Coupled influence of tectonics and surface processes on the drainage evolution in collisional orogens: an example from the three rivers region in Southeast Tibet

ADVANCING EARTH AND SPACE SCIENCE

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Introduction

The three river region (TRR, Salween, Mekong, and Yangtze Rivers) in southeast Tibet provides an example of drainage evolution in active orogenic system. Over decades of investigations based on geomorphic evidence analysis, or landscape evolution modeling, the main factor resulting in the unusual drainage patterns in this area remains controversial. Some studies argued that the horizontal tectonic deformation has brought the previous rivers to be nearly parallel in extraordinary close space. In contrast, others suggested that can be explained by drainage reorganization, and the capture and reversal events merely appeal to the surface uplift.

Tectonics and surface processes integrate to shape the topography of fluvially conditioned mountain ranges, and important two-way feedbacks exist between them. The direct feedback through isostatic response is related to the vertical aspect of exhumation and surface uplift. Surface processes also alter the thermal and stress field in the lithosphere by redistributing significant volumes of materials, which further affect both horizontal and vertical components of tectonic displacement.

We study the drainage evolution in theTRR using a fully coupled 3-D model built by the *UWGeodynamics* module, which coupled the geodynamics code *Underworld 2* with landscape evolution model code *Badlands*.

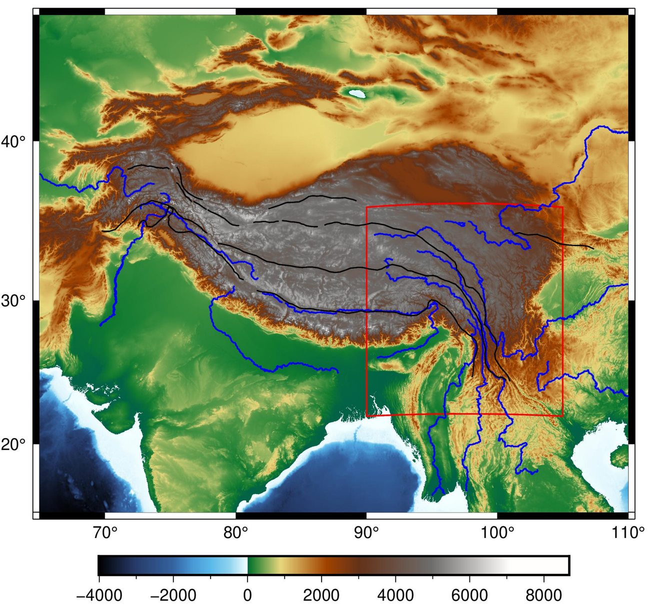

Fig. 1 (a) Topographic image of the India-Asia collision zone and major rivers in this area (From glocal relief data in 30 arc sec resolution).

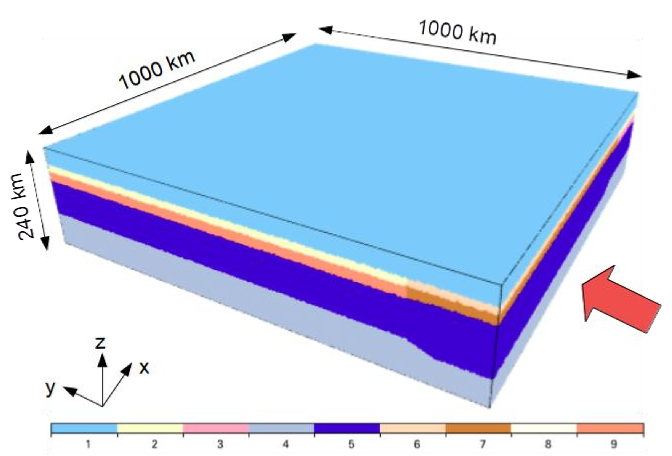

Fig. 1 (b) Model setup

- Unusual drainage patterns:
Rivers nearly parallel in extraordinary close space

- What is the causing factor?
Past studies:
(1) Drainage reorganization due to surface uplift *vs*
(2) horizontal tectonic deformation

Our assumption:
Tectonics + surface processes
Horizontal tectonic deformation (main factor)

The codes used for this poster is sharing at https://github.com/NengLu/UWG_Rivers-Mountains.git.

