

# Quantification of the ice-cored moraines' short-term dynamics in the high-Arctic glaciers Ebbabreen and Ragnarbreen, Petuniabukta, Svalbard

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**Abstract:** Extensive ice-cored moraine complexes are common elements, marking the last advance of many Svalbard glaciers. Sediment gravity flows are among the most dynamic processes, transforming these landforms. The short-term (yearly and weekly) dynamics of mass-wasting processes were studied in a cm-scale using repetitive topographic scanning. We monitored several active sites on the forelands of two glaciers, Ebbabreen and Ragnarbreen, both of which are located near the Petuniabukta at the northern end of Billefjorden in Spitsbergen.

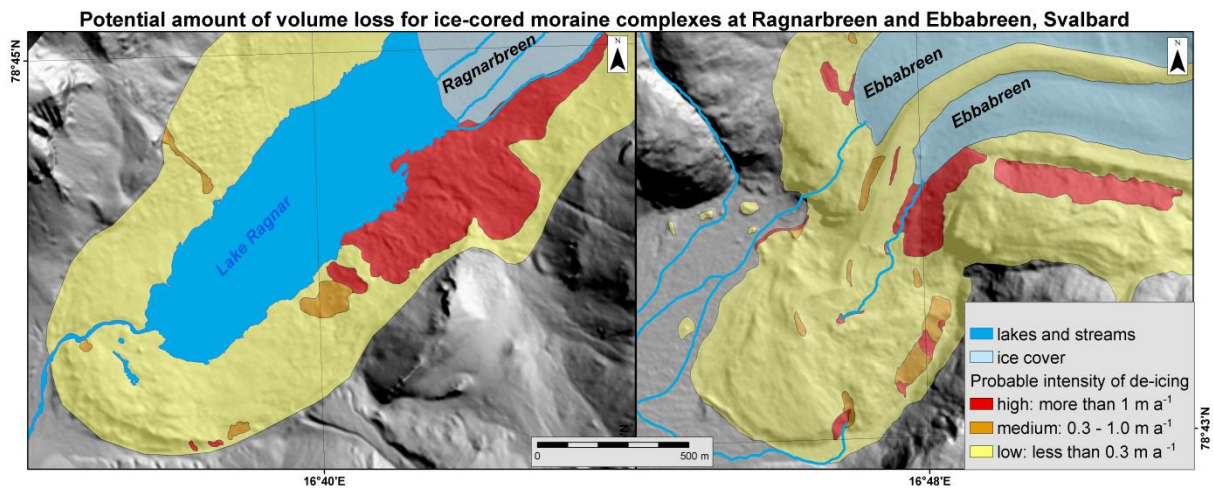
The surveys indicate high dynamic rates of landforms' transformation. The mean annual volume loss of sediments and dead-ice for the most active parts of the moraines was up to  $1.8 \text{ m a}^{-1}$ . However, most of the transformation occurred during summer, with the short-term values of mean elevation changes as high as  $-104 \text{ mm day}^{-1}$ . In comparison, the dynamics of the other (i.e. non-active) parts of the ice-cored moraines were much lower, namely, the mean annual lowering (attributed mainly to dead-ice downwasting) was up to  $0.3 \text{ m a}^{-1}$ , whereas lowering during summer was up to  $8 \text{ mm day}^{-1}$ . Our results indicate that in the case of the studied glaciers, backwasting was much more effective than downwasting in terms of landscape transformation in the glacier forelands. However, despite the high activity of localised mass movement processes, the overall short-term dynamics of ice-cored moraines for the studied glaciers were relatively low. We suggest that as long as debris cover is sufficiently thick (thicker than the permafrost's active layer depths), the mass movement activity would occur only under specific topographic conditions and/or due to occurrence of external meltwater sources and slope undercutting. In other areas, ice-cored moraines remain a stable landsystem component in a yearly to decadal time-scale.

**Key words:** Dead-ice melting; Ice-cored moraine; Debris flow; DEM; GIS; Spitsbergen

## Highlights

- We quantified annual and weekly volume changes of ice-cored moraine complexes on Svalbard
- The mean elevation loss due to active mass movement processes and dead-ice melting was up to almost  $2 \text{ m a}^{-1}$
- The amount of elevation loss attributed to dead-ice downwasting alone was significantly lower, up to a maximum of  $0.3 \text{ m a}^{-1}$

## Graphical abstract



## 1. Introduction

Ice-cored moraines on a number of Svalbard glaciers have been the subject of many qualitative studies (e.g. Boulton, 1967, 1968, 1970a, b, 1972; Bennett et al., 1996, 2000; Hambrey et al., 1997; 1999; Glasser and Hambrey, 2001, 2003; Lyså and Lønne, 2001; Sletten et al., 2001; Lønne and Lyså, 2005; Midgley et al., 2007, 2013; Ewertowski et al., 2012). Quantitative studies of Svalbard glaciers, however, have concentrated mainly on transformations in glacier geometry, dynamics and mass balance (e.g. Hagen and Liestøl, 1990; Hagen et al., 1993; Jania and Hagen, 1996; Melvold and Hagen, 1998; Ziaja, 2001; Bamber et al., 2005; Ziaja, 2005; Nuth et al., 2007; Rachlewicz et al., 2007; Zagorski et al., 2008, 2012; Sund et al., 2009; Moholdt et al., 2010a,b; Nuth et al., 2010; Kristensen and Benn, 2012; Mansell et al., 2012; Murray et al., 2012; Błaszczyk et al., 2013; Małecki, 2013). Quantification of changes in glacial landforms, including transformations due to dead-ice melting, has been made in a much smaller number of studies (e.g. Bennett et al., 2000; Etzelmüller, 2000a,b; Ziaja, 2004; Lønne and Lyså, 2005; Lukas et al., 2005; Schomacker and Kjær, 2008).

Quantification of the short-term dynamics of ice-cored moraines is of great importance in terms of glacial landsystem studies. As most glaciers around the world are presently not in equilibrium with current climatic conditions, the retreat of these glaciers and the creation of freshly exposed ice-cored moraine complexes are common situations (Oerlemans, 2005; Barry, 2006; Evans, 2009). It suggests that ice-cored moraines were also important elements of past glacial environments. Thus, understanding the transformation of modern ice-cored moraines is crucial for a proper interpretation and reconstruction of past glacial events.

Ice-cored moraines are degraded actively by mass movements and dead-ice melting, or passively by degradation of the ice-cores alone as a result of dead-ice melting. Still, our knowledge about the quantitative aspect of the ice-cored moraines' degradation remains unsatisfactory (Schomacker, 2008). In many Arctic and mountain environments, ice-cored moraines constitute a significant proportion of the ice within the catchments (Schomacker and Kjær, 2007; Schomacker, 2008). For example, in 2004, the volume of the dead-ice in the distal part of Holmströmbreen, Spitsbergen, was estimated by Schomacker and Kjær (2008) to be 3.54 km<sup>3</sup>. Thus, its melting can cause serious changes to the local environment.

Most of the quantitative studies of glacial landforms in Svalbard have used time-series of aerial photographs/satellite images to assess the changes. Thus, time resolution was restricted to several or even several tens of years (e.g. Schomacker and Kjær, 2008). Quantification of the annual changes, e.g. using LiDAR (Irvine-Fynn et al., 2011), or implementation of terrestrial laser scanning (TLS) for geomorphological modelling (Kociuba, 2014; Kociuba et al., 2014) is much less common.

This study, however, deals with the short-term (weekly and yearly) dynamics of ice-cored moraines in two of Svalbard's glaciers. The most important questions are the following: Are the forelands in equilibrium with the current climatic conditions? Does dead-ice melting occur with uniform intensity over the entire glacier foreland? We focus on a detailed analysis of the debris flows and other gravitational mass movements, which are the most active components of moraine complexes. The main objectives are to:

- 1) Compare transformations of the ice-cored moraine surfaces due to active geomorphic processes (including dead-ice backwasting and debris mass movements) with transformations caused by dead-ice downwasting alone.
- 2) Analyse the spatial and temporal aspects of debris flow activity in cm-scale.
- 3) Quantify the short-term (seasonal and intra-seasonal) rate of volume changes.

## 2. Study setting

The study was carried out on Spitsbergen Island, which is part of the Svalbard archipelago, located in the high-Arctic (Fig. 1). We focused on the central part of the island, where substantial retreat of glaciers has been observed. About 26 km<sup>2</sup> of the glaciers' forelands have been exposed since the termination of the Little Ice Age (LIA). The exposed area was calculated based on an orthophoto which we generated from 2009 aerial photographs (courtesy of the Norsk Polar Institute) using ground control points measured with DGPS (Differential GPS). The maximum LIA extent of the glaciers was estimated using position of the moraine complexes; it was assumed that the maximum position of ice margins was according to the outer edges of these complexes. Glaciers' extents in 2009 (i.e. the area of glaciers' surfaces which were exposed, not covered with debris) were vectorised manually using the orthophoto.

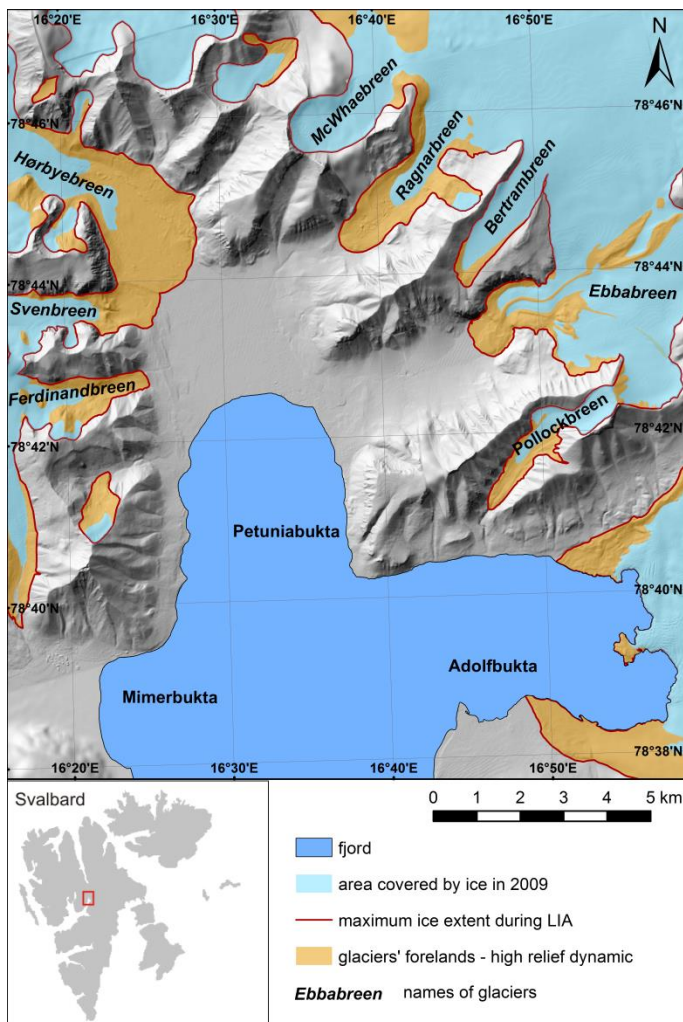


Figure 1. Location of the study area, with areas exposed after the termination of the Little Ice Age marked. Shaded model is based on a DEM generated from 2009 aerial photographs

The exposed forelands are supposed to be subjected to intensive geomorphological processes due to the paraglacial adjustment of the topography (e.g. Rachlewicz, 2010). To recognize how high is the activity of such processes, we monitored the transformation rates of ice-cored moraines on the forelands of two glaciers, Ebbabreen and Ragnarbreen, both of which are located near Petuniabukta at the northern end of the Billefjorden (Fig. 1). Previous works on glaciers and glacial landforms in the study area concern both geomorphology (e.g. Kłysz, 1985; Gonera and Kasprzak, 1989; Karczewski, 1989; Stankowski et al., 1989; Karczewski et al., 1990; Karczewski and Kłysz, 1994; Gibas et al., 2005; Rachlewicz and Szczuciński, 2008; Rachlewicz, 2009, 2010; Szuman and Kasprzak, 2010; Hanáček et al., 2011; Evans et al., 2012; Ewertowski et al., 2012; Ewertowski, 2014) and glaciology (e.g. Rachlewicz et al., 2007; Rachlewicz, 2009; Małecki, 2013, 2014; Małecki et al., 2013).

Svalbard is located in an area of continuous permafrost, and the thickness of the permafrost is from 100 m in the valley bottoms and near the coast to as much as 400–500 m in inland mountains (cf. Humlum et al., 2003; Etmüller and Hagen, 2005). The permafrost's active layer in the vicinity of Petuniabukta reaches a depth of 1.2 m close to the coast (Rachlewicz and Szczuciński, 2008) and varies between 0.5 and 2.5 m inland (Gibas et al., 2005).

