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Block-controlled hillslope form and persistence of topography in rocky landscapes

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ABSTRACT

Rocky hillslopes dotted with boulder-sized blocks and covered by a thin, nonuniform soil are common in both steep landscapes and arid environments on Earth, as well as on other planets. While the evolution of soil-mantled, convex-upward hillslopes in uniform lithology is reasonably well understood, the influence of heterogeneous lithology and geologic structure on hillslope form and evolution has yet to be properly addressed. Landscapes developed in layered sedimentary rocks feature sharp-edged landforms such as mesas and hogbacks that exhibit steep, linear to concave-upward ramps with scattered blocks calved from resistant rock layers overlying softer strata. Here we show that blocks can control the persistence of topography and the form and evolution of hillslopes in these landscapes. We present a numerical model demonstrating that incorporation of feedbacks between block release, interruption of soil creep by blocks, and sporadic downslope movement of blocks are necessary and sufficient to capture the morphology and evolution of these landscapes. Numerical results are reproduced by a simple analytical solution that predicts steady-state concave hillslope form and average slope angle from block size and spacing. Our results illuminate previously unrecognized hillslope feedbacks, advancing our understanding of the geomorphology of rocky hillslopes. On a landscape scale, our findings establish a quantitative method to address the migration of sharp edges and the persistence of topography in layered landscapes.

INTRODUCTION

Hillslopes cover the majority of Earth's land surface and exert a first-order control on landscape scale (Sweeney et al., 2015). Current theory posits that a collection of hillslope processes (e.g., bioturbation and freeze-thaw) results in bulk diffusion of soil (Kirkby, 1971) and predicts the evolution of convex-upward hilltops in homogeneous, soil-mantled, steady-state landscapes (e.g., Dietrich et al., 2013). However, many rocky, weathering-limited hillslopes are strongly influenced by geologic structure and heterogeneous lithology and do not exhibit this classic convex-upward form (Howard 1994; Selby, 1987; Moon, 1984; Koons, 1955; Cooke and Warren, 1973). While meaningful progress has been made over the past few decades, most notably a nonlinear flux theory that accounts for increased transport at steep gradients (Andrews and Bucknam, 1987; Roering et al., 1999, 2001), models of nonlocal transport (Tucker and Bradley, 2010), a method for modeling rock with variable susceptibility to weathering (Johnstone and Hilley, 2014), and a model of the evolution of scarps with well-developed rill networks (Ward et al., 2011), current theoretical and numerical models fail to fully capture the elements of a landscape that reflect its geology. Many examples of rocky hillslopes across the world are found in landscapes dominated by layered rocks (King, 1957). Iconic features such as hogbacks, flatirons, mesas, and dikes are easily observed in aerial and satellite imagery and generate striking topography in otherwise flat landscapes. These features reflect one or more layers of resistant, typically coarsely jointed rock embedded within softer strata (e.g., sandstone in shale) in a horizontal, tilted, or vertical configuration. Hillslopes or ramps adjoining the edge of the coarsely jointed resistant layer are typically linear to concave upward (Fig. 1A) and are mantled by large resistant blocks (Howard, 1994; Ward et al., 2011) (Fig. 2). Blocks are not found beyond the base of the ramp, where the slope transitions to a nearly flat plain, suggesting that the development and persistence of local relief may be tied to the presence of the blocks (Fig. 2A).

FIELD OBSERVATIONS AND CONCEPTUAL MODEL

We first develop a conceptual model of the evolution of a hogback, a tilted feature that exemplifies this class of landforms (Fig. 1C). Models