Methods

1. Numerical implementation

The *UWGeodynamics* module (Beucher et al., 2018) is used here to develop numerical models. This module is based on *Underworld 2* (Moresi et al., 2007) and combines it with *Badlands* (Salles et al., 2018). The model derived by UWGeodynamics is a two-way coupled thermo-mechanical model with surface processes, where the velocity field retrieved from the thermo-mechanical model is used to advect the surface in the surface processes model. The surface subjected to erosion and deposition. The distribution of materials in the model is then updated. *Underworld 2* is a Python API which provides functionality for the modelling of geodynamics processes. It utilizes a particle-in-cell finite element approach for the solution to Stokes flow type configurations. *Badlands* is a TIN (triangulated irregular network)-based long-term surface evolution model code, built to simulate topography development at various space and time scales.

2. Model setup

2.1 Tectonics model (TM)

The reference model is built based on a tectonics model (Model-3) from Chen et al., (2017) with similar geometry and rheology but different boundary conditions (see Table. 1). The model consists of a 3-D Cartesian domain of 1000 x 1000 x 240 km (x, y, z), which is solved by128 x 128 x 32 Eulerian nodes.

Free slip boundary condition is used at the back (y = 1000 km) and left (x = 0 km). A depth-constant horizontal velocity is imposed at the front wall (y = 0 km), which simulates the northward moving of the Indian lithosphere. The sticky air method is used at the top to simulate a free surface. The airy isostatic model is applied at the bottom. The thermal boundary conditions are the absolute temperatures as 0 °C in the air and 1360 °C in the mantle asthenosphere, and the heat flux at the bottom.

The strength of the crust and mantle are represented by the non-newtonian rheology as the combination of the viscous and plastic rheology (η = min { $\eta_{viscous}$, $\eta_{plastic}$ }). The viscous rheology is implemented through viscous diffusion and dislocation creep. The plastic rheology is defined using a Drucker-Prager yield-criterion (see Table. 2).

2.2 Landscape evolution model (LEM)

LEM is built based on the surface processes model (see Table. 3) with the time-aveage uplift rate caulated by the surface uplift of TM. The model contains two main surface processes: fluvial erosion and hilllslope diffusion, which are described by geomorphic equations and further solved using Badlands moudle.

2.3 Coupled model (CM)

The coupled model is built on TM by coupling with the surface processes.

Table 1: Model parameters applied in tectonic model

Layer	Δh (km)	ρ_0 (kg/m^3)	Index	Flow law
air	40	1	1	$\eta = 1.0 \times 10^{18}$ (Pa.s)
auc	17	2700	2	Wet Quartzite
alc	23	2800	3	Maryland Diabase ($0 < X < 200$ km)
			9	Mafic Granulite ($200 \leq X \leq 1000$ km)
aml	80	3300	5	Dry Olivine
iuc	15	2700	6	Wet Quartzite
ilc	20	2800	7	Plagioclase An_{75}
iml	105	3300	5	Dry Olivine
ma		3300	4	Dry Olivine
sediment		2700	8	Wet Quartzite

auc, Asian upper crust; alc, Asian lower crust; iuc, Indian upper crust; ilc, Indian lower crust; ml, mantle lithosphere; ma, mantle asthenosphere

