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GLACIOTECTONIC DEFORMATION ALONG A 70 KM SECTION OF THE DOG BAY LINE: BEAVER BROOK ANTIMONY MINE TO TEN MILE LAKE

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ABSTRACT

Glaciotectonized bedrock and subglacial traction till were observed in eight borrow pits, trenches and quarries, along a 70 km corridor, from the eastern margin of the Mount Peyton Intrusive Suite (MPIS), near the Beaver Brook Antimony mine north to Ten Mile Lake. Glaciotectonic deformation features resulting from brecciation, compression, shearing, thrusting, rotation and folding of the underlying Davidsville and Indian Islands groups siltstone and diamicton layers by north-northeastward to north-northwestward ice flow have been interpreted as Type-A glaciotectonites. The south-southwestward to south-southeastward dip of the axial traces of folds and fold limbs, and of inferred thrust planes, are oblique to nearby bedrock structural features, and are consistent with subglacial compression and shear caused by north-northeastward to north-northwestward ice flow.

At one site south of Gander Lake, compositional similarities between the coarse and fine fractions in units of a massive siltstone boulder to cobble diamicton, a southwestward-dipping, folded siltstone and silt glaciotectonite raft and an overlying thin (1 m), yellow subglacial traction till, suggests that they are part of the same stratigraphic sequence, that was deposited and deformed simultaneously during north-northeastward ice flow. A similar thin, yellow subglacial traction till overlies channel deposits on the eastern edge of the MPIS, and is noted down ice (northward) with fewer, smaller clasts and a more homogenized matrix north of Big Pond. Glacially deformed bedrock with minor diamicton layers is observed in a rock-cored drumlin near Ten Mile Lake.

*The glaciotectonic deformation features, and their stratigraphic position suggest they were formed by a thin, topographically constrained north-northeastward to north-northwestward flowing ice lobe (or lobes?) that were active during deglaciation (*e.g.*, the Gander Lake Ice Stream?). The resulting glaciotectonized diamictons are locally sourced, and have a higher coarse fraction content. In regions where basal till is not exposed or easy to sample, the coarse fraction of diamictons in the upper part of sections may assist in surface exploration sampling, using indicator mineral sampling or boulder tracing, with careful consideration as to how the diamictons were emplaced, the direction of emplacement in relation to possible mineralized sources.*

INTRODUCTION

This study is part of a collaborative mineral deposit, bedrock and surficial geology project in east-central Newfoundland in an approximately 200-km-long, 50-km-wide corridor (Figure 1). The study stretches from Dog Bay in the north, to St. Alban's in the south, and it overlies the tectonic break known as the Dog Bay Line (Williams *et al.*, 1993) in the north. The goal of this project is to address geoscientific knowledge gaps in both the bedrock and surficial geology deposits, and to assist ongoing mineral exploration efforts focusing on gold, antimony, tungsten and molybdenum occurrences. New airphoto imagery and recent research (*e.g.*, Blundon *et al.*, 2010; McHenry and Dunlop, 2016), along with the widespread recent staking in the region (Saltwire, 2021) have highlighted the need for a more in-depth look at the surficial geology. This report focuses on metre-scale glaciotectonic deformation features in the surficial environment observed at sites along a 70-km-long, 10-km-wide corridor over the central Dog Bay Line, stretching from west of the Northwest Gander River to east of Ten Mile Lake (*see* Figures 1 and 2).

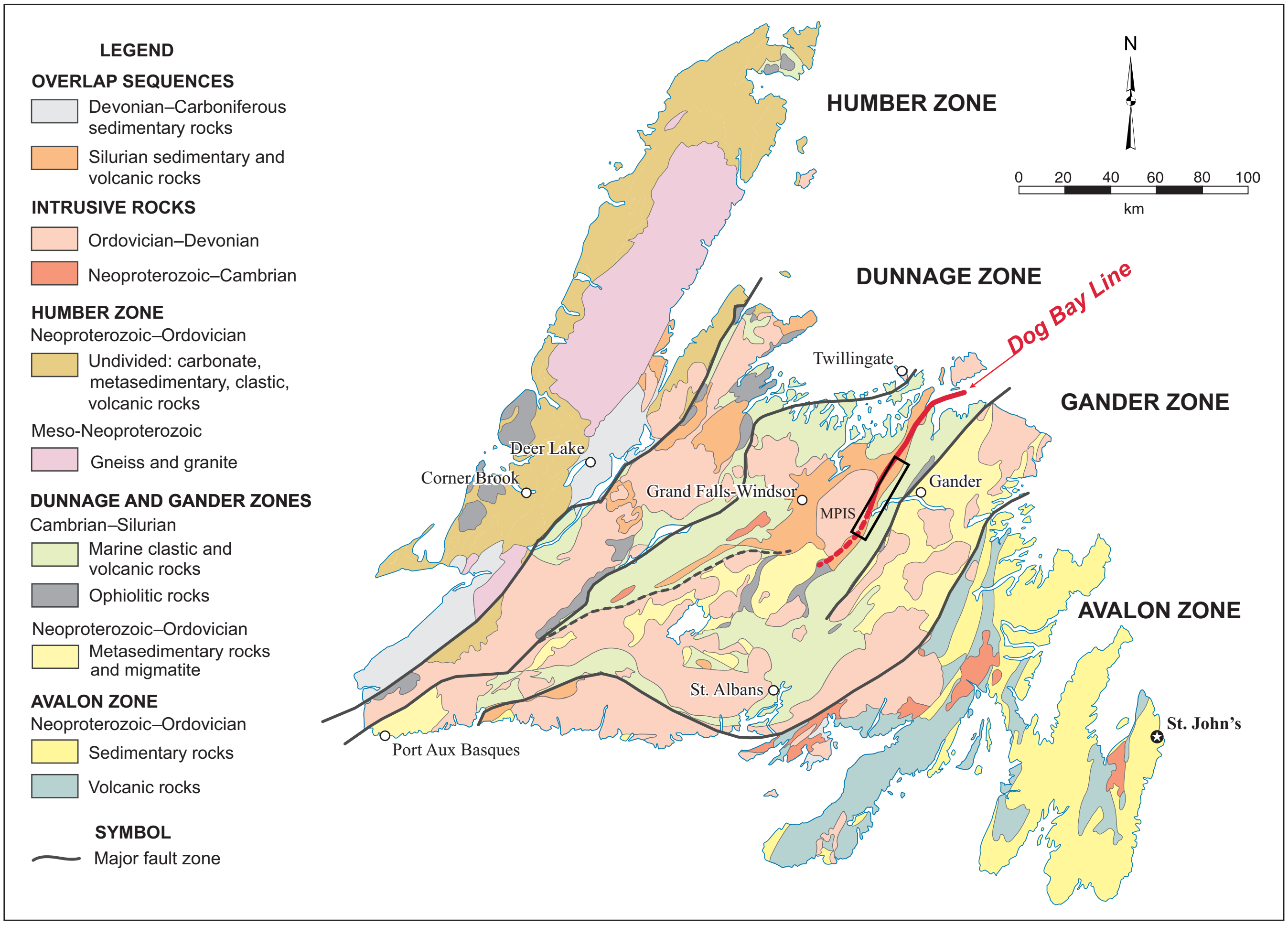

Figure 1. *Simplified geological map of Newfoundland showing the main tectonic zones (after Sandeman* et al.*, 2018). The study region is located east of the Mount Peyton Intrusive Suite (MPIS; Blackwood, 1982) and west of Gander (black box).*

GLACIOTECTONISM

Glaciotectonism occurs when the pressure of overriding ice mass deforms either bedrock, glacial or postglacial sediments, resulting in features that resemble those formed in fold and thrust belts in crustal collision zones (*see* Phillips, 2018; Figure 3). Glaciotectonic features occur in a wide variety of subglacial and proglacial environments, and include brittle (faults and fractures) and ductile (folding and shearing) deformation (*ibid.*). In the field, glaciotectonism can be recognized as faults, fractures, folds and shears that occur in unconsolidated sediments (*e.g.*, Davies *et al.*, 2009; Pedersen, 2014; Flindt *et al.*, 2018), fractured bedrock (*e.g.*, Broster, 1991; Broster and Park, 1993) and brecciated, and folded bedrock and diamicton mixes (*e.g.*, Heimstra *et al.*, 2007; Pedersen, 2014) that are oriented by subglacial shear, glacial unloading and glacial sediment collapse. The intensity and style of deformation is dependent on the amount of meltwater generated by pressure-induced melting at the basal interface of a glacier, and the competency contrasts within the substrate it deforms (Phillips, 2018).

Glaciotectonic structures were recognized in the late 1800s in Europe and as early as 1927 in Alberta, Canada (Slater, 1927). Researchers in Europe first adopted bedrock structural geology techniques to assist in unravelling stratigraphic complexities resulting from glacial deformation of bedrock and glacial sediments (Banham, 1977; Berthelsen, 1978; Pedersen, 1987).

Glaciotectonism has implications for mineral and geochemical dispersal studies (*e.g.*, Stea, 1994; Plouffe *et al.*, 2011) and paleoglacial reconstructions (*e.g.*, Banham, 1977; Berthelsen, 1978; Aber and Ber, 2007; Huntley and Broster, 1993; Phillips *et al.*, 2002; McCuaig, 2006; Davies *et al.*, 2009; Shaw *et al.*, 2012; Pedersen, 2014; Shaw and Longva, 2017). Glaciotectonism can also affect groundwater flow and rock permeability (*e.g.*, Broster and Park, 1993; Eyles

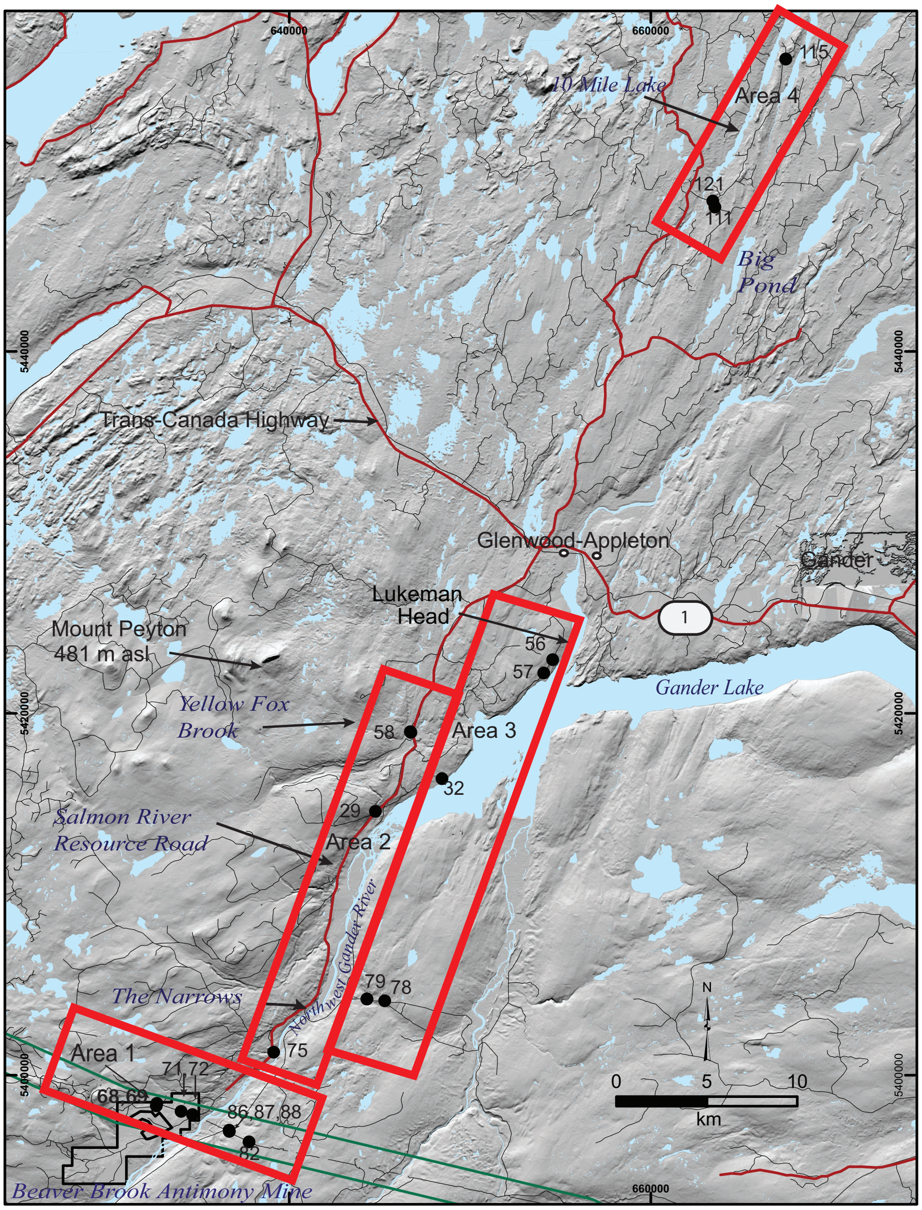

Figure 2. *Location and site map of the field area with numbered sites. Beaver Brook Antimony Mine is located on the lower left hand side of the figure (black box), near the hydro transmission lines (green) south of the study region. Red boxes outline the areas discussed in the text. A 3x vertical exaggeration has been applied to the Digital Elevation Model which is derived from airphotos of the region (A. Eaton, GIS and Mapping division, Government of Newfoundland and Labrador, personal communication, September, 2021).*

and Scheidegger, 1995; Lund and Naslund, 2009; Burt and Dodge, 2011; Nasir *et al.*, 2014; Selvadurai *et al.*, 2015; Mulligan, 2019; Hall *et al.*, 2020), rock breakage and slope stability (*e.g.*, Pedersen and Moller, 2004; Spooner *et al.*, 2020).

