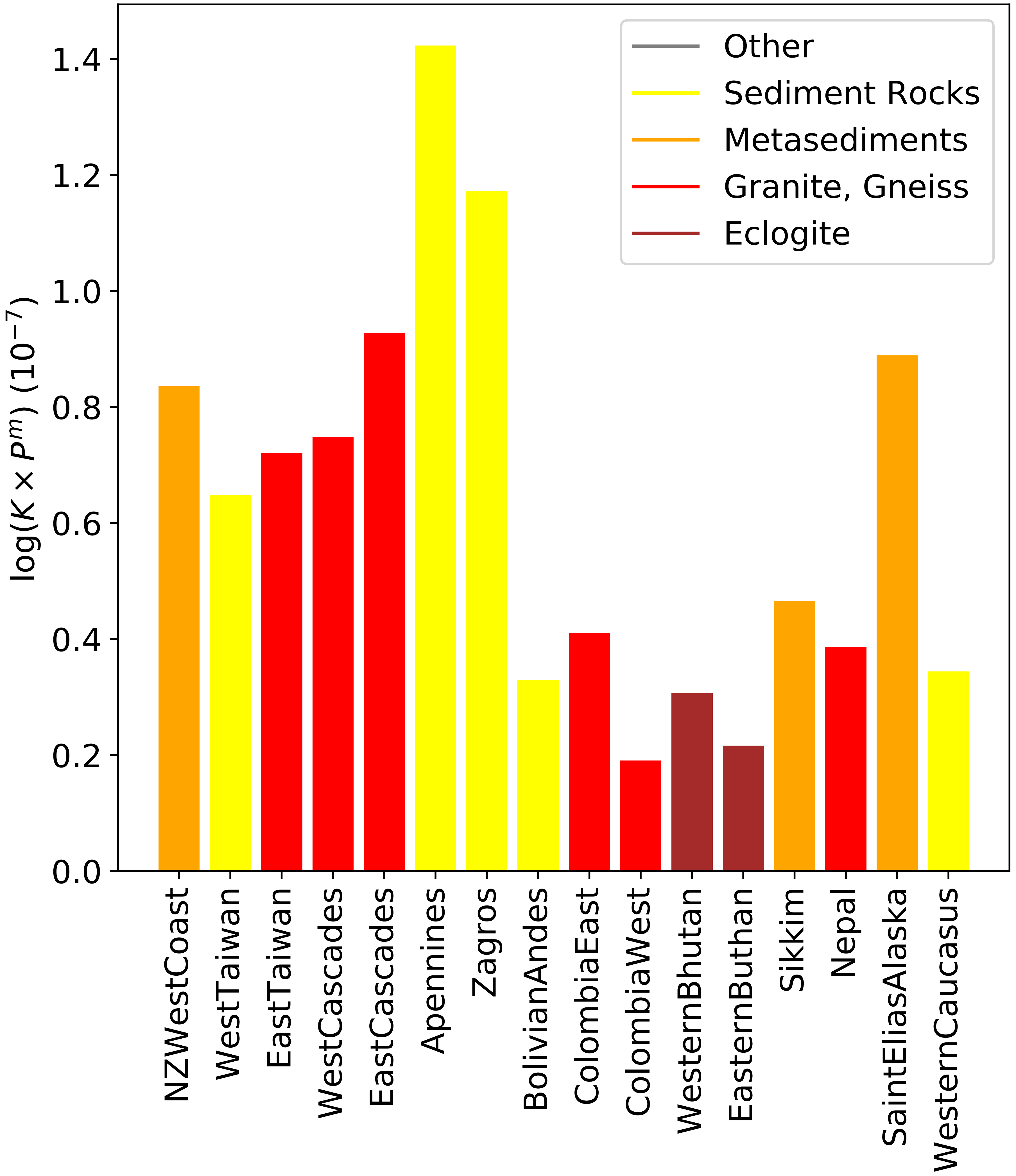
	Te (km)	U (km/Myr)	h0 (m)	L (km)	T (Myr)	P (m/yr)	Rock Type
NZ west coast	1	8	2000	15	6	10.00	3
West Taiwan	14	3	3500	60	6	2.50	2
East Taiwan	14	5	3500	50	6	3.50	4
West Cascades	35	0.4	1000	75	10	4.00	4
East Cascades	35	0.15	1000	150	10	1.00	4
Apennines	17	0.7	800	35	5	1.40	2
Zagros	43	0.35	2200	150	12	0.20	2
Bolivian Andes	71	0.7	4500	200	12	1.00	2
Colombia East	30	1.7	2500	30	3	4.00	4
Colombia West	30	0.2	2000	50	15	1.20	4
Western Bhutan	25	2	5000	200	5	3.00	5
Eastern Buthan	25	1	5000	195	5	1.50	5
Sikkim	20	3	5500	130	10	2.00	3
Nepal	25	3	5000	80	10	2.50	4
Alaska (St Elias)	20	1.2	2300	75	12	1.30	3
Western Caucasus	40	1	3500	40	20	1.25	2



Non-linearity of SPL - option 1: best *n* value

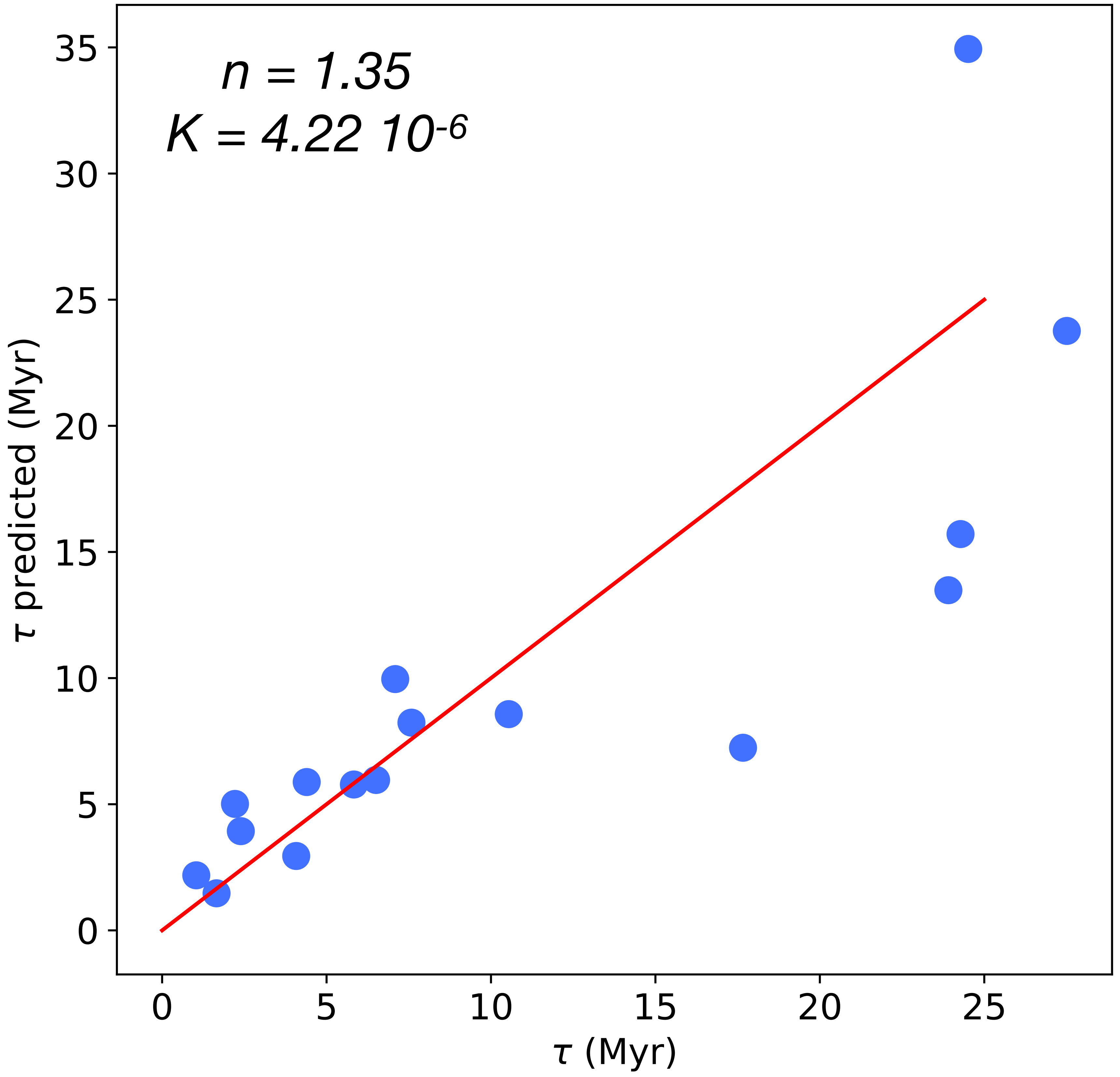
$$\tau = \frac{U^{1/n-1}L^{1-mp/n}}{\rho' K^{1/n} P^{m/n} k^{m/n}(1-mp/n)}$$





Non-linearity of SPL - option 2: best *n* and *K* values

$$\tau = \frac{U^{1/n-1} L^{1-mp/n}}{\rho' K^{1/n} P^{m/n} k^{m/n} (1 - mp/n)}$$



Optimum SPL expressions for coupling to a geodynamical model

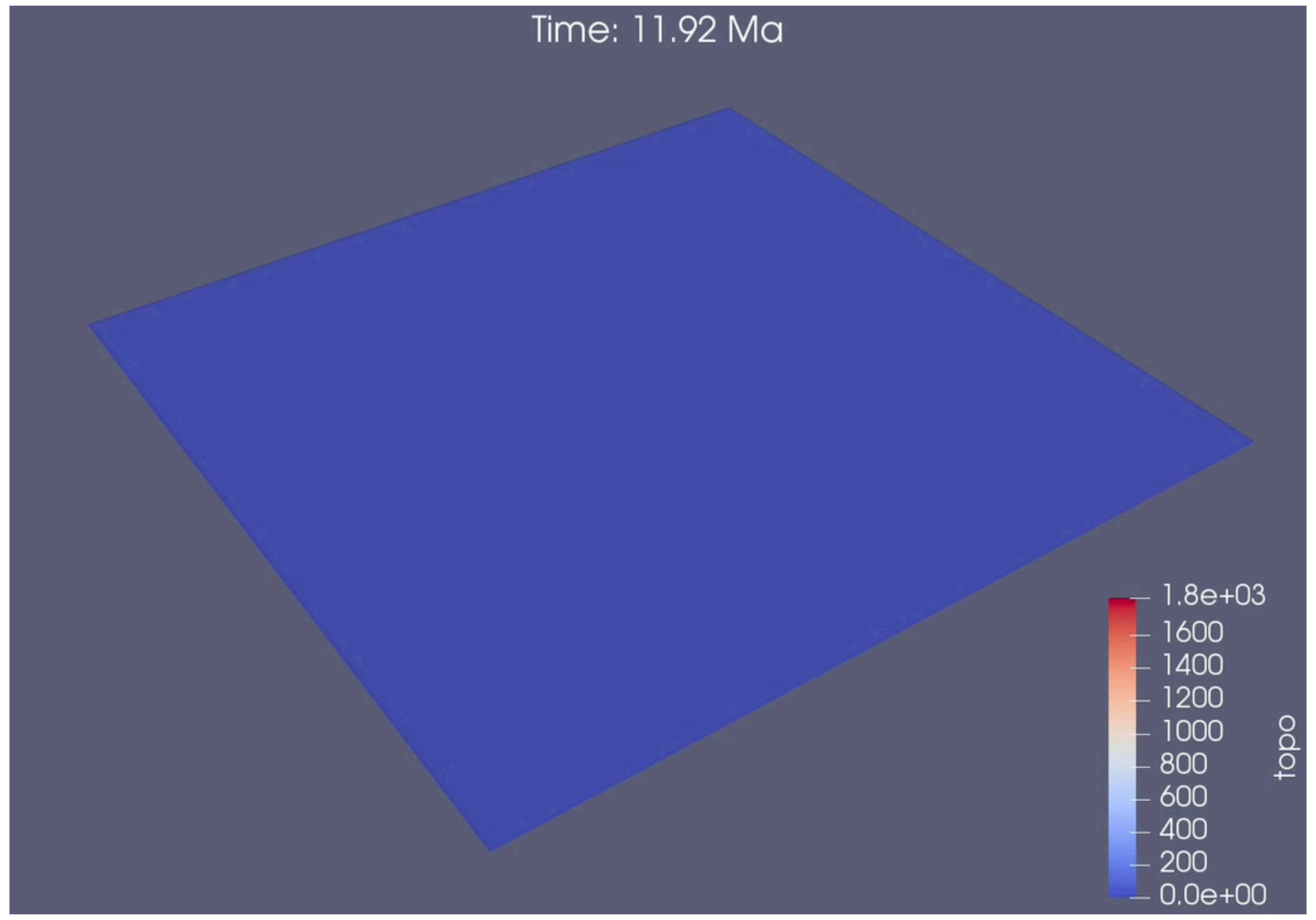
(should give the right rate and topography to create and "average" or "Earth-like" mountain belt.

$$\frac{\partial e}{\partial t} = 6.1 \times 10^{-7} P^{0.8} A^{0.8} S^{2}$$

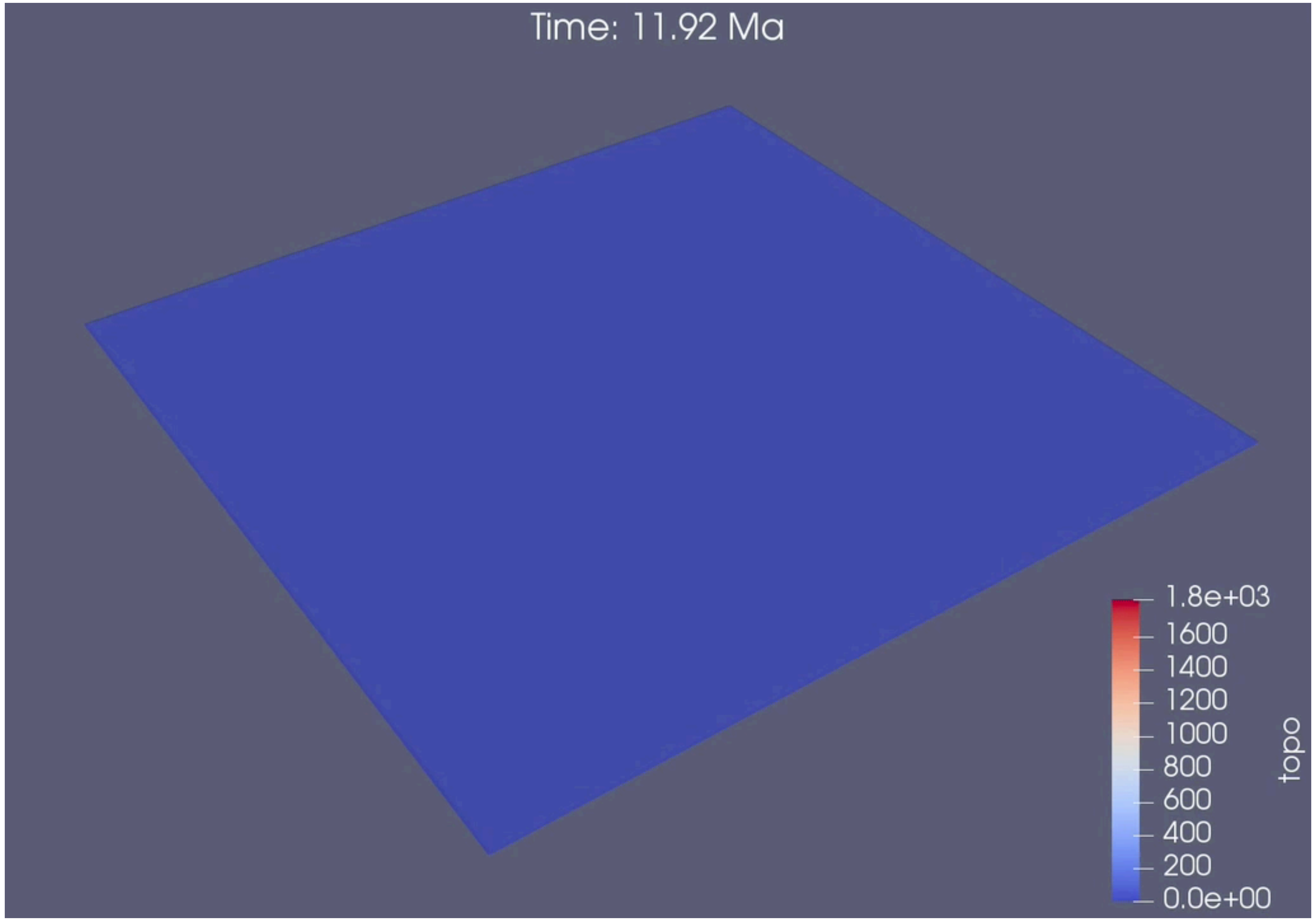
$$\frac{\partial e}{\partial t} = 4.22 \times 10^{-6} P^{0.54} A^{0.54} S^{1.35}$$

