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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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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 previously 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.

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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.

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Lucieer et al., 2013; Tonkin et al., 2014; Ryan et al., 2015; Smith and Vericat, 2015; Rippin et al., 2015; Clapuyt et al., in press). 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

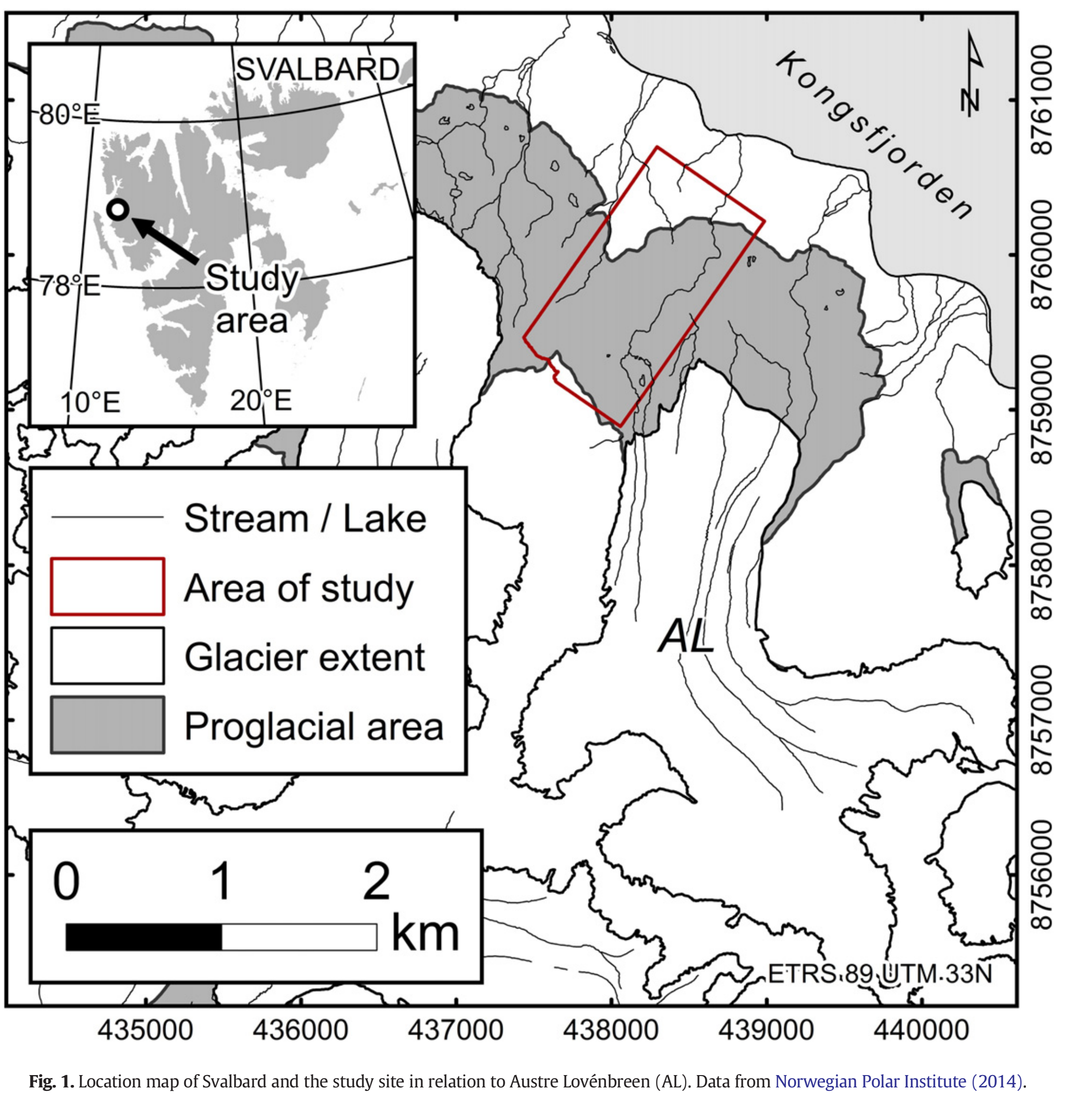

Fig. 1. Location map of Svalbard and the study site in relation to Austre Lovénbreen (AL). Data from Norwegian Polar Institute (2014).

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