DISTRIBUTION AND EVOLUTION OF GEOMORPHIC PROCESS ZONES IN THE EASTERN CORDILLERA OF BOLIVIA

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INTRODUCTION

Large mountain ranges exhibit striking regional scale heterogeneities in landscape form and geomorphic process which affect the rate and style of morphologic evolution of the landscape, control the rate and locus of sediment removal from mountains, thereby feeding back into tectonic processes (Koons, 1990; Beaumont et al., 1992; Isacks, 1992; Small and Anderson, 1995), and dictate regionally appropriate forms of land use. A mechanistic understanding of how these hillslope and fluvial geomorphic process zones evolve is necessary for interpreting the morphologic variability of mountain ranges and for predicting how shifts in climatic or tectonic regime would affect the distribution and rate of erosion and sedimentation both within mountain landscapes and beyond the range front, where human populations are often concentrated.

In this study, we document and explain the evolution of major regional patterns of morphology and geomorphic process within a large mountain range: the Eastern Cordillera and Subandes of Bolivia (hereafter referred to collectively as the Eastern Cordillera). These patterns are dominantly controlled by the incision history of the channel network, since fluvial incision 1) creates relief, which strongly modulates the type and rate of geomorphic processes acting on hillslopes; and 2) governs channel gradients throughout the network, which influences the ability of rivers to transport the sediment supplied to them. Therefore, our approach to explaining geomorphic patterns involves quantifying the fluvial incision history of two major drainage basins (Beni and Pilcomayo) in the Eastern Cordillera during the latest phase of Andean deformation (approximately 10 mya) and linking hillslope and fluvial characteristics resulting from incision to specific types and rates of geomorphic processes.

NATURE OF GEOMORPHIC VARIATION IN THE EASTERN CORDILLERA

In the Eastern Cordillera, downstream geomorphic variation is evident in basins that extend from the Altiplano to the foreland basin, such as the Beni and Pilcomayo basins. Systematic field surveys reveal that in the headwaters of the Beni, most streams are floored by bedrock and strewn with large cobbles and boulders, and deep-seated landslides >100,000 m^3 in volume are common in the steep, deeply dissected landscape. Further downstream, river channels are entrenched in narrow canyons alternating with reaches containing large gravel bars, broader valleys, and occasional patches of floodplain. High-relief hillslopes are scarred by numerous landslides several meters deep, tens of meters wide, and sometimes hundreds of meters long which remove the upper 1-3 m of colluvium and 1-3 m of weathered bedrock. In the Subandes, numerous reaches of trunk rivers lie in broad valleys and have permanent floodplains associated with them, relief is moderate, and many ridges exhibit shallow landsliding.

The Pilcomayo basin exhibits distinctly different downstream trends in geomorphic process and landscape morphology. Although landsliding occurs in some deeply incised valleys in the headwater region, extensive areas throughout the cordillera proper are characterized by extremely broad valleys and slightly rounded bedrock hillslopes with colluvium aprons dissected in some places by gullies. Satellite imagery illustrates these vast tracts of relatively subdued topography at high elevation, scored by a few deep canyons along which erosion is focused. Many streams in moderately dissected portions of the Pilcomayo basin occupy wide channels mantled by alluvium which appear to be actively widening. The western Subandean region of the basin is characterized by sharp ridges of moderate relief which support large, relatively shallow landslides of the kind described above, while in the easternmost Subandes, both landslides and gullies are rare.

Field observations and image interpretations of these landscapes were combined to produce a map, stored in a Geographic Information System, of regions dominated by particular geomorphic processes. Using Landsat TM and MSS imagery, SPOT imagery, SIR-C radar data, and aerial photographs, and guided by our field mapping, we delineated zones dominated by three major hillslope processes: 1) diffusive processes, such as soil creep and rock ravel; 2) shallow landsliding, primarily of colluvium and a thin layer of weathered bedrock; and 3) deep-seated landsliding with failure surfaces tens to hundreds of meters below the land surface. We also divided river reaches into three major regimes: 1) incisional, with little sediment deposition; 2) transitional, with some sediment deposition or alluvial mantle but no permanent floodplain; and 3) alluvial, with permanent floodplain.

Several types of morphometric analyses were performed on these landscapes to determine whether regional boundaries determined by eye on the basis of process are systematically reflected in form. For each geomorphic process zone, we calculated: a) fractal dimension, which has been shown by Outcalt et al. (1994) to be an effective discriminator of physiographic regions when applied to 30-arc-second digital elevation models of the United States; b) ruggedness number, which reflects degree of dissection of the topography; c) local relief (valley depth) and hillslope; and c) channel width to valley width ratio, which is strongly correlated with the presence of sediment in the valley bottom and therefore is a good predictor of fluvial regime. The topographic database used for these analyses consists of 1:50,000 topographic maps and swaths of digital topographic data derived from SIR-C and TOPSAR radar interferometry.

