ISSN 1476-1580

North West Geography

Volume 15, Number 1, 2015

Analysis of 'hummocky moraine' using Structure-from-Motion photogrammetry

Simon J. Cook[1*], Toby N. Tonkin[2], Nicholas G. Midgley[2], Anya Wicikowski[2]
[1]School of Science and the Environment, Manchester Metropolitan University,
[2]School of Animal, Rural and Environmental Sciences, Nottingham Trent University,
*Corresponding author: S.J.Cook@mmu.ac.uk

Abstract

This study presents results of a high-resolution topographic survey of the proglacial area of Austre Lovénbreen, Svalbard. Structure-from-Motion (SfM) was used to generate a digital elevation model (DEM) of the proglacial zone from aerial imagery. This DEM is used to explore the topography of a zone of hummocky moraine within the glacier's Neoglacial limit. The origin of hummocky moraine has proven controversial, but detailed morphological studies can contribute to a better understanding of how these features form, and the extent to which they may be preserved in the palaeo-glaciological record, including within northwest Britain. In cross-profile, hummocky moraine is characterised by a sequence of asymmetrical ridges, with longer, low angle up-glacier faces, and shorter, steeper down-glacier faces. This profile is interpreted to represent a sequence of ridges stacked-up against a bedrock riegel and reverse bedslope. Whilst the origin of these features is uncertain, the enhanced compression associated with glacier flow against a bedrock riegel, possibly during a glacier surge, may have been sufficient to have generated debris-rich englacial thrusts that subsequently melted-out to form the observed hummocky moraine. The significance of this research highlights ongoing studies aimed at understanding the origin and palaeo-glaciological significance of hummocky moraine in northwest Britain.

Keywords

Digital elevation models, Glacial geomorphology, Hummocky moraine, LiDAR, Structure-from-Motion, Svalbard

Introduction

Important information about the extent, character and dynamics of former glaciers can be gained from analysis of glacial landforms and sediments. One of the most basic characteristics of such landforms is their shape, which can be used to infer processes of sediment entrainment and transfer within the glacier from which they were deposited, and the glacier thermal regime required for such processes to operate (e.g. Hambrey *et al.*, 1997, 1999; Lukas, 2005; Evans, 2009). This case study demonstrates the use of digital elevation models (DEMs) generated from Structure-from-Motion (SfM) photogrammetry across the foreland of the high-Arctic valley glacier Austre Lovénbreen, Svalbard (Figure 1). Specifically, the study focusses on the topographic analysis of so-called 'hummocky moraine', which is found at several locations within northwest British mountains, and whose origin has become the subject of significant debate both in contemporary and past glacial contexts (e.g. Woodward *et al.*, 2002, 2003; Glasser *et al.*, 2003; Lukas, 2005, 2007; Graham *et al.*, 2007). The study highlights how future work on analysis of DEMs of hummocky moraine in northwest Britain acquired through a UAV (Unmanned Aerial Vehicle) survey will facilitate comparison between hummocky moraine in Britain and Svalbard.

Research Context

Several studies have reported the presence of hummocky moraine around the margins of contemporary glaciers. These moraines can be arranged in rectilinear networks, continuous or discontinuous bands of moraine, or apparently chaotically arranged mounds, often with an asymmetric cross-profile (e.g. Figure 2). Similar features have been observed in the UK, including a number of examples from glaciated uplands in northwest Britain (e.g. Benn, 1992; Bennett and Boulton, 1993; Graham and Midgley, 2000; Lukas, 2005; Graham and Hambrey, 2007). Two primary models for hummocky moraine origin have been proposed, each associated with different climatic and dynamic conditions.

