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SUBGLACIAL TILLS: A PROCESS MODEL BASED ON MICROSEDIMENTOLOGICAL CLUES

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ABSTRACT: **Subglacial sediments are subject to erosion, transport, and deposition in active, ephemeral, and spatially localized glacial environments. It is critical to determine how these mobilized sediments become immobilized in a time-transgressive process and can be frequently remobilized and reimmobilized. Microscopic sedimentary structural signatures provide invaluable information on subglacial processes and contribute to understanding till formation. Data were obtained from a series of field sites in Canada and Austria investigating the microsedimentological aspects of both alpine and continental glaciation tills to construct a conceptual model of subglacial deformation. Microstructures in these tills indicate rheological behaviors that can be summarized into a potential model for soft deforming subglacial sediments. Most microstructures noted in these subglacial till examples highlight the development of subglacial interface kinematics providing clues to till deposition mechanics, subglacial bedform development, and the processes involved in till provenance distributions. A conceptual process model of subglacial interface conditions in soft mobile sediments is developed that uses microsedimentological evidence and highlights how an active ice mass integrates with ongoing substrate deformation. In the model, interaction occurs between the ice and its sediment bed with internal sediment microstructures evolving where multiple transient shear deformation processes cause localized deformation linked to pervasive and nonpervasive sediment deformation.**

INTRODUCTION

The deformation of subglacial tills arises largely at "moderately" low effective stress that occurs at all scales in saturated sediments under actively flowing ice masses leading to sediment failure and mobilization. Deformation is commonly localized in regions of relatively high strain with intervening areas of moderately low strain. It is generally agreed that such regions are often only millimeters in thickness, are laterally variable, and can quickly be removed or replaced as remobilization occurs (e.g., Hart and Boulton 1991; Benn and Evans 1996; Hart and Rose 2001; Iverson and Zoet 2015; Halberstadt et al. 2018; Zoet and Iverson 2020). Subglacial sediment mobilization beneath ice masses occurs largely in response transmission of basal ice stress. Tills are heterogeneous in composition, and, in the evolving behavior of till deformation, it is likely that rheometric measurements of yield strength and rate-dependent shear resistance have limited relevance to subglacial till mechanics (Iverson 2003; Nagl et al. 2020; Zoet et al. 2023). Evidence from slurry experiments on intergranular mixes suggests that variability in pore pressure, liquefaction, and sediment strength are key aspects of till-like sediment-flow behavior. Deformation stresses can be quickly diffused in subglacial tills containing coarse clasts by the transmission of applied stresses at depth through grain-to-grain contact (Iverson et al. 1996; Tulaczyk 1999; Iverson 2003; Zhang and Kamrin 2017) or vertical porewater pressure fluctuations (Iverson et al. 1998; Tulaczyk et al. 2000; Damsgaard et al. 2015, 2016, 2020).

It is now acknowledged that extensive areas beneath the Quaternary ice sheets were underlain by deforming sediment beds (*inter alia* Boulton et al. 2001; Rose and Hart 2009; Leysinger et al. 2010; Stokes 2018). Additionally, considerable work has been carried out on modern ice masses where the presence of active deforming sediments is well known (Alley 1989a, 1989b, 1991; Boulton 1996; Tulaczyk et al. 2001; Graham et al. 2009; Smith and Murray 2009; Spagnolo et al. 2016; Davies et al. 2018; Fernández et al. 2018). As subglacial sediment becomes mobilized there is a substantial sediment flux towards the ice-mass margins (Nygård et al. 2007; Melanson et al. 2013; Batchelor and Dowdeswell 2014; Bradwell and Stoker 2015; Dowdeswell et al. 2015; Livingstone et al. 2016; Clayton 2017; Halberstadt et al. 2018; Stokes 2018; Brouard and Lajeunesse 2019; Hart et al. 2019; Damsgaard et al. 2020; Franke et al. 2020a, 2020b; Hogan et al. 2020). As subglacial sediment is entrained towards the ice margin, the deforming sediment moving over a relatively low gradient beneath an ice mass also contributes to movement or flow of the ice (Alley and MacAyeal 1994; Dowdeswell and Ó Cofaigh 2002; Dowdeswell et al. 2004; Bingham et al. 2010; Franke et al. 2020a, 2020b). For example, based on modeling, flow rates and net subglacial sediment fluxes predict that ice streams transporting sediments to the margin of the northern part of the Barents–Kara Sea ice sheet delivered sediment at a rate of up to 4 cm a^{-1} (0.13 cm a^{-1} averaged over the fan) to the 200-km-wide mouth of the Bear Island trough (Dowdeswell and Siegert 1999; Ottesen et al. 2005; Dowdeswell et al. 2010). Based on field observations,

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Anandakrishnan et al. (2007) suggested a vastly larger net sediment flux rate in the order of 150 to 10^5 cm^3 a^{-1} occurring beneath the present-day fast-moving Whillans Ice Stream in Antarctica. These findings suggest that an understanding of how sediments deform beneath an ice mass will provide valuable insights into ice mass stability and how ice-mass flows and transports sediments over time.

Sediment Structures in Tills

Sediment structures diagnostic of deformation processes in subglacial tills have long been described and interpreted at the macroscopic level (e.g., Slater 1926; Boulton 1979; Alley et al. 1986; Blankenship et al. 1986; Truffer and Harrison 2006; Atkinson 2009; Bougamont et al. 2019; Knight 2019; Damsgaard et al. 2020), and, over the past decades, at the microscopic level (e.g., van der Meer 1993; Kjær et al. 2006; Cowan et al. 2012; Phillips et al. 2018; Menzies and van der Meer 2018; Gehrmann et al. 2019; Mehlhorn et al. 2019; Narloch et al. 2020; Menzies 2022a, 2022b). The analyses of microshear orientations and fabrics, for example, have been shown to be illustrative of the presence of high and low shear zones in tills (Narloch et al. 2012, 2015, 2020; Piotrowski et al. 2014; Menzies and Reitner 2019; Menzies et al. 2019; Rice et al. 2019a; Reitner and Menzies 2020; Zoet et al. 2023). Based on the orientation of microshears, in relation to shear direction and thickness of deforming sediment, levels of shear stress can be estimated (Tchalenko 1968; Logan et al. 1992; Thomason and Iverson 2006; Narloch et al. 2012, 2020). It can be shown that, as shear-stress levels increase, the angles of the microshear to the horizontal decrease and that a value of approximately 25° can be set to differentiate between high ($< 25°$) and low ($> 25°$) stress levels (Logan et al. 1979; Menzies and Reitner 2016; Menzies et al. 2019). In the thin sections presented here, where microshear-angle data have been documented, variation in shear stress can be deduced. Unquestionably, microshears in till matrix are often subtle and lack the more obvious signs of displacement and shear direction often attributed to other shears in deposited sediments that have not undergone repeated deformation in both pervasive and nonpervasive modes (Stroeven et al. 2002; Passchier and Trouw 2005; Vernon 2018, Chapters 2 and 5). It is likely that shear localization in the deforming till is transient, and therefore evidence of deformation partitioning on a grain-to-grain basis may be reset or obliterated, owing to progressive deformation. Secondly, the microtexture of the thin sections reveals clear indications of subtle changes in particle orientations indicative of very localized stress changes related to the presence of décollement surfaces, previously defined as deformation front/bands (cf. Menzies et al. 2019) and shear-zone formation. Décollement surfaces develop at the junction between immobilized and mobile till units during active deformation that may be transitory and quickly redeformed or removed (cf. Evans et al. 2006 at the macroscale). In a sense, these shear surfaces are possibly only ephemeral in their existence such that only fragments may persist in thin section. In many instances, décollement surfaces are no longer horizontal, even though they likely first developed horizontally (parallel to shear stress of active ice (τ_i) and they show a wide variation in angle along the horizontal plane probably due to subsequent postdepositional rotation, as is common in deforming sediments, or because they conform to the local bedform (Roberts 1989; Müller and Schlüchter 2000; Hart and Rose 2001; Mandal et al. 2005; Thomason and Iverson 2006; McClay 2013; Iverson 2017; Zoet et al. 2023; Phillips, personal communication 2023).

Sediment mobilization is a complex system of processes related to sediment thermal and rheological states that is also influenced by overlying ice conditions. The sediments are rheologically highly variable in terms of their grain size, clast morphology, porewater content (pressure), and overall and internal structural geometry. Likewise, it must be recognized that these sediments, at various times and stages in the deformation process, may have undergone pervasive or nonpervasive deformation (Evans et al. 2006; Evans 2017; Le Heron et al. 2018; Menzies et al. 2018; Damsgaard et al. 2020; Zhang et al. 2020; Zoet et al. 2023). In the past, these sediments have often been termed lodgement tills, comminution tills, glacial tectonites, or more recently deformation tills, tectomicts, or subglacial traction tills (cf. Elson 1989; Hart and Rose 2001; van der Meer et al. 2003; Ruszczynska-Szenajch et al. 2003; Clarke 2005; Menzies et al. 2006; van der Meer and Menzies 2011; Menzies 2012; Evans 2017). An added complexity of the subglacial environment is the need to fundamentally understand critical changes in thermal regimes, sediment rheology, basal ice stress levels, sediment stratigraphy, basal topography, and geomorphological fluctuations. One important aspect is the thermal and geotechnical subdivision of subglacial into either being in part frozen or overconsolidated as hard (stiff) (H) or being unfrozen and soft (M) beds (e.g., Menzies 1989; Shipp et al. 2002; Cowan et al. 2012; Greenwood et al. 2016; Halberstadt et al. 2016; Brisbourne et al. 2017; Bougamont et al. 2019; Davies et al. 2018; Prothro et al. 2018). In many instances, the distinction between hard and soft beds remains difficult to determine and model (Ó Cofaigh et al. 2005, 2007; Reinardy et al. 2011; Campo et al. 2017; Larter et al. 2019; Robinson et al. 2021).

Several case studies are selected here to demonstrate the complexity of subglacial soft-bed sedimentology at the microscale and to better understand the overall deformation processes in subglacial sediments. Only a few studies can be discussed in any detail here, however references to many other studies demonstrates the commonality in terms of sedimentological signatures found in subglacial tills in many parts of the world in Quaternary, pre-Quaternary, and modern glacial sediments (e.g., Ferguson et al. 2011; Phillips et al. 2013, 2021; Skolasińska et al. 2016; Hart 2017; Menzies and van der Meer 2018; Gehrmann et al. 2019; Hermanowski et al. 2020; Le Heron et al. 2020; Narloch et al. 2020; Linnemann et al. 2021; Menzies 2022c).

Case Examples: Microscale Deformation in Subglacial Tills

The analysis and interpretation of deformed subglacial sediments are illustrated using six case studies on till thin sections from locations in Canada and Austria. These examples provide a spectrum of subglacial till types formed during the Pleistocene and Pliocene glaciations. The tills from these case studies were deposited by both mountain (alpine) glaciers and lowland (continental) ice sheets, containing a range of bedrock clast types and matrices composed of metamorphic, igneous, and sedimentary rock types with high and low clay contents under varying subglacial conditions. The glacial deposits, from these case examples, are subglacial tills from: 1) Aberdeen Lake, Nunavut, deposited by an ice sheet flowing out of the Keewatin sector or center of the Laurentide Ice Sheet (LIS), 2) Pine Point Mine, near Hay River, Northwest Territories, accumulated along the western margin of the LIS likely under fast ice-streaming conditions, 3) Attawapiskat, James Bay Lowlands, northern Ontario, formed in the lowland by an early ice sheet in the Pliocene spreading southwest from James Bay, 4) Aschbach, Austria, emplaced in a side tributary valley (Wildschönauer) by the Inn Glacier Ice Stream (IGIS), 5) Wegscheidalm, northern Austria, emplaced to the south of the Wilder Kaiser mountains in a side valley entered by a diffluent lobe of the IGIS, and 6) Weissbach, northern Austria, also deposited by the IGIS in the Wildschönauer valley some 4 km downvalley from the Aschbach site.

The choice of samples exhibits a range of microstructure examples found in subglacial tills (the figures of the samples are illustrated by showing the original thin-section image followed by subsequent mapped sets of individual microstructures (grain stacks, domains, microshears, rotation structures, and décollement surfaces) and finally an aggregate of all the microstructures mapped per thin section). The tills contain penecontemporaneous and postemplacement sets of microstructures. All the microstructures discussed here have been defined and discussed using examples in detail in Menzies and van der Meer (2018, Chapter 21). After these case studies, a glacial sedimentological conceptual model is developed to comprehend and integrate these microstructures as a whole and to place them within a contextual model framework of subglacial soft-sediment deformation processes. The glacial histories and settings of the individual sites are briefly described to provide an overall perspective of the thin sections. For details, readers can refer to the original publications as cited in the main text. Note that in this paper all thin-section images are in plane polarized light with the top of image directed toward the ground surface. In all figures the microstructures are annotated using the same color scheme and style.

Aberdeen Lake, Nunavut, Canada.—The drillcore is from the central lowland region of the Keewatin sector of the LIS (Fig. 1). The extensive and thick till sampled in the Aberdeen Lake area was deposited by an ice stream of the LIS which flowed to the north from an ice divide in the Keewatin dome that migrated across the study area (Hodder et al. 2016). A detailed analysis and correlation of ice-flow indicators, till fabric, and till provenance from riverbank and drillcore sections provide evidence for at least five ice-flow phases and associated till production phases (Klassen 1995; McMartin and Henderson 2004; Hodder et al. 2016).

The till from the sampled site (sample H, blue circle) was likely deposited/emplaced below an ice stream and consists of a matrix-supported massive diamicton (Figs. 1, 2A). The drillcore sample was sampled close to parallel with ice flow direction. The till sample presented here contains numerous subrounded and subangular clasts within a clay-rich banded matrix. Domains (purple) obliquely bisect the sample (Fig. 2B). Numerous grain stacks are dominantly in a vertical orientation at right angles to the banded domains, and most grain stacks overprint the domains, indicating that the domains pre-date the beginning of pervasive deformation, as evidenced by the grain stacks (Menzies 2022b) (Fig. 2B). Microshears (blue) occur having two predominant orientations nearly perpendicular to one another. Earlier formed shears will be progressively rotated or be overprinted as deformation continues and new shears develop, so there approximates a complex array of shears which can be developed within a till (Narloch et al. 2012, 2020) or mass-flow diamicton (Phillips and Kearsey 2020). One set of microshears appear to roughly follow the clay-rich bands, while the other set are offset typical of Reidel-style shears at an approximate angle of 22°. The microshears indicative of nonpervasive deformation (cf. Iverson 2003) are all relatively short length and cross only a very few of the clay-rich bands, indicating that sequentially they were largely confined to the non-clay rich matrix and formed within those matrices (Fig. 2C). The microshear fabrics in Figure 2D are bimodal with a stronger principal orientation parallel to the distinct shear band through the center of the thin section. Low angles ($< 25°$) account for 51.4% of the microshears, indicating a relatively high stress environment during emplacement of the till (see Logan et al. 1979, 1992). Two distinctive shear bands exist acting as décollement surfaces trending parallel with the clay-rich domains; likely the domains acted a locus of lubrication and temporally immobilization surfaces during emplacement (Fig. 2E). There are a few rotation structures (Fig. 2E) that indicate nonpervasive deformation within the non-clay-rich matrix occurring usually just below a décollement surface. The rotations are all strictly confined to rotating larger clasts within the deforming matrix. Rotations, based on overprinting of all other microstructures, indicate the late stage of development of these microstructures. The composite image of all the microstructures with yellow background matrix illustrates the very complex nature of this till from Aberdeen Lake (Fig. 2F).

Pine Point, Northwest Territories, Canada.—A sample collected from subglacial till in the Pine Point Pb-Zn Mining District is located along the southern shore of Great Slave Lake in northern Canada (Rice et al. 2019a; Menzies et al. 2019) (Fig. 3). The LIS advanced over the entire region, depositing a ubiquitous till cover of varying thickness subsequently overlain by glaciolacustrine sediments deposited by glacial Lake McConnell (Lemmen et al. 1994). The sample (blue dot) was taken from open pit O-28, where three tills, named in ascending order unit A, unit B, and unit C, were identified in a vertical section at the north end of the pit based on color, clast lithology and clast fabrics, and erosional bounding surfaces or contacts. The differences between the three tills in color and clast composition and orientation probably reflect variations in glacial provenance during differing glacial episodes or may simply, as seems more probable, the change in provenance of the till materials in a single accumulating till package during the last Wisconsinan glaciation, as the Keewatin dispersal center migrated considerably and caused ice flow directions to change significantly over time (McMartin and Henderson 2004; Oviatt et al. 2015; McClenaghan et al. 2018), therefore changing the provenance of the tills.

The sample is from till unit B, taken from the northeast section of the pit exposure (Fig. 4A) (Rice et al. 2019a; Menzies et al. 2019). The thin-section sample is a fine-grained grayish brown till with occasional larger subangular to subrounded clasts with subtle crosshatch (almost lattisepic in terms of S-matrix) banding. Thin-section mapping (Fig. 4B) reveals grain stacks with a random set of orientations and no obvious domains. Microshears show a strong near-horizontal orientation paralleling the dominant ice flow direction. As with the subtle banding on this thin section, the microshears are usually at two dominant angles (Fig. 4C, D) typical of pure shear and progressive deformation and associated rotation as R and P shears (Passchier and Trouw 2005, p. 157). Microshear fabrics (Fig. 4D) indicate that 62% are low-angle ($< 25°$) shears indicative of a relatively high strain environment. It is however essential that consideration is given to possible reorientation of shears so there is always a degree of uncertainty with these results that need to temper interpretations. The décollement surfaces are all short length and match the general microshear fabric trend (Fig. 4E). Rotation structures are scattered throughout this till sample and largely related to larger clast rotation. It must be pointed out that many of the rotation structures may have been totally or partially truncated by shearing before shear initiation leading to the lateral propagation of these microscale detachment surfaces. Most rotations occur below the décollement surfaces, likely indicative that the rotation occurred just before the formation of the décollement surface and the surfaces were subsequently partially destroyed and rotated themselves (Fig. 4E). These features together indicate that this till unit has undergone some form of shear partitioning (Johnson et al. 2004; Fossen 2010) probably because of local occurrences of rapid immobilization in the till during its emplacement (Fig. 4F). Of all the case examples presented here, the till at this site appears to possibly have the highest strain percentage, as evidenced by the high percentage of low-angle microshears, probably resulting from the topographic position of this site in an unimpeded relatively flat terrain permitting relatively rapid basal ice flow (cf. Attawapiskat site, Fig. 5).