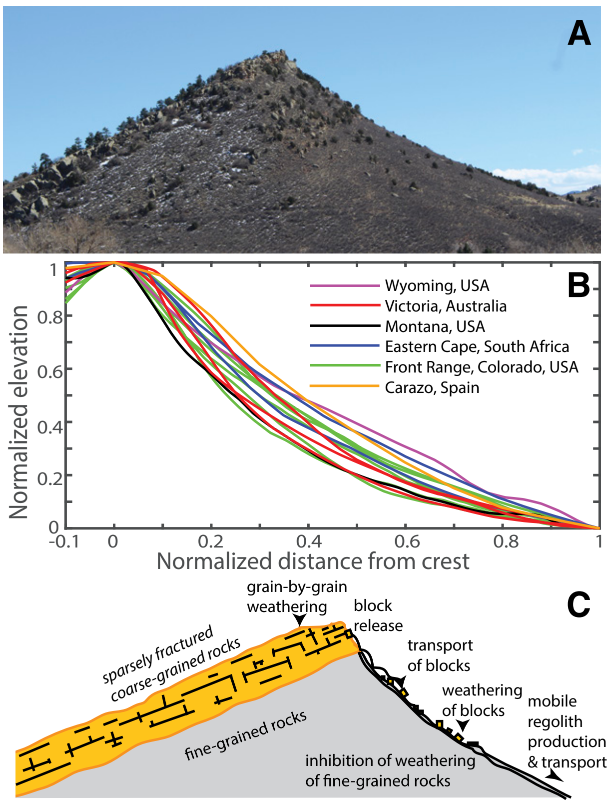

Figure 1. A: Photo of hogback in Morrison, Colorado (USA), demonstrating concave-upward slope profile. B: Google Earth–derived topographic profiles of hogbacks across the world, normalized by distance from crest and total relief (locations in the Data Repository; see footnote 1). C: Conceptual model of ingredients required to explain hogback evolution.

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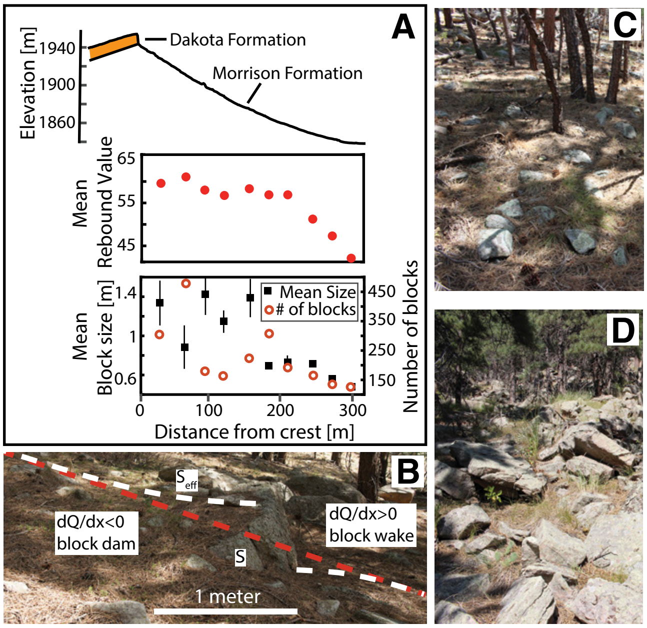

Figure 2. A: 1-m-resolution lidar profile of a hogback at Heil Valley Ranch, Colorado (USA) (courtesy of the Boulder Critical Zone Observatory). Schmidt hammer measurements of blocks show decreasing mean Schmidt hammer rebound values downslope; each point represents 75–150 individual measurements; standard error of the mean (SEM) error bars are smaller than data points. Mean block size and number measurements on the slope are also shown. Each block size data point is the mean value of both long and short axes of 10 blocks measured at each site. B: Photo of a block dam. Red line shows average slope (*S*); white lines show altered effective slope (S_{eff}) due to soil accumulation behind blocks. *Q* = soil flux; *x* = distance from the crest. C: Photo of block coverage near the bottom of the slope. D: Photo of block coverage further upslope.

of hillslope evolution require treatment of both the conversion of bedrock to soil and the subsequent transport of soil downslope. Hillslopes developed in layered rock require additional acknowledgment of block release from the resistant layer, the subsequent fate of those blocks as they move downslope, and weathering and transport interactions between blocks and underlying soft rock. Topographic profiles of hogbacks across the world show that slopes adjoining hogbacks are straight to concave (Figs. 1B and 2A). Field observations of hogbacks suggest that due to the back-tilt of the sandstone with respect to the adjoining ramp developed on shale, resistant layers are undermined block by block (Ahnert, 1960; Oberlander, 1977) as shale is removed from the base, releasing one joint-bounded segment at a time. Blocks appear to be released by rotational sliding and deposited only a short distance downslope from the scarp.

