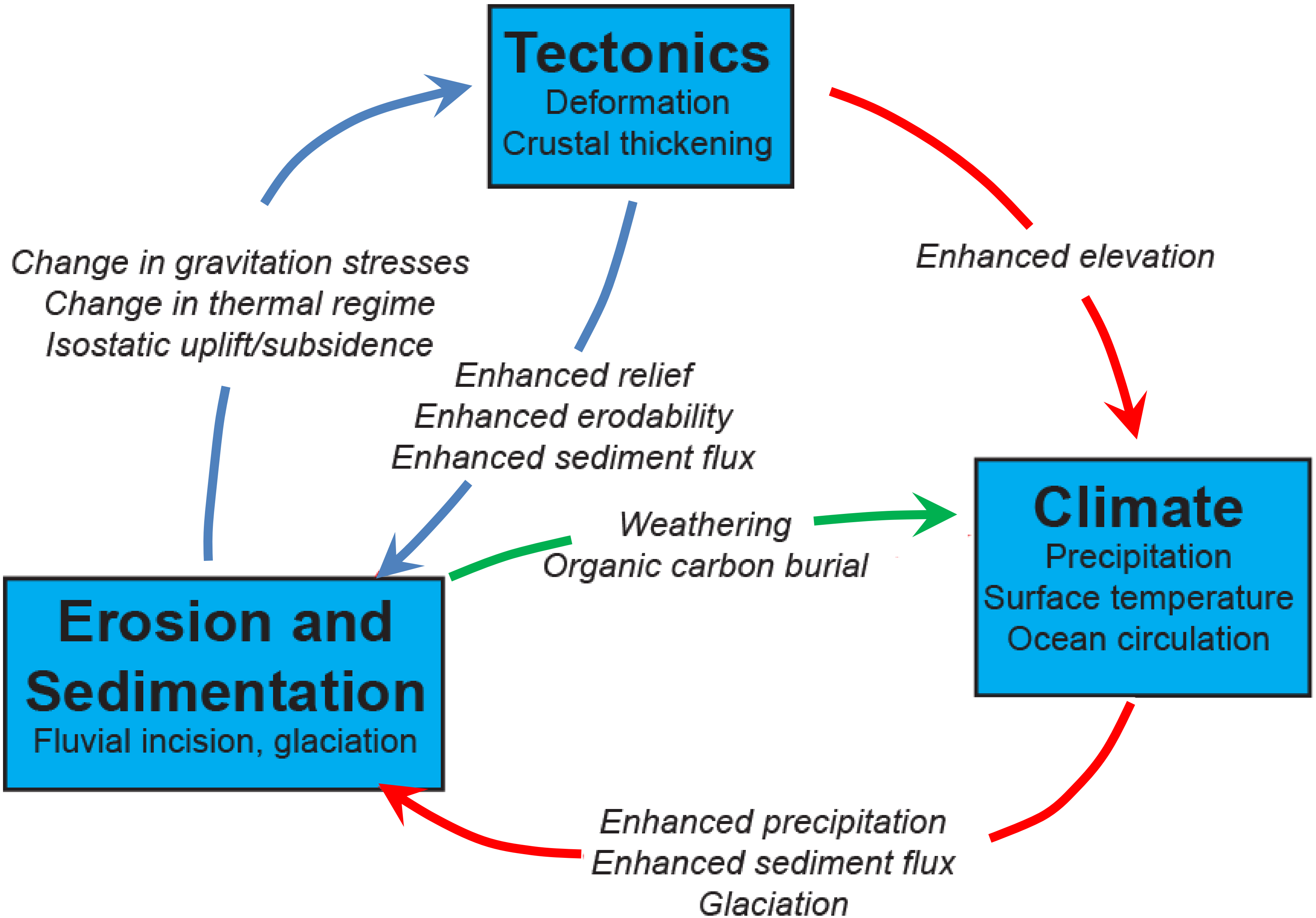
Coupling between tectonics, climate and surface processes

Mechanisms and effects

Guy Simpson - University of Geneva

11th international workshop on modeling of mantle convection and lithosphere dynamics (Braunwald, 2009)


Tectonics
Deformation
Crustal thickening
Change in gravitation stresses
Change in thermal regime
Isostatic uplift/subsidence
Enhanced elevation
Enhanced relief
Enhanced erodability
Enhanced sediment flux
Weathering
Organic carbon burial
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Surface temperature
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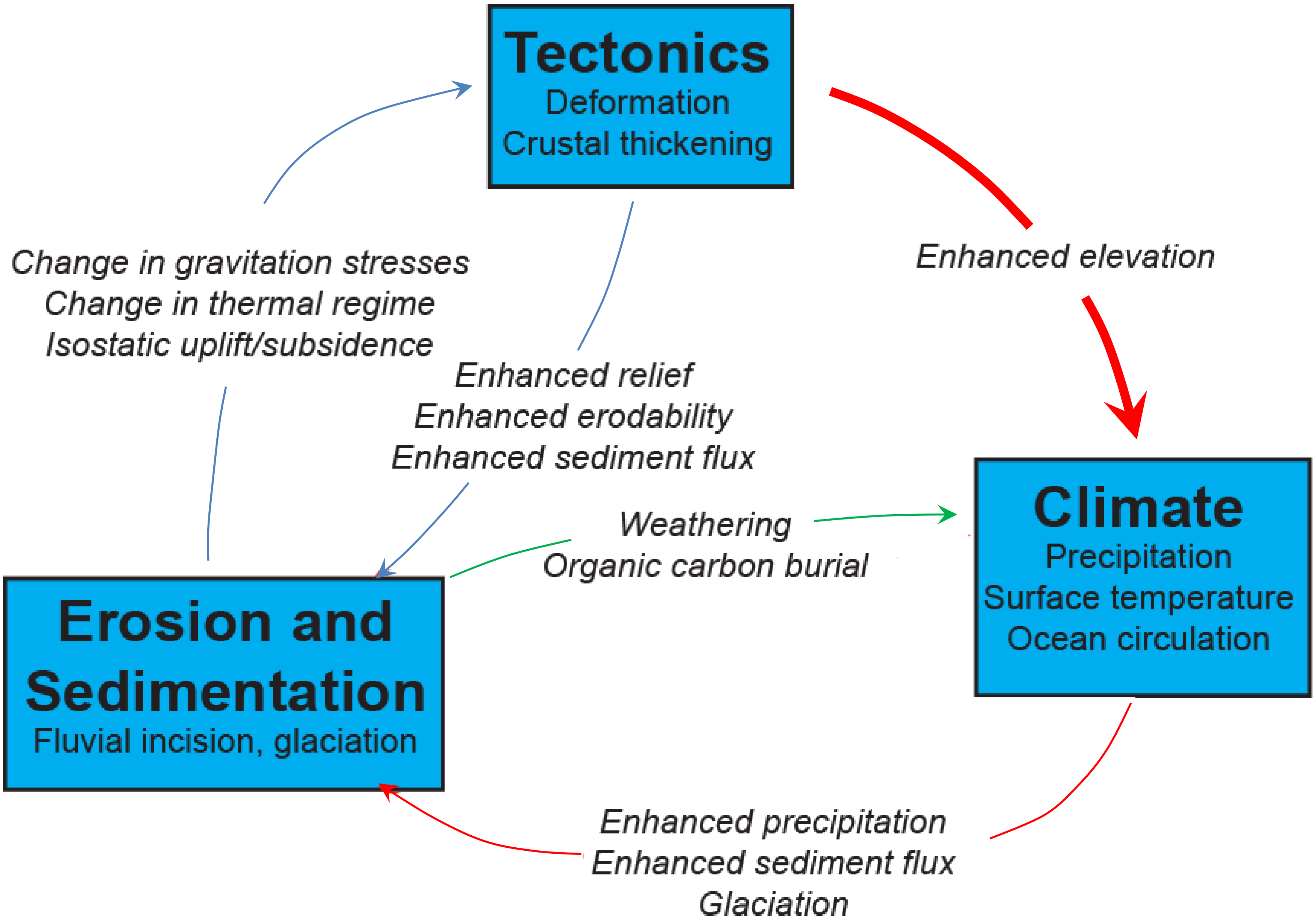
Fluvial incision, glaciation
Enhanced precipitation
Enhanced sediment flux
Glaciation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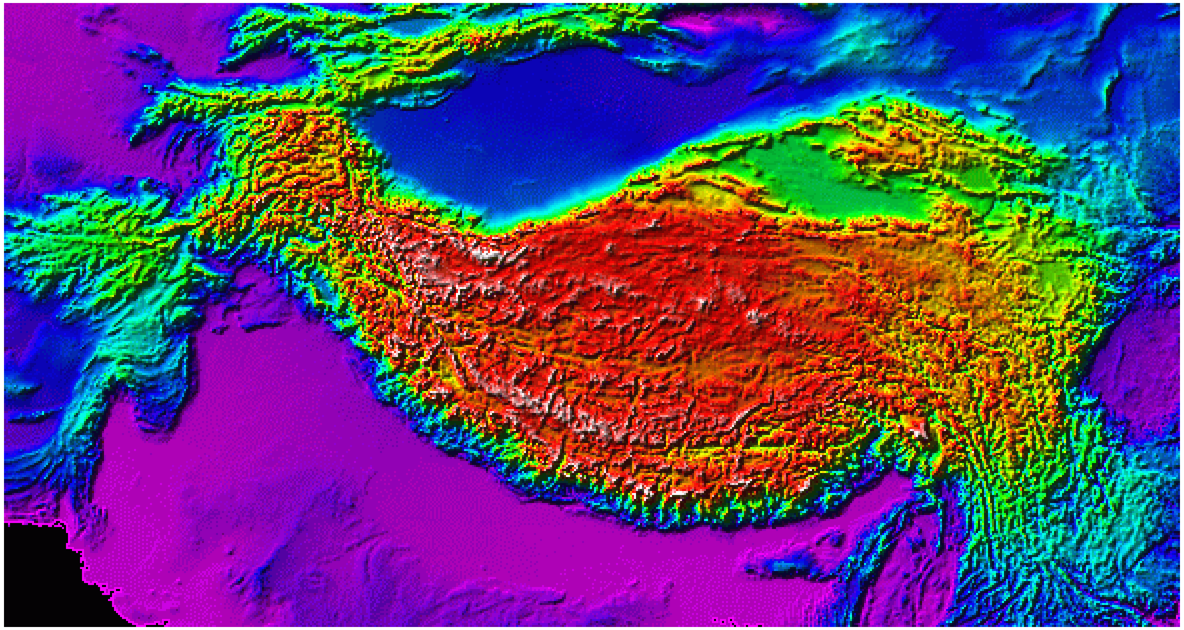
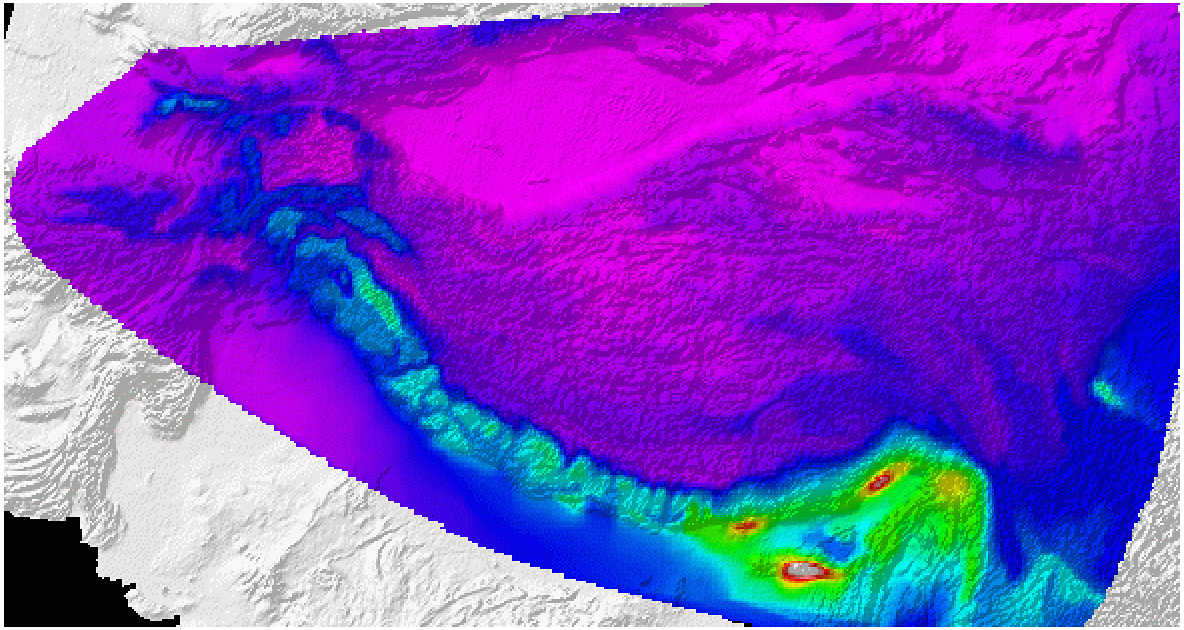
Precipitation patterns and topography

