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Shaping post-orogenic landscapes by climate and chemical weathering

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ABSTRACT

The spacing of hills and valleys reflects the competition between disturbance-driven (or diffusive) transport on hillslopes and concentrative (or advective) transport in valleys, although the underlying lithologic, tectonic, and climatic controls have not been untangled. Here, we measure geochemical and geomorphic properties of catchments in Kruger National Park, South Africa, where granitic lithology and erosion rates are invariant, enabling us to evaluate how varying mean annual precipitation (MAP = 470 mm, 550 mm, and 730 mm) impacts hill-valley spacing or landscape dissection. Catchment-averaged erosion rates, based on ^{10}Be concentrations in river sands, are low (3–6 m/m.y.) and vary minimally across the three sites. Our lidar-derived slope-area analyses reveal that hillslopes in the dry site are gentle (3%) and short, such that the terrain is low relief and appears highly dissected. With increasing rainfall, hillslopes lengthen and increase in gradient (6%–8%), resulting in less-dissected, higher-relief catchments. The chemical depletion fraction of hilltop regoliths increases with rainfall, from 0.3 to 0.7, reflecting a climate-driven increase in chemical relative to physical erosion. Soil catenas also vary systematically with climate as we observe relatively uniform soil properties in the dry site that contrast with leached sandy crests and upper slopes coupled with downslope clay accumulation zones in the intermediate and wet sites. The geomorphic texture of this slow-eroding, granitic landscape appears to be set by climate-driven feedbacks among chemical weathering, regolith fabric differentiation, hydrological routing, and sediment transport that enhance the vigor of hillslope sediment transport relative to valley-forming processes for wetter climates.

INTRODUCTION

Eroding terrain has a remarkable tendency to organize into hill-valley sequences that collectively define drainage basins of varying scale. On hillslopes, sediment transport usually originates from disturbance-driven processes that tend to smooth the surface (Culling, 1965), whereas in valleys, fluid-driven transport drives localized incisions that connect to form channel networks. This simple but powerful framework suggests that the spacing of hills and valleys (and thus landscape dissection or drainage density) can be modeled as a competition between diffusive transport on hillslopes and advective transport in channels (e.g., Dunne and Aubry, 1986; Smith and Bretherton, 1972) although the specific mechanisms that regulate diffusive and advective fluxes likely vary with geologic and climate setting.

Globally, drainage density and relief vary by several orders of magnitude, but we lack models to predict how these characteristic scales depend on climate (Collins and Bras, 2010). Following earlier workers (see Simpson and Schlunegger [2003] for a review), Perron et al. (2009) developed a framework for assessing landscape dissection by quantifying how the relative magnitudes of hillslope and valley-forming processes control the spacing of hills and valleys in soil-mantled terrain. Their model separates hillslope transport and valley incision processes into diffusive (D) and advective (K) components, respectively. Their preliminary analysis suggests that wetter climates correspond with higher values of D/K and thus greater hill-valley spacing. While this proposed climate-geomorphic linkage is appealing, it has not been field tested in settings where the potentially confounding variables of erosion rate and bedrock lithology are held constant.

Here, we quantify climate control on topography in a post-orogenic landscape with uniform bedrock lithology and base-level control. In settings with low erosion rates, long regolith residence times support development of strongly weathered and highly differentiated regolith fabrics that modulate hillslope hydrology and sediment transport processes (Bishop, 2007). Our analysis combines lidar-derived morphologic trends for drainage density and local relief with estimates of total and chemical denudation to evaluate the role of climate in shaping granitic catchments of South Africa that span arid to sub-humid climates. Despite similar catchment-averaged erosion rates, our findings reveal profound differences in landscape morphology that reflect the key role of chemical weathering and regolith development in modulating hydrology and the relative efficacy of hillslope and valley-forming processes.

STUDY AREA: KRUGER NATIONAL PARK, SOUTH AFRICA

Over the last 90 m.y., the southern part of Africa has risen slowly in isostatic response to erosion (Tinker et al., 2008; Flowers and Schoene, 2010; Decker et al., 2013). Pliocene–Pleistocene rock uplift rates have been measured at 10–15 m/m.y. (Erlanger et al., 2012), consistent with minimal recent tectonic activity. Kruger National Park lies east of the Great Escarpment on the northeastern edge of South Africa bordering Mozambique (Fig. 1). The park stretches 350 km in a north-south orientation and is primarily underlain by Kaapvaal granite and metagranite in its western half (Venter, 1990) and Karoo volcanics in the eastern half. Rivers that traverse the study area are sourced on the escarpment and exhibit bedrock or mixed alluvial-bedrock beds. The eastern edge of the park is bounded by the Lebombo Mountains that are composed of resistant rhyolite that forms a base level regulating incision rates throughout the park (Venter, 1990).

