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Movement of Foxfonna rock glacier in Svalbard between 2017-2019

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Bachelor's thesis, 15 credits, in *Physical Geography and Ecosystem Science*

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Abstract

The movement of a rock glacier located at the bottom of the Foxfonna glacier, Svalbard, Norway, was studied through the use of photogrammetry and feature tracking software, between the years of 2017-2019, as well as elevation changes between 2009 and 2019. This could aid in further knowledge about the rapid velocity changes of rock glaciers in a continuous permafrost environment. It was found that the front part of the rock glacier moved approximately 2m between 2017 and 2018, and up to 2.5m/y between 2018-2019. The elevation changes showed a large accumulation of mass in its frontal area over the years, where some features have moved around 20m since 2009. Further south on the upper part of the rock glacier, movement changes were few, but elevation changes still occurred. Factors, such as icing, internal hydrology, permafrost changes, that could influence the movement of the rock glacier have been discussed and suggestions for future studies, including ground penetrating radar (GPR) and temperature measurements, have been made.

Contents

1 Introduction

The geomorphological structure known as rock glaciers is a permafrost landform, which in its form resembles a glacier except that it is covered in rocks and sediments of different size. These glaciers are usually found in high relief areas where they slowly creep downslope. Typically, they are found in dry- to mildly humid climates (Humlum, 1998). Permafrost is defined as permanently frozen ground, at variable depths (Harland, 1997), and in Svalbard it penetrates the ground within the depth ranges of 100m closer to the coast and down to 500m in more mountainous areas. Permafrost can also be found in formations on top of the soil, such as rock glaciers (Humlum et al., 2003). Understanding the thermal and dynamic evolution of rock glaciers would increase the knowledge of how permafrost aggrades into deglaciated and/or melting glacial environments. Furthermore, this knowledge would be useful where hazardous situations related to rock glaciers can occur, either close to infrastructure or close to proximity areas where e.g. debris flow or rockfall can become more prominent (Schoeneich et al., 2015). Rock glaciers can also be affected by a growth in active layer thickness, the top layer of the soil between the permafrost and the atmosphere that thaws in the summer and freezes in winter (Anisimov et al., 1997), which can accelerate slope processes (Bilt et al., 2019). Water can also be dammed in an ice-cored terrain that undergoes accelerated changes, creating additional hazards in populated areas (Richardson and Reynolds, 2000).

It is important to study the movement of the rock glaciers to predict the changes in the hydrology and water balance that might result. For example, changes in the hydrology on Bogebreen glacier might lead to a shortage of fresh water to the main city in Svalbard (Kalinowska et al., 2020). This is being caused by the movements of the rock glacier in the terminus of the glacier that is causing the water to take different paths.

1.1 Aim

The main purpose of this study is to see how much movement occurs on the Foxfonna rock glacier annually between 2017-2019, as well as over a 10 year period between 2009-2019 based on DEMs, and to see if an unmanned aerial vehicle and photogrametry-based study is feasible for this, along with exploring features that might be contributing to this.

1.2 Research questions

- How much have the rock glacier advanced and what changes in velocities can be seen between different years?
- What topographical changes can be found on the rock glacier?
- What accuracies in DEMs and ortophotos can be achieved from the UAV images?

2 Background

2.1 Rock glaciers

Rock glaciers mainly form through two different processes, from a periglacial environment (Humlum, 1999) and from a glacial origin (Krainer and Mostler, 2000; Outcalt and Benedict, 1965). Periglacial rock glaciers, or talus derived rock glaciers are formed from dirty snow avalanches, i.e. a mixture of snow and rocks, which congregates into one large unit, while glacially derived ones are formed from rocks and ice which are left behind in the frontal area of a glacier during its retreat. Rock glaciers usually form in the shape of a tongue, reaching up to a length of 200-800m, but can stretch out further. The thickness of the tongues usually vary between 20-100m (Humlum, 1999). Rock glaciers creep downslope at a slow speed, from a few centimeters to some meters annually, and as a result of this they deform and can act as a mass transport system for debris (Kaufmann et al., 2018).

Rock glaciers with relatively high velocities (>1m/yr) can be found in e.g. the Alps, but no studies have been made about the causes of the high speeds in less temperate areas where continuous permafrost can be found, like Svalbard. Here, surface velocities of rock glaciers previously have been measured to move very slow (less to 10cm/year) (Sollid and Sørbel, 1992).

2.2 Climate change and glaciers

Areas affected by permafrost can be very sensitive to climate change, since the soil temperature usually stays close to 0°C (Christiansen et al., 2010). At Janssonhaugen, a mountain located close to the study area of this report, temperature changes of 1.5 ± 0.5°C in the permafrost have been detected to a depth of 80m (Isaksen et al., 2000a). Temperatures have also increased around 1°C between the little ice age (years ≈1350-1850) and 1990, and between 0.5°C - 1 °C from 1990-2010 (Etzelmüller et al., 2011) and at rates between 0.06°C - 0.15°C per year between 2009-2019, at a depth of 10m (Bilt et al., 2019). This change in the environment and soil temperature will affect the stability and movement of the rock glaciers (Haeberli et al., 1998).

