Local topography and erosion rate control regolith thickness along a ridgeline in the Sierra Nevada, California

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ABSTRACT: The ridgelines of mountain ranges are a source of geomorphic information unadulterated by the arrival of sediment from upslope. Studies along ridgecrests, therefore, can help identify and isolate the controls on important regolith properties such as thickness and texture. A 1.5-km section of ridgeline in the Sierra Nevada (CA) with a tenfold decrease in erosion rate (inferred from ridgetop convexity) provided an opportunity to conduct a high-resolution survey of regolith properties and investigate their controls. We found that regolith along the most quickly eroding section of the ridge was the rockiest and had the lowest clay concentrations. Furthermore, a general increase in regolith thickness with a slowing of erosion rate was accompanied by an increase in biomass, changes in vegetation community, broader ridgeline profiles, and an apparent increase in total available moisture. The greatest source of variation in regolith thickness at the 10–100-m scale, however, was the local topography along the

ridgeline, with the deepest regolith in the saddles and the thinnest on the knobs. Because regolith in the saddles had higher surface soil moisture than the knobs, we conclude that the hydrological conditions primarily driven by local topography (i.e., rapid vs. slow drainage and water-storage potential) provide the fundamental controls on regolith thickness through feedbacks incorporating physical weathering by the biota and chemical weathering. Moreover, because the ridgeline saddles are the uppermost extensions of 1st-order valleys, we propose that the fluvial network affects regolith properties in the furthest reaches of the watershed.

Introduction

The thickness of mobile regolith, defined here as material readily transported by biophysical processes (Yoo and Mudd, 2008; Mudd *et al.*, 2012; Anderson *et al.*, 2013) plays a critical role in numerous landscape processes. The regolith is the matrix for terrestrial life and its abundance at a particular location may modulate biological richness. For example, thick regolith is able to support a greater density of trees than thinner regolith because of its higher water-holding capacity (Meyer *et al.*, 2007). The regolith is also a reactor for chemical weathering processes (e.g., White *et al.*, 2002) and the longer average residence times of particles in a thicker mantle will yield an older and more weathered regolith (e.g., Mudd and Yoo, 2010). Furthermore, the thickness of regolith and its degree of weathering, as expressed by clay content, modulates its potential for landsliding in steep terrain (e.g., Selby, 1993). Finally, regolith thickness is thought to be an important factor in controlling the weathering rates of underlying bedrock (e.g., Heimsath *et al.*, 2001; Gabet and Mudd, 2010).

Studies have shown that, at the hillslope-scale, topographic curvature plays an important role in the spatial distribution of regolith thickness and other fundamental regolith properties (e.g., Hugget, 1975; Graham *et al.*, 1990), and this concept has been formalized within predictive numerical models (Pelletier and Rasmussen, 2009; Tesfa *et al.*, 2009). Convergent positions in the landscape, such as colluvial hollows, accumulate material from adjacent slopes which, when added to regolith produced *in situ*, form thick deposits (e.g., Reneau *et al.*, 1990). In contrast, divergent areas, such as hillslope noses, are only supplied with regolith from local weathering processes and, consequently, have a thinner mantle. However, it is difficult to isolate *in situ* controls of regolith thickness on hillslopes because its depth at any point may be determined, in large part, by colluvial inputs from upslope. In addition, whereas average regolith depths across a catchment can be reasonably well predicted by accounting for geomorphic processes at the broader scale (Pelletier and Rasmussen, 2009; Tesfa *et al.*, 2009), it is more difficult to predict the variability around that mean because of the strong effect of local conditions (Phillips *et al.*, 2005; Nicotina *et al.*, 2011; Marshall and Roering, 2014).

Ridgelines are sources of geomorphic information uncorrupted by sediment delivery from upslope such that the properties of the regolith at any one spot are, ideally, exclusively determined by the immediate environment (assuming a minimal amount of dust deposition). Cascade Ridge, in the Feather River watershed in the northern portion of the Sierra Nevada range of California, USA (Figure 1), is a particularly advantageous site because a wave of incision through its bounding channels has created a gradient in erosion rates along the ridge (Hurst *et al.*, 2013), thereby offering an opportunity to evaluate the role of erosion rate, among other factors, in controlling regolith properties. The character of the ridge, likely driven by the erosional gradient, changes rapidly over a short distance (1.5 km), and we were thus able to document changes in regolith properties at a relatively high spatial resolution. This latter point is important because, as Gerrard (1990) has emphasized, high sampling densities are critical where these properties are strongly determined by local conditions. In addition, although the potential role of aeolian inputs at the site cannot yet be dismissed, ongoing geochemical studies in the area (e.g., Yoo *et al.*, 2011) have not found any notable elemental and mineralogical differences between the soil and the bedrock and, therefore, do not support significant aeolian input of geochemically distinct materials.

