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SCIENCE

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A contoured surficial geology and geomorphology map of the forelands of the Hørbyebreen, Svenbreen and Ferdinandbreen valley glaciers in Petuniabukta, Svalbard was compiled from an orthophotograph based upon aerial photographs taken in 2009. The map reveals typical polythermal glacial landsystems, comprising ice-cored latero-frontal moraine arcs grading up valley into fluted till surfaces draped by supraglacially-derived longitudinal debris stripes. The additional occurrence on the Hørbyebreen foreland of linear esker and debris ridges arranged in a geometric ridge network is thought to be related to the infilling of densely spaced crevasses, created during a period of elevated meltwater pressures and ice hydrofracturing. These landforms were associated either with a *jökulhlaup* that was blocked by the frozen snout or an historical surge. The Hørbyebreen landform assemblage therefore constitutes an analogue for either: (1) spatial and temporal landsystem overprinting (polythermal and surging activity); or (2) a more refined polythermal landsystem in which the build up and release of meltwater reservoirs in warm-based interiors of polythermal glaciers give rise to a particularly diagnostic landform at the up-ice junction with the cold-based snout.

Keywords: glacial landsystem; polythermal glacier; geometric ridge network; ice hydrofracturing; Svalbard

1. Introduction

Hørbyebreen and the adjacent glaciers, Svenbreen and Ferdinandbreen are polythermal valley glaciers (Figure 1) located at 78°46′N at the north end of Petuniabukta, in central Svalbard, and have been the subject of previous geomorphological mapping by Karczewski et al. (1990). An early twentieth-century surge has been proposed for Hørbyebreen (Gibas, Rachlewicz, & Szczuciński, 2005; Karczewski, 1989) based upon looped medial moraines that are no longer visible, but otherwise the glaciers in the area have been in continuous recession since the end of the last Little Ice Age Type Event in the early twentieth century (Rachlewicz, Szczuciński, & Ewertowski, 2007). Such glaciological dynamics are typical for many Svalbard glacier snouts and therefore the landform–sediment associations that characterize the Hørbyebreen, Svenbreen and Ferdinandbreen forelands constitute an important modern landsystems analogue for palaeoglaciological reconstruction, not only for warm polythermal glaciers (*sensu* Pettersson, 2004) but also potentially for spatial and temporal landsystem overprinting. Contrasting aspects and radiation receipt in this mountainous terrain have resulted in more pronounced snout thinning on the east side of Hørbyebreen, creating an extensive subglacial landform assemblage that contrasts with the continuous glacier ice and ice-cored end moraine beneath the steep cliffs above the west margin. This has provided a window through to the glacier bed and additionally has recently exposed a network of eskers and associated rectilinear debris ridges, which record deposition in tunnels and fractures in the glacier snout and contrast with the landform assemblages at neighbouring Svenbreen and Ferdinandbreen. The origins and implications of such features in a polythermal glacier are most likely related to a period of hydrofracturing and possible surging activity, making the Hørbyebreen foreland an excellent location to test the concept of landsystem overprinting in Svalbard valley glaciers. The future development of the foreland geomorphology, due largely to ice melt-out, can be quantified through the construction of repeat mapping based upon new aerial photography and utilization of existing

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Figure 1. Overview of the forelands of Hørbyebreen and Svenbreen from the southwest.

ground survey control initiated for this project (e.g. Bennett & Evans, in press; Bennett et al., 2010; Schomacker, 2008; Schomacker & Kjær, 2008).

2. Map compilation

The Petuniabukta glacier forefields map (Main Map) was compiled from an orthophotograph constructed from aerial photographs taken by the Norwegian Polar Institute (NPI) on 27 July and 11 August 2009. Images were taken with an UltraCam Xp Large Format Digital Aerial Camera manufactured by Vexcel. In advance of the NPI flights, a network of reference markers (2 × 3 m white geofibre rectangles) were positioned in the field on suitable, highly visible natural features such as large rocks and rocky outcrops and surveyed with a Leica 1200 Differential Global Positioning Station to improve the precision of the constructed orthophotograph. In addition, 25 further ground control points (massive boulders) were surveyed across the Hørbyebreen proglacial zone in the summer of 2010. The orthophotograph and digital terrain model (DTM) were created in Leica Photogrammetry Suite 2010 by ERDAS and associated contours were extracted digitally from the DTM using ESRI ArcGIS 9.3. Each set of photographs was processed as for a digital camera. The projection used was UTM, with the spheroid WGS 84 for zone 33N.

