Challenging the southern boundary of active rock glaciers in West Greenland

Jakob Abermann¹,² | Kirsty Langley²

¹Department of Geography and Regional Science, University of Graz, Graz, Austria
²Asiaq, Greenland Survey, Nuuk, Greenland

Correspondence
Jakob Abermann, University of Graz, Department of Geography and Regional Science, Heinrichstraße 36, 8010 Graz, Austria.
Email: jakob.abermann@uni-graz.at

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Abstract
Rock glaciers (RGs) are landscape features impacting the composition and magnitude of runoff and, given their ice content, they are used as indicators for past and present climate conditions. While our knowledge of RG coverage has improved over recent years in many mountainous regions, there is very little information available for RGs in Greenland. Here, we provide evidence for an active RG in West Greenland, about 230 km south of what previously has been identified as the southern limit of active RGs. We present field evidence such as bottom temperature of the snow pack and surface displacements and indicate how these results could be utilized in further studies to better assess RG distribution or their ice content.

KEYWORDS
Greenland, permafrost, rock glaciers

1 | INTRODUCTION

Active rock glaciers (RG) are “the visible expression of cumulative deformation by long-term creep of ice/debris mixtures under permafrost conditions”.¹ They play a hydrological role in water routing² and store substantial volumes of water.³ They are climatically more resilient than glaciers and their hydrological significance may increase in a changing climate.⁴ RGs can be used as a indicators of past and present climates due to their hidden ice content.⁵,⁶

While internationally coordinated efforts have led to an impressive reduction of uncertainties in the quantification of global glacier coverage⁷ and volumes,⁸ corresponding information on RGs is much less constrained. A recent study (⁷; corrected in⁵) attempted to provide a near-global inventory of RG occurrence and found that in total 62.02 ± 12.40 Gt of water volume equivalent is stored in RGs and they derived an RG to glacier volume ratio of 1:618. This compilation relies on regional and national inventories of varying levels of detail.

RGs are known to occur in Greenland, but they have received very little attention in the literature compared to other features of the Greenland cryosphere, such as the Greenland Ice sheet and peripheral glaciers. Most studies covering RGs in Greenland have either been site-specific (e.g.,⁶,¹⁰–¹²) or limited to smaller regions.¹³ A compilation of the spatial coverage of RGs in Disko was made by Humlum,¹³ available through,¹⁴ putting the results in context with other known sites of active and inactive/fossil RGs in Greenland. In their figure 1 they clearly indicate that, while sporadic permafrost reaches all the way to the southern tip of Greenland, the southernmost known RG on the west coast occurs at around 66.5°N near the town of Sisimiut. More recent studies attempting to provide a worldwide inventory of RGs³ have based their estimates for Greenland on the spatially limited study by Humlum⁵ and extrapolated based on the Randolph Glacier Inventory.⁷ It therefore appears appropriate to challenge the limited knowledge on the spatial coverage of RGs in Greenland.

In the following we present observational evidence for an active RG in West Greenland, about 2 latitudinal degrees or 230 km further south than previously thought to be the southern boundary. We present first monitoring results based on 5 years of air temperature near the RG snout, a bottom temperature of snow pack and surface displacements and indicate how these results could be utilized in further studies to better assess RG distribution or their ice content.
summer RG spring temperatures, as well as DGPS (Differential Global Positioning System)-derived surface displacement rates that support the plausibility of an active RG.

2 | STUDY SITE

Our study area focuses on the northern part of Qoorup Qeqertarsuassua (colloquially known as Bjørneø, which is Danish for “Bear Island”), where in 2015 we identified an RG—hereafter BJRG for Bjørneø RG—as a landscape feature at ~64°30’N, 51°16’W. It is located around 45 km northeast of Nuuk, Greenland’s capital. The landscape feature covers an area of ~1.0 km² and an elevation range of between 250 and 750 m a.s.l. Despite a steep front and a steep root zone, the surface is moderately inclined with typical slopes of <20° (Figure 1a). The surface is covered with rocks of varying sizes—from small rocks to boulders on the order of several meters in diameter. The lower reaches of the RG are covered with ridges and furrows. There is a distinct transition of very large blocks and strong surface undulations in the central–upper part to smaller blocks and weaker undulations in the lower part, which may point towards two periods of activity. The geological setting of the study area is mainly Nuuk Gneiss with some intrusive amphibolite bands. The vegetation cover around BJRG is arctic tundra and small shrub vegetation, while there are lichens on some of the boulders on the BJRG.

Based on data from 2016 to 2021, average 2-m annual air temperature at an automated weather station at 199 m a.s.l. (this corresponds to the elevation of the RG front; see Figure 1 for location) was –2.2°C, which was 1.2°C lower than in Nuuk. Summers (JJA), however, are warmer at the RG front compared to Nuuk (7.1°C at RGBJ vs. 6.2°C in Nuuk, see Figure 2). Seasonal snow cover in the area typically builds up from October onward with maximum snow depths between March and April and snow-free conditions typically from June to September.

Water temperature measurements were taken from two springs near the snout of BJRG exist on two occasions. Temperatures were 0.1°C on September 21, 2016 and between 0 and 1°C between July 15 and 17, 2021, where on both occasions snow melt played a minor role in the catchment.

