Ice-cored moraine degradation mapped and quantified using an unmanned aerial vehicle: a case study from a polythermal glacier in Svalbard

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Highlights

- SfM photogrammetry used to produce topographic data from archive aerial imagery and UAV derived aerial imagery
- Datasets from 2003 and 2014 were compared to report on the de-icing of a lateral-frontal ice-cored moraine
- The moraine appears to be de-icing predominantly via down-wastage affording the moraine a higher degree of stability
- UAVs and SfM are shown to be useful tools for monitoring environmental change

Abstract

Ice-cored lateral-frontal moraines are common at the margins of receding high-Arctic valley glaciers, but the preservation potential of these features within the landform record is unclear. Recent climatic amelioration provides an opportunity to study the morphological evolution of these landforms as they de-ice. This is important because high-Arctic glacial landsystems have been used as analogues for formerly glaciated areas in the mid-latitudes. This study uses SfM (Structure-from-Motion) photogrammetry and a combination of archive aerial and UAV (unmanned aerial vehicle) derived imagery to investigate the degradation of an ice-cored lateral-frontal moraine at Austre Lovénbreen, Svalbard. Across the study area as a whole, over an 11-year period, the average depth of surface lowering was -1.75 ± 0.89 m. The frontal sections of the moraine showed low or undetectable rates of change. Spatially variable rates of surface lowering are associated with differences in the quantity of buried ice within the structure of the moraine. Morphological change was dominated by surface lowering, with limited field evidence of degradation via back-wastage. This permits the moraine a greater degree of stability than observed at other sites in Svalbard. It is unclear whether the end point will be a fully stabilised ice-cored moraine, in equilibrium with its environment, or an ice-free lateral-frontal moraine complex. Controls on geomorphological change (e.g. topography and climate) and the preservation potential of the lateral-frontal moraine are discussed. The methods used by this research also demonstrate the potential value of SfM photogrammetry and unmanned aerial vehicles for monitoring environmental change and are likely to have wider applications in other geoscientific sub-disciplines.

1. Introduction

In Svalbard, the Neoglacial maxima of land-terminating glaciers are typically demarcated by large lateral-frontal moraine complexes (e.g. Bennett et al., 1996; Lyså and Lønne, 2001; Glasser and Hambrey, 2003; Lønne and Lyså, 2005; Lukas et al. 2005; Ewertowski et al. 2012; Midgley et al., 2013). The persistence of relict ice in such moraines is testament to extensive permafrost conditions at the margins of these glaciers (Etzelmüller and Hagen, 2005). However, climatic amelioration and deglaciation are contributing to the de-icing of ice-cored landforms (e.g. Etzelmüller, 2000). Whilst the dynamics of de-icing have been studied (e.g. Schomacker 2008; Irvine-Fynn et al., 2011; Bennett and Evans, 2012), the resulting preservation potential of these landforms in the geomorphological record is unclear (Bennett et al., 2000; Evans, 2009). Knowledge regarding the formation and preservation of glacial landforms is of interest due to the potential for contemporary glacial environments to be used as analogues for formerly glaciated environments in the mid-latitudes (e.g. Hambrey et al., 1997; Graham and Midgley, 2000; Benn and Lukas, 2006; Graham and Hambrey, 2007; Midgley et al., 2007). Moraines are important palaeoenvironmental proxies (Kirkbride and Winkler, 2012), and understanding their genesis and potential for preservation in the geomorphological record is an essential prerequisite for robust interpretations of relict moraine assemblages. Rates of wastage on ice-cored moraines are understood to be principally driven by surface processes and topography, rather than climatic conditions (Schomacker, 2008). In the high-Arctic glacial environment, some ice-cored moraines are reported to be unstable and somewhat transient geomorphological features, with ultimately low preservation potential (Bennett et al., 2000; Lukas et al., 2005). Conversely, where debris cover is sufficiently thick, it has been reported that ice-cored moraine may stabilise, undergoing limited or negligible rates of transformation (Ewertowski, 2014; Ewertowski and Tomczyk, 2015).

Geoscientists now have access to a range of new technologies for monitoring the temporal evolution of geomorphological systems. Specifically, automated photogrammetric techniques such as SfM are an excellent tool for conducting high-resolution topographic surveys (James and Robson, 2012; Westoby et al., 2012; Carrivick et al., 2013; Fonstad et al., 2013). SfM photogrammetry has also been integrated with small format, low-level aerial imagery acquired from small UAVs (e.g. Lucieer et al., 2013; Tonkin et al., 2014; Ryan et al., 2015; Smith and Vericat, 2015; Clapyut et al., 2015; Rippin et al., 2015). Here, SfM photogrammetry was used to document the evolution of an ice-cored lateral-frontal moraine over an 11-year study period, based on images obtained with a UAV in 2014 and archive images from a piloted aircraft in 2003. The principal aims of this study were to: (1) report on the use of SfM for Digital Elevation Model (DEM) production from both archive and small-format low-level aerial imagery for the purpose of assessing environmental change in the high-Arctic; (2) investigate landform evolution at the margins of a high-Arctic glacier; and (3) discuss the geomorphological evolution of ice-cored moraine in relation to landform stability and preservation potential.

2. Study site

Austre Lovénbreen is a *c*. 5 km long valley glacier located on Brøggerhalvøya, Spitsbergen, Svalbard (78°53′12″N 12°08′50″E; Fig. 1). The thermal regime of the glacier was polythermal in 2010 based on our interpretation of GPR (ground-penetrating radar) profiles presented by Saintenoy et al. (2012); the extent of temperate ice appeared to be exceptionally spatially limited, with the glacier being almost entirely cold-based. Austre Lovénbreen has a strong negative mass balance according to Friedt et al. (2012), who reported a mean ablation rate of 0.43 m a^{-1}

between 1962 and 1995, which increased to 0.70 m a^{-1} for the 1995–2009 period.

The glacier is surrounded by mountainous terrain with peaks ranging from 583 m a.s.l. (Slattofjellet) to 879 m a.s.l. (Nobilefjellet) at the head of the basin. Surge-type glacier behaviour is widely reported in Svalbard (e.g. Jiskoot et al., 2000). The potential for surge-type behaviour at adjacent glaciers on Brøggerhalvøya has been discussed (e.g. Hansen, 2003; Glasser et al., 2004; Hambrey et al., 2005) and disputed (e.g. Jiskoot et al., 2000; King et al., 2008). However, Midgley et al. (2013) presented evidence that Austre Lovénbreen may have surged close to or at its Neoglacial maximum position based upon the interpretation of oblique Norsk Polarinstitutt (NPI) aerial imagery from 1936.

