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Detailed subglacial topography and drumlins at the marginal zone of Múlajökull outlet glacier, central Iceland: Evidence from low frequency GPR data

Kristaps Lamsters*, Jānis Karušs, Agnis Rečs, Dāvids Bērziņš

Department of Geography and Earth Sciences, University of Latvia, Rainis Boulevard 19, LV-1586, Rīga, Latvia

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A B S T R A C T

New ground penetrating radar (GPR) observations on the Múlajökull surge-type outlet glacier, central Iceland, are presented. Overall 10.5 km of GPR profile lines were recorded parallel to the glacier margin in August, 2015. Detailed GPR investigations combined with high-accuracy GPS measurements allowed to build a high-resolution model of the subglacial topography. We provide new evidence of streamlined ridges beneath Múlajökull's marginal zone interpreted as drumlins and show the location of the upper edge of the drumlin field. This discovery improves understanding of the location, morphology and development of drumlins as other geophysical observations of subglacial bedforms beneath modern outlet glaciers are quite rare. The location of drumlins corresponds with the position of the major sets of crevasses in the digital elevation model (2008) suggesting the presence of additional drumlins beneath such crevasses in the ice-marginal zone. We suggest this semi-circular pattern of crevasses to be formed due to the variable glacier strain rates created by the subglacial topography. Numerous hyperbolic diffractions representing reflections of englacial channels are found in radar profiles suggesting a well-developed channelized drainage system of a surge-type glacier in its quiescence phase. The calculated thinning of the ice surface in the investigated area (0.65 km^2) is on average 17.9 m during 2008–2015.

1. Introduction

Glacial landforms of surge-type glaciers have been widely studied in Iceland (e.g. Kjær et al., 2008; Evans, 2011; Ingólfsson et al., 2016), Svalbard (Farnsworth et al., 2016) and other localities but a lot of questions still remain. A characteristic surging glacier landsystem (Evans and Rea, 2003) can consist of many crevasse-fill ridges (Sharp, 1985), but drumlins are not common. Only individual drumlins, or a few small drumlin fields, are discovered in front of modern surge-type glaciers in Iceland (e.g., Kjær et al., 2008; Waller et al., 2008; Evans, 2011; Schomacker et al., 2014). Although drumlins are not common at other Icelandic surging glaciers, they are abundant at the Múlajökull forefield, and more drumlins are supposed to still lie under the ice (Jónsson et al., 2014).

Múlajökull is an outlet glacier that drains the SE part of the Hofsjökull ice cap in central Iceland. It is a surging glacier with a recognized surge history from 1924 to 2008 (Björnsson et al., 2003; Johnson et al., 2010). The field of over 50 drumlins was first described in Johnson et al. (2010) making it the only known active drumlin field in the world, and it was shown that the crevasse pattern on 1995 air photo is related to the exposed drumlins. Jónsson et al. (2014) mapped 110 drumlins in total, revealing that the more distant drumlins are wider, shorter, and lower than the proximal ones that have experienced more surges. It is unknown if there are more drumlins beneath the glacier, how far up-glacier drumlins are located, and if the contemporary pattern of glacier crevasses is related to the subglacial topography.

Direct observations of drumlins that are still forming beneath surging glaciers and ice streams could shed light on our understanding of ice dynamics and subglacial landform development. Radar and seismic observations of subglacial bedforms beneath contemporary glaciers are very rare and limited to the few studies in Antarctica (King et al., 2007, 2009; Smith et al., 2007). The goal of the present research was to map in detail the part of the subglacial topography of the Múlajökull marginal zone, identify possible drumlins beneath the glacier and their relation to the glacier crevasse pattern, show the actual extent of the drumlin field and outline its up-ice edge.

* Corresponding author. Tel.: +371 20383902.
E-mail address: kristaps.lamsters@gmail.com (K. Lamsters).