Non-linearity matters

n = 1



n = 2



The Stream Power Law

Rate of topographic change; Uplift rate; Drainage area; Precipitation rate; Slope

$$\frac{\partial h}{\partial t} = U - K' A^m S^n = U - K P^m A^m S^n$$

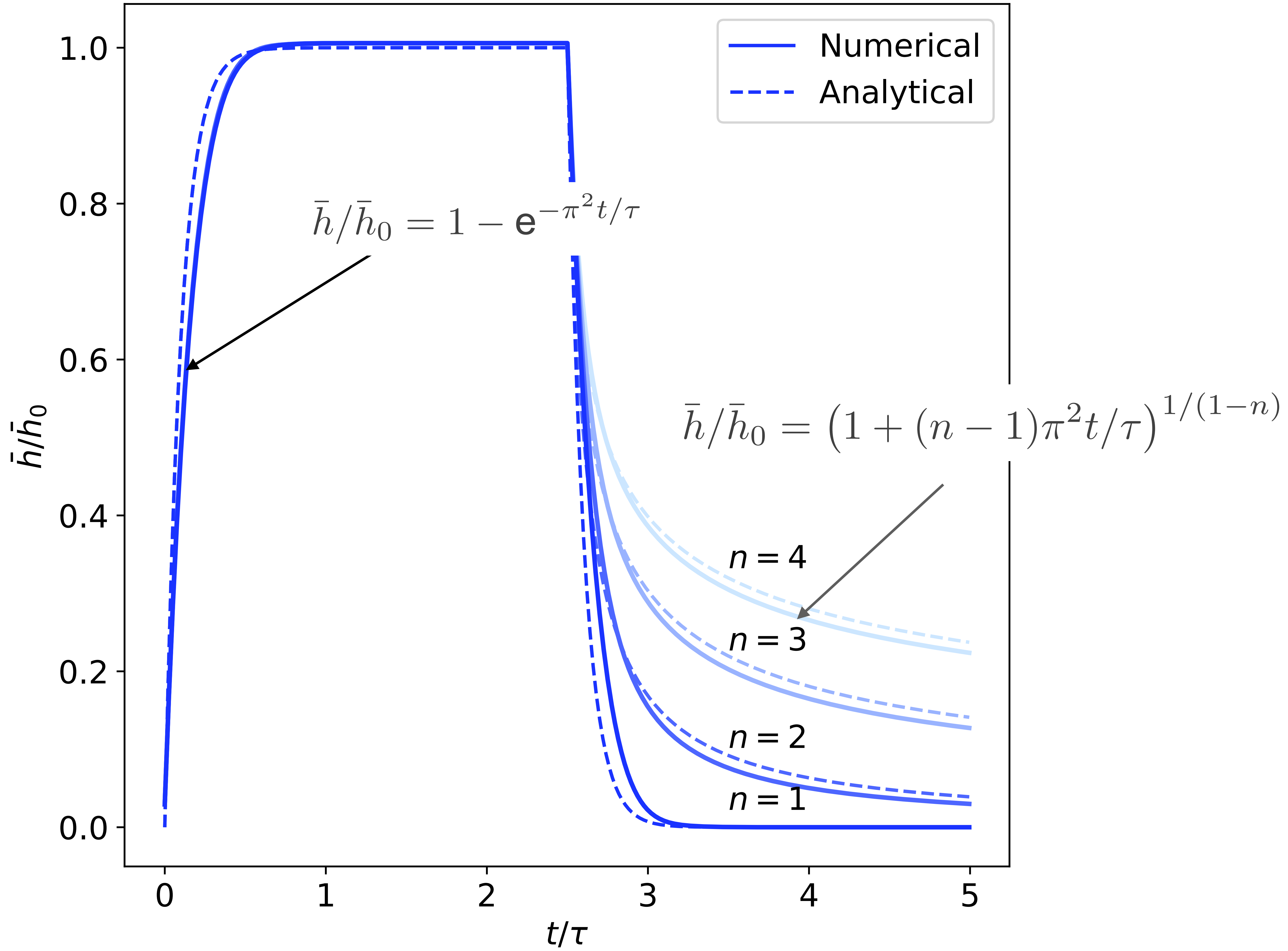
Response time $$\tau = \frac{h_0}{\rho' U}$$

Steady-state height $$h_0 = \frac{U^{1/n} L^{1-mp/n}}{K^{1/n} P^{m/n} k^{m/n} (1 - mp/n)}$$

Isostatic rebound per unit erosion $$\rho' = \frac{\partial h}{\partial e} = 1 - \frac{\rho_s}{\rho_a + \frac{D}{g}\left(\frac{\pi}{2L}\right)^4}$$

Hack's Law $$A = k(L - x)^p$$

Mean topography $$\bar{h}_0 = h_0 \frac{3n - mp}{2n - mp}$$



The longevity of ancient mountain belts

Southeastern Australian Highlands

Pyrenees

Isostasy and nonlinearity increase the topographic longevity of old orogenic areas

2. Response of surface processes to climatic forcing

Terra Nova
doi: 10.1111/ter.12185

Debate Article

The null hypothesis: globally steady rates of erosion, weathering fluxes and shelf sediment accumulation during Late Cenozoic mountain uplift and glaciation

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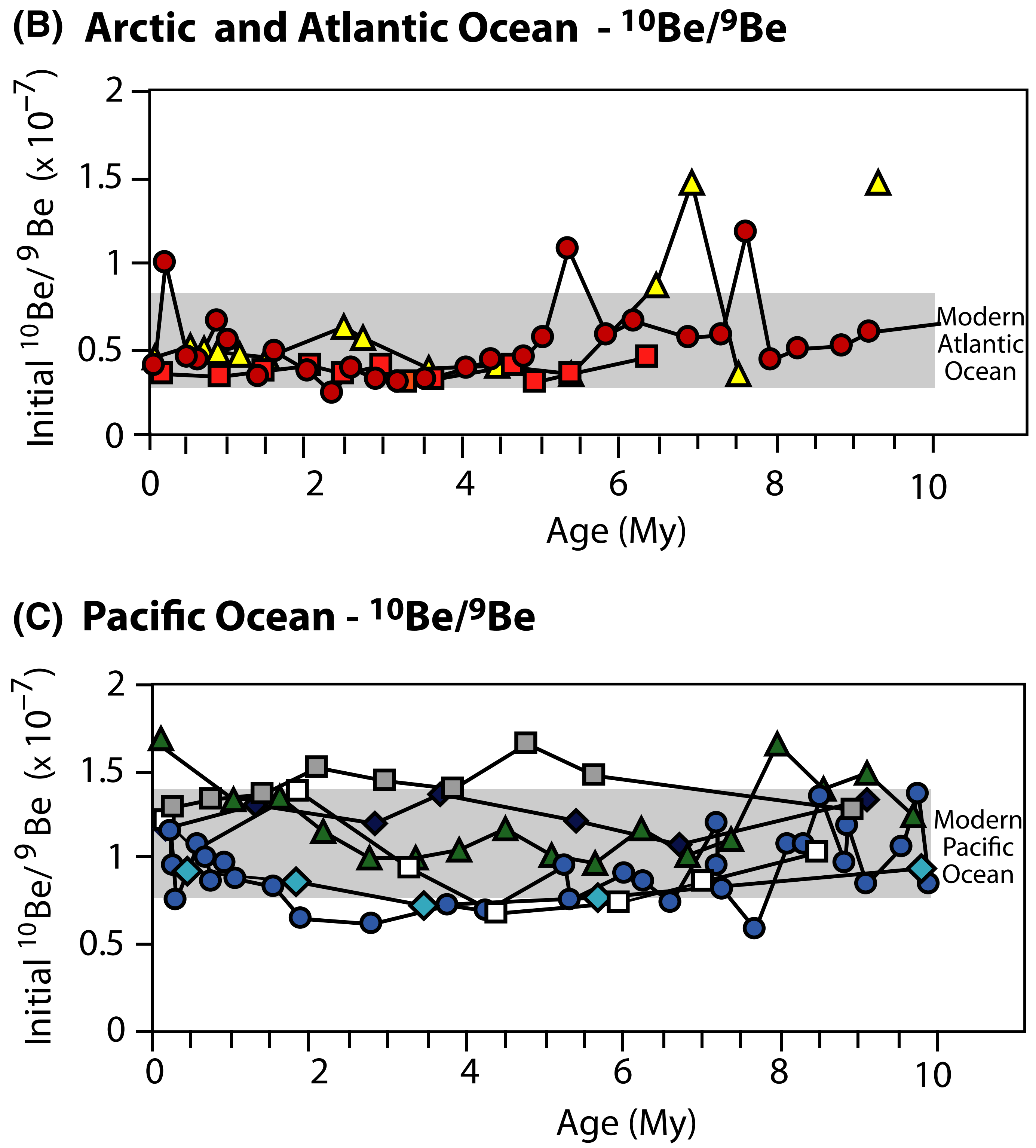

Terra Nova
doi: 10.1111/ter.12186

Debate Article

Plio-Pleistocene increase of erosion rates in mountain belts in response to climate change

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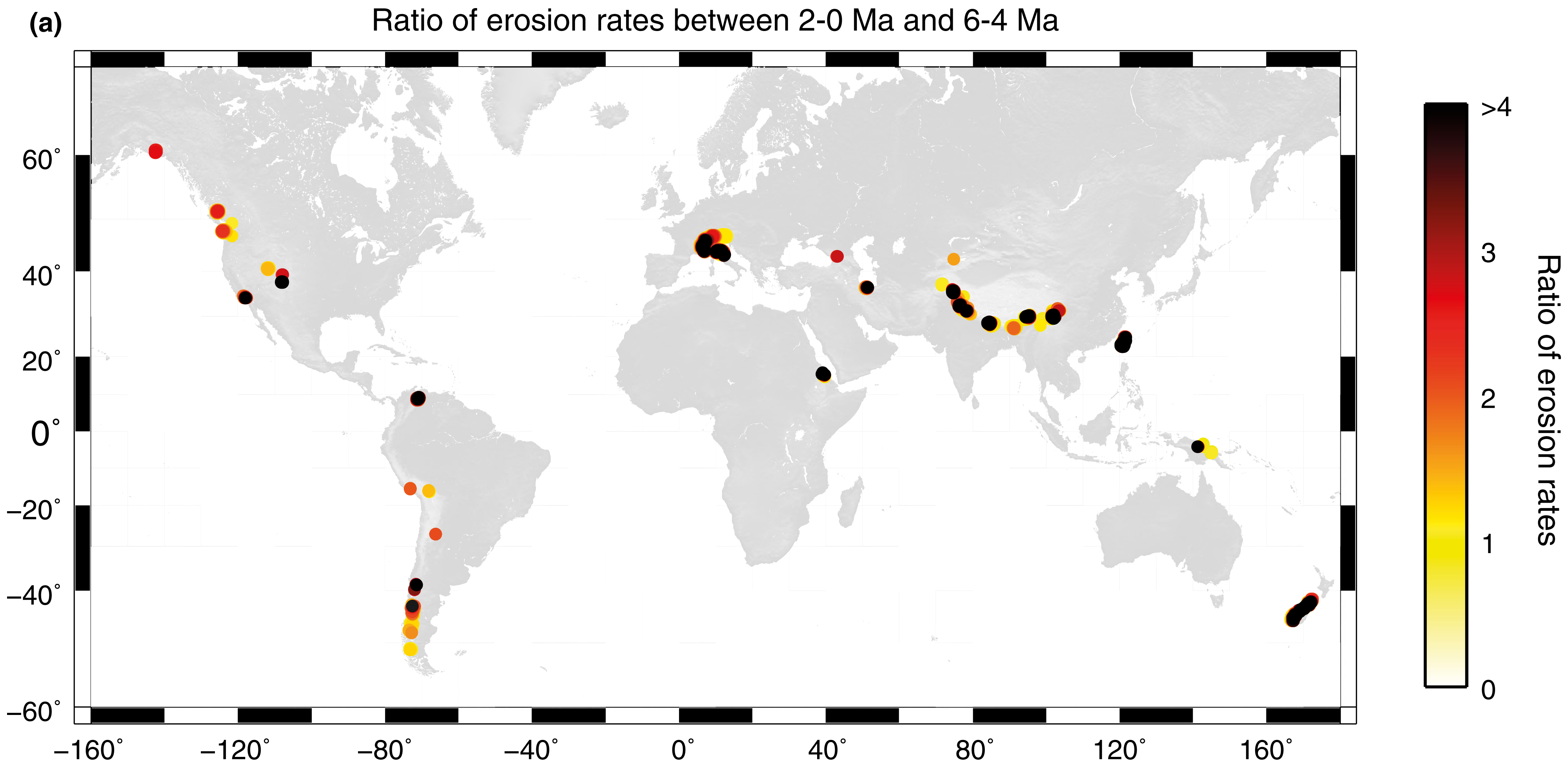


Glacial erosion

$$\frac{\partial h}{\partial t} = U - K_g u_s^l$$

Hallet, 1981

Ice sliding velocity

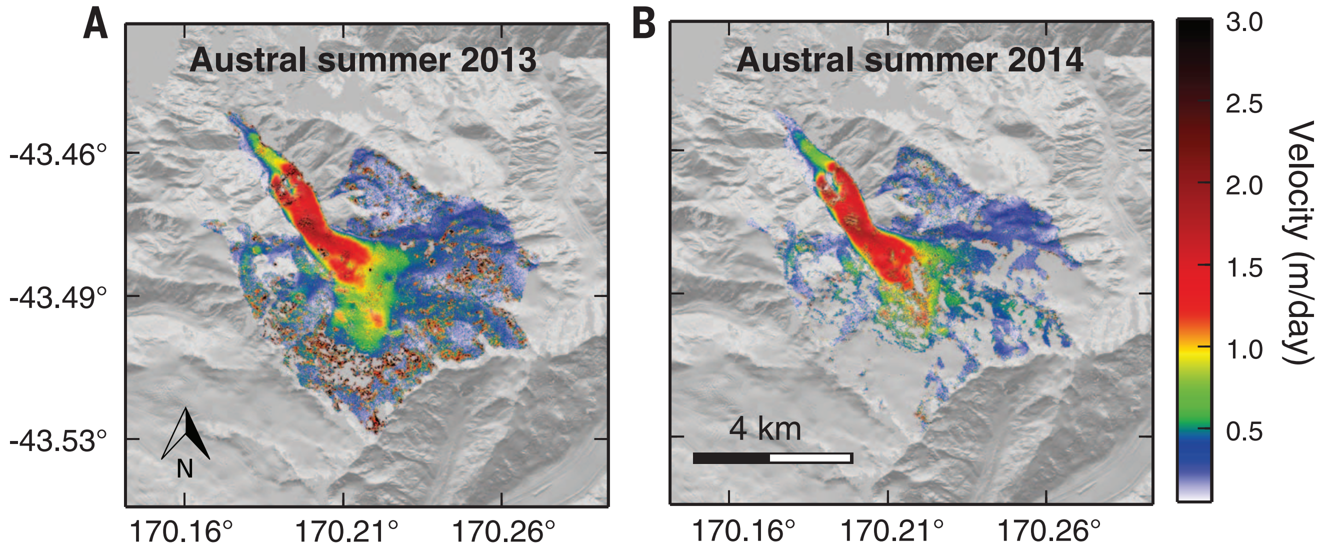
$$\frac{\partial H}{\partial t} = A + \nabla \cdot \mathbf{q}$$

