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Divide mobility controls knickpoint migration on the Roan Plateau (Colorado, USA)

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ABSTRACT

Knickpoints in longitudinal river profiles are proxies for the climatic and tectonic history of active mountains. The analysis of river profiles commonly relies on the assumption that drainage network configurations are stable. Here we show that this assumption must be made cautiously if changes in contributing area are fast relative to knickpoint migration rates. We study the Parachute Creek basin in the Roan Plateau, Colorado, United States, where knickpoint retreat occurs in uniform lithology so that drainage area is the sole governing variable. In this basin, we identify a catchment being anomalous in the degree to which a stream power based model predicts knickpoint locations. The catchment is experiencing area loss as the plateau edge is eroded by cliff migration in proximity to the Colorado River. Model predictions improve if the plateau edge is assumed to have migrated over the timescale of knickpoint retreat. Finally, a Lagrangian model of knickpoint migration enables us to study the kinematic links between drainage area loss and knickpoint migration and offers constraints on the temporal aspects of area loss. Modelled onset and amount of area loss are consistent with cliff retreat rates along the margin of the Roan Plateau inferred from the incisional history of the upper Colorado River.

INTRODUCTION

Topography is widely used to study the climatic and tectonic history of active mountains. Longitudinal river profiles provide proxies for changing environmental conditions because their geometry reflects variable rates of surface uplift and changes in base-level (Wobus et al., 2006), river discharge (Lague, 2014) and sediment supply (Jansen et al., 2011). The analysis of river profiles commonly relies on the stream-power law, which states that the elevation change $\partial z/\partial x$ [m y^{-1}] of a detachment-limited fluvial channel is a function of uplift U [m y^{-1}], erosional efficiency K [$\text{m}^{1-2m} \text{y}^{-1}$], drainage area A [m^2] and local channel gradient (dz/dx) to the exponents m and n , respectively (e.g., Howard and Kerby, 1983; Fox et al., 2014; Lague, 2014; Venditti et al., 2019).

$$\frac{\partial z(t, x)}{\partial x} = U(t, x) - KA(x)^m \left(\frac{dz(t, x)}{dx} \right)^n \quad (1)$$

An assumption in most river-profile analyses is that drainage configurations and areas remain unchanged (Fox et al., 2014; Whipple et al., 2017b). Recent studies, however, raise concern about this assumption and suggest that mobile divides provoke feedbacks with incision rates and thus response times to climatic and tectonic perturbations (Willett et al., 2014; Yang et al., 2015). Testing this hypothesis, however, is difficult in natural landscapes. Thus, much of our understanding on feedbacks between drainage reorganization and river profile development comes from numerical models and physical

experiments, yet with contrasting results. Numerical models predict that drainage configurations are sensitive to initial conditions but then quickly stabilize unless severely perturbed by river capture (Tucker and Hancock, 2010; Kwang and Parker, 2019). In these simulations, river profiles react quickly to variable drainage networks and topographic imprints remain subtle (Whipple et al., 2017b). Physical experiments demonstrate that divides migrate without external forcing so that channel networks continuously vary their lengths and contributing areas (Hasbargen and Paola, 2000), a phenomenon that is also observed in models that implement subgrid representations of flow routing (Armitage, 2019) and divide migration (Goren et al., 2014). This raises the possibility that natural landscapes are more dynamic than models suggest (Beeson et al., 2017). However, in natural landscapes, divide mobility and its impacts on and possible feedbacks with river longitudinal profiles remain largely unstudied.

We present a topographic analysis of the Roan Plateau, a high-elevation, low-relief relict landscape in Colorado, United States. Berlin and Anderson (2007) showed that Late Cenozoic incision of the upper Colorado River led to a wave of upstream migrating waterfalls (knickpoints) (Fig. 1A), whose locations are consistent with a stream-power based celerity model of knickpoint migration. We show that the prediction of knickpoint locations improves when accounting for area loss by cliff retreat along the plateau margin (Fig. 1B). We developed a knickpoint celerity model that accounts for time-variant areas and is able to unravel the area lost to cliff retreat as well as temporal aspects of divide migration.

