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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 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 m a^{-1}. However, most of the transformation occurred during summer, with the short-term values of mean elevation changes as high as -104 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 m a^{-1}, whereas lowering during summer was up to 8 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.

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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, 2005; Bamber et al., 2005; Nuth et al., 2007, 2010; Rachlewicz et al., 2007; Zagorski et al., 2008, 2012; Sund et al., 2009; Moholdt et al., 2010a,b; 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-

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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^3. Thus, its melting can cause serious changes to the local environment.

Most of the quantitative studies of glacial landforms in Svalbard 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) was 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^2 of the glaciers' forelands has 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 vectorized manually using the orthophoto.

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; Etzelmüller 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 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 characterized 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.

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

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