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Sedimentological characteristics of debris flow deposits within ice-cored moraine of Ebbabreen, central Spitsbergen

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Abstract: The Ebbabreen ice-cored moraine area is covered with a sediment layer of up to 2.5 m thick, which mostly consists of massive diamicton. Due to undercutting by lateral streams, debris flow processes have been induced in marginal parts of this moraine. It was recognized that the sedimentology of deposits within the deposition area of debris flows is the effect of: (1) the origin of the sediments, (2) the nature of the debris flow, and (3) post-debris flow reworking. Analysis of debris flow deposits in microscale (thin sections) suggests a common mixing during flow, even though a small amount of parent material kept its original structure. The mixing of sediments during flow leads to them having similar sedimentary characteristics across the deposition area regardless of local conditions (*i.e.* slope angle, water content, parent material lithology). After the deposition of sediments that were transported by the debris flow, they were then reworked by a further redeposition process, primarily related to meltwater stream action.

Key words: Arctic, Svalbard, debris flow, moraine, redeposition, micromorphology.

Introduction

The recent decades have been marked by a commonly observed rapid recession of glaciers, particularly in subpolar and mountainous regions (Oerlemans 2005). The effects of the recession are far-reaching because the melting glaciers contribute to rise in sea-level (Jacob *et al.* 2012). One of the regions where rapid changes in the glaciers' mass balance and geometry has been documented is Svalbard (*e.g.* Hagen and Liestøl 1990; Jania and Hagen 1996; Nuth *et al*. 2007; Sund *et al*. 2009; Małecki *et al*. 2013). Besides those glaciers, the increasing focus on Svalbard is also explained by the de-icing of ice-cored moraines (*e.g.* Bennett *et al*. 2000; Lønne and Lyså 2005; Lukas *et al*. 2005; Schomacker and Kjær 2008; Evans *et al.* 2012; Ewertowski 2014; Ewertowski and Tomczyk 2015) which, apart from being a water storage, are important temporal storage of sediments (Etzelmüller 2000; Szczuciński *et al*. 2009).

Formation of many ice-cored moraines in Svalbard occurred after the Little Ice Age (LIA) at the beginning of the 20^{th} century (Nordli and Kohler 2003) as a result of the shrinking and recession of glaciers in this high Arctic archipelago (Oerlemans 2005; Nuth *et al*. 2013). During the first phase of ice-cored moraines' formation, sediments are released from ice via melting-out (*e.g.* Etzelmüller *et al*. 1996) and being redistributed by pervasive debris flows (*e.g.* Sletten *et al*. 2001; Ewere-towski *et al*. 2012). The melting-out from the ice core is active beneath the sediments layer until the sediments would attain the thickness of the active layer (Sletten *et al*. 2001; Schomacker and Kjær 2008), and then it is limited only to exceptionally warm summers when the active layer starts to expand (Williams and Smith 1995). In this phase, the major factor in ice-cored moraines' de-icing process is debris flow which, often together with meltwater streams action, leads to exposition of those susceptible for melting ice-walls (Sletten *et al*. 2001; Schomacker and Kjær 2008; Ewertowski *et al.* 2012). This, in turn, results in profound morphological modifications and can lead even to topographic inversions (*e.g.* Bennett *et al*. 2000). It is therefore advisable to recognize the sedimentary record of debris flows, which are so typical of ice-cored moraines. This is particularly important because of the low fossilization potential of those forms (Sletten *et al*. 2001; Bennet *et al*. 2000; Lukas *et al*. 2005; Schomacker and Kjær 2008), and consequently their poor record from former glaciations.

This paper focuses on the sedimentology of debris flow deposits in the Ebbabreen ice-cored moraine. The main aim is to determine the degree of sediment transformation due to debris flows, and to establish the factors that determine the final characteristics of sediments within the debris flow deposition area. To achieve this aim, the following research tasks were adopted:

- sedimentological characterization of sediments exposed in debris flow scars representing the parent material for debris flows;
- grain size analyses of debris flow deposits in various ice-cored moraine zones;
- recognition and interpretation of debris flow deposits' microtextures and microstructures.

Study area

Ebbabreen is a glacier located west of Petuniabukta, which is the northernmost part of Billefjorden (central part of Spitsbergen) (Fig. 1A). The catchment in the Ebba Valley is mostly built of Carboniferous–Permian sedimentary rocks (sandstones, mudstones, gypsum, limestones, anhydrites, dolomites, conglomerates). However, the vicinity of the Ebbabreen ice-cored moraine is mostly built of metamorphic rocks from the Hecla Hoek succession (Dallmann *et al*. 1994).

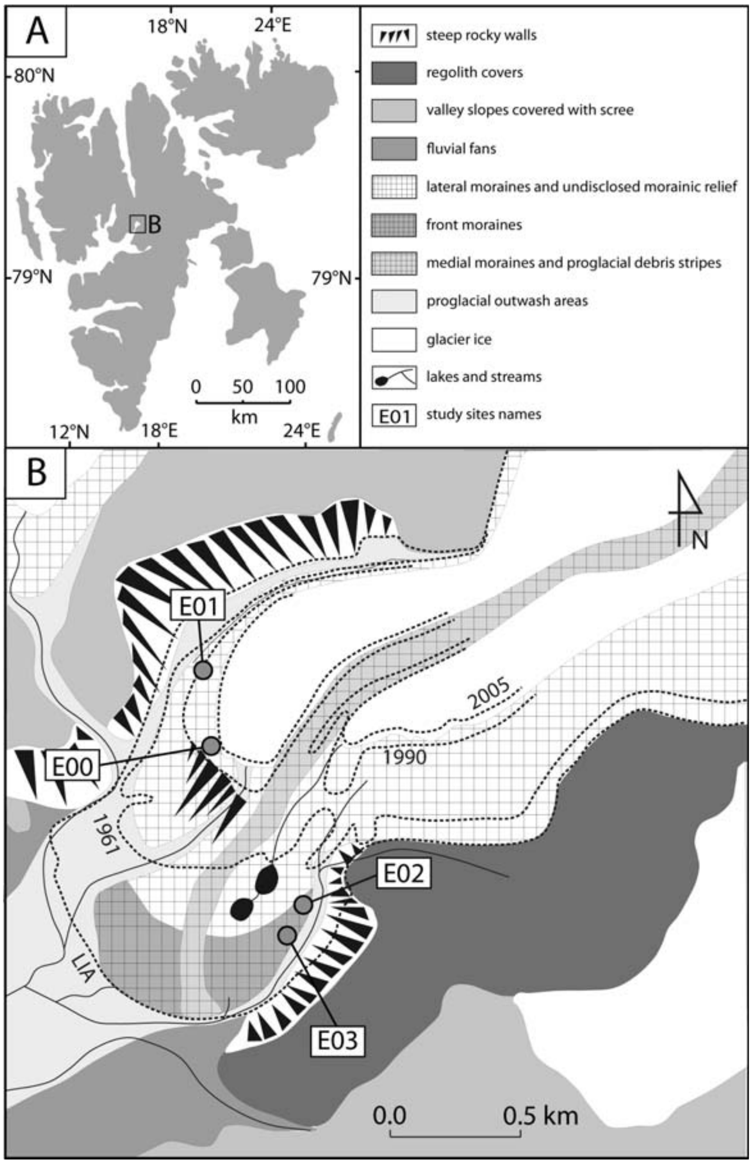

Fig. 1. Localization of the Ebbabreen on Spitsbergen (**A**) with marked study sites within ice-cored moraine (**B**), based on map from Rachlewicz (2009).