The proglacial landforms and surficial geology were mapped onto a coloured ink film overlay. Interpretations of surface materials and landforms were made by a combined approach involving stereoscopic mapping directly from the aerial photographs and a reconnaissance level of ground truth fieldwork, undertaken during the summer of 2010.

The map overlay containing the base data was manually digitized on a large format CalComp tablet digitizer using MapData vector digitizing software. The digitized vector files for the base data were converted from MapData format into ArcInfo 'generate' format for importing into Adobe Illustrator, utilizing the Avenza MAPublisher plug-in software to produce a fully editable and structured map file. Final design and production was undertaken in Adobe Illustrator CS5. The raster image used for the glacier surface was created by manipulating the panchromatic orthophotograph in Adobe Photoshop to create the colourized image. Because of the steep mountainous topography, the image reveals areas of shadow, which have been contrast adjusted in order to minimize their impact on the glacier surface features. The digital map needs to be printed on an A0 sheet in order to reproduce the 1:10,000 scale.

3. Sediment–landform associations

3.1. *Surficial geology*

There are seven surficial geology units in addition to areas of bedrock and glacier ice. Upland areas and steep valley sides are dominated by bedrock, residuum or weathered bedrock, and paraglacial deposits related to slope processes on recently abandoned glacial features. Additionally, a large rock glacier lies at the base of the steep rock wall on the south margin of the Hørbyebreen forefield; this feature could be either a talus-derived rock glacier or, more likely given its location, a rock-glacierized lateral moraine (cf. Evans, 1993; Humlum, 1982; Vere & Matthews, 1985). Glacifluvial deposits or complex braidplains predominantly occur as proglacial outwash fans (sandar), which coalesce to form a 2.2 km wide outwash plain beyond the Little Ice Age ice-cored moraine belts; they also form short ribbon sandar in corridors that have been incised through the ice-cored moraine belts and the subglacial landforms located up valley. Glacimarine sediments of varying thickness lie below the local marine limit of 80 m a.s.l., but only where they have survived reworking by proglacial outwash. Their thin character is best illustrated to the north of the outwash plain where bedrock lineations protrude through the glacimarine veneer. Glacigenic deposits indicative of complete melt-out of buried glacier ice are classified very generally as 'till and supraglacially-derived debris mounds'. These surfaces may be adorned by flutings, moraine ridges, eskers and crevasse fills, which are discussed in more detail below. Finally, the most significant glacial geomorphological assemblage on the forelands of the Petuniabukta glaciers is the 'ice-cored moraine'. This forms a high relief latero-frontal moraine arc around each glacier snout and marks the limit of the Little Ice Age advance in the area. It is characterized by controlled moraine (*sensu* Evans, 2009), longitudinal foliae/medial moraines and geometric ridge networks interpreted as crevasse fills and associated eskers (Figures 2–6).

Specific sediment–landform assemblages are instructive in terms of spatial and temporal glacial foreland evolution. They are, therefore, now described and analysed in turn.

3.2. *Glacial lineations (longitudinal foliae and flutings)*

Both the glacier surface and the subglacial till, freshly exposed by glacier thinning, are strongly lineated (Figures 2, 3, 7). The subglacial lineations are less well developed and constitute flutings produced at the ice-bed interface, and thereby indicative of warm-based conditions inside the ice-cored moraine arc. The more prominent supraglacial lineations are longitudinal debris stripes typical of most Svalbard glaciers and explained by Hambrey and Glasser (2003) as englacial debris bands subject to transpression where ice flows from several cirque basins into a major valley. Downwasting of clean ice rather than snout recession has resulted in the emergence of fluted till patches on high points of the bed through the lineated glacier surface (Figure 7). This superimposition and/or juxtaposition of supraglacially-derived debris stripes and subglacial flutings have been reported previously from Svalbard glacier forelands by Glasser and Hambrey (2003).

