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Preservation or piracy: Diagnosing low-relief, high-elevation surface formation mechanisms

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ABSTRACT

Absent clear lithologic control, the presence of elevated, low-relief topography in upland landscapes has traditionally been interpreted as a signature of relative surface uplift and incision of a paleo-landscape. Such interpretations are commonly supported and quantified using analyses of river longitudinal profiles under the assumption of a static drainage network topology. Drainage networks, however, are not static, and it has been proposed recently that divide migration and drainage capture can lead to the generation of low-relief upland topography that mimics that of incised paleo-landscapes and that might be falsely interpreted as recording surface uplift and/or the onset of accelerated incision. Indeed, the interpretation of the incised southeastern Tibetan Plateau, and thus the associated geodynamic implications, have been called into question. Here we use theory and one- and two-dimensional landscape evolution models to develop a set of morphometric criteria to distinguish these alternative mechanisms of low-relief upland formation. Application to the southeastern Tibetan Plateau illustrates the utility of these metrics and demonstrates that the topography is in no way consistent with the drainage network dynamics mechanism and is fully consistent with incision into an elevated, preexisting low-relief landscape.

INTRODUCTION

For more than 100 years geoscientists have used the elevation of low-relief, upland topography perched above deeply incised canyons to extract information about landscape evolution (e.g., Davis, 1899). Analysis of river longitudinal profiles is widely used to diagnose and quantify patterns of net surface uplift, providing key constraints on the history of climate and tectonics in mountain ranges (e.g., Kirby and Whipple, 2012; Whittaker, 2012). Analysis of river profiles generally involves assuming a negligible change in network topology, but an increasing number of studies reveal that river networks are dynamic, with non-static drainage configurations and internal temporal variability in erosion rate over a variety of time scales (e.g., Clark et al., 2004; Hasbargen and Paola, 2000; Prince et al., 2011). Under some circumstances interpretation of river profiles could be confounded by drainage reorganization (Willett et al., 2014; Yang et al., 2015). For example, river network dynamics associated with feedbacks among divide migration, spatio-temporal changes in drainage area, and bedrock river incision can lead to in situ development of low-relief, high-elevation patches within an otherwise rugged, fully dissected landscape that could be misinterpreted as recording a change in rock uplift or climate (Yang et al., 2015). As the history of rock uplift or climate is commonly inferred from similar low-relief, high-elevation surfaces (e.g., Miller et al., 2012; Olivetti et al., 2012; Schildgen et al., 2012; Whittaker et al., 2008), it is necessary to develop tests for discriminating among low-relief surface generation mechanisms.

While a number of scenarios have been proposed to explain the origin of upland low-relief surfaces worldwide (e.g., Babault and Van Den Driessche, 2013; Widdowson, 1997), here we develop and apply simple diagnostic criteria for discriminating between two alternative mechanisms: dissection of a preexisting, low-relief landscape versus in situ formation of low-relief landscape patches in response to a rise in local base level following drainage area loss (Yang et al., 2015). In these scenarios low-relief, high-elevation patches may be either preserved remnants of a preexisting landscape or a product of stream piracy. Both mechanisms can ultimately lead to similar morphologies but are marked by distinct pathways of landscape evolution.

We use theory and a combination of one- and two-dimensional (1-D and 2-D) landscape evolution models predicated on the well-known stream power river incision model (e.g., Howard, 1994) to characterize these pathways and to identify diagnostic signatures of the two formation processes. We use river longitudinal profiles and channel steepness k_{sn}—channel slope (S) corrected for drainage area (A) using a reference concavity (θ_{ref}), $k_{sn} = SA^{\theta_{ref}}$ (Wobus et al., 2006)—together with plots of elevation versus an upstream integral of drainage area, χ, that help visualize patterns in k_{sn} (Perron and Royden, 2012; see the GSA Data Repository[1] for methodological details) to illustrate model predictions and evaluate natural landscapes. Using these tools and diagnostic criteria, we evaluate the relative merits of the competing models for formation of dissected low-relief upland landscapes of the southeastern Tibetan Plateau.