The development of till forming processes is represented through progressive glaciotectonism, from the fracturing of bedrock to basal till formation (Evans *et al.*, 2006; Heimstra *et al.*, 2007). Pore waters derived from the pressure-induced melting of an overriding glacier assists in the comminution of bedrock-derived particles into a homogenized matrix of sand, silt and clay representing the end-member deformation product of bedrock by glaciers (Evans *et al.*, 2006). This matrix material is optimal for till-geochemical sampling programs (Brushett, 2014; McClenaghan and Paulen, 2018). Knowledge of the degree of homogeneity and erosion in diamictons helps determine dispersal distances from inferred sources.

In this study, the glacial deformation of bedrock is distinguished from the preglacial deformation of bedrock by: 1) the orientation of features in response to known ice-flow directions and; 2) the presence of diamicton infill in structural discontinuities (*e.g.*, Broster and Park, 1993). The objective here is to examine glaciotectonic deformation of bedrock and proglacial sediments, mechanisms of formation (*e.g.*, ice-streaming?), and the textural maturation of subglacial sediments within a preliminary stratigraphic framework.

TERMINOLOGY

Terms specific to glacial deformation studies or whose meanings are modified for particular use in a glaciotectonic context are defined in the following section (*see* Figure 3). Terms used in this paper are derived from Evans *et al.* (2006). Terms used in previous studies (*e.g.*, deformation till, comminution till, lodgement till and melt-out till) to describe some of the features noted in this study imply till genesis process(es) that are not always identifiable (*ibid.*), so they are not used in this study.

Diamicton – A non-sorted or poorly sorted terrigenous or marine sediment containing a wide range of particle

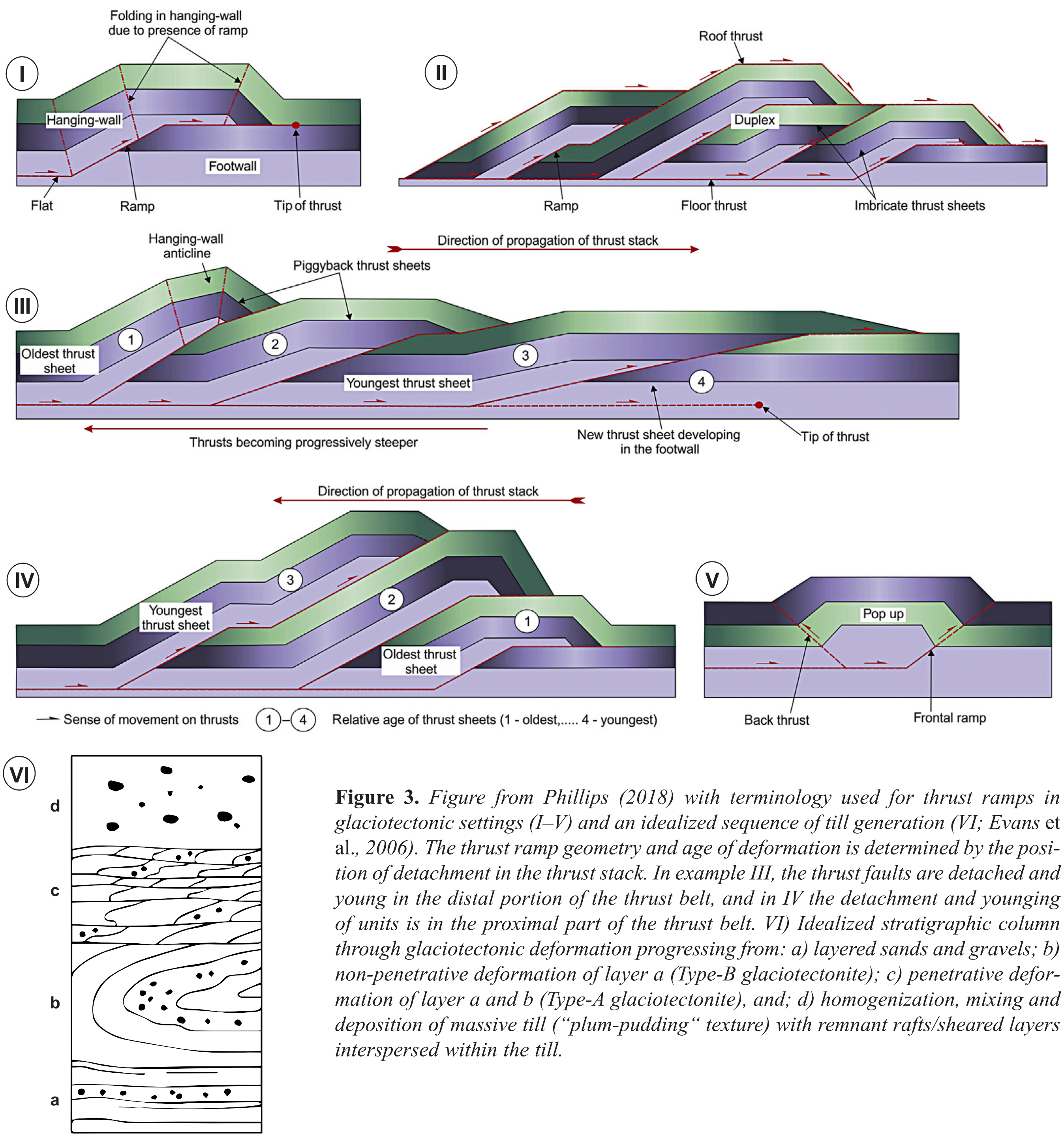

Figure 3. *Figure from Phillips (2018) with terminology used for thrust ramps in glaciotectonic settings (I–V) and an idealized sequence of till generation (VI; Evans* et al.*, 2006). The thrust ramp geometry and age of deformation is determined by the position of detachment in the thrust stack. In example III, the thrust faults are detached and young in the distal portion of the thrust belt, and in IV the detachment and younging of units is in the proximal part of the thrust belt. VI) Idealized stratigraphic column through glaciotectonic deformation progressing from: a) layered sands and gravels; b) non-penetrative deformation of layer a (Type-B glaciotectonite); c) penetrative deformation of layer a and b (Type-A glaciotectonite), and; d) homogenization, mixing and deposition of massive till ("plum-pudding" texture) with remnant rafts/sheared layers interspersed within the till.*

sizes from clay/silt/sand (matrix) to pebbles/cobbles and boulders (clasts). This term is non genetic, and refers to the material observed, without reference to the process that formed the material.

Clasts – The outsize (larger) pebble, cobble to boulder material that contrasts with finer particles in glacial deposits.

Matrix – The fine particle fraction of tills (sands, silts and clays).

Comminution – The grinding and abrading of rock into smaller particles under a glacier by friction between the underlying material and the base of the glacier (Heimstra *et al.*, 2007).

Glaciotectonite – Subglacially sheared rock and sediments (Banham, 1977; Pedersen, 1987), or rock or sediment that has been deformed by subglacial shearing (deformation) but retains some of the structural characteristics of the parent material. Glaciotectonites are subdivided into Type-A, which display evidence of penetrative, brittle or localized ductile deformation, and Type-B, which have undergone non-penetrative ductile deformation (*e.g.*, folded layers with preserved pre-deformational structures; Benn and Evans, 1996; Evans *et al.*, 2006). Glaciotectonites represent an essential part of the process-form continuum of till production, and not just the crushing and abrading known formerly as comminution till (*see* Heimstra *et al.*, 2007).

Subglacial traction till – Sediment deposited by a glacier sole, either sliding over and/or deforming its bed; the sediment having been released directly from the ice by pressure melting and/or liberated from the substrate and then disaggregated and completely or largely homogenized by shearing. Formerly, referred to as lodgement till, deformation till and comminution till in various studies (*see* Evans *et al.*, 2006).

Subglacial melt-out till – Sediment released by the melting of stagnant or slowly moving debris-rich glacier ice and directly deposited without subsequent transport or deformation (Evans *et al.*, 2006).

Texturally immature till – A till that has not completely been homogenized and may contain a mixture of bedrock rafts and/or high proportion of clasts that have not been ground down to a finer fraction.

Texturally mature till – A till that has been homogenized, with low clast content and high fines.

PHYSIOGRAPHY OF THE STUDY REGION

The study region is situated in the glacially polished lowlands of the Northwest Gander River valley (Figure 2). Mount Peyton is the most prominent topographic feature whose summit is a linear, north-eastward oriented, granite promontory that rises 481 m above sea level (asl), and 436 m above the river valley. Bedrock-cored, metre- to decimetre-scale ridges oblique and perpendicular to the east–west-trending Trans-Canada Highway (TCH) are interspersed with bog and fen-filled valleys north of Gander Lake from Gander to Glenwood. Gently rounded tree-covered hills occur on the south side of Gander Lake, with sand and gravel deposits along the lake shore at the outflow of the Northwest Gander River. Bedrock is commonly exposed along the Northwest Gander River, on the southwestern edge of the lake and in brooks along the eastern margin of Mount Peyton. This region is a drumlinized till plain comprising moderate stony soils derived from black, green and grey shale and siltstone and minor medium-grained granite with a compacted and slightly cemented subsoil (Wells and Heringa, 1972).

BEDROCK AND SURFICIAL GEOLOGY

BEDROCK

The glacial sections are primarily underlain by sedimentary units that outcrop east of the Mount Peyton Intrusive Suite (MPIS; Blackwood, 1982) and are illustrated in Figure 4. Rock units include: 1) the homogeneous steeply dipping, slaty and cleaved siltstone and sandstone of the Hunt's Cove Formation and the green–black siltstone, sandstone and conglomerate of the Outflow Formation of the Davidsville Group (this includes Katian–Sandbian black shale (Blackwood, 1982; O'Neill and Blackwood, 1989; Dickson, 2006; Sandeman *et al.*, 2018); 2) the Indian Islands Group (IIG; Dickson, 2006), a locally fossiliferous sequence of sparse limestone interbedded with dominant muscovite-bearing siltstone and sandstone that bound the eastern margin of the MPIS (Dickson, 1993, 1996); 3) the red siltstone and pink and green sandstones of the Ten Mile Lake Formation (Currie and Williams, 1995), and; 4) dark-grey, fine- to medium-grained, equigranular, hornblende biotite gabbro, pink, fine- to medium-grained equigranular hornblende–biotite granite; and diabase dykes of the MPIS (Blackwood, 1982; Dickson, 1996) exposed in the west and north of the study area. The granite, gabbro and diorite of the MPIS are not internally deformed, whereas the flanking sedimentary units of the Davidsville and Indian Islands groups black shale exhibit variable strain. The Ten Mile Lake Formation siltstone and sandstone are variably cleaved, folded, locally strongly deformed and have steeply dipping fabrics. The regional-scale structural foliation of the sedimentary units is generally oriented north-northeastward (Figure 4).

PREVIOUS STUDIES – SURFICIAL MATERIALS AND ICE FLOW

Ice-flow orientations determined in previous studies from striation measurements and analysis of fabrics in diamictons south and north of Gander Lake are similar, but there are differing interpretations of ice-flow chronologies. In studies from north of Gander Lake (St. Croix and Taylor, 1991), four ice-flow events are interpreted from striation data in the following chronological order: 1) east-southeast flow; 2) a north-northeastward flow; 3) a later northeastward to northwestward flow determined through crosscutting of earlier north-northeastward striations, and; 4) a late, localized east-southeast to southeast flow. A simplified ice-flow chronology presented in Batterson and Vatcher (1991)

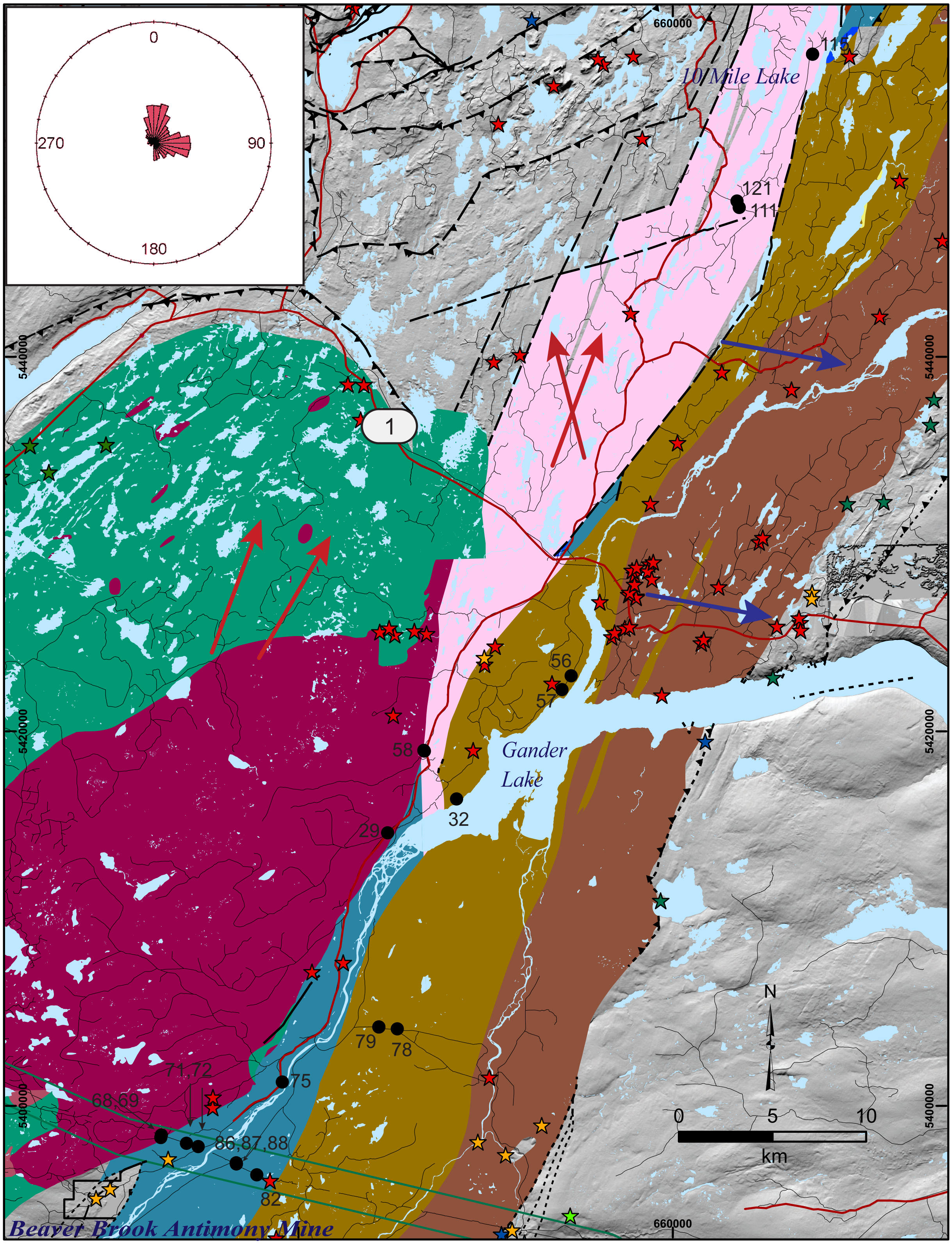

Figure 4. *Map showing site locations (black circles), bedrock units of interest, ice-flow directions (blue and red arrows: after St. Croix and Taylor, 1991; Batterson and Vatcher, 1991) overlying selected bedrock units in the study region (Blackwood, 1982; O'Neill and Blackwood, 1989; Currie and Williams, 1995; Dickson, 2006).*

