



Micromorphology of modern tills in southwestern Spitsbergen – insights into depositional and post-depositional processes

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Abstract: Textural properties and microstructures are commonly used properties in the analysis of Pleistocene and older glacial deposits. However, contemporary glacial deposits are seldom studied, particularly in the context of post-depositional changes. This paper presents the results of a micromorphological study of recently deposited tills in the marginal zones of Hansbreen and Torellbreen, glaciers in southwestern Spitsbergen. The main objectives of this study were to compare modern tills deposited in subglacial and supraglacial conditions, as well as tills that were freshly released from ice with those laid down several decades ago. The investigated tills are primarily composed of large clasts of metamorphic rocks and represent coarse-grained, matrix-supported diamictons. The tills reveal several characteristic features for ductile (*e.g.* turbate structures) and brittle (*e.g.* lineations, microshears) deformations, which have been considered to be indicative of subglacial conditions. In supraglacial tills, the same structures are common as in the subglacial deposits, which points to the preservation of the primary features, though the sediment was transferred up to the glacier surface due to basal ice layer deformation and redeposited as slumps, or to formation of similar structures due to short-distance sediment re-deposition by mass flows. This study revealed that it might not be possible to distinguish subglacial and supraglacial tills on the basis of micromorphology if the latter are derived from a subglacial position. The only noted difference was the presence of iron oxide cementation zones and carbonate dissolution features in supraglacial tills. These features were found in tills that were deposited at least a few years ago and are interpreted to be induced by early post-depositional processes involving porewater/sediment interactions.

Key words: Arctic, Svalbard, subglacial till, supraglacial till, microstructures, post-depositional changes.

Introduction

Tills often appear homogeneous in macroscopic studies, and in many cases it is not possible to reconstruct their precise mode of deposition. Catt (1986) stated that ‘... *it is probably unwise to identify any buried soil without examining it first in thin section*’. This statement is true for tills as well. The application of micromorphology in till research began to intensify in the 1980’s (van der Meer 1987) and has continued to develop over the past three decades (*e.g.*, van der Meer 1993, 1996, 1997; van der Meer *et al.* 2003; Menzies 2000; Carr 2001; Ruszczynska-Szenajch *et al.* 2003; Menzies *et al.* 2006, 2010; Evans *et al.* 2006; Piotrowski *et al.* 2006; Phillips 2006; Larsen *et al.* 2006a, 2006b; Kilfeather *et al.* 2009; Leszczynska *et al.* 2011; van der Meer and Menzies 2011; Narloch and Piotrowski 2013; Narloch *et al.* 2013). The inclusion of micromorphology in till research has contributed to a better understanding of till deposition conditions and the identification of a number of factors that influence the deposition mode: glacier velocity, water content, clay content, *etc.* (Khatwa and Tulaczyk 2001; van der Meer *et al.* 2003; Menzies *et al.* 2010; Phillips *et al.* 2013). In addition to qualitative analyses, quantitative micromorphological analyses have recently been developed (*e.g.*, Phillips *et al.* 2011; Zaniewski and van der Meer 2005; Tarplee *et al.* 2011; Narloch *et al.* 2015).

The examination of many till thin sections has resulted in the development of several schemes of till classification (van der Meer 1993; Carr 1999; Menzies 2000). These classifications are based on an understanding of rheological conditions under which certain structures and microfabrics are likely to form. The application of intense micromorphological examination of tills led to the discovery that all subglacial tills have undergone deformation processes and suffered the impact of porewater-induced effects during emplacement (van der Meer *et al.* 2003; Menzies *et al.* 2006). These processes are considered to be structural, not depositional, and the sediments are defined as ‘tectomicts’ (Menzies *et al.* 2006).

Although micromorphological analysis is a useful tool in glacial deformation studies, recent studies of modern deposits of various origins reveal that in many cases they might have microstructures similar to those described in micromorphological investigations of tills (Menzies and Zaniewski 2003; Menzies *et al.* 2010). In sediments from the margin of the Matanuska Glacier in Alaska, Lachniet *et al.* (2001) documented characteristic microstructures formed during brittle and ductile deformations and found that sediment flow deposits share many microstructures that are common within subglacially deformed sediments. It has been suggested that further research should focus on the characterization of microstructures in sediments of known origin to further establish the link between process and microstructure. In their studies on massive diamictons of various origins (*e.g.*, terrestrial, ice-marginal and glaciomarine), Phillips (2006),

Kilfeather *et al.* (2009) and Reinardy and Lucas (2009) concluded that very coarse debris flow deposits contain microstructures that have also been recorded within subglacial diamictos, *e.g.*, folds, faults, turbate structures and plasmic fabrics.

Moreover, as documented by Boulton and Dent (1974), post-depositional processes may significantly affect till properties. However, this problem was only scantily considered in studies that applied micromorphological analysis. The post-depositional changes currently documented are mainly connected to weathering and pedological processes (*e.g.*, Kemp 1985, 1999; Fedoroff *et al.* 1990).

There were two primary goals in this study. The first goal was to compare the micromorphological properties of diamictos that were observed to be deposited in subglacial and supraglacial environments. This comparison includes recently exposed subglacial traction tills in front of the Hansbreen and Torellbreen glaciers in southwestern Spitsbergen and supraglacial diamictos (mass flows) from Hansbreen. The latter sediments, as documented by Rachlewicz and Szczuciński (2000), were originally of subglacial origin. These sediments were transferred upward to a supraglacial position mainly by the folding deformation of a sediment-laden basal ice layer in the glacier marginal zone. Therefore, it was of particular interest to discover to what extent the primary subglacial fabric was still preserved during glacitectonic transport and subsequent modification under supraglacial conditions. The second goal was to assess the early post-depositional imprint on microstructures by examining diamictos that were freshly released from the ice with ten- to twenty-year-old glacial deposits.

Study area

Hansbreen and Torellbreen are tidewater glaciers located in the southern part of the Spitsbergen island, Svalbard Archipelago (Fig. 1). Hansbreen ends in the Hornsund fjord, descending to the south from the Amundsenisen ice plateau (800 m a.s.l.). The same ice mass nourishes Torellbreen, which debouches to the west directly to the Greenland Sea. Both glaciers form land-based marginal zones at the lateral parts of the tidewater ice cliffs (Fig. 2). The maximum extents of the glaciers in Holocene occurred during the Little Ice Age, which terminated at the end of the 19th century (*e.g.*, Hagen *et al.* 1993; Werner 1993; Majewski *et al.* 2009). They are marked by large, ice-cored front/lateral moraine ridges located 1000 to 1500 m from the present-day ice margin. The average retreat rate during the past century of the land-based glacier margins is in the range of 8 to 15 m a⁻¹, accelerating distinctly during the last few decades. These rates are similar to the retreat rates of land-terminating glaciers in Spitsbergen (Rachlewicz *et al.* 2007), but are much lower than the rates reported for the marine-terminating tidewater fronts (Jania 1988, 1998; Oerlemans *et al.* 2011; Błaszczuk *et al.* 2013).