Figure 1: Knickpoints in the Parachute Creek basin. A) Map of the Roan Plateau and the Parachute Creek basin. Colors of the stream network show values of χ . Cross-divide differences in χ reflect potential divide movements (from lower to higher values). Dots indicate knickpoints in river profiles (C). The size of the points shows the distance between actual knickpoint locations and those estimated by the knickpoint celerity model. The dotted line shows the profile shown in Fig. 3C. B) The eastern margin of the Roan Plateau is characterized by active divide mobility that beheads valleys of the East fork. C) River longitudinal profiles and knickpoints (white dots) in the Parachute Creek basin. D) χ -transformation of the river profile in C and nonparametric estimation of the distribution of knickpoint χ -values (black line). Shaded areas around the line are bootstrapped 95% confidence intervals.

CONSTRAINTS ON AREA LOSS

The Roan Plateau is located in the northeastern part of the Colorado Plateau. We study the 512 km² drainage basin of Parachute Creek, a tributary to the Colorado River which abuts the Roan Plateau to the east and south. With its spatially uniform rock erodibility and climate, the basin is regarded as a natural experiment for studying landscape response to changes in base level (Berlin and Anderson, 2007). Carving into Tertiary sedimentary rocks of the Green River Formation (Desborough, 1978), the Parachute Creek exposes resistant cliff-forming rocks. The most resistant unit is the Mahogany oil-shale zone, which forms prominent ledges and waterfalls. Dissection of the plateau has been linked to the incision of the Colorado River that accelerated due to drainage integration within the Colorado Plateau and rapid regional exhumation at 6–10 Ma associated with Neogene mantle flow (Lucchitta, 1972; Karlstrom et al., 2012; Aslan et al., 2019). Based on apatite fission track-derived cooling ages and ⁴⁰Ar/³⁹Ar dating of incised basalt flows, the onset of incision of the Parachute Creek was dated to ~8 Ma (Berlin and Anderson, 2007).

Using a 30-m digital elevation model and an automated procedure to detect knickpoints in TopoToolbox (Schwanghart and Scherler, 2014) (see GSA Data Repository), we identified 103 knickpoints in the Parachute Creek basin. The knickpoints are located 800±70 (1σ) m above the confluence with the Colorado River (1540 m a.s.l.) at an along-river distance of 26±6 km (Fig. 1C, DR Fig. 1). Assuming that all knickpoints originated at the confluence with the Colorado River, their current positions can be predicted based on knickpoint celerity $\partial x/\partial t = KA^m (dz/dx)^{n-1}$ (Berlin and Anderson, 2007). According to this model, a knickpoint requires the time τ [y] from a base level at $x = 0$ to a point along the river.

$$\tau(x) = \int_{x=0}^x \frac{1}{KA(x)^m} \left(\frac{dz}{dx} \right)^{-n+1} dx \quad (2)$$

Assuming that $n = 1$ and acknowledging that τ is inversely proportional to K allows us to introduce the variable χ [m]

$$\chi = A_0^m K \tau \quad (3)$$

with $A_0 = 10^6$ m² being a reference area (Fox et al., 2014). Plotting river profiles with χ as horizontal coordinate (calculated with $m = 0.4$) demonstrates the usefulness of χ because knickpoints that originate from a common base level cluster in χ space (Fig. 1D) (Perron and Royden, 2013).

Despite the peaked distribution, the remaining spread of knickpoint χ values (χ_{kp}) indicates uncertainties about knickpoint celerity, which we seek to explain by investigating the spatial patterns of χ_{kp} . These patterns highlight the East Fork subbasin (105 km²) where knickpoints migrated up to 2 km further (residual distances in Fig. 1A) than the most likely estimate obtained from the mode of χ_{kp} (Fig. 1D). The eastern divide of this catchment coincides with the margin of the Roan Plateau (coincident divide sensu Willett (2017)) and undergoes cliff retreat which is evident from numerous beheaded valleys (Fig. 1B, Fig. DR3–4). We hypothesize that modeled and observed knickpoint locations differ due to drainage-area lost by cliff retreat along the coincident divides of the plateau margin.