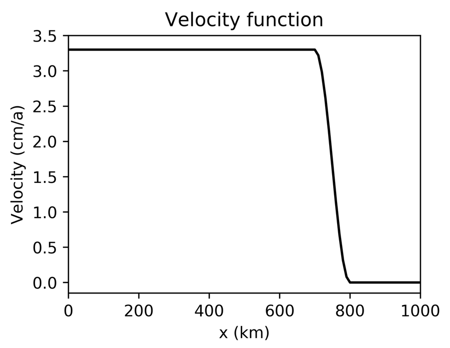

Fig. 2 (a) Velocity fuction of indender

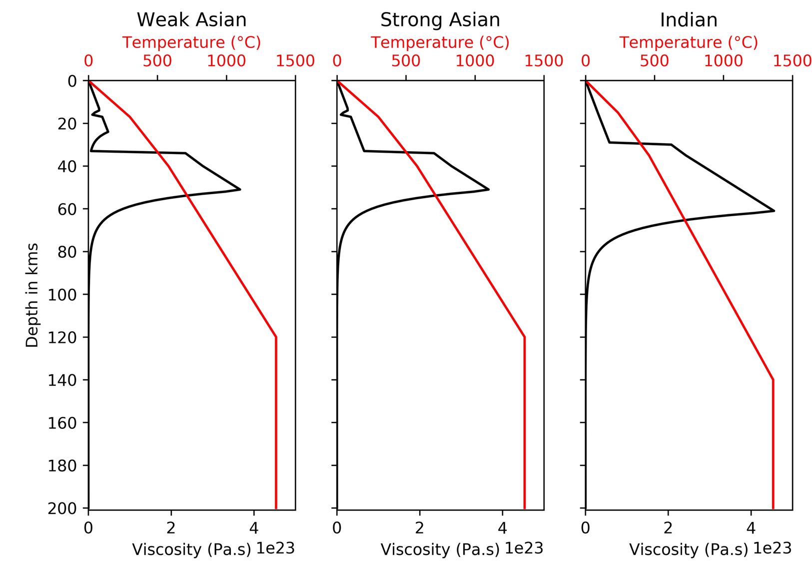

Fig. 2 (b) Effective viscosity and geotherm.

Table 2: Model parameters of rheology

Flow law	A_D (MPa^{n}s^{-1})	n	E_a (J)	V_a (J/cm^3)	tan(φ)	C (MPa)
Wet Quartzite	3.2×10^{-4}	2.3	1.54×10^5	0	0.15	1
Mafic Granulite	1×10^{-2}	3.2	2.44×10^5	0	0.15	1
Maryland Diabase	8.0	4.7	4.85×10^5	0	0.15	1
Plagioclase An_{75}	3.3×10^{-4}	3.2	2.38×10^5	0	0.15	1
Dry Olivine	2.5×10^4	3.5	5.32×10^5	8	0.60	1

Table 3: Model parameters applied in surface processes

Symbol (unit)	Value	Definition
p (m.a^{-1})	1.0	precipitation rate
m	0.5	expoent in stream-power law
n	1.0	expoent in stream-power law
κ_f (a^{-1})	5×10^{-6}	erosion rate of fluvial process
κ_d (m^2.a^{-1})	5×10^{-3}	diffusivity of hillslope process