The glacier is classified as both an outlet and valley glacier (Rachlewicz 2009). From the north, it drains from Mittag-Lefflerbreen, the main outlet glacier in the northern part of Lomonosovfonna, whereas from the south the glacier is fed from the accumulation fields located beneath the DeGeerfjellet massif and Bastion-, Jackson- and Flemingfjellet nunataks. Ebbabreen descends westward from 1000 to 100 m a.s.l. towards the Ebba valley. The glacier is 6.2 km long and covers an area of 20.4 km^2 (Rachlewicz *et al*. 2007). The Ground Penetrating Radar survey shows that the maximal thickness of the glacier is about 200 m (Małecki, personal communication). Due to the presence of naled ice on the foreland of Ebbabreen, Rachlewicz *et al*. (2007) classified this glacier as polythermal even though some authors note the presence of naled ice also in front of the cold glaciers (Bælum and Benn 2011; Naegeli *et al*. 2014). Rachlewicz (2004) has estimated that the maximum velocity of Ebbabreen is 10.8 m a^{-1}. Since the end of LIA, the glacier was constantly in a state of recession and by the year 2002 its area has shrunk by 1.1 km^2 (Rachlewicz *et al*. 2007).

Ewertowski and Kasprzak (2013) calculated the proglacial area to be 1.15 km^2, with most of it (1.12km^2) consisting of morainic material. There are also several small ponds and outwash fans in the immediate vicinity of the glacier front. The northern part of the ice-cored moraine has almost been completely eroded by meltwater action. Within the ice-cored moraine, frontal and lateral ridges as well as proglacial debris stripes can be distinguished (Fig. 1B).

Methods

Fieldwork was conducted during summer of 2012 on four active debris flow sites. Two of them were located in the frontal part of the ice-cored moraine, and the other two in the lateral part (Fig. 1B). The description of the sediments and lithofacies code is based on the system proposed by Krüger and Kjær (1999).

Samples were collected for grain size and micromorphological analysis. Grain size was analysed in 32 samples, 19 of which were taken from the flow scars (parent material for debris flows) and 13 from the debris flow lobes. Grain size distribution in fraction of >0.063 mm was analysed using dry sieving and in fraction of <0.063 mm, applying a Casagrande-type aerometric analysis. Four statistical grain size distribution parameters were calculated using the Folk and Ward (1957) method: Sk_1 (skewness), σ_1 (standard deviation), M_Z (mean value), and K_G (kurtosis). These parameters are commonly used in the interpretation of sedimentary environments and characteristics of sedimentary processes. For instance, variations in the mean grain size (M_Z) may indicate changes in water flow velocity, the degree of sorting (σ_1) may inform on maturity of the sediments, while skewness (Sk_1) shows enrichment in fine or coarse fraction in relation to the median grain size value.

Five undisturbed samples were collected for analysis of the microstructures and microtextures in thin sections (micromorphology). The preparation of thin sections consisted of drying of samples, impregnation by epoxy resin, as well as cutting and grinding to an approximate thickness of 25–30 μm according to Carr and Lee (1998). The description and interpretation of microstructures were based on Menzies (2000). The presence or absence of certain microstructures within debris flow deposits relates mainly to the amount of water during transport (Lachniet *et al*. 1999) and mechanism of transport (Menzies and Zaniewski 2003; Phillips 2005; Reinardy and Lukas 2009). For the measurement of microtextures, the method of Ramsay (1967) was used, following Phillips and Auton (2008). In this method, the ratios of long and short axis of skeleton grains (Rf) are juxtaposed against the angles of their collapsing (θ).

Results and interpretation

Macroscopic description and grain size composition of debris flow deposits. — Each of the investigated debris flows had south-facing exposure and was undercut by streams, which had initiated the debris flow processes. Their selection was motivated by the criterion of diversity. Two of them had well developed lobes (Figs 2B, 3B), the next two, in turn, were more complex with certain parts of the exposed clean ice (Figs 4B, 5B). The latter contributed to the enhanced amount of water available during the debris flow process. The topography of the studied sites varied from almost flat (<5°, Fig. 2B) to being very steep (>60°, Fig. 5B) slopes, which resulted in various dynamics of debris flows. There are also noticeable differences in the lithology of sediments. Rachlewicz (2009) found that limestones and dolomites are most common rocks in both frontal (above 50%) and lateral (*ca.* 30%) moraines. The contribution of metamorphic rocks (amphibolites and gneisses) is *ca.* 35% in frontal and *ca.* 25% in lateral moraines. Among the accessory rock types are quartzites, schists, sandstones and mudstones.

E00 study site

Description: The E00 study site is located near the glacier's edge, in the northern part of the lateral ice-cored moraine (Fig. 1B). The investigated sedimentological profile in the debris flow scar was almost 2 m in height and was entirely built of massive diamicton (Fig. 2A). Three units were distinguished in this profile, marked by a different colour, matrix type, and clast content (Fig. 2A). All of these units are matrix-supported. The lowermost unit is clast-rich with a gravelly sand matrix, while the upper units have a moderate amount of clasts with sandy silt and silty sand matrix. The lowermost layer contains a boulder (>50 cm) which is partly embedded in the ice-core. The differences are also visible in the grain size analyses, especially in the mean grain size (M_Z) values, which vary from about 1 phi in the lowermost unit to above 3.5 phi in the overlying sediments (Fig. 2A). The lowermost part of the sediments is also characterized by the lowest clay content (6.9%) in comparison to the average value of 10.4% in the overlaying sediments.

The debris flow lobe was slightly inclined (<5°) (Fig. 2B) and had *ca.* 25 m in length. Its sediments are soaked with water and small ponds were present locally on their surface. The central part of the flow lobe was mainly fine-grained, whereas on its edges coarser sediments prevailed. The samples analysed for grain size distribution revealed almost identical results (Fig. 2B). The obtained grain

