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Key Points:
- Large blocks of rock in knickpoints represent a hillslope-driven negative feedback on river incision
- A 1-D model shows that rapid river erosion causes an influx of blocks that inhibit further erosion
- This autogenic feedback may stall landscape evolution and complicate river profile analysis

Supporting Information:
- Data Set S1
- Supporting Information S1

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Hillslope-derived blocks retard river incision

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Abstract The most common detachment-limited river incision models ignore the effects of sediment on fluvial erosion, yet steep reaches of mountain rivers often host clusters of large (>1 m) blocks. We argue that this distribution of blocks is a manifestation of an autogenic negative feedback in which fast vertical river incision steepens adjacent hillslopes, which deliver blocks to the channel. Blocks inhibit incision by shielding the bed and enhancing form drag. We explore this feedback with a 1-D channel-reach model in which block delivery by hillslopes depends on the river incision rate. Results indicate that incision-dependent block delivery can explain the block distribution in Boulder Creek, Colorado. The proposed negative feedback may significantly slow knickpoint retreat, channel adjustment, and landscape response compared to rates predicted by current theory. The influence of hillslope-derived blocks may complicate efforts to extract base level histories from river profiles.

1. Introduction

Most widely used models treat river incision as a function of water quantity and slope while ignoring sediment effects [*Whipple and Tucker*, 1999]. Models incorporating sediment effects on bedrock incision generally use a median grain size value rather than honoring the heterogeneous grain size distributions found in bedrock rivers [*Sklar and Dietrich*, 2004; *Gasparini et al.*, 2006]. However, laboratory and modeling studies have shown that grain size influences the relative importance of the “tools” and “cover” effects that determine where sediment enhances or inhibits erosion [*Lamb et al.*, 2008; *Scheingross et al.*, 2014]. Bed sediment in bedrock rivers is often enriched in large (>1 m diameter) grains in and below knickpoints or reaches where the channel is unusually steep (Figure 1). This observation, made in the San Gabriel Mountains [*DiBiase et al.*, 2015], the Sierra Nevada [*Hurst et al.*, 2012; *Attal et al.*, 2015], and Boulder Creek (this study), defies conventional sediment transport theory in that with all else equal, transport capacity is highest in steepened (non-waterfall) reaches. Because large grains are not transportable through low-gradient upstream reaches, the large grains found in and below steep reaches must be derived from nearby hillslopes [*Attal et al.*, 2015]. Increased transport capacity in steep reaches must therefore be insufficient to consistently transport large, hillslope-derived grains. Previous work has shown that hillslope failures become more frequent after knickpoint passage and that the grain size delivered to the channel may influence river erosion [*Bigi et al.*, 2006; *Korup*, 2006; *Gallen et al.*, 2011; *Bennett et al.*, 2016]. *DiBiase et al.* [2015] hypothesized that fracture density may dictate the position of knickpoints by determining where hillslope-derived sediment provides erosive tools and where large blocks armor the channel. We explore the idea that rivers, through erosion and steepening of their adjacent hillslopes, can force an increase in the delivery of large blocks to the channel that in turn shield the bed and retard river incision (Figure 2).

Boulder Creek drains the eastern flank of the Colorado Front Range and exhibits little lithological variability, eroding granodiorite along the 20 river kilometers between the extent of the last glaciation and the mountain front. We observe the bedrock to be fractured on a 0.5 – 5 m scale with no systematic change in fracture density along the channel. The profile consists of two lower gradient reaches separated by a steep knickpoint, with a less steep upper knickpoint (Figure 1). The main knickpoint appears to have migrated upstream from the mountain front in response to rapid incision of the adjacent High Plains [*Anderson et al.*, 2006]. To understand spatial patterns of hillslope-derived blocks in Boulder Creek, we measured the long axis of all grains >1 m within the active channel along 10 m of channel length at 28 sites. We report the cumulative long axis length, separated by size class, divided by 10 m of channel length to normalize for the size of our measurement area

