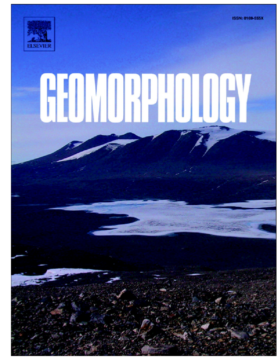

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Slow dynamics in debris-covered and rock glaciers in Hofsdalur, Tröllaskagi Peninsula (northern Iceland)

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Abstract

The results of previous work on the dynamics of the debris-covered and rock glaciers in Tröllaskagi are contradictory. To improve our knowledge of these dynamics and determine the origin and evolution of these landforms, we analyzed two case studies located in the Hofsdalur Valley: the Hofsjökull debris-covered glacier and the Júllogil rock glacier, using digital photogrammetry combined with GIS techniques. Our most accurate results were obtained for the period 1980 – 1994 as follows: for the Hofsjökull debris-covered glacier a mean block displacement velocity of 0.22 m yr^{-1}, a block elevation difference of -0.36 m and a horizontal displacement of linear ridges of 0.21 m yr^{-1} ; for the Júllogil rock glacier a mean block displacement velocity of 0.15 m yr^{-1}, a block elevation difference of -0.63 m and a horizontal displacement of linear ridges of 0.16 m yr^{-1} . The limits of these glaciers remained stable for ~70 years, from 1946 to 2017. All our data support the fact that these landforms are stable, and having lost their ice accumulation sources, their dynamics are fundamentally related to subsidence processes. Therefore, they are relict landforms whose origin seems to be related to paraglacial processes after rapid deglaciation of the valleys, and their stagnated ice is preserved, as it is above the permafrost level.

1. Introduction

Several studies of glacier dynamics have focused on Tröllaskagi peninsula (northern Iceland). The few debris-free glaciers in Tröllaskagi are very sensitive to climatic changes, especially to fluctuations in summer temperature, so they advanced and retreated frequently during deglaciation. The existing multiple moraines testify to those dynamics (Eythorsson, 1935; Caseldine, 1985; Fernández-Fernández et al., 2017; Fernández-Fernández et al., 2018). However, most of the Tröllaskagi cirques host debris-covered and rock glaciers, which have traditionally been considered much less sensitive to climatic changes than debris-free glaciers (Martin et al., 1991; Andrés et al., 2016; Tanarro et al., 2019).

Studies by various researchers have focused on some of these Tröllaskagi debris-covered glaciers and rock glaciers, applying different techniques and obtaining very different results, even for the same landforms. The most frequently used methods include: analysis of historical aerial photographs to obtain surface velocities using photogrammetric techniques (Martin et al., 1991; Wangensteen et al., 2006; Kellerer-Pirklbauer et al., 2007; Andrés et al., 2016; Tanarro et al., 2019); study of morphological characteristics and field observations (Hamilton and Whalley, 1995a; Björnsson et al., 2003); use of remote sensing (Brynjólfsson et al., 2012; Lilleøren et al., 2013); dating with Schmidt-hammer rebound values (Kellerer-Pirklbauer 2007; Kellerer-Pirklbauer et al., 2007); and lichenometric dating studies (Martin et al., 1994; Hamilton and Whalley 1995b).

Despite all these studies, the origin and dynamics of Tröllaskagi rock glaciers and debris-covered glaciers are still under discussion, because of the contradictory results obtained. Some researchers consider that they were formed during the Little Ice Age (LIA), based on lichenometric studies (Martin et al., 1994; Hamilton and Whalley 1995b; Whalley et al., 1995a) and deduce a maximum age of 200 years for the rock glaciers. However, the limitations of lichenometry as an absolute dating method in Tröllaskagi should be taken into account when evaluating these results, as has been reported in recent sysntheses (Decaulne, 2016; Fernández-Fernández et al., 2019). Other authors analyze surface displacement velocities, and from this data suggest that the debris- covered glaciers and rock glaciers were formed during the last 3 - 5 ka, assuming constant velocity throughout that period, as a reaction to neo-glacial impact in Iceland (Wangensteen et al. 2006). However, other authors take into account the surface displacement and application of Schmidt-hammer dating and propose that the debris-covered and rock glaciers started to form after the deglaciation at the end of the Pleistocene or the beginning of the Holocene, although they were reactivated later during the 8.2 ka event and the neo-glacial phases (Kellerer-Pirklbauer et al., 2007).

The origin of the debris-covered and rock glaciers is related to the intense geomorphological activity that has taken place on these cirque walls. Although there are no studies on wall retreat rates in Tröllaskagi, the intensity of rock avalanches, slides and rocks falls, especially during deglaciation, has been well established (Jónsson, 1976; Whalley et al., 1983; Mercier et al., 2013; Cossart et al., 2014; Feuillet et al., 2014; Decaulne et al., 2016). Moreover, these processes continue to occur in Tröllaskagi (Wangensteen et al. 2006; Sæmundsson et al. 2018)

Regarding the dynamics of these glaciers. Wangensteen et al. (2006) and Kellerer-Pirklbauer et al. (2007) calculated surface boulder velocities applying photogrammetry techniques; Lilleøren et al. (2013), used remote sensing to obtain important mobility rates, mainly for rock glaciers. Other studies suggest an almost unchanging glacier surface, based on aerial photograph observation and field monitoring (Martin and Whalley, 1987; Hamilton and Whalley 1995a, 1995b; Whalley et al., 1995a, 1995b; Andrés et al. 2016). Recently, Tanarro et al. (2019) worked in two cirques in the Holadalur Valley and studied the Hóladalsjökul debris-covered glacier and Fremi Grjótárdalur rock glaciers, where other authors had worked previously (Wangensteen et al. 2006; Kellerer-Pirklbauer et al., 2007; Lilleøren et al., 2013). Tanarro et al. (2019) applied high precision photogrammetric techniques with 3D restitution of surface elements (blocks, ridges and furrows), obtaining almost null surface velocity. They also calculated an important negative mean elevation difference. From their results, they concluded that the main dynamics of those glaciers were almost exclusively related to subsidence processes and that their origin cannot be deduced from their current dynamics.

Due to the lack of agreement between these studies, detailed knowledge is essential of the dynamics of other debris-covered glaciers and rock glaciers in the Tröllaskagi peninsula. The aim of this study is to analyze changes in the surface morphology and surface block movement of a debris-covered glacier and a rock glacier. The new cases selected for study here must be different from those studied by Wangensteen et al., (2006), Kellerer-Pirklbauer et al., (2007), Farbrot et al., (2007) and Tanarro et al., (2019), however they do share similar morphological characteristics.

In order to differentiate between a debris-covered glacier and a rock glacier, we have followed several criteria proposed by prior studies. For the purposes of this study, a glacier is debris-covered when 50% or more of the ablation zone is covered by debris and the thickness of the supraglacial debris layer is greater than 0.5 m (Kirkbride, 2000, 2011;

Brenning, 2005; Hambrey et al., 2008; Azócar and Brenning, 2010; Monnier and Kinnard, 2015). The surface morphology of debris-covered glacers consists mainly of longitudinal ridges (Clark et al., 1994). The Hofsjökull glacier (65˚40'09", 18 ˚58'26"W; 1050 m asl), located at the head of Hofsdalur Valley, meets these characteristics. We consider a rock glacier to be a glacier with a thicker rock layer on the surface compared to debris-covered glaciers, and for which the ice content is estimated to be 40–70% of the total mass (Haeberli et al., 2006). The surface morphology of rock glaciers consists mainly of transverse ridges and furrows perpendicular to the flow direction, a result of its viscous flow (Kirkbride, 2000, 2011; Brenning, 2005; Hambrey et al., 2008; Azócar and Brenning, 2010; Monnier and Kinnard, 2015). The rock glacier located in the Júllogil cirque (65˚40'23", 18 ˚55'25"W; 1030 m asl) has these characteristics. This cirque is adjacent to the Hofsjökull glacier, also in the Hofsdalur Valley.

Thus, the objective of this work is to study the current dynamics of the Hofsjökull debris-covered glacier and the Júllogil rock glacier, analyzing the current vertical and horizontal movement of their superficial boulders and comparing these results to other cases previously studied in Tröllaskagi. To achieve this objective we will compare the location of these boulders in high-resolution aerial photographs from different years. Thus, this research aims to reinforce previous studies and use the information about the dynamics of these glaciers to draw conclusions on the origin of these formations, how they behaved over time and their sensitivity to climatic change.

2. Study Area

The Hofsjökull debris-covered glacier and Júllogil rock glacier are located on the western side of Tröllaskagi Peninsula, at the headwalls of Hofsdalur Valley. This valley is a tributary of Hjaltadalur Valley, which flows into the Skagafjörður fjord. The village of Hólar is located in Hjaltadalur Valley (65˚42'N-65˚44'N and 18˚56'W-19˚02' W, 160 m asl) about 10 km from these glaciers to the northwest (Fig.1). The Hofsjökull debris-covered glacier is located just at the head of Hofsdalur Valley, facing the northwest, and can be seen from Hólar. The Júllogil (name of the cirque on some old maps) rock glacier is located in the next cirque, on the north slope of this valley.Tröllaskagi Peninsula is a mountainous area in central northern Iceland, extending from the central highlands between Skagafjörður fjord to the west and the Eyjafjörður fjord to the east. This region is located outside the active rift zone in east-central Iceland, with no volcanic activity (Rubin, 1990; Ipsen et al., 2018). The bedrock in Tröllaskagi consists almost entirely of Tertiary basaltic rocks, with intercalated sediment layers (Thordarson and Hoskuldsson, 2002; Lilleøren et al., 2013).

The Hofsjökull debris-covered glacier is in the Hofsdalur headvalley cirque and descends from 1250 m asl to 900 m asl. This glacier is 3 km long, divided into an ice-free upper sector and a ~1.7 km long debris-covered lower sector. The debris that covers this lower sector, which is around 1 to 2 m thick, is composed by particles that range in size, from large blocks to till. Its surface has abundant longitudinal ridges, which arcuate transverse lines near the front. The Júllogil rock glacier is in the north-facing cirque tributary of the Hofsdalur Valley and descends from 1150 m asl to 900 m asl. This glacier is 1.4 km long and is also divided into an ice-free upper sector and 1- km long debris-covered lower sector, with many steep steps formed by transverse arcuate ridges.

The climate of the Tröllaskagi Peninsula is characterized by a mean annual air temperature (MAAT) of 2 to 4 ˚C on the coasts and -2 to -4 ˚C on the summits. This high altitude air temperature is estimated from MAAT 1961-1990 data series from stations at lower altitudes (Etzelmüller et al., 2007). Precipitation on the Tröllaskagi summits has been modeled to be about 2000–2500 mm/year, according to 1971-2000 data series from lower altitude stations (Crochet et al., 2007). The Equilibrium Line Altitude (ELA) for the few debris-free glaciers in Tröllaskagi Peninsula varies from ~1010 m to 1100 m, these estimates were modeled using data from 2005 (Fernández-Fernández et al., 2017; Fernández-Fernández et al., 2019). Recent studies on mountain permafrost in Tröllaskagi, using modeling based on local climate, estimated that permafrost occurs above 850–950 m asl (Etzelmüller et al., 2007; Farbrot et al., 2007; Brynjólfsson et al., 2012; Lilleøren et al., 2013).

[Figure 1 near here]

3. Methodology

The use of photogrammetric techniques has been widely applied to the study of debris-covered and rock glacier dynamics in Tröllaskagi Peninsula (Martin et al., 1991; Wangensteen et al., 2006; Kellerer-Pirklbauer et al., 2007; Farbrot et al., 2007; Andrés et al., 2016; Tanarro et al., 2019). In this paper, we study the surface dynamics through the analysis of historical orthophotos from 1946, 1980, 1985, 1994, 2000 and a 2017 satellite image. From the analysis of these images, we have determined the position of some of the most characteristic elements of the landforms studied. To do so, the historical aerial photographs (1946, 1980, 1985 and 1994) were treated with a digital photogrammetric station (Digital Photogrammetric WorskStation -DPWS-), and high resolution orthophotos (0.25 cm) were obtained. The orthophoto from the year 2000 has been provided by Loftmyndir - the National Land Survey of Iceland, and has a resolution of 0.5 m, the satellite image from 2017 (Sentinel-2) has a resolution of 10 x 10 m. These images have been used to identify possible recent changes in the surface morphology of both glaciers. However, these procedures could not be carried out with the 1946 photograph, due to its lower quality, nor with the orthophoto from 2017, due to its low resolution. Therefore, accurate results were only obtained for the period between 1980 and 1994. In addition to the photogrammetric analysis, fieldwork was conducted in the summers of 2012, 2014 and 2015, to study the detailed surface morphology of the debris-covered and rock glaciers. In these campaigns a GPS handle was used to identify the limits of these formations and to georeference ridges, grooves, and boulders that helped create a geomorphological map. This process uses various steps: geomorphological analysis, creation of stereoscopic models and a geospatial study through GIS analysis.