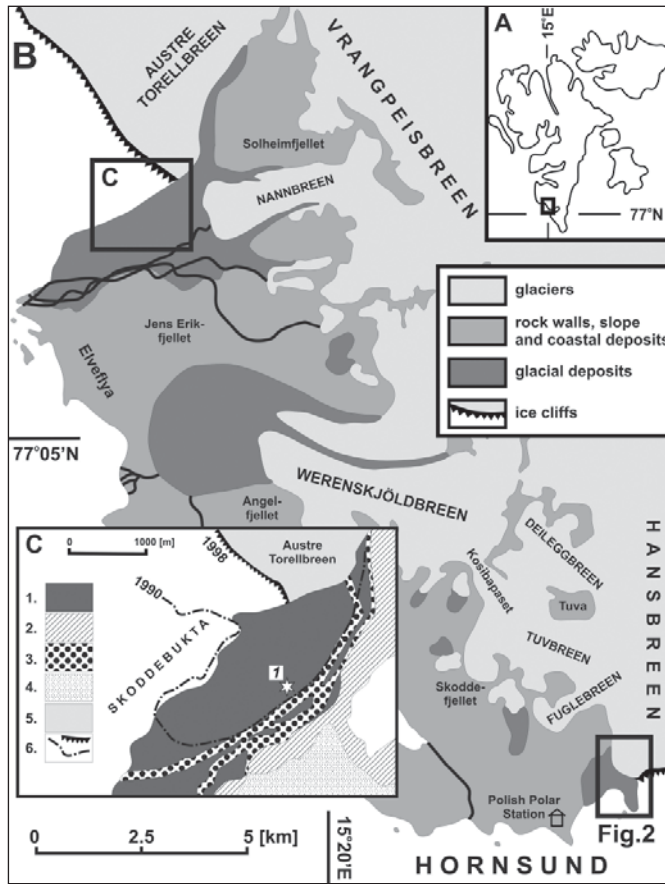


Fig. 1. Location of the study area on the island of Spitsbergen (A) and in the vicinity of Polish Polar Station in Hornsund (B), surface sediments and landforms distribution of Austre Torellbreen marginal zone (after Karczewski and Wiśniewski 1977) (C) and Hansbreen marginal zone location, presented in details on Fig. 2. Legend: 1 – glacial till, 2 – supraglacial covers, 3 – proglacial stream deposits, 4 – outwash plain deposits, 5 – glacier ice, 6 – historical ice front positions.

Several researchers have studied the geomorphology and distribution of glacial deposits in the Hansbreen marginal zone (Fig. 2A) (*e.g.*, Kłysz 1983, 1995; Karczewski *et al.* 1984, 2003; Rachlewicz and Szczuciński 2000), and the Torellbreen marginal zone (Fig. 2B) was described by Karczewski and Wiśniewski (1977). The outer portions of the marginal zones of both glaciers are marked by ice-cored ridges covered by approximately 2 m of diamictons (Karczewski *et al.* 2003). The inner part of the Hansbreen marginal zone (Fig. 2A) is characterised by two types of sediments. The southeastern portion of the area (Baranowski Peninsula) is covered with up to 1.0 m of diamicton, previously interpreted as a subglacial till, deposited directly on bedrock. The

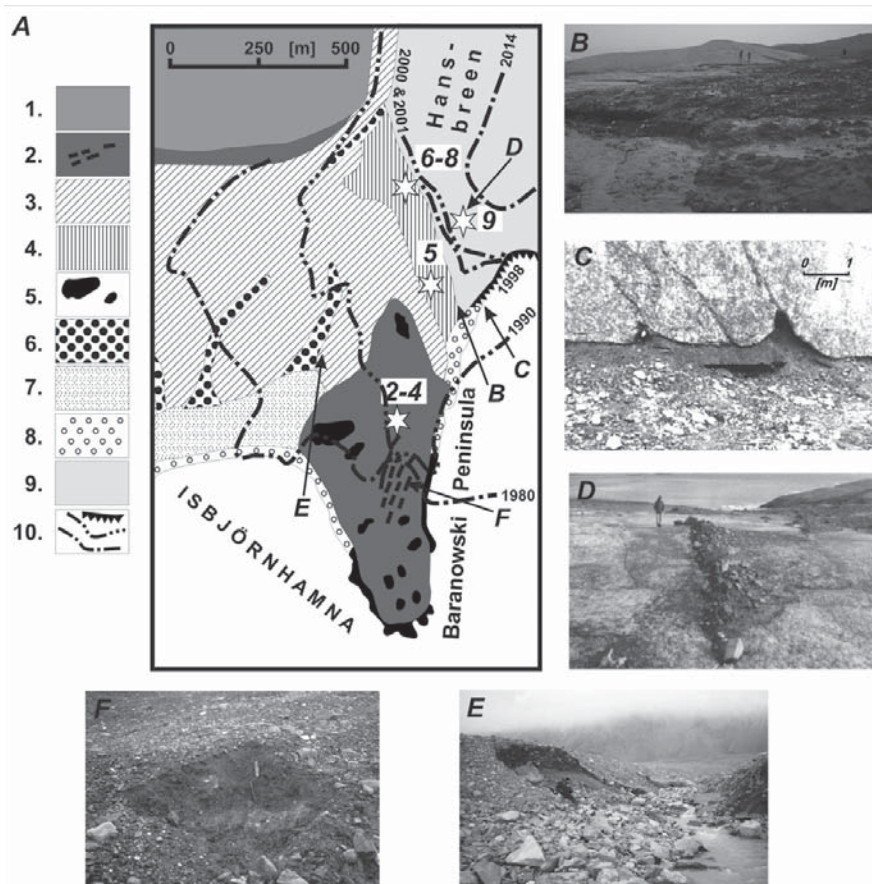


Fig. 2. Surface sediments and landform distributions in the marginal zone of Hansbreen (A) (after Karczewski *et al.* 2003). Legend: 1 – slope deposits, 2 – glacial till on bedrock/sediments, 3 – glacial till on dead ice, 4 – supraglacial covers, 5 – bedrock, 6 – proglacial stream deposits, 7 – outwash plain deposits, 8 – beach deposits, 9 – glacier ice, 10 – historical ice front positions. Sampling locations are marked with asterisks. Inset pictures are showing examples of sediments **B** – ice margin with freshly slumped sediments; **C** – dead ice cliff exposing deformations of basal ice layer; **D** – folded debris-rich band melted out on the glacier margin ice surface; **E** – supraglacial diamicton exposed in a niche on dead ice; **F** – diamicton in a cross section of fluted moraine.