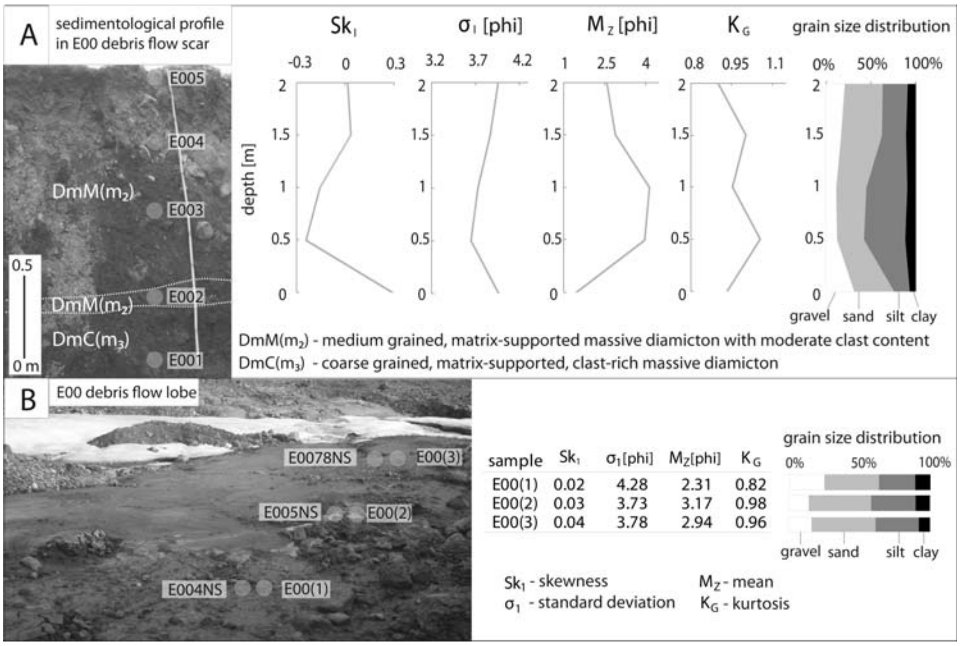

Fig. 2. Sedimentology of the lateral ice-cored moraine study site E00. **A**. Sedimentological profile in E00 debris flow scar with vertical changes in grain size statistical parameters and contribution of major grain size fractions. **B**. E00 debris flow lobe, grain size statistics and contribution of major fractions in the analysed samples. Dots mark samples locations.

size statistics for debris flow deposits are in the range of values documented for the above-described deposits sampled in the debris flow scar (Fig. 2B).

Interpretation: The occurrence of distinct units (layers) in the massive diamictons observed in the debris flow scar is likely connected with earlier redeposition of sediments by debris flows (Lawson 1979). The coarsest, lowermost unit is most likely due to melting-out of material from the ice-core, hence it would be the youngest. This interpretation is supported by the boulder that partly emerged from the ice-core. The overlaying units are interpreted as effects of two distinct debris flow events.

The observed similarity in sedimentological characteristics of the parent material (in the scar) and sediments from the flow lobe indicates that the material transported by debris flows was not significantly affected. The only major difference is in the range of grain size statistical parameters, which is much narrower in the case of debris flow deposits, likely due to the mixing and homogenisation of former source deposits during the flow event.

E01 study site

Description: The E01 study site is also located in a lateral part of the ice-cored moraine, about 200 m to the north of the E00 study site (Fig. 1B). The sediments exposed in the central part of the debris flow scar were about 1.5 m thick and built

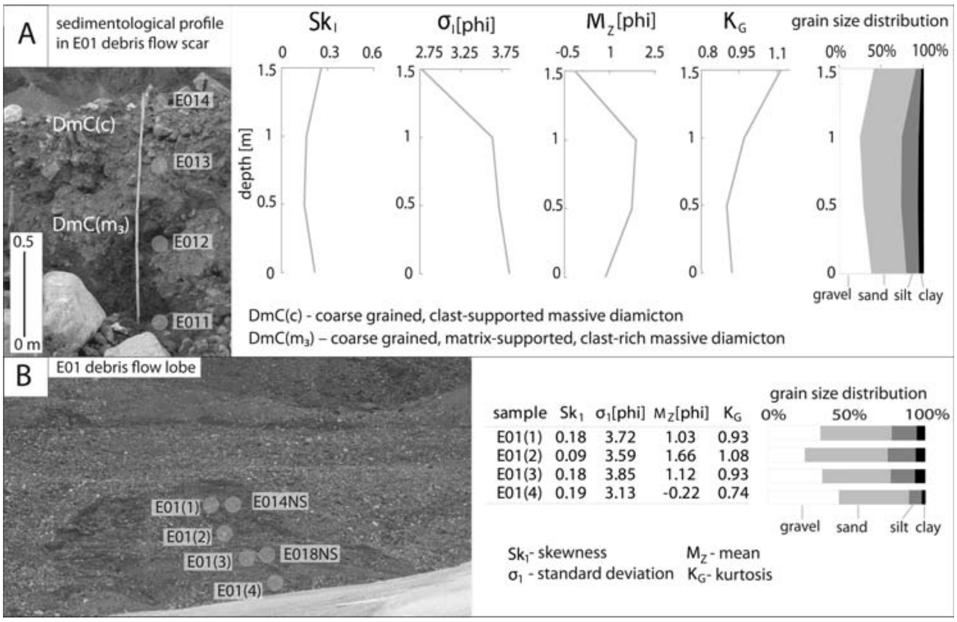

Fig. 3. Sedimentology of the lateral ice-cored moraine study site E01. **A**. Sedimentological profile in E01 debris flow scar with vertical changes in grain size statistical parameters and contribution of major grain size fractions. **B**. E01 debris flow lobe, grain size statistics and contribution of major fractions in the analysed samples. Dots mark samples locations.

of massive diamicton (Fig. 3A). Its upper part was clast-supported, while the lower part was clast-rich and matrix-supported. The matrix on this study site was mainly sandy-gravelly. In terms of grain size, the deposits in the debris flow scar were relatively uniform. Only the uppermost part is better sorted (the σ_1 values were lower by about 1 than in the rest of the profile) and coarser (mean values were lower by about 1 phi).

The debris flow lobe was significantly inclined (>20°) (Fig. 3B) and had *ca.* 30 m in length. However, local flattening and depressions were observed on its surface, which in a few cases were filled with water. The deposits contained a large amount of boulders, cobbles and pebbles. The grain size parameters revealed a great similarity between sediments from the debris flow lobe and its parent material in the scar (Fig. 3B). Only the sample taken from the lowermost part of the debris flow lobe had a slightly different characteristic with better sorted and coarser sediments compared to that from the upper part of the lobe.

Interpretation: The local flattening in some parts of the flow lobe is interpreted to be the effect of compression. The distinct characteristic of the uppermost part of the debris flow scar deposits and the lowermost part of the flow lobe, namely coarser grain size with reduced contribution of silt fraction and slightly better sorting, may be due to exposure of these places to strong katabatic winds, which winnow the finest fractions. The winnowed material is transported to the extraglacial

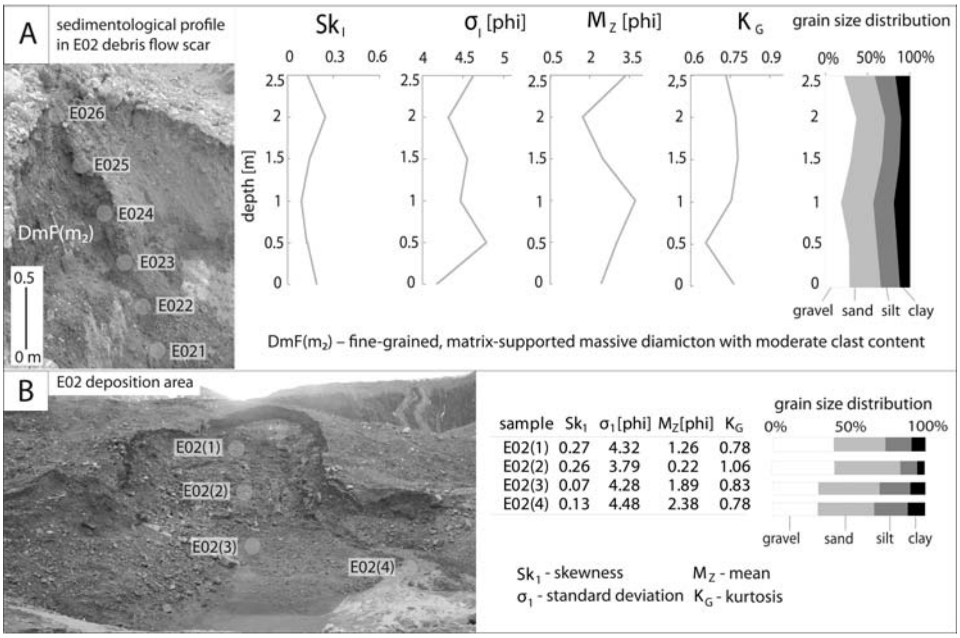

Fig. 4. Sedimentology of the frontal ice-cored moraine study site E02. **A**. Sedimentological profile in E02 debris flow scar with vertical changes in grain size statistical parameters and contribution of major grain size fractions. **B**. E02 deposition area, grain size statistics and contribution of major fractions in the analysed samples. Dots mark samples locations.