3.1. Geomorphological mapping.

As indicated, an exhaustive geomorphological analysis was carried out for each one of the landforms studied along three summers. With this information, a detailed traditional photointerpretation of aerial photographs was completed to produce a geomorphological map differentiating geomorphological units in the debris-covered glacier and rock glacier. This detailed map enabled more accurate photogrammetric and surface dynamic analysis (Fig. 2).

[Figure 2 near here]

3.2. Creation of the stereo-models and orthophotos.

The Digital Photogrammetric WorkStation Digi3d.NET (DPWS Digi3d) was used to obtain stereo-model for each date (1946, 1980, 1985 and 1994). This is a complete photogrammetric station integrating Computer-Aided Design (CAD), where geographical units can be recorded from historical aerial photographs, enabling digital 3D photogrammetric restitution and orthophoto generation.

Then, a geometrical correction was carried out for all the photographs to obtain stereo-models for each year. This process consists of internal orientation, using the camera calibration parameters, and absolute orientation based on georeferenced control points, whose coordinates were established from the 1:50000 topographical map and an orthophoto from the year 2000. This allowed us to calculate the root mean square error (RMSE) of the absolute correction for all the stereo-models. These steps were used to create orthophotos of the study area for each year, with spatial resolution 0.25 m.

3.3. Photogrammetric analysis.

With the orthophotos, GIS software (Esri ArcGIS 10.2) and the DPWS were used to identify and 3D stereo-plot of the boulders and ridges that could be observed in each image. The GIS software was used to make an inventory of as many boulders as possible, visible and located in the orthophotos of each year. Once the inventory had been completed, the DEPWS was used to obtain the accurate location of the highest point of each selected boulder, with the exact coordinates and altitude. To calibrate uncertainty in the data, we selected stable boulders close to the landforms to use them as ground control points (GCP) (Fig.3). Once all these highest points on the boulder surface and lines from each ridge had been restored, a "point-to-point" method (Janke, 2005, Tanarro et al., 2019) was applied to track the movements of these elements. Stable points located in external areas of the debris-covered and rock glacier were selected, to assess the degree of uncertainty inherent in the method.

3.4. GIS spatial processing

All the above data were used to study the horizontal and vertical displacement of the boulders and ridges of the rock glacier and debris-covered glacier.

Inthe ArcGIS environment, the 'XY to line' geoprocessing tool was selected to calculate the horizontal distance between the different positions of the blocks from year to year. The displacements were calculated for both landforms between 1946-1980, 1980-1985, 1980-1994, 1985-1994 and 1994-2000. The elevation changes of the boulders for those periods were also calculated, with the exception of the 1994-2000, as the photograms used to make the 2000 orthophoto could not be accessed, and therefore we could not build the 3D model. Thus, we calculated the boulder movement on x, y, z axes for all the years, obtaining the annual displacement velocity and vertical changes. Spatial distribution maps of the displacements were created, interpolating the data obtained for horizontal velocities and elevation differences for each year. The interpolation method used was kriging, applied through ArcGIS.

The movement of the ridges was measured by calculating the average position of each ridge between two periods, taking perpendicular measurements at several points. The contrast between years was obtained for the periods 1980-1985, 1980-1994 and 1985-1994. The contour lines for 1994 were also restored at 2 m intervals to improve the quality of the graphic representation of the figures and for use in subsequent work, and a Digital Elevation Model (DEM) with cell size 1 meter was created.

4. Results

The results of the geomorphological and photogrammetric analysis of orthophotos from 1946, 1980, 1985, 1994 and 2000 show the surface evolution and dynamics of Hofsjökull debris-covered glacier and Júllogil rock glacier.

4.1. Geomorphology of Hofsjökull debris-covered glacier.

This debris-covered glacier is composed of two sectors:

- The debris-free sector of the glacier (DFG), located at the foot of the cirque walls, with area 1.72 km^2 and average slope 12% (Fig.3), descends to 1150 m asl in the east and 990 m asl in the west. In its lower sector, two central lobes (CL) about 675 meters long and a lateral morainic arc in the west (SWLA1) overlap the debris-covered sector of the glacier (Fig. 2).

- The debris-covered sector of the glacier is formed by two main central depressions (NECD and SWCD) surrounded by lateral arcs (NELA, SWLA1 and SWLA2) ending approximately at altitude 975 m asl. This is the starting point for a lower central moraine (LCM), occupying an area of 0.4 km^2 and flanked by a lateral moraine on the east (NELM) and another lateral moraine on the west (SWLM). A large external morainic arc (EMA) surrounds the main part of the debris-covered sector of the glacier (Figure 4a), which reaches altitude 1080 m asl in the east and 960 m asl in the west, with an area of 0.32 km^2. This EMA ends in a very steep, abrupt front (DCGF).

[Figure 3 near here]

4.2. Geomorphology of Júllogil rock glacier

Júllogil rock glacier can also be divided into two geomorphological sectors: the debris-free glacier and the rock glacier (Fig.4b). The latter can be divided into several landforms, enabling a more detailed geomorphological analysis.

- The debris-free glacier (DFRG) located at the foot of the steep cirque walls with area 0.23 km^2 descends from 1160 m asl to 980 m asl (Fig. 4c).
- The rock-covered section of Júllogil glacier with surface area 0.45 km^2 starts at 980 m asl and descends to approx. 900 m asl. It can be divided into an eastern and a western sector. The eastern sector is formed by three landform lobes. The first lobe is a transversal ridge in the upper part of the rock glacier (EL2), which covers a previous moraine (EUL) (Fig. 4d). The second lobe is another transversal ridge located in the central part of the rock glacier (EL1). The third lobe is a transversal ridge complex (ETL) which forms the frontal area of the rock glacier, ending at 940 m asl. The western sector of the rock glacier (Fig. 2) is also divided into different landform units. The upper one is a depression (RGD) with maximum width approx. 120 m and descends to 975 m asl. There is a central lobe 600 m long (CL1) in the central sector. This has buried two previous transversal ridges (WL1 and WL2). The lower unit is another transversal ridge complex (WTL) with surface area 0.11 m^2. The front of this complex (RGF) has steep slopes (Fig. 3) and descends to 900 m asl.

[Figure 4 near here]

4.3. Observations from comparison of the orthophotos.

A general visual analysis of the orthophotos from different years shows no variations in the morphology of the debris-covered glacier and the rock glacier, and their limits have remained static during the ~70-year period between the 1946 and 1980 orthophotos and 2017 Sentinel 2 satellite image (Fig 5). During the 2014 and 2018 field surveys using a normal GPS we did not notice any significant change in the limits, morphology or geometry of the ridges in both landforms between the 1946 - 2017 images. The visual and field results that did not have detailed resolution have been confirmed in the subsequent photogrammetric analysis for the periods for which high-resolution aerial photographs were available.

[Figure 5 near here]

4.4. Photogrammetric analysis.

A significant number of common boulders was identified in the orthophotos from 1980, 1985 and 1994 (>300 for the debris-covered glacier and >90 for the rock glacier), while in the orthophotos from 1946 and 2000 only a small number of common blocks was identified (4 and 112 respectively for the debris-covered glacier, and 6 and 59 for the rock glacier).

4.4.1. Data uncertainty

The stable ground control points established close to the studied landforms were used to calibrate the data uncertainty. The stable blocks selected were considered fully fixed and immobile. For this reason, any movement resulting from the application of our method was considered to indicate the RMSE of the absolute orientation of the aerial photographs. On the other hand, the maximum horizontal and vertical movements obtained from the stable blocks were considered the result of human error when delimiting the blocks in each photo.

The average velocity of the stable points in Hofsjökull ranges from 0.053 m yr^{-1} (1980-1994) to 0.13 m yr^{-1} (1980-1985), with maximum displacement values of 0.27 m yr^{-1} (1980-1985), 0.25 m yr^{-1} (1985-1994) and 0.22 m yr^{-1} (1980-1994). For the rock glacier, the average velocities of the stable points range from 0.02 m yr^{-1} (1980-1994) to 0.12 m yr^{-1} (1980-1985), with maximum displacement values of 0.06 m yr^{-1} (1980-1994), and 0.12 m yr^{-1} (1985-1994). These values are considered as the uncertainty for the boulder displacement calculations in the debris-covered and rock glacier respectively. On the other hand, the mean values obtained in the block elevation calculations for the stable points in the debris-covered glacier were 0.29 m (σ = 0.418) (1980-1994), 0.16 m (σ =0.312) (1980-1985), and 0.09 m (σ =0.37) (1985-1994). The same mean values for stable points in the rock glaciers were 0.02 m (σ =0.35) (1980-1994), 0.35 m (σ =0.403) (1980-1985) and -0.29 m (σ =0.34) (1985-1994). Because of the difficulty in estimating the uncertainty of boulder elevations due to the orthophoto quality and human error, we used the maximum and minimum elevation data obtained in the analysis, with values 1.2 and -0.89 m (1980-1994), 1.25 and -0.33 m (1980-1985) and 0.94 and -0.95 m (1985-1994) for the debris-covered glacier. For the rock glacier the values are 0.77 and -0.73 m (1980-1994), 0.93 and -0.33 m (1980-1985) and 0.38 and -0.95 m (1985-1994).

4.4.2. Horizontal velocities of the Hofsjökull debris-covered glacier

Horizontal displacement was analyzed for 284 blocks during the period 1980-1994, obtaining mean velocity 0.22 m yr^{-1}, with velocities ranging from 0.006 m yr^{-1} to 0.55 m yr^{-1} (Table 1). The interpolation map of the velocities (Fig.6) shows that only slight displacements occurred in the mid-eastern sectors of the glacier, mainly in the LCM, (~0.27 m yr^{-1}) with maximum displacements of 0.55 m yr^{-1} at the front of the external morainic arc. This area coincides with the main debris-covered glacier drain. The lowest velocities are obtained in the upper western sectors (in the flow direction) of the debris-covered sector of the glacier, mainly in the SWCD, SWLA1 and SWLA2, obtaining velocities ranging from ~0.01 to 0.20 m yr^{-1} (Fig. 6). These values are within the range of the mean and maximum values of the stable blocks. Thus, the movement in these sectors of the debris-covered glacier are considered minimal. Analysis of the 954 common blocks for the 1985-1994 period shows similar results, with mean velocity 0.25 m yr^{-1} and velocities ranging from 0.02 m yr^{-1} in the SWLM to 0.89 m yr^{-1} in the western part of the LCM (Fig.7).

The interpolated velocities pattern is similar in all data periods, and also in 1994-2000, although the number of common blocks is low (80), with mean velocity obtained of 0.20 m yr^{-1}, and a range from 0.016 to 0.73 m yr^{-1}. In the 1946 photo we were unable to find monitored blocks that were identified in later years, and so this year could not be included in the analysis.

[Table 1 near here]

[Figure 6 near here]

[Figure 7 near here]

4.4.3. Elevation changes of the Hofsjökull debris-covered glacier

The application of photogrammetry using historical aerial photographs, with a relatively high flight altitude and the human error in restitution of the blocks, causes an error in vertical displacement (Z) greater than horizontal. The uncertainty values obtained in the stable blocks oscillate by almost 1 meter. Thus, the elevation difference values obtained in the block displacement on the surface should be considered with caution. However, if we consider only the degree of internal uncertainty of the results, the predominance of subsidence is clear.

The elevation analysis results of the 284 blocks for the 1980-1994 period show an average subsidence of -0.36 m (Table 2), with the highest values -2.6 m in SWLA1 and -2.52 m in NELA. Therefore, the greatest subsidence, with values higher than the margin of uncertainty, is concentrated only in the depressions and in the arcs that delimit them from the central-western sector. In contrast, the central body (LCM) and the outer moraine and its front (EMA) and front (DCGF), present positive elevation differences at the edges of both these units, and negative differences (on the north-eastern front), but within the margin of uncertainty (Fig 8).

