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Spectral roughness and glacial erosion of a land-terminating section of the Greenland Ice Sheet

K. Lindbäck *, R. Pettersson

Department of Earth Sciences, Air, Water, and Landscape Sciences, Uppsala University, Villavägen 16, Uppsala SE-752 36, Sweden

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ABSTRACT

Spectral roughness offers a significant potential for understanding the evolution of glaciated landscapes. Here, we present the first roughness study combining a high-resolution (250 to 500 m) DEM of a large land-terminating section ($12{,}000\ \mathrm{km}^2$) of the Greenland Ice Sheet with the topography of the proglacial area. Subglacial roughness shows a directional dependence with consistently lower values in the ice flow direction compared to the across–flow direction. We find a correlation between low basal roughness, fast ice flow, and subglacial troughs. The northern part of the subglacial study area has an undulating topography with variable roughness, resembling the landscape in the proglacial area. In this area, there is a glacially eroded, overdeepened trough with bed elevations 510 m below sea level, consistent with warm ice and a well-lubricated bed. The southern part of the subglacial study area has higher bed elevations and higher roughness than the northern part, possibly because the bedrock consists of hard granitic gneiss as in the adjacent proglacial area. The subglacial troughs, which have been eroded to various extents, are aligned with geological weakness zones suggesting a preglacial origin. In general, there is a major geological control on the distribution of bed variability.

1. Introduction

Digital elevation models (DEMs) from radio-echo-sounding measurements of the ice sheets of Antarctica and Greenland can provide geomorphological information about glacially hidden surfaces. The undulation of the bed beneath an ice mass has an important influence on its flow, and basal roughness provides insight into the role of topography on past, current, and future ice sheet dynamics (Rippin et al., 2011). Spectral roughness can be calculated from bed elevation measurements and is defined as the vertical variation in the subglacial interface with distance along a profile in the horizontal plane. Roughness has the advantage of being simple to calculate and offers a significant potential for understanding the evolution of glaciated landscapes (Bingham and Siegert, 2009). Roughness in wavelength scales of 10^2 to 10^4 m, however, is poorly understood in glaciated systems (Bennett, 2003; Taylor et al., 2004). This scale is nonetheless important as it includes a range of glacial bedforms and can shed light on the processes that formed them.

Subglacial roughness may depend on four factors (Siegert et al., 2005): (i) ice flow direction, where the bed is typically smoother in the flow direction; (ii) ice dynamics, as warm ice and a wet ice–bed interface will erode (and therefore smooth) the bed more than a frozen bed; (iii) lithology, where soft beds are generally smoother and will erode more easily; and (iv) geological structure, where folds and faults in the bedrock affect the subglacial topography. In the last decade, numerous ice-sheet wide and regional studies in Antarctica have used roughness calculations as a glaciological tool to infer basal processes and ice-sheet history (e.g., Bingham and Siegert, 2009; Rippin et al., 2011; Ross et al., 2012), where extensive bed elevation data have been available (e.g., Lythe et al., 2001). Few roughness studies have been carried out in Greenland and the first study of bed roughness was done by Layberry and Bamber (2001), who used a root-mean-square residual bed elevation deviation as an indication of roughness. Recently, Rippin (2013) performed a study of bed roughness for the entire Greenland Ice Sheet, at a spatial resolution of 1 km based on various data sets collected between 1993 and 2011, using the fast Fourier transformation (FFT) approach. These two studies identified two distinct roughness regimes in Greenland: rough marginal areas with elevated bed topography, especially in the southeast, and a smooth low-lying central region. In general, where the bed topography is high roughness is also elevated. These studies, however, were carried out on data with a relatively low sampling resolution (100-m sampling along profiles; Rippin, 2013), and higher resolution roughness studies are needed in Greenland to investigate further the hypothesis that marginal areas with fast flow have the highest roughness. Roughness must also be taken into consideration in future studies of the stability of the Greenland Ice Sheet, as basal roughness exerts a control on ice flow, together with other important parameters such as water availability and ice temperature.

Here, we present the first roughness study on Greenland combining a high-resolution DEM of a large land-terminating section of the ice sheet with the topography of the proglacial area to produce the highest

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* Corresponding author. Tel.: +46 18 471 25 16.
E-mail address: katrin.lindback@geo.uu.se (K. Lindbäck).

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resolution topographical map of the study area. The DEM of the ice-covered area consists of bed elevation based on a compilation of ground-based and airborne radar surveys of ice thickness and have a total area of ~12,000 km^2 at a resolution of 250 to 500 m (Lindbäck et al., 2014). We performed spectral roughness analysis on the bed data following the FFT method described by Taylor et al. (2004) with a sampling resolution of 30 m along profiles. The geology underneath the Greenland Ice Sheet is poorly known. We compare the spectral roughness of the well-studied proglacial area with less-studied subglacial area. The overall aim of the project is to improve the current understanding of hydrogeological processes associated with continental-scale glaciations, including the presence of permafrost and the advance/retreat of ice sheets.

1.1. Regional setting

The study area is located in West Greenland (67°N, 50°W) and includes both the ice-covered and proglacial area (Fig. 1).