The character of the glacier forefield was documented by Hambrey et al. (1997), with additional field observations reported by Graham (2002). The glacier forefield is characterised by a large arcuate lateral-frontal moraine, which is breached at two locations by the main contemporary glaciofluvial outlets. The lateral-frontal moraine demarcates the Neoglacial limit based upon interpretation of ground-level imagery from 1907 (Isachsen, 1912) and oblique Norsk Polarinstitutt (NPI) aerial images from 1936 (Fig. 6 in Midgley et al., 2013). The glacier has receded *c*. 1 km from this position. Within the Neoglacial limit, surface hummocks (‘hummocky moraine’) are identified. Fluted diamicton plains and lineated accumulations of supraglacial debris (e.g. Hambrey et al., 1997) have developed as Austre

Lovénbreen receded from its Neoglacial position. More recently, the structural characteristics of the lateral-frontal moraine around the western margin of the forefield were investigated by Midgley et al. (2013) using GPR. This research found that in lateral sections an ice-core constitutes a significant component of the landform, in contrast to the frontal sections where the occurrence of buried ice is limited. This paper maintains the focus on the western margin of the forefield, providing surface morphological data to complement the subsurface data presented by Midgley et al. (2013).

3. Materials and methods

3.1. Data acquisition

Five images from 2003 were obtained from the UK Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF) for DEM production. These images were collected on August 9th 2003 using a metric camera mounted in a Dornier 228 aircraft, and the contact prints scanned to give an approximate ground resolution of 0.2 m per pixel. In 2014, 10 UAV sorties were flown over a two-day survey period (15th and 16th July 2014). The total area covered by this survey is *c*. 676,000 m^2. A DJI S800 multi-rotor UAV equipped with an 18 MP Canon EOS-M consumer-grade digital camera was used for image acquisition. The UAV was flown at approximately 100 m above ground level, giving a ground resolution of 0.02 m per pixel. A total of 1856 images from this survey were used for DEM production. Further details on this survey setup and validation against a total station derived survey were documented by Tonkin et al. (2014).

Ground control points were surveyed using a Leica 1200 dGPS and post-processed using RiNEX data obtained from the EUREF Permanent Network station at Ny-Ålesund (http://www.epncb.oma.be/_networkdata/). For the 2003 imagery, three ground control points were used to georeference the point cloud, and to project it to the UTM 33N coordinate system (Fig. 2). These were the tops of boulders which were visible on the original scanned contact prints, and also readily identified in the field. As the parts of the glacier forefield are likely to be geomorphologically unstable (e.g. Irvine-Fynn et al., 2011), where possible control points were located outside of the Neoglacial moraine. The 2014 imagery was georeferenced using 27 ground control-points consisting of A3 sized paper targets placed on snow-free areas of the moraine (Fig. 2).

3.2. DEM generation

DEM generation was conducted in Agisoft Photoscan (v. 1.1.5), a commercial SfM software package. A total of 2035 tie-points were automatically identified on the five images from 2003. For the 2014 imagery, processing was split between two ‘chunks’ that were merged to form a single DEM of the lateral-frontal moraine. Photoscan identified a total of 5,660,015 tie points from the 1856 images with the resulting DEM produced from a dense point cloud of 106,484,427 points. Both SfM DEMs were produced at 0.5 m per pixel resolution to facilitate comparison between them. On the 2003 DEM, moraine distal slopes were subject to shading, resulting in excessively interpolated elevation data. Zones identified with these issues were removed prior to analysis.

3.3. Evaluation of DEM quality

LiDAR data, obtained concurrently with the 2003 aerial imagery were used to independently validate the 2003 DEM. DEM elevations were compared with LiDAR spot heights distributed across the area of interest, giving a vertical *RMSE* (root mean square error) value of 0.888 m (n = 768,296; σ = 0.812 m). The residuals appear to be spatially distributed and increase in areas subject to poor ground control, thus the 2003 SfM DEM may represent an overestimate of the surface topography. However, it is worth noting that the LiDAR data are not error free – the heights have been shown to have an *RMSE* value of < 0.15 m in the area of interest (Arnold et al., 2006) – but as the two datasets were obtained simultaneously their comparison provides an independent means of estimating DEM error.

Two interrelated issues are likely to account for the vertical *RMSE* value in this model: (1) the use of relatively low resolution of the imagery on which the DEM is based; and (2) the identification of appropriate ‘stable’ features to use as ground-control. The first issue reduces the accuracy with which the location of control points can be identified in the imagery. In practice, it is estimated that the identification of control points in the images introduced an error of approximately 1 m. The low resolution also meant that only a small number of large boulders were visible in the imagery, limiting the number of sites available for use as ground control points. This issue was confounded by the need to locate control points on features that were unlikely to have moved during the 11 years between image capture and the field survey. Use of existing ‘stable’ features for ground control is a limitation of studies that use photogrammetric methods to produce DEMs of changing geomorphological systems (e.g. Schiefer and Gilbert, 2007; Staines et al., 2015), and means it is rarely possible to achieve an optimal distribution of GCPs (ground control points). In this study only three suitable boulders were identified for use as GCPs, which is highly likely to have contributed to an increase in errors (e.g. Clapuyt et al., 2015).

For the 2014 DEM, errors were calculated for 12 dGPS surveyed check points, which were paper targets visible in the imagery, additional to the 27 control points used to generate the model (Fig. 2). Sub-decimetre vertical errors were obtained for these points (*RMSE* = 0.048 m; n = 12). These error estimates give us confidence that the DEM provides an excellent representation of the moraine morphology. For additional validation, randomly generated spot heights (n = 4370) from more geomorphologically ‘stable’ areas (e.g. Staines et al., 2015) outside the Neoglacial limit on the 2003 and 2014 SfM DEMs were compared. Values from these areas show lower error levels (*RMSE* = 0.374 m; σ = 0.274 m), giving confidence in the validity of the two SfM DEMs.

