Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL099049

Key Points:

- Erosion is reduced under debris-covered ice because of compounding effects between reduced surface melt and the subglacial environment
- Till accumulates under debris-covered ice because surface melt is suppressed by surface debris cover
- Debris cover on glaciers promotes subglacial fluvial conditions that can store sediment in alpine environments, altering erosional patterns

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

I. Delaney and L. S. Anderson,
ianarburua.delaney@unil.ch;
leif.anderson@utah.edu

Citation:

Delaney, I., & Anderson, L. S. (2022). Debris cover limits subglacial erosion and promotes till accumulation. *Geophysical Research Letters*, *49*, e2022GL099049. https://doi.org/10.1029/2022GL099049

Received 11 APR 2022
Accepted 22 JUN 2022

Ian Delaney and Leif S. Anderson contributed equally to this work.

Author Contributions:

Conceptualization: Ian Delaney, Leif S. Anderson
Formal analysis: Ian Delaney, Leif S. Anderson
Investigation: Ian Delaney, Leif S. Anderson
Methodology: Ian Delaney, Leif S. Anderson
Software: Ian Delaney, Leif S. Anderson
Validation: Ian Delaney, Leif S. Anderson

Debris Cover Limits Subglacial Erosion and Promotes Till Accumulation

Ian Delaney[1] and **Leif S. Anderson**[1,2]

[1]Institut des dynamiques de la surface terrestre (IDYST), Université de Lausanne, Bâtiment Géopolis, Lausanne, Switzerland,
[2]Department of Geology and Geophysics, University of Utah, Frederick Albert Sutton Building, Salt Lake City, UT, USA

Abstract Glaciers are commonly conceptualized as bodies composed of snow and ice. Yet, many glaciers contain a substantial amount of rock, especially those abutting steep mountains. Mountain slopes erode, depositing rocks on glaciers below. This loose rock (or debris) is buried in glaciers and melts out lower down creating a debris cover. Debris cover reduces ice melt, which changes the shape and movement of glaciers. Glacier movement, specifically basal sliding, efficiently sculpts landscapes. To date, we know little about the impacts of surface debris on conditions below glaciers. To help remedy this, we run numerical model simulations which show that debris-covered glaciers erode slower than glaciers unaffected by debris. Reduced melt under surface debris lowers sliding speeds and causes sediment to accumulate at the bed, potentially establishing conditions for surging. The influence of surface debris cover on the subglacial environment may hold substantial implications for alpine sediment storage and landscape evolution.

Plain Language Summary Glaciers are imagined as bodies composed entirely of snow and ice. But many glaciers, especially those in steep mountains contain a substantial amount of rock as well. Rocks are deposited on glaciers from steep mountain slopes above them. This loose rock (or debris), buried by snow, can completely cover glaciers' lower reaches as it melts out of the ice. Debris reduces melt, which changes the glacier shape and in turn how glaciers move down valley. To test how debris-covered glaciers erode and sculpt landscapes we use numerical models. Our simulations show that debris-covered glaciers erode landscapes at lower rates than glaciers unaffected by debris. The reduced amount of melt from debris cover causes glaciers to slide slower and causes sediment to accumulate under debris-covered ice, shielding bedrock from erosion. The tendency for debris-covered glaciers to build sediment layers at their bed may lead to the rapid speed up and advancement of glaciers, also known as surges. The influence of surface debris cover on the subglacial environment may hold substantial implications for alpine sediment storage and landscape evolution.

1. Introduction

Glaciers are efficient agents of erosion, which sculpt some of the most iconic landscapes on Earth. Glaciers modify mountain landscapes primarily by eroding their beds through the processes of abrasion and plucking (Herman et al., 2021; Iverson, 2012; Ugelvig et al., 2018). These processes are closely linked to ice dynamics through the sliding of glacial ice at the bed. The role of basal sliding and erosion has been elegantly explained for clean glaciers producing explanations for U-shaped valleys and flattened longitudinal profiles (Egholm et al., 2009; Harbor et al., 1988; Herman et al., 2011).

Glaciers also tend to steepen the headwalls above them through basal erosion (MacGregor et al., 2009) and also by encouraging processes such as frost cracking at the base of headwalls (Heimsath & McGlynn, 2008; Sanders et al., 2012). Hillslope erosion in mountain settings is mostly accomplished via landslides, rock falls, and avalanches all of which deposit loose rock (or debris) on glaciers below (e.g., Sanders et al., 2013; Scherler, 2014). Debris deposited high on glaciers is buried by accumulating snow and is then transported passively through the interior emerging low on the glacier (Figure 1). Where hillslope erosion rates are high, enough debris can melt out onto glacier surfaces that a nearly continuous mantle of debris forms.

Debris-covered glaciers are especially common in mountains steepened by active tectonics, like High Mountain Asia, Alaska, or the Andes (Herreid & Pellicciotti, 2020; Scherler et al., 2018). The most important effect of debris on glacier surfaces is that it insulates glacier ablation zones from melt (Östrem, 1959). Some features scattered on debris-covered glaciers like ponds, ice cliffs, and streams enhance surface melt locally (e.g., Benn

Writing – original draft: Ian Delaney, Leif S. Anderson
Writing – review & editing: Ian Delaney, Leif S. Anderson

et al., 2012; Sakai et al., 2002). These features increase area-averaged melt, but are not enough to overcome the melt-reducing effects of the more spatially extensive debris cover (e.g., L. S. Anderson et al., 2021).

To date, the impact of surface debris cover on basal conditions and erosion remains poorly understood. Debris-covered glaciers likely erode and transport sediment subglacially in distinct ways from clean glaciers. Debris reduces surface melt, glacier driving stress, and basal sliding, which is a direct control on glacial erosion. Debris cover also lengthens glaciers (e.g., L. S. Anderson & Anderson, 2016), extending the footprint over which glacial erosion occurs.

The distribution of till (sediment layers; Evans et al., 2006) under glaciers can control the erosion pattern and dynamics of glaciers unaffected by debris (e.g., Brinkerhoff et al., 2017; Delaney et al., 2019; de Winter et al., 2012). Under debris-covered portions of glaciers low surface melt reduces glacier surface slopes and meltwater input to the bed. This reduces the potential for subglacial rivers to transport sediment. Reduced erosion under debris-covered ice could alter the long-term landscape evolution in high-relief mountain settings.

Here, we seek to quantify how debris on the surface of glaciers affects basal erosion and sediment storage. We couple a glacier model that considers feedbacks between debris, ice dynamics, glacier melt, and climate with subglacial erosion and sediment transport models.

