

Aspect-dependent variations in regolith creep revealed by meteoric ^{10}Be

Nicole West¹, Eric Kirby², Paul Bierman³, and Brian A. Clarke¹

¹Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802, USA

²College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331, USA

³Department of Geology, and Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, Vermont 05405, USA

ABSTRACT

Although variations in insolation and emergent feedbacks among soil moisture, vegetation, and soil cohesion are commonly invoked to explain topographic asymmetry that depends on aspect, few studies have directly quantified the efficiency of regolith transport along hillslopes of opposing aspect. We utilize meteoric ^{10}Be concentrations in regolith ($n = 74$) to determine mass flux along equatorial-facing and polar-facing hillslopes in three forested upland watersheds in and adjacent to the Susquehanna Shale Hills Critical Zone Observatory in central Pennsylvania (USA). In combination with regolith depth measurements and high-resolution topography, these fluxes allow us to evaluate transport rate laws and the efficiency of regolith creep. Concentrations of meteoric ^{10}Be in regolith along six separate transects imply that regolith flux is similar along all hillslopes, despite differences in topographic gradient and regolith thickness. Comparison of flux with regolith depth and topographic gradient reveals that transport depends on regolith depth, and that regolith creep is twice as efficient along low-gradient, south-facing slopes with thin regolith as compared to steep, north-facing slopes mantled with thicker regolith. We suggest that the observed topographic asymmetry in these watersheds has evolved over geologic time as a result of differences in the frequency of freeze-thaw events between hillslopes of opposing aspect.

INTRODUCTION

Topographic asymmetry that depends on the facing direction, or aspect, of hillslopes is a common yet enigmatic characteristic of natural landscapes (e.g., Melton, 1960; Hack and Goodlett, 1960). Global analyses of topographic asymmetry suggest that equatorial-facing hillslopes are, on average, shallower than polar-facing hillslopes at mid-latitudes (Poulos et al., 2012), although deviations exist in some arid and glacial landscapes (e.g., Gilbert, 1904; Naylor and Gabet, 2007; Burnett et al., 2008). Aspect-dependent differences in hillslope angles present a challenge to models that consider transport efficiency to be uniform across landscapes (e.g., Perron et al., 2009) as they implicate potentially important feedbacks between microclimate and topography. In arid and semiarid landscapes, differences in insolation are thought to lead to variations in soil moisture, vegetation, runoff processes, and effective soil cohesion (e.g., Istanbuloglu et al., 2008) that in turn influence the efficacy of regolith creep (e.g., Pierce and Colman, 1986). Recent studies suggest that asymmetry may also evolve in alpine landscapes as a consequence of thermally driven differences in frost shattering and creep efficiency (Anderson et al., 2013). However, no studies have directly measured mass transport rates or efficiency across asymmetric watersheds and, thus, our understanding of these phenomena remains largely inferential.

Hillslope gradients reflect the dynamic balance between relative base level fall and

downslope regolith flux (e.g., Culling, 1963; Kirkby, 1971). We define regolith as the layer of chemically and physically altered material formed from weathered, but intact, parent bedrock. The simplest description of downslope regolith flux asserts that transport is linearly proportional to the local hillslope gradient, which in one dimension is

$$q = K_1 \frac{dz}{dx}, \quad (1)$$

where q is the volumetric regolith flux per unit width along slope ($\text{cm}^2 \text{ yr}^{-1}$), K_1 is analogous to a diffusion coefficient ($\text{cm}^2 \text{ yr}^{-1}$) describing the transport efficiency of creep processes, and dz/dx is the local hillslope gradient. Equation 1 successfully describes much of the first-order structure of landscape topography; however, emerging evidence suggests that a depth-dependent transport rule may be more appropriate for disturbance-driven regolith creep (Heimsath et al., 2005; Yoo et al., 2007; Roering, 2008; Pelletier et al., 2011). Considering that the probability of disturbance-driven regolith transport decreases with depth, a transport law that considers regolith flux to depend on local hillslope gradient, regolith depth, and some characteristic mixing depth can be written as