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2. Materials and methods

2.1. GPR surveys and data processing

Ground penetrating radar (GPR) has been used extensively to map glacier bed topography. It has been shown that it is possible to map subglacial features with high accuracy (e.g., Blindow et al., 2010; Engel et al., 2012; Fischer and Kuhn, 2013; Martín-Español et al., 2013; Farinotti et al., 2014). In order to determine the subglacial topography of Múlajökull, GPR measurements were performed on the ice-marginal zone. The research area covers approximately 0.65 km^2 10.5 km of profile lines in total were recorded in August 2015. Altogether 22 GPR profiles were aligned parallel to the Múlajökull margin (Fig. 1) to better detect drumlins beneath the glacier in the research area. The first profile was measured 80 m from the glacier margin, and each subsequent profile 50 m further up-glacier. Each GPR profile consisted of several 50-m-long separately recorded sections, which were merged during data post-processing. Exact location of the research area was selected using aerial photographs, LIDAR DEMs of Múlajökull and direct exploring of ice surface. We selected a sufficiently large area near the glacier margin representing the ice-marginal zone, where the most prominent crescent crevasses were observed on LIDAR data from 2008. The exact number of measured profiles resulted also from the field logistics, weather conditions and power availability for equipment.

During the research the Zond 12-e GPR system was used. To suppress GPR signal scattering of local ice inhomogeneities and to obtain a clear reflection of the glacier bed, an antenna with a low frequency (38 MHz) was used. During data acquisition, the maximum available time window for the applied GPR system was used (2000 ns), which allowed us to detect the reflection of a