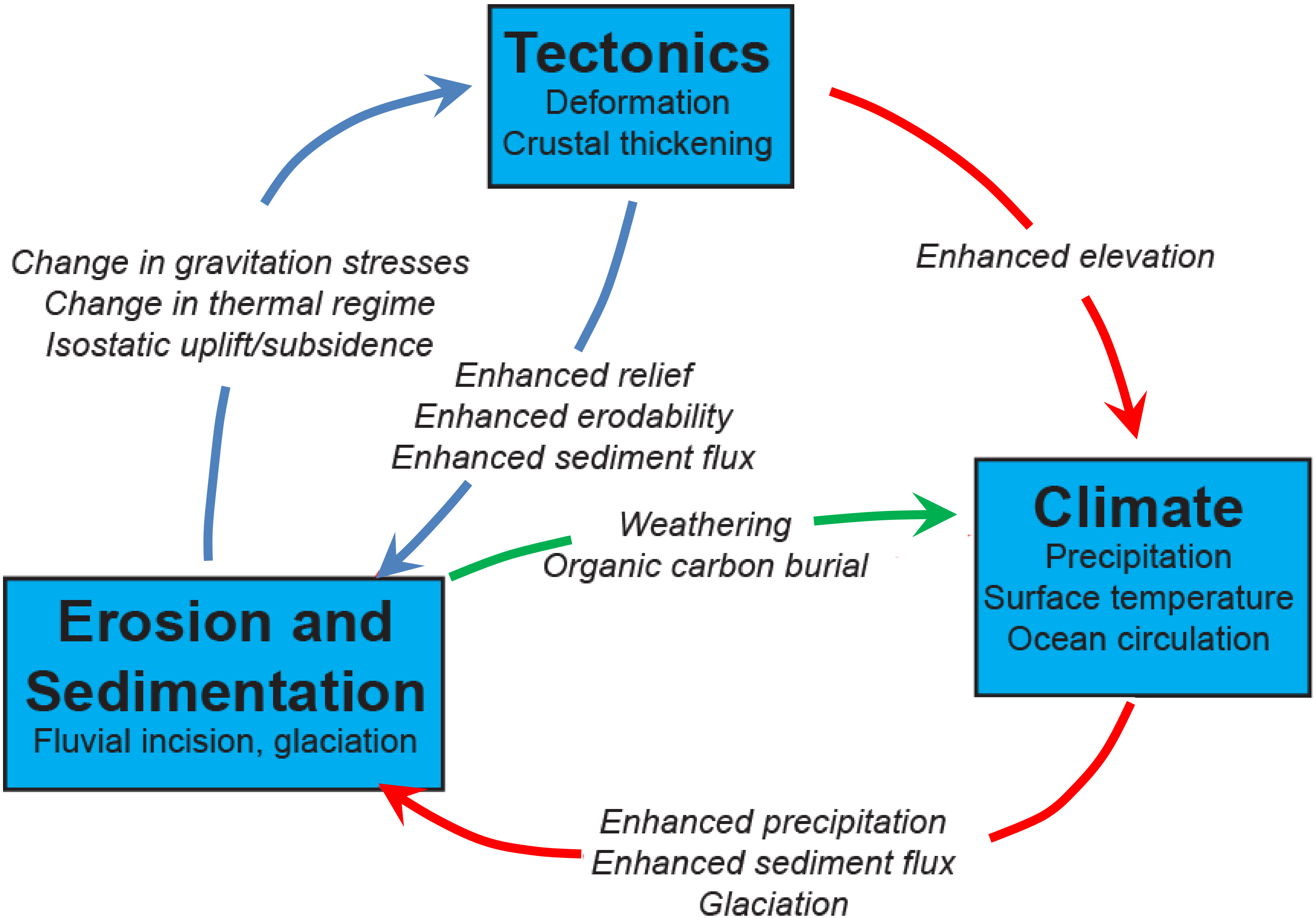
Images: C. Duncan



Topographic elevation



Mean annual precipitation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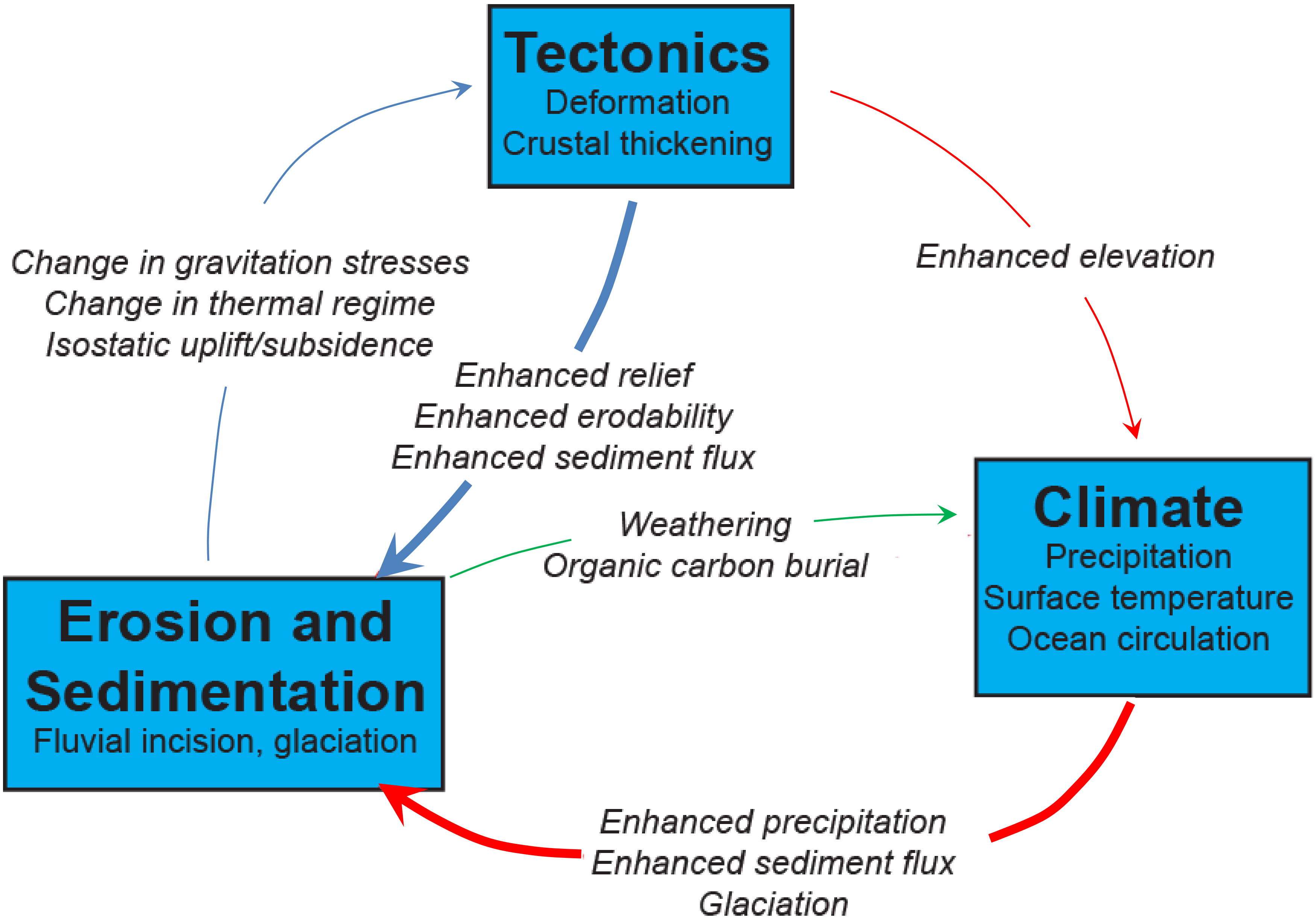
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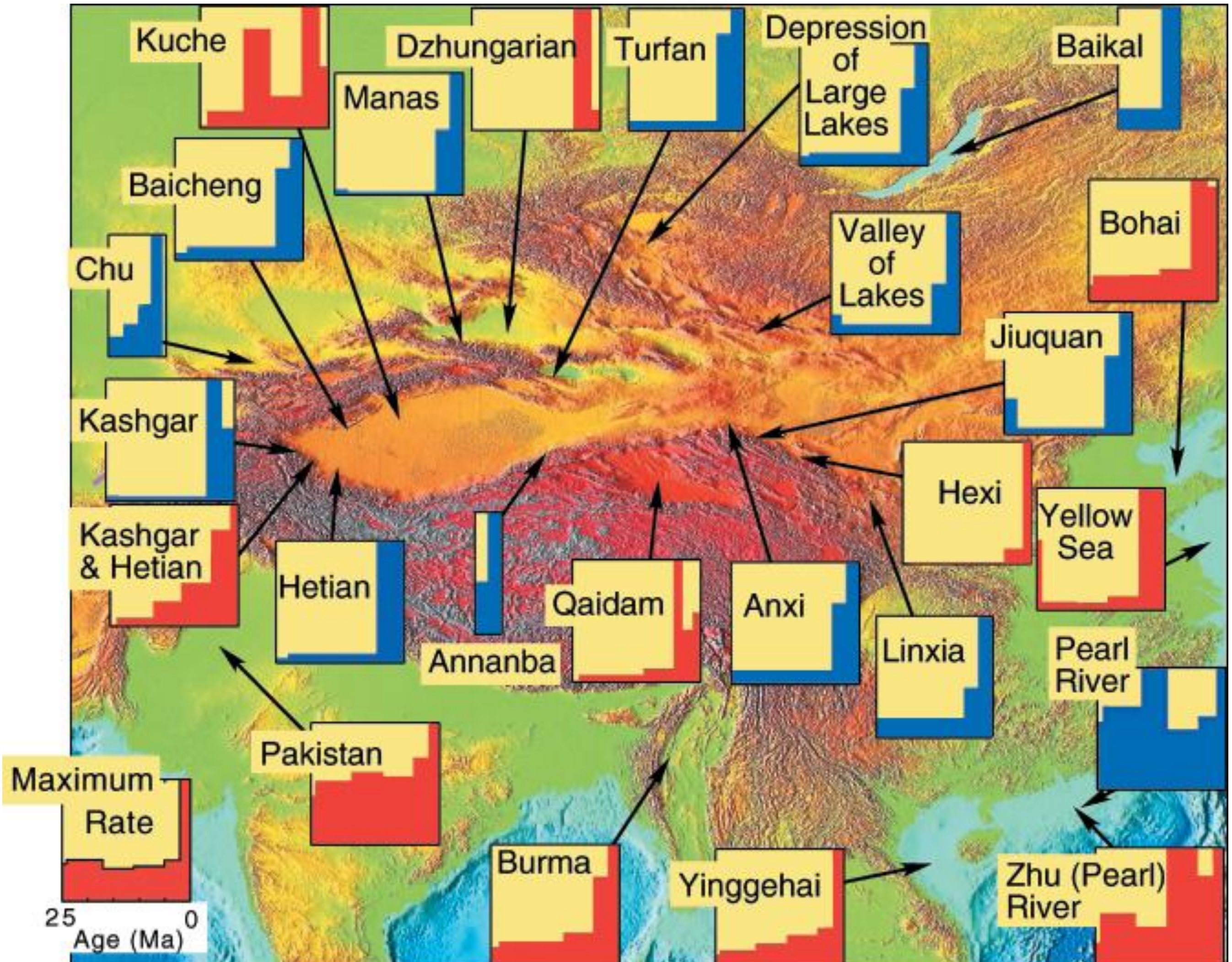
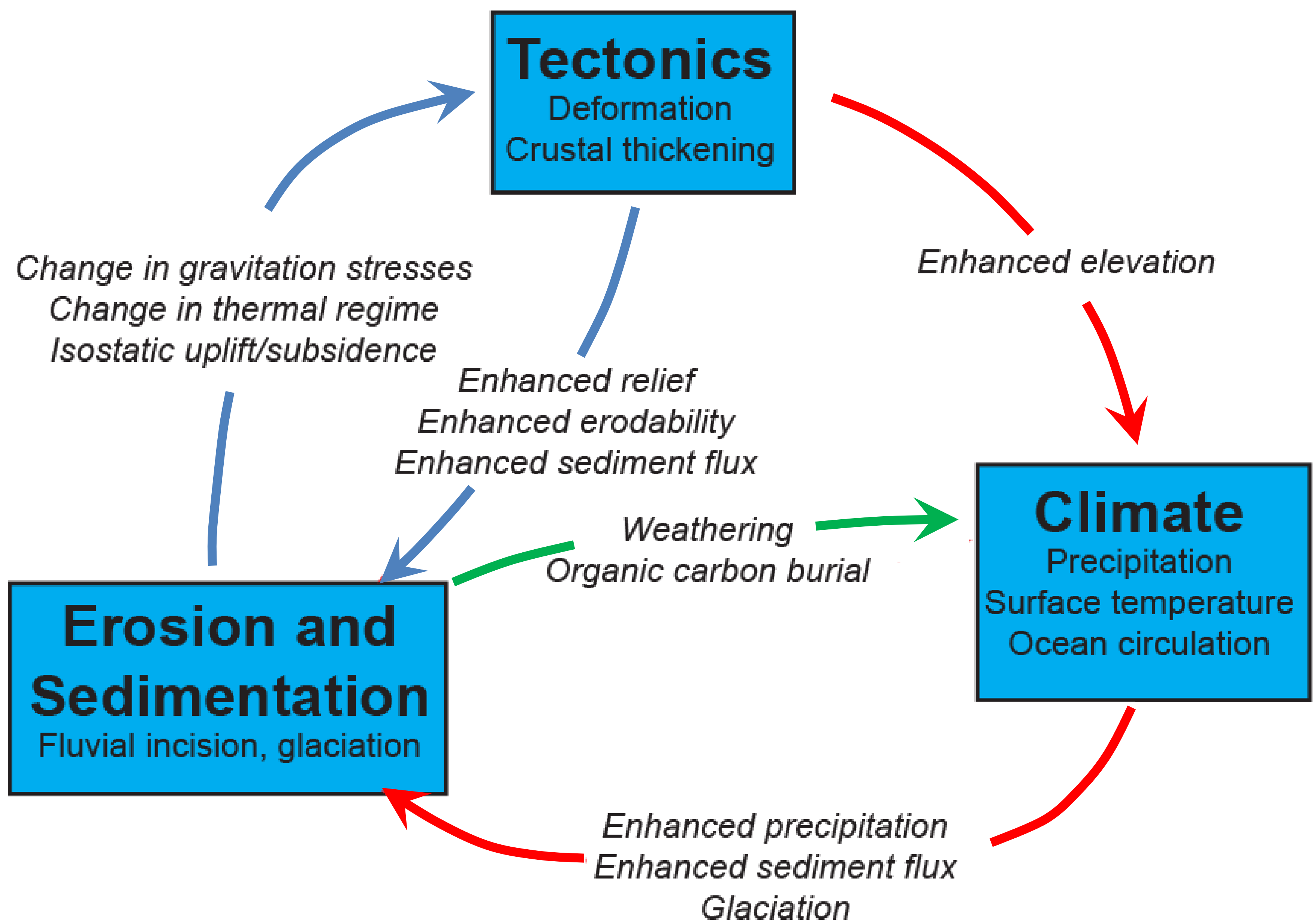
Impact of uplift and climate change on erosion and sediment fluxes



Sedimentation rates over last 25 My *Molnar et al. (2001)*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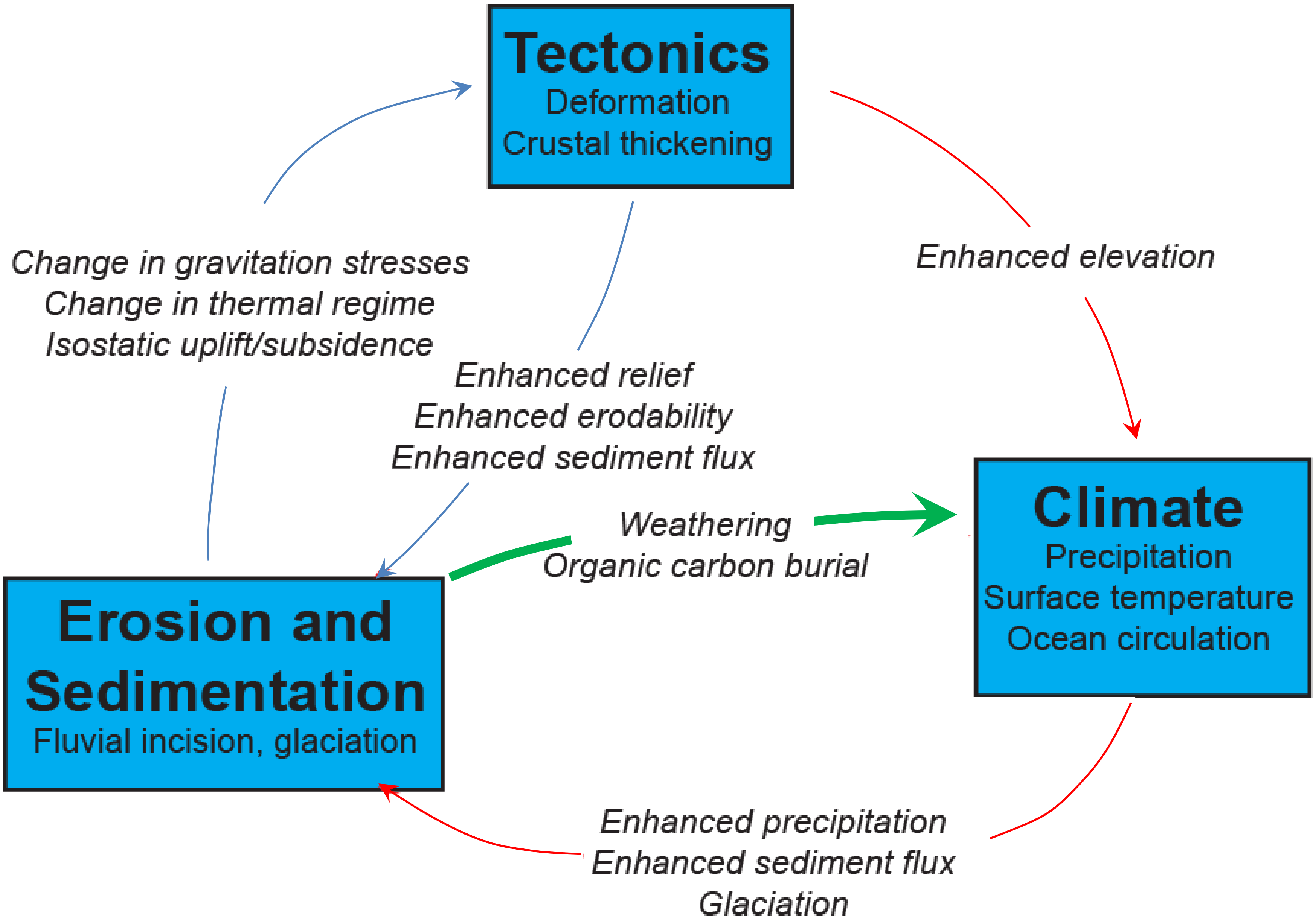
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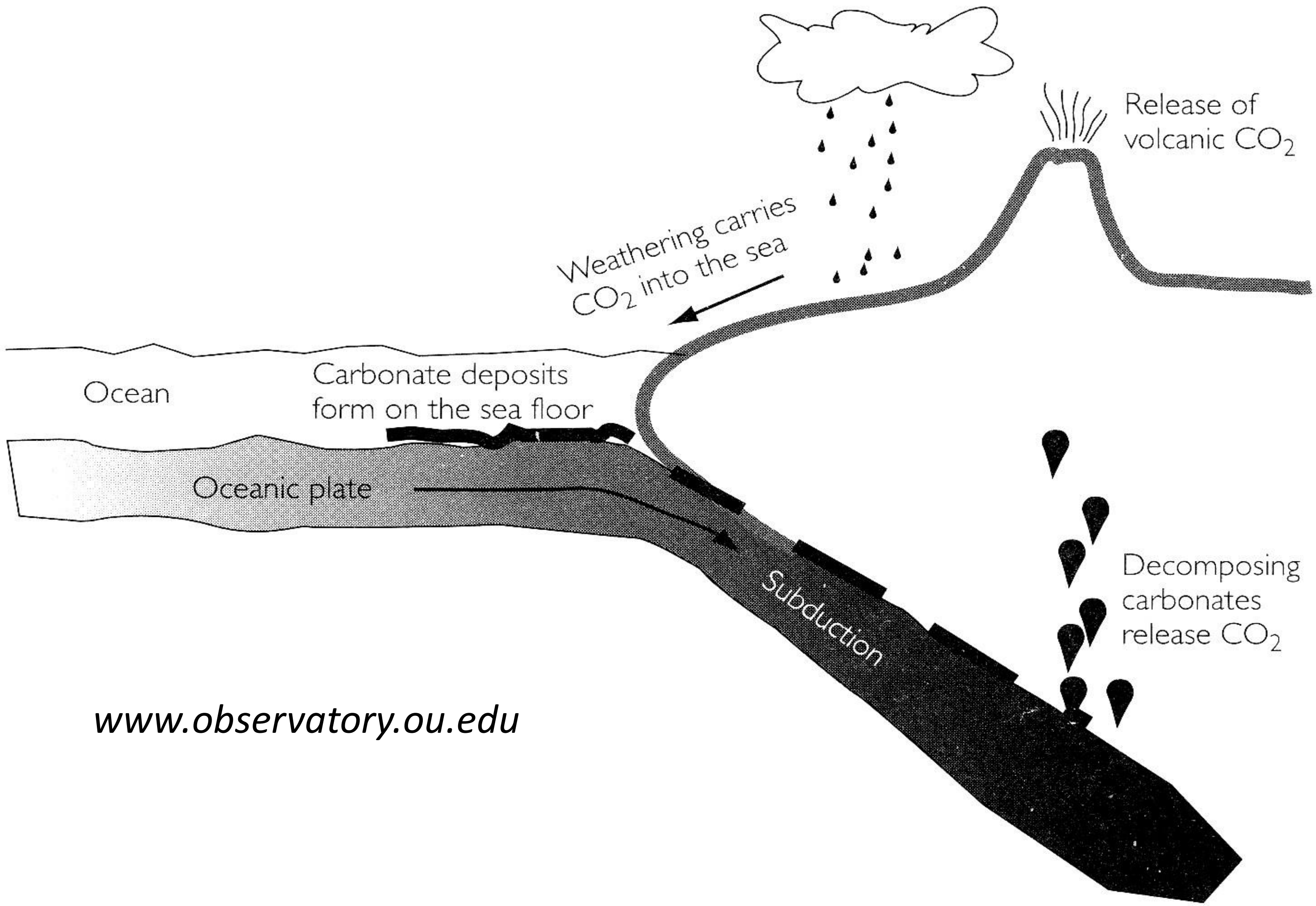
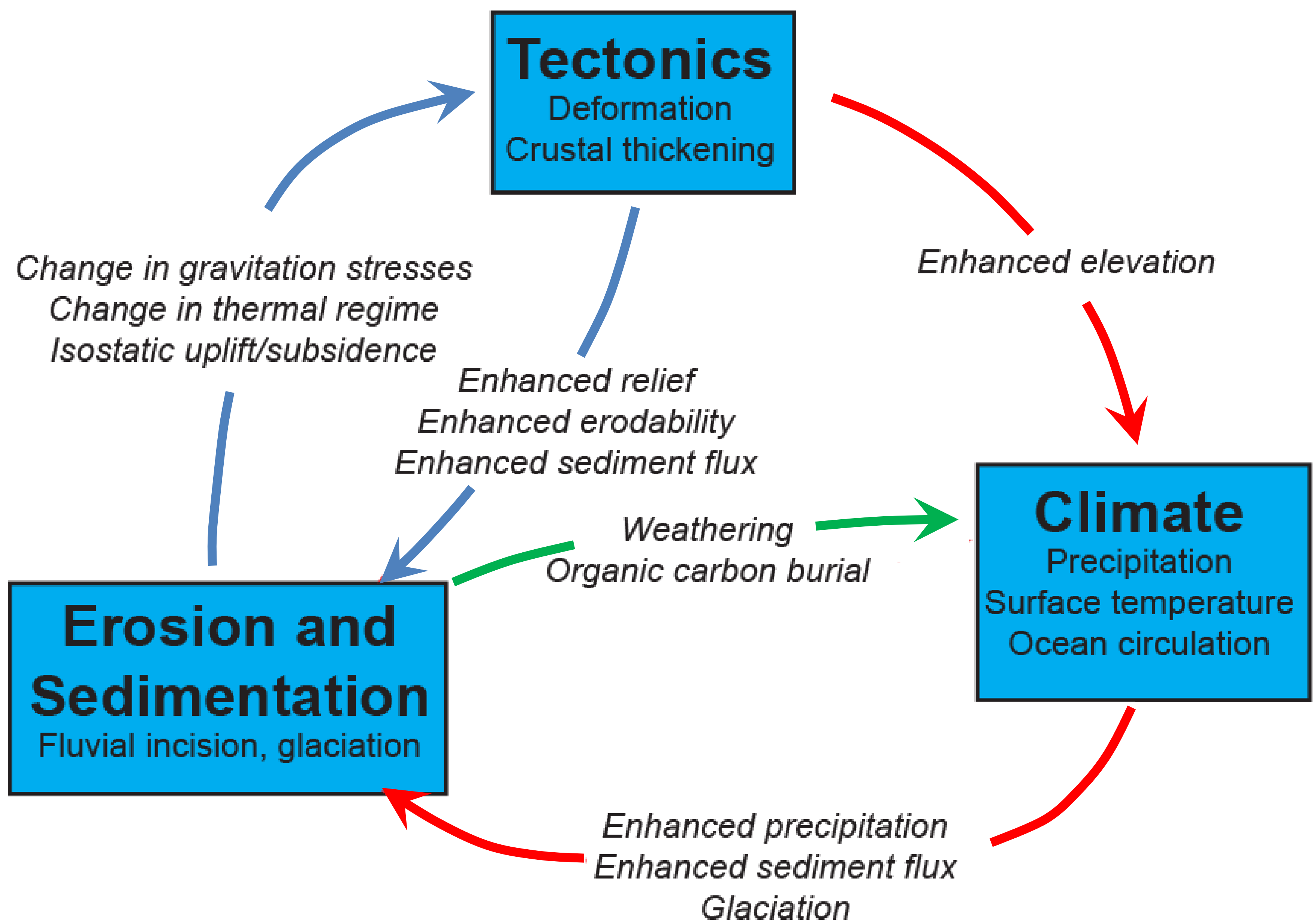
Weathering climate change