Rainfall in Kruger primarily occurs in the austral summer and is controlled by onshore air flow associated with the warm Mozambique current as well as orographic effects that are in turn controlled by high topography along the Great Escarpment (Chase and Meadows, 2007). Climate in the park ranges from mildly arid in the north to sub-humid in the southwest where the park abuts the Great Escarpment (Fig. 1) (Gertenbach, 1980). Warmer temperatures in the north magnify this climate gradient by decreasing effective moisture. In the north, we sampled watersheds in the Phugwane River valley, which receives 470 mm of rain annually and has a mean annual air temperature (MAAT) of 23.1 °C (Venter et al., 2003). In the south, we sampled watersheds in the Nwaswitshaka River valley with 550 mm of rain annually and a MAAT of 21.9 °C, and in the Nsikazi River valley with 730 mm of rain annually and a MAAT

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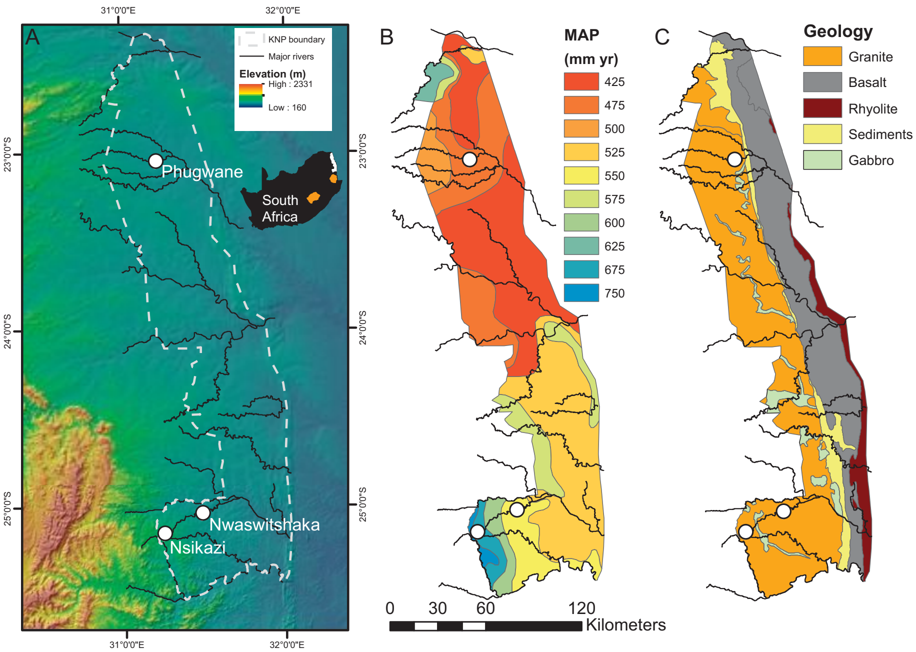

Figure 1. A: Shaded relief and elevation map showing boundary of Kruger National Park (KNP, South Africa), edge of Great Escarpment in the west, Lebombo Mountains (slight ridge along eastern edge of park), and rivers where erosion rates were measured. B: Mean annual rainfall (MAP) map. C: Geologic map. Catchment sampling sites are shown as white circles on each graphic.

of 21.6 °C (Fig. 1) (Venter et al., 2003). Evidence suggests that the rainfall gradient, which derives from an Indian Ocean source for atmospheric moisture and orographic control, has been a consistent feature for millions of years (see the GSA Data Repository[1]).

Regoliths (soil and saprolite) in the park are dominated by ~60-cm-thick Aridisols in the northern arid zone, ~100-cm-thick Inceptisols and Alfisols in the semi-arid zone, and ~200-cm-thick, highly weathered Inceptisols and Alfisols in the sub-humid zone (Khomo et al., 2011). With increasing rainfall, hillslope regolith fabric becomes strongly differentiated into highly leached and collapsed, but porous, ridge crests and upper side slopes that contrast with lower side slopes that are packed with low-permeability clays translocated from upslope (Khomo et al., 2013; Bern et al., 2011) (Fig. DR1 in the Data Repository). In the site with 550 mm of rainfall, the upper edge of the clay-rich zone occurs about halfway between hillcrests and channel margins, whereas in the site with 730 mm of rainfall, it occurs along the lower 20% of most slopes. Within each rainfall zone, these soil-hillslope patterns are spatially consistent as revealed by distinctive patterns of vegetation and termite mounds (Levick et al., 2010). In the intermediate and wet sites, the clay accumulation zones control seasonal seep lines along the contour defined by the upper edge of the clay accumulation zone. The seeps are created by subsurface flow returning to the surface where it can produce gullies and soil slips that deliver sediment from near-stream positions into the valley network (Venter, 1990). By contrast, catenas in the site with 470 mm of rainfall exhibit less clay redistribution and more evidence of dispersive overland flow and sheetwash.