The general climate in Svalbard is heavily influenced by the West Atlantic Spitsbergen Current, from which small variations in position and strength can affect the climate (Ślubowska et al., 2005). The heat released from this current contributes to the wetter climate which can be found in Svalbard, compared to other larger landmasses which are located at the same latitude (Walczowski and Piechura, 2011). Svalbard, and the polar regions in general, is also more sensitive to climate change due to the polar amplification which causes a higher temperature change here, due to heat rising up in the atmosphere closer to the equator, then being transported by global wind patterns towards the poles (Holland and Bitz, 2003).

Many glaciers have shifted from a polythermal state to become more cold based. Cold based, meaning that the temperature at the bottom of the glacier that is in contact with the ground is below freezing, and polythermal which is a partly cold based and partly warm based glacier, where a warm based has the ice-ground contact at or above 0°C (Bishop et al., 2011). One reason that more glaciers are becoming cold based is because they no longer have the same amount of snow cover that isolates them during summer periods (Bælum and Benn, 2011; Björnsson et al., 1996; Hodgkins et al., 1999). This thermal transition of glaciers leads to concurrent permafrost aggregation underneath them, but the speed at which this happens is poorly known. Glacier ice is also known to be insulated from debris cover, an effect that also should be significant for glacier-derived rock glaciers (Reznichenko et al., 2010).

2.3 UAV monitoring

UAVs (Unmaned Aerial Vehicles) have been used more and more in remote sensing processes and monitoring of different phenomenon, e.g. landslides (Lindner et al., 2016), coastlines changes (Gonçalves and Henriques, 2015) and the retreat of glaciers (Bhardwaj et al., 2016). Rock glaciers have also been studied in a similar way as in the present study to some extent (Kaufmann et al., 2018). UAVs have become cheaper and more accessible for anyone to use and can be used to produce digital elevation models (DEMs) through photogrametic softwares with similar accuracy to LiDAR (Polat and Uysal, 2018) and orthophotos with similar or even higher resolutions, down to a few centimeters or even millimeters, compared to areal images (Klemas, 2011; Polat and Uysal, 2018). The resolution of UAV derived ortophotos depends on different factors, such as what type of camera model the UAV have and at what height the drone is flying.

3 Material and methods

3.1 Study area

The rock glacier examined in this study is located in front of the Foxfonna glacier system (Figure 1) (78.14°N, 16.15°E), which consists of a low valley glacier and an upper ice cap. The study area is placed around 12.5km south-west of Longyearbyen, which is the largest town and the administrative center of Svalbard, Norway, with around 2000 inhabitants.

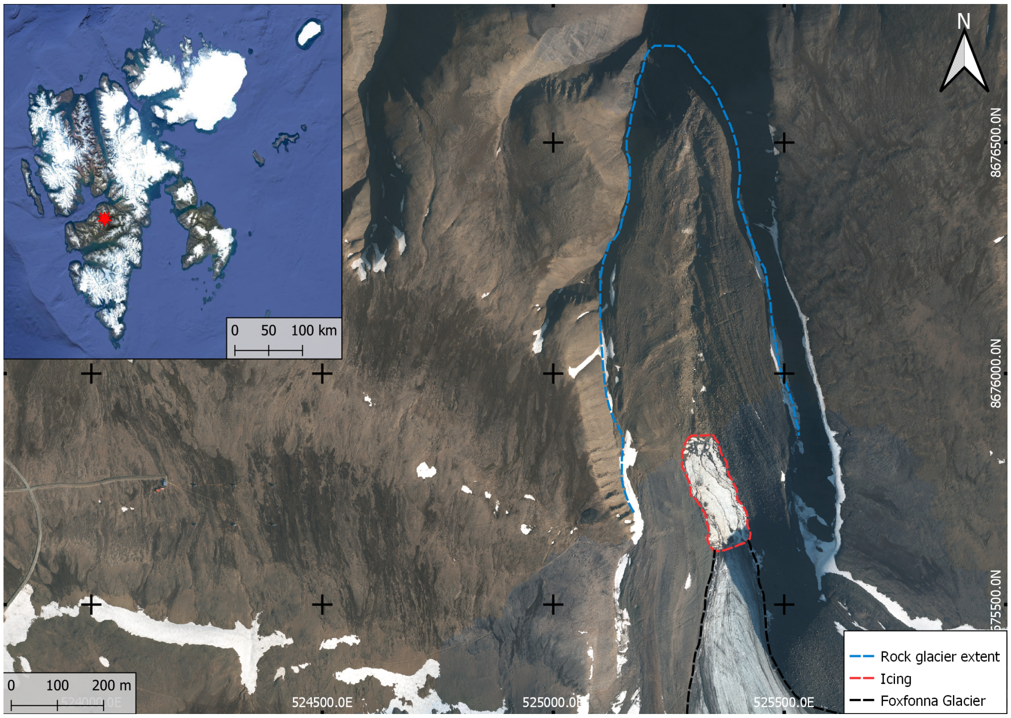

Figure 1: Location of the Foxfanna glacier on Svalbard (top-left inlet), and an aerial photo of the studied area.