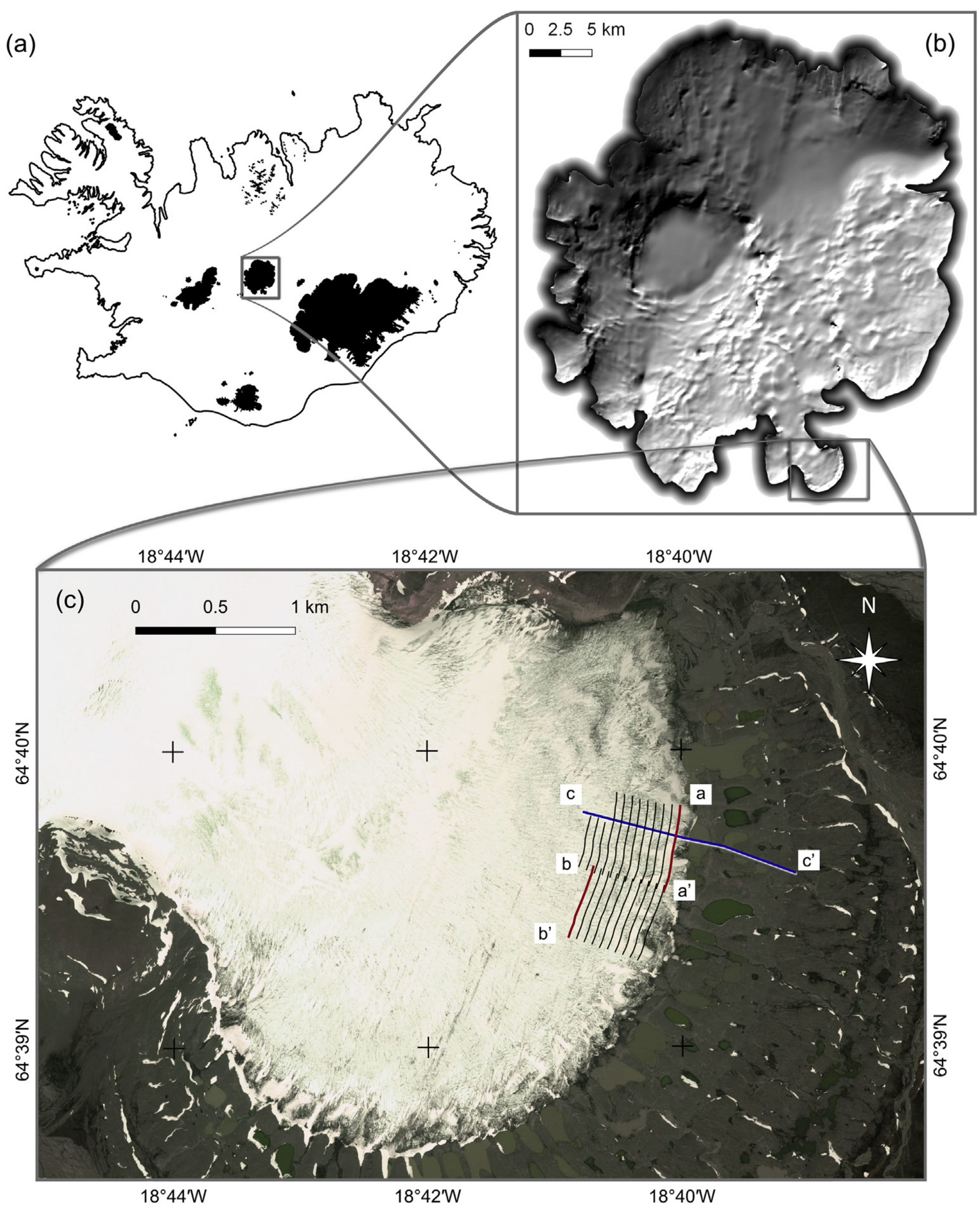

Fig. 1. (a) Overview map showing the location of Hofsjökull and other ice caps in Iceland, based on the data from the National Land Survey of Iceland. (b) Laser scan hillshade model of Hofsjökull ice cap from 2008. (c) Close-up of the study area (Google Earth image in the background). GPR profiles are shown in black and red, where red denotes profiles shown in Fig. 2. c – c′ line marks the location of the profile in Fig. 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

glacier bed 160 m beneath the ice surface. The GPR data were processed and analysed with *Prism 2.5* software. Processing included the application of time-dependent signal gain function, background removal filter, and Ormsby band-pass filter with a low frequency cut off at 4 MHz and a high frequency cut off at 91 MHz.

The GPR signal propagation speed was determined by using englacial reflections represented as hyperbolas (Moore et al., 1999; Bradford and Harper, 2005). In order to determine the GPR signal propagation speed and its corresponding dielectric permittivity (ε) value from each separately identifiable hyperbola, the hyperbola fitting function available on *Prism 2.5* software was used. Altogether 251 hyperbolas were inspected. It was calculated that $\varepsilon = 3.87 \pm 0.11$ at 99% confidence level (corresponding GPR signal propagation speed − 152.4 m/ms) that corresponds to 1% error in the calculated ice thickness values to approximately 0.2 m error of ice thickness near the glacier margin and up to 1.5 m error of ice thickness in the upper part of the research area. The calculated value of ε fits well in the interval of values of ε for temperate glaciers (3.2–4.6) reported by other researchers (Bradford and Harper, 2005; Bradford et al., 2009, 2013; Blindow et al., 2010; Martín-Español et al., 2013).

During the analysis of the obtained GPR measurements, the two-way travel time for the basal reflection was determined at each start and end point of the GPR profile sections, as well as additional readings that were performed on locations where GPR profiles suggested pronounced changes of basal topography. Using determined time values and calculated GPR signal propagation speed, the ice thickness was calculated. The thin Plate Spline (Global) interpolation method and *SAGA GIS* software was used to create a model of the subglacial topography and ice surface.

2.2. GPS surveys and data processing

The altitude and coordinates of the start and end point of each GPR profile section was determined by using the GPS system *Magellan Promark 3* with an accuracy of 1 cm. All measurements were measured in the Iceland National Coordinate system (*ISN2004*), whereas the elevations were calculated from ellipsoidal heights to orthometric heights on *ISH2004* (The Icelandic Height System) using the *IceGeoid2011* geoid model (IceGeoid, 2011). The standard deviation of this model is 1.7 cm, while the maximum deviations are up to 5.1 cm. The coordinates and elevations for two points on the glacier surface were measured using the static measure mode and the Fjórðungsalda base station from the IceCORS regional positioning service (latitude N 64°52′29.7552299", longitude W 18°00′21.7732296", ellipsoidal height 1034.8943 m, orthometric height 974.723 m). Data were downloaded and post-processed with GNSS Solution software. Since the distance to the base station is about 39.3 km, both of the points were measured in sessions of at least 3 h. This made it possible to obtain coordinates and heights with a standard deviation of less than 5.5 cm.

The *Magellan Promark 3* system is composed of two GPS receivers, and, because of its specificity, this makes it possible to take measurements and post-processing results with geodetic accuracy, but without GSM or radio support. The processed points were used as local base stations during the GPR surveying. The average horizontal accuracy at the 95% confidence level is 10 cm and the average vertical accuracy at the 95% confidence level is 12 cm for sample points, which is enough to generate high precision DTM and to combine with GPR accuracy.

