# Dead-Ice Under Different Climate Conditions: Processes, Landforms, Sediments and Melt Rates in Iceland and Svalbard

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# Dead-ice under different climate conditions: processes, landforms, sediments and melt rates in Iceland and Svalbard

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Abstract

Modern dead-ice environments in the glacier forefields of Brúarjökull, Iceland and Holmströmbreen, Svalbard were investigated with focus on landform and sediment genesis, as well as quantification of melting. Field monitoring and studies of multi-temporal aerial photographs, satellite imagery, and Digital Elevation Models (DEMs) provided data for the melting quantification. Sedimentological and geomorphological data were achieved through field investigations and image analyses.

Different measures for dead-ice melting (backwasting, downwasting, ice-walled lake area, glacier retreat and thinning) are assessed in relation to local air temperature data going back to the beginning of the instrumental period.

A geomorphological map in scale 1:16 000 of the forefield of the surge-type glacier Brúarjökull was produced through digital aerial photograph interpretation and high-resolution DEM analyses. The map was used for the interpretation of landforms and sediments, and provided an overview of the surging glacier landsystem at Brúarjökull.

A conceptual model for the formation of transitional-state ice-cored landforms – ice-cored drumlins – was also constructed, based on the research in the Brúarjökull forefield. After a complete melting, the model proposes that such drumlins will disintegrate into patches of hummocky dead-ice moraine.

Three years of fieldwork combined with analyses of multi-temporal DEMs and aerial photographs revealed that multiple generations of ice-cored moraines are currently exposed to melting at Brúarjökull. Quantifying the melting progression suggests that in the current climate, a complete de-icing of ice-cored landforms is not likely to occur. Some dead-ice bodies are recycled into new ice-cored landforms, because the total melt-out time exceeds the duration of the quiescent period in the surge cycles. Long-term surface lowering due to dead-ice melting takes place with a rate of *c*. 0.10-0.18 m/yr.

At the stagnant snout of Holmströmbreen, an extensive dead-ice area with ice-cored moraines, eskers and kames has developed since the Little Ice Age glacial maximum. Backwasting of ice-cored slopes and mass-movement processes continuously expose new dead-ice and prevents the build-up of an insulating debris-cover. Currently dead-ice melting progresses with a long-term surface lowering rate of *c*. 0.9 m/yr. The most prominent impact of dead-ice melting is the development of an extensive ice-walled, moraine-dammed lake receiving sediment from the adjacent slopes.

Based on a literature review and the results presented here, dead-ice melting in different climatic settings is discussed, with focus on melt rates and sediment-landform genesis. Because identical processes operate with similar rates in different climates, dead-ice deposits provide little information on the climate at the time of deposition. The glaciodynamic significance of dead-ice deposits is that of stagnation of debris-covered glaciers.



Key words: Dead-ice, ice-cored, glacier surge, Little Ice Age, Brúarjökull, Iceland, Holmströmbreen, Svalbard

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This thesis is based on four papers listed below (Appendices I-IV). All papers are published in or submitted to peer-reviewed international journals. Papers I and IV have been submitted to the journals indicated and are under consideration for publication. Papers II and III are reproduced with permission from John Wiley & Sons, Ltd. and Taylor & Francis AS, respectively. In the following, the papers are referred to by their Roman numeral.

**Appendix I**
Kjær, K.H., Korsgaard, N.J. & Schomacker, A. Impact of multiple glacier surges - a geomorphological map from Brúarjökull, East Iceland. Manuscript submitted to *Journal of Maps*. With one map sheet (in the book cover).

**Appendix II**
Schomacker, A., Krüger, J. & Kjær, K.H. 2006. Ice-cored drumlins at the surge-type glacier Brúarjökull, Iceland: a transitional-state landform. *Journal of Quaternary Science 21*, 85-93.

**Appendix III**
Schomacker, A. & Kjær, K.H. 2007. Origin and de-icing of multiple generations of ice-cored moraines at Brúarjökull, Iceland. *Boreas 36*, in press.

**Appendix IV**
Schomacker, A. & Kjær, K.H. Quantification of dead-ice melting in ice-cored moraines at the high-Arctic glacier Holmströmbreen, Svalbard. Manuscript submitted to *Boreas*.

# Contents

## Preface and acknowledgements

This thesis results from four years of research during which the author was employed at the Department of Geology, Lund University. Initially, field investigations were planned to take place in Iceland, Svalbard, and Siberia but during the progress of the project, focus was directed towards dead-ice environments in Iceland and Svalbard. Stays in other glaciated areas in North Greenland, Scandinavia, and Tierra del Fuego, however, served as sources of inspiration.

First of all, I want to thank my main supervisor Kurt H. Kjær for his continuous and enthusiastic support and interest in my work during the last four years. Johannes Krüger is also acknowledged for highly qualified supervision and for initially awaking my interest for glacial geology. Per Möller, Ólafur Ingólfsson, and Lars Eklundh are thanked for supervising and discussing different parts of this work.

I had the pleasure to spend the summers of 2003-2006 in the field together with numerous enthusiastic colleagues. Without their great company and support, this research would not have been possible. In addition to my supervisors, I am especially indebted to the following individuals: Ívar Örn Benediktsson, Carita G. Knudsen, Eiliv Larsen, Silvana Correa, Svante Björck, Jaap J. M. van der Meer, Rasmus Haugaard Nielsen, Svend Funder, Nicolaj K. Larsen, and Henriette C. Linge.

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Aerial photographs and digital elevation models from Svalbard appear in several figures in this thesis. The Norwegian Polar Institute kindly permitted publication of these data.

My deepest thanks go to my family and close friends. I am grateful for your never-ending care, interest, and support over the last years.

## 1. Introduction

### *1.1 Background*

Dead-ice is stagnant glacial ice where movements by glacier flow have ceased (e.g. Benn & Evans, 1998; Evans, 2003). Most commonly, it occurs as stagnant, debris-covered glacier snouts (e.g. Sharp, 1949; Clayton, 1964; Boulton, 1972; Eyles, 1979; Kirkbride, 1993; Lyså & Lønne; 2001; Lønne & Lyså, 2005; Paper IV; Fig. 1A-B), in ice-cored landforms (e.g. Pickard, 1984; Krüger & Kjær, 2000; Kjær & Krüger, 2001; Spedding & Evans, 2002; Evans & Rea, 2003; Papers II-III; Fig. 1C-E), and as remnants of Pleistocene glacial ice preserved in permafrost areas (e.g. Astakhov & Isayeva, 1988; Ingólfsson & Lokrantz, 2003; Lokrantz *et al.*, 2004; Murton *et al.*, 2005).

Whenever glaciers experience negative mass balance and a significant debris cover accumulates on the surface of the marginal zone, dead-ice may form. Surge-type glaciers may also produce

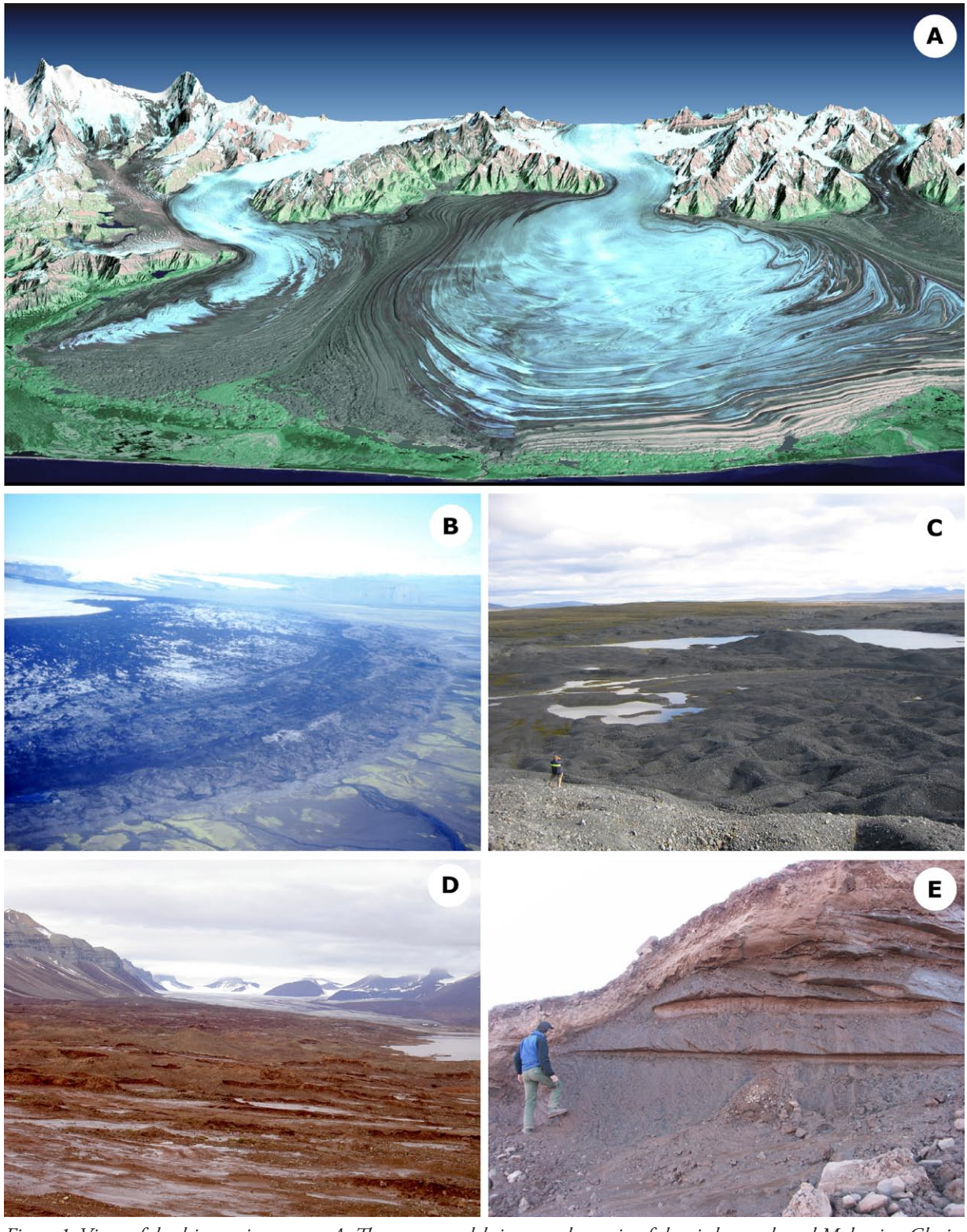


*Figure 1. Views of dead-ice environments. A. The stagnant, debris-covered margin of the piedmont shaped Malaspina Glacier in Alaska, USA seen towards North. Note the pitted topography in the marginal zone. False-color Landsat 7 satellite image recorded on August 31st 2000 draped on a DEM. The glacier lobe has a length of c. 30 km. Imagery from NASA, USA. B. The stagnant margin of the piedmont shaped Kötlujökull in South Iceland. Dead-ice occurs in the grey zone of ice-cored and dead-ice moraines surrounding the margin. Mid-August 2001. C. Hummocky ice-cored moraines produced by the 1963-64 surge of Brúarjökull, Iceland. For further descriptions see Papers I-III. August 25th 2003. D. Ice-cored moraines at Holmströmbreen, Svalbard. Sediment gravity flows transport debris from the ice-cored slopes towards the ice-walled lake in the background. In the far distance, 6 km from the photographer, the clean glacier margin is visible. Mid-July 2004. For further description see Paper IV. Photographer: J. Krüger. E. Close-up of dead-ice with debris bands and a mantle of melt-out till. Holmströmbreen, July 7th 2004. Photographer: K. H. Kjær. For further description see Paper IV.*

