KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-FOURTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2011
Union College, Schenectady, NY

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2010-2011 PROJECTS

FORMATION OF BASEMENT-INVOLVED FORELAND ARCHES: INTEGRATED STRUCTURAL AND SEISMOLOGICAL RESEARCH IN THE BIGHORN MOUNTAINS, WYOMING
Faculty: *CHRISTINE SIDDOWAY*, *MEGAN ANDERSON*, Colorado College, *ERIC ERSLEV*, University of Wyoming
Students: *MOLLY CHAMBERLIN*, Texas A&M University, *ELIZABETH DALLEY*, Oberlin College, JOHN *SPENCE HORNBUCKLE III*, Washington and Lee University, *BRYAN MCATEE*, Lafayette College, *DAVID OAKLEY*, Williams College, *DREW C. THAYER*, Colorado College, *CHAD TREXLER*, Whitman College, *TRIANA N. UFRET*, University of Puerto Rico, *BRENNAN YOUNG*, Utah State University.

EXPLORING THE PROTEROZOIC BIG SKY OROGENY IN SOUTHWEST MONTANA
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Students: *JESSE DAVENPORT*, College of Wooster, *KRISTINA DOYLE*, Amherst College, *B. PARKER HAYNES*, University of North Carolina - Chapel Hill, *DANIELLE LERNER*, Mount Holyoke College, *CALEB O. LUCY*, Williams College, *ALIANORA WALKER*, Smith College.

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO
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Students: *ERIN CAMP*, Amherst College, *EVAN N. DETHIER*, Williams College, *HAYLEY CORSON-RIKERT*, Wesleyan University, *KEITH M. KANTACK*, Williams College, *ELLEN M. MALEY*, Smith College, *JAMES A. MCCARTHY*, Williams College, *COREY SHIRCLIFF*, Beloit College, *KATHLEEN WARRELL*, Georgia Tech University, *CIANNA E. WYSHNYSZKY*, Amherst College.

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Faculty: *KELLY MACGREGOR*, Macalester College, *CATHERINE RIIHIMAKI*, Drew University, *AMY MYRBO*, LacCore Lab, University of Minnesota, *KRISTINA BRADY*, LacCore Lab, University of Minnesota

Students: *HANNAH BOURNE*, Wesleyan University, *JONATHAN GRIFFITH*, Union College, *JACQUELINE KUTVIRT*, Macalester College, *EMMA LOCATELLI*, Macalester College, *SARAH MATTESON*, Bryn Mawr College, *PERRY ODDO*, Franklin and Marshall College, *CLARK BRUNSON SIMCOE*, Washington and Lee University.

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Students: *BRIANA BERKOWITZ*, Beloit College, *DAENA CHARLES*, Union College, *MELLISSA CROSS*, Colgate University, *JOHN MICHAELS*, North Carolina State University, *ERDENEBAYAR TSAGAANNARAN*, Mongolian University of Science and Technology, *BATTOGTOH DAMDINSUREN*, Mongolian University of Science and Technology, *DANIEL ROTHBERG*, Colorado College, *ESUGEI GANBOLD*, *ARANZAL ERDENE*, Mongolian University of Science and Technology, *AFSHAN SHAIKH*, Georgia Institute of Technology, *KRISTIN TADDEI*, Franklin and Marshall College, *GABRIELLE VANCE*, Whitman College, *ANDREW ZUZA*, Cornell University.

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Students: *MARY BADAME*, Oberlin College, *MEGAN D'ERRICO*, Trinity University, *STANLEY HENSLEY*, California State University, Bakersfield, *JULIA HOLLAND*, Trinity University, *JESSLYN STARNES*, Denison University, *JULIANNE M. WALLAN*, Colgate University.

EOCENE TECTONIC EVOLUTION OF THE TETONS-ABSAROKA RANGES, WYOMING
Faculty: *JOHN CRADDOCK*, Macalester College, *DAVE MALONE*, Illinois State University
Students: *JESSE GEARY*, Macalester College, *KATHERINE KRAVITZ*, Smith College, *RAY MCGAUGHEY*, Carleton College.

