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Transient Hillslope Response to an Incision Wave Sweeping up a Watershed: A Case Study from the Salmon River

Ryan Wood
San Jose State University

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TRANSIENT HILLSLOPE RESPONSE TO AN INCISION WAVE SWEEPING UP
A WATERSHED: A CASE STUDY FROM THE SALMON RIVER

A Thesis

Presented to

The Faculty of the Department of Geology

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Ryan W. Wood

May 2013

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The Designated Thesis Committee Approves the Thesis Titled

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A WATERSHED: A CASE STUDY FROM THE SALMON RIVER

by

Ryan W. Wood

APPROVED FOR THE DEPARTMENT OF GEOLOGY
SAN JOSÉ STATE UNIVERSITY

May 2013

Dr. Manny Gabet	Department of Geology
Dr. Paula Messina	Department of Geology
Dr. Robert Miller	Department of Geology

ABSTRACT

TRANSIENT HILLSLOPE RESPONSE TO AN INCISION WAVE SWEEPING UP A WATERSHED: A CASE STUDY FROM THE SALMON RIVER

by Ryan W. Wood

Base level lowering often leads to the migration of knickpoints up the fluvial network as the channel profile adjusts to the new lower boundary condition. In steep terrain, the passage of a knickpoint can oversteepen valley walls and trigger a wave of erosion up the hillslopes. As soil is stripped from hillslopes, the previously diffusive hillslopes are transformed to landslide-dominated. Soils in diffusive landscapes are well developed until erosion exposes the underlying saprolite by shortening the soil residence times. During base level adjustments, the erosion of hillslopes can leave relict patches of the original landscape juxtaposed with the newly evolving landscape. Recent incision in central Idaho has produced large channel-to-ridge relief along the Salmon River and has resulted in the propagation of large knickpoints into many of its tributaries. These knickpoints mark the boundaries between pre-uplifted terrain (relict landscapes) and freshly eroded terrain (refreshed landscapes). In this study I aimed to analyze the hillslope response to the passage of a knickpoint by comparing morphological characteristics between relict and refreshed landscapes. A transect situated on both relict and refreshed landscapes was established to measure soil properties and ridgecrest morphology. The spatial analysis used the National Elevation Dataset (NED) and high resolution Light Detection and Ranging (LiDAR) elevation data. Soil

analysis showed 1) higher percentage of gravel in the refreshed landscape, 2) a higher percentage of carbon in the relict landscape, and 3) similar average soil depths in both landscape types (~18 cm). Spatial analysis showed the mean slope angle in the relict landscape is $18 \pm 7^\circ$ and $33 \pm 7^\circ$ in the refreshed landscape. Prospect Ridge has three distinct values of curvature: 0.0033 ± 0.001 (relict), 0.0219 ± 0.008 (refreshed), and 0.0668 ± 0.009 (close to Salmon River). Three sets of increasing relative levels of erosion were therefore inferred from these curvature values. The erosion rate corresponding to the refreshed landscape is responsible for the formation of the large knickpoints within the site. Hillslopes downstream of the large knickpoints are subject to rapid oversteepening and complete landscape transformation from diffusive to landslide-dominated. Conversely, a less dramatic hillslope response was observed upstream of the knickpoint based on evidence of slight channel lowering, partially oversteepened valley walls, and pockets of hillslope steepening in tributary sub-basins. Reconstruction of relict hillslopes and the pre-incisional relict channel suggest that a much smaller, extinct knickpoint preceded the larger knickpoint and rapidly diffused into the headwaters.

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INTRODUCTION

Changes to the landscape can be attributed to many factors including tectonics, climate change, anthropogenic disturbance, or adjustments to the topographic boundary conditions. Such mechanisms span a wide range of processes that often work together to form most geomorphic features. However, the lowering of base level is one process alone that has an extreme effect on the landscape, resulting in dramatic life cycles of mountain ranges (Davis, 1902).

When base level drops, the longitudinal profile of the channel adjusts to the new lower boundary condition as a wave of incision migrates up the fluvial network (e.g., Gardner, 1983; Seidl et al., 1994; Pazzaglia et al., 1998; Bishop et al., 2005). The highest rate of bedrock channel incision along the channel profile marks the crest of the incision wave; the crest is located just below the lip of the steepened reach where stream power is greatest (Garcia et al., 2004). As the main stem of the river incises relative to its tributaries, a pulse of incision can initiate knickpoint migration within tributaries (Seidl and Dietrich, 1993).