debris-charged dead-ice masses when the surge ceases and the glacier enters its quiescent phase (e.g. Clapperton, 1975; Johnson 1992). Supraglacial debris accumulations originate from different sediment sources, such as thrusting of subglacial material (Huddart & Hambrey, 1996; Hambrey *et al.*, 1999; Krüger & Aber, 1999, Glasser & Hambrey, 2002), melt-out of englacial debris bands (Sharp, 1949; Boulton, 1970b, 1971; Kirkbride & Spedding, 1996; Hambrey *et al.*, 1999), channel-, and tunnel-fill material (Fitzsimons, 1991; Kirkbride & Spedding, 1996; Vatne, 2001), crevasse-squeezing of subglacial sediment (Johnson, 1975; Sharp, 1985a, 1985b), rockfall and avalanching from mountain sides and nunataks (André, 1990; Hambrey *et al.*, 1999; Glasser & Hambrey, 2002), meltwater bursts through the crevasse and conduit system (Näslund & Hassinen, 1996; Krüger & Aber, 1999; Russell & Knudsen, 1999; Roberts *et al.*, 2000) or aeolian deposition directly on the glacier surface (Kirkbride, 1995; Krüger & Aber, 1999; Adhikary *et al.*, 2000; Kjær *et al.*, 2004). Hence, the nature of debris cover on dead-ice reflects both the initial sediment source and any subsequent modification by resedimentation in the dead-ice environment.

In dead-ice environments, debris-cover is exposed to cycles of resedimentation processes due to melting of buried ice before a final product is left in the geological record. By far the most important processes are mass movements governed by gravity (Sharp, 1949; Boulton, 1968, 1970a, 1971, 1972; Lawson, 1979, 1982, Krüger, 1994; Kjær & Krüger, 2001; Lyså & Lønne, 2001; Lukas *et al.*, 2005; Lønne & Lyså, 2005). Water plays an important role through the liquefaction and, thus, reduction of the shear strength of the debris-cover (Lawson, 1979, 1982; Krüger, 1994; Benn & Evans, 1998; Paper IV). Localized melting of dead-ice may cause collapse of the overlying debris cover, resulting in sinkhole formation (Clayton, 1964; Johnson, 1971, 1992; Krüger, 1994; Evans & Rea, 2003). More rarely other surface processes – for example removal of fines by the wind – may alter the debris cover (Lawson, 1979).

The geomorphological and sedimentological products of dead-ice melting has been studied in modern glacial environments as well as reconstructed from landforms and sediments in past glacial environments. Numerous depositional models based on investigations at modern glaciers suggest that the product of wasting of debris-covered dead-ice is hummocky dead-ice moraines (e.g. Boulton, 1972; Boulton & Eyles, 1979; Eyles, 1979, 1983; Krüger, 1994; Bennett *et al.*, 1996; Hambrey *et al.*, 1997; Kjær & Krüger, 2001; Spedding & Evans, 2002; Glasser & Hambrey, 2003). Accordingly, vast areas of hummocky moraine at Pleistocene ice sheet margins have been interpreted as formed by wasting of stagnant, debris-covered dead-ice (e.g. Smed, 1962; Clayton & Moran, 1974; Krüger, 1983; Benn, 1992; Johnson *et al.*, 1995; Ham & Attig, 1996; Eyles *et al.*, 1999, Boone & Eyles, 2001; Johnson & Clayton, 2003; Knudsen *et al.*, 2006).

Despite the numerous conceptual process-sediment-landform models for the melt-out of dead-ice bodies as well as the easy accessibility to dead-ice environments at modern glacier margins, few quantitative studies of dead-ice melting have been carried out (e.g. Østrem, 1959; Pickard, 1984; Syverson & Mickelson, 1995; Etzelmüller, 2000; Krüger & Kjær, 2000; Bennett *et al.*, 2000; Nicholson & Benn, 2006; D'Agata & Zanutta, 2007; Papers III-IV). Hence, in this thesis, a quantitative approach is taken to studies of dead-ice environments in the field and from multi-temporal aerial photographs and satellite imagery. Recent advances in remote sensing, an increasing number of satellites, and digital aerial photograph processing techniques provide new methods and data to monitor and quantify geomorphological processes such as dead-ice melting. At Brúarjökull, focus is directed towards dead-ice melting of multiple generations of dead-ice in a glacier forefield where several glacier surges have superimposed landforms on older surfaces. At Holmströmbreen, dead-ice originates from one glacier advance in the Little Ice

Age. Studies of dead-ice environments are currently attractive because many glaciers experience negative mass balances and stagnation (e.g. Oerlemans, 2005; Knight, 2006; D'Agata & Zanutta, 2007). This may increase the occurrence of dead-ice areas.

### 1.2 Research aims

The aim of this study is to identify and quantify processes of dead-ice melting in modern glacial environments using remote sensing and field based techniques. It might be expected that different processes and melt rates operate in different climates, and in order to explore this, two sites with different climate conditions were selected. The Brúarjökull glacier in Iceland was selected for its moderate annual precipitation and mean annual air temperatures around 0°C, whereas Holmströmbreen, Svalbard was selected for its semi-arid conditions with mean annual air temperatures around -5°C and continuous permafrost. Furthermore, sediments and landforms formed in dead-ice environments are described and their depositional processes are interpreted.

A key objective for process-sediment-landform studies in modern glacial environments is also to provide analogue models for formerly glaciated areas. Ultimately, results from this study might support reconstructions of landforming processes and rates, and climate from past dead-ice environments at the time of deposition. Observations from modern dead-ice areas under different climate conditions may facilitate the deciphering of depositional environments for ancient dead-ice deposits.

## 2. Study areas

Fieldwork was undertaken in dead-ice areas in two glacier forefields: Brúarjökull, Iceland and Holmströmbreen, Svalbard (Fig. 2). The main study area was at Brúarjökull where three summer field seasons were spent (2003-05). At Holmströmbreen, fieldwork was carried out during a four-week summer field campaign in 2004.

### 2.1 Brúarjökull, Iceland

The surge-type glacier Brúarjökull is the largest northern lobate extension of the Vatnajökull ice cap. It descends from 1500 to 600 m a.s.l., terminating with a 55 km long glacier margin (Björnsson *et al.*, 1998; Fig. 3). The forefield is glacially streamlined with widely spaced and elongated bedrock hills culminating at 700-750 m a.s.l. The most prominent features of the surging lowland-glacier landsystem in front of Brúarjökull are thrust-block and push end moraines, crevasse-squeeze ridges, eskers, flutings, ice-cored landforms, and patches of ice-free hummocky moraine. The rivers Kringilsá and Jökulsá á Brú drain meltwater from Brúarjökull through broad channels and canyons. Brúarjökull surged in 1963-64, 1890, 1810, ~1775, ~1730, and in 1625 (Thorarinsson, 1964, 1969; Björnsson *et al.*, 2003). During the 1890 surge the glacier advanced 10 km, and in the 1963-64 surge the maximum advance was 8 km (Thorarinsson, 1969). At present, the glacier snout is inactive and partly covered by a thin layer of sediments from the disintegration of emerging crevasse-squeeze ridges and debris bands in the ice (Kjær *et al.*, 2006). In topographic depressions the thin glacier snout is overlain by glaciolacustrine sediment bodies and minor ice-contact fans.

Automated measurements of air and ground temperatures and precipitation give a mean annual air temperature of -0.3˚C and a mean annual precipitation of 643 mm in the period August 2003 – August 2005. The ablation period lasts from mid-April to mid-September. The melting season for dead-ice bodies with a debris cover thickness of *c.* 1.3 m is, however, limited to the period from the beginning of August to mid-October. van Vliet-Lanoë *et al.* (1998) and Etzelmüller *et al.* (2007) suggested that permafrost occur in the Brúarjökull area, and patches of permafrost were also observed in the glacier forefield during the fieldwork for this study.

