Numerical modeling of mountain building: Interplay between erosion law and crustal rheology

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[1] Coupling between erosion and tectonics is thought to play a determinant role in orogenic evolution. Here, we investigate the interplay in this coupling between the assumed erosion law and the crustal rheology at the margin of a collisional plateau, like the Himalaya of Central Nepal. Lithospheric deformation is calculated over a time scale of 100 kyr by a 2D finite element model that incorporates the rheological layering of the crust and the main features of the convergence across the range. For the upper boundary condition, two surface processes were tested: a linear diffusion model and a 1D1/2 integrative model including fluvial incision along the fluvial network and hillslope erosion by landsliding. Model results and their sensitivity to the chosen combinations of erosion law and crustal properties are discussed in light of the constraining geologic and geomorphologic observations. In contrast with the conclusions of *Cattin and Avouac* [2000], where a compliant quartz-rich crustal rheology and diffusion law were required, we combine a composite quartz-diabase rheology for the crust with fluvial incision erosion law to account for erosion and elevation profiles across the Himalaya of Central Nepal. More generally, it is proposed that, because of the interplay between the dominant denudation conditions and the rheology of the crust, both well documented erosion rates and processes can provide significant constraints on crustal properties within an active orogen. *INDEX TERMS:* 1815 Hydrology: Erosion and sedimentation; 2753 Magnetospheric Physics: Numerical modeling; 1236 Geodesy and Gravity: Rheology of the lithosphere and mantle (8160). **Citation:** Godard, V., R. Cattin, and J. Lavé (2004), Numerical modeling of mountain building: Interplay between erosion law and crustal rheology, *Geophys. Res. Lett.*, *31*, L23607, doi:10.1029/2004GL021006.

1. Introduction

[2] The land surface is a dynamic interface that results from the combination of tectonic uplift and denudation. Knowledge of the linkages between those two processes is essential for the understanding of the structure and the evolution of mountain belts. Few 3D simulations with full coupling between tectonics and erosion have been conducted so far. Most of the thermomechanical finite element models are 2D, where erosion processes are usually reduced to a 1D process acting on the surface profile. Erosion is either reduced to a diffusion law [*Avouac and Burov*, 1996; *Cattin and Avouac*, 2000], or to a linear function of the surface slope [*Beaumont et al.*, 2001], or to a simple river incision law where the mean topographic profile is represented by a river profile [*Willett*, 1999]. These simplified models ignore the respective role of river network and hillslopes in controlling the morphology and evolution of the landscape. In this paper we investigate the influence of the assumed erosion law and of the rheological properties of the crust on crustal deformation through the use of a 2-D mechanical model, as applied to the Himalaya of Central Nepal. After a short presentation of the geodynamical setting, we describe the modeling approach and the two distinct erosion laws we want to test. Then, from the comparison to existing data, we discuss the sensitivity of our results and try to highlight the most critical observations for unraveling rheologic and erosional conditions prevailing in a mountain range.

2. Geodynamical Setting and Characteristics of the Fluvial Network

[3] The Himalayan belt has resulted from the ongoing collision between the Indian and Asian plates. It is characterized by a steep topographic front descending from the 5000-m-high Tibetan Plateau to the Gangetic plain. This topographic step traverses four major morphotectonic domains: the rugged South Tibetan plateau, the High Himalaya (HH) with deep gorges and $\sim$8000 m summits, the lower relief of the Lesser Himalaya (LH), and the frontal low elevation relief of the Siwaliks Hills. The Himalayan range is affected by an intense ongoing seismicity [e.g., *Pandey et al.*, 1995], and displays abundant evidence of active deformation. The long term shortening rate across the range is $\sim$20 mm.yr^{-1} [*Lyon-Caen and Molnar*, 1985; *Armijo et al.*, 1986]. During the Holocene, this convergence has been mostly transferred to the southernmost thrust or Main Frontal Thrust (MFT) [*Lavé and Avouac*, 2000]. This frontal fault branches on the Main Himalayan Thrust (MHT) which roots at 30–40 km depth beneath Southern Tibet [*Zhao et al.*, 1993], and displays a ramp-flat geometry beneath the HH and LH domains [*Schelling and Arita*, 1991]. Several major north-south rivers drain the Himalaya of Nepal from southern Tibet down to the Indo-Gangetic plain. In Central and East Nepal, across the HH, those Transhimalayan rivers flow $\sim$50 km apart before joining two major river systems, the Narayani and Sapt Kosi basins, both tributaries of the Ganga. Precipitation in Nepal is