Attawapiskat, James Bay Lowlands, northern Ontario, Canada (Fig. 5A).—The Pliocene diamicton at Attawapiskat is up to 50 m thick and consists of a compact, noncalcareous, clayey to sandy subglacial till (Gao et al. 2012; Menzies et al. 2013). The till is light to dark brown in color and has a relatively high clay content ($> 20\%$) (Fig. 5B, C), containing many subrounded to dominantly subangular and faceted clasts, many of exotic provenance (e.g., quartzite pebbles). It also includes occasional small units of thin but spatially extensive organics and organic-rich muds, with some silt and clay layers. In thin section (Fig. 6A) the till has a high concentration of subangular clasts within a high clay-rich matrix that can be subdivided into zones of clast-free clay matrix. Strong evidence can be observed of flow within the matrix in the form of movement around large clasts within a subtle banding across the thin-section sample. Distinctive domains appear to be flowing from left to right across the image

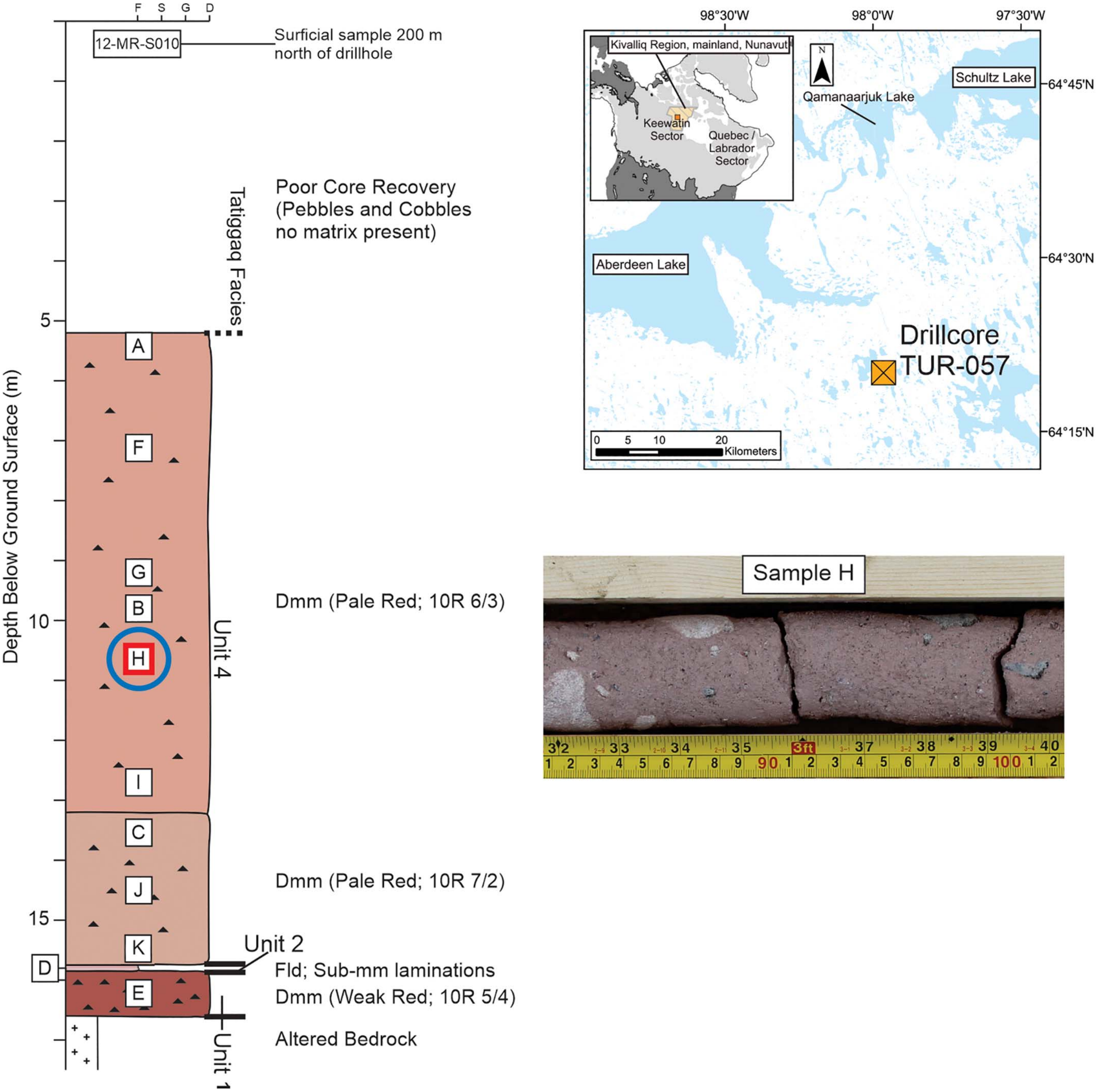

FIG. 1.—Quaternary sediments in drill core TUR-057, sample (blue circle) collected near Aberdeen Lake, Nunavut, northern Canada (inset), including a sedimentological facies diagram from where the sample was collected (red box) from TUR-057-H (modified from Hodder et al. 2016). Note sample in core box.

(Fig. 6B) that were in place before grain stacks developed in the pervasively deforming matrix. There are relatively few microshears in this till and it exhibits two distinct subsets of dipping shears indicative of ice-flow shear effects (cf. Zoet et al. 2023) (Fig. 6D). The microshear fabrics show only 23.1% of shears less than 25° to the horizontal, indicative of a possibly relatively low strain effect. Several prominent décollement surfaces (that are consistent with development at the late stage of localized deformation) can be noted that parallel the general left-to-right flow pattern seen in the image, and again rotation structures appear to mirror the surfaces likely developed just below the immobilization surface before final development of the surfaces that were subsequently partially deformed and, in places, likely destroyed. The image in Figure 6F illustrates the relationship of all the microstructures in this till and the prominent role played in deformation partitioning by the presence of the large clasts and domains in the subsequent development of this till during emplacement.

Aschbach, Austria.—The site at Aschbach is situated in a small valley off the main Wildschönauer Valley south-southwest of Wörgl, Austria, in typical Alpine topography (AB in Fig. 7). The site lies in a 6-meter-thick

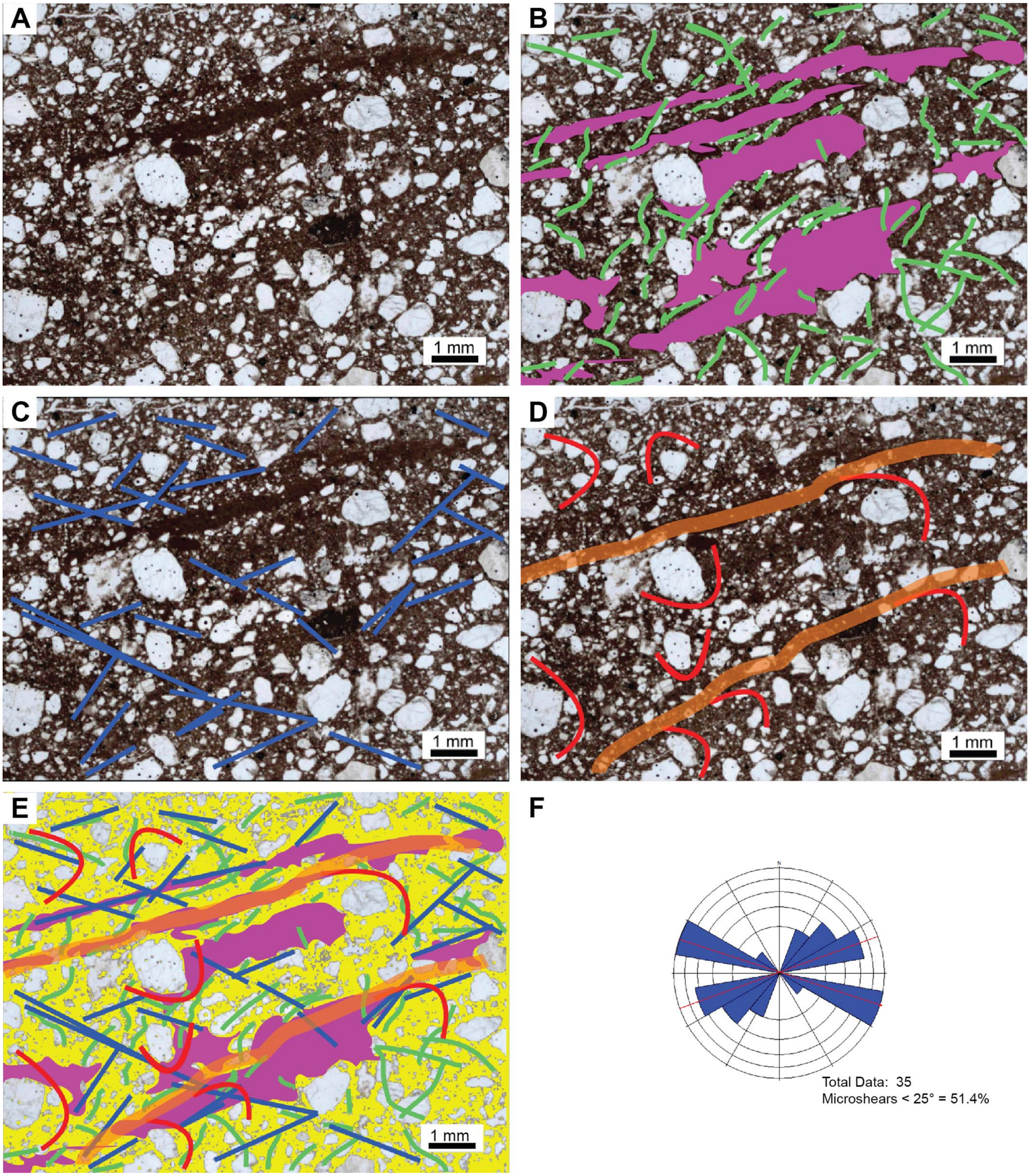

FIG. 2.—**A)** Thin section is a coarse clast-rich sediment. Note scale bar. Annotated thin section with **B)** grain stacks (gst) in green, and domains (purple), **C)** microshears (ms) in blue, **D)** microshear fabrics with red lines to separate those microshear orientation below and above 25°, showing 51.4% below 25°, **E)** rotation structures (rt) in red, and décollement surfaces (dcs) in orange. Note the alignment of the décollement surface is situated, in part, on top of the clay rich zone (domain) exhibiting considerable deformation at the contact between the two domains. **F)** Composite mapped thin section, yellow background is matrix. Note that colors used in the mapped thin sections are the same in all other thin section maps (Figs. 4, 6, 9, 11, 13). Note that ice flow direction is shown as a thin blue arrow.

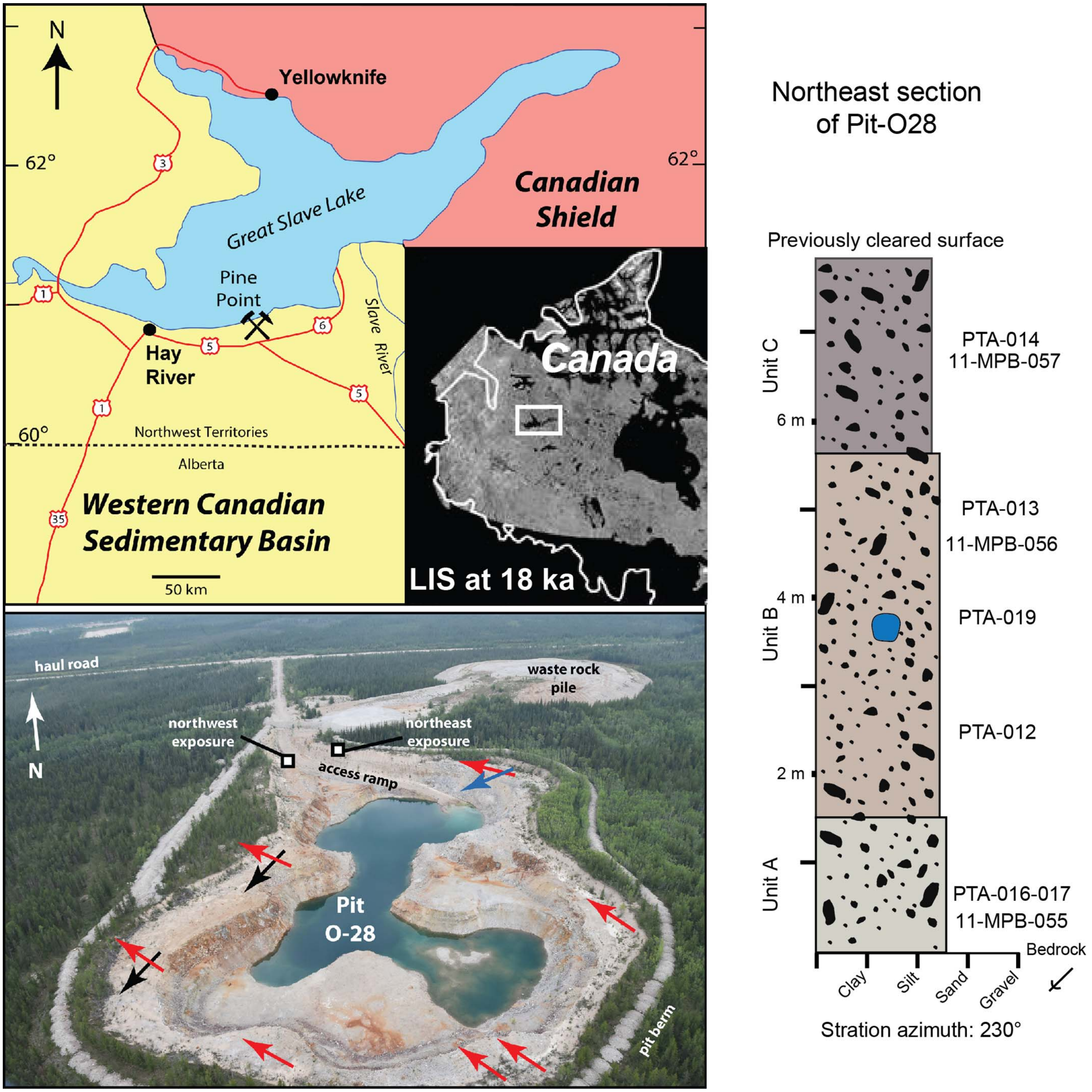

FIG. 3.—Pine Point, Northwest Territories, Canada. A thin section sampled from the northeast corner of Pit O-28 (blue dot). Local ice flow is indicated via the black (oldest ice-flow phase), red (intermediate ice-flow phase), and blue arrows (youngest ice-flow phase) as measured from regional striations and clast fabric analysis (Oviatt et al. 2015).

section of various till units underlain and overlain by proglacial deltaic to glaciolacustrine sediments (blue dot) (Fig. 8). The till, which is the dominant deposit in the section, is an approximately 1.5-meter-thick unit of gray to dark brown, matrix-supported diamicton, deposited in a side valley of the larger IGIS system where ice firstly flowed up valley from the Inn Valley to the south and finally from south-southwest to north-northeast down the small valley (Menzies and Reitner 2019). In thin section (Fig. 9A), the sample is densely compact fine-grained till with occasional subrounded to subangular clast fragments. The clay-rich matrix is heavily deformed with no obvious banding or stratigraphy. No domains can be discerned in this till sample and grain stacks are randomly distributed with a slightly dominant vertical orientation (Fig. 9B). Microshears are typically approximately parallel to the dominant ice flow direction (Fig. 9C). Microshear fabrics (Fig. 9D) are bipolar with 43.9% $< 25°$ suggesting emplacement in a relatively high-strain environment, as is likely indicated by the evidence of strong matrix deformation (Fig. 9A). There are a series of post-emplacement contorted décollement surfaces (Fig. 9E), and, as in almost all other thin sections here, rotation structures are typically related to the to rotation of larger clasts and occur below the décollement surfaces, a pre-immobilization artefact of deformation. The composite images in Figure 9F illustrate the complexity of this till and the

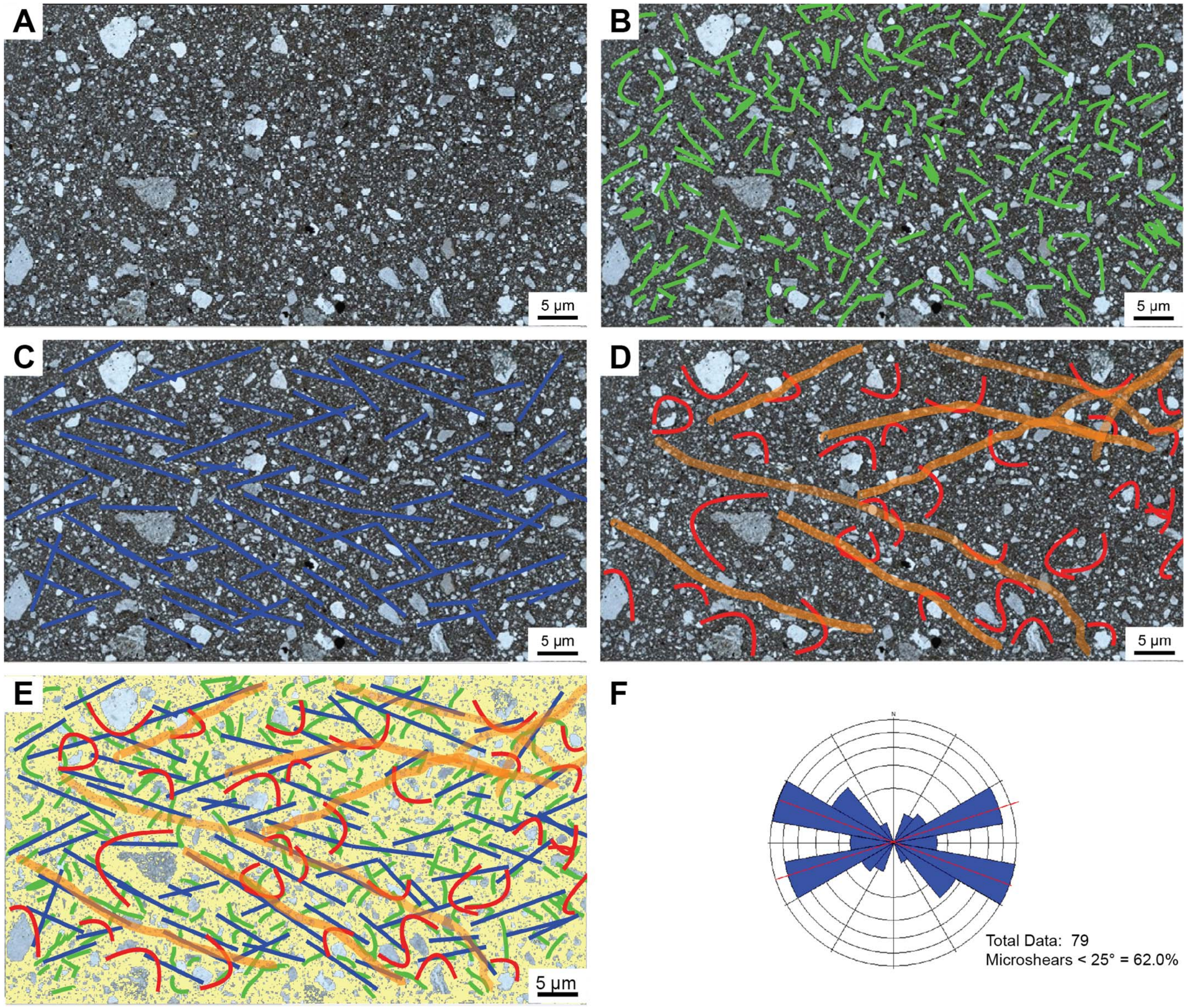

FIG 4.—**A)** This thin section shows a dense clay-rich sediment, **B)** grain stacks (gst) in green, **C)** microshears (ms) in blue, **D)** microshear fabrics with red lines to separate those microshear orientations below and above 25°, showing 62.0% below 25°, with a high number of closely parallel microshears, **E)** rotation structures (rt) in red, and décollement surfaces (dcs) in orange. Both sets of décollement surfaces parallel the microshears. **F)** Composite mapped thin section, yellow background is matrix. The mapped thin section reveals the parallelism between microshears (blue lines) and décollement surfaces (orange) both with most structures angled from top left to bottom right (modified from Rice et al. 2019b; Menzies et al. 2019). Note that ice-flow direction is shown as a thin blue arrow.

issues present in deciphering the interplay and crossover of microstructures present in this and all tills.