However, blocks are found scattered along the full length of the ramp, much further from the scarp than they are initially deposited (Fig. 2), suggesting that they must move downslope at some time after release. This has most recently been shown in the Stolowe Mountains, Poland, where comparison between field data and rock-fall models demonstrates that blocks are found much further from the source than would be expected from rock fall alone (Duszyński and Migoń, 2015). We hypothesize that the presence of blocks on the slope enacts two related feedbacks. First, large blocks obstruct the downslope motion of soil, essentially serving as dams (Fig. 2B). This causes soil accumulation upslope of the block, while the ramp immediately downslope is starved of soil. Over time this generates a depression downhill of the block, into which the block may topple or slide once the relief and the local slope are sufficient. Second, the presence of the block and the perturbation of soil thickness around it alter the rate at which the underlying shale (or other easily weathered rock) can be converted to soil. The blocks weather and decline in size through time. We hypothesize that these weathering and transport interactions are sufficient to explain both the shape of the ramp and the distribution of blocks observed in the field.

We hypothesize that blocks should decrease in size and become more weathered with distance from the crest. To test this, we collected field data from Heil Valley Ranch along the Front Range in Colorado (USA), a segment of the Dakota Ridge, which is a notable example of a hogback. Our study site, a 300-m-long Morrison shale slope perpendicular to the strike of the resistant Dakota Sandstone layer, displays the expected concave-upward topographic profile characteristic of hogbacks (Fig. 2A). The slope is well vegetated by trees, and displays no evidence of overland flow, rills, or accumulation of soil at the base of the slope. Our data show that both block size and areal coverage decrease with distance from the crest (Figs. 2A–2D). Schmidt hammer measurements demonstrate that the compressive strength of blocks, which serves as a proxy for degree of weathering (Goudie, 2006, and references therein), also decreases with distance from the crest (Fig. 2A) (see the GSA Data Repository[1] for detailed methods). Similar data collected in the Stolowe Mountains reveal a similar decrease in rock strength away from the crest (Duszyński and Migoń, 2015). Soil buildup can clearly be seen behind numerous blocks scattered across the ramp (Fig. 2B). While it is difficult to determine specific hillslope processes at play in any landscape, frost creep, wetting-drying cycles, and tree throw are most likely the dominant sediment transport processes at this field site. (See the Data Repository for further discussion of potential weathering and transport processes.)

NUMERICAL MODEL

We develop a numerical model to test whether our proposed feedbacks between weathering and transport of blocks and soil can explain the shape of these landforms. Our model marries discrete and continuum approaches in order to account for the effects of blocks while using a simple formulation of hillslope soil flux. The model setup consists of a tilted resistant bedrock layer of specified thickness, dip, and fracture spacing, interbedded within more easily weathered bedrock. The two lithologies are differentiated by the maximum rate at which bare bedrock may be converted to soil, w_0. The soil conversion rate for both lithologies depends on soil thickness, with an exponential decrease (Ahnert, 1977; Heimsath et al., 1997; see Fig. DR5 in the Data Repository). We employ a linear hillslope transport law in which soil flux depends on both the local slope and thickness of soil (e.g., Anderson, 2002; Johnstone and Hilley, 2014; Mudd and Furbish, 2007). We initiate the model with flat topography and lower the boundaries, assumed to be channels, with a prescribed constant rate of fluvial incision. For simplicity, we treat blocks as cubes of uniform size that are released when the shale hillslope ramp erodes deeply enough to initiate motion on the next joint set. A certain number of blocks, determined by layer thickness and block side length, is then removed from the scarp and deposited immediately downslope, one block in each model cell (see the Data Repository for algorithms capturing the processes involved).

We treat these blocks as bedrock with a low soil conversion rate and track the height of each block as it weathers. Shale underlying each block continues to produce soil at a rate determined by the sum of the thickness of soil and block height. Blocks become increasingly susceptible to downslope movement as the elevation drop between the block and the next cell increases (Tucker and Bradley, 2010).

Model results demonstrate that our treatment of block release, weathering, and movement downslope captures the essence of hogback evolution and hits a number of targets expected from field observations (Fig. 3).

