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A numerical model testing the role of climate in high plateau formation

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1. Introduction

Most investigations regard the formation of high plateaus as the result of tectonic processes disrupting surface mass transport within an orogen. Inherited tectonic structures predating or coeval with compression are often invoked to explain the partitioning of tectonic topography and the hydrological isolation of the plateau from the surrounding areas (internal drainage). Syn- or post-tectonic uplift related to the accommodation of shortening at deep crustal levels is frequently invoked to account for the elevation of the plateau, and open questions remain on whether this deformation consists of a lateral viscous flow in the lower crust (e.g., Isacks, 1988), and/or brittle failure by means of crustal, imbricated megathrusts. In the case of the Andes-Altiplano, measured along-strike variations in tectonic shortening allegedly control the variations in timing and style of deformation (e.g., McQuarrie, 2002). In this context, surface processes have been mostly seen as passively responding to these tectonic events by eroding the orogen and filling the intramountain sedimentary basin.

However, modeling studies have shown that erosion has a significant influence on lithosphere dynamics during orogenesis (e.g., Avouac & Burov, 1996). For example, climatic parameters determining the side of the orogen receiving most precipitation seem to be critical in determining the later tectonic evolution and structure of a mountain belt (Willet, 1999). Meanwhile, recent numerical modeling techniques (Sobel et al., 2003; Garcia-Castellanos et al., 2003; Garcia-Castellanos, 2005) have demonstrated that precipitation and basin evaporation are as important as tectonics in controlling the formation and duration of tectonic, internally-drained basins.

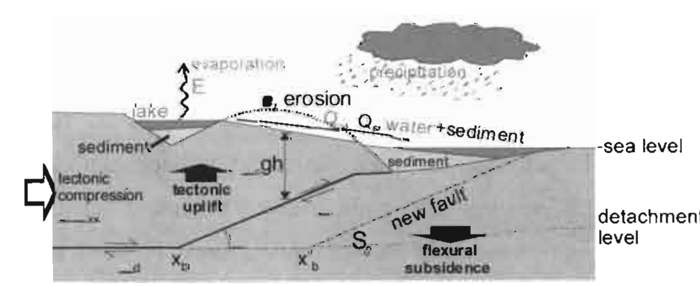

Fig. 1.- Conceptual model. Tectonic deformation is calculated with a minimum-work criterion of fault propagation. Erosion and transport is calculated via a stream power law model of fluvial incision and transport. Water flow is calculated assuming a constant evaporation at lakes and a constant precipitation all over the model.

In this study, we address the role of these climatic factors on the development of orogens and intramountain basins to check the hypothesis that climate can be as important as tectonics in determining the formation of a closed intra-orogenic basin and in controlling the development of a high-plateau. For this purpose we use a computer cross-section model of orogen and basin evolution that accounts for the interactions between four processes (Fig. 1): 1) dynamic propagation of thrusting; 2) a basic hydrological balance; 3) surface erosion / sediment transport / sedimentation; and 4) flexural isostasy.

2. Model assumptions and formulation

We develop a finite difference code based on *tAo* (e.g., Garcia-Castellanos, 2005) that operates in 6 time-iterative steps: 1) Calculation of the formation of new faults and the corresponding tectonic deformation; 2) Determination of the changes in topography related to tectonic deformation; 3) Determination of precipitation and the drainage network following a maximum slope criteria; 4) Determination of the extension of lakes in

topographic minima, accounting for evaporation and possible endorheism; 5) Determination of the amount of material eroded/deposited at each location; and 6) Isostatic compensation of surface and tectonic mass flow.
For the sake of simplicity, the initial topography of the model is assumed to be flat at sea level (Fig. 1). Tectonic shortening is accommodated along faults. Two initial thrusts of opposite vergence accommodate the initially imposed shortening rate V. We follow the simplest approach capable to reproduce the dynamics of fault propagation towards the external parts of the orogen. This model is based on a minimal work criterion of brittle deformation (Masek & Duncan, 1998). The rate of dissipated frictional work $\dot{W}_f$ along a fault is approached as:

$$\dot{W}_f = V \int \tau \, dx \qquad (1)$$

where, τ is the shear stress along the fault and x is the horizontal coordinate. τ is approached as the component of normal stress (perpendicular to the fault plane) multiplied by a slip friction coefficient μ (Masek & Duncan, 1998):

$$\tau = \mu \left(\rho_c \cdot g \cdot (z_t - z_f) + \frac{\Delta\sigma_{xx}}{2}(1 - \cos 2\theta) \right) \qquad (2)$$