Wegscheidalm, Austria.—The sample site Wegscheidalm is located along the southern flank of the Wilder Kaiser Mountains in a W–E trending depression (Ellmau-Scheffau) (S in Fig. 7). Samples of a pale reddish-brown till (Munsell 4.5YR) (blue dot) were taken from this site 100 m southeast of the Wegscheid–Niederalm hut, some 2 km north-northeast of the community of Scheffau in the Wegscheid Creek valley (Fig. 10). Reitner (2007) established that the tills are derived from the IGIS in contact with the ice-dammed lakes filled with glaciolacustrine sediments. Wegscheidalm till was deposited by a local glacier (Menzies and Reitner 2016). The sample thin section (Fig. 11A) is dense clast-supported diamicton with occasional larger subangular and subrounded clasts. Evidence of deformation can be seen in the image. Two domains of slightly denser units with higher clay content, possibly modified due to subsequent deformation, thus can no longer be seen (light green and pink) in the image ((Fig. 11B). Grain stacks can be observed crossing the domains evidence of them post-dating the domains and developing before pervasive deformation began. There are only a few microshears evident in this thin section, all closely parallel to the décollement surfaces (Fig. 11C, E). With only 14 microshears the fabric results are rather limited, showing only 35.7% $<$ 25° which indicates a moderate strain effect during shear development. Décollement surfaces are often warped indicative of post-deformation after formation (Fig. 11E). The surfaces seem less related to the presence of rotation structures than in other thin-section examples mapped here. The rotation structures in many places appear related to complex deformation of small

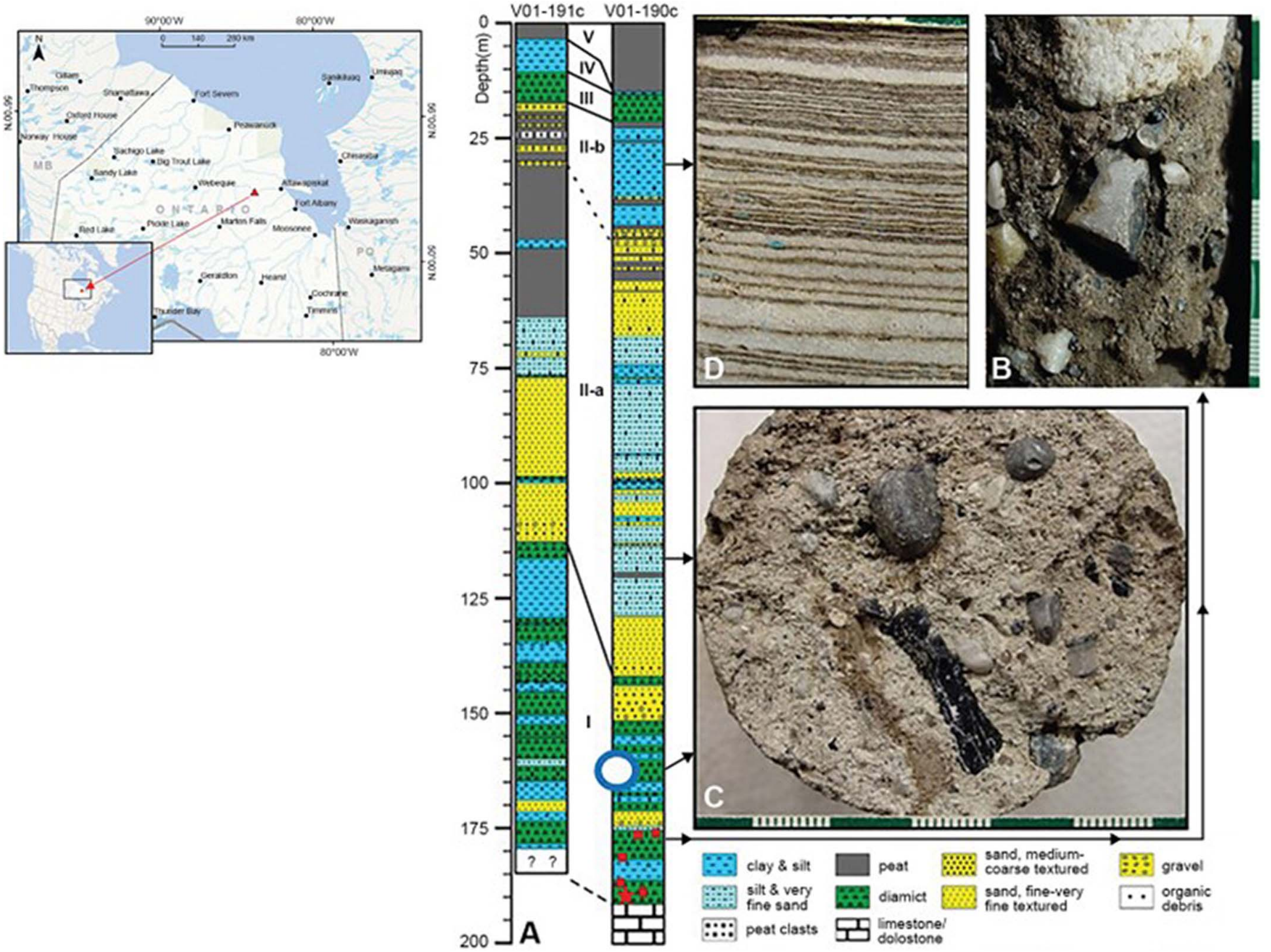

Fig. 5.—Sample site (blue circle) at Attawapiskat, northern Ontario, Canada (modified after Gao et al. 2012; Menzies et al. 2013). Note this is a Pliocene age till, and note the site location southwest of James Bay.

areas of matrix (Fig. 11E). The composite of the mapped microstructures (Fig. 11F) perhaps best displays the spatial variation in décollement surfaces.

Weissbach, Austria.—The sample site at Weissbach (WB, Fig. 7) sits in the same Wildschönau Valley as Aschbach (AB) but is located ~ 4 km down valley toward the main IGIS system in the Inn valley. The till from Weissbach is a reddish to gray, brown diamicton (blue dot) (Fig. 12) which is derived from the IGIS in contact with the ice-dammed lakes filled with glaciolacustrine sediments. In thin section (Fig. 13A), this till is marked by a distinct oblique partition of sediments in what appears as an oblique possible shear zone in a variably scattered clast-supported matrix. A few subrounded to subangular clasts occur on either side of the central possible shear zone. A domain (light green) can be observed (Fig. 13B) that essentially separates the till on either side of the shear zone, and a small domain cap that surrounds the large subrounded clast in the left-hand side of the image. Grain stacks occur randomly across the sample and appear unaffected by the central zone, which suggests that the zone is not of a shear origin but was already emplaced before pervasive deformation occurred. The microshears in this sample show typical R and Y or P formation (Fig. 13C). The microshear fabrics exhibit a 39.5% $<$ 25°, indicating a moderate-strain environment on emplacement (Fig. 13D). A large décollement surface occurs through the central (shear) zone and others all more or less at least subparallel to the doming ice flow direction. Rotation structures are confined to surrounding the large clasts in the till and appear related only to localized nonpervasive deformation events (Fig. 13E). The composite mapped thin section shows the central décollement surface as separating the till in two distinct halves unrelated to other domains (Fig. 13F).

Mapped Thin Sections: Interpretation

All the thin sections mapped in this study exhibit typical microstructures found in subglacial tills (e.g., Phillips et al. 2011; Menzies and van der Meer 2018). Each example differs from one another, but nevertheless, commonalities exist with all subglacial tills at the microscale. The tills have all been advected beneath variable ice-flow regimes, as shown by extensive evidence of various forms of deformation and microstructures. It is clear that considerable variations in strain occurred in the tills, varying over time as well as space. Local "patches" of fluctuating strain may be linked to areas close to larger clasts or between décollement surfaces (note variability in low-angle microshears as shown in the fabric diagrams). Also, patches occur where local pockets of higher or lower porewater content occur, possibly even temporarily, leading to greater or lesser mobile deformation. It is likewise apparent that generations of microstructures were typically overprinted such that complex

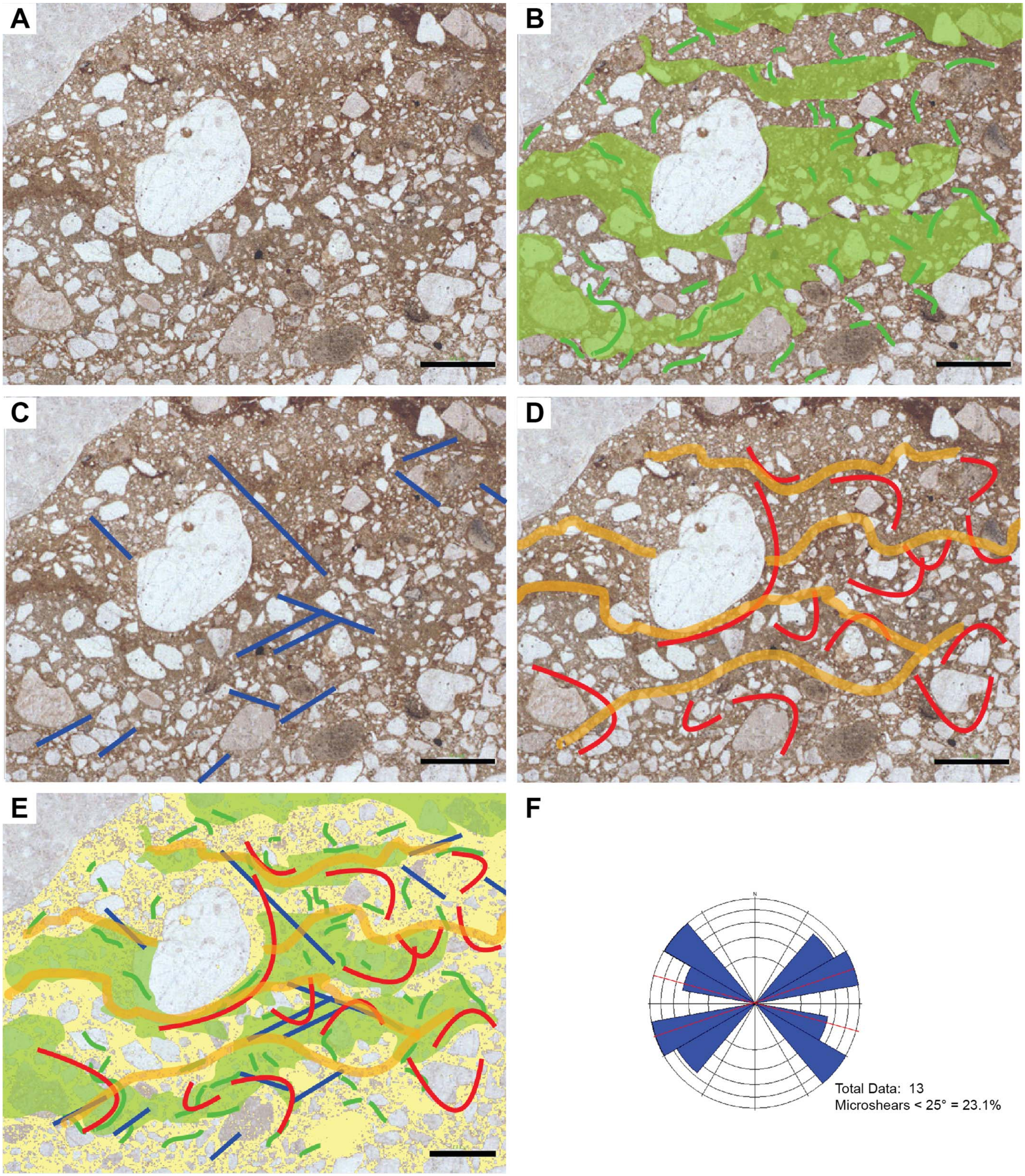

FIG. 6.—**A)** Thin-section sample showing oblique banding and a wide range of clast sizes and a distinctive clay rich band around a prominent clast in the center left of image, **B)** grain stacks (gst) in green, with light green domains, **C)** microshears (ms) in blue, **D)** microshear fabrics with red lines to separate those microshear orientation below and above 25°, showing 23.1% below 25°, **E)** rotation structures (rt) in red, and décollement surfaces (dcs) in orange, **F)** composite mapped thin section, yellow background is matrix. Décollement surface appearing as bands of higher clay content in light orange occur with evidence indicating that these surfaces closely follow the higher clay areas. Evidence of rotation around several clasts suggests that the till was sheared locally and thus banded during emplacement. This is a clast-rich, clast-supported till with two distinct clay layers where décollement surfaces occur. Note ice-flow direction shown as a thin blue arrow.

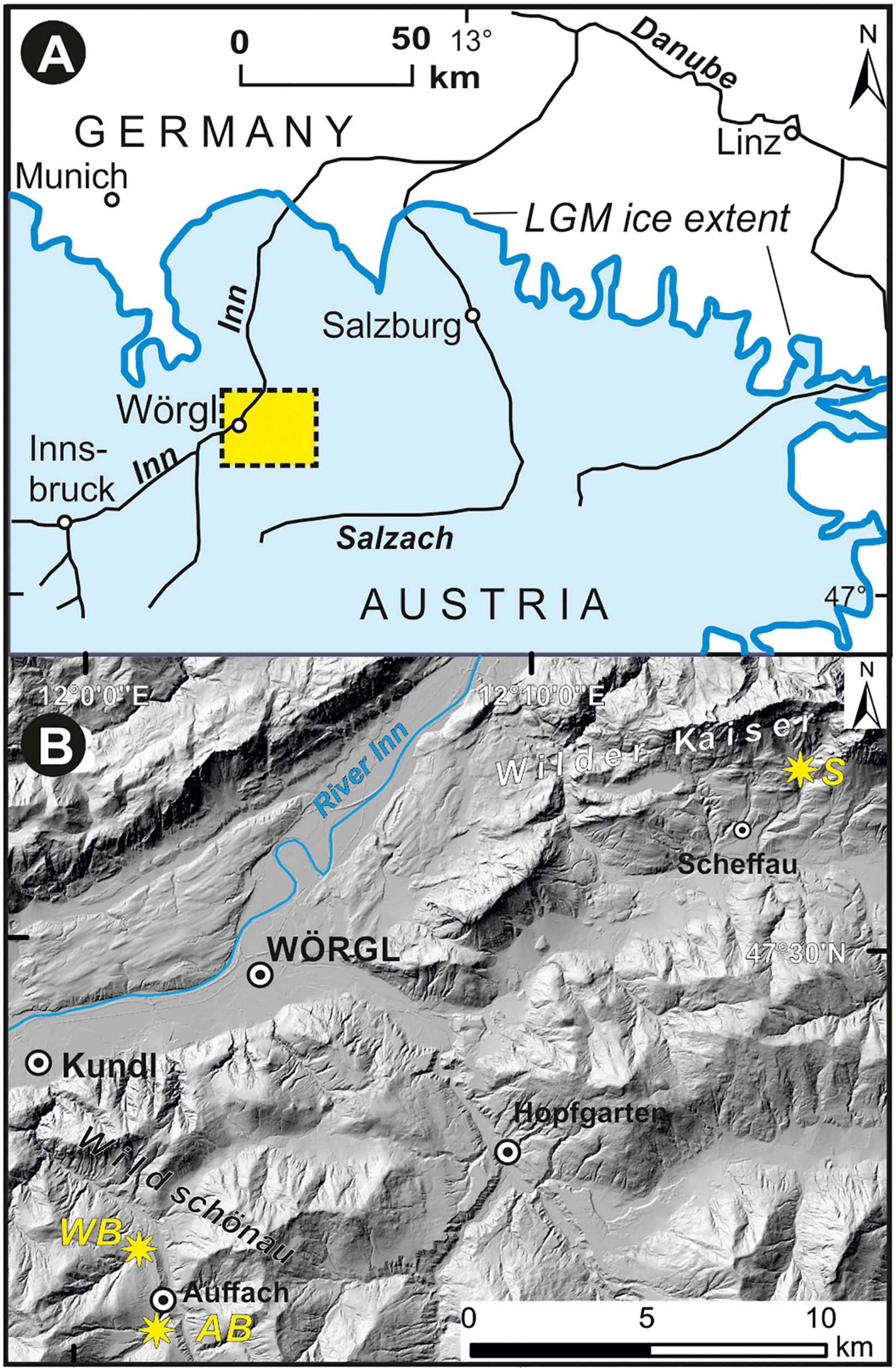

FIG. 7.—Map of northern Austria with sites at Aschbach (AB), Weissbach (WB), and Wegscheidalm (S) shown with yellow stars (modified after Menzies and Reitner 2016). Note extent of LGM ice and location of Inn Valley.

mosaics of microstructures were developed, and at times and places, partially removed and others extant. The question of chronology of microstructure formation is a fraught aspect in any till. Much can be made of overprinting and crossover formative microstructures, but the chronosequence of such structures remain, a very tangled and complex issue difficult but essential to resolve through further research.

Most of the tills described here have extensive and, in places, contorted domains, some relatively rounded in appearance while others

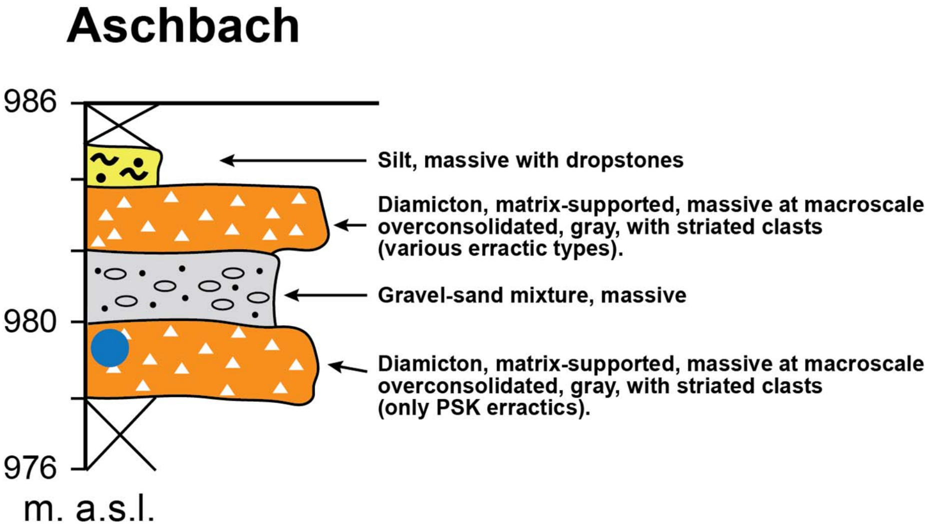

FIG. 8.—Aschbach site in the Wildschönau Valley, Austria (AB) sediment log showing location of sample (blue dot) (modified after Menzies and Reitner 2016).

almost boudinaged such that in both instances later transported in the deforming till matrix. The domains can be perceived as intercalations in the tills but, in general, domains form part of the original matrix and occur by contemporaneous emplacement. The domains likely represent relicts of pre-existing sediments which have been incorporated into actively accreting and deforming till, and/or are the remnants of laminations in originally bedded sequences which have been largely overprinted because of subglacial deformation (Phillips, personal communication 2023). The presence of the domains is part of what tills represent as a byproduct of sediment incorporation due to source availability (cf. McMartin and Paulen 2009).

Grain stacks are likely one of the first microstructures developed as the till matrix begins to initially deform, probably under pervasive flow (cf. Hooke and Iverson 1995). Grain stacks are ubiquitous, with lines of small clasts (grains) "flowing" around larger clasts and typically overprinting domains. In many instances, grain stacks quickly become distorted with subsequent deformation. Grain-to-grain interaction occurs, producing even smaller grain fragments.

