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The influence of basal-ice debris on patterns and rates of glacial erosion

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A B S T R A C T

Glaciers have played a key role for shaping much of Earth's high topography during the cold periods of the Late Cenozoic. However, despite of their distinct influence on landscapes, the mechanisms of glacial erosion, and the properties that determine their rate of operation, are still poorly understood. Theoretical models of subglacial erosion generally highlight the influence of basal sliding in setting the pace of erosion, but they also point to a strong influence of other subglacial properties, such as effective bed pressure and basal-ice debris concentration. The latter properties are, however, not easily measured in existing glaciers, and hence their influence cannot readily be confirmed by observations.

In order to better connect theoretical models for erosion to measurable properties in glaciers, we used computational landscape evolution experiments to study the expected influence of basal-ice debris concentration for subglacial abrasion at the scale of glaciers. The computational experiments couple the two erosion processes of quarrying and abrasion, and furthermore integrate the flow of ice and transport of debris within the ice, thus allowing for the study of dynamic feedbacks between subglacial erosion and systematic glacier-scale variations in basal-ice debris concentration. The experiments explored several physics-based models for glacial erosion, in combination with different models for basal sliding to elucidate the relationship between sliding speed, erosion rate and basal-ice debris concentration. The results demonstrate how differences in debris concentration can explain large variations in measured rates. The experiments also provide a simple explanation for the observed dependence of glacier-averaged rate of erosion on glacier size: that large glacier uplands feed more debris into their lower-elevation parts, thereby strengthening their erosive power.

1. Introduction

Measurements of sediment yield from glaciers worldwide infer catchment-averaged rates of glacial erosion ranging from 10^{-2} to 10^{2} mm y^{-1} (Hallet et al., 1996; Koppes et al., 2015). The large span in rates of glacial erosion includes significant variation in both time (Herman et al., 2013; Koppes et al., 2015) and space (Fabel et al., 2004; Dühnforth et al., 2010). Some of the measured variation is linked to bedrock lithology and structure (Glasser et al., 1998; Dühnforth et al., 2010; Krabbendam and Bradwell, 2011). Yet, rates of glacial erosion can vary orders of magnitude between glacial catchments, even where lithology and tectonic history are largely similar (Koppes et al., 2015).

Measurements of subglacial sediment production, ice flux, sliding speed, and mean annual temperature suggest that besides ice dynamics, climate and melt-water production are main controls on the pace of glacial erosion (Beaud et al., 2014; Koppes et al., 2015). In a large-scale data compilation study, Hallet et al. (1996) furthermore demonstrated that average rates of glacial erosion correlate with glacier size, however the explanation for this correlation has yet to be found (Hallet et al., 1996). The links between subglacial erosion and ice dynamics thus appear complex, and this complicates efforts to understand and model the influence of late Cenozoic cooling on global topography and sediment fluxes. For this reason, the interest in formulating erosion laws that address abrasion and quarrying as distinct, but coupled, processes has recently increased (Hildes et al., 2004; MacGregor et al., 2009; Melanson et al., 2013; Beaud et al., 2014; Ugelvig et al., 2016).

Glaciers erode their beds through a number of processes, e.g. abrasion of bedrock by friction from debris particles that are dragged across the bedrock by sliding ice; quarrying of bedrock blocks due to differential stress between ice-loaded bedrock and subglacial cavities, and incision of bedrock by subglacial debris-loaded melt-water streams. Abrasion and quarrying are often considered the most important processes (Boulton, 1974; Hallet, 1996), and we therefore focus on them here. Theoretical models

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for both abrasion and quarrying point to basal sliding as a primary factor, and most empirical studies have consequently searched for correlations between observed sliding speed and rates of erosion estimated from pro-glacial sediment yields. Measurements from catchment-scale studies have indicated both linear (Humphrey and Raymond, 1994) and non-linear (Herman et al., 2015; Koppes et al., 2015) temporal correlations between rates of erosion and subglacial sliding speed.

The linear relation, where erosion rate is proportional to sliding speed, u_b, or ice flux, q_{ice}, is widely used in glacial landscape evolution models:

$$\dot{E} = K_l u_b, \text{or } \dot{E} = K_l q_{ice} \quad (1)$$

where K_l is a scaling parameter. The linear erosion law is simple to implement in landscape evolution models because it depends only on one variable (sliding speed), and it successfully reproduces primary features of glacial landscapes such as U-shapes valleys, cirques and hanging valleys (Harbor et al., 1988; MacGregor et al., 2000; Hildes et al., 2004; Anderson et al., 2006; Egholm et al., 2009; Tomkin, 2009; Herman et al., 2011). However, the linear dependence on sliding speed or ice flux lacks a clear connection to the physical processes driving glacial erosion, like abrasion (Hallet, 1979) and quarrying (Iverson, 1991, 2012; Hallet, 1996), and this makes the linear erosion law inadequate for studies addressing how different subglacial physical conditions influence erosion and interact to form glacial landscapes.