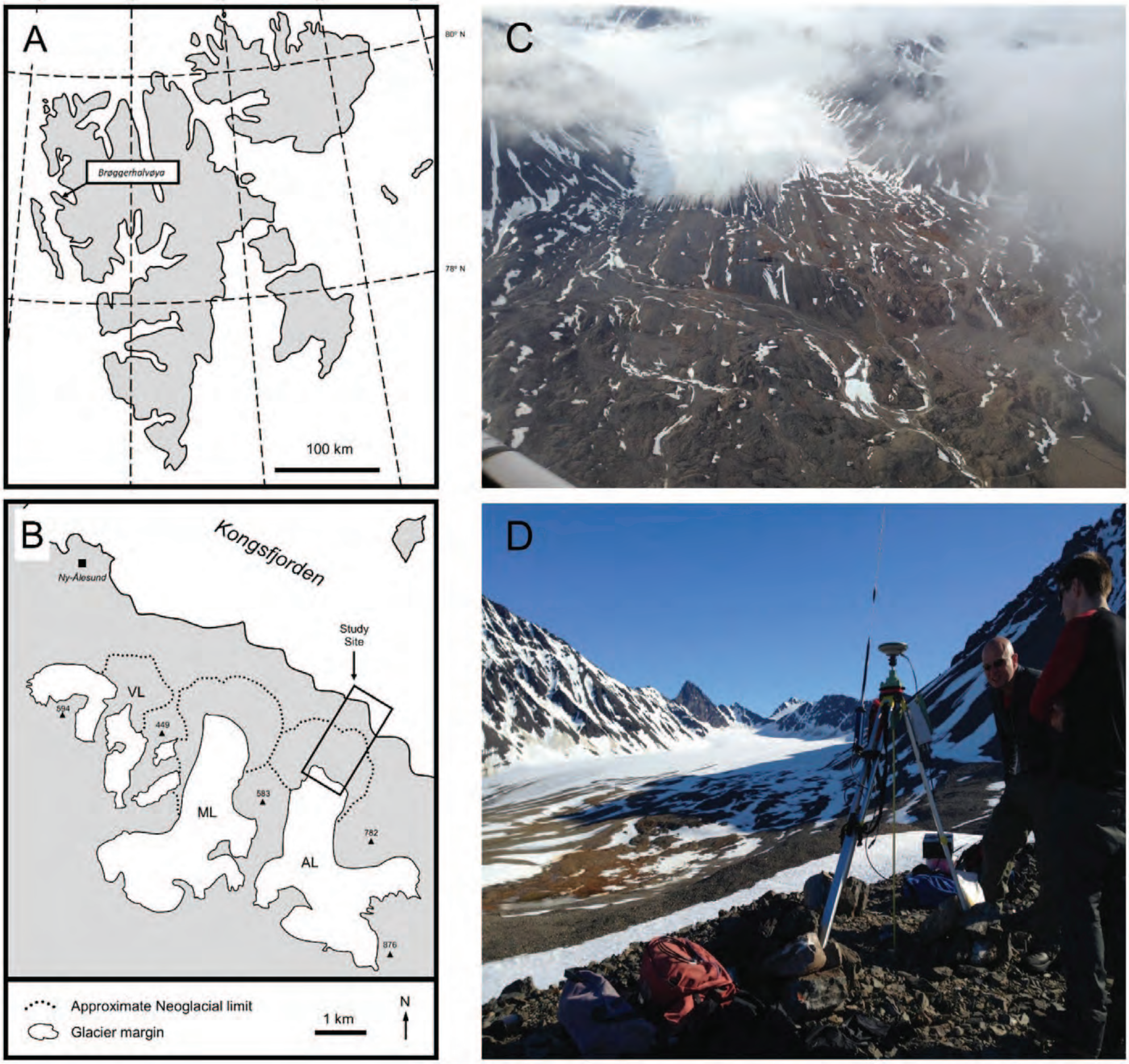

Figure 1: Location of (A) Kongsfjorden, Svalbard, and (B) Austre Lovénbreen (AL) and the area surveyed. Neighbouring glaciers Midtre Lovénbreen (ML) and Vestre Lovénbreen (VL) are also shown. (C) is an aerial view of Austre Lovénbreen and the proglacial area. (D) shows the terminus of Austre Lovénbreen with part of the GNSS setup. (Photos: Simon Cook).

In Svalbard, the origin of these moraines has often been linked with the melt-out of debris-rich structures associated with the process of englacial thrusting (e.g. Hambrey *et al.*, 1996, 1997, 1999; Bennett *et al.*, 1998; Midgley *et al.*, 2007). In this scenario, the terminus of the polythermal glacier is frozen to its substrate. Up-glacier, temperate basal conditions prevail under thicker ice, permitting the operation of glacier sliding. It has been suggested that the differential motion between sliding temperate ice and cold-based marginal ice induces stress sufficient to initiate thrust faulting in glacier ice at this thermal boundary, elevating basal sediment through the glacier thickness toward the glacier surface. Thrust faulting may be promoted by flow against a reverse slope (e.g. Graham and Midgley, 2000; Swift *et al.*, 2006; Graham and Hambrey, 2007). Originally, it was thought that basal sediment was 'scraped' into thrusts (Chamberlin 1895; Salisbury, 1896; Swinzow, 1962), although it is now generally recognised that these debris-rich structures are in fact composed of basal ice, which can be produced by a range of freezing and entrainment processes at the glacier bed (e.g. Hubbard *et al.*, 2004, 2009). Ultimately, melt-out of the debris-rich thrusts generates asymmetric

Figure 2: Cwm Idwal, Snowdonia, Wales. Hummocky moraine exists around the lake margins and on the lower valley slopes. A prominent area of hummocky moraine is circled. (Photo: Nicholas Midgley).

ridges and hummocks in the glacier foreland, which in cross-section tend to have a long stoss face and short lee face, and are often stacked in sequences of melted-out thrusts (e.g. Bennett *et al*., 1998).

Alternatively, in temperate systems, hummocky moraines are produced by pushing and dumping at the ice-margin followed by retreat to the next position where a new moraine is formed, and so on (e.g. Eyles, 1983; Benn, 1992; Lukas, 2005). Lukas (2005) reviewed the specific processes involved in the formation of Younger Dryas-age Scottish hummocky moraine. Here, ice-contact fans were envisaged to have been deposited at stationary ice margins that were then pushed by a fluctuating ice margin to create a push moraine. Supraglacial and englacial sediment was then deposited on top to create a chaotic, hummocky shape. Ridges can also be moulded subglacially where overridden.

Clearly, the identification of thermal regime from hummocky moraine form and sedimentology has important implications for understanding the nature of former glaciers in places like northwest Britain. However, this endeavour has sparked significant debate. For example, polythermal glacier conditions have been inferred from a range of locations in Snowdonia, Cumbria and Scotland from analysis of hummocky moraines (e.g. Bennett *et al*., 1998; Hambrey *et al*., 1997; Graham and Midgley, 2000; Graham and Hambrey, 2007). Alternatively, similar landforms have been interpreted as the product of active ice margin retreat under temperate conditions (Benn, 1992; Lukas, 2005). The englacial thrusting hypothesis in particular has suffered from two key criticisms: (1) some studies question whether englacial thrusting can occur in glacier ice; and (2) some studies question the interpretation that hummocky moraine found in palaeo-glaciological contexts is produced by melt-out of debris-rich thrusts (Woodward *et al*., 2002, 2003; Lukas, 2005, 2007; Moore *et al*., 2010, 2011), or that such features could be preserved in the geomorphological record (Evans, 2009).

This study investigates the morphology of hummocky moraine at Austre Lovénbreen, Svalbard (Figure 1), where sediment transfer processes within the glaciers are well documented, including the melt-out of features suggested previously to be englacial thrust structures (e.g. Hambrey *et al*., 1999; Hubbard *et al*., 2004). This is achieved through the generation of a high-resolution DEM from aerial imagery using SfM (e.g. Westoby *et al*., 2012; Tonkin *et al*., 2014).