Microshears are indicative of localized shear or deformation partitioning and are largely viewed as distinct discontinuities of localized fracture planes within nonpervasive deforming subglacial tills. Microshears, in most of the tills here, exhibit Riedel shear-style relationships with marked crosscutting correlation (Passchier and Trouw 2005). Microshears indicate that the sediment has been differentially "adjusted" or brittle sheared through strain partitioning. They indicate that a local readjustment due to shear-stress application has occurred at some stage in their evolution. In most instances, this local movement is the result of external stress of overlying basal ice movement that has overcome the local sediment matrix yield strength in these tills. The evidence in the till images presented here are of microshears at differing orientations and declinations in the form of repeated crosscutting microstructures indicative of repeated phases of deformation at different levels of shear in what must have been a soft-sediment subglacial mobile zone (Fig. 14B).

The microshear fabrics presented here reflect stress-failure orientations typically partly aligned with orientation of the principal shear stress due to ice-flow direction (the principal axis of stress) and the general nonpervasive flow direction of local deformation mechanics (cf. Hart and Rose 2001; Larsen et al. 2006; Thomason and Iverson 2006; Hart 2017). Where the matrix shearing process abuts against larger clasts or existing previous décollement surfaces, microshears may be terminated or change direction in relation to the plane of the thin section presented here. In terms of strain in the tills sampled here, the samples show different local strain levels, with the highest being Pine Point (62.0%), followed by Aberdeen Lake (51.4%), Aschbach (43.9%), Weissbach (39.5%), Wegscheidalm (35.7%), and Attawapiskat (23.1%). These data must be carefully examined and considered in terms of likely other causes of microfabric strengths given that deformation (loading/compaction) may occur once the ice had stopped moving, and that dewatering effects on tills and/or partial remobilization of the till by mass-flow processes after the ice retreat. However, any relationships between the locations of the tills under varying styles of ice mass and differing topography (unconfined at Pine Point, Attawapiskat, and Aberdeen Lake as opposed to more confined-valley settings at Aschbach, Wegscheidalm, and Weissbach) is hard to distinguish. It is evident from previous work that large fluctuations in strain are typically found in tills (e.g., Menzies et al. 2019, their Fig. 8) to the extent that such data are of only limited overall value when investigating bulk till samples and broader basal till units. The microshears reflect conditions of nonpervasive flow deformation after initial pervasive grain-stack alignments (Iverson et al. 1996; Hooke et al. 1997; Thomason and Iverson 2006). This response indicates that in each deformation cycle following grain-stack development, under pervasive deformation, microshear development happens under conditions of nonpervasive deformation.

The thin sections all carry evidence of décollement surfaces, although in some instances only contorted fragments exist. Décollement surfaces are, at times, referred to as shear bands and, in the past, as deformation fronts. As mobile sediment units become immobilized, shear surfaces develop ephemerally at the mobile–immobile interface. Likewise, where multiple microshears coalesce, such surfaces are likely to develop. Often microshears crosscut the décollement surfaces, indicating that two or more different deformation stages occurred in a subglacial till as expected and is repeatedly shown in the mapped thin sections. Décollement surfaces tend to occur in subglacial tills that have a $>$ 20% clay content. Also, in the tills thin sections examined in this paper, décollement surfaces occur or "spread across" zones of relatively fine-grained subglacial tills. The presence of these décollement surfaces, and likely associated plasmic unistrial fabrics, are both indicative of relatively high strain conditions, as can be seen in the values of microshear fabrics. As rheological conditions change, both external and internal, in the basal deforming sediment body, the position of the "boundary surface" will fluctuate in the sediment package as porewater fluctuates, either mobilizing or immobilizing sediments (as shown in the model in Fig. 14).

Rotation structures occur throughout the thin sections but appear to have little relationship to specific sets of microshears and grain stacks, which likely reflect their later development (ten Grotenhuis et al. 2002; Mandal et al. 2005; Phillips 2006; Griera et al. 2013). The rotation

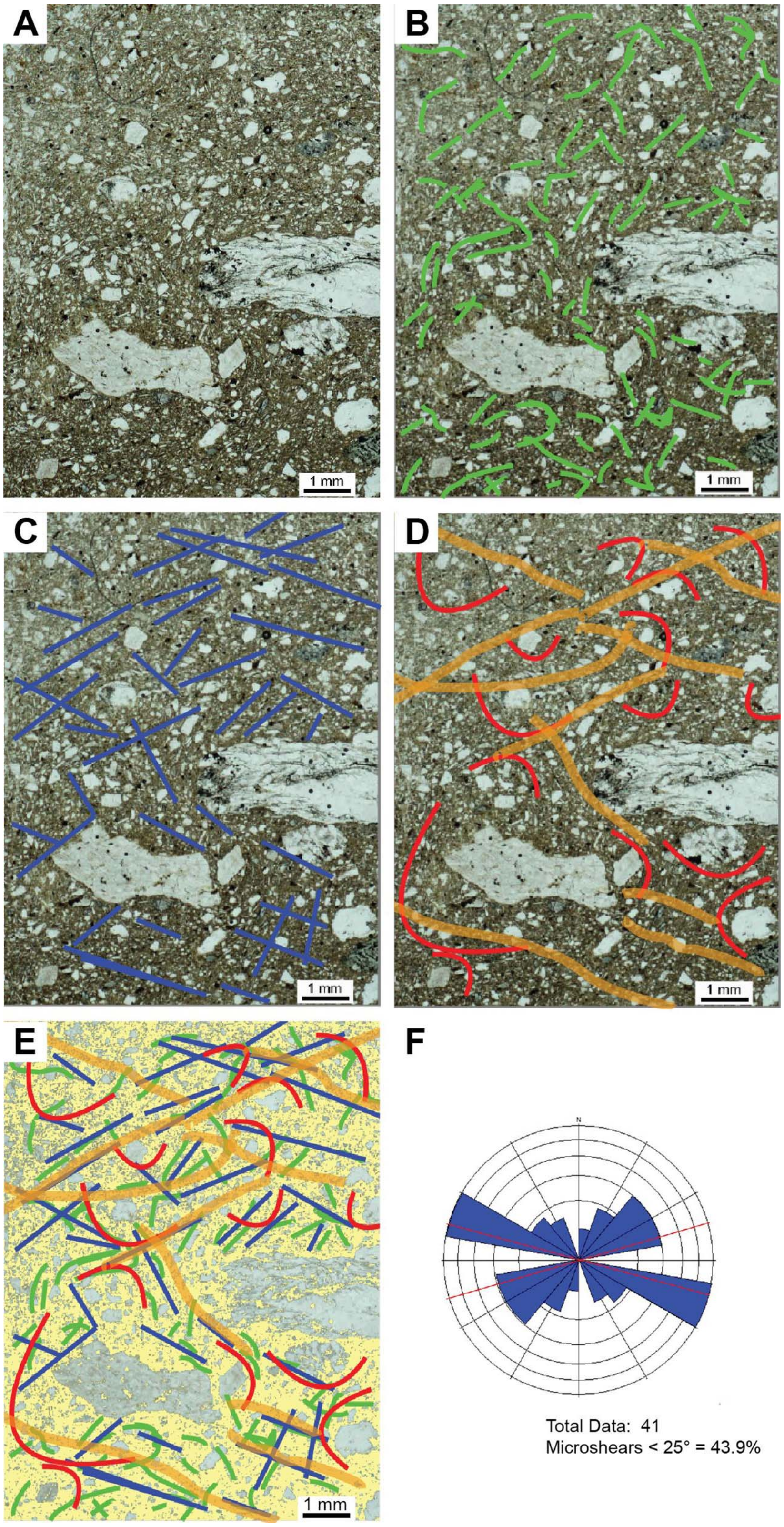

FIG. 9.—**A)** The sample exhibits a wide range of clast sizes and microstructures with obvious evidence of rotational deformation, **B)** grain stacks (gst) in green, **C)** microshears (ms) in blue, **D)** microshear fabrics with red lines to separate those microshear orientation below and above 25°, showing 43.9% below 25°, **E)** rotation structures (rt) in red, and décollement surfaces (dcs) in orange. **F)** Composite mapped thin section, yellow background is matrix. Note ice flow direction shown as a thin blue arrow.

structures, therefore, are developed during nonpervasive or partitioned deformation around larger clasts and/or "clots" of possibly more cohesive matrix units. In those thin sections with high clay content matrices and larger numbers of clasts, it is possible that more rotation structures developed as a function of sediment rheological processes (cf. Menzies 2000). This variability in the number and size of rotation structures is apparent in the thin sections examined in this paper. It must be recalled that often rotation structures only appear as partial micro-forms as the

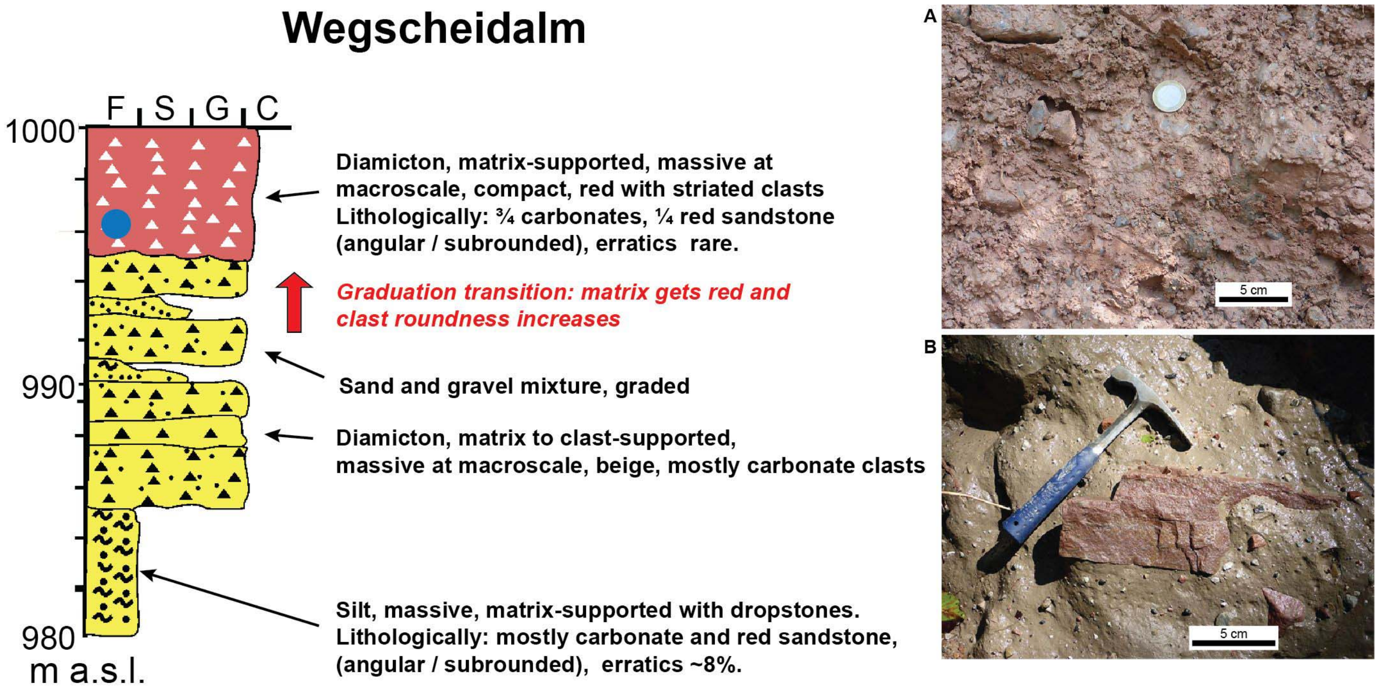

FIG. 10.—Wegscheidalm, Austria (S) some 2 km north to northeast of the community of Scheffau in the Wegscheid Creek valley. Sediment log showing location of sample (blue dot) (modified after Menzies and Reitner 2016).

plane of the thin section may "cut off" parts of the rotation. From the thin sections mapped here it is perhaps correlative that rotation structures appear at the "underside" of many décollement surfaces. Such juxtaposition may indicate the effect of late strain conditions across the mobile sediment as it immobilizes, and the surface develops soon thereafter, or it could be that décollement surfaces may also represent the boundaries of ductile shear zones with rotational structures developing in response to simple shear (rotational deformation) occurring between these shear surfaces (Phillips, personal communication 2023).

The mapped thin sections carry the signature of multiple microstructure generations where some survive whilst others are presumably destroyed during subsequent deformation (cf. Phillips et al. 2011, 2018, 2021; Gehrmann et al. 2019; Cartelle et al. 2021). The use of multiple thin-section images for each original thin section attempts to increase our ability to unravel the complex nature of till sedimentology (Figs. 2, 4, 6, 9, 11, 13).

These examined subglacial till units, as is the case with all subglacial tills worldwide, show widespread evidence of great complexity in the deformation processes. This is exemplified by the various microstructures mapped here that reveal that multiple transfers of small units of mobile sediments often parallel with deformation shearing while others, due to rotation and fragmentation, become detached and autonomous (Bloomfield and Covey-Crump 1993; Ji and Xia 2002; Treagus 2002; Gardner et al. 2017). To comprehend the myriad of microstructures and their various forms a conceptual model is needed that encompasses all these aspects related to till microsedimentology. The locations of microstructures in the till matrix, their relationship to each other and other structures, coupled with mixed rheology conditions during deformation and likely redeformation from remobilization after initial emplacement is necessary in such a model (Fig. 14A, B).

A Conceptual Model Based on Subglacial Microsedimentological Data

In any subglacial deforming sediment package, there is an upper interface at the ice-sediment contact where the ice above slides and, below it within the sediment, one or more lower interfaces (décollement surfaces) along which mobilized till material moves within the sediment matrix in the down-ice direction (Fig. 14A, B) (Evans et al. 2006; Kjær et al. 2006; Damsgaard et al. 2013; Phillips et al. 2013; Evans 2017). The development of these interfaces is poorly understood. Depending on basal meltwater availability and drainage style (e.g., channelized or distributed), thermal states, and basal ice and sediment velocities, a shear boundary may be established, or, in other instances, a gradational ephemeral freeze-on or inertial contact may develop (cf. Mueth et al. 2000; Nitsche et al. 2013). The lower interface(s) where mobile sediment is in contact with the underlying immobile substrate that may be bedrock or deeper sediment substrate (Fig. 14B) is poorly recognized. For instance, in the underlying substrate, several transient deformation shear surfaces (décollement surfaces) may be established that can potentially lead to multiple local and more widespread sediment deformations that may even evolve into bedforms (e.g., Evans et al. 2006; Menzies et al. 2016; Rice et al. 2019a; Ely et al. 2023). The model proposed here is of a simple uniform till with little variation in till sediment stratigraphies or rheological changes, to permit a first exposition of conditions of soft deforming sediment beneath a moving ice mass.

As soft-sediment deformation is taking place below an ice mass, there are likely to be multiple deformed packages or layers stacked on top of each other in a subglacial sediment sequence (Fig. 14B). As subglacial sediment is deformed, due to transient localized high porewater pressures and low effective normal stress, transport of the sediment down ice can be rapid at shallow depths (Virkkala 1952; Boulton et al. 1974; Hart and Rose 2001; Damsgaard et al. 2016, 2020; Evan et al. 2016; Evans 2017). As each or part of a package ceases to be deformed, a new deforming unit may be advected over it. In examining an exposure of soft deforming till, multiple packages, although essentially identical in grain size, clast provenance, microfabric, and other sedimentary characteristics at the macro-scale, contain minute subtle differences in sedimentary structures indicative of the effect of deformation and such deformation microstructures are discernible at the microscale in each package. Many of the packages are likely to be of limited areal extent and depth (e.g., Hart and Rose 2001; Spagnolo et al. 2016; Phillips et al. 2018; Damsgaard et al. 2020). These packages, formed at depth in the deforming

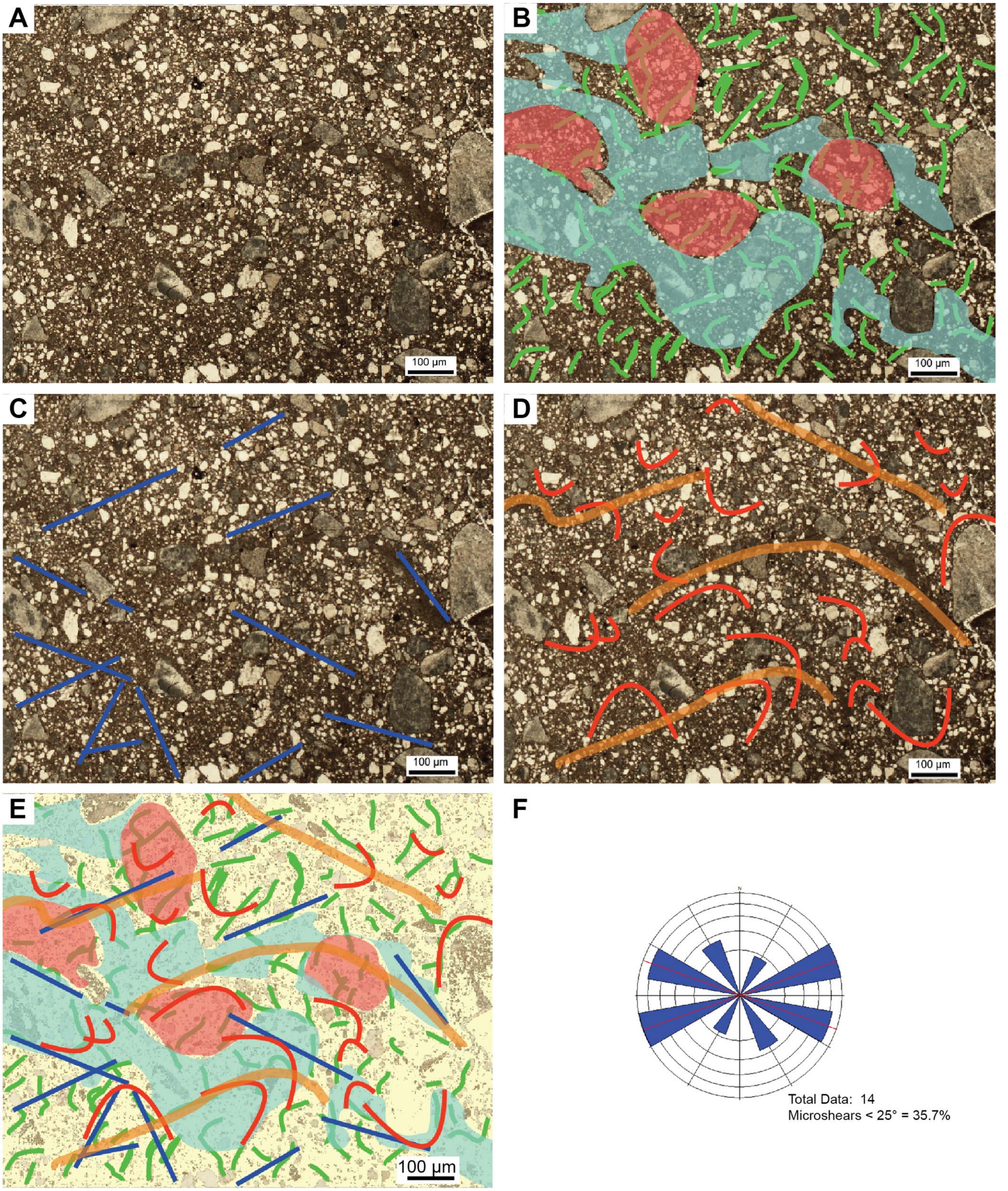

FIG. 11.—**A)** A scall clast-dominated diamicton with obvious evidence of rotational deformation structures, **B)** grain stacks (gst) in green, with two domains, one showing obvious signs of rotational transport (pink) the other elongated and likely intrusive intercalation (light blue green, **C)** a few microshears (ms) in blue, **D)** microshear fabrics with red lines to separate those microshear orientation below and above 25°, showing 35.7% below 25°, **E)** rotation structures (rt) in red, and décollement surfaces (dcs) in orange. **F)** Composite mapped thin section, yellow background is matrix. Note ice-flow direction shown as a thin blue arrow.