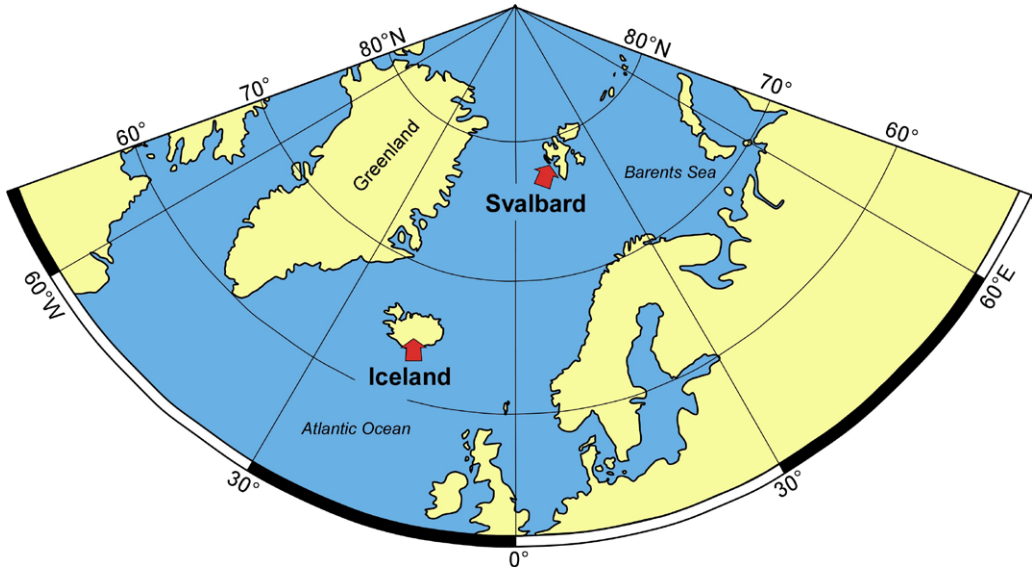


*Figure 2. Location of the main study areas: Iceland and Svalbard.*

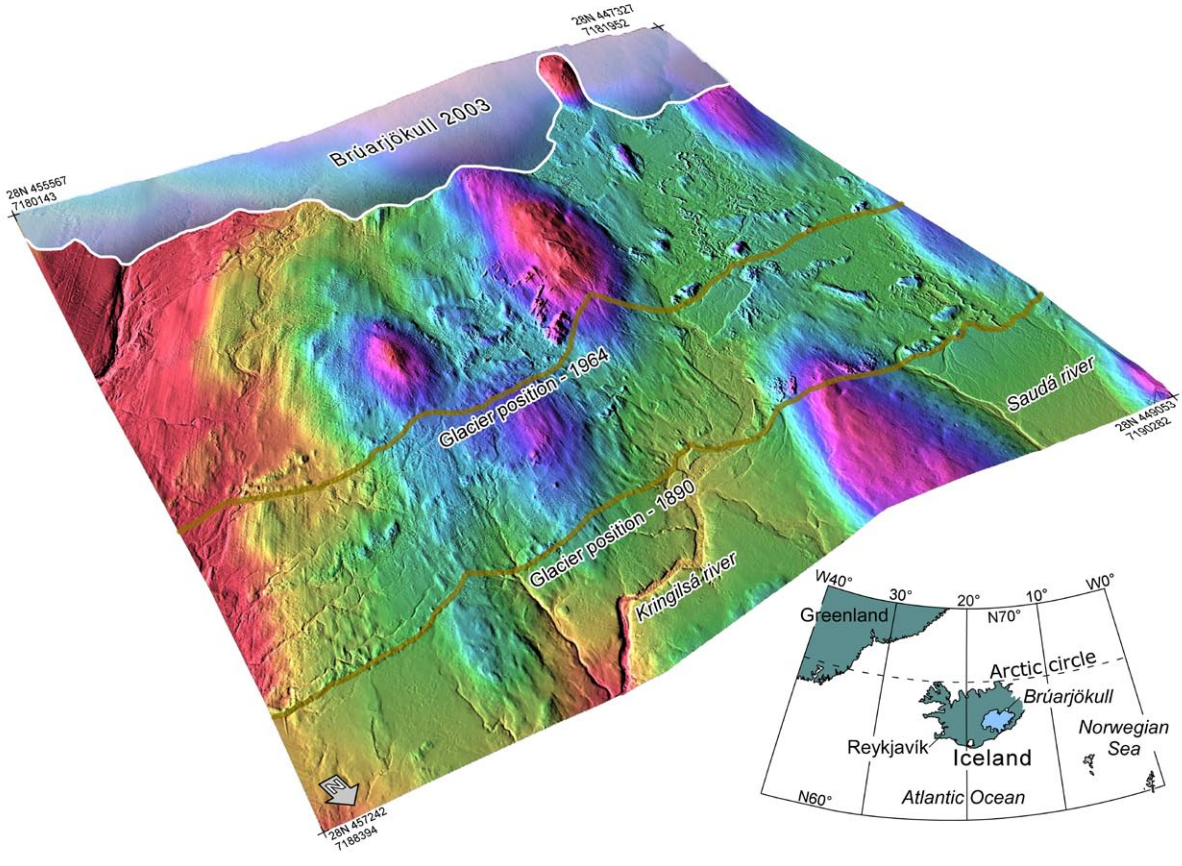


*Figure 3. The forefield of the surge-type glacier Brúarjökull, eastern Iceland. Terrain Shade Relief (TSR) model draped over a DEM (3 m grid). Ice-marginal positions at the last two surge maxima are indicated. Map projection and datum: UTM 28N, WGS 84. Modified after Kjær et al. (2006).*

### 2.2 Holmströmbreen, Svalbard

Holmströmbreen is a 28-km long glacier draining the Holtedahlfonna ice cap on central Spitsbergen, Svalbard. It descends from *c*. 1100 to 20 m a.s.l. terminating as a *c*. 5.5 km wide glacier tongue confluent with the Morabreen and Orsabreen glaciers (Hagen *et al*., 1993; Fig. 4). The climate in the terminus area is characterized by continuous permafrost and low annual precipitation with a mean around 200 mm. At sea level, the mean annual air temperature is *c*. -5 °C (Førland *et al*., 1997; Humlum *et al*., 2003; Humlum, 2005). The ablation period on central Spitsbergen lasts approximately from June to mid-September (Nordli *et al*., 1996; Førland *et al*., 1997; Hagen *et al*., 2003a,b).

The bedrock in the catchment area of Holmströmbreen consists of characteristic 'Old Red' Devonian sandstones, siltstones, conglomerates, and shales (Hjelle, 1993; Harland, 1997). Ice-cored moraines are located between a prominent 50 m high arcuate push moraine and the clean glacier margin. The moraine-dammed 'Lake Emmy', 14 $km^2$ in size, is located within the ice-cored area. Currently, meltwater from Holmströmbreen is evacuated across tidal mudflats to Ekmanfjorden mainly by Red River which has eroded a deep gully through the eastern part of the marginal deposits.

No direct evidence exists of the timing and magnitude of the last advance of Holmströmbreen. However, a series of photographs from around AD 1900 demonstrates that Holmströmbreen had its margin at the proximal part of the push moraine (van der Meer, 2004). This suggests that Holmströmbreen advanced to its maximum neoglacial position during the Little Ice Age similar to many glaciers in Svalbard (Croot, 1988; Hagen & Liestøl, 1990; Hagen *et al*., 1993, 2003a,b; Humlum *et al*., 2005; Lønne & Lyså, 2005; Mangerud & Landvik, 2007). Looped lateral and medial moraines detached from the margins of tributary glaciers as well as the large push moraine complex suggest that the last advance of Holmströmbreen was a surge (Meier & Post, 1969; Croot, 1988; Hart & Watts, 1997; Boulton *et al*., 1999).

## 3. Methods

### 3.1 Geomorphological mapping

It appears from Papers I-IV that during this study, the method of geomorphological mapping was continuously developed and refined. Paper II was written in 2003-04 and represents a first attempt to map a part of the Brúarjökull forefield. The maps (Fig. 4 in Paper II) were based on interpretation of aerial photographs and verification in the field. However, the mapping was performed on raw imagery and not on orthorectified photographs. Production of these maps was carried out in software designed for preparation of illustrations (Canvas 9 and Canvas X).

During 2004-05, all aerial photographs from Brúarjökull were transferred to a Digital Photogrammetric Workstation (DPW). On the DPW, image pairs can be viewed in stereo directly on a monitor, when the user wears special polarizing 'glasses'. The DPW allows digital zooming to a very high level which greatly improved the interpretation process and the completeness of maps compared to traditional mapping. Mapping was done subsequent to DEM and orthophotograph production which ensured true coordinates on all mapped objects (Section 3.2). In the stereoscopic view mode, map objects were digitized and saved into feature databases. After completion of the mapping on the DPW, all feature classes were exported as shape files for further handling in a Geographical Information System (GIS). The mapping procedure on the DPW proved very successful, resulting in a geomorphological map with high completeness which may be customized and used for further analyses and presentation purposes (Paper I). Field verification of the map was carried out during three field seasons in the Brúarjökull forefield. The older

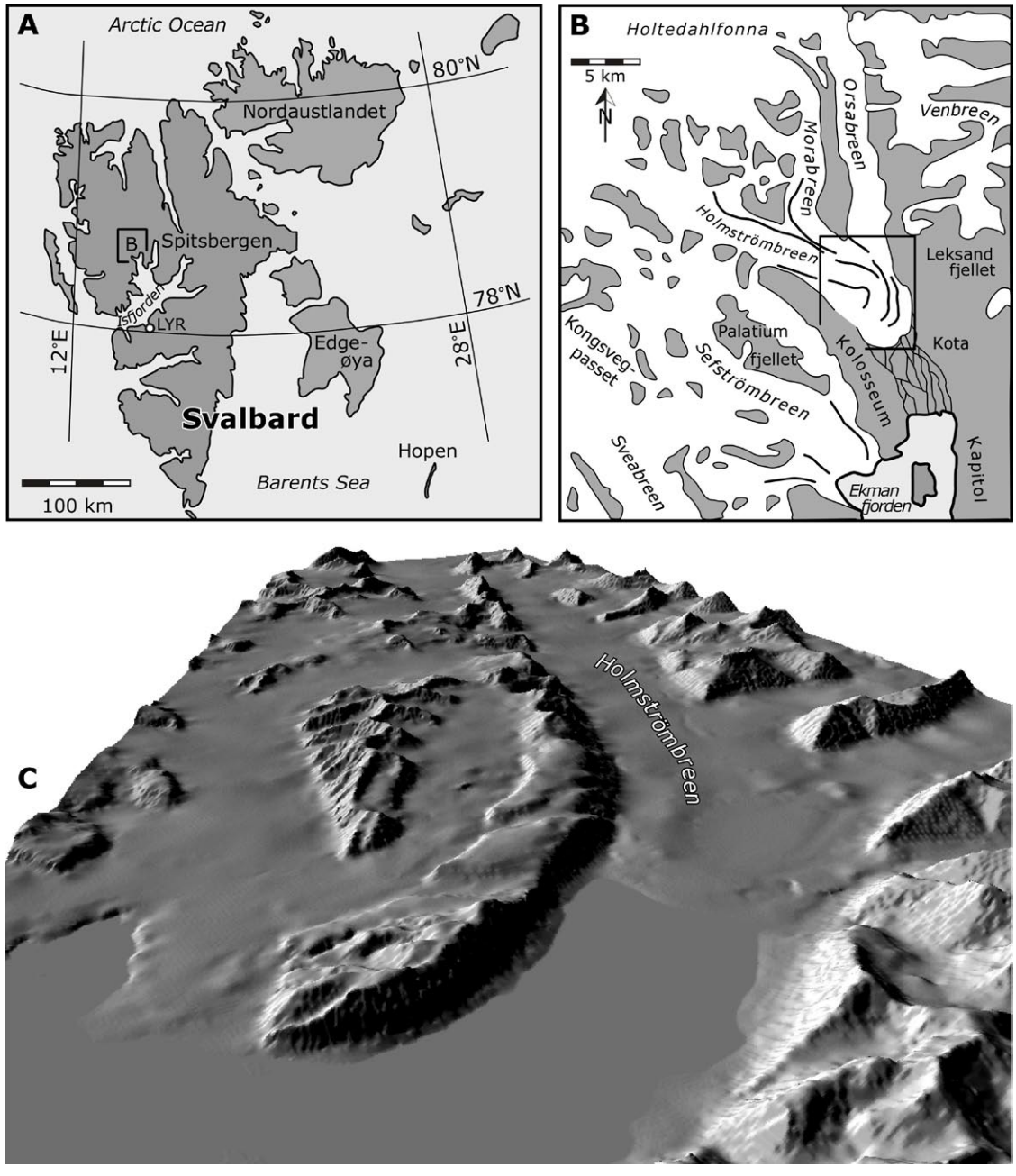


*Figure 4. A. Location of Holmströmbreen, the Svalbard archipelago. B. Map of Holmströmbreen and its tributary glaciers. C. TSR model draped over a DEM (20 m grid). View towards Northwest with 1.25× vertical exaggeration. © The Norwegian Polar Institute.*

aerial photograph series were also studied on the DPW, selected landforms were mapped (e.g. ice-cored landforms, ice-marginal positions), and image series were prepared for DEM production for each year of photography (Paper III; Section 3.2).