3.3. *Ice-cored and controlled moraine*

The historical (Little Ice Age) maximum limits of Hørbyebreen and neighbouring glaciers are clearly marked by latero-frontal moraine arcs comprising linear hummocky terrain and more continuous linear ice-cored, transverse ridges or 'controlled moraine' (*sensu* Evans, 2009; Figures 3, 5, 6, 8). Melting ice cores are manifest in numerous kettle holes, retrogressive flows and hollows bordered by tension cracks (e.g. Lukas, Nicholson, Ross, & Humlum, 2005; Lyså & Lønne, 2001). Although relief is locally significant (>20 m), areas of advanced melt-out are apparent as low-amplitude, rubble-covered undulations and are mapped separately as 'till and supraglacially-derived

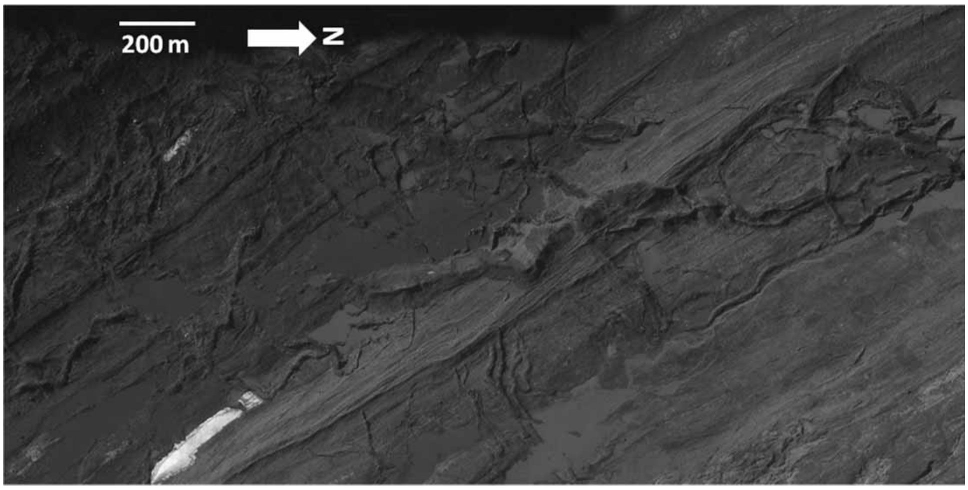

Figure 2. Aerial photograph extract (2009) of geometric ridge network and sinuous ridges emerging through linear debris stripes on the west margin of Hørbyebreen snout, representing esker construction in major tunnels and adjacent crevasses. Centre of image is at 531750/874150.

Figure 3. Aerial photograph extract (2009) of the ice-cored latero-frontal moraine arc of Ferdinandbreen. Areas of strongly fluted terrain occur on the foreland and linear debris stripes occur in juxtaposition with crevasse fills ridges in the ice-cored moraine. Centre of image is at 530200/873800.

debris mounds relating to complete melt-out of ice-cored moraine'. The ice-cored latero-frontal moraine arcs have been termed 'moraine-mound complexes' by Hambrey, Huddart, Bennett, and Glasser (1997) and Bennett, Hambrey, Huddart, and Glasser (1998), who relate them to englacial debris transfer along thrusts in the glacier snout. The thrusting concept has remained controversial (cf. Glasser, Hambrey, Bennett, & Huddart, 2003; Woodward, Murray, & McCaig, 2002, 2003) but regardless of its efficacy in the transfer of debris, a variety of processes, in addition to thrusting, are likely responsible for the production of the remarkable debris-rich ice and controlled moraine around polythermal glacier snouts (Evans, 2009; Glasser & Hambrey, 2003; Lukas et al., 2005; Sletten, Lyså, & Lønne, 2001).

3.4. *Eskers and crevasse fills*

Eskers on the Petuniabukta glacier forelands can be classified into three sub-types: (1) linear esker ridges; (2) sinuous eskers; and (3) localized engorged eskers (Figures 2, 4–8). The former are concentrated on the west side of the snout, are associated with ice-flow transverse and rectilinear debris ridges, and often branch off from major sinuous eskers. Because the linear esker and debris ridges form a rectilinear, cross-cutting pattern with a small range in orientations, it is considered most likely that they were deposited in crevasses created during the surge of the snout reported by Karczewski (1989) and Gibas et al. (2005). This implies compatibility with zig-zag eskers and crevasse-squeeze ridges typical of surging glacier geomorphology (Evans & Rea, 2003; Rea & Evans, 2011; Sharp, 1985), although the transverse debris ridges at Hørbyebreen have been interpreted as englacial thrust features by Szuman and Kasprzak (2010; cf. Bennett et al., 1998; Hambrey et al., 1997).

