Climate, tectonics, and the morphology of the Andes

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ABSTRACT

Large-scale topographic analyses show that hemisphere-scale climate variations are a first-order control on the morphology of the Andes. Zonal atmospheric circulation in the Southern Hemisphere creates strong latitudinal precipitation gradients that, when incorporated in a generalized index of erosion intensity, predict strong gradients in erosion rates both along and across the Andes. Cross-range asymmetry, width, hypsometry, and maximum elevation reflect gradients in both the erosion index and the relative dominance of fluvial, glacial, and tectonic processes, and show that major morphologic features correlate with climatic regimes. Latitudinal gradients in inferred crustal thickening and structural shortening correspond to variations in predicted erosion potential, indicating that, like tectonics, nonuniform erosion due to large-scale climate patterns is a first-order control on the topographic evolution of the Andes.

Keywords: geomorphology, erosion, tectonics, climate, Andes.

INTRODUCTION

The presence or absence of mountain ranges at the global scale is determined by the location and type of plate boundaries. Other factors become important in the evolution of individual mountain systems. In particular, spatially variable erosion resulting from climate gradients may localize exhumation and deformation in orogens and thereby influence the geologic structure and morphology of mountain ranges (Beaumont et al., 1991; Zeitler et al., 1993; Avouac and Burov, 1996). Earlier studies of climatic geomorphology have limited relevance to this issue because they simply classify Earth into normal (fluvial), glacial, and arid zones and generally depict an alpine area as a single morphoclimatic zone that crosscuts multiple low-elevation morphoclimatic zones (Tricart and Cailleux, 1972). Even though the large-scale morphology of mountain belts must record the combined effects of climatic and tectonic processes, only a few studies explore climatic factors (Willett et al., 1993; Brozovic et al., 1997).

Here we show that geomorphometric parameters such as cross-range asymmetry, hypsometry, and maximum elevation of the Andes reflect the influence of zonal climate regimes on the nature and intensity of erosional processes. In addition, we show that consequent latitudinal gradients in erosion potential are correlated with the crustal mass distribution and inferred orogenic shortening of the range, suggesting an ambiguity in the current interpretation of crustal mass distribution as the result of variations in the tectonic environment. On the basis of these observations we argue for the first-order importance of large-scale climate zonations and resulting differences in geomorphic processes to the morphology of mountain ranges.

TECTONIC AND CLIMATIC SETTING OF THE ANDES

The influences of climate, erosional processes, and tectonics on orogen morphology may be deconvolved in the Andean orogen because it is a hemisphere-scale, north-south–oriented range with large gradients in temperature and rainfall across a single convergent margin. Uplift of the Andes began ca. 25 Ma, concomitant with accelerated convergence between the Nazca and South America plates (Allmendinger et al., 1997). Early theories of formation of the Andes emphasized crustal growth by magmatic processes, but estimates of structural shortening and evidence for symmetric paleomagnetically defined rotation on the northern and southern flanks of the Altiplano gave rise to the hypothesis that the variable size and thickness of the range result from nonuniform crustal shortening, with maximum shortening and consequent thickening at the center of the Andean orocline (Isacks, 1988; Gregory-Wodzicki, 2000). However, direct structural shortening estimates are limited to the Eastern Cordillera and Subandean fold and thrust belt. In the Altiplano and Western Cordillera, crustal structures are obscured by sedimentation or volcanism, and global positioning system measurements (Norabuena et al., 1998; Kendrick et al., 1999) may be influenced by short-term strain accumulation associated with the subduction-zone earthquake cycle. Some studies have attributed local variations in structural, metamorphic, and geomorphic characteristics of the central Andes to erosion (Gephart, 1994; Masek et al., 1994; Horton, 1999), but none has considered variations in erosional mass removal at the scale of the entire mountain range.

