SIGNUM: NUMERICAL MODELING IN THE EARTH SCIENCES

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INTRODUCTION

In this work a numerical model for simulation of surface processes and landforms is briefly described. The model is called SIGNUM (Simple Integrated Geomorphological NUmerical Model): it is a landscape evolution model, written in the Matlab programming language, based on topographic surface discretization using TINs (Triangulated Irregular Networks).

SIGNUM simulates the evolution of topographic surfaces through application of mathematical expressions for geomorphic processes such as hillslope and fluvial erosion, channel sediment transport and geological processes such as tectonic uplift. Emphasis in development has been posed on flexibility (processes are managed in a modular fashion and can be easily switched on and off by the user) and integrability with existing and third-party terrain analysis tools (the Matlab environment offers many optimized visualization and analysis tools).

State-of-the-art techniques are used for process analytical modeling, which ensures faithful simulation of natural landscape evolution. For instance, a particular example is shown to reproduce a topographic feature similar to real landscapes, namely the approximately regular spacing of valleys at linear mountain fronts.

THE STATE OF ART OF LANDSCAPE EVOLUTION MODELS

Although work in the field of computer simulation of geomorphological processes of landscape evolution is at its beginning, the results and insights from numerical models, such as the one presented in this work, are gaining more and more attention in the scientific community, justifying and encouraging increasing research efforts. In the last two decades, many landscape evolution models have been proposed by several research groups such as hydrology (*Garrote & Bras*, 1995), soil erosion (*Laflen et alii*, 1997), hillslope stability (*Montgomery & Dietrich*, 1994), vulcanology (*Miyamoto & Sasaki*, 1997) and landscape evolution studies (*Willgoose et alii*, 1991a; *Howard*, 1994; *Johnson & Beaumont*, 1995; *Tucker & Slingerland*, 1994; *Tucker & Bras*, 1998). All these models have the common purpose of understanding processes and laws governing landscape evolution by simulating either water, sediments or magma flux onto the topographic surface.

Numerical models are also frequently used to understand complex geomorphological systems. These landscape evolution models have mainly two purposes: first, testing quantitative assumptions on processes acting on those complex systems, providing a linkage between field measurable processes and their geomorphological implications on long term evolution; second, providing a support tool in geo-environmental studies and hazard prediction. Geomorphology is going toward a period of great development driven mainly by the availability of high resolution topographic data and high performance computer environments. Geomorphologist are able, in an unprecedent manner, to analyze the Earth surface at the scale (1 m or finer) of the geomorphological processes acting on hillslope and in fluvial systems and to measure rates of landform change and then explore how physics and chemistry of surface processes influence different paths of landscape development. The numerical models represent a linkage, in a quantitative manner, between the surface processes and the resulting landforms in complex and non-linear geomorphological systems, that is important for prediction of future landscape evolution also in term of geomorphological hazards and planning.

SIGNUM: A MATLAB, TIN-BASED LANDSCAPE EVOLUTION MODEL

SIGNUM is a TIN-based landscape evolution model: it is capable of simulating sediment transport and sedimentation by river flow at different space and time scales. TIN-based landscape evolution models, allow a variable spatial resolution and a dynamic discretization of the topographic surface. SIGNUM is a multi-process numerical model not only providing a numerical framework but simulating some important processes that shape real landscapes. Particularly, with its last version, SIGNUM is capable of simulating hill-slope processes such as linear and non-linear diffusion, fluvial incision into bedrock, tectonic uplift and base-level or climate changes.

Changes in elevation of the topographic surface are described by the equation of mass continuity for real surfaces (*Anderson*, 2008, *Tucker*, 2009):

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

where z is elevation of a generic point of the surface, t is time and U is tectonic uplift or base-level changes. The divergence of the sediment flux qs includes several terms, describing different geomoprhic transport laws. By solving this equation, SIGNUM can calculate at each time step the rate of change of elevation for each node of the TIN. Two main structure concepts are used in SIGNUM, one related to the points on which the landscape height is sampled, the other connected to the TIN structure, usually a Delaunay triangulation (*Delaunay*, 1934). Associated to these main structures are other support arrays which help in bookkeeping of links and indices. The simulation is a run on several user defined cycles (epochs). At each new iteration, the height of the TIN nodes is updated based on the processes selected to solve the mass conservation equation.

A NUMERICAL EXPERIMENT

Here I present a simple experiment in which the application of a simple set of simulated surface processes is able to reproduce a certain organization and order in the landscape.

The organization I explore here is a fascinating, not really well understood example of apparent regular spacing between transverse rivers in linear sections of mountain ranges. Hovius (1996) analysed the drainage network of eleven different linear mountain belts worldwide. His study revealed that the outlets of the major transverse rivers at the front of these orogens are regularly spaced and also that their spacing S is on average proportional to the half-width W of the mountain range (measured from the drainage divide to the front), following the relation R=W/S. Further he showed that the measured spacing ratio R falls in a narrow range of values (1.91 - 2.23) around a mean of 2.1 despite strong differences in climate and rock uplift rates.