Fieldsite and Methods

Fieldwork was undertaken in July 2014 in the proglacial zone of Austre Lovénbreen, Svalbard (Figure 1). The glacier is located near Ny-Ålesund on Brøggerhalyøva on the island of Spitsbergen, part of the Svalbard archipelago, in the Norwegian high-Arctic. Austre Lovénbreen is a small polythermal valley glacier that is currently receding and thinning (Hambrey *et al*., 2005; Saintenoy *et al*., 2013); the glacier has receded by around 1 km from its Neoglacial maximum extent at the end of the nineteenth century. The zones of hummocky moraine exist within the Neoglacial maximum, which is demarcated by a large lateral-frontal moraine ridge (Midgley *et al*., 2013).

The principal objective of the fieldwork was to provide high precision ground control for ortho-rectification of a series of six raw aerial images that were acquired in

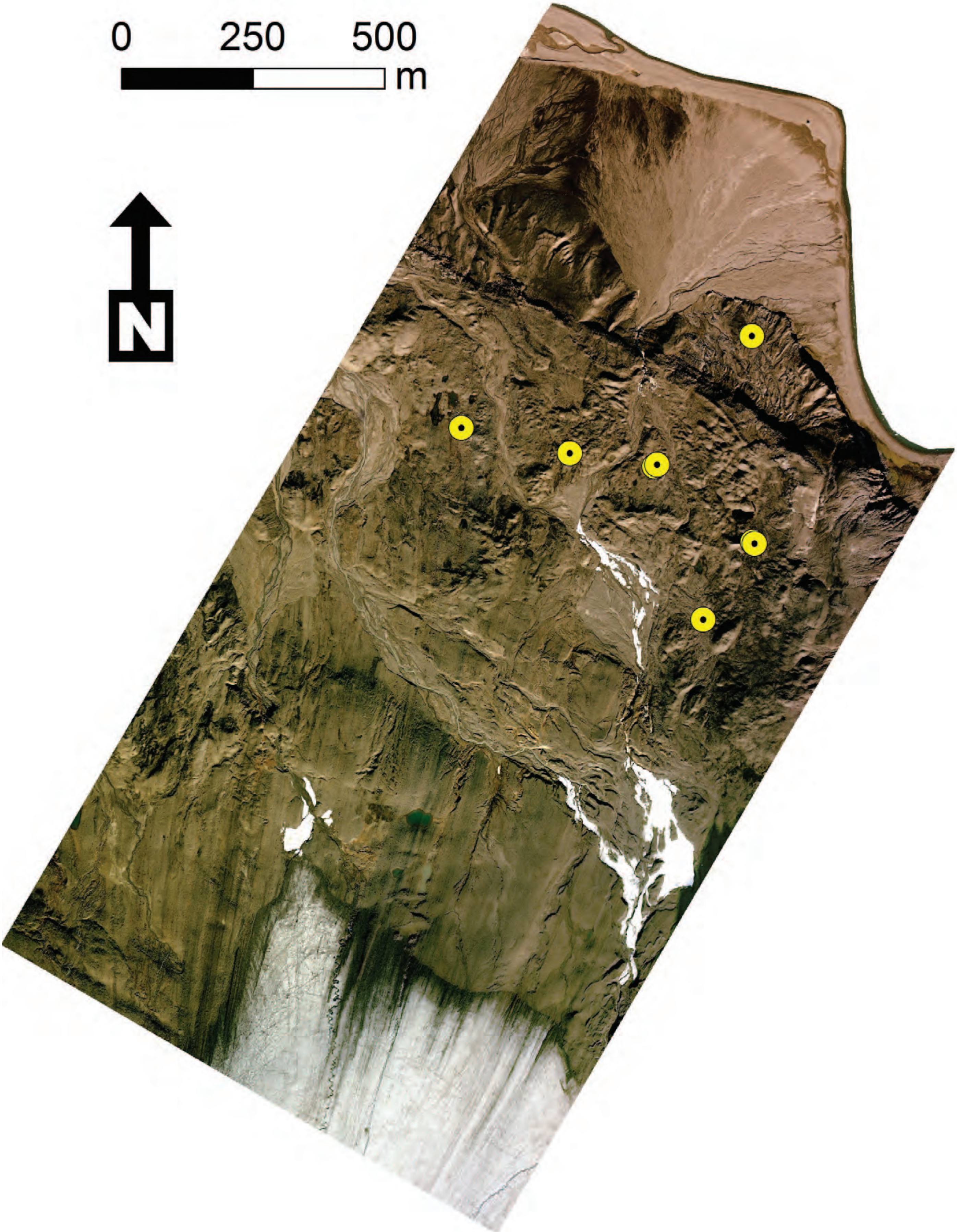

Figure 3: Ortho-rectified aerial image of the terminus of Austre Lovénbreen, its proglacial zone, and the distribution of ground control points (yellow circles) across the zone of hummocky moraine.

2003 by the NERC ARSF (Natural Environment Research Council Airborne Research and Survey Facility; see http://arsf.nerc.ac.uk/). This was achieved using a global navigation satellite system (GNSS; Figure 1D) to record the position of 8 ground control points (GCPs) on stable positions that could be identified from the aerial images (e.g. distinctive bedrock structures, large boulders). The GCPs were focused around the area covered by hummocky moraine to provide better ground control for the principal area of interest (Figure 3).

Ortho-rectification of the imagery and DEM generation was achieved using Agisoft Photoscan SfM software (Agisoft, 2014). The locations of the GCPs were identified in each of the six overlapping images, and the XYZ coordinates for each GCP were input from the GNSS survey. Agisoft Photoscan searches for and matches common points on the photographs, and reconstructs the positions of the camera that took the images. From this, the software is able to build a point cloud of the three-dimensional form of the landscape. The resultant ortho-photo and DEM were exported to ArcGIS 10.2.2 for visualisation and topographic analysis.