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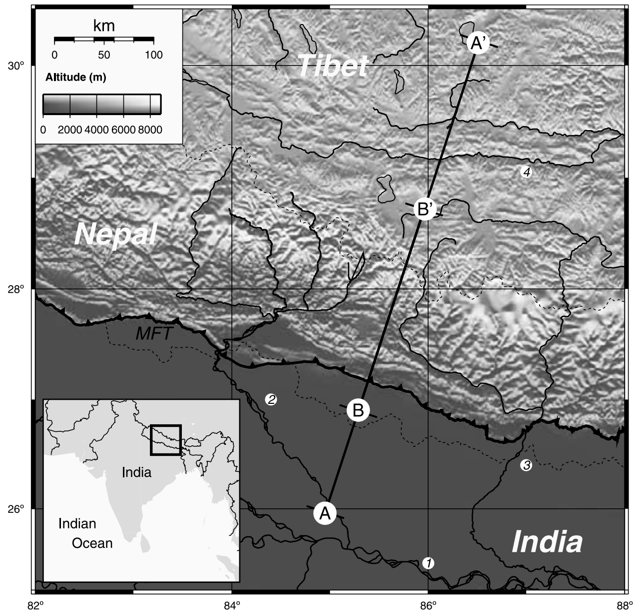

Figure 1. Topographic map of the study region (GTOPO30 DEM), showing the principal hydrographic features, the position of the Main Frontal Thrust, and the cross sections AA′ (Figure 2) used in the modeling and BB′ presented on Figures 3 and 4. 1-Ganga, 2-Narayani, 3-Sapt Kosi, 4-Tsangpo.

controlled by topography: forceful condensation against the HH of the moist air coming from the Indian Ocean during the monsoon leading to active fluvial denudation on the south flank of the HH. Recent studies [*Lavé and Avouac*, 2000, 2001; *Burbank et al.*, 2003] suggest that erosion is maximal across the Siwaliks and the HH, lower in the LH, and minimal in South Tibet.

3. Modeling Approach

[4] Following *Cattin and Avouac* [2000], our model is based on a 700-km-long N18° cross section perpendicular to the range, from the Gangetic Plain to the Tibetan Plateau (see Figure 1). We use a 2D finite element model [*Hassani et al.*, 1997] that accounts for the mechanical layering of the crust and the non-Newtonian viscous rheology of rocks as a function of temperature and pressure. Three lithological layers are distinguished: the upper and lower crust, and the upper mantle. We use empirical rheological equations and laboratory-derived material properties for quartz, diabase and olivine (see supplemental material 2[1]). Those rheologies are dependent on temperature which is prescribed as an initial condition [*Henry et al.*, 1997] and do not evolve during the simulation, considering the typical duration of ∼100 kyr. This duration limit is imposed by the distortions of the mesh supporting the mechanical model, for the different runs it was usually sufficient to reach a stabilized topographic profile, i.e., an average equilibrium between uplift and erosion (see supplemental material 1). The principal geometric characteristics of our model are similar to *Cattin and Avouac*'s [2000] model (Figure 2). We account for convergence by imposing a 20 mm.yr^{-1} horizontal velocity on the northern vertical face to a depth of 40 km. The coupling between uplift and erosion is, in part, allowed by applying an hydrostatic pressure at the base of the structure. A fault with a simple Coulomb friction law is introduced and follows the ramp and flat geometry proposed for the MHT. Due to the duration of our simulations, we do not consider the seismic cycle, and slip on a low friction MHT is considered as continuous. Our main goal is to test the importance of the upper boundary condition imposed by surface processes on the evolution of the system.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL021006.