3. Results

3.1. Observed variations of ice thickness, surface elevation and position of glacier front

Múlajökull has experienced a frontal retreat of 2 km from its maximum Little Ice Age extent (Jónsson et al., 2014), which is marked by the prominent terminal moraine formed between A.D. 1717 and 1760 (Benediktsson et al., 2015), as well as surface thinning of several meters per year in the last few decades (Jóhannesson et al., 2013). If LIDAR data from 2008 (September) and glacier surface measurements of the present research (August 2015) are compared, it is evident that during 2008–2015 the ice thickness in the research area has decreased by an average of 17.9 m. This corresponds to approximately 2.5 m of thinning per year. The largest surface elevation changes during 2008–2015 were 34.1 m at the lowest altitudes (640 m a.s.l.) near the ice margin, while the least thinning of 8.8 m was observed at the highest elevations (705 m a.s.l.) of the research area. Our observed ice thinning during 2008–2015 is slightly lower than during 1999–2008 at the lowest altitudes of Hofsjökull ice cap, where the annual lowering of Hofsjökull margins were reported to be >5 m per year (Jóhannesson et al., 2013). The maximum retreat of the glacier margin in the study area during 2008–2015 corresponds to 220 m, or 27.5 m/yr.

3.2. Subglacial topography and the internal structure of the glacier

The subglacial topography in the study area ranges from 578 m to 649 m a.s.l. The largest undulations in subglacial topography are observed close to the present ice margin, but there are no prominent subglacial features evident in the research area further up-ice where the ice thickness reaches 120 m (Fig. 2). With the exception of these undulations the subglacial relief decreases up-glacier.

We detected five elongated ridges, which we interpret as drumlins (Fig. 3). The largest drumlins extend up to 420 m in length, are 250 m in width, and reach almost 20 m in height. Because these drumlins lie on the slope of a subglacial overdeepening and not on a flat surface, their height cannot be calculated as the maximum difference between the altitudinal range, which is almost double than the correct relief. Due to this possible bias, we calculated drumlin relief accordingly to the concept of Spagnolo et al. (2012) that the correct drumlin relief is equivalent to the longest line perpendicular to the flat drumlin base.

The dimensions of subglacial drumlins exceed somewhat the dimensions of the exposed drumlins in the forefield of Múlajökull, which were described by Johnson et al. (2010) and Jónsson et al. (2014). The occurrence of drumlins corresponds very well to the position of major crescent crevasses in digital elevation model (from LIDAR data in 2008) (Fig. 4).

There are numerous reflections from englacial features in the recorded radargrams. These reflections are represented as hyperbolas (Fig. 2) and most of them are interpreted as reflections of englacial channels. This suggests a well-developed channelized drainage system, which is able to drain all supra- and englacial water. A high amount of meltwater is discharged into proglacial lakes, and some portals of subglacial channels with fast meltwater streams are clearly visible. A great number of moulins as well as entrances of englacial channels were observed on the Múlajökull in the study area supporting the evidence of englacial channels seen in radar profiles.