The highly variable climate of the Andes reflects its position transverse to hemisphere-scale, Hadley cell-driven precipitation regimes (Fig. 1). In the Intertropical convergence zone (10°N–3°S), both sides of the range receive annual rainfall exceeding 2 $m \cdot yr^{-1}$. In the subequatorial northern Andes (3°S–15°S), orographic interception of the trade winds delivers >2 $m \cdot yr^{-1}$ of rainfall to the Amazon side of the range and <0.2 $m \cdot yr^{-1}$ to the Pacific side, and westerly winds produce the opposite relationship in the temperate latitudes south of 33°S. The central part of the range (15°S–33°S) is in the subtropical belt of deserts, where there is little precipitation on either side of the range, or on the high plateau of the Altiplano. These major climate boundaries in the Andes are not dependent upon orographic effects, but are robust features of the general circulation in the Southern Hemisphere, and therefore may be considered a priori conditions under which the mountain range developed.

TOPOGRAPHIC ANALYSIS

We focus on four aspects of the large-scale geomorphology of the Andes: (1) a generalized index of erosion intensity based on regional slope and fluvial discharge, (2) cross-range asymmetry, (3) regional hypsometry

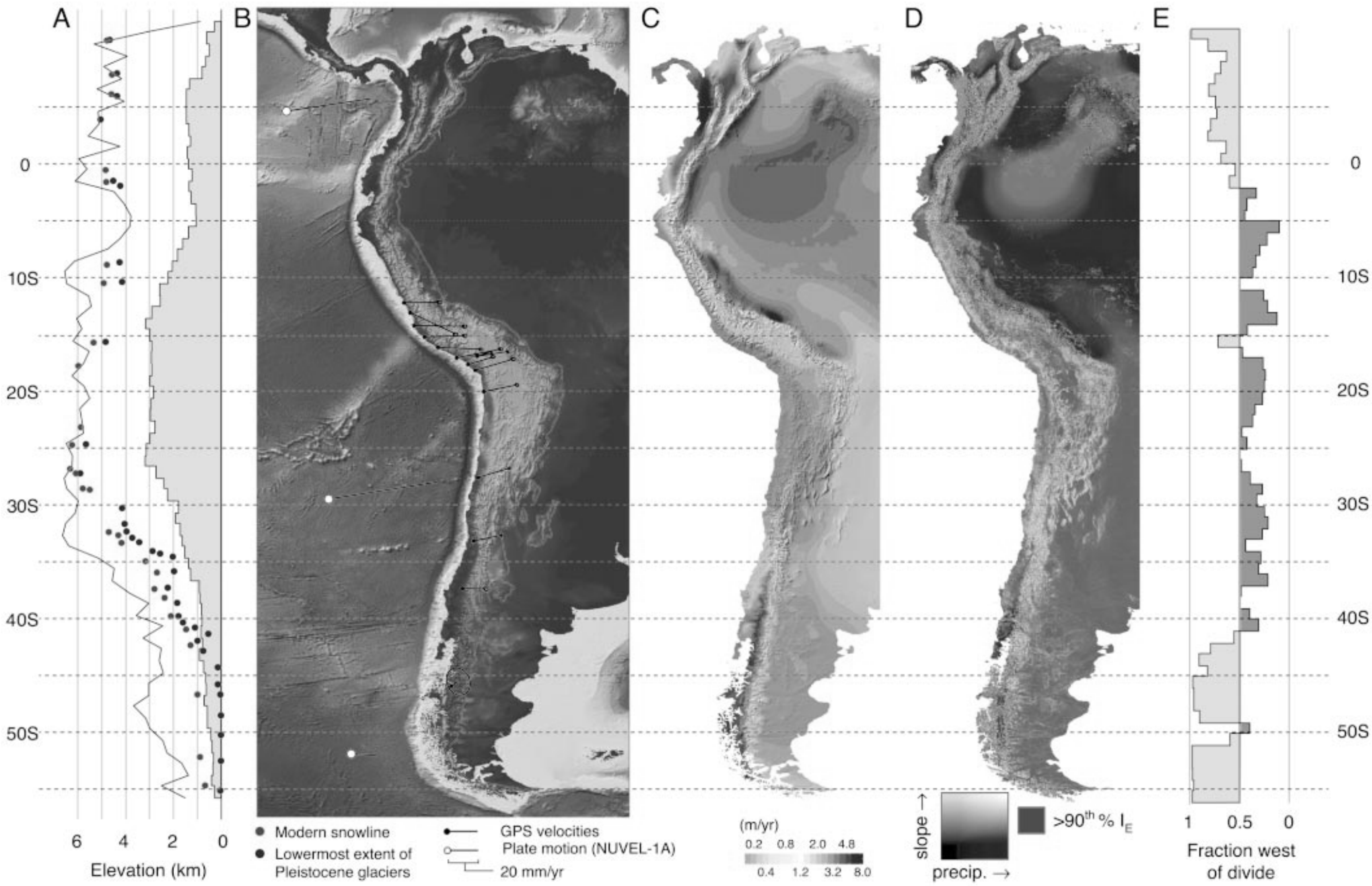

Figure 1. A: Maximum (dark line) and mean (gray area) elevation in 1° latitude bins. Red circles are elevations of modern perennial snowline and blue circles are lowest elevation of Pleistocene glacier extent, both from Schwertfelder (1976). B: Topography and convergence velocity. Vectors headed in open circles denote long-term velocity of Nazca and Antarctic plates relative to South American plate (DeMets et al., 1994); those headed in closed circles denote global positioning system (GPS) velocities at coastal sites, relative to stable South America (Norabuena et al., 1998; Kendrick et al., 1999). C: Mean annual precipitation, overlain on shaded-relief map of western South America. D: False-color image of South America showing areas with steep slope in yellow, high precipitation in blue. Red pixels have calculated I_E above 90th percentile relative to all pixels in image. E: Cross-range asymmetry, defined to be fraction of range volume above sea level that drains to west: values greater than 0.5 (lighter shade of gray) indicate that bulk of range is west of divide.