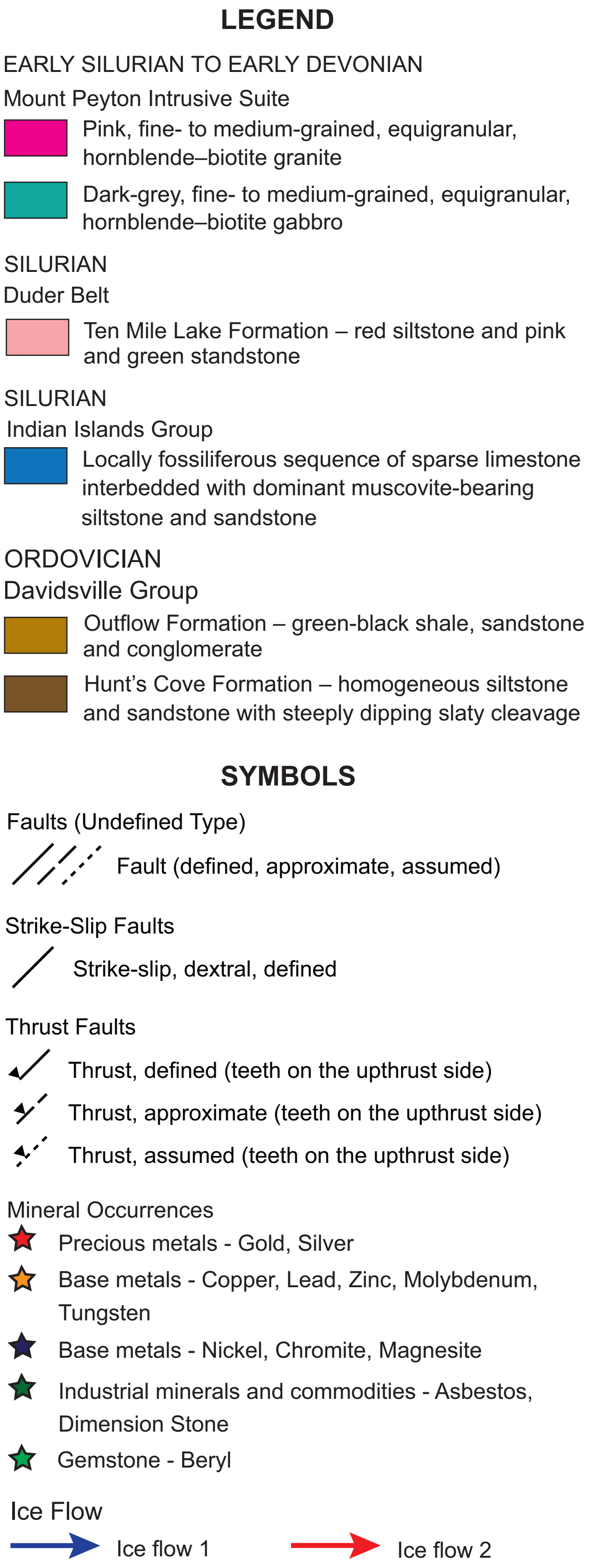

Figure 4. *Legend.*

is based on studies involving fabrics and striations south and northeast of Gander Lake and suggests only two ice-flow events; an east-southeastward flow followed by a north-northeast flow, that trends to the northwest north of Big Pond. The east-southeastward and north-northeastward to north-northwestward ice-flow directions are displayed in Figure 4, and abundances and orientations presented in the rose diagram (Figure 4 inset). This figure uses the latter simplified chronology, as most of the sites in the current study are located in the region mapped by Batterson and Vatcher (1991) and further investigations are needed to clarify the ice-flow chronology north of Gander Lake (Jennifer Organ, personal communication, December, 2021). The erosional footprint of north-northeast ice-flow is also evident in large-scale (10–100 m scale) eroded landforms immediately west of Mt. Peyton proper (*see* Figures 2 and 4). The last flow was topographically confined to the west of the map area by the rigid, crystalline rocks of the MPIS.

The region is overlain by glacial diamictons (*e.g.*, Batterson and Vatcher, 1991; Scott, 1994; Batterson, 1999), juxtaposed with sandy proglacial deposits, observed in stratigraphic sections south of Gander Lake, that also exhibit fabrics consistent with the last ice-flow direction (*e.g.*, north-northeastward; Batterson and Vatcher, 1991). Sorted lenses of sand and gravel are noted in diamictons north of Gander Lake and near Ten Mile Lake, with diamicton fabrics in this region trending to the north, east and southeast (Scott, 1994). Subglacial melt-out diamicton, glacigenic debris flows and loading structures are noted north and east of Gander Lake (Scott, 1994; McCuaig, 2006). Detailed studies on the eastern side of Gander Lake suggest that the glacial sedimentation occurred in an ice-contact, proglacial environment, with deposition in Gander Lake and a switch in lake drainage from east to north (McCuaig, 2006).

Sand deposits have been identified along the Northwest Gander River (Ricketts, 2006). Most of these deposits contain less than 15% silt and clay and lie below 64 m, coinciding with the indicated marine elevation limit in this region (Batterson and Vatcher, 1991). Sand deposits lie along both sides of the modern Northwest Gander River and in some of its tributaries (*e.g.*, Yellow Fox, Clarks Brook; Figure 2). The sand may have been deposited by ice-contact or subglacial channels that eroded till veneer from the eastern slope of Mount Peyton (Batterson, 1999). These channels are visible from the Beaver Brook Antimony Mine northwards to Yellow Fox Brook (Figure 2).

FIELD OBSERVATIONS

Some of the glaciogenic structural features noted include dewatering structures, breccias, thrust ramps, faults, folds, fractures, and rotation, in a variety of glacial materials that were formed by subglacial shear and compression, and by sediment loading. Glacially deformed features were identified in 4 main areas: 1) on the hydro-line near the Beaver Brook Antimony Mine Lease; 2) south of the Narrows up to Yellow Fox Brook; 3) east of the Northwest Gander River and south of Lukeman Head; and, 4) on the eastern side of Ten Mile Lake north of the Trans-Canada Highway (Figure 2). The following section describes observations at sites surveyed while conducting reconnaissance stratigraphic studies in the region and includes sites where stratigraphic relationships were important to establish, or where glacially deformed features were observed. The orientations of glacial features are measured from section-scale glaciotectonic deformation structures and represent preliminary field observations.

The diamictons are temporarily classed into three main types, based on field observations of clast content, colour and texture, and are referred to as Dm1, Dm2 and Dm3. The coarse fraction and pebble analysis of these diamictons has yet to be studied in detail.

The three diamictons are summarized as:

Dm1 – Massive tan-brown, sandy diamicton with up to 20% local (MPIS gabbro and diorite, granite and altered sedimentary rocks of the IIG?) and minor distal pebbles. On the southeastern margin of the MPIS, Dm1 is overlain by poorly to moderately sorted massive silty sands, and intermittent bedding and subangular to subrounded boulders;

Dm2 – Massive dark-brown, variable sand- and gravel-rich diamicton that varies in texture, compactness and thickness; and,

Dm3 – Yellow to grey, silty-sand with locally derived pebbles, cobbles and boulders. This unit is loosely consolidated near Beaver Brook Antimony Mine and is cemented, flattened or deformed in the upper (0.6 m) layer in the northern part of the study area. This material may be re-worked and/or weathered-brown diamicton (Dm2) and is commonly deformed.

AREA 1: WEST–EAST TRANSMISSION LINE TRANSECT – NORTHWEST GANDER RIVER NORTH OF GREENWOOD BROOK NEAR BEAVER BROOK ANTIMONY MINE

The west to east sites are located along the hydro transmission line that crosses the U-shaped valley comprising the Gander River, with road-cuts along the transmission line revealing glacial stratigraphy from the western granitic high ground to the eastern ridge of Davidsville Group metasedimentary rocks (Figure 4). The westernmost site (site 68) exposes hornfelsed IIG sedimentary rocks at 200 m along an irregular intrusive contact with MPIS granite. North (150 m) of this bedrock contact, at site 69, a 0.4-m-thick, compact, tan silt and clay-rich diamicton with a minimal clast content is noted (Plate 1A–Dm1). At site 71 (*not shown*), located at 145 m asl, 0.6 m of Dm1 is covered by a 0.4–0.6 m layer of loose silty sediment and IIG siltstone clasts that may be a thin draping of subglacial meltout material derived from Dm1. Farther eastward, at site 72, sitting at 110 m asl, a compact, fissile tan diamicton with eastward-dipping, imbricated, MPIS diorite and granite clasts (Dm1) is overlain by a 0.7-1 m layer of oxidized loose silt and sand diamicton (Dm3?) with altered siltstone clasts (Plate 1B). Cobbles of angular and faceted MPIS granite and diorite and angular hornfelsed siltstone clasts are noted at the site. Farther east, at site 73, a thick (4 m), massive, imbricated siltstone, sand and silt unit (Dm3?) is observed at 90 m asl. (Plate 1C). South of this site, at the same elevation (sites 65, 66 and 67 (*not shown*)), moderate- to well-sorted, 2.5–3-m-thick silt-rich sand and gravel layers overlie compact tan diamicton (Dm1). On the east side of the Northwest Gander River, at sites 86 and 87 at 90–110 m asl, a 0.5–0.7-m-thick, variably sorted yellow silty layer (Dm3) with granite cobbles overlies a 1 m section of poorly sorted, loose sand with minor clay and silt and siltstone clasts (Plate 1D, E). Siltstone bedrock (site 88) of the IIG crops out nearby at 120 m asl. At site 82, a 0.6-m-thick layer of clay-rich, clast-poor tan till (Plate 1F), similar to that shown in Plate 1A, is noted intermittently in the area at 170 m asl. (Dm2).

AREA 2: EAST SIDE OF MOUNT PEYTON – SOUTH OF THE NARROWS NORTH TO YELLOW FOX BROOK

Poor to moderately sorted glacial sections are exposed in borrow pits at 60–90 m asl along the Salmon River Resource Road south from the Beaver Brook Antimony Mine to the west of the Gander Lake outflow. The sections surveyed are on the down-stream side of channel features in the Digital Elevation Model (Figure 2). Most of these sections are underlain by a 0.6-m-thick, compact, tan, silty-sand diamicton with subangular granite and diorite pebbles (Dm1), eroded by a 1–4-m-thick unit interpreted as subglacial or ice-marginal channel deposits that range from silty sands and gravels with angular to subrounded, striated, locally sourced boulders to moderately sorted sand and gravel layers. The ice-contact units are overlain by an upper layer of compact, cemented, yellowish, silty-sand and clay, granite-cobble-rich diamicton ranging from 0.6–1.0 m in thickness. Three of these glacial sections contain moderately to well-sorted gravels and sands with dipping beds.