In addition to thickness, we measured a set of basic regolith properties that are paramount to understanding pedogenic processes: texture, moisture, and organic carbon concentration. The texture of regolith can yield information on its age and weathering intensity (Birkeland, 1990). In addition, because water is a critical ingredient in chemical weathering, consistent spatial variations in regolith moisture should drive spatial differences in weathering depth and intensity (Pennock and de Jong, 1990). Finally, the organic matter in regolith is important for water-holding capacity (Birkeland, 1999) and provides a first-order assessment of the input of carbon from the biota.

Field site

Cascade Ridge separates the Middle Fork Feather River (hereafter referred to as the Feather River) from one of its tributaries, Cascade Creek (Figure 1). The field area is underlain by Mesozoic plutonic rocks, primarily quartz diorite and tonalite (Saucedo and Wagner, 1992). In late Cretaceous-early Cenozoic times, the northern Sierra Nevada was at high altitudes, likely forming the western ramp of a high plateau (e.g., Cassel *et al.*, 2012 and references therein). As a result, deep valleys that traverse the range today, such as the canyons of the South Yuba River and the South Fork of the American River, had already been formed by the Eocene-Oligocene (e.g., Gabet, 2014 and references therein); although the antiquity of the Middle Fork Feather River canyon is not known, it is likely similar in age. Since this early period of uplift, the nothern Sierra Nevada has been tectonically quiescent (Cassel *et al.*, 2012; Gabet, 2014). Moreover, from the Eocene to the Miocene, this section of the range was buried and preserved by vast quantities of fluvial sediment and volcanic rocks. This material has been eroding away to re-expose the early Cenozoic landscape. Indeed, the remnants of these early-to-mid Cenozoic fluvial and volcanic sediment on upland surfaces and deep within valleys indicate that there has been little net topographic evolution of the northern Sierran landscape for much of the Cenozoic (Cassel *et al.*, 2012; Gabet, 2014). This long period of relatively slow erosion into basement rock, however, has been interrupted by recent incision of the Feather River and its tributaries in the vicinity of Cascade Ridge (Hurst *et al.*, 2012). Strath terraces along the trunk stream and the emergence of corestones from a thinning regolith along slopes bounding the Feather River attest to a significant increase in erosion rate. Although the timing of the accelerated incision is unknown, we suspect that it is related to the Ice Ages in the Sierra, a period when glaciers delivered gravels and cobbles to the rivers and coarsened a bedload that was previously too fine to efficiently abrade resistant bedrock (Gabet, 2014).

This recent incision along the Feather River has propagated into Cascade Creek and up the hillslopes bracing Cascade Ridge. The lower end of the ridge, the one closer to the junction between the Feather River and Cascade Creek, is at the crest of the incision wave. Here, the ridge is sharp, narrow, rocky, bounded by steep slopes, and vegetated with chaparral vegetation, such as manzanita (*Arctostaphylos spp*). As the ridge reaches up into the older, low-relief part of the landscape, it becomes mantled with regolith, it becomes progressively broader, and the aboveground biomass increases (Milodowski *et al.*, 2015); concomitantly, the manzanita gives way to California black oak (*Quercus kelloggii*) and canyon live oak (*Quercus chrysolepis*) trees. At the upper end of the ridge, Douglas fir, sugar pine, and ponderosa pine dominate (*Pseudotsuga menziesii*, *Pinus lambertiana*, and *Pinus ponderosa*, respectively). The climate in the area is semi-arid, with 1750 mm of mean annual precipitation, and minimum/maximum monthly temperatures typically ranging from -1/9 °C in the winter to 12/30 °C in the summer (Daly *et al.*, 2008; PRISM, 2014). Soils along the ridge are rocky with an average coarse fraction (>2 mm) of 50% (Soil Survey Staff, 2015). The soils lack B horizons or have minimally developed B horizons which are yellowish, indicating that they are well drained and in an early stage of chemical weathering. A horizon thicknesses are highly variable but can be as thick as ~30 cm when determined solely based on color.

Depending primarily on the presence of B horizons, the soils are classified as either Sandy-skeletal, mixed, mesic Lithic Xerorthents (Waterman Series) or Coarse-loamy, mixed, superactive, mesic Typic Dystroxerepts (Chaix Series) (Soil Survey Staff, 2015).

