

Geomorphology and till architecture of terrestrial palaeo-ice streams of the southwest Laurentide Ice Sheet: a borehole stratigraphic approach

Sophie L. Norris^{1,2}, David J.A. Evans¹ & Colm Ó Cofaigh¹

- Department of Geography, Durham University, South Road, Durham DH1 3LE, UK
- Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2H4, Canada

Corresponding author: Sophie Norris slnorris@ualberta.ca

Abstract

A multidimensional study, utilising geomorphological mapping and the analysis of regional borehole stratigraphy, is employed to elucidate the regional till architecture of terrestrial palaeo-ice streams relating to the Late Wisconsinan southwest Laurentide Ice Sheet. Detailed mapping over a 57,400 km² area of southwestern Saskatchewan confirms previous reconstructions of a former southerly flowing ice stream, demarcated by a 800 km long corridor of megaflutes and mega-scale glacial lineations (Ice Stream 1) and cross cut by three, formerly southeast flowing ice streams (Ice Streams 2A, B and C). Analysis of the lithologic and geophysical characteristics of 197 borehole samples within these corridors reveals 17 stratigraphic units comprising multiple tills and associated stratified sediments overlying preglacial deposits, the till thicknesses varying with both topography and distance down corridor. Reconciling this regional till architecture with the surficial geomorphology reveals that surficial units are spatially consistent with a dynamic switch in flow direction, recorded by the cross cutting corridors of Ice Streams 1, 2A, B and C. The general thickening of tills towards lobate ice stream margins is consistent with subglacial deformation theory and variations in this pattern on a more localised scale are attributed to influences of subglacial topography including thickening at buried valley margins, thinning over uplands and thickening in overridden ice-marginal landforms.

Key words: Palaeo-ice stream; borehole stratigraphy; till architecture; Laurentide Ice Sheet palaeoglaciology; glacial landsystems

1. Introduction and rationale

Ice streams are fast flowing, highly dynamic corridors within ice sheets capable of obtaining high velocities (12 km a⁻¹) (Price and Whillans, 2001) and play a dominant role in regulating ice-sheet mass balance (Boulton et al., 1985; Clark, 1992). Although ice streams typically occupy the same flow path, particularly those that are topographically constrained (Vaughan et al., 2001; Lowe and Anderson, 2002), contemporary glaciological research has demonstrated that marine-based ice streams are capable of large changes in flow configuration, causing major shifts in flow trajectories over relatively short time scales (10²-10³ yrs) (Jacobel et al., 1996; Conway et al., 2002; Hulbe and Fahnestock, 2004; Dowdeswell et al., 2006). The susceptibility of marine-based ice streams to rapid dynamic flow changes may be a consequence of being characteristically underlain by saturated, fine-grained, deformable substrates (Thomas, 1979; Dyke and Morris, 1988; Dyke et al., 1992).

Recent work, focused on ancient terrestrial ice streams associated with the Late Wisconsinan, Laurentide Ice Sheet (LIS) deglaciation of the western Canadian Prairies, has revealed that major flow reorganisations are not limited to marine terminating ice streams but also characterise their terrestrial counterparts. Mapping of the distribution of streamlined glacial landforms within southwestern Saskatchewan (Ross et al. 2009; Ó Cofaigh et al. 2010), suggests that this reorganisation involved 90° shifts in flow direction over a single glaciation. Such shifts are proposed to result from temporal and spatial variations in the interaction between frozen and thawed bed conditions, with thinning and shutdown of one ice stream triggering fast flow in another. This dynamism explains the overprinting (cross cutting) of ice flow indicators (flow-sets) such as drumlins, flutings and mega scale glacial lineations (MSGs). Although current work in SW Saskatchewan has provided a regional scale assessment of surface geomorphology, there is a distinct lack of detailed geomorphological mapping and sub-surface sedimentary analysis relating to palaeo-ice stream behaviour. We address this limitation by providing the first comprehensive sub-surface stratigraphic and high resolution geomorphic assessment of a 57,400 km² area, covering the majority of SW Saskatchewan (hereon termed southwestern Saskatchewan swath; SWSS) in order to present a more in-depth regional reconstruction and understanding of the spatial and temporal dynamics of terrestrial palaeo-ice streams in the SW Laurentide Ice Sheet.

The main aim of the research presented here is to improve current understanding of the relationship between data that are undoubtedly connected to glacial processes (e.g. till architecture) and landform assemblages that are thought to relate to glacial dynamics (e.g. palaeo-ice stream landsystems). In detail this involves: 1) a reconstruction of the depositional history of the SWSS (Figure 1); 2) an assessment of the spatial dynamics and regional sedimentary architecture of palaeo-ice streams; and 3) an evaluation of the significance of ice stream depositional patterns in testing theoretical models of regional till architecture (Boulton 1996a, b).

2. Methods

To address the aims outlined above it was important to accurately map the glacial geomorphology of the SWSS from SRTM and Landsat ETM+ imagery and to define Pleistocene stratigraphic units within the swath according to lithologic properties, thickness, distribution and genesis, using stratigraphic modelling techniques available in Rockworks 16™. A workflow model is presented in Figure 2 that summarizes the various stages of data compilation.