3.4. DEM differencing and minimum levels of detection

DEM differencing – subtracting spatially coincident raster grid cells from each other – was used to assess the amount of morphological change between 2003 and 2014. DEM differencing was conducted using the GCD (Geomorphologic Change Detection, ver. 6) plugin of Wheaton et al. (2010) in ArcGIS 10.2.1. The GCD plugin allows for robust error assessment through the use of ‘minimum levels of detection’ (minLOD). This approach minimises the likelihood of making spurious interpretations of apparent morphological differences that are actually associated with uncertainty in the data. Minimum levels of detection were calculated using a propagated error value derived from error assessments undertaken on both topographic surfaces (e.g. Braslington et al., 2003). The technique assumes error within topographic datasets are spatially uniform, and discards changes below this threshold. For the 2003–2014 time period, vertical differences under 0.89 m were regarded as potentially erroneous, and therefore disregarded for the purposes of assessing morphological change. The majority of this uncertainty results from errors in the 2003 DEM. Three zones (Z_1, Z_2 and Z_3) were clipped from the differenced DEM and used to report on spatial variations in geomorphological change across the landform (Fig. 3A).

3.5. Feature mapping

The relative abundance of features indicative of ice-cored moraine degradation were mapped and used to validate the reported rates of surface change derived from the DEM differencing. Features were identified and mapped from ultra-high resolution (2 cm per pixel) orthorectified imagery produced from the 2014 survey data. These observations were supplemented by field observations collected simultaneously to the acquisition of the 2014 topographic data. The study area was split into 50 x 50 m grid squares (*n* = 234) to allow the relative abundance of geomorphological features indicative of surface change to be qualitatively assessed across the study area. As the precise mode of formation for micro-topographic features indicating landform degradation was unclear, we adopted the non-genetic classification of ‘surface linear undulations’ to refer to features developed by the slumping and/or the extensional surface fracturing of materials in response to surface lowering (e.g. Kjær and Krüger, 2001; Krüger et al., 2010). The location of a large-scale arcuate edge and a linear back-wasting edge were also mapped.

4. Results

4.1. DEM differencing

A total area of 461,429 m^2 was assessed for surface elevation change (Fig. 3A). The lateral-frontal moraine shows a level of geomorphological stability, with change detected on 52% (238,476 m^2) of the study area. Ninety-six percent of the area where change was detected was associated with surface lowering. The total volume difference for the study area was −377,490 ± 201,292 m^3.

A clear spatial trend characterises the pattern of morphological change. The lateral up-glacier sections are subject to higher rates of surface lowering. Average surface change in Z_1 was −2.56 m for the study period. Nearly all grid cells in this area were observed outside the minimum level of detection.

Z_2 and Z_3, which are located in more frontal positions show diminishing rates of detectable change (92.3% and 19.9% of each study area, respectively) and lower rates of average net surface change (−1.49 and −0.52 m, respectively). Profiles 1, 2 and 3 in Fig. 4 also demonstrate reduced surface lowering in frontal positions. On profile 1, surface lowering is clearly evident on the moraine ridge crest, and less extensively on the ice-proximal and distal slopes. Profiles 2 and 3 show limited geomorphological change with a significant proportion of change falling close to or below the minLOD (Fig. 4). Detectable change on the outwash-plain was limited. Areas of deposition principally occur on moraine distal slopes and in proximity to glaciofluvial drainage systems. Areas that have experienced deposition across the study averaged a depth of 1.42 ± 0.89 m. However the deposition was extremely spatially and volumetrically limited, only accounting for the movement of 17,952 ± 11,267 m^3 of material (4% of the area of detectable change) opposed to 413,394 ± 212,243 m^3 of change associated with surface lowering across the study area (Fig. 3B). It should be noted that in 2014 *c*. 11% of the study area was covered by exceptionally late-lying snow, which was typically located in sheltered areas between pronounced ridges and contributes to the lowering of estimates of surface change over the study period.

4.2. Geomorphological evidence of surface change

The occurrence of features indicative of surface evolution were mapped to validate the derived rates of surface change (Fig. 5). Mapped surface features indicative of surface change were identified in the lateral-zone of the moraine complex; however, the features were less readily identified on the frontal zone of the landform. Out of the 234 survey grid squares assessed, 150 (64%) had no observable evidence of surface evolution. One ice-free actively back-wasting slope was located on the frontal zone of the analysis area adjacent to the western fluvial outlet channel which dissects the Neoglacial lateral-frontal moraine. An additional inactive arcuate back-wasting edge was identified in the lateral zone of the landform (Fig. 5). The spatial occurrence of evidence associated with surface change gives us confidence in the results of the DEM differencing.

5. Discussion

5.1. Comparisons with other glaciers

A range of studies provide rates of ice-cored landform degradation. Here, rates of landform degradation appear to be limited in comparison to some sites in Svalbard and elsewhere. For example, Irvine-Fynn et al. (2011) report a moraine surface lowering rate of -0.65 ± 0.2 m a^{-1} at neighbouring Midtre Lovénbreen between 2003 and 2005. Longer-term changes (1984–2004) at Holmstrombreen (Svalbard) were reported to have occurred at a rate of -0.9 m a^{-1} (Schomacker and Kjær, 2008). Rates of surface lowering in temperate Icelandic glacial environments are variable (between -0.015 and -1.4 m a^{-1}; e.g. Krüger and Kjær, 2000; Schomacker and Kjær, 2007; Bennett and Evans, 2012). On average, surface lowering for the entire study area was considerably lower at -0.16 m a^{-1} than reported at some sites in Svalbard. It should be noted that the rate of change may not have remained consistent throughout the study period with moraines known to be subject to short-term changes over consecutive years (e.g. Ewertowski and Tomczyk, 2015). Even in areas with the highest levels of surface lowering (e.g. Z_1), only modest rates of average surface change per year were detected (-0.23 m a^{-1}), which at worst, can be considered an overestimate of surface change, for example, due to errors on the 2003 SfM DEM. These results are similar to the findings of Ewertowski and Tomczyk (2015) who report on surface lowering at the margins of Ebbabreen and Ragnarbreen in Petuniabukta. Here, whilst areas of back-wasting ice were quantified to undergo changes of up to 1.8 m a^{-1}, lower levels of transformation (e.g. below 0.3 m a^{-1}), were quantified, highlighting the relative stability of some ice-cored moraine in Svalbard. Similarly, at Austre Lovénbreen, just over half of the study area (52%) was below the minimum level of detection implying no or exceptionally limited geomorphological change between 2003 and 2014.