DISSECTION OF A PREEXISTING LOW-RELIEF LANDSCAPE

Landscape evolution during dissection of preexisting low-relief topography is well studied and could reflect any one of several drivers: (1) an increase in rock uplift rate, (2) a decrease in erosional efficiency resulting in a decrease in erosion rate and thus increased surface uplift rate (England and Molnar, 1990), or (3) an increase in the rate of local base-level fall as might be associated with a cessation of focused rock uplift downstream, integration of drainage across a plateau margin, or an increase in runoff that triggers incision into an undissected plateau. For simplicity, we illustrate profile evolution for an increase in rock uplift rate from U_i to U_f for the stream power river incision model (see the Data Repository), where U_i indicates the rock uplift rate of a steady-state initial landscape with uniform erosion rate $E_i = U_i$ (Fig. 1A; Fig. DR1a in the Data Repository), and U_f indicates the present rock uplift rate such that $U_f > U_i$. Note that all mechanisms triggering incision into a preexisting low-relief landscape produce behavior similar to that detailed below and illustrated in complementary 2-D simulations using the CHILD landscape evolution model (Tucker et al., 2001) (see Fig. DR2a and Movies DR1–DR2 in the Data Repository).

For the scenario of incision into a preexisting low-relief landscape (Fig. 1A; Figs. DR1a,

[1]GSA Data Repository item 2017023, methodological details and supplementary visualization of observations and model results in Figures DR1–DR7 and Movies DR1 and DR2, is available online at http://www.geosociety.org/pubs/ft2017.htm or on request from editing@geosociety.org.

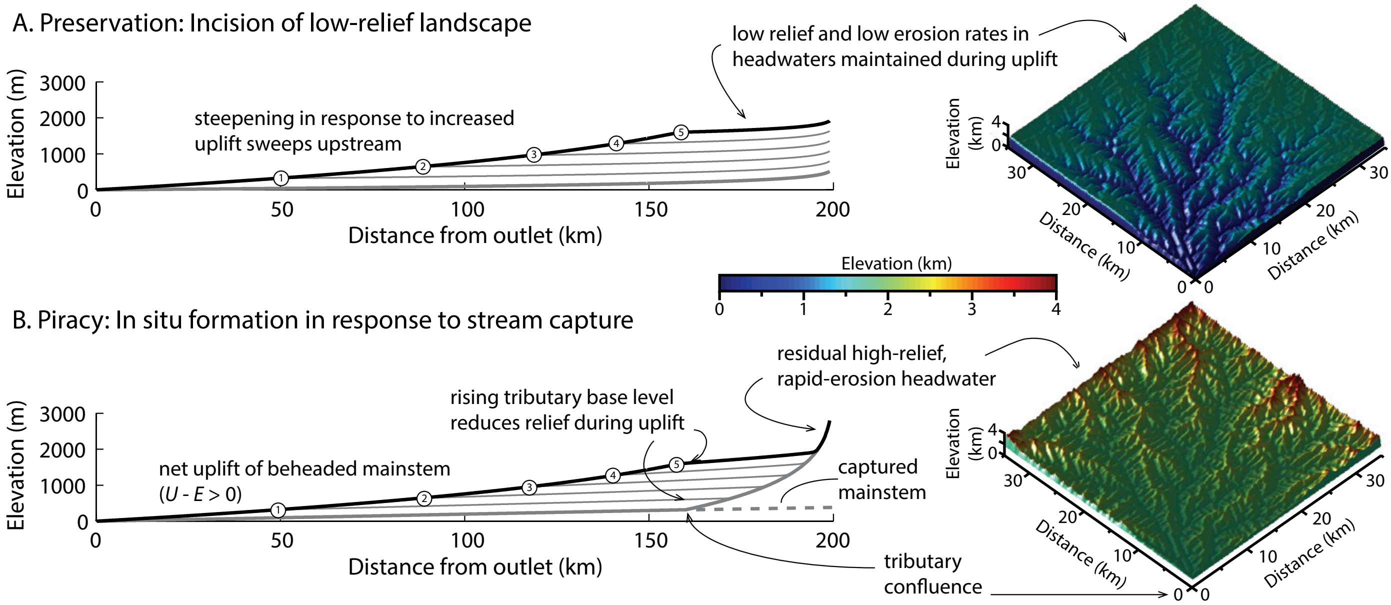

Figure 1. Diagnostic characteristics of low-relief, high-elevation surface formation mechanisms. A: Preservation: Incision following increase in rock uplift rate relative to base level. B: Piracy: Tributary relief reduction in response to rising local base level following trunk river beheading. Shown at left for both cases are profiles for initial steady state (thick gray), four intermediate time steps (thin gray), and final time step (black). Exaggeration is 10×. Slope-break knickpoints associated with each time step shown (1–5) are labeled accordingly. Shown at right are perspective digital elevation models from two-dimensional model simulations of upper portions of each landscape (see Data Repository [see footnote 1]). No vertical exaggeration. *U*—rock uplift rate; *E*—erosion rate.