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Keck Geology Consortium: Projects 2010-2011
Short Contributions— Front Range, CO

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO
Project Faculty: DAVID P. DETHIER: Williams College, WILL OUIMET: University of Connecticut

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Research Advisor: Anna Martini

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METEORIC ^{10}BE IN GORDON GULCH SOILS: IMPLICATIONS FOR HILLSLOPE PROCESSES AND DEVELOPMENT
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Research Advisor: Will Ouimet and Peter Crowley

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EXAMINING KNICKPOINTS IN THE BOULDER CREEK CATCHMENT, COLORADO

EVAN N. DETHIER, Williams College
Research Advisor: David P. Dethier

INTRODUCTION

The apparent stasis of our current landscape belies the constant change it has undergone for millions of years before the present. The landscape continues to transform as erosional denudation balances slow uplift of rock material. Interaction between tectonics, climate, and surface processes are linked by channels, and their transmission of signals through the landscape. (Whipple and Tucker, 1999; Zaprowski et al, 2005; Wobus et al, 2010).

In rapidly eroding landscapes, a knickpoint—a steep reach bounded on both sides by relatively shallower reaches—is a physical indicator of transient channel response to climate and tectonic signals. In post-orogenic landscapes, knickpoints may also reflect rock strength or slow, complex response to external forcing. Explanations for the existence of knickpoints are varied, but consensus holds that these features are transitory, migrating in a front from an initial source at the head or foot of the channel (Crosby and Whipple, 2006; Wobus et al, 2010). If the knickpoint is migrating upstream, the topography below will have undergone greater adjustment than the topography upstream of the knickpoint, and vice versa if the knickpoint is migrating downstream (Crosby and Whipple, 2006; Wobus et al, 2010). Studying the location and characteristics of knickpoints can help us understand the dynamics of topographic response to different forcings (Crosby and Whipple, 2006; Wobus et al, 2010).

Most knickpoint research has focused on regions with high uplift rates, weak rock, and rapid landscape evolution. In contrast, the Front Range in Colorado—in the interior of the North American continent—is a region with low uplift and low precipitation, relatively strong rock, and thus comparatively low rates of incision.

Studying streams in the Front Range can provide insight into the behavior of a slowly evolving environment. Profiles of steady-state channels and hillslopes have different concavity. Steady-state channels are concave up, and steady-state hillslopes are concave down in the upper reach and concave up near the channel (Anderson, 2008). These shapes are disturbed by the introduction of a knickpoint to the system, or prevented from occurring by a permanent knickpoint. As knickpoints travel through the river system, the long profile of the river becomes locally convex, with shallow reaches bounding a steep section. Adjacent hillslopes respond to the resulting changes in boundary conditions, often exhibiting greater concavity and roughness as a result of increased incision. Examining these features around knickpoints allows us to characterize the ways a landscape moves back towards equilibrium.

The thrust of this project is to identify knickpoints, characterize the morphology of the channels that include the knickpoints, and describe the nature of the adjacent hillslopes. After this identification, I hope to draw conclusions by contrasting the basin area above the knickpoint with the area below, and comparing the area within the knickpoint with the area that bounds it.

RESEARCH AREA

I conducted my field research in the Middle Boulder Creek watershed (Fig. 1). I focused on Middle Boulder Creek and its tributaries, particularly two small channels: Gordon Gulch and Betasso Gulch.