4. Surface Processes

[5] We distinguish two domains in term of surface processes: the foreland, south of the MFT, with active sedimentation (where we assume a constant ∼0 m elevation) and the mountain range dominated by active erosional processes. In the range, two distinct erosion models are explored: a classical diffusion model, and a detachment-limited fluvial incision model including an implicit description of the tributaries and hillslope (J. Lavé, manuscript in preparation, 2004). If the diffusion model can describe the evolution of small-scale topographic features, we suspect that it does not apply for large-scale morphologies because it can not account for the advective nature of fluvial processes and their key role in denudating landscape [e.g., *Whipple and Tucker*, 1999]. Whereas different functional forms have been proposed to model fluvial incision, in an attempt to develop a simple approach, we have used a detachment-limited relation that provides satisfactory first-order results in the Subhimalaya [*Lavé and Avouac*, 2001]. This relation states that bedrock incision rate of a river is proportional to the fluvial shear stress τ in excess of some threshold

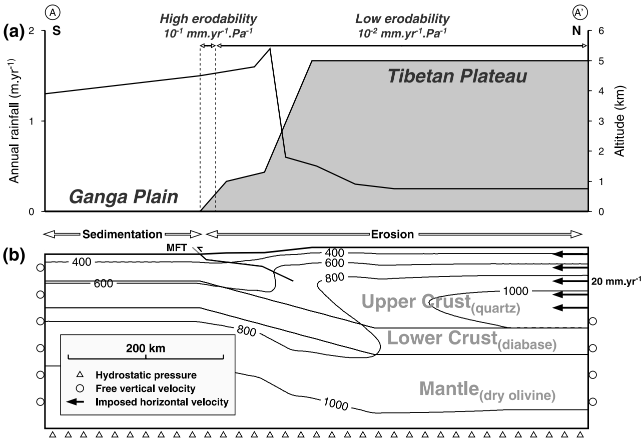

Figure 2. Main features of the model. (a) Rainfall profile (black line, from *Lavé and Avouac* [2001]) and initial topography (gray area, derived from the current topography). Dashed line gives the location of the high erodability area allowing a strong uplift in the Siwaliks [*Lavé and Avouac*, 2001]. (b) Geometry of the system, temperature field (K), rheological units, and boundary conditions used for the modeling. In the foreland sedimentation balances subsidence. In the range landscape evolution is controlled by the chosen erosion law.