www.observatory.ou.edu

The chemical weathering that accompanies erosion plays a major role in regulating climate by buffering carbon dioxide levels in the atmosphere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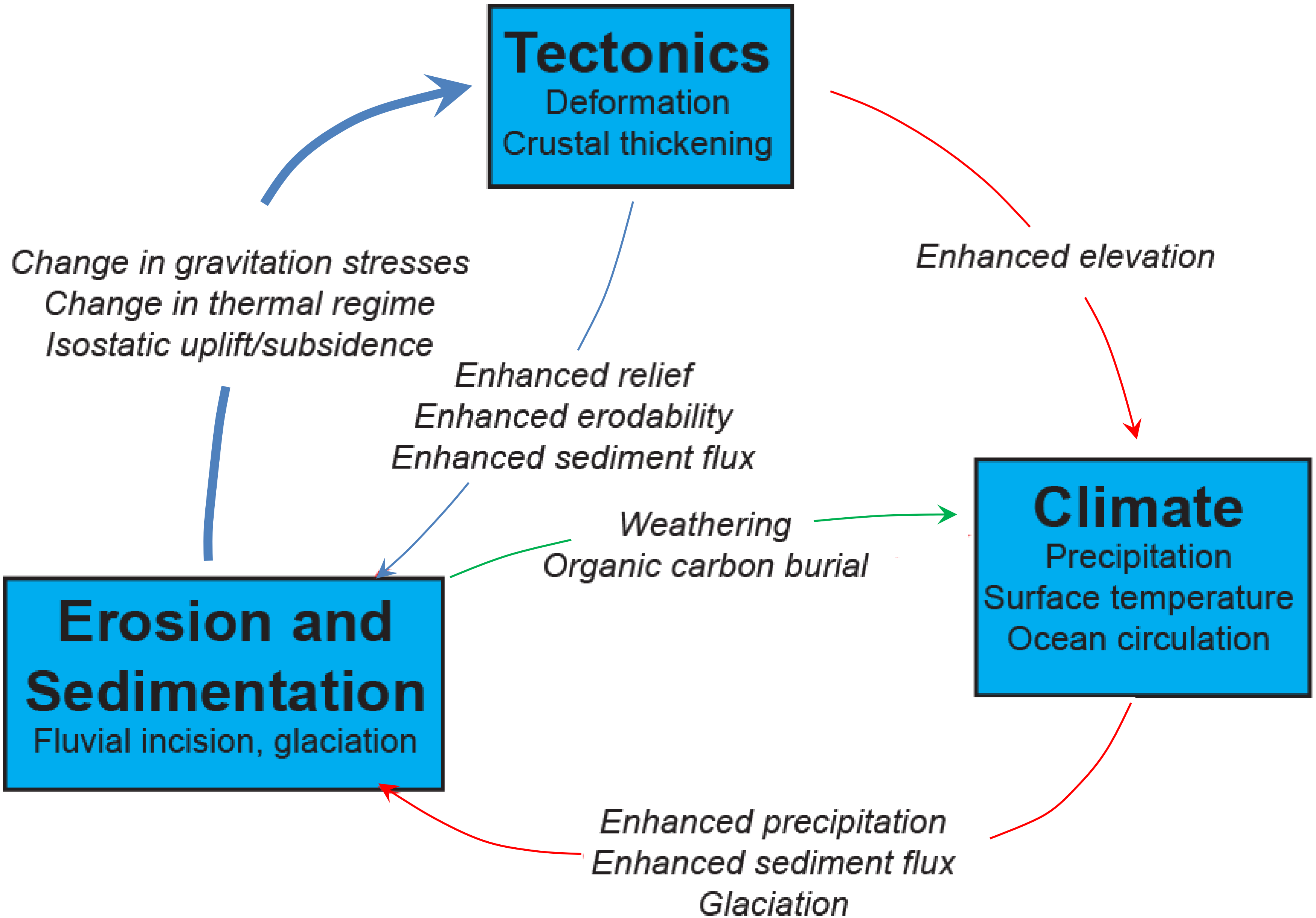

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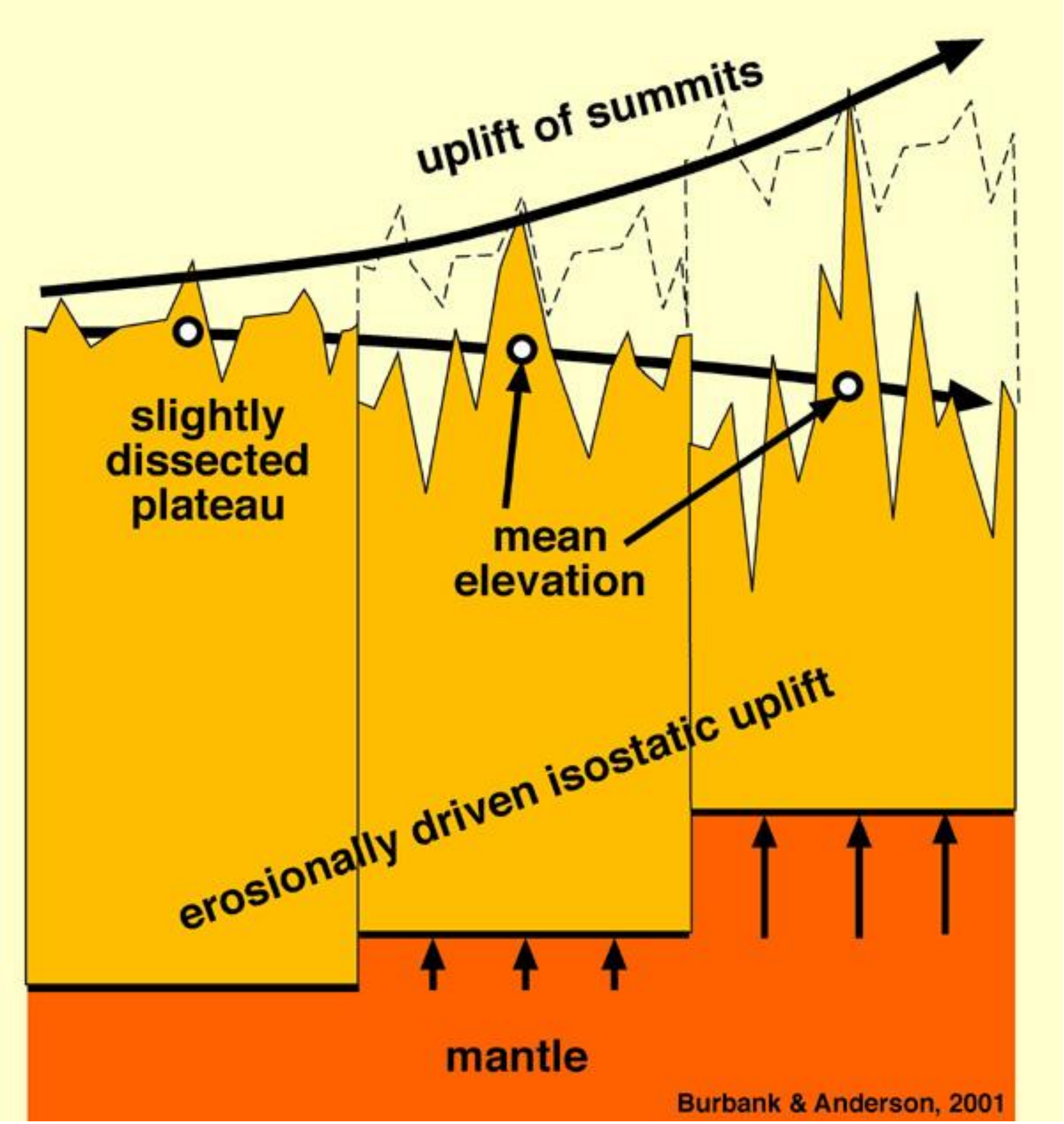
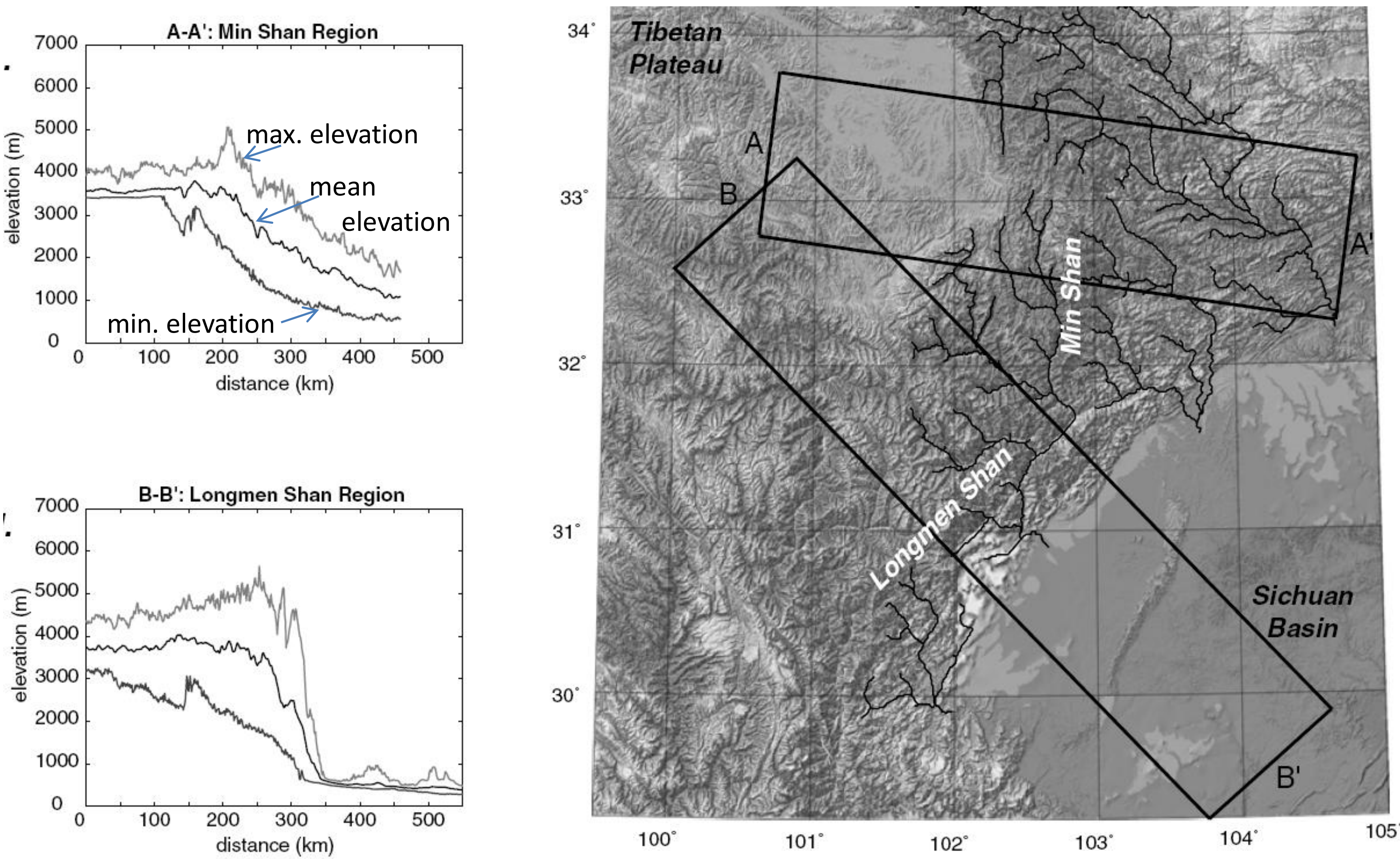
Erosion and isostatic uplift

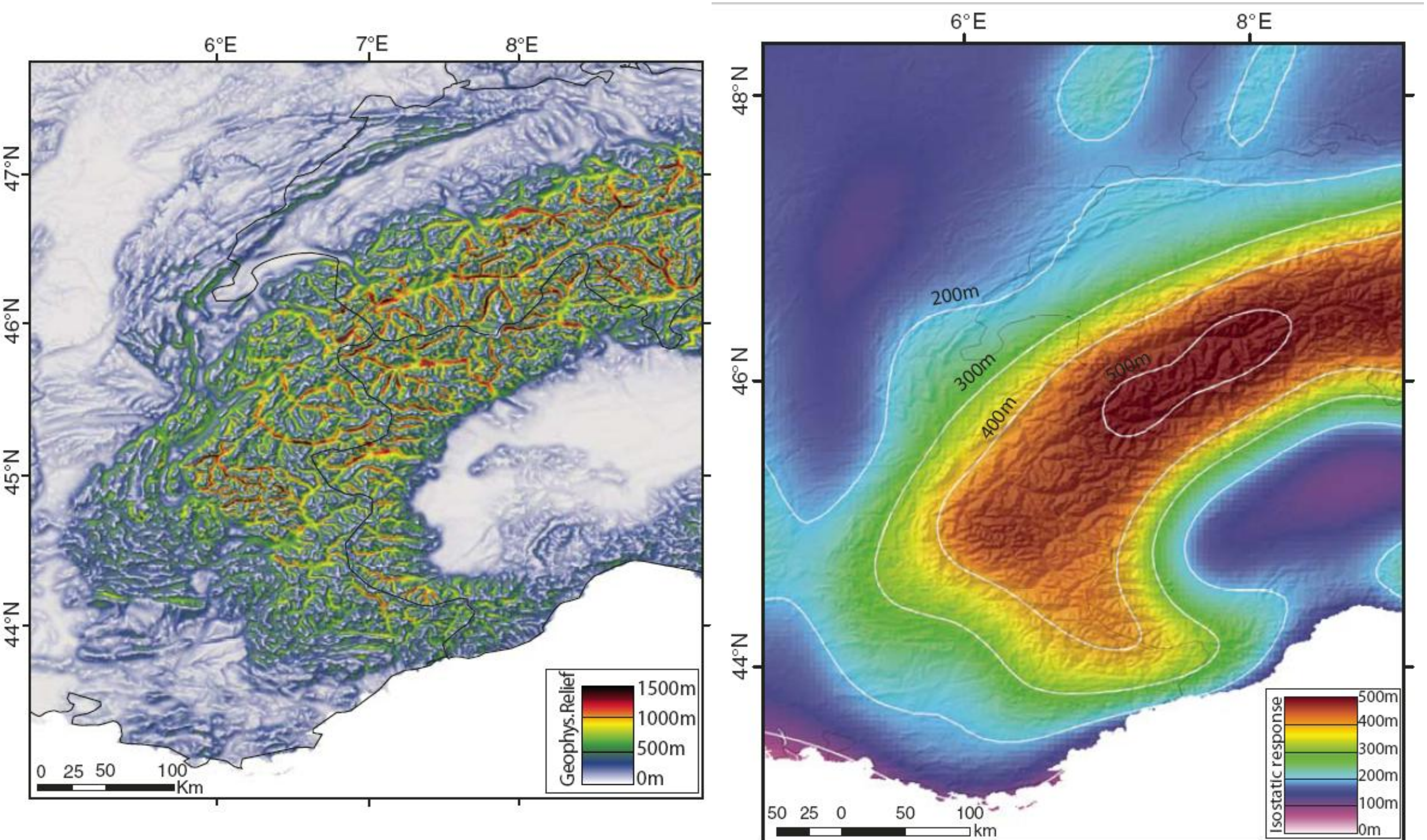


Erosion and isostatic uplift of plateau-margin peaks



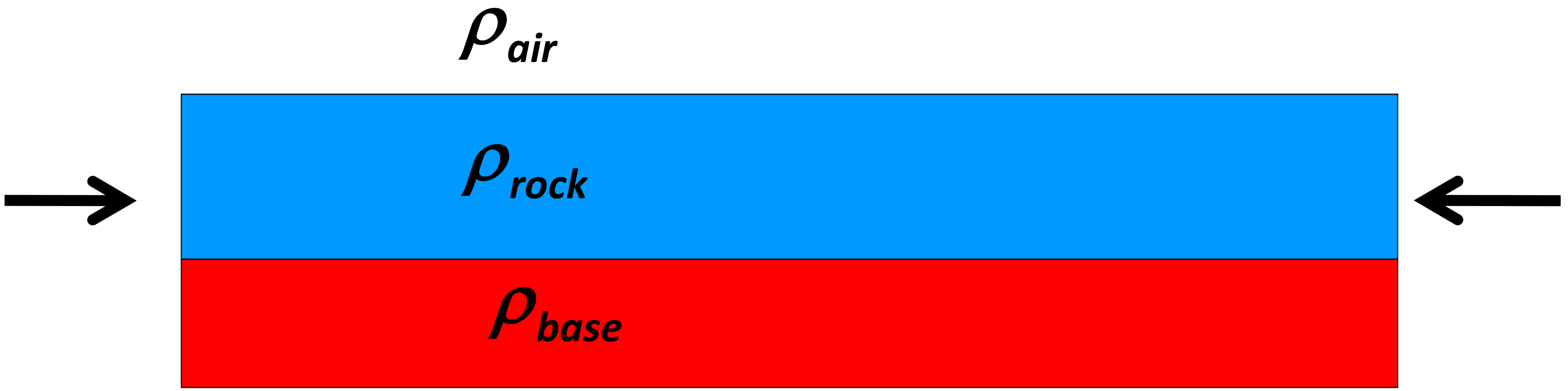
Kirby et al (2002)

Quaternary erosion and isostatic uplift of Alps

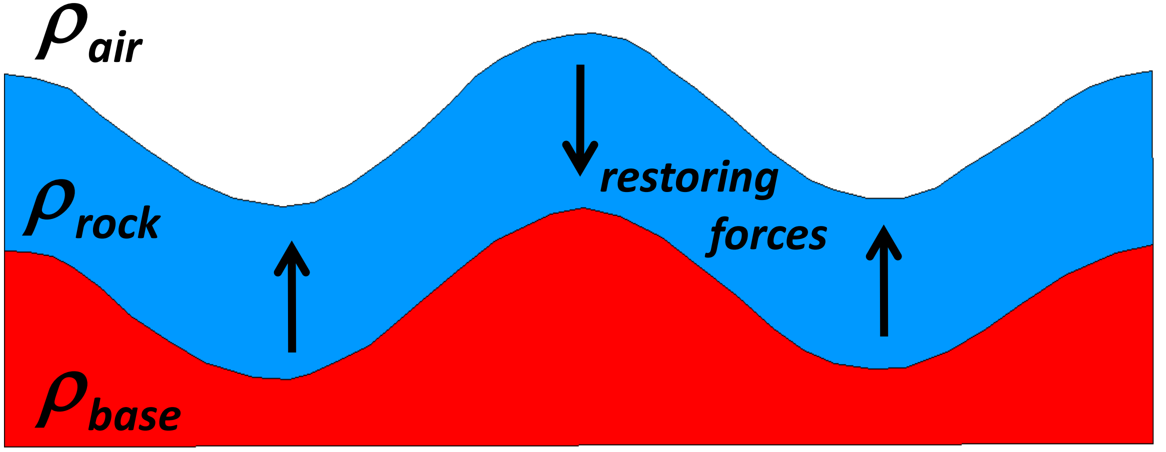


Champagnac et al. (2007)