Time series of aerial photographs of Holmströmbreen were also used for producing the maps in Paper IV. As a new data source, QuickBird 2 satellite imagery of Holmströmbreen was recorded and included in the analyses. Because precise Ground Control Points (GCPs) were not measured in the field, DEMs could not be produced from the aerial photographs. Instead, the QuickBird 2 imagery and all vertical aerial photographs were rectified

and geocoded using the official DEM of Svalbard (Section 3.2). The geomorphological mapping was performed in a GIS using the QuickBird 2 imagery as a base. Contemporaneous stereoscopic interpretation of analogue vertical aerial photographs supported the satellite image interpretation. Both panchromatic and multispectral QuickBird 2 data were analyzed. The multispectral data contains 4 bands: red, green, blue, and infrared. Different band combinations and contrast stretching were explored during the mapping process in order to fully exploit the spectral and geometric resolution of the data.

The quality of the maps produced by the latter procedure is also high (Paper IV). However, more exact geocoding and orthorectification could have been achieved if precise GCPs had been available. In addition, this could have provided the possibility to produce multi-temporal DEMs and perform the mapping in stereo view mode on the DPW similarly to the method used in Papers I and III.

### 3.2 Digital Elevation Model (DEM) production

During this study, multi-temporal DEMs of the Brúarjökull forefield were produced by digital aerial stereophotogrammetry (Boberg, 2004; Geoforum, 2004). From Holmströmbreen, an official DEM (20 m grid) of the area was obtained from the Norwegian Polar Institute.

DEMs of the Brúarjökull forefield were produced from blocks of aerial photographs recorded in 1945, 1964, 1988, and 2003 (Fig. 5). Calibration reports gave information about the focal length, distortion, and interior orientation of the cameras. An airborne GPS-log of camera lens coordinates and the heading, pitch and roll of the aircraft at the time of photography was delivered with the 2003 images providing a first-order geocoding of the images. The overlap between pairs in a strip of aerial photographs was used to create stereo models of the area. GCPs collected with GPS in the field as well as aerotriangulation of a point network levelled with a TopCon GTS-226 total station provided the base for absolute orientation of the stereo models into UTM WGS84 coordinates. Using time-homologous GCPs and tie points, DEMs were automatically generated from the stereo models.

After DEM production, the raw frame imagery was orthorectified using the orientation parameters and the DEM. The orthophotographs have no distortion and can be directly used for mapping and navigation.

All stages of the DEM and orthophoto production were carried out on the DPW. The DPW was run with the SocetSet software package from BAE Systems (BAE Systems, 2004). After production completion at the DPW, data were exported and handled in a GIS. Analyses of multi-temporal DEMs in GIS were used to quantify surface lowering caused by dead-ice melting (Paper III).

One elevation model was produced by ordinary Kriging interpolation in ArcGIS (Fig. 4 in Paper III). This is because the input data were derived from leveling in the field with the TopCon GTS-226 instrument giving a more accurate elevation model of that specific area than available from stereophotogrammetry.

### 3.3 Field surveying of transects and points

All transects and points presented in this thesis were leveled with a TopCon GTS-226 precision leveling instrument. The instrument has an accuracy of ± 5 mm. The level of profiles or points for field monitoring of dead-ice melting were measured relative to stable surfaces on bedrock or large boulders.

### 3.4 Detailed mapping of resedimentation processes

A representative ice-cored moraine area of 2000 $m^2$ was selected for detailed field recordings of resedimentation processes in the Brúarjökull forefield (Paper III). The TopCon GTS-226 levelling instrument was used to log the x, y, and z coordinates

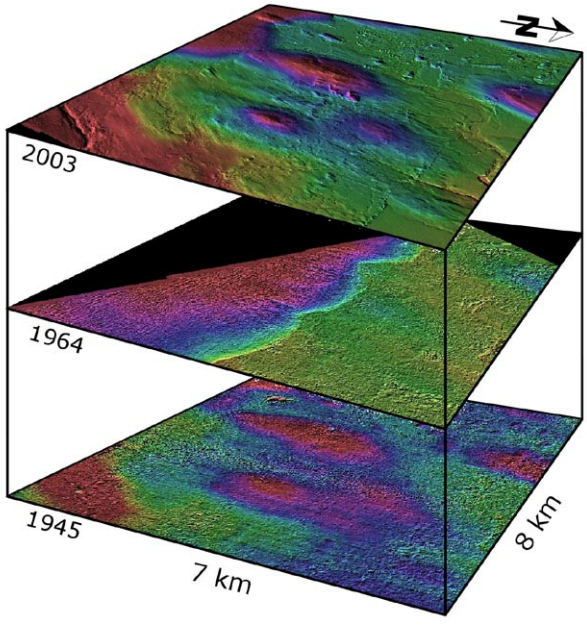


*Figure 5. An example of multi-temporal DEMs from Brúarjökull. The DEMs are visualized as Terrain Shade Relief models (TSRs) and represent the following three time slices: the modern (2003) surface, the surface at the termination of the 1963-64 surge, and the surface in 1945 before the last surge.*

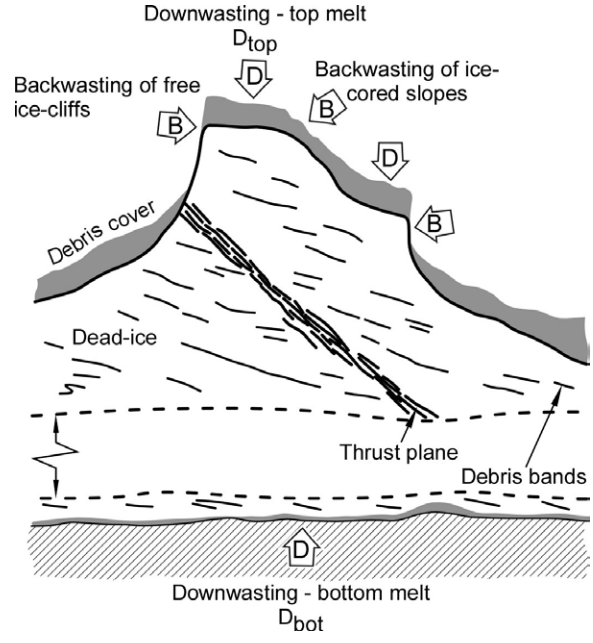


*Figure 6. Definition of melt processes in ice-cored moraines: backwasting (B), downwasting (D) by top melt and bottom melt. Modified after Kjær & Krüger (2001).*

and a code for the process at the point in question. 2214 points were included in this analysis. Based on the recordings, a process map and a detailed elevation model were produced. This allows the possibility to link resedimentation processes to the local topography.

### 3.5 Field monitoring of dead-ice melting

Two processes of dead-ice melting were monitored in the field: backwasting and downwasting (Fig. 6). Backwasting is defined as the lateral retreat of near-vertical ice-walls or ice-cored slopes (Papers III-IV; Pickard, 1984; Krüger & Kjær, 2000). In the field, backwasting was measured with tape as the distance from the retreating edge above each ice-cored slope to a fixed benchmark (Fig. 6B in Paper IV). At Brúarjökull, backwasting was monitored annually, and at Holmströmbreen on a daily basis.

Downwasting is defined as the thinning of dead-ice bodies by melting at the top and/or bottom surfaces (Papers III-IV; Krüger & Kjær, 2000). The total annual downwasting was measured along transects and in points in ice-cored moraines at Brúarjökull and Holmströmbreen. The lowering of the surface of ice-cored moraines relative to a stable benchmark was taken as the total downwasting ($D_{tot}$). At Brúarjökull, annual downwasting by top melt ($D_{top}$) and bottom melt ($D_{bot}$) was determined at two sites according to the method by Krüger & Kjær (2000). $D_{top}$ was measured by annual readings of the ice surface level on a wooden stick drilled into the top of the dead-ice body. When $D_{tot}$ and $D_{top}$ was measured, $D_{bot}$ could be calculated as $D_{bot}=D_{tot}-D_{top}$ (Paper III).

### 3.6 Sedimentological investigations

Sedimentological studies were carried out where sediment exposures were naturally available along rivers, flow headwalls etc. Sediments were also investigated in pits when no natural exposures occurred. Lithological units were recognized based on lithofacies classification (Miall, 1977; Eyles *et al.*, 1983; Krüger & Kjær, 1999). Sedimentological data were recorded in sedimentary logs or in data

charts for glacial diamicts and associated sediments (Eyles *et al.*, 1983; Krüger & Kjær, 1999). The data chart by Krüger & Kjær (1999) was preferred when several types of laboratory data, classifications, and interpretations were to be presented in addition to the sedimentary log (Paper III).

#### *3.6.1. Analyses of glacial striae and clast fabrics*

In the Brúarjökull forefield, striations on boulders in the surface of diamicts were measured with a compass (Papers II-III). Orientation measurements were performed on the upper surface of deeply rooted boulders in order to ensure that the clasts had not been dislocated after deposition.

Clast fabric analyses were carried out in diamicts at Brúarjökull and Holmströmbreen following the method of Kjær & Krüger (1998). Each analysis was performed by gently exposing 25 clasts by scraping on a horizontal till surface of about 25 cm by 25 cm. The dip and dip direction of clasts with a length of 0.6-6.0 cm and a width-to-length axis ratio less than 0.67 was recorded.

Clast fabric data were plotted and analyzed in the SpheriStat 2.2 software from Pangaea Scientific (1998). Eigenvectors, eigenvalues, and contours were calculated in this programme.