Results and Discussion

Figure 4 presents three-dimensional views of the study area visualised in ArcScene. Here, the ortho-rectified aerial image has been draped over the DEM produced using SfM. Figure 4b shows the area of hummocky moraine and the apparently asymmetrical form of the hummocky ridges. Generally, ridges have a longer, low angle stoss face (nearest the glacier), and a shorter, steeper lee face (furthest from the glacier).

The asymmetric form of the hummocky moraine ridges is shown in Figure 5. Three example profiles of between ~90m and ~120m in length are shown across transects A-A′, B-B′ and C-C′. In each profile, there are several segments where the stoss face is longer, and generally shallower, than the lee face, as indicated by the grey bars.

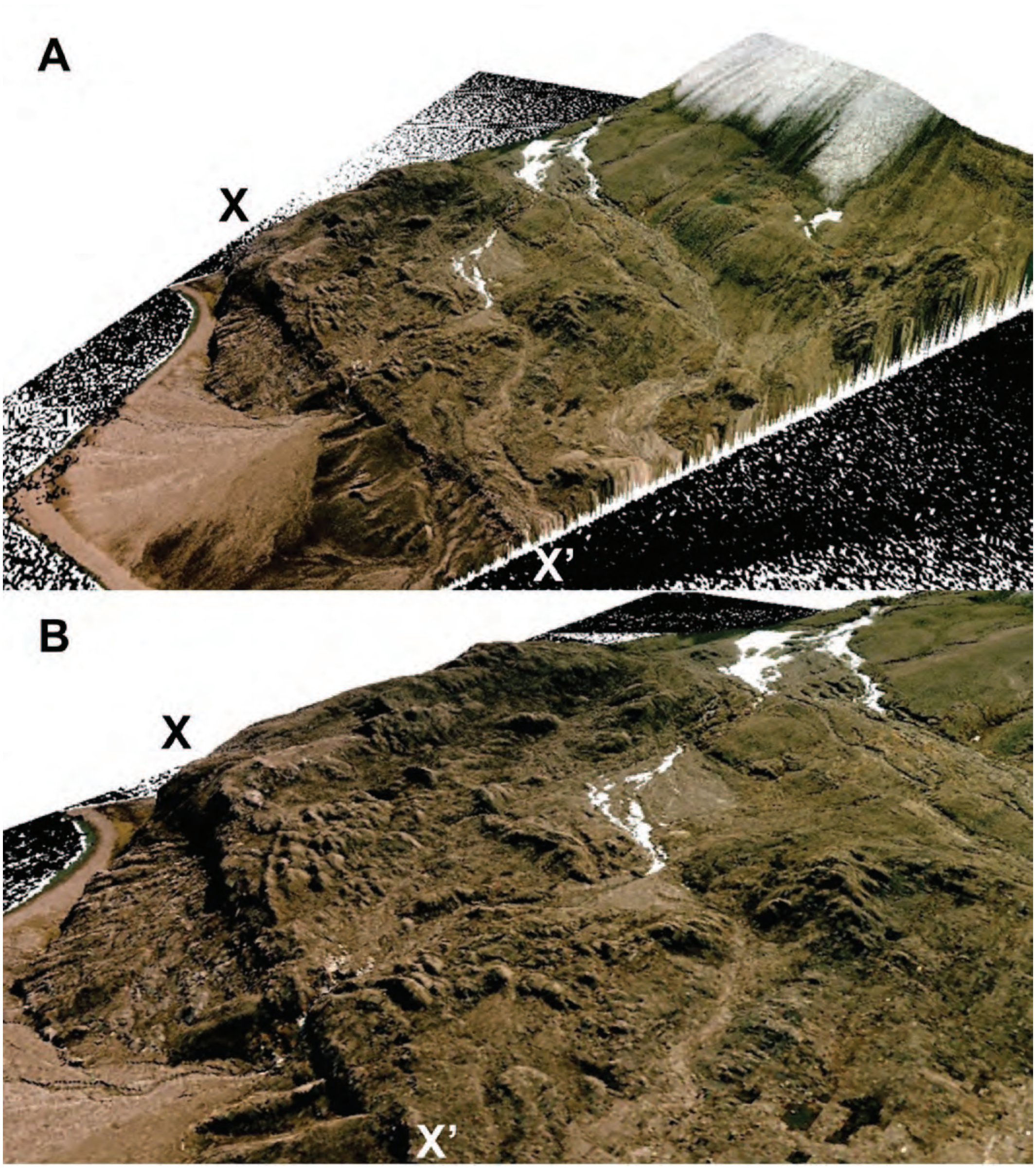

Figure 4: Oblique view of (A) the overall study area, and (B) the zone of hummocky moraine. The profile X-X′ in each image shows the location of a prominent bedrock riegel.