Where θ is the dip angle of the fault, ρ_c is the density of the crust, z_t the topographic altitude, and z_f the altitude of the fault (Fig. 1). $\rho_c g(z_t - z_f)$ is therefore the lithostatic pressure at the fault, whereas $\Delta\sigma_{xx}$ represents the horizontal tectonic stress, assumed constant along the modeling profile. Hereafter it will be assumed that thrusts follow a horizontal detachment level at z_d=35 km depth. These thrusts reach the surface from the detachment level following an angle of θ=30 degrees. The friction coefficient equals μ_d=0.1 along the detachment level and μ=0.5 elsewhere. For the examples below, shortening rate is set constant to V=12 km/Myr during a 18-Myr-long tectonic period. The implied 216 km total shortening is accommodated 50% at each side of the orogen.
As topography grows, pressure along the active fault increases and so does the work necessary to accommodate shortening along the active fault. Because of the lower friction along the detachment level, this work can eventually become larger than the work along a potential new fault located further into the undeformed foreland. This triggers the activation of a new thrust that will accommodate all shortening in that side of the orogen. The tectonic units defined by faults move towards the undeformed foreland preserving their mass and following a vertical shear approach. This tectonic model must be seen as the simplest way to calibrate the first order influence of surface transport on the propagation of tectonic deformation.
Erosion is modeled via a combination of fluvial incision and hill-slope rock flow. For its simplicity and versatility, here we adopt the stream power formulation developed by Beaumont et al. (1992). In turn, this implies accounting for a simplified balance between precipitation, surface water flow and evaporation in the surface of lakes. In the model, lakes form at topographic minima and the sediment they receive from surface water flow is deposited. Erosional parameters are taken from previous studies using the same surface processes formulation (e.g., Garcia-Castellanos et al., 2003).
Mass redistribution related to tectonic deformation, surface sediment transport, and changes in water volume are isostatically compensated via a 1D thin-plate flexural approach with laterally constant elastic thickness T_e (15 km in the models shown here).

3. Two examples

Two sets of climatic parameters are chosen to represent two extreme cases (models M1 (dry) and M2 (humid).
Model M1 *(dry)*. The results shown in Fig. 2 assume a laterally constant precipitation rate of 600 mm/yr and an evaporation rate of 1300 mm/yr. The low amount of water flowing on this orogen has a low erosional power that

is easily defeated by tectonic uplift. This promotes the formation of closed-drainage basins that retain sediments within the orogen becoming progressively peneplane and increasing in altitude. This sediment trapping reverts in a further propagation of thrusting towards the external parts of the orogen.

***Model M2** (humid).* In this model (Fig. 2) a precipitation rate of 1600 mm/yr and an evaporation rate of 900 mm/yr are used. Note that all other kinematic, dynamic, erosional, and geometrical parameters are identical to Model 1, and therefore all differences with that model, including those visible in the final orogen structure and fault distribution, are caused by the distinct climatic situation and its effects on erosion and transport. The high precipitation/evaporation ratio also implies that closed basins can not develop, and one single drainage divide is formed in this model (Fig. 3). Because erosion rates are much higher than in Model M1, topography grows slower here, and so does the pressure at which faults are confined. This allows a longer active period for each fault, diminishing the total amount of faults and the lateral growth of the orogen.

Comparing both model predictions (Fig. 3) suggests that dry climatic conditions in the highlands (promoted in real orogens by orographic isolation) favor the defeat of rivers draining the orogen, promoting lake formation, intramountain deposition, and eventual formation of a long-lived internally-drained high-plateau. Drainage closure extends the life and volume of the intramountain basin by preventing erosion along any outlet river. In turn, the mass trapped within the orogen leads to deactivate central faults and further propagate deformation into the foreland. Finally, this propagation of tectonism further isolates the central parts of the orogen from incoming precipitation. This feedback phenomenon may explain the formation of long-living high-plateaus without invoking tectonic controls or inherited structural heterogeneities in the crust.