Knickpoints ultimately migrate toward catchment divides at a rate proposed to be a function of channel slope and watershed area (a proxy for discharge) or simply a function of watershed area (Seidl and Dietrich, 1993; Bishop et al., 2005; Crosby and Whipple, 2006). Additionally, gradients upstream of the knickpoint are generally steepened, leading to a small zone of incision just above the knickpoint (Berlin and Anderson, 2009).

In mountainous terrain, where hillslopes and channels are tightly coupled, the passage of a knickpoint oversteepens valley walls, thus triggering landslides and propagating a wave of erosion up the hillslopes (Bishop et al., 2005; Bigi et al., 2006; Korup and Schlunegger, 2007; Gallen et al., 2011). During a lag period, the initial hillslope response is often outpaced by knickpoint propagation, and the channel continues to evolve (Mudd and Furbish, 2007; Hilley and Arrowsmith, 2008). Once the hillslope adjustment begins, soil is stripped from hillslopes, and an abundant supply of sediment is suddenly deposited into the channel network (Mudd and Furbish, 2007). During this adjustment period, hillslopes that were previously controlled by diffusive processes become dominated by hillslope failures (Roering et al., 2007).

With an increase in hillslope erosion, soil properties are dramatically affected by a decrease in the soil residence time (soil residence time = soil thickness / erosion rate) (Yoo and Mudd, 2008). Landsliding and erosion remove well-developed soils from the hillslope, exposing unweathered minerals subject to the highest rates of chemical and physical weathering; this leads to an increase in the rate of conversion of bedrock to saprolite (Raymo and Ruddiman, 1992; Heimsath et al., 1997; Riebe et al., 2004; West et al., 2005; Yoo et al., 2007; Graham et al., 2010). Hence, soils of diffusive landscapes are well developed until erosion is capable of rejuvenating the soil by exposing the underlying saprolite.

Although erosion has a significant effect on hillslopes, erosion rates and hillslope gradients become uncorrelated in steep terrain (Roering et al., 2007). At steep slopes, diffusional sediment flux can be modeled as a non-linear function of slope (Roering et al., 1999). However, in a steady state landscape dominated by soil creep, sediment flux on convex hilltops with shallow slopes can be modeled with linear diffusion and correlates to erosion rates (Gilbert, 1909; Culling, 1960; Gabet et al., 2003; Roering et al., 2007). With the assumption that linear diffusion holds true at hilltops due to shallow slope gradients, Hurst et al. (2012) found that ridgecrest curvature correlates with measured erosion rates in a steep, transient landscape.

During some base level adjustments, the landscape transformation is incomplete. Erosion of hillslopes adjacent to the actively incising channel can leave relict patches of the original landscape juxtaposed with the newly evolving landscape (Reinhardt et al., 2007). Additionally, entire regional landscapes of the pre-uplifted terrain may exist upstream of knickpoint incision (Binnie et al., 2007). These transient conditions provide an opportunity to document a landscape in transition and to compare topographic and soil properties.

In central Idaho, recent incision has propagated headward along the Salmon River and into its tributaries (Fig. 1A, B). This has produced nearly two kilometers of channel-to-ridge relief along the Salmon River and has resulted in dozens of knickpoints preserved in the tributary headwaters. These knickpoints

Figure 1. Site location map for Harrington Creek watershed. (A) Map of the Western United States showing the field site located in central Idaho. (B) Shaded relief map of the Salmon River Mountains showing the Salmon River and the extent of the Harrington Creek watershed. Coordinates shown are in UTM Zone 11N.

mark the boundaries between pre-uplifted terrain (herein referred to as relict landscapes) and freshly eroded terrain (herein referred to as refreshed landscapes) (Fig. 2). In this thesis, I aimed to 1) analyze topographic metrics using digital elevation models (DEMs) and 2) analyze soil properties to chronicle the transient hillslope response to knickpoint propagation by documenting the differences in these attributes (*i.e., between the relict and refreshed landscapes*).