(the elevation distribution of the topography), and (4) the relationship between the maximum elevation and the perennial snowline. We used topography from the global 30 s GTOPO30 digital elevation model; topography, slope, and flow direction from the 1 km HYDRO1K DEM; and mean annual precipitation digitized from Hoffmann (1975). For purposes of our analysis, we defined the eastern boundary of the Andes as the approximate limit of Tertiary or older units mapped on continental-scale geologic maps (UNESCO, 1978).

Erosion Index

Rates of fluvial and hillslope erosion are governed by processes characterized by different erosion laws, but the net large-scale erosional potential of a landscape increases with precipitation, drainage area, and slope. Thus, we evaluated large-scale patterns in erosion potential by using a simple parametric measure of erosional intensity (I_E) based on the product of local slope (S) and discharge determined by summing the annual precipitation (P) over the matrix of upslope grid cells each of drainage area A:

$$I_E = \left[\sum P_i A_i\right] S. \qquad (1)$$

We used this simple approach because (1) it is not clear which process formulation is most appropriate for modeling landscape-scale erosion rates across 1 km grid cells in which net erosion reflects an aggregation of finer scale effects from multiple, interacting processes; (2) vegetation and land use, which cannot be predicted from digital elevation models, complicate simple relationships between precipitation and erosion rate; (3) erosion models at this scale inherently require calibration because slopes calculated from coarse-resolution grids are gentler than actual gradients (Zhang and Montgomery, 1994); and (4) data on differences in erosivity due to soil type and parent lithology generally are not available at the scale of interest. In the Andes, the pattern of I_E values shows that the zone of maximum predicted erosion is on the eastern side of the range in the northern Andes and on the western side in the southern Andes. Only small, localized areas of high I_E are predicted in the central Andes (Fig. 1D).