METHODS

We estimated long-term erosion rates by measuring ^{10}Be concentrations in the quartz fraction of river channel sediments (Table DR1). In each climate zone, we sampled first- to fourth-order catchments within the Kaapvaal granite to minimize differences in bedrock erodibility. The broadly convex soil-mantled hillslopes do not evidence deep-seated landsliding or other processes that could preferentially contribute sediment from depths below the attenuation length of cosmic rays. Because cosmogenic nuclides accumulate over thousands of years, they are unaffected by any recent land-use changes and are also insensitive to changes in sediment storage given that storage area is negligible relative to total catchment area at our sites. We characterized the weathering status of ridge-crest regoliths by estimating the depth-averaged chemical depletion fraction (CDF) referenced to local rock (Riebe et al., 2004), which represents the portion of denudation that is achieved through chemical means. Particularly for the intermediate and wet sites, we note that the CDF value depends on hillslope position relative to the clay accumulation zone (Khomo et al., 2013). We did not correct the catchment-averaged erosion rates for the weathering status of bounding hillslopes (e.g., Riebe and Granger, 2013) because the complex nature of the catenas would require accounting for the areal distribution of differing weathering profiles.

We used slope-area plots to characterize morphologic trends, including variations in hill-valley spacing and local relief. These plots are diagnostic because they describe how the local gradient increases downslope from hilltops and reaches a maximum before decreasing downstream in the valley network (Fig. DR2). The drainage area where the convex hillslope and concave valley trends intersect (denoted here as A_{HV}) serves as an objective proxy for the average hill-valley spacing or drainage density (Roering et al., 2007; Collins and Bras, 2010) (Fig. DR3). We acquired airborne lidar data for large swaths of terrain in each of the three climate zones using the Carnegie Airborne Observatory (http://cao.ciw.edu) and generated bare-earth digital elevation models (DEMs) with a 1.12 m grid spacing (Asner et al., 2007). We digitally excised ~2-m-high termite mounds and other ephemeral roughness features by performing a wavelet transformation with an ~16 m Mexican hat wavelet and removing nodes with a correlation value greater than 8. We filled in the "no data" nodes and smoothed the topography by fitting a second-order weighted polynomial to a 25 × 25 node array of neighboring points, following Wood (1996). The fitting algorithm outputs include a smoothed elevation value at each grid node as well as polynomial coefficients used to calculate topographic derivatives, including local gradient. We used the D-infinity multi-direction flow routing algorithm to calculate drainage area for every node on the smoothed DEMs (Tarboton, 1997).

RESULTS

Catchment-averaged erosion rates are low (Fig. 2A) and consistent with values typical of post-orogenic landscapes worldwide, particularly those measured in southern Africa (Decker et al., 2013; Flowers and Schoene, 2010). Specifically, erosion rates across first- to fourth-order streams average 5.9 ± 0.7 m/m.y. at the 470-mm-rainfall site, 6.6 ± 1.0 m/m.y. at the 550-mm-rainfall site, and 4.0 ± 0.8 m/m.y. at the 730-mm-rainfall site. Within-site erosion rate variation does not depend on stream order (Table DR1). Between-site variation is minimal and may be attributable to non-quantified factors, such as minor local bedrock-controlled knickpoints and the influence of hillslope weathering

[1]GSA Data Repository item 2013326, paleoclimate information, catena weathering properties, ^{10}Be data table, slope-area plot explanatory figures, graph of bare earth quantity for sampling sites, and photograph of soil slips in lower part of wet catena, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

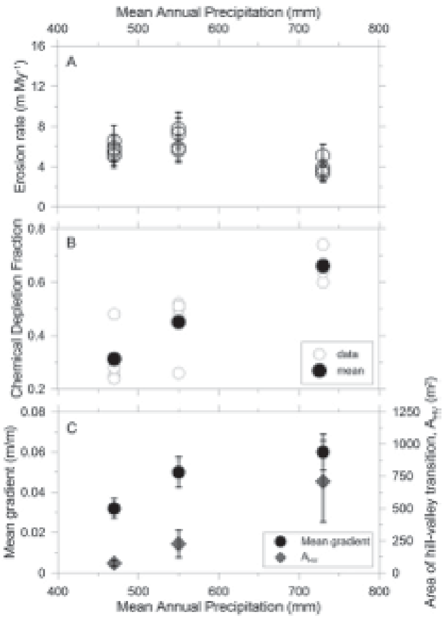

Figure 2. Plot of variations in erosion rate (A), chemical depletion fraction (B), and mean hillslope gradient and drainage area of the hill-valley transition (A_{HV}) (C) with annual precipitation for our three study sites. Erosion rates do not exhibit systematic variations with precipitation, whereas the chemical depletion fraction, mean gradient, and A_{HV} increase with annual precipitation.