Methods

Field measurements

The field study was carried out along a 1.5-km long section of Cascade Ridge; the transect begins in the rapidly eroding section of the ridge and, after gaining 200 m in elevation, ends in the slowly eroding section. The transect followed the visually-determined spine of the ridge as closely as possible although, in some instances, dense vegetation and steep rock outcrops forced lateral deviations of several meters. Measurements and soil samples were taken in late spring of 2011 and 2012, several weeks after the last significant rainstorms before the summer drought. Regolith thickness was measured with a tile probe (Mighty Probe^{TM}), a 135-cm shaft of reinforced steel with a T-handle and a sharpened tip. The probe was manually pushed into the regolith until refusal, and the depth of insertion was taken to be the thickness of the regolith. To validate the use of the instrument, measurements from the probe were compared to the boundary between the regolith and the undisturbed bedrock visually identified from four soil pits. Every 20 m along the transect, 10 regolith thickness measurements were taken with the tile probe at evenly spaced intervals within a 1 m^2 grid. If rock impeded the instrument at the regolith surface, we noted whether it was a clast or bedrock; if the former, its intermediate axis was measured. The location of each measurement site was recorded with a GPS. At every other measurement site (i.e., every 40 m), a ~1-kg sample of the regolith surface, taken from the top 5 cm, was collected and stored in a sealed plastic bag. While awaiting analysis, the samples were kept in a refrigerator.

Laboratory analyses

The particle size distribution of the coarse fraction (> 63 µm) of each regolith sample was measured by sieving according to standard techniques (Burt, 2009). The particle size distribution of the fine fraction (≤ 63 µm) was determined with a Micromeretics (Norcross, GA) Sedigraph 5100 particle size analyzer. The regolith moisture content of each sample was determined as the percent difference between the original mass of a 10-15 g subsample and its mass after drying for 24 hours at 110° C (Burt, 2009). The amount of organic carbon in each sample was measured from a dried 5-10 g subsample of material passed through a 1-mm sieve to exclude plant litter. The subsamples were heated for 4 hours at 550° C in a muffle furnace and the loss on ignition (LOI) was determined as the percent difference between the original mass and the post-furnace mass (Burt, 2009).

Topographic analyses

Quantitative descriptions of the ridgeline topography along the transect are important for two reasons. First, knobs (local peaks) and saddles along the ridgeline create local environments important in regolith production. For example, the flow divergence from knobs is greater than from saddles and, thus, saddles should have greater regolith moisture to drive chemical weathering processes. The 1-dimensional (1D) topography along the crest was characterized by manually extracting the ridgeline from a 1-m DEM (digital elevation model) created from LiDAR data (NCALM, 2008). Because there is 200 m of relief along the ridge, the local topography was isolated from the long-wavelength topography by fitting a 2nd order polynomial to the ridgeline elevation and subtracting the fitted elevation values from the actual elevations (Figure 2). To objectively identify saddles and knobs along the undulating topography of the ridgecrest, the 1D topographic curvature at each point along the transect was calculated by fitting a 2nd order polynomial over successive sections of the ridge, delineated by a sliding window advanced in 10-m increments, and taking its 2nd derivative (Figure 3). The window size, 320 m, was based on the average topographic wavelength along the ridgeline (i.e., the average distance between the main saddles) (Figure 3B).

The ridgeline topography was also used to estimate erosion rates. In the same area as the present study, Hurst et al. (2012) used ^{10}Be ages (n=21) to derive a significant relationship between the 2-dimensional (2D) curvature of ridgetops and their erosion rates. Following this approach, a 6-term polynomial function describing a 2D surface was used to fit the digital topography within a 12-m x 12-m sliding window. This window size corresponds to the scaling break that separates hillslope rugosity from broader hillslope morphology (Roering *et al.*, 2010; Hurst *et al.*, 2012). The 2D curvature at the midpoint of each window's position was determined as the 2nd derivative of the polynomial function. The erosion rate (E; m/y) was calculated from the 2D ridgeline curvature (C_{2D}; 1/m) with

$$E = -\frac{\rho_s}{\rho_r} D C_{2D} \qquad (1)$$

where ρ_s is the bulk density of the regolith (1300 kg/m^3), ρ_r is the density of rock (2600 kg/m^3), and D (0.0086 m^2/y) is the diffusion coefficient for soil creep processes (Hurst *et al.*, 2012).