$$q = -K_2 \left[1 - e^{-h/h^*} \left(1 + \frac{h}{h^*} \right) \right] \frac{dz}{dx}, \quad (2)$$

where K_2 is a diffusion coefficient ($\text{cm}^2 \text{ yr}^{-1}$), h is the creeping regolith thickness (cm), and h^* is the characteristic mixing depth (cm) of processes driving downslope regolith creep such

as freeze-thaw and/or bioturbation (e.g., Anderson, 2002). In contrast to some depth-dependent models that consider transport to be linearly dependent on the product of regolith depth and slope (e.g., Heimsath et al., 2005; Roering, 2008), this formulation acknowledges that regolith depth and the base of a mobile layer need not be coincident.

During the past two decades, the application of meteoric ^{10}Be to the study of Earth surface processes (e.g., Monaghan et al., 1992; McKean et al., 1993; Jungers et al., 2009; West et al., 2013) has allowed direct estimates of downslope regolith flux on eroding hillslopes, provided that the delivery rate of ^{10}Be can be estimated (Willenbring and von Blanckenburg, 2010; Graly et al., 2011). Accounting for the mass balance of meteoric ^{10}Be in creeping regolith, the volumetric downslope flux (q) of regolith (in $\text{cm}^2 \text{ yr}^{-1}$) can be calculated as:

$$q_s = \frac{Dm_a}{C_{\text{re}}\rho_{\text{re}}} (x - x_0), \quad (3)$$

where D is the meteoric ^{10}Be delivery rate (in atoms $\text{cm}^{-2} \text{ yr}^{-1}$), m_a is the atomic mass of ^{10}Be , C_{re} is the concentration of ^{10}Be in regolith (g/g sample), ρ_{re} is the depth-averaged bulk density of regolith, and $x - x_0$ is the distance between the sample location and the ridge top (Monaghan et al., 1992; McKean et al., 1993; West et al., 2013).

In this study, we use meteoric ^{10}Be to explore the origin of asymmetric regolith-mantled hillslopes within three first-order watersheds in and adjacent to the Susquehanna Shale Hills Critical Zone Observatory (SSHO), located in central Pennsylvania (USA). During the late Pleistocene, the terminus of the Laurentide ice sheet was ~ 75 km due north, and the region of the SSHO had a periglacial climate (Clark and Colkosz, 1988). All three watersheds have a central channel oriented approximately east-west, and all exhibit steeper north-facing hillslopes than south-facing hillslopes (Fig. 1). Hillslopes are characterized by convex-up ridge tops, planar mid-slopes, and concave-up toe slopes (West et al., 2013). Bedding strikes at a high angle to the axis of the catchments ($\sim 50^\circ$) and dips steeply to the northwest ($\sim 50^\circ$), thus, the topographic asymmetry is not a direct reflection of dipping strata. Although previous studies noted this asymmetry (Ma et al., 2013; West et al., 2013), the cause of its development remains unknown.

