Deformation ‘boundary front’ movements in subglacial tills—A microsedimentological perspective from till sequences near Pine Point, NWT, Canada

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Abstract
Investigations of glacial sediment exposures in a former open pit in the Pine Point Mining District, Northwest Territories, reveal evidence of changes in stress magnitude as exhibited by the movement of deformation ‘fronts’ within subglacial tills, as evident through micromorphological analysis. Indications of deformation, driven by stress fluctuations, were observed throughout a set of vertical subglacial till samples associated with the Laurentide Ice Sheet. These tills exhibit multiple sub-lithofacies variations in concert with marked changes in microshear orientation, which can be directly related to changing stress levels within a subglacial deforming bed. The evidence of changes in till stress conditions is typical of subglacial tills occurring beneath an active temperate ice mass within a soft deforming bed. As differing ‘layers’ of till that form a mosaic-like pattern become immobilized and ‘detached’ subjacent to the deforming bed sediments, a signature of this action is recorded within the tills as sequences of specific microstructures. These microstructures are part of a spectrum of micro-forms that develop as consequence of changes in stress, pore-water content and clay content within the ‘fault-gouge’—like environment formed beneath an active temperate ice sheet. A model is developed that uses data from Pit O-28 demonstrating where deformation ‘boundary front’ evidence in the form of deformation bands has developed as basal driven stress levels have penetrated active deforming sediments. The evidence from Pine Point indicates that till acts as an excellent palaeo-strain record of past active glacial processes, subglacial basal thermal conditions and sediment mobility.

KEYWORDS
Canada, deformation fronts, glacial, microsedimentology, microstructures, NWT, Quaternary, subglacial, subglacial deforming beds, till depositional/emplacement mechanics, tills

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1 INTRODUCTION

This paper examines the relationship between subglacial till emplacement and the mechanics of sediment deposition within a vertical section of tills in Pit O-28 in the past-producing Pine Point Mining District, Northwest Territories. Broader studies of tills at Pine Point have indicated that a considerable thickness (>20 m) of till was emplaced beneath an active soft sediment deforming bed (Rice, Paulen, Menzies, & McClenaghan, 2014; Rice, Paulen, Menzies, McClenaghan, & Oviatt, 2013). The tills were deposited under various ice-flow trajectories of the Laurentide Ice Sheet (LIS), and potentially represent successive accretion through three main glacial phases (Oviatt, Gleeson, Paulen, McClenaghan, & Paradis, 2015). This paper focusses on the microsedimentological findings from till exposures in Pit O-28 to determine stress fluctuations within the subglacial sediment deforming layer during till deposition and the progression of an active deformation front as subglacial till is being emplaced.

2 GLACIAL GEOLOGY

The site under investigation is within the former Pine Point Pb-Zn Mining District located on the southern shore of Great Slave Lake in northern Canada, approximately 180 km south of Yellowknife (Figure 1). This area is part of the Great Slave Plain of the Interior Plains of western Canada (Bostock, 1970). The LIS covered the entire Great Slave Regio, depositing a ubiquitous till cover of varying thickness which was subsequently overlain by glaciolacustrine sediments deposited by glacial Lake McConnell (Lemmen, 1998a, 1998b; Lemmen, Duk-Rodkin, & Bednarski, 1994; Prest, Grant, & Rampton, 1968). Due to the regional westward dip of the low-relief Palaeozoic bedrock surface, the glacial sediments thicken westward from less than 1 m proximal to the Canadian Shield east of Pine Point to more than 25 m in open pits 60 km to the west (Rice et al., 2013). Thicker sections of glacial sediment locally have infilled bedrock karst-collapse structures. After retreat of the LIS, the area was inundated by glacial Lake McConnell and consequently upper surfaces of the tills were winnowed and a thin cover (<2 m) of littoral glaciolacustrine sediments were deposited (Lemmen, 1990; Lemmen et al., 1994; Oviatt & Paulen, 2013). The Pine Point region was deglaciated sometime after 11.1 ka BP (Dyke, 2004; Oviatt & Paulen, 2013).