To refine the preliminary glacial landform mapping of the SWSS undertaken by Ó Cofaigh et al. (2010) and Ross et al. (2009), new mapping was undertaken at a higher resolution (1:10,000 scale), using a combination of space borne imagery (SRTM, and Landsat ETM+). Specifically, 1 arc (30 m resolution) Shuttle Radar Topography Mission (SRTM) imagery was employed to create DEMs of the landform record, and in order to minimise azimuth bias, multiple illumination angles were used to aid mapping (cf. Smith & Clark, 2005). Additional mapping was conducted using the Landsat 7 panchromatic band (band 8: 0.52-0.90 μm) Enhanced Thematic Mapper Plus (ETM+), from which eight scenes were mosaicked. Mapping was conducted by on-screen digitisation of features within ArcMap 10.3, with features saved as separate polygon or line shapefiles. The final map (Figure 3; comprising Map Sheets

1 and 2) was compiled by exporting vector layers (.esp files) into Adobe Illustrator CS4 and is intended for printing at A1 paper size.

The compilation and analysis of the regional Quaternary stratigraphy was undertaken using the Rockworks 16™ three-dimensional geological modelling software to interpret continuous stratigraphic surfaces, which were stacked to form a 3D stratigraphic model. Other functions enabled the creation of individual logs and multiple log sections, fence diagrams and isopach maps (Rockware Inc, 2013). This specialised GIS modelling software has been used relatively little in the context of glacial sedimentology and stratigraphy and so the procedures are now briefly described. Subsurface geological data was compiled from boreholes (auger holes) drilled by government agencies (Saskatchewan Research Council, Saskatchewan Department of Agriculture and Saskatchewan Institute of Pedology), and multiple private oil companies between 1962 and 1978. A total of 197 continuously cored boreholes, to depths >288 m below ground surface, were used to create a subsurface database covering the 57,400 km² study area. This includes information from electric logs, field log descriptions, and information from drill cuttings and sidewall samples. Borehole locations were established from borehole records and their locations mapped (Figure 3). Borehole records, containing coded information and driller sediment descriptions, unit thicknesses, and a start (collar) height (z), were entered into an Excel spreadsheet. The drillers' descriptive logs were entered by translating the inconsistent and informal descriptors used to a consistent set of lithologies. For example, the clay category included tough clay, brown clay and clayey deposit. Compound descriptions were broken down into fractions for tabulation. The resulting consistent set of lithologies allowed for the conversion of hundreds of unique descriptive terms, to a limited vocabulary of 35 lithologic keywords, which were considerably more suitable for use in geological modelling. Records were then reformatted for entry into Rockworks to form a digital database composed of two file types; index files and log files (Rockware Inc, 2013). Using the DIGIDATA extension, logging curves (self-potential and electrical resistance) were digitised and then recreated using the LOGPLOT extension to aid in lithologic interpretation (Rockware Inc, 2013).

Critical throughout the analysis of the borehole records was the interpretation of drillers' logs and the application of a consistent set of lithofacies classifications and textural descriptions, allowing the conversion of hundreds of unique descriptive terms to a less cumbersome nomenclature of ~35 lithologic keywords. Composite lithologic striplogs were then created for all 197 boreholes, which could then be compared and interpreted. The identification and differentiation of stratigraphic units was accomplished via careful analysis of: 1. lithological properties including, colour, grain size on materials smaller than gravel, structure, stratification, partings, inclusions, and the nature of contacts; and 2. geophysical properties, recorded by electrical resistivity and self-potential. Details are summarized in Table 1 and an example of one of the composite borehole logs (BH-038) is presented in Figure 4. Although a stratigraphic nomenclature does exist for Saskatchewan (see below), for the sake of objectivity it was considered appropriate to apply simple genetic labels to the deposits as follows: Till units 1-7; Intertill/Stratified units A-F; and Empress Group units 1-3. Correlations of these units with those previously defined in the region (cf. Whitaker and Christiansen 1972; Christiansen 1992; Barendregt et al., 1998) were then attempted only at the later stages of the investigation.

After the creation of stratigraphic striplogs, the cross section function in Rockworks was used to produce well-to-well cross sections (Figure 3, Map Sheet 3), which are fundamental to adjusting stratigraphic picks, refining correlations, and improving the understanding of not only the succession

of units, but also spatial variations in their thickness and elevation. In order to further check the consistency of the correlations, many 'closed' sections were constructed (starting and ending at the same borehole) allowing individual stratigraphic units to be traced back to their original stratigraphic position. In addition to cross sectional diagrams, 2D surface models of the tops of major stratigraphic units were created to evaluate trends and further check tentative correlations. Computer-generated isopach maps were also reviewed in order to identify anomalous data points. These data points were evaluated and in some cases manually edited in selected places to remove outliers that were well outside the main part of a unit, resulting in more consistent isopach trends.