Results

Erosion rates

The erosion rates calculated from the 2D ridgeline curvature (and converted to units of mm/y) range from 0.7 mm/y to 0.002 mm/y (Figure 4). The topography along the crest, however, has an important influence on the erosion rates calculated from the curvature. Because the 2D curvature of local peaks is relatively high, the knobs appear to be eroding more quickly than the saddles, thus obscuring the general trend in erosion rate along the ridgeline (Figure 4). To damp this topographic effect and capture large-scale differences in erosion rate, the calculated erosion rates were averaged over a 320-m sliding window (Figure 5); as before, the window size is the average topographic wavelength along the ridgeline. The smoothed erosion rate reveals three distinct erosional regimes along the transect: the end nearest the tributary junction is eroding at ~0.52 mm/y, the middle section at ~0.22 mm/y, and the end furthest from baselevel changes at ~0.06 mm/y. The rate calculated for the fastest-eroding section, however, comes with an important caveat. Equation 1 assumes that the ridgeline has a cover of mobile material diffused by creep processes; this end of the ridge, however, is rocky and lacks a continuous regolith mantle. Moreover, 0.52 mm/y exceeds the range of cosmogenically determined erosion rates used to calibrate Equation (1). For these reasons, we cannot be certain that it is eroding at ~0.52 mm/y, only that it is eroding more quickly than the rest of the ridge.

Regolith and Surface Properties

Rockiness

From the tile probe measurements, the *rockiness* (%) was calculated as the frequency that the probe hit a large clast or bedrock at the surface within each 1-m^2 grid (note, this is a different metric than the rock fragment estimates commonly given in soil descriptions). A plot of the rockiness along the transect reveals two trends (Figure 6); first, the lower portion of the transect where the landscape is eroding quickly is substantially rockier than the rest of the ridgeline. Second, the rockiest portions of the ridgeline are generally along the knobs and steep side-slopes. Where clasts were present at the surface, their diameters ranged from 10 to 50 cm but there was no trend in clast size along the ridge.

Regolith texture

The regolith texture classes of the surface samples along the ridge ranged from sand to sandy loam but there was no clear spatial trend in this property. The clay-sized particles (< 3.9 µm) changed significantly (t-test; $p < 0.001$) from one end of the transect to the other. In the rapidly eroding section of the ridgeline (0 – 200 m), the clay concentration averaged 0.6 ± 0.5% (by weight relative to the bulk soil mass), whereas, along the rest of the transect, it averaged 2.2 ± 0.7%. Although the highest clay concentration was found in a saddle and the lowest on a knob, this soil surface property did not vary systematically with local topography. The coarse fraction concentration (> 2 mm) averaged 23 ± 12 % along the transect but did not appear to vary with either erosion rate or local topography. Recall, however, that we only sampled the soil surface along the ridgeline; in a more detailed study of particle sizes in this field area, Attal et al. (2014) found that hillslope soils coarsened with an increase in slope angle and erosion rate.

Regolith moisture

Although the regolith samples were taken from only the top 5 cm of the surface, their moisture content nevertheless showed a strong association with topographic position. Expressing the moisture of the surface samples as '%-dryness' (i.e., 100 - % moisture content) illustrates clearly the spatial correlation between the water content of the regolith and the local topography (Figure 7). The driest regolith was found on the knobs and the wettest was in the saddles.

Loss on ignition

The LOI of the <1 mm size fraction of the surface samples ranged from 5 – 25 % but did not change systematically along the ridgeline and, thus, did not appear to be influenced by erosion rate. Similarly, there was no clear effect of topography on LOI. The absence of any relationships between LOI and topography or erosion rate may be due to short-term sediment transport events (e.g., faunalturbation) that introduce noise into underlying, long-term spatial trends. It is again important to note that the samples were taken from the surface of the regolith and likely do not reflect the total organic carbon in the regolith.

Regolith thickness

The penetration of the tile probe rarely came to a stop at a hard boundary, which would suggest the presence of a buried clast. Instead, the advance of the probe's tip was typically hindered by a transition to a gritty layer. At 4 sites along the ridge, the gritty refusal depth matched within 10 cm the regolith boundary visually identified from soil pits. Of the 750 thickness measurements, 72 were indeterminate because the regolith was deeper than the length of the tile probe (135 cm); the majority of these (78%) were in the slowly eroding portion of the ridge beyond the 1250-m mark. For the ensuing analyses, a value of 135 cm was assigned to these undetermined depths, thereby underestimating the true thicknesses.