5.2. Moraine preservation potential

Moraines in the high-Arctic glacial environment are understood to be highly vulnerable to thermo-erosion and mass movement facilitated by fluvial undercutting. This can result in high rates of landform transformation (Ewertowski and Tomczyk, 2015). The evidence presented here indicates that such surface processes are less important with regard to the transformation of the lateral-frontal moraine at Austre Lovénbreen. A surface excavation in proximity to Z_1 showed that the debris mantle was surprisingly thick at 1.6 m. At this site, and potentially others, whilst rates of moraine surface lowering may be rather high, a relatively thick and evenly distributed debris-layers can permit the relative stabilisation of ice-cored moraine where the coupling of slope and fluvial processes (e.g. Etzelmüller et al., 2000) exert less influence on moraine transformation. This is largely due to the less topographically confined setting of the lateral-frontal complex at Austre Lovénbreen, which results in the glaciofluvial system being well separated from the moraine. The result is a low level of transformational activity, which principally occurs via down-wasting (e.g. Fig. 5). An implication of this study is that the ice-cored moraines formed at Austre Lovénbreen, and potentially other valley glaciers in Svalbard (e.g. the recent results of Ewertowski and Tomczyk, 2015), may have higher preservation potential than previously recognised as insulating debris is not reworked and remains *in situ*.

During the final stage of moraine development, two end-points are envisaged: (1) a fully stabilised ice-cored moraine, which is in equilibrium with its environment; or (2) an ice-free lateral-frontal moraine complex (Fig. 6). The first scenario requires a thick debris mantle to develop that exceeds the permafrost active layer allowing buried-ice to be a persistent landscape feature. It is unclear whether the first scenario is plausible. Ice-cored 'controlled' moraines are understood to be poorly preserved in the geomorphological record (Evans, 2009). Buried-ice up to 200 years of age has been documented in moraines at the margins of temperate Icelandic glaciers (e.g. Everest and Bradwell, 2003). Examples of where the preservation of buried-ice has been permitted on longer timescales include formerly glaciated continental settings (e.g. Ingólfsson and Lokrantz, 2003; Murton et al., 2005), and cold deserts where buried-ice is suggested to have existed for several millennia under permafrost conditions (Sugden et al., 1995; Schäfer et al. 2000). Waller et al. (2012) highlighted that the preservation of buried-ice may be permitted on geological timescales if it is located at depths unaffected by seasonal thaw. However, the high-Arctic glacial environment in Svalbard is known for its highly unstable ice-cored moraine, and rapidly progressing mass wasting processes (Bennett et al., 2000; Schomacker, 2008; Irvine-Fynn et al., 2011; Ewertowski and Tomczyk, 2015). Schomacker (2008) showed that climatic variables are only weakly correlated with rates of ice-cored back-wastage occurring at 14 different glaciers; the implication being that surface processes and topography are more important determinates of moraine disintegration. However, this result may not hold at Austre Lovénbreen, where very limited evidence of back-wasting was observed in the field by the authors in 1999, 2009 and 2014 (e.g. Fig. 5).

Alternatively, the second end-point requires complete de-icing of the moraine, where the active layer may continue to exceed the depth of the debris mantle for the duration of the secondary deglaciation process resulting in continued and complete melting of buried-ice despite an increasing debris thickness. The findings of Midgley et al. (2013) indicated that sediment concentration within the moraine is low in lateral positions compared to frontal positions. As a result, following complete de-icing the lateral features which have a significant ice component are likely to be topographically low and diffuse relative to the frontal features where the total volume of sediment appears to be much larger. This is an important consideration where high-Arctic polythermal glaciers are used as an analogue for relict glacial landsystems in the geomorphological record.

5.3. Controls on rates of down-wasting

The physical properties of the insulating debris layer such as its thickness, water content and thermal conductivity influence rates of moraine down-wastage (Schomacker, 2008). The importance of rainwater depends on the extent to which the influence of heat advection via percolation is countered by evaporation from the ground surface (Sakai et al., 2004). Rainwater has been shown to be important in facilitating top-melt in highly permeable substrates (Reznichenko et al., 2010), at least where cool and damp atmospheric conditions limit evaporation. Conversely, block-rich material with high surface roughness has low thermal conductivity and can obstruct the development of winter snow-cover depressing the lower limit of permafrost in mountain terrain (Etzelmüller and Frauenfelder, 2009). At Austre Lovénbreen, the substrate typically consists of clast-rich diamictons which are overlain by gravels with a variable fine component in many places. Diamictons have been associated with variable porosity values (e.g. Parriaux and Nicoud, 1990; Kilfeather and van der Meer, 2008; Burki et al., 2010; Worni et al., 2012). Diamicton with silt and clay components and frozen horizons will lower the permeability of the debris, and serve to impede heat advection by water during summer months, thus limiting ice-ablation (e.g. Reznichenko et al., 2010).

Local topographic controls also influence air-temperature and subsequently permafrost distribution (Harris et al. 2009). Strong topographic shading has been reported as an influence on de-icing at other sites in Svalbard (e.g. Lyså and Lønne , 2001). Given the proximity of the landform to Slattofljettet (582 m), rates of moraine down-wastage in up-glacier sections of the landform may be influenced. Modelling of these shading effects is likely to be an interesting avenue of research in relation to moraine disintegration and more generally, permafrost distribution and properties in mountainous terrain.

A further confounding factor is snow-cover which is known to limit the influence of atmospheric heat on ground temperature (Stieglitz et al., 2003). Whilst in winter snow may permit higher ground temperature in relation to mean air temperatures (Stieglitz et al., 2003), late lying snow is likely to play an additional role limiting the susceptibility of buried-ice to surface warming. Further work investigating the influence of snow cover and snow-depth in relation to moraine down-wastage could elucidate how significant a role it plays in reducing down-wastage.

5.4. Spatial variations within the moraine system

Diminishing rates of landform change from areas Z_1 to Z_3 (Fig. 3) correspond with an increase in the proportion of debris relative to ice from lateral to frontal positions (e.g. Midgley et al., 2013). Spatially variable amounts of buried-ice imply that the mode of moraine formation is not consistent across the moraine complex (e.g. Hambrey and Glasser, 2012). Lateral sections conform to the ‘controlled’ ice-cored model of moraine formation (e.g. Evans, 2009) where the release of material from debris-rich folia result in surface linearity and form an insulating surface layer for underlying glacier-ice. The reduced rates of observed surface lowering in the frontal sections, and the presence of surface hummocks indicate that separate glaciological and geomorphological processes are responsible for the emplacement of moraine at different locations along the lateral-frontal complex. Here, structural glaciology and the preferential entrainment of basal debris in frontal locations are likely to be important. For example, studies have investigated the development of surface hummocks (‘hummocky moraine’) in relation to the stacking of englacial material along thrusts planes (e.g. Hambrey et al., 1996; 1997; Bennett et al., 1998; Graham, 2002; Midgley et al., 2007). The processes described in these papers may, in part, be responsible for areas of surface hummocks on the moraine complex and lower levels of ice incorporation. It is worth noting that additional moraine forming processes such as pushing and permafrost deformation are documented to occur in ice-marginal environments in Svalbard (Etzelmüller et al., 1996; Boulton et al., 1999).