3 | METHODS

We combine several field-based methods to assess the activity status of the RG. A network of points marked by spray paint crosses was established in 2016. Since the intention was to both have stable points that can be used as ground control points (GCPs) for unmanned aerial vehicles (UAVs), and to determine surface displacement, we placed the crosses on and around BJRG (Figure 1). The points were remeasured in subsequent years (2017, 2019, 2021) using DGPS/GNSS systems that give accuracies of better than 2.5 cm.

BTS has previously been used to estimate the likelihood of permafrost. We took BTS measurements using a temperature sensor mounted on an avalanche probe and measured 27 individual points distributed across the RG and its surroundings (Figure 2). The duration of the measurement at each site was between 2 and 5 min, until thermal equilibrium was reached and the temperature values no longer varied. The distribution of point measurements was impacted by accessibility, where the steep parts of the RG, the complex surface features, and large boulders made consistent transects difficult. We performed BTS monitoring on March 27, 2017, which is close to the maximum winter snow depths of the season. Snow depth was heterogeneous and between 1.0 and 2.9 m at the individual measurement sites.

4 | RESULTS

We combine several independent monitoring results from the past 5 years to challenge the hitherto postulated southern boundary of active RGs in West Greenland.

4.1 | Morphological and qualitative evidence

Ridges and furrows are typical features of RGs and are prevalent on BJRG. They become filled with seasonal snow cover that can remain well into, or throughout, the summer. During a visit in August 2017 we observed compacted snow in several furrows that may have remained in place for the entire summer season, possibly due to cooling from below.

4.2 | Surface motion

Figure 1b shows average annual surface displacement, while the overall displacement is shown in Figure 1c. In general, surface motion is very small for all points (<3 cm/yr), but for the entire study period 2016–2021, GCPs 7 and 8 show a horizontal displacement toward the northwest (downward flow) that is clearly beyond the uncertainties of the DGPS acquisition, while the other GCPs remain within the uncertainties (±2.5 cm; indicated with gray circles).

4.3 | Temperature regime

While absolute thresholds of BTS are questionable and other, more adequate measures to determine permafrost occurrence exist, the relative distribution of BTS during a winter campaign from March 28, 2017 reveals interesting patterns (Figure 2): BTS values around the BJRG were typically higher than –3°C; on the BJRG they were significantly lower with values reaching –10°C in parts. There was a slight anticorrelation where deeper snow cover showed slightly lower temperatures, but the variability was too large to draw significant conclusions.
FIGURE 1  (a) Aerial photograph of BJRG from September 2017. (b) Mean surface displacement (cm/yr) at selected GCPs between 2016 and 2021 (1–8) and 2017–2019 (9–11) with the slope based on the ArcticDEM16 in the background. (c) Total horizontal displacement (in x and y directions) of points 1–8 between 2016 and 2021, including the estimated upper bounds of the uncertainty of the DGPS measurements. (d) Greenland with an overview of published RG-related studies and their locations [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 2  (a) Bottom temperature of snow (BTS) cover measurements on March 28, 2017 on top of a UAV-derived Orthophoto from September 2017. (b) BTS measurements on BJRG. (c) Daily mean 2-m air temperature at the automated weather station (AWS) (2016–2021). Gray dots show diurnal means for individual days; the blue line indicates the average for each day from all available measurements between 2016 and 2021 and the red line shows the same subset from the AWS in Nuuk, where long-term records exist. Note, that during winter, BJRG is colder, and during summer warmer than Nuuk. The elevation difference between Nuuk and the AWS at BJRG is ca. 150 m [Colour figure can be viewed at wileyonlinelibrary.com]
5 | DISCUSSION AND CONCLUSION

There is evidence for a site in southwest Greenland that shows several independent indicators pointing towards the existence of an active RG at a latitude of ca. 64°30’N. Flow velocities are very low and on the order of other studies in the high latitudes.19 The major part of the RG is gently inclined with slope angles below 20° (cf. Figure 1a and b). Cicola et al.20 revealed the dependence of RG creep rates on slope angle based on a thorough literature survey. They find very low (sub-meter) creep for slope angles <20°, which supports the fact that little shear stress develops. The strong BTS differences between the RG and its immediate surroundings lend credence to an ice body below.

The current study provides a first assessment of an active RG, potentially allowing the southern limit of active RGs in West Greenland to be extended considerably southwards. An important next step will be the deployment of additional geophysical methods such as electric resistivity tomography and ground-penetrating radar, which may shed light on the ice content of BJRG. Furthermore, relative or absolute dating approaches may allow us to assess the genesis and age of this landscape feature.

On a regional and Greenland-wide scale, a state-of-the-art RG inventory should be established to both provide the basis for climate/permafrost assessments and better constrain the ice volume stored in these understudied features. Rasch21 provided an overview of neighboring areas to our study site based on qualitative analysis of optical remote sensing images. They found several candidates with surface features that could contain RGs, which we display in Figure S1 along with an oblique photograph of another potentially active RG. While their assessment is relevant for determination of further RG occurrence, the qualitative approach does not allow us to assess the activity state of the RGs. Satellite-retrieved products of high-resolution surface displacement such as synthetic aperture radar may prove powerful for assessing the activity level of RGs.12

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Jakob Abermann  https://orcid.org/0000-0003-1285-1868
Kirsty Langley  https://orcid.org/0000-0002-0500-8971

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