Preliminary Results

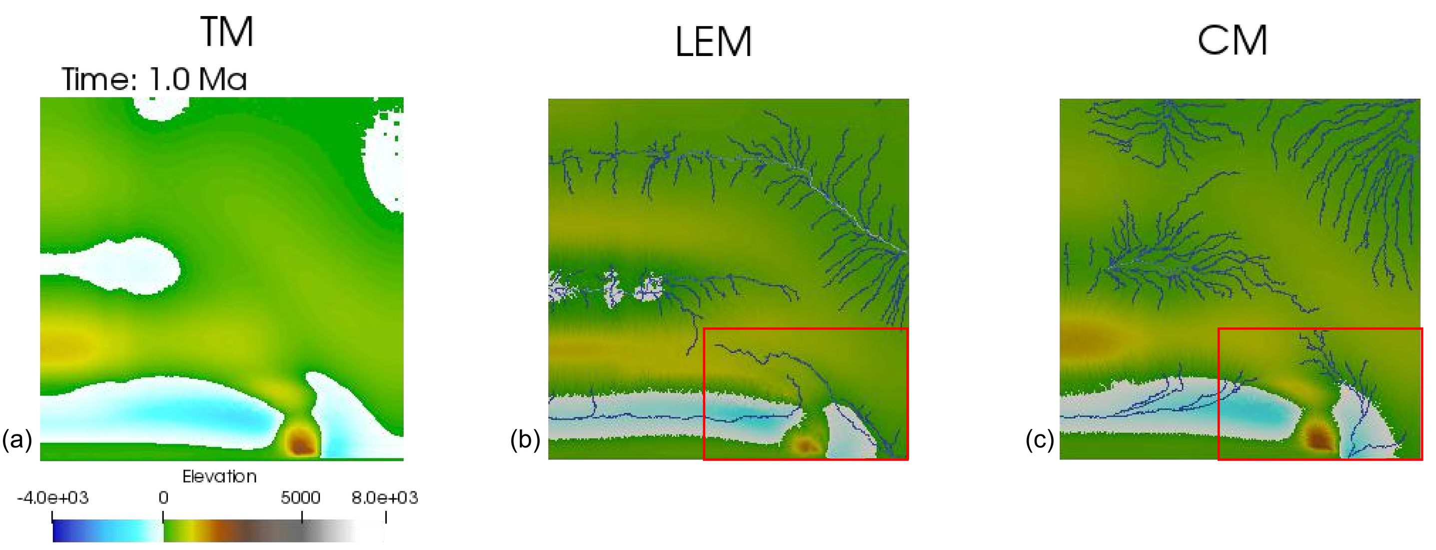

Fig. 3 (a) (b) (c)

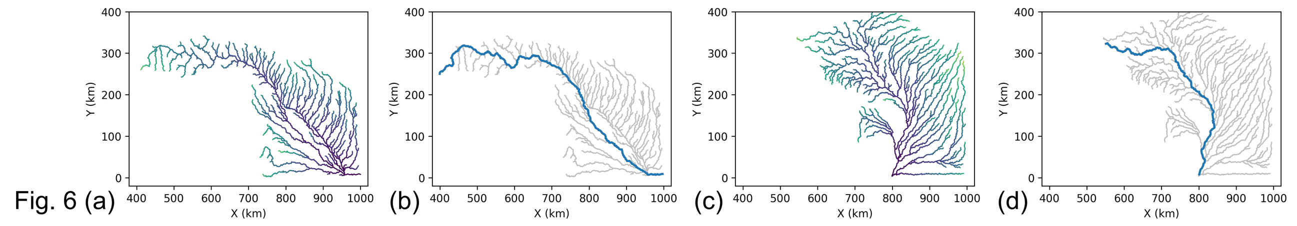

Fig. 6 (a) (b) (c) (d)