Fieldwork conducted by the Geological Survey of Canada in 2010 documented cross-striated bedrock surfaces on the shoulders (i.e. bedrock benches) of several exposed open pits (McClenaghan, Paulen, & Oviatt, 2018; Oviatt, 2013; Oviatt et al., 2015; Oviatt, Paulen, McClenaghan, Gleeson, & Paradis, 2011). Striation measurements and cross-cutting relationships (Figure 2), combined with aerial-photograph and satellite-imagery landform analyses, have determined a minimum of three ice-flow trajectories (McClenaghan et al., 2018; Oviatt et al., 2015). The earliest flow phase was to the south-west (~230°), a subsequent significant flow phase to the northwest (~300°) and a final west south-westward (~250°) deglacial flow were identified in several pits, including O-28. Landforms in the region are streamlined flutings parallel to the last phase (~250°) of ice-flow direction (Figure 2), which eroded sediments from the larger, older oriented landforms that were formed during the intermediate northwest glacial event (Oviatt, McClenaghan, Paulen, & Gleeson, 2013). These youngest
reshaped landforms have high length:width ratios (>15:1), and as mega scale glacial lineations (MSGL), are indicative of formation by a former ice stream, possibly a northeastward extension of the Hay River ice stream (IS#176) (Margold, Stokes, & Clark, 2015; Margold, Stokes, Clark, & Kleman, 2014; McClenaghan et al., 2018).

3 | MACROSEDIMENTOLOGY

Tills in the Pine Point area have a sandy-silt matrix containing an average of 14% clay, 50% silt and 36% sand (Figure 3) and contain on average 25% CaCO₃, as determined by borate fusion/ICP-MS (Oviatt et al., 2013), which reflects the underlying Palaeozoic carbonate bedrock as the dominant provenance. Three tills were identified in a vertical section at the north end of the O-28 Pit based on colour, clast lithology, and clast fabric results but are not readily discernable by matrix geochemistry or texture (Tables 1 and 2). The lowest till (T1) immediately overlying bedrock, contains the greatest abundance of Shield-derived clast lithologies, which are derived from Precambrian bedrock east of the Slave River, approximately 100 km to the east (Figure 1) and the least amount of Palaeozoic carbonate clasts (i.e. local bedrock) (Rice et al., 2013). Till macrofabrics were obtained from the northeast exposure. Three macrofabrics are presented in Figure 4. The macrofabrics were obtained for T1 and T2 approximately in the middle of each till lithofacies unit, while T3 was taken slightly lower in the upper till lithofacies unit to avoid any near-surface disturbance. The bedrock underlying T1 was striated at 231°, based on multiple field measurements, as was the case with all striation data. The macrofabrics for T1 and T3 are not too dissimilar with approximately north-south azimuths (T1 = 349.8°, T3 = 348.9°) whereas T2 (69.3°) has a much stronger east-west azimuth. Striation directions of ~300° for the last ice flow direction related to MSGL would appear to accord with the macrofabric in Till T3. The macrofabrics for T1 and T2, however, do not equate with the recorded bedrock striation at the base of the NE section and striation directions measured on the bedrock bench around Pit O-28. Given the sediment deformation recorded in these tills and the vagaries of till fabric analyses it is not unexpected that there is a dissonance between bedrock striations and macrofabrics (cf. Larsen, Piotrowski, & Kronborg, 2004). The mechanics of microsediment rheology recorded in these tills is of such fluctuation that macro and microfabrics often will not be similar (cf. Benn & Ringrose, 2001; Bennett, Waller, Glasser, Hambrey, & Huddart, 1999; Catto, 1998; Evenson, 1971; Gentoso et al., 2012; Hopkins, Evenson, Kodama, & Kozlowski, 2016; Neudorf, Brennand, & Lian, 2015; Phillips, Evans, Meer, & Lee, 2018).