area is marked with distinct flutings oriented parallel to the direction of the former ice flow. However, the major portion of the marginal zone consists of a complex, partly ice-cored, hummocky moraine cut by proglacial streams. The contemporary margin of the glacier is covered by supraglacial sediment that Rachlewicz and Szczuciński (2000) observed to be largely of subglacial origin. Due to the compressional flow regime, the subglacial sediments are transferred upward by folding of the basal, sediment-rich ice layer (Fig. 2C) and melt

out at the glacier surface (Fig. 2D) (Rachlewicz and Szczuciński 2000). The sediments range in thickness from a few centimetres to more than 0.5 m, and are susceptible to re-deposition by mass movement. The inner portion of the Torellbreen marginal zone (Fig. 1C) is dominated by an approximately 1 m thick subglacial till with locally well-developed flutings. This zone forms a relatively flat surface intersected by several proglacial meltwater streams.

The bedrock in the study area is composed of various types of metamorphic rocks: schists, gneisses, amphibolites, marbles and quartzites of the so-called Hecla Hoek succession of pre-Devonian age (Birkenmajer 1990; Manecki *et al.* 1993; Dallmann *et al.* 1999). Fragments of these rock types are commonly found in the sediments deposited in the marginal zones of the both Hansbreen and Austre Torellbreen (Karczewski *et al.* 2003).

The studied deposits are in an area characterised by permafrost with a surface active layer of up to 2 m thick (Dolnicki *et al.* 2013). The ground is frozen for approximately 8 months each year (Dolnicki 2010). The annual average precipitation in the study area is 430 mm, approximately 44% of which occurs as rain (Łupikasza 2013). The precipitation is measured at the Polish Polar Station in Hornsund, which is located in the vicinity of the western margin of Hansbreen.

Methods

The field works including sampling and observations of modern glacial sedimentation were made during several summer expeditions lasting for up to 2.5 months in years 1996, 1997, 1998, 2000, 2001 and 2016. Moreover, the origin of sediments and former glacial position were confirmed by eyewitness accounts and collection of old photographs of members of year-around polar expeditions to the Polish Polar Station in Hornsund (app. 3 km from the Hansbreen margin), which was built in 1957 and have been in continuous operation since 1978.

Samples were collected from the southern margin of Austre Torellbreen and the western margin of Hansbreen (Fig. 2) and represent subglacial and supraglacial tills, the latter in some cases were subjected to short redeposition (often “in block”) by debris flows or slides. Prior to sampling undisturbed samples for micromorphological analyses, the sites were documented for macroscopic features, sediment colour, skeleton particle types and sizes, sedimentary structures (Fig. 3, Table 1) and sampled for grain size and calcium carbonate content analyses. The grain size analysis was performed by combining a sieving method (for > 63 μm fraction) with the Casagrande-type aerometric method (for silt and clay fractions). The granular skeleton (size fraction > 10 mm) was excluded from the laboratory investigations of the particle size distribution. Grain size statistics (mean and sorting) were calculated using the formula from Folk and Ward (1957). The calcium carbonate content analyses were performed using the

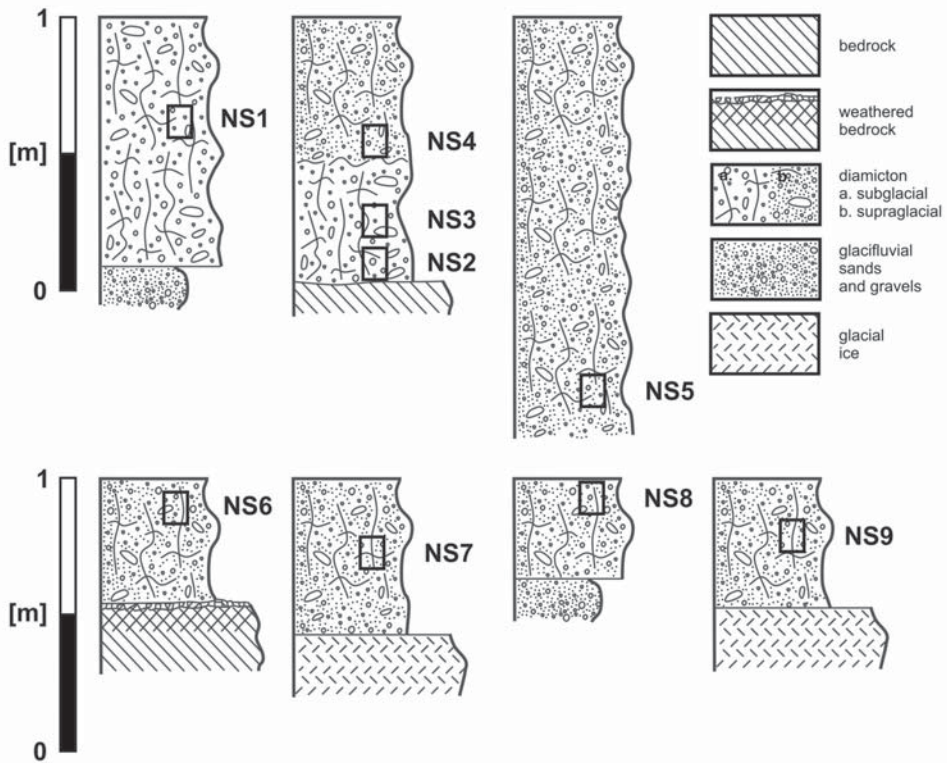


Fig. 3. Sedimentological sketches of the sampling sites with marked positions of non-disturbed samples (NS) used for thin section analyses.

Scheibler method. Basic textural properties (grain size) of the samples from the Hansbreen marginal zone were described in previous research (Rachlewicz and Szczuciński 2000; Karczewski *et al.* 2003).