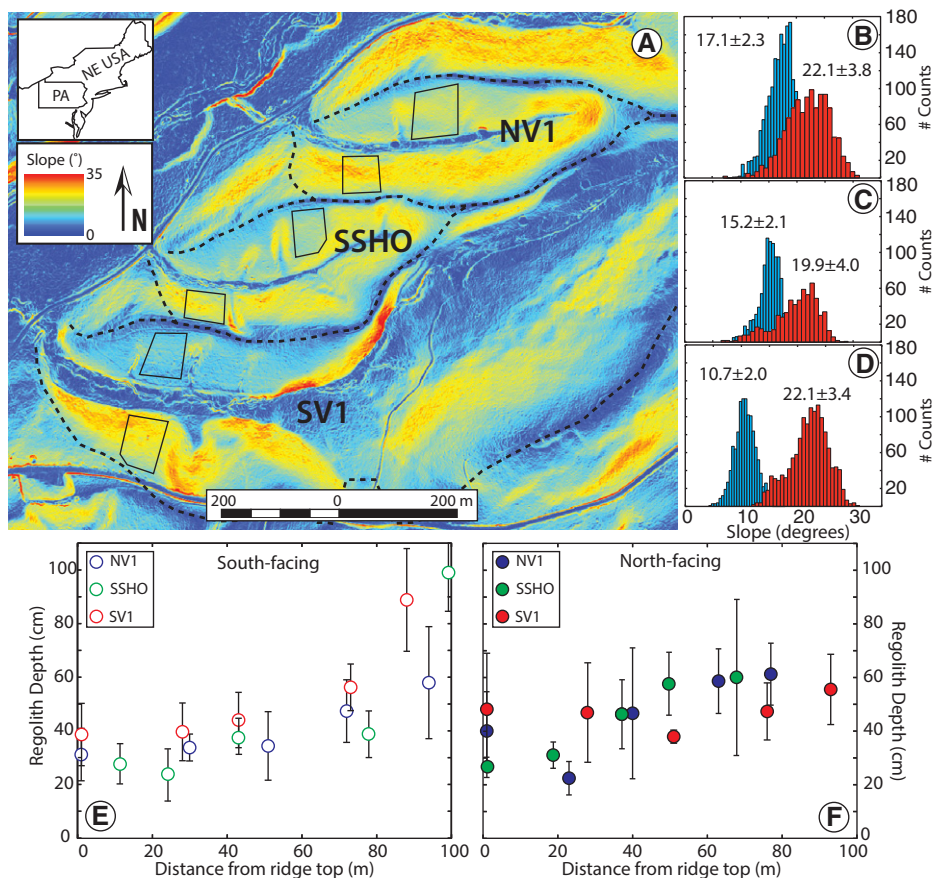


Figure 1. A: Topographic gradient of watersheds in and adjacent to Shale Hills Critical Zone Observatory (SSHO). NE—northeast; PA—Pennsylvania; NV1—north valley; SV1—south valley. **B–D: Distribution of gradients from sampled regions of planar hillslopes (solid black boxes) along north-facing (orange) and south-facing (blue) hillslopes.** B: NV1. C: SSHO. D: SV1. **E: Depth to refusal for hand auger along south-facing hillslopes.** Error bars represent one standard deviation of the mean auger depth at each position. **F: Depth to refusal for hand auger along north-facing hillslopes.**

METHODS

This work builds upon an initial study of West et al. (2013), which presented data for two hillslopes within the SSHO watershed. Our expanded data set includes 44 new meteoric ^{10}Be measurements from 4 additional hillslopes (2 north-facing and 2 south-facing); collectively, the 6 hillslopes span a range of average gradients from $\sim 10\text{--}25^\circ$ (SSHO range $15\text{--}20^\circ$; Fig. 1). Regolith samples were collected with a 5-cm-diameter hand auger until refusal in a 5×5 grid on planar hillslopes in each watershed (Fig. 1A). Sample locations were spaced ~ 5 m across slope and ~ 20 m downslope. Samples at each site were amalgamated by depth. We further mixed samples to the east and west of the central transect, so that three samples were analyzed for ^{10}Be from ridge-top, mid-slope, and toe slope positions (Fig. DR1 in the GSA Data Repository¹). At the upper and lower slope positions, all five depth-amalgamated samples

were mixed to one representative sample. Previous work showed that measured meteoric ^{10}Be inventories are not affected by amalgamation (e.g., Jungers et al., 2009; West et al., 2013); therefore, we follow this approach here. Using these meteoric ^{10}Be measurements, we evaluate transport rate laws and coefficients using gradients determined from a high-resolution digital elevation model.

RESULTS

Our results reveal that regolith thickness at the SSHO varies systematically with hillslope aspect (Figs. 1E and 1F). Along low-gradient, south-facing hillslopes, augerable regolith is relatively uniform (30–40 cm), with thicker (~ 80 cm) regolith present only at the toe of the slope. In contrast, augerable regolith is thicker (40–60 cm) along north-facing slopes and exhibits considerable variability in both the downslope and cross-slope directions (Fig. 1F).