Mass redistribution and the modification of gravitational stresses

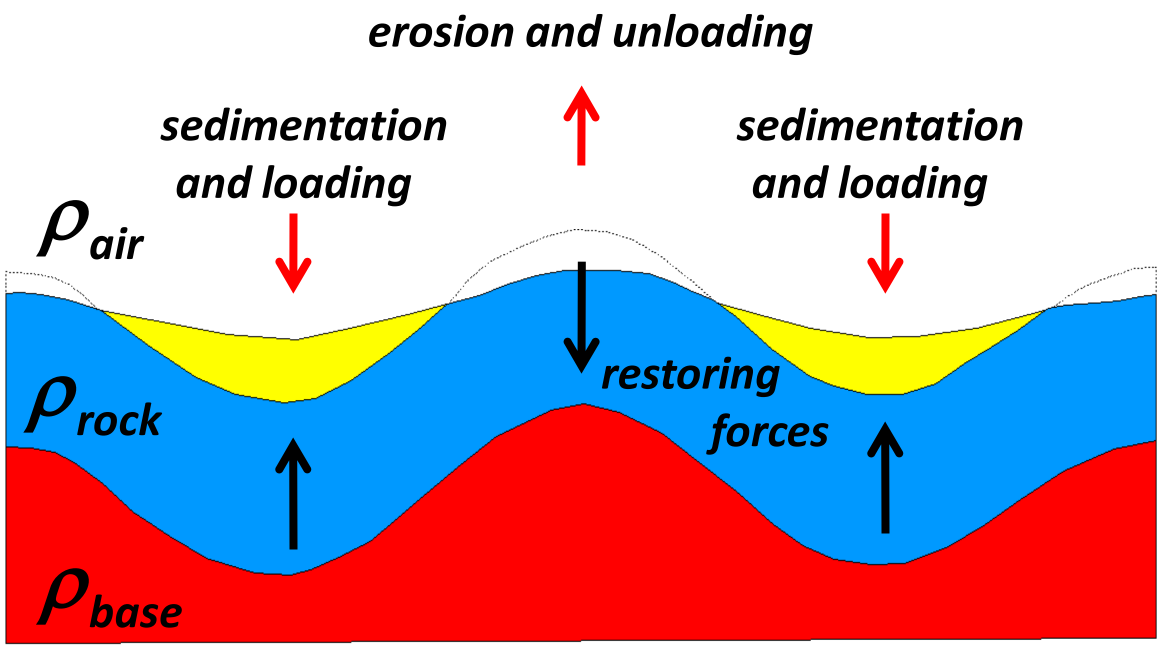


Mass redistribution and the modification of gravitational stresses



➢ ***Deformation of density surfaces creates restoring forces that inhibit deformation***

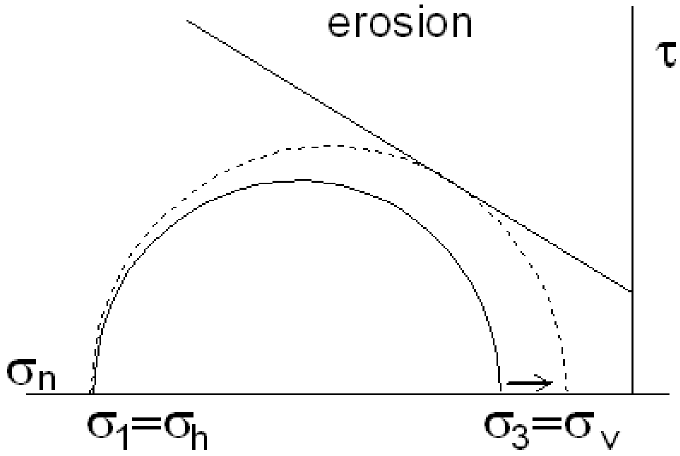
Mass redistribution and the modification of gravitational stresses



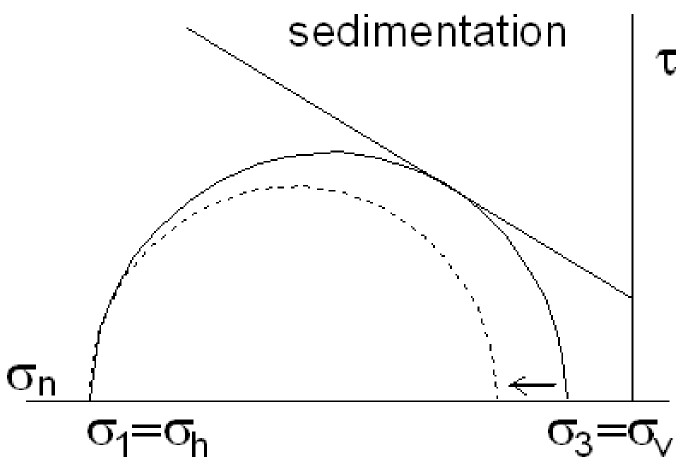
- ***Surface mass redistribution facilitates deformation by counteracting restoring forces***

The importance of rheology……

Compressive tectonic setting, elastic plastic material



→ Plastic strain localisation

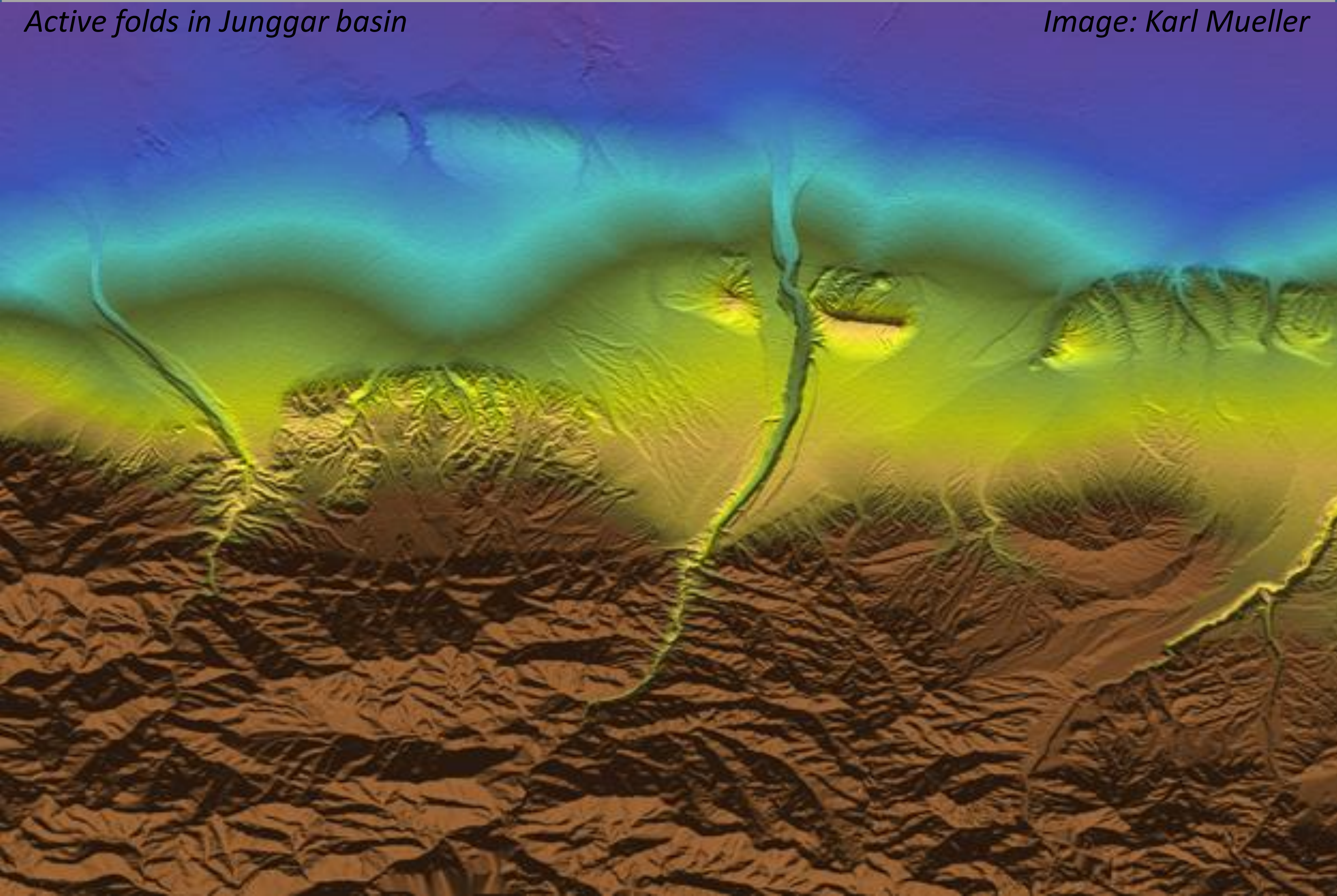


→ Strengthening
(no longer plastic)

Erosion-amplified folding

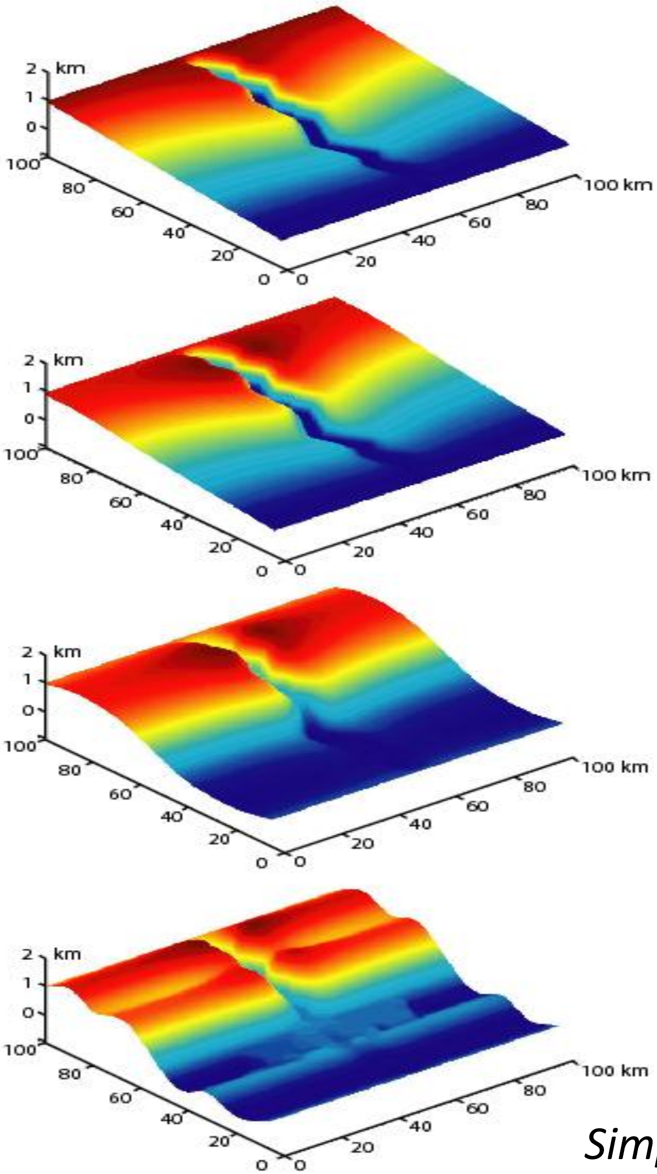
Active folds in Junggar basin

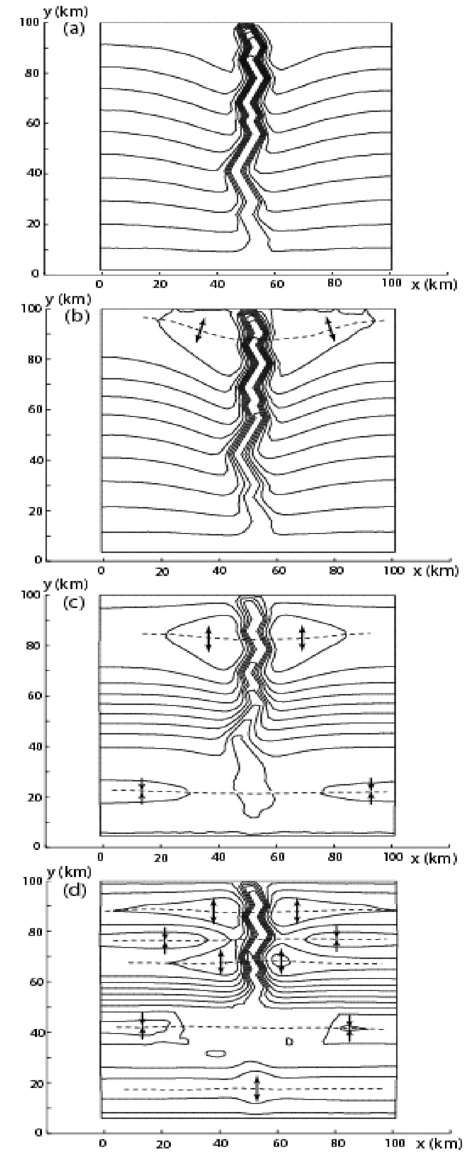
Image: Karl Mueller



Interaction between folding and river incision

Numerical results from an elastic-plastic thin plate model

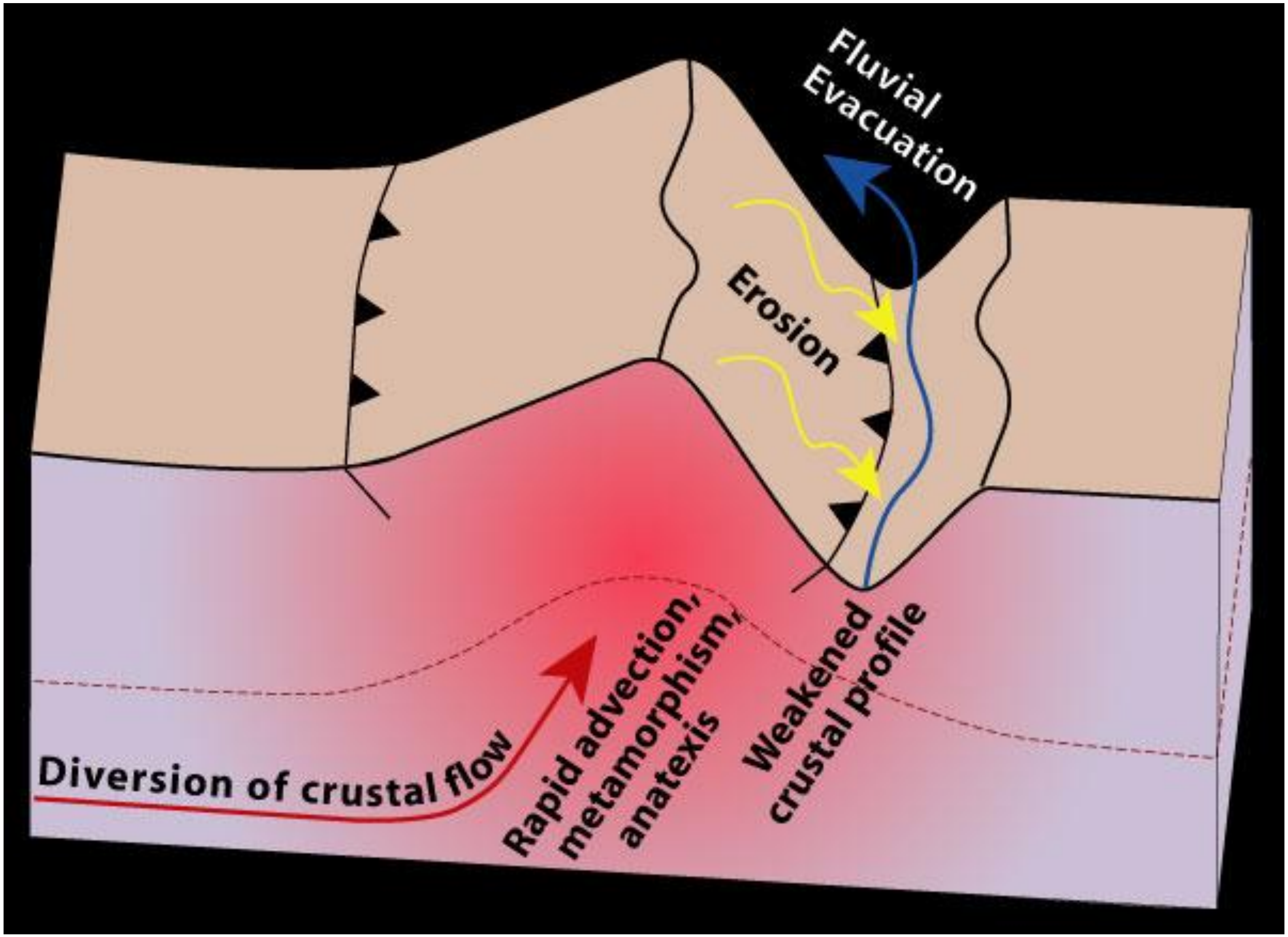




Simpson (2004)

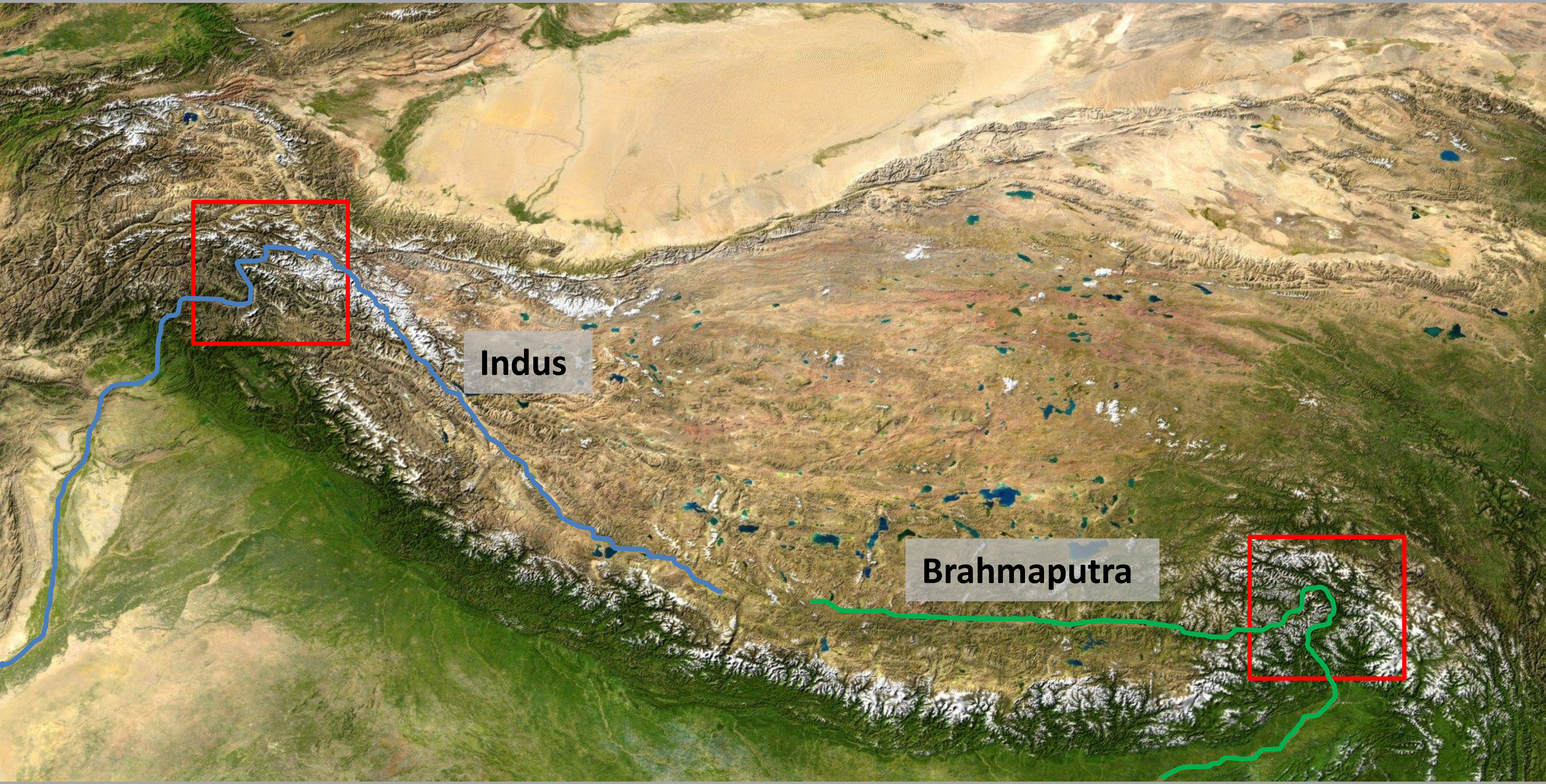
Erosional thermo-mechanical coupling

(tectonic aneurysm)



Koons (1990), Zeitler et al. (2001)