zone. The similarity of sediments' grain size from the flow lobe and that of the flow scar indicates that in conditions reported in the E01 study site as well, significant changes in the material characteristic have not occurred.

E02 study site

Description: The E02 study site is located in the frontal part of the ice-cored moraine, and is separated by a periodical stream channel from a nearby wall built of metamorphic rocks (Fig. 1B). A long (*ca*. 500 m) scar, which runs in an E-W direction, was visible in the moraine above the studied debris flow (Fig. 6). The thickness of the sediments covering the ice-core in the scar reached more than 2.5 m, which is the highest value recorded in the Ebbabreen ice-cored moraine (Kłysz 1985; Gibas *et al*. 2005) (Fig. 4A). The deposits were built of fine-grained matrix-supported massive diamicton with an average clast content. Macroscopically, there are no variations in the sediments' characteristics. The statistical grain size parameters are also similar, except the Mz values which vary from 1.7 to 3.7 phi.

The area below the scar formed three distinct zones (Fig. 4B). In the highest and steepest zone (>55°), the ice-core was exposed with almost no sediment cover. In the middle zone, where the slope angle decreases (<50°), a debris flow lobe (*ca*. 20 m in length) was observed. The third zone is the remnant of a pond covered by a thin layer of sediments. In the lowermost part of this zone, a small alluvial fan has developed. The debris flow deposits are similar in the analysed samples, however, they revealed a downslope increasing trend that contributes to fine-grained fractions (Fig. 4B). The content of clay fraction in the lowermost zone was 11.3%, while in the middle zone it was 4.9%. The sediments from the scar and debris flow lobe showed a great convergence of sediment characteristics.

Interpretation: Above the described site, an extensive old debris flow scar was still visible (Fig. 6). It implies that the studied debris flow scar was likely built of older debris flow deposits. The recorded significant thickness of these sediments may suggest that during previous debris flows, this area was the local depocentre. The homogeneity of the material suggests that the sediments may be a result of a single debris flow event, with a widespread mixing of sediments during the flow.

The formation of zones in the deposition area are interpreted as mainly the effect of different slope angles. On the steepest, uppermost part, sediments are unstable and are transported to the middle zone. In the latter, the decrease in the slope angle and possibly increase as well in the bottom friction allow for the deposition of a portion of the sediments. These sediments, which have not been stabilized, can be reincorporated into the debris flow and moved towards the ephermal pond. Most of the sediments deposited in the pond were washed out by the stream during its activity. After drainage of the pond, new sediments were supplied by debris flows. Thin sediment layer in this zone reflects a short time of deposition. The higher content of clay fraction in the lowermost zone is likely the effect of the washing out of the finest particles from the middle zone by meltwater and their deposition in the former pond as small fans. However, similarity with sediments from the upper zone suggests a dominant role for the debris flow process.

E03 study site

Description: The E03 study site is located in close proximity to the E02 study site, *i.e.* also in the frontal part of the ice-cored moraine, and as in the previous study site in the old deposition area of debris flows as well (Figs 1B, 6). The sediment profile is exposed in the debris flow scar (Fig. 5A), which is 1.5 m in height, and is built of coarse-grained, matrix-supported massive diamicton with an average content of clasts. The lower portion of the deposits is water-saturated. The grain size composition of the sediments, although generally similar, reveals a clear upward grain size fining trend (Fig. 5A).

The deposition area was very steep (>60°) and without continuous cover of sediments (Fig. 5B). In the ice-core morphology, one can distinguish a few niches. Debris-rich ice layers were visible within the ice cliff. At the foot of the steep ice cliff, small sediment fans had developed as well as little depression that is partly filled with water. The samples were taken from the niche in the ice-core and from the fan located at the foot of ice cliff (Fig. 5B). The sediments' characteristics var-

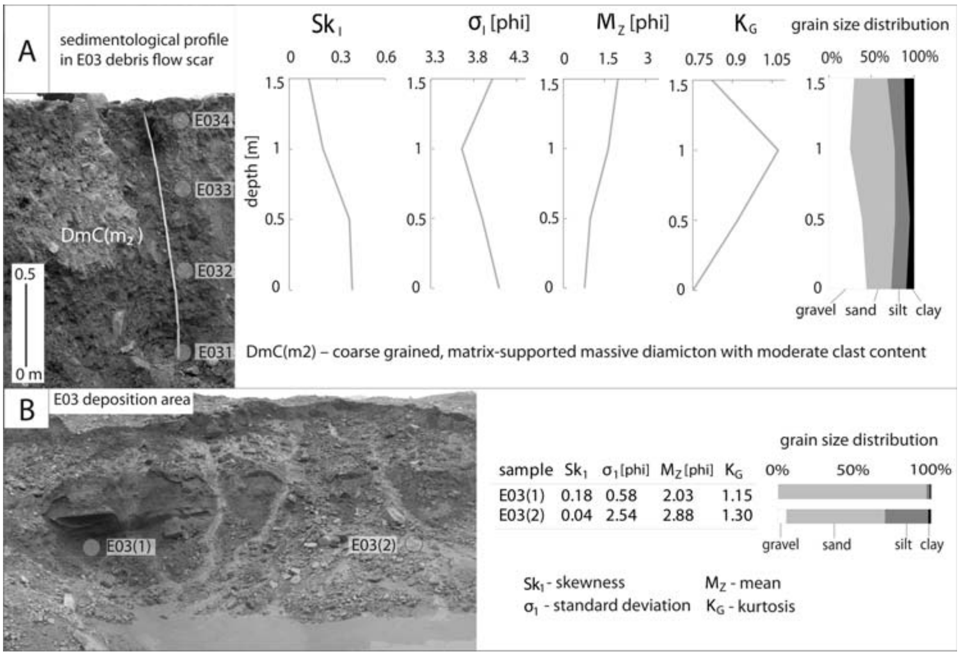

Fig. 5. Sedimentology of the frontal ice-cored moraine study site E03. **A**. Sedimentological profile in E03 debris flow scar with vertical changes in grain size statistical parameters and contribution of major grain size fractions. **B**. E03 deposition area, grain size statistics and contribution of major fractions in the analysed samples. Dots mark samples locations.

ied (Fig. 5B). The sediments from the niche were almost entirely sandy and relatively well sorted (σ = 0.58), while the sample from the fan was poorly sorted (σ = 2.54) and had a greater admixture of finer fractions.