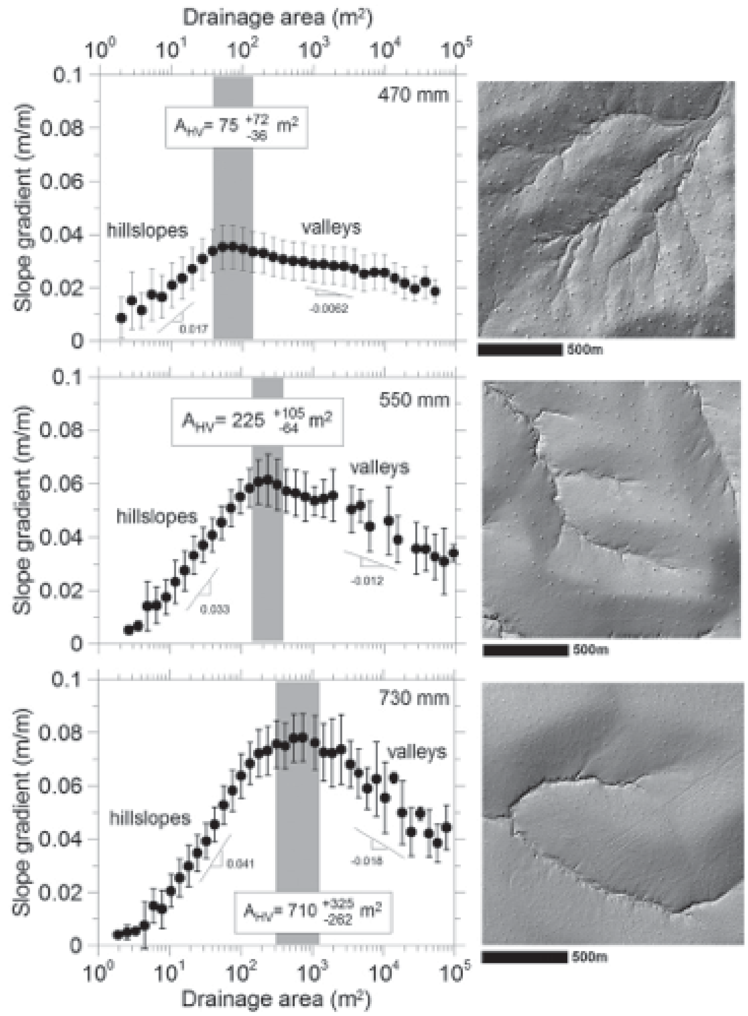

Figure 3. Slope-area plots for 1.5 × 1.5 km patches of terrain in each of the three climate zones (see Fig. DR4 [see footnote 1]). Drainage area of hillslope-valley transition (shaded vertical band) increases with mean annual precipitation (noted in upper right corner of each plot). Slope symbols in lower part of each plot refer to average convexity for hillslopes and concavity for valleys, and have units of gradient/log(area). Error bars represent one standard deviation of slope for each log bin of drainage area. Width of shaded bar approximates standard error of hillslope gradient and drainage area of hill-valley transition (A_{HV}) estimate, and is derived from uncertainty analysis of a spline fit to the binned area-slope curve.

status on stream sediment ^{10}Be concentrations (cf. Riebe and Granger, 2013). Despite similar erosion rates, mean CDF values for hillcrest regoliths increased from 0.3 to nearly 0.7 with increasing rainfall (Fig. 2B). This pattern implies a considerable shift from physically dominated erosion in dry catchments to chemically dominated erosion in wet catchments, and corresponds with a thickening of regolith with rainfall (Khomo et al., 2011, 2013). Using average regolith depth and catchment-averaged erosion rate estimates, we infer long hillcrest regolith residence times of 0.11, 0.15, and 0.57 m.y. for the dry, intermediate, and wet sites, respectively.