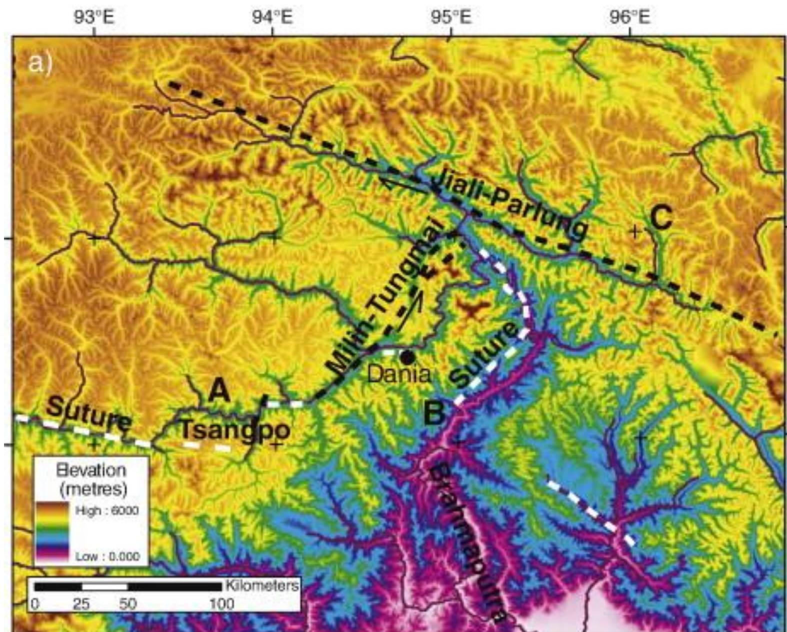
Tectonic aneurysm and the Himalayan syntaxes

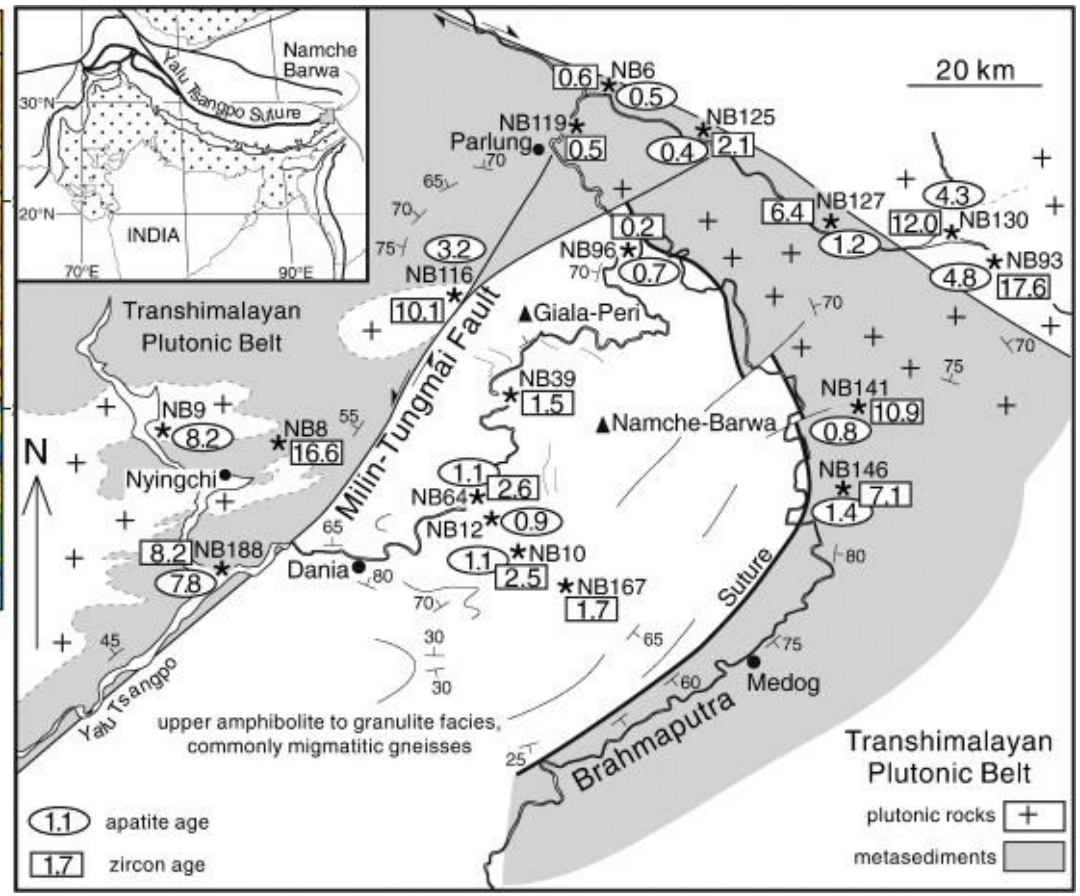


Namche Barwa (eastern) syntaxis

Photo: Brian Zurek

Erosion and growth of the Namche Barwa syntaxis





Seward and Burg (2008)

Effects of coupling between tectonics, and surface processes

Insight from numerical models

Modeling challenges……

1. **Elasto-visco-plastic deformation**
   - **Strain localisation**
   - **Large deformation**
   - **Stress memory (due to elasticity)**

2. **Large amounts of erosion and sedimentation**
   - **Tracking of stratigraphy and exhumation paths**

3. **Three dimensional + time**

Governing equations

$$\frac{\partial \sigma_{ij}}{\partial x_i} + \rho g_i = f$$

Quasi-static force balance

$$\frac{\partial u_i}{\partial x_i} + \frac{\partial P}{\partial t}\frac{1}{K} = 0$$

Mass balance (weakly compressible)

Simpson (2006a)

Rheology

$$\sigma_{ii} = 3K\varepsilon_{ii}$$

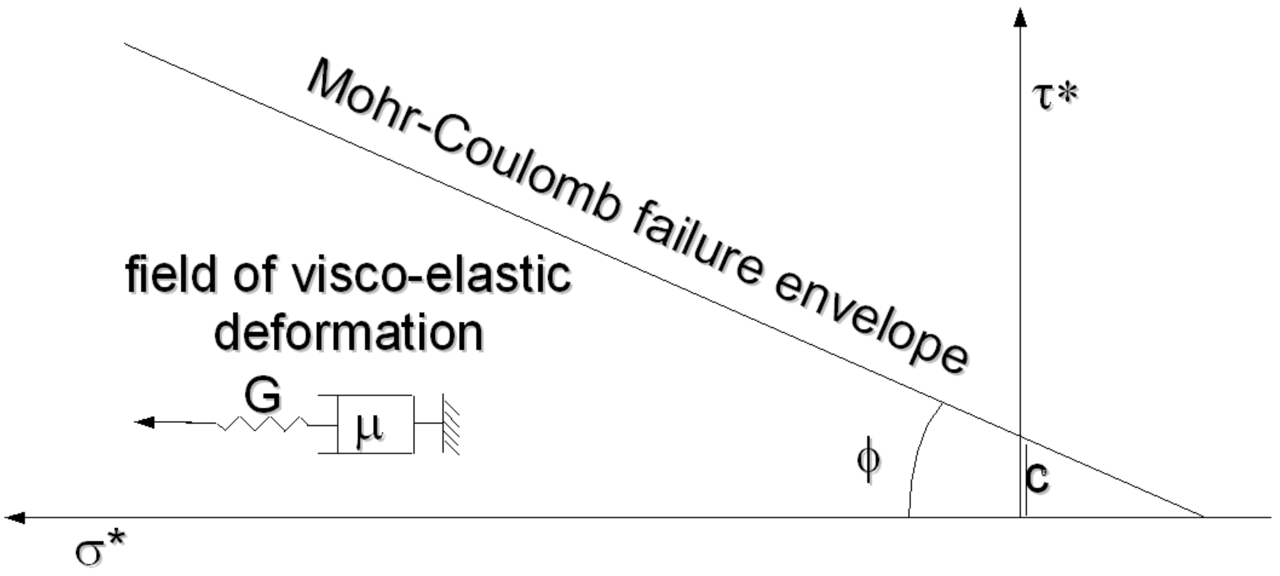
Volumetric: Elastic

$$\frac{\partial \tilde{\varepsilon}_{ij}}{\partial t} = \frac{\hat{\sigma}_{ij}}{2G} + \frac{\tilde{\sigma}_{ij}}{2\mu}$$

Deviatoric: Maxwell viscoelasticity

$$F = \tau^* + \sigma^* \sin\phi - c\cos\phi$$

Non-associated Mohr-Coulomb



Other effects…..

$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\kappa \frac{\partial h}{\partial x}\right)$$

Surface mass redistribution

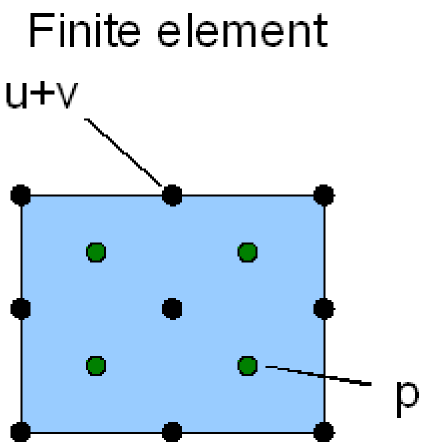
$$\frac{\partial^2}{\partial x^2}\left(D \frac{\partial^2 w}{\partial x^2}\right) + \Delta\rho g w = q$$

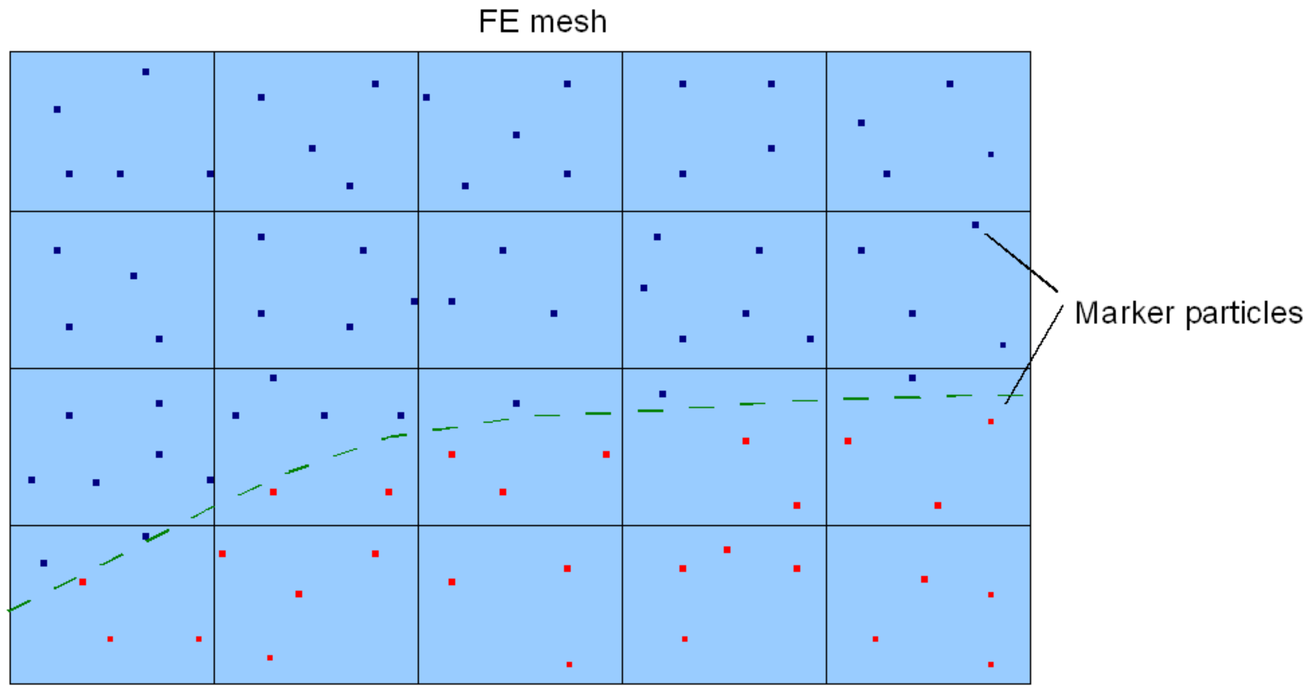
Flexure (on base of model)

$$D = \frac{E T_e^{\,3}}{12(1-\nu^2)}$$

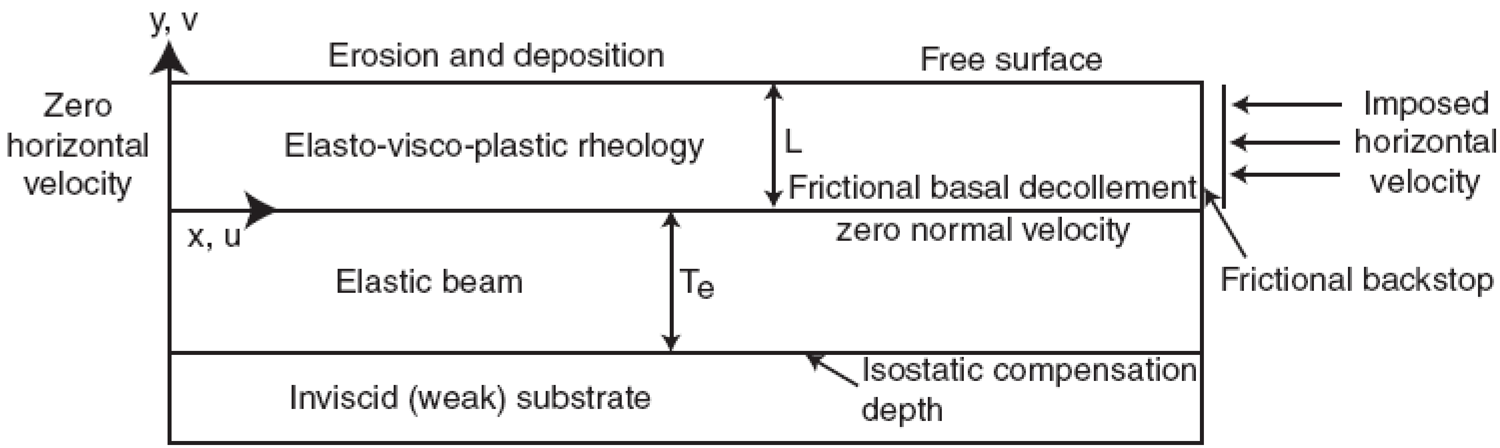
Numerical method

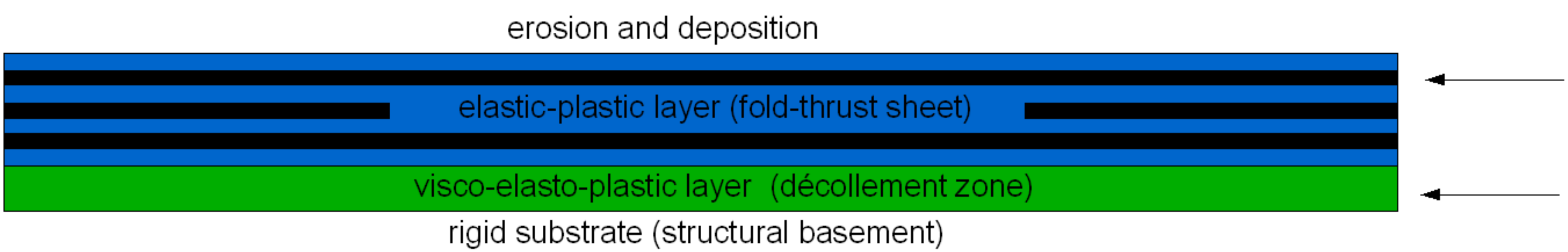
- Galerkin Finite Element Method
- 9-node quadrilaterals (for u-v) + 4-pressure nodes
- Lagrangian marker particles store history variables





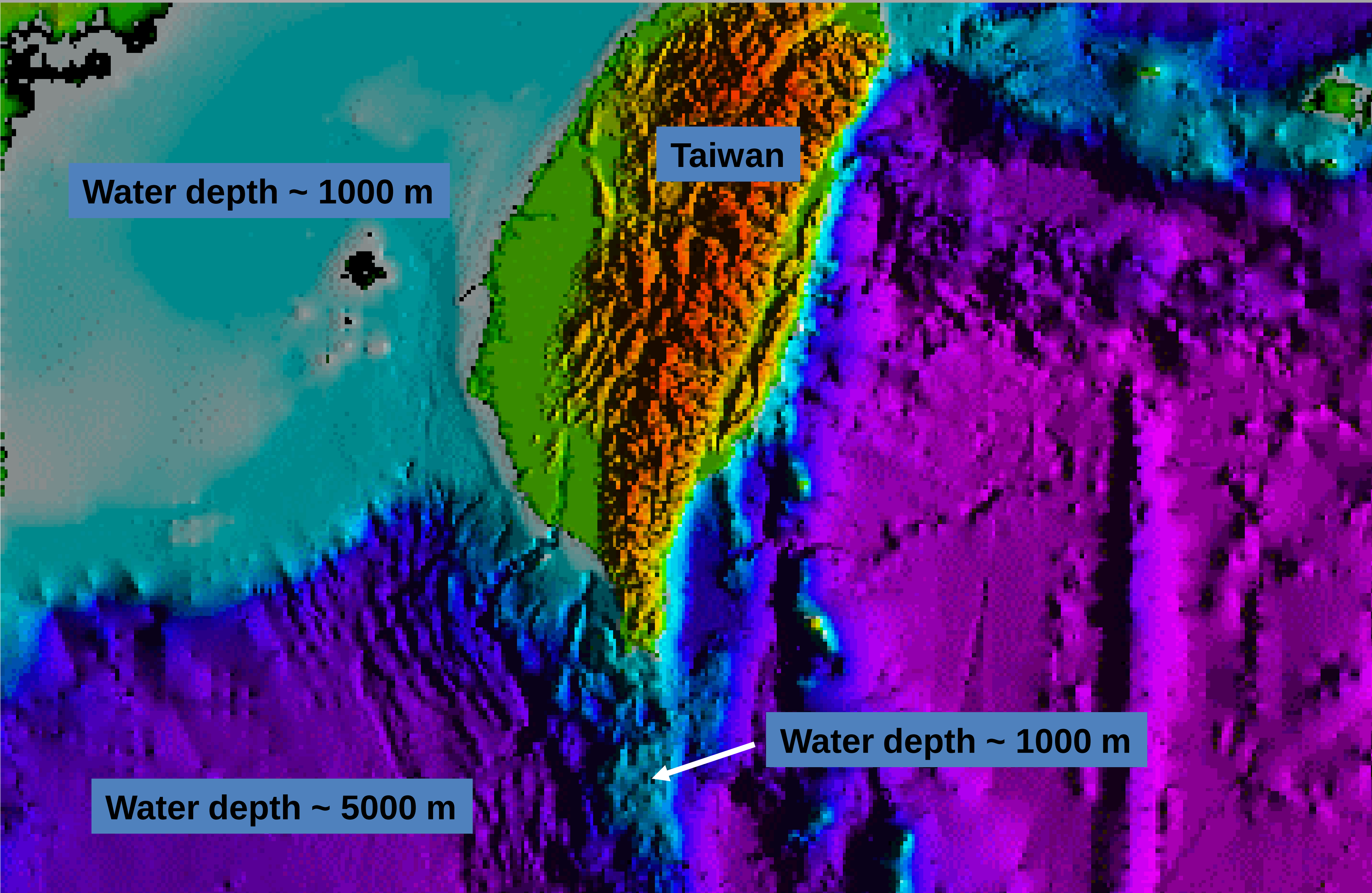
Initial model setup and boundary conditions





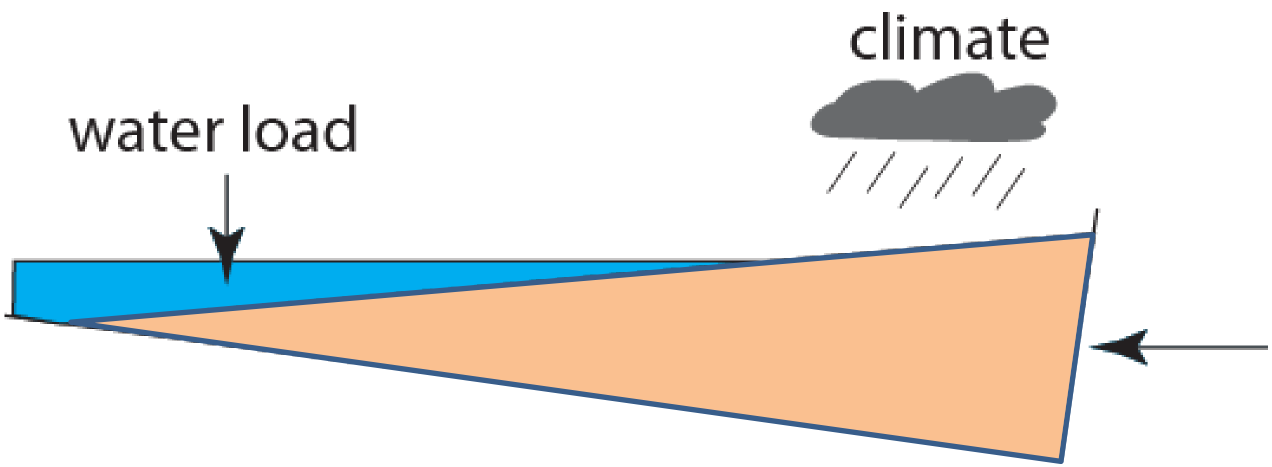
Does the emergence of orogens above sea level influence their tectonic evolution?