Finally, 3D geological models were constructed using the import of individual stratigraphic surfaces into a single 3D grid model (Rockware Inc, 2013). This involves the use of an inverse modelling algorithm to extrapolate numeric codes that represent a single stratigraphic class (Rockware Inc, 2013). Grid nodes situated surrounding drill holes are assigned a value that corresponds to a stratigraphic class based on the proximity of a grid node to the boreholes that surround it. In this manner, interpretation continues until the program finds a cell that is already assigned a stratigraphic class (Rockware Inc, 2013). One limitation of this type of numerical interpolation is the sensitivity to the distribution of boreholes, with values from isolated drill holes tending to extrapolate outward to fill an inordinate amount of the model area (Rockware Inc, 2013). During preliminary modelling this effect was particularly noticeable in the north of the study area where very few boreholes were available. To minimise this problem the study area was cropped from a former 61,000 km² area to the 57,400 km².

3. Study area and previous research on the glacial history of southwestern Saskatchewan

Numerical modelling predicts that subglacial thermo-mechanical conditions favouring fast ice flow were widespread over the Canadian prairie region during the last glaciation (Marshall et al., 1996) and therefore analysis of the glacial geomorphological signatures is central to advancing our understanding of ice stream operation and dynamics. The SWSS is situated in the Interior Plains physiographic province where the gently rolling landscape is the product of an extended period of pre-Quaternary fluvial incision succeeded by multiple Quaternary glaciations and interglaciations, as recorded by sediment sequences that locally attain thicknesses of up to 300 m (Klassen, 1989). The 57,400 km² study area is located in the southwestern sector of the Interior Plains (Figure 1) between 110°-109° W and 50°-54° N and comprises National Topographic System (NTS) Maps 72K, 72N, 73C and part of 73F.

The bedrock of the study area is part of the Western Canada Sedimentary Basin (Cummings et al., 2012), which overlies crystalline Precambrian rocks and thickens towards the southwest to form a sedimentary wedge near the Alberta foothills (Mossop and Shetsen, 1994). The preglacial landscape was dominated by rivers flowing in large valleys that drained to the north and northeast (Cummings et al., 2012; Figure 5). These valleys were eroded into the bedrock and infilled with sediment ranging in age from Tertiary/Early Quaternary (Empress Group) to Wisconsinan (Stalker, 1968; Whitaker and Christiansen, 1972; Evans and Campbell, 1995). Three lithologically distinct units have been identified in the Empress Group including: Unit 1, a basal sand and gravel comprising clasts derived only from the Rocky Mountain Cordillera and local bedrock; Unit 2, a middle silt and clay, with minor sand and gravel beds; and

Unit 3, an upper glacial sand and gravel with clasts derived from the Canadian Shield (Andriashek and Fenton, 1989).

The Quaternary sediments covering SW Saskatchewan are of glacial, fluvial, lacustrine, organic and aeolian origin. The majority of this sediment is glacial, predominantly classified as till, and has been differentiated and correlated within southern Saskatchewan on the basis of carbonate content, weathering zones, and geophysical and geotechnical properties and traditionally represented as comprising a 'layer cake' stratigraphy (Figure 6; Christiansen, 1968a, b, 1971, 1992; Sauer and Christiansen, 1991; Whitaker and Christiansen 1972; Barendregt et al., 1998). Christiansen (1968a, b) divided the Quaternary deposits in southern Saskatchewan into the lower Sutherland and upper Saskatoon groups and proposed the name Battleford Formation for the surficial tills. The Floral Formation was defined as the tills lying between the Sutherland Group and the Battleford Formation, while the Sutherland Group (composed of the Warman, Dunburn and Mennon Formations) was defined as the deposits lying between the Empress Formation and the Saskatoon Group. The upper till of the Floral Formation has been assigned to the Early Wisconsinan and the Battleford Formation tills to the Late Wisconsinan. Chronological constraints on the ages of these units are lacking, with the Battleford Formation being the oldest dated unit. The only chronological control on sediments is provided by two sets of radiocarbon ages of $24,500-28,600 \pm 560$ yrs BP (wood) to $18,000 \pm 450$ yrs BP (carbonaceous silt) from the stratified layer that underlies the Battleford Formation (Christiansen, 1971). The two tills of the Battleford Formation are generally thin (<1-3 m combined) and based upon consolidation characteristics have been interpreted by Sauer and Christiansen (1991) as a normally consolidated "supraglacial melt-out till" overlying a moderately over-consolidated "basal melt-out till". Over-consolidation of the pre-Battleford sediments has been interpreted as the result of repeated glacial loading (Sauer et al., 1993) and their relatively high montmorillonite clay contents related to their derivation from the local bentonitic shales (Scott, 1976; Christiansen, 1992). This is significant in that they consequently have a low matrix permeability (Van der Kamp, 2001), which, together with proposals that the southern lobes of the LIS exhibited low surface gradients (Mathews, 1974), has prompted many researchers to link ice-sheet instabilities (surging behaviour) in this area to high subglacial water pressures and low bed strength (Clark, 1994) or ice-bed decoupling (Marshall et al., 1996).