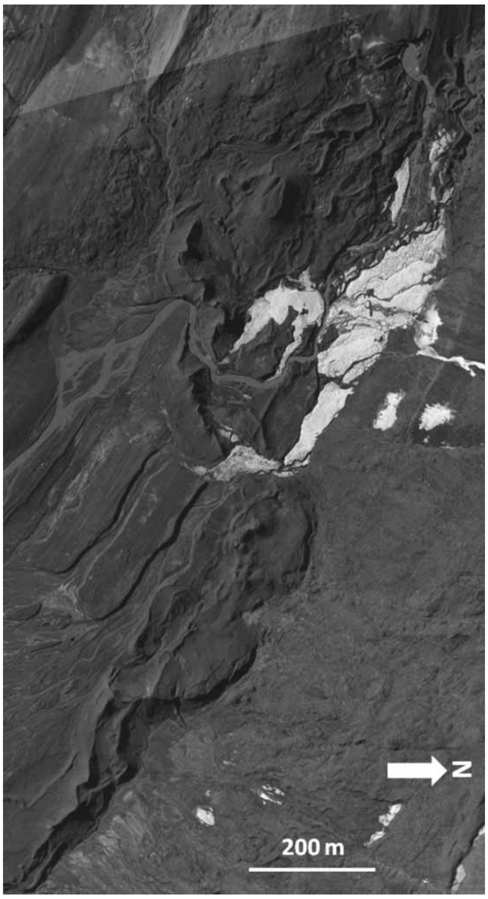

Figure 4. Aerial photograph extract (2009) of the main esker drainage network on the east side of the Hørbyebreen snout, concentrating on the present glacier margin (top) and the occurrence of a braided esker system at the glacier margin which grades down-valley into a simple, single ridge esker. More localized linear ridge segments document crevasse infill due to meltwater leakage from esker tunnels. Centre of image is at 530200/874300.

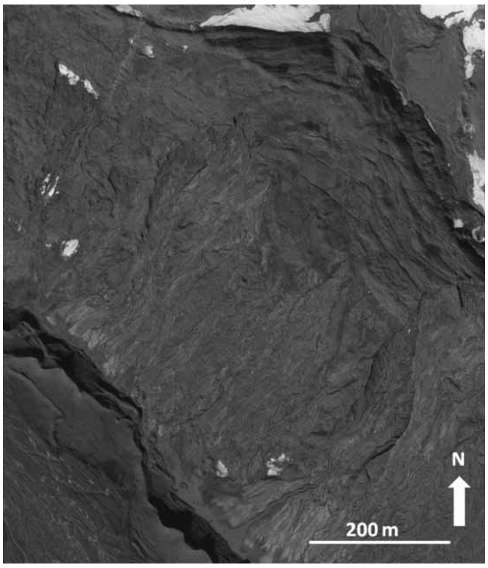

Figure 5. Aerial photograph extract (2009) of the ice-cored moraine belt on the east side of Hørbyebreen, showing controlled ridges and melt-out hollows at the top of the image grading into areas of tension cracks and retrogressive flows on the lower slopes. The main esker ridge of the east margin is visible at the bottom of the image. Centre of image is at 531000/874300.