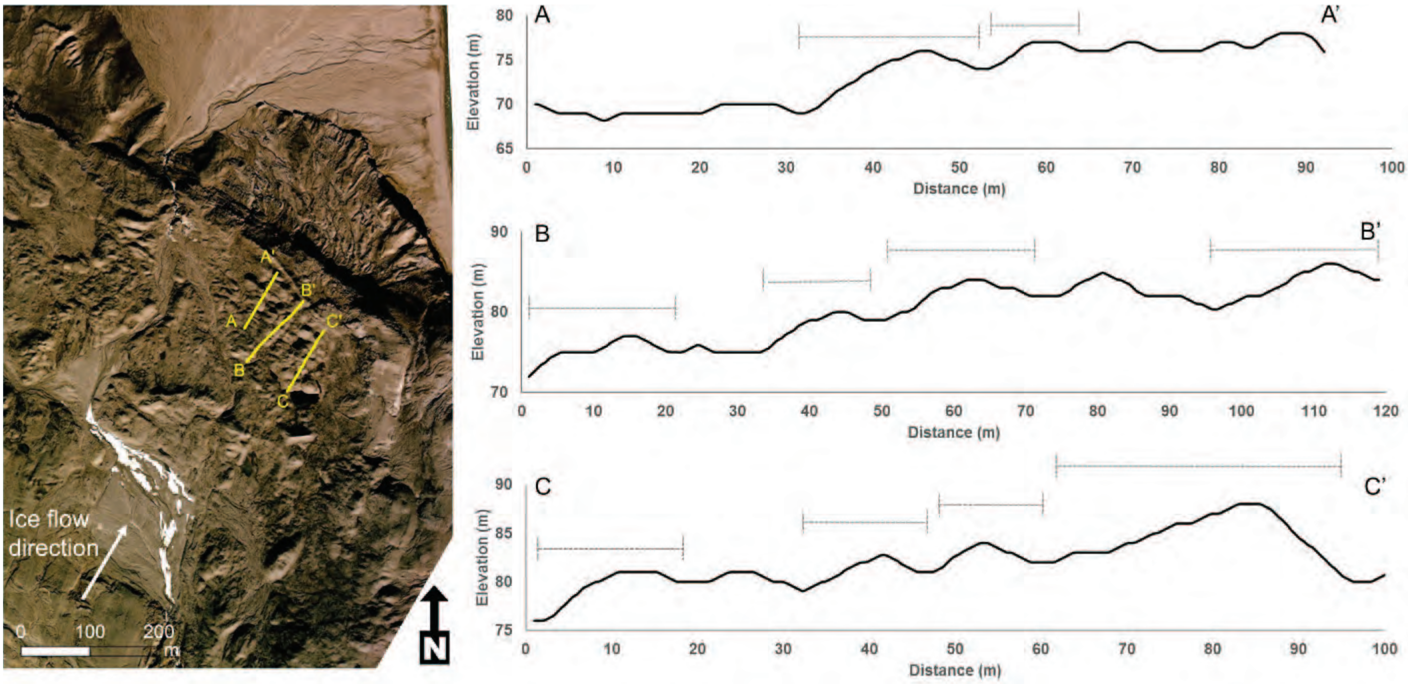

Figure 5: Location of three transects across the zone of hummocky moraine. Grey dashed lines indicate segments of the cross-profiles where the stoss face is longer and generally shallower than the lee face.

Shape is a fundamental property of glacial landforms, and can provide important clues about landform origin, and hence the dynamic characteristics of the glaciers that created them (e.g. thermal regime, surging behaviour, etc.). The hummocky moraines at Austre Lovénbreen have a distinctive cross-sectional shape that may be used to assist in determining landform origin, and serve as a useful analogue for ancient moraines in Britain. Broadly, it is the pattern of debris-rich folia in the parent ice that gives rise to the linear arrangement of hummocks as the ice recedes and thins (Evans, 2009), although previous studies have attempted to interpret the asymmetrical shape of hummocky moraine as a product of specific sediment transfer processes. Most prominent among these hypotheses are (i) englacial thrusting, and (ii) deposition from incremental, actively retreating ice.

The entrainment of sediment into and melt-out from englacial thrusts is an appealing model for the generation of hummocky moraine observed at Austre Lovénbreen, although the cause of englacial thrusting requires some consideration. Much of the debate about the efficacy of englacial thrusting for sediment entrainment and the generation of hummocky moraine has focused on the necessary conditions to cause thrust-faulting in ice (Woodward *et al.*, 2002, 2003; Moore *et al.*, 2010, 2011). A number of studies have suggested that flow compression associated with polythermal conditions can generate englacial thrusts (e.g. Hambrey *et al.*, 1997, 1999; Bennett *et al.*, 1998). However, both modelling (Moore *et al.*, 2010) and field measurements (Moore *et al.*, 2011) indicate that flow compression at the temperate-cold thermal transition is insufficient to cause thrust-faulting in ice. Hence, whilst basal thermal conditions may have influenced compression at Austre Lovénbreen during moraine formation, it may not have been sufficient to generate thrusts. Hence, other causes of flow compression may have been required.

Figure 5 reveals a generally climbing elevation profile toward the north, and Figure 4 reveals a distinct, linear bedrock riegel (shown as X-X') extending across the survey area. Hence, at the Neoglacial maximum, the glacier would have been flowing against this bedrock riegel, and up along a reverse slope. These conditions would have enhanced flow compression significantly, with the potential to cause englacial thrusting and associated sediment entrainment (Swift *et al.*, 2006; Graham and Hambrey, 2007; Cook and Swift, 2012). Another potential contributor to enhanced flow compression is glacier surging. Svalbard has a high concentration of surge-type glaciers (e.g. Jiskoot *et al.*, 2000), but until recently, Austre Lovénbreen was not thought to have exhibited surge-type behaviour (Hambrey *et al.*, 1999, 2005). However, Midgley *et al.* (2013) noted the presence of an apparent surface bulge on Austre Lovénbreen in an oblique aerial photo taken in 1936. This bulge was interpreted to indicate that Austre Lovénbreen had surged in the past. Flow compression associated with surges is one of the few conditions where thrust faulting has been observed unequivocally (Raymond *et al*., 1987; Moore *et al*., 2010; Murray and Booth, 2010). In 1936, the glacier extended to the position of the Neoglacial maximum moraine, and hence occupied the area where hummocky moraine is now observed. It is likely, therefore, that any such surge (in 1936 or before) would have affected flow compression and sediment transfer in this area. Hence, the combination of surging flow against a reverse bedrock slope, possibly influenced by a basal thermal transition, may have created enough compression to have generated thrust-faults that melted out to produce the hummocky moraine at Austre Lovénbreen.