The Colorado Front Range, which formed and evolved during the Laramide orogeny from 65 to 40 Ma, extends westward from the piedmont at Boulder to the Continental Divide. Initially formed by rapid uplift, since 40 Ma the Front Range has been tectonically inac-

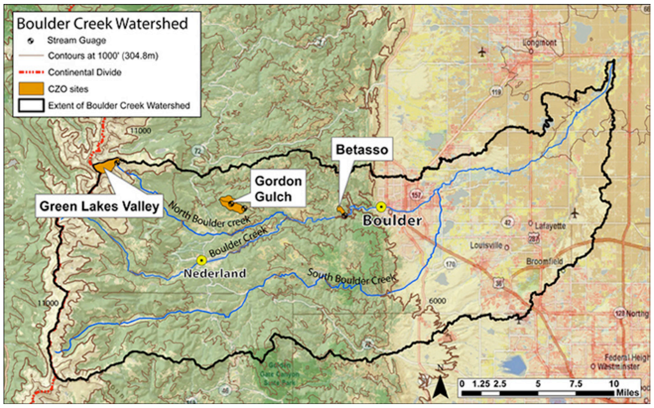

Figure 1. Map showing the Boulder Creek Catchment, outlined in black. Betasso Gulch and Gordon Gulch are shown in orange. Middle Boulder Creek is traced to its headwaters at the Continental Divide, and to its outlet in the South Platte River on the plains.

tive, with isostatic response driving rock uplift in the region (Kellogg et al, 2008). Melt from small glaciers and seasonal snowpack in upland areas runs down numerous tributaries of Middle Boulder Creek and eventually empties onto the Great Plains. The relatively high relief alpine and subalpine zone has been sculpted by glacial and periglacial activity. Below ~2500 m, a rolling upland landscape is deeply incised by narrow canyons that extend up from the piedmont. Due to high evapotranspiration rates during the summer months, many small drainages east of the glacial limit are ephemeral. The vegetated low-relief surface has not been affected by glaciation, and away from the deep canyons, locally thick weathered deposits overlie fresh bedrock (Birkeland et al 2003). Hillslope and channel processes govern landscape evolution in this montane zone, which includes the Gordon Gulch and Betasso Gulch catchments.

Climate in the Front Range is largely dependent on elevation and proximity to the continental divide, which runs North-South roughly 30 km west of Boulder. Annual precipitation is highest near the divide and low on the plains (PRISM Climate Group). The orographic effect is strong in the winter, with significant snow accumulation near the continental divide and lighter precipitation down low. Frequent, low elevation thunderstorms during the summer months mitigate this orographic effect.

METHODS

I surveyed channel longitudinal profiles in the field, while measuring numerous river parameters, hillslope character, and rock strength, and used DEMs based on Lidar (Gordon Gulch and Betasso Gulch) and USGS maps (Boulder Creek) to characterize channels and hillslopes.

At the Gordon Gulch and Betasso catchments, we surveyed the longitudinal profile of the stream, using a tripod-mounted Tru-Pulse 360 Laser Rangefinder. All measurements were parallel to the stream channel. I recorded the vertical distance, horizontal distance, and azimuth for each section of stream. I also measured channel width and estimated bankfull width using a tape measure I estimated d_{50} and dmax grain sizes, and boulder percentage for the reach. Prominent tributaries of the main stream were also surveyed using the same process.

We also conducted a series of cross-valley surveys using the channel as a base and measuring perpendicular to the channel, using a GPS point for location. At each survey point on the hillslope, I recorded bedrock and boulder percentages and noted bedrock lithology, the presence of vegetation, and local slope characteristics. We completed five cross-valley profiles for each main stream, and three for each of the tributaries. As we surveyed we measured rock strength with a Schmidt hammer on outcrops in the channel and at selected outcrops on the hillslopes. A Schmidt hammer measures rock strength by applying a specific amount of force to a rock with a spring loaded piston, then recording the force of the piston as it rebounds

Figure 2. Schmidt hammer measurements being taken on Betasso Gulch hillslopes.

off the outcrop.