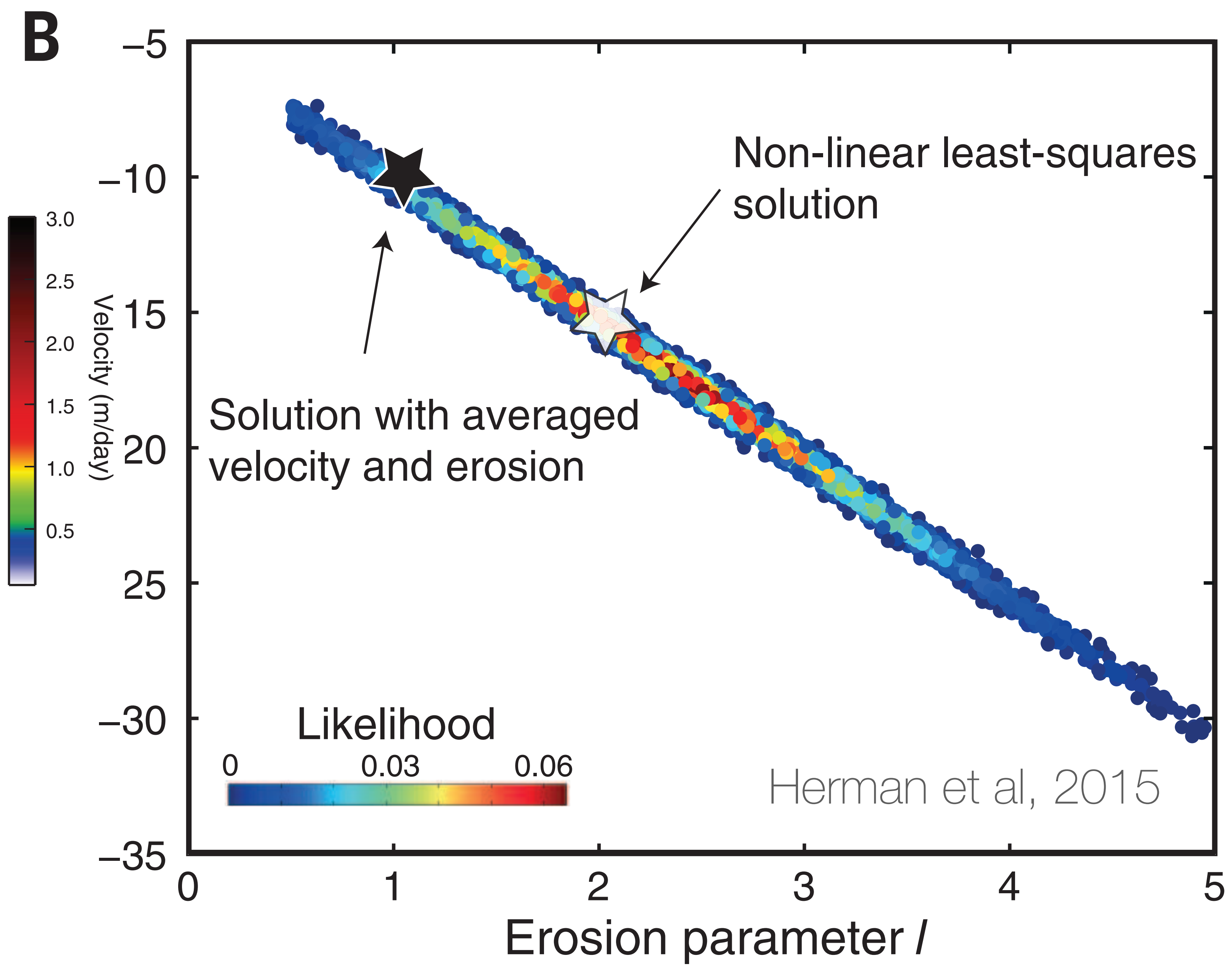
$$A = \min(\beta(h - E), c)$$

ELA

$$\mathbf{q} = H\mathbf{u}$$

$$\mathbf{u} = f_d H^{n+1} |\nabla h|^{n-1} \nabla h + f_s H^{n-1} |\nabla h|^{n-1} \nabla h$$

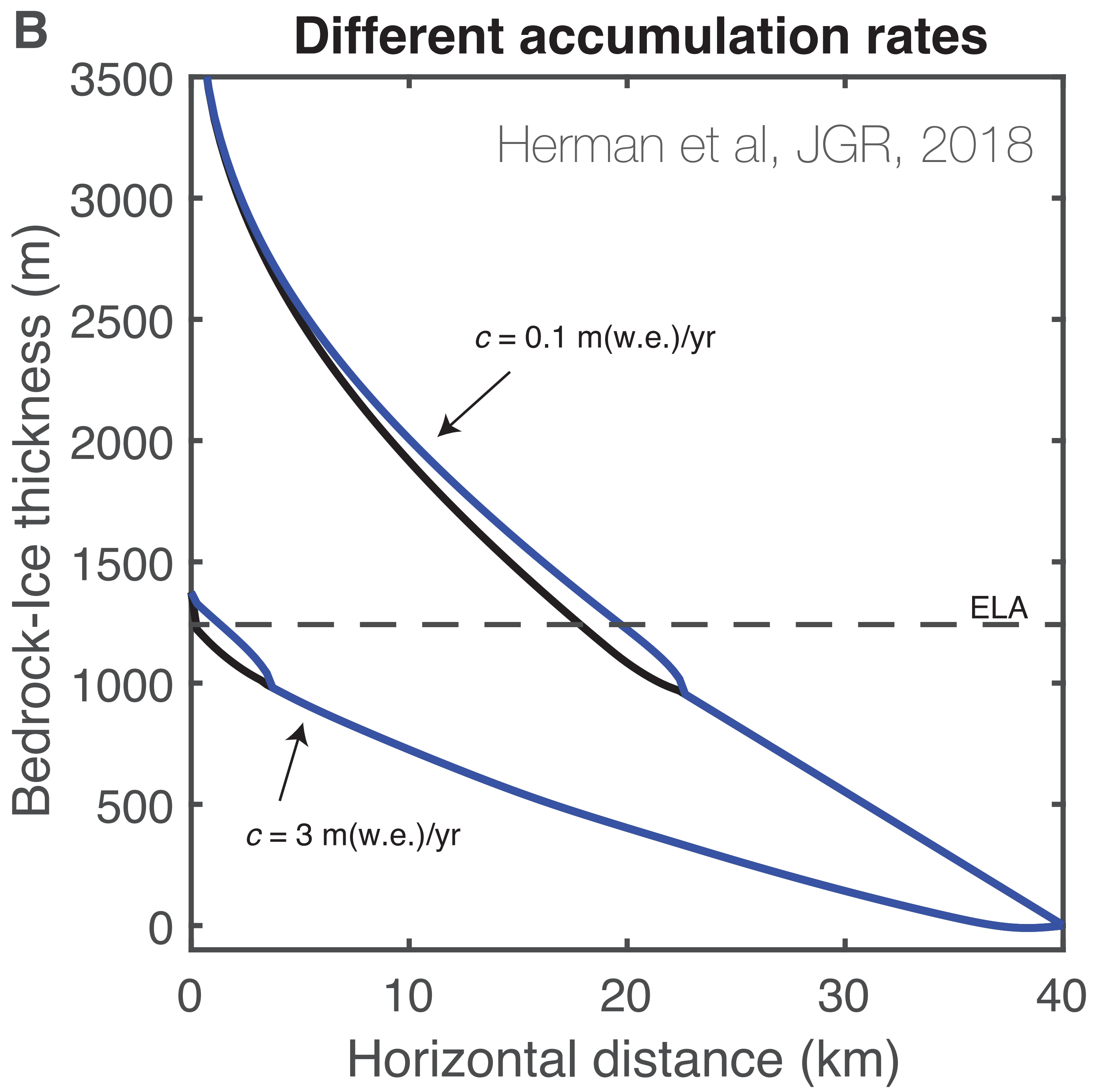


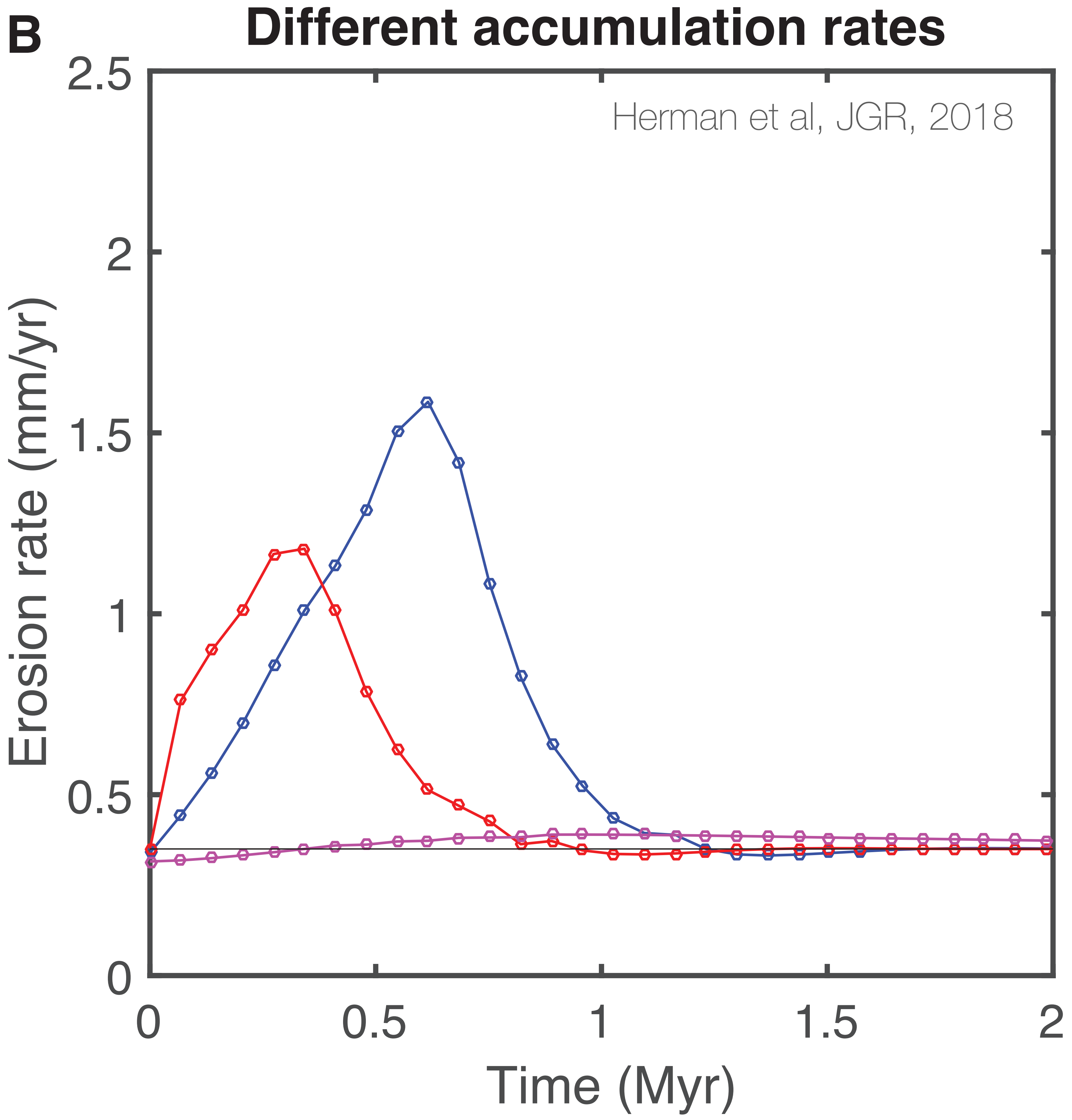


Response time(s) to changes in ELA

$$\tau_i = L\left(\frac{K_g}{U}\right)^{1/n}$$ 10 to 10,000 yrs

$$\tau_e = \frac{L^{1/n}}{K_g^{1/l} f_s^{1/n} A^{1-1/n} U^{1-1/l}}$$ 10 kyrs to 10 Myrs