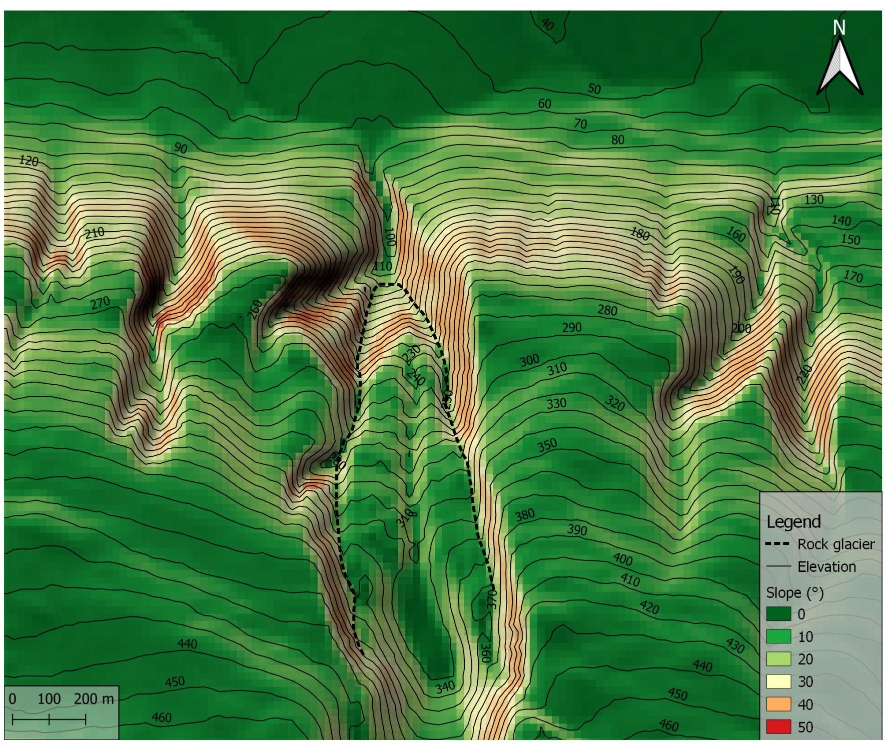

Figure 2: Slope and elevation map of study area, with Adventdalen located in the top part of the map.

The surrounding rock formation mostly consists of sandstone, siltstone and shale (Major and Nagy, 1972). The valley that the water runs out into is about 60 masl (meters above sea-level), whilst the top of the rock glacier is around 350 masl. The rock glacier is around 1km tall, and is located on a slope between two rock-faces and is 380m wide at its widest point, with the melt water flowing out into Adventdalen (Figure 2). The surface topography of the rock glacier is especially interesting, due to its transverse ridges that have developed on top of it over time, which usually is an indicator of deforming and fast flowing ice (Roer et al., 2008). Underneath Foxfonna, the Gruve-7 mine passes where temperatures at a depth of 290m were recorded to be 0°C, which could be assumed to be the the approximate depth of the permafrost in the area (Christiansen et al., 2005).

A feature that is occurring in the upper part of the rock glacier where it meets the front of the Foxfonna glacier is icing (Figure 1), also known as naled or aufeis, which is common in proglacial areas in high latitudes (Hodgkins et al., 2004). The source of this icing is upwelling water, in this case ground water that has a subglacial or subpermafrost origin (Wadham et al., 2000). When ground water is exposed to air, oxidation will happen that leads to oxygen evolution and the release of iron (Champ et al., 1979). Presence of traces of iron on the surface is usually present where ground water is flowing. Due to the high conductivity of the ground water, water flow is still occurring even with sub zero temperature (Montgomery, 2007). This water will freeze after some distance forming icing. Upon freezing, latent heat is released providing the permafrost with heat to keep its temperature closer to 0 °C (Osterkamp, 1987). Icing has been studied on many different glaciers on Svalbard to see how it affects the water balance, the thermal regime of the permafrost and the hydrology (Mallinson et al., 2019). A 2m thick icing was found at the terminus of Scott Turnebreen glacier and icing was present in the terminus of the different glaciers in the Bayelva watershed, Svalbard (Nowak and Hodson, 2013; Hodgkins et al., 2004))

3.2 Data and photogrametry

In order to examine the Foxfonna rock glacier, aerial images from a UAV (Mavic 2 pro) were studied in this paper, combined with a DEM (digital elevation model) from 2009. The UAV images are from 2017 (5th of September), 2018 (27th of July) and 2019 (15th of July), covering the whole extent of the Foxfonna rock glacier. This data was processed to provide the basis of the intended monitoring of Foxfonna rock glacier, using both high resolution digital orthophotos and DEMs. A comparison between these different data sets then provided data for surface changes, both in movement and surface height. The imagery collected from the UAV surveys was processed in Agisoft Metashape version 1.5.1 (Agisoft LLC, St. Petersburg, Russia), where DEMs and orthophotos can be produced.