Figure 2: A) Quantification of area-loss in the East Fork. The red circle illustrates the estimated area lost and the dashed lines show the 95%-confidence intervals. The red-shaded area has the same area as the estimate and illustrates a hypothetical shape that follows the area of cliff retreat. B) Close-up of the kernel-based distribution of knickpoint χ values in Fig. 1D based on the present day drainage area (gray line, bright gray confidence intervals) and with an additional 41.9 km² drainage area in the East Fork subbasin (black line, red confidence intervals). Confidence intervals were derived from 1000 bootstrap samples.

To quantify area loss, we first optimized the parameters m and K by minimizing the sum of squared differences between the onset of incision at $t_0=8$ Ma and response times $\tau_{kp} = \chi_{kp}/(KA_0^m)$ of k knickpoints excluding those of the East Fork subbasin.

$$\min_{m,K} \sum_{i=1}^k (t_0 - \tau_{kp,i})^2 \quad (4)$$

We obtain values of $K = 2.35 \times 10^{-6} \text{ m}^{1-2m} \text{ y}^{-1}$ and $m = 0.38$ (Fig. DR2). In a second step, we again minimized the dispersion of τ_{kp} , yet this time we kept m and K constant and varied area at one of the beheaded valleys contributing to the East Fork subbasin (Fig. 2A). Whether we add area to the four beheaded valleys or only one of them makes no difference because the knickpoints are located downstream of the confluences. We determine a value of area loss of $41.9 \pm 20.2 \text{ km}^2$ (95% confidence intervals (CI)) of the East Fork, that minimizes the scatter of χ_{kp} . The CI of area loss range between 19.5 and 66.1 km² if uncertainties in K and m are propagated to the estimate of area loss (see DR). Although the overall reduction of χ_{kp} variability is low, the probability densities of χ_{kp} differ significantly (based on 95% bootstrapped CI) when accounting for the lost area (Fig. 2B).

Changing area at one location in the basin changes χ_{kp} in other parts of the basin as well. Moreover, other subbasins may have also undergone area changes due to mobile divides. To test the robustness of our findings, we added variable areas at three more channelheads of 4th-order tributaries (Fig. DR5). Using the nonlinear regression that minimizes the dispersion of τ_{kp} , yet this time with four free parameters, we find that the East Fork subbasin has a significant ($p=0.007$) area loss of $48 \pm 29 \text{ km}^2$ (95% CI) while there are no significant area changes in the other subbasins ($p < 0.05$). The Middle Fork shows no significant area changes although it has beheaded valleys along its eastern fringe, too. However, there are fewer and less distinct beheaded valleys (Fig. 1A) and a smaller proportion of coincident divides (9% of 96 km divide length compared to 21% of 79 km) than in the East Fork, which also abuts against the wider valley of the Colorado River.

Figure 3: A) Results of the knickpoint migration model at 5 Ma, 2 Ma and today. Black dots show the actual distribution of knickpoints. Blue dots show the results of a model with no area loss and red dots show the results of a model that best agrees with the actual distribution of knickpoints in a scenario of area loss (60 km² area loss that started at 1 Ma, see star in panel B). B) Consistency between locations of observed and simulated knickpoints for variable combinations of area loss and onset of area loss. Contours are calculated by summing Gaussian kernel densities (bandwidth = 300 m) around observed knickpoint locations at modelled knickpoint locations. The best estimate is indicated by the black star. C) Incision model of the upper Colorado River based on cosmogenic nuclide derived ages of Colorado River gravels (Aslan et al., 2019) and inferred cliff retreat rates. Two scenarios, first, incision and lateral migration, and second, incision only (indicated by *), would result in ~8 km and ~2 km cliff retreat since 2 Ma, respectively.

The excess distance covered by knickpoints in the East Fork subbasin suggests that area loss started when knickpoints had passed the East-Fork Parachute confluence at 4.5 Ma (Eq. 2). Earlier onset of area loss might also explain the differences in χ_{kp} , but requires a larger area loss. To study the kinematics of knickpoints and their relation to area loss, we developed a Lagrangian model which solves the knickpoint celerity model with time-variant areas. The model simulates the movement of a knickpoint, which originates at the confluence with the Colorado River at 8 Ma and splits up at tributary junctions, while upstream areas at channelheads can vary. We simulated 420 scenarios with variable onsets (equally spaced between 6 Ma and present) and areas (equally spaced between 0 and 200 km²) of loss in the East Fork subbasin. Following onset, we assume a constant rate of area-loss until areas equal those of today. We evaluated the results against network-based kernel density distributions of observed knickpoints (Fig. DR6). Simulated and observed knickpoint locations agree best if area loss is between 40 and 80 km² and started at 3–0.2 Ma (Fig. 3B). Assuming a constant divide length, we estimate a total divide movement between 2.4–4.8 km. A best estimate (onset at 1 Ma, area loss of 60 km²) yields a time-averaged rate of divide migration of 4 mm y⁻¹. In contrast, the fastest knickpoint in the Parachute Creek basin attains a velocity of 2.5 mm y⁻¹.