6. Summary

The evolution of an ice cored lateral-frontal moraine over an 11-year period was assessed at the high-Arctic polythermal glacier Austre Lovénbreen, Svalbard. Repeat DEMs and DEMs of difference were generated from archive and UAV-derived aerial imagery using SfM and minLOD methods. Average depth of surface lowering for the entire study area was estimated to be −1.75 ± 0.89 m. Landform evolution occurred most rapidly on lateral sections of the landform. In contrast to many other sites in Svalbard, field evidence highlights that the moraine appears to be de-icing predominately by down-wastage, affording the landform higher levels of stability. Atypical of de-icing moraines in the high-Arctic, slope and fluvial driven change appear to be less significant. There may be potential for the buried-ice to be stabilised and preserved as a palaeoglaciological archive of former Neoglacial ice dynamics. The high-resolution UAV-derived dataset serves as a benchmark for future studies monitoring geomorphological change on the lateral-frontal moraine at Austre Lovénbreen, achieving a vertical *RMSE* value of 0.048 m for independent check points. This study adds to the growing body of evidence that a combination of UAV-derived imagery, a consumer-grade digital camera and SfM methods are highly appropriate for monitoring of geomorphological change. The errors associated with DEM generation from archived conventional aerial imagery were substantially larger, partly as a result of the lower image resolution, and partly the limited availability of appropriate features to use for ground control. Such issues are common to the extraction of topographic data from archive imagery in changing environments, and may limit the application of this approach. Nevertheless, the derived DEM was of sufficient quality to be useful for estimating the rate of de-icing over the 11-year period investigated. It is concluded that the use of SfM photogrammetry for extracting morphological data from a range of aerial imagery is appropriate for monitoring environmental change and is likely to have wider applications in other geoscientific sub-disciplines.

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Fig. 1. Location map of Svalbard and the study site in relation to Austre Lovénbreen (AL). Data from Norwegian Polar Institute (2014).

Fig. 2. Locations of ground-control applied to the 2003 and 2014 topographic datasets and the independent check-points used for error analysis on the 2014 DEM. The black line indicates the extent of the 2003 SfM DEM. The orthophoto is produced from aerial image data collected in 2003 by the UK Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF). These data are provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).

Fig. 3. Surface change over the western lateral-frontal moraine of Austre Lovénbreen. (A) DEM of difference for 2003–2014. The black lines are contour data (m.a.s.l.) derived from the 2014 DEM. The locations of three zones of analysis (Z_1, Z_2 and Z_3) are shown. (B) Surface change in relation to area and volume. (C) Average surface change for Z_1, Z_2 and Z_3 with the minimum level of detection (minLOD) highlighted by the dotted line.

Fig. 4. Surface evolution over the 11-year study period demonstrated by three topographic profiles. (A) The locations of the three profiles. (B) Surface change along profiles 1-3 between 2003 and 2014.

Fig. 5. Relative abundance of geomorphological features indicative of surface change across the study area.

Fig. 6. Conceptual model for the evolution of the lateral-frontal moraine under the scenarios of partial and complete de-icing.