The colour differences between the tills probably reflect variations in glacial provenance and indicate that the tills may be of differing glacial episodes or may simply, as seems more probably, reflect the change in provenance of the units within a single accumulating till package during the Wisconsinan, as the Keewatin dispersal centre migrated through time and so ice flow directions change considerably at times (McMartin & Henderson, 2004). Although the tills are different in colour, at both the macro and microscale (as discussed below), the tills (T1, T2 and T3) are all remarkably similar in texture and geochemistry (see McClenaghan et al., 2018). It might be assumed that T1 at the base of the succession, lying directly on bedrock is a He-bed with limited
subjacent drainage, indicative of a traction till and not like the other tills (cf. Evans, 2017; Evans, Phillips, Hiemstra, & Auton, 2006; Menzies, 2012). Instead, all the tills all display the characteristics of subglacial deformation tills emplaced under wet-based ice with high sediment availability (as discussed below). However, given the limited basement drainage below any such till in this lowest position, it is possible that the sediment between the basal ice and bedrock might have been ‘liquified’ and so mobilized thus garnering a similar appearance to the other overlying tills (T2 and T3) (cf. Philips et al., 2018). Over time, changes in ice flow trajectories with variations in till provenance occurred and may account for till colour variations, fabric azimuth changes and clast type and provenance differences.

4 | MICROSEDIMENTOLOGY

4.1 | Methodology

Microsedimentological samples were taken from two till exposures, from bedrock to surface, along the northwest and northeast sides of the Pit O-28, which provided excellent access for sediment logging and sampling for till pebble provenance, till macrofabrics, till matrix geochemistry and microsedimentological structure analysis (Figure 5). By sampling vertical profiles in two locations no more than 100 m apart, it was anticipated that a close comparison of structures within the tills could be achieved. The purposes of the microsedimentological analyses were to: (a) identify microstructures present within two vertical till sections; (b) compare the microstructures with the macrofabricology characteristics of clast provenance and till macrofabric analyses; (c) determine when, where and how the microstructures formed and evolved; and (d) document the evidence of change in stress in the vertical sections. This final objective has a primary goal of identifying changes in till stress elements, which can be identified in thin section, providing insights into the evolving subglacial conditions (cf. Lee & Phillips, 2008; Phillips et al., 2018).

At each site, samples were taken either as bulk samples or in Kubiena tins for subsequent impregnation and thin section production (Lee & Kemp, 1992; Rice et al., 2014). Oriented, ‘undisturbed’ samples were collected from each of the visually different till units. Typically, samples 10 × 10 cm in size and 5–8 cm in thickness were collected, wrapped in air-tight bags, and transported to the Brock University Petrology Laboratory (van der Meer, 1987; Rice et al., 2014). The production of thin sections followed the steps and techniques outlined by Lee and Kemp (1992), and Menzies and van der Meer (2017, fig. 21.4). Samples were air-dried for approximately 2–3 weeks, then submerged in a resin bath (a blend of acetone and Ecopoxy©—an organic-based hardening solvent). A resin hardener was combined with the Ecopoxy© resin prior to immersion in the ‘soaking’ bath. Samples were left to impregnate for ~1 week in a vacuum chamber (at 12–17 hg/cm) where the acetone drove out moisture within the sediment, allowing it to be replaced by resin. After approximately 7 days, the sample solidified and a block ~1 cm thick was cut from each sample using a diamond saw. This small block was then ground down, polished and mounted on a glass plate (75 mm × 50 mm × 1 mm). The block was hand-ground to a thickness of ~30 μm and cleaned, after which a cover slip was added, and the thin section was then examined using a petrological microscope. Each thin section shown in this paper is in plain polarized light with an annotated image to the right or below the actual thin section image. In all cases, the top of the sample is at the top of the image. Initially
| NW samples PTA# | 004 | 002 | 011 | 010 | 009 | 008 | 007 | 006 | 005 |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Colour          | Dbg | Dbg | Drb | Drb | Lb  | Drb to Lb | G   | Dbr to Dbg | Dbr to Dbg |
| Munsell         | 7.5 YR 4/4 | 7.5 YR 4/4 | 7.5 YR 5/4 | 7.5 YR 5/4 | 7.5 YR 6/4 | 7.5 YR 6/4 | 7.5 YR 6/2 | 7.5 YR 7/2 |
| Clast shape     | Sr  | Sr  | Sr-Sa | R, Sr-Sa | A few Sr | A few Sr | A few R | A few A | A few Sa |
| Domain (dm)     | ●   | ●   | ●   | ●   | ●   | ●   | ●   | ●   | ●   |
| Grain stacks (gls) | ●   | ●   | ●   | ●   | ●   | ●   | ●   | ●   | ●   |
| Rotation (rt)   | ●   | ●   | ●   | ●   | ●   | ●   | ●   | ●   | ●   |
| Edge-to edge (ee) | ●   | ●   | ●   | ●   | ●   | ●   | ●   | ●   | ●   |
| Microshears (ms) (lineations) | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| Plasmic fabric  | ma  | lat | lat and ma skelsepic | ma | lat | lat | lat | ma |
| Deformation bands | ●   | ●   | ●   | ●   | ●   | ●   | ●   | ●   | ●   |
| Remarks         | T1—lowest till Evidence of clast and rotation structure alignments | T1—lowest till Note rhomboidal structure to grain stacks alignments | T2—middle till Sampled just above T1 contact Necking structures | T2—middle till | T3—upper till Sampled 30 cm above basal contact with T2 | T3—upper till Sampled 75 cm above basal contact with T2 | T3—upper till Sampled 50 cm above Sample 008 Necking structures | T3—upper till Sampled 20 cm above Ground surface | T3—upper till Sampled 80 cm below Many parallel ms |