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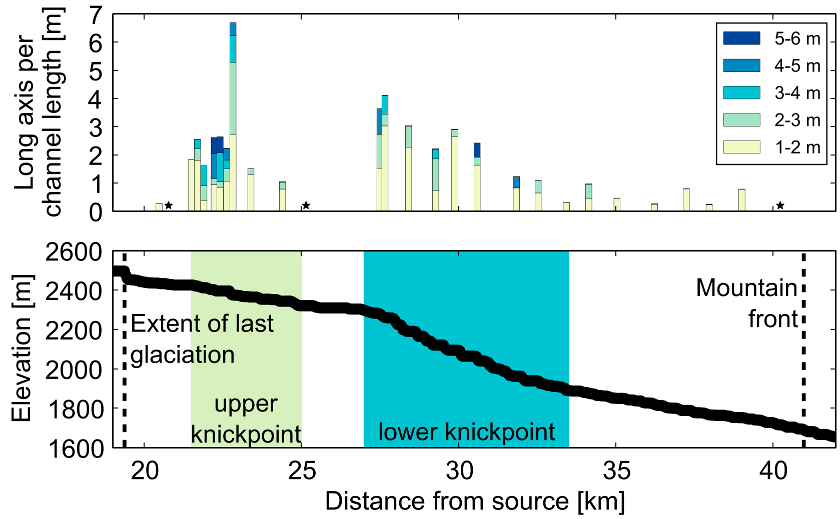

Figure 1. Boulder Creek grain size and longitudinal profile data. Bars represent the sum of long axes of all grains >1 m found along 10 m of channel length. Stars show sites with no blocks >1 m. Large grains are much more prevalent in the knickpoints than upstream or downstream.

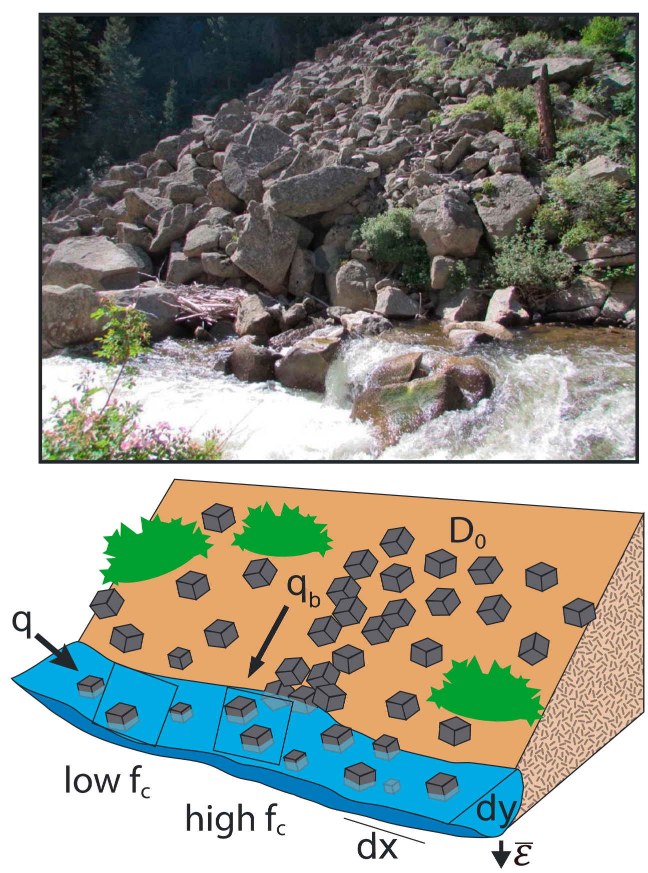

Figure 2. Photograph from Boulder Creek showing hillslope block delivery and diagram illustrating the hypothesized influence of blocks on river erosion. Hillslopes deliver cubes of initial side length D_0 as a block flux per channel length per time q_b, altering the cover fraction f_c in each model cell of dimensions $dxdy$. The channel is eroding at an average rate of $\bar{\varepsilon}_c$ given a specified discharge q.