345 blocks were analyzed for the period 1980-1985, with average subsidence 0.25 m, with maximums -1.09 and -1.08 m in the LCM and EMA sectors respectively. Even though the elevation changes were minor in this 5-year period, there were positive elevation changes in some sectors, as for example the NELM and NECD, with 0.77 m and 0.73 m respectively (Table 2). These result values are within the margin of uncertainty.

During the period 1985-1994, average sinking was -0.66 m for the 954 blocks analyzed, with highest values -4.28 m in the NELA sector, and -3.49 m in the SWLA1 sector. These highest values are in the same sectors as display greater subsidence 1980-1985, probably indicating a collapse in those areas. The period 1985-1994 also shows greater subsidence in the NECD and SWCD, upper areas close to the debris-free part of the glacier (Fig. 9), indicating further thinning of the ice in these areas. In contrast, elevation changes in the central body and at the front of the debris-covered glacier (LCM and EMA), do not show a clear trend, since positive and negative values alternate, within the margin of uncertainty.

However, the average values are negative (-0.33 m and -0.08 m respectively), indicating a trend to subsidence, if we consider the internal uncertainty of the analysis performed.

[Table 2 near here]

4.4.4. Horizontal velocities of the Júllogil rock glacier

Block surface displacements obtained from analysis of 64 blocks for the 1980-1994 period show a mean velocity of 0.15 m yr^{-1}, ranging from 0.02 to 0.3 m yr^{-1} (Table 3). If the degree of uncertainty of the stable blocks is assumed (0.22 m yr^{-1}), the highest displacement velocities occurred at the RGF and the lower part of the WTL, ETL and CL1, where the velocities oscillate between 0.20 and 0.30 m yr^{-1}, as observed in the interpolated velocity map (Fig.6). The rest of the rock glacier displays low velocities, indicating that no significant block movement occurred. The lowest mean velocities are found in EL2 (0.099 m yr^{-1}), EUL (0.11 m yr^{-1}), and EL1(0.11 m yr^{-1}). WL1 also displays very low mean velocity (0.05 m yr^{-1}), but this data can be discarded since only 1 block was monitored in that sector.

In the other periods studied, the displacements obtained are similar. For the 1980-1985 period 73 blocks were analyzed, obtaining a mean velocity of 0.18 m yr^{-1}, with minimum and maximum velocities of 0.003 m yr^{-1} (ETL) and 0.94 m yr^{-1} (CL1). (Table 3). Since only one block was analyzed in CL1, the following maximum velocity (0.54 m yr^{-1}) was found in the WTL, where 15 blocks were analyzed. In the period 1985-1994 the velocity pattern is similar to the other years analyzed (Fig.7). The mean displacement velocity of the 393 analyzed blocks was ~0.19 m yr^{-1}, ranging from 0.02 m yr^{-1} (EUL) to 0.59 m yr^{-1} (ETL). Even though we consider the 1946-1980 and 1994-2000 periods, with 6 and 35 blocks respectively, do not provide enough data for analysis, the results obtained in these periods are similar to those above, with 0.19 m yr^{-1} (1946-1980) and 0.16 m yr^{-1} (1994-2000). These similar, very low displacement velocities from 1946 to 2000 indicate that the Júllogil rock glacier can be considered a static rock glacier. Despite its lack of displacement, its landforms, clearly derived from a viscous flow, are preserved intact, which open a debate on the degree of durability of flow landforms in an inactive rock glacier.

[Table 3 near here]

4.4.5. Elevation changes of the Júllogil rock glacier

For the 1980-1994 period, 64 blocks were analyzed, obtaining a change in mean elevation of -0.63 m (Table 4), with maximum subsidence -1.73 m in the WTL. The interpolated elevation changes map shows that almost all units show negative values between -1.37 m and -1.73 m (Fig.8 and Table 4). In this cirque, the elevation differences obtained in stable blocks were approximately -0.72 m. Therefore, it can be confirmed that the rock glacier displays subsidence of 0.65 - 1 m.

For the 1980-1985 period, the mean elevation change was 0.26 m, with maximum subsidence -0.58 m in the ETL sector and a maximum positive elevation change of 0.99 m in the same sector, although in this period (1980-1985) these values are included in the range of uncertainty. Finally, a mean elevation change of -0.86 m was obtained for the 393 blocks analyzed for the period 1985-1994, with maximum subsidence -1.94 m in the WTL. The map of the interpolated elevation changes (Fig. 9) is very similar to the 1980-1994 map, however the surface lowering processes are greater during this period. Although the degree of uncertainty is around -0.95 m, many of the rock glacier lobes register losses greater than 1.4 m.

[Table 4 near here]

[Figure 8 near here]

[Figure 9 near here]

4.4.6. Ridge displacement

We also analyzed the horizontal displacement of the outstanding ridges detected in both landforms, for 1980-1985, 1985-1994 and 1980-1994 (Fig.10).

[Figure 10 near here]

(i) *Hofsjökull debris-covered glacier*. 27 ridges were delimited for the 1980-1985 period in Hofsjökull obtaining mean displacement ranging from 0.36 m to 3.01 m (Table 5). Mean displacement 0.38 m and maximum displacement 4.8 m were obtained for the period 1985-1994 period, with 43 ridges delimited. Finally, for the 14-year period 1980-1994, the data obtained from the analysis of 33 ridges show a mean displacement range of 0.65 m - 6.55 m (Table 5). The maximum mean displacement values (>6 m) are probably due to a collapse. The mean displacement ratio per year is similar in the three periods and very low (0.24, 0.20 and 0.21 m, respectively,) for each period, which indicates that there is practically no displacement of these morphological landforms.

[Table 5 near here]

(ii) *Júllogil rock glacier.* Most of the ridges analyzed are concentrated in the EL1 and ETL of the east sector of the rock glacier and in the WL1 and WTL of the west sector of the glacier (Fig.10). The data obtained from the 18 ridges analyzed in the 1980-1985 period show an average displacement range between 0.40 m and 4.58 m (Table 6), with this maximum probably due to a collapse, as the following mean maximum displacement is 1.96 m. For the 1985-1994 period, analysis of 15 ridges obtained a range from 0.43 to 2.37 m. Finally, for the whole 1980-1994 period we obtained an average displacement range from 0.65 m to 5.64 m after analyzing 17 ridges (Table 6).

The ratios of the mean maximum displacement per year in the rock glacier are lower than those obtained in the debris-covered glacier, which indicates a minor ridge displacement on the Júllogil, as occurs with the horizontal block displacement analysis.

[Table 6 near here]

5. Discussion

5.1. Dynamics of the Hofsjökull debris-covered glacier

The Hofsjökull debris-covered glacier has not been studied before, but Hóladalsjökull, a very similar debris-covered glacier, is found in Hóladalur, the valley contiguous with Hofsdalur to the north. Wangensteen et al., (2006) studied the block surface displacements of Hóladalsjökull for the period 1985-1994. These authors applied cross-correlation matching of multi-temporal orthophotos from these years and obtained average velocities of 0.37 m yr^{-1}, with maximum value of 0.84 m yr^{-1}. Tanarro et al., (2019) also studied block surface displacements of Hóladalsjökull, applying photogrammetric techniques and GIS spatial analysis for the period 1980-1994. These authors obtained different results, with average velocities of 0.33 m yr^{-1} and maximum velocities of 0.65 m yr^{-1}. Tanarro et al., (2019) also analyzed the Hóladalsjökull ridge displacements 1980 – 1994, obtaining an average displacement of 0.22 m yr^{-1}. Finally, these authors calculated block elevation changes in Hofsjökull and obtained -0.72 m average subsidence.

Hóladalsjökull and Hofsjökull debris-covered glaciers are very similar in relation to dynamics of boulder movement. In this study, we used a methodology similar to that applied by Tanarro et al. (2019). Our results indicate that the Hofsjökull block velocities are even more reduced than those previously proposed for Hóladalsjökull by Tanarro et al. (2019), and far more than proposed by Wangensteen et al. (2006). Our data show very low mean velocities (0.22 m yr^{-1}) almost within the level of uncertainty shown by the stable points considered outside the glacier. The maximum velocities obtained in our study (0.55 m yr^{-1}) differ from those obtained by Tanarro et al. (2019) (0.65 m yr^{-1}) but differ even more from those obtained by Wangensteen et al. (2006) (0.89 m yr^{-1}). In this study, we have also analyzed the displacement of linear forms such as ridges. Our results show mean velocities (0.21 m yr-^{1}), very similar to those obtained by Tanarro et al. (2019) for the same period (0.22 m yr^{-1}).

Tanarro et al. (2019) included analysis of the vertical displacement of surface blocks in their study of the debris-covered glacier dynamics. Their results show a general trend to subsidence in Hóladalsjökull. Our results, with average movement of -0.36 m for the period 1980-1994, although somewhat inferior to those obtained in Hóladalsjökull (-0.72 m in the same period) seem to support this subsidence trend, with negative mean values. However, this trend can not be fully confirmed, since results in some units show maximum elevation differences within the limits of uncertainty. In fact, subsidence is mainly shown in the depressions and moraine arcs that enclose them.

Taking into account the reduced horizontal displacement of surface blocks and their incipient tendency to collapse, we can deduce that Hofsjökull was almost static during the entire period studied. Minor displacement of blocks on the debris-covered glacier is mainly found in its northeastern sector, just where the incipient drainage network is established, so that there seems to be a direct relationship between the two processes. The subsidence affects the whole glacier, but mainly the moraine arcs that enclose the current depression where the debris-free glacier is found. In the rest of the debris-covered glacier the subsidence in these 14 years is less than 1 m.

5.2. Dynamics of the Júllogil rock glacier

Other authors conducted earlier studies of the dynamics of rock glaciers located in Tröllaskagi. Martin and Whalley, (1987) and Whalley et al., (1995a, 1995b) analyzed the dynamics of Nautárdalur, a rock glacier located 20 km south-southwest of Akureyri, with a theodolite and obtained surface velocities of 0.2 - 0.25 m yr^{-1} for the 1977-1994 period. However, the rock glaciers which have attracted most attention are located in the Fremri-Grjótárdalur cirque, a tributary of Hóladalur Valley, near Hóladalsjökull, very close to our study area. Wangensteen et al., (2006) worked on these rock glaciers and calculated velocities ranging from 0.11 m to 0.74 m yr^{-1} for the period 1985-1994. Kellerer-Pirklbauer et al., (2007) also worked on the same rock glaciers, obtaining maximum velocity of 0.74 m yr^{-1}. Lilleøren et al., (2013) studied several Tröllaskagi rock glaciers, including those in our study area, analyzing them using remoting sensing during a 46-day period in early autumn 2007 obtaining surface velocities from 0.2 - 0.5 m yr^{-1}, with maximum velocities exceeding

3 m yr^{-1}. Tanarro et al., (2019) also worked on the Fremri-Grjótárdalur rock glaciers and obtained very different results from earlier authors. Tanarro et al., (2019) obtained mean horizontal velocities for the surface blocks of 0.15 m yr^{-1} for the 1980-1994 period. These authors also analyzed the ridge displacement of Fremri-Grjótárdalur rock glaciers 1980 – 1994, obtaining mean displacement of 0.14 m yr^{-1}. These authors also calculated the surface block vertical movement, obtaining an mean subsidence of -0.24 to -0.37 m.

Our results from the Júllogil rock glacier are similar to those obtained by Martin and Whalley, (1987), Whalley et al., (1995a, 1995b) in Nautárdalur, and Tanarro et al., (2019) in Fremri-Grjótárdalur rock glaciers, and they contradict the results of other authors, mainly the rock glacier dynamics proposed by Lilleøren et al., (2013). Our results show very low surface block horizontal movement (mean velocity 0.15 m yr^{-1}), similar to the results obtained by Tanarro et al., (2019) in Fremri-Grjótárdalur (0.14 m yr^{-1}). Our results also coincide with these authors during the same period (1980-1994) for ridge displacement analysis in both rock glaciers (0.14/0.15 m yr^{-1}), and for vertical movement, with average subsidence between -0.24 and -0.37 m in Fremri-Grjótárdalur, and -0.36 m for the Júllogil rock glacier.

Our results therefore show the static nature of the Júllogil rock glacier, where the reduced horizontal movement rate is only related to the surface subsidence of the rock glacier itself.

5.3. Relationship between the dynamics of Hofsjökull debris-covered glacier and Júllogil rock glacier and their origin, age and climatic sensibility.