Alternatively, the asymmetric moraine profiles could be interpreted as the product of active ice retreat. In the situation at Austre Lovénbreen, active ice retreat would have taken place along a reverse slope meaning that, during retreat from the moraine, supraglacial sediment and melt-out of englacial debris would have been lowered onto a reverse slope, possibly with some degree of debris flow or reworking down-slope. This combination of deposition and reworking may have given the asymmetrical profile observed in the hummocky moraine at Austre Lovénbreen. The extent to which this model is applicable for Svalbard glaciers close to their Neoglacial maximum is uncertain. The active retreat model is generally regarded to be most applicable at temperate glaciers, such as those in Iceland (Eyles, 1983), rather than in Arctic glaciers. As Lukas (2005) suggests, detailed sedimentology of the internal structure of these moraines would be required to test this model further.

Landforms at glacier margins are commonly polygenetic, and it remains possible that some combination of the processes discussed above would have contributed to moraine formation at Austre Lovénbreen. Whatever the origin of the moraines, it is also important to consider the influence of post-depositional processes on moraine form (e.g. Bennett *et al*., 2000; Evans, 2009). It is possible that the hummocky moraine at Austre Lovénbreen is ice-cored, and that as the ice core degrades, the shape of the moraine will change. Ice cored moraine lowering rates at neighbouring Midtre Lovénbreen have been measured at an average of 0.56 ± 0.14 m per year (Irvine-Fynn *et al*., 2011). Certainly, parts of the Neoglacial moraine at Austre Lovénbreen are

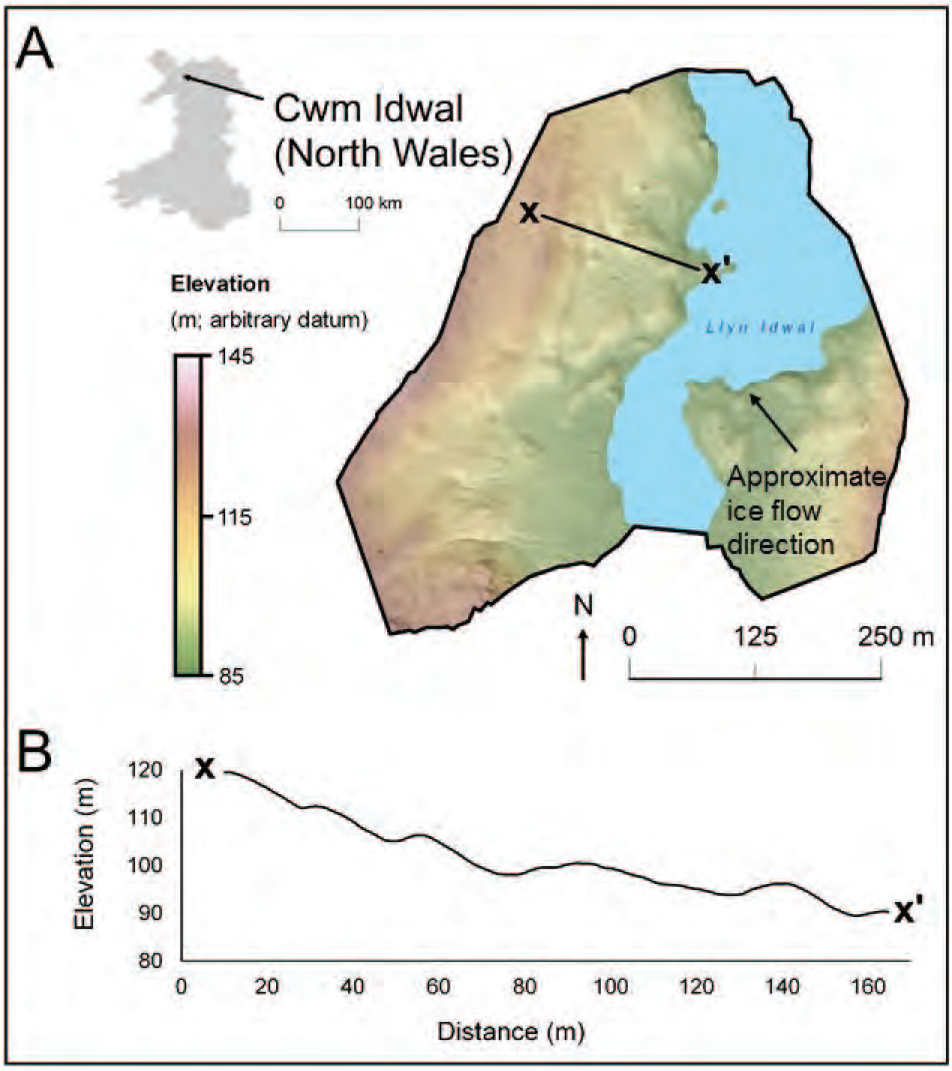

Figure 6: (A) DSM of Cwm Idwal, Wales, derived from imagery obtained with a UAV (Tonkin et al., 2014). (B) Cross-section X-X′ of an area of prominent hummocky moraine. The inset map of Wales is sourced from the Edina Digimap service (© Crown Copyright/database right 2014. An Ordnance Survey/EDINA supplied service).

ice-cored (Midgley *et al*., 2013), and the extent to which moraine morphology is evolving over time as climate ameliorates and ice-cores degrade is the subject of our ongoing investigations.