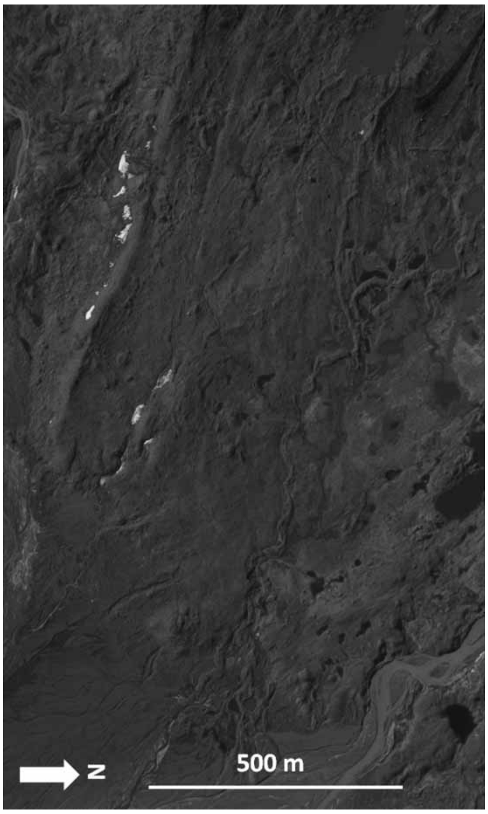

Figure 6. Aerial photograph extract (2009) of controlled ridges, eskers and crevasse fill ridges on the outer ice-cored moraine of Hørbyebreen, where melt-out is at an advanced stage. The prominent ridge towards the left of the image is the former medial moraine between Hørbyebreen and Svenbreen; therefore the eskers at the top left of the image are from Svenbreen drainage. Centre of image is at 531250/874050.

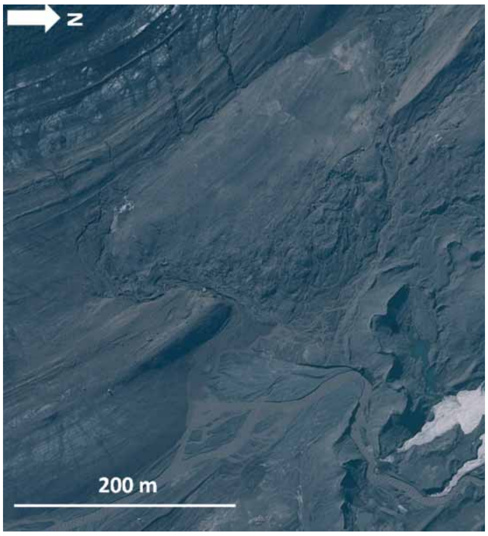

Figure 7. Aerial photograph extract (2009) of fluted subglacial till surface emerging from the downwasting snout of Hørbyebreen. Note that the subglacial flutings are less prominent than the strong lineation created by supraglacial debris stripes. Eskers are emerging from the more contracted margin of the east side of the snout at the top right of the image. Centre of image is at 529800/874280.

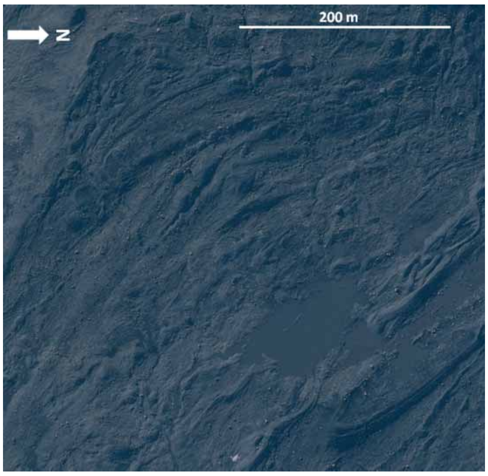

Figure 8. Aerial photograph extract (2009) of the controlled moraine and supraglacial debris stripes on the SW margin of the Hørbyebreen foreland. Esker ridges also occur at the bottom of the image and lie just inside the medial moraine (dark coloured prominent ridge complex) between the main Hørbyebreen trunk ice and the ice debouching from two unnamed cirque glaciers on the west margin of the valley. Centre of image is at 530500/874050.

The branching of linear eskers from a prominent large sinuous esker network indicates that a regular subglacial drainage system was in operation when meltwater and sediment was siphoned off to adjacent crevasses. This suggests a phase of elevated discharge and diversion of meltwater and sediment into the crevasses created by an increasingly fractured snout. Some of the linear esker ridges, as well as some debris ridges, could represent hydrofracture fills similar to those produced during dewatering of the snout of Skeiðararjökull during the *jökulhlaup* of 1996, as described by Roberts, Russell, Tweed, and Knudsen (2000, 2001) and Bennett, Huddart, and Waller (2000). The linear esker and debris ridge assemblages on the Hørbyebreen foreland resemble the ‘geometrical ridge networks’ of Bennett, Hambrey, Huddart, and Ghienne (1996), which are interpreted as superimposed longitudinal and transverse debris accumulations produced by separate processes but appearing to be cross-cut after melt-out. This explanation does not appear to be applicable to the Hørbyebreen examples, because the linear debris ridges do not parallel the longitudinal debris stripes melting out of the enclosing ice.