Interpretation: The lack of clear layers and small variability of the debris flow deposits exposed in the scar suggest that they were formed during a single debris flow event. The water-saturated sediments in their lower portion indicate an active melting of the ice-core beneath.

The niches undercutting the ice-core below the aforementioned deposits are probably the effect of thermo-erosion action of the periodical stream. They likely provided a shelter from the above debris flow deposits and protected the sandy sediments deposited within it by the meltwater stream. As a consequence, the sediments kept their fluvial characteristic. The sediments from the nearby fan, which in the recent past was a channel of meltwater stream, were covered by the new debris flows.

Micromorphological features of debris flow deposits. — Micromorphology allows for a complex analysis of clasts, matrix and other components present in the sediments (van der Meer 1996). As such, it opens up new possibilities in the analysis of the investigated material and constitutes an important tool in modern sedimentology (van der Meer and Menzies 2011). In this paper, micromorphology

Fig. 6. View of the southern part of the Ebbabreen ice-cored moraine (photo by J. Barabach). Dotted lines indicate old debris flow scar running above E02 and E03 study sites marked by arrows.

analysis was used to acquire a more accurate characterization of debris flow deposits. The investigated thin sections were prepared using sediments from two study sites – E00 and E01.

E00 study site

Description: The E00 study site was sampled in three places, *i.e.* in transect along the flow lobe; from top to bottom: E004NS, E005NS, and E0078NS thin sections. In all the investigated thin sections from this locality, contact with edges of the skeleton material (*i.e.* particles thicker than the thin section's thickness) is very rare. Among the skeleton material, the subangular particles prevail. Plasma (*i.e.* particles thinner than the thin section's thickness) was of pale brown colour. The plasmic fabric was not recorded, as well as the lamination and water escape structures.

All of the thin sections had approximately the same small amount of rotational structures (small grains with a circular arrangement with or without grain core) (Fig. 7A) and halo structures (fine fractions around clasts) (Fig. 7B). In the E0078NS thin section, well-rounded till pellets were found (Fig. 7C). The orientation measurements of skeleton grains show a chaotic arrangement, while the mean elongation of grains was similar in all thin sections (Fig. 8).

Interpretation: The rare contact with clastic edges indicates that the collisions of skeleton grains during the flow were infrequent in the studied debris flow, thus implying a cohesive flow. The morphology of skeleton grains (dominance of

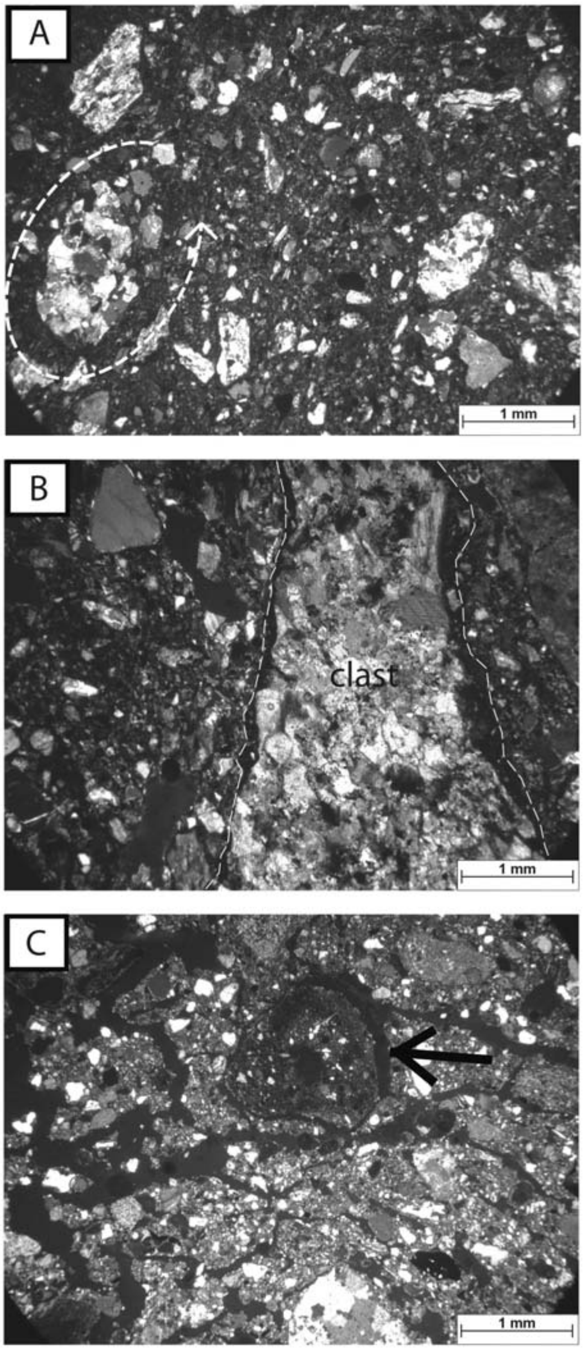

Fig. 7. Examples of microstructures from the investigated thin sections. **A**. Rotational structure from middle part of E00 flow lobe. **B**. Halo structure (fine fractions around clast) from the upper part of E01 flow lobe. **C**. Till pellet (marked with arrow) from the lower part of E00 flow lobe. Images made under cross polarized light.