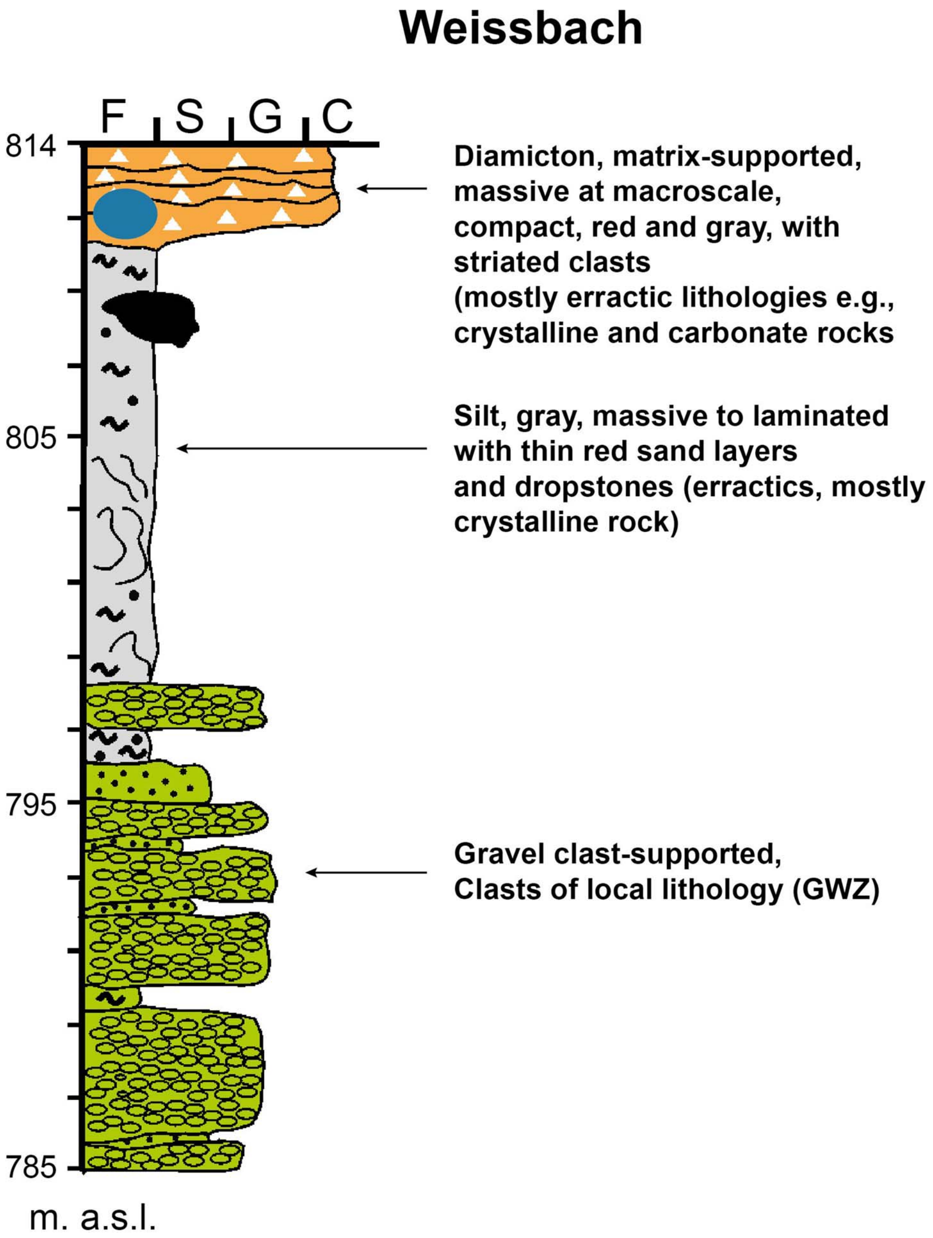

FIG. 12.—Weissbach sample in the Wildschönau Valley, Austria (WB). Sediment log showing location of sample (blue dot) (modified after Menzies and Reitner 2016).

sediment under subglacial conditions—far from the ice margins when created—overlie, intersect, and intercalate with each other, and in many places may have been erased or overprinted by subsequent deformation events. Therefore, a mosaic of deformation units and patterns occurs and can be detected with microsedimentological mapping. Based on the analyses of multiple thin sections mapped and examined during this study, a hypothetical model is put forward to explain many of the findings observed.

A Model of Basal Ice: Subglacial Sediment Interaction

For the proposed conceptual the model (Fig. 14A, B), it is important to understand that shear stress due to basal ice flow can be transmitted at depth within the sediment pile (cf. Boulton et al. 1974, 2001; Hart 2013, 2017). However, the form of stress diminution with depth is difficult to quantify but any diffusion of stress within the sediment is likely exponential, at least at the bulk scale (Zhang and Kamrin 2017, their Fig. 1; Zoet et al. 2023). In the sediment pile, where applied stresses become less than the internal yield strength of the sediment, immobilization starts, and incipient deposition (emplacement/accretion) occurs (cf. Menzies 1989, Evans et al. 2006). Even with the myriad of field observations of basal ice-sediment deformation, our understanding of these subglacial processes remains incomplete (Damsgaard et al. 2020). On the other hand, microsedimentological studies provide immense value in deciphering the processes as the "prime forensic tools to unravel the history of a [sediment] that allows us to deduce the succession of strain rates, stresses, diagenetic conditions and the [sediment's] rheology during deformation" (Piazolo et al. 2019, p. 112; Hanáček et al. 2021).

The general conceptual model proposed here demonstrates the likely interactions between the basal ice movement, soft subglacial sediments, and the underlying bedrock under active temperate ice (Fig. 14). In this setting the ice mass is "coupled to" the soft substrate bed, and shear (décollement) surfaces lie within the deformable substrate. Evidence of subglacial sediment deformation in the form of multiple generations of microstructures formed, partially destroyed, and rotated or contorted, can

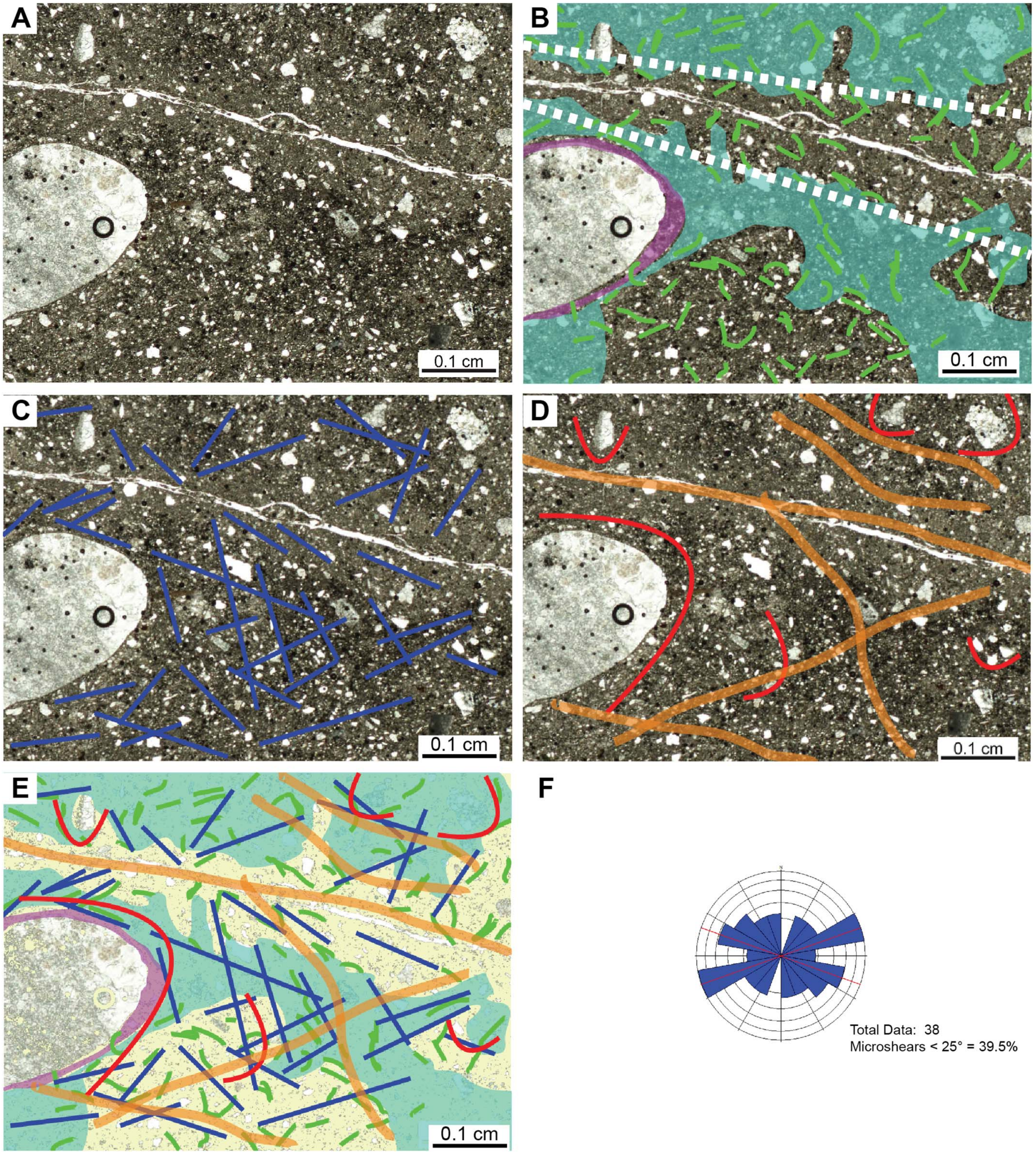

FIG. 13.—**A)** Thin-section of a fine-grained matrix-supported sediment with a wide range of subangular and subrounded clasts embedded in the sediment with a diffuse oblique zone relatively clast free across the sample, **B)** grain stacks (gst) in green, with two domains the larger light blue-green diffusing across the sample but not in central broad oblique clast-free zone. The other domain in purple lies to the margins of a large clast in center left of the image, **C)** microshears (ms) in blue, **D)** microshear fabrics with red lines to separate those microshear orientation below and above 25°, showing 39.5% below 25°, **E)** rotation structures (rt) in red, and décollement surfaces (dcs) in orange, with relatively long structure through the central oblique clast-free zone. **F)** Composite mapped thin section, yellow background is matrix. Note white dashed lines on Part B delineating a possible shear zone. Note ice-flow direction shown as a thin blue arrow.

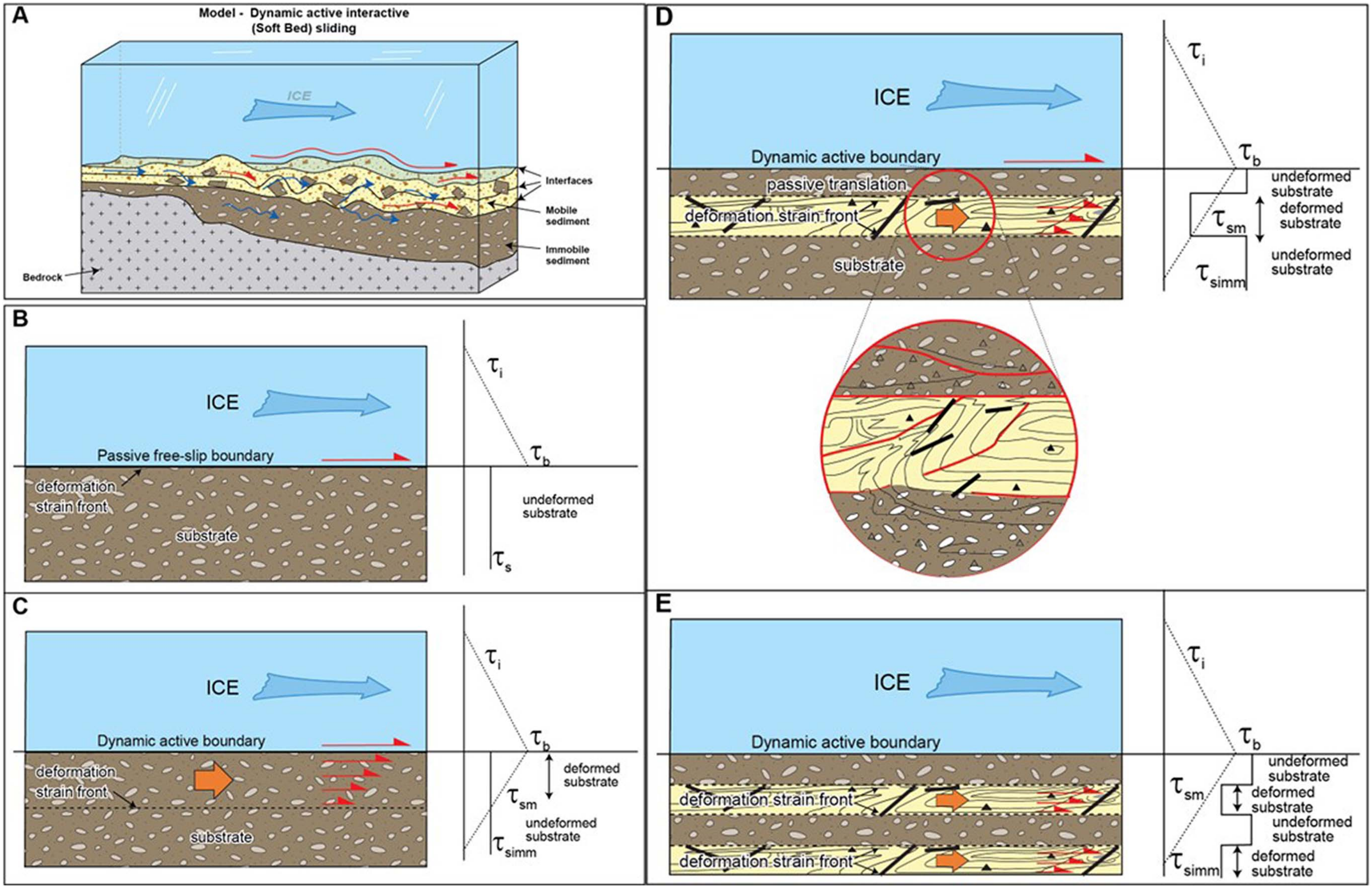

FIG. 14.—**A)** Model of subglacial interface interactions between the sediment bed and an active ice mass. The model illustrates a soft deforming bed with multiple interfaces. Note that blue arrows represent meltwater and/or porewater flow directions and red arrows shear direction. Note that patches of immobile sediment (dark brown material) are found in the mobile sediments as intraclasts. In this model three interfaces are shown to

be

← exist: ice–mobile interface, mobile–mobile interface, mobile–immobile interface. There would be many more of varying length and location in the sediment pile. **B)** Model of shear-stress distribution in sediment beneath an active ice mass, illustrating passive and dynamic slip interface conditions. In Part A passive hard-bed conditions with zero substate deformation are illustrated (where τ_i is the shear stress exerted by the ice mass, τ_b is the basal ice stress at the upper interface between the base of the ice mass and its bed, and τ_s is the yield strength of the underlying sediment). **B**, **C**, **D)** Dynamic movement caused by stress transmission are shown dissipating into underlying soft sediment leading to décollement-surface development, sediment stacking, and sediment scavenging, where τ_{sm} is the yield stress in soft deforming sediment (mobile), and τ_{simm} is the yield stress in immobilized sediment (undeforming). Inset in Part C shows a closer view of an extensive sediment band or intraclast in the sediment pile where microstructures and macrostructures of shearing and glacitectonic evidence can be observed (see Lee and Phillips 2008). In Parts B, C, and D stages, décollement-surface development is dependent on the stress transmission of overlying active ice coupled with rheological constraints of mobile and immobile sediment stacked on top of each (modified from Sobiesiak et al. 2018). Note that in most cases, a decrease or increase in stress levels is likely to be exponential, rather than linear, as shown here only for the purposes of illustration (n.b. Zhang and Kamrin 2017, their Fig. 1).

expected, and is observed (Figs. 2, 4, 6, 8, 11, 13) (cf. van der Meer 1993; McCarroll and Rijsdijk 2003; Meer and Menzies 2011 Phillips et al. 2013, 2018; Narloch et al. 2020). Wherever sediment bulk shear strength is overcome by extrinsic applied shear stress, i.e., the overlying basal ice stress, mobilization takes place, usually resulting from meltwater assimilation into the underlying sediment pile followed by sediment failure and corresponding movement (Iverson 2010; Bougamont et al. 2019). Under these conditions rates of internal till mobility will likely vary locally as a function of mixed rheological conditions (cf. Hooke et al. 1997; Hart and Rose 2001; Iverson 2003; Rathbun et al. 2008; Austin 2011; Caballero et al. 2014), varying beneath individual ice masses (e.g., Bougamont et al. 2019; the Pine Island Glacier, West Antarctica).

As shown in Figure 14, at the base of a temperate ice mass where a soft-deforming bed occurs, there are likely to be a series of widespread and complex interfaces. In the model, there is active stress-related interaction between the overlying ice and the subglacial sediment in the bed with transient shear zones and décollement surfaces forming in the underlying substrate, leading to erosion, entrainment, and subsequent deposition at the bed interface or "scavenging" across underlying substrate sediments, and sediment deformation (e.g., Stanley 2009; Hooke et al. 2013; Menzies et al. 2016b; Le Heron et al. 2020; Schaetzl et al. 2020). These deformation processes within the substrate sediment led to localized erosion and accretion of the sediments at various sub-interfaces linked to pervasive and non-pervasive deformation.

In addition to the upper interface immediately below basal ice and the underlying sediment contact, there are likely lower interfaces at various depths between mobile and immobile sediments (Fig. 14A–D) (cf. Menzies 1989; Lee and Phillips 2008). These in-sediment interfaces are complex in nature and, depending on thermal and mixed rheological states and the depth at which they develop, may be sharply defined shear surfaces or somewhat diffuse contacts of a very ephemeral nature. In terms of where and to what depth deformation occurs in the accreted sediment pile, it can be expected that beneath any part of an ice mass, where thawed subglacial sediment with sufficient thickness may permit infiltration of porewater (as evidence by the presence of argillans) to deeper subjacent units, a low level of effective stress will develop leading to potential sediment failure and mobilization due to increased porewater pressure (Boulton 1979; Engelhardt and Kamb 1998; Alley 1989b; Hart and Rose 2011; Tulaczyk et al. 2001a, 2001b; Iverson 2010; Stokes 2018; Bougamont et al. 2019). In the subglacial sediment, it is the upper parts of the sediments that are subjected to the greatest influence by applied overlying stress from the ice mass and consequent elevated porewater pressures and hence are most likely to experience sediment mobilization. A proviso needs to be added in complicated till sedimentologies, where aquitards, clay, and/or sand lenses and aquifers exist, as the model described here is simplified in terms of mobilized and immobilized sediment conditions regarding downward dissipation of the elevated porewater pressures to a depth in sediment of mixed stratigraphies. In simpler terms, where internal sediment strength overcomes the applied stress, sediment mobilization ceases (Fig. 14B).