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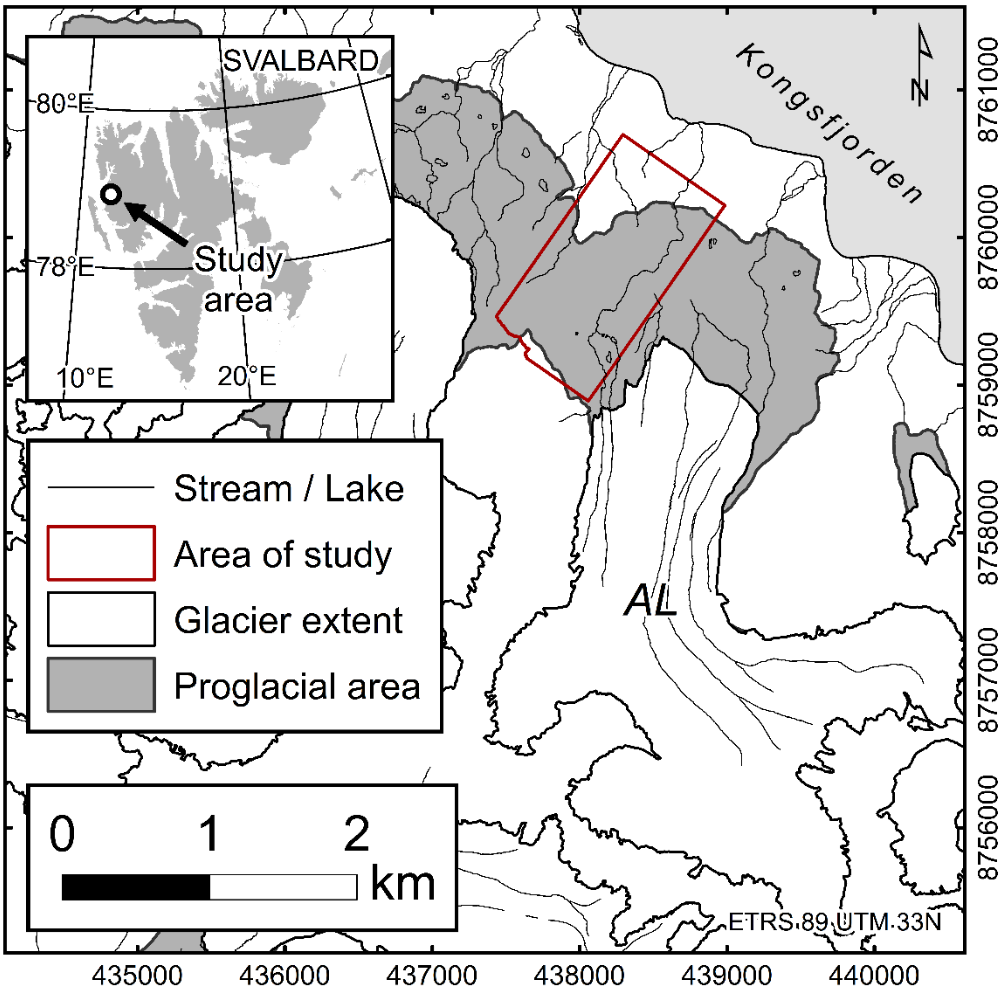
SVALBARD
80°E
78°E
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Study area
Kongsfjorden
AL
Stream / Lake
Area of study
Glacier extent
Proglacial area
0
1
2
km
ETRS 89 UTM 33N
435000
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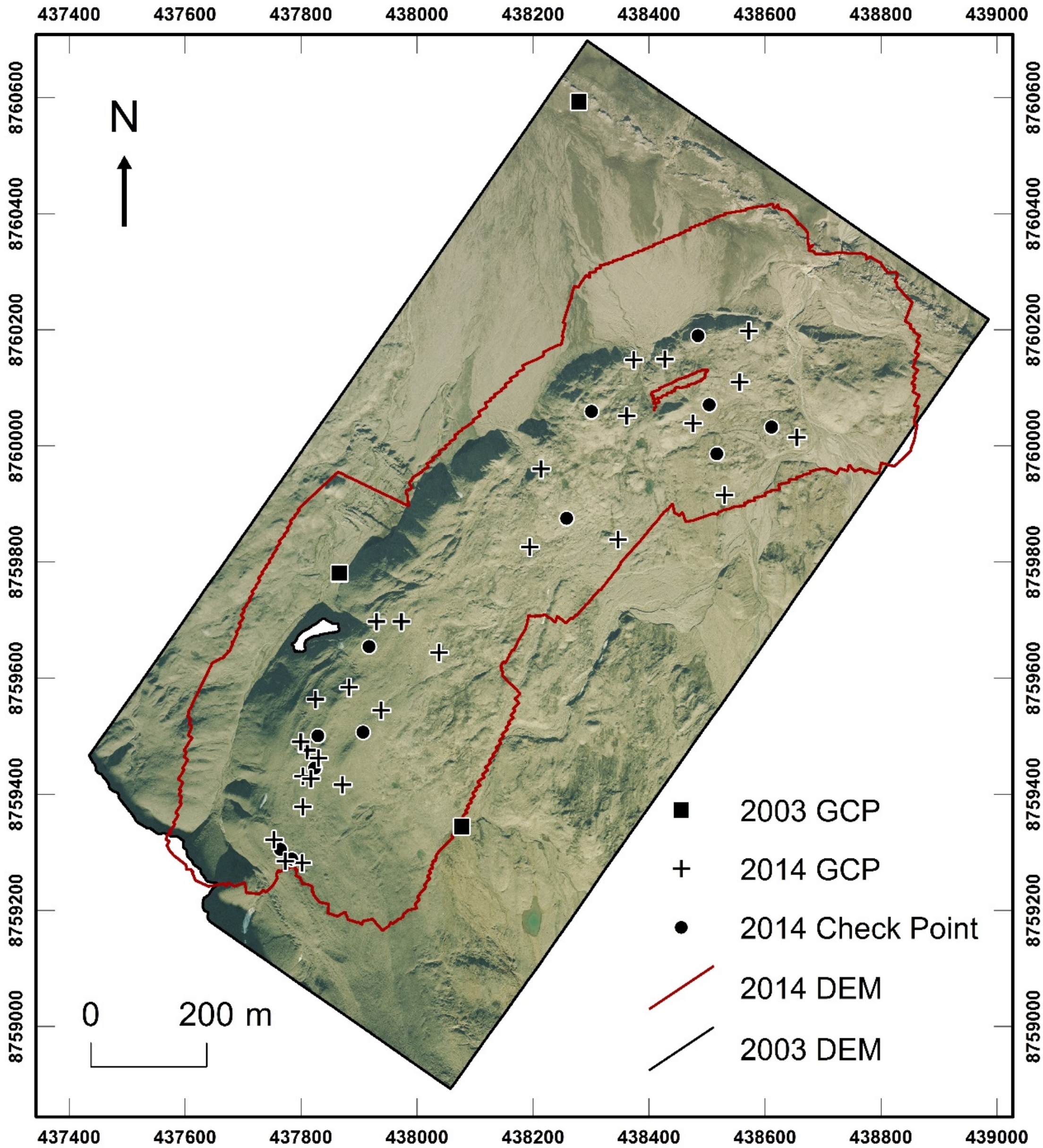
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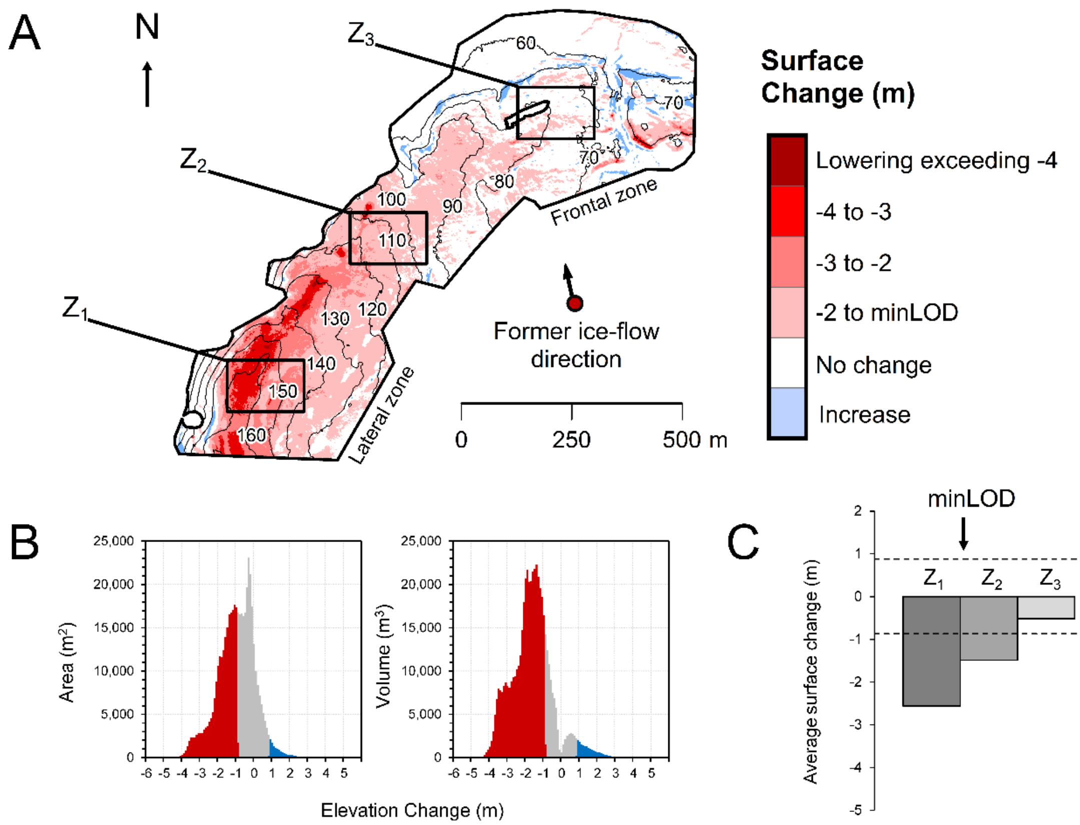
802