Note: Colour: dbg—dark brown grey, drg—dark red grey, drb—dark red brown; Munsell: all 7.5YR; Clast Size: sfl—small, a few large > 35μm; wr—wide range of clast sizes; wide range of clasts sizes but few clasts; Clast provenance: le—local and exotic sources; Clast shape: sr wr—subrounded to well-rounded; ● indicates microstructure present; Plasmic Fabric: ma—masepic; om—omnisepic; lat—lattisepic; Wu—weak unistrial.
16 till samples were collected in Pit O-28 resulting in 15 thin sections.

4.2 | Thin Sections

The fundamental data from each thin section are shown in Tables 1 (northwest exposure) and 2 (northeast exposure). A glossary of the terms used in microsedimentology and micromorphology can be found in van der Meer and Menzies (2011).

4.2.1 | Northwest Site

Several characteristics of each thin section are worth noting here. For example, two distinct domains can be seen in both the left and right-hand sides of the image for sample 004 (T1) (Figure 6A; Table 1). This thin section contains several subrounded clasts that exhibit some preferred orientation. It is noteworthy that the rotation structures display a degree of alignment. Several distinct (micro-) deformation bands obliquely cross this thin section image but are largely confined to each separate domain suggesting that, at least, one of the sets of bands have been inherited prior to being incorporated into the final emplacement of the till. Sample 002 (T1) (Figure 6B) exhibits a very large percentage of low angle microshears (60%). It is also apparent that two sets of grain stacks occur at an angle approximately oblique to one another forming a type of rhomboidal structure (as annotated in Figure 6C). In Sample 011 (T2) (Figure 6C) two domains were identified, one in the left side of the image to the left of the large central clast, the other to the right of the clast. The domains are recognized by the slightly more clast-rich matrix on the right side of the image. The several larger clasts are surrounded with a skelsepic fabric of fines skirt-ting the clast edges (cf. Dalrymple & Jim, 1984; Jim, 1988; Lee & Phillips, 2008). Distinctive ‘necking’ structures occur between the large clasts (indicated by a red box). Several deformation bands are noted that again are related to different domains, one being inherited as in Figure 6A. In Sample 010 (T2) (Figure 6D) many of the rotation structures and sets of grain stacks parallel the microshears. However, the deformation bands are of a different chronological period to the other microstructures, as they are unrelated to either the microshears or rotation structures or detectable domains in terms of orientation and cross-cut the microshears. Sample 009 (T3)’s thin section image shown in plain light (Figure 6E), is a fine grained diamicton with no obvious domains present. There are subparallel microshears throughout the
sediment with grain stacks and rotation structures present. The voids around the large clast in the lower centre of the image is probably the result of drying preparation. In Sample 008 (T3) (Figure 6F), there are numerous microstructures with a strong alignment and subhorizontal deformation bands, as well as a small separate domain, the rest of the matrix is located at the bottom left-hand corner of the image. The microshear sets appear to form an indistinct rhomboidal pattern in line with a lattiseptic plasmic fabric. In Sample 007 (T3) (Figure 6G), a close parallel relationship between microshears and grain stacks can be observed. Again, as in Sample 008, a distinct rhomboidal structure linked to microshears and deformation bands can be observed. Sample 006 (T3; Figure 6H) was obtained 20 cm above Sample 007 and was captured in plain light. This thin section shows a distinct set of horizontal microshears with many grain stacks.
perpendicular to the microshears direction. At the top of the northwest exposure, Sample 005 (T3) (Figure 6I) is shown in plain light and characterized by a high number of near vertical microshears, possibly indicative of formation under relatively low-stress conditions (cf. Narloch, Piotrowski, Wysota, Larsen, & Menzies, 2012). The change in microshear direction between almost horizontal in Sample 006 and vertical in Sample 005 probably indicate there was a switch in the stress conditions between these samples, possibly during deposition.