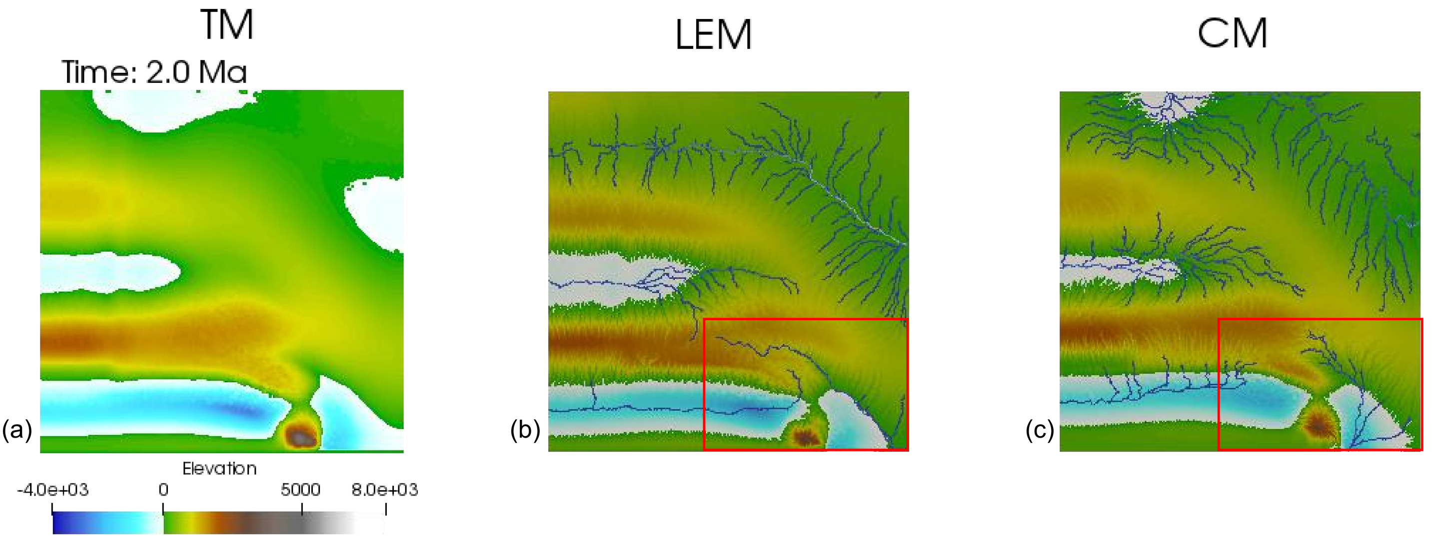

Fig. 4 (a) (b) (c)

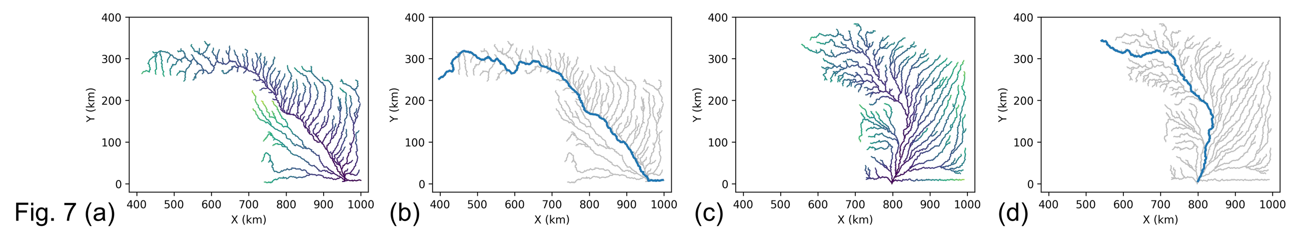

Fig. 7 (a) (b) (c) (d)