A
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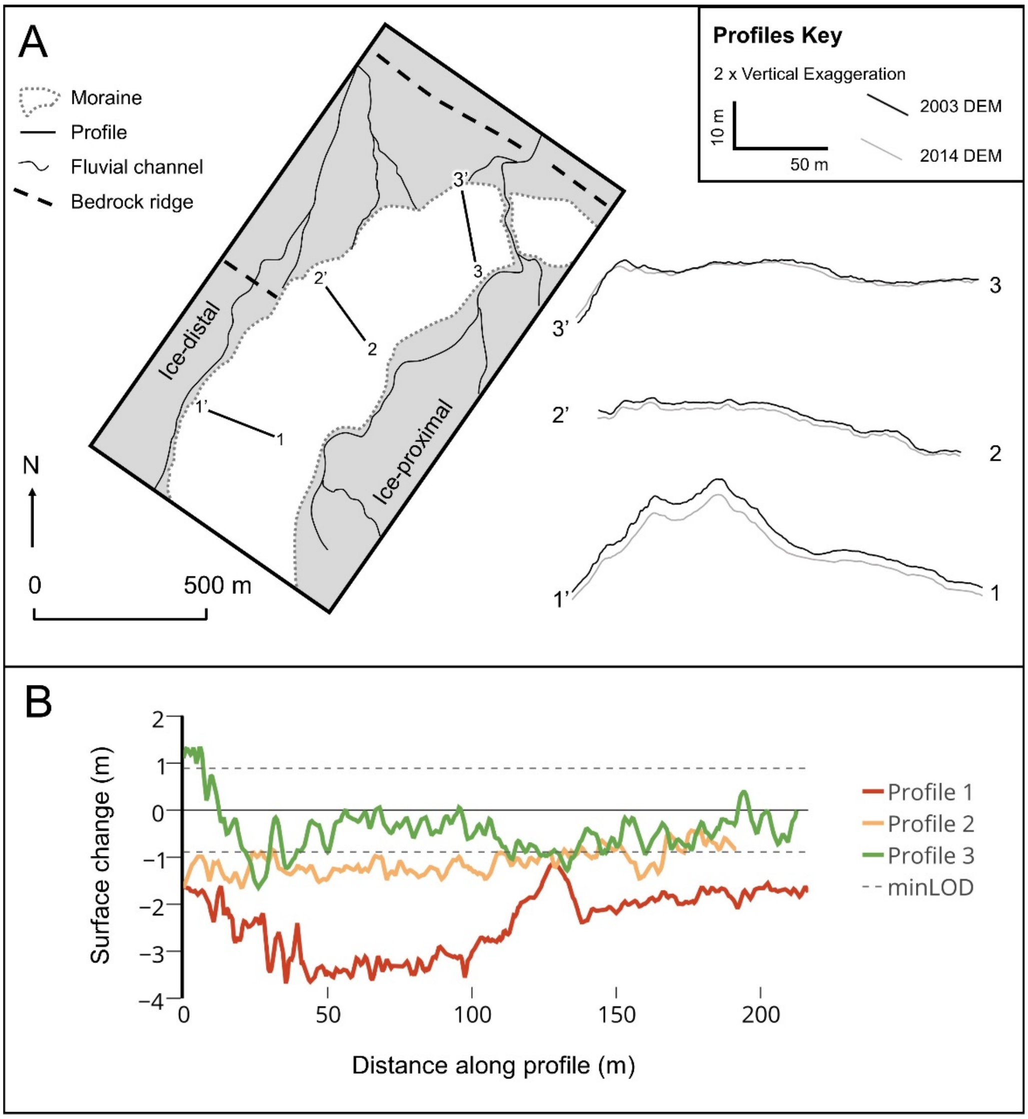
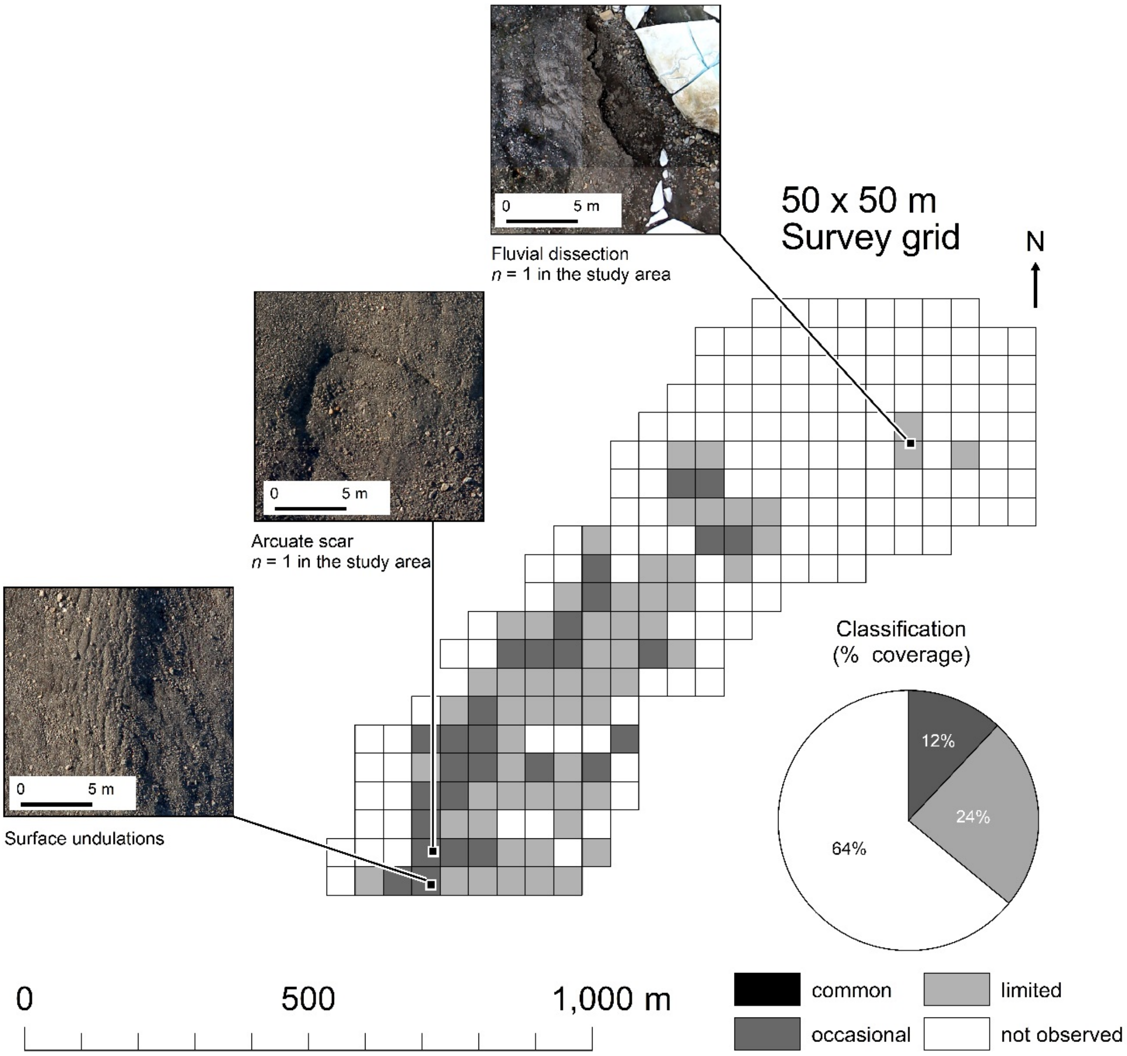
Z3
Z2
Z1
60
70
70
80
90
100
110
120
130
140
150
160
Frontal zone
Lateral zone
Former ice-flow direction
0
250
500 m
Surface Change (m)
Lowering exceeding -4
-4 to -3
-3 to -2
-2 to minLOD
No change
Increase
B
Area (m²)
Volume (m³)
Elevation Change (m)
C
minLOD
Average surface change (m)