Simpson (2006)

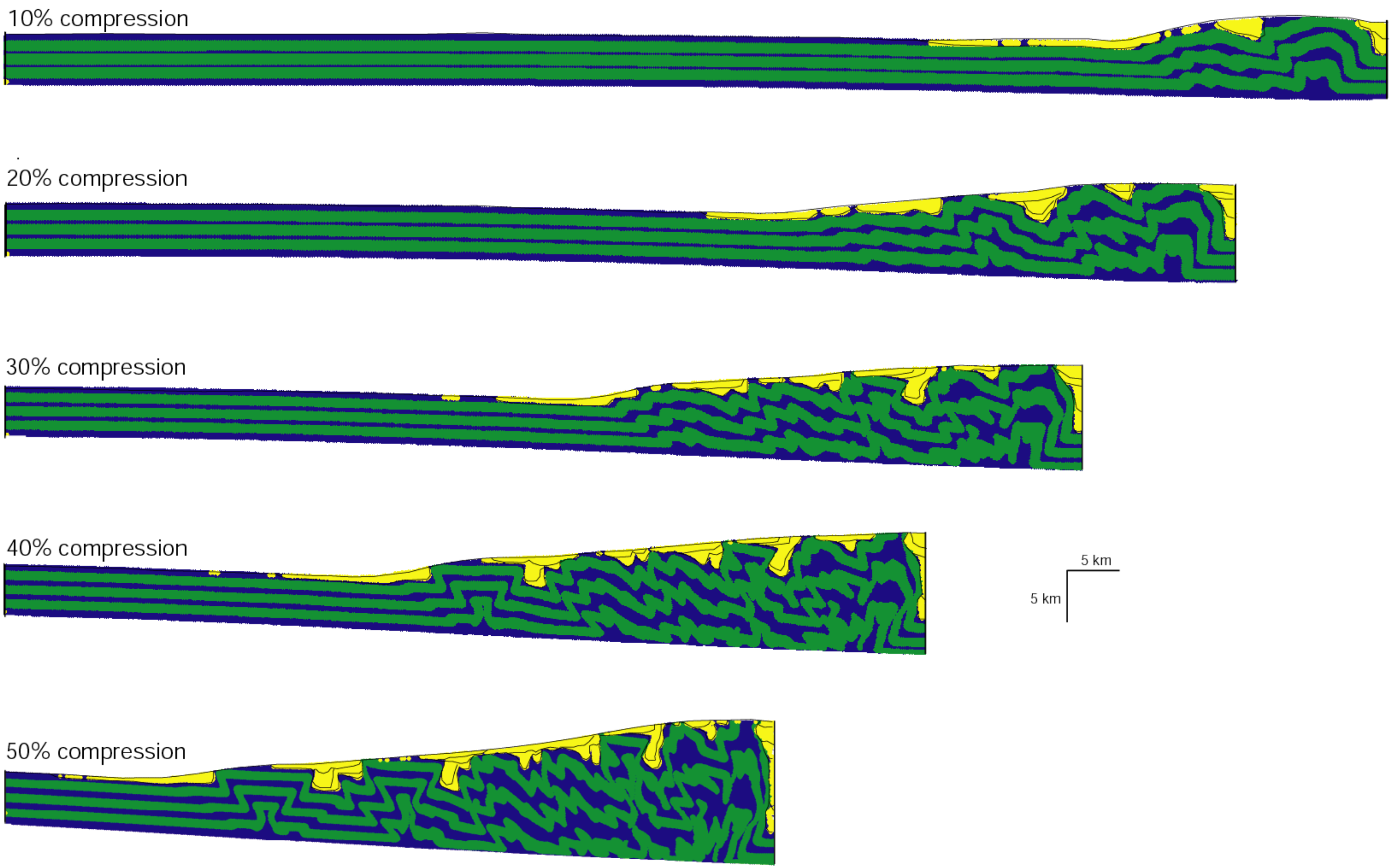


How could emergence potentially influence deformation?

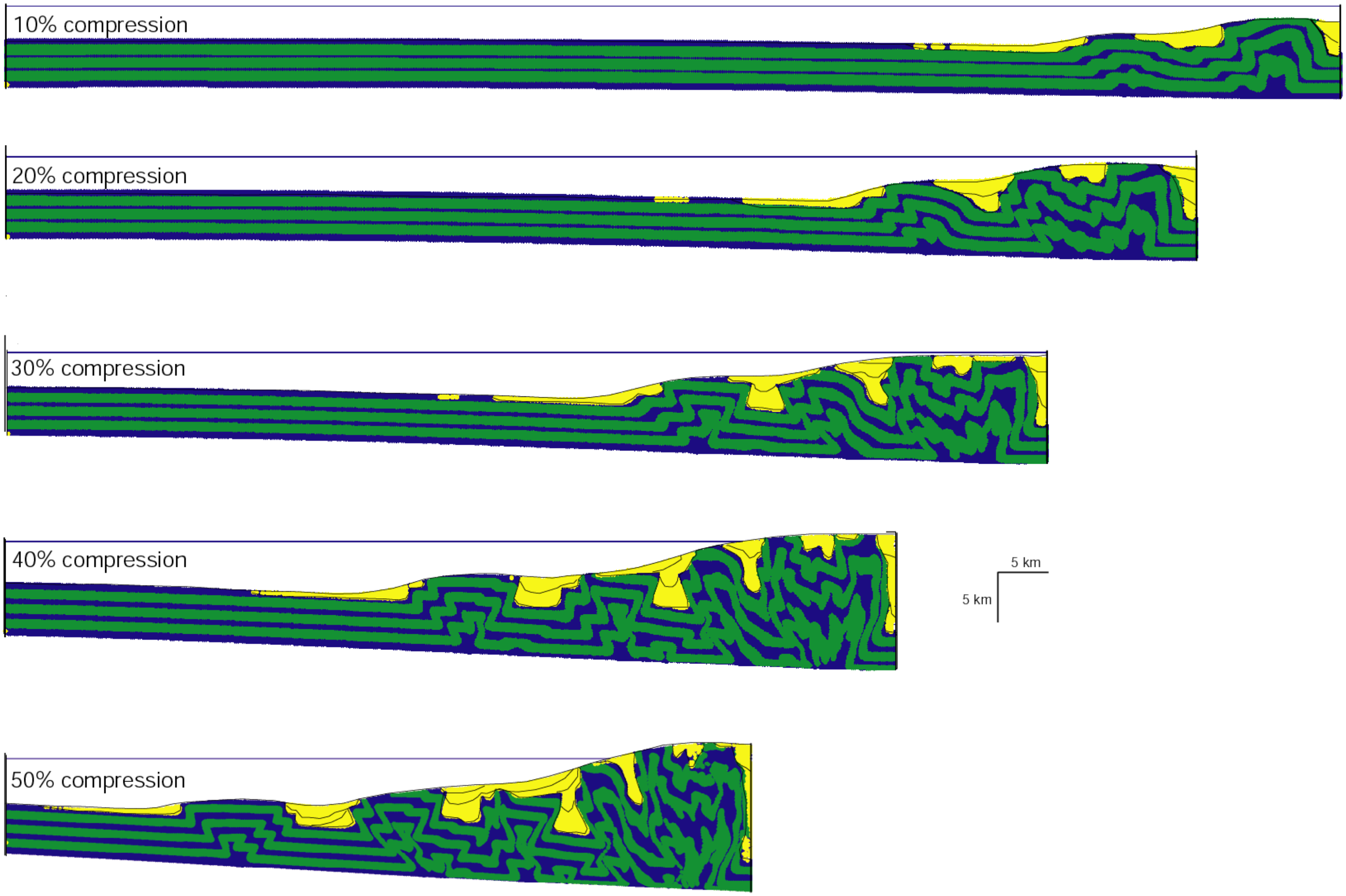
- *Change in water loads*
- *Change in efficiency of surface processes*