Our results support those obtained by Tanarro et al., (2019) and conclude that both the debris-covered and rock glaciers in Tröllaskagi are landforms with no real flow. This means that they have lost their ice source and therefore do not incorporate ice from their accumulation area. If our results are correct, the deductions made by Wangensteen et al., (2006), Kellerer-Pirklbauer et al., (2007) and Lilleøren et al., (2013), integrating the measured displacements and streamlines over time to estimate the ages of Hóladalsjökull glacier and Fremri-Grjótárdalur rock glacier, may not be adequate and should not be applied to the Hofsjökull and Júllogil formations. In fact, the displacement rate of a superficial block would not indicate the velocity along its trajectory, from the wall where it fell to the front of these formations. The displacement of an individual block would in fact be a local movement indicating the subsidence of the entire debris surface covering stagnant ice, with no flow. In fact, our results show that throughout the period studied, the fronts of these formations have not advanced at all, and their surface morphology has not changed, except for the appearance of some collapse depressions.

The state of the Tröllaskagi debris-covered glacier and rock glaciers has been detected in many other cases, with very low block displacement rates, lack of surface transformation, subsidence and stagnantn ice (Potter et al., 1998; Janke et al., 2015) and there are other examples of debris-covered glaciers with similar dynamics to the Hofsjökull glacier. In the Mount Everest region (Nepal), Hambrey et al., (2008) studied four avalanche-fed debris-covered glaciers, applying low-frequency ground-penetrating radar (GPR) and electrical resistivity tomography (ERT). They concluded that these glaciers were in recession, marked by stagnation of their tongues. Also in the Everest region, Benn et al., (2012) analyzed the response of debris-covered glaciers to recent warming and pointed out that many of these glaciers have become stagnant, with surface lowering and drastic reduction in velocity. In the Peruvian Andes, Emmer et al. (2015) monitored the surface movements of the Jatunraju debris-covered glacier using remote sensing images and determined velocities of >1 m yr^{-1} for 2001-2013. However, they concluded that the frontal sector of the glacier had been stationary for at least the last 66 years. Very low velocity rates have been described in many rock glaciers. Janke (2005) calculated mean horizontal velocities of 0.14-0.2 m yr^{-1} for 1978-1999 for the Front Range rock glaciers (Rocky Mountains) and obtained slight overall growth or thinning of 0.01-0.02 m yr^{-1}, concluding that if strong climatic warming occurs, rock glaciers may respond by increasing subsidence and decreasing horizontal velocities as ice is removed. In a recent article, Kenner et al., (2018) using Terrestrial Laser Scanning (TLS) found that the body geometry of Ritigraben rock glacier, (W Swiss Alps), remained unchanged 2012-2015. Moreover, the dynamics of debris-covered glaciers and rock glaciers may remain stagnant for several thousand years: >10 ka (Krainer et al., 2014), even >1 million (Mackay and Marchant, 2016) or >2 million years (Bibby et al., 2016).

In this paper, we analyze the dynamics of debris-covered glaciers and rock glaciers of Tröllaskagi from 1946. The problem is then to know how long they have been in this state and how long they have remained without real flow. Fernández-Fernández et al. (2019) have recently applied cosmogenic dating methods to erratics and small moraines located in front of Hóladalsjökull glacier and Fremri-Grjótárdalur rock glacier. Their results show that during the Early Preboreal, the glacier fronts were already inside the cirques around 11 ka, a few hundred meters ahead of the fronts of the present rock glacier and debris-covered glacier. These authors also dated several boulders from fossil rock glaciers, with fronts located a few meters behind an 11 ka erratic. The results show stabilization of these blocks 11 - 9 ka, with increasingly earlier dates as the boulder altitudes rise. Finally, these same authors dated some boulders from Fremri-Grjótárdalur rock glaciers which still conserve interior ice, with homogeneous results around 5 ka. They also dated three boulders from the front of Hofsjökull glacier. The results show very similar ages for the three: 5.9 ± 0.5 ka (n=3).

These data coincide with the glacial and climatic evolution of northern Iceland. The last important advance in the fjord was during the Preboreal period, around 11 ka. After this advance, the icecap glacial tongues retreated quickly (see synthesis in Pétursson et al., 2015; Andrés et al., 2018). All the central Iceland glaciers are assumed to have disappeared by around ~9 ka (Geirsdóttir et al., 2018) and also those in the north (Harning et al., 2016; Anderson et al, 2018a). Between 8 and 5 ka, during the Holocene Thermal Maximum (HTM), the maximum expansion of birch forest occurred in Tröllaskagi (Wastl et al., 2001; Caseldine et al. 2006; Mercier et al. 2013; Decaulne et al. 2016) and in central Iceland the average temperature would have been 3ºC above the present (Anderson et al., 2018b; Geirsdóttir et al., 2018). Neoglacial cooling started in Iceland from 5 ka, with the formation of the important current icecaps and successive glacial advances, culminating in the Little Ice Age (LIA) (See synthesis in Geirsdóttir et al., 2018). The maximum extent of the Tungnahryggsjökull debris-free glaciers, practically coalescent with the Hofsjökull debris-covered glacier in the north, was ~1.5 ka. From that time up to the present, the glaciers advanced and retreated, leaving moraines from at least 16 different phases. These glaciers reached the maximum LIA advance in the 15th century (Fernández-Fernández et al., 2018). Fernández-Fernández et al. (2017) propose 3 cold periods between 1950 and 1986 when the Tungnahryggsjökull debris-free glaciers advanced, within a general trend to retreat. In fact, the snouts of these glaciers have retreated between 1300 m and 1700 m from the neoglacial maximum to the present (Fernández-Fernández et al., 2017).

While these great variations occurred in Tungnahryggsjökull debris-free glaciers throughout the Holocene, in the contiguous debris-covered glaciers and rock glaciers of Hofsjökull, Hóladalsjökull, Fremri-Grjótárdalur and Júllogil the only sign of change since the retreat of the glaciers 11 ka ago is the fossilization of lower altitude rock glaciers 11 - 9 ka and the stability of debris-covered glaciers and rock glaciers with internal ice since the HTM, without showing any reaction to Neo-glacial cold phases (Fernández-Fernández et al., 2019) and much less to that of the twentieth century, as we have demonstrated here.

To understand the reaction of these debris-covered and rock glaciers, we should consider that their dynamics depend not only on climate, but also on geomorphological processes and evolution of the slopes surrounding them (Humlum, 2000; Deline et al., 2015; Anderson and Anderson, 2016; Gibson et al., 2017). The walls of the Tröllaskagi cirques are in fact very unstable, with intensive rock falls and slides (Jönsson, 1976; Whalley et al., 1983). These slope processes are considered to have been very intense in Tröllaskagi during the intensive deglaciation of the valleys and fjords just after 11 ka (Mercier et al., 2013; Cossart et al., 2014; Feuillet et al., 2014; Coquin et al., 2015; Decaulne et al. 2016). The importance of paraglacial slope processes in the origin and subsequent evolution of debris-covered and rock glaciers has recently been highlighted (Knight et al., 2019). Paraglacial processes can interfere in the evolution of these formations and transform them with, e.g. a slow transition converting a debris-free glacier into a debris-covered glacier which then becomes a rock glacier (Janke et al., 2015; Monnier and Kinnard, 2015; Anderson et al., 2018b). However, paraglacial processes may also be sudden (Humlum, 2000; Hambrey et al., 2008), or even catastrophic, immediately after deglaciation, when the walls are freed from glacial ice, triggering macro rock avalanches and slides, as happened on many slopes of the valleys and fjords in Tröllaskagi (Jönsson, 1976; Whalley et al., 1983; Mercier et al., 2013; Cossart et al., 2014; Feuillet et al., 2014; Sæmundsson et al. 2018). Logically, this must have occurred with greater intensity on the vertical cirque walls, but in this case the debris fell on small retreating glaciers. These ice and debris landforms are still above the permafrost level (Etzelmüller et al., 2007; Sæmundsson et al. 2018), which has facilitated their survival, as has been demonstrated in other rock glaciers (Winkler and Lambiel, 2018).

More work is needed to reach a reliable conclusion, but everything seems to indicate that the low dynamism of these debris-covered glaciers and rock glaciers of Tröllaskagi did not only happen recently, but long ago. These landforms must have originated after the great glacial retreat of 11 ka ago and lost their internal ice during the intense warming of the first half of the Holocene. Their total stabilization seems to have occurred during the HTM, and since then they have remained almost static, with slow ice melt and subsidence. If this hypothesis is confirmed, it would come to support the idea that some rock glaciers survive in permafrost environments but may originate in warming periods (Kenner, 2019).

6. Conclusions

The application of photogrammetric techniques combined with GIS analysis has shown to be useful for analysis of the surface dynamics of the Hofsjökull debris-covered glacier and Júllogil rock glacier in the Tröllaskagi Peninsula. The results obtained in both landforms support recent studies in the similar Hóladalsjökull debris-covered glacier and in Fremri-Grjótárdalur rock glaciers, located in an adjacent valley. In all these cases, the dynamics analyzed of surface blocks and ridges are only linked to the subsidence processes. Throughout the period studied, from 1946 to 2017, there has been no change in their surface or any reaction similar to those occurring in the nearby Tungnahryggsjökull debris-free glacier, which advanced and retreated displaying great sensitivity to short warm and cold cycles. The characteristics of the landforms, together with the dates obtained in previous studies, seem to indicate that these are landforms generated by paraglacial processes after the Preboreal and that they have definitively remained static since the HTM, undergoing a slow subsidence process, due to the fact that they are still above the permafrost level.

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Table captions

Table 1. Horizontal displacements of the surface blocks of the debris-covered glacier.

Time Period	Blocks	name	Geomorphologic Unit	Nº blocks/Unit	Min. vel. (m/year)	Max. vel. (m/year)	Avg. vel. (m/year)	Standard Deviation (σ)
		DCGOUT	Stable Ground	42	0,0062	0,2256	0,0538	0,0362
		EMA	External Morainic Arc	40	0,1056	0,3634	0,2242	0,0620
		LCM	Lower Central Moraine	133	0,0368	0,5540	0,2658	0,1135
		NECD	NE Central Depression	30	0,0226	0,3507	0,1599	0,1209
1980-1994	326	NELA	NE Lateral Arc	40	0,0063	0,3666	0,1610	0,1120
		NELM	NE Lateral Moraine	18	0,0939	0,3279	0,2141	0,0702
		SWLA1	SW Lateral Arc 1	11	0,0349	0,1319	0,0828	0,0240
		SWLM	SW Lateral Moraine	12	0,1154	0,2242	0,1647	0,0320
			All Units	284	0,0063	0,5540	0,2194	0,1133
1946-1980	4	DCGOUT	Stable Ground	4	0,0060	0,1650	0,0584	0,0737
		DCGOUT	Stable Ground	34	0,0431	0,2703	0,1292	0,0604
		EMA	External Morainic Arc	49	0,0232	0,7235	0,2243	0,1479
		LCM	Lower Central Moraine	174	0,0306	1,0315	0,2900	0,1522
		NECD	NE Central Depression	28	0,0210	0,4182	0,2208	0,1159
1980-1985	379	NELA	NE Lateral Arc	45	0,0064	0,5210	0,2080	0,1265
		NELM	NE Lateral Moraine	20	0,0486	0,5001	0,2186	0,1227
		SWLA1	SW Lateral Arc 1	16	0,0161	0,2526	0,1165	0,0631
		SWLA2	SW Lateral Arc 2	2	0,1679	1,2463	0,7071	0,7626
		SWLM	SW Lateral Moraine	11	0,0863	0,2230	0,1447	0,0422
			All Units	345	0,0064	1,2463	0,2500	0,1556
		DCGOUT	Stable Ground	78	0,0004	0,2497	0,0609	0,0370
		EMA	External Morainic Arc	132	0,0396	0,6754	0,2571	0,0985
1985-1994	1032	LCM	Lower Central Moraine	410	0,0293	0,8939	0,3070	0,1307
		NECD	NE Central Depression	90	0,0348	0,6922	0,2249	0,1102
		NELA	NE Lateral Arc	147	0,0221	0,6393	0,2085	0,1144
		NELM	NE Lateral Moraine	68	0,0962	0,4100	0,2379	0,0714
		SWCD	SW Central Depression	2	0,0927	0,1340	0,1133	0,0292
		SWLA1	SW Lateral Arc 1	48	0,0349	0,2947	0,1236	0,0541
		SWLA2	SW Lateral Arc 2	9	0,0522	0,1627	0,0984	0,0333
		SWLM	SW Lateral Moraine	48	0,0220	0,2822	0,1730	0,0724
			All Units	954	0,0220	0,8939	0,2539	0,1252
		DCGOUT	Stable Ground	32	0,0611	0,2873	0,1388	0,0415
		EMA	External Morainic Arc	14	0,0166	0,3600	0,1745	0,0856
		LCM	Lower Central Moraine	23	0,0319	0,4359	0,1754	0,1047
		NECD	NE Central Depression	12	0,1004	0,6486	0,2394	0,1424
1994-2000	112	NELA	NE Lateral Arc	17	0,0484	0,3746	0,1827	0,0841
		NELM	NE Lateral Moraine	6	0,1288	0,7332	0,3314	0,2098
		SWLA1	SW Lateral Arc 1	6	0,0288	0,5900	0,2172	0,2048
		SWLM	SW Lateral Moraine	2	0,1068	0,1140	0,1104	0,0051
			All Units	80	0,0166	0,7332	0,1996	0,1268

Table 2. Block elevation changes of the debris-covered glacier.