Agisoft starts with aligning all the photos, with structure from motion (SFM) techniques. The alignment also produces a sparse cloud of points where different images overlap and where the software can identify these points in 2 or more images. These points are also put into perspective with the help of depth maps, which are produced during the same steps. From this, the points are aligned in a XYZ-direction, making the primary structure of the 3D-model. After the alignment is done, a dense cloud is produced, from where the software takes a similar approach but focuses even more on obtaining points which it can identify between different images. A DEM can be produced from the dense cloud, as well as an orthophoto and a tiled model.

3.2.1 Ground control points

Ground control points (GCPs) were used to georeference the 3D-model. Although the drone used to gather the imagery has it's own built-in GPS system, which works well with northing and easting, but errors can occur in altitude. This is because the drone acts as if its starting point is 0 meters above sea level. The GCPs are then used to both correct the altitude value, but also improve the northing and easting values for the 3D-model and its results.

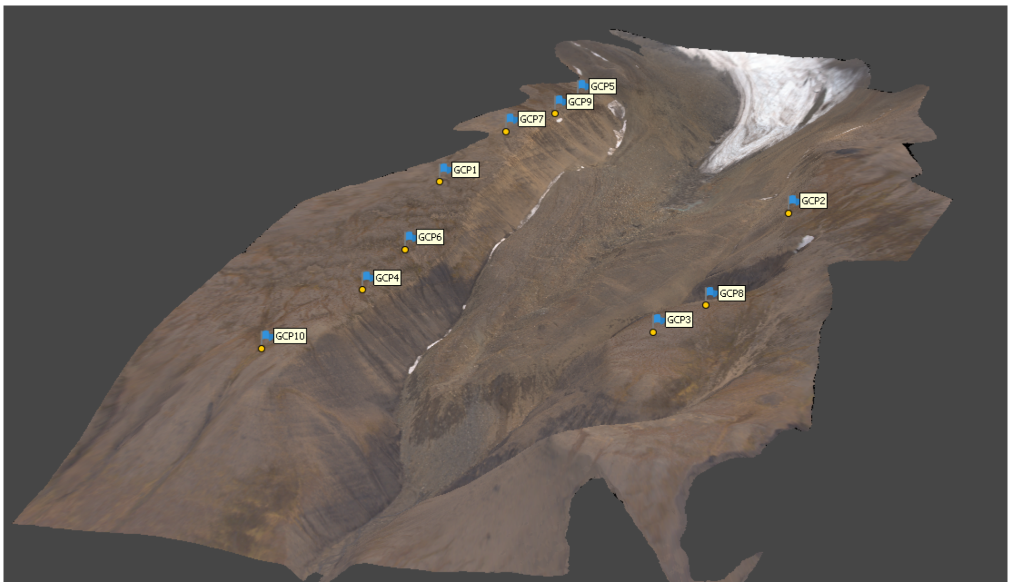

Figure 3: Tiled model made in Agisoft Metashape with images from 2017, with locations of the used GCP points.

To do this, points were added to features that were easily identified, e.g. corners on larger rocks, in both Agisoft Metashape (Figure 3) and on a reference satellite map of Svalbard (Polarinstitutt, 2012), which had a resolution of 0.15x0.15m. In Qgis, a point layer was created to represent these points from which the northing and easting values were imported from the reference map, with the help of the field calculator in the attribute table. Altitude values were collected through the Sample Raster Values tool from a DEM layer (Polarinstitutt, 2012) with a resolution of 5x5m, which covers Svalbard. With the coordinates for easting, northing and altitude in the point layer, the file was imported to Agisoft Metashape. GCPs in Agisoft was then updated with the new coordinate information from the point layer, which lowered the error estimations and corrected the altitude for the whole 3D model.

The orthophotos were then imported to Qgis (Team et al., 2016), and a tool called imcorr from the GRASS toolbox was used to find the offset between the orthophotos from different years, i.e. 2017-2018 and 2018-2019. The images also had to be colour corrected and transformed into a gray-scale image, for the imcorr software to work properly. The results of offset were then plotted in Python.

Elevation changes between 2009 and 2019 were also calculated. A DEM from 2009 was imported from the Norwegian Polar Institute in a resolution of 5x5m, while the 2019 DEM is a product from the drone images in Agisoft Metashape from the present study. This DEM originally had a resolution of 0.3x0.3m, but was resampled with cubic spline interpolation, to 5x5m with the Warp tool from the SEGA toolbox, so that it would match the one from 2009. The changes were calculated using a raster calculator in Qgis, by subtracting the values of 2009 from 2019.

Structures that had similar surface features, i.e. crevasses that could potentially indicate a rapid movement, were manually identified and mapped over Svalbard in Qgis, using an orthomosaic from the Norwegian polar institute (Polarinstitutt, 2012).

4 Results

Twelve different structures, speculated to be rock glaciers with the same surface features as the one located at Foxfonna were identified and mapped out (Figure 4). All of them were found in the central part of Svalbard, in Nordenskiöld Land. Most of these are located on an altitude of approximately 250m-350m, and also facing northwards.