803

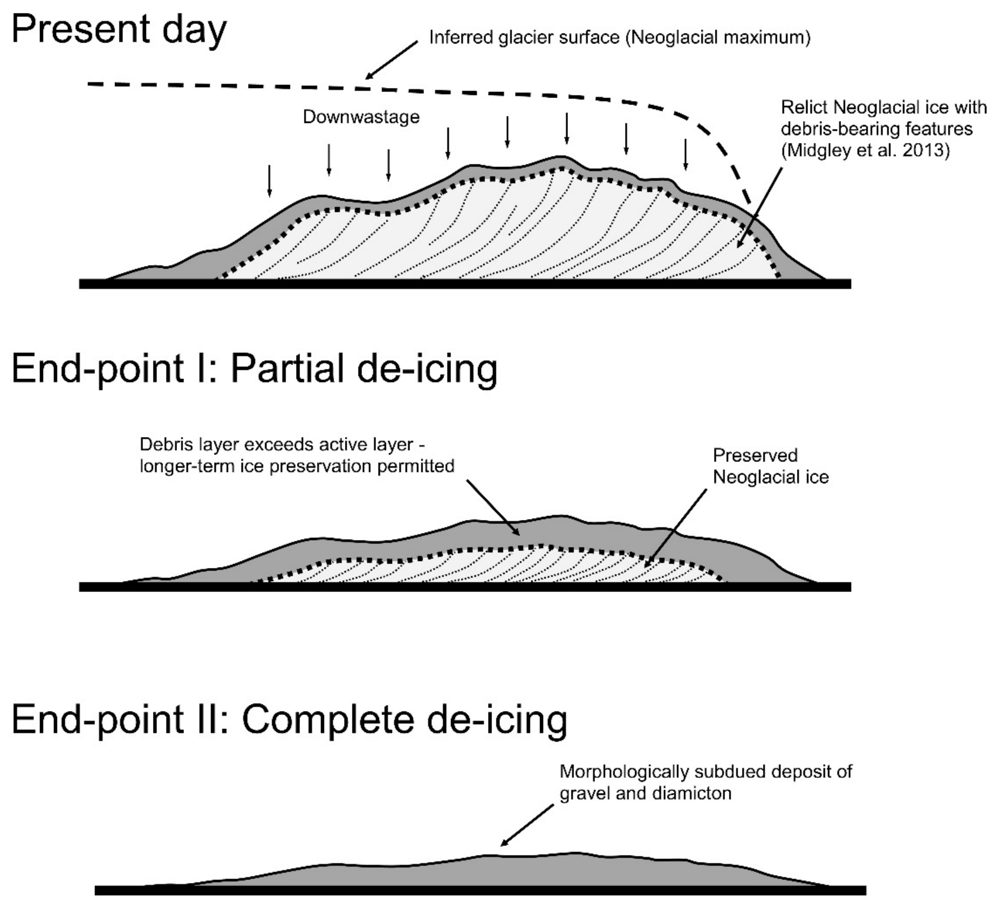

A
Moraine
Profile
Fluvial channel
Bedrock ridge
Ice-distal
Ice-proximal
N
0
500 m
Profiles Key
2 x Vertical Exaggeration
10 m
50 m
2003 DEM
2014 DEM
1
1'
2
2'
3
3'
B
Surface change (m)
Distance along profile (m)
Profile 1
Profile 2
Profile 3
minLOD

804



0 5 m
Fluvial dissection
n = 1 in the study area
50 x 50 m
Survey grid
N
0 5 m
Arcuate scar
n = 1 in the study area
0 5 m
Surface undulations
Classification
(% coverage)
12%
24%
64%
0
500
1,000 m
common
limited
occasional
not observed

805



Present day
Inferred glacier surface (Neoglacial maximum)
Downwastage
Relict Neoglacial ice with debris-bearing features (Midgley et al. 2013)
End-point I: Partial de-icing
Debris layer exceeds active layer - longer-term ice preservation permitted
Preserved Neoglacial ice
End-point II: Complete de-icing
Morphologically subdued deposit of gravel and diamicton