2. Methods

2.1. Debris-Covered Glacier Mass Balance and Ice Dynamics Model

We use the debris-covered glacier flowline model of L. S. Anderson and Anderson (2016) to represent the effects of debris cover on melt and ice dynamics on a generic valley glacier. The model uses a finite difference scheme and the shallow-ice approximation formulation as derived by Jarosch et al. (2013). Basal sliding is represented following the formulation of Kessler et al. (2006). Debris is deposited on the modeled glacier at a steady rate in the accumulation zone. The model advects debris in and on the glacier and modifies surface melt using the hyper-fit formulation relating melt to debris thickness:

$$\dot{b}_{debris} = \dot{b}\frac{h_*}{h_* + h_{debris}} \tag{1}$$

$\dot{b}_{debris}$ represents the surface ice melt under the debris layer, $\dot{b}$ represents ice melt independent of debris (and as it increases down glacier), h_* is the characteristic debris thickness (we use the global average value of 6.5 cm), h_{debris} is the thickness of debris on the glacier surface. In this formulation, for every 6.5 cm (the value of h_*) increase in debris thickness, melt rates are reduced by 50%. A backwasting ice cliff at the terminus removes debris from the modeled glacier. For a complete description of the model, refer to L. S. Anderson and Anderson (2016).

2.2. Subglacial Sediment Transport Model

To quantify subglacial sediment transport and erosion we use SUGSET (Delaney et al., 2019). This model operates by evolving a subglacial till-layer underlain by bedrock in response to subglacial erosion and sediment transport conditions along a glacier's flowline. To accomplish this, the model implements the mass conservation relationship

$$\frac{\partial H}{\partial t} w = \underbrace{-\frac{\partial Q_s}{\partial x}}_{\text{sediment transport}} + \underbrace{\dot{m}_t\, w}_{\text{bedrock erosion}}, \tag{2}$$

H represents the till height, w is the glacier width, Q_s is the sediment discharge, and $\dot{m}_t$ is till production rate from bedrock erosion.

The model calculates Q_s in response to hydraulic conditions in a subglacial conduit using the Engelund and Hansen (1967) total sediment transport relationship, which largely depends on subglacial water velocity. SUGSET considers sediment transport in both supply- and transport-limited regimes by reducing sediment mobilization when the till-height is below 3×10^{-3} m.

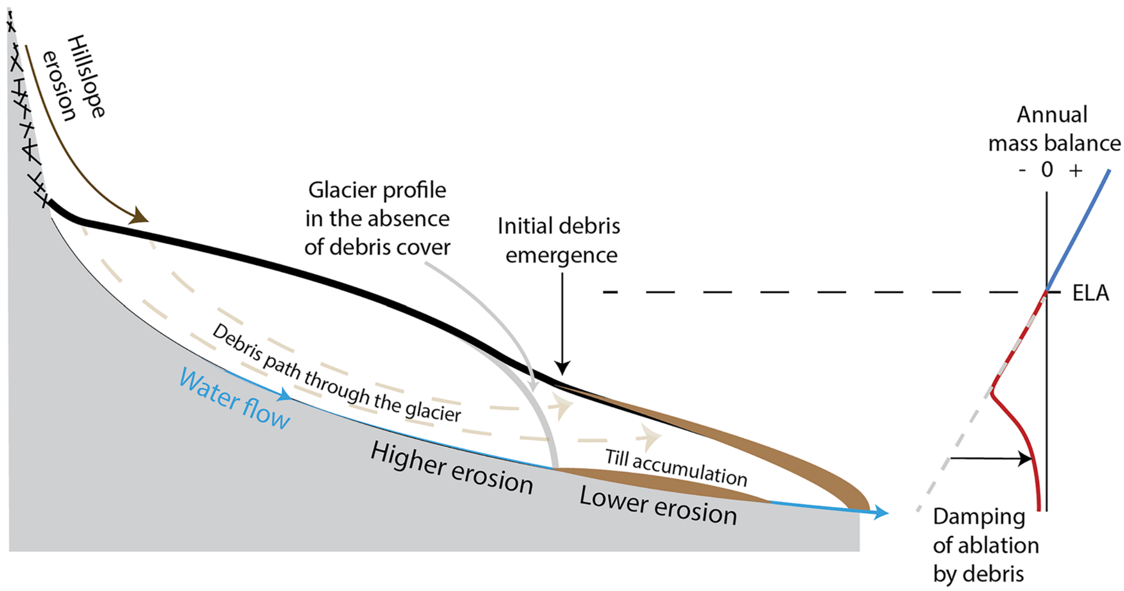

Figure 1. The debris-covered glacier system including subglacial water flow and sediment transport. Debris deposited in the accumulation zone of the glacier is advected through the glacier interior. Debris emerges on the glacier surface reducing melt rates. Reduced surface melt rates change the glacier shape, which promotes sediment deposition and reduces basal erosion on the lower sections. In steady state, the increasing glacier surface slope, typical for debris-free and debris-covered glaciers, near the terminus promotes till removal. Note that simulations use a linear bed, instead of the curved one shown in this schematic.

We limit bedrock erosion with regard to till height H in Equation 2 to account for armoring of the glacier bed by till (e.g., Brinkerhoff et al., 2017),

$$\dot{m}_t = \dot{\epsilon}\left(1 - \frac{H}{H_{\max}}\right), \tag{3}$$

where $H_{\max}$ is the maximum till height parameter that we estimate, beyond which no further bedrock erosion occurs. $\dot{\epsilon}$ is the potential bedrock erosion rate, based on an empirical relationship between glacier sliding velocity and bedrock erosion (Herman et al., 2015), defined as

$$\dot{\epsilon} = K_g\,|u_b|^l. \tag{4}$$

Here K_g and l are erosional constants (Herman et al., 2015) and u_b is the basal sliding velocity. For a complete model description refer to Delaney et al. (2019).

2.3. Model Setup and Numerical Experiments

We consider a clean ice scenario (*CLEAN*) and a debris-covered scenario (*DEBRIS*) to evaluate erosion and subglacial sediment transport for each. *CLEAN* and *DEBRIS* scenarios are forced with identical numerical parameters and grid-spacing. They have identical debris-free mass balance profiles, flow factors, sliding coefficients, and maintain constant widths of 1 km along their lengths. Both lie on beds with a uniform 5° slope. The only difference is that in the *DEBRIS* case a steady flux of debris is deposited on the glacier surface in the accumulation zone near the headwall. We neglect the role of debris deposited on the ablation zone as it is typically deposited near the edge of glaciers and is advected to the margin by flow away from the centerline (L. S. Anderson & Anderson, 2018; Hooke, 1991). Debris is advected through the glacier, melts out in the ablation zone, reduces surface melt, and lengthens the *DEBRIS* glacier relative to the *CLEAN* glacier. The linear bed isolates the role of debris on glacier dynamics and does not conflate bed shape with the effects of the debris (L. S. Anderson & Anderson, 2016).

The glacier model is run to a steady state for both the *DEBRIS* and *CLEAN* glaciers, then values of annual melt, surface elevation, bed elevation, and sliding velocity are imported into SUGSET using a splining algorithm. Values of annual surface melt are translated into a meltwater source term and scaled so melt occurs

10.1029/2022GL099049

Table 1
Erosion Rate (mm a^{-1}) Comparison Between Clean Ice Scenario and Debris-Covered Scenario Simulations

	CLEAN	*DEBRIS*	Relative change
n	1000	1000	
Erosion rate (mean) without till effects (Equation 4)	7.1	5.5	−22.5%
25th and 75th quantile	2.3–10.1	1.9–7.7	
Erosion rate (mean) with till effects (Equation 3)	3.3	2.4	−27.3%
25th and 75th quantile	1.8–4.1	1.4–2.7	

Note:Differences between *DEBRIS* and *CLEAN* outputs are significant at the <0.0001 level (Mann-Whitney).

three melt-season months per year. We tune the Darcy-Weissbach friction factor and the Hooke angle (Delaney et al., 2019) so that water velocities along the *CLEAN* glaciers are 0.6–0.7 m s^{-1}, inline with dye-tracing observations on clean alpine glaciers (e.g., Werder et al., 2010).