The melting season in Svalbard lasts usually for about three months. The meteorological observation from the Petuniabukta in the period 2000–2003 (Rachlewicz, 2003; Rachlewicz and Styszyńska, 2007) and 2010–2012 (Láska et al., 2012) showed that the mean monthly air temperatures in the study area were above 0°C in the period June–September, with the highest temperatures in July and at the beginning of August (Rachlewicz, 2003; Rachlewicz and Styszyńska, 2007; Láska et al., 2012). The mean daily air temperature was above 5°C for more than 50% of the days in the period July–August 2009; the maximum monthly means for solar radiation were also observed in July 2009 and June 2010 (Láska et al., 2012). The aforementioned data suggest that the highest activity of dead-ice melting and mass wasting processes should be expected during July and at the beginning of August.

Mass wasting processes actively contribute to the transformation of Ebbabreen's and Ragnarbreen's ice-cored moraines. Debris flows and falls are common elements in both forelands. However, their spatial distribution and intensity varied during the deglaciation period. For example, when glaciers started to retreat from their LIA maximum extent, debris flows were common within the end moraines complexes (Ewertowski et al., 2012). In the subsequent periods, the highest intensity of debris flows migrated up-valley following the retreating exposed ice surface, and at present most of the active debris flows occur within lateral moraines whereas end-moraine complexes are much less dynamic in terms of geomorphic activity (Ewertowski, 2014). Despite their temporal stabilization, end-moraines still contain large amounts of dead-ice (Gibas et al., 2005). In this study, we focused on transformation of the end-moraine complexes to show how the degradation of ice-cores can impact other geomorphic processes and to determine the intensity of ice-cored moraines' degradation.



### 3. Materials and methods

#### 3.1. Designation and characteristic of the test sites

Several locations containing mass movement areas (including debris flows and falls), as well as parts of the moraines that were not actively transformed by the mass movement processes were investigated (Fig. 2). In total, we selected seven sites containing active debris flows or other mass wasting processes for monitoring and quantifying their dynamics. Sites were chosen to ensure representation from different parts of the end moraine, different types of dominant processes (e.g., debris flows and debris falls) as well as different types of morphology (e.g., exposed ice cliffs, steep debris slopes, and gentle debris flows lobes). In 2012, we chose four sites which were also active in previous years, so they represent objects characterised by a relatively long period of

instability. Three further sites were added in 2013 – these sites are examples of parts of the moraine which only recently switched from a stable condition to being actively transformed. In addition, we also surveyed areas over which no active processes were observed in order to estimate the transformation related to the dead-ice downwasting alone. Table 1 shows characteristics of the selected sites during the first and the last surveying session. We defined a “site” as an area over which active mass wasting processes were observed between two survey sessions. It implies that the borders of sites changed from one period to another, i.e. studied sites were delineated using a dynamic approach and their area varied for each period. The most common mechanisms of surface transformation for the selected sites were the flowing of debris as well as falling, rolling and sliding downwards of dead-ice slopes.

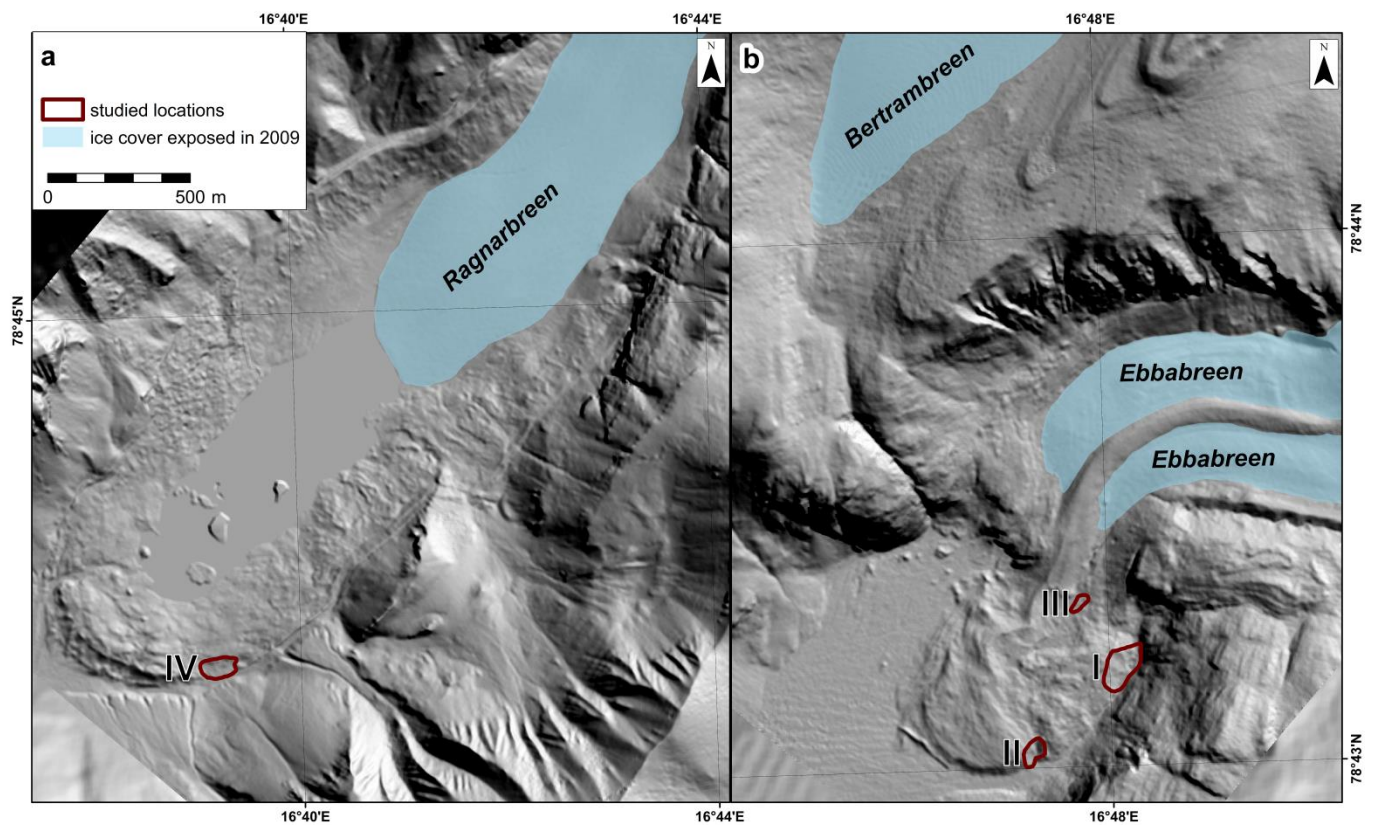


Figure 2. Study site locations in the foreland of Ebbabreen and Ragnarbreen. Shaded model is based on a DEM created from 2009 aerial photographs.

Table 1. Characteristics of surveyed locations. Note: ‘-’ means that no active processes were observed.

	First survey session					Last survey session					Number of measurement sessions
	Area [m <sup>2</sup> ]	Elevation min [m a.s.l.]	Elevation max [m a.s.l.]	Elevation mean [m a.s.l.]	Elevation range [m]	Area [m <sup>2</sup> ]	Elevation min [m a.s.l.]	Elevation max [m a.s.l.]	Elevation mean [m a.s.l.]	Elevation range [m]	
<b>Location I</b>											
Site 1	205	60.9	74.0	67.8	13.1	1687	57.0	82.4	65.9	25.4	10
Site 2	44	59.0	61.6	60.2	2.6	145	56.1	63.3	59.4	7.2	10
Site 3	154	57.9	64.9	61.3	7.0	1682	53.1	77.7	63.0	24.6	10
Inactive area	6679	57.6	83.0	68.7	25.4	3797	53.5	82.4	67.4	28.9	10
<b>Location II</b>											
Site 4	205	41.6	56.4	47.6	14.7	0	-	-	-	-	5
Site 5	910	44.0	64.8	55.0	20.9	1166	43.8	65.2	54.9	21.4	4
Inactive area	1540	41.3	65.4	52.2	24.1	1489	41.3	62.6	49.9	21.4	5
<b>Location III</b>											
Site 6	299	75.2	85.7	80.0	10.5	0	-	-	-	-	5
Inactive area	436	75.4	87.4	82.7	11.9	735	74.6	87.3	81.2	12.7	5
<b>Location IV</b>											
Site 7	1223	91.3	98.1	94.2	6.8	0	-	-	-	-	7
Inactive area	4061	83.6	98.2	89.7	14.6	5284	83.5	97.9	90.6	14.4	7

### 3.2. Precise measurements of elevation

A Topcon Imaging Station (IS) in a reflectorless, robotic scanning mode was used to acquire accurate and detailed topographic data. The device works with the same principle as terrestrial LiDAR, performing automatic scanning during which it measures the distance using laser ray. The device operates by reading the horizontal and vertical angles as well as the distances from the laser ray's source to the target point. The accuracy of the distant measurements is 1 mm, and the accuracy of the angle reading is 3". The IS instrument was set up on base-points with known coordinates, surveyed by DGPS and then post-processed. The base-points were stabilized and marked, which enabled performing repetitive surveys for quantification of the transformation rates. Surveys were performed in a UTM 33N coordinate system.

In total, four different locations were scanned, containing seven active debris flows or other mass wasting processes, and including non-active surfaces. Altogether, the total scanned area was about 14,200 m<sup>2</sup>, of which 5,500 m<sup>2</sup> were transformed by the active mass movement processes. Due to the topography, several different base-points had to be used for each location.

Ten measurement sessions were carried out for locations I and IV (three in summer of 2012, three during summer of 2013, and four in summer of 2014), which allowed for assessing the seasonal (annual) and intra-seasonal (weekly) variations. Locations II and III were scanned in 2013 and 2014, which added more details to the analysis

of short-term (weekly) dynamics. Each of the measurement sessions included surveys of scattered points around the test sites. The density of the surveyed points varied from 40 to 70 m<sup>-2</sup>. Photographic monitoring was also carried out along with the survey sessions.

### 3.3. Analysis of the micro-relief transformation

The results of the surveys in the form of cloud points with known coordinates N, E, Z were used to create digital elevation models (DEMs) with cell size 0.05×0.05 m. A set of 60–70 points from each cloud served as checkpoints to assess the quality of the processed DEMs; they were not used for DEM creation but to evaluate errors. The root mean square error (*RMSE*) was between 0.016 and 0.030 (Supplementary Table A1). DEMs generated from each measurement session were subsequently subtracted from each other, providing a spatial picture of the loss or deposition of material in each cell of the model between survey sessions. Subtracting DEMs from subsequent time periods created DEMs of Differences – DoDs (e.g. Wheaton et al., 2010; Tomczyk and Ewertowski, 2013), which enabled us to calculate the amount of material that was moved within the test sites and to investigate the spatial patterns of transformations. Afterwards, the value of changes was multiplied by cell size, and thus the volume of relocated mineral material was obtained. Cells, whose value of changes was within the limits of *RMSE*, were treated as if there has been no change or that the

transformation of relief was smaller than the model error; in other words, the value 0 was attributed to them.

## 4. Results

Locations I and IV were monitored in 2012, 2013 and 2014, which enabled us to assess the annual changes. Locations II and III were scanned in 2013 and 2014, which also allowed us to investigate short-term (weekly) transformations in detail as well as to demonstrate different phases of mass wasting activity. We calculated volume loss and gains as well as mass balance between each survey session for each of the sites. Quantification of the volume and elevation changes is presented in a supplementary material (Supplementary Table A2). A brief description of the results of the surveys for each of the locations is shown below.

### 4.1. Ebbabreen – Location I

Three sites with active mass movement processes, including debris flows and falls, were situated in the southern part of the moraine complex of the Ebbabreen foreland. Traces of old headwalls and debris flow deposits suggest that this part of the moraine has been transformed in the past by larger scale mass wasting processes; however, during the study period, only three smaller debris flows and falls occurred. Clast-supported, heterogenous diamicton with silty-sandy matrix was the most common coverage of the dead-ice. Several debris-rich ice layers were also visible in the exposed ice-cliffs. Diamicton was interpreted as the effect of previous mass-flow processes; however, the initial origin of the debris and the way of delivery to the ice margins were not known. Mass wasting processes in this part of the moraine complex were activated mainly due to the stream flowing from the higher part of the valley. Three small ponds developed along the stream due to local topographic conditions and dead-ice melting, thereby contributing to the slope destabilization and mobilization of debris flows. Lake levels, however, varied greatly between the measurement sessions. For example, the lake in site 1 was drained completely in the third week of July 2014, but it appeared again a week after.

#### 4.1.1. Site 1

Site 1 can be seen as a typical example of debris flow within an ice-marginal environment (Fig. 3). It consisted of four elements. The first was a cirque-shaped headwall of near vertical face consisting of dead-ice and overlying sediments with thickness of 1.5 to 2.3 m. A niche was located below, constituting a gentle sloped surface of ice, covered by a sediment slump that extended away from the headwall base, creating a “mixing area” in which debris was saturated by water. The third element was a transportation channel that transferred the saturated debris downslope. The fourth element was a depositional fan, partly protruding into the small pond.