4. Discussion

The Múlajökull drumlin field is considered to be active, because

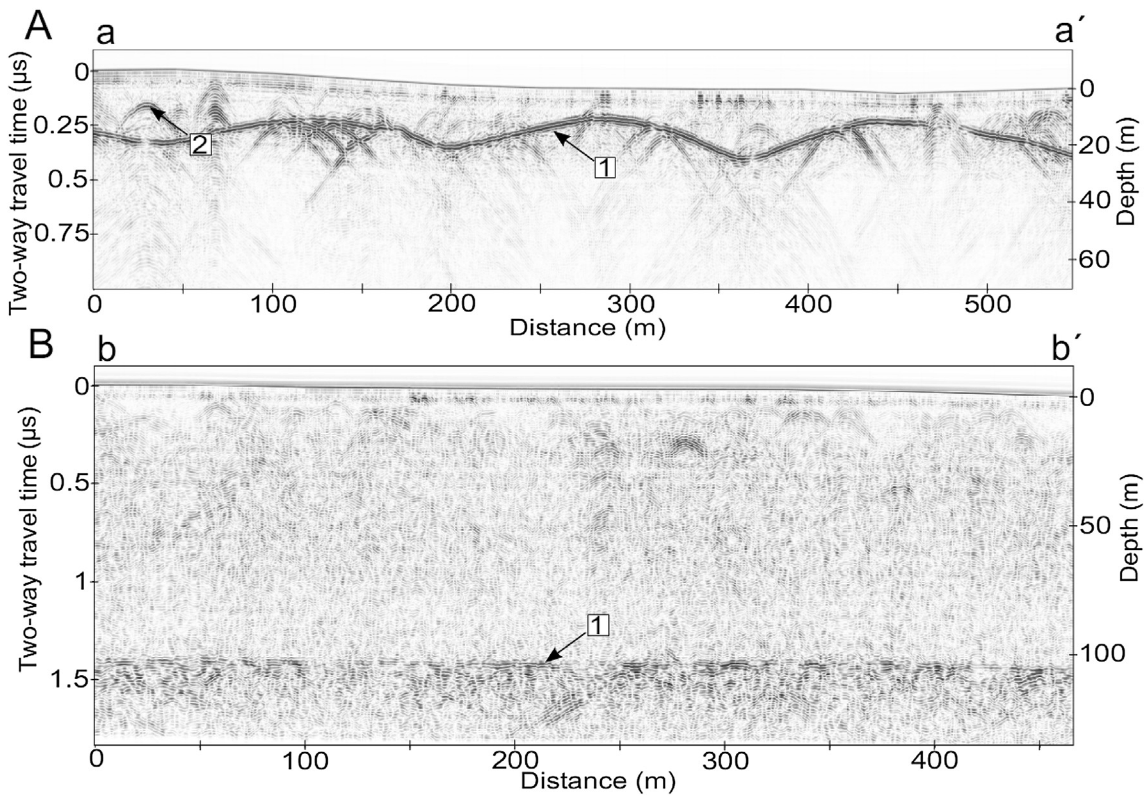

Fig. 2. (A) GPR profile a-a′ recorded near the glacier margin. (B) GPR profile b-b′ recorded in the upper part of the research area. 1 – Basal reflection. 2 – Reflection of englacial channel. See location of profiles in Fig. 1.

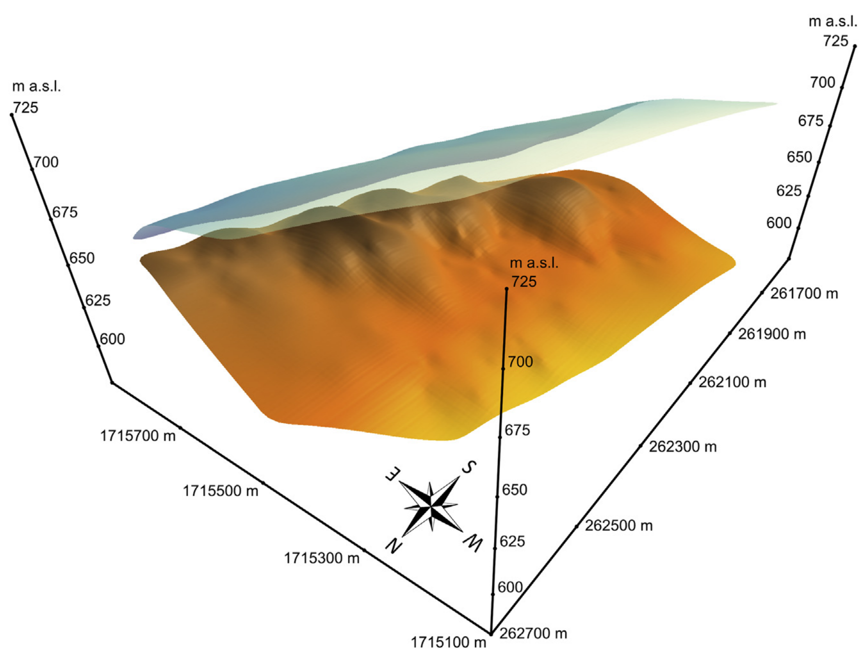

Fig. 3. Perspective view of subglacial topography (orange and brown) and glacier surface (light blue) at the Múlajökull marginal zone. Coordinates in Iceland National Coordinate system (ISN2004).