At site 75, (65 m asl), in one of the moderately well-sorted sections, grey sand beds dip gently to the south-southwest

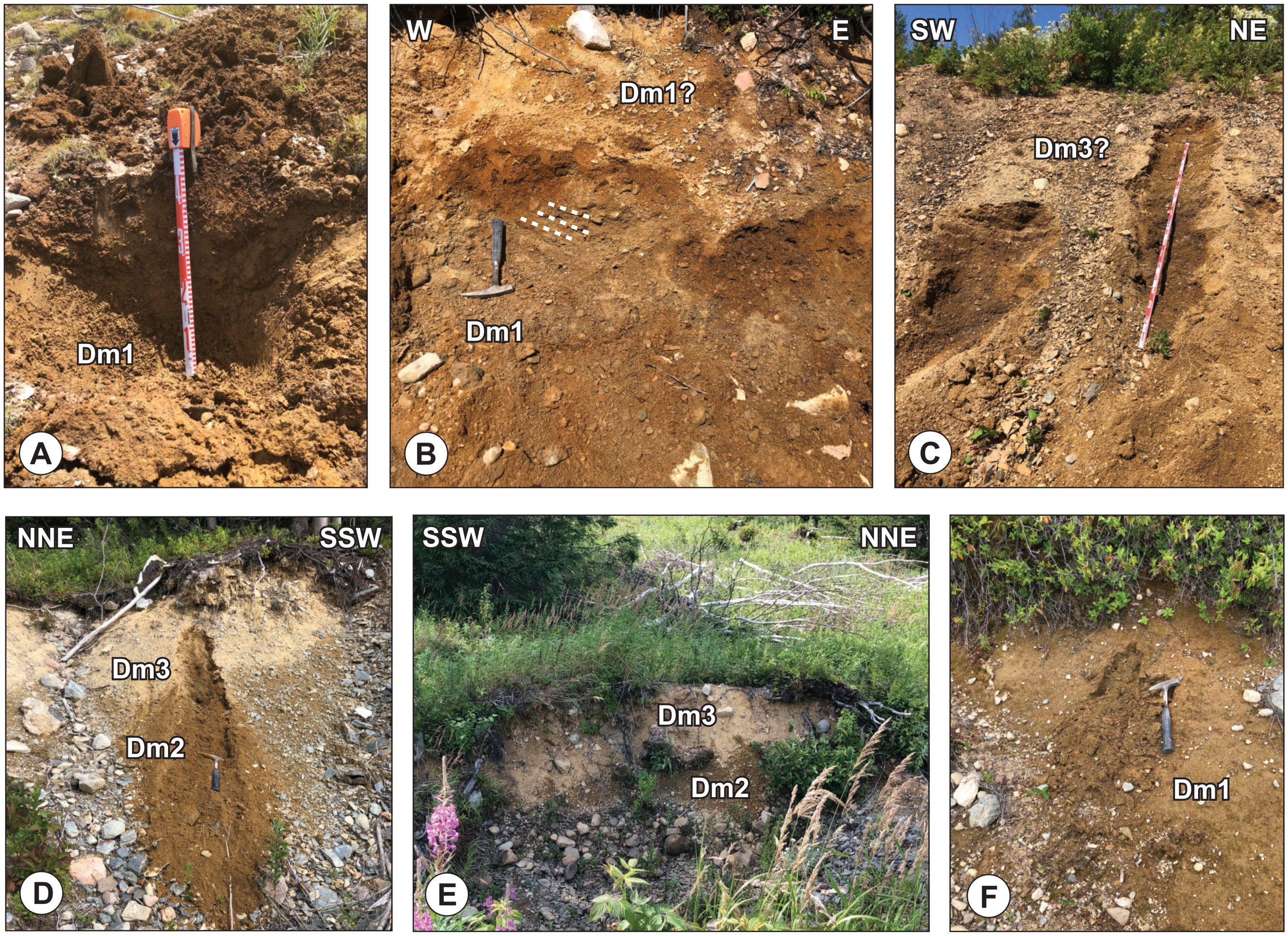

Plate 1. *Photographs showing the variation in till from 200 down to 90 m asl, with UTM coordinates (NAD27 Zone 21). A) Site 69 (632666E, 5398466N) silt and clay-rich, tan-brown till at 183 m asl; B) Site 72 (633476E, 5398177N) compact diamicton with angular eastward-dipping clasts (dotted white lines) overlain by loose oxidized diamicton at 120 m asl; C) Site 73 (634632E, 5397842N) 1.5-m-thick brown sandy diamicton overlain by 0.6 m of yellow-brown silty layer at 90 m asl; D) Site 85 (636669E, 5396977N) massive siltstone clast-rich, sand and silt layer overlying bedrock at 90 m asl; E) Site 86 (636676E, 5396926N) 0.6-m-thick brown diamicton layer capped by a cobble-rich yellow silt and sand layer at 75 m asl; F) Site 82 (637761E, 5396334N) a 0.6-m-thick silty-sand diamicton layer at 170 m asl.*

(Plate 2A), and appear to be truncated by an upper layer of subangular to subrounded, pebble- to cobble-rich, yellow, silty sand diamicton (Dm3). The contact between the bedded units and the upper diamicton on the southwestward side of the section is marked by a fine sand and clay layer that truncates the gently dipping beds, and coarsens upwards. A vertical pipe (dewatering structure) initiating from a 0.6-m-long, 0.15-m-wide lens of pebbly, yellow silty sand diamicton/gravel unit below the bedded sands cuts vertically through these layers and terminates in the upper diamicton (Dm3). On the northeast side of the section, sands are not exposed or are absent, with massive 3-m-thick beds of silty-sand gravel that coarsens upward. The pebble roundness increases toward the bottom of the section, suggesting the lower sedimentary units were transported farther from source, and coarsens upward into units that may have been deposited nearer to source. The abrupt increase in the number and angularity of cobbles and boulders toward the upper part of the unit suggests the upper layer was deposited during proglacial advance. The grey matrix contrasts with the reddish hue of similar sections along the eastern MPIS, possibly due to the sourcing of material from this section to a small sliver of MPIS gabbro (Dickson, 1993, 1996; Sandeman *et al.*, 2017) located 2 km to the west of the section.

Approximately 5.5 km north, at site 29 (103 m asl, *not shown*), 8 m of northeastward-dipping (~5–10°) poorly to well sorted sand and gravel beds with angular and subrounded boulders and cobbles are noted in a large gravel quarry. These are overlain by a massive (1–1.5 m) layer of

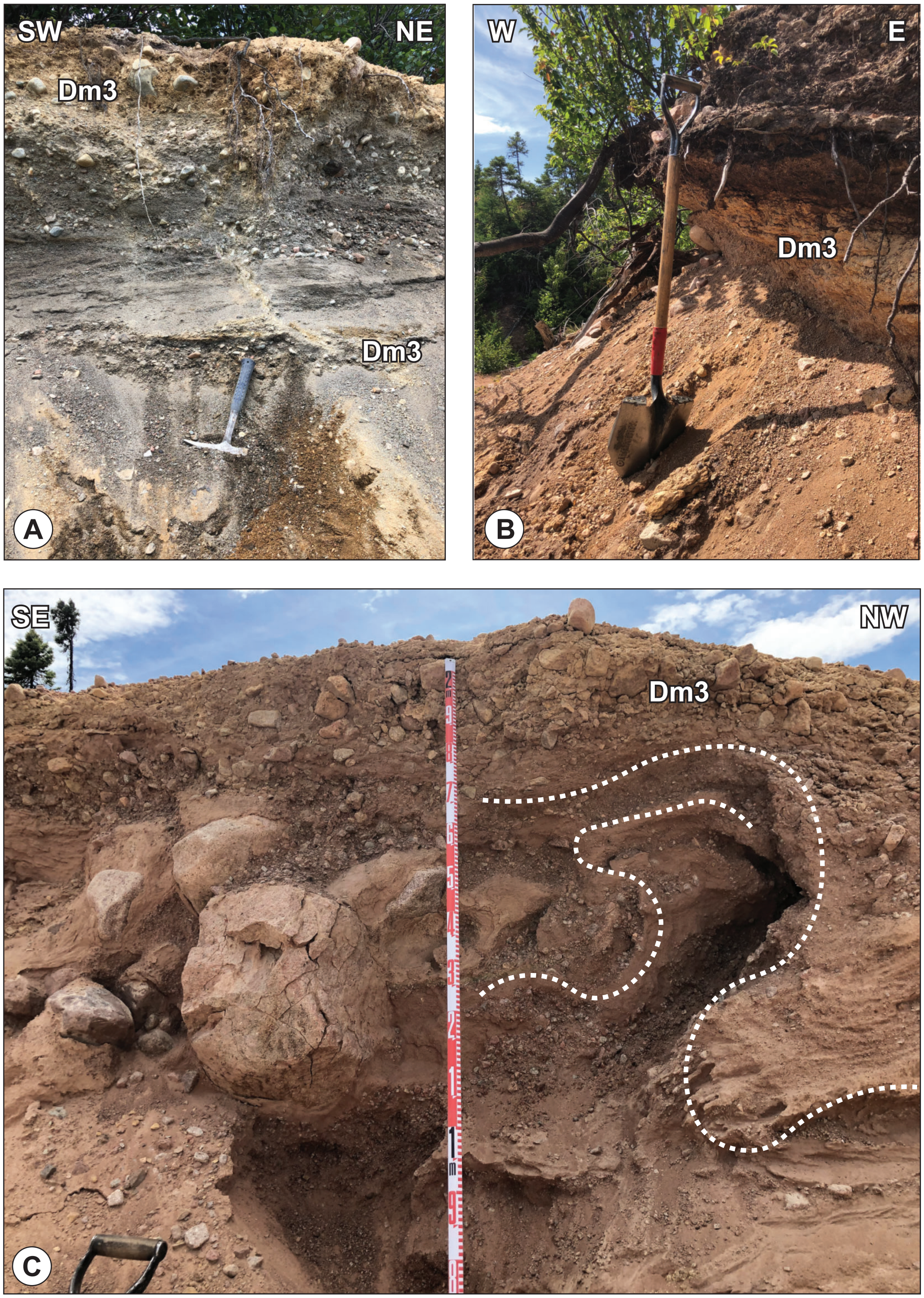

Plate 2. *Glacial deposits along the mouth of the Northwest Gander River on the eastern margin of the MPIS with UTM coordinates (NAD27 Zone 21). A) Site 75 (639126E, 5401292N at 65 m asl) yellow, silty, indurated and poorly sorted layer (Dm3) overlying gently dipping, grey, fine- to coarse-grained sand layers that are cut by a yellow silt and clay-rich wedge; B) Site 58 (646738E, 5418947N at 76 m asl) cemented pebble- to cobble-rich brown-pink diamicton unit that dips north-north eastward, overlying a loose medium- to coarse-grained sand unit; C) Site 58 646698E, 5418986N at 76 m asl ductile fold in boulder-rich to layer that is interspersed with clay and gravel layers, with the axial traces of the fold (outlined in white dashes) dipping gently south-southwestward.*

poorly sorted sands, clays and boulders that dip 45° to the northeast, and appear to truncate the beds in the lower unit in the northeast part of the quarry. This section may have been an ice-proximal delta, formed on the margins of a retreating ice sheet that drained into a proglacial lake or marine environment. The boulders in this quarry contain abundant sericite (muscovite)–pyrite-altered MPIS granite (Sandeman and Spurrell, 2020) similar to that observed at the Yellow Fox Brook showing 6.2 km to the north. At site 58 (76 m asl), in a roadside quarry near Yellow Fox, a loosely consolidated 2-m-thick, medium- to coarse-grained unit of brown-pink sand; gravel and silt is overlain by a 1-m-thick yellow diamicton (Dm3). Unit Dm3 is compacted and cemented (Plate 2B, C) and contains angular to rounded pebbles, cobbles and boulders of sericite (muscovite)–pyrite-altered MPIS granite similar to those observed at the Yellow Fox showing 2.5 km to the northwest (*ibid.*). In the southern part of site 58 (Plate 2B), the loosely consolidated units are truncated by the cemented yellow pebble-and-cobble silt and clay diamicton unit, which dips 30° to the north-northeast. The contact between the two units is sharp but undulating, and is defined by the change in colour, compactness, sand content and clast size. In the northern part of site 58 (Plate 2C), the loosely consolidated unit is 3 m thick, and consists of brown–pink silty sand and local gravels overlain by the yellow diamicton unit. The contact between the two units is marked by a mixed package of rounded-to-subangular boulder-bearing clay with alternating layers of gravel and clay that form a ductile fold; the fold has a gently inclined south–southeast-dipping (10–20°) axial trace and limbs. The overlying diamicton unit may be a matrix-supported subglacial traction till, deposited and folded during the advance of a late ice sheet over subglacial channel deposits or a proglacial outwash that was pushed by an advancing glacier, deforming the underlying section.

AREA 3: SOUTHWEST GANDER LAKE NEAR THE OUTFLOW – SOUTH OF LUKEMAN HEAD

Glacially deformed bedrock and diamicton are noted in sites 78 and 79 north of The Narrows, at site 32 near Gander Lake near the mouth of the Northwest Gander River, and sites 56 and 57 near Lukeman Head (Figure 2). The quarry at site 78 is situated on the up-ice side of a drumlinoid ridge (111 m asl) underlain by strongly cleaved siltstone of the Davidsville Group (Blackwood, 1982) along a woods road that veers north and eastward of The Narrows. A 2–4 m layer of sand and siltstone breccia, locally rotated around non- to moderately imbricated angular cobbles and boulders is overlain by a 1–1.5-m-thick, 4-m-long raft of compressed, brecciated and folded siltstone that has been thrust to the north-northeast (Plate 3A). South-southwestward-dipping thrust traces define the contact between the two layers. The siltstone layers are pervasively deformed and internally re-folded (drag folds) within the thrust panels, and rotated in the upper part of the raft. The lower unit appears to be a flow diamicton or postglacial colluvium that has been slightly tectonized (Type-B glaciotectonite?) and transformed in the upper layers of the unit to a Type-A glaciotectonite. The glaciotectonite raft is compressed in the upper layers and is overlain by 0.5–1.0 m of yellow silt and sheared siltstone-rich diamicton (Dm3) that appears to have been subglacially emplaced (subglacial traction till). Other than well-cleaved siltstone, minor (5%) subrounded to rounded biotite ± hornblende-bearing (MPIS?) granite clasts are noted in the section. In an industry exploration trench at site 79, 1 km to the west, at 60 m asl, a 1–2-m-thick matrix-supported dark-brown, fissile, (sheared?) silty-sand diamicton with small flat-lying siltstone clasts, and isolated larger granite (MPIS?) cobbles in a fine matrix (similar in appearance to a "plum-pudding") (Plate 3B) is overlain by a thick (1 m) yellow, clast-rich (including a chunk of Katian–Sandbian shale), silty-sand and clay diamicton that is variably compressed and imbricated (Plate 3C–Dm3). The contact (?) between these layers is marked by the change in clast content, weathering (oxidation of matrix) and till fabric, and appears to dip 10° to the northeast (Plate 3C). The texturally more mature "plum-pudding' fabric of Dm2 suggests it is a basal till overlain by a coarser grained, texturally immature upper unit that may be a thrusted panel of siltstone-rich diamicton (Type-A glaciotectonite). At site 57, near Lukeman Head, at 70 m asl, folded and brecciated siltstone is interspersed with a brown, silty-sand diamicton (Dm2) comprising a 2-m-thick section in a borrow pit on the up-ice side of a drumlinoid ridge (Figure 3D). Metre-scale folds in a siltstone-rich silt and clay breccia are defined by the rotation of siltstone clast and diamicton layers. An isoclinally folded and thrusted breccia with the fold limbs and thrust plane dipping 45° to the south is positioned on the south side of the section, with an M-fold having subvertical to vertical limbs and axes on the north side of the section (Plate 3D). The displacement distance along the thrust plane is difficult to determine because of the homogeneity of the diamicton and siltstone layers and absence of marker horizons. This folded unit has been interpreted as a Type-A glaciotectonite that has formed *in-situ* due to the homogenous nature of the diamicton and siltstone mix. One kilometre north, at site 56, a flat-lying siltstone glaciotectonite (Type-A) is thrust over a tan-brown till (Dm1) overlying bedrock (*not shown*). To the south, at site 32 toward Gander Lake, at 50 m asl, a 2 m section of imbricated, brecciated and folded siltstone clasts embedded in a silty yellow and grey diamicton (Dm3), is exposed in a borrow pit on the road to the lake (Plate 3E). This section displays a multitude of smaller folds, defined by clasts and diamicton in various orientations, with one large north-vergent overfold, marked by a thin (5 cm) layer of Dm3 that might have been derived from the upper surface of the fold. The grey hue of the diamicton differs from