The surface of the site was unevenly transformed during the study period. The upslope propagation and intensification of mass wasting processes were clearly visible (Fig. 4). The area transformed by active geomorphic processes increased from 205 m<sup>2</sup> in the first week of survey in 2012 to almost 1690 m<sup>2</sup> in the last (seventh) week of survey in 2013. The weekly volume of changes due to mass wasting processes and ice-cores melting was between –26 m<sup>3</sup> (week 7) to –482 m<sup>3</sup> (week 5). The largest lowering, by up to 2.8 m, was related to the retreat of the headwall (Figs. 4 and 5). The mass balance in weekly scale was negative, ranging from –0.14 to –0.40 m per week. Only during week 7 the amount of loss and deposition was almost the same, which gives –0.02 m as mean elevation change. Most of the deposition took place in the niche or in the lake at the base of the debris flow.

Within both years of observation (Year 1: July 2012 – July 2013; Year 2: July 2013 – July 2014), a considerable lowering of the site surface was recorded (Fig. 6). In total, 1141 m<sup>3</sup> of debris and ice were removed during Year 1 and 2738 m<sup>3</sup> in Year 2. The site almost doubled in area. The yearly mass balance was –1.04 m a<sup>-1</sup> in Year 1 and –1.40 m a<sup>-1</sup> in Year 2. The local maximum loss of elevation was even up to 4.2 m, mainly because of the headwall retreat and dead-ice melting. Debris deposition took place in a limited area – around 4% and 7% of the site area – mainly within the niche. Locally, the surface was raised by up to 0.7 m. Some of the debris were also delivered and stored in the lake or removed by the stream and transported down-valley.



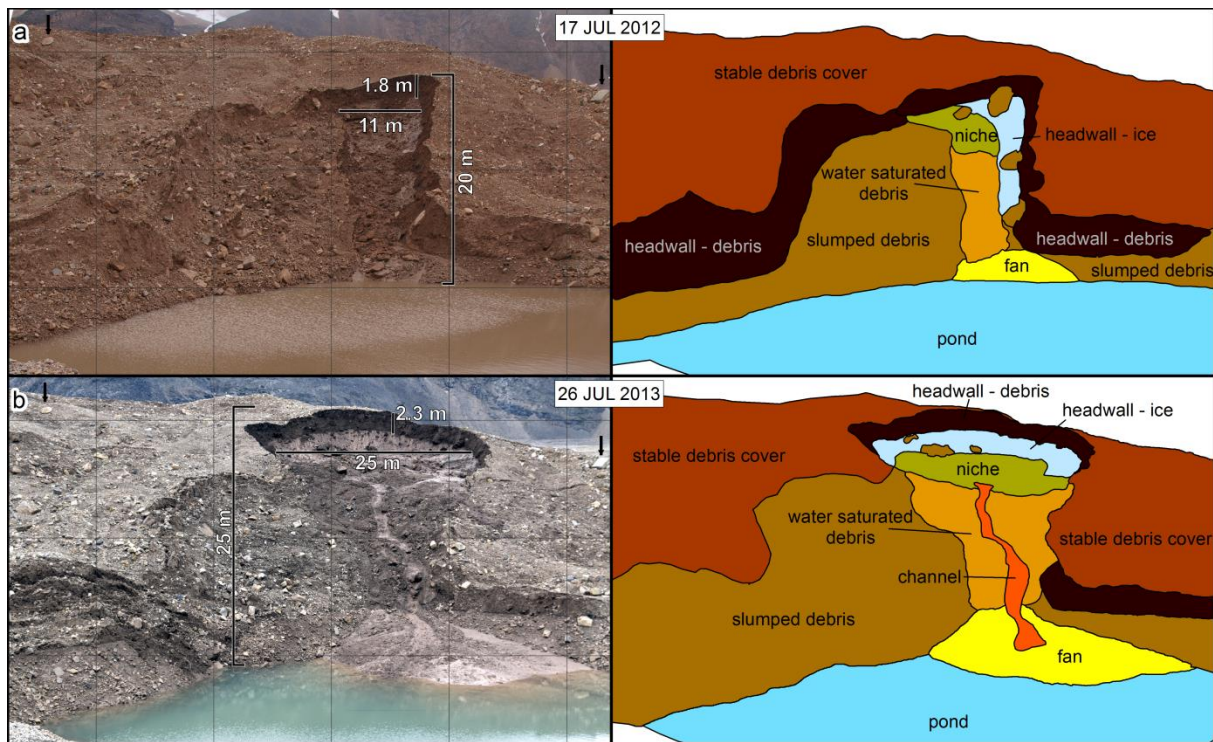


Figure 3. Photographs and sketches of the debris flow in Site 1, Ebbabreen, for July 2012 (a) and July 2013 (b). Note that some of the boulders remain in the same position within a year of observation (some examples are marked by black arrows).

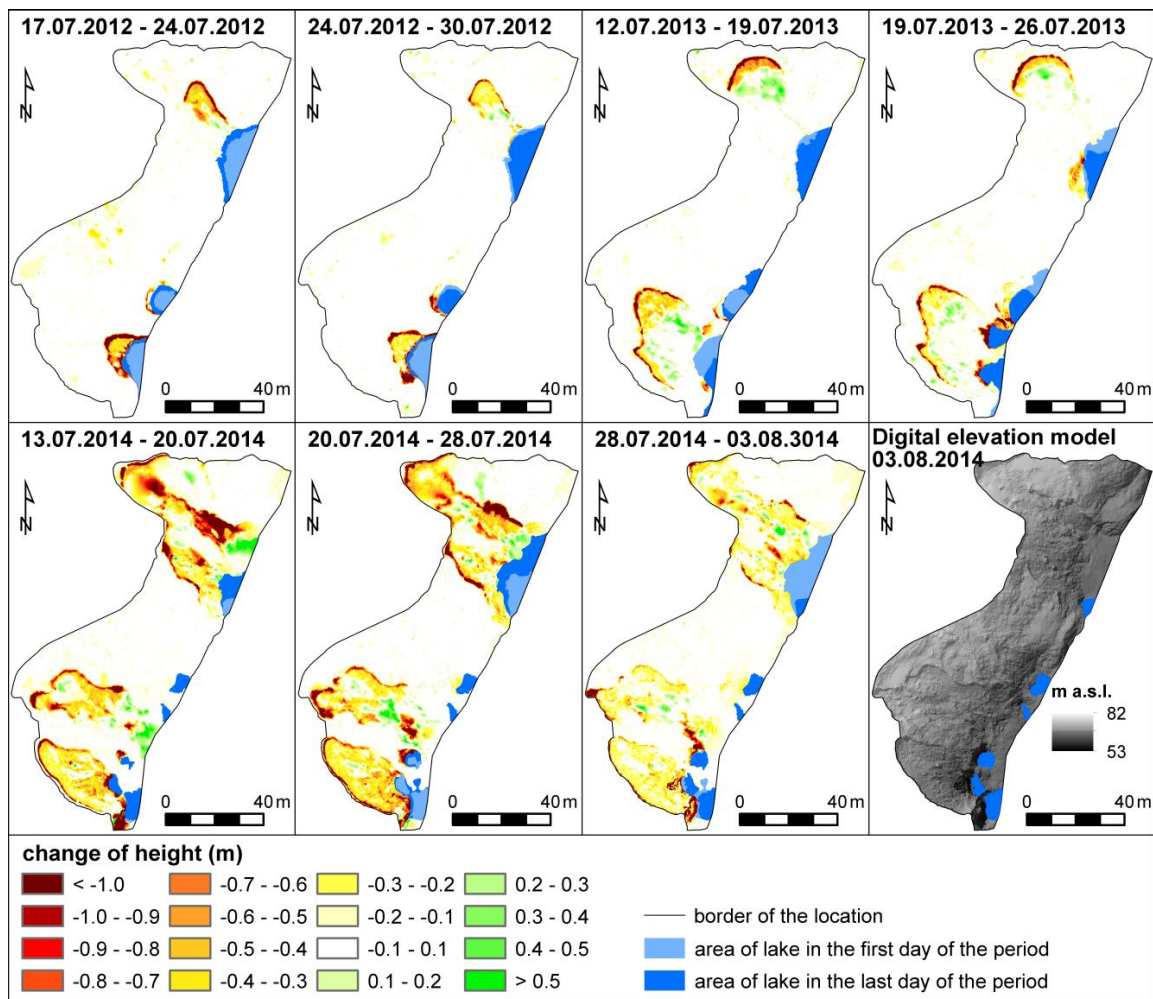


Figure 4. DEMs of Differences (DODs) showing the spatial distribution of surface transformation – location I, Ebbabreen



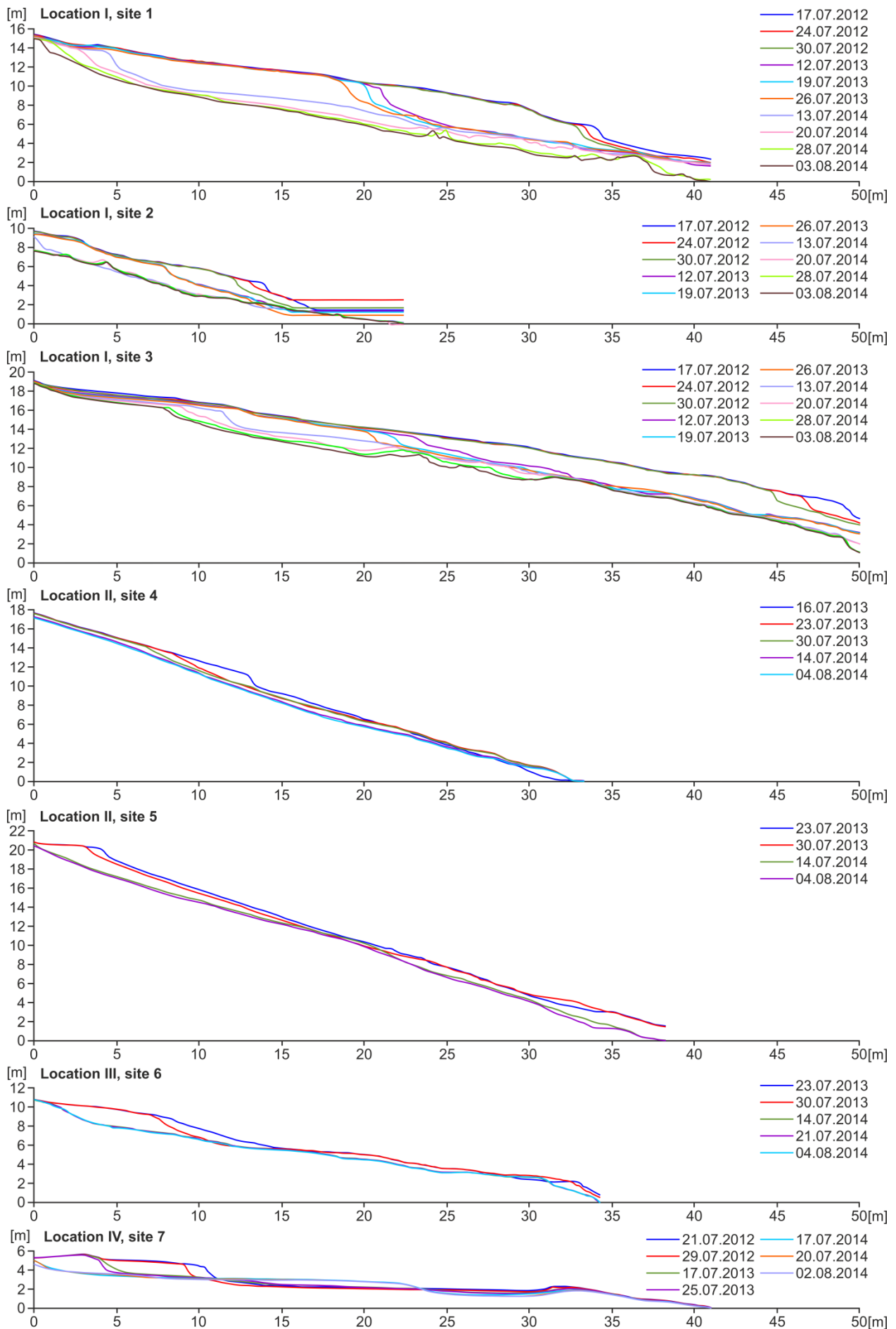


Figure 5. Examples of surface profiles for each site. Note the changes in elevation as well as retreat of the headwalls

#### 4.1.2. Site 2

In 2012, Site 2 was relatively small (44 m<sup>2</sup>). It consisted of a vertical headwall (up to 1.1 m in height) and built of diamicton. At the beginning of summer 2012, no dead-ice was exposed. During the survey period, however, the topography changed a lot. Debris fell intensively into the pond and, as the headwall retreated, dead-ice was exposed. The site expanded not only upslope, but also into sides.

Short-term volume changes were between  $-8$  and  $-30$  m<sup>3</sup> per week in 2012 and 2013. Most of the mass wasting processes stopped working at the end of July 2013, and the site became inactive. At the end of July 2014, the mass wasting processes had been reactivated and the site started to expand again with volume loss of  $-5$  m<sup>3</sup> in week 6 and  $-20$  m<sup>3</sup> during week 7. During the period of activity, mass balance was negative and the mean elevation loss was greater than 0.14 m per week. The largest lowering of the surface, linked to the headwall retreating (up to 1.3 m per week), was up to 1.8 m within a week. The amount of recorded deposition was minimal, mainly because most of the sediments had been delivered into the pond.