The scale of Middle Boulder Creek and North Boulder Creek precluded the comprehensive field surveys that we carried out in Gordon Gulch and Betasso Gulch. The level of detail provided by Digital Elevation Models (DEMs) is sufficient for analysis of these channels. To supplement the digital analysis we surveyed individual, representative reaches distributed along the Boulder Creek channels. Beginning by taking a GPS point in the middle of a reach, we surveyed slope, width, and reach length with the rangefinder. We described each reach and photographed the channel and the surrounding hillslopes. We measured river and valley width with the rangefinder, estimated d_{50} where cobbles could be seen through the water, and estimated dmax by identifying the largest boulder in the reach. We noted the presence of hillslope features such as rock slides and falls, tributary entrances, and cliffs. We also applied the same Schmidt hammer process described above to each section that we recorded, measuring bedrock if it was present at the water level or stationary boulders where bedrock was not exposed in the channel. In sections with cliffs adjacent to the channel, we searched for evidence of sculpting, potholes, or polish on the bedrock, and used the rangefinder to measure the vertical distance above the current channel.

I supplemented my field data with extensive remote sensing analysis. Using 1m-resolution LIDAR data for Gordon Gulch and Betasso Gulch, and 10m resolution DEMs for Middle Boulder Creek, I calculated additional cross-valley profiles and basin slopes. I corroborated my surveyed long profiles with the LIDAR and DEMs, and calculated power relationships with drainage area, downstream distance, and slope. To ease comparison between basins of different magnitudes, I normalized longitudinal profiles and mean basin slope profiles, setting the lowest distance and elevation values equal to zero, and the highest values equal to one.

RESULTS

The project focuses on relationships between knickpoints, mean basin slope, channel slope, and rock strength, so I will focus on data in those areas. Distance from the headwaters is correlated with drain-

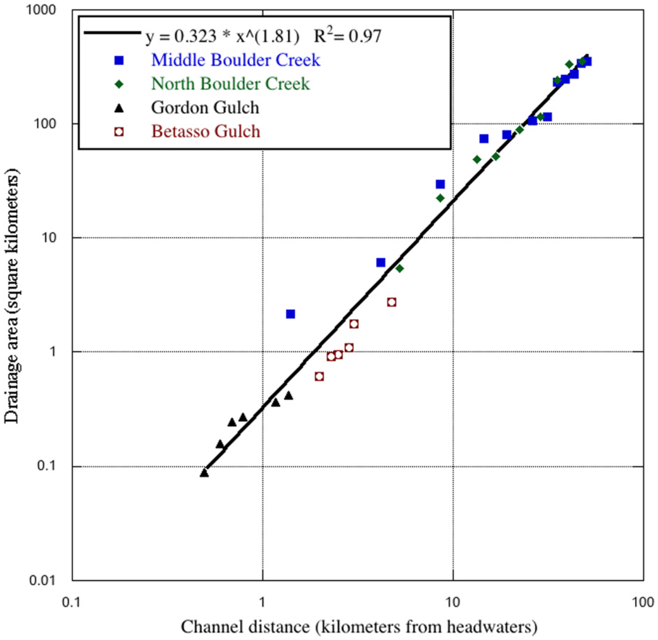

Figure 3. A comparison of four basins, showing remarkable similarity in catchment shape despite a large disparity in magnitude.

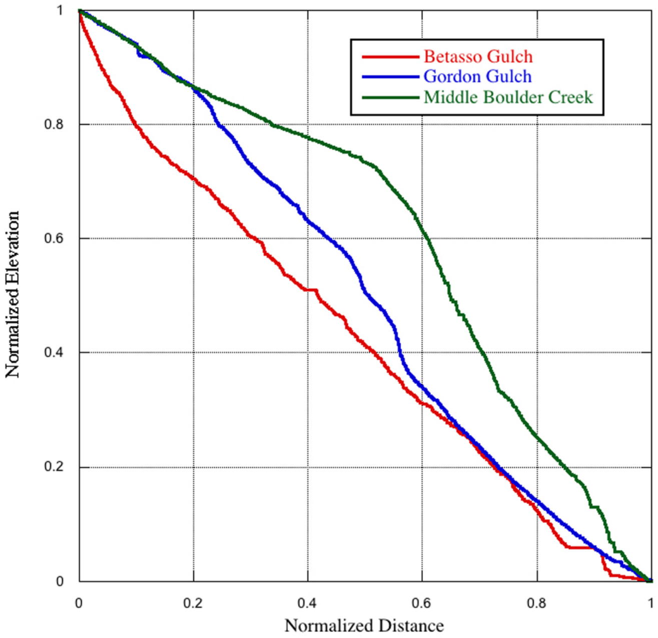

Figure 4. Normalized longitudinal profiles for the channels of Betasso Gulch, Gordon Gulch, and Middle Boulder Creek. The profiles are made by setting the minimum elevation and distance equal to 1 and the maximum elevation and distance equal to 0, then adjusting each intermediate point by dividing its value by the maximum value.