The model is run with a steady forcing over 100 years with no seasonal or diurnal variations, in order to establish the representative effects of subglacial sediment transport over a prolonged period. We set the initial till height in the model to 5 cm.

No sediment is allowed into the glacier at its upper end. This is conservative, as rockfall from glacier headwalls can introduce sediment to the glacier bed via bergschrunds and crevasses (Sanders et al., 2013). We also neglect the potential for englacial debris to be transferred to the subglacial system or vice versa.

SUGSET is run 2,000 times in total, 1,000 times for each of the *CLEAN* and *DEBRIS* glaciers. In these simulations we vary sediment grain size (D_m; range: 0.1–2 cm) and the erosional constants K_g (range: 10^{-6}–10^{-4}) and l (range: 1.5–4). The same random parameter combinations are applied to both *CLEAN* and *DEBRIS* test cases (Figure S1 in Supporting Information S1). For all simulations, the average bedrock erosion rates across the glacier are between 1 and 20 mm a^{-1}, which span the typical erosion rates from glaciers in high-relief mountain ranges (Hallet et al., 1996).

3. Results

Our simulations reveal consistent differences between the *DEBRIS* and *CLEAN* cases. Differences are evident in the patterns of erosion as well as the volumes of sediment produced and transported.

3.1. Reduced Erosion Rates Under Debris-Covered Ice

The *DEBRIS* simulations (compared to *CLEAN* simulations) exhibit lower erosion rates with or without the effects of till armoring (Table 1). Erosion rates that ignore till layer effects and depend only on sliding velocity (Equation 4), are on average 22% (1.5 mm a^{-1}) higher in *CLEAN* case than the *DEBRIS* case. With till shielding included, erosion rates are 29% higher (1 mm a^{-1}) in the *CLEAN* case than the *DEBRIS* case. The armoring of the bed by till reduces bedrock erosion limiting the further production of till (Equation 3).

The melt-reducing effects of debris extends glaciers down valley. Owing to the larger area over which *DEBRIS* erodes the total volume of rock eroded in *DEBRIS* exceeds *CLEAN* (without including till shielding effects: *DEBRIS*: 83, 700 m^3 a^{-1}, *CLEAN*: 74, 500 m^3 a^{-1}, $p < 0.0001$, with till shielding effects: *DEBRIS*: 36, 900 m^3 a^{-1}, *CLEAN*: 35, 900 m^3 a^{-1}, $p < 0.0001$). This occurs despite *DEBRIS* eroding at a slower rate (Figure 2, Table S1 in Supporting Information S1).

Below the upper reaches of the glacier in both the *CLEAN* and *DEBRIS* cases, basal erosion exceeds sediment transport leading to till accumulation (Figure 3). Till does not accumulate near the termini of either the *CLEAN* or *DEBRIS* case. It is important to note that the steepening of the glacier front near the toe of the steady state *CLEAN* and *DEBRIS* glaciers increases sediment transport capacity causing till to be evacuated. As discussed later, the changes terminal geometry due to negative mass balance can decrease surface slopes (e.g., Huss et al., 2010; Jóhannesson, 1997) and encourage till deposition near the toe (e.g., Beaud et al., 2018).

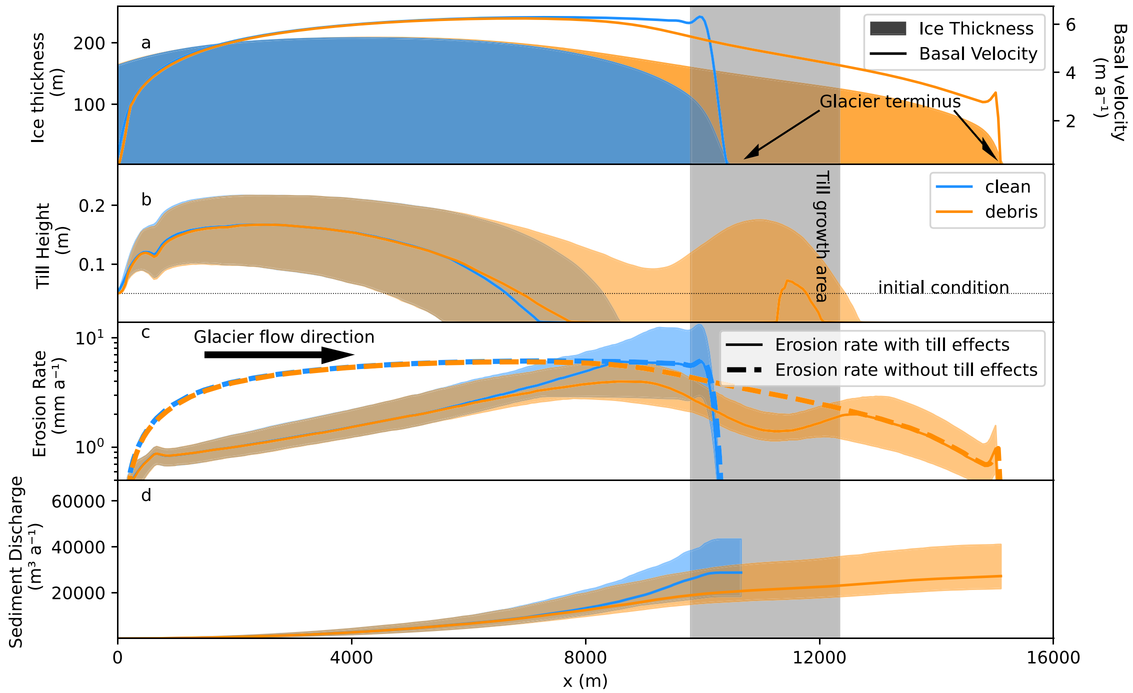

Figure 2. Model output from the ensemble runs for the clean ice scenario (*CLEAN*) (blue) and debris-covered scenario (*DEBRIS*) (orange) cases. Reduced melt due to debris cover in the *DEBRIS* cases causes the glacier to extend further compared to *CLEAN* (a). *DEBRIS* and *CLEAN* cases have similar basal velocities on the upper parts of the glaciers but *DEBRIS* values are reduced on the lower reaches where the glacier extends beyond *CLEAN*. Till height underneath the upper glaciers remains similar between the two cases. The till is relatively thick here due to the reduced melt water input at high elevations. For *CLEAN* the till height decreases toward the terminus, while for *DEBRIS*, till growth can occur below the lower glacier as a result of stabilized sediment transport capacity relative to sediment availability there. Both *DEBRIS* and *CLEAN* glaciers experience similar erosion patterns with and without the till effects on their upper reaches, while erosion decreases under the debris cover especially where debris is thin (c). The till layer on the upper reaches of the glacier limits erosion, insulating the bed from erosion, due to low melt inputs (c). Despite the differences in geometry and melt patterns, sediment discharge monotonically increases down glacier and sediment discharge quantities are roughly equal at the termini in both *CLEAN* and *DEBRIS* cases (d). Solid lines represent median values while the shaded regions span the 75th and 25th percentiles (b–d).