Within two years of observation, a reduction by 178 m<sup>3</sup> (Year 1) and 527 m<sup>3</sup> (Year 2) in the debris volume was recorded. There was lowering of the surface locally at up to 3.7 m. No debris deposition was recorded, as the pond changed the water level and all sediments were delivered into the ponds.

#### 4.1.3. Site 3

Site 3 comprised three elements: a vertical diamicton headwall of up to 1.3 m in height, a slope built of exposed dead-ice, and small fans protruding into the lake. Commonly observed processes included: falling and slumping of debris from the headwall, mixing of debris with water, and flowing down along the ice-slope. Part of the debris was deposited within fans; others were delivered into the lake. The headwall retreated (even up to 26 m during year of observation – see Fig. 5), and the site expanded horizontally, leading to the exposition of much more dead-ice than it was at the beginning of the study period (Fig. 7).

The relief of the site was unevenly transformed during the study period (Fig. 4). Short-term volume changes varied between 101 m<sup>3</sup> (week 2) and 481 m<sup>3</sup> (week 6). The largest relief changes were related to the headwall retreat

and ice cliff melting. The mean elevation changes varied from  $-0.12$  to  $-0.73$  m per week.

On an annual scale, considerable transformations of the surface as well as expansion of the site and upslope propagation of mass wasting processes were recorded (Fig. 6). Reduction in the volume of debris and dead-ice was  $-1823$  m<sup>3</sup> during Year I and  $-3629$  m<sup>3</sup> during Year 2, whereas only a very small amount of deposition was recorded. The very limited recorded deposition suggests that all debris transported by mass flows to the base of the slope was subsequently removed by the stream and/or that the lowering of the surface due to dead-ice melting was of higher magnitude than the deposition of debris within the niche. The annual mass balance was  $-1.59$  m a<sup>-1</sup> in 2012/2013 and  $-1.83$  m a<sup>-1</sup> in 2013/2014.

#### 4.1.4. Inactive part of the moraine

The part of the moraine that was not altered by active debris flows or falls was also transformed; however, changes were much lower than for the active parts. Short-term mean elevation changes were from  $-0.01$  m per week (weeks 3 and 6) to  $-0.05$  m per week (week 7). On an annual scale, the total reduction in volume, interpreted as a result of dead-ice downwasting, was 1014 m<sup>3</sup> in Year 1 and 515 m<sup>3</sup> in Year 2. The mean annual elevation changes for Year 1 and Year 2 were  $-0.21$  and  $-0.20$  m a<sup>-1</sup>, respectively.

#### 4.2. Ebbabreen – Location II

Location II was situated near the sub-moraine outflow of the meltwater stream. The stream drained the southern unit of the Ebbabreen and subsequently flowed under the ice-cored moraine. Two steep sections with high activity of mass movement processes developed. The main cause of debris remobilization was sediments' undercutting of the moraine slope by the stream (site 4), and removal of debris by the stream flowing from under the moraine (site 5); dead-ice was exposed in both cases. Debris covering the ice comprised a mixture of a whole range of clastic shapes and morphologies. Some clasts exhibited characteristics of supraglacially transported debris (elongates and very angular or angular shape). Others were characterised by subangular or subrounded edges and striations which suggested subglacial transport. The amount of matrix was smaller than in the case of location I.

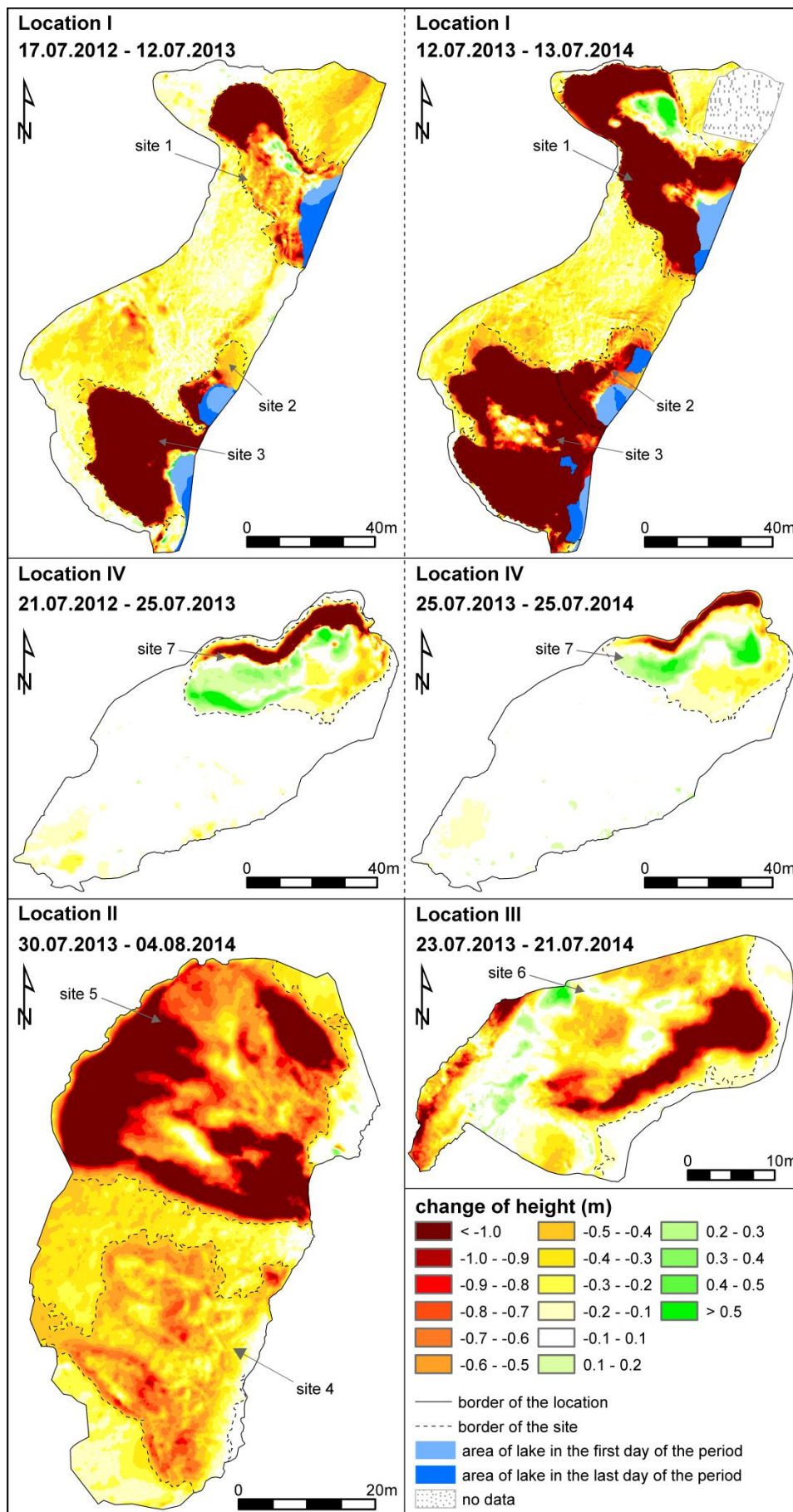


Figure 6. DEMs of Differences (DODs) showing the spatial distribution of surface transformation for all studied locations on an annual temporal scale



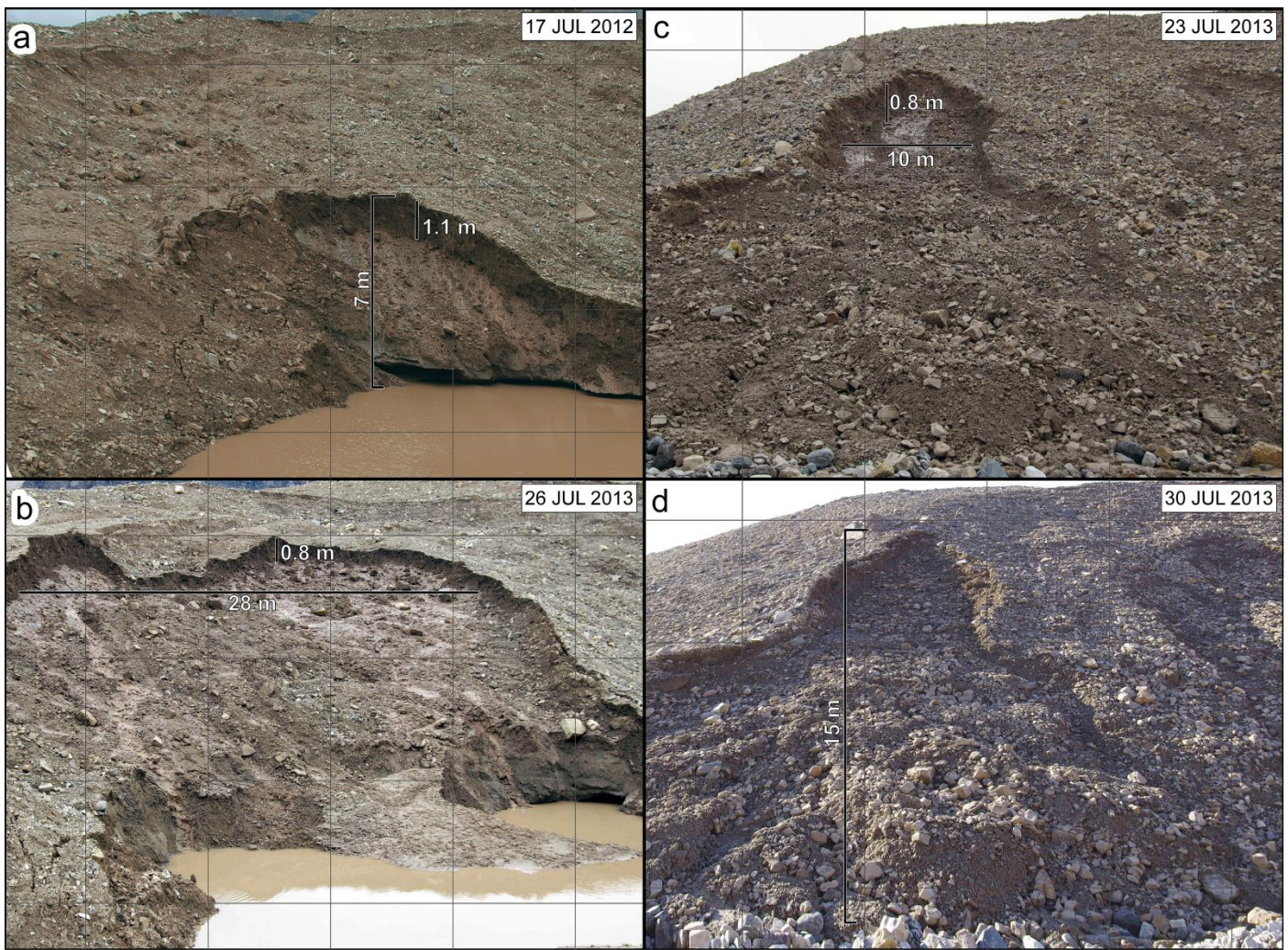


Figure 7. Examples of annual changes for Site 3 (a and b) and weekly changes for Site 4 (c and d). Note the expansion of the dead-ice exposure and retreat of the headwall for Site 3 (a and b).

#### 4.2.1. Site 4

Site 4 was composed of two, only partly separated objects representing mass wasting processes which started in 2013, shortly before we began to monitor them. The objects consisted of two separate debris headwalls of up to 0.8 m thick, as well as a common steep ice slope and talus that were deposited at the base of the slope. A small stream undercut the slope base, causing instability as well as removal of some of the falling debris. Site 4 was much more active during the first week (week 3) than in the second week (week 4) of the survey (Fig. 8). Most of the activities were observed shortly after the initiation of mass wasting processes, i.e. during week 3. Almost 99 m<sup>3</sup> of debris was removed, mainly from the headwall area. The maximum surface lowering was about 1.4 m, and erosion took place in over 60% of the site area. Part of the

removed debris (~45 m<sup>3</sup>) was deposited within the slope. Mass movement processes were much less active during the second week of monitoring (week 4), leading to coverage of dead-ice exposure (Fig. 7). Only 17 m<sup>3</sup> of debris was removed and, again, the highest amount of debris was removed from the headwall area; however, lowering also occurred more or less evenly in most parts of the site (~85% of its area). Deposition was much less prominent. Only less than 2 m<sup>3</sup> of debris was deposited – for the most part immediately below the headwall. In the second year of observation, active mass wasting processes stopped completely and the site became inactive.

The annual change (2013–2014) in the volume was –330 m<sup>3</sup> and the mean elevation lowering was –0.45 m a<sup>-1</sup>. There was a reduction in the surface of the site – locally by 1.4 m (Fig. 6).