drumlins are still forming in the current glacial regime (Johnson et al., 2010). Our obtained data provide new evidence of drumlins located beneath the Múlajökull marginal zone. The dimensions and divergent fan distribution of the Múlajökull drumlins make them a good analogue to many drumlin fields formed beneath Pleistocene ice sheet lobes (e.g. Colgan and Mickelson, 1997; Lamsters and Zelčs, 2015). The drumlins of Múlajökull are located on the lip of a prominent subglacial hollow, which dips in an up-glacier direction (Fig. 5). As revealed by previous radio echo soundings of Hofsjökull (Björnsson, 1986), the over-deepening up to 100 m lower

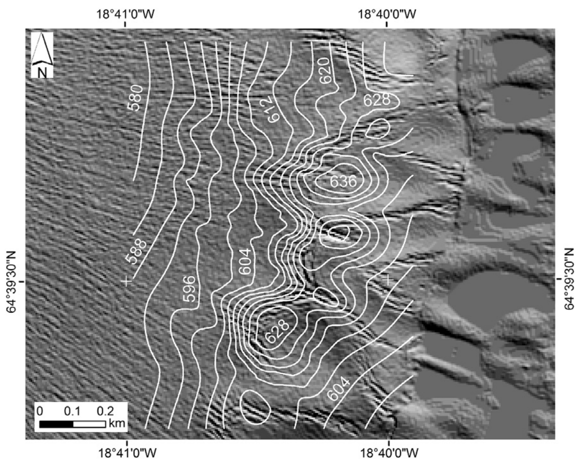

Fig. 4. Contour lines of Múlajökull subglacial topography superimposed on a 5 m resolution laser scan hillshade model from 2008. Contour line intervals are 4 m. Note the major sets of crevasses located above the position of subglacial drumlins.

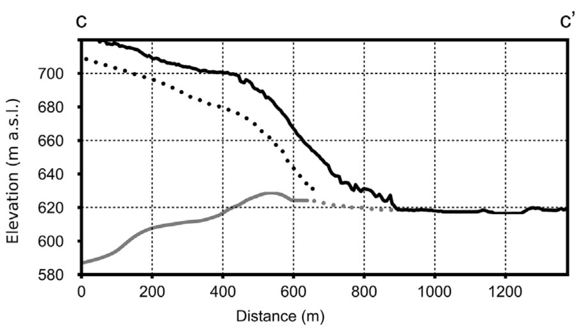

Fig. 5. Subglacial topography (gray line), glacier surface in 2015 (black dotted line), and glacier surface and Múlajökull forefield topography (black line) in 2008 (from LIDAR) along the profile c-c′ perpendicular to Múlajökull margin. See location in Fig. 1.

than the glacier forefield is situated beneath Múlajökull, being also the lowest on Hofsjökull. We confirm the existence of this over-deepening and the margin of it, which corresponds very well to the beginning and upper limit of the actual Múlajökull drumlin field. The existence of drumlins further up-glacier, where our data did not extend, seems quite unlikely due to the more pronounced over-deepened basin and lack of crescent crevasses associated with the location of drumlins in this and previous studies (Johnson et al., 2010). This drumlin field has a sharp upper boundary and further investigations of glacier substrate could show if there are any substrate control on the morphology of drumlin and initial position of drumlins. The location of the Múlajökull drumlins clearly show the distinct drumlin formation zone (up to 1.5 km wide) located close to the ice margin. This is a case also for some Pleistocene ice lobes, for example, the Green Bay Lobe, Wisconsin, USA (Colgan and Mickelson, 1997), where drumlin fields have definite up-ice boundaries and have developed in a narrow (20–70 km) zone behind ice margin.