[1]GSA Data Repository item 2017091, field methods, modeling methods, and additional model runs, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

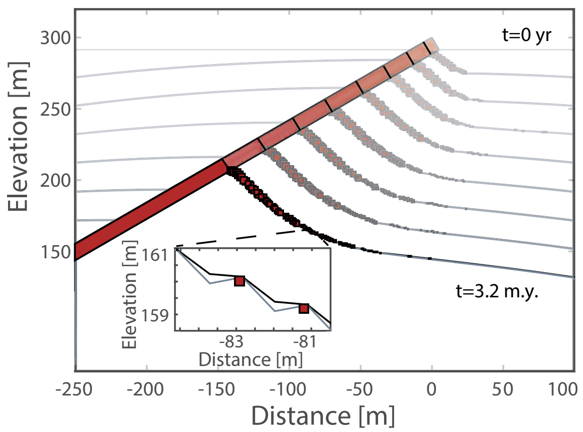

Figure 3. Modeled hogback evolution plotted every 400 k.y. Red squares represent locations and relative sizes of blocks, broken into four size classes. By 2 m.y., the adjoining slope reaches a quasi-steady state of parallel retreat in which hillslope form and block release rate remain constant. Slopes are concave upward. Blocks decrease in size as they weather and move downslope, and do not persist beyond the base of the ramp. Here sandstone thickness = 10 m, dip = 30°, and k = 0.5 m/yr (*k* is a hillslope efficiency constant; *t* is time). Bare shale soil production rate = 10^{-3} m/yr, bare sandstone soil production rate = 10^{-5} m/yr, and the characteristic length scale for decline of soil production rate, H_w = 0.2 m. Fluvial incision is steady at 5 × 10^{-5} m/yr. Inset shows example of a series of soil dams in the model (an animation of the model is in the Data Repository; see footnote 1). The inset shows an example of a block dam; the black line represents soil surface and the gray line represents bedrock surface.

Our model reproduces the characteristic concave-upward ramps. Blocks tend to cluster together, with larger blocks near the top of the ramp and smaller, more weathered blocks toward the bottom. Large blocks are not found beyond the slope break at the base of the ramp. Blocks also act as soil dams, which force accumulation of soil upslope of each block and allow a depression to develop downslope (Fig. 3). On the dip slope (left side of Fig. 3), soil develops on the easily weathered rock above the resistant layer, and a convex hillslope evolves, ultimately leaving the hard bedrock bare at the angle of dip. Similarly, the low-angle slope beyond the block-covered ramp (right side of Fig. 3) displays a slight convexity characteristic of a typical steady-state Gilbert hillslope (Gilbert, 1909). With a constant incision rate, the ramp eventually reaches a quasi-steady-state form, in which block release rate remains constant and the ramp retreats parallel to itself and maintains a constant concave form, length, and relief (Fig. 3). Control runs using the same parameters but without blocks develop purely convex-upward hillslopes and exhibit ~60 m less relief than runs with blocks. This demonstrates that hillslope form and the persistence of relief in our model is controlled by the presence of blocks, and not by boundary conditions (see Fig. DR6). Model runs using different values for thickness, block size, dip, weathering rates, and incision rates preserve the concave form and general behavior illustrated by the example of Figure 3.

DISCUSSION AND CONCLUSIONS

Model results show that blocks can dictate the shape of the hillslope and profoundly influence the creation of relief and persistence of topography. The block-free, low-relief slopes on the right and left sides of Figure 3 can be viewed as a control case, and show the slightly convex form expected for a hillslope developed in homogeneous easily weathered lithology. We next seek to understand the quasi-steady-state form and slope angle of the ramp produced in the model. In the face of uniform rate of conversion of rock to soil, w, and the simplest soil flux law $Q = -kS_{eff}$, a steady-state hillslope requires that slope, S, increase linearly downhill such that $S = wx/k$, where x is the distance from the crest, and k is a hillslope efficiency constant. In the absence of block dams, this results in the classic parabolic hilltop described by Gilbert (1909). In the presence of block dams, however, the local slope is altered by blocks. The effective gradient relevant to the transport of soil, S_{eff}, is lower than S, the gradient averaged over many such block dams (Fig. 4):

$$S_{eff} = S - \frac{D}{Xs}, \quad (1)$$

where D is the thickness of a block, and X_s is the spacing between blocks. In order to reach steady state, the average slope must match the required steady-state slope distribution. This yields

$$S = \frac{wx}{k} + \frac{D}{Xs}. \quad (2)$$

In the absence of blocks ($D = 0$), Equation 2 recovers the classic steady-state solution. When blocks are present, the second term on the right side influences, and can even dominate, the shape of the slope. For blocks of uniform size and spacing, when $D/X_s >> wx/k$, slopes are linear and steeper than the non-block case. For the case in which blocks decay downslope, as in our model, slope angle decreases with distance from the crest because block size decreases, leading to a concave form. Beyond the slope break, where $D = 0$, only the first term on the right side of Equation 2 remains, and the slope should subtly increase toward the bounding stream. In Figure 4 we compare the space and time-averaged slope observed in the numerical model with the expected analytical average slope for the ramp (see the Data Repository for a discussion of methods). The analytical solution agrees well with the steady linear decrease in slope observed in our model, as well as lidar-derived slope trends (see Fig. DR1). Equation 2 successfully captures the full range of forms (convex, linear, concave) observed in the field for both homogeneous and blocky hillslopes.