Subaerial fold-thrust belt

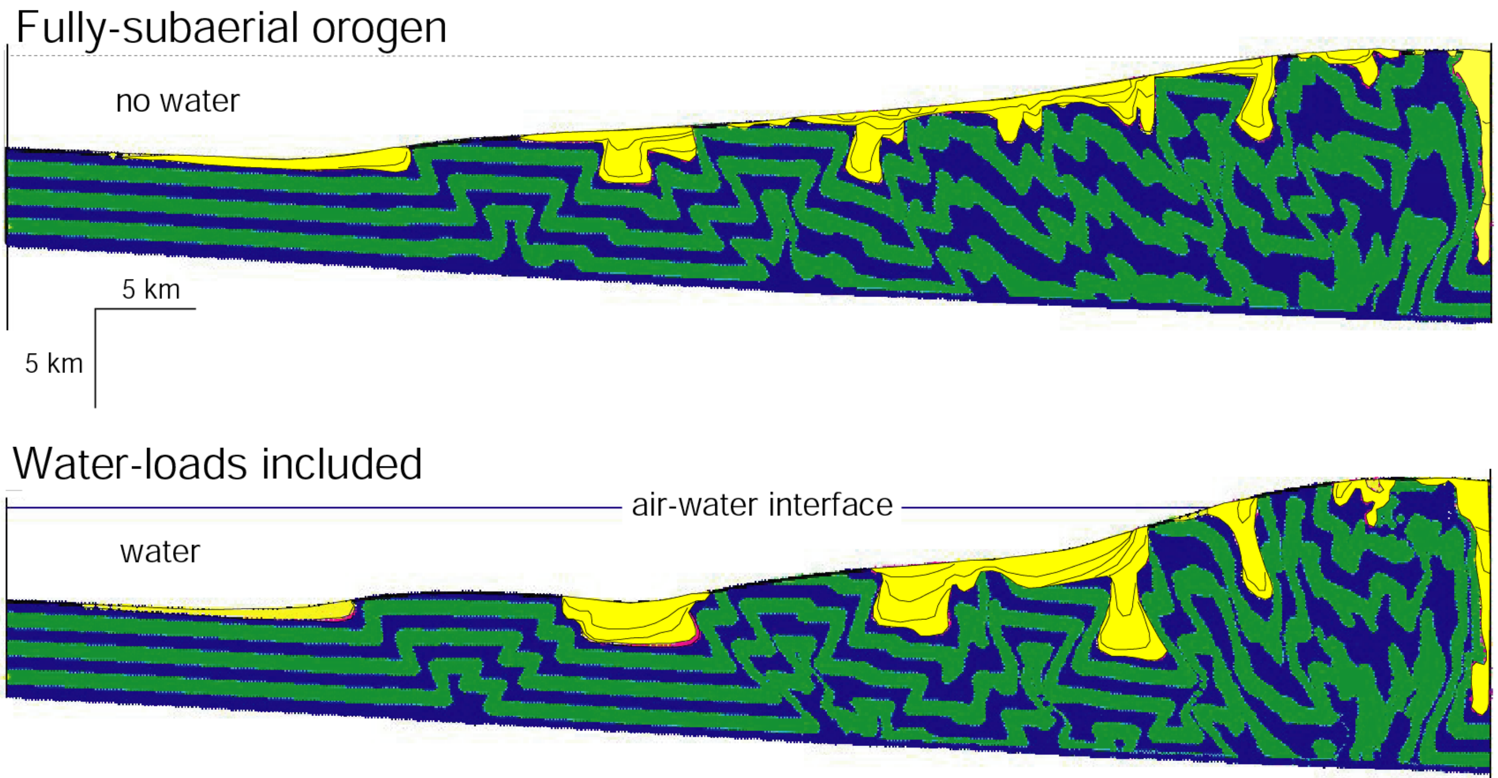


Submarine fold-thrust belt

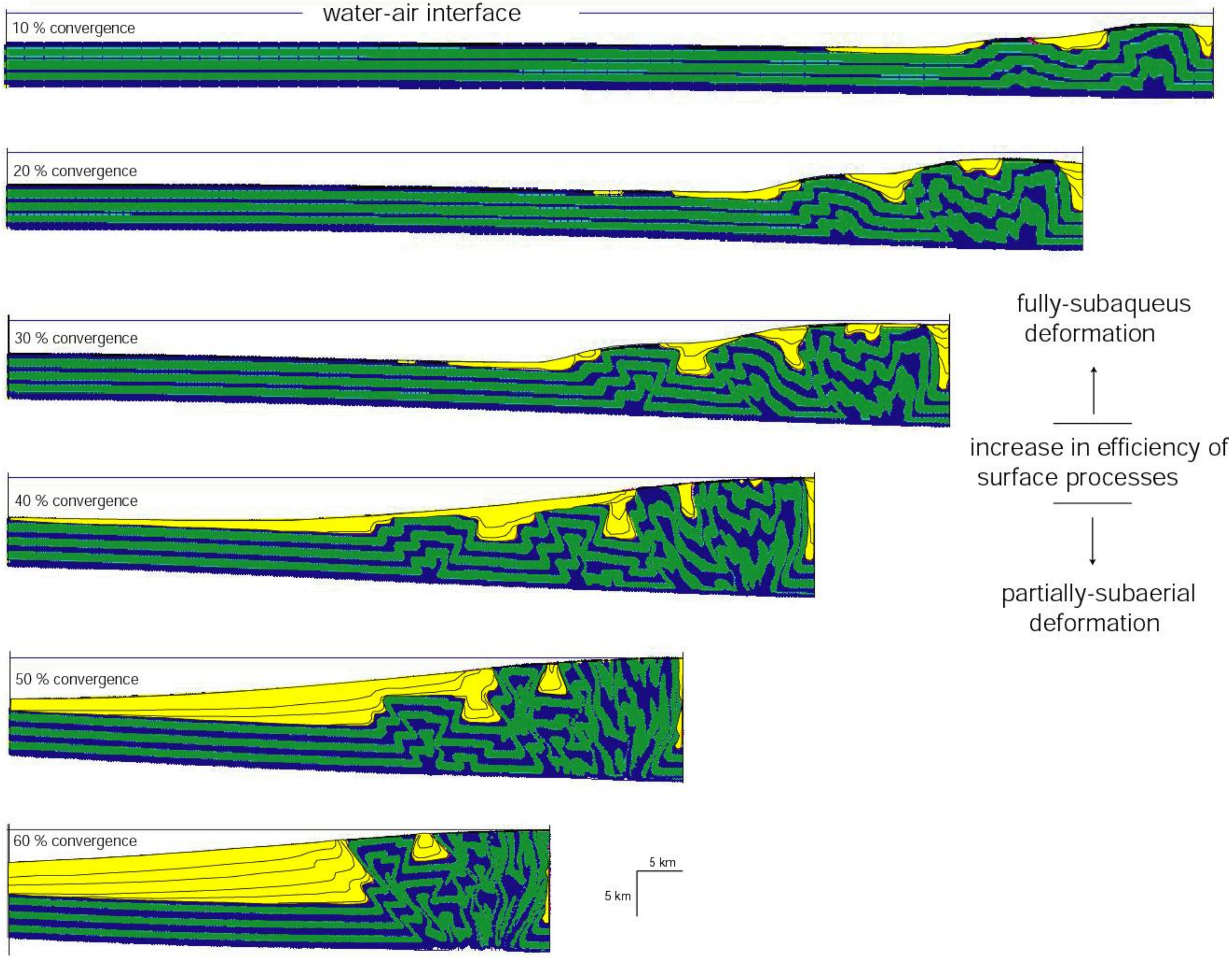


Effects due to water loads

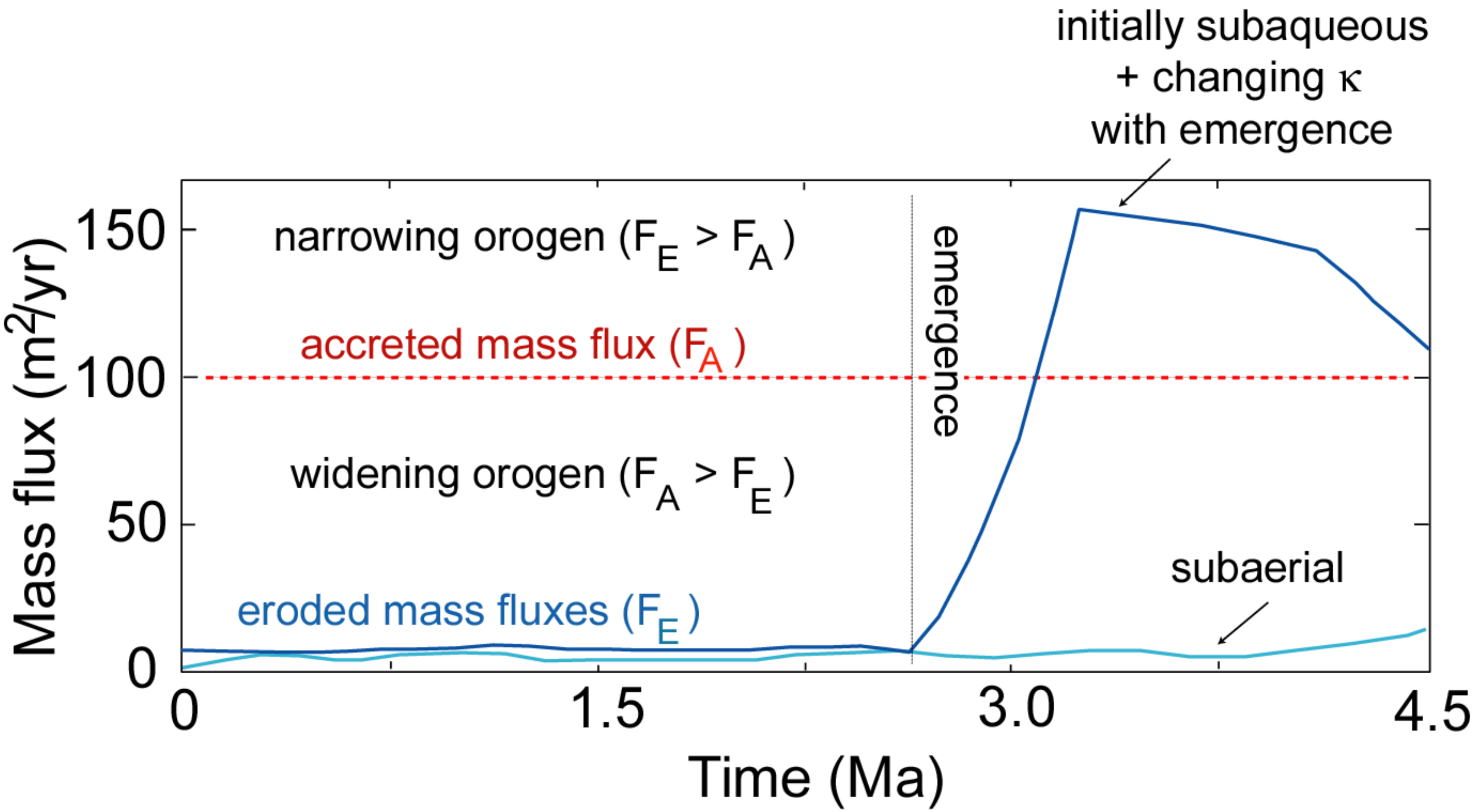
50% convergence



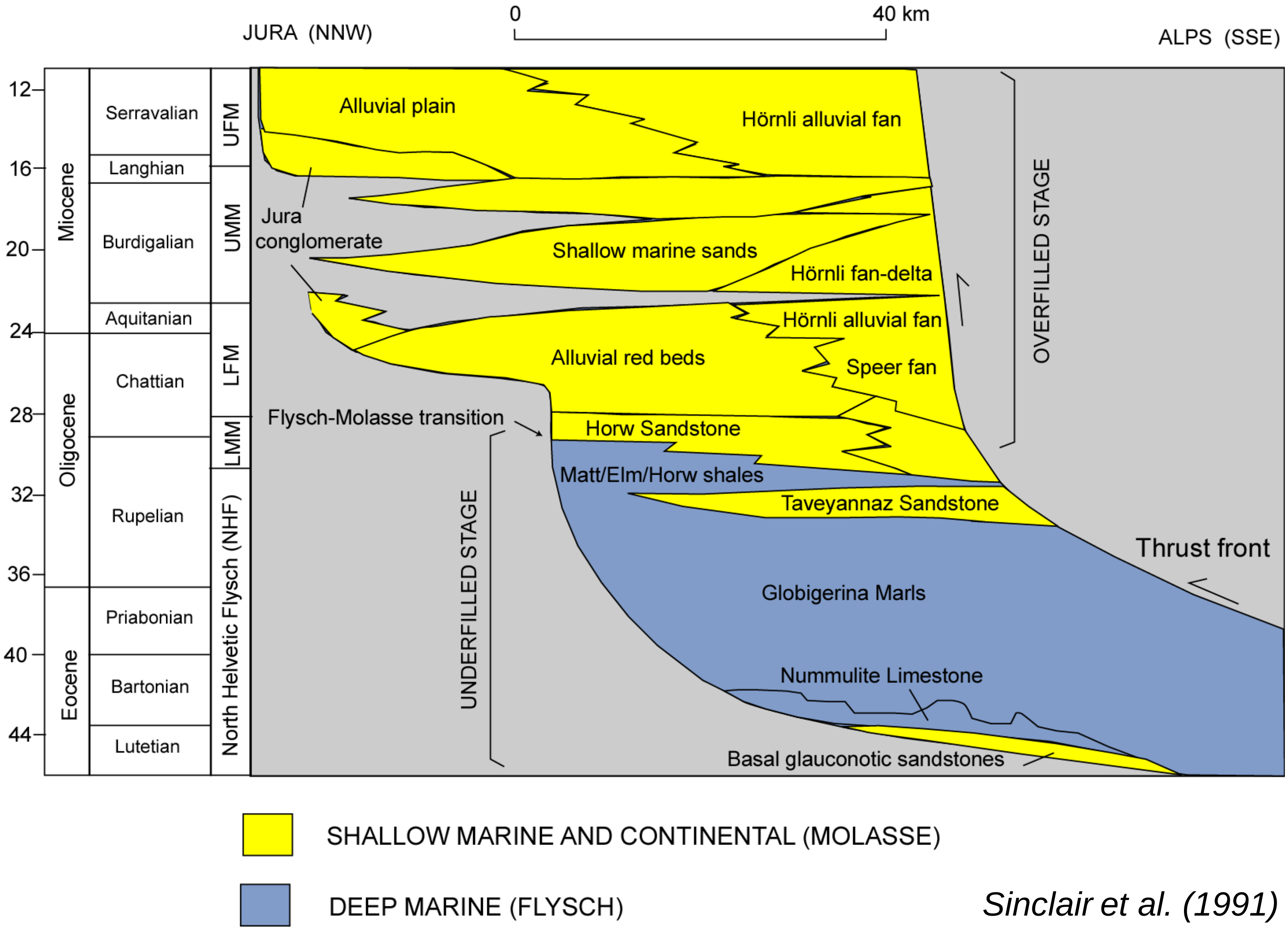
Emergence-related change in rate of surface processes



Orogen-scale mass balance



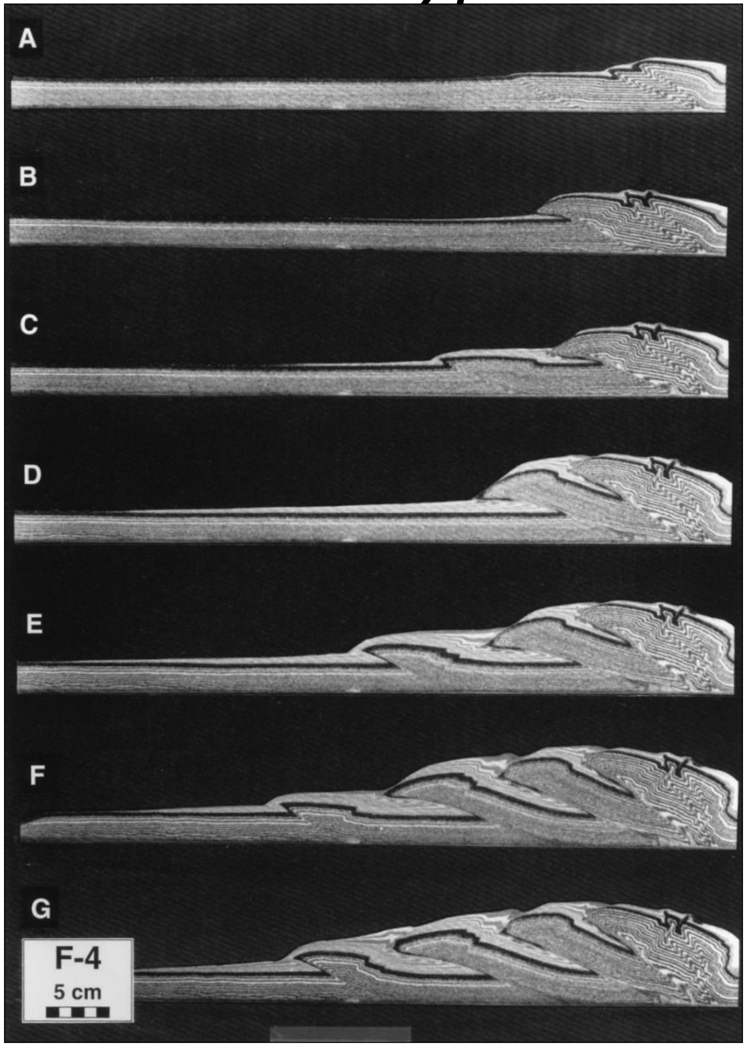
Flysch-molasse transition: N Alpine Foreland Basin



Sinclair et al. (1991)

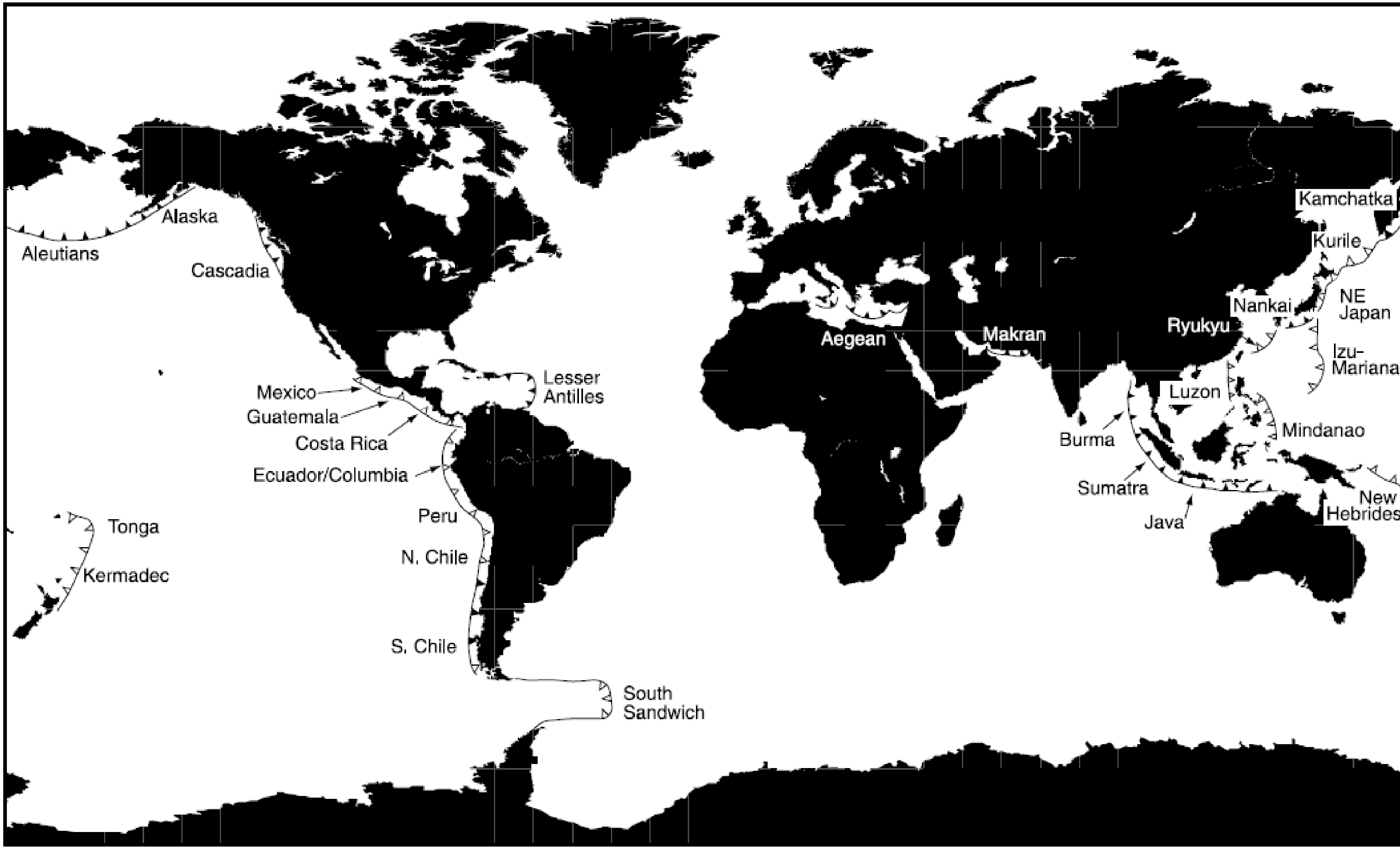
How are accretionary prisms influenced by the hinterland sediment supply ?

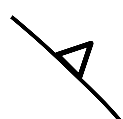
Classic accretionary prism model

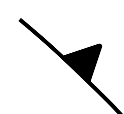


Stori and McClay (1995)

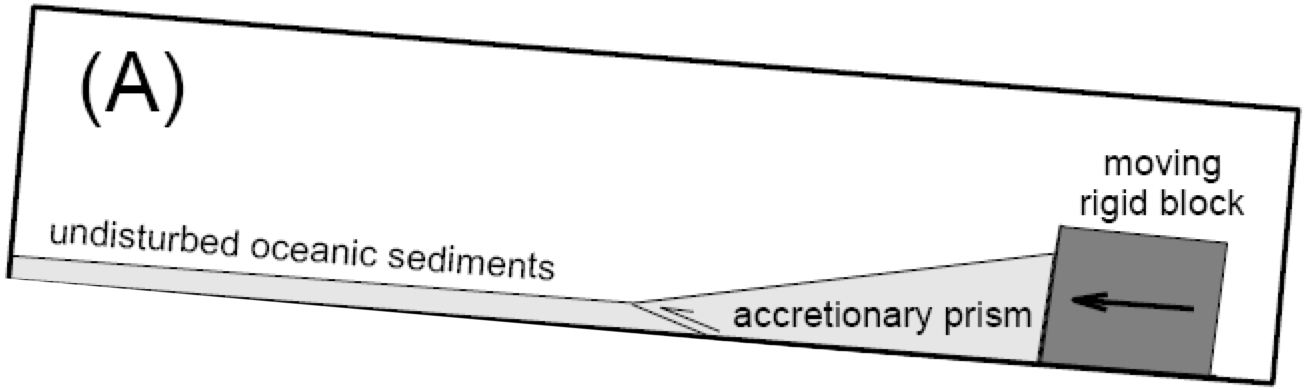
Accretionary prisms and hinterland sediment supply



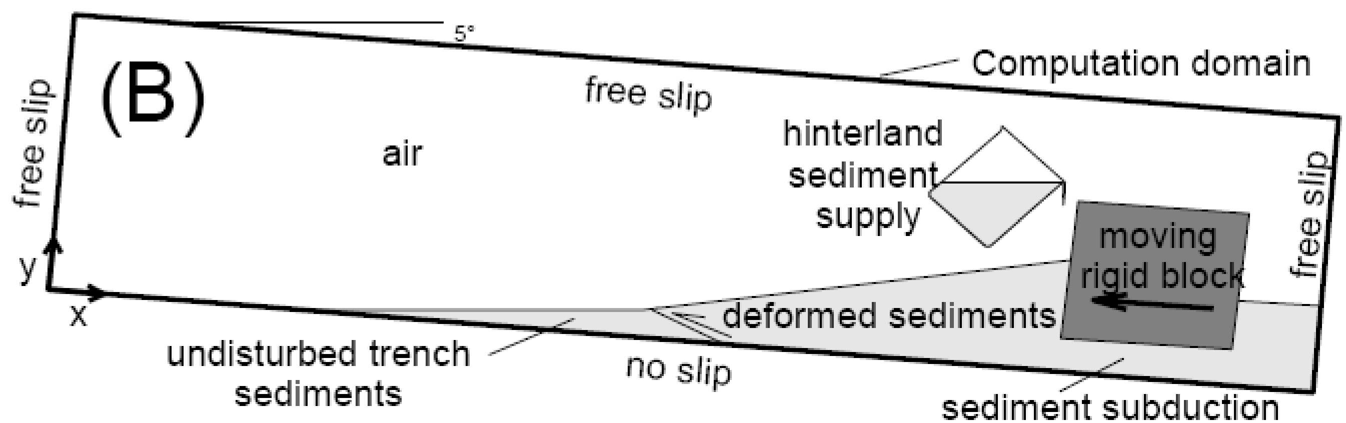

erosive margins

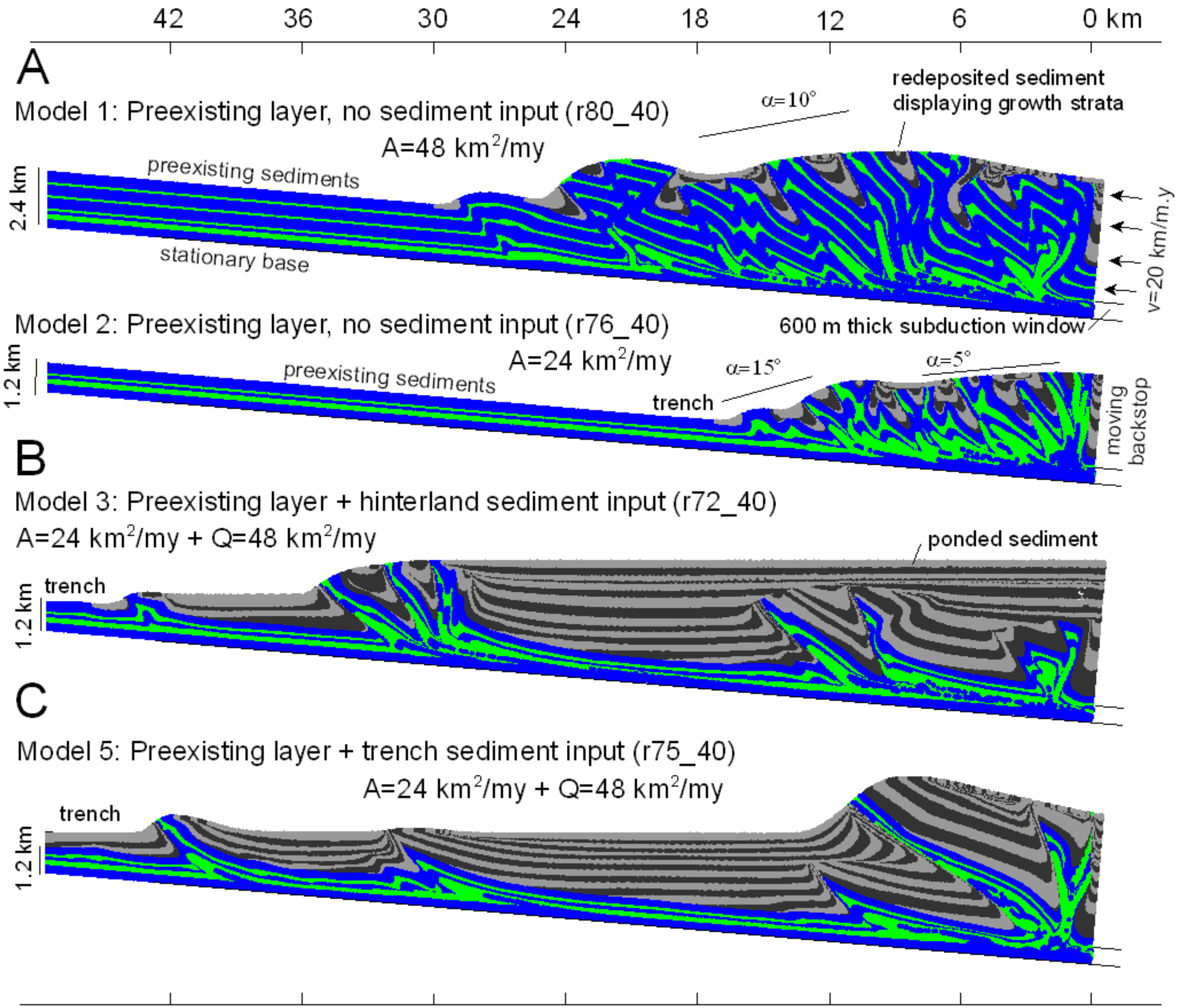

accretionary margins

Classic accretionary prism model



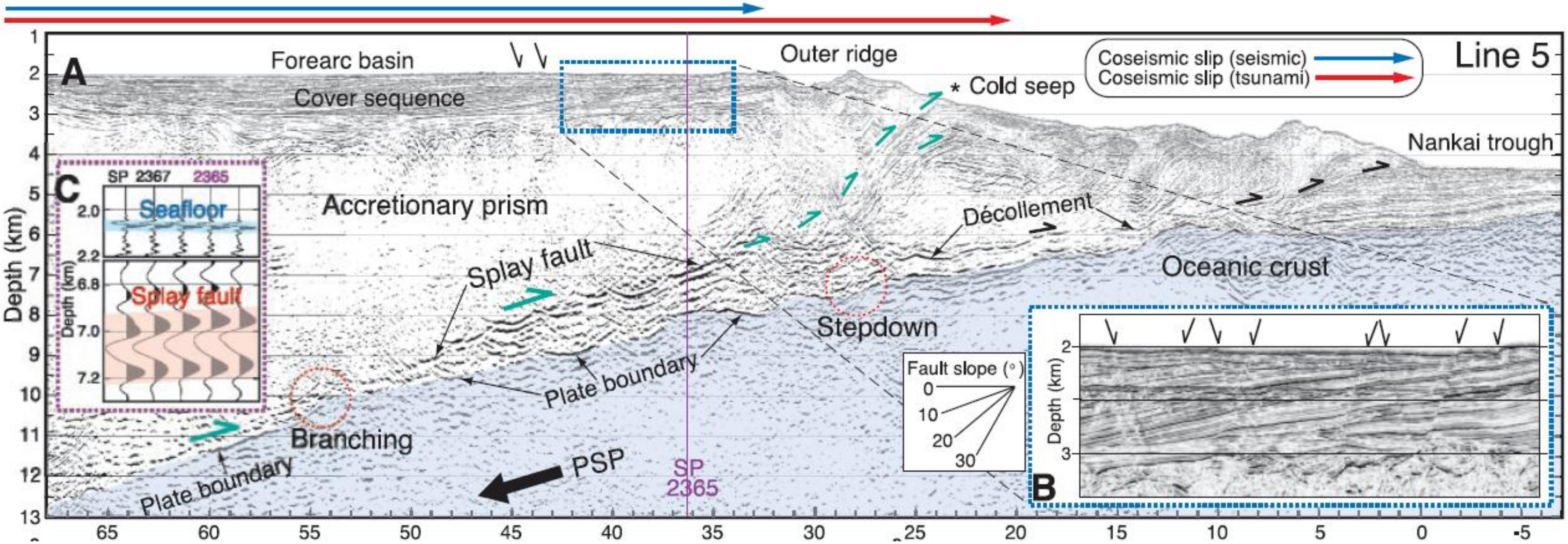
Accretionary prism fed by a hinterland sediment supply