Engorged eskers are very short (<50 m long), sinuous ridges presently developing in tunnels in the ice-cored moraine and orientated at right angles to valley slope due to the gravity-driven drainage of water melting from the buried ice. Such features are common in ice-cored moraine arcs on the forelands of both polythermal and surging glaciers (Evans, Twigg, Rea, & Orton, 2009a; Evans, Twigg, & Orton, 2010) but have been only rarely identified in the ancient landform record where they are often termed ‘valley eskers’ (e.g. Bird, 1967; Mannerfelt, 1945). Further research on these landforms is warranted, especially as they appear to be closely associated with, and therefore potentially diagnostic of, debris-rich glacier snouts in valley settings.

4. Glacial landsystem classification

Recent identification of modern glacial landsystem analogues for palaeoglaciological reconstruction has demonstrated that dominant landform–sediment assemblages indicative of specific styles of glaciation (e.g. ice stream, surge-type, active temperate, plateau icefield, etc.; Benn & Evans, 2010; Evans, 2003, 2006, 2007) often contain sub-ordinate landsystem signatures (e.g. sporadic surging during active temperate recession; Evans & Twigg, 2002) or are overprinted or sequentially replaced (‘intrazonal landsystem change’; Evans, in press) due to spatial and/or temporal changes in glacier dynamics (e.g. Evans, 2011; Evans et al., 2010; Krüger, 1994). Such overprinting and intrazonal change has been identified also in ancient glacial landform records (e.g. Benn, Kirkbride, Owen, & Brazier, 2003; Colgan, Mickelson, & Cutler, 2003; Dyke, Morris, Green, & England, 1992; Evans, 2009; Evans, Clark, & Rea, 2008; Evans, Livingstone, Vieli, & Ó Cofaigh, 2009b; Livingstone, Ó Cofaigh, & Evans, 2008; Ó Cofaigh, Evans, & Smith, 2010; Wilson & Evans, 2000), demonstrating that landsystems have the potential to inform our reconstructions of the complexities of temporal and spatial evolution of ice sheets and glaciers. The landforms on modern Svalbard glacier forelands have been used, somewhat controversially, as analogues for polythermal palaeoglaciers in locations such as upland Britain during the Younger Dryas (cf. Bennett et al., 1998; Evans, 2009; Graham & Midgley, 2000; Graham, Bennett, Glasser, Hambrey, Huddart, & Midgley, 2007; Hambrey et al., 1997; Lukas, 2005, 2007; Wilson & Evans, 2000), although the controversy is centred more on the process of debris entrainment than on the landsystem signature of polythermal glaciation. The latter is particularly consistently well developed on Svalbard (Glasser & Hambrey, 2003), but the other prominent style of glacier behaviour on the archipelago, that of surging, gives rise to a very conspicuous landsystem of its own, especially in tidewater systems (e.g. Bennett et al., 1996; Glasser, Hambrey, Crawford, Bennett, & Huddart, 1998; Kristensen, Benn, Hormes, A., & Ottesen, 2009; Ottesen & Dowdeswell, 2006; Ottesen et al., 2008). The impact of surging on landform development in the polythermal valley and extended cirque glaciers may be more difficult to decipher; it likely accounts for at least some of the great complexity in debris entrainment patterns observed in the receding snouts over the last few decades. Short timescale changes in the dynamics of Svalbard valley glaciers have been identified by Glasser and Hambrey (2001) and Hambrey et al. (2005), verifying that landsystem overprinting and intrazonal change may well be a characteristic of these glacial systems.