The thicknesses reported here are the averages of the 10 measurements made within a 1-m^2 grid at each site. The average thicknesses were smoothed with a 100-m moving window to damp local variability (e.g., due to individual trees) and to resolve spatial trends more clearly at a scales relevant to the ridgeline geomorphic units (i.e., knobs, saddles, and side-slopes) (Figure 8A). Much of the variation in regolith thickness appears to be related to the local topography (Figure 8B). The deepest regolith is found in the saddles and the thinnest is on the knobs. However, partially obscured by the topographic influence, the role of erosion rate can be detected as the regolith thickens toward the more slowly eroding portions of the ridgecrest. A comparison of the calculated erosion rate and regolith thickness suggests a linear relationship (albeit weak) between the two (Figure 9). The data also reveal that the range of regolith thickness increases with decreasing erosion rate; throughout the gradient in erosion rate, the minimum regolith thickness remains constant at ~10 cm while the maximum increases.

These analyses suggest that local topography and erosion rate exert the dominant controls on regolith thickness along Cascade Ridge. With the topography represented by the 1D ridgeline curvature (C_{1D}; m^{-1}), this hypothesis was tested with multiple regression analysis. Several equations of the form $H = f(C_{1D}, E)$ were explored, where H is regolith thickness (cm) and E is erosion rate (mm/y), including one in which an exponential form of E was assumed (i.e., $H = f(C_{1D}, e^{-aH})$ where a is a constant). The equation that yielded the best fit was a linear expression ($R^2 = 0.80$):

$$H(cm) = 10458C_{1D} - 155E + 81 \qquad (2)$$

where the erosion rate (mm/y) was determined with the 2D curvature (Equation 1) and smoothed over a 320-m sliding window (Figure 5). Recall that the regolith thickness at some sample sites in the slowly eroding portion of the transect was undetermined (i.e., deeper than 135 cm) and, thus, Eqn. (2) only represents a minimum regolith thickness at erosion rates < 0.1 mm/y.

It is important to note that, although the erosion rate was determined from the 2D curvature, this topographic metric is uncorrelated with the 1D curvature and, therefore, the predictor variables in Eqn. (2) are independent of each other (Figure 10). A comparison of the modeled and actual thicknesses smoothed with a 100-m sliding window indicates that the regression equation captures much of the variation in this property at the 100-m scale although, in the mid-range of thicknesses, there are errors as high as 25 cm (Figure 11). A regression of the predicted thicknesses against the raw (i.e., unsmoothed) thicknesses returned an R^2 of only 0.28, demonstrating that, at the meter-scale, variations in regolith depth are controlled by micro-site factors, such as the location of individual trees (e.g., Phillips and Marion, 2005; Phillips *et al.*, 2005; Roering *et al.*, 2010). In addition, the non-random distribution of regression residuals indicates that the topographic influence on regolith thickness is not fully captured by the 1D ridgeline curvature (Figure 12): regolith depths are consistently under-predicted on the knobs and over-predicted in the saddles. Different widths of the 1D curvature window were tried (from 6 – 400 m) but none resulted in better predictions. Finally, we emphasize that Equation (2) has not been tested elsewhere and may only be applicable at Cascade Ridge within the range of erosion rates determined along the transect.

Discussion

Regolith properties and ridgeline topography

To those familiar with mountainous terrain, it may not be surprising that the knobs along Cascade Ridge are rocky with thin regolith whereas the saddles have a thicker mantle. Although it could be argued that the saddles host a deeper regolith because of the accumulation of material from the bounding side-slopes, this does not appear to be the case. The accumulation area (as determined with the ARCGIS D8 algorithm) for 61% of the sample sites along the spine of the ridge was either 0 or 1 m^2; four drainage area values in the slowly eroding portion of the ridge, however, exceeded 30 m^2. Importantly, a linear regression of regolith thickness against accumulation area returns an R^2 of 0.20 and, if the four values mentioned above are excluded, the R^2 falls to 0.07. Thus, the assumption that regolith properties, including thickness, is dependent on *in situ* conditions appears reasonable.

Of these conditions, the residence time of subsurface moisture may be the most important in setting the spatial distribution of regolith thickness (Graham *et al.*, 1990). Because of lower flow divergence and more topographic shading, the saddles retain moisture for longer periods of time (Figure 7), thus driving higher rates of chemical weathering compared to the knobs (e.g., Gabet *et al.*, 2006; Maher, 2010). A more chemically weathered bedrock will be more hospitable to vegetation because it is weaker, thereby allowing easier penetration by plant roots, and will have more pore space to store water (Graham *et al.*, 2010). The plants, in turn, will accelerate physical weathering of the bedrock (e.g., Phillips and Marion, 2005; Gabet and Mudd, 2010). The additional moisture in the saddles, therefore, initiates a positive feedback loop between deepening regolith and vegetation. The role of lithology at Cascade Ridge may be particularly important because of the bimodal weathering behavior of plutonic rocks. Unweathered plutonic rock is strong and resistant to physical weathering; however, under a mantle of moist regolith, it becomes friable and weak because small fractures allow fluid flow that leads to shattering by biotite hydration (Wahrhaftig, 1965; Bazilevskaya *et al.*, 2013). The positive feedback between regolith weathering and vegetation growth, as well as the bimodal weathering of plutonic rocks, may explain the increasing range in regolith thickness as erosion rate slows (Figure 9). Indeed, as erosion rate decreases along the ridge, topographic variations appear to play an increasingly important role in the magnitude and spatial distribution of regolith thickness. Even subtle changes in topography may lead to significant differences in regolith properties; for example, spatial variations in erosion rate inferred from pedogenic hematite (Sweeney *et al.*, 2012) may, instead, be due to differences in local hydrological conditions (J. Roering, pers. comm.).