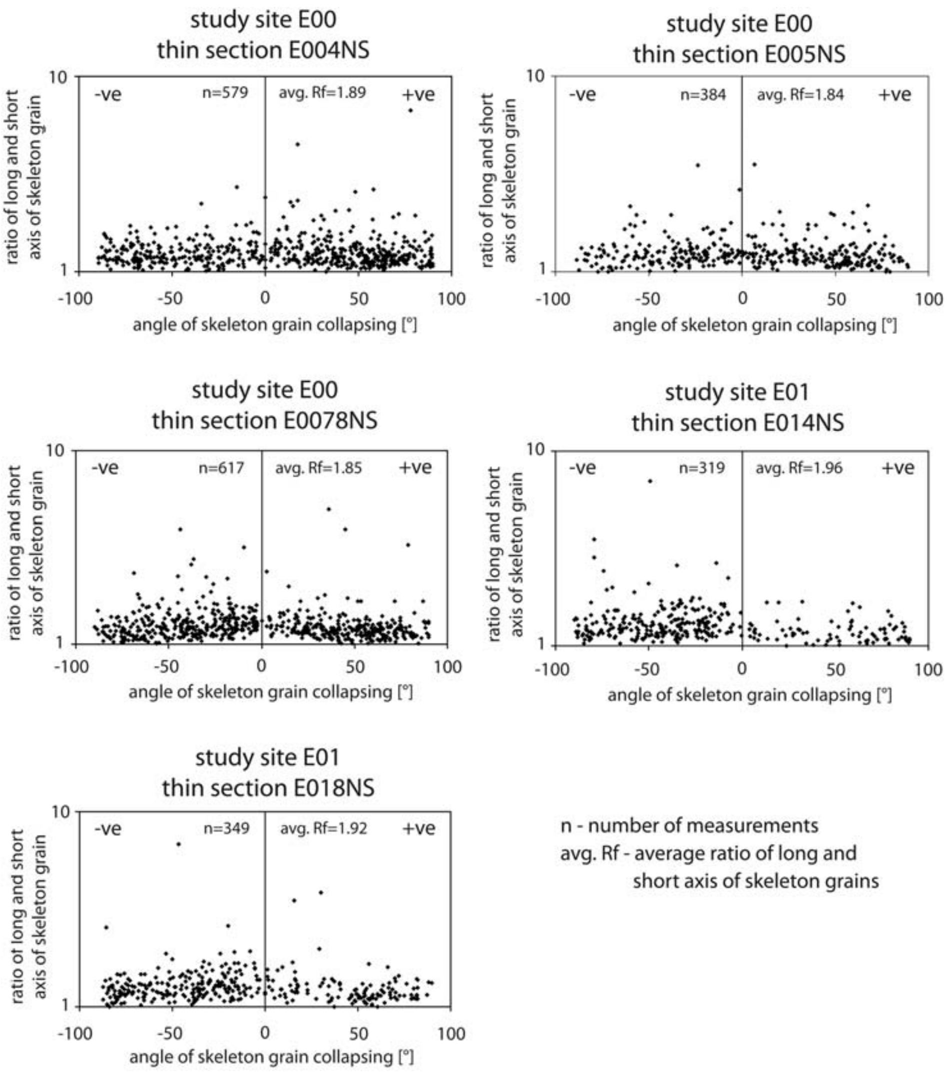

Fig. 8. Orientation *vs*. elongation of grains as measured in thin sections from the investigated sites. The clustering of the data on plots refers to preferred clast alignment within thin section – the more distinct alignment, the narrower the cluster.

subangular grains) in combination with the fact that the moraine has been deposited by a polythermal glacier surrounded by relatively steep valley sides in a high arctic environment may suggest that most material in the glacier foreland is supraglacially derived. The lack of plasmic fabric may be related to the small content of clay in the samples, high concentration of carbonates, or low stresses during flow. The absence of laminations and water escape structures allows for classifying this debris flow as type I or II of Lawson's sediment gravity flows (Lachniet *et al*. 1999), *i.e.* with a water content between 8–19%.

Rotational and halo structures indicate rotation during the flow (Menzies 2000). Till pellets are interpreted as aggregates inherited from the parent material (*e.g.* Carr 2001). The small amounts of till pellets suggest that most of the initial features are lost. The survival of part of the material may be due to a freeze of sediments. However, even these particles are partially modified, which is marked by the well roundedness of such particles. The sediment-forming process (debris flow) has not resulted in preferential orientation of the clasts in this particular setting.

E01 study site

Description: The E01 study site was sampled in two places along the debris flow axis: upper sample – E014NS; lower sample – E018NS. Despite the coarser appearance of sediments from this study site in comparison to the E00 locality, contact with skeleton grains was also rarely observed. Laminations and water escape structures were not found. Most of the clasts on both thin sections were subangular, and plasma was of a dark brown color.

On both thin sections, a small number of rotational and halo structures were recognized. On the E018NS sample, a chaotic arrangement was recorded (Fig. 8). In the E014NS sample, a slightly more preferential, but still chaotic, orientation occurred. It should be noted that all particles in this thin section with Rf above 3 collapse to the same direction (the same ve), albeit at different angles (Fig. 8). The particles on both thin sections were slightly more elongated than those in the E00 locality.

Interpretation: The thin sections from the E01 study site have very similar characteristics to those from the E00 locality. Hence, the interpretations of transport mechanism, source of material, and content of water during flow are analogous. The only difference is the slightly more preferential orientation of clasts in the E014NS thin section. This may well be the effect of postdepositional modification of sediments (*e.g.* from loading), even though its generation due to the debris flow process is also possible.

Discussion

Several factors influence the characteristics of sediments within the debris flow deposition area of the Ebbabreen ice-cored moraine. These factors may be divided into three main categories (Fig. 9): (1) pre-debris flow history of the debris flow deposits, (2) nature of the debris flow, (3) post-debris flow reworking. Each of these determines to some extent the final set of sedimentological characteristics.

Pre-debris flow history of the debris flow deposits. — The first factor that determines the sedimentological features of debris flow deposits is their pre-flow history. As was shown by Lukas *et al*. (2005) among others, the sediments' charac-

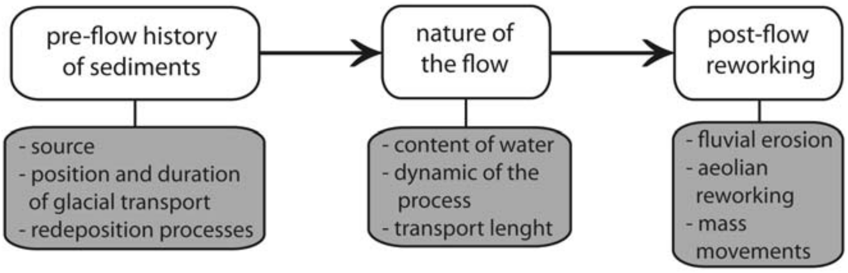

Fig. 9. Conceptual figure listing major factors determining the sedimentological characteristics of debris flow deposits within the Ebbabreen ice-cored moraine.

teristic of ice-cored moraines is the result of activity by many agents. At first, sediments are differentiated by the source, *i.e.* the type of rock, process and position (sub- or supraglacial) of supply (*e.g.* Lukas *et al.* 2013). Further, the sediments are reworked according to the manner of transport and its length (Bennett *et al.* 1999). Finally, after deposition on the surface of the ice-core, sediments are reworked by a number of redepositional processes, among which debris flows are the most common (*e.g.* Bennett *et al.* 2000).

In the Ebbabreen ice-cored moraine, most of the studied sediments were already reworked by debris flows. This is concluded from multiple layers observed in the debris flow scar in the E00 study site (Fig. 2A) and by older debris flow scars present in the morphology above the E02 and E03 localities (Fig. 6). Debris flow origin of sediments exposed in the scar of the E01 study site was not recognized in the sediment structure. However, they are very likely to have been formed by previous debris flows as they are localized in a steep and unstable part of the lateral moraine. The lowermost sediment layer in the E00 site is the only case found to be likely of melt-out origin. Hence, most of the studied sediments are examples of debris flow deposits which were transformed by debris flows in the past (samples from the scars) or more recently (samples from debris flow lobes).

Nature of the debris flow. — One of the most important controlling factors of the debris flow process is the water content in sediments. Lawson (1979) distinguished four types of flows on the basis of this property. The thin sections' characteristics from two study sites (E00 and E01) allow for classifying these sediments as the effect of Lawson type I or II sediment gravity flow (*i.e.* 8–19% water content). Lachniet *et al.* (1999) suggest that arrangement of fine material in these types of flow is chaotic, which generally accords with data from the Ebbabreen ice-cored moraine. Thus, it does not seem possible to define the flow direction on the basis of the microfabric measurements, which may not be compatible with some macrofabric measurements (Krüger and Kjær1999; Schomacker and Kjær 2008).