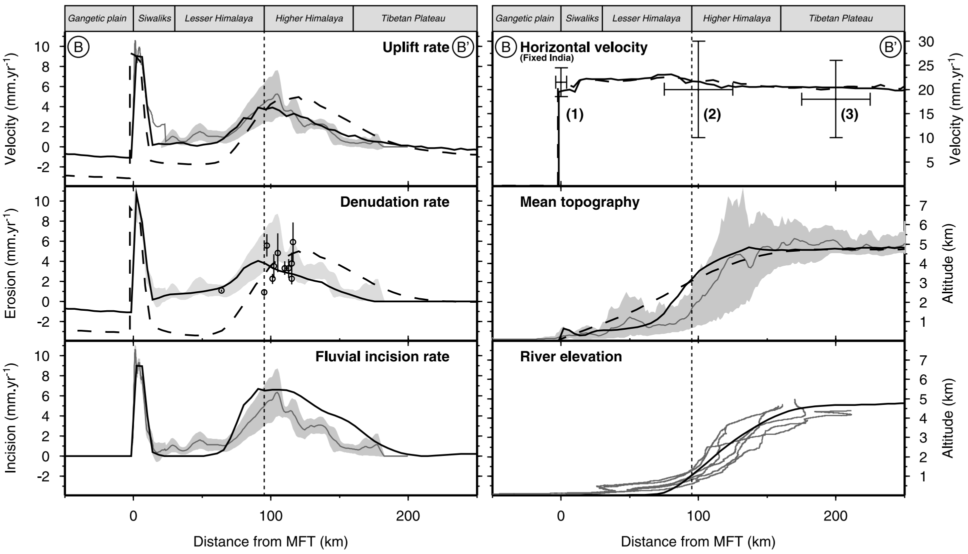

Figure 3. Fluvial incision model (black line) and diffusive model (dashed line). Uplift, denudation and incision profiles are compared to profiles from *Lavé and Avouac* [2001], and to fission track data from *Burbank et al.* [2003] for the denudation profile (denudation rates obtained using the thermal model from *Henry et al.* [1997]). Within the gray zone (marking $\pm 1\sigma$ confidence interval) the solid line indicate the mean value. The control points on horizontal velocity are derived from folding of fluvial terraces in the Siwaliks (1) [*Lavé and Avouac*, 2000], progradation of the sediments in the Gangetic Plain and flexure of the indian plate (2) [*Lyon-Caen and Molnar*, 1985] and Quaternary grabens extension in Southern Tibet (3) [*Armijo et al.*, 1986]. Topography is derived from GTOPO30 DEM (extreme and mean values), and river elevation from *Lavé and Avouac* [2001].

τ_c, computed from the river slope S_x and flood discharge derived from rainfall profile:

$$\left(\frac{\partial h_{riv}}{\partial t}\right)_x^{(incision)} = K_x(\tau - \tau_c) \tag{1}$$

with,

$$\tau = k_1(\bar{P}_x - P_r)^{\gamma}(L(X - x))^{\beta}\left(\frac{S_x}{s_0}\right)^{\alpha}, \tag{2}$$

where K_x is the erodability coefficient (Figure 2) depending on rock strength, k_1 a coefficient that depends on the river network geometry, sediment size and flood distribution, L the width of the watershed, s_0 the sinuosity of the river and α, β, γ are exponents considered as constant in our study area. $\bar{P}$ is the average precipitation on the watershed and P_r some threshold runoff. X is the abscissa of the drainage divide. The values of the parameters come from *Lavé and Avouac* [2001] or from measurements of himalayan rivers (see supplemental material 3). Despite their critical role, the main rivers do not account for the mean topography, which represents the pertinent variable for the upper boundary condition of mechanical modeling. The elevation profile of Transhimalayan rivers is, in fact, the base level for the network of tributaries which are draining the whole topography, from their sources at the base of the hillslopes to their confluence with the trunk stream. At a given abscissa, the mean elevation of the topography is therefore the sum of three contributions: (1) the elevation of the main river, (2) the fluvial relief associated to the tributaries that we assume to be controlled by the same incision law as the main river and (3) the relief of the hillslope from the fluvial network to the crest. In active orogens, hillslopes are dominated by landslides [*Hovius et al.*, 1997]: we thus assume that they display a critical slope angle of repose and that they react instantaneously to any local base level drop. A new formalism to integrate the relief associated to the tributaries and hillslopes is proposed by J. Lavé (manuscript in preparation, 2004) and enables computation at each time step of the changes in the elevation of the trunk stream (fluvial incision rate) and the mean topography (denudation rate), in response to tectonic uplift and horizontal advection.

5. Sensitivity to the Erosion Law

[6] To investigate the influence of the denudation law, the rheological layering used is quartz (upper crust), diabase (lower crust), and olivine (mantle) as on Figure 2. The comparison between the two tested erosion laws is carried out on 4 different profiles: mean elevation, horizontal velocity, uplift rates, and erosion rates (Figure 3). The two models display very similar profiles of horizontal velocity: the southward transfer of the Himalayan shortening is allowed by the low friction condition on the MHT [*Cattin and Avouac*, 2000]. In contrast, the uplift and erosion rates display distinctly different profiles suggesting that part of the vertical motion is controlled by deformation in lower crust in response to erosional unloading. Diffusion processes localize the highest erosion at the southern edge of Tibetan Plateau, coincident with the maximum slope variations along the profile, and lead to relatively smooth topographic profiles, with continuous slope variations. By contrast, models with the incision law yield a clear slope transition between the LH and HH. This behavior emphasizes that, in addition to being the most realistic of the two erosion laws,