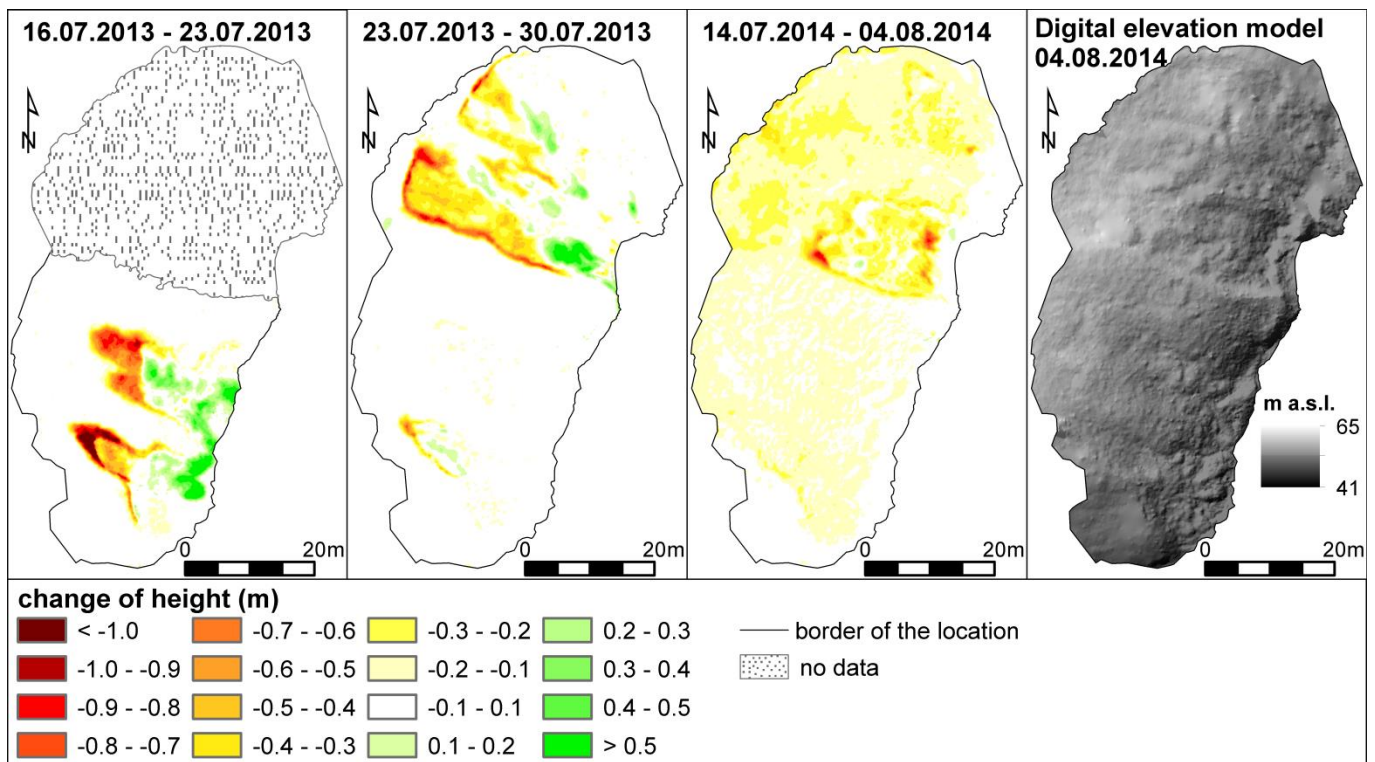


Figure 8. DEMs of Differences (DODs) showing the spatial distribution of surface transformation – location II, Ebbabreen

#### 4.2.2. Site 5

Site 5 consisted of three elements: (1) headwall built of ca. 0.3–1.2 m of debris; (2) steep ice slope; and (3) talus partly reworked by the stream. Material was falling and slumping down, often sliding over the ice. The surface of site 5 was unevenly lowered during the study period (Fig. 8). The short-term activity was similar in both 2013 (week 4) and 2014 (weeks 5–7). The amount of volume changes was  $-105$  and  $-217$  m<sup>3</sup>, respectively. The annual changes were substantial (Fig. 6). Almost 1105 m<sup>3</sup> of debris and dead-ice was lost, whereas no deposition was recorded. The mean elevation changes were  $-0.93$  m a<sup>-1</sup>.

#### 4.2.3. Inactive part of the moraine

The part of the moraine that was not affected by debris flows and falls was also transformed, but to a lesser degree (Figs. 6 and 8). The mean surface lowering was between  $-0.02$  and  $-0.05$  m per week. The total volume loss, which was interpreted as the effect of dead-ice downwasting, was from 30 to 45 m<sup>3</sup> per week. On an annual scale, the mean elevation changes were  $-0.26$  m a<sup>-1</sup>.

#### 4.3. Ebbabreen – Location III

Location III was situated close to the clean ice margin (~300 m) within the inner part of the moraine complex. Clast-supported diamicton with silty-sandy matrix was the

dominant lithofacies. The primary source of the debris was most probably lateral moraine, from which debris was transported further downslope by gravitational processes. One debris flow (site 6) was surveyed in 2013 and 2014. It consisted of a 20 m wide vertical headwall (up to 0.7 m thick of diamicton cover), a gentle sloped transition zone with exposed dead-ice, and a narrow channel and depositional fan, which was partly removed by the stream. Debris from the headwall fell into the transition zone, where, after saturation, it started to move downslope. Subsequently, the debris flow was channelized and flowed down into the stream.

#### 4.3.1. Site 6

The surface of site 6 was unevenly transformed during the first week of survey (week 3) (Fig. 9). Almost 50 m<sup>3</sup> of debris and ice was lost. Changes covered an area that made up almost 90% of the site area. The largest lowering of the surface, by up to 1.5 m, was in the headwall area. The amount of deposition was slightly more than 22 m<sup>3</sup> per week. Deposition occurred mostly within the transition zone, as well as within the fan. The maximum elevation of the surface uprising was 0.5 m. In 2014, the site became inactive – debris flow stopped and the ice-core was covered by debris, which protected it from melting. On an annual temporal scale, the amount of volume change was almost  $-280$  m<sup>3</sup>, and the mean elevation changes were  $-0.43$  m a<sup>-1</sup> (Fig. 6).

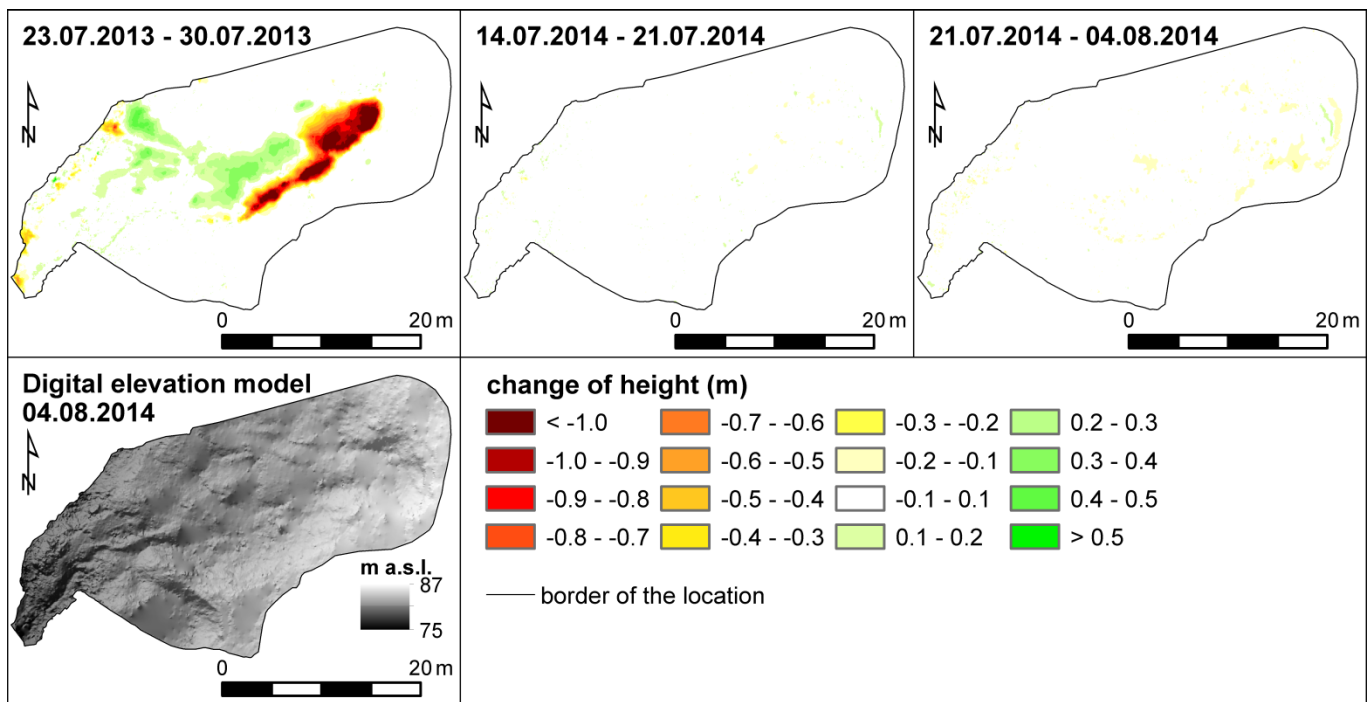


Figure 9. DEMs of Differences (DODs) showing the spatial distribution of surface transformation – location III, Ebbabreen

#### 4.3.2. Inactive part of the moraine

For the part of the moraine not affected by debris flow, deposition had a slight advantage over erosion; however, this part was generally stable and in ~50% of the surveyed area no changes were recorded. The gain in debris of almost  $7 \text{ m}^3$  during week 3 and almost  $10 \text{ m}^3$  in week 5, mostly delivered from the upper part of the slopes, locally upraised the moraine surface by almost 0.3 m (Fig. 9). Short-term mean elevation changes were between  $-0.03$  and  $0.01 \text{ m}$  per week, whereas during the year of observation the mean elevation changes were  $-0.06 \text{ m a}^{-1}$ .

#### 4.4. Ragnarbreen – location IV

Location IV was situated in the foreland of Ragnarbreen, in the transition zone between the lateral moraine and frontal moraine complex. Massive, medium-grained, matrix-supported diamicton with a moderate amount of clasts was the most common in that part of the moraine. The matrix was comprised mainly of sands and fines. Clasts, usually subangular, were scattered within the matrix. A large debris flow (site 7) was surveyed. The main activation mechanism was related to the removal of

debris cover by the stream flowing from the small valley, next to the glacier. The total scanned area for this location was almost  $5300 \text{ m}^2$ . Active debris flow was between  $1200$  and  $1500 \text{ m}^2$  during the first year of survey. The active part consisted of a  $1.8 \text{ m}$  vertical headwall of diamicton. Dead-ice was exposed underneath. The relatively flat niche became the transition zone into which debris fell. Subsequent dead-ice melting and saturation of sediments mobilized the debris flow. Finally, the material was delivered to the stream and transported down the valley.

##### 4.4.1. Site 7

The surface of the site was unevenly transformed during the survey period (Fig. 10). The short-term (weekly) rates of change in 2012 were much higher than those in 2013. During the week of survey in 2012 (week 2), more than  $130 \text{ m}^3$  of debris were removed. Erosion took place in over 55% of the site area. The largest lowering of the surface by up to  $2.1 \text{ m}$  was related to the retreating of the headwall. The amount of deposition was slightly less than  $60 \text{ m}^3$  per week, leading to accumulation of the debris within the niche. During the week of survey, the maximum value of the surface lowering was  $0.6 \text{ m}$ .



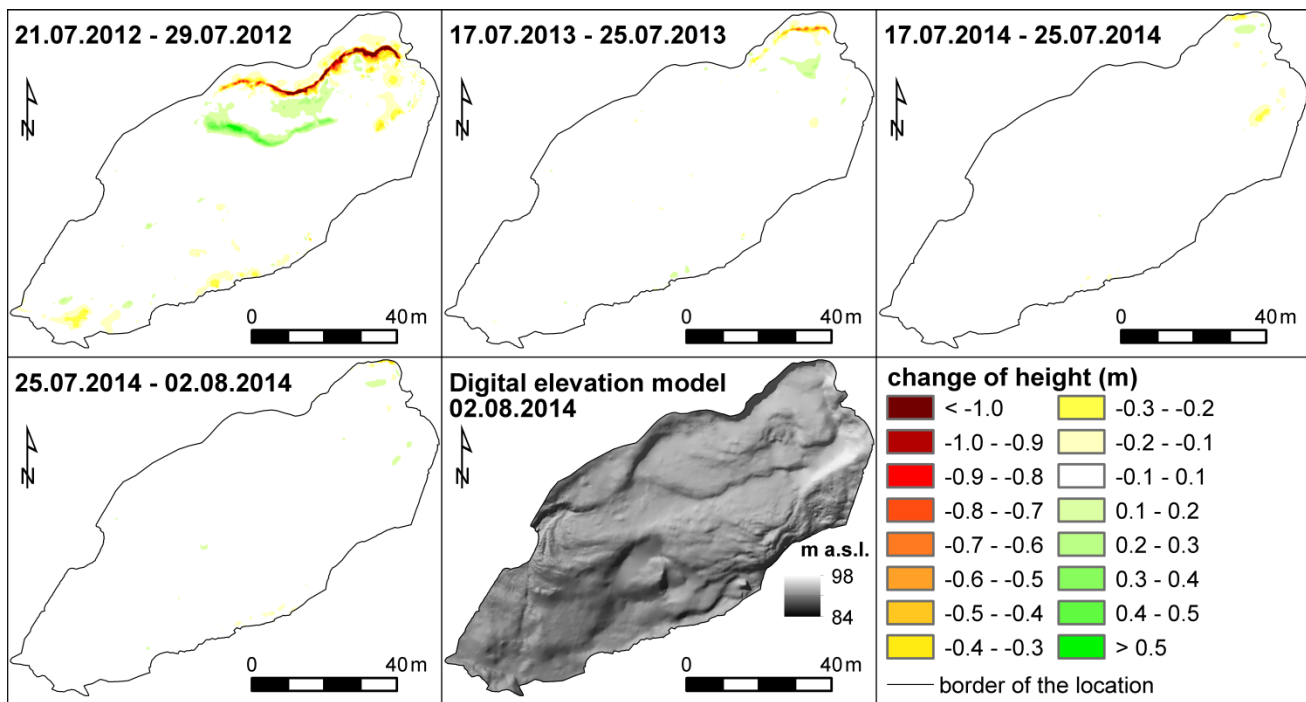


Figure 10. DEMs of Differences (DODs) showing the spatial distribution of surface transformation – location IV, Ragnarbreen.