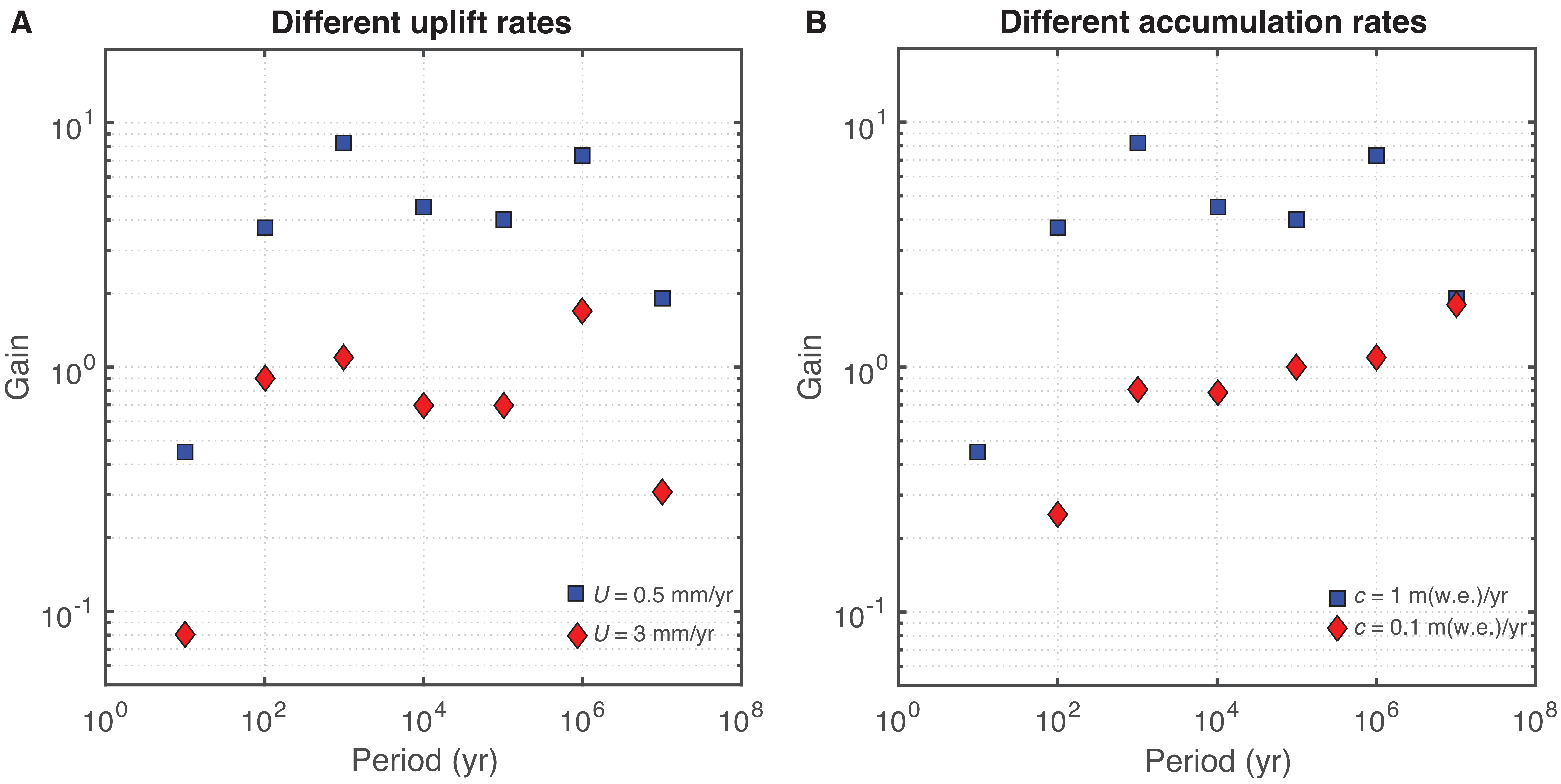


$\tau_e \propto A^{-2/3}$ if $l = 1$ and $n = 3$

$\tau_e \propto U^{-4/9} A^{-2/3}$ if $l = 2$ and $n = 3$

Response time(s) to periodic variations in ELA: the Gain function

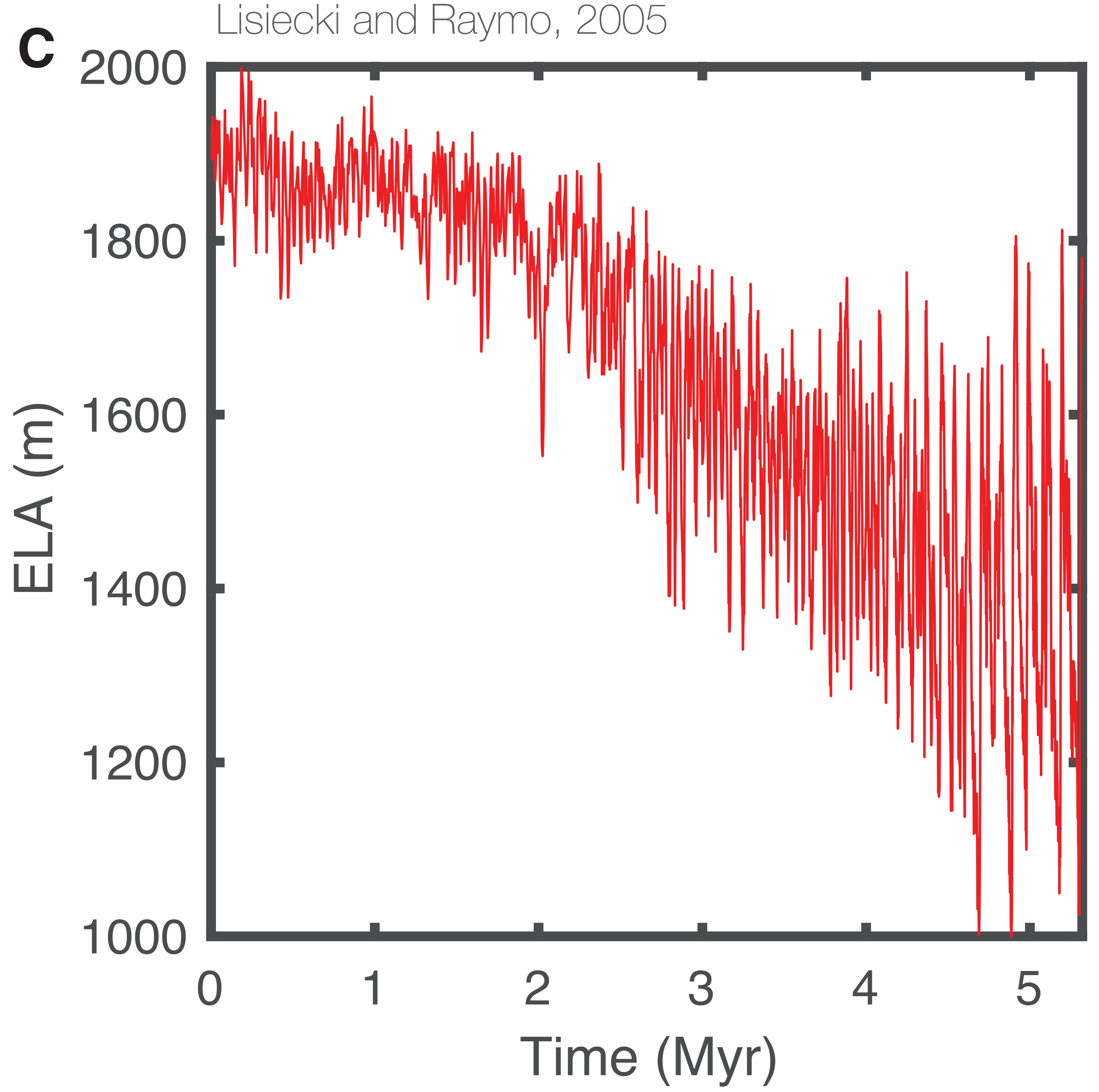
Herman et al, JGR, 2018

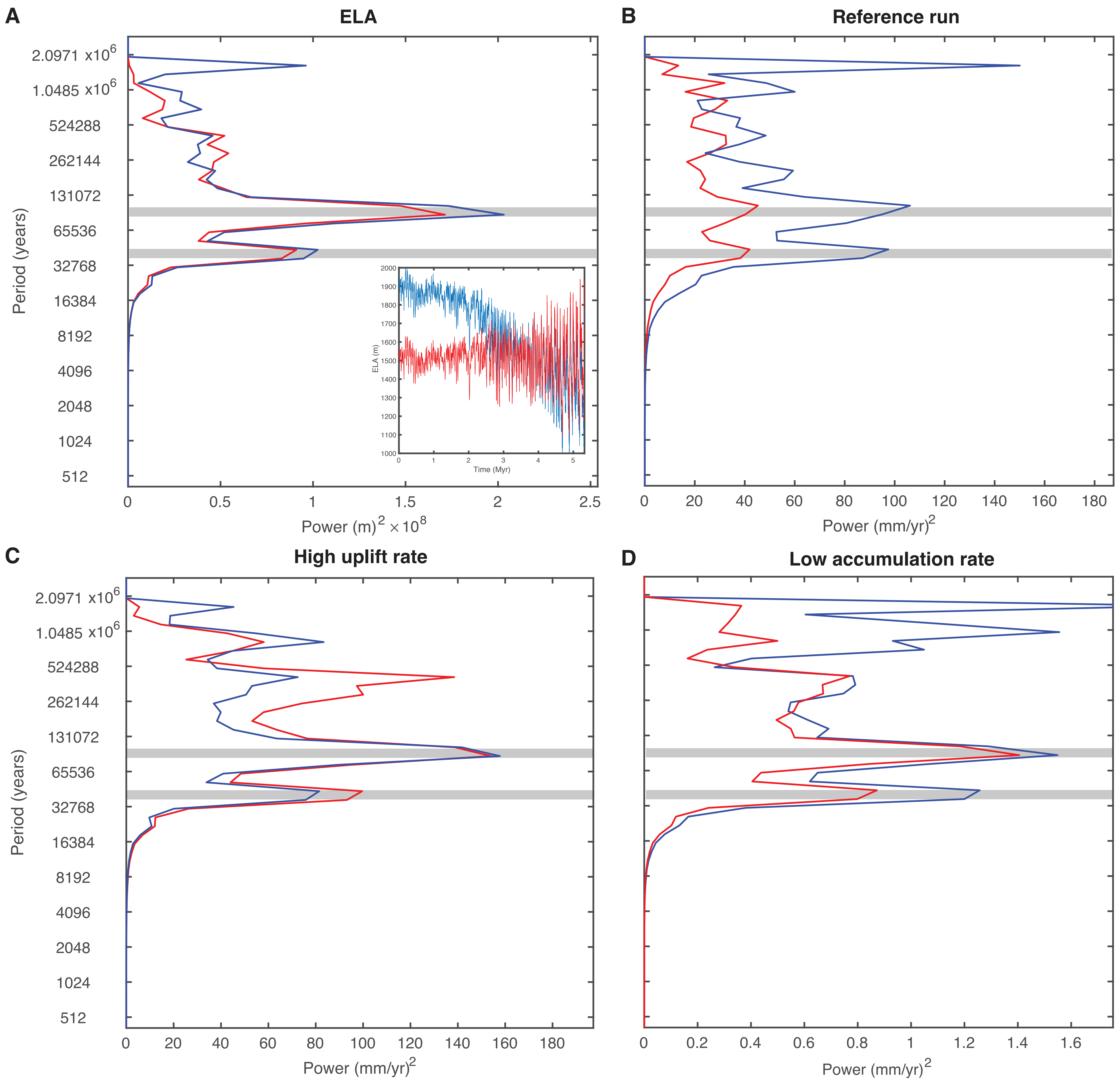


Response to Late Cenozoic cooling

Herman et al, JGR, 2018

Herbert et al, 2016
Lisiecki and Raymo, 2005



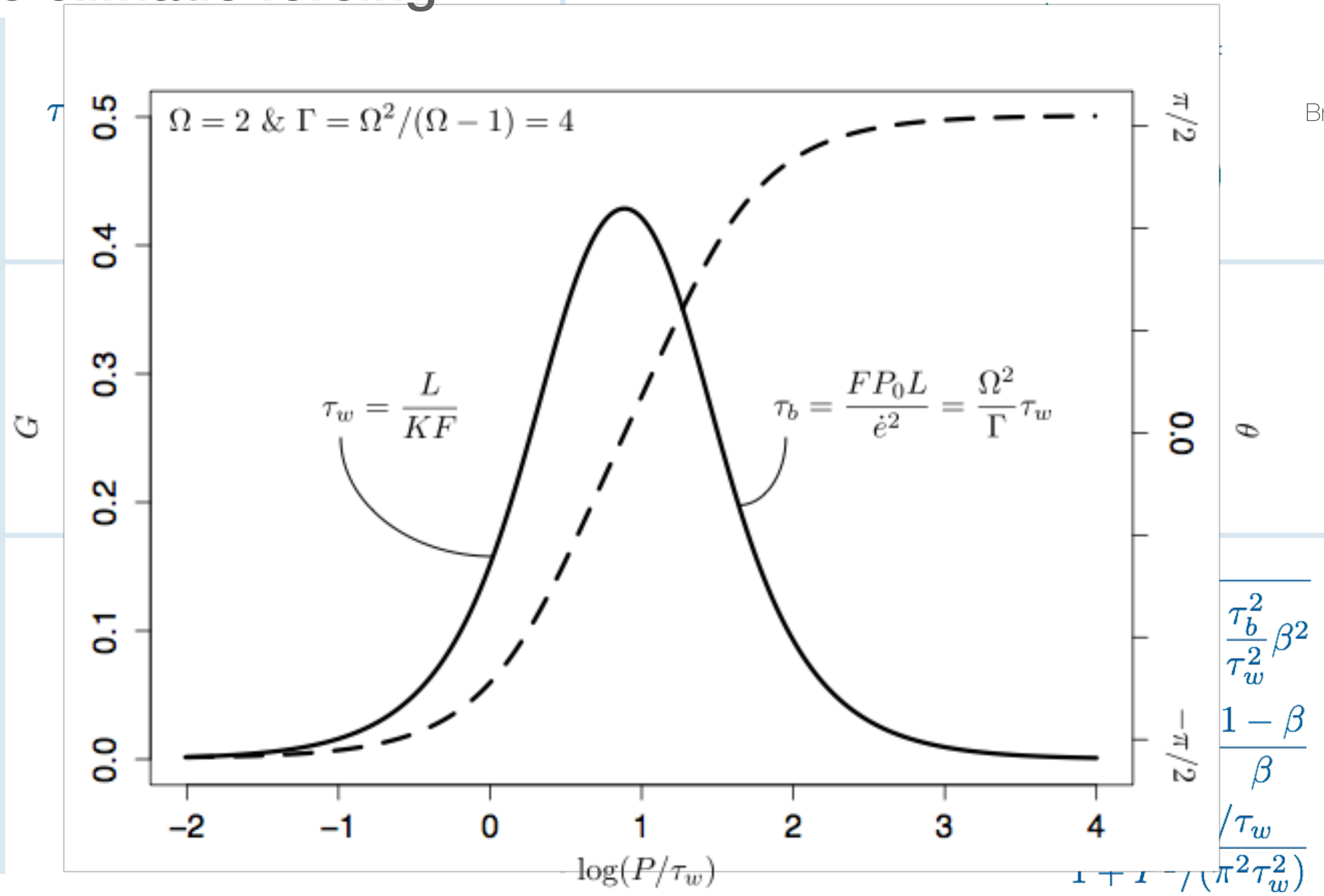


Analytical expressions for surface processes response to periodic climatic forcing