Cross-Range Asymmetry

We defined a cross-range asymmetry index as the ratio of the volume of the topography above sea level on the west side of the divide to that of the entire range within a given latitude band (Fig. 1E). Between 2°S and 42°S most of the range is to the east of the drainage divide, whereas south of 42°S most of the range is west of the drainage divide. North of 2°S, the inclusion of the areas draining to the Caribbean Sea with areas draining to the Pacific Ocean places most of the range on the west side of the drainage divide. Cross-range asymmetry tracks latitudinal variations in moisture delivery due to prevailing wind directions.

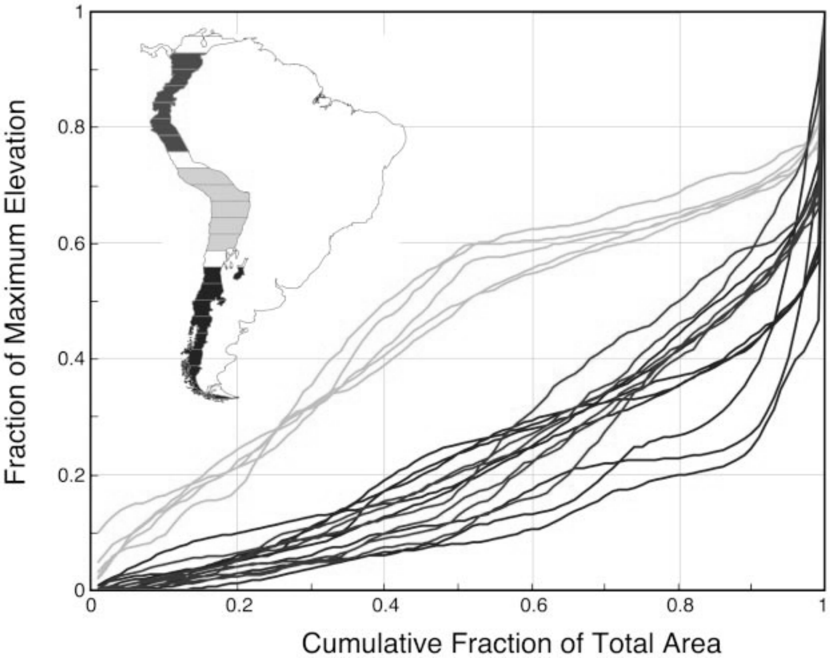

Figure 2. Normalized hypsometric curves for 3° latitude bins of Andes; curve color corresponds to location in northern (red), central (yellow), and southern (blue) Andes.

Hypsometry

Hypsometric curves, which show the proportions of a landscape at different normalized elevations, have strikingly different, but regionally consistent, shapes in the northern, central, and southern Andes (Fig. 2). These latitudinal variations suggest that fluvial, tectonic, and glacial processes, respectively, dominate the morphology of the range in these different zones. Although individually these hypsometric curves could reflect different developmental stages in a classical interpretation (Strahler, 1957), here the aggregate pattern is geographically consistent with variations in erosional processes. In the northern Andes, concave-up hypsometric curves, which are characteristic of fluvially dissected landscapes, reflect the dominance of fluvial erosion in a wet tropical climate. In the southern part of the range, glaciers have selectively eroded high elevations, creating a shoulder in the hypsometric curves. In the central Andes, the hypsometric curves are nearly linear, with a convexity imposed by the relatively flat hypsometry at elevation of the Altiplano. This form describes a weakly incised tectonic wedge and mechanically limited plateau, implying that fluvial incision is ineffective relative to tectonic uplift. This strong association of hypsometry with climatically driven variations in geomorphologic processes demonstrates that both the nature of the dominant erosional mechanism and its rate relative to tectonic uplift are fundamental to the overall topographic expression of the Andes.