During the survey in 2013 (week 4), the direction and pattern of changes were similar to the previous year. However, the changes were much smaller. Material loss occurred in 47% of the site area. The loss of 9 m<sup>3</sup> of debris locally lowered the site surface by 1.9 m (Figs. 6 and 10). The amount of deposition was ~3 m<sup>3</sup> of material, and the maximum increase in the elevation of the surface was 0.7 m. Deposition concerned 16% of the site area, and the material was deposited mainly in the niche. In 2014, the site became inactive. Debris flow stopped acting and only minor transformations related to the debris falling from the headwall were recorded.

On an annual time scale, some differences have been noticed between 2012/2013 and 2013/2014 (Fig. 6). In Year 1, active processes operated over a larger area and in a more intensive way – the volume change was –325 m<sup>3</sup> and the headwall retreated by more than 6 m. The study area was lowered locally by 2.1 m. Debris deposition took place in 40% of the site area – mainly within the niche, where a debris flow lobe was formed and some finer material was washed out (Fig. 10). Locally, the surface was raised by 0.4 m. The mean elevation changes were –0.22 m a<sup>-1</sup>. In Year 2, the active area decreased and the volume change was –176 m<sup>3</sup>. The headwall retreat was 3.9 m, and the mean elevation change was –0.14 m a<sup>-1</sup>.

#### 4.4.2. Inactive part of the moraine

The part of the moraine that was not altered by the active debris flow also underwent some transformations;

however, in more than 60% of the scanned area no changes were recorded during week 2. Transformations in week 4 (2013) and in weeks 6 and 7 (2014) were also small, and most of the area remained stable. The mean short-term elevation changes were from –0.01 to 0.0 m per week.

During Year 1, the volume loss was about 126 m<sup>3</sup> and took place in over 49% of the scanned area, whereas a deposition of 13 m<sup>3</sup> took place in over 40% of the scanned area. The maximum surface lowering was up to 0.4 m, whereas elevation increased locally at up to 0.2 m. In Year 2, the amount of volume gain and loss was almost the same (~75 m<sup>3</sup>), and the mean elevation changes were 0.0 m a<sup>-1</sup>.

#### 4.5. Intensity of the disintegration of ice-cored moraines

##### 4.5.1. Transformations due to active mass wasting processes

The surfaces of the seven studied sites were altered by a wide range of active processes including debris flows, debris falls and slides, and dead-ice melting (from both downwasting and backwasting). Negative mass balances of all sites indicate that melting of the ice-cores and removals of the debris out of the surveyed sites were more important than debris deposition. The intensity of the ice-cored moraine's wastage, however, was distributed

unevenly in time and space. The examined sites differed in dimensions. To compare them with each other, we used standardized data, namely, the total change in volume (the loss of debris and dead-ice + deposition of debris) in a given field divided by its surface area (Supplementary Tables A3 and A4), which resulted in the average elevation changes recorded for a given site.

The average annual change in the elevation of the surfaces (Fig. 11) that were actively remodelled by the mass movement processes in Year 1 (between July 2012 and July 2013) ranged from  $-0.22 \text{ m a}^{-1}$  for site 7 to  $-1.59 \text{ m a}^{-1}$  for site 3. During Year 2 (between July 2013 and July 2014), the mean elevation changes varied from  $-0.14 \text{ m a}^{-1}$  for site 7 to  $-1.83 \text{ m a}^{-1}$  for site 3. The extreme changes were also quite diverse. Within the two years of survey, the maximum amount of local reduction in moraine surfaces ranged from  $-1.0 \text{ m}$  for site 4 to  $-7.9 \text{ m}$  for site 3. The highest values of surface elevation changes were related to the retreat of the headwalls and backwasting of ice-cliffs. The mean annual rate of the retreat also varied

greatly from 3.9 to 25.8 m (Fig. 12). However, the material removed from the headwalls was often partly deposited subsequently within the sites. The maximum values of local deposition within a year ranged from 0 m for site 5 to 1.1 m for site 3. Much smaller rates of debris deposition compared to erosion indicated the importance of material removal outside the moraine complex and/or dead-ice melting. The relief transformations were, however, not evenly distributed during the year, and with considerable intensive actions during the summer period. Thus, we also focused on comparing the short-term changes during the melting season's peak.

Weekly transformations during summer (Fig. 13) ranged from  $-0.02 \text{ m}$  per week for site 7 to  $-0.73 \text{ m}$  per week for site 2, which correspond to an average daily value of  $-2.5 \text{ mm}$  per day and  $-104.4 \text{ mm}$  per day, respectively. Moreover, some of the sites were much more active during one week, only to become far less active during the subsequent week.

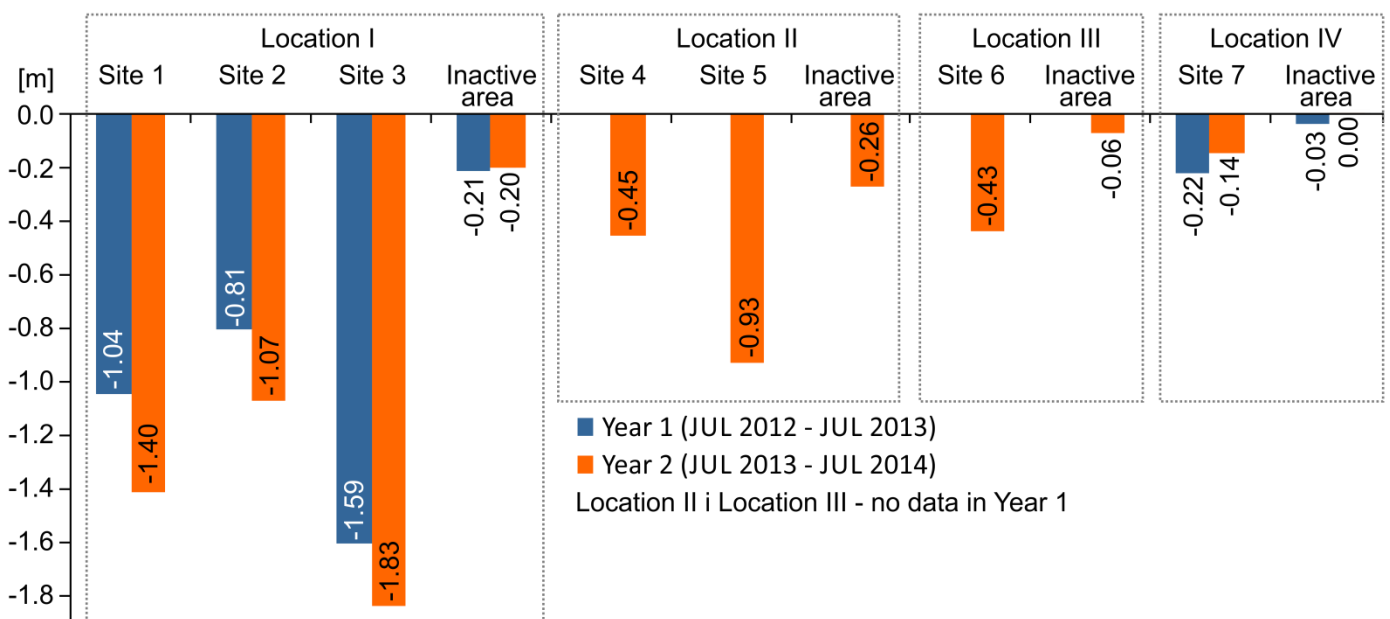


Figure 11. Mean annual elevation changes for studied sites, Ebbabreen (Locations I, II and III) and Ragnarbreen (Location IV)

For three sites (Sites 1, 2 and 3 – Ebbabreen foreland), the short-term dynamics of surface transformation were extremely intensive. The weekly amount of volume loss (including both debris removal by erosion and dead-ice melting by backwasting and downwasting) was usually more than  $0.15 \text{ m}^3 \text{ m}^{-2}$ , which caused serious changes in the relief. The main mechanisms of the surface transformations were debris flows on more gentle slopes and debris falls and slides on steeper sections of the ice

walls. The main factors contributing to these substantial changes were the following:

- Continuous delivery of meltwater from glacier or other non-glaciated valleys, which contributes to the removal of debris (sliding and falling downslope) from the bottom of the slope.
- Exposition of ice cores which contributes to the amount of excess meltwater and mobilization of debris.

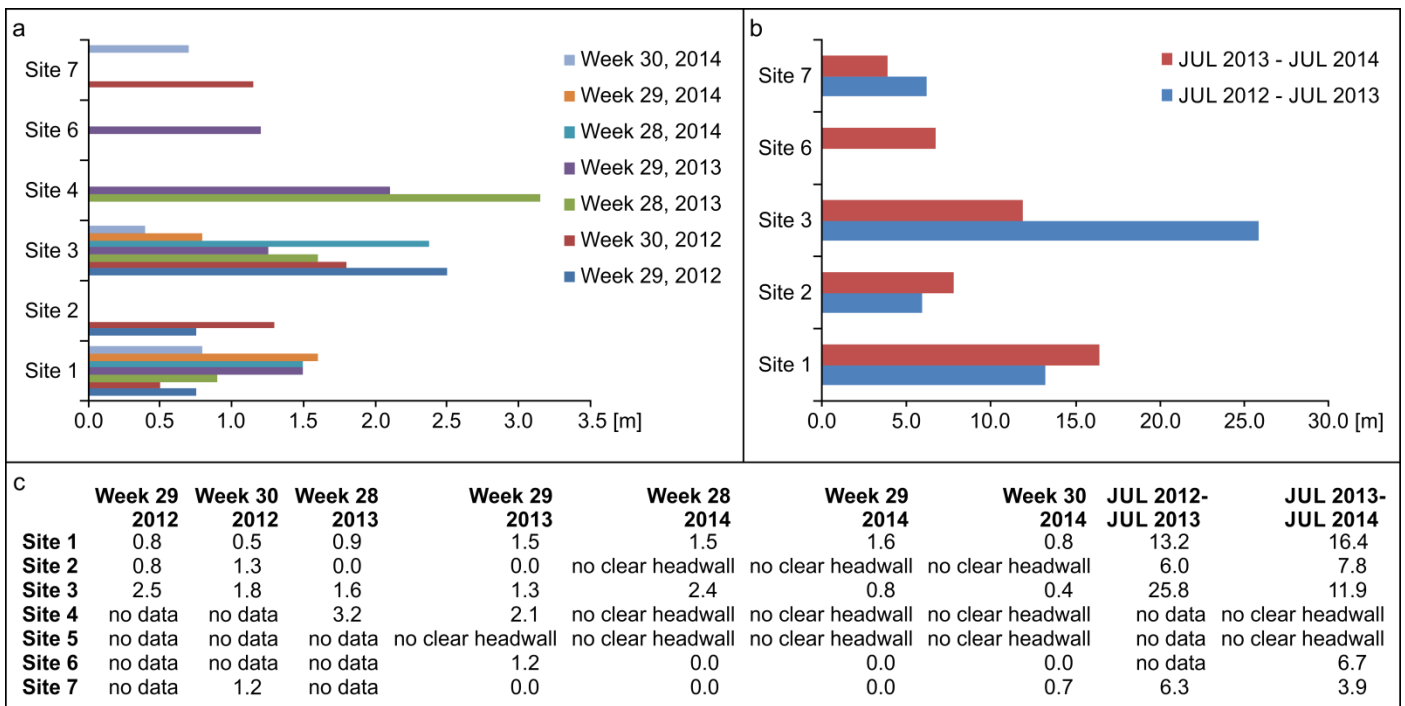


Figure 12. Weekly (a) and annual backwasting rates (b). Note that for some of the periods, no data were available or no clear headwalls were visible for some sites (c). Site 5 was not included due to lack of a clear headwall