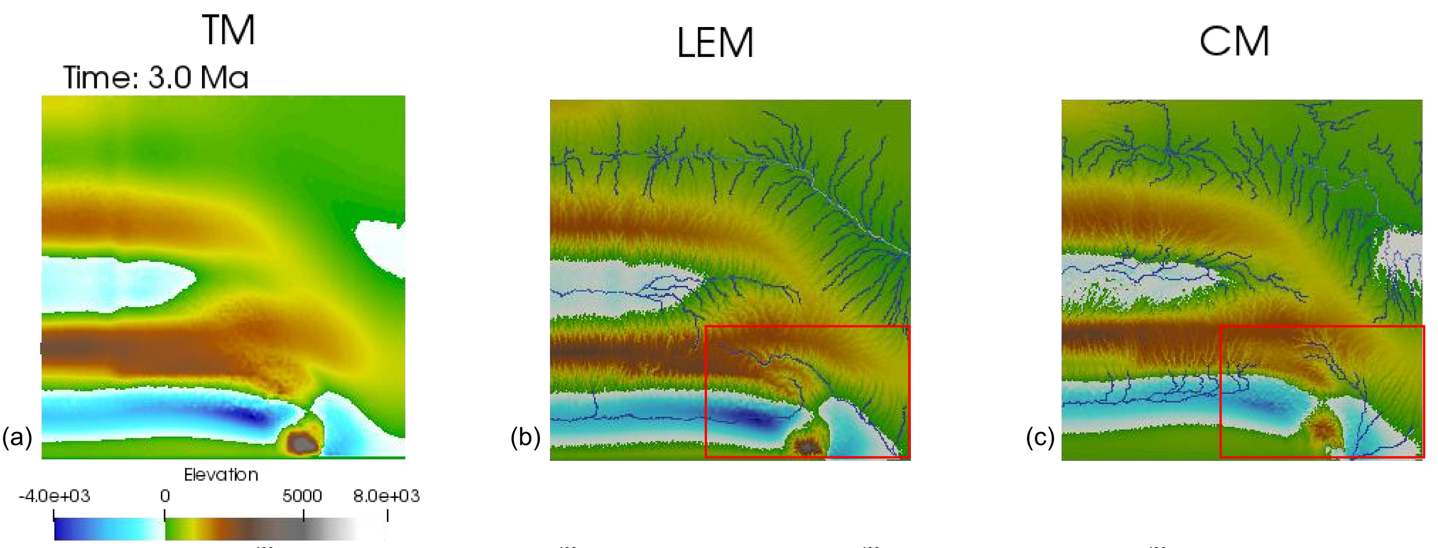

Fig. 5 (a) (b) (c)

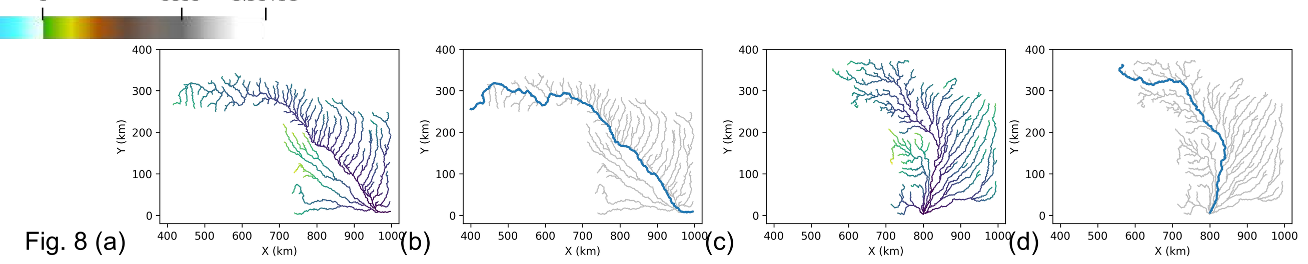

Fig. 8 (a) (b) (c) (d)

Fig. 3-5 show the drainages and topography of the models. It suggests that the drainages develop radially around the indenter front depending on the topographic gradients. The drainages of LEM and CM are initiated in the very early developing stage of the models, which is consisted of the assumption from Hallet and Molnar (2001) that the rivers are antecedent.

Fig. 6-8 show the specific catchments of the models which represent the "three rivers region". In Fig. 6-8 (b) and (d), the grey lines show the streams and the blue line represents the mainstream in this catchment. The LEM has more flat and continues river systems near the front of the indenter. And in the CM, rivers tend to become parallel fluvial systems instead of capturing with each other. That suggests that the interactions of tectonics and surface processes tend to create the parallel patterns of the drainage systems, in which, the horizontal motion of tectonics may play a dominant role. In other words, the acceleration in uplift rate (Clark et al., 2004) is not required to form the main landscape of TRR.

Fig. 6-8 (a) and (c) are the χ-map of the catchments, scaled from blue (low) to red (high). χ serves as a metric for the steady-state elevation of channels (higher means more disequilibrium). There are more discontinuities in χ across water divides trough time. It shows the drainage basins are dynamic reshaping either by pure vertical tectonic deformation or whole deformation.