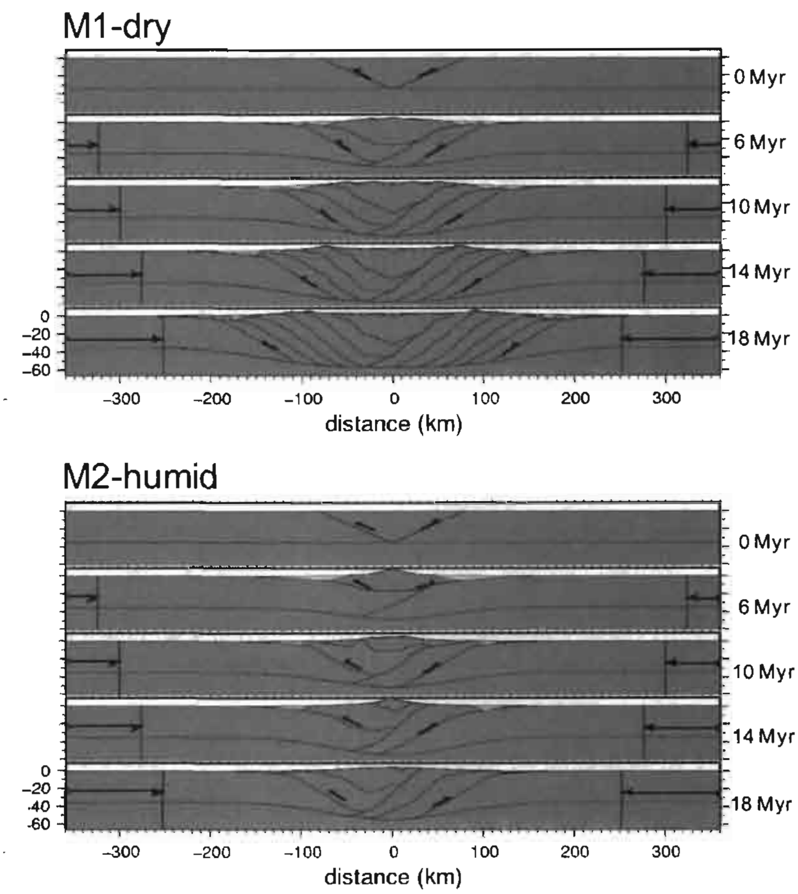

Fig. 2.- Evolution of models M1-dry (left) and M2-humid (right). Note the different location and timing of thrusts due to different surface mass transport imposed by climatic parameters. Dry climate promotes the development of closed intra-orogenic basins that trap most erosional products from the orogen. This promotes faster propagation of thrusting towards the external parts of the orogen. In contrast, a humid weather implies higher erosion rates that efficiently eliminate mass from the orogen and reduce pressure along active faults, prolonging their activity and impeding the activation of new faults further towards the foreland.

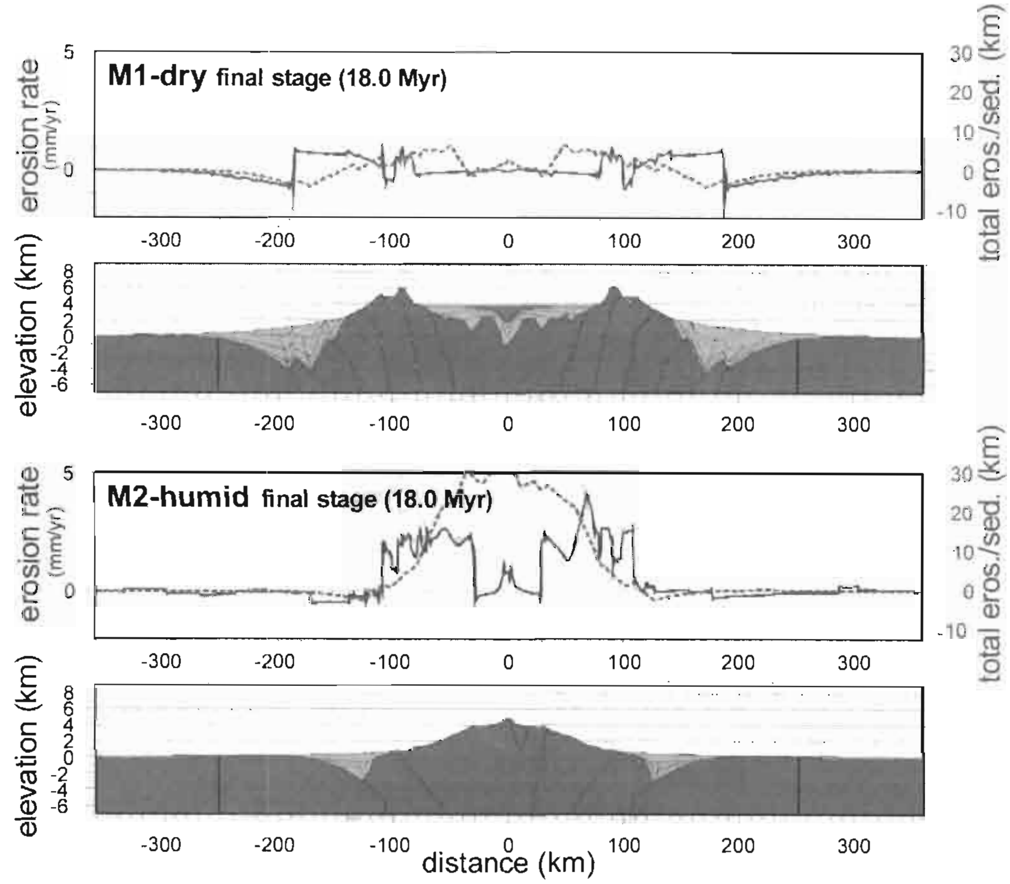

Fig. 3.- Final stage of models M1-dry (upper panels) and M2-humid (lower panels). The upper kilometers of the section are shown for each model with a vertical exaggeration of 1:8 (yellow: sediment; blue: water). Plots indicate the erosion/sedimentation rate profile at 18 Myr (plain line) and the total cumulative erosion/deposition at each location (dashed line). In M1, sediment accumulation flattens and progressively increases the altitude of the endorheic area, located at nearly 4000 m a.s.l. in this example. In contrast, the erosion rates in M2 are high enough to defeat tectonic uplift above thrusts, impeding drainage closure and facilitating removal of erosional products from the orogen. This in turn allows for a longer activity of each individual fault, diminishing lateral orogenic growth (orogen widening) and impeding the formation of a high-plateau.

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