Fluvial incision

Hillslope Diffusion

Weathering front propagation

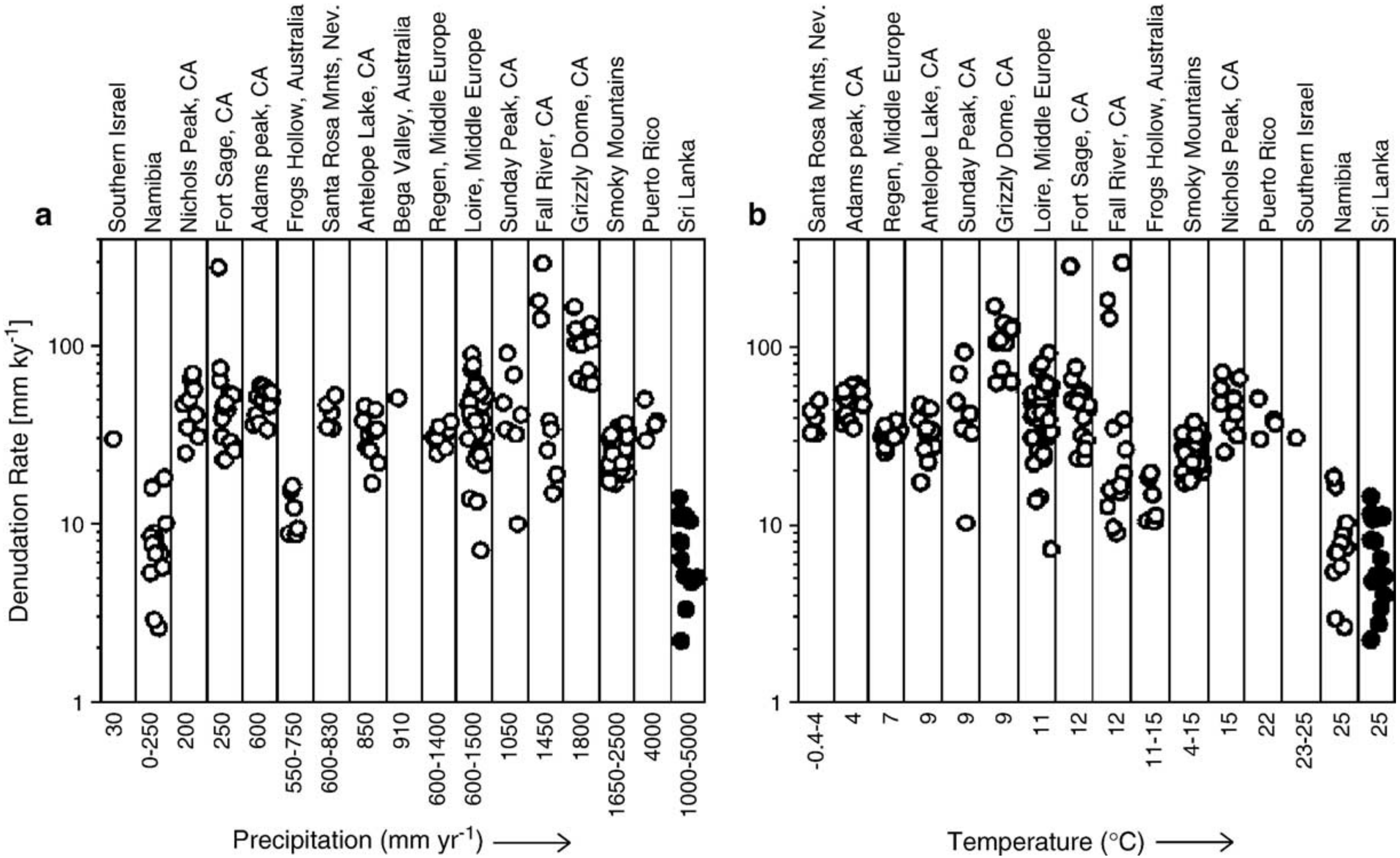


Braun et al, ESURF, 2015

Braun et al, JGR, 2017

3. Response of surface processes to weather conditions

Erosion rate and rainfall



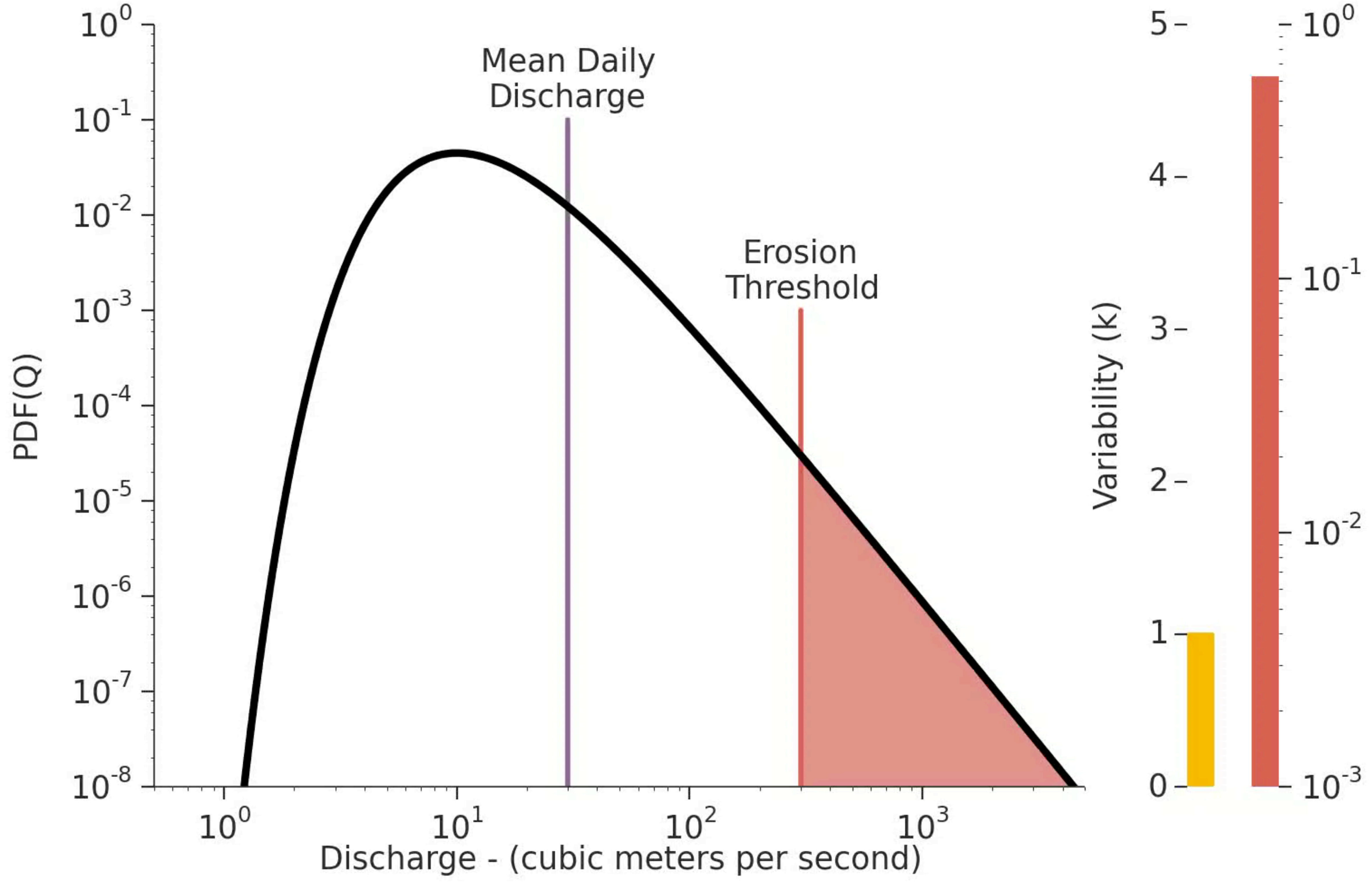
Von Blanckenburg, 2005

Climate variability matters…

Because surface processes depend on rainfall and are characterized by thresholds

- **Bedrock incision**
- **Channel head initiation**
- **Fluvial transport of bed-load sediments**
- **Debris flows**
- **Shallow landsliding**
- **Solifluction**
- **Soil creep**

Mean and variability



- Low variability systems are more clustered around the mean
- Erosion frequency is the probability of exceeding the erosional threshold
- Erosion efficiency = erosion rate/ mean forcing (precipitation)

- Erosion efficiency should depend on the value of the threshold
- It should depend on forcing (climate) variability
- It should depend on the tail of the forcing distribution
- It should depend on the nonlinearity of the erosional process
- (to the forcing)

Climate variability matters…

Deal, Botter and Braun, JGR, 2018

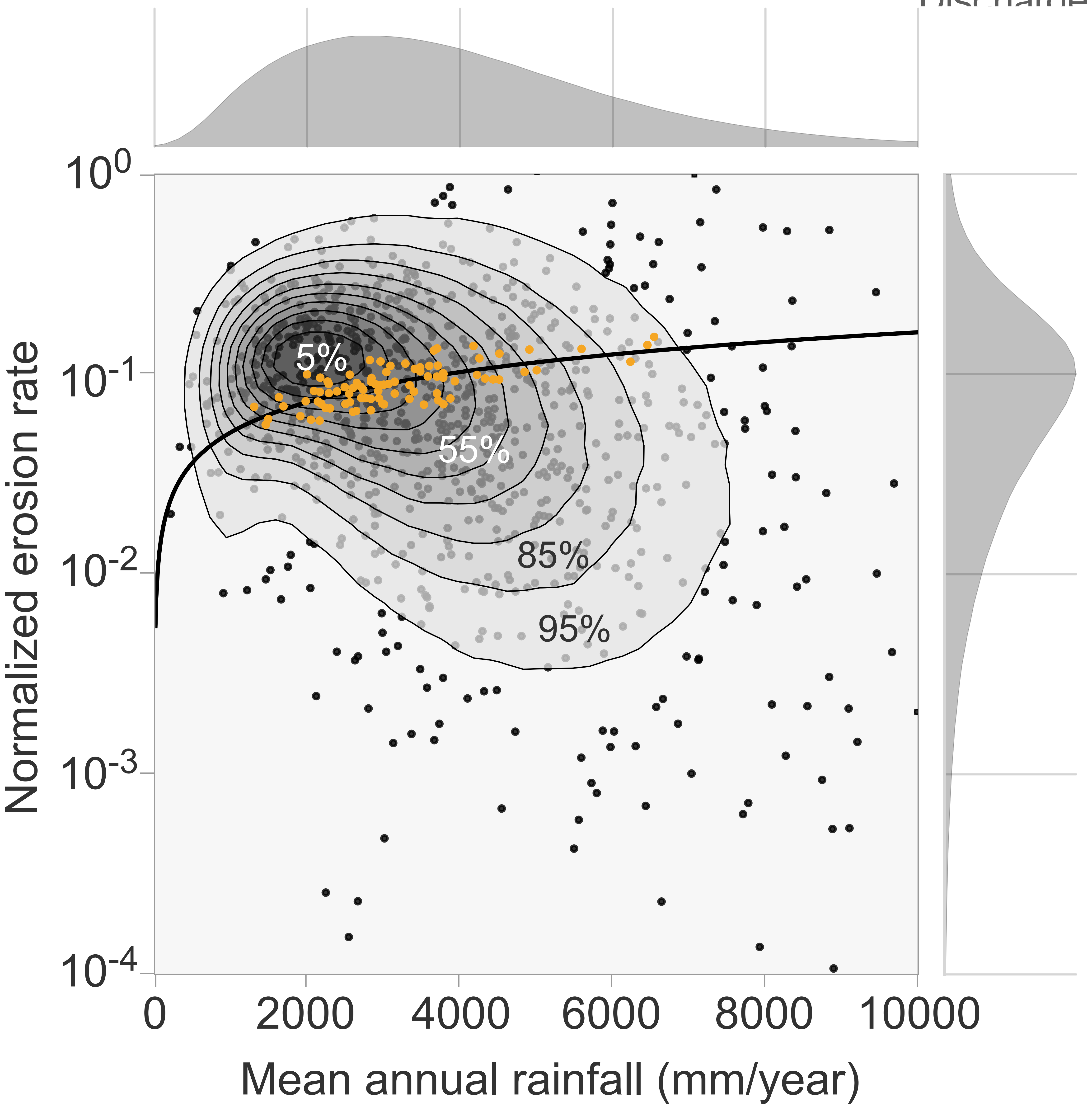
$$\frac{\partial h}{\partial t} = U - \mu_\epsilon K \mu^{m_c} A^m$$

$$\mu_\epsilon = \int_{q_c^*}^{\infty} q_*^\gamma f_{Q^*}^t (q_*$$

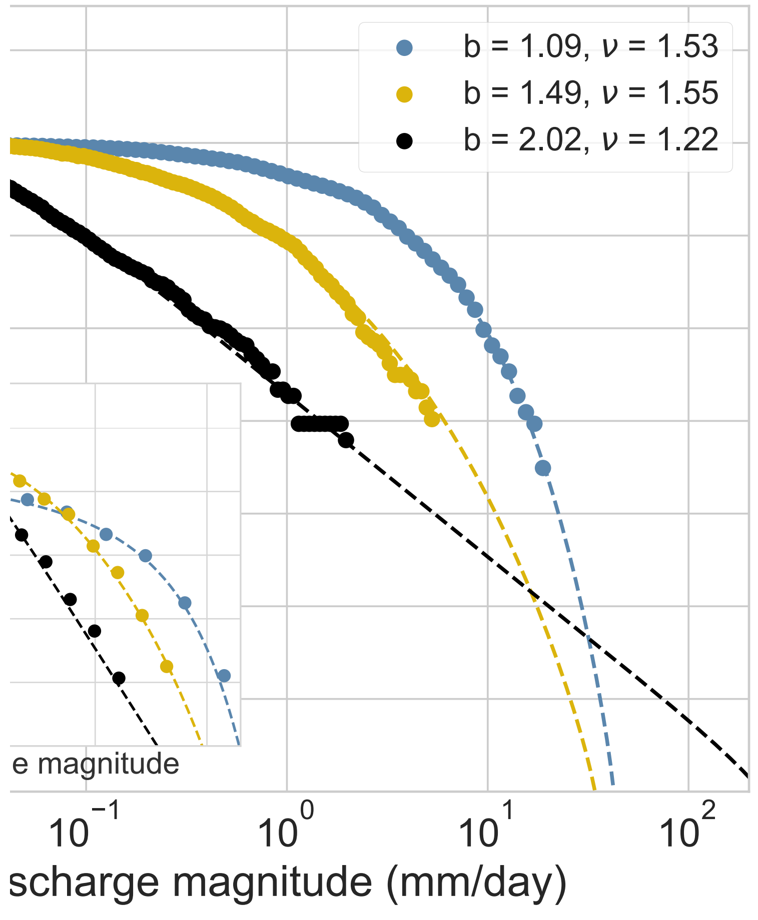
$$\lambda_\epsilon = \int_{q_c^*}^{\infty} f_{Q^*}^t (q_* | q_r$$

$$f_{Q^*}(q_*) = C q_*^{-b} \exp\left[-\omega\lambda\tau\left(\frac{q_*^2}{2}\right.\right.$$

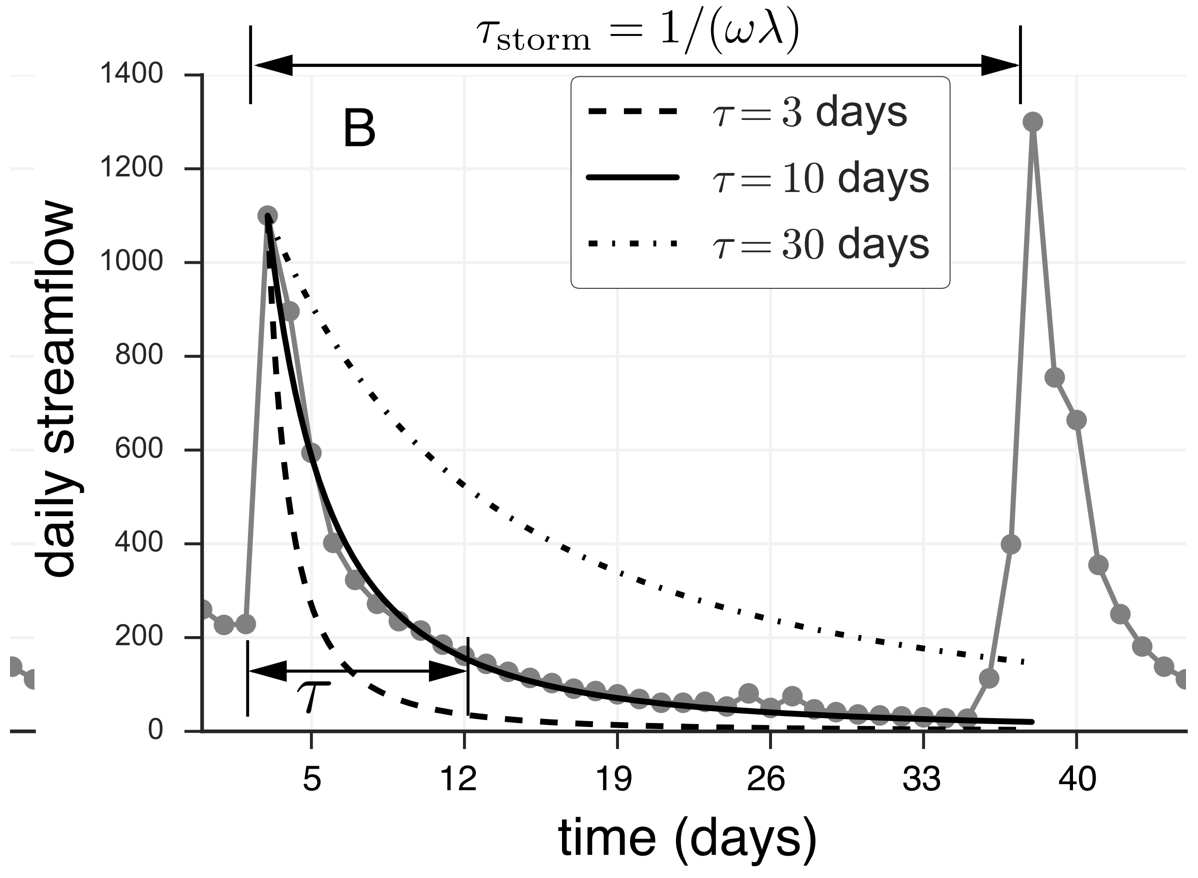
$$\nu = \frac{\tau_{storm}}{\tau} = \frac{1}{\omega\lambda}$$



Discharge PDF/CDFs “fitting”



on curve “fitting”