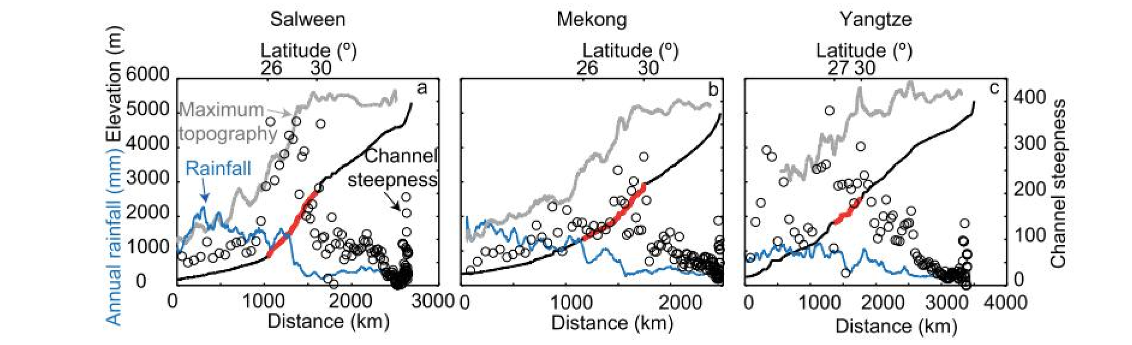

Fig. 9 River profile for the (a) Salween, (b) Mekong, and (c) Yangtze with maximum topography (grey line), annual rainfall (blue line), and channel steepness (small circles). (from Yang et. al., 2016)

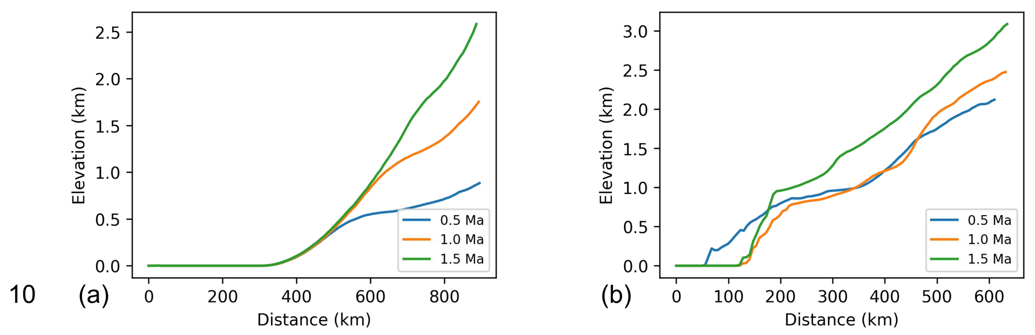

Fig. 10 (a) (b)

Fig. 10 (a) and (b) are the river profiles through the time of the main streams in LEM and CM. The profile of LEM follows relatively smooth equilibrium patterns and has no massive knick points occurring. While the profile of CM has convex parts due to the complex crust deformation, which is more similar to the real river profile of Yangtze river in nature.

Limitations:

(1) In our model, some capture events happened downstream can be observed while the northward streams captured by the eastward streams don't happen. This may be due to the block in the east (Sichuan Basin) is not being considered.

(2) The fluvial processes in our models are being addressed as the detached-limited model (unit stream power law), which should be applied in steady-state and uniform boundary conditions. Other models like saltation-abrasion model may be a better option.

Conclusion

We present the 3-D thermo-mechanical models in orogenic contexts built by the UWGeodynamics module that couples Underworld 2 to the surface process code Badlands. The fully coupled models have the advantages of considering complex interactions. Results demonstrate that tectonics and surface processes both influence the drainage evolution, and the large-magnitude tectonic shear is the primary control on the parallel drainage patterns.

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