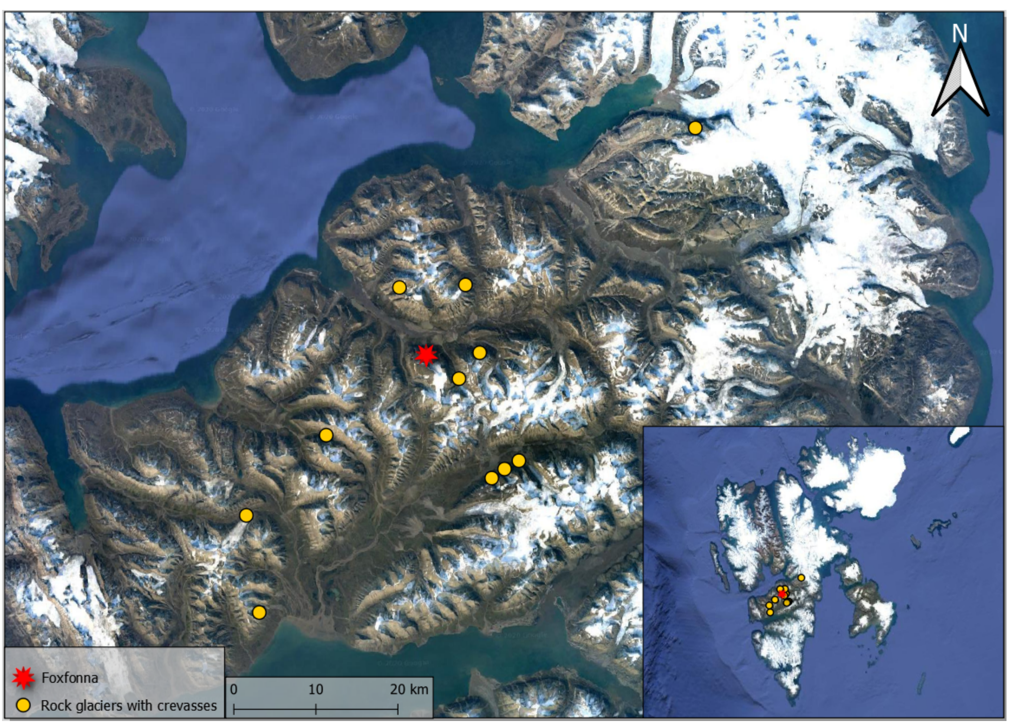

Figure 4: Locations of rock glaciers with similar surface features as Foxfonna.

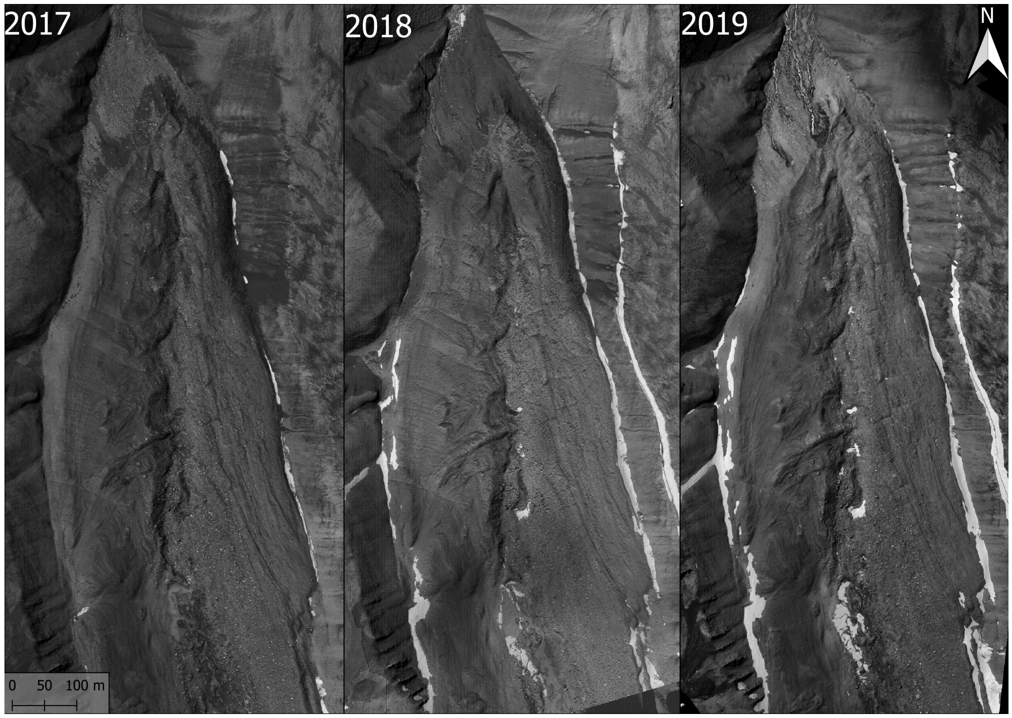

Figure 5: Orthophotos from drone images of the rock glacier from 2017, 2018 and 2019.

The orthophotos produced from the drone images over the different years (Figure 5) attained a resolution of 9cm/pixel.

Table 1: Error estimations of GCPs, created in Agisoft Metashape.