The role of topographic stresses in creating bedrock fractures (Miller and Dunne, 1996) may also contribute to the divergent evolutionary paths taken by the knobs and saddles. The knobs in the more quickly eroding sections of the ridge were often composed of large blocks separated by relatively wide (5 – 10 mm) fractures. Fractures of this size, combined with the impermeable bedrock surface, would help to rapidly drain precipitation from the knobs and create relatively dry conditions. The bedrock in the saddles was covered by regolith and, thus, we cannot offer a comparison; however, it is reasonable to postulate that bedrock underlying knobs and saddles would be affected by different topographic stresses (Slim *et al.*, 2015).

Considering the potentially different physical and chemical weathering regimes between knobs and saddles, we propose that the rate of regolith production along the ridgeline is not solely dependent on regolith thickness (e.g., Heimsath *et al.*, 2001) but also on topographic position. The magnitude of the soil production function, typically represented as a plot of regolith production rate vs. regolith thickness, may vary along the ridgeline such that, for the same thickness of regolith, the production rate is greater in the saddles than on the knobs (Figure 13). A soil production function sensitive to topography implies that knobs and saddles could be eroding at the same rate, despite different regolith thicknesses.

Regolith properties and erosion rate

The topographic control on regolith thickness is imprinted over the general trend between thickness and erosion rate (Figure 9). Along the proximal section of the ridge, the erosion rate is too high to allow for the accumulation of a continuous mantle of regolith. In addition, the rate of regolith production is likely depressed by the sparseness of the vegetation (Figure 14) and the inability of the fractured bedrock surface to retain water. Consequently, the regolith there is thin, rocky, and limited to isolated patches. Moreover, the lower clay concentrations relative to the rest of the ridge attest to short residence times of weathered particles. As erosion rates slow beyond the 200-m mark on the ridgeline, the minimum regolith thickness remains approximately constant but the maximum regolith increases, leading to a greater average thickness.

Just as feedbacks between regolith development, regolith moisture, and vegetation appear to modulate the local topographic control on regolith thickness, similar relationships may also be important with respect to erosion rate. Hiking along the Cascade Ridge transect in June 2012, we passed through a striking range of sensible humidity in only 1.5 km: the ambient air at the faster-eroding end was quite dry while the air at the slowly-eroding end felt substantially more humid. This steep gradient in available moisture is reflected in the vegetation. The dry end is dominated by vegetation adapted to arid conditions, such as manzanita (*Arctostaphylos*), while the wetter end is vegetated by plants requiring more water, including patches of California corn lily (*Veratrum californicum*), which is usually associated with meadows. In addition to a difference in vegetation community along the transect, there is also a gradient in aboveground biomass, with the slowly eroding section supporting about four times more vegetation than the fastest eroding end (Figure 14); this pattern is consistent with other observations across the region (Milodowski *et al.*, 2015). Given the short distance (~1.5 km) and the 200 m change in elevation between the two ends of the transect, an orographic effect on precipitation is likely not the source for the marked difference in hydrological conditions along the ridge. We propose, instead, that the local hydrological environment is ultimately controlled by the erosion rate and its effect on the ridgeline's topography. Along the quickly eroding section, rapid drainage is encouraged by the sharpness and narrowness of the ridge. Furthermore, the regolith is thin or absent and precipitation runs quickly off the bedrock surfaces via widely spaced fractures. Bedrock fractures at this location, therefore, may inhibit weathering by reducing the regolith-water contact time (Twidale and Bourne, 1993; Gabet *et al.*, 2006) and slow the rate of regolith production; this hypothesis contrasts with observations made elsewhere (Phillips *et al.*, 2008; Marshall and Roering, 2014). The discrepancy may be due to different topographic and climatic settings: one site was flat (Phillips *et al.*, 2008) and the other was in a humid climate (Marshall and Roering, 2014). In both of these cases, the near-surface environment can remain moist for long periods of time. However, the steep slopes, thin regolith, and fractured rock along the rapidly eroding section of Cascade Ridge dictate that, regardless of the absolute volume of precipitation, the amount of moisture that can be stored is low and this is reflected in the drought-tolerant vegetation and the relatively low biomass (Figure 14). Further up the transect to the east, the slower erosion rates have formed a broader ridge mantled with thicker regolith. Here, water infiltrates into the subsurface and gentle slopes prevent it from draining quickly from the ridge. The higher regolith moisture favors chemical weathering that creates porosity (Graham *et al.*, 2010) and weakens the bedrock to render it more hospitable to biotic penetration. In addition, the higher regolith moisture combined with the more weathered bedrock can support greater biomass which, in turn, deepens the regolith even further through bioturbation. Positive feedbacks between topography, hydrology, and vegetation can amplify small differences in the water balance to yield large differences in regolith thickness (Goodfellow *et al.*, 2013).