The critical questions are at what depth does stress penetration reach and at what depth does sediment deformation no longer occur? As shear-stress levels and sediment rheology are likely to vary over the subglacial bed and fluctuate over time, the location where deformation ceases to occur is highly variable, both across the subglacial bed and in any given sediment (e.g., Houssais et al. 2019). There has been considerable debate about the possible depths where sediment immobilization occurs with estimates ranging from a few centimetres (Hooke et al. 1997; Hart and Rose 2001; Mair et al. 2003; Truffer and Harrison 2006) to several meters (Alley et al. 1986, 1987; Boulton 1996; Hindmarsh 1998; Evans et al. 2006; Piotrowski et al. 2006; Stokes et al. 2013; Davison et al. 2019; Damsgaard et al. 2020). Interestingly, thick, and seemingly homogeneous Quaternary till sheets have been interpreted to reflect much thicker deforming layers for decades (e.g., Piotrowski et al. 2001, 2006), but whether it is physically plausible is still debated because the possibility that such till sheets from episodic differing of distinct glacial episodes leading to accretion cannot be excluded (e.g., Damsgaard et al. 2020; Zoet and Iverson 2020).

Subglacial sediments are subject to repetitive erosion, transport, and deposition (emplacement) in very active, ephemeral, and often spatially localized, environments (e.g., Stanley 2009, their Fig. 8; Hooke et al. 2013; Paulen 2013). In attempts to understand the depths of deforming substrate the following variables need to be considered: 1) the physical properties, i.e., texture, particle density, internal angle of friction, and variable rheological properties of the substrate, whether the sediments are already deposited and immobile, the stratigraphic layering, if any, and the contribution of other sediment sources, e.g., basal melt rate of debris-rich ice and any bedrock erosion supplying new material to the deforming layer, 2) the overlying ice velocity and basal shear stresses, and 3) the presence and distribution of "weak" or "strong" (deformable or undeformable) layers in the substrate (Alves and Lourenço 2010; Rice et al. 2019b). Under dynamic subglacial conditions, it is perhaps more relevant to observe how these mobilized sediments change from mobile deformable sediments to immobile sediments and vice versa over time (Hicock and Dreimanis 1992; Iverson 2003; Menzies et al. 2006; Stanley 2009; Menzies 2012; Melanson et al. 2013; Phillips et al. 2018; Zoet and Iverson 2020). As such, it is crucial to understand the mechanism on how such a "transformative switch" occurs from mobile to immobile sediments.

The various interface interactions relating to different stress distributions in the mobile layer beneath an active ice mass is illustrated in Figure 14. Figure 14B illustrates a scenario adopted to indicate zero deformation in the substrate; the ice–bed interface is either completely decoupled and basal ice is sliding onto soft sediment, or the sediment yield strength exceeds basal shear stress through its entire thickness. In Figure 14B the sediment yield strength is greater than the applied shear stress down to a certain depth where a strain (deformation) décollement surface develops along the boundary below which yield strength exceeds shear stress. In Figure 14B, multiple strain fronts (décollement surfaces) can be observed at various depths within the sediment substrate, probably due to subsurface stratigraphy and related changes in material rheology. In Figure 14B, the décollement surface ascends in the sediment package as illustrated by "steps" in stress distribution with multiple deformed zones episodically developing. Signatures of these strain décollement surfaces are detectable at the microscale, as shown in the thin section images mapped here In Figure 14B, décollement surfaces (shown in orange) were illustrated in the inset which curve upward in the down-ice direction as more sediment is emplaced (cf. Lee and Phillips 2008). As stress levels vary, décollement surfaces will likely penetrate farther into the substrate if stress levels increase (Lee and Phillips 2008; Goren et al. 2011; Damsgaard et al. 2016 2020; Le Heron et al. 2020). Where scavenging of already-emplaced sediment occurs, it can be expected that overall sediment thicknesses will decrease locally, and décollement surface signatures may be destroyed or contorted.

Décollement surfaces develop at a location in the sediment unit where a potential plane of discontinuity is likely to form. In the thin sections examined here the microscale décollement surface is often a thin zone or area of microshears that coalesce into a broader zone of discontinuity. It needs to be stated that since this is a two-dimensional plane that is being viewed, often displacement is not readily apparent; thus, collecting oriented samples and taking a thin section cut parallel to the main ice movement direction identified at the site is critical to understanding the deformation history recorded by the till. The location of this discontinuity or slip zone marks the interface between mobile and immobile sediment where a décollement surface develops (Fig. 14A, B). The plane is likely to be an agglomeration of microplanes that may coalesce into a décollement (cf. Torabi and Fossen 2009; Fossen et al. 2019). As stress levels change, or as porewater content increases or decreases, or thermal fluctuations between thawed and frozen patches occur, the plane of décollement, under progressive deformation, is likely to change angles and migrate between deeper or shallower levels across an approximately horizontal area of the mobile/immobile till interface or occur parallel to the axis of maximum shear stress (Fig. 14B). If, for example, stress levels rapidly decrease, the position of the décollement surface will migrate towards the upper surface of the deforming unit, and under increasing stress levels, the surface will propagate deeper into the sediment, thereby mobilizing more sediment. The migration of the décollement surface results (as seen in the thin sections examined above) in differentiating between mobile and immobile sediments and thus two distinct rheological groups may be either relatively small in area (a few centimeters to several square meters) or possibly occur over wide expanses of the subglacial bed (cf. Piotrowski et al. 2004; Trommelen et al. 2014; Fossen and Cavalcante 2017; Pennacchioni and Mancktelow 2018; Gauthier et al. 2019; Fossen et al. 2019). Depending on sediment supply and the down-ice sediment flux and outflow rates, the thickness of any deforming part of the subglacial bed may thicken or thin, consistent with the general observations and previous studies (Goren et al. 2011; Melanson et al. 2013; Damsgaard et al. 2016, 2017, 2020; Bougamont et al. 2019; Hogan et al. 2020). It is therefore plausible that local thickening, caused by accumulating immobilized sediment, may act as "growing" sticky spots or nuclei around which deforming sediment may accrete and begin to form drumlins and other bedforms (Eyles et al. 2018; Hermanowski et al. 2020; Sookhan et al. 2021); of course, in contrast, erosion sediment around a "sticky" spot may likewise take place.

One of the ongoing goals of till microsedimentology is to examine the microstructures in thin section and understand how they relate to till sediment deposition (emplacement) (*inter alia* Evans 2017; Menzies and van der Meer 2018; Phillips et al. 2018; Hermanowski et al. 2020; Menzies 2023; Zoet et al. 2023). An understanding of the processes responsible for soft-sediment microstructures in tills is essential for making reliable interpretations and inferences as to how tills are deposited (cf. Piazolo et al. 2019). From the thin sections examined here it is clear that multiple microstructures are symptomatic of repeated deformation phases before, during, and after emplacement of subglacial till. Therefore, interrelationships that exist between all these structures are critical to understanding the development of microstructures in subglacial tills. In analyzing these subglacial tills, extensive kinematic deformation relationships can be observed between microstructures (Davies et al. 2009; Menzies et al. 2016a, 2016b; Robinson et al. 2021). As subglacial till is deformed or strained during its transport and emplacement under varying conditions of porewater content, rheology, percentage of clays present, and changing thermal regimen, a series of different microstructures, as demonstrated here, sequentially evolve. Previous research suggests that, before deformation, domains are already mostly present. In most cases, domains form because of different sediment sources being incorporated into the mobile layer before emplacement and/or the effects of porewater elutriation of clay particles within the till units post emplacement due to changes in overlying porewater flow pressure (cf. Hiemstra and van der Meer 1997; Major and Iverson 1999; Ravier et al. 2014; Menzies et al. 2016b; Thomson et al. 2019). Initially, under conditions of pervasive deformation, grain stacking occurs, and as sediment deformation becomes increasingly nonpervasive, microshear structures and rotation structures develop (e.g., Menzies et al. 2016a; Phillips and Hiemstra 2022; Menzies 2022b). This sequence is repeated multiple times as conditions evolve. During recurring deformation events, décollement surfaces and larger shear zones will form. As localized till units become immobilized during the movement of a mobilized subglacial sediment unit, décollement surfaces form at the upper surfaces of these immobilized units. In many cases, as manifested in the thin sections (Figs. 2, 4, 6, 9, 11, 13), the signatures of décollement surfaces can become disturbed and partially destroyed because of the consequent remobilization. This sequence of microstructural development is indicative of subglacial till deformation under wet-bed temperate ice masses, and the model proposed provides important insights into the complex subglacial sedimentary conditions under which tills develop (Fig. 14A, B) (Leighton et al. 2013; Vernon 2018).

CONCLUSIONS

Based on microsedimentological observations and interpretations from Quaternary and pre-Quaternary till deposits, a model of subglacial bed processes postulated here to better understand the sedimentary conditions where an active ice mass moves across a soft deforming sediment bed. Data from the mapped thin sections provide supporting evidence of the graphic hypothesis illustrated in Figure 14. The main conclusions of this work, with a focus on the model presented here, are based on the microsedimentological evidence that can be summarized as:

- Mapped microstructures illustrate the complexity and interrelated nature subglacial till sedimentology.
- The microstructures show the impact of various forms of deformation mechanics at various stages of till emplacement and subsequent redeformation.
- A crude chronology of microstructure formation can be derived in the mapped thin sections that indicates a process of microstructure evolution related to conditions of overlying stress and rheology affecting the mobile sediment units.
- The impact of overlying stress, whether from overlying moving ice or deforming sediment, transfers into the subjacent sediment imparting strain signatures in the form of microshears that can be assessed in terms of overall stress levels on formation.
- A consequence of this formative timeline is that a time-transgressive repetition of microsedimentological processes occurs subglacially in the sediment and can be traced in these tills.
- A significant "marker" are those microstructures left by a décollement surface in the sediment. The surfaces may be scavenged, partially to completely removed, or overprinted with the preceding ones due to remobilization of previously immobilized sediment. Additionally, in many cases, parts of the features of the previous décollement will be rotated and repositioned within the sediment pile.
- The development and microstructural evolution of décollement surfaces is a complex process of changing stress levels and thermal and rheological conditions (Menzies et al. 2019).
- The model predicts the development of microstructure types including décollement surfaces that, typically with abundant sediment supply, might be expected to ascend through an immobilizing till package.

Much remains to be explored both in laboratory and field settings in terms of the type and nature of microstructure development in subglacial tills (cf. Menzies 2022b; Zoet et al. 2023). For example, a quantitative reexamination of microclast fabrics, grain stack orientations, and microshear fabrics may reveal a clearer interrelationship and a connection with formation of décollement surfaces and their locations in till units. Further investigations are crucial as to whether microstructures can be shown quantitatively and spatially in subglacial till chronological sequences. Likewise, investigation of shear fabrics should allow a closer differentiation of décollement surface locations (Gehrmann et al. 2017). At a more fundamental level, whether there are likely intrinsic or causal relationships between discrete sets of microstructures and décollement surfaces and the mixed rheology of subglacial tills needs further study (e.g., Menzies et al. 2016a; Menzies 2022a; Zoet et al. 2023). All these questions remain to be further investigated if the mechanics of the creation and emplacement of subglacial till in a soft wet-based subglacial environment is to be fully understood.

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REFERENCES

Alley, R.B., 1989a, Water-pressure coupling of sliding and bed deformation: I. Water system: Journal of Glaciology, v. 35, p. 108–118.

Alley, R.B., 1989b, Water-pressure coupling of sliding and bed deformation: II. Velocity: depth profiles: Journal of Glaciology, v. 35, p. 119–129.

Alley, R.B., 1991, Deforming-bed origin for southern Laurentide till sheets?: Journal of Glaciology, v. 37, p. 67–76.

Alley, R., and MacAyeal, D., 1994, Ice-rafted debris associated with binge/purge oscillations of the Laurentide Ice Sheet: Paleoceanography, v. 9, p. 503–511.

Alley, R.B., Blankenship, D.D., Bentley, C.R., and Rooney, S.T., 1986, Deformation of till beneath ice stream B, West Antarctica: Nature, v. 322, p. 57–59.

Alley, R.B., Blankenship, D.D., Rooney, S.T., and Bentley C.R., 1987, Till beneath ice stream B, a coupled ice–till flow model: Journal of Geophysical Research, v. 92, p. 8931–8940.

Alves, T.M., and Lourenço, S.D., 2010, Geomorphologic features related to gravitational collapse: submarine landsliding to lateral spreading on a Late Miocene–Quaternary slope (SE Crete, eastern Mediterranean): Geomorphology, v. 123, p. 13–33.

Anandakrishnan, S., Catania, G.A., Alley, R.B., and Horgan, H.J., 2007, Discovery of till deposition at the grounding line of Whillans Ice Stream: Science, v. 315, p. 1835–1838.

Atkinson, N., 2009, Surficial Geology and Quaternary History of the High Prairie Area (NTS 83N/SE): Alberta Energy Resources Conservation Board, 34 p.

Austin, N.J., 2011, The microstructural and rheological evolution of shear zones, *in* Prior, D.J., Rutter, E.H., and Tatham, D.J., eds., Geological Society of London, Special Publication 360, p. 193–209.

Batchelor, C., and Dowdeswell, J., 2014, The physiography of High Arctic cross-shelf troughs: Quaternary Science Reviews, v. 92, p. 68–96.

Benn, D.I., and Evans, D.J., 1996, The interpretation and classification of subglacially-deformed materials: Quaternary Science Reviews, v. 15, p. 23–52.

Bingham, R.G., King, E.C., Smith, A.M., and Pritchard, H.D., 2010, Glacial geomorphology: towards a convergence of glaciology and geomorphology: Progress in Physical Geography, v. 34, p. 327–355.

Blankenship, D.D., Bentley, C.R., Rooney, S.T., and Alley, R.B., 1986, Seismic measurements reveal a saturated, porous layer beneath an active Antarctic Ice Stream: Nature, v. 322, p. 54–57.

Bloomfield, J.P., and Covey-Crump, S.J., 1993, Correlating mechanical data with microstructural observations in deformation experiments on synthetic two-phase aggregates: Journal of Structural Geology, v. 15, p. 1007–1019.

Bougamont, M., Christoffersen, P., Nias, I., Vaughan, D.G., Smith, A.M., and Brisbourne, A., 2019, Contrasting hydrological controls on bed properties during the acceleration of Pine Island Glacier, West Antarctica: Journal of Geophysical Research: Earth Surface, v. 124, p. 80–96.

Boulton, G.S., 1979, Processes of glacier erosion on different substrata: Journal of Glaciology, v. 23, p. 15–37.

Boulton, G.S., 1996, Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation: Journal of Glaciology, v. 42, p. 43–62.

Boulton, G.S., Dent, D.L., and Morris, E.M., 1974, Subglacial shearing and crushing, and the role of water pressures in tills from south-east Iceland: Geografiska Annaler, v. 56A, p. 134–145.

Boulton, G.S., Dobbie, K.E., and Zatsepin, S., 2001, Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system: Quaternary International, v. 86, p. 3–28.

Bradwell, T., and Stoker, M.S., 2015, Submarine sediment and landform record of a palaeo-ice stream within the British–Irish Ice Sheet: Boreas, v. 44, p. 255–276.

Brisbourne, A.M., Smith, A.M., Vaughan, D.G., King, E.C., Davies, D., Bingham, R.G., Smith, E.C., Nias, I.J., and Rosier, S.H.R., 2017, Bed conditions of Pine Island Glacier, West Antarctica: Journal of Geophysical Research, Earth Surface, v. 122, p. 419–433.

Brouard, E., and Lajeunesse, P., 2019, Ice-stream flow switching by up-ice propagation of instabilities along glacial marginal troughs: The Cryosphere, v. 13, p. 981–996.

Caballero, L., Sarocchi, D., Soto, E., and Borselli, L., 2014, Rheological changes induced by clast fragmentation in debris flows: Journal of Geophysical Research, Earth Surface, v. 119, 2013JF002942.

Campo, J.M., Wellner, J.S., Domack, E., Lavoie, C., and Yoo, K.-C., 2017, Glacial geomorphology of the northwestern Weddell Sea, eastern Antarctic Peninsula continental shelf: shifting ice flow patterns during deglaciation: Geomorphology, v. 280, p. 89–107.

Clarke, G.K.C., 2005, Subglacial processes: Annual Review of Earth and Planetary Sciences, v. 33, p. 247–276.

Clayton, A.I., 2017, In situ monitoring and physical modelling of sub-glacial deformation at Skalafellsjokull [Ph.D. Thesis]: University of Southampton, 232 p.

Cowan, E.A., Christoffersen, P., and Powell, R.D., 2012, sedimentological signature of a deformable bed preserved beneath an ice stream in a late Pleistocene glacial sequence, Ross Sea, Antarctica: Journal of Sedimentary Research, v. 82, p. 270–282.

Damsgaard, A., Egholm, D.L., Piotrowski, J.A., Tulaczyk, S., Larsen, N.K., and Tylmann, K., 2013, Discrete element modeling of subglacial sediment deformation: Journal of Geophysical Research, Earth Surface, v. 118, p. 2230–2242.

Damsgaard, A., Egholm, D.L., Piotrowski, J.A., Tulaczyk, S., Larsen, N.K., and Brædstrup, C.F., 2015, A new methodology to simulate subglacial deformation of water saturated granular material: The Cryosphere (Discussion), v. 9, p. 3617–3660.

Damsgaard, A., Egholm, D.L., Beem, L.H., Tulaczyk, S., Larsen, N.K., Piotrowski, J.A., and Siegfried, M.R., 2016, Ice flow dynamics forced by water pressure variations in subglacial granular beds: Geophysical Research Letters, v. 43, p. 12,165–12,173.

Damsgaard, A., Suckale, J., Piotrowski, J.A., Houssais, M., Siegfried, M.R., and Fricker, H.A., 2017, Sediment behavior controls equilibrium width of subglacial channels: Journal of Glaciology, v. 63, p. 1034–1048.

Damsgaard, A., Goren, L., and Suckale, J., 2020, Water pressure fluctuations control variability in sediment flux and slip dynamics beneath glaciers and ice streams: Communications Earth & Environment, v. 1, p. 1–8.

Davies, B.J., Roberts, D.H., Ó Cofaigh, C., Bridgland, D.R., Riding, J.B., Phillips, E.R., and Teasdale, D.A., 2009, Interlobate ice-sheet dynamics during the last glacial maximum at Whitburn Bay, County Durham, England: Boreas, v. 38, p. 555–578.

Davies, D., Bingham, R.G., King, E.C., Smith, A.M., Brisbourne, A.M., Spagnolo, M., Graham, A.G.C., Hogg, A.E., and Vaughan, D.G., 2018, How dynamic are ice-stream beds?: The Cryosphere, v. 12, p. 1615–1628.

Davison, B.J., Sole, A.J., Livingstone, S.J., Cowton, T.R., and Nienow, P.W., 2019, The influence of hydrology on the dynamics of land-terminating sectors of the Greenland Ice Sheet: Frontiers in Earth Science, v. 7, 24 p.

Dowdeswell, J.A., and Ó Cofaigh, C., eds., 2002, Glacier-influenced sedimentation on high-latitude continental margins: Geological Society of London, Special Publication 203, 378 p.