1.1.1. Ice-covered study area

The ice-covered study area includes the informally named Isunnguata Sermia, Russell, Leverett, Ørkendalen, and Isorlersuup glaciers and their catchment areas (Fig. 2) and extends a farther 100 km south of the Isorlersuup Glacier and ~90 km inland to the 21-year-mean mass balance Equilibrium Line Altitude (ELA) at ~1600 m above sea level (asl) (van de Wal et al., 2012). The study area is well covered by automatic weather stations (Steffen and Box, 2001; van de Wal et al., 2012), and the climate at the ice margin is defined as low Arctic and experiences average summer highs of 16 °C and average winter lows of −24 °C. The area is one of the most studied regions of the Greenland Ice Sheet with studies of mass balance (e.g., van de Wal et al., 2012), ice dynamics (e.g., van de Wal et al., 2008; Bartholomew et al., 2011; Palmer et al., 2011; Sole et al., 2013), and supraglacial lakes (Fitzpatrick et al., 2014). The ice flow direction in the area generally runs from east to west, with a mean surface velocity of ~150 m year^{-1} (Fig. 2B; Joughin et al., 2010).

1.1.2. Proglacial study area and glaciogeological setting

Our study includes the proglacial area extending ~100 km to the west from the ice margin toward Kangerlussuaq Fjord. The land ends at the coast of the Davis Strait and is one of the largest continuous ice-free areas in Greenland (Fig. 1). The Precambrian basement is exposed, and the bedrock consists of primarily Archaean orthogneiss (North Atlantic Craton) with minor amounts of amphibolites and metasedimentary rocks that were reworked under high-grade metamorphic conditions (Wilson et al., 2006; Garde and Hollis, 2010). The southern part of the proglacial area, including the elevated area of the Sukkertoppen Ice Cap in the southwest, consists of hard Archaean orthogneissic rock with granitic intrusions. Sukkertoppen and its adjacent ice cap have elevations up to ~1800 m asl, and to the northeast (i.e., toward the ice margin) a low-relief highland is located at ~1000 m asl. Farther north, the plateau becomes progressively lower and the landscape changes to an undulating terrain with irregular hills. The extent of erosion is unevenly distributed and is, in general, larger within areas of gneiss with amphibolite facies than within areas of gneiss with granulite facies. Two planation surfaces occur across different types of basement rocks suggested to be created during three phases of Cenozoic uplift and erosion (Bonow et al., 2006). The upper planation surface has been preferentially preserved in the southern plateau area and shows limited evidence for erosion. The lower planation surface mainly forms a valley generation. Valleys have been deepened and widened to different degrees by fluvial and glacial erosion during repeated glaciations and interglacials. The paleosurfaces have also been obliterated between valleys by glacial erosion. At the highest elevations (above 1000 m asl), Bonow et al. (2006) argued that cold-based ice has preserved the upper planation surface.

The Holocene deglaciation history of the proglacial region has been extensively studied since the 1970s with radiocarbon dating of moraine systems, glaciomarine, and aeolian and lake deposits (Storms et al., 2012, and references therein). The ice sheet had its maximum extent during the Last Glacial Maximum ~20 M year Before Present (YBP) and extended beyond the present day coastline, depositing off-shore moraines. The ice sheet thickness was relatively thin (500 to 1000 m), and the area was influenced by shelf-based coalescent ice stream systems, of which little is known of their history today (Roberts et al., 2009). The ice sheet retreated slowly during the Holocene, with moraines marking temporary halts or readvances (van Tatenhove et al., 1996). Approximately 4000 YBP, during the mid-Holocene climatic optimum, the ice sheet reached its most landward location. The minimum extent of the ice sheet during the Holocene is uncertain and models show a wide variety in timing and extent (Storms et al., 2012). Nevertheless, clear evidence in the proglacial landscape indicates that the retreat was beyond the present margin, during the mid-Holocene. The evidence is mainly that (van Tatenhove et al., 1996) (i) older material was deformed or pushed into soil horizons close to the margin; (ii) large-scale redistributions of aeolian sand deposits by wind took place

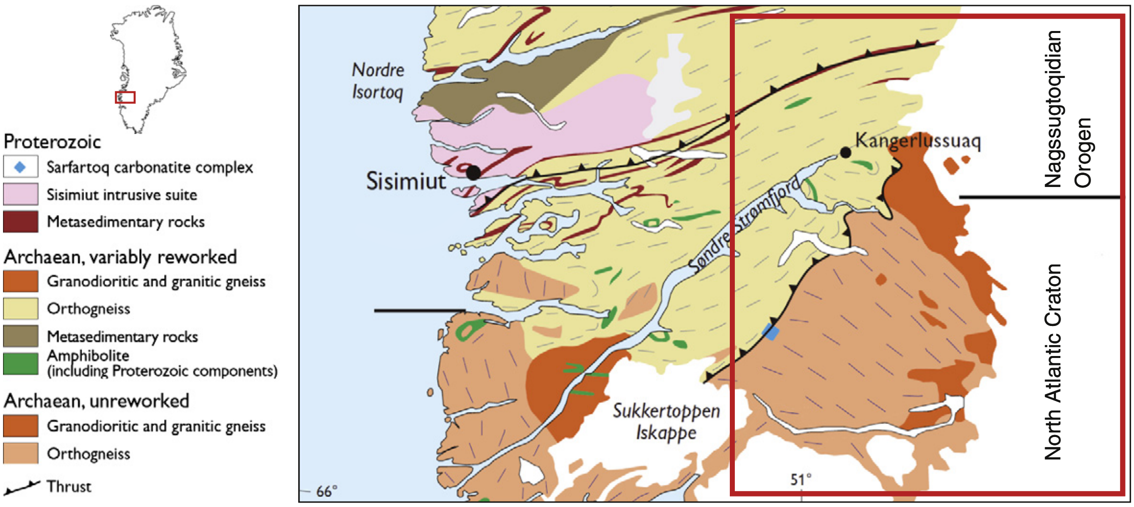

Fig. 1. Geological map of the west Greenland region (modified from van Gool and Marker, 2007). The location of the study area is indicated by the red box.