Year	Easting(m)	Northing(m)	Altitude(m)	Images
2017	0.350	0.268	0.371	573
2018	0.382	0.197	0.523	314
2019	0.482	0.538	0.658	410

RMSE errors, extracted from the Agisoft software, of the 10 GCPs for each 3D-model were mostly lower than half a meter (Table 1), only exceeding it in three instances, one in Northing positioning and two in altitude. Overall, 2017 shows the lowest error estimations and 2019 the highest.

4.1 Movement 2017-2019

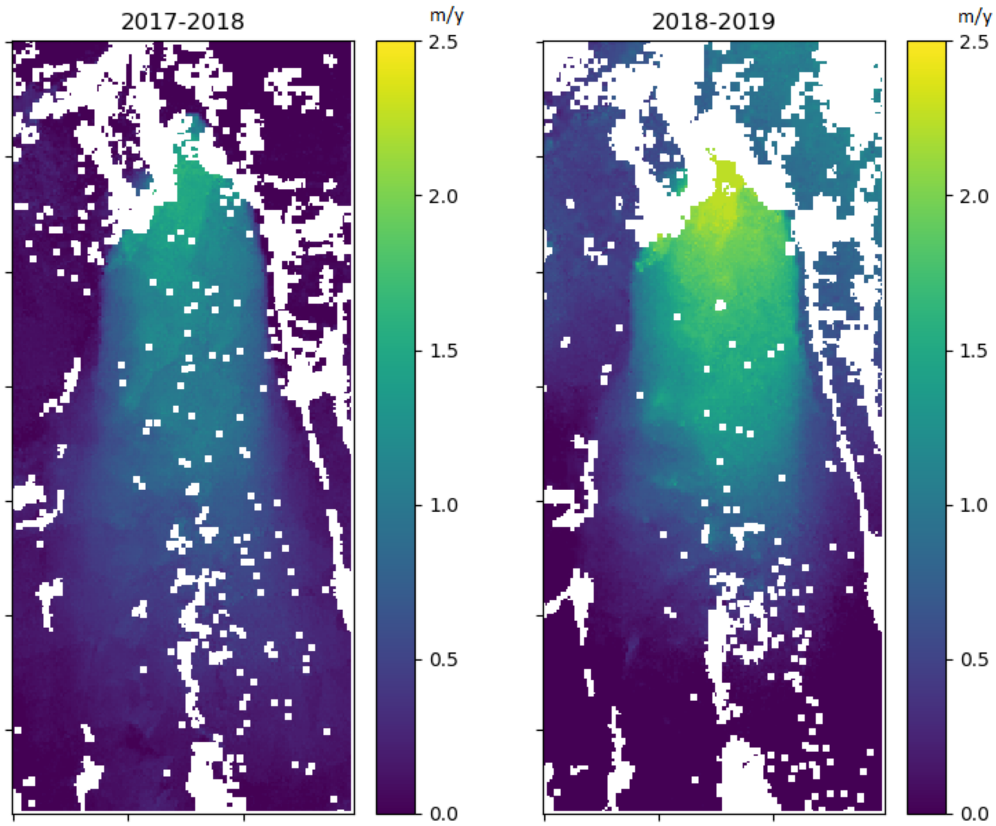

Figure 6: Movement of Foxfonna rock glacier between 2017-2018 and 2018-2019.

The rock glacier's advance from 2017-2019 (Figure 6), shows the results from the offsets of certain features in the ortophotos, and movement in the order of 0-2.5m/y can be found throughout the map.

The movement range from no (black) or very slow (dark purple), to higher (yellow). No-data values are shown as white areas, where the software couldn't compute differences due to not being able to match features. Higher velocities can be found in the northern part of the area for both periods, shifting towards a slower rate further south on it. The 2017-2018 period doesn't quite reach a change up to 2.5m/yr, but movements of 0.5m-1.5m/yr can be found throughout the majority of the area. In 2018-2019, changes up to 2m/yr are seen in a large area in the front of the rock glacier, indicating a rapid movement in this area.

4.2 Elevation changes 2009-2019

Between the years 2009-2019 the rock glacier has undergone elevation changes from its movement (Figure 7). A zero value indicates that no significant changes can be identified in those areas, while higher values indicate a positive accumulation of mass, and negative numbers indicate a loss. The highest values can be found in the northern part of the rock glacier, while lower values can be seen in the middle along the back of the rock glacier. Some of the features of the 2009 and 2019 DEMs were manually identified, which showed movements of up to 20m difference in the front, and up to 10m in the center of the back of the ridge. Low movements of around 1m, or even nothing at all, were detected from features in the southern part of the ridge, but elevation changes up to 5m were still identified in the map.