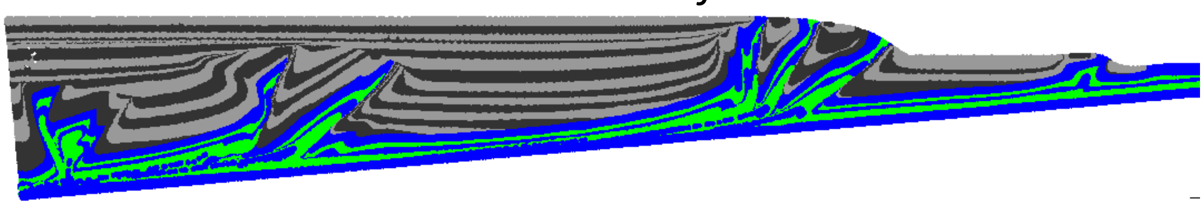
42
36
30
24
18
12
6
0 km
A
Model 1: Preexisting layer, no sediment input (r80_40)
A=48 km²/my
α=10°
redeposited sediment
displaying growth strata
preexisting sediments
2.4 km
stationary base
v=20 km/m.y
600 m thick subduction window
Model 2: Preexisting layer, no sediment input (r76_40)
A=24 km²/my
1.2 km
preexisting sediments
α=15°
α=5°
trench
moving
backstop
B
Model 3: Preexisting layer + hinterland sediment input (r72_40)
A=24 km²/my + Q=48 km²/my
ponded sediment
trench
1.2 km
C
Model 5: Preexisting layer + trench sediment input (r75_40)
A=24 km²/my + Q=48 km²/my
trench
1.2 km

Nankai accretionary prism

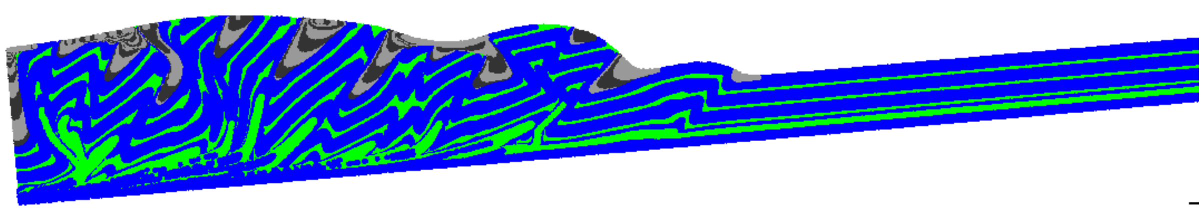


Parks et al. (2002)

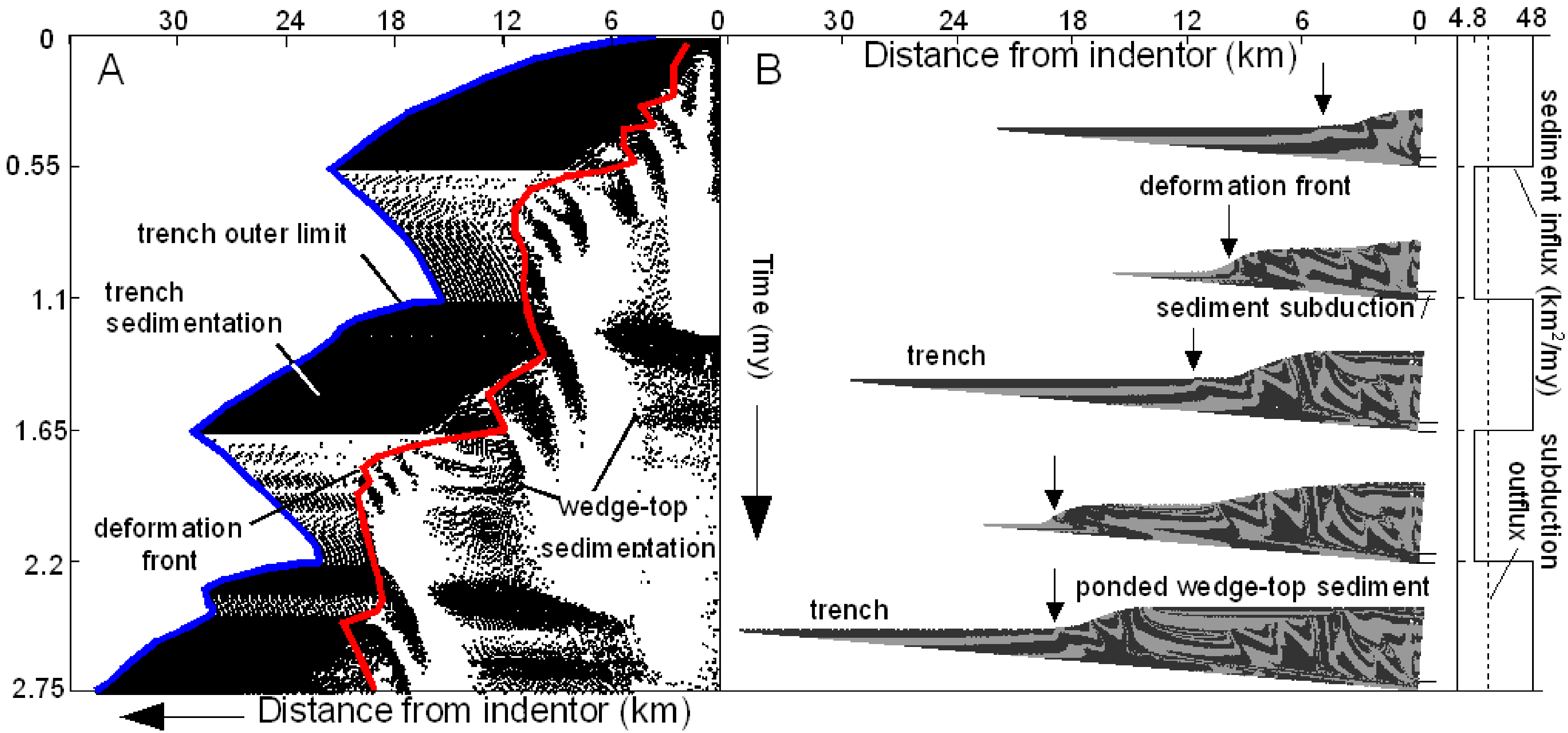
Accretionary prism forming in response to hinterland sediment flux



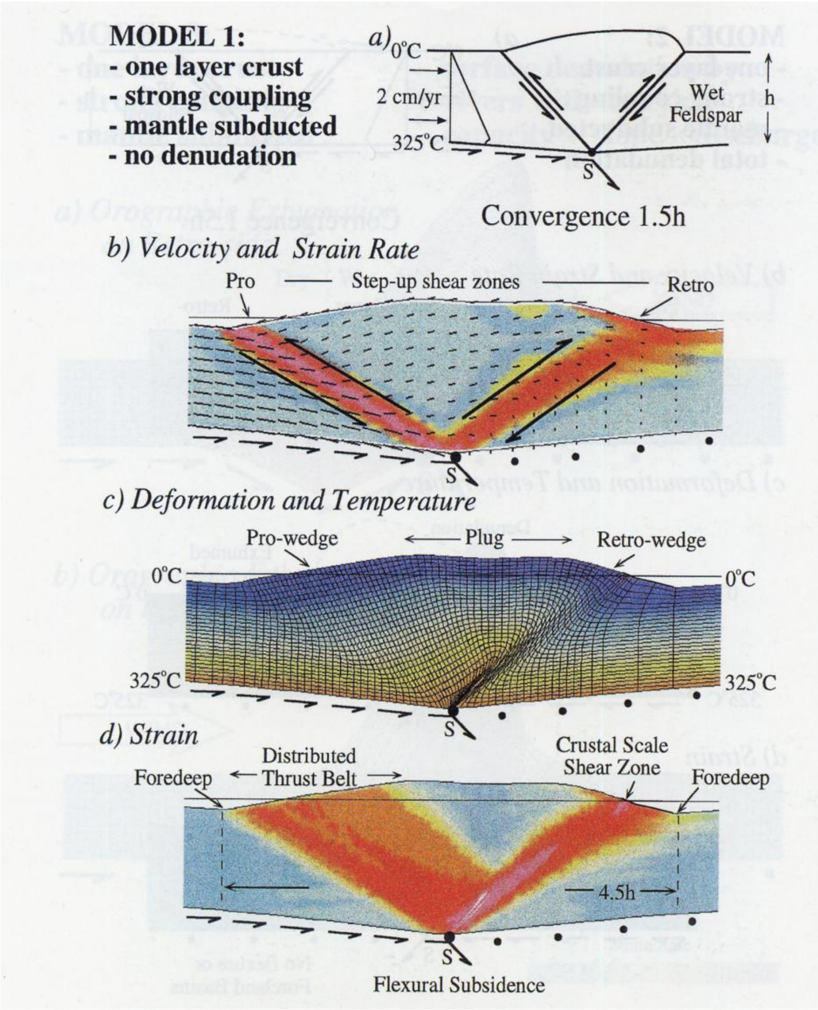
Classic accretionary prism

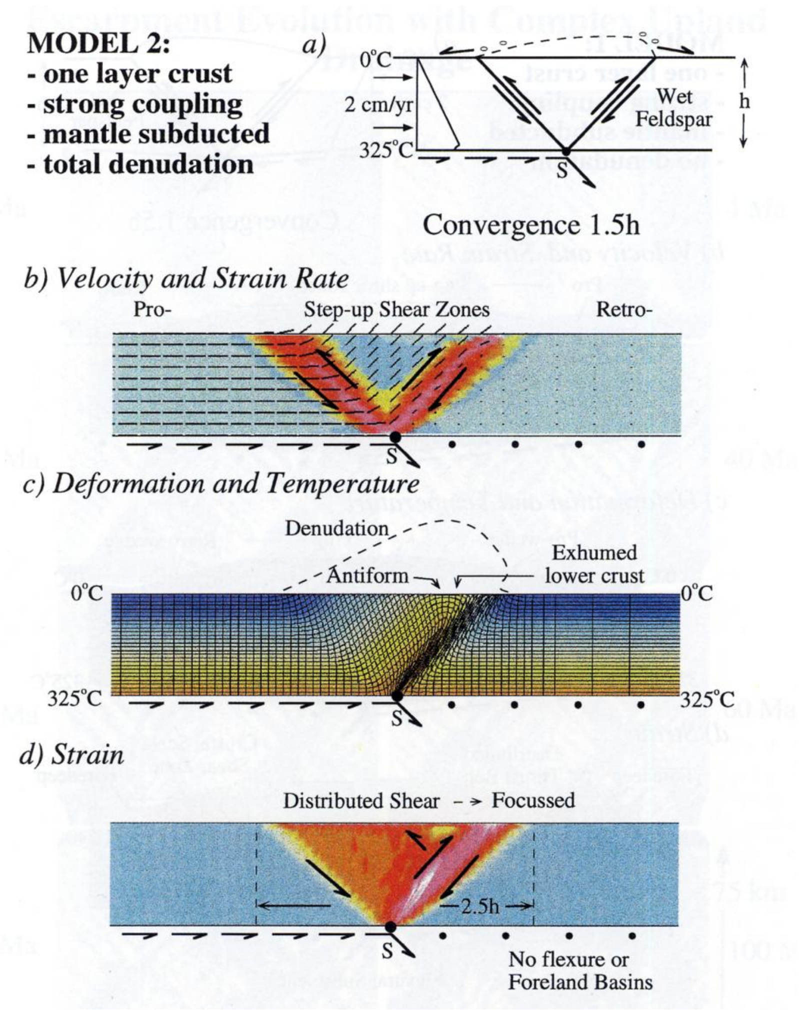


Prism response to sediment flux variations



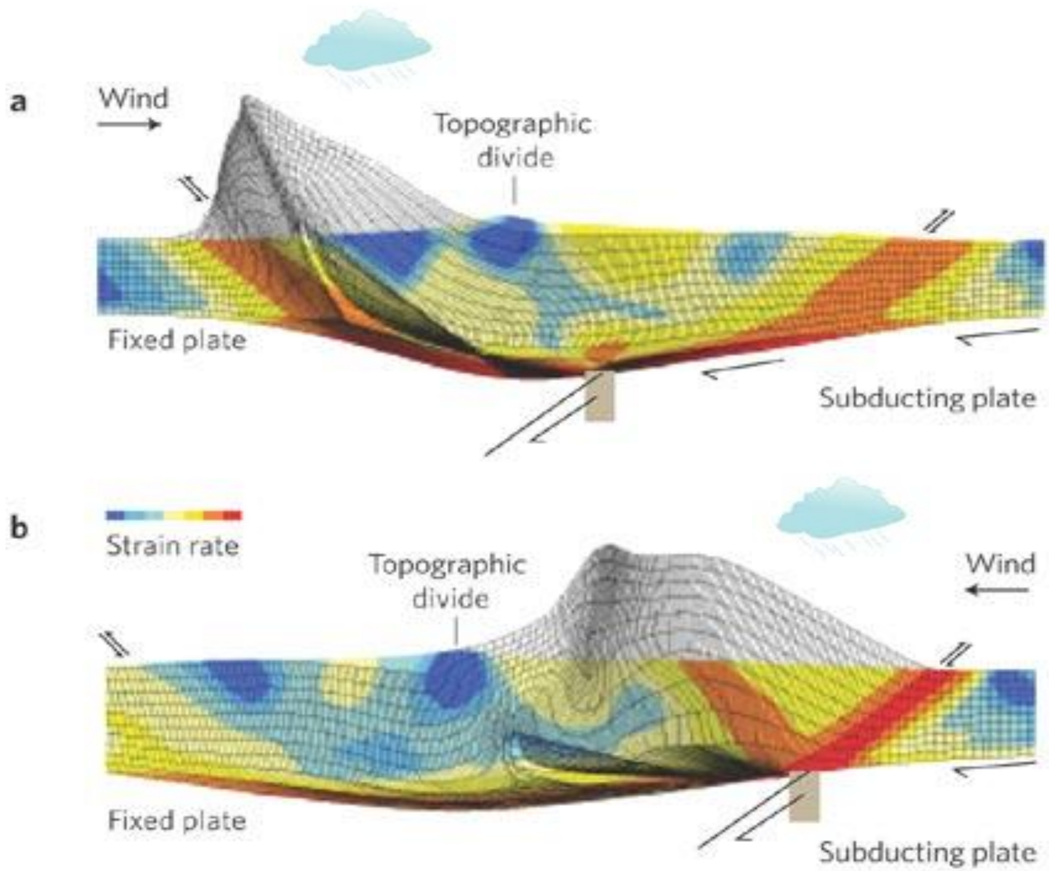
Erosional impact at orogen-scale





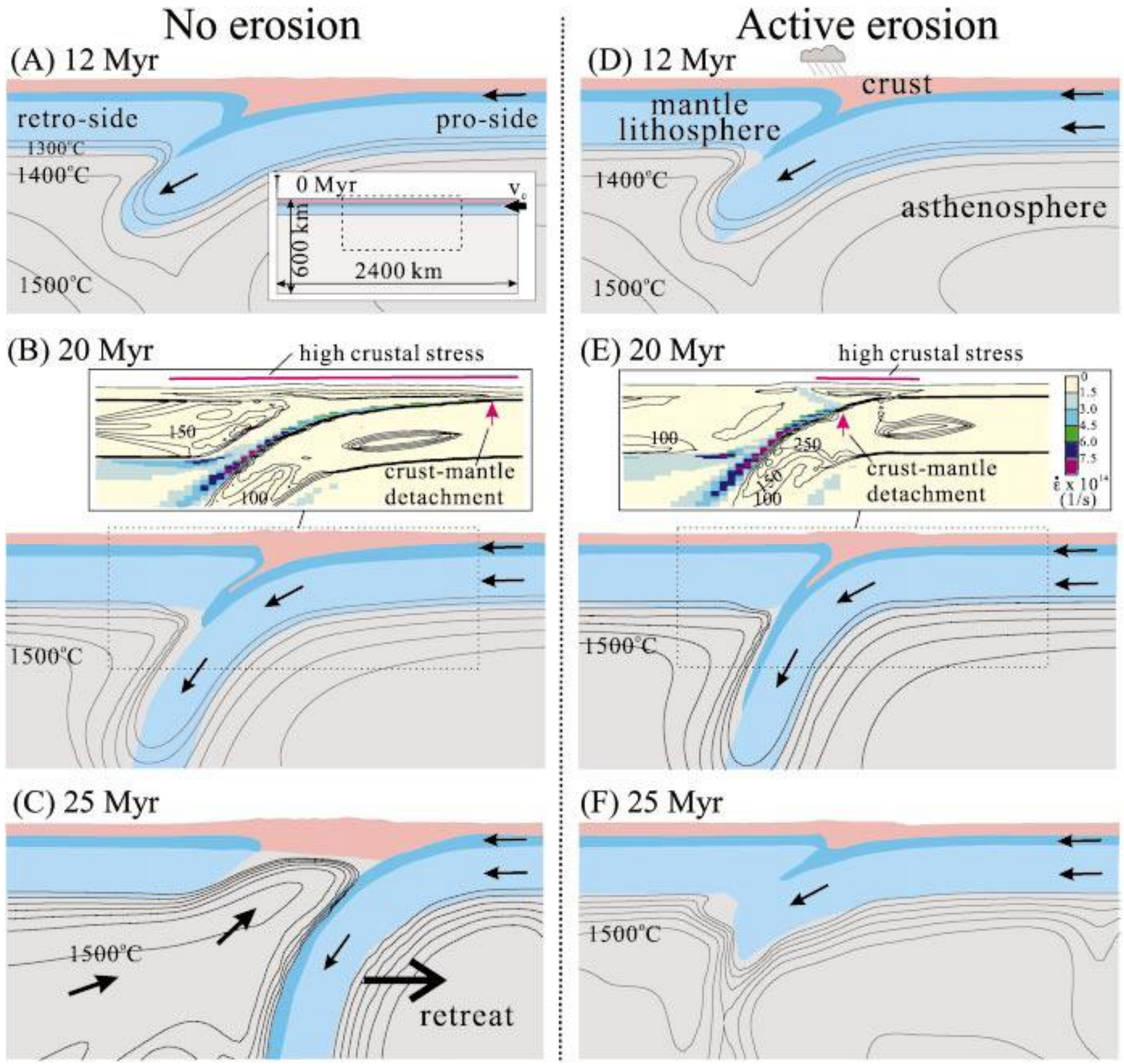
Beaumont et al *(2000)*

Orography and orogensis



Willett (1999)

Erosional impact on deep structure



Pysklywec *(2006)*

Conclusions

•*Tectonics-climate and surface processes are part of a dynamic system which displays a range of positive and negative feedback loops*

•*Surface mass redistribution impacts on tectonics via three independent mechanisms:*

1. *Isostacy*
2. *Modification of gravitational stresses coupled with deformation*
3. *Erosional thermo-mechanical coupling*

•*Surface mass redistribution has an important influence on deformation of the lithosphere at a range of time and spatial scales*

•*Generally, erosion localises deformation whereas sedimentation inhibits deformation*