Long-term evolution of Cascade Ridge

An interesting question is whether the corrugated topography of the ridgeline can be maintained over long time-scales. Paradoxically, some evidence might suggest that the knobs are eroding more quickly than the saddles. The peaks in local erosion rate, calculated from the 2D curvature, generally correspond to the high points in the local topography (Figure 4) – a geomorphologically reasonable conclusion since sediment is transported from knobs over a wider range of directions than the saddles, which are bounded on two sides by higher side-slopes. But if the knobs are eroding more quickly, why are they there?

One possible explanation is that the difference in erosion rate between the knobs and saddles is illusory. Recall that, according to Equation 1, the local erosion rate was calculated as the product of the local 2D curvature and a diffusion coefficient assumed to be constant along the entire length of the ridge. However, the diffusivity in the saddles may be higher than on the knobs because of greater regolith thickness (e.g., Furbish, 2003; Pelletier *et al.*, 2011) and because greater moisture may stimulate greater biotic activity which could drive faster rates of sediment transport (McGuire *et al.*, 2014). In addition, the long-term average diffusivity may be effectively lower on the knobs due to occasional supply-limited conditions. If, indeed, the diffusion coefficient oscillates along the ridgeline, the saddles could be eroding as quickly as the knobs, and the knob-and-saddle topography may be a steady-state condition. In addition, as noted earlier, differences in regolith thickness between the knobs and saddles do not necessarily imply that they are eroding at different rates if regolith production is sensitive to topography.

Ultimately, the topographic wavelength of the ridge may be set by the spacing of the tips of the channel network. Saddles along Cascade Ridge are typically the uppermost extent of colluvial hollows hosting the heads of 1st order channels. Similarly, the knobs are the terminal ends of spur ridges coming up from the valley bottoms

(Figure 15). Therefore, the ridgeline topography and its associated properties, such as the spatial distribution of regolith, may be dictated by the reach of the fluvial network. Because drainage density increases with erosion rate at this site (Hurst *et al.*, 2013), the topographic wavelength along the ridgeline eventually may lengthen when the pulse of incision has passed through the landscape and the channel network is pruned.

Conclusion

We exploited a 10-fold increase in erosion rate along a ridgeline in the Sierra Nevada to explore the controls on regolith properties. We found that regolith thickness generally decreases with erosion rate but that ridgeline topography (i.e., knobs and saddles) plays a dominant role in controlling the variation in thickness. Indeed, the local topography is so important that the subtle influence of erosion rate might not have been recognized without the high-resolution sampling strategy that we adopted. The thicker regolith in the saddles, attributed to longer water-residence times and a positive feedback between water-holding potential and weathering, suggests that process-based soil production functions should incorporate the role of subsurface hydrology. Finally, because the saddles are the uppermost extent of 1st-order valleys, we propose that the variation in regolith thickness along Cascade Ridge may ultimately be controlled by the tips of the fluvial network.

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Figure captions

Figure 1. Site map. (Inset) Map of California with star indicating field site. (Main) Hillshade of Cascade Ridge with transect delineated by the black line. The Middle Fork of the Feather River is to the north of the ridge and Cascade Creek is to the south. The Feather River, truncated by the left boundary of the image, flows from NE to SW and forms a tributary junction with Cascade Creek (shown with the white star) and serves as its baselevel. The 'A' and 'B' indicate the ends of the transect and are referred to in later figures.

Figure 2. Second-order polynomial fit to ridgeline elevations along study reach. Ridgeline elevations were subtracted from the polynomial to isolate the local topography. 'A' and 'B' refer to transect ends shown in Figure 1.