In the *DEBRIS* case, till accumulates under the debris-covered ice in 491 of the 1,000 runs. Till growth tends to occur downglacier from where debris emerges on the glacier surface (Figure 3). Till growth here does not occur under debris-covered ice in simulations with low erosion rates and small sediment grain sizes (without till growth 0.81 cm and with till growth 1.31 cm), because the sediment production is small compared to the sediment transport capacity across entire simulated glacier beds (Delaney et al., 2019).

3.2. Reduced Melt and Surface Slopes Perturb Basal Erosion Patterns Under Debris-Covered Ice

In the *DEBRIS* case, debris cover reduces melt and surface slopes leading to reduced erosion rates. The first order cause of this is the reduction of surface slope and driving stresses under debris cover. This leads to lower average sliding speeds and thus erosion rates (via Equation 4) than in the *CLEAN* case (Figure 2).

The tendency for till layers to form under debris-covered ice and not under clean ice allows for further differences in erosion rates between *DEBRIS* and *CLEAN*. At about 8,000 m down glacier in the *CLEAN* case, sediment transport exceeds sediment production, and till is no longer present so sediment transport enters a supply-limited regime, where sediment transport capacity far exceeds the available sediment. This occurs because of the linear increase in surface melt rate down glacier in *CLEAN* which causes subglacial water discharge, surface slopes, and the sediment transport capacity to increase rapidly towards the terminus.

Near the terminus in the *CLEAN* case, debris emerges on the glacier surface in *DEBRIS*, lowering surface melt and surface slopes (Figure 3). Subglacial till accumulates because of excess sediment production compared to sediment transport capacity (Delaney et al., 2019). Essentially, sediment is eroded but the subglacial hydrological system is unable to transport it away. This occurs because debris cover: (a) reduces water delivery from the

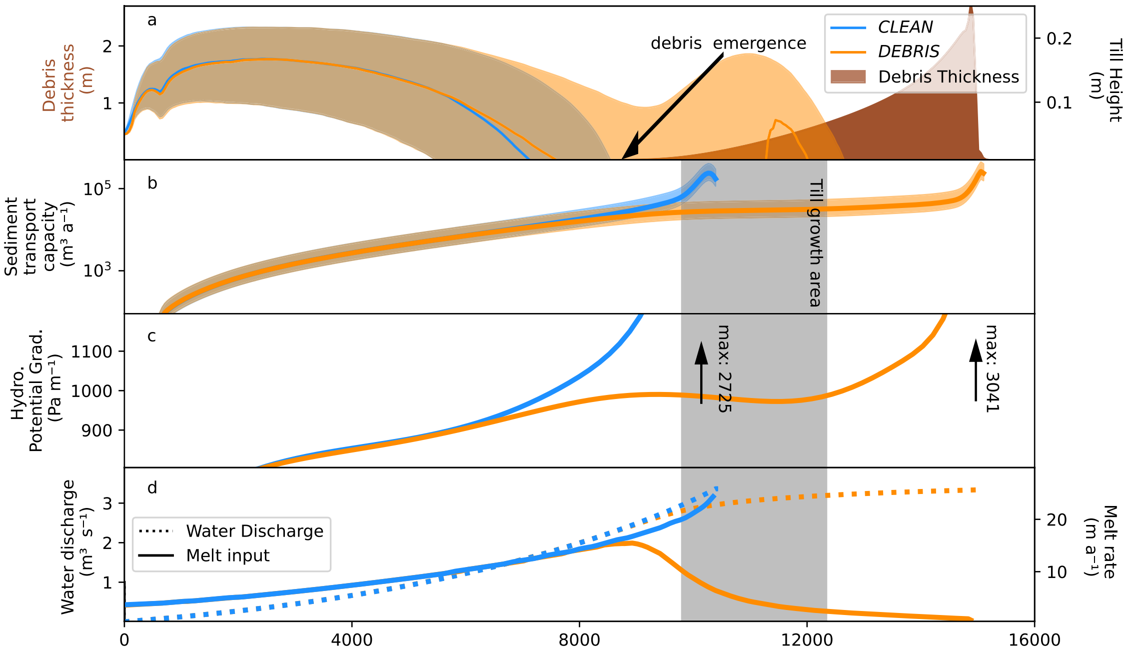

Figure 3. Hydraulic processes controlling subglacial till layer height. (a) Till accumulation under debris cover is caused by sediment deposition due to stabilization in (b) sediment transport capacity down glacier with increasing sediment availability (given by till height). This decrease begins where debris emerges onto the glacier surface. The debris cover reduces the (d) melt rate and (c) hydraulic potential gradient. The reduced melt rate causes water discharge in the debris-covered scenario to increase slower downglacier under the debris-covered ice. (c) Increased hydraulic gradient at the terminus causes (b) sediment transport capacity to increase therefore preventing till accumulation.

surface to the bed and (b) lowers surface slopes. Both processes stabilize basal water velocities and sediment transport capacity, resulting in till accumulation (Figure 3c).

The reduction of surface slope due to debris cover is not enough to cause till accumulation in our model set up. We ran 100 simulations that use the ice geometry of the *DEBRIS* case but with the surface melt pattern (linearly increasing down glacier) of the *CLEAN* case (Figure S2 in Supporting Information S1). Till layers did not accumulate under the debris-covered ice in any of these simulations. This suggests that the melt-reducing effects of debris on water discharge at the bed are more important than the surface slope lowering effects of debris cover when it comes to till accumulation.

4. Discussion

Debris cover on glacier surfaces has a compounding effect on the subglacial environment, by reducing surface meltwater and lowering surface slopes. These debris-specific effects, in turn, reduce glacier sliding speeds, melt input to the bed, and subglacial hydraulic gradients, all of which lower bedrock erosion and promote till accumulation.

4.1. Experimental Limitations

We assume that a steady debris input rate captures the typical surface mass balance and ice dynamical state of debris-covered glaciers. Simulations of the debris-covered glacier model alone, and forced by stochastic debris input produce results that vary around a similar mean state to simulations forced by a steady debris input. We therefore expect that a more realistic, stochastic debris delivery forcing will not change our conclusions about connections between debris and the subglacial environment.

Our model design assumes that subglacial sediment transport is dominated by water flow. While this is a common assertion (e.g., Alley et al., 1997; Riihimaki et al., 2005), the role of further sediment transport processes under debris-covered ice like the entrainment of sediment in the glacier sole (e.g., Iverson, 1993) or subglacial till deformation (e.g., Hansen & Zoet, 2022) should be explored.