4.2.2 | Northeast Site

Samples taken from the northeast exposure display a similar set of microsedimentological characteristics as those in the northwest site. In Sample 017 (T1) (Figure 7A; Table 2), the thin section exhibits large deformation bands and many subparallel microshears. Deformation bands separate the thin section into several domains, based on clast size and content, giving the sediment an oblique ‘banded appearance’. Rotation structures are closely linked to larger clasts within the sediment and are largely restricted to these locations. Sample 016 (T1) (Figure 7B), sampled close to Sample 017, contains many microstructures that are similar but lacks a ‘banded’ aspect. This thin section also exhibits no apparent domains and has sets of deformation bands crossing at an oblique angle. Within the T2 unit, Sample 012 (Figure 7C) displays strong subdivisions within the sediment due to deformation bands that parallel microshears. Sample 013 (T2, Figure 7D) contains two separate domains characterized by their difference in clay content (lighter and darker). This thin section contains several large clasts that have resulted in edge-to-edge grain crushing events, necking structures and grain stacks of large clasts. Finally, at the top of the northeast exposure, Sample 014 (T3, Figure 7E), shown in plain light, has a high clay content and three subparallel deformation bands with parallel microshears. Within the upper deformation bands, a series of rotation structures appear to ‘line-up’ in relation to microshears found on either side of the deformation bands within which they occur.

The data from the thin sections taken from both exposures show a remarkable similarity in terms of matrix composition, microstructure types and disposition (Tables 1 and 2). All the thin section samples exhibit varying degrees of sediment deformation, most thin sections contain deformation bands, and all sections show sets of microshears at differing angles to the horizontal.

5 | THIN SECTION INTERPRETATIONS FROM O-28 PIT, PINE POINT

The sediments examined at Pit O-28 are interpreted as being of glacial origin based on the poorly sorted nature of the matrix (clay to coarse sand), clast provenance analysis (see McClenaghan et al., 2018), preferred clast fabrics (Figure 4), the presence of
striated clasts (Rice et al., 2014, 2013) and the microstructures present in the thin sections (cf. van der Meer, 1993; van der Meer & Menzies, 2011; Phillips et al., 2018). It can be further argued that the diamicton present in Pit O-28 is a subglacial till most probably formed under deforming bed conditions—a mélange, or tectomict (cf. Phillips, Everest, & Reeves, 2013; Phillips, Lipka, & van der Meer, 2013; Phillips et al., 2018).