The regional till architecture is largely unknown. Geophysical log signatures of the till units are used extensively in the correlation of Quaternary units as well as differentiating tills from stratified deposits and hence regional correlations for the entire Interior Plains are tentative (Figure 6; Andriashek and Fenton 1989). The LIS is thought to have advanced across the plains at least five times (Fenton, 1984; Klassen, 1989), with the earliest advance into southern Saskatchewan dating older than 1.8 Ma (Foster and Stalker, 1976; Fenton, 1984; Klassen, 1989), however, little is known about the exact dynamics of these ice sheet advances or the details of the interglacials/interstadials between them. Thus the detailed subsurface investigation provided in this study affords an ideal opportunity to advance current understanding of the glacial evolution of the region.

The glacial landforms within Saskatchewan display the prominent geomorphological imprint relating to Late Wisconsinan palaeo-ice streams and lobate margins of the LIS (Ross et al., 2009; Ó Cofaigh et al., 2010). Reconstructions by Dyke et al. (2003) indicate that the regional ice flow was toward the southwest at $\sim 18,000$ ^{14}C yrs BP and gradually shifted southward at about $15,000$ ^{14}C yrs BP and then southeastward by $13,000$ ^{14}C yrs BP. Fisher et al. (1985) and Dyke and Prest (1987) suggest that this marked deglacial ice stream flow shift was driven by soft deforming beds (Alley 1991), which became active due to changes in

the basal thermal regime; thinning ice also became more susceptible to the constraints of the regional bed slope, more specifically the NW-SE trending extension of the Missouri Coteau. Clayton et al. (1985), Aber (1993) and later Evans et al. (2008, 2014) focussed on surging events and their importance to the later stage glacial dynamics of the southwestern LIS, concluding that the fast-flowing ice was caused by more substantial proglacial lakes and subglacial meltwater systems and was also constrained to areas of low substrate permeability. Greater details of these dynamic ice stream shifts have been presented by Ross et al. (2009) and Ó Cofaigh et al. (2010) based upon the identification of two cross cutting palaeo-ice stream landsystems. Ice Stream 1 or the Maskwa Ice Stream flowed southwest while Ice Stream 2 (a and b) or the Buffalo Ice Stream flowed southeast, guided by preglacial thalwegs, representing pure and topographically constrained ice streams respectively.

4. Glacial geomorphology of the southwest Saskatchewan swath

4.1 Descriptions

The glacial geomorphology is compiled in Figure 3 (Map Sheet 1). Lineation mapping highlights a prominent smoothed corridor of N-S aligned lineation or streamlining (Figure 3), hereafter referred to as Corridor 1 to enable compatibility with previous work (Ó Cofaigh et al., 2010). This corridor terminates at a series of densely spaced arcuate ridges (TR-1; see below) orientated perpendicular to the lineation long axes. Within its upper reaches the corridor displays a characteristic convergent flow shape, narrowing from ~120 km wide to a ~60 km wide trunk zone, and widens again into a terminal zone (170 km wide) (Figure 3). Three narrower (~40 km wide), NW-SE aligned corridors of streamlined terrain cross cut Corridor 1 (hereafter named Corridors 2A, B and C (Figure 3). The lateral boundaries of all four corridors are demarcated by prominent moraines and hummocky terrain. The lineations consist of longitudinal ridges and furrows with high levels of spatial coherency (Figure 7) and are most densely spaced (≤ 150 m apart) within Corridors 1 and 2 A and B. The longest examples are >60 km long and occur in Corridor 1. In contrast, the features in Corridor 2C are less densely spaced and shorter (2-20 km long). Elongation ratios (ERs) for the lineations are predominantly >10: 1.

Four types of transverse ridges are identified within the SWSS, so called because they are largely aligned transverse to the predominant lineation orientations. They are mostly non-streamlined but some examples appear smoothed and adorned with flutings. Type 1 transverse ridges (TR-1; Figure 7) mainly occur as densely spaced arcuate ridges collectively displaying lobate planforms and are sub-classified into minor TR-1 (1-10 m high, 50-100 m wide, ≤ 2 km long) and major TR-1 (≤ 50 m high, 1-3 km wide, ≤ 60 km long). A total of 154 examples of TR-1 occur in the study area, of which ~40 % have been reported previously (Campbell, 1986a, b, 1987a, b; Ross et al., 2009; Ó Cofaigh et al., 2010). The largest series of major TR-1 occurs at the southern end of Corridor 1 and coincides with an abrupt rise in topography at the Cypress Hills Tertiary monadnock, extending into southern Alberta. Several prominent major TR-1 are orientated parallel to the long axes of smoothed corridors and thereby demarcate the division between corridors and their adjacent hummocky terrain. The largest of these are mapped along the western edge of Corridor 1, forming a 70 km discontinuous ridge. In profile these features comprise a single asymmetric ridge a few kilometres long and 20-30 m wide. Additionally along the NW-SE trending Corridors 2A and B, concentrations of minor TR-1 occur in several well preserved concentrations displaying an inset lobate form and following the local slope contours. Type 2 transverse ridges (TR-2) are best described as geometric ridge networks and occur in two clusters in the SWSS (Figure 7). The first covers a distance of ~300 km within Corridor 1, sub-