DR2a), the essential, diagnostic characteristics of landscape evolution are: (1) steady, uniform surface uplift (surface uplift rate = $U_f - U_i$) results in preservation of remnants of the low-relief surface at a common elevation (allowing for variability in the relief and regional dip of the initial low-relief landscape) at all times; (2) the low-relief headwater areas ultimately preserved as low-relief surface remnants are always the high points in the landscape; and (3) these preserved remnants are coeval and maintain a relict low-relief form and low erosion rates (E_i) throughout the simulation. Additionally, knickpoints that demarcate the boundary between upstream, relict channel reaches with low steepness and downstream, adjusted channel reaches with high steepness (Fig. 1A) are predicted to occur at approximately equal elevations in channel profiles throughout the landscape (Niemann et al., 2001; Wobus et al., 2006) (see Fig. DR2a).

Although stream power models predict a concordance of knickpoint elevations following a spatially uniform increase in uplift rate relative to base level, some variability in knickpoint elevation is expected because this prediction depends on a number of assumptions: (1) the initial landscape is in steady state with spatially uniform rock uplift rate (U_i), erosion rate (E_i), and erodibility; (2) the imposed increase in rock uplift rate is spatially uniform; (3) channel concavity does not change during uplift and incision; and (4) all channel reaches respond by steepening in the same proportion to the increase in uplift rate. In most landscapes, one or more of these assumptions will be violated to some degree (e.g., DiBiase et al., 2015), resulting in modest variability in knickpoint elevation even where uplift rate is approximately uniform (Fig. DR3). However, despite this expected variability in knickpoint elevation and channel steepness, roughly uniform or smoothly varying low-relief surface remnants are diagnostic of regional base-level fall.

FORMATION OF LOW-RELIEF REGIONS IN RESPONSE TO DRAINAGE AREA LOSS

Under some circumstances, drainage area loss due to drainage capture or divide migration can produce analogous low-relief landscape patches perched above surrounding canyons (Yang et al., 2015). This follows because loss of drainage area reduces flood discharge and sediment supply, leading to a decrease in erosion rate. As a result, there is an increase in the rate of net surface uplift ($U > E$) that depends on the fractional change in drainage area (typically $\Delta E = \Delta A^{-0.5}$; see the Data Repository). Although a beheaded river will experience this net uplift, its position low in the landscape makes it difficult to ever form an elevated, low-relief landscape. Tributaries to the beheaded river positioned near the capture point, however, will experience a period of relative base-level rise that triggers a reduction in relief that sweeps upstream in each tributary, eventually leading to formation of low-relief, high-elevation surface patches. As this response is restricted to individual tributary catchments, the resulting low-relief patches are always bounded by drainage divides. The loss of mainstem drainage area results in a decrease in erosion rate, with the resulting surface uplift leading to a temporary and local rising base level for the tributary. A low-relief surface forms in the tributary catchment by simultaneous relief reduction and surface uplift at the rate of base-level rise. These effects sweep upstream, preserving an ever-diminishing high-relief catchment rim, as illustrated in simulations with the stream power model (Fig. 1B; Figs. DR1b and DR2b). For comparison to the scenario of incision into a preexisting low-relief surface, we set the size of the beheaded mainstem reach in our 1-D model such that the resulting rate of base-level rise experienced by the tributary is approximately the same as the rate of net profile uplift rate in Figure 1A.

Unlike the case for dissection of a preexisting surface (Fig. 1A), low-relief uplands produced by the drainage capture mechanism are predicted: (1) to be distributed randomly in elevation, depending on the time since capture and the rate of net surface uplift dictated by the fractional change in drainage area; (2) to vary significantly in relief (and thus erosion rate), depending on the time since capture and the fractional mainstem area loss, which dictates the degree of disequilibrium and the rate of base-level rise experienced by tributaries; (3) to be bounded by drainage divides defined by the affected tributaries; and (4) to be surrounded by a rim of high-relief topography that persists until the final stages of landscape response to drainage reorganization. In addition, because relief reduction occurs during surface uplift, surface elevation and the degree of relief reduction will be strongly correlated (Fig. 1B; Figs. DR1b and DR2b).

The model predictions above provide useful diagnostic guidelines, but additional considerations emerge in natural landscapes. First, high sediment yields in streams draining the high-relief catchment rim will trigger aggradation of valley floors, leading to high-concavity river profiles and transport-limited conditions, in turn potentially leading to a rounding of resulting knickpoints. Second, the large fractional drainage area losses required to significantly reduce erosion rate limit the extent and distribution of low-relief surfaces plausibly produced by drainage network dynamics. Last, in the case of incision into a preexisting low-relief surface, the inevitable development of spatial contrasts in erosion rate will trigger divide migration and increase the probability of drainage capture. However, the presence of mobile divides in such a scenario is a result, and not the driver, of the formation of elevated low-relief surfaces.