Observations from hand excavations and soil pits within the SSHO watershed suggest that this variability reflects the presence of a buried 1–1.5-m-thick layer of angular colluvium on the north-facing hillside that mantles fractured bedrock (West et al., 2013). Within soil pits, we observe a distinct stratigraphy on the north-facing hillslope; massive, poorly structured regolith overlies a clast-supported framework of shale fragments as large as 5–10 cm in diameter (Fig. DR2). In contrast, the augerable, poorly structured regolith along south-facing hillslopes directly overlies weathered bedrock, and no coarse underlying colluvial material is present (Fig. DR2).

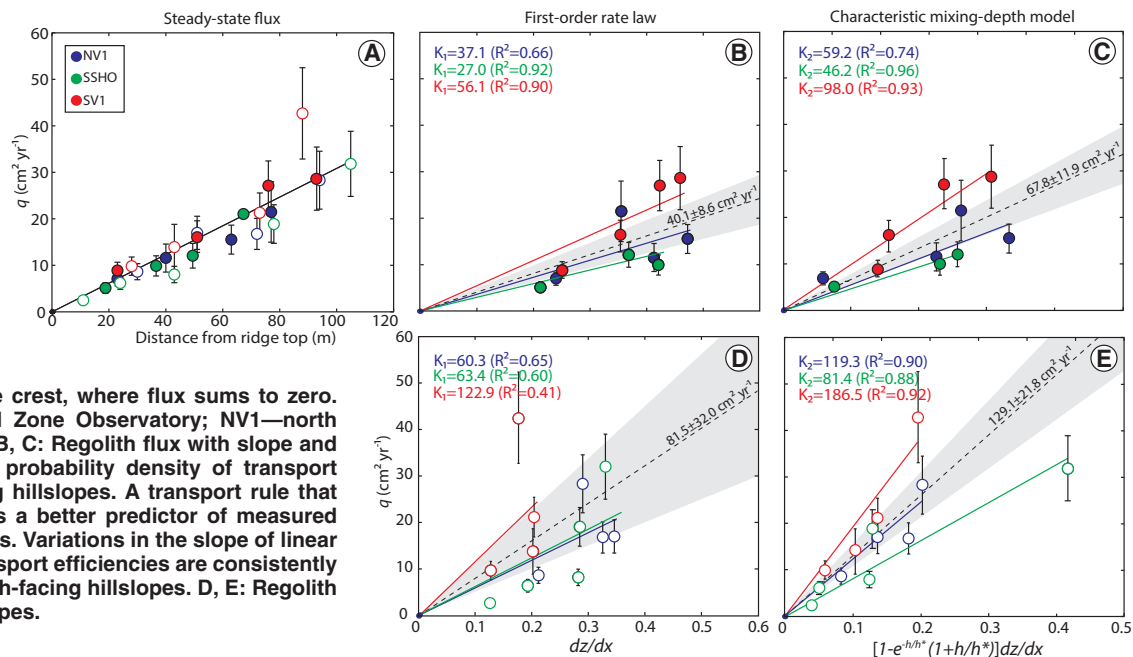
Meteoric ^{10}Be concentrations in regolith are similar across all hillslopes and do not vary systematically with hillslope position, amalgamation technique, or aspect (Table DR1). Combining meteoric ^{10}Be concentrations with depth-averaged regolith densities and an assumed meteoric ^{10}Be delivery rate of 1.8×10^6 atoms $\text{cm}^{-2} \text{yr}^{-1}$ (Graly et al., 2011), we estimate regolith flux (Equation 3). Our results suggest that regolith flux increases linearly with distance from ridge crests, and does not appear to vary with hillslope aspect (Fig. 2A). Rather, the similarity of flux patterns along sample transects appears to be consistent with spatially uniform lowering of the landscape at rates of $\sim 20\text{--}30$ m/m.y. over the past 10–15 k.y. (West et al., 2013). This similarity between regolith flux along north-facing and south-facing hillslopes suggests that ^{10}Be is retained in the upper regolith and is not lost to deep colluvium.