Additionally, we neglect seasonal variations in melt, yet, the subglacial water velocities in the model are high compared to those observed in other studies (e.g., Werder & Funk, 2009). Independent of climate variations, the processes identified here show debris cover will still tend to limit subglacial erosion.

4.2. Indications That the Experimental Setup Is Conservative

Our simulations are conservative in that they favor till removal from below debris-covered ice. We assume that all surface melt reaches the bed. If we reduced the volume of surface melt reaching the bed, thicker and more extensive till layers would form. The pathways for surface meltwater to reach the bed (Fountain & Walder, 1998) under debris cover are likely reduced. Debris cover lowers surface velocities and spatial gradients in velocity (L. S. Anderson & Anderson, 2018), which limits crevasse formation. Dye tracing experiments suggest that most of the meltwater from sub-debris melt and melt hot spots (e.g., ice cliffs and ponds) does not reach the bed (Fyffe et al., 2019; Miles et al., 2019). Lastly, evidence suggests that meltwater can leave the base and termini of debris-covered glaciers through groundwater flow (Hambrey et al., 2008), where sediment transport ceases.

Debris-covered glaciers can also form large impounding latero-frontal moraines built from the wasting of surface debris off glacial margins (see Ngozumpa and Khumbu Glaciers; e.g., Hambrey et al., 2008). Moraines provide topographic confinement and can create moraine-dammed lakes, both of which flatten the hydraulic gradient under glaciers (Cuffey & Paterson, 2010). This will reduce subglacial sediment transport capacity, further encouraging till accumulation that armors the bed.

4.3. Thin Debris Cover Most Readily Leads to Till Deposition

Based on our simulations, sediment deposition most readily occurs where surface debris is thin and thickens down glacier. This occurs because of the shape of the melt-debris thickness relationship (Equation 1; Figure 1; Östrem, 1959). Slightly increasing the thickness of thinner debris reduces melt much more effectively than slightly increasing the thickness of thicker debris (Figure 1). More broadly, this means that thin debris causes larger reductions in surface melt rates, locally lowering glacier surface slopes more rapidly down glacier than where debris is thick (L. S. Anderson & Anderson, 2016). Where debris is thin the hydraulic potential gradient will be reduced most rapidly downstream, tending to promote till accumulation.

4.4. Debris Input Rate and Deposition Location

The results here represent a range of erosional and sediment transport conditions for a single glacier, with a single steady debris input rate and debris input location. As debris input into glaciers increases we anticipate that subglacial till layers will tend to thicken and lengthen. If debris input increases, the debris-covered portion of the glacier would lengthen, decreasing the relative length of the glacier affected by the terminal steepening and till removal effect described above. Additionally, greater quantities of surface debris will thicken more rapidly on the glacier surface creating a more pronounced change in the hydraulic gradient and decline in meltwater production (L. S. Anderson & Anderson, 2016). For these reasons we expect the till layer to thicken and expand as debris input increases to glaciers.

The closer debris is deposited on the glacier to the headwall, the further down glacier the debris will emerge and the more pronounced the change in glacier surface melt rate and slope will be (L. S. Anderson & Anderson, 2016). As a result, thicker till layers may form. The other end member is the case in which debris covers the entire ablation zone (e.g., Lirung Glacier, Nepal). In this case there may be no transition from clean ice to debris-covered ice, so hydraulic potential will not rapidly change down-glacier as in the *DEBRIS* case presented here (Section 4.3). However, in this case minimal surface melt would still reduce subglacial water flow, again promoting till accumulation (Benn et al., 2017; Gulley & Benn, 2007).

4.5. Impact of Subglacial Sediment Accumulation on Glacier Dynamics

Our results show that surface debris cover can impact subglacial processes. Previous work has suggested that reduced water velocities on the adverse slope of subglacial overdeepenings can result in sediment deposition there, and the armoring of the bed from erosion (Alley et al., 2003; Creyts et al., 2013). Our results suggest that sediment deposition and armoring of the glacier bed by till can also occur due to variable surface conditions caused by debris cover. In turn, conditions on glacier surfaces may also result in armoring of the glacier bed and reduced glacier erosion. Similar to processes influencing the formation of eskers (Beaud et al., 2018; I. Hewitt & Creyts, 2019), our simulations show that subglacial sediment deposition (with or without debris cover) depends in part on sediment supply to the subglacial drainage system through the bedrock erosion rate (Figure S1 and Table S1 in Supporting Information S1).

The subglacial sediment deposited below debris cover may pre-condition glaciers for unstable flow. Sediment and till layers are observed below many surging glaciers globally (Harrison & Post, 2003). Failure can occur in till layers, potentially initiating surges (e.g., Minchew & Meyer, 2020). It could well be that debris cover itself promotes surging behavior by encouraging sediment deposition. For 19 surging glaciers in the Karakorum, it was found that more heavily debris-covered glaciers were more likely to surge (Barrand & Murray, 2006). Indeed, the process connections identified here are consistent with regional-scale observations: 187 of 221 surging glaciers (>84%) identified in the Karakorum Mountains are heavily debris-covered (Bhambri et al., 2017).

Landslides deposited on glaciers can have similar, yet more punctuated, effects on glaciers than the continuous debris covers modeled here. Landslides deposited on glacier ablation zones add weight to glaciers while also locally reducing surface melt and surface slopes (Shugar et al., 2012; Vacco et al., 2010). Large landslides on glaciers have been linked to surges (Gardner & Hewitt, 1990; K. Hewitt, 2009). Further research is needed to evaluate the role of loading by landslides and the impact melt reduction from landslides on the subglacial system.

4.6. Debris-Covered Glaciers and Alpine Landscape Evolution

Our simulations show that debris cover and its effects on glacier geometry could enhance the flattening of valley bottoms over millennia. Cirques with steep headwalls and flat valley bottoms can form due to glacier sliding and basal erosion independent of debris cover (e.g., R. S. Anderson et al., 2006; MacGregor et al., 2009). Our results suggest that glacier sliding and till accumulation below debris-covered ice will further flatten glacier beds, likely in ways distinct from what we expect from glaciers without debris cover (e.g., Hooke, 1991; MacGregor et al., 2000).

Over sufficiently long time periods, flatter glacial valleys could result in slower flowing glaciers due to reduced bedslopes. This will increase debris thickness (L. S. Anderson & Anderson, 2018), and through the reduced erosion effects highlighted in this paper, erosion under the debris cover will be further reduced. In time, this leads to longer and longer debris-covered glaciers with thicker and thicker debris with low sliding speeds and thick till packages beneath them. Indeed in the Mount Everest (Khumbu) region of Nepal, longer debris-covered glaciers tend to have shallower surface slopes than clean glaciers (Scherler, 2014).

Debris-covered glaciers facilitate the storage of sediment high in alpine landscapes. Our simulations show why subglacial sediment is likely to be stored below debris-covered glaciers (Hambrey et al., 2008). Sediment can also reside in the alpine landscapes for extended periods due to landslide damming (Korup et al., 2010) and sedimentation in glacially-carved bedrock lakes (e.g., Anselmetti et al., 2007). More generally, alpine sediment storage creates lags in sediment routing (Blöthe & Korup, 2013) and complicates the identification of links between glacial erosion and climate change (Jonell et al., 2018; Lai & Anders, 2021; Seguinot & Delaney, 2021).