Time Period	Blocks	name	Geomorphologic Unit	Nº blocks/Unit	Min. Elev changes (m)	Max. Elev changes (m)	Mean Elevation changes (m)	Standard Deviation (σ)
		DCGOUT	Stable Ground	42	-0,8975	1,2656	0,2912	0,4182
		EMA	External Morainic Arc	40	-0,9817	1,1301	-0,0783	0,4908
		LCM	Lower Central Moraine	133	-1,3505	0,9692	-0,2127	0,5003
		NECD	NE Central Depression	30	-1,4339	0,0292	-0,7209	0,4005
1980-1994	326	NELA	NE Lateral Arc	40	-2,5277	1,3245	-0,8386	0,7512
		NELM	NE Lateral Moraine	18	-1,0184	0,4428	-0,1922	0,4164
		SWLA1	SW Lateral Arc 1	11	-2,6067	0,1630	-1,3692	0,8586
		SWLM	SW Lateral Moraine	12	-0,3993	0,7567	0,1647	0,3416
			All Units	284	-2,6067	1,3245	-0,3632	0,6370
1946-1980	4	DCGOUT	Stable Ground	4	0,1028	0,9787	0,6185	0,4209
		DCGOUT	Stable Ground	34	-0,3318	1,2550	0,1637	0,3120
		EMA	External Morainic Arc	49	-1,0849	1,3735	-0,0258	0,4507
		LCM	Lower Central Moraine	174	-1,0977	1,5401	0,1508	0,5187
		NECD	NE Central Depression	28	-0,8796	1,3961	0,7302	0,5204
1980-1985	379	NELA	NE Lateral Arc	45	-0,5473	1,5631	0,6043	0,5075
		NELM	NE Lateral Moraine	20	0,0005	1,4717	0,7743	0,4387
		SWLA1	SW Lateral Arc 1	16	-0,7738	1,1402	0,0181	0,4941
		SWLA2	SW Lateral Arc 2	2	-0,1016	0,6551	0,2768	0,5351
		SWLM	SW Lateral Moraine	11	-0,7053	0,4808	-0,0252	0,3530
			All Units	345	-1,0977	1,5631	0,2570	0,5616
		DCGOUT	Stable Ground	78	-0,9515	0,9496	0,0091	0,3703
1985-1994	1032	EMA	External Morainic Arc	132	-1,3826	1,0053	-0,0821	0,4360
		LCM	Lower Central Moraine	410	-1,5830	0,7279	-0,3354	0,3718
		NECD	NE Central Depression	90	-2,6945	0,7541	-1,5216	0,5218
		NELA	NE Lateral Arc	147	-4,2823	-0,3141	-1,3537	0,5139
		NELM	NE Lateral Moraine	68	-1,7379	0,2354	-0,9803	0,4742
		SWCD	SW Central Depression	2	-1,0257	-0,7329	-0,8793	0,2071
		SWLA1	SW Lateral Arc 1	48	-3,4937	-0,3680	-1,3340	0,7769
		SWLA2	SW Lateral Arc 2	9	-1,7092	-0,3424	-1,0583	0,3859
		SWLM	SW Lateral Moraine	48	-0,9593	0,9511	-0,1159	0,4023
			All Units	954	-4,2823	1,0053	-0,6623	0,6992

Table 3. Horizontal displacements of the surface blocks of the rock glacier.

Time Period	Blocks	name	Geomorphologic Unit	Nº blocks/Unit	Min. vel. (m/year)	Max. vel. (m/year)	Avg. vel. (m/year)	Standard Deviation (σ)
1980-1994	91	RGOUT	Stable Ground	27	0,0010	0,0652	0,0205	0,0135
		EL1	E Lobe 1	6	0,0680	0,1515	0,1152	0,0364
		EL2	E Lobe 2	13	0,0184	0,2051	0,0992	0,0496
		ETL	E Terminal Lobe	26	0,0248	0,2984	0,1914	0,0781
		EUL	E Upper Lobe	5	0,0706	0,1409	0,1123	0,0288
		WL1	W Lobe 1	1	0,0540	0,0540	0,0540	-
		WTL	W Terminal Lobe	13	0,0538	0,2865	0,1761	0,0745
			All Units	64	0,0184	0,2984	0,1541	0,0764
1946-1980	6	CL1	Central Lobe 1	2	0,2861	0,3395	0,3128	0,0378
		ETL	E Terminal Lobe	1	0,1758	0,1758	0,1758	-
		WL1	W Lobe 1	1	0,0580	0,0580	0,0580	-
		WL2	W Lobe 2	1	0,1329	0,1329	0,1329	-
		WTL	W Terminal Lobe	1	0,1438	0,1438	0,1438	-
			All Units	6	0,0580	0,3395	0,1893	0,1045
1980-1985	97	RGOUT	Stable Ground	24	0,0201	0,7816	0,1230	0,1499
		CL1	Central Lobe 1	1	0,9399	0,9399	0,9399	-
		EL1	E Lobe 1	4	0,0352	0,1416	0,0747	0,0464
		EL2	E Lobe 2	13	0,0194	0,2174	0,1196	0,0511
		ETL	E Terminal Lobe	29	0,0034	0,4393	0,1952	0,0915
		EUL	E Upper Lobe	5	0,0859	0,3758	0,1650	0,1193
		WL1	W Lobe 1	5	0,0774	0,1311	0,1039	0,0210
		WL2	W Lobe 2	1	0,1002	0,1002	0,1002	-
		WTL	W Terminal Lobe	15	0,0429	0,5461	0,2251	0,1214
			All Units	73	0,0034	0,9399	0,1819	0,1333
1985-1994	425	RGOUT	Stable Ground	32	0,0092	0,1185	0,0572	0,0318
		CL1	Central Lobe 1	11	0,0795	0,4034	0,2433	0,0852
		CL2	Central Lobe 2	8	0,0790	0,3572	0,2208	0,0789
		EL1	E Lobe 1	48	0,0390	0,2947	0,1852	0,0489
		EL2	E Lobe 2	57	0,0213	0,4026	0,1110	0,0583
		ETL	E Terminal Lobe	135	0,0371	0,5942	0,2201	0,0769
		EUL	E Upper Lobe	39	0,0205	0,3924	0,1536	0,0697
		RGD	Depression	1	0,1374	0,1374	0,1374	-
		WL1	W Lobe 1	22	0,0566	0,2594	0,1457	0,0481
		WL2	W Lobe 2	2	0,1287	0,2248	0,1767	0,0679
		WTL	W Terminal Lobe	70	0,0642	0,3526	0,2209	0,0614
			All Units	393	0,0205	0,5942	0,1896	0,0781
1994-2000	59	RGOUT	Stable Ground	24	0,0478	0,2976	0,1276	0,0563
		EL1	E Lobe 1	5	0,1057	0,1846	0,1351	0,0311
		EL2	E Lobe 2	5	0,0869	0,2174	0,1510	0,0571
		ETL	E Terminal Lobe	12	0,0141	0,2904	0,1505	0,0924
		EUL	E Upper Lobe	4	0,1382	0,1916	0,1609	0,0261
		WL1	W Lobe 1	3	0,0659	0,4083	0,1912	0,1888
		WL2	W Lobe 2	1	0,3192	0,3192	0,3192	-
		WTL	W Terminal Lobe	5	0,0952	0,2395	0,1398	0,0601
			All Units	35	0,0141	0,4083	0,1563	0,0828

Table 4. Block elevation changes of the rock glacier.

Time Period	Blocks	name	Geomorphologic Unit	Nº blocks/Unit	Min. Elev changes (m)	Max. Elev changes (m)	Mean Elevation changes (m)	Standard Deviation (σ)
1980-1994	91	RGOUT	Stable Ground	27	-0,7291	0,7717	0,0212	0,3517
		EL1	E Lobe 1	6	-1,4023	-0,1380	-0,9329	0,5169
		EL2	E Lobe 2	13	-1,6660	0,7468	-0,2438	0,6730
		ETL	E Terminal Lobe	26	-1,3747	0,1935	-0,5393	0,3855
		EUL	E Upper Lobe	5	-1,0851	-0,5093	-0,8565	0,2303
		WL1	W Lobe 1	1	-1,3979	-1,3979	-1,3979	-
		WTL	W Terminal Lobe	13	-1,7340	0,0335	-0,9259	0,4413
			All Units	64	-1,7340	0,7468	-0,6329	0,5304
1946-1980	6	CL1	Central Lobe 1	2	-1,6349	-1,2098	-1,4224	0,3006
		ETL	E Terminal Lobe	1	-1,0560	-1,0560	-1,0560	-
		WL1	W Lobe 1	1	1,1644	1,1644	1,1644	-
		WL2	W Lobe 2	1	-6,7107	-6,7107	-6,7107	-
		WTL	W Terminal Lobe	1	-2,0753	-2,0753	-2,0753	-
			All Units	6	-6,7107	1,1644	-1,9204	2,6008
1980-1985	97	RGOUT	Stable Ground	24	-0,3302	0,9323	0,3538	0,4032
		CL1	Central Lobe 1	1	0,0920	0,0920	0,0920	-
		EL1	E Lobe 1	4	-0,2826	0,4353	0,1696	0,3163
		EL2	E Lobe 2	13	-0,2299	0,9532	0,3133	0,3439
		ETL	E Terminal Lobe	29	-0,5815	0,9979	0,3940	0,3417
		EUL	E Upper Lobe	5	-0,0101	0,6833	0,3639	0,3433
		WL1	W Lobe 1	5	-0,4877	-0,2945	-0,3769	0,0817
		WL2	W Lobe 2	1	-0,3909	-0,3909	-0,3909	-
		WTL	W Terminal Lobe	15	-0,4894	0,7834	0,2428	0,3419
			All Units	73	-0,5815	0,9979	0,2665	0,3773
1985-1994	425	RGOUT	Stable Ground	32	-0,9480	0,3783	-0,2910	0,3465
		CL1	Central Lobe 1	11	-1,4630	-0,3375	-0,8076	0,3783
		CL2	Central Lobe 2	8	-1,4346	-0,6352	-1,0933	0,2829
		EL1	E Lobe 1	48	-1,9069	-0,1340	-1,0234	0,3624
		EL2	E Lobe 2	57	-1,4808	0,3295	-0,5023	0,5221
		ETL	E Terminal Lobe	135	-1,6784	0,0924	-0,7670	0,3221
		EUL	E Upper Lobe	39	-1,3622	-0,2872	-1,0647	0,2374
		RGD	Depression	1	0,1940	0,1940	0,1940	-
		WL1	W Lobe 1	22	-1,5585	-0,6622	-1,0626	0,2831
		WL2	W Lobe 2	2	-1,2222	-0,9104	-1,0663	0,2205
		WTL	W Terminal Lobe	70	-1,9435	0,1678	-1,0362	0,4292
			All Units	393	-1,9435	0,3295	-0,8608	0,4227

Table 5. Displacement of the Hofsjökull debris-covered glacier ridges (in m). 'O' indicates a ridge overlap during years analyzed.