4.1. *Polythermal glacial landsystem*

Former glacier beds characterized by well-developed subglacial bedforms, such as flutings and eskers, lying up-valley from controlled moraine or ice-cored moraines, have been widely used to infer the existence of temperate or warm-based conditions giving way to a frozen snout zone (Dyke & Evans, 2003; Dyke & Savelle, 2000; Evans, 2009, 2011; Evans, Twigg, & Shand, 2006; Evans et al., 2010; Glasser & Hambrey, 2001, 2003; Hambrey, Bennett, Dowdeswell, Glasser, & Huddart, 1999). Such polythermal conditions are common in Svalbard glaciers and give rise to the typical landform assemblage seen of the forelands of Hørbyebreen, Svenbreen and Ferdinandbreen, where large volumes of debris have been frozen on at the warm–cold-based transition zone in the glacier snout. However, the fast flow and accelerated rates of sub-marginal debris entrainment proposed for surging glaciers (Clapperton, 1975; Humphrey & Raymond, 1994; Sharp, Jouzel, Hubbard, & Lawson 1994), could potentially give rise to a similar landsystem signature. Therefore it is important that we begin to develop a conceptual landsystems model for the intermittently surging polythermal glaciers of Svalbard. Similar historical changes in glacier dynamics have been recognized in the landsystem signatures of some Icelandic glaciers; particularly pertinent in this respect is the foreland of Satujökull, on the northern margin of Hofsjökull (Evans, 2011; Evans et al., 2010), where ice-cored moraine arcs and flutings indicative of Little Ice Age advance limits lie beyond two inset sequences of surge-related landforms. A non-surge origin for the ice-cored moraine in such settings is inferred, because the constituent debris is emerging as controlled moraine ridges fed directly by extensive, snout-wide debris-rich foliae that resemble regelation ice. Nevertheless, similar marginal accumulations of debris have been associated with surging by Hambrey, Dowdeswell, Murray, and Porter (1996), Murray, Gooch, and Stuart (1997) and Glasser et al. (1998).

4.2. *Surge signatures*

Diagnostic geomorphological criteria for former glacier surging are summarized in the surge-type glacier landsystem by Evans and Rea (2003). Few of these criteria are visible at Hørbyebreen, being potentially present in the linear esker ridges and crevasse fill landforms, which record deposition into a rectilinear pattern of ice fractures. In the surge landsystem, the emplacement of sediments into crevasse networks is manifest as zig-zag eskers and basal crevasse-squeeze ridges, whose orientations conform to the fracture patterns created in the glacier snout during its surge phase (Rea & Evans, 2011). However, the lack of distortion of the longitudinal debris stripes and their apparent dominance over the transverse ridges, is incompatible with a former surge, because flow lineations of this sort would have been compressed to produce 'looped medial moraines'. Additionally, the transverse ridges do not cross cut the longitudinal debris stripes, but are emerging instead from areas of lower relief on the downwasting snout, indicating that they were emplaced in the basal ice facies and their enclosing crevasses did not extend to the glacier surface. This pattern of emplacement and its implications for the lack of full depth crevassing, suggest that the emplacement of the transverse ridges could have been by hydrofracture networks induced by elevated meltwater pressures and the overwhelming of the normal englacial and subglacial drainage tunnels. This could have taken place in the absence of a surge, as documented at Skeiðarárjökull during the 1996 *jökulhlaup* (Bennett et al., 2000; Roberts et al., 2000, 2001), whereby a catastrophic subglacial drainage event initiated in the warm-based part of the glacier was blocked by the frozen toe of the snout and forced to escape along pre-existing fractures in the ice. Whether or not this was related to the surge of Hørbyebreen reported by Karczewski (1989) and Gibas et al. (2005) is unknown.

5. Conclusions

The surficial geology and geomorphology map of the forefields of the Hørbyebreen, Svenbreen and Ferdinandbreen polythermal valley glaciers reveals a glacial landsystem comprising ice-cored latero-frontal moraine arcs, constructed during the Little Ice Age maximum, that grade up-valley into fluted till surfaces draped by supraglacially-derived longitudinal debris stripes. Such landform associations have been widely associated with polythermal glacier characteristics, but on the Hørbyebreen foreland the additional occurrence of linear esker and debris ridges arranged in a geometric ridge network are thought to be related to the infilling of densely spaced crevasses, created during a period of elevated meltwater pressures and ice hydrofracturing. A smaller area of such forms occurs also on the Svenbreen foreland. Whether these were associated with a *jökulhlaup* that was blocked by the frozen snout or with an historical surge is unknown, but nonetheless, the landform assemblage depicted in our map constitutes an important modern landsystems analogue for palaeoglaciological reconstruction. In this respect, it is an analogue for either: (1) spatial and temporal landsystem overprinting (polythermal and surging activity); or (2) a more refined polythermal landsystem in which the build up and release of meltwater reservoirs in warm-based interiors of polythermal glaciers give rise to a particularly diagnostic landform at the up-ice junction with the cold-based snout. This is of course not entirely unrelated to surge initiation mechanisms.

Acknowledgements

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