Younger Dryas-age hummocky moraine has been identified at a number of sites within northwest Britain, and both the active retreat (Lukas, 2005) and thrusting (e.g. Hambrey *et al*., 1997; Graham and Hambrey, 2007) models have been applied here. The next phase of this work will focus on Ennerdale, Cumbria, where hummocky moraines have been interpreted as the product of a combination of thrusting and active retreat (Graham and Hambrey, 2007). The research will conduct a high-resolution topographic survey using an Unmanned Aerial Vehicle (UAV) to acquire aerial imagery that can subsequently be integrated with SfM software to generate a DSM (Digital Surface Model) of the moraines. This can then be compared with the moraines at Austre Lovénbreen and elsewhere to facilitate a better understanding of moraine origin, and hence of Younger Dryas climate and glacier dynamics in northwest Britain.

As an example of the use of UAV and SfM to generate DSMs of British hummocky moraine, we present results from recent work by Tonkin *et al*. (2014) for Cwm Idwal, Wales. Figure 6 presents a DSM and cross-section of the hummocky moraine in the area highlighted on Figure 2. The cross-section shows similar stacked, asymmetric ridges, which may have been generated by melt-out of englacial thrusts stacked against the valley side by ice flow from the south east, out of Cwm Cneifion (a small cwm above Cwm Idwal; Graham and Midgley, 2000).

Conclusions

This study demonstrates the utility of SfM in the generation of high-resolution DEMs that can be used to investigate glacial geomorphology. Specifically, the study focused on topographic analysis of hummocky moraine within the proglacial zone of Austre Lovénbreen, Svalbard. Results indicate that these moraines have an asymmetric cross profile that resembles other descriptions of moraines produced by melt-out of englacial thrust structures. Whilst any inference of thrusting is speculative, the enhanced compression required for thrusting could have been provided by surging glacier flow against a reverse slope and bedrock riegel, possibly with the influence of temperate ice from the glacier interior flowing against cold-based ice at the terminus. Post-depositional modification of moraines may affect their morphology, and this is the subject of ongoing investigation. The hummocky moraines at Austre Lovénbreen may serve as a useful analogue for features observed in northwest Britain. The next phase of this work will be to investigate the morphology of such features using a UAV (drone) survey and the same SfM techniques employed in this study.

Acknowledgements

SJC would like to thank the Manchester Geographical Society for research funds to support his involvement in this project. NGM, TNT and AW acknowledge funding from Nottingham Trent University. The fieldwork benefited from the logistical support provided by Nick Cox of the UK Arctic Office, hosted at the British Antarctic Survey (BAS). We thank an anonymous reviewer for their helpful review of our manuscript.

References

Agisoft., 2014. Agisoft PhotoScan User Manual: Professional Edition, Version 1.1. Agisoft LLC.

Benn, D. I., 1992. The genesis and significance of 'hummocky moraine': evidence from the Isle of Skye, Scotland. *Quaternary Science Reviews*, 11, 781–799.

Bennett, M. R. & Boulton, G. S., 1993. A reinterpretation of Scottish 'hummocky moraine' and its significance for the deglaciation of the Scottish Highlands during the Younger Dryas or Loch Lomond Stadial. *Geological Magazine*, 130, 301–318.

Bennett, M. R., Hambrey, M. J., Huddart, D. & Glasser, N. F., 1998. Glacial thrusting and moraine-mound formation in Svalbard and Britain: the example of Coire a' Cheud-chnoic (Valley of hundred hills), Torridon, Scotland. *Quaternary Proceedings*, 6, 17–34.

Bennett, M.R., Huddart, D., Glasser, N.F., Hambrey M.J., 2000. Resedimentation of debris on an ice-cored lateral moraine in the high-Arctic (Kongsvegen, Svalbard). *Geomorphology*, 35, 21–40.

Chamberlin, T.C., 1895. Recent glaciological studies in Greenland. *Bulletin of the Geological Society of America*, 6, 199-220.

Cook, S.J., Swift, D.A., 2012. Subglacial basins: Their origin and importance in glacial systems and landscapes. *Earth-Science Reviews*, 115(4), 332-372.

Evans, D.J.A., 2009. Controlled moraines: origins, characteristics and palaeoglaciological implications. *Quaternary Science Reviews*, 28, 183-208.

Eyles, N. 1983: Modern Icelandic glaciers as depositional models for 'hummocky moraine' in the Scottish Highlands. In Evenson, E. B., Schlüchter, C. & Rabassa, J. (eds.): *Tills and Related Deposits*, 47–59. Balkema, Rotterdam.

Glasser, N.F., Hambrey, M.J., Bennett, M.R., Huddart, D., 2003. Comment: Formation and reorientation of structure in the surge-type glacier Kongsvegen, Svalbard. *Journal of Quaternary Science*, 18(1), 95-97.

Graham, D.J., Hambrey, M.J., 2007. Sediments and landforms in an upland glaciated-valley landsystem: upper Ennerdale, English Lake District. In Hambrey, M.J., Christoffersen, P., Glasser, N.F., Hubbard, B.P. (eds.). *Glacial Sedimentary Processes and Products: Special Publication 39 of the IAS*. Blackwell Publishing, Oxford.

Graham, D.J. and Midgley, N.G., 2000. Moraine-mound formation by englacial thrusting: the Younger Dryas moraines of Cwm Idwal, North Wales. In: A.J. Maltman, B. Hubbard and M.J. Hambrey (editors), *Deformation of Glacial Materials*. London: Geological Society, pp. 321-336.

Graham, D.J., Bennett, M.R., Glasser, N.F., Hambrey, M.J., Huddart, D., Midgley, N.G., 2007. 'A test of the englacial thrusting hypothesis of "hummocky" moraine formation: case studies from the northwest Highlands, Scotland': Comments. *Boreas*, 36(1), 103-107.

Hambrey, M.J., Bennett, M.R., Dowdeswell, J.A., Glasser, N.F., Huddart, D., 1999. Debris entrainment and transfer in polythermal valley glaciers. *Journal of Glaciology*, 45(149), 69-86.