To evaluate the applicability of geomorphic transport laws used to describe creeping regolith (Equations 1 and 2), we plot measured regolith flux against topographic gradient and mean regolith depth (Fig. 2). Along north-facing hillslopes, downslope regolith flux correlates with local topographic gradient (Fig. 2B), consistent with a slope-dependent transport rule (Equation 1). This correlation is poor along south-facing slopes (Fig. 2D), suggesting that such a rate law does not completely describe regolith creep. The correlation between regolith flux and a characteristic mixing depth model (Equation 2) is significantly stronger along both north-facing and south-facing slopes (Figs. 2C and 2E). Thus, our data imply that regolith flux depends on both regolith thickness and local gradient at this field site.

Our data suggest that transport efficiency (K_1 or K_2) is approximately two times greater along south-facing (equatorial-facing) slopes than along north-facing (polar-facing) slopes at the SSHO (Figs. 2B–2E). Assuming a characteristic mixing depth of 100 cm, consistent with the depth of root and frost penetration (Gaines

¹GSA Data Repository item 2014180, sampling and analytical methods with Figures DR1 and DR2, Table DR1 (meteoric ^{10}Be concentrations), and Table DR2 (measured flux, hillslope gradient, and regolith depth), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure 2. A: Regolith flux (q ; see text) with distance from ridge crest. Error bars represent one standard deviation from the mean flux at each position. Regolith flux increases linearly with position downslope in all three watersheds, and is similar between north-facing (closed symbols) and south-facing (open symbols) hillslopes. Regression lines forced to pass through zero at ridge crest, where flux sums to zero. SSHO—Shale Hills Critical Zone Observatory; NV1—north valley; SV1—south valley. **B, C:** Regolith flux with slope and the product of slope and probability density of transport with depth for north-facing hillslopes. A transport rule that considers regolith depth is a better predictor of measured regolith flux on all hillslopes. Variations in the slope of linear regressions show that transport efficiencies are consistently a factor of 2 higher on south-facing hillslopes. **D, E:** Regolith flux for south-facing hillslopes.



et al., 2013; nsidc.org/cryosphere/frozenground/whereis_fg.html), K_2 ranges from ~46–98 cm² yr⁻¹ on north-facing slopes (Fig. 2C), and 81 to 187 cm² yr⁻¹ on south-facing slopes (Fig. 2E). This difference is also apparent in the linear transport model; K_1 is 27–56 cm² yr⁻¹ on north-facing slopes, but 60–123 cm² yr⁻¹ on south-facing slopes (Figs. 2B and 2D). The difference in transport efficiency between hillslopes of opposing aspect is greater than variability in transport efficiency among hillslopes of similar aspect (Figs. 2B–2E). That the apparent asymmetry in transport efficiency does not depend on the form of the transport rule suggests the difference in efficiency between polar- and equatorial-facing slopes is a robust result of our study.

DISCUSSION

Several lines of evidence suggest that the deep colluvial material along the north-facing slope of the SSHO does not currently participate in downslope creep or in the transport of meteoric ¹⁰Be. First, the rooting depth of large woody vegetation (Gaines et al., 2013) and the scale of pit-and-mound topography associated with tree-throw events appear to be ~1 m, near the top of the buried colluvium. Similarly, average freezing depths reach ~1 m in central Pennsylvania (nsidc.org/sites/nsidc.org/files/images//NA_permafrost.jpg), suggesting that freeze-thaw does not currently activate motion in the buried colluvium. In addition, the colluvial mantle retains a crude clast alignment reminiscent of structure in periglacial deposits (e.g., grèzes litées). Meteoric ¹⁰Be data from south-facing hillslopes, where the depth to refusal coincides directly with the boundary between disaggregated regolith and mechanically intact

(but fractured) rock, yields fluxes identical to those along north-facing hillsides, suggesting that these data capture most, if not all, of the mobile regolith transport.