(Figure 1). Blocks tend to cluster in the steep reaches, and block size declines with distance from the steepest part of the main knickpoint. We hypothesize that clustering of large, hillslope-derived blocks in the Boulder Creek knickpoint and other steep reaches of mountain streams is a manifestation of an autogenic (internal) feedback generated by rapid river incision in well-jointed bedrock. Slowing of incision by block delivery from steepened adjacent hillslopes may inhibit knickpoint propagation and landscape adjustment. While increased hillslope sediment flux may enhance incision if the sediment is small enough to be entrained as tools [*Gasparini et al.*, 2006; *Turowski et al.*, 2007], we focus only on the effects of large, hillslope-derived blocks. We use a numerical model to explore whether incision rate-dependent delivery of blocks can explain their distribution in Boulder Creek, and whether this distribution requires enough hillslope block delivery to alter channel form and adjustment rates. We argue that the channel-hillslope feedbacks implied by this grain size distribution may cause real landscapes to differ significantly from those predicted by present landscape evolution theory.

2. Model Development

We present a 1-D reach-scale numerical model of bedrock river incision in the presence of large blocks supplied by the adjacent hillslopes. The domain is a river reach assumed short enough to have constant drainage area and is intended to mimic Boulder Creek (Figure 1). While our model could be scaled up to a full longitudinal profile, using a constant drainage area reach allows simpler prediction of the behavior of transient features (for example, knickpoint retreat rates are expected to be constant). Our model combines a shear stress bedrock erosion rule with discrete tracking of the size and position of individual blocks (assumed to be cubes) supplied by the adjacent hillslopes.

2.1. Fluvial Erosion

Vertical river erosion per time ε is modeled with a modified shear stress rule [*Howard and Kerby*, 1983; *Howard*, 1994; *Tucker*, 2004]:

$$\varepsilon = k_b(\tau_b - \tau_c)^a(1 - f_c), \tag{1}$$

where k_b is an erodibility constant encompassing the effects of lithology, local hydrology, sediment flux, and the dominant bedrock erosion process [*Whipple et al.*, 2000]. τ_b is bed shear stress, τ_c is the critical bed shear stress required to erode bedrock (held constant), and a is an exponent set to unity. f_c is the fraction of bed covered by blocks, making $(1 - f_c)$ the fraction of bed exposed to erosion [*Sklar and Dietrich*, 2004]. τ_b is the bed shear stress after accounting for the drag stress on in-channel blocks. We adapt the method of *Kean and Smith* [2010] to treat blocks as large roughness elements such that

$$\tau_b = \frac{\rho_w g h S}{1 + \sigma_D}, \tag{2}$$

where ρ_w is water density, g is gravitational acceleration, h is flow depth, S is local slope, and σ_D, the dimensionless drag stress on all blocks in the model cell, is given by

$$\sigma_D = \frac{1}{2} C_D \beta^2 \frac{h_b D}{\lambda^2}. \tag{3}$$

C_D is the drag coefficient of a cube (0.8) [*Carling and Tinkler*, 1998], h_b is the average depth to which blocks are submerged (equal to block height for submerged blocks and equal to h for blocks protruding above the flow), D is average block side length, and λ is the mean spacing of blocks, calculated by dividing model cell length by number of blocks in the cell. While there is no explicit connection between λ and f_c, the two quantities generally vary inversely. β, a dimensionless roughness coefficient, and flow depth h are calculated using the variable power equation of *Ferguson* [2007]:

$$h = \frac{q}{u_* \beta} = \frac{q}{u_*} \frac{\left[(h/z_0)^{5/3} + (a_1/a_2)^2\right]^{1/2}}{a_1(h/z_0)} \tag{4}$$

where q is prescribed discharge in m^2/s, u_* is shear velocity, a_1 and a_2 are constants set to 6.5 and 2.5, respectively [*Ferguson*, 2007], and z_0 is a constant roughness height of 0.1 m. The discharge distribution is generated from a Pearson type III distribution fit to 106 years of daily mean flood data from Boulder Creek [*Interagency Advisory Committee on Water Data*, 1982; *Hancock et al.*, 2011]. We explore the effects of blocks on river incision without including explicitly the roles of sediment flux (except block motion) or changes in drainage area and channel width.