divided into three areas by the cross-cutting of corridors 2A and B. These include more than 70 ridges, which are thin, sharp crested and largely 100-400 m long, with a few extending up to 5 km in length (Figure 7). Their internal composition is reported to be diamicton, based upon borehole records and field analysis (Campbell 1986a, b, 1987a, b). The second cluster lies at the centre of Corridor 2A and extends over a distance of ~10 km, with ridge length varying between 100-400 m. Orientations of individual TR-2 ridges reveal a prominent WNW-ESE with a subordinate WSW-ENE alignment for the first cluster and a NNE-SSW alignment for the second cluster. Type 3 transverse ridges (TR-3), visible throughout the study area, are large sub-parallel, generally arcuate, sharp crested ridges 10-60 m high and 150-300 m wide (Figure 7). Many of these ridges are accompanied by a depression (typically lake-filled) on their ice-proximal side. They are common on the Canadian Prairies and are widely described as glaciectonic hill-hole pairs. Type 4 transverse ridges (TR-4) are large, wide and low amplitude ridge complexes (10 m high, 20 km wide) and located in the north of the study area (Figure 7). Apparent surface smoothing and overprinting with lineations indicates that they have been glacially overrun. The ridges occur in two concentrations that form a southwesterly oriented arc.

Some assemblages of glacial landforms display no clear linearity or orientation. These assemblages are classified as inter-corridor and hummocky terrain, because they constitute large areas that lie between, and thereby delimit, the margins of smoothed and lineated corridors (Figure 3, Map Sheet 1).

Elongate sinuous ridges are prominent throughout the study area and those mapped have heights of 5-10 m and lengths of 2-10 kms. Due to the resolution of the imagery, only the largest ridges can be identified with confidence and therefore it is likely that many smaller or discontinuous ridges may exist but are not mapped at this scale. While the majority of sinuous ridges are isolated examples, a small complex of such ridges, 10-15 km long, is present within Corridor 1 and is named the Glidden Esker Network (Christiansen, 1987). The sinuous ridges identified along Corridor 1 exhibit a NW-SE orientation following the surface slope. Further to the north in this corridor, another sequence of prominent ridges forms a 10 km network that occurs in close association with a collection of TR-3 ridges. Additionally, multiple sinuous ridges are also present within Corridors 2A, B and C and here exhibit a more W-E orientation (Figure 3, Map Sheet 1).

Extensive systems of relict (abandoned) channels occur throughout the study area. Within Corridor 1, abandoned channels predominantly have a NE-SW orientation but within Corridors 2A, B and C channels exhibit a more easterly orientation. Abandoned channels are also common throughout the hummocky terrain areas, often occurring as a complex network of interconnected but chaotically orientated features.

4.2 Interpretations

The smoothed cross cutting corridors 1 and 2A, B and C (Figure 3, Map Sheet 1) are interpreted as zones of former subglacial streamlining within the southwest margin of the LIS, representing 'rubber stamp' imprints of palaeo-ice streams (Clark and Stokes, 2003), as previously proposed by Ross et al. (2009) and Ó Cofaigh et al. (2010). Henceforth we refer to corridors 1 and 2A, B and C as ice stream 1 and 2A, B and C (Figure 3, Map Sheet 2). In contrast, the hummocky terrain lying outside these corridors is associated with slow moving, cold based ice and stagnation (Dyke and Morris, 1988, Stokes and Clark, 2002a, Evans et al., 2008; Ó Cofaigh et al., 2010). With a length of >600km, Ice Stream 1 is

the largest palaeo-ice stream in the region and it flowed against the regional slope, unconstrained by the local topography of the Tyner and Battleford buried valley systems, defining it as a pure ice stream. It also exhibits a convergent flow signature, comprising a wide onset zone (~105 km) located upflow from a narrow trunk zone (~58 km wide) and then a progressive widening to the terminus (~170 km wide). The zone of flow convergence contains MSGs that are highly attenuated (11-60 km long) and is bounded by lateral (shear margin) moraines (Figure 3, Map Sheet 1). Based on comparisons with the spatial signatures of modern ice streams, in which an increase in flow convergence is typically associated with an increase in flow rate, it is inferred that this region of the ice stream was characterised by high velocities (Rignot, 2006; Joughin et al., 2001).

The north-south flow path of Ice Stream 1 is crosscut at 90° by the subglacially streamlined landforms of relatively more topographically confined Ice Stream 2, which comprises the two major flow-sets 2A and 2B. A further west-east orientated ice stream footprint occurs to the south of 2b but is not clearly linked to Ice Stream 2; because it is of the same ice streaming phase we classify it as Ice Stream 2C, while at the same time recognizing that it might be an offshoot of the CAIS. Ice Stream 2A records a southeastwards flow confined within the buried North Battleford Valley, as defined by a concentration of 8-17 km long MSGs, previously reported by Gravenor and Meneley (1958) and Grant (1997) as the 'North Battleford Fluting Field'. The flow path of this ice stream was up to 40 km wide and at least 180 km long, and possibly extended much farther to the northwest, as proposed by Andriashek and Fenton (1989) and Evans et al. (1999), who map lineations (Lac La Biche Lobe) in the bordering Sand River area 73L of Alberta. Ice Stream 2B also records southeastwards topographically confined flow (Figure 3, Map Sheet 1: cross section A-A') as a 50 km wide zone of MSGs bordered by fragmented lateral (shear margin) moraines. The MSGs in this corridor are superimposed by several moraine lobes and ice thrust ridge concentrations identified by Evans et al. (2016). The 50 km wide Ice Stream 2C has not previously been identified, although earlier mapping by Campbell (1986a, b, 1987a, b) does identify linear drumlinoid features in this area.