APPLICATION AND IMPLICATIONS

As an example, we apply the diagnostic criteria developed above to resolve a recent debate over the history and drivers of landscape evolution on the southeastern margin of the Tibetan Plateau, a region characterized by 2–3-km-deep canyons along the Salween, Mekong, Yangtze, Yalong, and Dadu River systems inset into a mosaic of extensive low-relief, high-elevation landscape patches (Fig. 2) (Clark et al., 2006; Liu-Zeng et al., 2008; Ouimet et al., 2010). The simplest, and standard, interpretation is that the low-relief surface patches are remnants of a formerly continuous, if complex, low-relief continental-scale landscape that is undergoing the initial stages of fluvial dissection, resulting in a ten-fold difference in short- and long-term erosion rates on low-relief surfaces and in canyons (Clark et al., 2006; Liu-Zeng et al., 2008; Ouimet et al., 2010) (see Figs. DR4 and DR5). In contrast, Yang et al. (2015) recently argued that these surfaces reflect the internal dynamics of divide migration and river capture arising from regional deformation.

Detailed topographic analysis reveals that the southeastern margin of the Tibetan Plateau is not consistent with the expectations for low-relief upland landscapes formed in response to drainage area loss: (1) low-relief landscape patches are approximately co-planar, arguably formerly continuous (Fig. 2B), and decrease in elevation smoothly and systematically from northwest to southeast across the plateau margin (Clark et al., 2006) (Fig. DR4); (2) observed variation in slope-break knickpoint elevations bounding the low-relief patches is within bounds expected for natural landscapes with non-ideal initial conditions and spatial variability in rock properties (Fig. 2; Figs. DR3 and

