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Waterfalls on the eastern side of Rocky Mountain National Park, Colorado, USA

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ABSTRACT

We examined 30 waterfalls on the eastern side of Rocky Mountain National Park in Colorado, USA, to evaluate whether drainage area or bedrock properties as reflected in joint characteristics correlate more strongly with the location and characteristics of individual waterfalls. Longitudinal profiles tend to be more concave for larger drainages, to have a smaller proportion of total elevation loss in waterfalls, and to have vertical drops rather than angled or ramp waterfalls: we interpret these trends to indicate greater overall incisional capability for larger catchments. Shape of individual waterfalls and height of drop correlate more strongly with bedrock properties: waterfalls in bedrock lacking prominent vertical joints perpendicular to flow are more likely to have a single drop rather than multiple drops, and taller waterfalls correlate with more widely spaced horizontal joints. Waterfalls also noticeably correspond to resistant bedrock outcrops that form steep segments along hillslopes adjacent to the channel. We interpret these results to indicate that the location and characteristics of waterfalls along headwater streams in the study area reflect primarily a limited ability to incise through more resistant segments of the underlying bedrock.

1. Introduction

Knickpoints in the form of waterfalls are one of the most visually arresting indicators that adjustment of river longitudinal profiles can be spatially discontinuous. A knickpoint represents an abrupt vertical discontinuity in the profile, and the rate of knickpoint erosion limits upstream transmission of relative base level change (Berlin and Anderson, 2009). Knickpoint morphology can be diverse, including stepped, buttressed, and undercut forms (Young, 1985). Knickpoints can maintain a constant geometry during upstream retreat (Lamb and Dietrich, 2009) or rotate so that the angle of the knickpoint face with the vertical decreases with time and develops into rapids (Gardner, 1983). Knickpoints are more likely to maintain a steep face in strongly bedded or jointed substrates (Holland and Pickup, 1976; Bishop and Goldrick, 1992; Frankel et al., 2007; Lamb and Dietrich, 2009).

Knickpoints have been interpreted as reflecting a transient response to base level fall (e.g., Crosby and Whipple, 2006), as well as limited ability to incise through more resistant bedrock (e.g., Miller, 1991): these alternatives are not mutually exclusive. Knickpoints that form where a particularly resistant material outcrops in the channel bed maintain a strong vertical stability during river incision, in contrast with knickpoints resulting from lowering of relative base level, which migrate upstream at a rate controlled by river discharge (Crosby and Whipple, 2006; Larue, 2008). Despite numerous studies of knickpoint morphology and dynamics, distinguishing the relative importance of discharge versus bedrock erosional resistance on knickpoint location and characteristics remains challenging (Phillips et al., 2010).

Numerous knickpoints that form waterfalls punctuate the downstream course of rivers draining the eastern side of the continental divide in Rocky Mountain National Park (RMNP), Colorado, USA. Each of the headwater rivers in RMNP is tributary to the Poudre River, Big Thompson River, or North St. Vrain Creek. These major drainages had at least three major episodes of valley glaciation during the Pleistocene Epoch, culminating in the Pinedale glacial period, with glaciers achieving their maximum extent circa 20,000 years ago (Madole et al., 1998; Ward et al., 2009; Dühnforth and Anderson, 2011). Mountain glaciers can effectively deepen and widen valleys, as described in the glacier buzz-saw model (Brozovic et al., 1997), in which glaciated valleys experience more rapid and substantial erosion than do otherwise analogous valleys experiencing only river erosion. Differences in glacial and fluvial erosion are also reflected in persistent differences in valley morphology long after deglaciation (Montgomery, 2002; Amerson et al., 2008). As the Pinedale glaciers in RMNP melted between circa 20,000 and 10,000 years ago, tributary valleys that had been adjusted to the upper level of the ice in the glaciated valleys were left as hanging or oversteepened valleys. This history is evident in the longitudinal profiles of channels tributary to glaciated valleys such as North St. Vrain Creek, where each tributary valley has a relatively low gradient upper portion and then drops precipitously into the main valley, with profile steepening at or just above the level of the Pinedale glacier. Following glacial retreat, each tributary began to incise at a rate partly reflecting its drainage area and discharge. Thus, the contemporary location of many of the waterfalls on the eastern side of RMNP could reflect the rate of