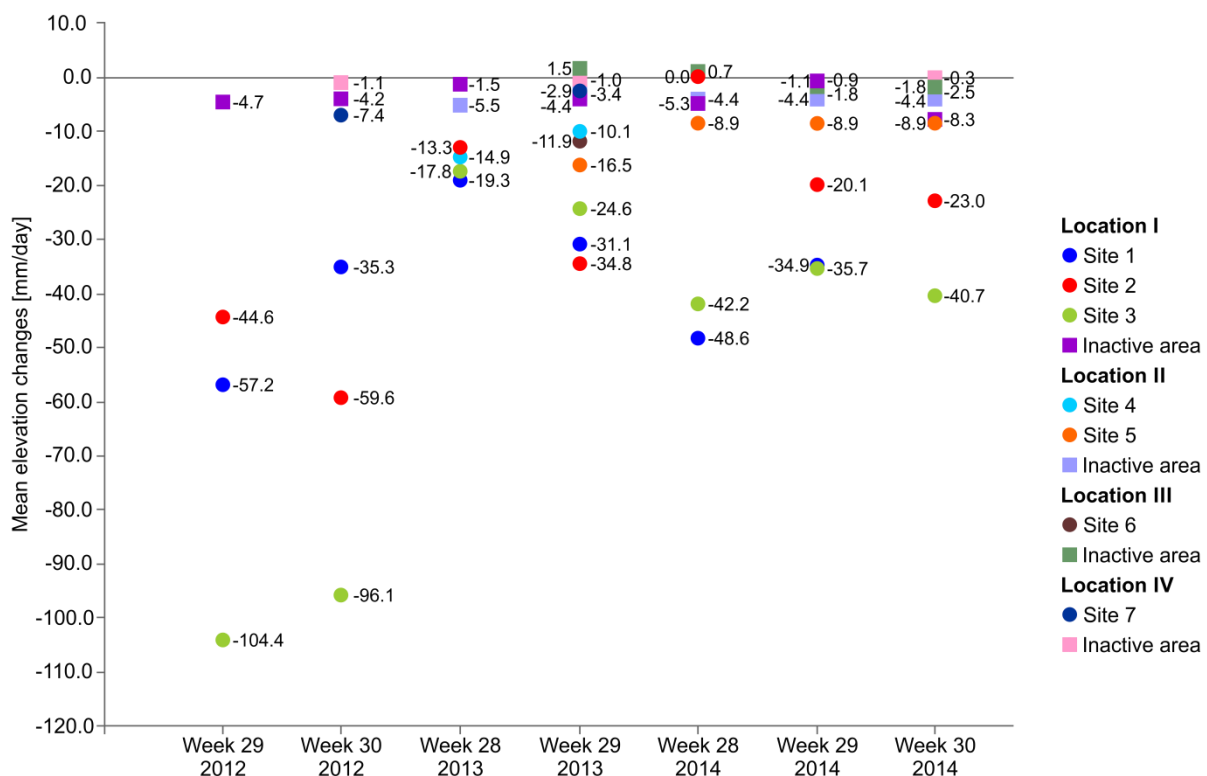


Figure 13. Mean daily elevation changes during the melting season's peak, Ebbabreen (Locations I, II and III) and Ragnarbreen (Location IV).

- General steepness of the slope, causing it to become unstable.

were of less importance. Limitation of surface changes was mainly due to the topography. More gentle slopes caused slower processes, as well as limited exposition of the ice-cores and favoured debris flows over sliding and falling of grains and boulders.

Four other sites showed a moderate degree of transformation. The short-term volume loss was between 0.02 and 0.15 m<sup>3</sup> m<sup>-2</sup> per week. The most common process for these sites was debris flows. Debris falls and slides



#### 4.5.2. Transformations attributed to dead-ice downwasting only

The remaining parts of the surveyed areas showed no signs of intensive mass movement processes and sediments remobilization during the studied periods. Therefore, we attributed changes in the surface relief and volume mostly to dead-ice downwasting alone. The average annual change in elevation was from 0.0 m a<sup>-1</sup> for Ragnarbreen (location 4) to -0.26 m a<sup>-1</sup> for Ebbabreen (location 3) (Fig. 11). However, the maximum localised lowering was much larger, reaching -1.4 m for Ebbabreen and -0.4 m for Ragnarbreen. The weekly surface elevation change rates also varied, reaching average values of +0.01 m to -0.06 m per week (1.5 to -8.3 mm per day; Fig. 13).

## 5. Discussion

### 5.1. Comparison with short-term dead-ice melting rates

A direct comparison of our main results (i.e. volumetric changes of landforms attributed to both dead-ice melting and sediment redistribution) with findings reported in other studies was limited, as repetitive scanning and assessment of the volume changes were not common. In a recent study, Irvine-Fynn et al. (2011) reported an average annual transformation of the Midtre Lovénbreen (ML) foreland at -0.05 m a<sup>-1</sup>, based on two LiDAR surveys in 2003 and 2005. However, a much higher transformation attributed to the degradation of the ice core was observed for the western moraine ridge of ML (-0.65 m a<sup>-1</sup> of elevation changes and -219 000 m<sup>3</sup>). Our results showed that annual, passive transformations related to dead-ice melting were between 0.0 and -0.3 m a<sup>-1</sup>, while active transformations related to common impact of dead-ice melting and mass wasting processes were larger, reaching even more than 1.8 m a<sup>-1</sup>. These differences most probably resulted from 1) different approaches – Irvine-Fynn et al. (2011) provided averaged values over the entire area of the western moraine ridge, whereas our study only focused on changes related to the active parts; and 2) different resolutions of the elevation data (1×1 m versus 0.05×0.05 m cell size). Most of the other studies dealing with short-term changes focused on the quantification of dead-ice melting, and used different methods like measuring backwasting rates or assessing downwasting values. Hence, to evaluate our results we compared backwasting rates (mean daily and annual values) with results obtained for other glaciers based on the most recent comparison of

the short-term dead-ice melting rates provided by Schomacker (2008).

The retreat of the debris headwalls was used as a proxy for dead-ice backwasting. Results of our study indicate that the mean daily values of the headwall retreat (for the sites where retreat occurred) varied from 7 to 45 cm per day. Values reported in other studies from Svalbard varied significantly, e.g.: 2 cm per day (Etzelmüller, 1995 in Schomacker, 2008), 5–30 cm per day (Bennett et al., 2000), 3–15 cm per day (Schomacker and Kjær, 2008), and 3.5–7.8 cm per day (Lukas et al., 2005).

The measured annual values of the headwall retreat for Ebbabreen and Ragnarbreen ranged from 3.9 to 25.8 m a<sup>-1</sup>. The mean annual value of headwall retreat for five sites with clearly defined headwalls and for two survey seasons (i.e. 2012–2013 and 2013–2014) was 10.9 m a<sup>-1</sup>. This is higher than most of the normalized backwasting values reported for other sites (cf. Schomacker, 2008). The values provided in our study are based on actual surveys of the same sites in different periods (i.e. they are not extrapolated values based on a series of daily measurements), which may at least partly explain the difference. Moreover, our data showed that the transformations even within one moraine complex were not uniform in time and space, and that the sites which are active in one season can be almost completely stable in the next. To sum up, the results from Ebbabreen and Ragnarbreen are higher than previously reported from Svalbard, and are also higher than or of similar magnitude to the values reported from different climatic zones such as Iceland, the Himalayas and the European Alps (Krüger and Kjær, 2000; Benn et al., 2001; Kjær and Krüger, 2001; Han et al., 2010; Pelfini et al., 2012). Together with the evidently high local variability in dead-ice melting and sediment redistribution, it confirms the suggestion of Schomacker (2008) that these processes are more related to local factors such as topography and abundance of meltwater than climatic conditions.

### 5.2. Short-term versus long-term dead-ice melting

This study deals with short-term transformations of ice-cored moraines in the period 2012–2014. We demonstrated that the short-term dynamic of volume changes (mass balance) in the active part of ice-cored moraines was substantial, with volume lowering even up to 1.8 m a<sup>-1</sup>. Much more limited transformations (0.0 to

$-0.3 \text{ m a}^{-1}$ ) were attributed to the degradation due to dead-ice downwasting alone.

On the other hand, the mean long-term values of ice-cored moraine degradation are usually not so high. The mean elevation change for the whole end moraine complex of Ragnarbreen in the period 1961–2009 was  $-0.033 \text{ m a}^{-1}$  (Ewertowski, 2014). Schomacker and Kjær (2008) reported  $0.9 \text{ m a}^{-1}$  of mean annual surface lowering for the ice-cored moraines of Holmströmbreen in the period 1984–2004. Values of a similar magnitude were also presented for several Icelandic glaciers:  $0.015\text{--}0.80 \text{ m a}^{-1}$  for ice-cored moraines of Kvíárjökull (Bennett and Evans, 2012),  $0.10\text{--}0.18 \text{ m a}^{-1}$  for Brúarjökull (Schomacker and Kjær, 2007), and  $0.3\text{--}1.4 \text{ m a}^{-1}$  for Kötlujökull (Krüger and Kjær, 2000).

In order to check if the recent high values of dead-ice melting rates were related to the possible increase in air temperature, we plot the mean monthly temperature for the period 1976–2014 (Fig. 14). The data are from the nearest all-year round operating automatic weather station located near the Longyearbyen (Svalbard Lufthavn),  $\sim 60 \text{ km SW}$ . The correlation between mean air temperatures at Petuniabukta and Svalbard Lufthavn was reported to be

high, and summer temperatures were similar or slightly warmer at Petuniabukta (Rachlewicz and Styszyńska, 2007; Láska et al., 2012). The mean air temperature in the summer months of 2013 and 2014 was slightly higher than the long-term mean for the warmest month. In our opinion, it is not very probable that such relatively small increase in the temperature could impact dead-ice melting rate to a significant degree. However, to fully assess the impact of long-term summer temperature rise on dead-ice melting rate, it would be necessary to have a detailed, long-series meteorological data for the studied sites or their direct vicinity. More probably, the main reason for the apparent disagreement between short-term and long-term melting values is related to the high variability of the debris flow activity in time and space. Most of the debris flows and exposed ice walls are active only for relatively short periods. For example, some of the studied sites were only active during one or two seasons before their activity stopped altogether. Moreover, the presented values are restricted to the melting season's peak and are mainly related to the most active part of the moraines. The short-term changes in the non-active parts of the moraines (i.e. attributed to the dead-ice downwasting only) were between  $0$  and  $-0.3 \text{ m a}^{-1}$ , which generally accord with long-term melting rates observed elsewhere.

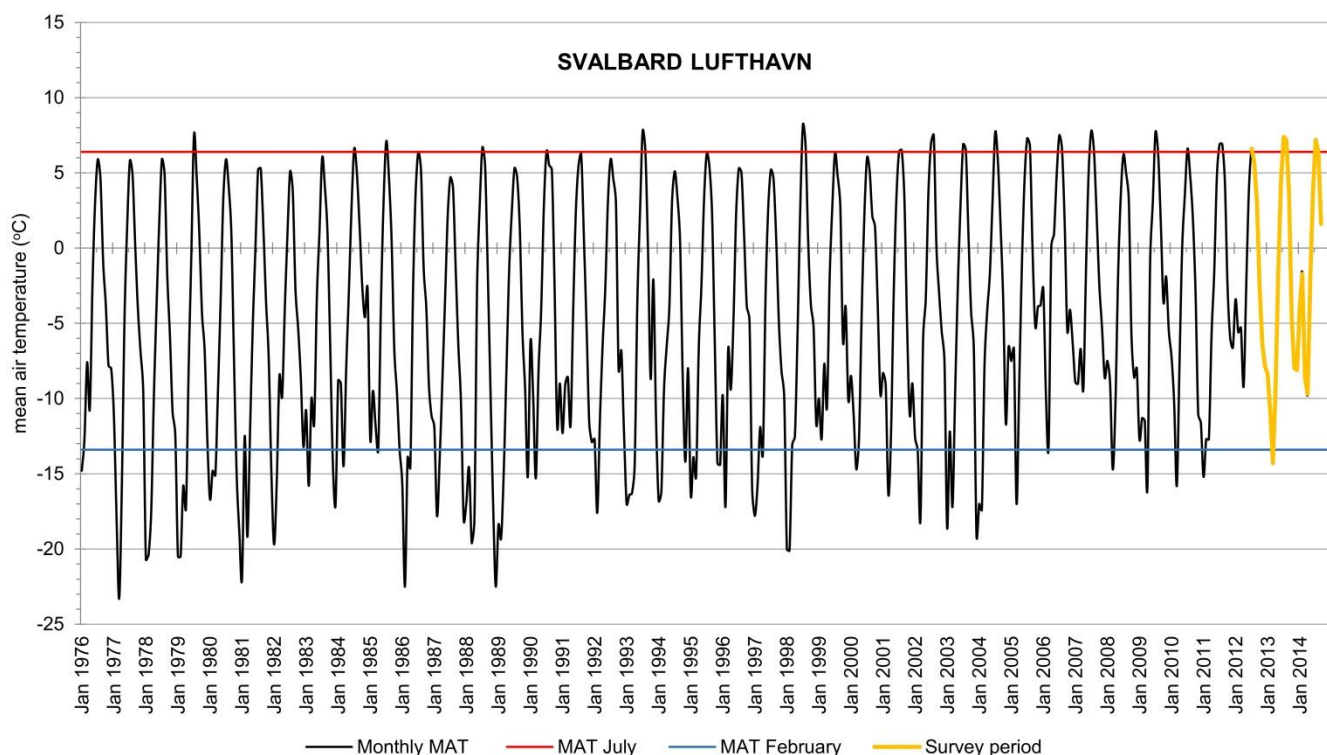


Figure 14. Mean monthly air temperature for Svalbard Lufthavn based on data from the Norwegian Meteorological Institute (<http://eklima.met.no>) for the period 1976–2014

### 5.3. Spatial distribution of the transformation intensity

All of the studied locations contained large amounts of dead-ice covered by a relatively thin veneer of debris (0.6–2.3 m). The recorded changes, however, varied greatly. Based on dynamics of the studied areas, we proposed three types of transformation of the ice-cored moraines:

- High transformation activity – with rapid and intensive mass wasting movements driven by external factors (e.g. meltwater streams) or the exposition of ice cores and steep slopes.
- Medium transformation activity – with mainly debris flows developed on more gentle surfaces.
- Low transformation activity – with no active debris flows observed, hence transformed mainly by dead-ice downwasting.