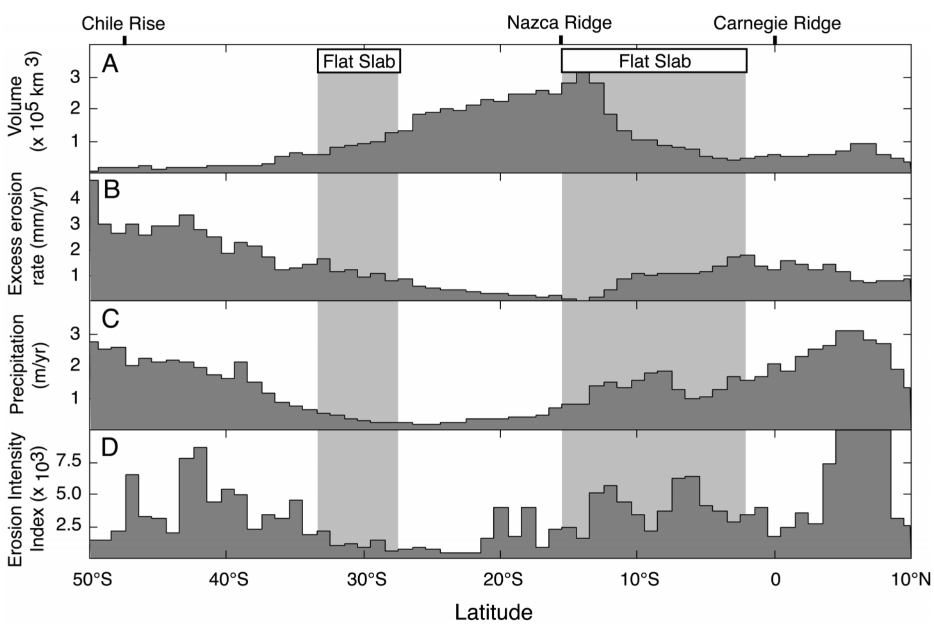

Figure 3. A: Volume of Andes above sea level calculated from 1° latitude bins. B: Excess erosion rate, relative to largest 1° bin, is required to explain volume difference under uniform tectonic convergence. We calculated required latitudinal variation in erosion rates under constant tectonic convergence by calculating missing mass above sea level in each 1° latitude bin as $V_{XS}\alpha/At$, where V_{XS} is excess volume in given bin compared to largest bin (14°–15°S), *A* is bin area, *t* is time (taken to be 25 m.y.), and $\alpha = \rho_c/(\rho_m - \rho_c)$, where $\rho_c = 2.7$ g·cm^{-3} and $\rho_m = 3.3$ g·cm^{-3}. Note that because of selection of strictly east-trending bins for analysis, region between 13°S and 17°S, where range trends northwest rather than north, has anomalously large volume in each bin. C: Mean annual precipitation. D: Mean erosion intensity index value.

Maximum Elevation

The tendency for the elevation of the perennial snowline to track mountaintops is well known (Mill, 1892), but the causal basis for this relationship and the relative efficiency of glacial erosion remain more controversial. In the Andes, the maximum elevation and the snowline are greater than 5 km north of 30°S, and both decrease toward the pole thereafter, such that only a small fraction of the topography remains above the snowline at any latitude (Fig. 1A). The distinct shoulder to the hypsometry of the southern Andes also descends with the perennial snowline. The correspondence betweeen total relief and snowline elevation supports the hypothesis that higher rates of erosion in glacial and periglacial environments effectively limit the relief of mountain ranges (Brozovic et al., 1997). This implies that high topography cannot persist at high latitudes and that the high Andes terminate at 35°S in part because they intersect the perennial snowline at this latitude.