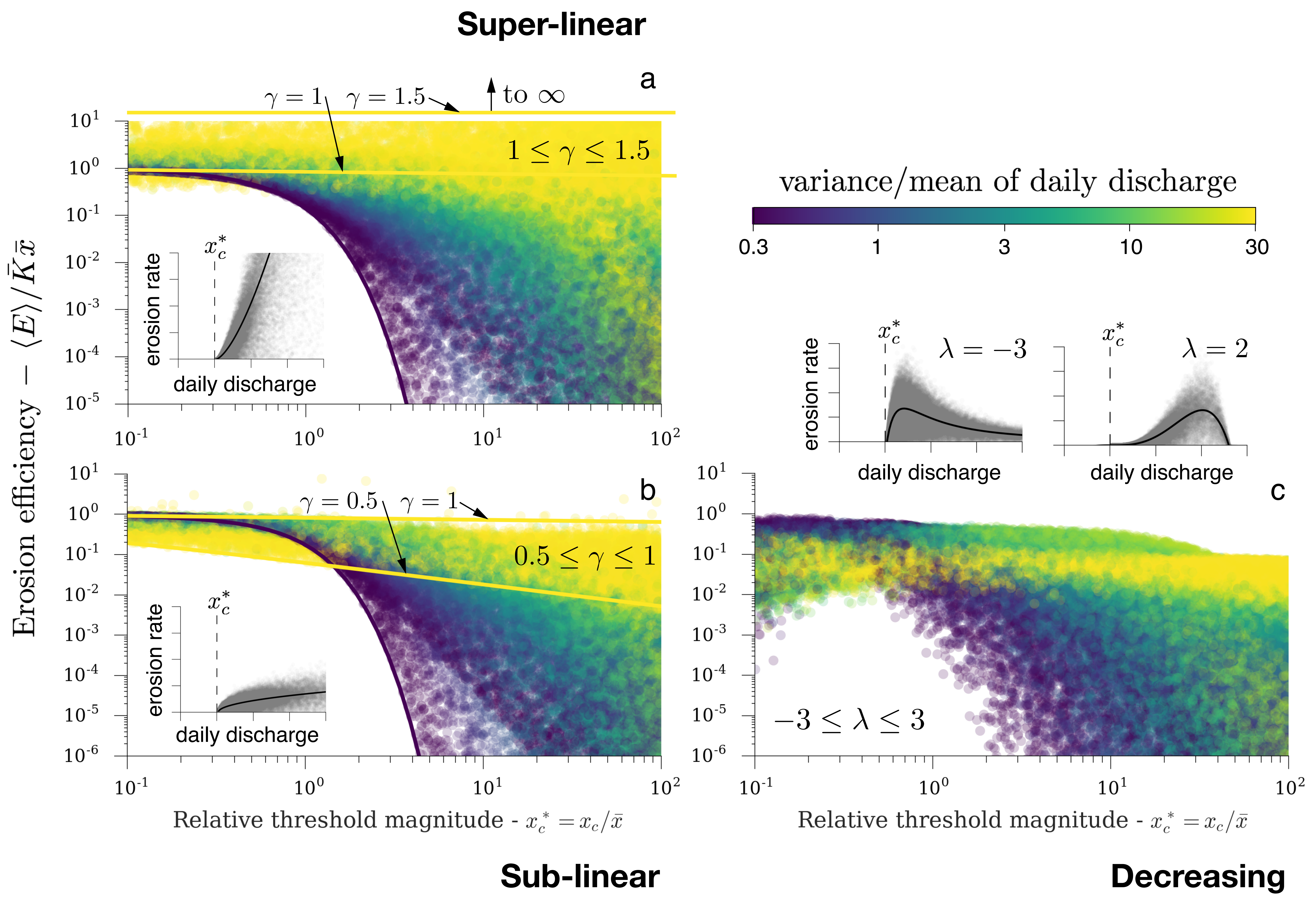
Variability

Hydrological response time scale

The effect of climate variability is independent of process

Deal and Braun, subm

- High vs low variability systems diverge when the threshold is close to the mean
- This is almost independent on the erosion process law
- This is independent of the type of the forcing PDF (heavy-tailed vs light-tailed)
- Nonlinearity of erosional response to forcing matters slightly
- Our results confirm previous work by Tucker, 2004, Lague et al, 2005, Rossi et al 2016, etc. and generalizes it

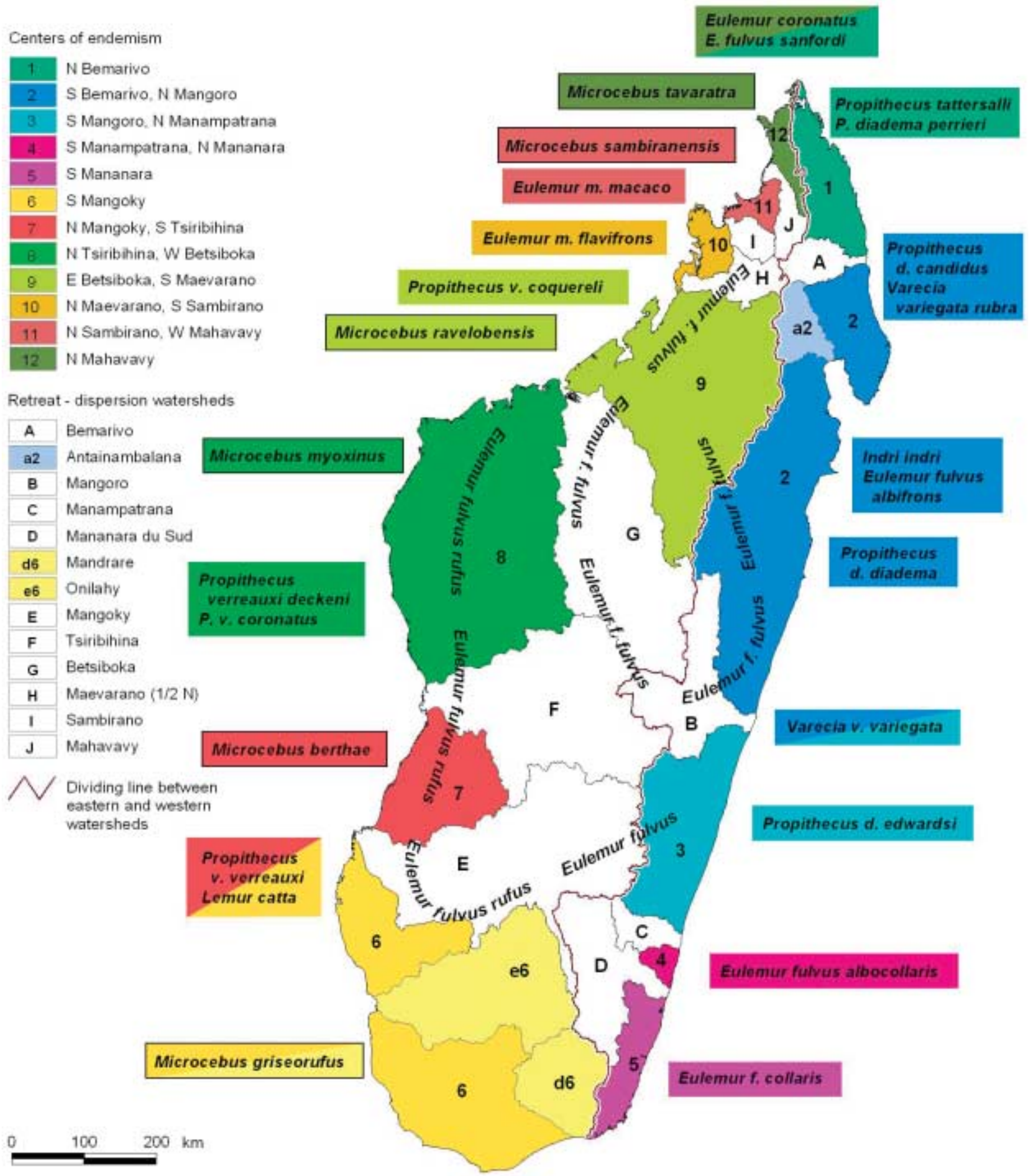


Implications for the way surface processes respond to climate change

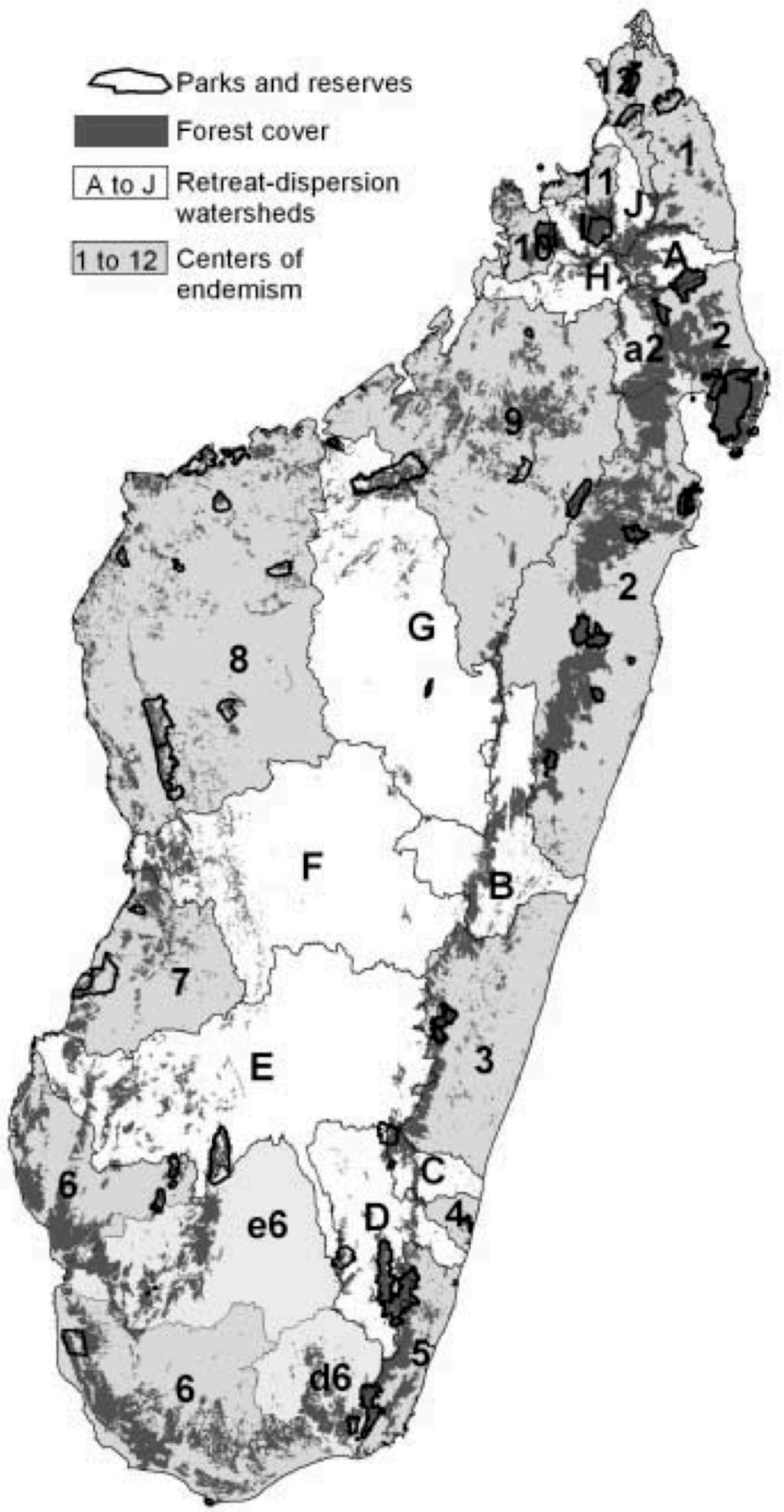
- Climate change affects both mean and variability of rainfall
- Regions with high rainfall or river discharge tend to exhibit low variability and vice-versa
- Intensity of rainstorms increases with increasing temperature
- Low thresholds systems will respond to changes in mean annual rainfall
- High thresholds systems will respond to changes in mean annual rain fall AND temperature
- Thresholds decease in high relief/ slope environments
- Steep landscapes are less sensitive to variability

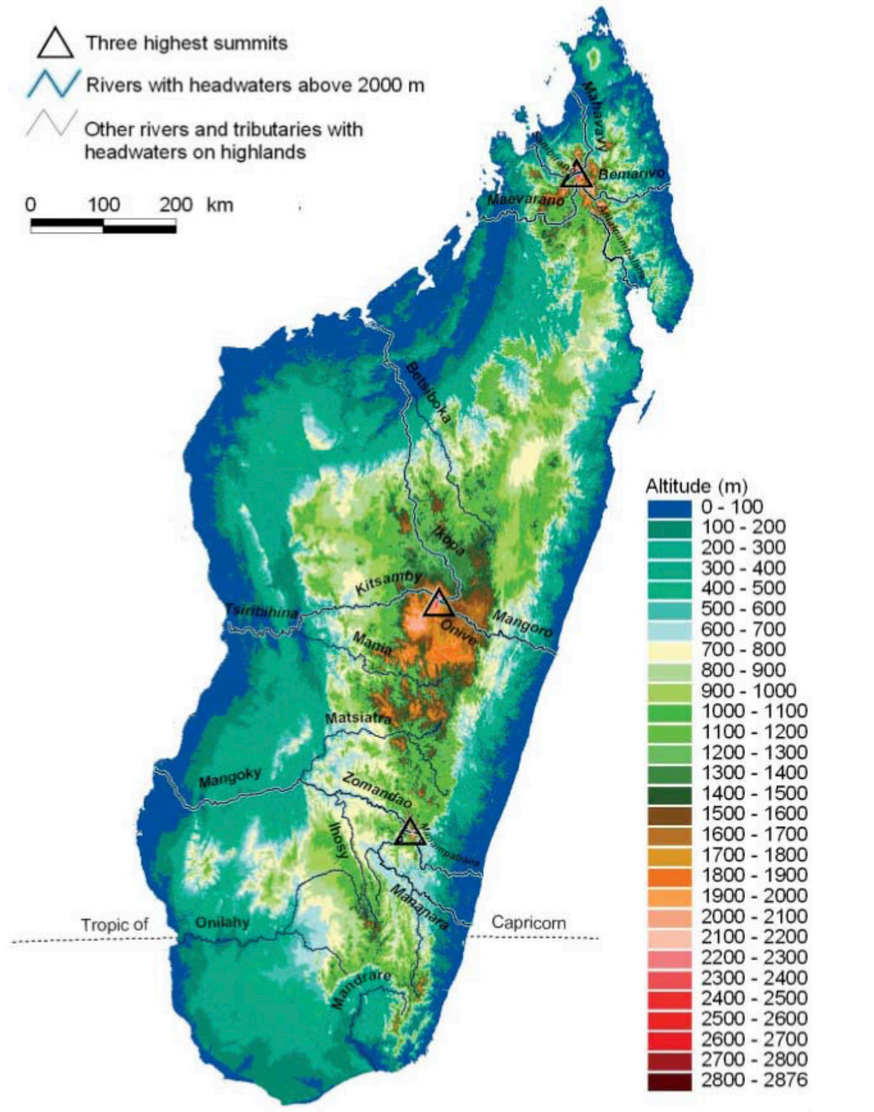
4. Flexure, drainage basins, co-evolution of life and landforms