The observation that regolith flux is equivalent on north-facing and south-facing slopes despite systematic differences in regolith depth and topographic gradient on opposing hillslopes provides quantitative evidence that microclimate variations associated with hillslope aspect influence the efficiency of regolith transport on soil-mantled hillsides. Although the total regolith flux from north-facing and south-facing hillslopes in our studied watersheds is equivalent within uncertainty (Fig. 2A), the differences in gradient and regolith depth along these hillslopes require more efficient regolith transport on south-facing hillslopes.

Our tests of transport rules at the SSHO suggests that considering the probability distribution of disturbance with regolith depth (e.g., Anderson, 2002; Anderson et al., 2013) provides a better characterization of regolith transport and erosion on hillslopes than a first-order rate law that depends solely on gradient. Our study thus bolsters a growing body of evidence in support of rules that incorporate regolith depth and/or velocity gradients into landscape evolution models (e.g., Heimsath et al., 2005; Pelletier et al., 2011).

Tree species, tree density, and rooting depths are similar across the watershed (Gaines et al., 2013), suggesting no difference in bioturbation on north-facing and south-facing slopes. However, heave during freeze-thaw cycles may be controlled by aspect at the SSHO. Variations in stable isotope ratios in modern soil waters at the SSHO suggest enhanced snow melt and infiltration on south-facing hillslopes (Thomas et al.,

2013), as regolith on north-facing hillslopes remains frozen and shielded under snow pack for a greater fraction of the winter. Thus, these proxy data suggest the possibility that greater insolation on the south-facing hillslopes is associated with more frequent freeze-thaw and wetting-drying events. Because these processes are associated with slope-normal volumetric expansion and gravitational collapse of regolith that drive downslope creep (e.g., Anderson et al., 2013), we suggest that they provide a ready explanation for both the depth dependence of regolith transport and the variability in transport efficiency.

If we further consider that transport largely occurs during frost heave, we can relate transport to the contribution of freeze-thaw events. In this case, the transport efficiency of frost heave reflects the frequency and magnitude of freeze-thaw events, and K_2 is then transformed to

$$K_2 = \frac{1}{2} f \beta h^2, \quad (4)$$

where f is the frequency of freezing events (yr⁻¹), β is the strain associated with regolith expansion during freezing, and h^* is the maximum frost penetration depth (Anderson, 2002). Assuming that frost penetration depth and freezing strain do not change with aspect, freeze-thaw events must be twice as frequent on south-facing hillslopes as on north-facing hillslopes at the SSHO in order to account for the differences in transport efficiency. Therefore, the transport efficiencies observed at the SSHO suggest freeze-thaw frequencies of 0.1–0.2 yr⁻¹ for north-facing slopes and 0.2–0.4 yr⁻¹ for south-facing slopes. These values are consistent with modeled return periods of frost penetration to 100 cm in bare soil (no snow) for central Pennsylvania (DeGaetano et al., 1996).

The asymmetric topography in our study area suggests that the difference in transport efficiency has been sustained over geologic time. The combination of the location of the SSHO in the mid-latitudes, where annual fluctuations in temperature allow freeze-thaw processes to be relatively efficient, and the slow erosion and lowering of the Appalachian landscapes (Portenga et al., 2013) appears to have allowed microclimatic differences to be expressed in topography (e.g., Poulos et al., 2012). The proximity to the terminus of the Laurentide ice sheet would have enhanced frost-heave mediated transport during Pleistocene climate variations, potentially setting the stage for the modern observed aspect-related topographic asymmetry. Our data imply that topographic asymmetry observed at the SSHO, and perhaps elsewhere in the mid-latitudes, represents an equilibrium solution to aspect-related microclimate differences even under conditions of uniform lowering and erosion over geologic time.

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