DISCUSSION

The observation that topographic changes along the Andes correspond with large-scale variations in climate suggests that zonal climate patterns affect the orogen-scale morphology of the Andes. This conclusion has implications both for general understanding of landscape evolution and for specific large-scale tectonic interpretations for the Andes. For example, Isacks (1988) neglected the effect of mass removal by erosion when inferring latitudinal variations in convergence from a crustal mass balance. However, the latitudinal variations in mean I_E also track variations in present excess crustal volume in the Andes (Fig. 3). An extreme interpretation of this correlation, taking the opposite assumptions to the analysis of Isacks (1988), would hold net convergence constant from 45°S to 5°N and explain the current width of, and crustal volume in, the Andes as the result of latitudinal variations in erosion rate. In this case, the observed distribution of crustal volume requires latitudinal variations in average erosion rate during the lifetime of the Andes of <2 mm·yr^{-1} (excluding the glaciated southern Andes). These required variations are within the range of reasonable erosion rates and broadly correlate with the independently determined I_E values. Hence, it is reasonable to suggest that climatically influenced gradients in erosion rates contribute to the latitudinal variation in range width and crustal volume.

Other local structural variations may be the result of variable erosion. Range-wide changes in geology are broadly consistent with this idea: the crystalline rocks of the northern and southern Andes reflect deeper exhumation, and the preserved sedimentary and volcanic cover of the central Andes indicates that exhumation there has been minimal. For example, the Eastern Cordillera and Subandean zone of Bolivia have undergone 2–6 km of exhumation since 10 Ma north of 19°S (Benjamin et al., 1987), but <1 km since that time to the south (Masek et al., 1994; Gregory-Wodzicki, 2000). This difference is immediately apparent in the truncation of the prominent fold-and-thrust belt by the apparent erosional ''bite'' in the area with high rainfall to the north.

We are not arguing that tectonic variations are unimportant in the evolution of the Andes. In fact, the major changes in the topography and mass distribution in the Andes also correlate with tectonic parameters such as the orientation and dip of the subducting slab (Jorden et al., 1983; Gephart, 1994) and major geologic provinces (Gansser, 1973). For example, the high volume segment of the central Andes between 10°S and 30°S corresponds to the steeply dipping segment of the Nazca slab, particularly when one recognizes that our analysis likely overestimates the mass between 13°S and 17°S (Fig. 3). This situation complicates the interpretation of crustal mass distribution as the result of one or the other of these two seemingly covariant forcings. We view tectonics and erosion as a coupled system, with potential for feedback between climate-driven erosion and tectonic forcing on shallow crustal processes (Willett, 1999), or even deep, mantle processes. Could the large accumulation of mass in the Altiplano, which seems to have been permitted by slow surface erosion, also affect the dynamics of the subduction zone?

CONCLUSIONS

Our results support the idea that global climate patterns influence orogen morphology. Specifically, we see three archetypes of climatic control on large-scale landscape form: (1) normal fluvial erosion in the northern Andes where high precipitation rates maintain a narrow mountain range; (2) tectonic dominance of landscape form in the central Andes, where there is little erosion except in big river valleys, leading to crustal thickening by tectonic wedge propagation, the formation of a mechanically limited plateau, and linear hypsometry; and (3) glacial land sculpting that preferentially erodes the highest ground in the southern Andes, resulting in an excess of elevation at the glacial limit and a systematic decline in maximum elevation toward the pole. The coincidence of low inferred erosion rates (on the basis of calculated I_E values) in the desert latitudes and the greatest width of the Andes suggests that lack of erosion plays an important role in mass accumulation in the mountain belt. If the development of the Altiplano reflects the mechanical limit to crustal thickening (Pope and Willett, 1998), then its existence implies that tectonic thickening has outpaced erosional mass removal; its position in the global desert belt suggests that this dominance of tectonic shortening was possible, at least in part, because of the arid climate of this latitudinal band. We conclude that the large-scale distribution of crustal mass in a mountain belt is controlled by not only tectonic shortening, but also by the type and intensity of erosional processes.

ACKNOWLEDGMENTS

Supported by a Hertz Foundation Graduate Fellowship (to Balco) and in part by National Science Foundation grant EAR-9903157. We thank Peter Zeitler and Bryan Isacks for their constructive critiques of the manuscript.

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Manuscript received November 7, 2000
Revised manuscript received March 7, 2001
Manuscript accepted March 15, 2001

Printed in USA