	1980-1985			1985-1994			1980-1994		
Ridge	Min. Dist	Max. Dist	Average	Min. Dist	Max. Dist	Average	Min. Dist	Max. Dist	Average
1	0,78	1,87	1,34	1,29	2,45	1,85	2,34	3,24	2,67
2	1,42	2,32	1,85	1,81	2,54	2,14	3,50	4,70	4,02
3	0,94	2,02	1,43	1,33	2,74	2,01	2,66	4,15	3,64
4	O	O	O	4,03	5,88	4,85	3,77	6,25	5,20
5	0,80	1,43	1,01	1,24	4,40	2,82	1,21	3,16	2,08
6	0,37	4,41	2,22	2,53	5,91	4,04	5,21	6,92	5,89
7	0,99	3,22	2,22	2,41	5,71	4,01	6,39	6,74	6,55
8	0,12	1,37	0,65	2,77	3,49	3,21	4,08	4,60	4,33
9	0,46	2,01	1,24	3,00	4,58	3,67	4,29	4,83	4,61
10	0,40	2,74	1,92	3,30	5,44	4,19	4,72	5,89	5,45
11	0,82	1,36	1,05	0,19	1,57	0,90	1,03	2,73	2,01
12	0,79	1,48	1,14	1,57	2,83	2,01	2,56	3,07	2,80
13	O	O	O	1,45	4,05	2,38	0,90	5,32	2,87
14	2,41	3,76	3,01	2,00	2,58	2,36	5,14	5,45	5,25
15	1,27	2,43	1,89	3,45	4,25	3,97	6,02	6,41	6,19
16	0,90	1,35	1,18	3,22	4,45	3,80	4,31	6,23	5,13
17	0,18	0,57	0,36	1,81	3,72	3,01	1,32	3,18	2,54
18	0,37	1,15	0,67	0,41	1,82	1,14	1,28	2,00	1,60
19	O	O	O	1,58	2,02	1,84	1,83	2,69	2,21
20	0,17	0,72	0,50	1,88	2,30	2,03	2,32	2,62	2,47
21	0,34	2,19	1,08	0,96	3,52	1,94	2,49	3,74	3,15
22	0,41	1,59	1,00	0,57	1,96	1,31	1,74	2,65	2,30
23	0,47	2,92	1,43	O	O	O	0,48	3,12	1,63
24	0,09	6,78	2,47	1,34	1,84	1,62	1,82	1,96	1,87
25	O	O	O	1,11	1,85	1,41	0,43	2,03	1,19
26	0,43	1,27	0,91	0,82	2,20	1,38	1,19	2,45	1,66
27	0,57	0,83	0,69	1,43	2,34	1,79	1,11	1,67	1,45
28	0,11	1,09	0,57	1,17	1,70	1,45	1,52	2,50	1,86
29	0,53	0,70	0,59	0,81	2,05	1,56	0,55	1,22	0,94
30	0,44	1,26	0,76	1,35	1,58	1,44	0,53	2,45	1,35
31	0,16	0,66	0,39	0,53	1,43	1,11	0,41	1,15	0,80
32	O	O	O	0,45	1,50	0,80	0,43	1,03	0,65
33	O	O	O	O	O	O	0,54	1,61	1,12
34	-	-	-	0,62	1,61	1,18	-	-	-
35	-	-	-	0,85	1,31	1,09	-	-	-
36	-	-	-	1,14	1,92	1,44	-	-	-
37	-	-	-	0,22	0,68	0,48	-	-	-
38	-	-	-	O	O	O	-	-	-
39	-	-	-	0,16	0,56	0,38	-	-	-
40	-	-	-	O	O	O	-	-	-
41	-	-	-	0,51	1,96	1,31	-	-	-
42	-	-	-	0,76	1,20	1,04	-	-	-
43	-	-	-	0,48	0,86	0,64	-	-	-
44	-	-	-	0,69	1,54	0,99	-	-	-
45	-	-	-	0,94	2,81	1,65	-	-	-
46	-	-	-	1,21	1,72	1,54	-	-	-
47	-	-	-	0,23	0,86	0,60	-	-	-

Table 6. Displacement of the rock glacier ridges (m). 'O' indicates ridge overlap during the years analyzed.

	1980-1985			1985-1994			1980-1994		
Ridge	Min. Dist	Max. Dist	Average	Min. Dist	Max. Dist	Average	Min. Dist	Max. Dist	Average
1	O	O	O	O	O	O	O	O	O
2	O	O	O	O	O	O	O	O	O
3	O	O	O	-	-	-	-	-	-
4	O	O	O	1,61	2,29	2,00	1,26	2,94	2,31
5	O	O	O	1,67	2,00	1,79	0,64	1,85	1,29
6	1,00	2,11	1,46	O	O	O	0,18	2,07	1,20
7	0,17	0,56	0,40	0,16	1,25	0,53	O	O	O
8	O	O	O	O	O	O	O	O	O
9	0,29	1,86	1,21	O	O	O	O	O	O
10	0,69	6,75	4,58	0,25	2,13	1,18	2,33	8,43	5,63
11	-	-	-	-	-	-	O	O	O
12	0,83	2,03	1,24	O	O	O	O	O	O
13	0,18	0,93	0,47	O	O	O	0,26	0,72	0,49
14	0,21	1,45	0,67	O	O	O	O	O	O
15	0,65	0,96	0,79	1,85	2,17	2,06	2,13	2,97	2,44
16	0,18	1,05	0,75	0,84	2,37	1,72	0,59	3,88	2,63
17	0,58	1,97	1,19	-	-	-	1,05	2,45	1,94
18	-	-	-	0,83	1,72	1,33	0,64	2,60	1,68
19	0,24	1,00	0,66	1,47	1,90	1,62	0,82	2,98	1,97
20	0,29	1,86	1,09	1,22	1,57	1,39	1,50	2,57	1,96
21	1,03	1,64	1,30	1,28	2,98	2,13	2,84	3,76	3,37
22	0,84	2,87	1,81	0,94	1,62	1,29	2,77	4,10	3,51
23	0,10	2,44	1,31	1,00	1,90	1,53	0,91	3,40	2,22
24	0,56	0,72	0,62	2,23	2,55	2,37	2,49	3,32	2,81
25	0,58	1,30	0,95	0,64	2,05	1,19	1,95	2,95	2,37
26	1,67	2,48	1,96	0,25	0,70	0,43	0,75	3,02	1,86

Figure captions

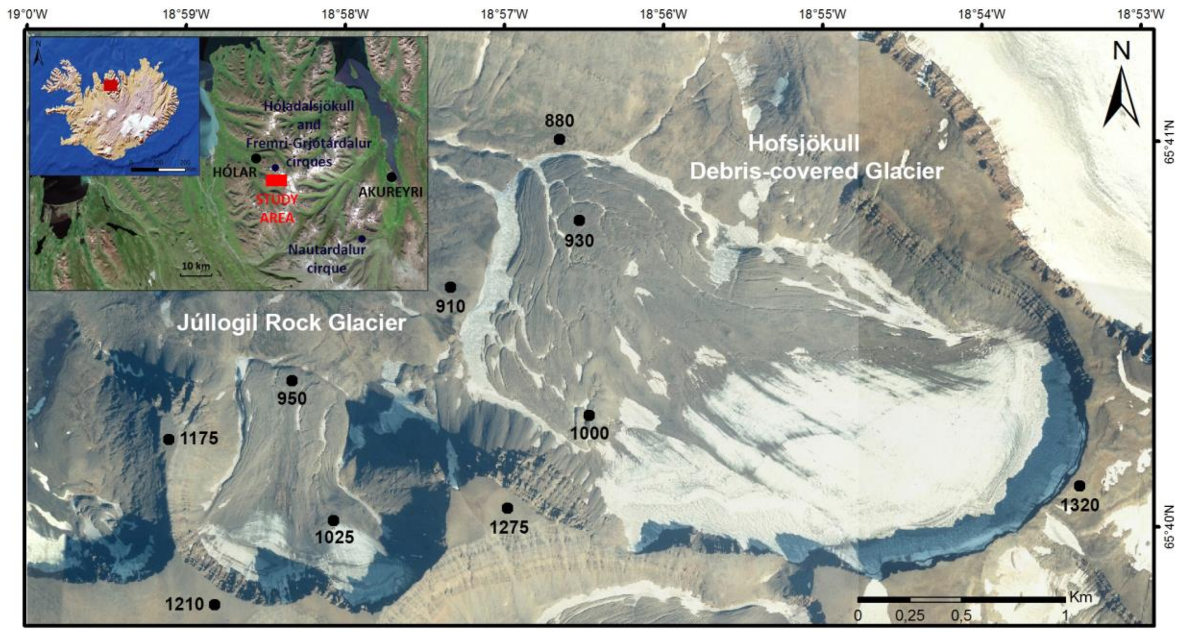
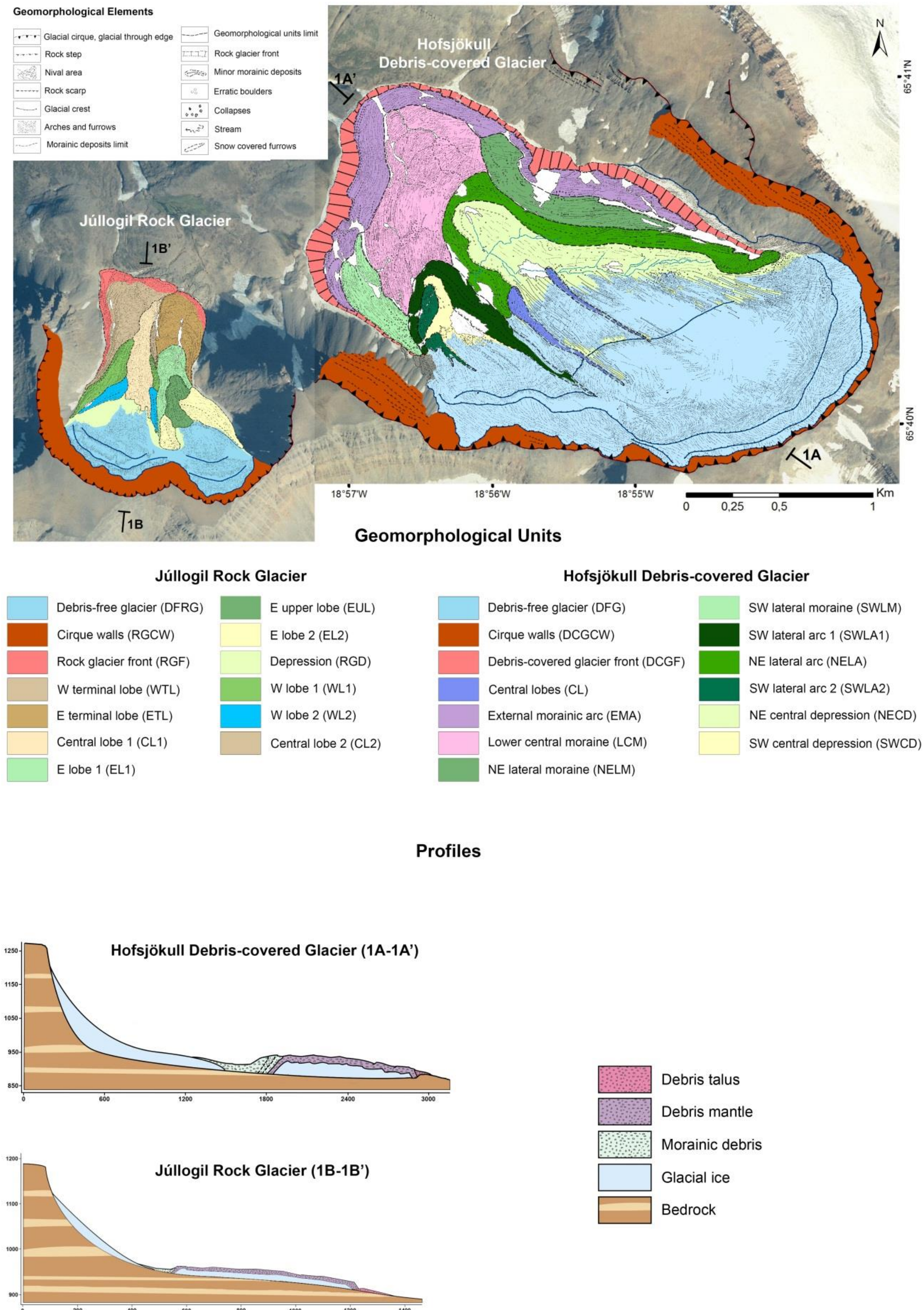


Figure 1. Location of the study area showing Hofsjökull debris-covered glacier (right) and Júllogil rock glacier (left). Black dots are the altitude (in meters). Source of the back image: Orthophoto from 2000.