Using subglacial mechanics as a starting point, Hallet (1979) presented an abrasion law from theoretical considerations of forces acting on debris particles in the basal ice pressed against the bed. The law predicts the abrasion rate from the product of debris (particle) concentration in the basal ice, C, the particle velocity along the bed, u_p, and the effective drag force between the particles and the bed, F:

$$\dot{E}_a = K_l C u_p F \quad (2)$$

In order to simplify this relation, Hallet (1979, 1981) argued that on a rough subglacial bed, both particle velocity, u_p, and the drag force, F, approximately scale with the sliding speed of the ice, u_b, which, when variations in debris concentration are ignored, leads to a quadratic relation between abrasion rate and sliding speed:

$$\dot{E}_a = K_l u_b^2 \quad (3)$$

This non-linear sliding-abrasion relation has also been used as a general erosion model by landscape evolution models (e.g. Anderson, 2014; Beaud et al., 2014; Harbor et al., 1988; Herman et al., 2011; Egholm et al., 2017). The non-linearity of Eq. (3) is supported by the overall large variation in estimated rates of glacial erosion from place to place, simply because a non-linear erosion law is more sensitive to variations in sliding speed than its linear companion (Herman et al., 2015; Koppes et al., 2015). However, the simple quadratic sliding-erosion law ignores the dependency of variation in debris-concentration, and the basic assumption that the particle-bed drag force scales with sliding speed is associated with considerable uncertainty. For example, studies have also suggested that basal melt rate (Hallet, 1979), or effective pressure (Boulton, 1974) contribute to this force, perhaps depending on the debris concentration in the basal ice (Hallet, 1981).

Starting instead from a macroscopic principle that avoids direct parameterization of the force between debris particles and the bed, Hallet (2011) used work-energy to discuss the general dependency of abrasion on sliding speed and average bed shear stress. The basic assumption is that the amount of frictional energy produced by the sliding movement of debris over bedrock scales the bedrock abrasion rate (Hallet, 2011).

Since frictional energy can be represented by the product of sliding speed, u_b, and shear stress along the bed, τ_b:

$$\dot{E}_a = K_l C u_b \tau_b \quad (4)$$

where again C is the concentration of debris in the basal ice, and K_l represents angularity of the debris and the hardness of the bed.

It is not straightforward to derive a simple relation between abrasion rate and sliding speed from Eq. (4) because 1) sliding speed and basal shear stress are interdependent parameters linked non-linearly through the mechanics of basal sliding, and 2) we can expect feedbacks between erosion and debris concentration. Given the potentially complicating effect of variations in basal-ice debris concentration, it may hence be very difficult to directly explore erosion mechanisms alone from combined measurements of sliding speed and sediment yields. However, using a computational landscape evolution model to integrate ice dynamics, glacial erosion and debris transport, we can develop numerical experiments that may help interpret measurements from real glaciers and perhaps test the assumptions in the erosion laws. In particular, using the full transparency of a computational experiment, we can 'sample' all grid cells of a model glacier and study predicted correlations between sliding and erosion and gain new insights by comparing these to measured correlations. In this study we followed the strategy described above with the aim of bridging current gaps between small-scale theory for subglacial erosion and large-scale observables. We tested two types of erosion laws, both independently and coupled: 1) Hallet's work-energy abrasion law (Eq. (4)) with and without the effect of varying debris concentration, and 2) a newly developed erosion law for quarrying, where quarrying rates are scaled by effective pressure, sliding speed and bed slope (Ugelvig et al., 2016). In the coupled experiments, quarrying produces the debris-tools that drive abrasion, and the two processes are hence linked. Our main objective was to study the patterns and rates of erosion produced by these erosion laws, and to explore possible mechanisms behind measured correlations between erosion rate and sliding speed (Herman et al., 2015; Koppes et al., 2015), and between average erosion rate and glacier size (Hallet et al., 1996).

2. Methods

2.1. The ice model

Ice flow was modeled using the *integrated second-order shallow ice approximation* (iSOSIA) (Egholm et al., 2011). iSOSIA is a depth-integrated higher-order ice model that includes effects from longitudinal and transverse stress gradients in the ice. The higher-order terms increase the sensitivity to topography (Egholm et al., 2011), which allows for accurate simulation of depth-integrated ice-flow in steep landscapes with a grid resolution of few hundred meters (Brædstrup et al., 2016). Ice pressure along the subglacial bed is represented by the dynamic stress normal to the bed, which takes into account that ice flow can enhance pressure on the stoss sides of bed bumps (that are large enough to be resolved by the grid resolution) and decrease pressure on the lee sides. A more in-depth description of the iSOSIA ice dynamics can be found in Egholm et al. (2011, 2012a, 2012b) and Brædstrup et al. (2016).

Mass balance, M, was modeled as a simple linear function of the mean annual atmospheric temperature, T:

$$M = \begin{cases} -m_{acc}T, & \text{if } T \leq 0 \text{ (accumulation)} \\ -m_{abl}T, & \text{if } T > 0 \text{ (ablation)} \end{cases} \quad (5)$$

where T is assumed to decrease linearly with elevation:

$$T = T_{sl} - dT \times h \quad (6)$$