The transverse ridges of the SWSS relate to a variety of process-form regimes. The TR-1 types are similar in form and size to active, recessional push moraines (Price, 1970; Matthews et al., 1979; Evans and Twigg, 2002; Evans, 2003) and their appearance as multiple, densely-spaced arcuate ridges defines the lobate pattern of the Ice Stream 1 terminus zone (Campbell 1986a, b, 1987a, b; Ross et al., 2009; Ó Cofaigh et al., 2010). Some TR-1 features appear to be small scale thrust moraines similar to TR-3 ridges (e.g. Handel Moraine; Evans et al. 2016), which because they are juxtaposed with crevasse squeeze ridges, were likely formed during a late stage of ice streaming. Other ice marginal features in the streamlined corridors include several well preserved lobate moraines north of Ice Stream 2B, which were likely formed by a small, thin ice lobe, because they are topographically controlled. Similarly, minor TR-1 moraines within Ice Streams 2A, B and C collectively form small lobate arcs in several places, and where juxtaposed with multiple thrust block moraines, represent deglacial surge signatures produced by ice flowing from the northwest (Figure 8). Together with the overprinted ice stream trunk landforms, these moraines indicate that the SWSS comprises a palimpsest landscape of cross-cutting palaeo-ice streams and younger recessional or readvance ice stream lobes.

The lateral margins of Ice Streams 1 and 2B are delineated by lateral moraines that extend discontinuously for distances of >60 km and >30 km respectively. Moraine profiles usually comprise a single asymmetric ridge a few kilometres wide and 20-30 m high and are thus analogous to shear

margin moraines formed between the rapidly moving ice stream and adjacent slower moving or stagnant ice (Raymond et al., 2001; Stokes and Clark, 2002b; Hindmarsh and Stokes, 2008).

The TR-2 features or geometric ridge networks were first identified by Campbell (1987a, b) and were variously classified as 'crevasse fillings' and 'minor ridged moraines'. Their diamictic composition and densely-spaced cross-cutting pattern, being identical to modern features created by surging glacier snouts, are used by Evans et al. (2016) to interpret them as crevasse-squeeze ridges (CSRs), an origin that is favoured here. The large assemblage of TR-2 on the bed of Ice Stream 1 overprints the MSGLs in the trunk zone (Figure 3, Map Sheet 1) and it is clear from the landform relationships that the development of these ridges took place during internal flow unit reorganisation, immediately prior to ice stream shutdown. The prominent WNW-ESE alignment (with a subordinate WSW-ESE alignment) likely reflects fracture development transverse to former ice flow, which would have been predominantly NNE-SSW based upon MSGL alignment. Due to their occurrence within a narrow corridor that is smaller than the ice stream footprint, as well their non-arcuate appearance, Evans et al. (2016) proposed a formation mechanism for these CSRs that relates to lateral shear zones formed between flow units within ice streams, not necessarily characterised by surging. The much smaller concentration of TR-2 features on the beds of Ice Streams 2A and B, are also interpreted as CSRs but likely represent ice stream surging, especially as they are more curvilinear in plan form and are juxtaposed with MSGL, several hill-hole pairs and thrust block moraines to form a typical surging glacier landsystem imprint (cf. Sharp, 1985; Evans and Rea, 1999; 2003; Evans et al., 2007).

TR-3 ridges are interpreted as glacitectonic moraines or ice thrust ridges and hill-hole pairs, an origin that is consistent with their multiple crests and occurrence in close proximity to small depressions (Kupsch, 1962). Where ridges appear sharp crested they are interpreted to have formed proglacially during overall ice recession. In contrast, where they appear as streamlined and/or smoothed they are interpreted as features originally constructed during initial ice advance and then overridden; some TR-4 features could constitute such landforms. Data on the internal composition of these thrust features is limited due to the small number of internal boreholes, but exposures through glacitectonic landforms in the region reveal highly variable compositions typically including two or more layers of diamicton, stratified sediments or even bedrock comprising sandstone, ironstone or mudstone. The proportion of bedrock in such thrust masses is likely controlled by the thickness of the pre-existing Quaternary sediment and this is generally >50 m thick in the SWSS, so many of the large thrust hills are presumed to be composed entirely of glacial sediment; hence where they comprise very few composite ridges, thrust masses can be difficult to differentiate from TR-1 features.