#### *3.6.2. Clast morphology analyses*

Morphological analyses of clasts from diamicts at Brúarjökull and Holmströmbreen were undertaken. Clast morphology may be divided into clast shape and clast roundness (Benn & Ballantyne, 1993,1994; Evans & Benn, 2004). Clast shape describes the relative dimensions of the clast, and clast roundness is the overall smoothness of the clast outline.

On samples of 50 clasts, the lengths of the three axes of each particle were measured with a caliper. Subsequently, the shapes of all clasts in a sample were plotted in triangular diagrams (Paper II). In Papers III-IV, only the $C_{40}$ index of the clast population, i.e. the percentage of clasts with c:a axis ratios ≤ 0.40 was presented.

The roundness of each clast in the samples was visually determined using the system of Powers (1953). The system has six roundness classes: very angular (VA), angular (A), subangular, subrounded, rounded, and well-rounded. Following the classification, the percentage of clasts in the VA and A categories – the RA index – was calculated for each sample.

#### *3.6.3. Grain size analyses*

Grain size analyses were performed on samples from Holmströmbreen (Paper IV). Bulk diamict samples were dried at 105 °C and the fraction ≤ 22.4 mm was wet sieved through a 63µ sieve for determination of the total silt and clay content. After redrying the remaining fraction, it was dry sieved for determination of the grain size distribution of the sand-gravel fractions. Hydrometer analyses were used to determine the grain size distribution of the fraction < 63 µ.

## 4. Summary of papers

The results of this study build on contributions from several researchers. Those who are deeply involved in data contribution, scientific discussions and preparation of publications appear as authors on Papers I-IV. However, the main workload for this thesis has been carried out by the present author. An overview of contributors appears in Table 1.

### *4.1 Paper I*

*Kjær, K.H., Korsgaard, N.J., & Schomacker, A. Impact of multiple glacier surges – a geomorphological map from Brúarjökull, East Iceland. Submitted to Journal of Maps.*

Paper I aims to describe the geomorphology of the Brúarjökull forefield based on a map in scale 1: 16 000. The map demonstrates the impact of multiple glacier surges on the landscape. Aerial

| Task | Paper I | Paper II | Paper III | Paper IV |
|---|---|---|---|---|
| Fieldwork | Schomacker<br>Kjær | Schomacker<br>Krüger<br>Kjær | Schomacker<br>Kjær<br>Krüger<br>Benediktsson | Schomacker<br>Kjær<br>Krüger |
| Lab analyses | - | Schomacker | Schomacker | Schomacker |
| Image analyses | Kjær<br>Korsgaard<br>Schomacker | Schomacker | Schomacker | Schomacker |
| DEM production | Korsgaard<br>Schomacker<br>Kjær | - | Schomacker<br>Korsgaard | Norwegian Polar Institute |
| Data interpretation | Kjær<br>Korsgaard<br>Schomacker | Schomacker<br>Krüger<br>Kjær | Schomacker<br>Kjær | Schomacker<br>Kjær |

*Table 1. Contributors to the research results presented in Papers I-IV.*

photographs recorded in August 2003 in scale 1: 15 000 were used to produce Digital Elevation Models (DEMs) and orthorectified imagery of the area. Landforms were manually classified and registered directly in a stereoscopic view on a digital photogrammetric workstation. This allows the operator to take the relief, texture and spatial context fully into account during the mapping procedure. The mapped features were exported to ESRI ArcMap (ArcGIS) for cartographical processing and to Adobe Illustrator CS2 for final layout handling.

The value of stereoscopic visualization cannot be overemphasized, when interpreting small landforms and the extent and delineation of larger ones. Therefore, the resulting map has a very high completeness of *c*. 90-99%. A total of 20 268 features were registered in the area of interest, covering 67.5 $km^2$.

The distribution of landforms on the Bruárjökull forefield has close resemblance to landform assemblages of palaeo-ice streams. Modern ice streams all terminate in marine environments, and have topographically confined flow. Therefore, lobate surge-type glaciers terminating on sedimentary beds in lowlands may provide a modern analogue to Pleistocene ice streams terminating in terrestrial environments.

### 4.2 Paper II

*Schomacker, A., Krüger, J., & Kjær, K.H. 2006. Ice-cored drumlins at the surge-type glacier Brúarjökull, Iceland: a transitional-state landform. Journal of Quaternary Science 21, 85-93.*

The aim of Paper II is to describe the geomorphology and sedimentology of an ice-cored drumlin in the Brúarjökull glacier forefield and to reconstruct its genesis. The drumlin was shaped by the last surge of Brúarjökull in 1963-64. To our knowledge, ice-cored drumlins had not previously been described in the literature. In their present stage of development, areas with ice-cored drumlins display the characteristics of a subglacial landsystem. However, ice-cored drumlins gradually transform into hummocky moraine due to melting of the core. A qualitative sequential model for ice-cored drumlin formation was proposed based on sedimentological field investigations and aerial photograph interpretation. The subsequent melting and transformation of the ice-cored drumlin into ice-free hummocky moraine was included in the model.

Aerial photographs from 1961, 1964, and 2003 demonstrated three time slices of the geomorphology at the drumlin site: before, during, and after the last

surge. Sedimentological data were collected from the drumlin mantle and the surrounding till plain. Clast fabrics, striae on boulders rooted in the diamict, and clast shape and roundness analyses showed that the drumlin mantle and the surrounding till plain formed subglacially during the last glacier surge. In particular, the spatially consistent pattern of ice-flow parallel sedimentary directional elements supported this interpretation.

It was concluded that ice-cored drumlins form by subglacial till deformation and deposition on older ice-cored moraines. Because of dead-ice melting, the drumlins collapse and evolve into patches of hummocky moraine surrounded by a basal till plain. Therefore ice-cored drumlins should be regarded as transitional-state landforms.

### 4.3 Paper III

*Schomacker, A. & Kjær, K.H. 2007. Origin and de-icing of multiple generations of ice-cored moraines at Brúarjökull, Iceland. Boreas 36 (in press).*

In Paper III, the aim is to explore the distribution, origin, and simultaneous de-icing of multiple generations of ice-cored landforms in the Brúarjökull glacier forefield. The dead-ice originates from at least the last three glacier surges in 1810, 1890, and 1963-64.

Mapping of ice-cored landforms and hummocky, ice-free moraine was performed on aerial orthophotographs and verified in the field. Detailed mapping of resedimentation processes was carried out by fieldwork. The sedimentology of ice-cored features was also investigated in the field. We quantified dead-ice melting by field measurements and by analyses of multi-temporal Digital Elevation Models (DEMs) derived from stereopairs of aerial photographs.

Dead-ice in the Brúarjökull forefield appears in ice-cored moraine patches, ice-cored outwash fans and eskers, and ice-cored drumlins. The main locations for dead-ice are in the valleys and on the proximal slopes of end moraines. Sedimentological investigations showed that the debris-cover on dead-ice consists of subglacial traction till, melt-out till, glaciotectonite, and sands and gravels deposited in braided river environments.

Detailed studies of a representative, 2000 $m^2$ ice-cored area demonstrated that the most frequent resedimentation process is sediment gravity flow. The flows originated from niches with backslumping and fracturing of the sediment cover. Approximately 50% of the study area experienced ongoing resedimentation at the time of survey in August 2003.

Measurements from 2003-2005 revealed that ice-cored slopes retreat with a mean 'short-term' backwasting rate of *c*. 30 cm/yr. Monitoring in ice-cored moraines with a debris cover thickness of 1-1.5 m showed a mean 'short-term' downwasting rate of *c*. 7-8 cm/yr. 'Long-term' melt rates were extracted from DEMs for the years 1945, 1964, 1988, and 2003. The long-term surface lowering rate in the period 1945-2003 was 9.8 cm/yr for dead-ice from 1890 or older located proximal to the 1964 end moraine. For dead-ice deposited by the 1963-64 surge, the mean downwasting rate was 17.7 cm/yr in the period 1988-2003. Comparison of the long-term melt rates and the mean annual air temperatures at Brúarjökull may indicate that dead-ice melting has accelerated due to the late 20$^{th}$ century temperature rise.

In the present climate at the limit of permafrost, dead-ice below thick debris cover persists or melts only very slowly. Because the time required for a total melting of each dead-ice generation exceeds the length of the quiescent phases of Brúarjökull, dead-ice may be overridden by new surges and incorporated in new ice-cored landforms. A de-icing model summarizes the age of dead-ice in the different ice-cored landforms in the Brúarjökull forefield as well as the volume of each dead-ice generation as a function of time.

### 4.4 Paper IV

*Schomacker, A. & Kjær, K.H. Quantification of dead-ice melting in ice-cored moraines at the high-Arctic glacier Holmströmbreen, Svalbard. Submitted to Boreas.*

Paper IV aims to investigate the dead-ice environment at Holmströmbreen, central Spitsbergen, Svalbard. Focus is directed towards the distribution, origin, and disintegration of ice-cored landforms as well as quantification of dead-ice melting since the termination of the Little Ice Age.

The geomorphology of a dead-ice area of *c*. 6.5 km × 5.5 km was mapped using multi-temporal aerial photographs and QuickBird 2 high-resolution satellite imagery. Field verification and studies of photographs back to AD 1882 supported the mapping. In the field, the sedimentology of ice-cored features with different debris-cover types was documented through sedimentological logging. Measurements of backwasting and long-term surface lowering were also carried out in the field. For quantification of the long-term effect of dead-ice melting, we analyzed the time series of aerial photographs and satellite imagery.

Dead-ice appears mainly below sediment gravity flows (*c*. 55% of the slope area) but also as ice-cored eskers and ice-cored kames. The sedimentological investigations demonstrate that the debris-cover consists of diamict mass-flow deposits, supraglacial melt-out till, glaciolacustrine, and glaciofluvial sediments. During resedimentation processes on the ice-cored slopes, the diamict is exhausted of fines due to meltwater activity. Most of the material subjected to resedimentation is transported to the ice-walled Lake Emmy at the base of the ice-cored slopes.

The short-term melt rates measured in July 2004 indicate a mean backwasting of 9.2 cm/day. Assuming a 90-day ablation period, the annual rate of backwasting amounts 8.3 m/yr.

On a long-term basis, analyses of multi-temporal aerial photographs and satellite imagery reveal the de-icing progression. Since 1966, a moraine-dammed, ice-walled lake has evolved at the stagnant glacier snout with a near-exponential growth rate, now occupying *c*. 14.65 $km^2$. From 1966-2004, the active glacier margin retreated 6.5 km. Repeated field surveying of a 2500 m long transect indicate an annual surface lowering of 0.9 m from 1984-2004 in ice-cored moraines. The total volume of dead-ice melted in the outermost 6.5 km of the forefield since the last glacier maximum is estimated to 2.72 $km^3$. This volume corresponds to a surface lowering of *c*. 76 m.