Figure 3. (A) Example of a ridgeline section fitted with a 2^{nd}-order polynomial over a 320-m sliding window. The topographic curvature at the midpoint of this section, designated with the diamond, is the 2^{nd} derivative of the polynomial function, -0.0014. (B) 1D curvature along ridgeline derived from 2^{nd}-order polynomial. Local topography shown here to emphasize correspondence between curvature values and topography. High positive curvatures are at the saddles and low negative curvatures are at the knobs.

Figure 4. Erosion rate calculated from 2D curvature compared to the local ridgeline topography. The erosion rate calculation appears to be influenced by the local topography whereby the knobs have higher erosion rates than the saddles.

Figure 5. Erosion rate calculated from 2D ridgeline curvature averaged over a 320-m window to reduce the effects of the local topography. There appear to be 3 different erosional regimes along the transect: ~0.52 mm/y along the proximal portion, ~0.22 mm/y in the middle, and ~0.06 mm/y along the distal section. The transition between each section is not sharp, likely a consequence of a gradual geomorphic adjustment to the advance of the incision wave(s).

Figure 6. Comparison of surface material and local topography. The rapidly eroding end of the transect (0 – 200 m) has a substantially greater amount of large clasts and bedrock at the surface than the slowly eroding portions. Knobs and steep sideslopes tend to be more rocky although the relationship between rockiness and topography is not strong.

Figure 7. Soil dryness (i.e., 100 - % moisture) and local topography along the ridge. The driest regolith is associated with knobs and southwest-facing sideslopes. Wettest regoliths in the saddles. Dashed line fit by eye to emphasize trends in regolith moisture. Regolith moisture represented by 'dryness' to facilitate comparison with the local topography.

Figure 8. (A) Regolith thickness along the transect. A 5-pt moving average of thickness reveals a sinusoidal pattern along the ridge. (B) Regolith thickness (moving average) and local topography are nearly mirror images of each other. The regolith is thickest in the saddles and thinnest on the knobs. Note the general increase in regolith thickness towards the distal end of the transect where the erosion rates are lower.

Figure 9. Regolith thickness vs. calculated erosion rate. The erosion rate used here is the smoothed rate shown in Figure 5. Because regolith thickness exceeded the reach of the probe in the slowly eroding portion of the ridge, the data points in the upper left of the plot under-represent the true thickness and, as a result, the slope of the regression should be steeper. Although the data might also be fit with a negative logarithmic function (i.e., the steady-state solution to an exponential soil production function), granite weathering is best described by a humped soil production function (SPF) (Wahrhaftig, 1965). Furthermore, invoking a single SPF for all topographic positions along the ridgeline is likely not appropriate. Given these complications, a linear fit to the data is the most conservative approach.

Figure 10. Plot of 2D curvature and erosion rate vs. 1D ridgeline curvature. Although the erosion rate was calculated from the 2D curvature, it is uncorrelated with the 1D curvature. The spatial autocorrelation in the raw data is due to the sliding-window technique of calculating the 1D curvature. The ‘smoothed erosion rate’ was determined

by averaging over a 320-m sliding window to damp the effects of local topography on the calculation of erosion rate (see Figure 5). The three erosional regimes create the three plateaus seen in the line plot.

Figure 11. Regolith thickness modeled from the 1D ridgeline curvature and the calculated erosion rate. Measured regolith thickness values were smoothed with a 5-pt moving window to damp meter-scale variations not captured in our study. The similarity between the modeled and actual regolith thicknesses suggest that 1D curvature and erosion rate are the primary factors in controlling regolith thickness along Cascade Ridge at the 10^2-m scale. The constant in the regression indicates that regolith thickness is consistently underpredicted, albeit by a small amount.

Figure 12. Residuals from the regolith thickness regression equation compared to the local topography. The non-random distribution of the residuals indicates that the 1D ridgeline curvature is not fully capturing the effects of the local topography.

Figure 13. Different soil production functions depending on topographic position. Although knobs and saddles may be eroding at the same rate, they may host different steady-state regolith thicknesses because of different local conditions (indicated by stars). For example, saddles may have higher rates of regolith production for a given regolith thickness because they remain wetter for longer periods of time.

Figure 14. Aboveground biomass and local topography along the ridge. Biomass increases nearly 4-fold from the rapidly eroding portion of the ridge to the slowly eroding portion. Biomass determined with mean canopy heights derived from LiDAR data (Milodowski *et al.*, 2014).

Figure 15: Knobs (stars) and basins along Cascade Ridge. The knobs along Cascade Ridge are often the uppermost extent of spur ridges bounding the basins that drain from the ridge to the valley bottom (shaded).