METHODS

Study Area

This field area was located along the Main Salmon River in Idaho within the Frank Church River of No Return Wilderness, approximately 40 km SSW of the Bitterroot Mountains (Fig. 1A, B). The Salmon River has cut a 500 m deep gorge characterized by triangular facets. Incision of the Salmon River has triggered knickpoints up its tributaries; analysis of aerial imagery shows apparent knickpoints in more than 25 tributary watersheds within a 600 km² area. In addition, the patches of relict landscape are easily identified because they have a much higher tree density than the refreshed parts of the landscape, which have been denuded of trees by landslides. Indeed, this field site is interesting and unique because the relict and refreshed landscapes can be easily distinguished on the basis of tree cover (Fig. 2). The bedrock of this area has been mapped

Figure 2. Google Earth image of Prospect Ridge. The image shows the mapped boundary between the relict and refreshed landscapes. Note the sharp forest boundary between the two landscape types. The black line shows the location of the soil pit transect along Prospect Ridge.

as a single rock unit within the Idaho batholith (Lewis et al., 2012), which is important for this study because it eliminates differences in lithology as a control on knickpoint location, hillslope morphology, and soil properties. Additionally, there are no faults running through the site: three thrust faults and several steeply dipping normal faults are located 20 to 40 km north and west of the field site (Lund et al., 1992). The field site includes the 53 km² catchment area of Harrington Creek watershed, which has six sub-basins with apparent knickpoints and relict landscapes (Fig. 3A). A transect located on the western boundary of Harrington Creek watershed was selected along Prospect Ridge and will be discussed in later sections (Fig. 3B). Figure 3C shows longitudinal profiles of each of the six tributaries containing knickpoints.

Lithology

Geologic units within Harrington Creek watershed include Cretaceous fine-grained foliated biotite tonalite (orthogneiss) related to the Idaho batholith, and small inclusions of Eocene aged rhyolite and dacite dikes related to the Challis Volcanics (Lewis and Stanford, 2002). This section of the Idaho batholith is located between the Atlanta lobe (dated 83-67 Ma) and the Bitterroot lobe (dated 75-69 Ma), but is unassigned to any specific grouping (Gaschnig et al., 2011). Fission track dating has suggested that exhumation occurred shortly after emplacement of the pluton and that much of the Idaho batholith has been at shallow depths (<1 km) beginning 50 Ma (Sweetkind and Blackwell, 1989).

Figure 3. Site detail map of Harrington Creek watershed. (A) Shaded relief map of Harrington Creek watershed and stream network. The numbers represent tributaries with apparent knickpoints and the black triangles show the approximate location of the knickpoint lip. Coordinates shown are in UTM Zone 11N. The confluence of Harrington Creek and Salmon River is located at a northing of 5037500 m and an easting of 659200 m. (B) Zoomed-in view of transect and soil pit locations along Prospect Ridge located along the western boundary of the watershed. (C) Longitudinal stream profiles with knickpoint locations. Numbers correspond to tributaries identified in Fig. 3A.

Despite a general lack in understanding of the geomorphic history of central Idaho, it is likely that much of the area consisted of a flat upland following exhumation, and the present-day terrain has since been sculpted by incising stream networks (Ross and Forrester, 1958). Further examination of the fission track record in the Idaho batholith shows that the average rates of erosion were 0.03-0.1 mm/y 50-10 Ma, increasing to 0.3 mm/y 10 Ma to present (Sweetkind and Blackwell, 1989; Ferrier et al., 2012). On a shorter timescale, erosion rates ranged from 0.02-0.12 mm/y over the last 1,000 to 10,000 years based on inferred erosion rates from cosmogenic dating (Ferrier et al., 2012). Additionally, dating of terraces along the Middle Fork of the Salmon River shows that recent incision may have reached the Middle Fork between 0.4 and 1.1 Ma (Meyer and Leidecker, 1999).

Soil Sampling Techniques

Soil pits were established along a transect located on Prospect Ridge in the western region of Harrington Creek watershed (Fig. 3B). One of the more prominent ridges in the study area, Prospect Ridge trends approximately 7.5 km southward from the summit of Harrington Mountain (2495 m) to the confluence of Harrington Creek and the Salmon River (830 m). Prospect Ridge was selected because the upper portion is within the densely forested relict landscape, and the lower portion lies within the refreshed landscape (Fig. 2). This is important because morphological differences between the two landscape types can be

identified along a horizontal spatial axis. The transect depicted in this study extended approximately 3.5 km and included eight soil pit locations spaced at even intervals of 500 m (Fig. 3B). The lower five soil pits were within the refreshed landscape and the upper three soil pits were within the relict landscape.

Each soil pit consisted of a 1 m² area that was excavated from the ground surface to the soil-saprolite boundary. The depth to saprolite was recorded along with soil horizon descriptions based on changes in color using the Munsell Color Guide, accumulated secondary minerals, or abrupt changes in grain size. The location of each soil pit was situated on flat terrain positioned away from any large boulders or exposed bedrock – both common features of the ridgeline topography.