Dowdeswell, J.A., and Siegert, M.J., 1999, Ice-sheet numerical modeling and marine geophysical measurements of glacier-derived sedimentation on the Eurasian Arctic continental margins: Geological Society of America, Bulletin, v. 111, p. 1080–1097.

Dowdeswell, J.A., Ó Cofaigh, C., and Pudsey, C.J., 2004, Thickness and extent of the subglacial till layer beneath an Antarctic paleo-ice stream: Geology, v. 32, p. 13–16.

Dowdeswell, J.A., Ottesen, D., and Rise, L., 2010, Rates of sediment delivery from the Fennoscandian Ice Sheet through an ice age: Geology, v. 38, p. 3–6.

Dowdeswell, J.A., Hogan, K.A., Arnold, N.S., Mugford, R.I., Wells, M., Hirst, J.P.P., and Decalf, C., 2015, Sediment-rich meltwater plumes and ice-proximal fans at the margins of modern and ancient tidewater glaciers: observations and modelling: Sedimentology, v. 62, p. 1665–1692.

Elson, J., 1989, Comment on glacitectonite, deformation till, and comminution till: genetic classification of glacigenic deposits: International Union for Quaternary Research, Commission on Genesis and Lithology of Glacial Quaternary Deposits, Final Report, p. 85–88.

Ely, J.C., Stevens, D., Clark, C.D., and Butcher, F.E.G., 2023, Numerical modelling of subglacial ribs, drumlins, herringbones, and mega-scale glacial lineations reveals their developmental trajectories and transitions: Earth Surface Processes and Landforms, v. 48, p. 956–978. doi:10.1002/esp.5529.

Engelhardt, E.K., 1998, Basal sliding of Ice Stream B, West Antarctica: Journal of Glaciology, v. 44, p. 223–230.

Evans, D.J., 2017, Till: A Glacial Process Sedimentology: John Wiley & Sons, 400 p.

Evans, D.J.A., Phillips, E.R., Hiemstra, J.F., and Auton, C.A., 2006, Subglacial till: formation, sedimentary characteristics and classification: Earth-Science Reviews, v. 78, p. 115–176.

Evans, D.J., Roberts, D.H., and Evans, S.C., 2016, Multiple subglacial till deposition: a modern exemplar for Quaternary palaeoglaciology: Quaternary Science Reviews, v. 145, p. 183–203.

Eyles, N., Mulligan, R.P.M., Paulen, R.C., and Sookhan, S., 2018, Subglacial bedforms in southern Ontario: from flood paths to flow sets: Geological Survey of Canada, Open File 8481. doi:10.4095/313040.

Ferguson, A., van der Meer, J.J.M., and Phillips, E., 2011, Micromorphology and microstructural analysis of polyphase deformation of tills, West Runton: Glacitectonics: Quaternary Research Association, Field Guide, p. 154–161.

Fernández, R., Gulick, S., Domack, E., Montelli, A., Leventer, A., Shevenell, A., and Frederick, B., 2018, Past ice stream and ice sheet changes on the continental shelf off the Sabrina Coast, East Antarctica: Geomorphology, v. 317, p. 10–22.

Fossen, H., 2010, Deformation bands formed during soft-sediment deformation: observations from SE Utah: Marine and Petroleum Geology, v. 27, p. 215–222.

Fossen, H., and Cavalcante, G.C.G., 2017, Shear zones: a review: Earth-Science Reviews, v. 171, p. 434–455.

Fossen, H., Cavalcante, G.C.G., Pinheiro, R.V.L., and Archanjo, C.J., 2019, Deformation: progressive or multiphase?: Journal of Structural Geology, v. 125, p. 82–99.

Franke, S., Jansen, D., Binder, T., Dörr, N., Helm, V., Paden, J., Steinhage, D., and Eisen, O., 2020, Bed topography and subglacial landforms in the onset region of the Northeast Greenland Ice Stream: Annals of Glaciology, v. 61, p. 143–153.

Franke, S., Jansen, D., Beyer, S., Neckel, N., Binder, T., Paden, J., and Eisen, O., 2021, Complex basal conditions and their influence on ice flow at the onset of the Northeast Greenland Ice Stream: Journal of Geophysical Research, Earth Surface, v. 126, no. e2020JF005689.

Gao, C., McAndrews, J.H., Wang, X., Menzies, J., Turton, C.L., Wood, B.D., and Pei, J., Kodors, C., 2012, Glaciation of North America in the James Bay Lowland, Canada, 3.5 Ma: Geology, v. 40, p. 975–978.

Gardner, R., Piazolo, S., Evans, L., and Daczko, N., 2017, Patterns of strain localization in heterogeneous, polycrystalline rocks: a numerical perspective: Earth and Planetary Science Letters, v. 463, p. 253–265.

Gauthier, M.S., Hodder, T.J., Ross, M., Kelley, S.E., Rochester, A., and McCausland, P., 2019, The subglacial mosaic of the Laurentide Ice Sheet: a study of the interior region of southwestern Hudson Bay: Quaternary Science Reviews, v. 214, p. 1–27.

Gehrmann, A., Hüneke, H., Meschede, M., and Phillips, E., 2017, 3D microstructural architecture of deformed glacigenic sediments associated with large-scale glacitectonism, Jasmund Peninsula (NE Rügen), Germany: Journal of Quaternary Science, v. 32, p. 213–230.

Gehrmann, A., Hüneke, H., Meschede, M., and Phillips, E., 2019, Sea cliff at Wissower Bach (Pleistocene stripe 5): microstructural evidence of large-scale glacitectonism and glacier kinematics: German Quaternary Association, Special Publication 2, p. 29–33.

Goren, L., Aharonov, E., Sparks, D., and Toussaint, R., 2011, The mechanical coupling of fluid-filled granular material under shear: Pure and Applied Geophysics, v. 168, p. 2289–2323.

Graham, A.G.C., Larter, R.D., Gohl, K., Hillenbrand, C.-D., Smith, J.A., and Kuhn, G., 2009, Bedform signature of a West Antarctic palaeo-ice stream reveals a multi-temporal record of flow and substrate control: Quaternary Science Reviews, v. 28, p. 2774–2793.

Greenwood, S.L., Clason, C.C., Helanow, C., and Margold, M., 2016, Theoretical, contemporary observational and palaeo-perspectives on ice sheet hydrology: processes and products: Earth-Science Reviews, v. 155, p. 1–27.

Griera, A., Llorens, M.-G., Gomez-Rivas, E., Bons, P.D., Jessell, M.W., Evans, L.A., and Lebensohn, R., 2013, Numerical modelling of porphyroclast and porphyroblast rotation in anisotropic rocks: Tectonophysics, v. 587, p. 4–29.

Halberstadt, A.R.W., Simkins, L.M., Greenwood, S.L., and Anderson, J.B., 2016, Past ice-sheet behaviour: retreat scenarios and changing controls in the Ross Sea, Antarctica: The Cryosphere, v. 10, p. 1003–1020.

Halberstadt, A.R.W., Simkins, L.M., Anderson, J.B., Prothro, L.O., and Bart, P.J., 2018, Characteristics of the deforming bed: till properties on the deglaciated Antarctic continental shelf: Journal of Glaciology, v. 64, p. 1014–1027.

Hanáček, M., Nývlt, D., and Jennings, S.J., 2021, Thermal basal regime of the Elsterian ice-sheet marginal zone in a hilly mountain foreland, Rychleby Mts., Eastern Sudetes: Boreas, v. 50, p. 582–605.

Hart, J.K., 2013, Depositional processes A2, *in* Shroder, J.F., Treatise on Geomorphology: San Diego, Academic Press, p. 113–126.

Hart, J.K., 2017, Subglacial till formation: microscale processes within the subglacial shear zone: Quaternary Science Reviews, v. 170, p. 26–44.

Hart, J.K., and Boulton, G.S., 1991, The interrelation of glaciotectonic and glaciodepositional processes within the glacial environment: Quaternary Science Reviews, v. 10, p. 335–350.

Hart, J., and Rose, J., 2001, Approaches to the study of glacier bed deformation: Quaternary International, v. 86, 45–58.

Hart, J.K., Martinez, K., Basford, P.J., Clayton, A.I., Robson, B.A., and Young, D.S., 2019, Surface melt driven summer diurnal and winter multi-day stick–slip motion and till sedimentology: Nature Communications, v. 10, p. 1599.

Hermanowski, P., Piotrowski, J.A., and Duda, P., 2020, Till kinematics in the Stargard drumlin field, NW Poland constrained by microstructural proxies: Journal of Quaternary Science, v. 35, p. 920–934.

Hicock, S.R., and Dreimanis, A., 1992, Deformation till in the Great Lakes region: implications for rapid flow along the south-central margin of the Laurentide Ice Sheet: Canadian Journal of Earth Sciences, v. 29, p. 1565–1579.

Hiemstra, J.F., and van der Meer, J.J.M., 1997, Pore-water controlled grain fracturing as indicator for subglacial shearing in tills: Journal of Glaciology, v. 43, p. 446–454.

Hindmarsh, R.C.A., 1998, The stability of a viscous till sheet coupled with ice flow, considered at wavelengths less than the ice thickness: Journal of Glaciology, v. 44, p. 285–292.

Hodder, T.J., Ross, M., and Menzies, J., 2016, Sedimentary record of ice divide migration and ice streams in the Keewatin core region of the Laurentide Ice Sheet: Sedimentary Geology, v. 338, p. 97–114.

Hogan, K.A., Jakobsson, M., Mayer, L., Reilly, B.T., Jennings, A.E., Stoner, J.S., Nielsen, T., Andresen, K.J., Nørmark, E., and Heirman, K.A., 2020, Glacial sedimentation, fluxes and erosion rates associated with ice retreat in Petermann Fjord and Nares Strait, north-west Greenland: The Cryosphere, v. 14, p. 261–286.

Hooke, R.L., and Iverson, N.R., 1995, Grain-size distribution in deforming subglacial tills: role of grain fracture: Geology, v. 23, p. 57–60.

Hooke, R.L., Hanson, B., Iverson, N.R., Jansson, P., and Fischer, U.H., 1997, Rheology of till beneath Storglaciären, Sweden: Journal of Glaciology, v. 43, p. 172–179.

Hooke, R.L., Cummings, D.I., Lesemann, J.-E., and Sharpe, D.R., 2013, Genesis of dispersal plumes in till 1: Canadian Journal of Earth Sciences, v. 50, p. 847–855.

Houssais, M., Maldarelli, C., and Morris, J.F., 2019, Soil granular dynamics on-a-chip: fluidization inception under scrutiny: Lab on a Chip, v. 19, p. 1226–1235.

Iverson, N.R., 2010, Shear resistance and continuity of subglacial till: hydrology rules: Journal of Glaciology, v. 56, p. 1104–1114.

Iverson, N.R., 2017, Determining glacier flow direction from till fabrics: Geomorphology, v. 299, p. 124–130.

Iverson, N.R., and Zoet, L.K., 2015, Experiments on the dynamics and sedimentary products of glacier slip: Geomorphology, v. 244, p. 121–134.

Iverson, N.R., Hooyer, T.S., and Baker, R.W., 1998, Ring-shear studies of till deformation: Coulomb-plastic behavior and distributed strain in glacier beds: Journal of Glaciology, v. 44, p. 634–642.

Iverson, N.R., Hooyer, T.S., and Hooke, R.L., 1996, A laboratory study of sediment deformation: stress heterogeneity and grain-size evolution: Annals of Glaciology, v. 22, p. 167–175.

Iverson, R.M., 2003, The debris-flow rheology myth, *in* Rickenmann, D., and Chen, C., eds., Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment: International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proceedings, p. 303–314.

Ji, S., and Xia, B., 2002, Rheology of polyphase earth materials: Polytechnic International Press, Montreal, 260 p.

Johnson, S.E., Vernon, R.H., and Upton, P., 2004, Foliation development and progressive strain-rate partitioning in the crystallizing carapace of a tonalite pluton: microstructural evidence and numerical modeling: Journal of Structural Geology, v. 26, p. 1845–1865.

Kjær, K.H., Larsen, E., van der Meer, J.M.M., Ingólfsson, Ó., Krüger, J., Benediktsson, Í.Ö., Knudsen, C.G., and Schomacker, A., 2006, Subglacial decoupling at the sediment/bedrock interface: a new mechanism for rapid flowing ice: Quaternary Science Reviews, v. 25, p. 2704–2712.

Klassen, R.A., 1995, Drift composition and glacial dispersal trains, Baker Lake area, District of Keewatin, Northwest Territories: Geological Survey of Canada, Bulletin 485, 68 p.

Knight, J., 2019, Coeval brittle and ductile deformation beneath the late Wisconsinan Puget Lobe, Washington State, USA: Annals of Glaciology, v. 60, p. 1–15.

Larter, R.D., Hogan, K.A., Hillenbrand, C.-D., Smith, J.A., Batchelor, C.L., Cartigny, M., Tate, A.J., Kirkham, J.D., Roseby, Z.A., and Kuhn, G., 2019, Subglacial hydrological control on flow of an Antarctic Peninsula palaeo-ice stream: The Cryosphere, v. 13, p. 1583–1596.

Larsen, N.K., Piotrowski, J.A., and Christiansen, F., 2006, Microstructures and microshears as proxy for strain in subglacial diamicts: implications for basal till formation: Geology, v. 34, p. 889–892.

Lee, J.R., and Phillips, E.R., 2008, Progressive soft sediment deformation within a subglacial shear zone: a hybrid mosaic, pervasive deformation model for middle Pleistocene glaciotectonised sediments from eastern England: Quaternary Science Reviews, v. 27, p. 1350–1362.

Le Heron, D.P., Tofaif, S., and Melvin, J., 2018, The early Palaeozoic glacial deposits of Gondwana: overview, chronology, and controversies, *in* Menzies, J., and van der Meer, J. J.M., eds., Past Glacial Environments, Second Edition: Elsevier, p. 47–73.

Le Heron, D., Heninger, M., Baal, C., and Bestmann, M., 2020, Sediment deformation and production beneath soft-bedded Palaeozoic ice sheets: Sedimentary Geology, v. 408, p. 105761.

Leighton, I.D., Hiemstra, J.F., and Weidemann, C.T., 2013, Recognition of micro-scale deformation structures in glacial sediments: pattern perception, observer bias and the influence of experience: Boreas, v. 42, p. 463–469.

Lemmen, D.S., Duk-Rodkin, A., and Bednarski, J.M., 1994, Late glacial drainage systems along the northwestern margin of the Laurentide Ice Sheet: Quaternary Science Reviews, v. 13, p. 805–828.

Leysinger Vieli, G.J.M.C., and Gudmundsson, G.H., 2010, A numerical study of glacier advance over deforming till: The Cryosphere, v. 4, p. 359–372.

Linnemann, U., Hofmann, M., Gärtner, A., Gärtner, J., Zieger, J., Krause, R., Haenel, R., Mende, K., Ovtcharova, M., and Schaltegger, U., 2021, An Upper Ediacaran Glacial Period in Cadomia: the Granville tillite (Armorican Massif): sedimentology, geochronology and provenance: Geological Magazine, v. 159, p. 1–15.

Livingstone, S.J., Stokes, C.R., Ó Cofaigh, C., Hillenbrand, C.-D., Vieli, A., Jamieson, S. S., Spagnolo, M., and Dowdeswell, J.A., 2016, Subglacial processes on an Antarctic ice stream bed 1: sediment transport and bedform genesis inferred from marine geophysical data: Journal of Glaciology, v. 62, p. 270–284.

Logan, J.M., Friedman, M., Higgs, N., Dengo, C., and Shimanmodo, T., 1979, Experimental studies of simulated fault gouges and their application to studies of natural fault of Actual Fault Zones in Bedrock: U.S. Geological Survey, Open File Report 1239, p. 305–343.

Logan, J.M., Dengo, C.A., Higgs, N.G., and Wang, Z.Z., 1992, Fabrics of experimental fault zones: their development and relationship to mechanical behavior, *in* Brian, E., and Wong, T.-F., eds., International Geophysics: Academic Press, p. 33–67.

Mair, D., Willis, I., Fischer, U.H., Hubbard, B., Nienow, P., and Hubbard, A., 2003, Hydrological controls on patterns of surface, internal and basal motion during three "spring events": Haut Glacier d'Arolla, Switzerland: Journal of Glaciology, v. 49, p. 555–567.

Major, J.J., and Iverson, R.M., 1999, Debris-flow deposition: effects of pore-fluid pressure and friction concentrated at flow margins: Geological Society of America, Bulletin, v. 111, p. 1424–1434.

Mandal, N., Misra, S., and Samanta, S.K., 2005, Rotation of single rigid inclusions embedded in an anisotropic matrix: a theoretical study: Journal of Structural Geology, v. 27, p. 731–743.

McCarroll, D., and Rijsdijk, K.F., 2003, Deformation styles as a key for interpreting glacial depositional environments: Journal of Quaternary Science, v. 18, p. 473–489.

McClay, K.R., 2013, The Mapping of Geological Structures: John Wiley & Sons, 176 p.

McClenaghan, M.B., and Paulen, R.C., 2018, Application of till mineralogy and geochemistry to mineral exploration, *in* Menzies, J., and van der Meer, J.J.M., eds., Past Glacial Environments, Second Edition: Elsevier, p. 689–751.

McMartin, I., and Henderson, P., 2004, Evidence from Keewatin (central Nunavut) for paleo-ice divide migration: Géographie Physique et Quaternaire, v. 58, p. 163–186.

McMartin, I., and Paulen, R., 2009, Ice-flow indicators and the importance of ice-flow mapping for drift prospecting, *in* Paulen, R.C., and McMartin, I., eds., Application of Till and Stream Sediment Heavy Mineral and Geochemical Methods to Mineral Exploration in Western and Northern Canada: Geological Association of Canada, Short Course Notes, v. 18, p. 15–34.

Meer, J.J.M., van, der, 1993, Microscopic evidence of subglacial deformation: Quaternary Science Reviews, v. 12, p. 553–587.

Meer, J.J.M., van, der, and Menzies, J., 2011, The micromorphology of unconsolidated sediments: Sedimentary Geology, v. 238, p. 213–232.

Meer, J.J.M., van der, Menzies, J., and Rose, J., 2003, Subglacial till: the deforming glacier bed: Quaternary Science Reviews, v. 22, p. 1659–1685.

Mehlhorn, P., Winkler, L., Grabbe, F.-C., Kenzler, M., Gehrmann, A., Hüneke, H., and Rother, H., 2019, Coastal cliff at Lenzer Bach on Jasmund Peninsula, Rügen Island (Pleistocene Stripe 4): reconstructed history of glacitectonic deformation based on fold geometry and microstructural mapping: German Quaternary Association, Special Publication 2, p. 35–41.

Melanson, A., Bell, T., and Tarasov, L., 2013, Numerical modelling of subglacial erosion and sediment transport and its application to the North American ice sheets over the Last Glacial cycle: Quaternary Science Reviews, v. 68, p. 154–174.

Menzies, J., 1989, Subglacial hydraulic conditions and their possible impact upon subglacial bed formation: Sedimentary Geology, v. 62, p. 125–150.

Menzies, J., 2000, Micromorphological analyses of microfabrics and microstructures, indicative of deformation processes, in glacial sediments, *in* Maltman, A.J., Hubbard, B., and Hambrey, M.J., eds., Deformation of Glacial Materials: Geological Society of London, Special Publication 176, p. 245–258.

Menzies, J., 2012, Strain pathways, till internal architecture and microstructures: perspectives on a general kinematic model: a "blueprint" for till development: Quaternary Science Reviews, v. 50, p. 105–124.