The appearance of intraclasts (‘scavenged’) sediment units (cf. Eyles, Sladen, & Gilroy, 1982; Hoffmann & Piotrowski, 2001 and the range of clast sizes and morphologies accompanied by the strongly differing microshear orientations, coupled with the macrosedimentological aspects of macrofabrics and provenance changes, suggest emplacement of the subglacial tills at Pit O-28 were from a mobile bed. Sets of microstructures at various stages of development support the conclusion of a deforming soft bed environment within which the tills have been formed and deposited (Menzies, Meer, & van der Shilts, 2017).
In each of the thin section samples, the orientation of each microshear was measured and plotted on a stereo net from which a rose diagram was developed (Figure 4). Research by Haines, Kaproth, Marone, Saffer, and Pluijim (2013), Narloch et al. (2012), and Iverson and Zoet (2015), based upon experimental research by Tchalenko (1968), Logan, Dengo, Higgs, and Wang (1992) and Thomason and Iverson (2006), indicate that the orientation of microshears in relation to shear direction and deforming sediment thickness is indicative of stress levels. Logan, Friedman, Higgs, Dengo, and Shimanmomo (1979) demonstrated that as applied stress increases, the angle of microshear fractures reduces and that a value of approximately 25° can be set to differentiate between low (>25°) and high stress levels (<25°) (Iverson & Zoet, 2015; Menzies & Reitner, 2016; Morgenstern & Tchalenko, 1967) (Figure 6A and B). Under drier sediment conditions, of course, higher angles of friction might develop that would change these shear angles. Work both experimentally by Dahlen, Suppe, and Davis (1984) and Nieuwland, Leutscher, and Gast (2000) and in the field applied to Quaternary sediments by Lee, Phillips, Rose, and Vaughan-Hirsch (2017) demonstrate this possibility. However, under subglacial conditions of soft sediment movement, sediment mobility is probably to cease under
such drier conditions unless other evidence not observed at Pine Point indicates drier conditions locally prevailed (J. Lee, pers. comm.). Microshears act as proxy evidence of stress levels since each microshear is an individual shear structure or slip surface (Fossen, Schultz, Shipton, & Mair, 2007; Schultz & Fossen, 2008). Microshears may be best described as shear localization fabrics (Haines et al., 2013; Tembe, & Wong, 2010). In themselves, microshears indicate that a local readjustment due to shear stress application has occurred. In analysing microshear angles, care must be taken to cut the sediment as a thin section parallel to the dominant local direction of the macrofabric (cf. macro-fabrics in Rice et al., 2014; Figure 4). As the microshears seen in the sediments are probably of several generations, some formed at the time of immediate emplacement while others probably formed due to later compaction, possibly even subsidence of the sediment after porewater pressures dissipated (cf. Bateman, Swift, Piotrowski, Rhodes, & Damsgaard, 2018; Phillips, Meer, & Ferguson, 2011). In most instances, microshears can be recognized due to local micron-size readjustments or in other cases linear parallel grain separations. The data are, at best, cumulative averages for any given area of till and represent those shear structures that have been retained and survived until final deposition/emplacement. The data are plotted with microshears <25° (low angle, high strain) shown in red and microshears >25° in black (high angle, low strain). The percentage of microshears above and below 25° was used, rather than the actual number, to measure the change, as a percentage, in low and high-angle microshears across the till exposures (Ballas et al., 2013). The microshear fabric diagrams in Figure 6A and B display two sets of microshear angles from Pit O-28. Plots showing the change in stress are located on the right-hand side of lithofacies columns in Figure 8A and B. The data show that there is considerable variation in stress within the tills as might be expected, however, to suggest there is a discernible trend in any of the data would be inaccurate, at this stage. Before embarking on an examination of the microstructures and microstructural fabric of these tills it seems probable, given the rheology of these tills with relatively high clay contents, that the grain stacks pre-dated the microshears and may indicate extension and boudinage within the till (Goscombe, Passchier, & Hand, 2004; Passchier & Trouw, 1996). In discussions on the evolution of microstructures in sediments it has been shown that there is a set of microstructure development types that passes from grain stacks to edge-to-edge grain crushing, to microshears and finally deformation bands (Fossen et al., 2007; Haines et al., 2013; Haines, Marone, & Saffer, 2014; Hiemstra & van der Meer, 1997; Menzies et al., 2016; Skurtveit et al., 2014; Figure 9).