2.2. Block Supply and Degradation

Blocks in natural systems may be supplied to the channel by plucking from the channel bed or from the adjacent hillslopes by landslides, rockfall, and debris flows. Because the surface area of hillslopes far exceeds that of the channel bed, hillslope-derived blocks must vastly outnumber plucking-derived blocks. We therefore treat only hillslope-derived blocks. For simplicity, we avoid explicitly modeling the release and transport of blocks on hillslopes and instead model hillslopes probabilistically. We seek to honor the positive relationship between river incision, steepening of adjacent hillslopes, and accelerated influx of blocks [e.g., *Korup*, 2006; *Riebe et al.*, 2015]. Block delivery is treated as a Poisson process in which the mean block flux to the channel per unit channel length per time $\overline{q}_b$ is the product of the mean number of blocks delivered per unit length per time $\overline{N}_b$ and the mean block volume $\overline{V}_b$:

$$\overline{q}_b = \overline{N}_b \overline{V}_b. \tag{5}$$

Using a constant initial block size D_0 and assuming cubic blocks,

$$\overline{q}_b = \overline{N}_b D_0^3. \tag{6}$$

The average block delivery rate $\overline{N}_b$ depends on the time-averaged channel incision rate at that location $\bar{\epsilon}_c$ and a factor γ, with dimensions of L^{-2}, which describes the efficiency of block release and transport. The volume flux of rock to the channel per unit length per time may then be rewritten:

$$\overline{q}_b = \bar{\epsilon}_c \gamma D_0^3. \tag{7}$$

To account for the lag time between channel incision and hillslope response, $\bar{\epsilon}_c$ is the vertical channel erosion rate averaged over a response timescale T, estimated to be 50 kyr from the relationships derived in *Hurst et al.* [2012]. Equation (7) incorporates the effects of hillslope steepening by rapid river incision. γ encapsulates the efficiency of block release and transport processes that are currently poorly understood, and is likely influenced by lithology, structure, climate, vegetation, and process dominance.

Once blocks are delivered to the channel, f_c is computed in each cell:

$$f_c = 1 - e^{-\Sigma A} \tag{8}$$

where A is the area covered by each block per unit channel bed area. The f_c in every cell changes each time step due to block delivery, degradation, and motion. This exponential relationship is expected because each additional block delivered is likely to overlap with blocks already in the channel. Block motion by sliding is computed using a force balance following *Lamb et al.* [2015] (supporting information). Block degradation is driven by the shear stress on the blocks, which is the difference between the total boundary shear stress and the shear stress on the bed:

$$\frac{\mathrm{d}D}{\mathrm{d}t} = -k_b \left((\rho_w g h S - \tau_b) - \tau_c \right) \tag{9}$$

such that block side length is reduced (on all axes) in proportion to available shear stress. The k_b and τ_c are the same for blocks and bedrock, assuming that blocks and bedrock are lithologically similar. A complete model description including parameter values is in the supporting information.

3. Experiment Description

We present three model experiments that simulate channel response to a step increase in base level lowering rate. The first is a control run in which the hillslopes do not deliver blocks in response to channel incision ($\gamma = 0$). The control run should exhibit the expected incision pattern for detachment-limited river erosion theory, including steady knickpoint retreat rates and adjustment to a new uniform slope that brings the reach into equilibrium with the new base level lowering rate [*Tucker*, 2004].