QUANTIFYING FLUVIAL INCISION

To explain the modern distribution of geomorphic process zones, and to illustrate the evolution of these processes throughout a large mountain drainage basin, we utilized a simple one-dimensional model of fluvial incision into an uplifting landmass. The incision model is constrained by field data on rock mass quality, a significant control on incision rates, and by data on downstream variations in channel geometry and discharge. The uplift history of the Eastern Cordillera over the last 10 mya is derived from the geodynamic model of Masek et al. (1994) and is constrained by estimates of the timing and magnitude of shortening in different parts of the range (e.g., Allmendinger et al., 1983; Roeder, 1988; Hérail et al., 1990; and Kley and Reinhardt, 1994). Specifically, the incision model generates relief and dictates slope down the drainage network according to a widely cited hypothesis that the rate of fluvial incision, ε, is related to stream power, a measure of work done on the channel bed by the flow, and the rate of change of bed elevation (z) is therefore:

$$\frac{\partial z}{\partial t} = \varepsilon + U(x,t) \qquad (1)$$

where

$$\varepsilon = -K(x,t)A^m S^n \qquad (2)$$

Here, A is drainage area, S is slope, U is a temporally and spatially variable rate of uplift, m and n are exponents that vary among environments (Howard et al., 1994), and K(x,t) is a measure of rock mass quality.

The fluvial incision component of the model described above simply cuts vertically through topography according to equation (1). From this information we obtained an estimate of the pattern and maximum amount of exhumation that has occurred during the last 10 mya. This pattern will be checked against exhumation rates derived from fission-track analyses on igneous and metamorphic rocks collected in each basin which we are currently performing.

GEOMORPHIC IMPLICATIONS OF INCISION

Based on the results of the fluvial incision model, a series of off-line calculations were made to determine: 1) the distribution of hillslopes currently at the limit of relief they can support; 2) hillslope-averaged rates of denudation required to convert hillslopes previously at the limits of their relief to their current shape and relief; and 3) temporal changes in the loci of incisional and depositional regimes.

The depth of canyons created by fluvial incision is limited by the strength of the rock mass into which the rivers incise. Topographically induced stresses in the rock mass eventually become great enough to produce extensive cracking at certain loci (Miller, 1993), and a portion of the canyon wall fails as a deep-seated, bedrock landslide. The morphologic conditions -- gradient, relief -- under which such failures will occur have been calculated simply with a Culmann wedge stability calculation (Spangler, 1951). This calculation also identifies the location of the failure plane and the post-failure geometery. Continued incision of the river causes renewed slope instability and migration of the break in gradient between the undissected plateau and the slope adjacent to the channel toward the midpoint between channels. When the entire hillslope has failed back to a stable angle and has reached its maximum length (approximately half the distance between channels), the rate of ridgecrest lowering becomes equal to or greater than the rate of fluvial incision. Since the model describes the spatial and temporal distribution of incision rates throughout the network, we calculated the time required to incise a canyon deep enough to produce a hillslope unstable to deep-seated bedrock failure, as well as the time required to produce subsequent failures and the time required to reach steady-state. Because we also know the hillslope morphology after each failure, we were able to calculate rates of hillslope lowering by bedrock failures.

Hillslope morphology is also altered through processes other than bedrock failures. We observe that the gradients of some hillslopes are lower than the angle at which hillslopes are just stable with respect to bedrock landsliding, which indicates that interfluve lowering has occurred faster than slope toe lowering for some portion of the hillslope's history. Because we have observed in the field that the resulting slopes are only very slightly convex and can be well-approximated by planes, the reduction of hillslope gradient by processes other than bedrock landsliding can be described with an erosion rate that decreases linearly from ridgecrest to channel and immediately adjacent to the channel is equal to the rate of fluvial incision. Because we have a model of fluvial incision rate through time, and because this model tells us when hillslopes reached their limits of relief, we can calculate the subsequent average interfluve lowering rate required to produce the current hillslope morphology. We will compare our calculated lowering rates to rates derived from field measurements. The average lowering rate of a hillslope or of all the hillslopes in a small basin can be determined by analysis of cosmogenic isotopic abundance in the colluvium at the base of the slope or in the alluvium at the mouth of the basin (Bierman and Steig, in press). We are currently conducting such analyses on sediment samples collected at a number of points throughout the Beni and Pilcomayo basins from places where deep-seated bedrock landsliding is not the dominant hillslope lowering process.

To identify the loci of the three types of fluvial regime, we focused only on the Beni basin and made three simple assumptions based on field observations: 1) where long-term transport capacity of a river, T_c, is greater than or equal to long-term sediment supply rate, Q_s, the fluvial regime is incisional, with valley width and channel width approximately equal; 2) where $T_c = Q_s$, the channel is in a transitional state, is mantled with patchy alluvium, and may be both widening its valley and incising; 3) where $T_c < Q_s$, the river becomes alluvial, with a permanent floodplain. To estimate long-term sediment transport capacity throughout the drainage network, we used a water balance and flow routing model to calculate the probability distribution of daily discharge at every point in the modern drainage network of the Eastern Cordillera, given an empirically defined precipitation pattern and a probability distribution of daily rainfall amounts that represents the climate. We then determined the quantity of sediment moved by each of these flows using Bagnold's (1980) sediment transport equations for gravel-bedded rivers. Finally, we calculated the total amount of sediment transported at each point in the drainage network and fit the results with a statistical model that is a function of local slope, drainage area, and upstream precipitation. To estimate sediment supply throughout the network, we assumed a steady-state landscape has persisted throughout the latest phase of uplift of the Eastern Cordillera, so the local sediment supply was assumed to equal the rate of fluvial incision times the drainage area. This allows us to illustrate generally how the loci of incision and deposition change as a channel network incises an uplifting mountain range.

CONCLUSION

The distribution and evolution of geomorphically distinct regions in a large mountain range can be explained with a quantitative model of the history of fluvial incision into the range and several simple, related calculations. Geochronologic data are currently being analyzed which will allow more specific and quantitative tests of our landscape evolution model.

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