Hambrey, M.J., Dowdeswell, J.A., Murray, T., Porter, P.R., 1996. Thrusting and debris entrainment in a surging glacier: Bakaninbreen, Svalbard. *Annals of Glaciology*, 22, 241-248.

Hambrey, M.J., Huddart, D., Bennett, M.R., Glasser, N.F., 1997. Genesis of 'hummocky moraines' by thrusting in glacier ice: Evidence from Svalbard and Britain. *Journal of the Geological Society*, 154, 623-632.

Hambrey, M.J., Bennett, M.R., Dowdeswell, J.A., Glasser, N.F. and Huddart, D., 1999. Debris entrainment and transfer in polythermal valley glaciers, *Journal of Glaciology*, 45, 69-86.

Hambrey, M.J., Murray, T., Glasser, N.F., Hubbard, A., Hubbard, B., Stuart, G., Hansen, S. and Kohler, J. (2005) Structure and changing dynamics of a polythermal valley glacier on a centennial timescale: Midre Lovénbreen, Svalbard. *Journal of Geophysical Research*, 110, F01006.

Hubbard, B., Glasser, N.F., Hambrey, M., Etienne, J., 2004. A sedimentological and isotopic study of the origin of supraglacial debris bands: Kongsfjorden, Svalbard. *Journal of Glaciology*, 50(169), 157-170.

Hubbard, B., Cook, S.J., Coulson, H., 2009. Basal ice facies: a review and unifying approach. *Quaternary Science Reviews*, 28, 1956-1969.

Irvine-Fynn, T.D.L., Barrand, N.E., Porter, P.R., Hodson, A.J., Murray, T., 2011. Recent High-Arctic glacial sediment redistribution: A process perspective using airborne lidar. *Geomorphology*, 125, 27-39.

Jiskoot, H., Murray, T., Boyle, P., 2000. Controls on the distribution of surge-type glaciers in Svalbard. *Journal of Glaciology*, 46, 412-422.

Lukas, S., 2005. A test of the englacial thrusting hypothesis of 'hummocky' moraine formation: case studies from the northwest Highlands, Scotland. *Boreas*, 34(3), 287-307.

Lukas, S., 2007. A test of the englacial thrusting hypothesis of "hummocky" moraine formation: case studies from the northwest Highlands, Scotland': Reply to comments. *Boreas*, 36(1), 108-113.

Midgley, N.G., Glasser, N.F. and Hambrey, M.J., 2007. Sedimentology, structural characteristics and morphology of a Neoglacial high-Arctic moraine-mound complex: midre Lovénbreen, Svalbard. In: Hambrey, M.J., Christoffersen, P., Glasser, N.F. and Hubbard, B (editors), *Glacial Sedimentary Processes and Products*, International Association of Sedimentologists, Blackwells, Oxford: pp. 11-22.

Midgley, N.G., Cook, S.J., Graham, D.J. and Tonkin, T.N., 2013. Origin, evolution and dynamic context of a Neoglacial lateral-frontal moraine at Austre Lovénbreen, Svalbard. *Geomorphology*, 198, 96-106.

Moore, P.L., Iverson, N.R., Brugger, K.A., Cohen, D., Hooyer, T.S., Jansson, P., 2011. Effect of a cold margin on ice flow at the terminus of Storglaciaren, Sweden: implications for sediment transport. *Journal of Glaciology*, 57(201), 77-87.

Moore, P.L., Iverson, N.R., Cohen, D., 2010. Conditions for thrust faulting in a glacier. *Journal of Geophysical Research-Earth Surface*, 115.

Murray, T., Booth, A.D., 2010. Imaging glacial sediment inclusions in 3-D using ground-penetrating radar at Kongsvegen, Svalbard. *Journal of Quaternary Science*, 25(5), 754-761.

Raymond, C., Johannesson, T., Pfeffer, T., Sharp, M., 1987. Propagation of a glacier surge into stagnant ice. *Journal of Geophysical Research-Solid Earth and Planets*, 92(B9), 9037-9049.

Saintenoy, A., Friedt, J.-M., Booth, A.D., Tolle, F., Bernard, É., Laffly, D., Marlin, C.,Griselin, M., 2013. Deriving ice thickness, glacier volume and bedrock morphol-ogy of the Austre Lovénbreen (Svalbard) using ground-penetrating radar. *NearSurface Geophysics*, 11 (2), 253–261.

Salisbury, R.D., 1896. Salient points regarding the glacial geology of North Greenland. *Journal of Geology*, 4, 769-810.

Swift, D.A., Evans, D.J.A., Fallick, A.E., 2006. Transverse englacial debris-rich ice bands at Kviarjokull, southeast Iceland. *Quaternary Science Reviews*, 25(13-14), 1708-1718.

Swinzow, G.K., 1962. Investigation of shear zones in the ice sheet margin, Thule area, Greenland. *Journal of Glaciology*, 4(32), 215-229.

Tonkin, T.N., Midgley, N.G., Graham, D.J., Labadz, J.C., 2014. The potential of small unmanned aircraft systems and structure-from-motion for topographic surveys: a test of emerging integrated approaches at Cwm Idwal, North Wales. *Geomorphology*, 226, 35-43.

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., and Reynolds, J.M. 2012. 'Structure-from-motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, 179, 300-314.

Woodward, J., Murray, T., McCaig, A., 2002. Formation and reorientation of structure in the surge-type glacier Kongsvegen, Svalbard. *Journal of Quaternary Science*, 17(3), 201-209.

Woodward, J., Murray, T., McCaig, A., 2003. Reply: Formation and reorientation of structure in the surge-type glacier Kongsvegen, Svalbard. *Journal of Quaternary Science*, 18(1), 99-100.