Due to the remote nature of the field site and the large quantity of coarse-grained material, all materials greater than 2 mm were processed using a field sieve technique (Reid and Dunne, 1996). Sediments finer than two mm were sieved in the laboratory. Sieve intervals were based on the Udden-Wentworth scale at phi (ϕ) units ranging from from -1 to 4 (2^1 mm to 2^{-4} mm) in the laboratory and -5 to -2 (2^5 mm to 2^2 mm) in the field (Prothero and Schwab, 2004). Materials coarser than 2^1 mm are classified as gravel and materials finer than 2^{-4} mm are classified as fine-grained. The organic carbon content of each soil column was determined with the loss on ignition method. Dry soils were burned at 550 °C for

two hours and the mass lost from each sample was recorded as a percentage (Heiri et al., 2001).

GIS Spatial Analysis

This study includes a Geographic Information System (GIS) spatial analysis. Elevation data were obtained from a Light Detection And Ranging (LiDAR) survey. The horizontal spatial resolution of the LiDAR raster file is 1-m with an elevation accuracy of 5 to 35 cm. The extent of the LiDAR survey includes most of the watershed for Big Squaw Creek, a major tributary sub-basin of Harrington Creek, and it contains two large knickpoints (Fig. 4A). For the rest of the field site not included in the LiDAR survey, 10-m resolution National Elevation Dataset (NED) raster files were downloaded from the United States Geological Survey (USGS) Seamless Server. In addition, 1-m resolution Digital Orthophoto Quarter Quads (DOQQ) aerial images were obtained from the USGS Seamless Server.

The DEM was used to derive stream networks, watershed boundaries, slope maps, longitudinal profiles, and hilltop curvature, whereas the aerial photos were utilized for determining relative tree densities throughout the study area. Knickpoint locations were determined by identifying steepened reaches of tributaries that generally mark the downstream boundaries of flat, relict terrains. A certain degree of interpretation was involved due to the variability of knickpoint morphology. Some knickpoints have vertical to sub-vertical slopes and are

Figure 4. Spatial analysis of Big Squaw Creek using LiDAR data. (A) Bare-earth hillshade showing the extent of LiDAR survey obtained from NCALM program. The surveyed area includes the Big Squaw Creek watershed which is a major tributary of Harrington Creek. (B) Slope map of the extent area identified in Figure 12A. Numbers 1-7 represent valley cross- sections used for the hillslope analysis illustrated in Figure 9.

classified as waterfalls or cataracts, whereas other knickpoints are defined by a more subtle convex-up profile (Fig. 3C). In order to evaluate differences between relict and refreshed landscapes, it was necessary to delineate their boundaries within the study area. Hillslopes of the refreshed landscapes are stripped of vegetation (Fig. 5), which contrasts with the dense forests in the relict landscapes. By using these forest boundaries in combination with knickpoint location, the relict and refreshed landscapes were mapped throughout Harrington Creek watershed. Within these boundaries, differences in slope angle were compared between relict and refreshed landscapes from slope maps generated from the DEM. Additionally, slope was measured along horizontal hillslope lengths with distances of 100 m and 300 m from each soil pit location on Prospect Ridge.

The difference in ridgetop curvature between the refreshed and relict landscapes can be observed both qualitatively (Fig. 6A, B) and quantitatively (Fig. 7). To measure curvature, topographic profiles were generated perpendicular to the trends of ridgelines. The extent of each profile includes the ridgetop summit where slope gradients are less than 0.5, with the assumption that soil creep is the dominant process. Each profile is then fitted with a second order polynomial expression; the second derivative of each expression, therefore, represents a curvature value based on topography (e.g., Hurst et al., 2012) (Fig. 7).

Figure 5. Photo of uprooted tree in the refreshed landscape. Note the freshly exposed saprolite in the root pit and fragments of bedrock located in the root ball.

A

B

Figure 6. Ridgecrests along Prospect Ridge. (A) View of refreshed landscape facing down-ridge toward the Salmon River. (B) View of relict landscape facing down-ridge toward the Salmon River.

Figure 7. Example of regression calculations for deriving ridgetop curvature values. Each point represents the elevation from the corresponding 10 m DEM raster pixel. Elevations were extracted only from the upper portions of the ridgetop where gradients did not exceed 0.5.