Strikingly, the long-term surface lowering rates at Holmströmbreen are at the same order of magnitude as dead-ice melt rates in a humid, subpolar climate in South Iceland. The permafrost prevents percolation of meltwater into the ice and the formation of glacier karst. This may explain the high melt rates because of the ubiquitous sediment gravity flow activity and the continuous exposure of new dead-ice to melting on the ice-cored slopes.

## 5. Discussion

### 5.1 What controls the rates of dead-ice melting?

Dead-ice melt rates depend on the climatic conditions at the location of dead-ice (Papers II-IV). In addition, downwasting rates are controlled by a number of other parameters than climate: holding all other factors constant, the downwasting rate by top melt ($D_{top}$) of buried ice declines exponentially with increasing debris cover thickness (h): $D_{top} = k_d T_0 / (hL\varrho_{id})$, where $k_d$ is the thermal conductivity of the debris layer, $T_0$ the debris surface temperature, L the latent heat of fusion of ice, and $\varrho_{id}$ the density of the ice with debris (Benn & Evans, 1998). This equation takes into account the effect of grain size distribution, porosity, and water content on the ablation rate through $k_d$, the thermal conductivity of the debris cover, whereas $T_0$ accounts for the climate (temperature). Thus, published downwasting rates from different localities reflect not only the climatic control on downwasting but also the effects of varying debris cover thickness, thermal conductivity

and water content. This makes it difficult to decipher the climatic control on downwasting rates from different sites because rates are not directly comparable between individual sites.

Backwasting rates of free ice faces are easier to compare from site to site because they can be expected to be closer amplified by the climate, and because debris-cover characteristics exerts less control on backwasting than on downwasting. It might be suspected that backwasting rates should be high in humid, mild climates and low in arid, cold climates (Eyles, 1983b; Kjær & Krüger, 2001; Johnson & Clayton, 2003). However, the backwasting rates on Svalbard reported in Paper IV are of the same magnitude as those obtained by Krüger & Kjær (2000) in the mild, humid climate of South Iceland. This suggests that backwasting rates might be governed not only by mean annual air temperature, but possibly by other climate parameters, such as the heat sum received during the melting season (degree days, threshold 0°C), mean summer air temperature, or summer precipitation. Backwasting rates from dead-ice areas under different climate conditions are compiled in Fig. 7 and Table 2. It appears that the lowest rates are found in the cool, dry climate in the Dry Valleys, Antarctica and the highest rates in the temperate, humid climate at the Tasman Glacier, New Zealand. However, the figure reveals little as to what controls the backwasting rates. As discussed in Paper IV, one controlling factor may be permafrost and the lack of glacier karst preventing percolation of meltwater into the ice, and thus causing sediment liquefaction and a high sediment gravity flow activity. The high flow activity exposes new dead-ice to backwasting on the ice-cored slopes and may work as a self-perpetuating process.

In Fig. 8, backwasting rates from the same sites as used in Fig. 7 are plotted with different climate parameters (see also Table 2). The highest correlation

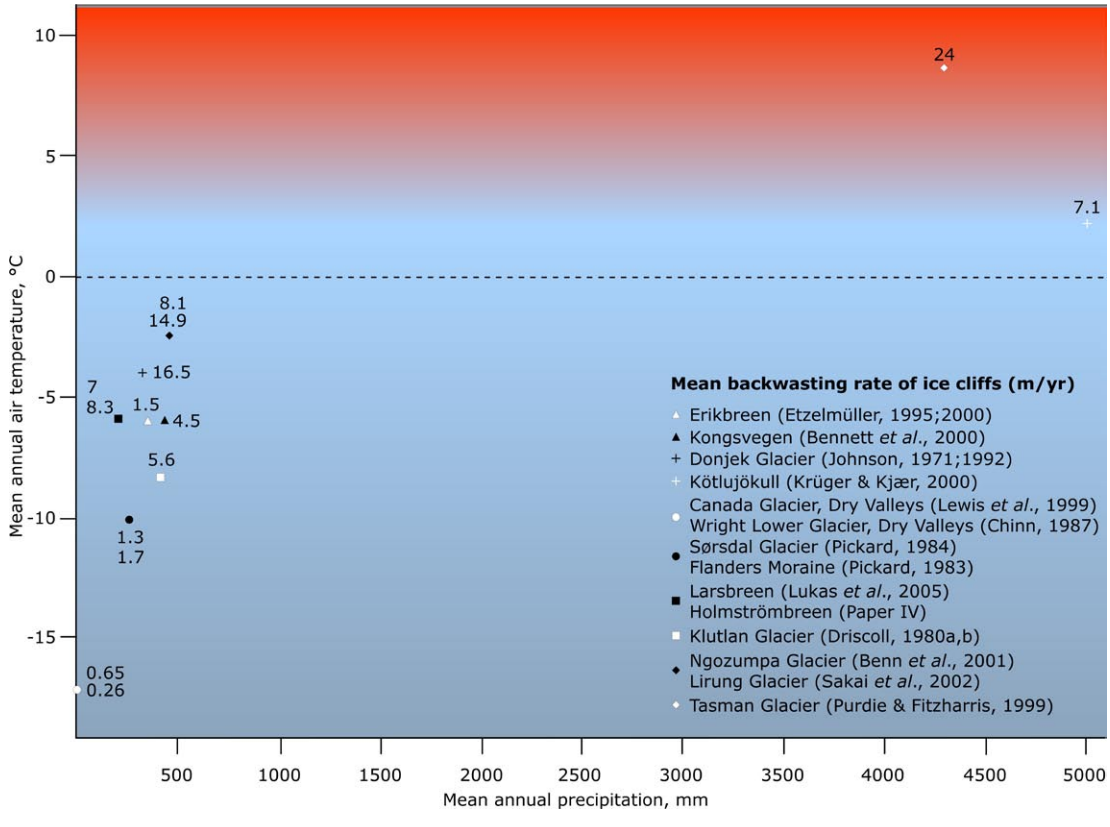


*Figure 7. Mean backwasting rates at ice-cliffs in 14 dead-ice areas. The backwasting rates are indicated in relation to the mean annual air temperature and mean annual precipitation at each site.*

| Glacier | Position | MAAT (°C) | MSAT (°C) | MAP (mm) | MSP (mm) | Pos. deg. days | BW (m/yr) | References |
|---|---|---|---|---|---|---|---|---|
| Erikbreen, Svalbard | 79°45'N; 13°E | -6 | 2.7 | 350 | 100 | - | 1.5 | Etzelmüller, 1995;2000 |
| Kongsvegen, Svalbard | 78°48'N; 13°E | -6 | 3 | 400 | 100 | 334 | 4.5 | Bennett *et al.*, 2000 |
| Larsbreen, Svalbard | 78°N; 15°E | -6 | 5 | 190 | 45 | 435 | 7 | Lukas *et al.*, 2005 |
| Holmströmbreen, Svalbard | 78°N; 12°E | -6 | 5 | 200 | 100 | 400 | 8.3 | Paper IV |
| Kötlujökull, Iceland | 63°35'N; 18°45'W | 2.6 | 7.5 | 5000 | 1950 | 1200 | 7.1 | Krüger & Kjær, 2000; Kjær & Krüger, 2001 |
| Canada Glacier, Antarctica | 77°35'S; 163°E | -17 | -2.3 | 0 | 0 | 0 | 0.26 | Lewis *et al.*, 1999 |
| Sørsdal Glacier, Antarctica | 68°35'S; 78°E | -10.2 | - | <250 | - | - | 1.7 | Pickard, 1984 |
| Flanders Moraine, Antarctica | 68°38'S; 78°12'E | -10.2 | - | <250 | - | - | 1.3 | Pickard, 1983 |
| Wright L. Glacier, Antarctica | 77°25'S; 163E | -17 | -8.5 | 0 | 0 | 0 | 0.65 | Chinn, 1987 |
| Donjek Glacier, Yukon | 61°N; 140°W | -3.8 | 12.8 | 280 | 200 | 1500 | 16.5 | Johnson, 1971;1992 |
| Klutlan Glacier, Yukon | 62°N; 141°W | -8.3 | 12.8 | 400 | 200 | 1500 | 5.6 | Driscoll, 1980a;b |
| Ngozumpa Glacier, Himalaya | 28°N; 87°E | -2.4 | 3.1 | 465 | 453 | 403 | 14.9 | Benn *et al.*, 2001 |
| Lirung Glacier, Himalaya | 28°N; 86°E | -2.4 | 3.1 | 465 | 465 | 403 | 8.1 | Sakai *et al.*, 2002 |
| Tasman Glacier, New Zealand | 43°41'S; 170°E | 8.8 | 13.5 | 4293 | 2000 | 3200 | 24 | Purdie & Fitzharris, 1999 |

*Table 2. Backwasting rates (BW) from dead-ice areas at 14 glaciers. Data shown in the table are extracted from the references indicated in the last column. Climate parameters are mainly derived from these references. In the case of missing information in the publications, climate data were obtained from the Meteorological Institute of the country in question. Abbreviations: MAAT – Mean Annual Air Temperature; MSAT – Mean Summer Air Temperature; MAP – Mean Annual Precipitation; MSP – Mean Summer Precipitation; Pos. deg. days – The sum of positive degree days.*

($R^2$ is 0.63 and 0.65) was found between backwasting rate and mean annual air temperature, and sum of degree days >0°C, respectively. The correlation between melting and the sum of positive degree days is well known from glacier mass balance studies (Paterson, 1994). Theoretically, the correlation between backwasting rate and mean summer air temperature should be higher than the correlation with the mean annual air temperature; this was however not the case for the backwasting data shown in Fig. 8. There was no significant correlation ($R^2$ is 0.22 and 0.34) between backwasting rate and mean annual, and mean summer precipitation, respectively. This suggests that precipitation exerts little control on the backwasting rates. Even though the mean annual air temperature and the sum of positive degree days appear to correlate better with the backwasting rates, the correlation coefficients are very low in comparison to those known from glacier ablation studies, sometimes reaching up to more than 0.90 (e.g. Paterson, 1994; Braithwaite, 1995). This most likely indicates that backwasting of ice-cliffs is more dependent local factors than ablation of clean glacier surfaces. Ice cliff exposure direction, ice cliff albedo, wind conditions, cloudiness, and proximity to water bodies probably contribute to the high variability of backwasting rates shown in Figs. 7-8. Despite the high variability of backwasting rates between the sites, the compilation provides an insight into the range of backwasting rates in modern glacial environments.