Geomorphological Elements
Glacial cirque, glacial through edge
Rock step
Nival area
Rock scarp
Glacial crest
Arches and furrows
Moraınic deposits limit
Geomorphological units limit
Rock glacier front
Minor morainic deposits
Erratic boulders
Collapses
Stream
Snow covered furrows
Hofsjökull
Debris-covered Glacier
Júllogil Rock Glacier
1A'
1A
1B'
1B
N
65°41'N
65°40'N
18°57'W
18°56'W
18°55'W
0
0,25
0,5
1
Km
Geomorphological Units
Júllogil Rock Glacier
Debris-free glacier (DFRG)
Cirque walls (RGCW)
Rock glacier front (RGF)
W terminal lobe (WTL)
E terminal lobe (ETL)
Central lobe 1 (CL1)
E lobe 1 (EL1)
E upper lobe (EUL)
E lobe 2 (EL2)
Depression (RGD)
W lobe 1 (WL1)
W lobe 2 (WL2)
Central lobe 2 (CL2)
Hofsjökull Debris-covered Glacier
Debris-free glacier (DFG)
Cirque walls (DCGCW)
Debris-covered glacier front (DCGF)
Central lobes (CL)
External morainic arc (EMA)
Lower central moraine (LCM)
NE lateral moraine (NELM)
SW lateral moraine (SWLM)
SW lateral arc 1 (SWLA1)
NE lateral arc (NELA)
SW lateral arc 2 (SWLA2)
NE central depression (NECD)
SW central depression (SWCD)
Profiles
Hofsjökull Debris-covered Glacier (1A-1A')
1250
1150
1050
950
850
0
600
1200
1800
2400
3000
Júllogil Rock Glacier (1B-1B')
1200
1100
1000
900
0
200
400
600
800
1000
1200
1400
Debris talus
Debris mantle
Morainic debris
Glacial ice
Bedrock

Figure 2. Geomorphological map of the glaciers studied (above) and glacier profiles (below). Source of the back image: Orthophoto from 2000.

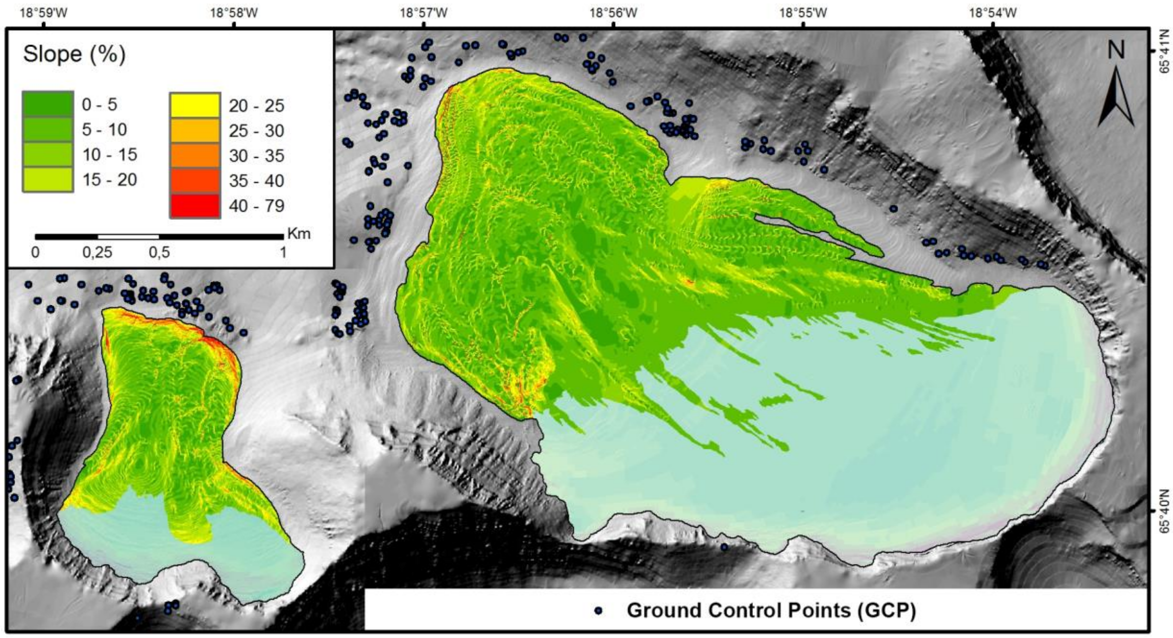


Figure 3. Slope map of Hofsjökull debris-covered glacier and Júllogil rock glacier and the ground control points used for the analysis. Source of the back image: Hillshade created from 1994 restituted contour lines.

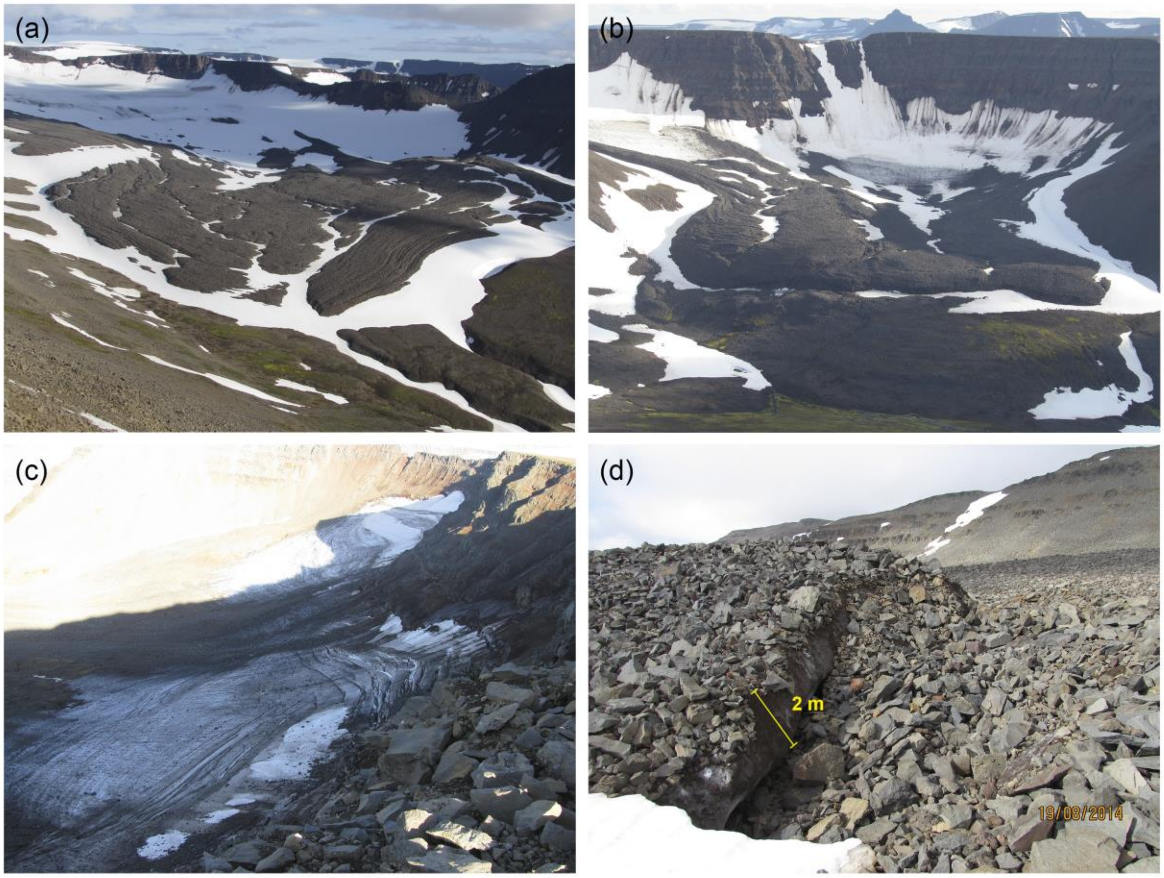


Figure 4. Several geomorphological landforms of the study area. (a) Hofsjökull debris-covered glacier. (b) Júllogil rock glacier. (c) Debris-free area of the Júllogil rock glacier. (d) Area of the Júllogil rock glacier with exhumed ice, where the thickness of the debris layer can be observed. Picturess from David Palacios, August, 2014

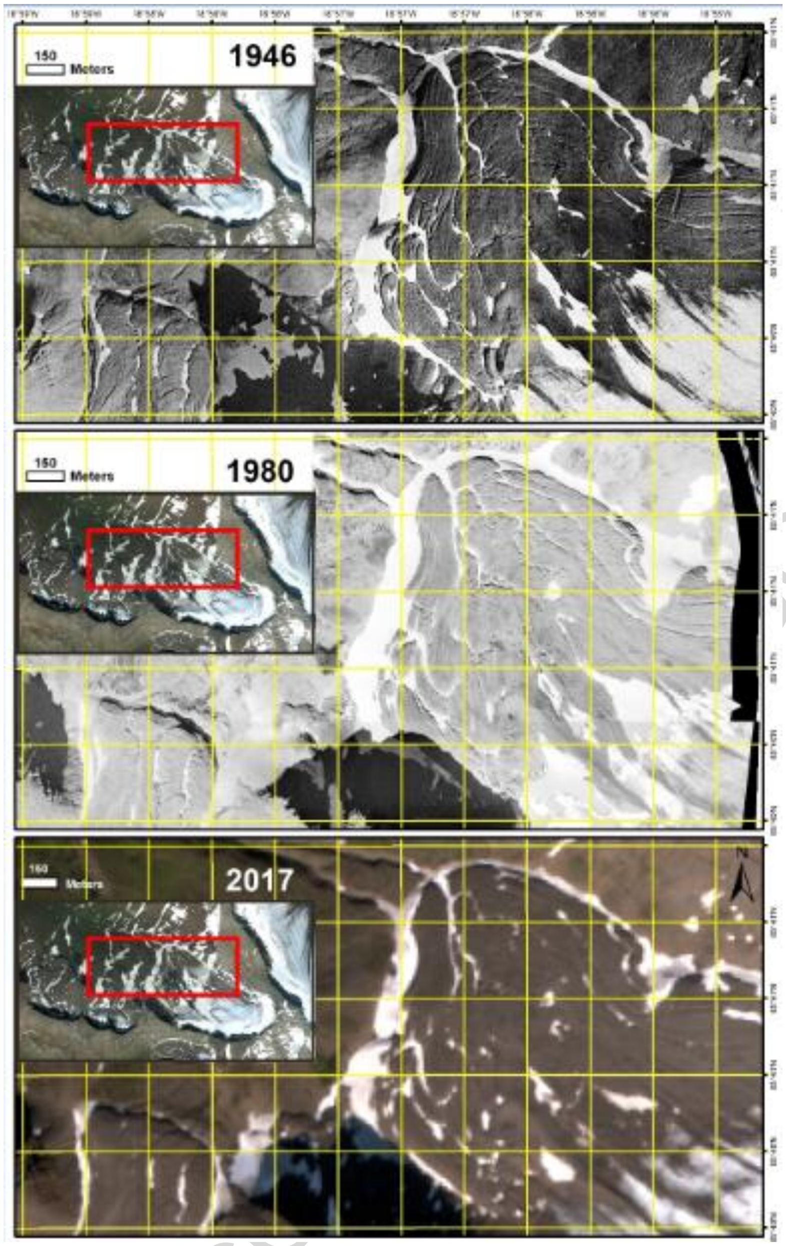


Figure 5. Visual comparison of the glacier front extent between different years (1946, 1980 and 2017). Source of the back images: high-resolution aerial photographs dating from 1946 and 1980 (supplied by the National Land Survey of Iceland) and Sentinel-2 image from 2017.