Micro-endemism in Madagascar

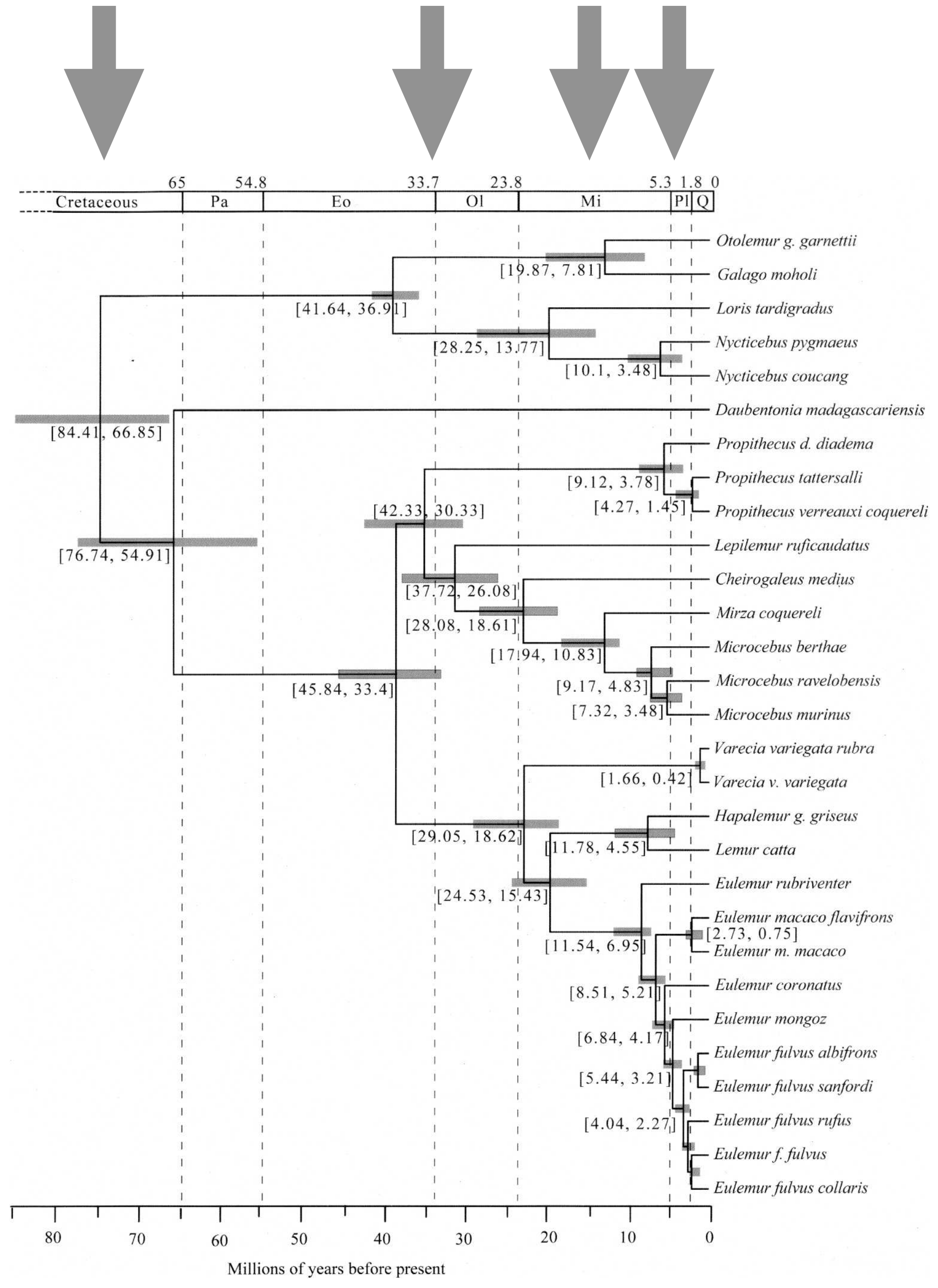


From Wilme et al, 2006



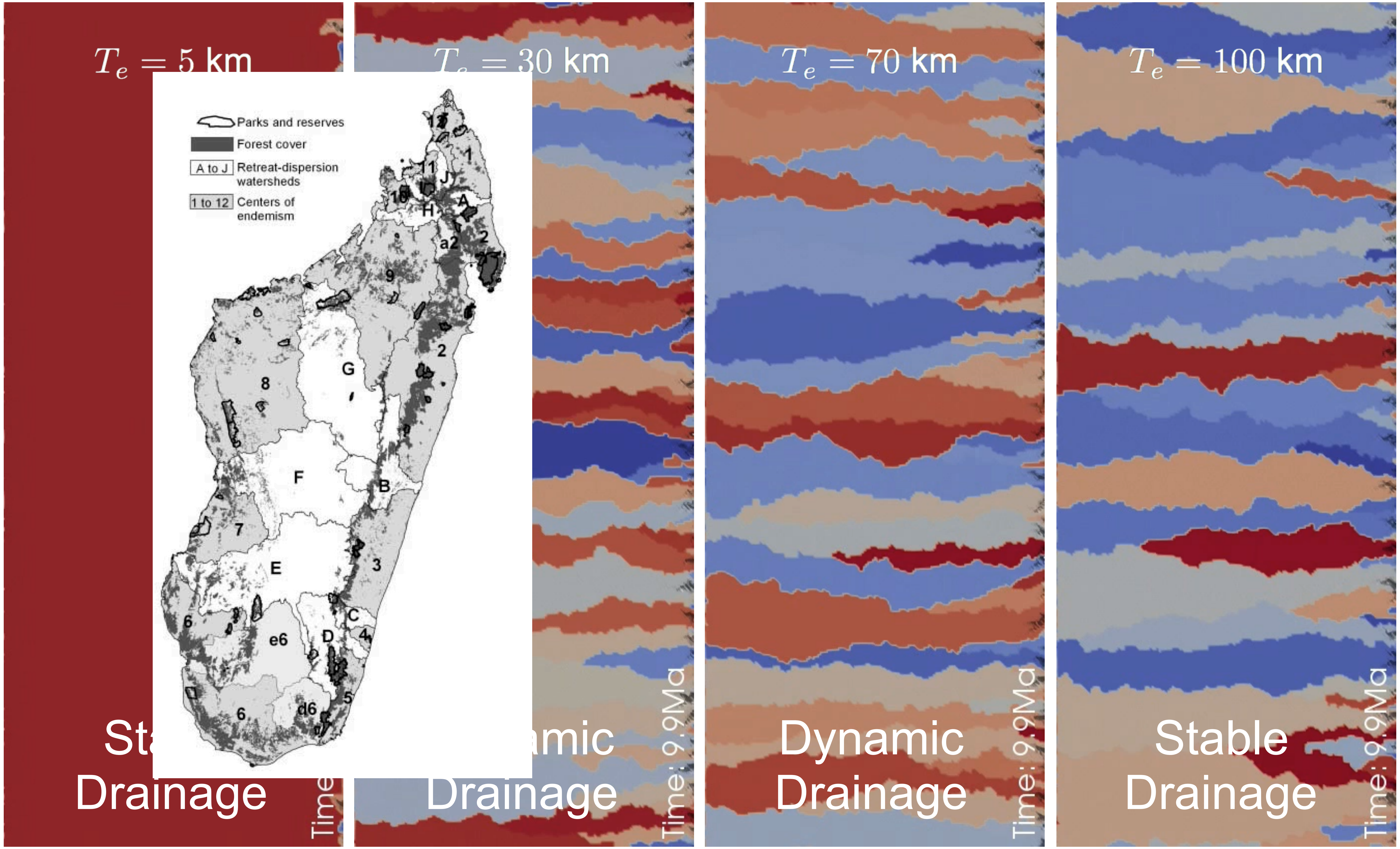


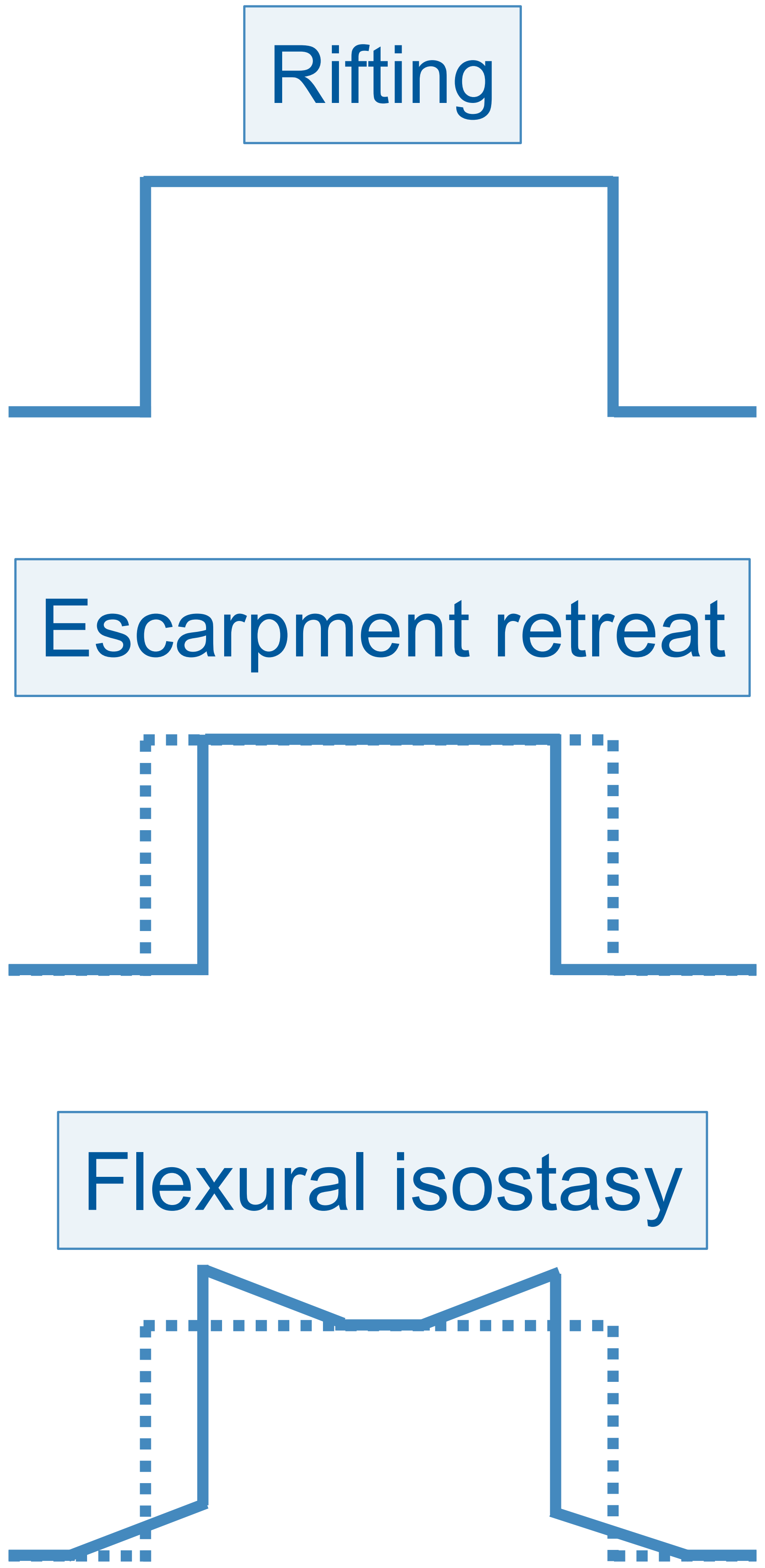
From Delaunay, 2018



From Horvarth et al, 2008

Flexure and watersheds form and evolution





Conclusions (1)

- Orogenic systems are complex systems
- They respond to changes in tectonic forcing and reach steady-state within a few million years
- If erosion rate is a non-linear function of height (slope, curvature, …) their erosional decay lasts much longer than their growth
- The response of erosional systems to variations in climate depends on the nature of the process, the size and the state of the system (climate, uplift rate)
- We should not expect a synchronous response of all parts of the Earth's system

Conclusions (2)

- Climate variability matters in erosional systems where thresholds exist AND when the threshold is close to the mean forcing
- This is independent of the erosional process

- There is a link between basin geometry, size and evolution, and biodiversity (species endemism and richness)
- Isostasy and flexure exerts a strong control on the shape and evolution of watersheds

Thank you

Effect of sedimentation

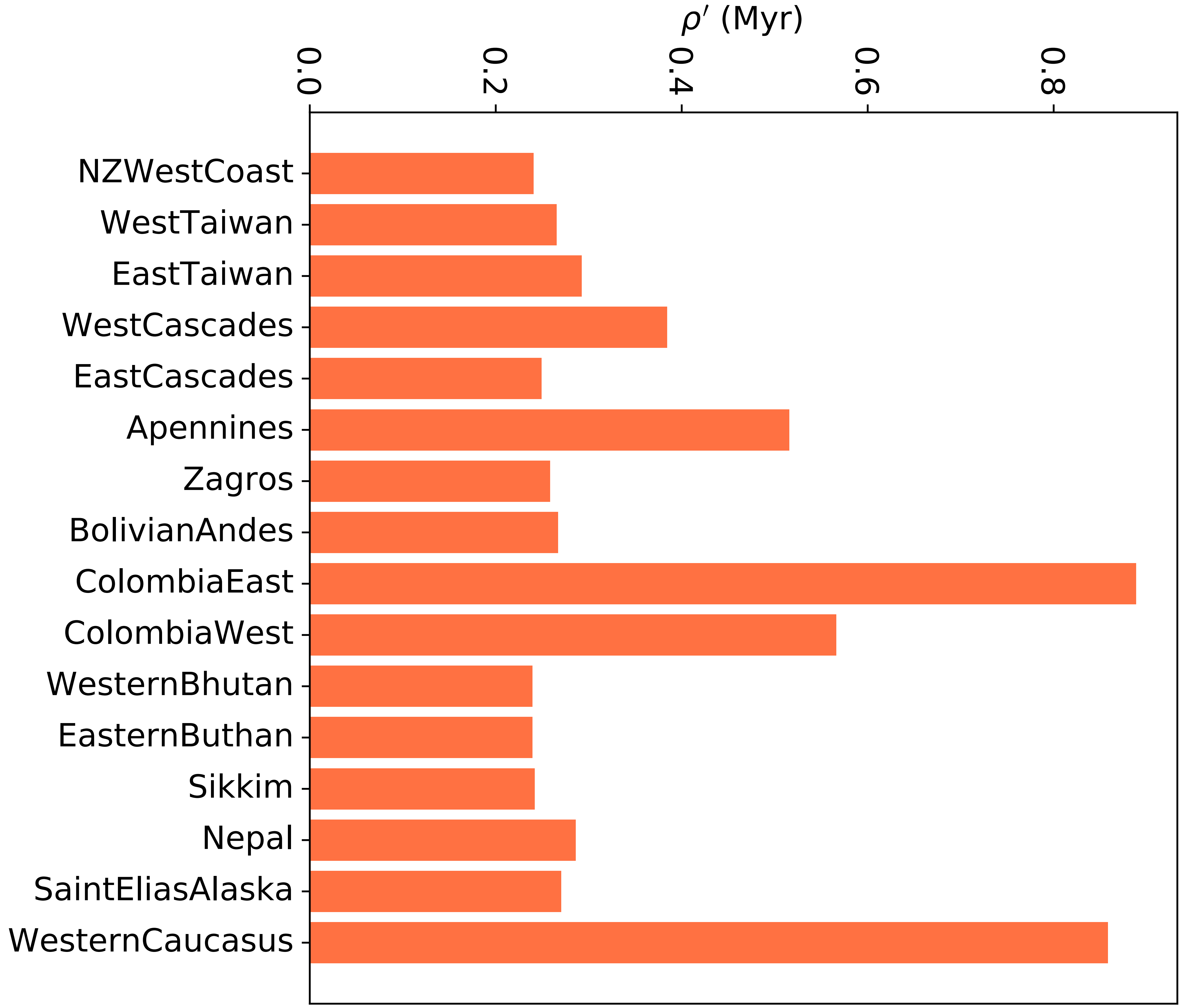
$$\frac{\partial e}{\partial t} = KA^m \frac{\partial h}{\partial x}^n - \frac{G}{A} \int_A (U - \frac{1}{\rho'} \frac{\partial h}{\partial t}) \, dA$$