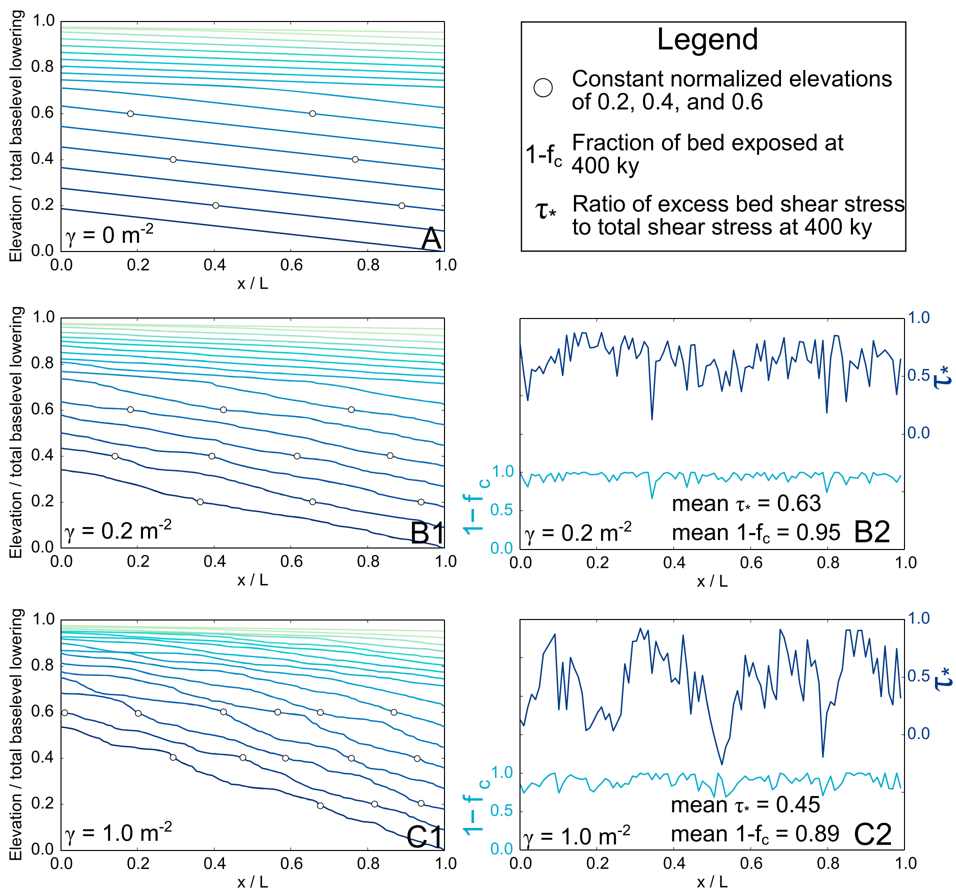

Figure 3. (a, b1, and c1) Longitudinal profiles normalized by domain length *L*, shown every 25 kyr over 200 kyr with 0.05 mm/yr base level lowering and 200 kyr with 0.15 mm/yr base level lowering. Horizontal distance between points of constant elevation shows that knickpoint retreat rates are constant in the control case but become much slower and highly variable at higher γ values. (b2 and c2) Fraction of exposed bed and ratio of excess bed shear stress (after reduction by blocks) to total boundary shear stress (before reduction by blocks). Excess bed shear stress is less than τ_c where $\tau_* < 0$.

The second and third experiments, in which hillslope block delivery depends on channel incision rate (equation (7)), explore the influence of large blocks on channel evolution and test the feasibility of the hypothesis that hillslope-derived blocks can inhibit incision. We predict that because the flux of blocks to the channel is controlled by the time-averaged incision rate, and blocks inhibit incision, initial rapid incision in response to the imposed base level drop will initiate a negative feedback in which a large influx of blocks slows further incision, knickpoint retreat, and channel adjustment. We expect the average block flux supplied per unit channel length per time $\overline{q}_b$ to set the magnitude of this feedback. We vary $\overline{q}_b$ by manipulating the block release and transport parameter γ to determine the influence of block flux on channel reach evolution. All experiments run for 200 kyr with a base level lowering rate of 0.05 mm/yr, followed by 200 kyr with a base level lowering rate of 0.15 mm/yr. These rates are chosen to approximate the forcing estimated for Boulder Creek [*Dethier*, 2001; *Schildgen et al.*, 2002; *Anderson et al.*, 2006]. The initial block size is 4 m with all other parameters held constant (see supporting information for values). The model time step is 1 year.

4. Results

4.1. Control Case

When blocks are never supplied in response to rapid incision, channel response to base level perturbations follows predicted shear stress behavior [*Howard and Kerby*, 1983; *Howard*, 1994; *Tucker*, 2004]. The reach profile steepens to accommodate the increased base level lowering rate, and the slope break dividing the relict and adjusted reaches migrates upstream at a constant rate as the channel adjusts to a new equilibrium slope (Figure 3a). By 75 kyr after the perturbation, all evidence of the old, low-gradient profile has disappeared.