The second major factor that determines the nature of the debris flow process is the slope angle. Data from micromorphological analysis suggest that regardless of the slope angle (>20° in E01 and <5° in E00), debris flows resulted in common mixing which is expressed by sediment structures indicative of grain rotation (rotational and halo structures). This suggests that the mixing in the flow does not depend on its dynamics, as already suggested in previous works (Lachniet *et al*. 1999; Menzies and Zaniewski 2003; Phillips 2005). The mixing of sediments explains the homogeneity of the flow lobe sediments in the E00 study site despite their initial heterogeneity in the flow scar. Although most of the sediments have lost their initial structures, some parts of the material still keep their primary characteristic in the form of till pellets. However, these till pellets are often well-rounded which points to their modification during the debris flow.

Irrespective of the local conditions, in all the investigated sites, similarities were found in the parent sediments exposed in debris flow scars and flow lobe sediment characteristics. This accords with the results of the debris flow investigations by Menzies and Zaniewski (2003), as well as others. Schomacker and Kjær (2008), in turn, suggest a fine fraction preferential transportation during the debris flows. They reported a clay fraction content being diminished down the slope. A similar situation was observed in the E02 study site. However, this was interpreted as a fine fraction washed-out by melting water rather than the effect of a debris flow process defined by Benn and Evans (2010) as the "flowage of concentrated sediment-water mixtures". Therefore, a clear distinction should be made between a number of downslope redeposition processes that are active within moraines, from which few have led to segregation of material as fall sorting does (Kjær and Krüger 2001).

Post-debris flow reworking. — In an ice-cored moraine environment, where changes in topography and meltwater streams courses are common, the sediments may be reworked by further redeposition processes. Fluvial reworking is of utmost importance within ice-cored moraines (Lukas *et al*. 2005). Streams and rivers re-mobilize channel sediments and incorporate sediments from riverbanks due to thermo-erosion (Etzelmüller 2000). This was clearly visible at the E03 study site, where fluvial activity was well marked in the sediments' characteristics.

The debris flow deposits may again be included in further debris flows or other mass movements, which are the most ubiquitous especially in the early stages of ice-cored moraine formation (Ewertowski *et al*. 2012). This is well exemplified by numerous older and present backwall scarps of debris flows as documented in the southern part of the investigated area (Fig. 6).

Another process for reworking the debris flow sediments is aeolian activity. Most of the deposition areas of the investigated sites were protected from wind action by steep scars. But in the case of the E01 locality, the lowermost part was exposed to strong katabatic winds, while variations in the silt grain size fraction contribution may be discussed in the context of potential winnowing by wind. Nevertheless, the aeolian activity's influence on debris flow deposits' characteristics is of negligible importance.

Conclusions

The analysis of the sedimentological properties of debris flow deposits from the Ebbabreen ice-cored moraine leads to the following conclusions.

- Almost all the parent material for the investigated debris flow deposits within the Ebbabreen ice-cored moraine have earlier been redeposited by debris flows.
- The sediment characteristics of debris flow deposits were similar to the parent material and did not change significantly down the slope regardless of local conditions.
- The studied debris flows belonged to type I or II of Lawson's (1979) sediment gravity flows, which are characterized by chaotic grains arrangement that is the effect of turbulent flow of the matrix and rotation of skeleton grains. The occasionally observed preferential grain orientations may be connected with the post-depositional modifications of the sediments.
- Till pellets show that, although debris flows resulted in a mixing of the transported material, some parts may have kept their original structure.
- Sediments within active debris flows are reworked by further redepositional processes, from which fluvial reworking and debris flows are of utmost importance.

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References

BENN D.I. and EVANS J.A. 2010. *Glaciers and Glaciation*. Arnold, London: 401 pp.

BENNETT M.R., HAMBREY M.J., HUDDART D., GLASSER N.F. and CRAWFORD K. 1999. The landform and sediment assemblage produced by a tidewater glacier surge in Kongsfiorden, Svalbard. *Quaternary Science Reviews* 18: 1213–1246.

BENNETT M.R., HUDDART D., GLASSER N.F. and HAMBREY M.J. 2000. Resedimentation of debris on an ice-cored lateral moraine in the high-Arctic (Kongsvegen, Svalbard). *Geomorphology* 35: 21–40.

BÆLUM K. and BENN D.I. 2011. Thermal structure and drainage system of a small valley glacier (Tellbreen, Svalbard), investigated by ground penetrating radar. *The Cryosphere* 5: 139–149.

CARR S.J. 2001. Micromorphological criteria for discriminating subglacial and glacimarine sediments: evidence from a contemporary tidewater glacier, Spitsbergen. *Quaternary International* 86: 71–79.

CARR S.J. and LEE J.A. 1998. Thin-section production of diamicts: problems and solutions. *Journal of Sedimentary Research* 68: 217–220.

DALLMANN W.K., OHTA Y., BIRJUKOV A.S., KARNOUSENKO E.P. and SIROTKIN A.N. 1994. *Geological map of Svalbard 1:100,000, sheet C7G, Dicksonfjorden.* Norsk Polarinstitutt, Oslo.

ETZELMÜLLER B. 2000. Quantification of thermo-erosion in pro-glacial areas – examples from Svalbard. *Zeitschrift Fur Geomorphologie* 44 (3): 343–361.

ETZELMÜLLER B., HAGEN J.O., VATNE G., ØDEGÅRD R.S. and SOLLID J.L. 1996. Glacial debris accumulation and sediment deformation influenced by permafrost: examples from Svalbard. *Annals of Glaciology* 22: 53–62.

EVANS D.J., STRZELECKI M., MILLEDGE D.G. and ORTON C. 2012. Hørbyebreen polythermal glacial landsystem, Svalbard. *Journal of Maps* 8 (2): 146–156.

EWERTOWSKI M. 2014. Recent transformation in the high-Arctic glacier landsystem. Ragnarbreen, Svalbard. *GeografiskaAnnaler: Series A, Physical Geography* 96 (3): 265–285.

EWERTOWSKI M. and KASPRZAK L. 2013. Processes, sediments and landforms in the forelands of Spitsbergen Glacier: the case of the glaciers in the vicinity of Petuniabukta. *In*: Z. Zwoliński, A. Kostrzewski and M. Pulina (eds) *Ancient and modern geoecosystems of Spitsbergen*. Bogucki Wydawnictwo Naukowe, Poznań: 287–329.

EWERTOWSKI M. and TOMCZYK A. 2015. Quantification of the ice-cored moraines' short-term dynamics in the high Arctic glaciers Ebbabreen and Ragnarbreen, Petuniabukta, Svalbard. *Geomorphology* 234: 211–227.

EWERTOWSKI M., KASPRZAK L., SZUMAN I. and TOMCZYK A. 2012. Controlled, ice-cored moraines: sediments and geomorphology. An example from Ragnarbreen, Svalbard. *Zeitschrift für Geomorphologie* 56 (1): 53–74.

FOLK R.L. and WARD W.C. 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology* 27 (1): 3–26.

GIBAS J., RACHLEWICZ G. and SZCZUCIŃSKI W. 2005. Application of DC resistivity soundings and geomorphological surveys in studies of modern Arctic glacier marginal zones, Petuniabukta, Spitsbergen. *Polish Polar Research* 26 (4): 239–258.

HAGEN J. and LIESTØL O. 1990. Long-term glacier mass balance investigations in Svalbard, 1950–88. *Annals of Glaciology* 14: 102–106.

JACOB T., WAHR J., PFEFFER W.T. and SWENSON S. 2012. Recent contributions of glaciers and ice caps to sea level rise. *Nature* 482: 514–518.