For microfabric analysis, undisturbed, oriented samples of glacial deposits were collected using metal Kubiëna tins (10×8×4 cm). Care was taken to avoid very coarse-grained deposits. The study of the microstructures was performed using nine 5×7 cm thin sections (samples 1, 6, 7A–C, 8A–C and 9) and eight 3×5 cm thin sections (samples 2–5 containing two thin sections from each sample). The thin sections were made in the laboratories of the Institute of Geological Sciences in Wrocław, Poland and the Micromorphological Laboratory at Brock University in St. Catharines, Canada. The thin sections were examined using a *Petroscope* and an *Olympus BX-50* petrographic microscope. The microstructure nomenclature used follows Menzies (2000). The micromorphological fabric of a till was subdivided into three categories: (1) a fabric related to plasma (particles < 20 µm in size) – plasmic microfabric,

Table 1

Micromorphological analyses were performed on nine till samples. Sample information includes the sampling site, macroscopic properties of the tills, the mean grain size, sorting, clay fraction content and carbonate content.

Location	Samples	Depth [m] beneath surface	Facies	Macroscopic features	Granulometric results and CaCO ₃ content			
					Mean [mm]	Sorting [mm]	< 2 μm [%]	CaCO ₃ [%]
Austre Torellbreen	1	0.5–0.6	subglacial tills	grey, coarse-grained, distinct fissility	–	–	–	–
Hansbreen, Baranowski Peninsula	2	0.9–1.0		grey, coarse-grained, massive	2.69	4.10	10.7	–
	3	0.6–0.7		grey, coarse-grained, massive	2.67	4.13	9.50	–
	4	0.4–0.5	supraglacial tills	grey, coarse-grained, massive	1.93	4.17	7.30	–
	5	1.4–1.5		grey, coarse-grained, massive	1.82	4.08	6.50	–
Hansbreen	6	0.1–0.2	grey, coarse-grained, massive, with iron oxide cementation zones	2.64	3.92	6.39	10.09	
	7	0.2–0.3	grey, coarse-grained, massive, with iron oxide cementation zones	2.16	4.10	6.48	9.88	
	8	0–0.1	grey, coarse-grained, massive	1.54	4.29	5.04	9.93	
	9	0–0.3	grey, coarse-grained, massive	1.68	4.41	6.31	6.11	

– not analysed

(2) a fabric that combined plasma and skeleton grains – S-matrix microfabric and (3) a fabric that developed from plasma particles oriented around skeleton grains – skelsepic fabric.

The smaller thin sections (samples 2–5) were also examined in terms of petrographical composition of skeleton grains. At least 100 grains were counted and classified in 8 groups: mica schists, schists without mica and phyllites, carbonate rocks, quartzites, gneisses, amphibolites, quartz and opaque minerals. The results are presented as the percentage of the area covered by skeleton grains of a certain class.

Results

The macroscopic characteristics and texture of the glacial deposits. — Sample 1 was taken from the southern margin of Torellbreen (Fig. 1C), from the region where subglacial till was observed to emerge from the melting glacier front according to eyewitness accounts. Moreover, the glacier margin was reported to be very poor in any supraglacial material (Karczewski and Wiśniewski 1977). The sample was collected from the middle of an approximately 0.8 m thick grey, massive structure, matrix-supported diamicton resting on a sequence of glaciofluvial deposits (Fig. 3). The diamicton possesses a distinct horizontal fissility and was released from the glacier about 25 years ago.

Samples 2, 3 and 4 were collected from an approximately 1 m deep trench in glacial deposits on Baranowski Peninsula (Figs. 2A and 3). The Hansbreen glacier retreated from the site approximately 20 years ago revealing about 1 m thick diamicton composed of two distinct units. The photographic documentation, eyewitness accounts (Andrzej Karczewski, personal communication) and the presence of flutings nearby indicate that the lower unit is of subglacial origin, while the topmost layer was deposited in supraglacial conditions. The diamicton is matrix-supported, massive and coarse-grained, with distinct horizontal fissility. This till was deposited directly on the bedrock. Two samples were taken from this unit: one from the lowermost part of the section (sample 2) and one from the middle part of the section (sample 3). The grain size properties of both samples were similar with a mean grain size of 2.7 mm, a clay content of approximately 10% and an extremely poorly sorted distribution (Table 1). Sample 4 was taken from the lower portion of an approximately 0.5 m thick supraglacial till. This diamicton was less consolidated, lacking distinct fissility and was finer than the lower unit, although the clay content was slightly lower (7.3%).

Sample 5 was taken from the lowermost part of a 1.5 m thick diamicton cover on glacial ice exposed in a slump niche located approximately 30 m from the sediment free ice margin (Fig. 3). The diamicton is massive, possesses a high water content, and shows textural properties similar to samples 2, 3 and 4 described above (see Table 1).

Samples 6 and 7 were collected approximately 2 m apart from each other in a supraglacial diamicton outcrop in a slump scar that developed at the glacier margin (Figs. 2A and 3). The till layer was deposited no earlier than three years prior to sampling, as confirmed by our earlier observations of that site. In the northern part of the slump scar, a diamicton layer (approximately 0.4 to 0.5 m thick) covered the bedrock (amphibolites) with a several centimetre-thick layer of very angular bedrock debris at the lower boundary. Sample 6 was taken from the upper part of this section (0.1–0.2 m). Towards the south, the till layer thickness increased to approximately 0.6 m, and it was lying directly on glacier ice, on which the slump developed. Sample 7 was taken from the section

above the glacier ice (0.2–0.3 m below the surface). The diamicton is massive and contains boulders, mainly of quartzite, up to 0.4 m in diameter. The grain size parameters were similar for both of the samples with a mean grain size in the range of 1.8 to 1.9 mm, an extremely poorly sorted distribution and a clay fraction content of approximately 7% (Table 1).

Sample 8 was collected from debris flow deposits, which form an approximately 30 cm thick and 3 m wide tongue that extended to within approximately 10 m of the scar, where samples 6 and 7 were collected (Fig. 3). The debris flow was observed to develop in years 1997–1998. Thus, sample 8 represents supraglacial deposits reworked by debris flow, *i.e.* flow till. The sample was taken from a 0.1 m thick surficial layer. The sediments were similar to those in the niche of the debris flow except that they were slightly finer with a mean grain size of 1.54 mm (Table 1).