The TR-4 features are interpreted as overridden moraine ridge complexes, exemplified by several overridden transverse ridge complexes in the north of the study area. These features form a broadly arcuate lobate shape that coincides with the limit and thickening of DU-4 and so they are interpreted as ice-marginal complex push moraines, constructed in association with glacial sub-marginal till thickening during phases of ice-marginal stability (cf. Evans & Hiemstra 2005; Eyles et al. 2011), rather than large glacitectonically thrust masses of pre-existing sediment or bedrock (i.e. TR-3).

The inter-corridor hummocky terrain lying outside the flow paths of Ice Streams 1, 2A, B and C is interpreted as the product of a change in subglacial regime and hence is used to further demarcate the flow paths of the ice streams (Dyke and Morris, 1988; Patterson, 1998; Evans et al., 2008; Ó

Cofaigh et al., 2010). Previous work in Saskatchewan (Klassen, 1989; Kulig 1996; Cummings et al., 2012) and eastern Alberta (Gravenor and Kupsch, 1959; Stalker, 1960; Bik, 1969) identified that significant proportions of these features are composed of till and hence a supraglacial origin has been traditionally assumed using simple form analogy (Clayton, 1967; Boulton, 1972; Patterson, 1997; 1998; Jennings, 2006). Evans et al. (2014) have elaborated upon this by proposing that some extensive arcuate zones of chaotic to discontinuous linear hummock chains record changes in ice sheet sub-marginal thermal regime and hence constitute a continuum of landforms ranging from push moraines to controlled moraine with ice-walled lake plains. In contrast, Eyles et al. (1999) have proposed a subglacial origin by elaborating on Stalker's (1960) concept of ice pressing. In this region some subglacial pressing of heavily saturated sediments against ice stream margins is likely (Klassen, 1989). Therefore, hummocky terrain in the SWSS is almost certainly a polygenetic landform of both supraglacial and subglacial origin, and is in need of further investigation.

The sinuous ridges large enough to be recognized and mapped are interpreted as eskers and esker networks, in agreement with Campbell (1986a, b, 1987a, b) and Ó Cofaigh et al. (2010). The N-S orientated, relatively linear, straight limbed eskers on the bed of Ice Stream 1 are interpreted as being associated with the drainage of this ice stream; the Glidden Esker Network, for example, documents subglacial water concentrated on the ice stream bed (Evans et al., 2008). Similarly, the concentration of sinuous ridges in the Great Sand Hills Lowland also suggests that subglacial meltwater formed eskers in association with NNW-SSE flowing Ice Streams 2A, B and C. Where eskers cross cut MSGs (Figure 3, Map Sheet 1) they are interpreted to have formed after lineation production, most likely during ice marginal recession (Stokes and Clark, 2003; Stokes et al., 2008).

The extensive systems of relict (abandoned) channels are interpreted as the former courses of meltwater drainage, because they form continuous chains of elongate depressions and water-filled depressions, often in close association with eskers. Within the Ice Stream 1 flow path, channels are often N-S orientated (e.g. Tramping Lake; Figure 3, Map Sheet 1), indicating that they formed subglacially in association with Ice Stream 1. In contrast to these features, meltwater within Ice Streams 2A, B and C are often more continuous and occur in association with large hill-hole pairs. In contrast to channels associated with ice stream activity, the channel networks within hummocky terrain resemble those of fluvial drainage networks rather than those created under subglacial hydraulic gradients and hence they were likely formed as ice stagnated and downwasted; in many cases they were cut by the decanting of proglacial lakes (cf. Evans 2000).

5. Quaternary and glacial stratigraphy

5.1 Descriptions

Seventeen stratigraphic units are recognised within the study area based upon stratigraphic position, grain size, lithic composition and geophysical properties (Table 2) and the stratigraphic model compiled within Rockworks is displayed in Figure 9. This includes seven glacial diamictons, which are traditionally classified as tills in the region; we retain this genetic classification because systematic sedimentological analysis of these materials to determine a more precise genesis is not possible. Similarly, as it is also common practice within Saskatchewan and Alberta to refer to all 'stratified gravel, sand, silt and clay that overlies bedrock and underlies till' as the preglacial Empress Group (EMP) (Whitaker & Christiansen, 1972; Evans & Campbell, 1995; Cummings et al., 2012), this classification is retained but three lithologically distinct sub-units are identified (EMP-1 – EMP-3). EMP-

1 is a sand and gravel containing clasts, EMP-2 is a silt and clay with minor sand and gravel beds, and EMP-3 comprises glacial sand and gravel. The distribution of the Empress Group is dictated by the buried valleys of the region of which they are a partial infill. This bedrock topography also strongly controls the physiography of the land surface in the SWSS and therefore it influences palaeo-ice stream behaviour. The buried, preglacial valleys in the study area comprise two major systems (Stalker, 1961). Firstly, the Battleford Valley is the most extensive and is likely the preglacial valley of the ancestral North Saskatchewan River. It enters the northwest corner of the study area above Manitou Lake as three SE-trending tributaries called the Lloydminster and Wainwright channels and the North Battleford Valley. Secondly, the Tyner Valley is likely the ancestral South Saskatchewan River, whose present day path it closely follows. In contrast to the Battleford Valley system it is wider with more gently sloping walls.

