Investigating valley spacing dynamics in linear mountain fronts through terrain numerical modeling

D. Capolongo[1], A. Refice[2], E. Giachetta[1]

[1] *Dipartimento di Geologia e Geofisica, Università degli Studi di Bari, Italy.* [2] *Istituto di Studi sui Sistemi Intelligenti per l'Automazione, Consiglio Nazionale delle Ricerche (ISSIA-CNR), Bari, Italy*

Introduction

Competition and synergy between tectonic and erosional processes are recognized as the main factors influencing the shape of many landscapes.
While considerable efforts are dedicated to the explanation of particular landscape forms and features, such as those found in some parts of the Earth surface, another aspect which is rising interest in the scientific community is the emergence of similar patterns and regularities in a variety of situations and environmental conditions.
Recent investigations, for instance, have been dedicated to the analysis of landscape features such as regular valley spacing in drainage networks evolving on slopes affected by competing tectonic uplift and terrain erosion.

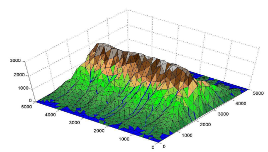
In this work, we use numerical modeling to analyze synthetic landscapes evolving under a combination of surface processes, typical of evolving mountain fronts.

The basin mean spacing is analyzed on such simulated landscapes obtained by application of uplift, hillslope diffusion and fluvial erosion. The LEM is completely implemented in Matlab, thus leaving ample access to a number of available terrain analysis and visualization tools.

Some comments on the temporal evolution of such synthetic landscapes are proposed, based on the analogy of these experiments with both real-world topographic analyses and similar experiments performed over indoor “sandbox” models, reported in the literature.

A Matlab TIN based numerical model -- SIGNUM

SIGNUM (Simple Integrated Geomorphological Numerical Model) is a TIN-based landscape evolution model: it is capable of simulating sediment transport and erosion by river flow at different space and time scales.
SIGNUM is a multi-process numerical model written in Matlab, providing a simple and integrated numerical framework for the simulation of many processes that shape real landscapes.
Particularly, at the present development stage, SIGNUM is capable of simulating processes such as hillslope diffusion, fluvial incision, tectonic uplift or changes in base-level.



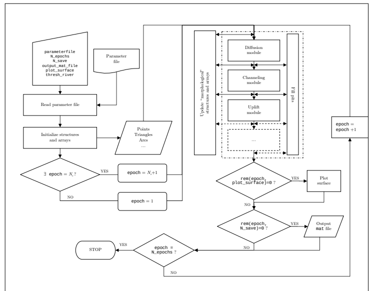
PROCESS	EQUATION	REFERENCES
Non linear diffusion	$q_s = \frac{K\nabla z}{1-\left(\frac{\lvert\nabla z\rvert}{S_c}\right)^2}$	*Roering* (1999)
Linear diffusion	$\left.\frac{\partial z}{\partial t}\right\rvert_{diffusion} = k_d \nabla^2 z$	*Braun e Sambridge* (1997)
Fluvial incision	$\frac{\partial z}{\partial t} = -KA^m S^n$	*Howard* (1980) *Stock e Montgomery* (1999)
Tectonic uplift or Base level changes	$\frac{\partial z}{\partial t} = U(x,y,t)$	*Tucker et al.* (2001)
Rainfalls	$b = K_b \bar{Q}^d = K_b (K_r \bar{i}_r \bar{t}_r A)^d$	*Tucker e Bras* (2000)
Surface water runoff	$D = P - E_t - I$	

Surface processes

Changes in elevation of the topographic surface are described by the equation of mass continuity for real surfaces:

$$\frac{\partial z}{\partial t} = -\nabla q_s + U(x,y,t)$$

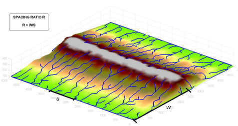
where *z* is elevation of a generic point of the TIN, *t* is time and *U* is tectonic uplift. The first term on the right includes several terms, describing different forms of erosion, whose expressions are reported in the Table above.