As debris-covered glaciers thin in response to rising temperatures, their surface profiles remain concave-up, their surface slopes lower even more, their velocities decrease, and their debris covers expand up glacier (Dehecq et al., 2019; Scherler et al., 2011). This leads to the expectation that, for debris-covered glaciers, subglacial till layers could thicken and propagate up glacier in response to modern warming. When substantial glacier retreat and thinning do occur, we anticipate that exposed expanses of both supra- and sub-glacially derived sediment will be available for transport (e.g., Delaney & Adhikari, 2020). As climate warms, this sediment stored high in alpine landscapes will likely contribute to increased river sediment discharge from glacierized regions (e.g., Delaney et al., 2018; Li et al., 2021; Micheletti et al., 2015).

5. Conclusions

We revealed new processes controlling alpine landscape evolution by coupling a debris-covered glacier with a subglacial sediment transport model. Our simulations show that bedrock erosion is likely reduced below debris-covered ice. This occurs because debris cover reduces sliding speeds and therefore bedrock erosion rates. Debris cover also promotes subglacial till deposition that can protect the underlying bedrock from erosion.

The accumulation of till under debris-covered ice is caused by two effects stemming from the strong insulating effects of debris cover. (a) Debris cover reduces meltwater delivery to the bed which reduces the rate of increase of subglacial water discharge and sediment transport capacity down glacier. (b) Debris cover also lowers glacier surface slopes which reduces sediment transport capacity relative to sediment availability. These effects together promote the deposition of till and the damping of erosion under debris-covered ice.

Debris cover, by creating the conditions for subglacial till formation, may increase the propensity for glaciers to surge. This connection between the supraglacial and subglacial environments may explain why a high percentage of surging glaciers in the Karakorum are heavily debris covered (Bhambri et al., 2017).

Reduced erosion under debris cover leads to the expectation that over millennia debris-covered glaciers will lower bed slopes in ways distinct from debris-free glaciers. High subglacial erosion rates up glacier from the debris cover and reduced erosion under debris cover can cause long-term bed slope lowering. Perhaps this newly identified erosional pattern between clean and debris-covered ice can even form overdeepenings.

This work highlights how hillslope, glacial, and subglacial processes interact to shape alpine landscapes and store sediment. It is essential that we continue to quantify and model these processes if we are to anticipate the coming changes to alpine landscapes as they respond to climate change.

Data Availability Statement

Runner scripts and files with the debris-covered glacier model output used to conduct the experiments are available at https://doi.org/10.5281/zenodo.6794728. This repository also contains the SUGSET version used along with examples.

Acknowledgments
I. Delaney acknowledges funding from SNF Project No. PZ00P2_202024. L. S. Anderson acknowledges funding from ERC Grant No. 851614. We are grateful for support from F. Herman and G. King in completing this research. I. S. Evans and an anonymous reviewer provided thoughtful comments that substantially improved the manuscript. Both authors contributed equally to this work.

References

Alley, R. B., Cuffey, K. M., Evenson, E. B., Strasser, J. C., Lawson, D. E., & Larson, G. J. (1997). How glaciers entrain and transport basal sediment: Physical constraints. *Quaternary Science Reviews*, *16*(9), 1017–1038. https://doi.org/10.1016/S0277-3791(97)00034-6

Alley, R. B., Lawson, D. E., Larson, G. J., Evenson, E. B., & Baker, G. S. (2003). Stabilizing feedbacks in glacier-bed erosion. *Nature*, *424*(6950), 758–760. https://doi.org/10.1038/nature01839

Anderson, L. S., & Anderson, R. S. (2016). Modeling debris-covered glaciers: Response to steady debris deposition. *The Cryosphere*, *10*(3), 1105–1124. https://doi.org/10.5194/tc-10-1105-2016

Anderson, L. S., & Anderson, R. S. (2018). Debris thickness patterns on debris-covered glaciers. *Geomorphology*, *311*, 1–12. https://doi.org/10.1016/j.geomorph.2018.03.014

Anderson, L. S., Armstrong, W. H., Anderson, R. S., Scherler, D., & Petersen, E. (2021). The causes of debris-covered glacier thinning: Evidence for the importance of ice dynamics from Kennicott Glacier, Alaska. *Frontiers of Earth Science*, *723*, 1–19. https://doi.org/10.3389/feart.2021.680995

Anderson, R. S., Molnar, P., & Kessler, M. A. (2006). Features of glacial valley profiles simply explained. *Journal of Geophysical Research*, *111*(F1), F01004. https://doi.org/10.1029/2005JF000344

Anselmetti, F. S., Bühler, R., Finger, D., Girardclos, S., Lancini, A., Rellstab, C., & Sturm, M. (2007). Effects of Alpine hydropower dams on particle transport and lacustrine sedimentation. *Aquatic Sciences*, *69*(2), 179–198. https://doi.org/10.1007/s00027-007-0875-4

Barrand, N. E., & Murray, T. (2006). Multivariate controls on the incidence of glacier surging in the Karakoram Himalaya. *Arctic Antarctic and Alpine Research*, *38*(4), 489–498. https://doi.org/10.1657/1523-0430(2006)38[489:MCOTIO]2.0.CO;2

Beaud, F., Venditti, J., Flowers, G., & Koppes, M. (2018). Excavation of subglacial bedrock channels by seasonal meltwater flow. *Earth Surface Processes and Landforms*, *43*(9), 1960–1972. https://doi.org/10.1002/esp.4367

Benn, D., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L., et al. (2012). Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. *Earth-Science Reviews*, *114*(1), 156–174. https://doi.org/10.1016/j.earscirev.2012.03.008

Benn, D., Thompson, S., Gulley, J., Mertes, J., Luckman, A., & Nicholson, L. (2017). Structure and evolution of the drainage system of a Himalayan debris-covered glacier, and its relationship with patterns of mass loss. *The Cryosphere*, *11*(5), 2247–2264. https://doi.org/10.5194/tc-11-2247-2017

Bhambri, R., Hewitt, K., Kawishwar, P., & Pratap, B. (2017). Surge-type and surge-modified glaciers in the Karakoram. *Scientific Reports*, *7*(1), 15391. https://doi.org/10.1038/s41598-017-15473-8

Blöthe, J. H., & Korup, O. (2013). Millennial lag times in the Himalayan sediment routing system. *Earth and Planetary Science Letters*, *382*, 38–46. https://doi.org/10.1016/j.epsl.2013.08.044

Brinkerhoff, D., Truffer, M., & Aschwanden, A. (2017). Sediment transport drives tidewater glacier periodicity. *Nature Communications*, *8*(1), 1–8. https://doi.org/10.1038/s41467-017-00095-5

Creyts, T. T., Clarke, G. K. C., & Church, M. (2013). Evolution of subglacial overdeepenings in response to sediment redistribution and glaciohydraulic supercooling. *Journal of Geophysical Research: Earth Surface*, *118*(2), 423–446. https://doi.org/10.1002/jgrf.20033

Cuffey, K. M., & Paterson, W. S. B. (2010). *The physics of glaciers* (4th edn.). Butterworth-Heinemann.