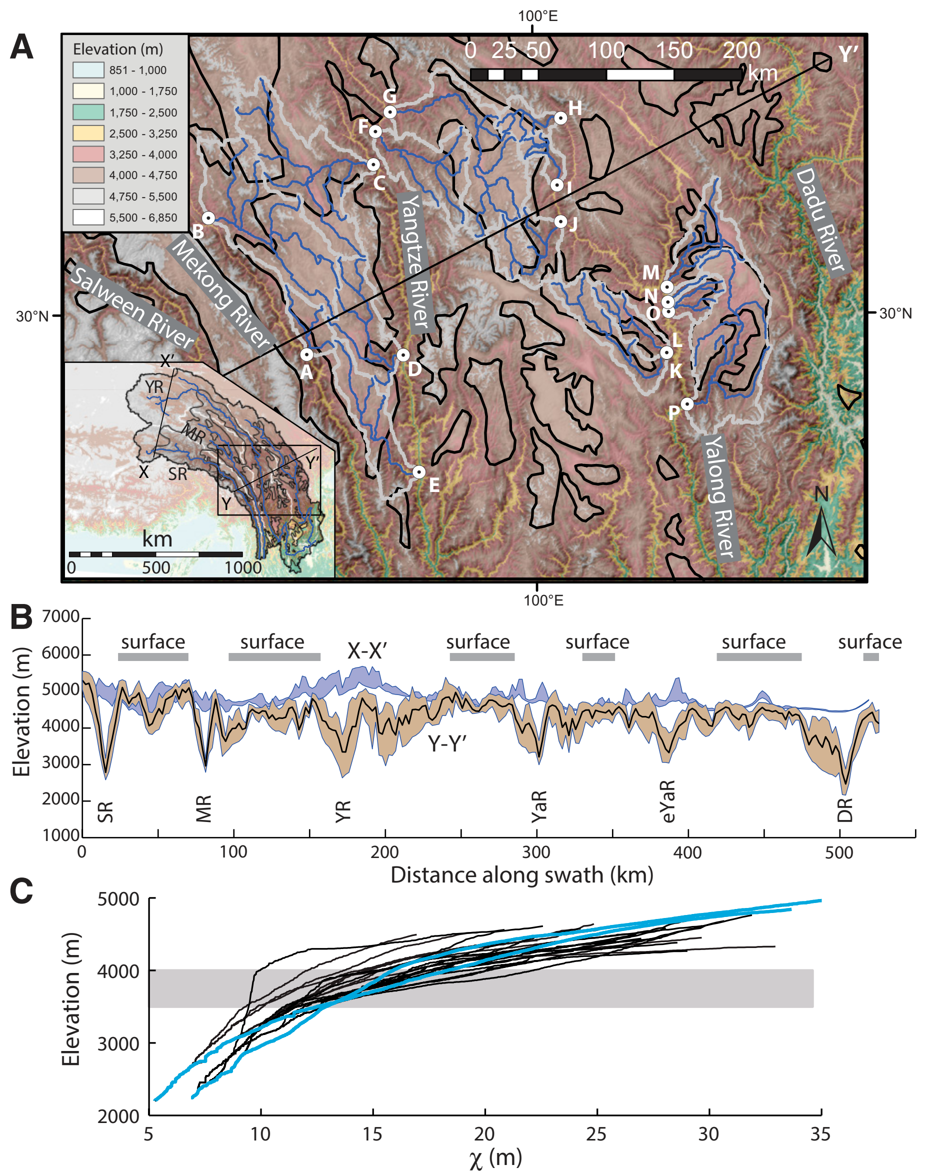

Figure 2. Evidence for low-relief landscape preservation, southeast Tibetan Plateau. A: Hillshade colored by elevation and shaded by local relief (2.5 km radius), with low-relief surface patches from Clark et al. (2006) (black lines). Outlets to main catchments draining four large surface patches are marked with white circles and labeled A–P. Note that drainage divides (gray) are not at surface margins (black) and that surface patches lack high-relief margins and occur at generally consistent elevations. Lower left inset shows regional context, watersheds of Salween (SR), Mekong (MR), and Yangtze Rivers (YR), and location of swath profiles shown in B. B: Comparison of 10-km-wide swath profiles along X-X′ (light blue) and Y-Y′ (tan). Exaggeration is 24×. Intersection with mapped (Clark et al., 2006) low-relief surface patches along profile Y-Y′ indicated (gray bars) (X-X′ crosses only undissected plateau). YaR and eYaR are the main and east forks of the Yalong River, respectively. DR—Dadu River. C: χ-transformed profiles of all major streams (blue lines in A) in catchments A–E (see Fig. DR7 [see footnote 1] for profiles from catchments F–P). Slope of elevation versus χ plots is channel steepness (k_{sn}). All show similar form with significant slope-break knickpoints separating low-relief surfaces from rugged canyons below, between 3500 and 4000 m (gray band). Mainstem profiles (Mekong and Yangtze) are shown in blue. Single outlier is small, southernmost tributary in catchment D and may be a hanging valley (e.g., Crosby et al., 2007).

DR6); (3) the surface patches lack the high-relief rims expected for landscapes experiencing relief decline in response to a rising local base-level (Figs. 1 and 2; Figs. DR4and DR5); and (4) the low-relief surface patches are not bounded by drainage divides, as expected for the area-loss mechanism. Indeed, many surface patches host essentially radial drainage patterns, with low-relief headwater catchments characterized by gently sloping rivers draining in all directions and crossing convex slope-break knickpoints at surface margins (Fig. 2A). Moreover, similar topography on opposing sides of divides (Fig. 2; Figs DR5 and DR6) suggests stable divides.

Although there is evidence of drainage rearrangement (Fig. DR7), drainage capture appears to have occurred as a consequence of incision into the low-relief upland and has not contributed to the formation of the low-relief upland.

Recognition of the potential for internal drainage network dynamics to create elevated low-relief landscape patches absent external forcing is important for interpreting the history of landscape evolution encoded in topography. The southeast Tibetan Plateau case study demonstrates the power of simple diagnostic tests for determining whether divide mobility and river captures are important contributors to low-relief surface formation or whether a change in tectonics or river erosivity is required. Although aspects of the timing, driving mechanisms, the role of the glacial buzzsaw, and geodynamic implications of the dissection of the southeast Tibetan Plateau remain uncertain (e.g., Clark et al., 2005, 2006; Tian et al., 2015; Hoke et al., 2014; Liu-Zeng et al., 2008; Zhang et al., 2016), our analysis makes it clear that the topography records incision into a preexisting low-relief landscape. Similar determinations can be readily made by applying the above criteria for recognizing the drainage area-loss mechanism in other landscapes where elevated low-relief surfaces have been interpreted in terms of the history of rock uplift.

ACKNOWLEDGMENTS

Forte's efforts were supported by National Science Foundation grant EAR-1450970, and Ouimet's by grant EAR-1220453. We thank M. Oskin, P. Prince, and an anonymous reviewer for helpful criticisms and suggestions, and N. Gasparini for thoughtful discussion.

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Manuscript received 16 August 2016
Revised manuscript received 26 October 2016
Manuscript accepted 30 October 2016

Printed in USA