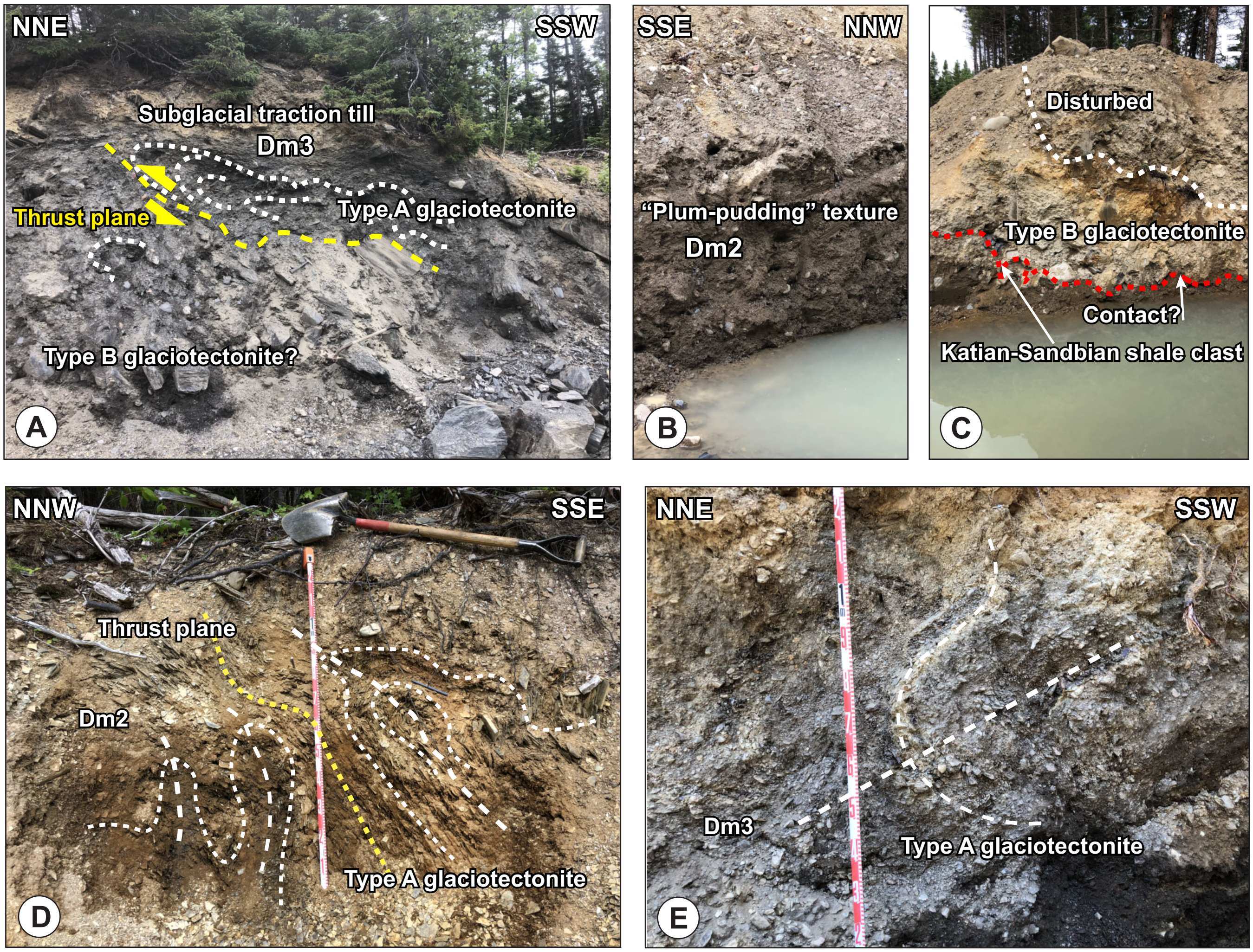

Plate 3. *Glacial deposits south of Gander Lake and along the outflow of the lake to Gander River with UTM coordinates (NAD27 Zone 21). A) Site 78 (645268E, 5404127N) at 111 m asl; a thrusted and folded raft (dotted white lines) of Davidsville Group siltstone and glacial diamicton dips south-southwestward along the thrust trace (dotted yellow line); B) Site 79 (644284E, 5404242N) at 60 m asl flat-lying brecciated siltstone clasts and diamicton (Dm2) with granite clasts (i.e., "plum-pudding" texture derived from the MPIS in a diamicton 1 km southeast of Plate A; C) Site 79, north side: matrix-supported yellow diamicton with chaotic foliation (Dm3) in contact with the "plum-pudding" diamicton in B; D) Site 57 (654051E, 5422255N) at 70 m asl folded and thrusted Davidsville Group siltstone and silt rafts. Rafts are dipping to the south; E) Site 32 (648430E, 5416413N) at 50 m asl folded yellow diamicton layer in siltstone clast breccia and silt diamicton unit.*

other sites overlying and derived from this bedrock unit and may represent contributions from earlier deposited marine or lacustrine sediments or entrainment of material from The Ten Mile Lake Formation, directly up-ice of this site (Figure 4). The fold axis plunges to the northeast (~45°). This penetratively deformed unit is also interpreted as a Type-A glaciotectonite.

AREA 4: BIG POND–TEN MILE LAKE REGION

The glacial sediments in the Big Pond–Ten Mile Lake region are exposed in borrow pits along a road parallel to the Salmon River Resource Road north of Long Pond and east of Ten Mile Lake (Figure 2). The brown diamicton (Dm2) is exposed in the lower 2 m of some of the pits, and is sandier than those described in the south. The yellow-grey diamicton (Dm3) is present only in the first and second borrow pits examined (sites 111 and 121), nearest the fork in the road north of Big Pond.

The southernmost borrow pit (site 111), at 60 m asl, has a 3-m tan-brown, loose diamicton with low to moderate clast content (10%) and a silty-sand matrix (Dm2) overlain by a yellow, siltstone clast-rich, compact, horizontally to slightly southwestward dipping, aligned angular cobble and boulder diamicton unit with ~2–5 % granite clasts (Dm3).

The contact between the units is undulating and dips gently (10–20°) northwest (Plate 4A). Both of these units have abundant fine material and are interpreted to be subglacial tills. The clast content of the lower brown till (Dm2) appears to be more varied than sites south of the TCH, with Ten Mile Lake Formation sandstones and non-MPIS gabbro clasts noted in the samples. At site 121, northwest of site 111, 2 m of loose, brown, silty sand with moderate pebble to cobble clasts (Dm2) is overlain by compact, yellow, pebble to boulder clast-rich till (Dm3) at the same elevation (Plate 4B). The contact between the upper unit, a possible subglacial melt-out till and the lower unit, an eroded basal till, dips 30° to the south.

Jointed and brecciated rock with minor yellow-silty sand and pebble diamicton (Dm3) layers are exposed at site 115 in a quarry 10 km north at 65 m asl, on a road northeast of Ten Mile Lake, in a rock-cored drumlin that includes purple (haematitized?) siltstone, gabbro and lamprophyre dykes (Plate 4C). Left of the lamprophyre dyke (Plate 4C, outlined in red), siltstone clasts have been oriented into metre-scale, fan-shaped, south-southeast-dipping thrust-ramps that

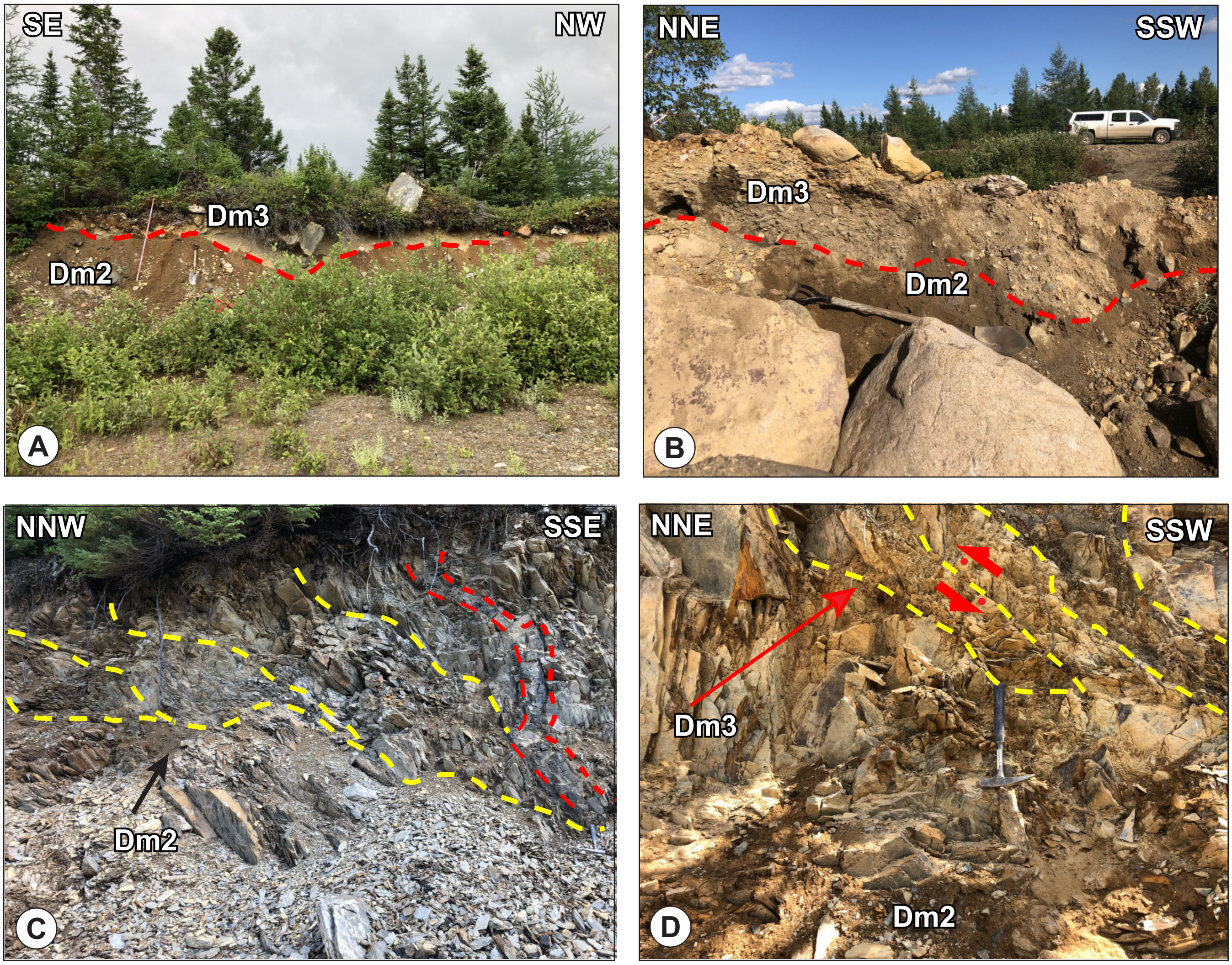

Plate 4. *Deformed diamictons and bedrock north of Glenwood, and near Ten Mile Lake with UTM coordinates (NAD27 Zone 21). A) Site 111 (663530E, 5447994N) at 72 m asl; cemented grey-yellow silty diamicton with angular to subrounded siltstone clasts overlying 2 m of loose, silty-sand diamicton; B) Site 121 (663408E, 5448343N) at 61 m asl; cemented yellow silty diamicton with angular siltstone and granite cobbles and boulders overlying 2 m of brown, silty sand with moderate subangular to subrounded clasts; C) Site 115 (667447E, 5456191N) at 63 m asl; north-northwest-thrusted siltstone, sandstone and diamicton layers (thrust planes outlined by yellow dotted lines) that have been intruded by a lamprophyre dyke (dashed outline in red with hammer at the bottom for scale); D) Site 115: Closeup layers of thrusted siltstone (thrust traces outlined by yellow dotted lines) on cm-wide silt and clay diamicton layers (red arrow). The thrust panels are oblique to steeply eastward-dipping bedrock in a rock drumlin east of Ten Mile Lake. The thrust panels are offset by only a few cm (*see *small red arrows).*

appear to have been emplaced along a tan, silty-sand diamicton. These ramps dip steeply (subvertical) to the right of the lamprophyre dyke and flatten from subvertical to horizontal, and are compressed into a Type-A glaciotectonite toward the diamicton/siltstone interface and toward a gabbro dyke/sill (*not shown*) immediately to the left of the photo. The lamprophyre dyke is offset to the north by .15 cm, by a joint in the upper 1 m of the outcrop. Highly fractured and jointed, sigmoidal-shaped bedrock rafts of centimetre-scale-bedded Ten Mile Lake Formation are thrust northward on thin lenses of pebbly diamicton (Dm3) that dip 45° south-southwestward at their steepest point (Plate 4D). Bedding and cleavage in bedrock dips moderately to steeply to the east-southeast.

DISCUSSION

Preliminary field observations suggest that outcrop-scale deformation features in the upper diamicton unit (Dm3) were formed by thin northward-flowing ice during deglaciation. This late ice flow appears to have entrained proglacial sediments and bedrock forming a "proto-till" (*i.e.*, glaciotectonite) that is further eroded into a subglacial traction till down-ice. The following discussion presents some comparison and preliminary conclusions of the results of the study in the context of previous and ongoing work elsewhere.