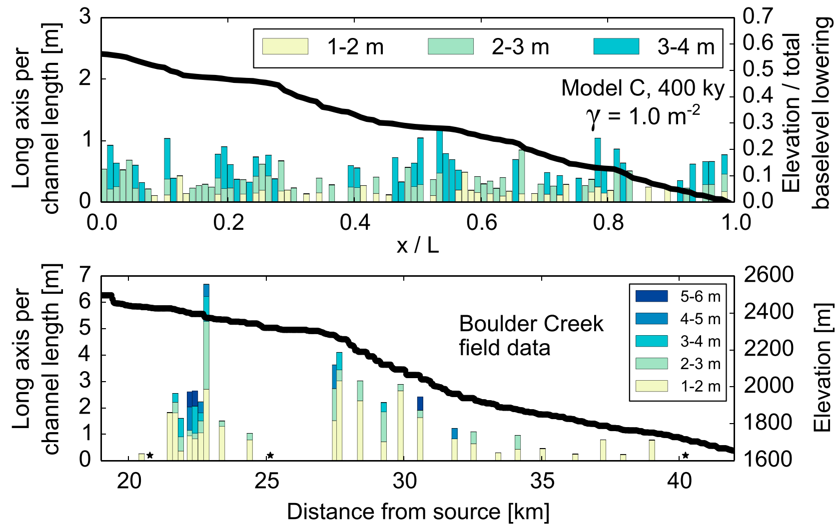

Figure 4. Model profile and block size data (400 kyr) when $\gamma = 1.0$ compared with field data. While our model does not replicate exact magnitudes of block long axis per unit channel length, it successfully captures the spikes in block frequency that accompany convexities in the profile and the decline in block frequency with distance from steepened reaches.

In a full longitudinal profile model, the slope break would migrate upstream at a drainage area-dependent rate [*Whipple and Tucker*, 1999; *Crosby and Whipple*, 2006; *Berlin and Anderson*, 2007].

4.2. Responsive Hillslopes

The mean volume of blocks delivered per channel length per time is set by the time-averaged incision rate and γ, which describes the efficiency of block release and transport. We vary γ and report the resulting longitudinal profiles and effects of block supply. To evaluate the influence of blocks on channel incision, we track $1 - f_c$, the fraction of each model cell exposed to erosion, and the ratio of excess bed shear stress to total boundary shear stress τ_*:

$$\tau_* = \frac{\tau_b - \tau_c}{\tau} = \frac{\tau_b - \tau_c}{\rho_w g h S} \quad (10)$$

where τ_b is the bed shear stress available after shear stress reduction by blocks (equation (2)). Both metrics are plotted at 400 kyr for responsive hillslope experiments (Figures 3b and 3c).

With low efficiency of block release and transport ($\gamma = 0.2$ m^{-2}), the reach response differs noticeably from the control run as $1 - f_c$ declines to 0.95 and τ_* to 0.63 on average (Figure 3b). The slope break propagates through the model domain as in the control run, but the reach profile exhibits steepened reaches and never fully readjusts to a linear form. The average slope of the reach at 400 kyr is almost twice the final slope in the control case.

In experiments with more efficient block delivery, the hillslopes respond to vertical incision with larger block fluxes and patterns of reach profile adjustment change significantly. When $\gamma = 1.0$ m^{-2}, the reach initially takes a convex upward form and maintains multiple knickpoints through 200 kyr of adjustment to the new base level lowering rate (Figure 3c). The upstream end of the model reach shows far less vertical erosion than the downstream end, whereas in the control run vertical erosion was uniform along the reach. The average reach slope at 400 kyr is almost three times the reach slope at the end of the control run. The large block flux supplied to the reach in response to incision is manifested as both lower $1 - f_c$ and lower τ_* after 400 kyr (Figure 3c).