Sample 9 was taken from an approximately 1 m high sediment ridge on the glacier and parallel to an ice margin covered by 0.3 to 0.5 m of compacted diamicton freshly released from the ice (Fig. 2D). The sample's location and relation to a glacial ice structure revealed also in nearby ice cliff suggest that it is part of a deformed basal ice layer (Fig. 2C). The diamicton is massive and possesses similar grain size parameters as most of the other samples but contained the lowest carbonate content of 6.11% (Table 1).

Petrography of skeleton grains of the tills. — The petrographical analysis of the skeleton grains from the diamictons on the Hansbreen margin revealed similar compositions for all of the investigated sections, including 6 samples from both subglacial and supraglacial tills. The most common components were mica schists (average of 24%, range of 18 to 29%) and other types of schists and phyllites (average of 8%, range of 5 to 13%). The next most common components were quartzites (average of 23%, range of 17 to 28%) and carbonate rocks (average of 15%, range of 10 to 19%) represented by limestones, marbles and dolostones. Vein quartz grains were also common (average of 10%, range of 7 to 18%), grains of gneisses (average of 8%, range of 1 to 14%), amphibolites (average of 4%, range of 2 to 11%), and opaque minerals (average of 7%, range of 4 to 11%). The skeleton grains in the tills were often weathered and crushed.

Micromorphology of the diamictons. — Features related to plasmic fabrics were not found in the studied sections. Thus, the following description focuses on S-matrix microfabric, which was classified using the terminology proposed by Menzies' (2000) ductile, brittle and porewater-influenced styles of deformation (Table 2). Figures 4 to 6 illustrate examples of the S-matrix microstructures with mapped structural elements. Additionally, till pellets and organic remnants were described (Fig. 6), which are referred to as the 'other till elements'.

Table 2

Microstructures identified in the studied thin sections. A, B and C represent the thin sections from the same sample cut along the x, y and z directions, respectively.

samples	S – matrix till microstructures								
	ductile deformation (rotational)			brittle deformation (planar)		other till elements		porewater influenced (postdepositional)	
	tu	ne	pl	lg	gcr	tp	or	Fe-vn	Car-sol
1	+		+	+					
2	+	+	+	+	+				
3	+		+	+					
4	+	+	+	+	+				
5	+	+	+	+	+				
6	+		+		+	+			
7A	+	+	+	+				+	+
7B	+		+	+	+			+	
7C	+	+	+	+					
8A	+		+	+				+	
8B	+	+	+	+				+	
8C	+		+	+			+	+	
9	+		+	+	+	+	+		
	tu – turbate structure ne – necking pl – plaster			lg – line of grains (lineation) gcr – grain crushing		tp – till pellets (intraclasts) or – organic remnants		Fe-vn – iron veins Car-sol – carbonates solution	

Ductile S-matrix microstructures including turbate structures, necking structures and surface grain coatings (Table 2) were found in all of the samples, but they were more common in subglacial tills. The turbate structures were roughly circular arrangements of skeleton grains. The diameters of the structures ranged from 1 to 7 mm. These structures occurred either with or without a core stone (Figs. 4A, 4B) and were often accompanied by necking structures, and lineations (microshears) (Fig. 4B). The necking structures are characterised by reorientation of smaller clasts, especially elongated, between larger grains. The elongated fine sand to silt sized grains within the matrix are oriented parallel to the surface of larger grains (Fig. 4C). The surface grain coatings were composed of mixed sandy, silty, clay-like matrix material on skeleton grains and were found in all of the sections. The coatings were usually finer and darker than the surrounding matrix material (Fig. 5A), discontinuous and thicker in places where the grain surface was concave (Fig. 5B).

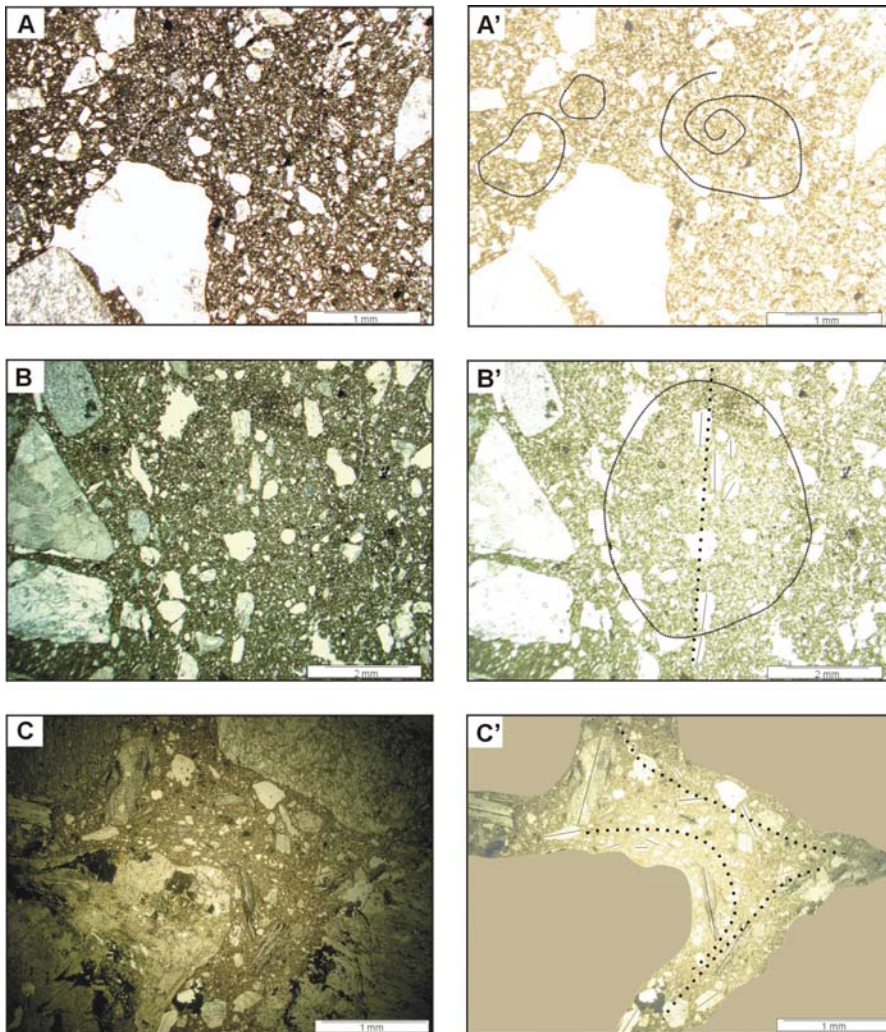


Fig. 4. Rotational microstructures: **A, A'** – turbate structure (sample 1, *ppl*); **B, B'** – juxtaposition of rotational and linear features (sample 1, *ppl*); and **C, C'** – necking structure (sample 8B, *ppl*), where *ppl* is plane-polarised light.