JANIA J. and HAGEN J.O. 1996. *Mass balance of Arctic glaciers. International Arctic Science Comittee Report 5*. University of Silesia, Faculty of Earth Sciences, Sosnowiec: 5–62.

KJÆR K.H. and KRÜGER J. 2001. The final phase of dead-ice moraine development: processes and sediment architecture, Kötlujökull, Iceland. *Sedimentology* 48: 935–952.

KŁYSZ P. 1985. Glacial relief and deposits of Ebba Glacier and its foreland (Petuniabukta region, Spitsbergen). *Polish Polar Research* 6 (3): 283–299.

KRÜGER J. and KJÆR K.H. 1999. A data chart for field description and genetic interpretation of glacial diamicts and associated sediments – with examples from Greenland, Iceland, and Denmark. *Boreas* 28: 386–402.

LACHNIET M.S., LARSON G.J., STRASSER J.C., LAWSON D.E., EVENSON E.B. and ALLEY R.B. 1999. Microstructures of glacigenic sediment-flow deposits, Matanuska Glacier, Alaska. *In*: D.M. Mickelson and J.W. Attig (eds) Glacial Processes Past and Present. *Geological Society of America Special Paper* 337: 45–57.

LAWSON D.E. 1979. Sedimentological analysis of the western terminus region of the Matanuska Glacier, Alaska. *US Army CREEL Report* 79 (9): 1–122.

LUKAS S., NICHOLSON L.I., ROSS F.H. and HUMLUM O. 2005. Formation, Meltout Processes and Landscape Alteration of High-Arctic Ice-Cored Moraines – Examples From Nordenskiold Land, Central Spitsbergen. *Polar Geography* 29 (3): 157–187.

LUKAS S., BENN D.I., BOSTON C.M., BROOK M., CORAY S., EVANS D.J.A., GRAF A., KELLERER-PIRKLBAUER A., KIRKBRIDE M.P., KRABBENDAM M., LOVELL H., MACHIEDOJ M., MILLS

S.C., NYE K., REINARDY B.T.I., ROSS F.H. and SIGNER M. 2013. Clast shape analysis and clast transport paths in glacial environments: A critical review of methods and the role of lithology. *Earth-Science Reviews* 121: 96–116.

LØNNE I. and LYSÅ A. 2005. Deglaciation dynamics following the Little Ice Age on Svalbard: implications for shaping of landscapes at high latitudes. *Geomorphology* 72: 300–319.

MAŁECKI J. 2013. Elevation and volume changes of seven Dickson Land glaciers, Svalbard, 1960–1990–2009. *Polar Research* 32: 18400.

MENZIES J. 2000. Micromorphological analyses of microfabrics and microstructures indicative of deformation processes in glacial sediments. *In*: A.J. Maltman, B. Hubbard and M.J. Hambrey (eds) Deformation of glacial materials. *Geological Society Special Publication* 176: 245–257.

MENZIES J. and ZANIEWSKI K. 2003. Microstructures within a modern debris flow deposit derived from Quaternary glacial diamicton – a comparative micromorphological study. *Sedimentary Geology* 157: 31–48.

NAEGELI K., LOVELL H., ZEMP M. and BENN D.I. 2014. Dendritic Subglacial Drainage Systems in Cold Glaciers Formed by Cut-and-Closure Processes. *Geografiska Annaler: Series A, Physical Geography* 96 (4): 591–608.

NORDLI P.Ø. and KOHLER J. 2003. The early 20th century warming. Daily observations at Greek Harbour, Grønfjorden, Spitsbergen. *DNMI KLIMA Rapp.* 12/03. Norwegian Meteorological Institute, Oslo: 20.

NUTH C., KOHLER J., AAS H., BRANDT O. and HAGEN J. 2007. Glacier geometry and elevation changes on Svalbard (1936–90): a baseline dataset. *Annals of Glaciology* 46: 106–116.

NUTH C., KOHLER J., KÖNIG M., VON DESCHWANDEN A., HAGEN J. O., KÄÄB A., MOHOLDT G. and PETTERSSON R. 2013. Decadal changes from a multi-temporal glacier inventory of Svalbard. *The Cryosphere* 7: 1603–1621.

OERLEMANS J. 2005. Extracting a climate signal from 169 glacier records. *Science* 308: 675–677.

PHILLIPS E. 2005. Micromorphology of a debris flow deposit: evidence of basal shearing, hydrofracturing, liquefaction and rotational deformation during emplacement. *Quaternary Science Review* 25: 720–738.

PHILLIPS E. and AUTON C. 2008. Microtextural analysis of a glacially "deformed" bedrock: implications for inheritance of preferred clast orientations in diamictons. *Journal of Quaternary Science* 23: 229–240.

RACHLEWICZ G. 2004. Measurements of the movement of glaciers in the vicinity of Petuniabukta – Billefjorden (central Spitsbergen). *In*: G. Nowak (ed.) *XXX Międzynarodowe Sympozjum Polarne. Streszczenia wystąpień*. Gdynia: 149 (in Polish).

RACHLEWICZ G. 2009. *Contemporary sediment fluxes and relief changes in high Arctic glacierized valley systems (Billefjorden, Central Spitsbergen)*. Seria Geograficzna nr 87, Wydawnictwo UAM, Poznań: 1–203.

RACHLEWICZ G., SZCZUCIŃSKI W. and EWERTOWSKI M. 2007. Post-"Little Ice Age" retreat rates of glaciers around Billefjorden in central Spitsbergen, Svalbard. *Polish Polar Research* 28 (3): 159–186.

RAMSAY J.G. 1967. *Folding and fracturing of rock*. McGraw-Hill, New York: 568 pp.

REINARDY B.T.I. and Lukas S. 2009. The sedimentary signature of ice-contact sedimentation and deformation at macro- and micro-scale: A case study from NW Scotland. *Sedimentary Geology* 221: 87–98.

SCHOMACKER A. and KJÆR K.H. 2008. Quantification of dead-ice melting in ice-cored moraines at the high-Arctic glacier Holmströmbreen, Svalbard. *Boreas* 37: 211–225.

SLETTEN K., LYSÅ A. and LØNNE I. 2001. Formation and disintegration of a modern high-arctic ice-contact system, Scott Turnerbreen, Svalbard. *Boreas* 30: 272–284.

SUND M., EIKEN T., HAGEN J.O. and KÄÄB A. 2009. Svalbard surge dynamics derived from geometric changes. *Annals of Glaciology* 50: 50–60.

SZCZUCIŃSKI W., ZAJĄCZKOWSKI M. and SCHOLTEN J. 2009. Sediment accumulation rates in subpolar fjords – Impact of post-Little Ice Age glaciers retreat, Billefjorden, Svalbard. *Estuarine, Coastal and Shelf Science* 85 (3): 345–356.

VAN DER MEER J.J.M. 1996. Micromorphology. *In*: J. Menzies (ed.) *Glacial environments*, Vol. 2. Butterworth & Heinemann, Oxford: 335–355.

VAN DER MEER J.J.M. and MENZIES J. 2011. The micromorphology of unconsolidated sediments. *Sedimentary Geology* 238: 213–232.

WILLIAMS P.J. and SMITH M.W. 1995. *The Frozen Earth*. Cambridge University Press, Cambridge: 306 pp.

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