It is not possible to compare the drumlins of Múlajökull, especially the geometry of the drumlin field and the relation of not yet exposed drumlins with other drumlin fields of modern surge-type glaciers, because drumlins are not characterised as being part of the surging-glacier landsystems (Evans and Rea, 2003). Geophysical investigations of subglacial bedforms beneath other Icelandic glaciers are unknown to us, except radio echo soundings at the scale of whole ice caps (Björnsson, 1986). Excavated basins beneath surging outlet glaciers have also been reported from outlets of Vatnajökull ice cap (Björnsson, 1996) suggesting prolonged glacial erosion. A bedrock trench beneath the Breiðamerkurjökull outlet extending below present sea level by 300 m was formed during the Little Ice Age advance (ibid.). The existence of similar excavated basin beneath Múlajökull that most likely formed by sustained sediment removal makes implausible also the existence of drumlins further under the glacier as proposed in this study.

In this study we demonstrate by high precision GPR data that the pattern of radial crevasses that are seen at the glacier surface and well represented in LIDAR elevation model (Fig. 4) is related to the location of drumlins. Although the assumption of the existence of drumlins under the glacier snout has been mentioned previously by the first study of the drumlins in the forefield of Múlajökull (Johnson et al., 2010), we provide clear evidence of drumlins located exactly beneath sets of crevasses (Fig. 3b). We also observe the lack of drumlins up-glacier where major crescentic crevasses are absent. Additional drumlins are suggested to exist northward and southward of the investigated area beneath the semi-circular or triangular sets of crevasses along the ice-marginal zone. We suppose this semi-circular pattern of crevasses to be formed due to the variable glacier strain rates created by subglacial topography. The influence of subglacial obstacles on the surface strain rates and formation of crevasses is observed at surging glaciers (Gudmundsson et al., 2003), and was also demonstrated at the margin of Russell glacier in West Greenland (Knight, 1992). In our case, the location of drumlins under the glacier snout also demonstrates the greatest ice surface extension and formation of extensional crevasses across the crests of drumlins. Therefore, these semi-circular crevasses are most likely created after the development of drumlins.

It has been shown that drumlins further away from the Múlajökull margin are wider, shorter, and have less relief, and this is suggested to be related to the number of surges they have experienced (Jónsson et al., 2014). The GPR data from this research indicate that the subglacial drumlins are higher, but they are also wider and have a more rounded shape than exposed drumlins in the front of the glacier margin. It seems that there could be an exception in the overall drumlin morphology trend, and less elongated drumlins are located up-glacier as well as down-glacier, although we cannot make a statistically significant comparison, because we mapped only five drumlins. The dimensions of the drumlins we found exceed those that were described in the Múlajökull forefield (ibid).

We recognize that the dimensions of exposed drumlins were measured via analysis of aerial photographs and an airborne 0.5-m LIDAR DEM, while in present study drumlins beneath glacier snout were assessed using GPR measurements. Yet the difference of exposed and subglacial drumlin morphometry could not have originated due to uncertainty of the GPR data. The estimated vertical uncertainty of GPR and GPS measurements are <1 m (see paragraph 2.1.), while uncertainty of lateral dimension of drumlins is no more than 24 m, taking into account that in present case drumlins are located approximately in depth of 70 m, where Fresnel zone radius is close to 12 m (Pellikka and Rees, 2009).

Unfortunately, we do not have data of the internal structure of the discovered drumlins, but the exposed drumlins consist of multiple till layers (Johnson et al., 2010). The greater dimensions of the drumlins found under the glacier snout could be explained in several ways. It could be related to: (1) the higher number of till layers deposited in surges, (2) the greater amount of sediments deposited because of the particular location of drumlins on the slope associated to ice stress differences or (3) the exclusive composition of drumlins, for example, bedrock or stiffer till that makes them more rigid and resistant to subglacial erosion.

5. Conclusions

The following main conclusions can be drawn from our analysis. The GPR investigations provide the evidence of drumlins beneath Múlajökull's margin. The location of drumlins corresponds with the position of the major sets of crescentic crevasses in 2008, which are formed due to the variable glacier strain rates created by the subglacial topography. We confirm the existence of an erosional overdeepening beneath Múlajökull and exactly the termination of it, which corresponds very well to the beginning and sharp upper edge of the Múlajökull drumlin field. The calculated thinning of the ice surface in the study area is on average 17.9 m during the period 2008–2015. The maximum retreat of the glacier margin in the study area during this period corresponds to 220 m. The obtained radargrams consists of numerous hyperbolic diffractions mostly representing reflections of englacial channels and suggesting a well-developed channelized drainage system of a surge-type glacier in its quiescent phase.

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