In experiments with incision-dependent block delivery, grain size patterns in the model broadly mirror field observations (Figure 4). While our model does not perfectly match the total long axis length found in Boulder Creek, the steeper reaches of the model domain contain more total blocks, as well as more blocks in the largest size class (3–4 m).

5. Discussion

5.1. Patterns of Block Delivery and Erosion Reduction

Our model successfully replicates the clusters of blocks in knickpoints noted in the field (Figure 4), suggesting that block delivery in response to channel incision may be responsible for the block size distribution in Boulder Creek. In the low block delivery ($\gamma = 0.2$) case, blocks reduce the average $1-f_c$ to 0.95 and the average τ_* to 0.63, and alter both the transient response and final form of the reach (Figure 3b). The channel exhibits a convex upward profile in response to the increased base level lowering rate, and the convexity retreats upstream much more slowly than in the control case (Figure 3b). In experiments where higher block delivery reduces the average $1-f_c$ to 0.89 and average τ_* to 0.45, incision initially occurs near the base level control just as in the low block flux experiment (Figure 3c). Before the zone of rapid erosion can propagate upstream, the adjacent hillslopes respond to rapid incision by supplying more blocks to the channel. Increased delivery of blocks, which inhibit erosion through bed cover and shear stress reduction, reduces the incision rate over 100 kyr timescales. Hillslope block delivery also noticeably slows knickpoint propagation. Figure 3 shows points of constant elevation plotted on longitudinal profiles every 25 kyr. The horizontal distance between pairs of points at equal elevation indicates how far a point has retreated over 25 kyr. In the control case, points of equal elevation are widely spaced, indicating rapid knickpoint propagation (Figure 3a). In experiments with hillslope block delivery, points of equal elevation become as little as half as far apart compared to the control run and their distance becomes more variable, showing that block delivery slows and adds variability to knickpoint propagation rates (Figures 3b and 3c).

Because erosion is linearly proportional to both the fraction of exposed bed $1 - f_c$ and excess bed shear stress $\tau_b - \tau_c$, we can compare $1-f_c$ and the shear stress ratio τ_* (equation (10)) to determine which is more effectively inhibiting erosion at any time (Figure 3). Figures 3b and 3c show that with responsive hillslopes, τ_* is reduced by a much greater proportion than $1 - f_c$, indicating that shear stress reduction by form drag on blocks is more important than bed cover in inhibiting erosion. This occurs because shear stress reduction by blocks (equation (3)) is influenced by not only block size but also the roughness coefficient β and average block spacing λ. Results suggest that blocks primarily inhibit erosion through the reduction of available bed shear stress, and that bed cover is secondary.

The parameter γ, which controls the relationship between channel incision rate and hillslope block delivery, governs the influence of block delivery on fluvial incision. γ may be estimated for real landscapes by assuming that block delivery $\overline{N}_b$ depends on hillslope length L_h, average hillslope erosion rate $\bar{\varepsilon}_h$, block size released from the hillslope D_0, and a factor f_b:

$$\overline{N}_b = f_b \frac{L_h \bar{\varepsilon}_h}{D_0^2}. \tag{11}$$

f_b ranges from 0 to 1 and describes the proportion of mass released from the hillslopes as blocks, approaching zero in landscapes dominated by grain-by-grain weathering and one in landscapes where block removal is the dominant erosion process. Combining (11) with (6) and (7):

$$\overline{N}_b = \bar{\varepsilon}_c \gamma, \tag{12}$$

γ may be expressed as a function of measurable landscape parameters:

$$\gamma = f_b \frac{L_h \bar{\varepsilon}_h}{D_0^2 \bar{\varepsilon}_c}. \tag{13}$$

If the landscape is in steady state ($\bar{\varepsilon}_c = \bar{\varepsilon}_h$), estimation of γ is simplified to

$$\gamma = f_b \frac{L_h}{D_0^2}. \tag{14}$$

A full derivation of equations (11)–(14) is in the supporting material. γ depends on poorly understood block release and transport processes; research quantifying the effects of relief, climate, lithology, and vegetation on hillslope block delivery would be valuable.