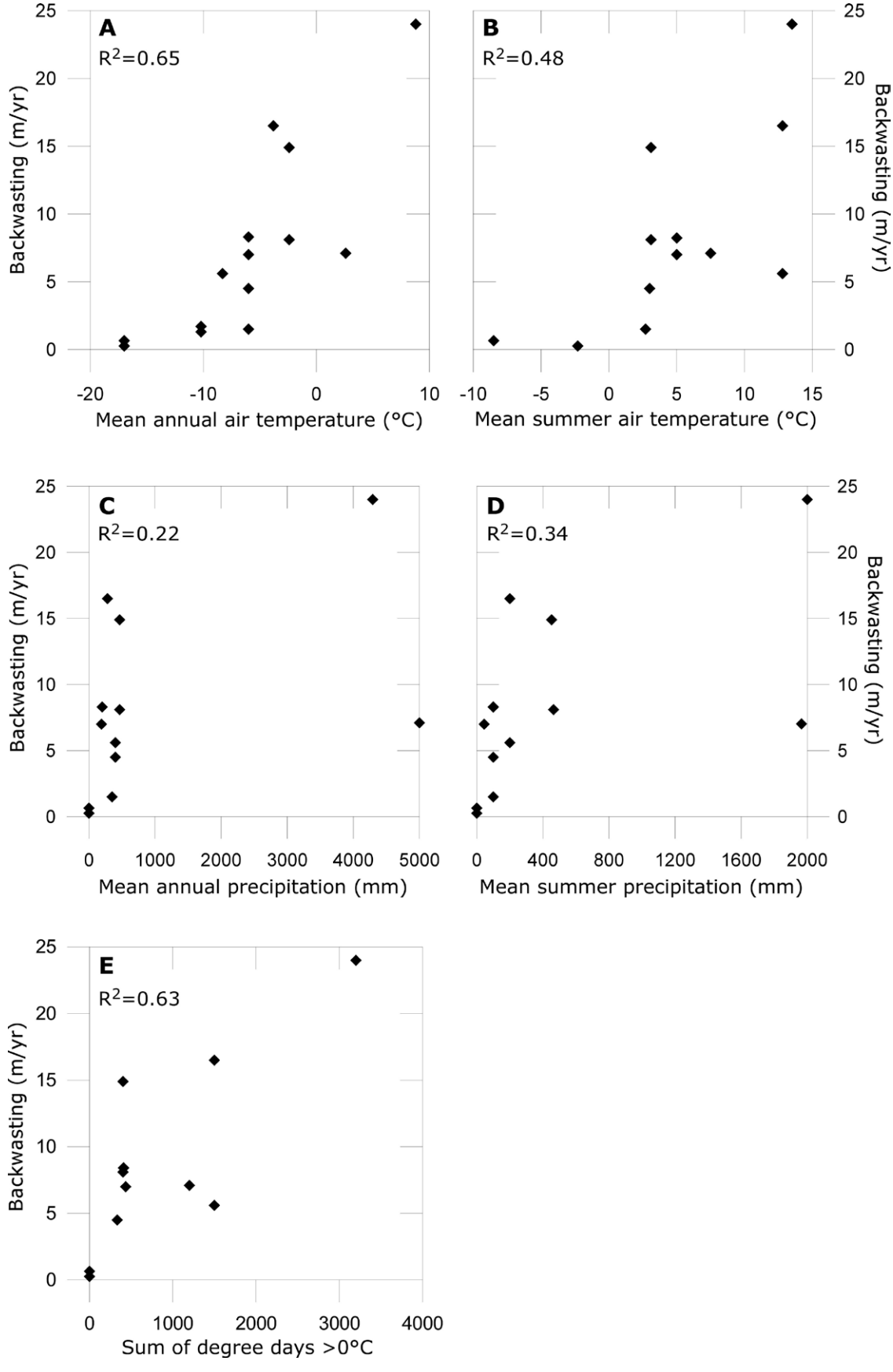


*Figure 8. Backwasting rates of ice-cliffs at the sites from Fig. 5 in relation to different climate parameters. The correlation coefficients ($R^2$) are shown on each plot.*

Johnson & Clayton (2003) suggest that present-day dead-ice areas might not be suitable analogues to the extensive Pleistocene dead-ice bodies, e.g. in North America, because of differences in scale and debris-cover thickness. However, modern dead-ice environments are currently the closest and only analogue to Pleistocene dead-ice areas. Furthermore, dead-ice melting on the scale of large glacier lobes as Brúarjökull (Papers I-III) resembles the scale of Pleistocene lowland glacier lobes (Kjær *et al.*, 2003; Jennings, 2006). In ancient dead-ice areas, palaeoclimate parameters can often be deciphered from e.g. proxy data from lake sediment cores, whereas dead-ice melt rates are difficult to establish. Measured de-icing rates in modern dead-ice environments (e.g. Papers III-IV) under well-known climate conditions may, therefore, serve as input to de-icing models for ancient dead-ice deposits. However, the high variability in backwasting rates (Figs 7 and 8) suggests that both minimum and maximum estimates should be the output of such de-icing models.

## 5.2 Geomorphological impacts of dead-ice melting

The presence of dead-ice deposits such as hummocky dead-ice moraines in past glaciated areas indicates stagnation of debris-laden glaciers (Benn, 1992; Ham & Attig, 1996; Johnson & Clayton, 2003). The results from modern dead-ice environments presented in this study support this interpretation. However, a more specific palaeoenvironmental significance of dead-ice deposits is not well established; similar landforms and sediments, such as mass-flow deposits in hummocky moraines, form in highly different climatic settings (e.g. Papers III-IV). The question, therefore, rises whether ancient dead-ice deposits provide any specific palaeoclimatic information in addition to their glaciodynamic signal of glacier stagnation (see also Kjær & Krüger, 2001).

In areas where backwasting and associated mass-movement processes are abundant, gravity sorted sediments should have higher abundance than in areas where downwasting dominates. Gravitational sorting at ice-cliffs and ice-cored slopes tends to produce boulder accumulations at the foot of slopes (Fig. 9). Such clusters of boulders are not easily separated because they are too coarse to be reworked by running water or other surface processes. Even though the areas studied here are not completely de-iced, it is suggested that in post-melt landscapes, a high occurrence of boulder accumulations in geological sections and on the surface indicates that ice-cored slopes or ice-cliffs were present during de-icing (see also Kjær & Krüger, 2001). Such features are, however, present in so many different climatic settings (Figs 7-8), that the palaeoclimatic significance is limited.

Depletion of fines from the debris-cover parent material through cycles of sediment gravity flows appears typical for dead-ice areas where backwasting is abundant (Krüger, 1997; Kjær & Krüger, 2001; Paper IV). In post-melt landscapes, the parent material is not easily identified, which in addition to the wide range of climates where backwasting occur, suggests a little palaeoenvironmental significance of this finding.

At Brúarjökull, the time required for a total de-icing of ice-cored landforms exceeds the duration of the quiescent phases in the surge cycles, and old

*Figure 9. Gravity sorting at ice-cored slope in the Brúarjökull forefield. Boulder accumulations at the base of slopes have high preservation potential in dead-ice environments. Spade for scale. August 24th, 2003.*

dead-ice may be recycled in new ice-cored landforms such as ice-cored drumlins (Papers I-III). If exposed to a complete melting, ice-cored drumlins will degrade into a patch of hummocky moraine (Paper II). If remnants of such features can be recognized in Pleistocene landscapes, they might indicate that dead-ice melting progressed slowly and possibly in a permafrost environment.

Both at Brúarjökull and at Holmströmbreen, backwasting of ice-cliffs and ice-cored slopes is much more effective than downwasting. At Holmströmbreen, where ice-cliffs are ubiquitous, this ensures that a high rate of de-icing is maintained as long as the build-up of an insulating debris mantle is prevented by mass movement processes (Paper IV). In addition, the permafrost at Holmströmbreen prevents percolation of meltwater and the formation of glacier karst (Clayton, 1964; Krüger, 1994). Meltwater, therefore, stays on the dead-ice surface and keeps sediment gravity flows and ice-cliff formation active. This may explain why the long-term de-icing rate at Holmströmbreen is higher than that of Brúarjökull even though the climate is cooler at Holmströmbreen. Free ice-cliffs are, namely, rare in the Brúarjökull forefield, and rain and meltwater do not stay long on the ice-cored moraines (Paper III).

### *5.3 Methodological considerations about mapping*

It appears from Papers I-IV that the methods of geomorphological mapping were significantly refined during this study (Section 3.1). Initially, mapping was carried out by digitizing map objects on raw digital aerial photographs. The aerial photograph distortion is therefore transferred to the output maps, implying that coordinates and directions are not completely correct (e.g. Fig. 4 in Paper II). When mapping on a DPW, the stereographic view and the orthophotographs ensures a very precise output map. The difference in quality is obvious when comparing Fig. 4 in Paper II to the geomorphological map of the Brúarjökull forefield printed in Paper I.

Thus, it is suggested that any detailed geomorphological mapping based on stereopairs of aerial photographs should be carried out on a DPW in order to achieve as high quality as possible of the output maps. The precise geocoding of the output products furthermore provides the possibility to detect and quantify changes when using multi-temporal aerial photographs and derived DEMs (e.g. Papers III-IV, D'Agata & Zanutta, 2007; Schiefer & Gilbert, 2007; Trouvé *et al.*, 2007). Field verification of the output maps remains essential.

## 6. Conclusions

Glacial geomorphological mapping of the Brúarjökull forefield by aerial photograph interpretation on a DPW yielded a map with high completeness and accuracy. The possibility to interpret aerial photographs in stereo and digitize map objects in the same view on a DPW yields a more reliable and accurate output than traditional mapping in non-stereo mode. Exporting the map feature databases to GIS format allows any user to analyze the data and to produce custom maps.

The Brúarjökull mapping revealed that dead-ice bodies are mainly located in valleys and proximal to end moraines. Production and analyses of multi-temporal DEMs from aerial photographs proved successful for change detection in the dead-ice areas. Quantification of dead-ice melting derived from DEMs yielded results agreeing with field measurements.

Currently, the climate at Brúarjökull is at the limit of permafrost. Ice-cores below thick debris-covers, therefore, persist or melt only at very low rates. The life-time of dead-ice is longer than the duration of the quiescent phases. Thus, new ice-cored landforms may form by glacier overriding of old dead-ice during surges. Such overriding and modification of dead-ice bodies may produce

transitional-state landforms such as ice-cored drumlins. If exposed to a complete de-icing, the ice-cored drumlins are likely to degrade into patches of hummocky dead-ice moraine.