DISCUSSION

Although the onset of area loss can only be broadly constrained to <3 Ma, we suggest that our results are consistent with the incision history and lateral migration of the Colorado River. Cosmogenic nuclide derived ages of Colorado River deposits show that the river has incised at rates of 0.20–0.32 mm y⁻¹ since ~2 Ma (Darling et al., 2012; Aslan et al., 2019) (Fig. 3B). The deposits are intermingled with Pleistocene alluvial and debris flows from the Battlement Mesa (Fig. 1A) (Cole and Sexton, 1981), which suggests that the Colorado River was episodically unable to excavate the sediments from tributaries draining the Battlement Mesa. Such sediment pulses can even laterally displace actively

incising rivers (Ouimet et al., 2008). That its deposits are unparalleled on northern adjacent slopes further suggests that the Colorado River was pushed northward while incising. Assuming the same slope up to the margin of the Roan Plateau as today, vertical and lateral mobility of the Colorado River translate into ~8 km northward cliff retreat at rates of 2.8–5.6 mm y⁻¹ sustained over ~2 Myr (Fig. 3C). A scenario of no lateral migration, but incision only, yields 2 km cliff retreat (Fig. 3C). Thus, we conclude that drainage truncation in the East Fork occurred by a migrating cliffline spawned by the incision of the Colorado River.

We showed that topographic analysis based on the stream power model helps to reveal the kinematic links between divide and knickpoint mobility. The high correspondence between predictions of the stream-power model (specifically its linear form with $n=1$) and knickpoint locations emphasizes that the model is a powerful concept for corroborating tectonic signatures in landscapes (Venditti et al., 2019). Our inferred direction of divide migration agrees with metrics of the relative stability of drainage divides (e.g., cross-divide differences in hillslope relief (Fig. DR3)) (Scherler and Schwanghart, 2019) and with cross-divide contrasts in χ (Willett et al., 2014) (Fig. 1A). Beyond these metrics, our analysis quantifies for the first time area changes from modelled knickpoint celerities and offers constraints on temporal aspects of plateau-edge migration. These results suggest that progressive divide migration and area loss occur at rates that outpace the erosional response of channels (Willett et al., 2017b).

Few studies explicitly address the role of area loss and exchange (e.g., Fox, et al. 2014) when inferring variations in rock uplift, climate, or rock properties from river profiles. Modelling studies show that these relations should be preserved even if divides migrate, because river profiles rapidly adjust to changes in drainage area (Whipple et al., 2017b), particularly in young and active orogens (Fox et al., 2014). However, if area changes are fast relative to knickpoint celerities, this assumption must be re-evaluated. Rapid area changes occur during major river capture events (Prince et al., 2011), and are most likely preserved in landscapes of low erosional efficiency (Whipple et al., 2017). Our approach may thus apply mainly to high-elevation low-relief landscapes that experience transient responses to drainage reorganization (Yang et al., 2015; Whipple et al., 2017a).

CONCLUSIONS

Knickpoints in the East Fork subbasin migrated further than other knickpoints in the Parachute Creek basin and our implementation of the stream-power incision model resolves these discrepancies by including a loss of drainage-basin area. Thus, our results shed light on an outstanding research issue that has so far only been addressed by numerical modelling and physical experiments but has eluded observation in natural landscapes. We show that, on the Roan Plateau, processes governing divide mobility and incision into a low relief landscape operate at similar time scales. This implies the potential for feedbacks between internal drainage basin dynamics and the evolution of longitudinal river profiles. These feedbacks have not sufficiently been taken into account by morphometric approaches that rely on stable configurations of drainage basins.

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