DIAMICTON UNITS AND PRELIMINARY GENETIC INTERPRETATIONS

Texturally mature diamicton (Dm1) was noted at higher elevations (~120 m asl) on either side of the Northwest Gander River (*e.g.*, sites 69 and 82), and underlying the sandy, channel deposits along the eastern margin of the MPIS. The similarities between the tills at sites 69 and 82 suggest they are from the same unit (Dm1) and were emplaced by an earlier ice-flow event than the one which formed Dm3, as it underlies the channel deposits east of Mount Peyton. Dm1 may have been deposited by eastward flow, but it appears to be texturally different than Dm2 and the 3 sandy diamicton units east of Mount Peyton described in Batterson and Vatcher (1991). Preliminary interpretations of Dm1 are that it was emplaced earlier and eroded by ice flow that created Dm2 and Dm3, but investigations of the stratigraphic position of Dm1 eastward of Mount Peyton will assist in understanding of its lateral extent and stratigraphic emplacement.

The most consistent unit through the study area is Dm3, the upper diamicton, which commonly exhibits outcrop-scale fabrics oriented in the direction of the last ice-flow orientations (*e.g.*, north-northeastward to north-northwestward flow 2 in Figure 4). Tills of varying textural maturity are exhibited in the study (Figure 5A–E). The textural maturity of Dm3 generally progresses from south to north in the down-ice direction from: 5A) a loosely consolidated, ice-marginal diamicton (sites 85 and 86, sites from Figure 2); to 5B) Type-B glaciotectonite (site 78, lower unit, sites from Figure 2); to 5C) Type-A glaciotectonite (sites 78 and 79 (upper unit), 32, 57 and 56, sites from Figure 2); to 5D) a sheared subglacial traction till (site 111, sites from Figure 2). The "plum-pudding" diamicton (5E) of site 79 (of Figure 2) may be a texturally mature facies of Dm3 in the aforementioned sites. The homogeneous, mixed texture of Dm2 at site 79 indicates the till was either formed under a thicker ice and or more erosive than that of the upper diamicton, and thus may represent an earlier flow phase (Ice Flow 1?), or that it is a subglacially developed till unconformably overlain by a glaciotectonite, derived from the same flow event (Ice Flow 2). The consistent stratigraphic position of Dm3 overlying Dm2, and the compositional similarities between the Dm2 and Dm3 at all the sites, suggest that Dm3 is formed from material re-entrained from Dm2. Examination of the coarse fraction using indicator mineral and pebble counts, and the matrix geochemistry would assist in determining if Dm3 and Dm2 are derived from the same source.

At site 121, the brown basal till (Dm2) and overlying yellow unit (Dm3) form 50–200-m-wide, irregularly shaped, sandy, hummocky ridges and both units appear to be less silt-and-clay rich, perhaps due to erosion from subglacial meltwater during final deglaciation. At 60 m asl, this is the northernmost extent of a metre-scale-thick Dm3 unit, although the unit may be preserved west and east of the corridor. The lower unit (Dm2) may have been basally emplaced and eroded by meltwater, and the upper unit deposited from a stagnant patch of ice. Both of these units could be genetically similar, and could be distinguished through coarse and fine fraction analysis.

The genesis of upper matrix-supported diamicton (Dm3), overlying proglacial outwash and channel deposits on the east side of the MPIS is not certain. At site 75, clast roundness suggests a distal, or subglacial channel origin for these units. At sites 29 and 58, the presence of angular boulders with striated surfaces in Dm3 indicate proximity to material that has been abraded in a subglacial environment. The upper layers at sites 29 and 58 may have been deposited by an advancing glacier over a coarsely stratified ice-marginal delta at site 29, whereas site 58 may have been overridden by thin ice to form a subglacial traction veneer overlying subglacial channel deposits at site 58, or deformed in-situ by compression from the advancing ice sheet.

GLACIOTECTONIC DEFORMATION

Subglacial brecciation, thrusting and folding in siltstone diamicton units south and north of Gander Lake, whereas

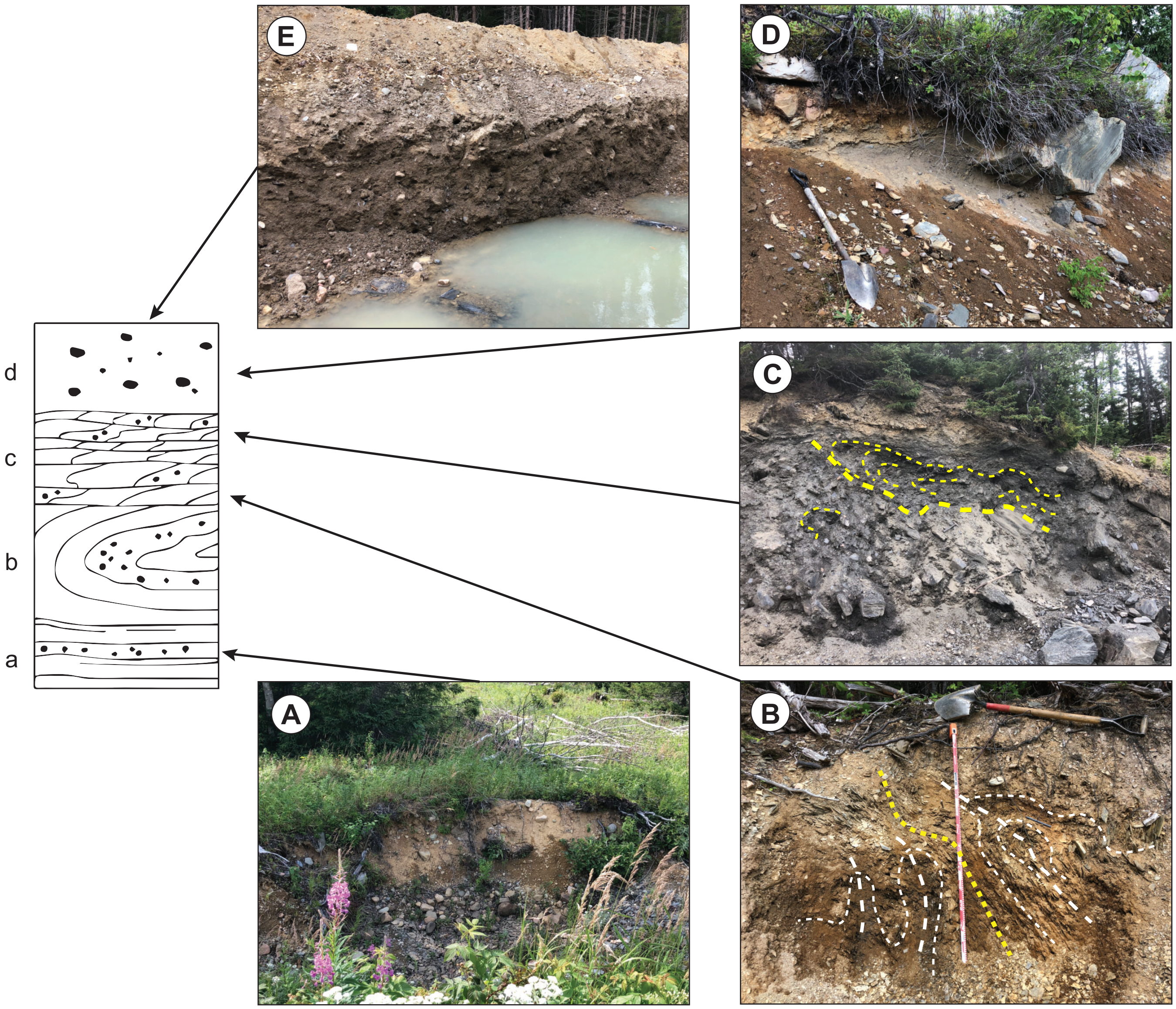

Figure 5. *Till textural maturity in sites from south to north;* see *Figure 2 sample site. A) Loosely consolidated yellow diamicton (Dm3) overlying a more compact brown diamicton (Dm2). The upper till does not appear to be compressed or oriented in any direction and represents relatively undeformed material (a in stratigraphic unit of Benn and Evans, 1996); B) Glacially brecciated, folded and thrusted and penetratively deformed siltstone and Dm2 diamicton (Type-A glaciotectonite, c on diagram to left); C) Moderately deformed proglacial Dm3 colluvium (Type-B glaciotectonite, b in the section on the left) and compressed, thrust and folded brecciated siltstone with penetrative deformation (Type-A glaciotectonite, c in section on the left); D) Compressed, subglacial traction till (Dm3) with relatively flat-lying fabric overlying basal till (Dm2) (both of these units may correspond to d in the section on the left); E) "Plum-pudding" textured fissile basal till (Dm2) corresponding to d in the section on the left. The photos labelled A, C and D are thought to have been deposited by the same flow event, with till texture evolving though time and down-ice distance.*

the deformation processes forming the ductile fold and compressed sediments along the eastern margin of the MPIS are uncertain, but tentatively attributed to subglacial shear or compression at the ice margin. The orientation of the glacially deformed features is oblique to the orientation of the primary bedrock foliation in many of the sections (Blackwood, 1980; Currie and Williams, 1995; *this study*) and is aligned with known north-northeastward and north-northwestward ice-flow directions (St. Croix and Taylor, 1991; Batterson and Vatcher, 1991; Scott, 1994). In addition, many of the units and their characteristics are comparable to glaciotectonic features noted in similar studies in Europe (*e.g.*, Phillips *et al.*, 2008; Davies *et al.*, 2009; Pedersen, 2014; Flindt *et al.*, 2018).

Dewatering structures and folds along the eastern margin of the MPIS are similar to those noted in Whitburn Bay in England (Davies *et al.*, 2009). Pipe structures in till in Whitburn Bay (Plate 5A) are the result of fluid being expelled from the lower, grey, gravel-rich diamicton into an upper, silty, gravel-poor diamicton by the weight of an overriding ice sheet. The pipes in Plate 5A are vertically emplaced with the increasing pressure of the ice sheet, and the tops of the pipes are re-oriented to the southeast by ice flow (*ibid.*). The top of the pipe structure along the eastern margin of the MPIS in site 75 is offset to the northeast in the lower part of the upper diamicton (Dm3), which is in keeping with the last ice-flow direction. However, although the upper diamicton is indurated, the clast roundness and the lack of shear structures at the base of the upper unit suggest that the upper unit is not a subglacial traction till. Thus the pipe structure may have been formed as moderately proximal outwash material deposited on top of a more distally derived sand and fine gravel unit, and the northeastward offset of the top of the pipe may have occurred from lateral movement of this outwash unit, perhaps into a lacustrine or marine outlet to the north.

The north-vergent overfold in brecciated siltstone, silt and clay layers, observed in site 32 close to the southwestern corner of Gander Lake (Plate 6A displays textural similarities to the brecciated bedrock and diamicton mixture forming a glaciotectonite overlying the Fur Formation in Mors, Denmark (Pederson, 2014; Plate 6B), and also those noted by Heimstra *et al.* (2007) in Ireland and Antarctica. The brecciated layer at Mors forms a glaciotectonite in a "mixing" zone between the lower unit, (that was entrained and deformed by ice), and the basal till (that was formed from the mixed layer). At site 32, the yellow diamicton units in the glaciotectonite may have been injected into fractures during the advance of the ice sheet, and are interpreted to have been entrained into the fold in response to compression from the south-southwest. The siltstone clasts have been entrained subglacially, and rotated north-northeastward in the direction of late ice flow (*e.g.*, Plate 6A). Smaller (parasitic?) folds are observed near the larger fold, and are tentatively interpreted as forming from north-northeastward ice flow. At 50 m asl, this section at site 32 falls below the inferred marine limit of 64 m (Batterson and Vatcher, 1991), and may have been formed by postglacial processes (*e.g.*, slumping), although the degree of brecciation, compaction, shearing and folding indicates this section was affected by subglacial erosion and deformation at some earlier point. Plate 6C displays ductile folds preserved in coarse gravels at Fiskarheden, central Sweden (Plate 6C; Flindt *et al.*, 2018).