age area in each of the catchments I worked in (Fig. 3).

I found knickpoints in each channel that I surveyed. A graph of normalized longitudinal profiles shows these knickpoints on a standard scale (Fig. 4).

The largest channel, Middle Boulder Creek, contains a prominent knickpoint located on a reach ~30.5-33 kilometers from the headwaters. This knickpoint has an average slope of 0.074, higher than the 0.042 channel average. Basin slopes are steepest at the knickpoint and just downstream (Fig. 5). There is a second minor knickpoint near the top of the reach we surveyed, though slopes in that reach are only locally as high as 0.04.

In Gordon Gulch, two knickpoints—located ~2.5 and 2.8 kilometers from the headwaters and separated by 300 meters of relatively low channel slope— are distinguished by an average slope of 0.153. These slopes are considerably higher than the mean reach slope of 0.108, and more than twice the average slope of the non-knickpoint reaches (0.067) (Fig. 5). Basin slope analysis shows that the average slope on the Gordon Gulch hillsides is higher normal to the knickpoints than other locations on the channel. Schmidt hammer rock strength values are highest on the hillslopes and in the channel at the knickpoints: mean values at the knickpoints are 45-55, as opposed to mean values of 30-40 elsewhere in the basin.

Betasso Gulch contains three small knickpoints (Fig. 5). Each knickpoint in the channel is a short, steep outcrop covered by little or no sediment. Ranging in height from 1.5-3 meters, these bedrock steps have generally higher Schmidt values than bedrock elsewhere in the channel. Hillslope rock strength is highest between the lowest and middle knickpoint. At the two lower knickpoints, Schmidt values range from 40-50, higher than the values of 25-25 elsewhere. At the upper knickpoint, the values are between 25-35, in contrast to values of 0-15 that pervade in the upper zone of Betasso Gulch. This uppermost knickpoint is near the low margin of a saprolite and colluvial zone: these disintegrated materials provide a thick cover for solid bedrock, which rarely crops out at the surface in the upper half of the basin. In this upper section, both