A basin-wide curvature analysis was conducted by calculating curvature at 60 locations along ridgecrests within Harrington Creek watershed (Fig. 8). Including the soil pit locations along Prospect Ridge, profiles were selected along the entire length of Prospect Ridge and at other locations along ridgelines selected at random throughout the rest of Harrington Creek watershed. In total, 37 ridgetop profiles are within the mapped refreshed landscape and 23 are within the relict landscape.

Upstream of the knickpoint located along Big Squaw Creek, LiDAR-derived slope maps reveal pockets of steeper slopes and the presence of an inner gorge (Fig. 4B). Although, the steepest slopes are observed downstream of the knickpoint lip, steep slopes are also located along an inner-gorge and in over-deepened tributary basins located in the relict terrain. To further examine the extent of steepening in the upstream region, cross-valley profiles were extracted from the LiDAR elevation dataset, and the upper hillslopes were then extrapolated downward in an attempt to reconstruct the pre-incisional hillslope and channel profiles (Fig. 9). Seven valley profiles were selected between the knickpoint lip and the upstream extent where the inner gorge is not present.

Figure 8. Map of calculated ridgetop curvature locations. Twenty three locations are located in the relict landscape and thirty seven locations are located in the refreshed landscape. The profiles extend from the top of the ridge and follow the path of steepest descent along the hillslope. The mean curvature in the relict landscape is 0.004 ± 0.002 (1σ) and 0.031 ± 0.018 (1σ) in the refreshed landscape. Boundaries were delineated based on observation of aerial imagery. Coordinates shown are in UTM Zone 11N.

Figure 9. Valley cross-sections in upstream knickzone region. The cross-sections were extracted from the LiDAR dataset at the locations identified in Figure 4B. Relict hillslopes were extrapolated downward to reconstruct the pre-incisional hillslope surfaces and channel bottoms. Note the greatest amount of observed incision is at locations 4 and 5. The longitudinal profile of the relict channel surface is displayed in Figure 14.

RESULTS

The data in this section are presented to provide a comparison between properties in the relict and refreshed landscapes. All values were reported as mean values $\pm$ one standard deviation (1σ). Additionally, a two-tailed Welch's T-test was conducted for all analyses at soil pit locations to determine if values between relict and refreshed landscapes varied significantly (Welch, 1947).

Analysis of Ridgecrest Curvature and Hillslopes

Ridgecrest curvature and hillslope angles were computed throughout the entire Harrington Creek watershed. The mean value of measured curvatures along 23 ridgetop profiles in the relict landscape is 0.004 ± 0.002 , and the mean value of measured curvatures along 37 hilltop profiles in the refreshed landscape is 0.031 ± 0.018 . In addition, there is a clear difference in mean slopes between the relict landscape ($18.2 \pm 7.4^\circ$) and refreshed landscape ($32.5 \pm 7.0^\circ$) (Fig. 10). Basin-wide curvature and slope values for Harrington Creek varied statistically with a >95% confidence interval.

Curvature was calculated and analyzed at 32 hilltop locations along Prospect Ridge (Fig. 11). Results showed three regimes of curvature: relict, refreshed, and close to Salmon River. The boundary between each regime is defined by distinct contrasts in curvature that lack intermediate or gradational

Figure 10. Slope map of Harrington Creek watershed. Landscape boundary shows the approximate location of the relict and refreshed landscapes. Coordinates shown are in UTM Zone 11N.

Figure 11. Plot of ridgetop curvature values along Prospect Ridge. Curvature values fall into three distinct categories: relict landscape, refreshed landscape, and close to Salmon River. The dataset includes curvature values at soil pit locations portrayed in Figure 12.

values. The mean curvature for each regime is 0.0033 ± 0.001 (relict), 0.0219 ± 0.008 (refreshed), and 0.0668 ± 0.009 (close to Salmon River).

Additionally, curvature and slope gradients were measured at each soil pit location on Prospect Ridge (Fig. 12A-C). Qualitative examination of the hilltop profiles at each soil pit location shows a clear difference in shape between the relict and refreshed landscapes (Fig. 13). Ridges in the relict landscape are broad-crested, while the ridges in the refreshed landscape are sharp-crested. In the relict landscape, the mean value of curvature is 0.004 ± 0.002 and, in the refreshed landscape, it is 0.022 ± 0.006 . These values varied significantly with a confidence interval of $>95\%$. In the relict landscape, the mean slope gradient 100 m from the ridge is 0.287 ± 0.10 and 300 m from the ridge is 0.369 ± 0.05 . In the refreshed landscape, the mean slope gradient 100 m from the ridge is 0.526 ± 0.03 and 300 m from the ridge is 0.572 ± 0.03 . Both 100 m and 300 m analyses showed significant variations in slope gradient with a confidence interval of $> 95\%$.

