The influence of fluvial incision on the lithospheric stress field: a numerical approach

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This presentation participates in OSPP
Outstanding Student & PhD candidate Presentation contest

INTRODUCTION

Background

Large rivers exhibit high variability in terms of channel and valley **cross-sectional morphology** and **incision rates**[1]

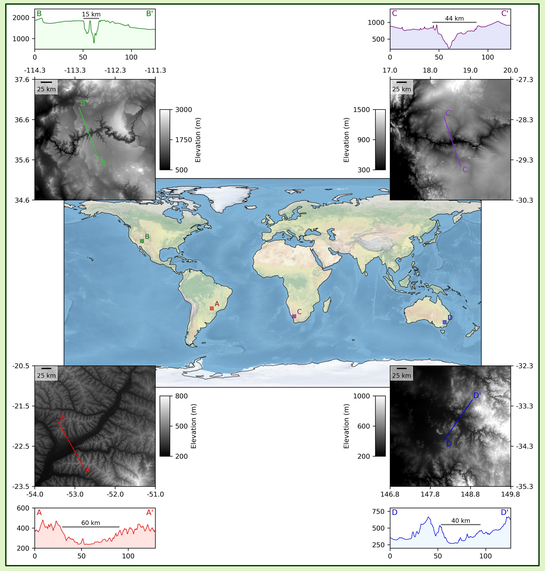
Fluvial erosion modifies the Earth's landscape and moves **large sedimentary loads** across continents over **geologic timescales**[2,3,4]

Load redistribution causes **isostatic rebound** and **stress development** in continental lithosphere, which may affect **intraplate seismicity**[5-8]

Objectives

To study the evolution of stresses caused by localized erosion in **tectonically quiescent**, **intracontinental settings** over several Myr as a function of **crust-mantle coupling** and **valley geometry**

To quantify the progression of surface uplift in response to **time-distributed** denudation **in large valleys**



METHODS

Mandyoc: the numerical code

Finite-element code for solving the continuity, momentum, and energy equations for **incompressible**, **high-viscosity** flow[9]

Viscoplastic rheology with ductile viscosity **nonlinearly dependent** on **pressure**, **temperature** and **strain rate**[10]:

$$\eta_{\text{duct}} = C \cdot A^{-\frac{1}{n}} \cdot \dot{\varepsilon}_{II}^{\frac{1-n}{n}} \exp\left(\frac{Q+PV}{nRT}\right)$$

Brittle yielding is modeled following the Drucker-Prager criterion:

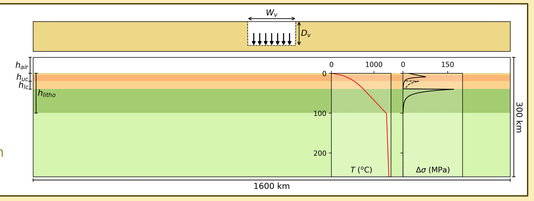
$$\sigma_{\text{yield}} = c_0 \cdot \cos\phi + P \cdot \sin\phi$$

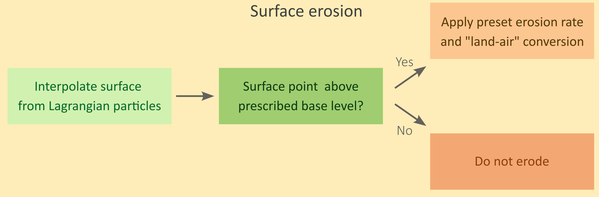
Tracking of the free surface is carried out using **Lagrangian particles** advected according the velocity field calculated for each element at each time step[11]

Numerical Setup

Model layers

Sticky air = 40 km
Sediment = 5 km
Upper crust = 15 km
Lower crust = 20 km
Litho. mantle = 60 km
Asthenos. = 140 km





D_v = 250 m; erosion rate = 0.2 mm/yr

Label	C_{lc}	W_v (km)
W30-C1	1	30
W30-C10	10	30
W80-C1	1	80
W80-C10	10	80
W150-C1	1	150
W150-C10	10	150