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post-glacial erosion as a function of time since deglaciation and upstream drainage area (here, a surrogate for discharge and incisional capability). Studies in other regions indicate that distance of headwater knickpoint recession can correlate with drainage area (Bishop et al., 2005), particularly for short distances upstream from mainstem–tributary junctions (Crosby and Whipple, 2006). Knickpoint position can also reflect a threshold drainage area for channel incision (Crosby and Whipple, 2006).

The relationship between waterfall location and drainage area in RMNP may also be complicated by the fact that at least three episodes of valley glaciation have occurred in the region during the past million years. Waterfall recession might be particularly slow along the small (<50 km^2) headwater streams in RMNP that flow over resistant bedrock, so some of the contemporary waterfalls might reflect continuing adjustment to the earlier Bull Lake (140,000–125,000 years) and pre-Bull Lake (700,000–500,000 years) glacial episodes (Pierce, 2003).

Waterfalls can also occur where a river flows over particularly resistant bedrock that slows the rate at which the river can adjust to continuing base level change. Most of the bedrock on the eastern side of RMNP is comprised of crystalline metamorphic or igneous lithologies (Braddock and Cole, 1990) with very similar erosional resistance. Differences in the spacing of joints, however, can create substantial differences in the resistance of the rock to weathering and erosion. Previous work in the region indicates that more closely spaced joints correlate with wider, lower gradient valleys (Ehlen and Wohl, 2002) and with the formation of strath terraces (Wohl, 2008), which led us to hypothesize that differences in joint spacing and geometry might also correlate with the location and characteristics of waterfalls on the eastern side of RMNP.

The research summarized here is designed to evaluate the relative influence of drainage area and bedrock properties on continuing adjustment to post-glacial base level fall on headwater streams in mountainous terrain with Pleistocene valley glaciations. We examined watershed-scale adjustment by evaluating whether concavity ratio and total elevation loss in waterfalls correlate with drainage area. We then tested whether drainage area and related variables such as discharge, or bedrock properties as reflected in joint characteristics, correlate more strongly with the location and characteristics of individual waterfalls in Rocky Mountain National Park. Although previous studies such as Miller (1991) and Lamb and Dietrich (2009) acknowledged the importance of bedrock joints in waterfall location and characteristics, the research reported here builds on this work by statistically testing the relative importance of drainage area and joint characteristics in explaining observed variability in height, angle, and shape among individual waterfalls.

2. Study area

Rocky Mountain National Park straddles the continental divide between streams draining eastward to the South Platte River and ultimately the Mississippi River, and streams draining westward into the Colorado River. Elevations along the continental divide are 3800 to 4300 m, and the eastern boundary of the park lies at ~2500 m. The park is underlain primarily by Precambrian-age crystalline rock units. The most extensive lithologies are Silver Plume granite and biotite schist (Braddock and Cole, 1990). Most bedrock outcrops are densely jointed, with lesser joints spaced a few centimeters apart and prominent joints <4 m apart. Compressive strength of the crystalline lithologies present in the park averages 50–60 using a Schmidt hammer: differences in joint geometry exert a much stronger influence on bedrock resistance to weathering and erosion (Wohl, 2008).