At Holmströmbreen dead-ice occur mainly below active sediment gravity flow areas with diamict debris-cover. The debris-cover originates as supraglacial melt-out till and supraglacially transported material. Analyses of multi-temporal aerial photographs and satellite imagery revealed the de-icing progression from 1936-2005. The melting analysis shows that the clean glacier margin has retreated 6.5 km from its maximum position in the Little Ice Age, a moraine-dammed supraglacial lake of 14.65 $km^2$ has developed during the last 40 years, and that the total dead-ice loss amounts *c*. 2.72 $km^3$ – equivalent to a surface lowering of 76 m. As long as backwasting and mass-movement processes prevent build-up of an insulating debris-cover and expose ice-cores to melting, the de-icing continues even though the Holmströmbreen area is within the zone of continuous permafrost.

Even though the climate at Brúarjökull is milder than at Holmströmbreen, de-icing takes place at a slower rate. This is due to the lack of extensive ice-cliff areas at Brúarjökull, where effective backwasting could have occurred. At Holmströmbreen where ice-cliffs appear in most of the dead-ice zone, continuous backwasting and sediment removal ensures a high long-term rate of de-icing resulting in an annual surface lowering of 0.9 m.

A compilation of published backwasting rates from dead-ice areas in a wide range of climates indicates that backwasting only correlates poorly with local air temperatures and heat sums. This suggests that local conditions play a major role in the backwasting of ice-cliffs. Dead-ice melting may therefore progress at similar rates in highly different climates. The glaciodynamic signal of dead-ice deposits is that of stagnant, debris-covered glaciers, whereas the palaeoenvironmental signal is limited due to the variety of climatic settings of dead-ice environments.

## 7. Implications for future research

Many glaciers currently experience negative mass balance, retreat and stagnation, and dead-ice areas are likely to be more abundant in the future (Knight, 2006; D'Agata & Zanutta, 2007). This may provide even more opportunities than today to study sedimentary processes and products of dead-ice melting under global warming. It is intriguing that the current widespread glacier retreat provides insights into hitherto unexplored glacial landscapes, processes and sediments at the same time as many glaciers face their obliteration! However, a deeper understanding of former deglaciations is also crucial in order to assess the effects of the ongoing glacier decay.

Multi-temporal DEM analyses combined with field monitoring campaigns is highly useful for change detection and quantification studies of dead-ice areas (Papers III-IV). Problems of poor aerial photograph time series for DEM production may be solved by using satellite-borne Interferometric Synthetic Aperture Radar (InSAR) data for DEM production. Since the early 1990s this method has successfully been used in change detection studies in other glacial environments (e.g. Massom & Lubin, 2006; Rignot & Kanagaratnam, 2006; Magnússon *et al.*, 2004, 2005, 2007). The monitoring of dead-ice melting at Brúarjökull will be continued in the future both by field measurements and by InSAR studies.

At Holmströmbreen, the lack of accurate GCPs prevented DEM production by stereophotogrammetry. The de-icing progression could have been quantified by multi-temporal DEM analyses if a GCP network had been available. If Holmströmbreen is accessed in the field again, a GCP network should be collected using a differential GPS.

It is important to recognize the present and future value of the initiated monitoring programmes, elevation measurements, and DEMs at both Brúarjökull and Holmströmbreen. If the monitoring

is continued in the future, a long-term record of glacier changes may be created. This provides an opportunity to provide 'ground truth', supporting the large number of remote sensing studies of ongoing glacier changes. As an analogue, one may look back in time on Emmy Mercedes Todtmanns meticulous field investigations documenting the Brúarjökull forefield prior to the last surge (Todtmann, 1960). Her work provided a unique time slice of the geomorphology and sediments, which could not have been obtained today, after the last surge. Similarly, the transect over the dead-ice area at Holmströmbreen surveyed by J.J.M. van der Meer in 1984 and re-surveyed by the present author in 2004 is of utmost value in a long-term monitoring perspective (van der Meer, 2004, pers. comm., 2004; Paper IV).

Papers II-IV described landforms and sediments underlain by dead-ice. Future research may shed light on the final products left in the geological record if de-icing has been completed. This, however, requires that the areas of interest are not overridden by new glacier surges. For instance, future revisits can test if the suggested end-product of ice-cored drumlins at Brúarjökull agrees with the proposed conceptual model (Paper II).

## 8. Summary in Swedish (svensk sammanfattning)

Recenta dödismiljöer framför Brúarjökull-glaciären på Island och Holmströmbreen på Svalbard har undersökts med speciellt fokus på landforms- och sedimentgenes samt kvantifiering av dödisavsmältningen. Fältmätningar, studier av tidsserier av flyg– och satellitbilder samt digitala terrängmodeller är dataunderlaget för kvantifieringen av dödisavsmältningen. Sedimentologiska och geomorfologiska data insamlades i fält och genom flygbildstolkning. Olika mått på dödisavsmältning ('backwasting', 'downwasting', utbredningen av issjöar, reträtten av glaciärfronter och uttunningen av glaciärer) jämförs med lokala temperaturserier, vilka går ända tillbaka till den tid instrumentmätningar började.

En geomorfologisk karta i skala 1:16 000 över Brúarjökull-området ritades med hjälp av digital flygbildstolkning och analys av terrängmodeller i hög upplösning. Kartan har använts som stöd för tolkningen av landformer och sediment och gav samtidig en överblick över glaciärsvämningslandskapet vid Brúarjökull, ett resultat av särskilt snabba glaciärframstötar.

En bildningsmodell för drumliner med kärnor av is togs fram med hjälp av data från undersökningarna vid Brúarjökull. Modellen indikerar att sådana drumliner disintegrerar till kulliga dödismoräner om kärnan smälter bort.

Tre fältsäsonger och analyser av multi-temporala terrängmodeller och flygbilder har avslöjat att flera dödisgenerationer existerar framför Brúarjökull. Smältningen av dessa dödiskroppar har kvantifierats och visar att smältningen under det nuvarande klimatet är så långsam att en komplett utsmältning är osannolik. Några av dödiskropparna "återvinns" i nya landformer med iskärnor därför att deras totala utsmältningstid är längre än viloperioden i svämningscykeln. Sett över lång tid orsakar dödissmältningen vid Brúarjökull en sänkning av terrängytan med 0.10-0.18 m/år.

Framför Holmströmbreens stagnerade glaciärfront har ett stort dödisområde med iskärnemoräner, rullstensåsar och kames bildats sedan slutet av Lilla Istiden. Sett över lång tid fortskrider dödissmältningen med en sänkning av ytan på 0.9 m/år. Backwasting av isslänter och massrörelser av sediment exponerar hela tiden ny dödis och hindrar därvid – till skillnad från vad som sker vid Brúarjökull – att ett isolerande sedimenttäcke ackumuleras på isen. Det mest markanta resultatet av dödisavsmältningen är utvecklingen av en stor ändmorändämd issjö, där sediment från isslänterna runt sjön ackumuleras.

Dödissmältning under olika klimatförhållanden diskuteras i avhandlingen med fokus på

smälthastigheter, sediment- och landformsgenes. Likadana processer pågår med nästan samma hastigheter i olika klimat. Fossila dödisavlagringer ger därför ganska lite information om miljön vid avlagringstilfället. Glacialdynamiskt sett indikerar dödisavlagringar stagnation av materialtäckta glaciärer.

## 9. Summary in Icelandic (samantekt á íslensku)

Í þessari rannsókn var sjónum beint að dauðísumhverfi við Brúarjökul á Íslandi og Holmströmbreen á Svalbarða. Áhersla var lögð á að kanna myndun landforma og setlaga, ásamt því að mæla bráðnun dauðíss. Nákvæm gögn um hraða dauðísbráðnunar voru fengin með vöktun og mælingum, sem og með túlkun á loftmyndum, gervihnattamyndum og hæðalíkönum frá mismunandi tímabilum. Setlaga- og landmótunarfræðilegra gagna var aflað með vettvangsrannsóknum og loftmyndatúlkun.

Ólíkir þættir í bráðnun dauðíss (s.s. hörfun, lóðrétt bráðnun, stækkun tjarna eða stöðuvatna, jökulhörfun og -þynning) voru metnir með tilliti til staðbundins lofthita á þeim tíma sem mælingar náðu yfir.

Landmótunarkort í kvarðanum 1:16 000 af svæðinu framan við Brúarjökul var unnið með því að túlka stafrænar loftmyndir og hæðalíkön í mikilli upplausn. Kortið nýttist síðan til túlkunar á landformum og setlögum, og sem yfirlitskort af því svæði sem mótast hefur af framhlaupum Brúarjökuls.

Líkan af myndun jökulalda með ískjarna var búið til með hliðsjón af gögnum sem aflað var við Brúarjökul. Líkanið sýnir að slíkar jökulöldur eru tímabundin landform sem breytast í haugaruðninga bráðni ískjarninn að fullu. Þriggja ára vettvangsvinna, ásamt greiningu hæðalíkana og loftmynda frá mismunandi tímabilum, leiddi í ljós þrjár kynslóðir dauðísgarða við Brúarjökul. Mælingar á bráðnun þessara dauðísgarða sýna að hún er svo hæg að við núverandi loftslag er ólíklegt að dauðísinn bráðni að fullu. Vegna þess að sá tími sem þarf til algerrar bráðnunar er lengri en sá tími sem líður milli framhlaupa Brúarjökuls, endurnýtir jökullinn dauðísinn og myndar ný landform með ískjarna. Mælingar hafa leitt í ljós að yfirborð dauðísgarða lækkar um 0.10-0.18 metra á ári vegna bráðnunar.

Við staðnaðan jaðar Holmströmbreen er víðáttumikið dauðíssvæði sem þróast hefur frá lokum Litlu ísaldar. Þar er að finna dauðísgarða ásamt malarásum og sethjöllum með ískjörnum. Hörfun dauðíss og tilheyrandi hreyfing á seti afhjúpar sífellt nýjan dauðís og kemur í veg fyrir að þykkt setsins verði svo mikil að dauðísinn einangrast og bráðnun minnkar eða stöðvast. Um þessar mundir lækkar yfirborð dauðísgarða vegna bráðnunar um 0.9 metra á ári. Bráðnun dauðíssins hefur einkum haft þau áhrif að stöðuvatn hefur myndast í dæld sem stífluð er af jökulgarði. Þegar dauðísinn umhverfis vatnið bráðnar fellur til set sem safnast í vatnið.

Í ritgerðinni er fjallað um bráðnun dauðíss í mismunandi loftslagi og áhersla lögð á hraða bráðnunar og myndun setlaga og landforma. Ljóst er að sams konar ferli eiga sér stað á svipuðum hraða í mismunandi loftslagi. Því veita dauðíssetlög og –landform litlar upplýsingar um loftslag þess tíma sem þau mynduðust á og gefa einungis til kynna stöðnun jökuls sem þakin hefur verið seti.

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