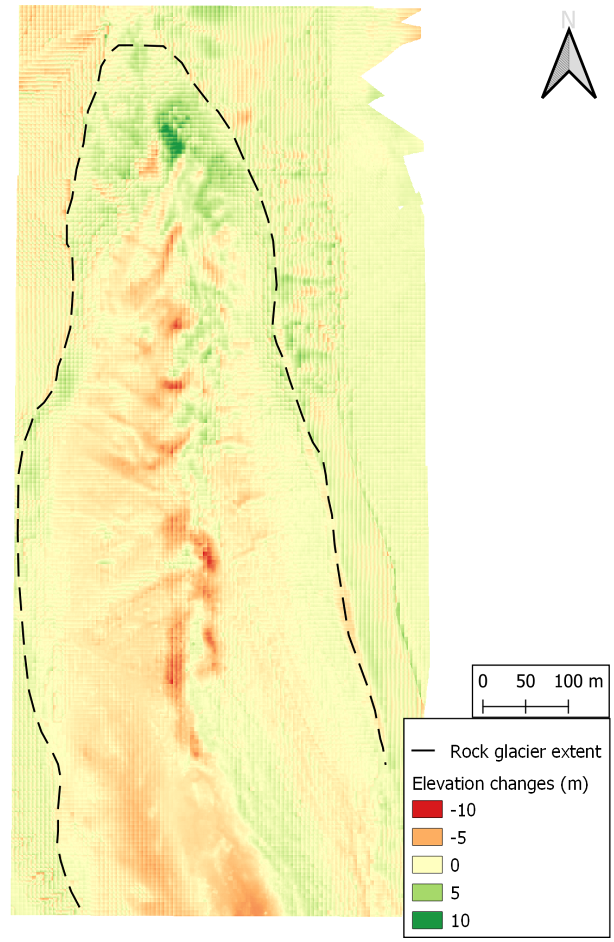

Figure 7: Elevation changes between 2009-2019.

5 Discussion

5.1 Feasibility of UAV images

In this study images from a drone were used, which enabled a high-resolution coverage of the area. More traditional measurements of rock glacier movements have been done with i.e. steel rods (Serrano et al., 2006), or more recently with LiDAR measurements (Avian et al., 2009), or through SFM with photos captured from manned air crafts (Vargo et al., 2017). Drones can be favourable for these types of studies both due to the accessibility it can provide, and due to it being a more cost efficient choice than most of the other methods. Adding to its advantages, rasters produced from SFM with drone imagery can also acquire equally high-resolution imagery as LiDAR (Polat and Uysal, 2018). Drones are however limited by whatever range it can be controlled by its operator, thus one need to first get to a selected study site, which if it is remote enough, a manned aircraft could easier research. Similar studies, done on glaciers, which have used GCPs to make an accuracy assessment of the results of drone images, have obtained an accuracy of around 20cm (Chudley et al., 2019; Gindraux et al., 2017), whilst in this study the error estimation averaged 36cm horizontally (Table 1).

5.2 General

More movement can be seen between the years 2018-2019 than 2017-2018 (Figure 6). Movement is also detected outside of the area of the rock glacier, which are slopes that have experienced erosion. Overall the two periods show a similar pattern, that more surface movement takes place further north on the rock glacier and less movement further south. This also correlates well with the elevation changes between 2009-2019 (Figure 7), where a large increase in elevation can be seen in the upper part of the map. The large loss in elevation located here could potentially be explained by meltwater tunnels that collapse, a phenomenon that occurs in both glaciers and rock glaciers (White, 1976; Elconin and LaChapelle, 1997), which is indicated by a comparison between the ortophotos from the years 2018-2019 (Figure 8).

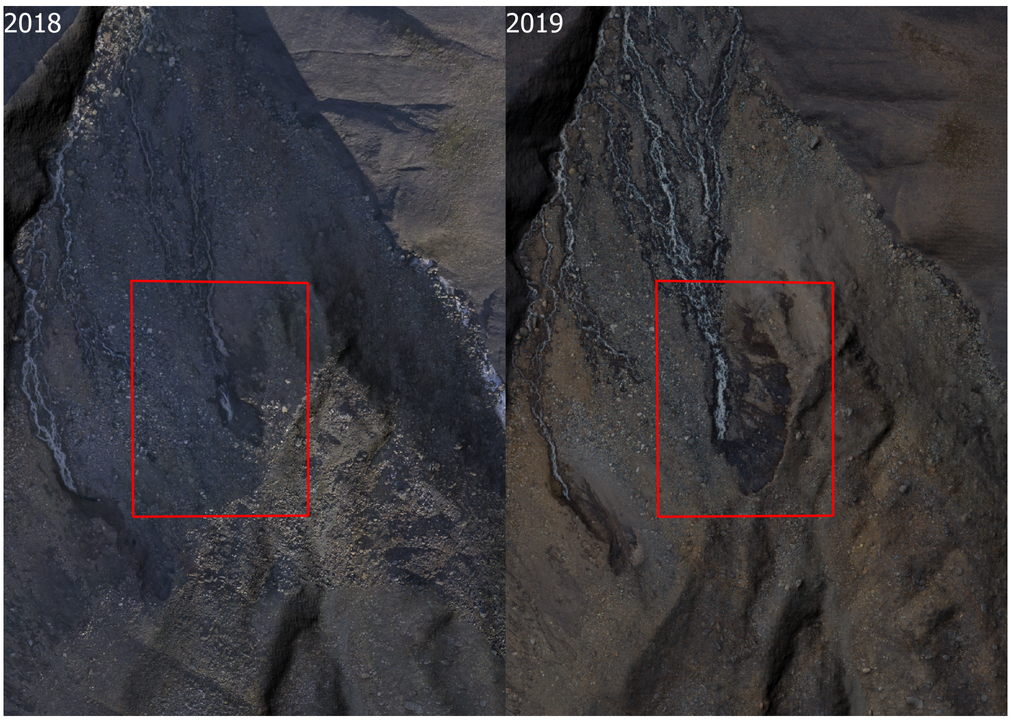

Figure 8: Collapse of a meltwater tunnel

Water can be seen flowing out from the rock glacier (Figure 8) in the area marked with a red square during 2017 and 2018 , while water instead can be seen flowing towards this spot during 2019. The negative elevation changes on the back of the rock glacier are most likely the transverse ridges that moves forward. Offsets can also be detected outside the rock glacier itself (Figure 6).