Brittle S-matrix microstructures were found in all of the samples in the form of grain lines or stacks, lineations (microshears) and/or crushed grains (Table 2). The grain stacks were observed as alignments of three or more clasts (Figs. 4B, 5C, 5D). These features were found in most of the sections. Microshears were relatively rare, mainly because of coarse-grained nature causing matrix to be secondary component of the sediments. The microshears were usually 4 to 8 mm long, reaching a maximum length of 15 mm. Some of the microshears were observed to superpose the turbate structures (Fig. 4B). Grain crushing was

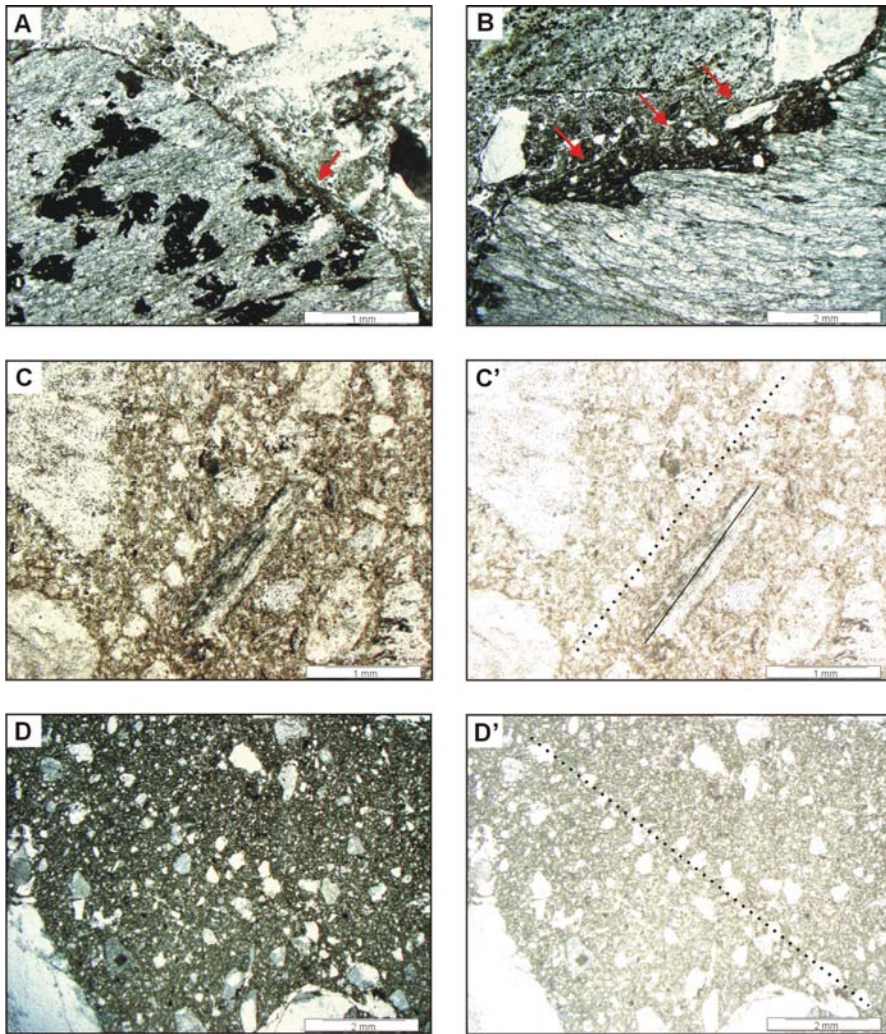


Fig. 5. Rotational and linear microstructures: **A, B** – plasters on grains connected with rotation (sample 6, *ppl*); **C, C'** – stacking of grains (sample 7C, *ppl*); and **D, D'** – lines of grains (sample 1, *ppl*), where *ppl* is plane-polarised light.

found in older subglacial and supraglacial tills as well as in sediments freshly released from ice (sample 9). The broken skeleton grains were in some cases found as an association of small crushed grains near the parent grains (Fig. 6F), possibly indicative of high local stresses and limited transport.

Porewater-influenced S-matrix microstructures, such as water escape structures or detached rafts of laminated sediments, were not identified. The only porewater-related characteristics were precipitation of iron in veins and dissolution features of carbonates. These characteristics were found only in supraglacial tills and