In both exposures, there appears to be a marked divergence of orientation between microshears and grain stacks near the top of the section which might indicate that the later microshears are the result of ice overriding the till during a late phase of ice flow. The overprinting evident in all thin sections is illustrative of the continual change in stress as the sediment is mobilized across this terrain and the continual change in till rheology on and immediately prior to till emplacement (Narloch et al., 2012). As noted above, the change in stress is symptomatic of microstructure overprinting. Deviations occur throughout the stratigraphic column but at no critical point in the column nor in any specific direction, but rather changes in strength and direction appear to be somewhat arbitrary, probably a function of changing sediment rheology, porewater content and stress (cf. Kjær et al., 2006; Hart, Rose, & Martinez, 2011; Phillips et al., 2018).

In all the tills samples, there is strong evidence of sediment scavenging. The scavenging consists of sediment rafting or reworking and may be indicated by microstructure overprinting, clast and microstructure lineation reorientation, realignment and redirection. All of these ‘micro-arts’ are indicative of episodes of repetitive event histories of sub-lithofacies units being incorporated (or intercalated) into the till body as a function of the mélange-type tills that form (cf. Leysinger Vieli & Gudmundsson, 2010). All the tills at Pit O-28 are Type 2—a mélange till deposited/emplaced as part of a deforming soft sediment subglacial set of units beneath a temperate ice sheet (cf. Menzies, 2012, fig. 10). In plotting the range of microshear angles in fabric diagrams from the base to top of the till exposures at Pit O-28, fluctuations can be observed and can be interpreted
as indicative of changes in stress within the deforming sub-glacial sediment packages at these sites. Future research should include closer spacing of sediment samples to further analyse changes in stress within the tills.

6 | SUBGLACIAL TILL DEFORMATION AND THE DEVELOPMENT OF A ‘TRANSLOCATING DEFORMATION BOUNDARY FRONT’

Interpretation of individual thin sections of till from Pit O-28 indicate that deforming conditions within the till were prevalent and fluctuated in intensity throughout its deposition. In consideration of general subglacial deforming bed conditions, it is apparent that mobile sediment moves as a function of the applied stress, porewater pressures, the grain-size composition of the sediment, and mobilizes in the form of a deformation ‘front’ (Alley, 2000; Boulton & Hindmarsh, 1987; Denis, Guiraud, Konaté, & Buoncristiani, 2010; Fleming, Stevenson, & Petronis, 2013; Hindmarsh, 1997; Kjaer et al., 2006; Phillips et al., 2018; Reinardy, Hiemstra, Murray, Hillenbrand, & Larter, 2011; Truffer & Harrison, 2006; Tulaczyk, 2006).

A subglacial deformation ‘boundary front’ is defined in this paper as the interface between mobile and immobile sediment within the basal sediment package (Figure 9). A dynamic balance develops between the mobilizing effect of the applied shear stress and the stabilizing effect of the normal stress. The ‘boundary front’, in three dimensions and over time, separates mobile, actively moving sediment from inactive, immobile sediment. As sediment rheology changes as a