Particle properties are **actually updated** upon conversion

Incision rates **decrease** after base level is reached

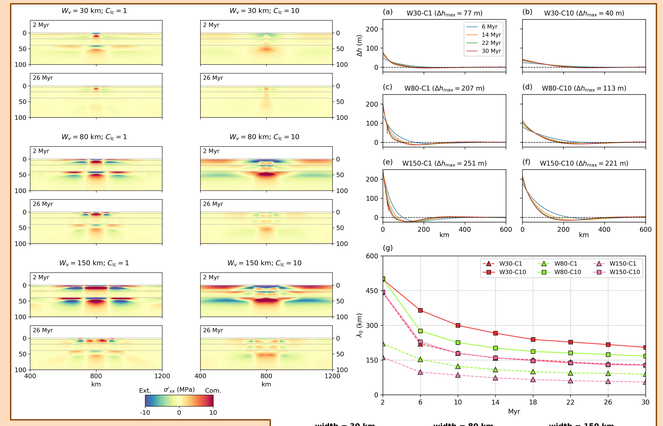
Erosion in the valley is then limited to **balancing uplift**

MAIN RESULTS

Crust-mantle coupling

Weakly coupled (C_{lc} = 1):
stress concentration in upper crust and lithospheric mantle; flank uplift with short wavelength

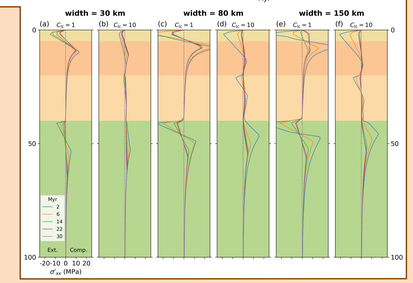
Strongly coupled (C_{lc} = 10):
stress is distributed more efficiently over the lithosphere, including lower crust; uplift with longer wavelength



Valley width

Wide valleys (W_v = 150 km end-member):
higher stress magnitudes at 2 Myr; stresses gradually focus beneath valley flanks; uplift exhibits larger amplitude and shorter wavelength for fixed C_{lc}

Narrow valleys (W_v = 30 km end-member):
moderate stress magnitudes; most of the deviatoric stress builds up under the valley center; uplift with smaller amplitude and longer wavelength



Implications for intraplate seismicity

These results suggest that:

Deviatoric stresses in the upper crust are highest **right after the valley floor has reached base level**, and for **wider valleys** incised into a **weakly coupled lithosphere**

Thus, triggering of preexisting brittle structures by fluvial incision is likely where:

The valley is being **actively excavated** or has been **recently** (e.g., Upper Miocene or later) **excavated**

The **incised area is wide** and stress concentrates in the upper crust due to **ductile flow in the lower crust**

Brittle zones are **shallow** (< 15 km), lie **close to the valley** (< 100 km), and are **favorably oriented**

[1]Schumm, S. A., Ethridge, F. G. (1994) - Origin, evolution and morphology of fluvial valleys
[2]Gilchrist, A. R., Summerfield, M. A. (1991) - Denudation, isostasy and landscape evolution
[3]Bishop, P., Brown, R. (1992) - Denudational isostatic rebound of intraplate highlands: the Lachlan River valley, Australia
[4]Geffroy, T., Yamato, P., Steer, P., Guillaume, B., Duretz, T. (2025) - Deformation and exhumation in thick continental crusts induced by valley incision of elevated plateaux
[5]Simpson, G. (2004) - Role of river incision in enhancing deformation
[6]Calais, E., Freed, A. M., Van Arsdale, R., Stein, S. (2010) - Triggering of New Madrid seismicity by late-Pleistocene erosion
[7]Vernant, P., Hivert, F., Chery, J., Steer, P., Cattin, R., Rigo, A. (2013) - Erosion-induced isostatic rebound triggers extension in low convergent mountain ranges
[8]Mazzotti, S., Vergeron, X., Malcles, O., Grosset, J., Vernant, P. (2023) - Impact of long-term erosion on crustal stresses and seismicity in stable continental regions
[9]Sacek, V., Assunção, J., Pesce, A., Silva, R. M. (2022) - Mandyoc: A finite element code to simulate thermochemical convection in parallel
[10]Huismans, R. S., Beaumont, C. (2014) - Rifted continental margins: The case for depth-dependent extension
[11]Silva, R. M., Sacek, V. (2022) - Influence of surface processes on postrift faulting during divergent margins evolution