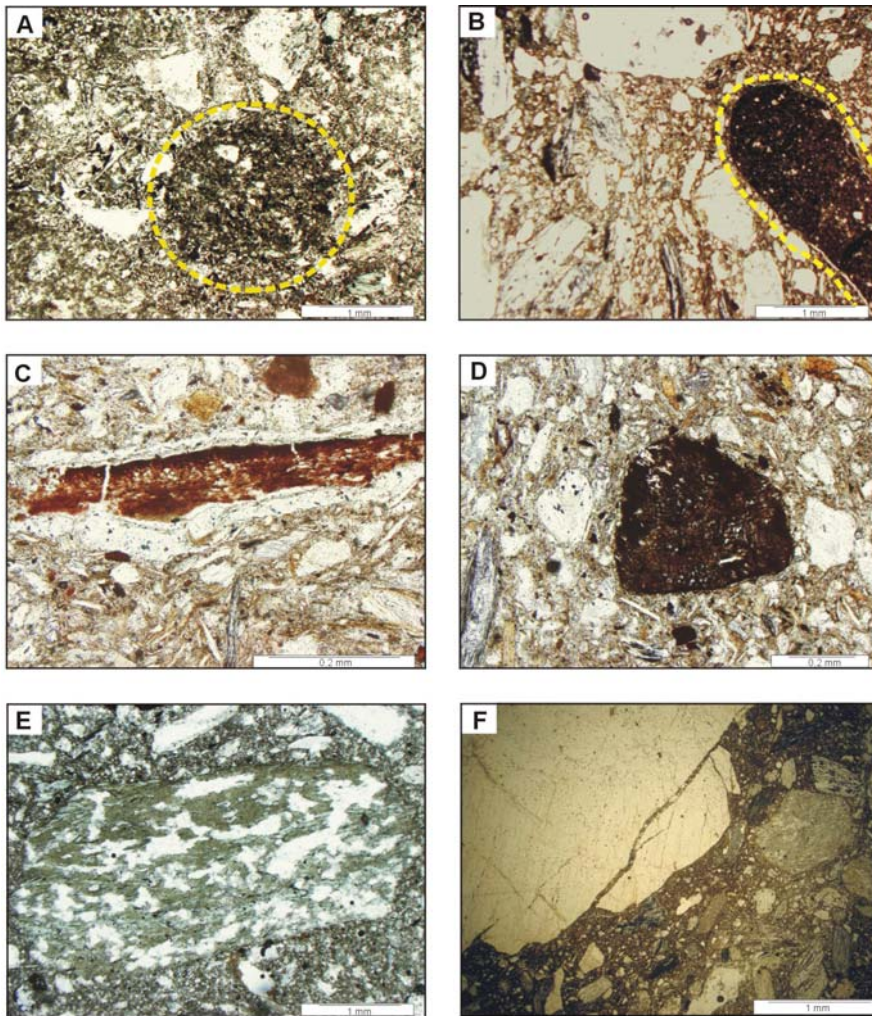


Fig. 6. Other till elements: **A** – oval intraclast of older till (sample 6, *ppl*); **B** – elongated intraclast of other – fine-grained till (sample 9, *ppl*); **C**, **D** – organic remnants (sample 9, *ppl*); **E** – weathered grain of amphibolites (samples 7A, *ppl*); and **F** – crushed up grain of quartzite (sample 8, *ppl*), where *ppl* is plane-polarised light.

debris flow deposits (Table 2). The iron veins were marked by an orange-brown colour and were related to precipitation of iron oxides or hydroxides in specific zones (Fig. 7). The iron compounds were typically in the form of veins arranged in various directions, but they also formed zones of iron cementation not connected to structural boundaries. The marbles and other carbonate grains were observed to have dissolution features on the grain borders (Fig. 7D).

Other till elements included till pellets, intraclasts, organic remnants, and irregular voids. The till pellets were found in older supraglacial tills as well as

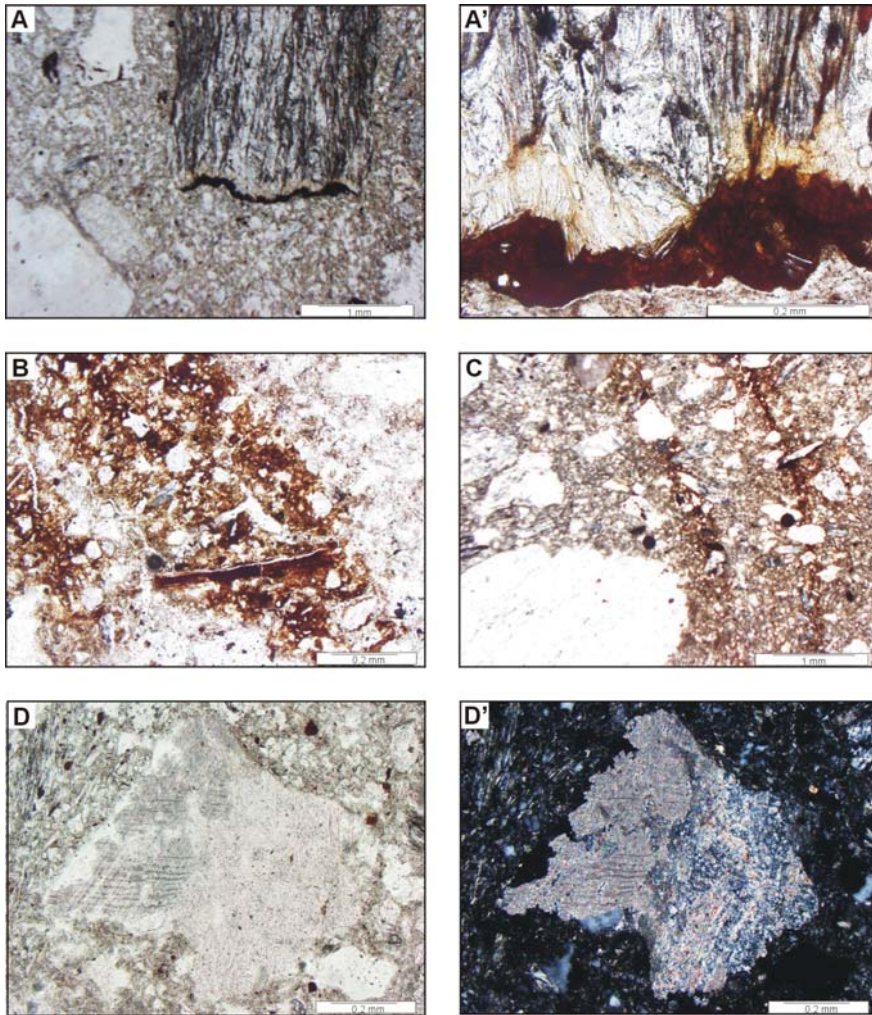


Fig. 7. Postdepositional structures: **A, A'** – weathered grain of biotite-rich schists with iron oxides on the edge (sample 9, *ppl*); **B** – zone of iron compounds cementation with fragment of organic remnants (sample 8C, *ppl*); **C** – two parallel veins of iron cementation, which go in random arrangement with grain skeleton (sample 8C, *ppl*); and **D, D'** – grain of carbonate rock partly dissolved (sample 7A, **D** – *ppl*, **D'** – *xpl*), where *ppl* is plane-polarised light and *xpl* is crossed-polarised light.

those freshly released from ice. The well-rounded till intraclasts were slightly darker and finer grained compared to the surrounding material (Figs. 6A, 6B). In two samples of supraglacial tills, plant remnants were found forming elements of till skeleton – bioclasts (Figs. 6C, 6D, 7B). Moreover, irregular voids were found in thin sections, but their formation during the sampling process cannot be ruled out.

Discussion

Micromorphology as a tool for identification of depositional environments.

— The primary aim of this study was to compare micromorphological properties of tills that were deposited under subglacial and supraglacial conditions. The two microstructures used in standard classification schemes are structures related to plasma (particles < 20 μm in size) and combined plasma and skeleton grains (van der Meer 1993; Menzies 2000). In this study, features related to plasma (plasmic fabric) were not visible. The primary reasons for this lack of observed plasma features are the relatively small contribution of the finest fraction in the studied sediments (clay fraction $\sim 6\%$, Table 1), poor in clay minerals and relatively high CaCO_3 content ($\sim 10\%$, Table 1) in the silty sand matrix. Other studies of modern tills in Svalbard have also not found the plasmic fabric (Larsen *et al.* 2006b).