We attempted to upscale the results of our study to the whole ice-cored moraines for both glaciers. This is based on: (1) field geomorphological investigations, which included mapping of active processes and other evidence related to them (e.g. active debris flows, dead-ice exposures, and tension cracks) as well as mapping of

records of former processes (e.g. inactive debris flow lobes, mass wasting deposits); and (2) analysis of remote sensing materials and DEMs (e.g. slope and aspect analysis) – we divided the moraine complexes of Ragnarbreen and Ebbabreen into one of the three categories described above (Fig. 15). For example, if active debris flows and exposed dead-ice have been observed during two summers, we classified such area as actively transformed. On the other hand, when no traces of geomorphic activity could be noticed, transformation of such area was classified as low. Each type of transformation activity has been related to the averaged amount of changes based on our studied sites, which allowed us to estimate the potential activity of the moraine complexes of Ebbabreen and Ragnarbreen during seasons 2012 and 2013. The main limitation of such approach is the fact that lateral moraines are transformed by much larger debris flows; hence it is possible that the volume of alterations is larger than expected. It also has to be stressed that the dynamics of these zones will be different in the future due to changes in debris cover and its insulating effect, as well as changes in slope topography. Despite the limitations, such an approach can be useful for comparison between glaciers.

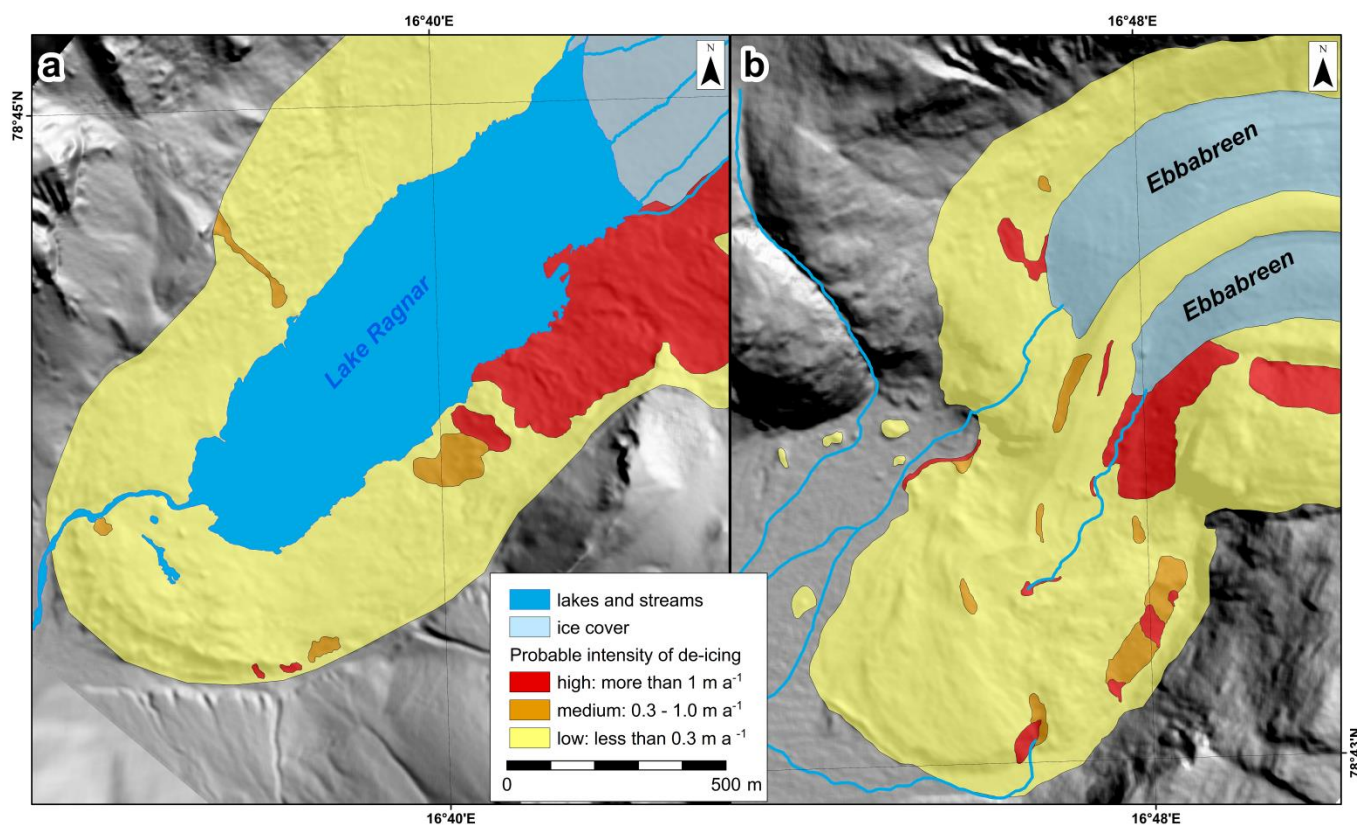


Figure 15. Potential amount of volume loss during the season 2012–2013 for ice-cored moraine complexes at Ragnarbreen (a) and Ebbabreen (b).



#### 5.4. Geomorphic activity - factors contributing to the transformation of ice-cored moraines

The three different degrees of transformation activity mentioned above (low, medium, and high) occur unevenly in space and time. Relatively large areas of ice-cored moraines in the foreland of the studied glaciers seemed to be stable or transformed to a very low degree, which suggest that they were in equilibrium with current topographic and climatic conditions. On the other hand, the remaining areas were transformed very intensely by various processes. There are a couple of factors which can contribute to the shift in a given area from one degree of transformation to another. The most important processes which led to the transformation of ice-cored moraines are gravitational mass movements (Boulton, 1968, 1970a; Lawson, 1979, 1982; Bennett et al., 2000; Kjær and Krüger, 2001; Lukas et al., 2005). However, their initiation is usually related to other factors. Gravitational mass movements occur when the force of gravity affecting the sediment is stronger than the friction forces which prevent grains from moving. The main factors causing the reduction in friction and shear strength are water and slope gradient (Lawson, 1979, 1982; Krüger, 1994; Schomacker, 2008; Schomacker and Kjær, 2008). Below, we present a short description of elements contributing to changes in the amount of water and degree of slope in the case of the studied sites:

##### 5.4.1. Water sources

In most cases, mass movements need a water source which can cause liquefaction of sediments and thus allows for lowering of the shear strength within the debris cover (Lawson, 1979; Pierson and Costa, 1987). Internal water sources within ice-cored moraines are related to degradation of the dead-ice (ice-cores). In the case of Svalbard, their susceptibility to melting depends on the thickness of the active layer. This means that when the thickness of the debris cover is lower than the thickness of the active layer, dead-ice can start to melt and deliver the water necessary to initiate the mass movement processes. The most important external water sources are related to the melting of snow which occurs mostly during spring and rainfalls. In the case of the central part of Spitsbergen, which is a dry, polar environment (Rachlewicz and Styszyńska, 2007; Rachlewicz, 2009), the amount of precipitation is very low; for example, in seasons 2000–2003, the sum of precipitation during summer months varied from 33 to 59 mm (c.f. Rachlewicz and

Szczuciński, 2008). Hence, this source is far less important than the internal water source from dead-ice melting.

##### 5.4.2. Drivers of topographical changes

The increase in slope gradient can cause an increase in the activity of mass movement processes. Some of the possible factors contributing to the over-steepening of a slope are streams and meltwater channels. They cut into a slope and remove the material from the basal part of the slope, thus changing the topographic profile and increasing the slope gradient. In that way, mass movements are facilitated. Subsequently, mass movements remove debris from slopes, leading to the creation of instability in the upper part of the slope, and thereby propagating mass movement development in the upslope direction.

Topography and water are usually related to each other. An increasing amount of water within a slope increases the mass of sediments, and at the same time separates grains, causing a reduction in friction and shear strength. If the critical value of the slope is then crossed, sediments will flow down, causing an increase in gradient and instability in the upper part of the slope (Lawson, 1979; Pierson and Costa, 1987). Sediments which slump, flow, or fall to the base of the slope can be subsequently removed by streams. Removal of sediments from the slope base efficiently eliminates support for the upper part of the slope, subsequently causing instability.

Transformations within ice-cored moraines change also in time, and are related to the period of deglaciation and debris cover development (Boulton, 1967; Lukas et al., 2005). At the first stage, shortly after deglaciation when the debris cover is thin (thinner than the permafrost active layer's thickness), mass movement processes become fairly common. They are facilitated by the dead-ice melting and steepness of the slopes (Lawson, 1979, 1982). This stage can be observed in many lateral moraines, which are characterised by steep slopes, abundance of active mass movement processes, and by consequence a high degree of transformation.

Ongoing mass wasting processes lead to the transfer of sediments from steep slopes to more stable positions. As the thickness of the sediments increases, the debris cover starts to protect the dead-ice from melting and also contribute to the decrease in slope gradient (Krüger and Kjær, 2000; Kjær and Krüger, 2001). Thus, the resulting landscape is relatively stable and in equilibrium with

current climatic and topographic conditions. This stage characterises most parts of the frontal (end) moraine complex of the studied glaciers; thus, their transformation rates are either very low or close to zero.

Some parts of this stable landscape can be subsequently transformed again into an unstable state, mainly due to the effect of external factors such as streams or meltwater channels. This can lead to the development of mass movement processes and further slope instability, which could facilitate subsequent generation of debris flows. Sites shown in this paper are examples of such situations, i.e., activation of formerly stable landscapes due to meltwater activity, and thus are characterised by a high rate of relief transformation.

Stages described above can occur in a sort of spatio-temporal cycle, and, depending on local and external factors, the changes between stabilization of landforms and activation of mass flows can be repeated several times for any given area until the dead-ice is completely melted.

## 6. Conclusions

Many of the modern moraine complexes on Svalbard are comprised of large amounts of dead-ice covered by a relatively thin veneer of debris often less than a couple of metres thick. During deglaciation, these ice-cored landforms are subjected to various resedimentation processes, which finally will lead to the creation of a more stable landscape. This study quantified the short-term cm-scale transformation of ice-cored landforms in the high-Arctic settings of Svalbard.

We applied repetitive reflectorless robotic scanning to quantify and monitor landform changes, which seemed to have been a proper method for use in a harsh Arctic environment. Developing DODs proved to be a valuable illustration of relief transformation and calculation of volume changes. The proposed method was used in seven sites located in the forelands of two glaciers, and was found to have been an effective workflow for assessing relief dynamics in an ice-marginal environment.

The amount of volume loss due to the active mass movement processes and dead-ice melting, including both backwasting and downwasting, was up to  $>1.8 \text{ m a}^{-1}$ . In comparison, the amount of volume loss due to dead-ice downwasting was significantly lower at a maximum of  $0.3 \text{ m a}^{-1}$ . The spatial and temporal distributions of volume changes, however, were quite diverse and for the most part

related to local geomorphic conditions such as slope gradient, occurrence of streams, and meltwater channels.

The results of this study and previous investigations based on the analysis of historical DEMs (Ewertowski, 2014) suggest that large parts of the frontal (end) moraine complexes of the studied glaciers are in equilibrium with current topographic and climatic conditions. However, where external drivers are behind slope instability, the transformation of landforms can be very high, leading to rapid degradation and dead-ice melting. Our results support the hypothesis of a spatio-temporal switching between stable and active conditions within an ice-marginal environment.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.geomorph.2015.01.023>.

## Acknowledgements

The project including research presented in this paper was funded by the National Science Centre as granted by decision number DEC-2011/01/D/ST10/06494. The Aleksandra Tomczyk Fellowship at York was funded by the Polish Ministry of Science and Higher Education within the framework of the “Mobility Plus” program. We also would like to extend our special thanks to members of the Poznań Polar Expeditions to Petuniabukta, whose help during the fieldwork is greatly appreciated. We are grateful to Margaret O'Donnell for proofreading the manuscript. Reviewers Grahame Larson and Anders Schomacker provided highly valuable comments and suggestions which greatly improved the quality and clarity of the manuscript. We also thank the editor, Takashi Oguchi, for his help and comments.

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