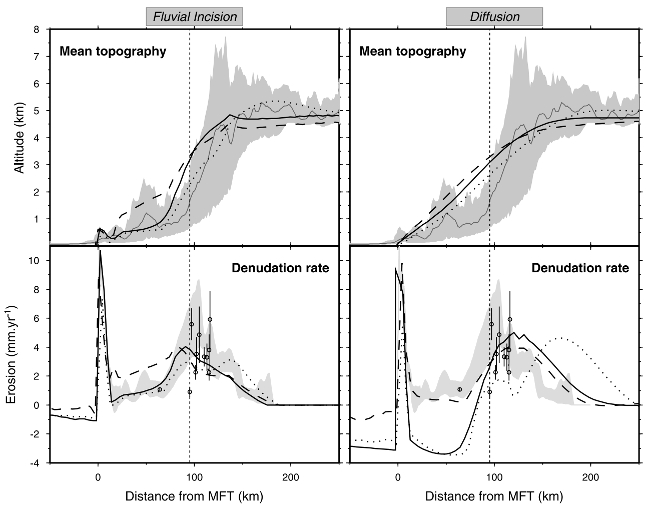

Figure 4. The model fit to topographic and denudation profiles based on the assumed erosion law (fluvial incison and diffusion) and the rheology of the crust. Black line: quartz (upper crust), diabase (lower crust). Dashed line: quartz (upper and lower crust). Dotted line: diabase (upper and lower crust).

only the fluvial incision model provides a good agreement with all the available observations: i.e., the highest rates of erosion and incision across the HH (x ~ 100 km in Figure 3) [*Lavé and Avouac*, 2001; *Burbank et al.*, 2003], low denudation rates in the LH, ≤1 mm.yr^{-1} of sedimentation in front of the MFT [*Lavé and Avouac*, 2000], and a sharp topographic transition between the LH and HH.

6. Sensitivity to the Crustal Rheology

[7] In contrast with our results, *Cattin and Avouac* [2000] employed a linear diffusion model to obtain a good fit to the geophysical data, including the estimated pattern of river incision. However, *Cattin and Avouac* [2000] used a homogeneous quartz-like rheology for the crust. We thus suspect a trade off between the assumed denudation law and the rheological properties of the crust. As shown in Figure 4, a complex interplay indeed exists between surface processes (diffusion or fluvial incision) and crustal properties (homogeneous or composite). A soft rheology for the lower crust (quartz) induces a gravitational collapse of the plateau. This localizes the maximum slope variation, and therefore the maximum erosion by diffusion across the HH. In contrast, with the fluvial incision model, this collapse increases river entrenchment and both denudation and uplift rates within the LH, which is inconsistent with available data in LH [*Lavé and Avouac*, 2001]. The other end-member diabase-like crustal rheology implies a stronger coupling between mantle and crustal deformation. Using diffusion law with this rheology gives sedimentation in the Lesser Himalaya, and a denudation peak far too the north.

7. Conclusion

[8] Among the reduced set of simulations presented in this paper, two combinations provide a good fit to denudation data: (1) the Cattin and Avouac's model in which an homogenous quartz-like rheology is associated with diffusion, and (2) our model with composite crustal rheology (quartz-diabase) associated with fluvial incision including erosion of the whole topography. However, the first combination does not provide a good fit to the whole set of observations: only a fluvial incision-based model preserves a clear slope transition between the LH and HH, and only a strong lower crust can account for ≤1 mm/yr of sedimentation in the Gangetic plain. Moreover, a diabase-like rheology for the lower crust, which minimizes the decoupling effect between crust and mantle, is required to produce the strength of the Indian lithosphere as inferred from gravity anomalies [*Cattin et al.*, 2001]. Our exploration of the different model parameters is far from exhaustive and long term stability including full thermomechanical coupling will need to be investigated. However, these preliminary results highlight several concerns when studying active orogens. First, the hypothesized dominant erosion law may have major consequences in terms of denudation and uplift patterns. Second, because of the trade off between the denudation pattern and the crustal rheology, the use of a realistic denudation law, calibrated with field measurements, allows significant constraints to be placed on the properties of the crust. Finally, several sets of different observations are necessary to fully discriminate among different combinations of rheologic, tectonic and erosion models. In our study of the Himalayas of central Nepal, incision and denudation rates, sedimentation rate in the foreland basin and topographic profile appear as the most constraining data.

[9] **Acknowledgments.** All the illustrations of this paper were prepared using GMT [*Wessel and Smith*, 1991]. We thank J.-P. Avouac for helpful discussions. We are also grateful to J. Chéry and R. Hassani for providing the finite element code. Constructive reviews by D. W. Burbank and one anonymous reviewer contributed to improve the manuscript.

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