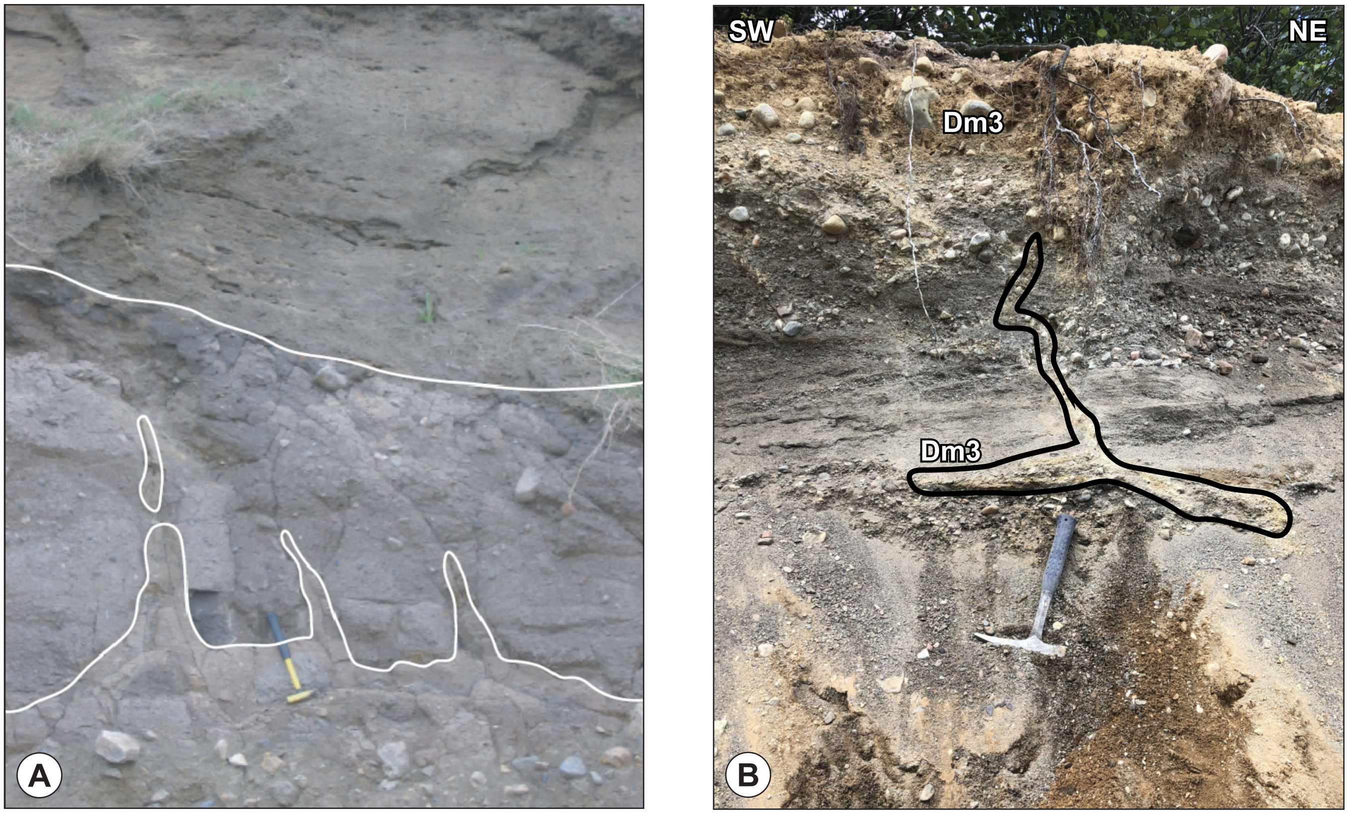

Plate 5. *A) Pipe structures in the lower diamicton layers from a glacial section in Whitburn Bay, Durham County, England (Davies* et al.*, 2009); B) A similar pipe-like structure in a section along the eastern margin of the MPIS (site 75).*

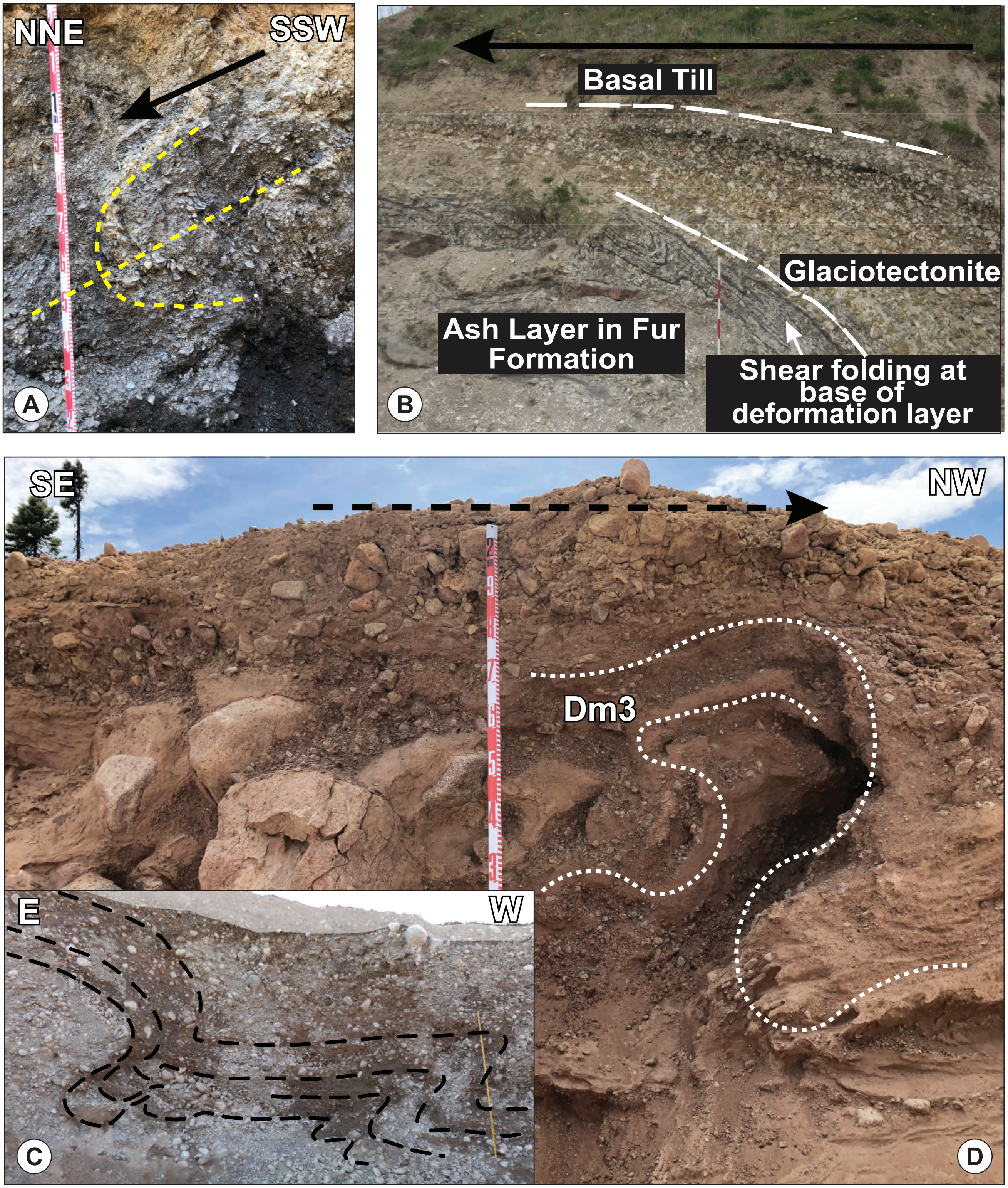

Plate 6. Examples form this study (A and D) (Pederson, 2014; Flindt *et al.*, 2018) and published examples (B and C) of glaciotectonites. *A) Brecciated glaciotectonite near Gander Lake at site 32, with similar texture as a glaciotectonite; B) In the Fur Formation in Mors, Denmark, with the black arrow representing ice-flow direction; C) Ductile folds in coarse-grained proglacial outwash sediments in Fiskarheden, central Sweden, formed by pushing of proglacial sediments by an advancing glacier from the west-northwest (Flindt* et al.*, 2018); D) Ductile Z-fold from this study in a mixed sand and diamicton/outwash? layer that is noted at site 58 east of the MPIS.*

These folds were formed by eastward compression of proglacial sediments by an ice flow from the west–northwest (*ibid.*). Similarly, at site 58, the ductile, Z-fold formed in gravel and silt lenses in the upper diamicton unit is interpreted to have resulted from compression and basal shear by a north–northwestward-flowing thin ice sheet (Plate 6D), but the fold may also be the result of ice-marginal pushing of outwash sediments into a soft substrate. A closer examination of the till macrofabrics on the basal portion of the ubiquitous upper, yellow indurated unit is needed to understand its genesis and relationship to the lower gravel and sand units along the eastern margin of sites along the MPIS, and to determine if the deformation features observed were the result of subglacial traction or ice-marginal compression.

The unusual compressed siltstone rafts overlying an ice-marginal diamicton/colluvium(?) south of Gander Lake (site 78; Plate 7A) are interpreted to have formed in an environment similar to that at Holm Lands Isbræ, northeastern Greenland (Pedersen, 2014; Plate 7B), where proglacial deposits are overridden by an ice sheet and younger, subglacially entrained material is thrust over the proglacial deposits. The lower unit in Plate 7A likely represents a proglacial, ice-marginal diamicton that was subsequently overridden by an advancing ice sheet, and glaciotectonized and mixed. This formed a silt-rich, poorly developed, siltstone matrix (Dm3) subglacial traction till (*e.g.*, Evans *et al.*, 2006). A similar sequence is documented in parts of Europe (*e.g.*, Benn and Evans, 1996; Evans *et al.*, 2006; Phillips *et al.*, 2008; Benediktsson *et al.*, 2010; Pedersen, 2014). In these settings, an advancing ice sheet mixes preglacial sediments with entrained material, deforms it, crushes it, and drags it at the base, where it is sheared.

The sequence at site 78 preserves a crucial step in the process of till generation (Evans *et al.*, 2006; Heimstra *et al.*, 2007), whereby a mixture of locally rotated and brecciated, rafted bedrock and diamicton (Type-B glaciotectonite) has been compressed and sheared into a Type-A glaciotectonite, then dragged and thrust northward in the direction of the ice flow. Friction from the base of the ice sheet may have produced the subglacial traction till observed at the top of the sequence, with eventual decoupling of the ice sheet and deposition of a thin layer of basal till on top of the glaciotec-

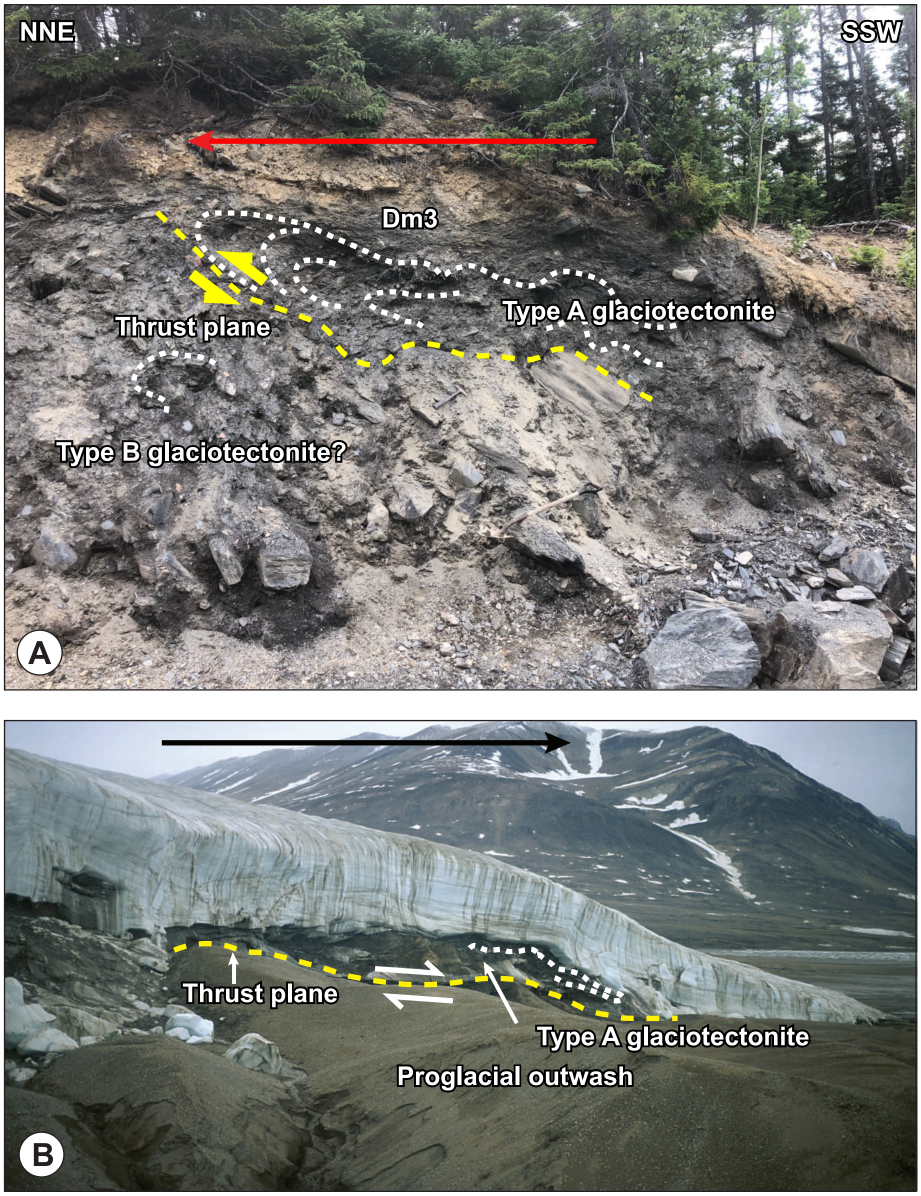

Plate 7. *A) Glaciotectonite unit (site 78) on the east side of the Northwest Gander River indicating a sheared layer on top of chaotically oriented, local angular siltstone clast-rich ice-contact diamicton. This section is similar to that of (B) glaciotectonite that has been thrusted over proglacial sediments in Holm Lands Isbrae, northeast Greenland (Pedersen, 2014). The glaciotectonite is considered a transitional unit between the sheared base of the glacier and the upper basal till layer (*e.g., *Pedersen 2011, 2014;* etc.*). Solid red and black arrows represent ice-flow direction.*

tonite. Site 78 appears to capture the transformation of a non-penetrative (outcrop-scale) fabric at the base of the section into a subglacial traction till (Plate 3A; Plate 7A).

The contrast between the homogenized "plum-pudding" appearance of Dm2 and the chaotically foliated, clast-rich overlying diamicton (Dm3; Plate 3B, C) strongly implies that the upper till must either be deposited from a separate ice-flow event, or that it may be the remnants of an englacial raft that was placed on top of basal till during deglaciation. Both Dm2 and Dm3 appear to be compositionally similar in this section, and contain clasts of dark-black Katian–Sandbian shale (Plate 3B, C), whose source is probably nearby, given the weakness and easily eroded surfaces of the shale in bedrock outcrop. Unfortunately, the limited exposure of, and the possibility of non-glacial disturbance and deposition, prevents a robust conclusion on the genesis of the units. In addition, a detailed analysis of each of the diamictons and the subglacial traction till in sites 78 and 79 (*e.g.*, macrofabric analysis, geochemistry and grain size and mineral identification studies) is needed to determine if they are derived from the same material, and their relationship to each other. Future efforts to locate similar units along the ridge and up- and down-ice of these sections might help in unravelling where these units occur with respect to the position of regional marine limits and proposed ice margins.