Menzies, J., 2022a, Differentiation of diamictons (glacigenic–non-glacigenic) using microstructure abundancies and types: Proceedings of the Geologists' Association, v. 133, p. 603–615. doi:10.1016/j.pgeola.2022.07.006.

Menzies, J., 2022b, Glacial microsedimentology: a new lens to investigate glacial sediments: a review: Canadian Journal of Earth Sciences, v. 60, p. 366–387. doi:10.1139/cjes-2022-0048.

Menzies, J., 2023, A micromorphological perspective on the neoproterozoic Smalfjord and Mortensnes formation diamictites: Varangerfjord, Norway: Canadian Journal of Earth Sciences, v. 60, p. 696–712. doi:10.1139/cjes-2022-0019.

Menzies, J., and Reitner, J.M., 2016, Microsedimentology of ice stream tills from the Eastern Alps, Austria: a new perspective on till microstructures: Boreas, v. 45, p. 804–827.

Menzies, J., and Reitner, J.M., 2019, Microstructures, subglacial till deposition, and shear band development revealing up-section changes in shear: a study from Weissbach, Austria: Proceedings of the Geologists' Association, v. 130, p. 196–209.

Menzies, J., and van der Meer, J.J.M., 2018, Micromorphology and microsedimentology of glacial sediments, *in* Menzies, J., and van der Meer, J.J.M., eds., Past Glacial Environments: Elsevier, p. 753–806.

Menzies, J., Gao, C., and Kodors, C., 2013, Microstructural analyses of a Middle Pliocene till from the James Bay Lowlands, Canada: evidence of "potential" fast ice streaming: Proceedings of the Geologists' Association, v. 124, p. 790–801.

Menzies, J., van der Meer, J.J.M., and Ravier, E., 2016, A kinematic unifying theory of microstructures in subglacial tills: Sedimentary Geology, v. 344, p. 57–70.

Menzies, J., van der Meer, J.J.M., and Rose, J., 2006, Till: as a glacial "tectomict," its internal architecture, and the development of a "typing" method for till differentiation: Geomorphology, v. 75, p. 172–200.

Menzies, J., van der Meer, J.J.M., and Shilts, W., 2018, Subglacial processes and sediments, *in* Menzies, J., and van der Meer, J.J.M., eds., Past Glacial Environments: Elsevier, p. 105–158.

Menzies, J., Hess, D.P., Rice, J.M., Wagner, K.G., and Ravier, E., 2016, A case study in the New York Drumlin Field, an investigation using microsedimentology, resulting in the refinement of a theory of drumlin formation: Sedimentary Geology, v. 338, p. 84–96.

Menzies, J., Paulen, R.C., Rice, J.M., McClenaghan, M.B., Oviatt, N.M., and Dhillon, N., 2019, Deformation "boundary front" movements in subglacial tills: a microsedimentological perspective from till sequences near Pine Point, NWT, Canada: The Depositional Record, v. 5, p. 230–246.

Mueth, D.M., Debregeas, G.F., Karczmar, G.S., Eng, P.J., Nagel, S.R., and Jaeger, H. M., 2000, Signatures of granular microstructure in dense shear flows: Nature, v. 406, p. 385–389.

Müller, B.U., and Schlüchter, C., 2000, Influence of the glacier bed lithology on the formation of a subglacial till sequence: ring-shear experiments as a tool for the classification of subglacial tills: Quaternary Science Reviews, v. 20, p. 1113–1125.

Nagl, G., Hübl, J., and Kaitna, R., 2020, Velocity profiles and basal stresses in natural debris flows: Earth Surface Processes and Landforms, v. 45, p. 1764–1776.

Narloch, W., Phillips, E.R., Piotrowski, J.A., and Ćwiek, M., 2020, Patterns of deformation within a subglacial shear zone: implications for palaeo-ice stream bed evolution: Sedimentary Geology, v. 397, p. 105569.

Narloch, W., Piotrowski, J.A., Wysota, W., Larsen, N.K., and Menzies, J., 2012, The signature of strain magnitude in tills associated with the Vistula Ice Stream of the Scandinavian Ice Sheet, central Poland: Quaternary Science Reviews, v. 57, p. 105–120.

Narloch, W., Piotrowski, J.A., Wysota, W., and Tylmann, K., 2015, Till formation under a soft-bedded palaeo-ice stream of the Scandinavian Ice Sheet, constrained using qualitative and quantitative microstructural analyses: Sedimentary geology, v. 326, p. 64–78.

Nitsche, F.O., Gohl, K., Larter, R.D., Hillenbrand, C.-D., Kuhn, G., Smith, J., Jacobs, S. S., Anderson, J., and Jakobsson, M., 2013, Paleo ice flow and subglacial meltwater dynamics in Pine Island Bay, West Antarctica: The Cryosphere, v. 7, p. 249–262.

Nygard, A., Sejrup, H., Haflidason, H., Lekens, W., Clark, C., and Bigg, G., 2007, Extreme sediment and ice discharge from marine-based ice streams: new evidence from the North Sea: Geology, v. 35, p. 395–398.

Ó Cofaigh, C., Dowdeswell, J.A., Allen, C.S., Hiemstra, J.F., Pudsey, C.J., Evans, J., and Evans, D., 2005, Flow dynamics and till genesis associated with a marine-based Antarctic palaeo-ice stream: Quaternary Science Reviews, v. 24, p. 709–740.

Ó Cofaigh, C., Evans, J., Dowdeswell, J.A., and Larter, R.D., 2007, Till characteristics, genesis and transport beneath Antarctic paleo-ice streams: Journal of Geophysical Research, Earth Surface, v. 112, F03006. doi:10.1029/2006JF000606.

Ottesen, D., Rise, L., Knies, J., Olsen, L., and Henriksen, S., 2005, The Vestfjorden–Trænadjupet palaeo-ice stream drainage system, mid-Norwegian continental shelf: Marine Geology, v. 218, p. 175–189.

Oviatt, N., Gleeson, S.A., Paulen, R.C., McClenaghan, B., and Paradis, S., 2015, Characterization and dispersal of indicator minerals associated with the Pine Point Mississippi Valley-type (MVT) district, Northwest Territories, Canada: Canadian Journal of Earth Sciences, v. 52, p. 776–794.

Passchier, C.W., and Trouw, R.A., 2005, Microtectonics: Springer Science & Business Media, 289 p.

Paulen, R., 2013, A revised look at Canada's landscape: glacial processes and dynamics, new frontiers for exploration in glaciated terrain: Ottawa, Geological Survey of Canada, p. 21–26.

Pennacchioni, G., and Mancktelow, N.S., 2018, Small-scale ductile shear zones: neither extending, nor thickening, nor narrowing: Earth-Science Reviews, v. 184, p. 1–12.

Phillips, E.R., 2006, Micromorphology of a debris-flow deposit: evidence of basal shearing, hydrofracturing, liquefaction and rotational deformation during emplacement: Quaternary Science Reviews, v. 25, p. 720–738.

Phillips, E., and Hiemstra, J.F., 2022, Micromorphology: the description and interpretation of glacial sediments in thin section, *in* Evans, D., ed., Glacial and Periglacial Materials: A Field-Based Sedimentology and Engineering Geology Workshop, North Wales: London, Quaternary Research Association, p. 117–127.

Phillips, E., and Kearsey, T.I., 2020, Mass flow and hydrofracturing during Late Devensian moraine emplacement, NE Scotland: Proceedings of the Geologists' Association, v. 131, p. 730–750.

Phillips, E., and Piotrowski, J.A., 2023, Modelling of till microstructure development during subglacial deformation using ring shear experiments: Quaternary Science Reviews, v. 312, p. 108–168.

Phillips, E., van der Meer, J.J.M., and Ferguson, A., 2011, A new "microstructural mapping" methodology for the identification, analysis and interpretation of polyphase deformation within subglacial sediments: Quaternary Science Reviews, v. 30, p. 2570–2596.

Phillips, E., Everest, J., and Reeves, H., 2013, Micromorphological evidence for subglacial multiphase sedimentation and deformation during overpressurized fluid flow associated with hydrofracturing: Boreas, v. 42, p. 395–427.

Phillips, E., Spagnolo, M., Pilmer, A.C., Rea, B.R., Piotrowski, J.A., Ely, J.C., and Carr, S., 2018, Progressive ductile shearing during till accretion within the deforming bed of a palaeo-ice stream: Quaternary Science Reviews, v. 193, p. 1–23.

Phillips, E., Carter, G., and Teasdale, D., 2021, Microscale evidence of the role of water during the emplacement of mass flows in glacial environments: Quarterly Journal of Engineering Geology and Hydrogeology. v. 55, 2 p., doi:10.1144/qjegh2021-026.

Piazolo, S., Bons, P.D., Griera, A., Llorens, M.G., Gomez-Rivas, E., Koehn, D., Wheeler, J., Gardner, R., Godinho, J.R.A., Evans, L., Lebensohn, R.A., and Jessell, M.W., 2019, A review of numerical modelling of the dynamics of microstructural development in rocks and ice: past, present and future: Journal of Structural Geology, v. 125, p. 111–123.

Piotrowski, J.A., Mickelson, D.M., Tulaczyk, S., Krzyszkowski, D., and Junge, F.W., 2001, Were deforming subglacial beds beneath past ice sheets really widespread? Quaternary International, v. 86, p. 139–150.

Piotrowski, J.A., Larsen, N.K., and Junge, F.W., 2004, Reflections on soft subglacial beds as a mosaic of deforming and stable spots: Quaternary Science Reviews, v. 23, p. 993–1000.

Piotrowski, J.A., Larsen, N.K., Menzies, J., and Wysota, W., 2006, Formation of subglacial till under transient bed conditions: deposition, deformation, and basal decoupling under a Weichselian ice sheet lobe, central Poland: Sedimentology, v. 53, p. 83–106.

Piotrowski, J.A., Tylmann, K., Narloch, W., Wysota, W., Damsgaard, A., Egholm, D., Larsen, N.K., and Lesemann, J., 2014, A soft-bed system under the Scandinavian Ice Sheet: 31st Nordic Geological Winter Meeting.

Prothro, L.O., Simkins, L.M., Majewski, W., and Anderson, J.B., 2018, Glacial retreat patterns and processes determined from integrated sedimentology and geomorphology records: Marine Geology, v. 395, p. 104–119.

Rathbun, A.P., Marone, C., Alley, R.B., and Anandakrishnan, S., 2008, Laboratory study of the frictional rheology of sheared till: Journal of Geophysical Research, Earth Surface, v. 113, F2, 14p.

Ravier, E., Buoncristiani, J.-F., Guiraud, M., Menzies, J., Clerc, S., Goupy, B., and Portier, E., 2014, Porewater pressure control on subglacial soft sediment remobilization and tunnel valley formation: a case study from the Alnif tunnel valley (Morocco): Sedimentary Geology, v. 304, p. 71–95.

Reinardy, B.T.I., Hiemstra, J.F., Murray, T., Hillenbrand, C.-D., and Larter, R.D., 2011, Till genesis at the bed of an Antarctic Peninsula palaeo-ice stream as indicated by micromorphological analysis: Boreas, v. 40, p. 498–517.

Reitner, J.M., 2007, Glacial dynamics at the beginning of Termination I in the Eastern Alps and their stratigraphic implications: Quaternary International, v. 164–165, p. 64–84.

Reitner, J.M., and Menzies, J., 2020, Microsedimentology of tills near Ainet, Austria: Were palaeo-ice streams in the European Alps underlain by soft deforming bed zones?: Austrian Journal of Earth Sciences, v. 113, p. 71–86.

Rice, J., Menzies, J., Paulen, R.C., and McClenaghan, M.B., 2019a, Microsedimentological evidence of vertical fluctuations in subglacial stress from the northwest sector of the Laurentide Ice Sheet, Northwest Territories, Canada: Canadian Journal of Earth Sciences, v. 56, p. 363–379.

Rice, J.M., Ross, M., Paulen, R.C., Kelley, S.E., Briner, J.P., Neudorf, C.M., and Lian, O., 2019b, Refining the ice flow chronology and subglacial dynamics across the migrating Labrador Divide of the Laurentide Ice Sheet with age constraints on deglaciation: Journal of Quaternary Science, 34, p. 515–535.

Roberts, J.L., 1989, The Macmillan Field Guide to Geological Structures: London, MacMillan Press, 250 p.

Robinson, D.E., Menzies, J., Wellner, J.S., and Clark, R.W., 2021, Subglacial sediment deformation in the Ross Sea, Antarctica: Quaternary Science Advances, v. 4, p. 100029.

Rose, J., and Hart, J.K., 2009, Quaternary glaciodynamics: editorial overview: Quaternary Science Reviews, v. 28, p. 577–579.

Ruszczynska-Szenajch, H., Trzcinski, J., and Jarosinka, U., 2003, Lodgement till deposition and deformation investigated by macroscopic observation, thin-section analysis and electron microscope study at site Dębe, central Poland: Boreas, v. 32, p. 399–415.

Schaetzl, R.J., Baish, C., Colgan, P.M., Knauff, J., Bilintoh, T., Wanyama, D., Church, M., McKeehan, K., Fulton, A., and Arbogast, A.F., 2020, A sediment-mixing process model of till genesis, using texture and clay mineralogy data from Saginaw lobe (Michigan, USA) tills: Quaternary Research, v. 94, p. 174–194.

Shipp, S.S., Wellner, J.S., and Anderson, J.B., 2002, Retreat signature of a polar ice stream: sub-glacial geomorphic features and sediments from the Ross Sea, Antarctica, *in* Dowdeswell, J.A., and Ó Cofaigh, C., eds., Glacier-Influenced Sedimentation on High-Latitude Continental Margins: Geological Society of London, Special Publication 203 p. 277–304.

Skolasińska, K., Rachlewicz, G., and Szczuciński, W., 2016, Micromorphology of modern tills in southwestern Spitsbergen: insights into depositional and post-depositional processes: Polish Polar Research, v. 37, p. 435–456.

Slater, G., 1926, Glacial tectonics as reflected in disturbed drift deposits: Proceedings of the Geologists' Association, v. 37, p. 392–400.

Smith, A.M., and Murray, T., 2009, Bedform topography and basal conditions beneath a fast-flowing West Antarctic ice stream: Quaternary Science Reviews, v. 28, p. 584–596.

Sobiesiak, M.S., Kneller, B., Alsop, G.I., and Milana, J.P., 2018, Styles of basal interaction beneath mass transport deposits: Marine and Petroleum Geology, v. 98, p. 629–639.

Sookhan, S., Eyles, N., Bukhari, S., and Paulen, R.C., 2021, LiDAR-based quantitative assessment of drumlin to mega-scale glacial lineation continuums and flow of the paleo-Seneca–Cayuga paleo-ice stream: Quaternary Science Reviews, v. 263, p. 107003.

Spagnolo, M., Phillips, E., Piotrowski, J.A., Rea, B.R., Clark, C.D., Stokes, C.R., Carr, S.J., Ely, J.C., Ribolini, A., Wysota, W., and Szuman, I., 2016, Ice stream motion facilitated by a shallow-deforming and accreting bed: Nature Communications, v. 7, p. 11.

Stanley, C.R., 2009, Geochemical, mineralogical, and lithological dispersal models in glacial till: physical process constraints and application in mineral exploration, *in* Paulen, R.C., and McMartin, I., eds., Application of Till and Stream Sediment Heavy

Mineral and Geochemical Methods to Mineral Exploration in Western and Northern Canada: Geological Association of Canada, Short Course Notes 18, p. 35–48.

Stokes, C.R., 2018, Geomorphology under ice streams: moving from form to process: Earth Surface Processes and Landforms, v. 43, p. 85–123.

Stokes, C.R., Fowler, A.C., Clark, C.D., Hindmarsh, R.C.A., and Spagnolo, M., 2013, The instability theory of drumlin formation and its explanation of their varied composition and internal structure: Quaternary Science Reviews, v. 62, p. 77–96.

Stroeven, A.P., van der Meer, J.J.M., Stroeven, P., Dalhuisen, D.H., Hiemstra, J.F., and Stroeven, M., 2002, Improved microfabric determination using stereological analysis: orientation directions of sand particles in Mount Feather Sirius Group tillite, Antarctica: Royal Society of New Zealand, Bulletin, v. 35, p. 327–344.

Tchalenko, J., 1968, The evolution of kink-bands and the development of compression textures in sheared clays: Tectonophysics, v. 6, p. 159–174.

ten Grotenhuis, S.M., Passchier, C.W., and Bons, P.D., 2002, The influence of strain localisation on the rotation behaviour of rigid objects in experimental shear zones: Journal of Structural Geology, v. 24, p. 485–499.

Thomason, J.F., and Iverson, N.R., 2006, Microfabric and microshear evolution in deformed till: Quaternary Science Reviews, v. 25, p. 1027–1038.

Thomson, P.-R., Hazel, A., and Hier-Majumder, S., 2019, The influence of microporous cements on the pore network geometry of natural sedimentary rocks: Frontiers in Earth Science, v. 7, p. 14.

Torabi, A., and Fossen, H., 2009, Spatial variation of microstructure and petrophysical properties along deformation bands in reservoir sandstones: American Association of Petroleum Geologists, Bulletin, v. 93, p. 919–938.

Treagus, S.H., 2002, Modelling the bulk viscosity of two-phase mixtures in terms of clast shape: Journal of Structural Geology, v. 24, p. 57–76.

Trommelen, M.S., Ross, M., and Ismail, A., 2014, Ribbed moraines in northern Manitoba, Canada: characteristics and preservation as part of a subglacial bed mosaic near the core regions of ice sheets: Quaternary Science Reviews, v. 87, p. 135–155.

Truffer, M., and Harrison, W.D., 2006, In situ measurements of till deformation and water pressure: Journal of Glaciology, v. 177, p. 175–182.

Tulaczyk, S., 1999, Ice sliding over weak, fine-grained tills: dependence of ice–till interactions on till granulometry: Geological Society of America, Special Paper 337, p. 159–178.

Tulaczyk, S., Kamb, W.B., and Engelhardt, H.F., 2000, Basal mechanics of Ice Stream B, West Antarctica. 2. Undrained plastic bed model: Journal of Geophysical Research, v. 105, p. 483–494.

Tulaczyk, S.M., Scherer, R.P., and Clark, C.D., 2001a, A ploughing model for the origin of weak tills beneath ice streams: a qualitative treatment: Quaternary International, v. 86, p. 59–70.

Tulaczyk, S., Kamb, B., and Engelhardt, H.F., 2001b, Estimates of effective stress beneath a modern West Antarctic ice stream from till preconsolidation and void ratio: Boreas, v. 30, p. 101–114.

Vernon, R.H., 2018, A Practical Guide to Rock Microstructure: Cambridge University Press, 443 p.

Virkkala, K., 1952, On the bed structure of till in eastern Finland: Commission Géologique de Finlande, Bulletin, v. 157, p. 97–109.

Zhang, Q., and Kamrin, K., 2017, Microscopic description of the granular fluidity field in nonlocal flow modeling: Physical Review Letters, v. 118, no. 058001.

Zhang, W., Randolph, M.F., Puzrin, A.M., and Wang, D., 2020, Criteria for planar shear band propagation in submarine landslides along weak layers: Landslides, v. 17, p. 855–876.

Zoet, L.K., and Iverson, N.R., 2020, A slip law for glaciers on deformable beds: Science, v. 368, p. 76–78.

Zoet, L., Hansen, D., Morgan-Witts, N., Menzies, J., Sobol, P., and Lord, N., 2023, An experimental baseline for ice–till strain indicators: Canadian Journal of Earth Sciences, v. 60, p. 537–549.

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