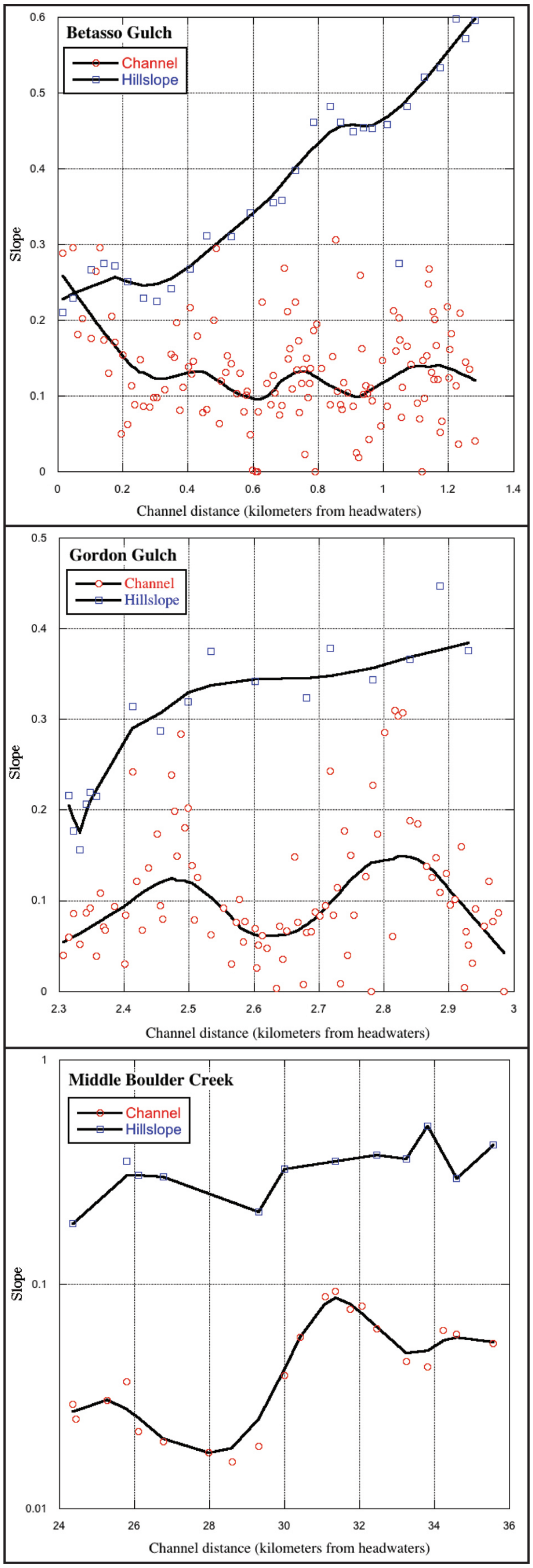

Figure 5. Plots of channel slope and mean basin slope orthogonal to the channel. The x-axis represents the distance in kilometers from the headwaters. Mean basin slopes are calculated by averaging the slopes of hillslope transects. The black line on the channel slopes is a moving average.

channel slopes and hillslopes are shallowest.

DISCUSSION

Though knickpoints take different forms in the three study areas, they mark the boundary between steady-state and adjusting landscapes in all catchments. Above the knickpoint, basin slopes adjust steadily to accommodate slow downcutting, and are shallower and smoother than the hillslopes below. The steeper channel slopes within a knickpoint focus higher stream power and greater incision rates on that reach in the channel. In the catchments in this study, the influence of a knickpoint on a longitudinal profile scales with the size of the basin in which it is located (Fig. 4). Middle Boulder Creek has the most prominent knickpoint: the zone of higher slopes is more than two kilometers long, and is almost twice as steep as the channel average. The knickpoint significantly disrupts the concave-up shape expected for a steady-state channel. Gordon Gulch, with intermediate drainage size, includes two closely spaced knickpoints with a slope disparity comparable to that of Middle Boulder Creek. But these knickpoints are less dominant features: they appear as large lumps within a generally smooth profile. The knickpoints in Betasso Gulch are less remarkable: they appear as small steps in the longitudinal profile but do not affect the concavity of the channel. The bedrock steps that mark knickpoint location are dramatic in the field but are less convincing when plotted (Fig. 4).

Rapid channel lowering in the knickpoint increases adjacent basin slope: as the knickpoint moves up the channel it leaves higher basin slopes in its wake. The rate at which hillslopes adjust to the new boundary conditions depends on the mobility of constituent material and the capacity of the channel to move the material downstream. Stronger rock resists weathering and preserves steeper hillslopes, whereas weak rock and colluvium are susceptible to weathering and mass movements. A stream with high competence can transport weathered debris and allow further weathering to occur, but for streams with low stream power hillslopes only slowly return to a steady state.

The most compelling relationship of hillslope to channel slope is in Middle Boulder Creek (Fig. 5). High rock strength has produced a lag in slope response to the migration of the knickpoint. Steep basin slopes persist below the main knickpoint, despite high stream power during snowmelt and summer thunderstorms. The hillslopes above the knickpoint are smoother and shallower: they are in relative steady state, having adjusted to the passage of a previous, smaller knickpoint through the system.