We averaged slope-area data for representative 1.5 × 1.5 km patches of terrain in each of the three rainfall zones (Fig. DR4) and estimated the average drainage area associated with the hill-valley transition, or A_{HV} (Fig. 2C). Within each rainfall zone, we observed characteristic convex hillslope and concave valley morphologic trends (Fig. 3). Values of hillslope convexity (defined here by the rate of slope increase with the log of upslope area) and valley concavity (the rate of slope decline with the log of upslope area) are lower for the dry site than for the intermediate and wet sites, reflecting lower hillslope and catchment relief. More importantly, the value of A_{HV} revealed by our slope-area analysis increases monotonically with rainfall, such that wetter conditions promote broader hillslopes, increased local relief, and lower drainage density (Fig. 2C).

DISCUSSION AND CONCLUSIONS

The topographic form of granitic hill-valley terrain in Kruger National Park can be approximated using a diffusion-advection model framework. The observation that hill-valley spacing and local relief increase with annual rainfall given constant rock type and erosion rate suggests that wetter climates increase the efficacy of hillslope transport relative to fluvial action. Below, we suggest that over the long regolith residence times associated with this post-orogenic landscape, the diffusive transport component may be partitioned differently into solute and particulate fluxes depending on climate controls on plant cover, overland flow, bioturbation, infiltration and throughflow, and the fate of weathering products.

The relative simplicity of the diffusion-advection framework, however, belies the spectrum of processes that serve as diffusive or advective transport mechanisms and thus facilitate this morphologic pattern in our study area. Field observations reveal different sediment transport mechanisms in the different climatic settings. At the dry site, rain-splash and intermittent slopewash processes dominate hillslope fluxes due to the relatively sparse vegetative cover (quantified as bare earth in Fig. DR5) and local concentrations of fine-grained particles associated with numerous termite mounds. Along these hillslopes, we observe pebble lags indicative of intermittent and discontinuous overland-flow erosion. At wetter sites, more extensive vegetative cover favors transport via bioturbation, including burrowing and tree turnover as evidenced by overturned root wads and localized collections of coarse bedrock clasts on the surface. In these sites, long-term water flux has transported chemical-weathering products downslope forming strongly differentiated catenas comprising highly permeable sandy crests and clay-rich lower-slope regoliths (Bern et al., 2011; Khomo et al., 2011, 2013; Fig. DR1). We suggest that differences in hydrological partitioning, which dictates transport mechanisms, among the three sites provide an important mechanism by which climate modulates hillslope-channel coupling and thus catchment morphology.

Our analysis of climate controls on hillslope-channel morphology assumes minimal transient response to perturbations in climatic or tectonic forcing. Given slow rock uplift rates and a persistent control on base-level lowering, the observed landform patterns must have persisted for millions of years, suggesting relatively steady-state conditions. This interpretation is supported by models of transient hillslope response, which suggest that hillslopes of the scale observed here require ~10^6 yr to adjust to changing boundary conditions (Mudd and Furbish, 2007), which is much less than the time since tectonic and climate conditions stabilized. More so, the erosion rates estimated here suggest that total denudation since the late Mesozoic has exceeded 100 m, which is more than four times the typical relief (~20 m), further lending support for an interpretation of steady-state conditions (Howard, 1994).

Despite ample support for relatively uniform erosion rates, our analyses have yet to reconcile the differentiated catena properties described here with an interpretation of steady-state conditions. Steady erosion requires that clay accumulation zones be maintained at their present positions through replenishment from upslope and physical denudation along their lower margins. Alternatively, a non-steady scenario would predict that clay accumulation zones are propagating upslope or downslope. We do not observe evidence of such a transient response, however, because for a given climate condition, the relative location of clay concentrations and seep lines is remarkably consistent (Levick et al., 2010). In the field, we do observe clay-zone erosion by ephemeral gully formation and soil slips (Fig. DR6), although these processes only locally disturb the clay-rich zone. Thus, conditions on Kruger hillslopes appear to approximate steady-state denudation while experiencing small-scale transient responses due to late Cenozoic climate change and/or autogenic variability.

In our post-orogenic study area with constant erosion rate and lithology, wetter climate conditions increase the vigor of hillslope processes relative to valley-forming ones. This occurs across the transition from relatively infrequent and short-lived overland events in the dry site to throughflow-dominated hydrologic response and enhanced bioturbation in the wetter sites. The increasing relative importance of hillslope processes under wetter climates is influenced by the weathering (and thus residence time) of regolith, given that catena fabric differentiation modulates hydrology and sediment transport. More generally, the interplay between chemical and physical denudation observed on hillslopes in this slowly eroding landscape is subject to feedbacks involving climate, vegetation, hydrology, and regolith development that have yet to be codified in theoretical landscape evolution models.

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