Foxfonna rock glacier has a far greater movement compared to other rock glaciers on Svalbard. Near Foxfonna is the Hiorthfjellet rock glacier, located across the valley, where annual movement were found to be between 0.08-0.10m/y (Isaksen et al., 2000b). Similar velocities can also be found on several other rock glaciers throughout Svalbard (Sollid and Sørbel, 1992), indicating that the rock glacier located at Foxfonna is experiencing something unique for this region.

Why this is happening can only be speculated from the results of this report, since it is limited to aerial imagery only. At least 2 other rock glaciers with similar behaviour as the one at Foxfonna are located in close proximity (Figure 4), at the glaciers Fleinisen and Hallwybreen both of which icing seems to occurs, and could also be studied in a similar manner for a larger overview of why these movements take place. Rock glaciers of similar velocities, up to 3m/y, can however be found in the alps, where it was found that neither the slope or the type of bedrock in the areas played a large role in contribution to the movement, but the amount of ice and a warmer ice temperature did (Krainer and He, 2006).

The accuracy of the GCPs has a strong influence on the georeferencing of the UAV data, which then also would make the final result of the velocity map more accurate. The GCPs, as done with this methodology, depend on that no movement has occurred on whatever object that is used for referencing, as well as the resolution of the map which is used as a reference. As stated in the method section, corners in objects such as rocks, which were located in flat areas, were used for this to minimize the risk of errors occurring due to movement. However, when the reference map is in a lower resolution, the location of the GCPs had to be estimated inside a raster cell. The problem with selecting low movement areas in the models used here is also that the orthophotos tend to be somewhat scewed towards the edges, since not as many images are taken over these areas. Another problem to account for while choosing rocks as GCPs is that the elevation of these are most likely not represented by the 5x5m DEM, which might further contribute to errors in the elevation changes. GCPs can also be attained by manually collecting GPS points on site, if this would produce a lower or higher accuracy however depends on the quality of the GPS and how many satellites that can be attained (Westoby et al., 2012). Collecting GCPs through remote sensing however would mean less fieldwork and could be easier for similar studies in remote areas, where it might be harder to reach the required locations.

5.3 Limitations & future studies

The study would benefit from data collected repeatedly over a time period extending several years for more solid results. And, while Svalbard in itself is quite a remote area to the rest of the world, Foxfonna is located close to both Longyearbyen and a road leading there, which allows for this to be done relatively easy. Snow cover and shadows could potentially disrupt the image correlation offsets, which can be seen to some extent in figure 6, where areas where the software could not calculate offsets are shown as white spaces instead. For future studies on this area, or in similar situations, a period during the summer where snow cover in the area is at its minimum, and the sun is in an optimal position would be recommended.

For a large scale remote sensing analysis of the rock glacier, older ortho- photos could also be included in this. For a more in-depth investigation of the larger factors that contributes to the rapid movements, a borehole could be used to reveal the internal structure of it, in which slope instabilities caused from internal composition have been suggested to play a large role (Arenson et al., 2002). A borehole could also create an opportunity to study the internal temperature of the rock glacier at different depths. GPR (Ground Penetrating Radar) data could also be accompanied with this, which would provide similar data but at a larger spatial extent, and also provide knowledge of ice content, water pockets and thickness of the rock glacier (Berthling et al., 2000).

Furthermore, meltwater processes can also play a role in movement of a rock glacier through heath transfer processes from both refreezing water, since summer temperatures might not provide enough heat for melting of the ice, and the effect of wind speed (Humlum, 1997).

6 Conclusion

The Foxfonna rock glacier had rapid movement in its central area, and even higher speed further forward, with a maximum speed of 2-2.5m/y within the years of 2017-2019. No or very low movement was detected further south on the rock glacier. During the time period of 2009-2019, manual feature detection of the rock glacier revealed that some areas moved 20m in the front, 10m in the center and again, show a very slow movement of either nothing or up to a maximum of 1m. However, these areas still experienced elevation changes. Different factors that could influence these movements have been discussed, such as internal composition, melt and ground water processes and wind speeds. Future studies should include a larger time frame, meaning more repeat measurements should be taken, and for more in depth on what causes the movements, GPR, boreholes and meteorological factors should be included. This study also proves that monitoring of rock glaciers could be executed on a relatively low cost, i.e. collecting images with a UAV instead of collecting imagery with e.g. airplanes, while also attaining a high resolution providing that the images from the UAV have a high enough overlap and that georeferencing is done properly.

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