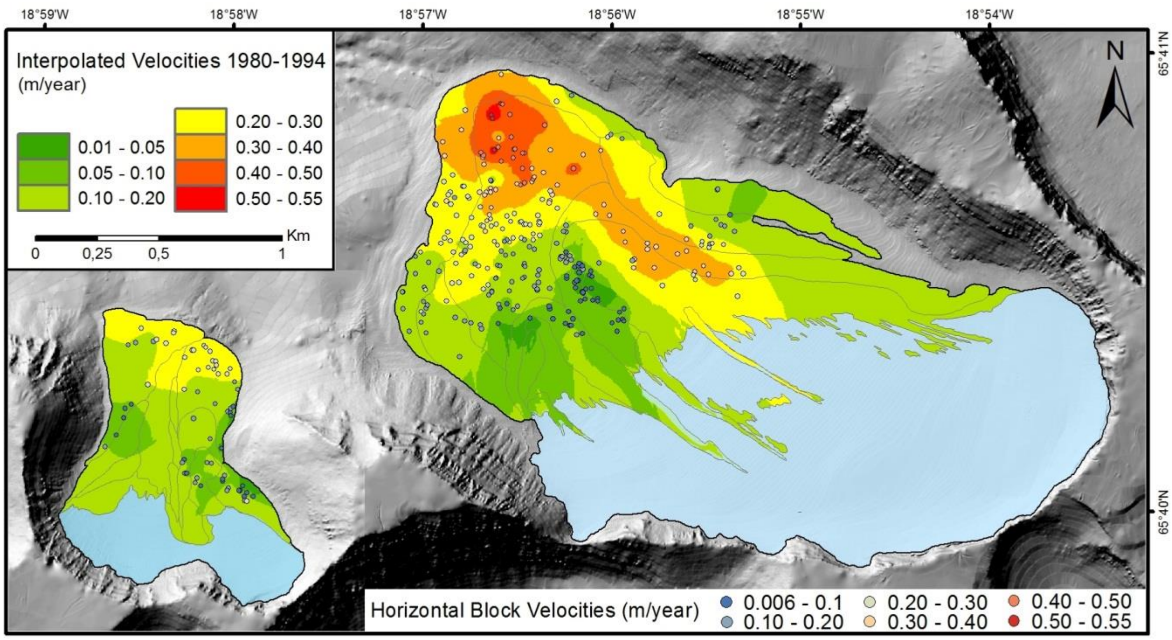


Figure 6. Interpolated velocities map (1980-1994). Source of the back image: Hillshade created from 1994 restituted contour lines.

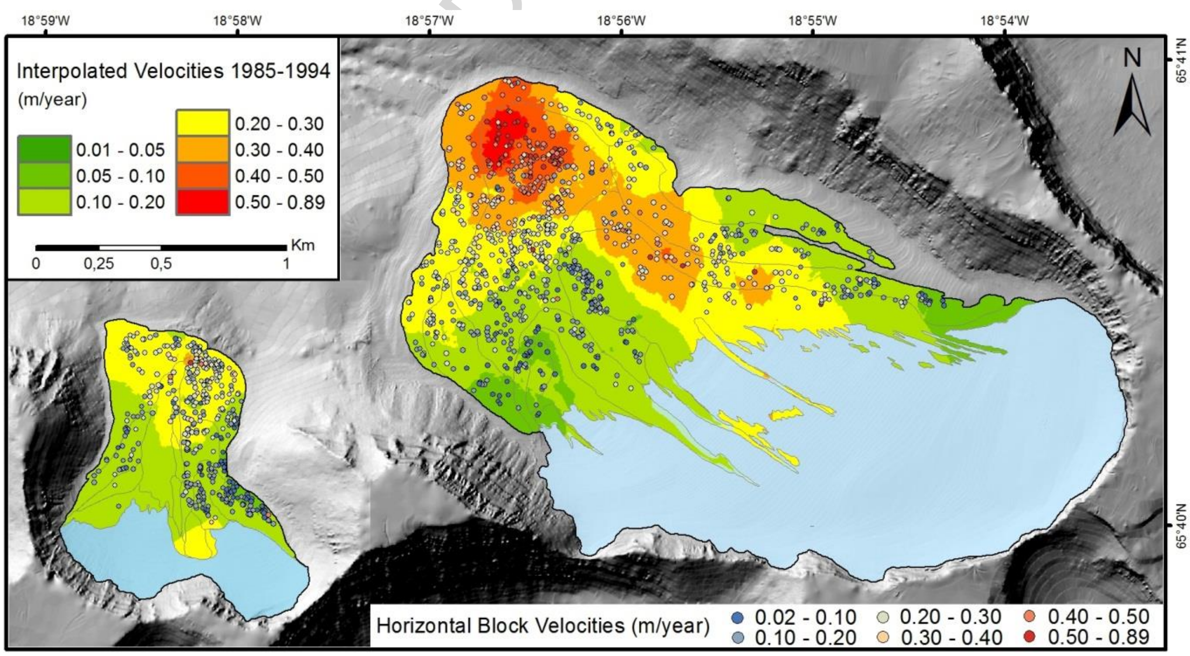


Figure 7. Interpolated velocities map (1985-1994). Source of the back image: Hillshade created from 1994 restituted contour lines.

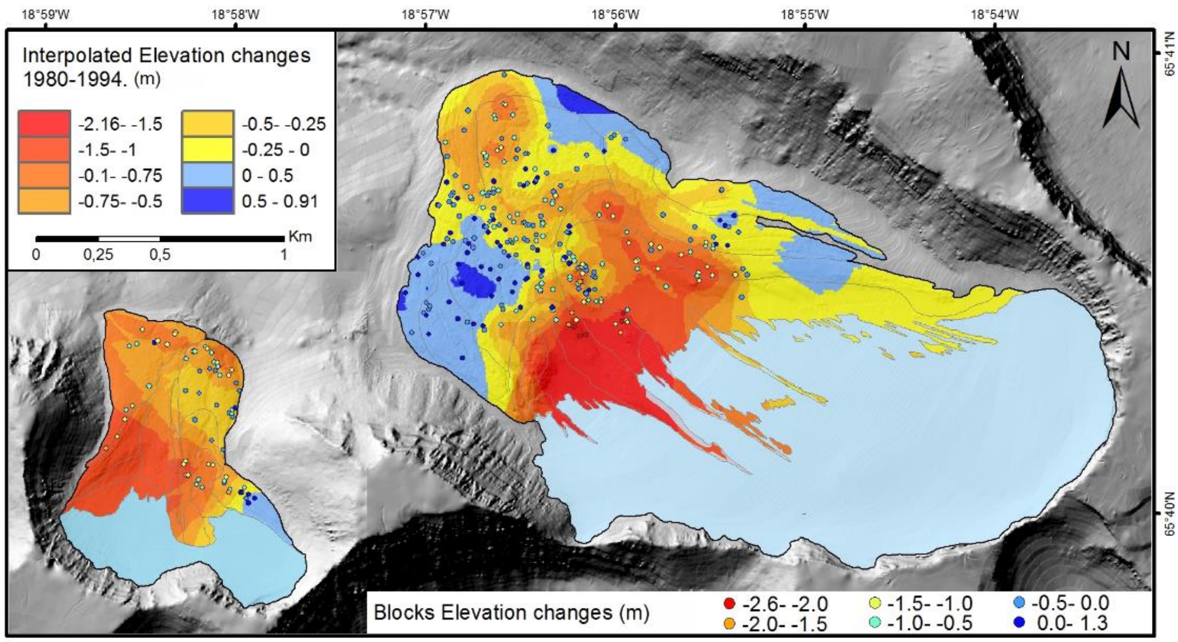


Figure 8. Interpolated elevation variations 1980-1994. Source of the back image: Hillshade created from 1994 restituted contour lines.

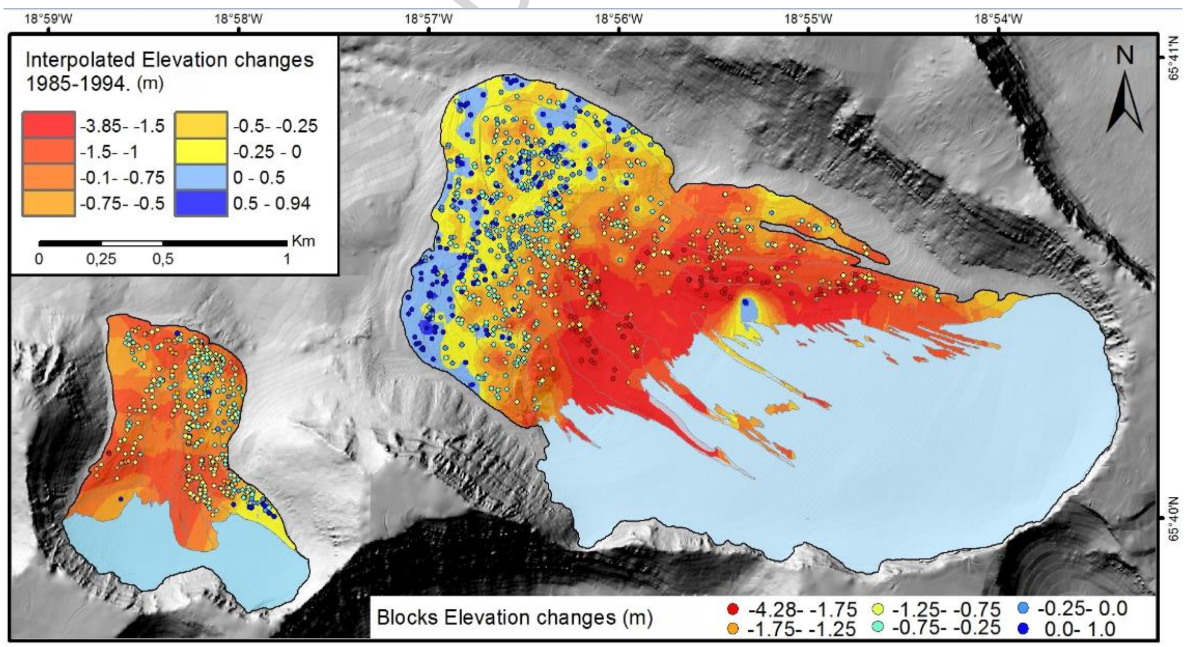


Figure 9. Interpolated elevation variations 1985-1994. Source of the back image: Hillshade created from 1994 restituted contour lines.

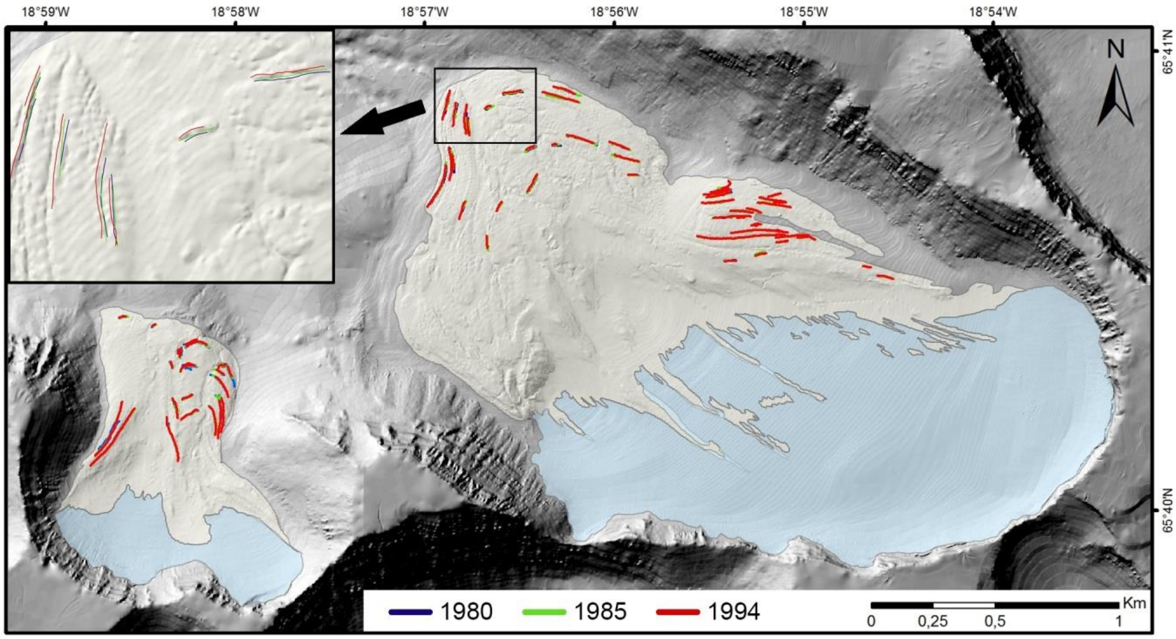


Figure 10. Location of the ridges in 1980, 1985 and 1994. The ridge structure did not change in the glaciers during these years (e.g.: zoomed section). Source of the back image: Hillshade created from 1994 restituted contour lines.