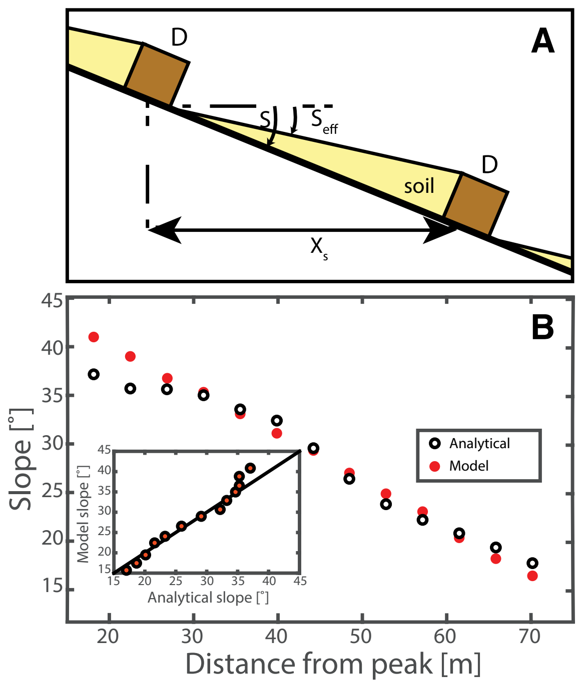

Figure 4. A: Conceptual diagram of rationale behind analytical solution. Effective slope relevant for local sediment transport, S_{eff}, is lower than the average slope, *S*. B: Comparison of model with analytic solution. Slopes roughly linearly decline with distance downslope. The inset compares the numerical and analytic slopes (line is 1:1 fit).

Our results demonstrate that the feedbacks we have proposed and implemented in this one-dimensional model can explain the basic form and evolution of hillslopes in landscapes dominated by layered rocks. Blocks play a vital role in allowing the migration and persistence of sharp-edged features in layered landscapes; an abundance of blocks can slow greatly the lateral migration of these features (see Figs. DR6 and DR11). Our model can easily be modified to explore the evolution of landscapes developed in layered rocks with different orientations and multiple resistant layers, as well as the effects of more complex fracture orientations and initial distribution of block locations (see Figs. DR7–DR9). In future studies we will explore the two-dimensional effect of soil flow around blocks and the evolution of landscapes developed in folded layered rocks as they are exhumed (e.g., exposed anticlines); future field work is needed to document the specific mechanisms of block movement, which may include toppling or sliding. Further work should explore the effects of climate in the development of rocky hillslopes; for example, one could compare the evolution of landforms in this study (developed without significant overland flow or large rock-fall events) with the evolution of heavily rilled, steep, blocky slopes in very arid landscapes (as described by Ward et al., 2011). In addition, vegetation may play an important role in the development of these landforms, as vegetation has been shown to dam soil in a manner similar to the block dams observed in this study (DiBiase and Lamb, 2013).

The importance of blocks is not limited to landscapes developed in layered rocks. Blocks have been shown to armor granitic slopes in mountainous terrain developed on crystalline rocks and to contribute to the persistence of local relief (Granger et al., 2001). Recent work has shown that blocks are also important in bedrock channels (Dubinski and Wohl, 2012; Lamb and Dietrich, 2009) and glacial landscapes (Anderson, 2014; Dühnforth et al., 2010). Furthermore, feedbacks between blocky hillslopes and stream incision in mountainous terrain can substantially alter landscape evolution patterns and the upstream propagation of climate and tectonic signals (Shobe et al., 2016). We therefore argue that models of landscape evolution must ultimately incorporate the effects of blocks and heterogeneous lithology in order to capture the essence of both small-scale hillslope form and large-scale persistence of topography.

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