In Big Squaw Creek, valley cross-sections were extracted to analyze how incision upstream of the knickpoint has affected the relict landscape (Fig. 4B and 9). Figure 14 shows the profile of the modern channel, the channel profile derived from the hillslope extrapolations, and the hypothesized pre-incision channel profile. The hypothesized relict profile was created to illustrate what the relict channel may have looked like prior to any influence from the knickpoint.

Figure 12. Summary of results along Prospect Ridge. (A-G) Boundary between the relict and refreshed landscape is shown by a vertical dashed line at the forest boundary. Horizontal lines are the mean value for the corresponding soil pits located in the relict and refreshed landscapes. (continued on next page)

Figure 12 (continued) Asterisk (*): *T*-test results vary at > 95% confidence interval. Plus sign (+): *T*-test results vary at > 90% confidence interval. (A) Longitudinal profile along Prospect Ridge showing the soil pit locations. (B) Calculated curvature values at each soil pit. (C) Slope gradient at each soil pit. Gradients were measured from the ridgetop to 100 m and 300 m horizontally to account for longer slope lengths. (D) Depth to saprolite measured at each soil pit. (E) Percent gravel content by weight at each soil pit. (F) Percent finer than 62.5 μm by weight. (G) Percent carbon calculated from loss on ignition procedure.

Figure 13. Topographic profiles of hilltops at soil pit locations. This figure includes all soil pits analyzed along Prospect Ridge. Normalized vertical distance is the difference between the elevation at the ridgetop and the elevation 100 m horizontally.

Figure 14. Longitudinal profile of Big Squaw Creek in knickzone region. The modern profile was plotted from the stream network (Big Squaw Creek) extracted from the LiDAR dataset (Fig. 4A). The data points for the measured relict profile correspond to the extrapolated channel bottoms measured from valley cross sections in Fig. 9. Note the presence of a relict knickpoint along the measured relict profile.

Data points 1-3 appear to reflect hillslopes that have already adjusted, and data points 4-7 appear to reflect the hypothesized pre-incisional conditions. Whereas the predicted profile follows the expected pattern of a well-adjusted channel, the hillslope-derived profile exhibits a small knickpoint approximately 1,000 m upstream of the present day knickpoint. Approaching the headwaters, the effect of upstream incision disappears approximately 1,800 m upstream of the knickpoint.

Soil Analysis

At each soil pit location, depth to saprolite, soil color, and horizon development were recorded (Table 1). Soils within the refreshed landscape had yellowish brown to light yellowish brown colored A horizons overlying pale brown weathered saprolite. The soil at pit S4 lacked an A horizon and consisted of weathered saprolite at the ground surface. Soils in the relict landscapes had dark brown to dark grayish brown A horizons rich in organic litter, overlying a lighter colored B horizon. Below all B horizons was the same pale brown weathered saprolite material observed in the refreshed landscape. The depth to saprolite varied inconsistently along the transect with depths ranging from 0 to 29 cm (Fig. 12D). In the relict landscape, the mean depth to saprolite is 18.3 ± 5.5 cm, and in the refreshed landscape, the mean depth to saprolite is 18.0 ± 10.8 cm. T-test results show that these values do not vary with any statistical confidence.

Table 1. Soil Properties along Prospect Ridge.

Soil Pit Location		Depth to Saprolite (cm)	% Gravel by Weight*	% Fines by Weight†	% Carbon by Weight§	Soil Color (Munsell)#	Horizon Development
Refreshed	S1	29	71.4	0.7	1.5	Yellowish Brown (10YR 5/4)	A only
	S2	18	83.3	0.2	1.6	Light Yellowish Brown (10YR 6/4)	A only
	S3	21	84.6	0.1	2.0	Light Yellowish Brown (10YR 6/4)	A only
	S4	0	66.3	0.3	0.7	Pale Brown (10YR 6/3)	None**
	S5	22	69.7	0.8	1.7	Light Yellowish Brown (10YR 6/4)	A only
Relict	S6	24	40.9	1.3	4.0	Dark Grayish Brown (10YR 4/2)	A and B
	S7	13	31.7	2.4	3.2	Dark Brown (10YR 3/3)	A and B
	S8	18	53.6	6.0	2.2	Brown (10YR 4/3)	A and B

Notes:

* Gravel defined as > 2 mm

† Fines defined as < 62.5 µm

§ Carbon content estimated by loss-on-ignition technique.