The set of microstructures presented in Table 2 and described above show that both subglacial and supraglacial diamictons have similar features, which are characteristic for subglacial deformation (*e.g.*, Menzies 2000; van der Meer *et al.* 2003) and mass flows (*e.g.*, Lachniet *et al.* 2001; Phillips 2006). The microstructural analysis confirmed earlier *in situ* observations on the origin of particular deposits (Rachlewicz and Szczuciński 2000), that tills, that have been transferred up to the glacier surface have microfabric characteristics similar to subglacial tills. After their redeposition via slumps and debris flows the microfabric of diamictons in a supraglacial position was still similar, although it is not clear if it was preserved or developed during the mass flow processes. Moreover these deposits demonstrate post-depositional changes.

These observations indicate that movement in the tills was rotational (*e.g.*, turbate and necking structures, surface grain coatings on grains) as well as planar (*e.g.*, microshears). In the studied tills, there is a juxtaposition of rotational and shear line features. Hiemstra and Rijdsdijk (2003) and Hart *et al.* (2004) showed that where turbates occur throughout a sediment, without any apparent relation to shear planes, the sediment might represent a mass movement deposit in which the flow was the predominant deformation mode. Turbates may be considered diagnostic for a subglacial deformation where they are closely related to planar shear structures, although shearing may take place also during mass flows. In the deposits investigated here the larger rotating clasts have likely generated mini-shear zones between grain boundaries. The linear forms were probably produced as a result of the rotation. Although the subglacial origin of these features is likely, it is not possible to exclude their formation during re-deposition by mass flows.

Grain coatings in the deposits can have different origins, *i.e.* pre-depositional, syndepositional and post-depositional (*e.g.*, Moraes and de Ros 1992; Wilson 1992; Harris 1998; Skolasińska 2006, 2012; Kilfeather *et al.* 2009; van der Meer and Menzies 2011). This study found 'surface grain coatings' that appear to form during

deformational processes. Coatings usually occur near coarse grains of irregular shape and smooth out irregularities on the grain surfaces. Such microstructures were found in tills and subaerial debris flow deposits (*e.g.*, Khatwa and Tulaczyk 2001; Hart *et al.* 2004; Phillips 2006). Well-developed surface grain coatings (turbate coatings) are usually asymmetric because the grains around which they form ‘drag’ the surrounding matrix *en masse*, illustrating that the sediments in which they form are cohesive. The mechanism of accretion to the pebble and sand grains probably consists of physical processes in which clast-matrix interactions result in the matrix material being ‘plastered’ against the side of the rotating grains (Kilfeather *et al.* 2009).

Grain fracturing was probably facilitated by the weathered metamorphic rock fragments and the coarse-grained nature of the till. The presence of broken-off microfragments near the parent grains supports likely *in situ* subglacial crushing (Hiemstra and van der Meer 1997). Crushed grains were also observed in samples revealing a circular arrangement of skeleton grains; such an association points to a deformational origin of the crushed grains.

This study shows that the observed subglacial tills, supraglacial tills and debris flow deposits do not differ in terms of microstructures. The results suggest that the transfer of subglacial deposits through glacial deformation (*e.g.*, folding of the basal ice layer, thrusting) and short-distance re-deposition through slumps and debris flows might not affect the primary structures formed in the subglacial environment or may produce very similar structures due to mass flow processes. This work concurs with earlier observations of similarities in subglacial and supraglacial debris flow deposits (*e.g.*, Lachinet *et al.* 2001; Phillips 2006; Pleskot 2015). The only set of features found exclusively in supraglacial deposits is the set related to post-depositional processes and the presence of pore water. The supraglacial and debris flow deposits are less consolidated and often become cracked during drying and re-deposition, allowing water to more easily penetrate the deposits and facilitate dissolution and precipitation processes.

Imprint of early post-depositional changes. — The most common post-depositional changes to recently deposited glacial sediments occur as a result of two major groups of processes: (a) cryogenic processes, such as involutions or ice wedges and (b) weathering and pedogenic processes, such as translocation of clays, dissolving unstable minerals (*e.g.*, carbonate, biotite) and regrowth of new iron hydroxides (neoforms) from pore solutions (Carr 2004). The early post-depositional changes visible in thin section documented here are related to the latter processes. The presence of water occurs due to rainfall, melting snow and the melting of ice cores beneath supraglacial covers. The observed features are related to geochemical changes associated with carbonates and iron oxides.

Calcium carbonate is a common mineral in these sediments (up to 10%). In previous studies from the region, it was documented that calcium carbonate is

a highly mobile compound, subjected to multiple dissolution and precipitation events (Bukowska-Jania 2007). For example, it was common to observe fresh calcite minerals precipitated on till surfaces after several dry days in places of former surface puddles or larger wet depressions. In thin-section, we have observed dissolution of carbonate rock skeleton.

The petrographic composition of the investigated tills reveals the presence of many iron-rich rock types, many of which are already partly weathered (*e.g.*, mica schists and amphibolites). This weathering facilitates the release of iron. The iron precipitates mostly in the form of veins of iron hydroxides chaotically winding through the sediments or dispersed in the matrix. This distribution suggests that they were formed *in situ*. Despite the low permeability of these tills, the veins are found in supraglacial tills after just 2–3 summer seasons.

In older tills, it is not uncommon to find that pre-weathered sediments have been picked up and reincorporated into the newer tills. It can not be excluded in the presented case as well, for instance in case of carbonate grains with dissolution features. However, lack of the features considered to be post-depositional in fresh deposits and in subglacial tills imply that they were likely formed after deposition of supraglacial deposits.

Conclusions

This study of microstructures in selected subglacial and supraglacial deposits, both freshly released and redeposited by slides and debris flows, leads to the following conclusions.

- Micromorphological properties of tills that were deposited in subglacial and supraglacial conditions are very similar and are related mostly to the S-matrix microfabric.
- The fabric of supraglacial sediments subjected to short-distance re-deposition by debris flows is very similar to subglacial sediment fabric. Thus, studies on ancient tills which interpret the microstructures in terms of subglacial conditions should consider the potential of a later sediment reworking.
- The only important differences between subglacial and supraglacial deposits and visible in thin section are the presence of dissolution features on carbonate grains and cements and veins composed of iron hydroxides in supraglacial tills. Both of these differences are ascribed to early post-depositional processes affecting supraglacial tills that are generally less consolidated and subjected to physical reworking.
- The identified post-depositional effects were observed in supraglacial deposits already within 2–3 years.

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