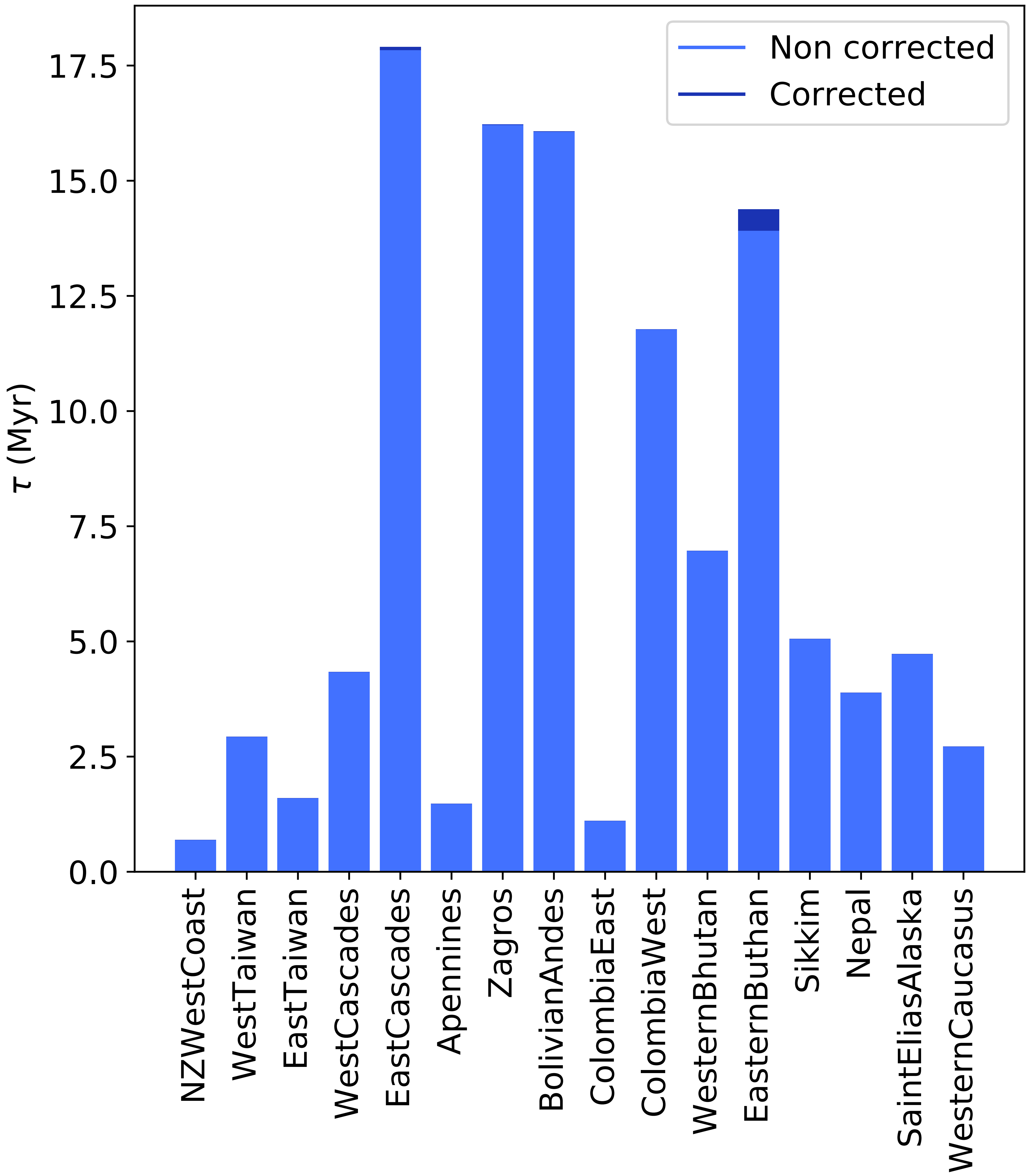
$$\tau = \frac{h_0}{\rho' U'}$$

where

$$U' = U(1 + G)$$

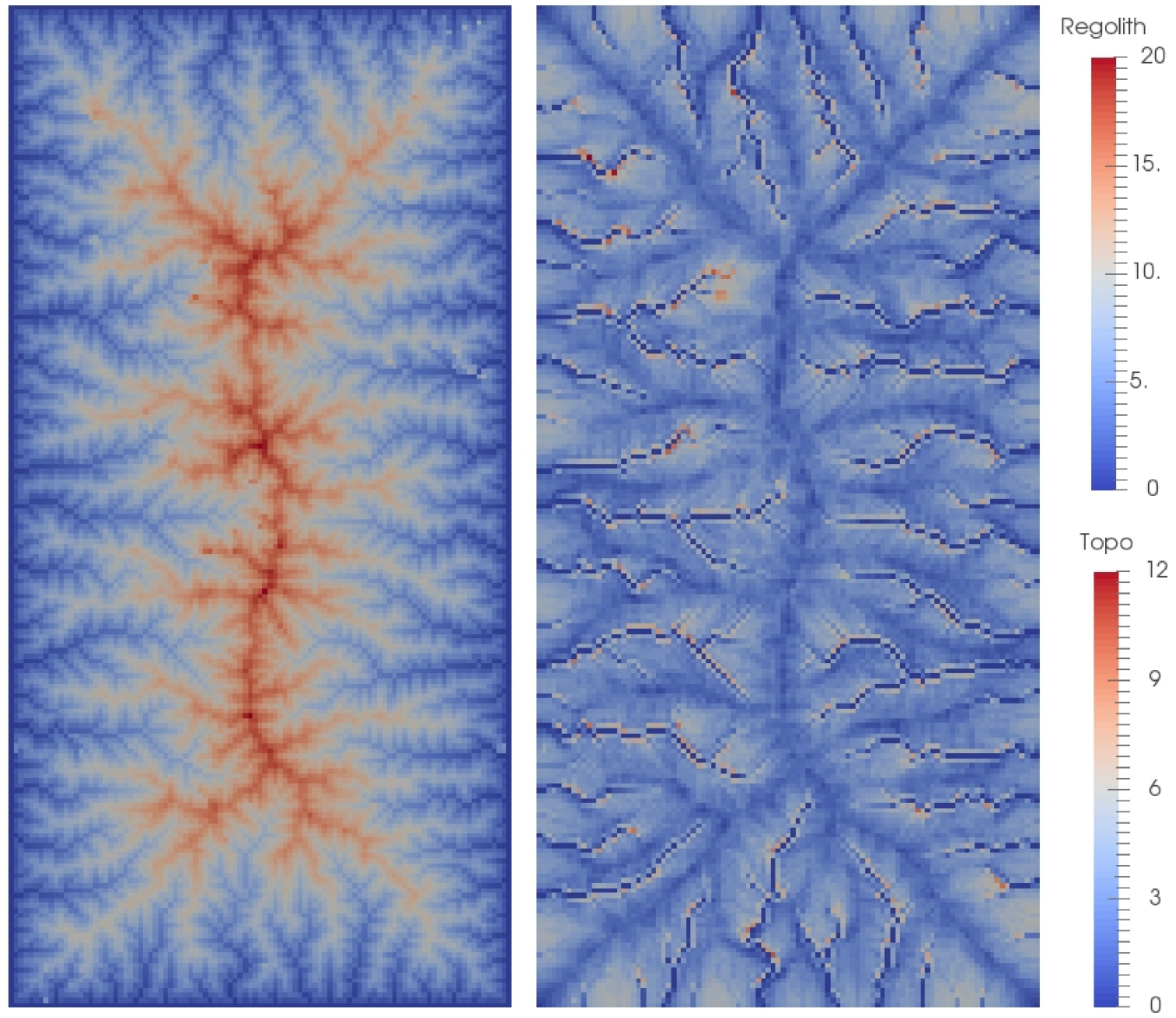
How important is isostasy?



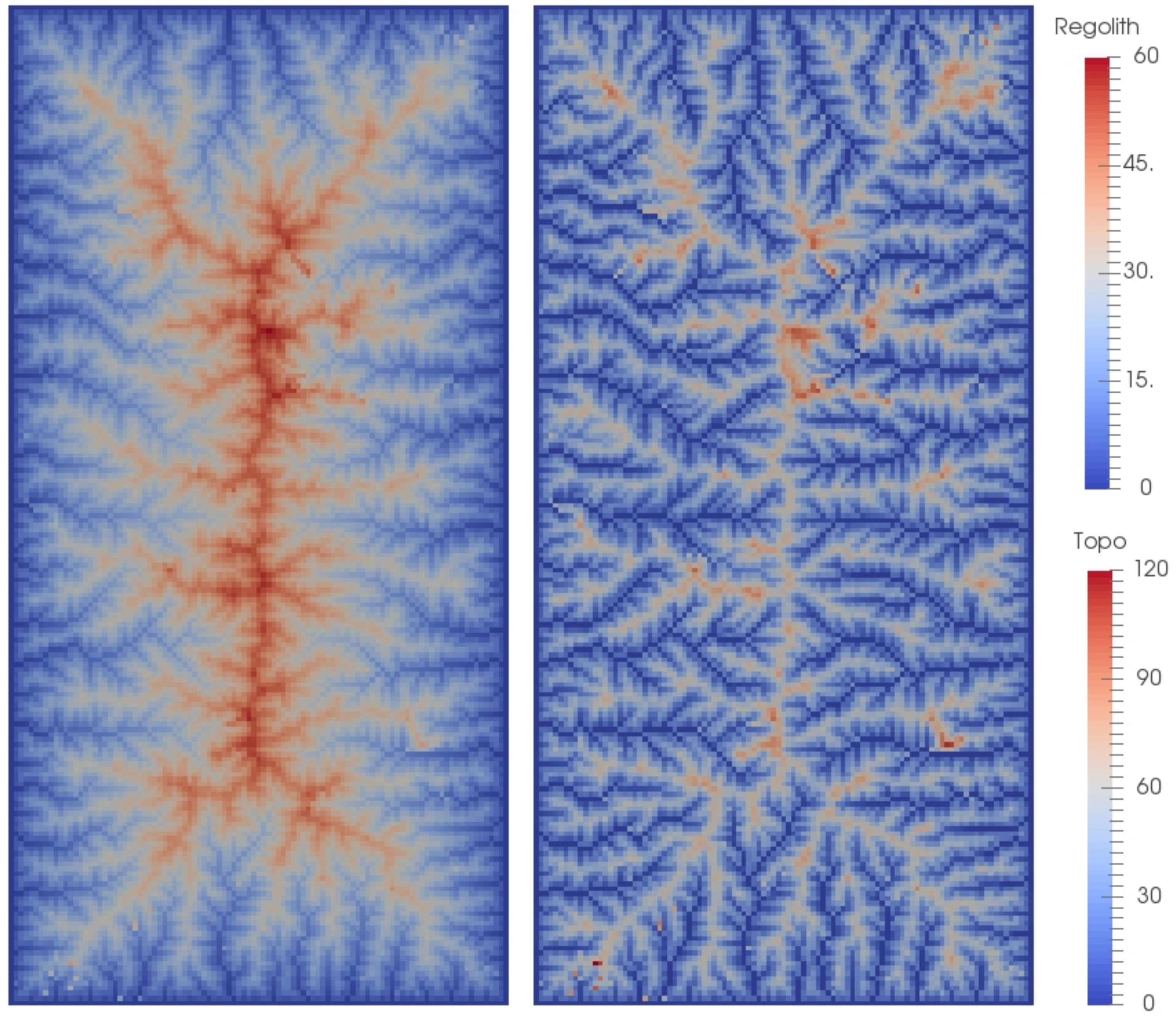


Weathering model

Low uplift rate (U = 50 m/Myr, D=0.001 m^2/yr)



High uplift rate (U = 500 m/Myr, D=0.001 m^2/yr)

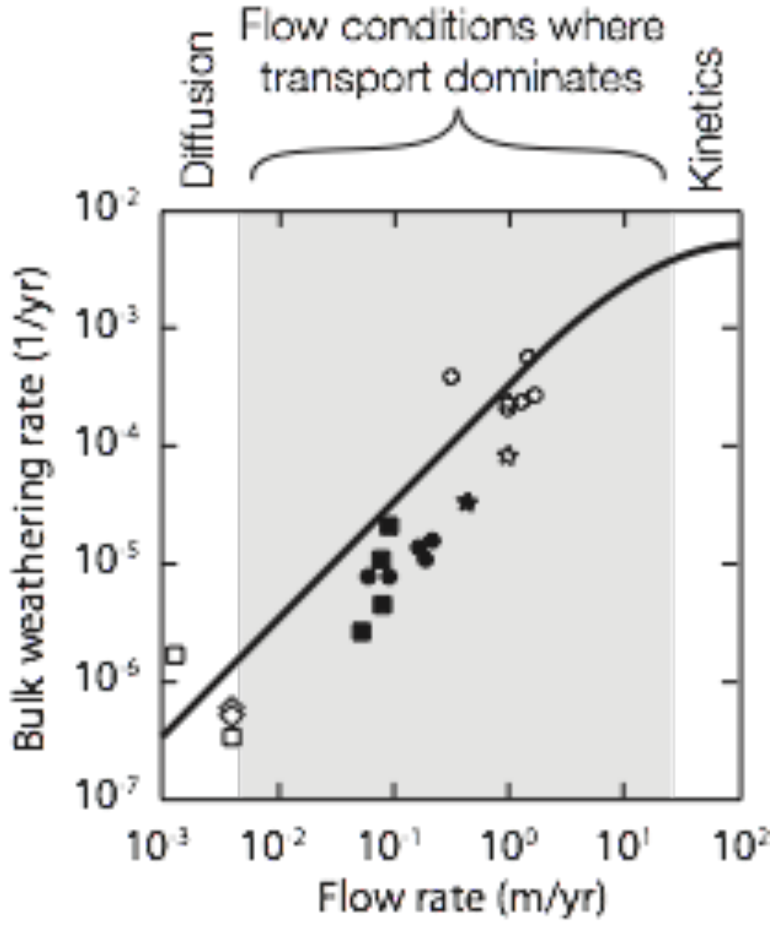


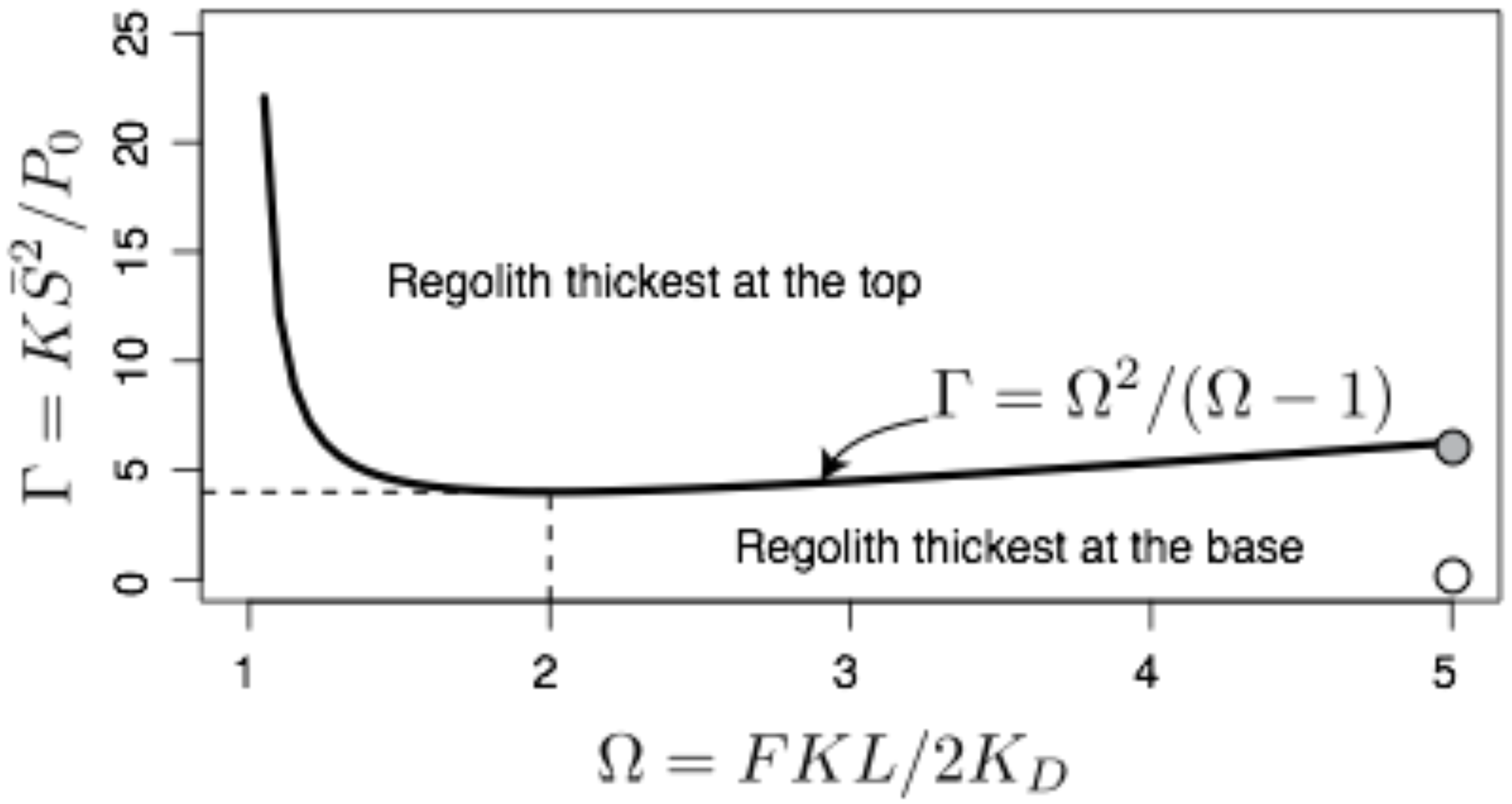
$$K(H - z + B)\frac{\partial H}{\partial x} + \int_L^x R\, dx' = 0$$

$$\frac{\partial z}{\partial t} = K_D \frac{\partial^2 z}{\partial x^2} + U_0$$

$$\frac{\partial B}{\partial t} = FK\frac{\partial H}{\partial x} + K_D \frac{\partial^2 z}{\partial x^2}$$

$$F = \frac{K_f}{K}\frac{d}{h}\frac{C_{eq}V_m}{M_p}$$





$$\Omega = \frac{FK\bar{S}}{U_0} \quad \text{and} \quad \Gamma = \frac{K\bar{S}^2}{P_0}, \quad \text{where} \quad \bar{S} = \frac{z_t}{L}$$