Munsell soil colors are for upper-most layer of soil.

** No horizon development at soil pit S4. Saprolite material present at surface.

Particle size curves were established from the sieve results to provide a comparison between the relict soils and refreshed soils (Fig. 15, Table 1). The mean value of percent gravel is $42.1 \pm 11.0\%$ in the relict landscape and $75.0 \pm 8.4\%$ in the refreshed landscape (Fig. 12E). A *T*-test results vary with a confidence interval of $>95\%$. The mean value of percent fine-grain material is $3.22 \pm 2.48\%$ in the relict landscape and $0.43 \pm 0.30\%$ in the refreshed landscape (Fig. 12F). *T*-test results showed that these values did not vary with statistical confidence. Additionally, loss on ignition test results showed a mean value of $3.10 \pm 0.90\%$ carbon in the relict landscape and $1.48 \pm 0.48\%$ carbon in the refreshed landscape (Fig. 12G). These results varied within a 90% confidence interval.

Figure 15. Particle size curves for soils along Prospect Ridge. Relict soils have a higher percentage of fines (< 0.0625 mm) and a lower percentage of gravel (> 2 mm).

DISCUSSION

Comparison of Soil Properties and Curvature to Soil Erosion

Clear differences in ridgecrest curvature are observed along Prospect Ridge that vary over one order of magnitude between the relict and refreshed landscapes (Fig. 11, 12B). The low curvature values of the relict landscape represent broad-crested ridgetops, while the high curvature values of the refreshed landscape represent sharp-crested ridgetops (Fig. 6, 13). Hurst et al. (2012) observed that curvature values of ridgetops, in a similar geomorphic setting as in this study, correlate positively to erosion rates inferred from cosmogenic radionuclide data. In an attempt to apply this concept to Prospect Ridge without the use of cosmogenic dating, soil properties are used as a proxy for determining the relative rate of erosion. Soils in the refreshed landscape are coarser-grained and have accumulated less organic carbon (Fig. 12E-G). These soils also lack the formation of well-developed soil horizons and resemble the underlying saprolite. Higher erosion rates were thus inferred within the refreshed landscape because the overlying topsoil is undergoing less development and the saprolite layer is rejuvenated at a faster rate.

To further explore inferred erosion rates along Prospect Ridge, curvature was analyzed not only across the relict and refreshed boundaries, but down the entire ridge from Harrington Mountain to the Salmon River (Fig. 11). In this case, measurement of curvature is critical for analyzing steep terrain such as this

because curvature values can help gauge rates of erosion that cannot be detected beyond a certain hillslope gradient (Hurst et al., 2012). The results indicate that Prospect Ridge is comprised of three regimes of curvature values that increase closer to the Salmon River. If the wave of erosion responsible for the formation of the refreshed landscape was initiated by a pulse of incision, the highest ridgecrest curvature would be expected near the leading edge. However, I found that the curvature along ridges remains relatively constant within each set of values. I interpret this as three sets of steady-state erosion rates; each set represents a newer, sustained increase in erosion. The oldest set represents the base level condition initially responsible for the relict landscape. Then a newer, prolonged period of erosion led to the formation of the refreshed landscape. Hence, the large knickpoints of the refreshed landscape were ultimately formed from this erosion rate. Finally, the lowest part of the ridge is very sharp, suggesting that a much higher, third erosion rate is influencing the area immediately adjacent to the Salmon River. Differently than expected, there is not a knickpoint associated with this jump in erosion.

Data from the soil profiles show that the average depth to saprolite, or soil thickness, does not differ between relict and refreshed landscapes (Fig. 12D). Although it was expected that higher erosion rates would result in thinner soils, similar soil depths in both landscape types can be attributed to soil thicknesses reaching a maximum value shortly after the exposure of saprolite. For example, the rooting depth of vegetation in both landscape types does not differ and may

act as a primary control on soil depth (Gabet and Mudd, 2010). Since there is no observed change in soil thickness between relict and refreshed landscapes, higher inferred erosion rates in the refreshed landscape indicate that the soil residence times are shorter (Yoo and Mudd, 2008). In contrast, soils in the relict landscape become well developed because of longer soil residence times. One point to consider is that there are significantly more bedrock exposures in the refreshed landscape, such as at the heads of landslide scarps or the bases of uprooted trees, which may affect average soil depths.