Dehecq, A., Gourmelen, N., Gardner, A., Brun, F., Goldberg, D., Nienow, P., et al. (2019). Twenty-first century glacier slowdown driven by mass loss in High Mountain Asia. *Nature Geoscience*, *12*(1), 22–27. https://doi.org/10.1038/s41561-018-0271-9

Delaney, I., & Adhikari, S. (2020). Increased subglacial sediment discharge during century scale glacier retreat: Consideration of ice dynamics, glacial erosion and fluvial sediment transport. *Geophyiscal Research Letters*, *47*(7), e2019GL085672. https://doi.org/10.1029/2019GL085672

Delaney, I., Bauder, A., Huss, M., & Weidmann, Y. (2018). Proglacial erosion rates and processes in a glacierized catchment in the Swiss Alps. *Earth Surface Processes and Landforms*, *43*(4), 765–778. https://doi.org/10.1002/esp.4239

Delaney, I., Werder, M., & Farinotti, D. (2019). A numerical model for fluvial transport of subglacial sediment. *Journal of Geophysical Research: Earth Surface*, *124*(8), 2197–2223. https://doi.org/10.1029/2019JF005004

de Winter, I., Storms, J., & Overeem, I. (2012). Numerical modeling of glacial sediment production and transport during deglaciation. *Geomorphology*, *167*, 102–114. https://doi.org/10.1016/j.geomorph.2012.05.023

Egholm, D., Nielsen, S., Pedersen, V., & Lesemann, J.-E. (2009). Glacial effects limiting mountain height. *Nature*, *460*(7257), 884–887. https://doi.org/10.1038/nature08263

Engelund, F., & Hansen, E. (1967). *A monograph on sediment transport in alluvial streams (Tech. Rep.)*. Technical University of Denmark.

Evans, D. J. A., Phillips, E. R., Hiemstra, J. F., & Auton, C. A. (2006). Subglacial till: Formation, sedimentary characteristics and classification. *Earth-Science Reviews*, *78*(1–2), 115–176. https://doi.org/10.1016/j.earscirev.2006.04.001

Fountain, A. G., & Walder, J. S. (1998). Water flow through temperate glaciers. *Reviews of Geophysics*, *36*(3), 299–328. https://doi.org/10.1029/97rg03579

Fyffe, C. L., Brock, B. W., Kirkbride, M. P., Mair, D. W. F., Arnold, N. S., Smiraglia, C., et al. (2019). Do debris-covered glaciers demonstrate distinctive hydrological behaviour compared to clean glaciers? *Journal of Hydrology*, *570*, 584–597. https://doi.org/10.1016/j.jhydrol.2018.12.069

Gardner, J. S., & Hewitt, K. (1990). A surge of Bualtar Glacier, Karakoram Range, Pakistan: A possible landslide trigger. *Journal of Glaciology*, *36*(123), 159–162. https://doi.org/10.3189/s0022143000009394

Gulley, J., & Benn, D. (2007). Structural control of englacial drainage systems in Himalayan debris-covered glaciers. *Journal of Glaciology*, *53*(182), 399–412. https://doi.org/10.3189/002214307783258378

Hallet, B., Hunter, L., & Bogen, J. (1996). Rates of erosion and sediment evacuation by glaciers: A review of field data and their implications. *Global and Planetary Change*, *12*(1), 213–235. https://doi.org/10.1016/0921-8181(95)00021-6

Hambrey, M. J., Quincey, D. J., Glasser, N. F., Reynolds, J. M., Richardson, S. J., & Clemmens, S. (2008). Sedimentological, geomorphological and dynamic context of debris-mantled glaciers, Mount Everest (Sagarmatha) region, Nepal. *Quaternary Science Reviews*, *27*(25), 2361–2389. https://doi.org/10.1016/j.quascirev.2008.08.010

Hansen, D. D., & Zoet, L. K. (2022). Characterizing sediment flux of deforming glacier beds. *Journal of Geophysical Research: Earth Surface*, *127*(4), e2021JF006544. https://doi.org/10.1029/2021JF006544

Harbor, J., Hallet, B., & Raymond, C. (1988). A numerical model of landform development by glacial erosion. *Nature*, *333*(6171), 347–349. https://doi.org/10.1038/333347a0

Harrison, W., & Post, A. (2003). How much do we really know about glacier surging? *Annals of Glaciology*, *36*, 1–6. https://doi.org/10.3189/172756403781816185

Heimsath, A. M., & McGlynn, R. (2008). Quantifying periglacial erosion in the Nepal high Himalaya. *Geomorphology*, *97*(1–2), 5–23. https://doi.org/10.1016/j.geomorph.2007.02.046

Herman, F., Beaud, F., Champagnac, J., Lemieux, J. M., & Sternai, P. (2011). Glacial hydrology and erosion patterns: A mechanism for carving glacial valleys. *Earth and Planetary Science Letters*, *310*(3), 498–508. https://doi.org/10.1016/j.epsl.2011.08.022

Herman, F., Beyssac, O., Brughelli, M., Lane, S. N., Leprince, S., Adatte, T., et al. (2015). Erosion by an Alpine glacier. *Science*, *350*(6257), 193–195. https://doi.org/10.1126/science.aab2386

Herman, F., De Doncker, F., Delaney, I., Prasicek, G., & Koppes, M. (2021). The impact of glaciers on mountain erosion. *Nature Reviews Earth & Environment*, *2*(6), 422–435. https://doi.org/10.1038/s43017-021-00165-9

Herreid, S., & Pellicciotti, F. (2020). The state of rock debris covering Earth's glaciers. *Nature Geoscience*, *13*(9), 621–627. https://doi.org/10.1038/s41561-020-0615-0

Hewitt, I., & Creyts, T. (2019). A model for the formation of eskers. *Geophysical Research Letters*, *46*(12), 6673–6680. https://doi.org/10.1029/2019GL082304

Hewitt, K. (2009). Rock avalanches that travel onto glaciers and related developments, Karakoram Himalaya, Inner Asia. *Geomorphology*, *103*(1), 66–79. https://doi.org/10.1016/j.geomorph.2007.10.017

Hooke, R. L. (1991). Positive feedbacks associated with erosion of glacial cirques and overdeepenings. *The Geological Society of America Bulletin*, *103*(8), 1104–1108. https://doi.org/10.1130/0016-7606(1991)103<1104:PFAWEO>2.3.CO;2

Huss, M., Jouvet, G., Farinotti, D., & Bauder, A. (2010). Future high-mountain hydrology: A new parameterization of glacier retreat. *Hydrology and Earth System Sciences*, *14*(5), 815–829. https://doi.org/10.5194/hess-14-815-2010

Iverson, N. R. (1993). Regelation of ice through debris at glacier beds: Implications for sediment transport. *Geology*, *21*(6), 559–562. https://doi.org/10.1130/0091-7613(1993)021<0559:ROITDA>2.3.CO;2