I used SIGNUM to simulate the geomorphotectonic mountain front evolution in different tectonic settings. The TIN-based, modular process structure of SIGNUM allows to reproduce the development of complex tectonic structures such as thrust faults. By varying regional uplift, faults propagation velocity, precipitation rates coupled with stream power based river incision and linear and non linear hillslope diffusivity, SIGNUM is able to reproduce realistic first-order topographic features, such as that shown below in figure 1, convincingly analogous to real-world active mountain fronts.

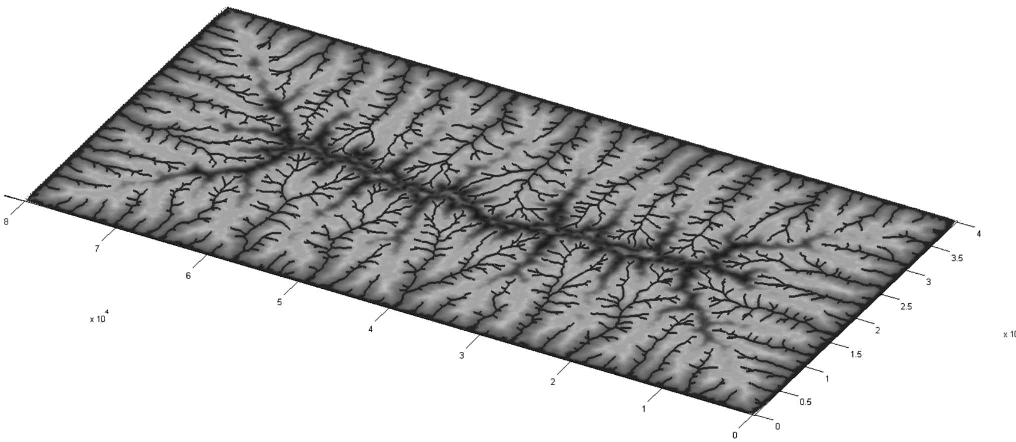

FIGURE 1. The lattice surface evoluted with SIGNUM, after a 5 My simulation.

The simulated domain is a TIN of 40 x 80 km and the initial condition is a flat undissected surface. It can be easily seen a regularity of the drainage features flowing through the mountain front as the range grows.

Now the questions are: is this regularity proportional to the width of the mountain range? And what is the value of R simulated by the numerical model? In fig. 2, I plotted the mean value of R and the standard deviation computed every 500 kyr for 5 Ma. The value of R vary between 0.5 and 3.5 and the mean value of R, after a constant increase in the early stage of the landscape evolution, tends to circa 2 at the end of the numerical experiment.

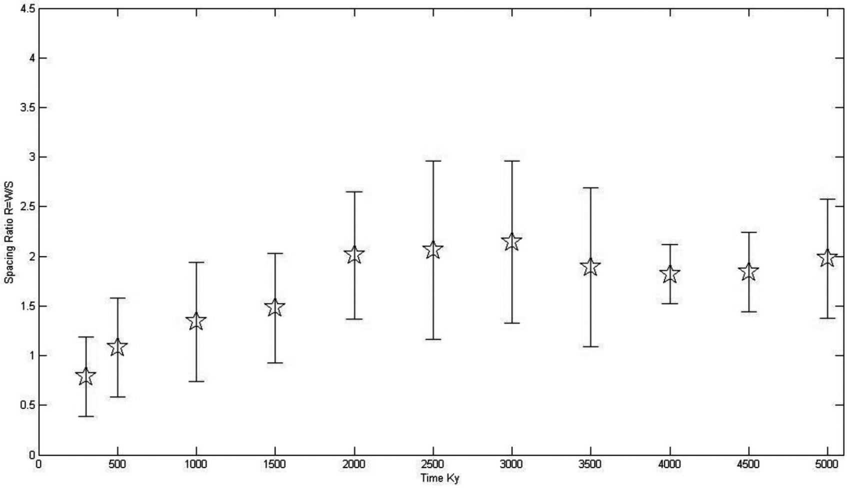

FIGURE 2. Plot showing the average valley spacing ratio R = W/S, calculated along the simulated mountain front in Fig. 1 every 500 ky. Error bars have widths equal to the R standard deviation.

CONCLUSIONS

Geomorphology and others Earth sciences are going toward a period of great development driven mainly by the availability of high resolution topographic data and high performance computing environments. One of the pillars of this development is the principle of conservation of mass. Exercising the principle of mass conservation (*Anderson*, 2008), either in the field (with natural experiments) or with numerical models, geomorphologists can explore how factors such as hydrology, vegetation, material properties and humans can affect landform distribution in the landscape and their rate of change. I presented here a simple numerical experiment using SIGNUM, my Matlab, TIN-based landscape evolution model. I showed that, by applying simple rules that simulate erosion and transport of selected surface processes such as hillslope degradation, bedrock river incision and surface uplift due e.g. to tectonics, SIGNUM is able to reproduce quite common features of linear mountain fronts, such as regular valley spacing and drainage diversion and captures. I also found that the numerical experiment reproduces the characteristic morphometric value of the valley spacing ratio R that many authors found in several linear mountain fronts in different climatic and tectonic settings.

These results and further numerical experiments can help Earth scientists to speculate about some still poorly understood questions on the factors and process that control such features of real landscapes.

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