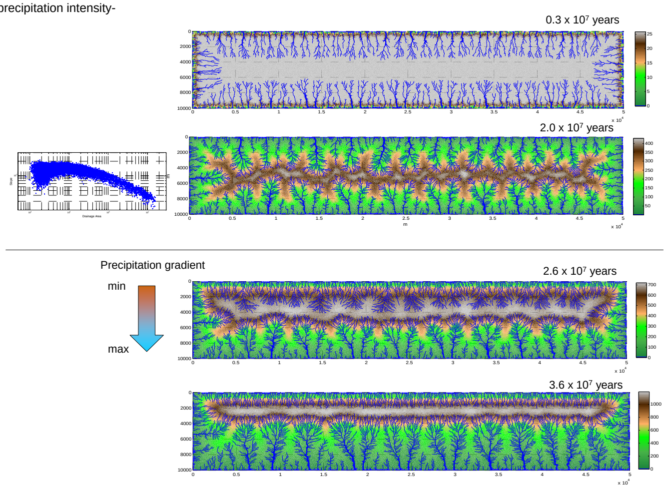


Experiments

Analysis of digital terrain models reproducing either actual features, or simulated surfaces obtained through application of landscape processes to synthetic terrain, have shown how the emergence and persistence of considerable degrees of regularity in the terrain dissection into parallel river basins is a feature common to both types (real and simulated) of landscapes. Such a regularity has been observed in linear mountain fronts, in different types of tectonic and climatic settings [Hovius 1996, Talling et al. 1997, Castelltort & Simpson 2006].
Regular river spacing has been also observed in simulated landscapes obtained through application of numerical models [Perron et al. 2009], or indoor scaled reproductions of an orogen subject to erosion by rain-wash [Bonnet 2009]. Several classes of explanations have been proposed for the onset and persistence of such spacing regularities. In particular, one critical aspect is the transient phase of reorganization that involves landscapes undergoing changes in geometry.
In this work, we investigate the temporal evolution of mean river basin aspect ratio, R, defined as the ratio between mountain front width W and basin outlet spacing S, averaged over a number of basins spanning at least a given fraction (say, 2/3) of W.

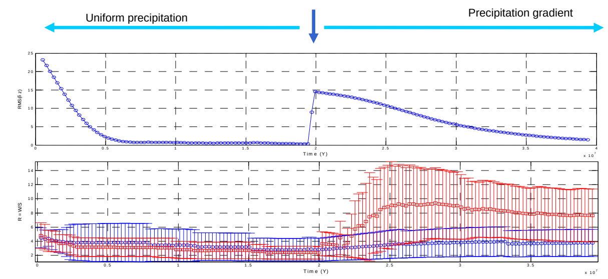
Our evolving surface is an initially flat TIN defined on a rectangular domain of size 10x50 km.
The surface is evolved through application of an uplift of the order of 0.1 mm/y, spatially uniform across the surface, except for the boundaries, which are kept at base level.
The surface elements are subject to linear diffusion and to river erosion processes, with uniform and constant parameters, for an initial time internal of approximately 2×10^7 years. During this initial time interval, a river network develops on the surface, and an apparent steady state is reached in the surface evolution, witnessed by the consistent power-law trend in the slope-area pot for the simulated surface.
Then, a spatial gradient is introduced in the river erosion pattern, with erosion increasing linearly along the side of the simulated mountain front. This pattern simulates the effect of a precipitation gradient, which is often used to simulate, at first order, the orographic effect on the windward / leeward asymmetry in precipitation intensity-



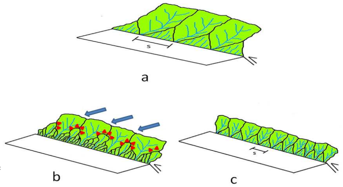


Results & Interpretation

We show the basins pattern development along both sides of a mountain range as the main drainage divide migrates toward the leeward side. After steady-state topography is achieved under uniform precipitations, a gradient of rainfall is applied across the mountain range.
The spacing ratio between the basin outlets, which had reached a stable value on both sides of the surface at steady state, undergoes an abrupt change at the time of the onset of the gradient, then gradually returns toward stable values more similar to the original ones, considering the new relative process weights.



Since the simulated topography represents a result of different competing processes acting on the simulated surface, such as climate, uplift and erosion, the channeling erosion becomes relatively more efficient on the windward side, on which a higher precipitation rate insists once the precipitation gradient is applied. This causes the larger catchments on the windward side of the range to erode the adjacent smaller catchments and the main drainage divide, which moves toward the leeward side. Additionally, the triangular facets interposed to the larger catchments, on which the smaller catchments are located, get wider.
In this way, the ratio between the length and the spacing of the outlets of the main basins increases at first, then tends to decrease as topography tends to a new steady state.



On the leeward side, instead, the numerical experiment shows a different evolution with respect to the windward side of the range: the decrease of precipitation leads to a less efficient channeling erosion; then the topographic evolution is affected mostly by surface uplift. Given this increased uplift influence, a general steepening is observed in all the basins along the leeward side. Here, some smaller catchments located on the triangular facets at the border, because of the steepening of their topographic surface, can compete again with larger catchments, growing and lengthening toward the main drainage divide. Also, the simultaneous migration of the main divide toward the dry side of the range emphasizes the shortening of the larger catchments. The process goes on modifying the average length to width ratio. The final result of this complex mechanism of basins pattern reorganization seems to be a new steady state topography and a spacing ratio closer to the value observed under uniform precipitation (taking into account the relative process effects).
As shown in the cartoon below, the spacing ratio is gradually restored, in part, through a process of basins “cannibalism” and a new arrangement in response to climatic change. In the end, we observe the spacing ratio gradually converging to stable values on both sides of the range. We explain these results essentially with the growth of certain basins at the expense of others.

References

Bonnet, S. (2009). Shrinking and splitting of drainage basins in orogenic landscapes from the migration of the main drainage divide. *Nature Geoscience.* **2,** 766–771
Castelltort S. & Simpson G. (2006) - River spacing and drainage network growth in widening mountain ranges. *Basin Research, 18, 267-276*.
Hovius N. (1996) - Regular spacing of drainage outlets from linear mountain belts. *Basin Research, 8, 29 - 44.*
Perron, J. T., Kirchner, J. W. & Dietrich, W. E. (2009). Formation of evenly spaced ridges and valleys. *Nature* **460,** 502–505.
Talling, P. J., Stewart, M. D., Stark, C. P., Gupta, S. & Vincent, S. J. (1997) - Regular spacing of drainage outlets from linear faults blocks. *Basin Research Journal, 9, 275-302*