Hillslopes in Gordon Gulch have responded similarly to the presence of knickpoints. A trend of steepening hillslopes with distance from the headwaters is broken only by the shallow section between knickpoints (Fig. 5). These low slopes can be explained by weak rock—reflected in low Schmidt hammer measurements—that underlies the area between knickpoints. Additionally, the proximity of the lower knickpoint—with its associated higher stream power—may help to efficiently transport material and accelerate the hillslope adjustment to the new baselevel. Steep hillslopes below the lower knickpoint suggest that the landscape there continues to adjust.

Betasso Gulch displays the most dramatic basin slope increase with distance down the channel (Fig. 5). The shallow sloped colluvial and saprolite hillslopes above the knickpoints stand in stark contrast to the steep, outcrop-dominated hillslopes that flank the knickpoints and below. Several factors can account for the steep lower slopes. The relative strength of the rock below the knickpoints may have prevented the lower hillslopes from readjusting. Even if material was available to move, the tiny channel in Betasso Gulch has a low capacity for transport, and hillslope evolution would be slowed by that limiting factor. These characteristics of Betasso Gulch have prevented its basin from adjusting to the passage of several knickpoints.

CONCLUSION

Catchments of dramatically different sizes can be compared effectively: general knickpoint mechanics are similar in each basin we examined. Knickpoints mark the boundary between hillslopes in steady state and hillslopes that are struggling to adjust to new boundary conditions. The disruption of previous steady state is driven by increased incision rates associated with knickpoints. Hillslopes at and below knickpoints become steeper with a rapid baselevel fall. Rock strength, stream power, and continued disruption limit the ability of a hillslope to approach a new steady state after a knickpoint passes. In each study area, we found steep, rough hillslopes downstream from knickpoints, as opposed to comparatively smoother and flatter hillslopes above. We found high rock strength within and below knickpoints, perhaps the result of recent exposure with enhanced denudation following the knickpoint-driven baselevel lowering. The parameters involved in channel and hillslope evolution—channel slope, rock strength, hillslope shape, sediment transport, and weathering—all are inherently linked in these systems to the presence of knickpoints. The catchments in my study area have not fully adjusted to the passage of knickpoints. This lack of response suggests a slowly evolving landscape dominated by strong rock, subdued weathering, and low stream power.

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REFERENCES

Anderson, R. S. (2008), The Little Book of Geomorphology: Exercising the Principle of Conservation.

Anderson, R. S. and Anderson, S. P. (2010), Geomorphology: The Mechanics and Chemistry of Landscapes (Cambridge University Press) textbook, 640 pp., published June 2010.

Birkeland, P.W., Shroba, R.R., Burns, S.F., Price, A.B. and Tonkin, P.J. (2003), Integrating soils and geomorphology in mountains - an example from the Front Range of Colorado, Geomorphology 55, p. 329-344.

Crosby BT, Whipple KX. 2006. Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand. Geomorphology 82: 16–38.

Kellogg, K.S., Shroba, R.R., Bryant, Bruce, and Premo, W.R. (2008), Geologic map of the Denver West 30’ x 60’ quadrangle, north-central Colorado: U.S. Geological Survey Scientific Investigations Map 3000, scale 1:100,000, 48-p. pamphlet.

PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 2011.

Whipple, K. X., and G. E. Tucker (1999), Dynamics of the stream power river incision model: Implications for height limits of mountain ranges, landscape response time scales, and research needs, J. Geophys. Res., 104, 17,661–17,674.

Wobus, C. W., G. E. Tucker, and R. S. Anderson (2010), Does climate change create distinctive patterns of landscape incision?, J. Geophys. Res., 115, F04008, doi:10.1029/2009JF001562.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K. (2001), Trends, rhythms, and aberrations in global climate 65 Ma to present. Science, 292, p. 686-693.

Zaprowski, B. J., et al. (2005), Climatic influences on profile concavity and river incision, J. Geophys. Res., 110, F03004, doi:10.1029/2004JF000138.

Zhang, P., P. Molnar, and W. R. Downs (2001), Increased sedimentation rates and grain sizes 2 – 4 Myr ago due to the influence of climate change on erosion rates, Nature, 410, 891–897.