The outcrop of folded and thrusted glaciotectonic antiforms in the Davidsville Group siltstones at site 57 (Plate 3D) may represent a transitional Type-B to Type-A tectonite, where layers of diamicton and siltstone/sandstone have been folded and compressed from local bedrock and retain original glacial deformation features with some secondary deformation (kinking).

The homogeneity of the diamicton and siltstone units, as well as the lack of foreign clasts in the glacially deformed siltstone and diamicton layer, suggest that these features were formed by *in-situ* glaciotectonism of the siltstone bedrock unit. The scarcity of massive diamicton at these sites indicates a lower abrasion rate, or removal of sediment prior to deformation. The overriding pore-water pressure between the bedrock surface and glacier may have been lower, and water from subglacial drainage through pre-glacially cleaved and glacially deformed siltstone would have frozen to the bedrock. This would cause brittle deformation of the subglacial substrate (*e.g.*, Phillips, 2018), and may have precipitated the formation of the thrust plane at this site. The strain from the approaching ice was accommodated by the siltstone clasts as they were deformed, rotated, folded and thrust against more competent sandstone units located 10 m northwest, that acted as an obstruction to ice. At site 56, approximately 1 km down-ice from site 57, a horizontally imbricated and mixed, siltstone clast-rich diamicton (glaciotectonite, likely Type-A) is thrust over a silt- and clay-rich diamicton (Dm1), resulting from comminution of larger clasts. This site probably represents a more texturally mature section of the glaciotectonite at site 57.

The glaciotectonic deformation immediately east of Ten Mile Lake at site 115 (Plate 4C, D) is thought to have augmented preglacial to glacial weathering and jointing by injecting tan to yellow, silty-sand diamicton along cleavage and fracture planes into siltstone-sandstone of the Ten Mile Lake Formation. This process further compressed and rotated the bedrock along thrust ramps, dipping variably from horizontal to subvertical (Plate 4A) in the up-ice direction of the upper 2.5 m of the outcrop. More competent units (*e.g.*, the lamprophyric dyke, Plate 4C-outlined in red) were fractured, jointed and offset in response to northward compression. The competency contrast between the lamprophyric dyke and the surrounding siltstone, and between the siltstone and a mafic dyke/sill on the north side of the outcrop, may have influenced the geometry of the thrusted units (*e.g.*, their dip and dip direction). In addition, the variable orientation of the dipping layers suggests that the detachment surface may have been shallowly dipping. The detachment surface is presumed to be on the down-ice side of the exposure with successive thrust panels dipping steeply in the up-ice direction. Structural measurements of the variably dipping fabric in the upper few metres of this outcrop, comparison to non-glaciotectonized bedrock units in the area, and careful mapping of the location of diamicton layers by uncovering the collvium throughout this section would assist in clarifying the relationship between preglacial and postglacial deformation.

The consistent south-southwest to south southeastward dip of the fold axial traces, limbs, siltstone clasts and thrust planes within the glaciotectonized units suggests that they were emplaced by a north-northeast to north-northwestward-flowing ice sheet. The yellow oxidized and cemented diamicton (Dm3) that lies on top of the channel deposits, east of the MPIS must have been emplaced after the eastward flow and channel formation off the MPIS, and may have been deposited in an ice-contact (sites 29 and 58) to ice-marginal (site 75) environment, with sufficient force (shear or compression or both) to fold the soft sediment layers in site 58 and to create the pipe structure in site 75. The thinness, textural immaturity, and local clast provenance of Dm3 suggest that it was formed underlying and proximal to a thin, local ice stream (*e.g.*, Gander Lake Ice Stream, Blundon *et al.*, 2010). The trace of the Gander Lake Ice Stream, based on SRTM imagery (*ibid.*), falls north of Gander Lake, but the preliminary results suggest the ice-stream may have propagated farther south, toward the outflow of Gander Lake into the northwest Gander River. Brittle deformation, and transport of thrusted glaciotectonites indicate that bedrock debris must have been entrained (frozen) and deformed subglacially, emplacing units in their current position, however, the relationship of the glaciotectonized units with the underlying diamicton and ice-marginal sediments requires more detailed study. Continued investigations should assist in placing the glaciotectonic units in context with regional ice flow and ice retreat in the region.

IMPLICATIONS FOR EXPLORATION

Most of the diamictons explored in this study are texturally immature – they have low percentages of fines – and they may be unimodal (MPIS derived cobbles and pebbles east of the MPIS), or bimodal (siltstone with MPIS cobbles, boulders and pebbles south of Gander Lake), or grade into texturally mature tills with polymodal clasts (*e.g.*, north of Big Pond). The unimodal diamictons overlie large sand (channel) deposits, derived from the till veneer overlying the eastern slope of the MPIS (Batterson, 1999). The sand deposits have low fines (Ricketts, 2006), and are deposited farther from the source than the basal till they are derived from. Although the diamicton overlying the sands may have fines, the layer appears to be oxidized; thus geochemical sampling of the fines may not produce the best results for mineral exploration programs. The basal till that underlies some of the sand units in this region (Dm1) would be a better geochemical sampling medium due to the higher content of fines and homogeneity of material (Brushett, 2014; McClenaghan and Paulen, 2018). However, this unit is not always present or easy to uncover. In the absence of basal till, the coarse fraction (*i.e.*, angular and striated cobbles and boulders) of other diamictons should be examined, particularly in the upper layers of material sourced from the eastern side of the MPIS, as it contains altered and mineralized debris, such as the sericite–pyrite-altered, Yellow Fox-type (Sandeman and Spurrell, 2020) granite boulders and cobbles located in the two aggregate quarries (sites 29 and 58) along the eastern margin of the MPIS (*e.g.*, Plate 2C; Figure 6 inset). The aggregate pits are not down-ice from the Yellow Fox showing, based on the northeast, east and north flow directions that have been recorded in the striation record (Batterson and Vatcher, 1991). Thus, the most likely source for the boulders and cobbles would be within a 2–3 km radius, either south, southwest or west of the quarries; either up drainage in the paleo channels, or up-ice of the final ice flow (south–southwest; Figure 6). Consideration of both glacial and fluvial flow is necessary in evaluating sediments in this region as there are two distinct paleo-channels, south and west of the quarries that may have transported the boulders from the west, where they could have been re-entrained and dispersed northward, or transported from the west by eastward ice flow. Given the angularity and abundance of the Yellow Fox-type altered boulders, and their tendency to disintegrate, the source may be closer to the locations where the boulders were found.

Diamictons that occur in the sections where glaciotectonism is noted tend to be texturally immature, with high clast content and non-homogenous matrices. The diamictons have not been comminuted down to the fine fraction that is ideal for till-geochemical matrix sampling (McClenaghan and Paulen, 2018). In these sections, and many places in the region, heavy mineral fraction sampling (15 kg buckets – *see* McClenaghan *et al.*, 2020) may be more successful than till geochemistry for identifying contributions from mineralization. In addition to characterizing the coarse fraction of samples, gold grain counts in heavy mineral samples can assist in determining transport distances, and indicator mineral picking can identify grains that may be characteristic of individual mineral occurrences through this region (*e.g.*, gold, stibnite, arsenopyrite, goethite, base metals, pyrite, and rutile; *see* Evans, 1996; Sandeman *et al.*, 2017, 2018; Sandeman and Spurrell, 2020). South and west of Gander Lake, the textural heterogeneity and predominant local bedrock clast content in the upper diamicton in glaciotectonized sections suggest that they were derived from nearby outcrop. Coarse fraction analysis will assist in characterizing the near-source contributions to diamictons, and will be compared to geochemical analysis in the same samples to understand the differences between the matrix and coarse fractions of samples. In addition, the trace-element associations between Sb, Au, As, Pb, W, Mo, Hg, Bi and Te (Sandeman *et al.*, 2017, 2018) suggest that application of suitable analytical methods (*e.g.*, Hydride Generation AAS coupled with ICP-OES/MS finish (Hall and Pelchat, 1997; Fitzpatrick *et al.*, 2009) should be assessed to maximize the response of As, Bi, Sb, Se and Te in tills.

North of Big Pond, some diamicton units (*e.g.*, site 112) tend to be sandier and may have been eroded by subglacial water. In these areas, and other areas where diamictons have low fines, heavy mineral sampling may assist in detecting glacially dispersed mineral content.

CONCLUSIONS AND FUTURE WORK

Texturally immature, glaciotectonized diamictons and subglacial traction till are located at elevations of ≤120 m asl between the Beaver Brook Antimony Mine and Ten Mile Lake, and overlie ice-marginal channel deposits and diamictons. Texturally mature till (preserved at elevations greater than 120 m, and underlying the channel deposits east of the MPIS), was most likely deposited by an earlier, less confined ice flow, and eroded (and entrained?) by later ice flow at lower elevations. However, future studies will assist in

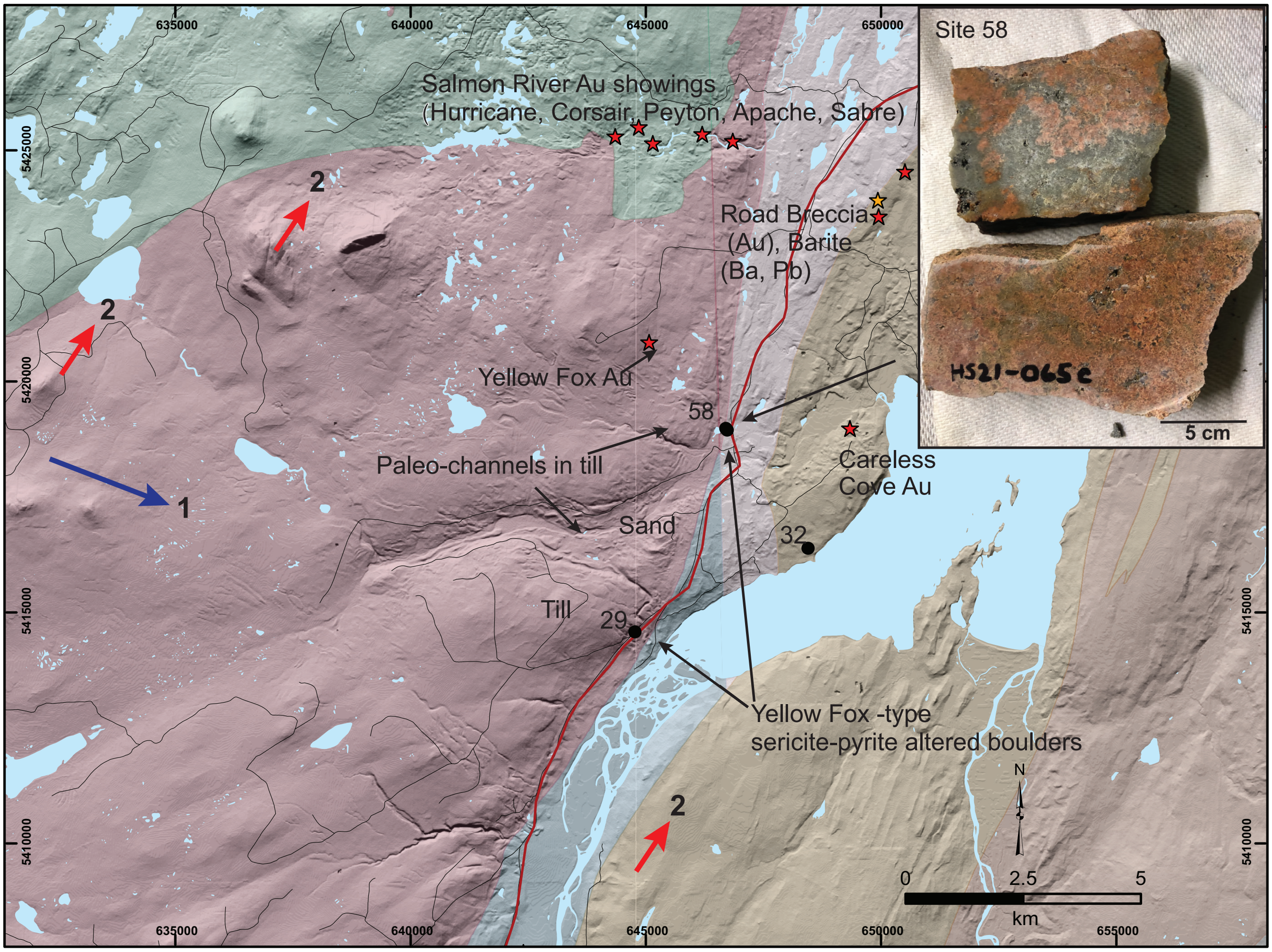

Figure 6. *Map displaying the quarry where the Yellow Fox-type mineralization was found in boulders (inset) at site 58, southeast of the Yellow Fox deposit. Inset - Altered Yellow Fox-type boulders were found at site 29 as well as in site 58. Blue arrows = ice-flow 1, red arrows = ice-flow 2.*

constraining the extent and emplacement of the texturally mature tills in comparison to the texturally immature tills.

The southward dip of the Type A glaciotectonite rafts and fold structures west and south of Gander Lake, and in the northernmost section on the east side of Ten Mile Lake, indicate that they were thrust to the north by a north-northwestward and north-northeastward-moving sheet of ice. However, the sections south of Gander Lake need to be further examined in order to establish the relationship between the ice-rafted glaciotectonite and the lower, massive till unit (Dm2). Folds and dewatering structures in the older ice-marginal (channel?) sediments on the eastern margin of the MPIS are inferred to have formed by north-northeastward to north-northwestward-flowing ice, although they may also have been formed by earlier eastward-flowing ice, or by postglacial processes. Further studies are needed to establish the width of the northward-flowing ice sheet that formed the glaciotectonites. Such investigations, including pebble counts, fabric analysis, mineral counts and fine-fraction geochemistry are needed to clarify the relationship of the orientation of glaciotectonic structures to ice flow, and to identify the possibility of earlier or later structures that may not have been observed in this reconnaissance mapping study.

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