FIGURE 8 (A) Lithological logs of the northwestern exposure and (B) northeastern exposures: lithofacies units, microshear fabric diagrams, location of microsedimentological samples and plotted stress-level fluctuations at the right-hand side. Note n equals the number of microshears measured per sample
complex function of stress, porewater content and grain size of the sediment, there comes a location within the sediment where yield strength changes in relation to applied stress and a ‘shear partition’ or ‘boundary front’ develops that separates the bulk sediment into two distinctive rheologies (cf. Drake, 1990; Hanes & Inman, 1985; Stipp et al., 2013). As conditions, both external and internal, change within the basal sediment body, the position of the ‘boundary front’ will fluctuate within the sediment package as porewater fluctuates, either mobilizing or immobilizing sediments (Figure 9). These fluctuations in sediment mobility or otherwise are probably to vary temporally and spatially such that larger or smaller units of the mobile/immobile sediments are affected. In many cases, penetrative stress conditions lead to re-mobilization of previous immobile sediments (scavenging), due to increased porewater content and decreased effective stress levels, into the mobile soft sediment moving at the interface between the basal ice and the subjacent sediment. Figure 9 models a time sequence illustration that shows the slow upward movement of the deposited (immobilized) till package. The impact of a moving deformation ‘boundary front’ is probably pervasive in a subglacial deforming bed affecting the till such that the effect of the polyrheology of the till is to cause deformation ‘boundary fronts’ to be continuously moving during active subglacial mobilization. Where changes in stress occur that are less than past strain conditions, previously formed microstructures will survive and vice versa (cf. Włodarski, 2005; Menzies, 2012). The evidence of mosaic fluctuations can be observed within subglacial sediments as variations in stress manifested by the presence and orientation of various microstructures (specifically microshears, microclast fabrics and grain stacks) (cf. Phillips et al., 2018; Piotrowski, et al., 2004; van der Meer, et al., 2003). For example, as stress increases within the basal sediment package, microstructure fabrics are probably to become increasingly parallel (en echelon) in orientation to the principal axis of strain which is typically perceived as increasing horizontality of many microshears and the development of deformation bands or zones of low and high stress mobilization (cf. Bateman et al., 2018; Carr & Rose, 2003; Iverson, Hooyer, Thomason, Graesch, & Shumway, 2008; Narloch et al., 2012; Thomason & Iverson, 2006). Under lower stress levels, microshears are probably to be found at steeper angles to the horizontal assuming the principal axis of strain is approximately horizontal (Figure 7I). As demonstrated in earlier work on tills in Austria, these fluctuations in ‘attitude’ of microshears can be mapped and correlated with changing subglacial stress conditions (Menzies & Reitner, 2016).

As the ‘deformation boundary front’ moves within the subglacial sediments, in some areas till will become re-activated under increasing stress; elsewhere, with a reduction in stress, till becomes immobilized and begins to accrete. This patchwork or mosaic of till mobilization or re-mobilization that the deformation ‘boundary front’ prescribes can be recognized (in the thin sections at Pit O-28) as fluctuations in microshear ‘aspect’ and numerous small but distinct deformation bands in the till (cf. van der Meer et al., 2003, fig. 10; Piotrowski et al., 2004; Kjaer et al., 2006; Trommelen & Ross, 2014). Where increasing stress occurs, tills are probably to become increasingly mobile, all other factors being consistent. In contrast, reduction in stress probably results in decreasing till mobility and eventual emplacement/ deposition. As till accretion occurs and the deformation ‘boundary
front’ moves upward within the till package (higher in the exposure) the vicissitudes of stress fluctuations are readily detectable within the till exposures. The upward-moving boundary front, and re-entrainment (i.e. scavenging) of mineralized subglacial till with down-ice accretion supports mineral dispersal models (McClenaghan & Paulen, 2017, fig. 20.11; Stanley, 2009).

7 | SUMMARY

The three till units (T1, T2, T3) show little difference in the types and abundances of microstructures present. To some extent this result is surprising because the authors had assumed that T1, at the base of the till succession and formed upon a hard bed (‘He’ in Menzies, 2012), would exhibit different characteristics from the overlying tills (T2 and T3). It is probably that T1 is not the primary depositional unit on bedrock as initially assumed but instead is a till that was emplaced under soft bed conditions after the original traction till was eroded or totally homogenized and overprinted, as were tills, T2 and T3. As might be anticipated in such a diverse and complex till sedimentological environment, variations in macrofabrics and microstructures types occur in the tills and there is no apparent correlation between their position within the stratigraphic column and these variations.

In noting the microstructures present in these tills, an awareness of when, where and how these structures formed and evolved can be ascertained in the sense that as stress conditions change, various microstructures formed while others were probably destroyed through overprinting during the periods of till emplacement and deposition. This work identifies the relationship between groups of microshears and their angles to stress application and the development of deformation ‘boundary fronts’ that are probably detectable in the form of fluctuations in stress throughout these tills and the formation of distinctive deformation bands. This paper demonstrates the data that can be obtained from microsedimentological examinations of tills in multiple and in thick till sequences. Many research questions remain in terms of the presence and persistence of deformation bands and deformation ‘boundary fronts’ within tills as they are actively deposited. More detailed examination of tills at the centimetre-scale will be required both within single till exposures and between exposures to answer these questions.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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