Our results indicate that hillslope block fluxes may cause channel response to base level perturbations to deviate from the predictions of detachment-limited river erosion models. While the total sediment flux to the channel is important in providing erosive tools and alluvial cover, even small amounts of rock delivered as blocks can significantly alter channel evolution rates and patterns.

5.2. Implications for Landscape Transience

In a channel reach with uniform drainage area and uniform equilibrium gradient, theory predicts steady knickpoint retreat rates [*Whipple and Tucker*, 1999; *Crosby and Whipple*, 2006; *Berlin and Anderson*, 2007]. Our control experiment exhibits steady knickpoint migration (Figure 3a). Even when block flux from the hillslopes only reduces $1 - f_c$ and τ_* to 0.95 and 0.63 on average, respectively, the slope break delineating the upper reach from the steeper downstream reach migrates upstream at a slowed and unsteady rate (Figure 3b). In the rapid block flux experiment where $1 - f_c$ and τ_* drop to 0.89 and 0.45 on average, respectively, knickpoint retreat rates differ substantially from patterns predicted by the simple shear stress incision model (Figure 3c). Retreat rates become >50% slower on average and highly variable. While the imposed knickpoint in our control experiment retreats out of the model domain in less than 75 kyr (Figure 3a), our other experiments show that hillslope-derived blocks greatly slow knickpoint retreat (Figures 3b and 3c). Because knickpoint retreat is slow and base level lowering continues, the knickpoints become much steeper than in the control case. Our findings may account for differences between predicted and observed channel profiles along the Colorado Front Range. *Anderson et al.* [2006] modeled knickpoint retreat on Boulder Creek and found that the modeled profile showed greater upstream knickpoint propagation than the observed profile. We propose that blocks delivered to Boulder Creek have slowed knickpoint propagation.

Our results illustrate a potential complication in using knickpoints to extract information about landscape history. The along-profile position, steepness, and elevation of knickpoints are frequently employed to constrain timing and causes of landscape transience [*Kirby and Whipple*, 2012; *Miller et al.*, 2013]. While this information may be salvageable in landscapes without hillslope-derived blocks, our data indicate that the presence of blocks can alter knickpoint form and retreat rates. While comparison of knickpoint positions and elevations between drainage basins may still prove useful, the potential for significant variability in hillslope response to channel incision associated with variations in lithology or fracture density means that caution is necessary when inverting river profiles for landscape forcings.

6. Conclusions

We have modeled a negative feedback on river erosion in which rapid incision leads to an influx of large, immobile blocks from channel-adjacent hillslopes, which then inhibit further incision. This feedback is autogenic in landscapes with access to large grains and exerts a visible influence on the long-term evolution of channels even at block delivery rates low enough for the bed cover fraction to remain <0.5. Large, hillslope-derived grains inhibit downcutting primarily by reducing the shear stress available to erode bedrock and also by directly shielding the bed from erosion. The importance of erosion inhibition by blocks depends on the degree of coupling between the in-channel incision rate and block delivery by the hillslopes, as well as on the persistence of blocks in the channel (i.e., blocks must be infrequently mobile and not easily erodible). If incision drives delivery of large, competent blocks, the channel reach profile remains convex upward over 100 kyr timescales and upstream retreat of knickpoints is inhibited. Our experiments suggest that the degree of channel-hillslope connectivity governs whether channel reaches are linear, convex, or a combination of the two over 100 kyr timescales. The influence of hillslope-derived blocks on channel incision is supported by field data showing clusters of large grains in knickpoints of mountain rivers, as well as observations of anomalously high channel steepness along landslide-prone hillslopes [*Attal et al.*, 2015; *Bennett et al.*, 2016]. Our model provides a process-based explanation for spatial patterns of block size and position observed in the field (Figure 4). Attempts to use knickpoint position and elevation to reconstruct climatic or tectonic perturbations should strive to untangle landscape-scale signals from these autogenic channel-hillslope interactions. Block delivery in response to river incision may contribute to the preservation of high-elevation, low relief topography by inhibiting the transmission of perturbations up the drainage system. The block delivery feedback may significantly influence rates and patterns of landscape evolution in active orogens and other erosive environments.

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