Iverson, N. R. (2012). A theory of glacial quarrying for landscape evolution models. *Geology*, *40*(8), 679–682. https://doi.org/10.1130/G33079.1

Jarosch, A., Schoof, C., & Anslow, F. (2013). Restoring mass conservation to shallow ice flow models over complex terrain. *The Cryosphere*, *7*(1), 229–240. https://doi.org/10.5194/tc-7-229-2013

Jóhannesson, T. (1997). The response of two Icelandic glaciers to climatic warming computed with a degree-day glacier mass-balance model coupled to a dynamic glacier model. *Journal of Glaciology*, *43*(144), 321–327. https://doi.org/10.3189/S0022143000003270

Jonell, T. N., Owen, L. A., Carter, A., Schwenniger, J.-L., & Clift, P. D. (2018). Quantifying episodic erosion and transient storage on the Western margin of the Tibetan Plateau, upper Indus River. *Quaternary Research*, *89*(1), 281–306. https://doi.org/10.1017/qua.2017.92

Kessler, M. A., Anderson, R. S., & Stock, G. M. (2006). Modeling topographic and climatic control of east-west asymmetry in Sierra Nevada glacier length during the Last Glacial Maximum. *Journal of Geophysical Research*, *111*(F2), F02002. https://doi.org/10.1029/2005JF000365

Korup, O., Montgomery, D. R., & Hewitt, K. (2010). Glacier and landslide feedbacks to topographic relief in the Himalayan syntaxes. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(12), 5317–5322. https://doi.org/10.1073/pnas.0907531107

Lai, J., & Anders, A. M. (2021). Climatic controls on mountain glacier basal thermal regimes dictate spatial patterns of glacial erosion. *Earth Surface Dynamics*, *9*(4), 845–859. https://doi.org/10.5194/esurf-9-845-2021

Li, D., Lu, X., Overeem, I., Walling, D. E., Syvitski, J., Kettner, A. J., et al. (2021). Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia. *Science*, *374*(6567), 599–603. https://doi.org/10.1126/science.abi9649

MacGregor, K. R., Anderson, R. S., Anderson, S. P., & Waddington, E. D. (2000). Numerical simulations of glacial-valley longitudinal profile evolution. *Geology*, *28*(11), 1031–1034. https://doi.org/10.1130/0091-7613(2000)28<1031:NSOGLP>2.0.CO;2

MacGregor, K. R., Anderson, R. S., & Waddington, E. D. (2009). Numerical modeling of glacial erosion and headwall processes in alpine valleys. *Geomorphology*, *103*(2), 189–204. (Mountain glaciation and landscape evolution). https://doi.org/10.1016/j.geomorph.2008.04.022

Micheletti, N., Lambiel, C., & Lane, S. N. (2015). Investigating decadal-scale geomorphic dynamics in an Alpine mountain setting. *Journal of Geophysical Research: Earth Surface*, *120*(10), 2155–2175. https://doi.org/10.1002/2015JF003656

Miles, K. E., Hubbard, B., Quincey, D. J., Miles, E. S., Irvine-Fynn, T. D. L., & Rowan, A. V. (2019). Surface and subsurface hydrology of debris-covered Khumbu Glacier, Nepal, revealed by dye tracing. *Earth and Planetary Science Letters*, *513*, 176–186. https://doi.org/10.1016/j.epsl.2019.02.020

Minchew, B. M., & Meyer, C. R. (2020). Dilation of subglacial sediment governs incipient surge motion in glaciers with deformable beds. *Proceedings of the Royal Society A*, *476*(2238), 20200033. https://doi.org/10.1098/rspa.2020.0033

Östrem, G. (1959). Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges. *Geografiska Annaler*, *41*(4), 228–230. https://doi.org/10.1080/20014422.1959.11907953

Riihimaki, C. A., MacGregor, K. R., Anderson, R. S., Anderson, S. P., & Loso, M. G. (2005). Sediment evacuation and glacial erosion rates at a small alpine glacier. *Journal of Geophysical Research*, *110*(F3), F03003. https://doi.org/10.1029/2004JF000189

Sakai, A., Nakawo, M., & Fujita, K. (2002). Distribution characteristics and energy balance of ice cliffs on debris-covered glaciers, Nepal Himalaya. *Arctic Antarctic and Alpine Research*, *34*(1), 12–19. https://doi.org/10.2307/1552503

Sanders, J., Cuffey, K., MacGregor, K., & Collins, B. (2013). The sediment budget of an alpine cirque. *Bulletin*, *125*(1–2), 229–248. https://doi.org/10.1130/b30688.1

Sanders, J., Cuffey, K., Moore, J., MacGregor, K., & Kavanaugh, J. (2012). Periglacial weathering and headwall erosion in cirque glacier bergschrunds. *Geology*, *40*(9), 779–782. https://doi.org/10.1130/g33330.1

Scherler, D. (2014). Climatic limits to headwall retreat in the Khumbu Himalaya, eastern Nepal. *Geology*, *42*(11), 1019–1022. https://doi.org/10.1130/G35975.1

Scherler, D., Bookhagen, B., & Strecker, M. R. (2011). Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geoscience*, *4*(3), 156–159. https://doi.org/10.1038/ngeo1068

Scherler, D., Wulf, H., & Gorelick, N. (2018). Global assessment of supraglacial debris-cover extents. *Geophysical Research Letters*, *45*(21), 11–798. https://doi.org/10.1029/2018GL080158

Seguinot, J., & Delaney, I. (2021). Last-glacial-cycle glacier erosion potential in the Alps. *Earth Surface Dynamics*, *9*(4), 923–935. https://doi.org/10.5194/esurf-9-923-2021

Shugar, D. H., Rabus, B. T., Clague, J. J., & Capps, D. M. (2012). The response of Black Rapids Glacier, Alaska, to the Denali earthquake rock avalanches. *Journal of Geophysical Research*, *117*(F1), F01006. https://doi.org/10.1029/2011JF002011

Ugelvig, S. V., Egholm, D. L., Anderson, R. S., & Iverson, N. R. (2018). Glacial erosion driven by variations in meltwater drainage. *Journal of Geophysical Research: Earth Surface*, *123*(11), 2863–2877. https://doi.org/10.1029/2018JF004680

Vacco, D. A., Alley, R. B., & Pollard, D. (2010). Glacial advance and stagnation caused by rock avalanches. *Earth and Planetary Science Letters*, *294*(1–2), 123–130. https://doi.org/10.1016/j.epsl.2010.03.019

Werder, M. A., Bauder, A., Funk, M., & Keusen, H. R. (2010). Hazard assessment investigations in connection with the formation of a lake on the tongue of Unterer Grindelwaldgletscher, Bernese Alps, Switzerland. *Natural Hazards and Earth System Sciences*, *10*(2), 227–237. https://doi.org/10.5194/nhess-10-227-2010

Werder, M. A., & Funk, M. (2009). Dye tracing a jökulhlaup: II. Testing a jökulhlaup model against flow speeds inferred from measurements. *Journal of Glaciology*, *55*(193), 899–908. https://doi.org/10.3189/002214309790152375