Rocky Mountain National Park lies within the Colorado Front Range, which has been relatively tectonically quiescent since the early Tertiary (Crowley et al., 2002; Anderson et al., 2006). Range crests at 4000 m elevation take the form of narrow, glaciated spines. Widespread surfaces of low relief at 2300–3000 m elevation are deeply incised by fluvial canyons. During the past few million years, incision of the South Platte River has driven exhumation of the Denver basin, which forms the eastern border of the Front Range. Tributaries of the South Platte, including those examined in this study, continue to incise the crystalline core of the Front Range in response to this exhumation (Anderson et al., 2006); and fluvial longitudinal profiles display an inflection point, with deeper incision downstream from the inflection. The inflection point on each of the major drainages (Poudre, Big Thompson, North St. Vrain) is well downstream from RMNP and our study area. The headwater tributaries examined here experienced proximal base level change associated with Pleistocene valley glaciation, as noted above. Pleistocene terminal moraines lie at elevations between 2590 and 2370 m within RMNP. Of the seven headwater drainages examined in this paper, only two were not glaciated (Table 1).

Climate and vegetation within RMNP vary strongly with elevation. Mean annual precipitation decreases from 100 cm at the continental divide down to 36 cm at the eastern boundary of the park (Doesken et al., 2003). Stream flow is dominated by snowmelt runoff that produces an annual peak in late spring and early summer. Peak discharge per unit drainage area does not exceed 1.7 m^3/s/km^2 (Jarrett, 1993). Alpine vegetation above 3400 m gives way to subalpine forest of spruce, fir, and pine (*Picea*, *Abies*, and *Pinus* spp., respectively) at elevations of 2740 to 3400 m and montane forest of pine and Douglas-fir (*Pinus* and *Pseudotsuga* spp., respectively) at 1830 to 2740 m elevation (Veblen and Donnegan, 2005).

Valleys in RMNP are longitudinally segmented and vary downstream over lengths of 10^2–10^3 m between unconfined valleys of low gradient and relatively wide valley bottom, partly confined valleys, and steep, narrow, confined valleys. Valley segmentation reflects Pleistocene glaciation and spatial variations in joint density (Ehlen and Wohl, 2002), with unconfined valleys typically occurring immediately upstream from Pleistocene terminal moraines and/or having more densely spaced joints (Wohl and Beckman, in press). The waterfalls that we examine here (Fig. 1) occur in confined or partly confined valley segments. Channels within confined valley segments have bedrock or large boulder substrate and cascade or step-pool morphology and are more likely than unconfined valley segments to include bedrock waterfalls. Bedrock is exposed at waterfall locations partly because of high transport capacity within the active channel, although exposed bedrock typically extends beyond the immediate vicinity of the channel; i.e., a ledge or exceptionally steep section of hillslope is commonly at the same elevation as the waterfall that extends laterally for hundreds of meters away from the channel. Channels within partly confined valley segments can have discontinuous bedrock exposure along the active channel, as well as boulder to cobble substrate, and cascade, step-pool, or plane-bed morphology. Our observations of sediment dynamics around channel-spanning logjams during the past few years indicate that cobble-size and finer sediments move each snowmelt season.

3. Methods

3.1. Field methods

Streams in RMNP contain numerous small drops, particularly in step-pool reaches; and very tall steps in steep channel segments grade into waterfalls. Vertical drops in the stream that were ≥ 1 m tall and formed in bedrock were designated as waterfalls. For each of the 30 waterfalls that we characterized, we mapped the location using a handheld GPS with ± 3 m horizontal accuracy. We categorized waterfall shape as vertical (free falling water over a vertical lip) or ramp (water flowing down a steeply inclined planar surface formed by exposed bedrock), and measured the angle of ramp waterfalls. We measured the height of the vertical drop and length of ramped falls, as well as channel width upstream and at the base of the falls (Fig. 2). Waterfall height was recorded from the edge of the waterfall lip to the bankfull flow level in the plunge pool. Most waterfalls in RMNP do not have deep plunge pools: depths are <2 m and typically <1 m, at least in part because of very large boulders immediately below the plunging flow. We measured joint characteristics in bedrock exposures at each falls,