Knickpoint and Hillslope Evolution

The recent base level drop along the Salmon River resulted in knickpoint migration along the main trunk stream. Triangular facets, large channel-to-ridge relief, and high curvature values suggest that the trunk stream is rapidly incising. Additionally, if the speed of knickpoint migration is a function of watershed area (e.g., Crosby and Whipple, 2006), knickpoint migration was rapid due to the large drainage area of the Salmon River. As the knickpoint rapidly passed by tributary junctions, oversteepening along the main channel caused secondary knickpoints to migrate headward into the tributaries. These knickpoints are showcased within Harrington Creek watershed and are clearly distinguishable as convex-up stretches of stream seen in longitudinal profile (Fig. 3C). As the knickpoint continues its headward migration, the upstream catchment area shrinks. This may be responsible for slowing knickpoint migration because the erosive

upstream power approaches a small enough threshold that cannot sustain the migration of the knickpoint (Crosby and Whipple, 2006).

While the newly adjusting Harrington Creek experienced an increased incision rate downstream of the large knickpoints, the pre-uplifted channel network was left relatively undisturbed in the upper reaches of the watershed. Downstream of the knickpoints, the lowering channel bed is responsible for oversteepening the toes of adjacent hillslopes, transforming the diffusive hillslopes of the relict landscape into the landslide-dominated hillslopes of the refreshed landscape (e.g., Dietrich et al., 1992; Hilley and Arrowsmith, 2008). Additionally, I find that the entire hillslope is affected from channel to ridge (Fig. 10, 12C).

Although most hillslope steepening is occurring downstream of the knickpoint, slope analysis using high resolution LiDAR has revealed pockets of steeper slopes in the relict landscape (Fig. 4B). These steeper slopes could be associated with channel incision that often occurs just upstream of the knickpoint lip (e.g., Berlin and Anderson, 2009). The steepened areas are found along channel banks upstream of the knickpoint and within over-deepened tributary sub-basins in the Upper Big Squaw Creek. Reconstruction of pre-incisional hillslopes indicates that the greatest over-steepening of valley walls occurs approximately 1,000 m upstream of the large knickpoint lip, and coincides with the location of a relict knickpoint seen in the extrapolated profile (Fig. 9, 14). The location of the relict knickpoint also coincides with the over-deepened tributaries;

the steeper slopes less than 1,000 m from the large knickpoint lip help to confirm that channel incision occurred, possibly by the passage of a smaller, extinct knickpoint.

The analysis of the spatial pattern of hillslope steepening observed in the upstream knickzone provides a unique snapshot of the early stages of landscape adjustment prior to the passage of a large knickpoint (e.g., Mudd and Furbish, 2007). Steepening upstream of the large knickpoint was initiated by a premonitory knickpoint that may have exploited weathered and fractured bedrock of the original landscape. The absence of the relict knickpoint from the modern profile suggests that it quickly diffused into the headwaters of Big Squaw Creek at some threshold distance from the divide: likely located near the farthest extent of the upstream inner-gorge. After the passage of this small knickpoint, the response of adjacent hillslopes has been relatively slow, as indicated by the limited extent of the oversteepened valley walls. Contrastingly, in the landscape refreshed by the main knickpoint, hillslopes are steep and straight along the entire hillslope length, suggesting that the lag time between channel lowering and hillslope adjustment here is very short.

CONCLUSIONS

Analysis of topographic metrics and the physical properties of soils indicate that clear differences exist between the relict and refreshed landscapes. A higher rate of erosion is inferred in the refreshed landscape based on the observation of coarser, poorly developed soils, steeper slopes, and higher ridgecrest curvature values. Additional curvature analysis along Prospect Ridge shows three distinct regimes of curvature values, which implies that there are three sets of steady state erosion rates: each set representing a newer, sustained increase in erosion. The intermediate inferred erosion rate is associated with the refreshed landscape and coincides with the spatial distribution of the large knickpoints within Harrington Creek watershed. The migration of the large knickpoints has undercut rounded, diffusive hillslopes, creating linear hillslopes dominated by landslides. Upstream of the large knickpoints, knickzone leakage has lowered the channel bed leading to locally oversteepened valley walls and pockets of rejuvenated tributary sub-basins. Reconstruction of relict hillslopes and the pre-incision relict channel suggests that a much smaller, extinct knickpoint may have preceded the larger knickpoint and was responsible for the initiation of upstream channel incision.

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