The preglacial unit EMP-1 comprises <20 m of basal gravel overlain by 5-40 m of sand and gravelly sand, occupying the floor of the Tyner and Battleford buried valley systems and containing clasts derived from either local sandstone or the Cordillera. The light-coloured quartzite and dark coloured chert in this unit is reflected in the 'salt and pepper' appearance in log descriptions. Unit EMP 2 consists of grey coloured (5Y 6/1 to 7/1), laminated silt and clay and minor sand and gravel. Along the Battleford Valley system, EMP-2 is 2-46 m thick but within the Tyner Valley it is thinner (2-31 m) and more sporadic, with the exception of the northern Tyner tributary, where silt and clay thicken to 70 m. Unit EMP 3 is dominated by sands and gravels with very small amounts of silt and clay and is a very distinct pinkish brown (oxidised) or pinkish grey (unoxidised). This is likely due to the abundant potassium feldspar within the sand, which importantly is derived from granitic and metamorphic rocks of the Precambrian Canadian Shield, as are clasts within the gravels, indicating the first influence of Laurentide Ice Sheet incursions into the region. These characteristics make the differentiation of EMP-3 from later sand and gravel deposits difficult, a problem that led Evans and Campbell (1995) to propose that the term Empress Group be applied to all stratified units in the complex Quaternary stratigraphy of the Canadian prairies.

Diamicton unit DU-1 comprises clayey diamicton, which is predominantly unoxidised and dark grey brown in colour (2.5Y 4/2) and has very low resistivity. The unit is generally 20 m thick and is interbedded with well-sorted sediment, predominantly clay but also silt and sand of undetermined origin. It is distributed primarily along major buried valleys but also at the edges of some uplands, especially in the south of the study area. It is thickest in the southwestern North Battleford Valley (58 m) and the western end of the Tyner Valley (28 m). In a number of boreholes (e.g. BH-005 and BH-038) drillers' logs describe inclusions of 'ice rafted shales' and 'claystone' within DU-1, indicating that bedrock may have been plucked and then incorporated into DU-1.

Stratified unit A (SU-A) comprises 10-30 m thick, unoxidised, light to medium grey coloured, coarse-grained sand and gravel but also contains minor amounts of interbedded silt and clay. Within buried valleys and channels, SU-A overlies either DU-1 or the Empress Group but covers a larger area than those units and hence overlies bedrock between some valleys. It is at its thickest in the eastern Tyner Valley and the southern tributary of the North Battleford Valley.

Diamicton units DU-2 and DU-3 are very similar and hence differentiated either by a thin intervening layer of stratified clay, sand and gravel (Stratified unit B; SU-B) or, in the vast majority of cases, on

slight differences in electric log response; DU-2 has a slightly lower resistivity than DU-3. Both units are very dark grey (5Y 3/1) when unoxidised and commonly olive brown (2.5Y 4/3) when oxidised. Due to the similarity of DU-2 and DU-3 and the lack of SU-B in the majority of boreholes, these three units are discussed together. The majority of DU-2 is located within the Battleford and Tyner buried valley systems but also occurs on the Western Hills Upland and the Turtlelake Upland. The thickest deposits occur within the North Battleford Valley, where a localised thickening of the unit is present and as much as 64 m is overlain by 2-18 m of SU-B. In contrast, DU-3 is more widespread, being absent only along a thin strip of upland centred on the Western Hills, and reaches a thickness of 69 m in the Turtlelake Upland, where the combined thickness of both units locally exceeds 100 m.

Stratified unit C (SU-C) comprises an unoxidised, dark grey to olive grey (5Y 4/1 to 5Y 5/2) stratified silty clay, containing small amounts of coarse sand and gravel. SU-C covers the majority of the SWSS although it is not recognised to south of the Tyner Valley. It is at its thickest (38 m) within the main Tyner Valley and its northern tributary. SU-C can only be differentiated from other stratified units where it overlies DU-3 and where it is in turn overlain by DU-4. As a result, in the south of the study area, where DU-4 is absent, SU-C cannot be identified. In order to be consistent when identifying units, the approach taken by previous authors (Christiansen, 1987; Andriashek and Fenton, 1989) within the Canadian Prairies is adopted. Thus it is assumed that all clay, silt, sand and gravel deposits that overlie DU-3 and that are overlain by DU-5/6 are the stratigraphically higher SU-D and E. It is therefore possible that in the south of the study area some of the sediment included in SU-D/E is actually SU-C.

Diamicton unit DU-4 is a dark grey (5Y 4/1 to 5Y 3/1) sandy-clay diamicton, in places containing silts and clays similar to underlying DU-3. Large amounts of calcareous material, particularly dolostone in the sand fraction and dolomite in the silt-clay fraction, are recorded in DU-4. In a small number of boreholes the top of DU-4 is recognised by the occurrence of a thin layer of sand and gravel classified as Stratified unit D (SU-D). The spatial distribution of DU-4 appears lobate, extending southwestwards from the northeast part of the SWSS and terminating ~110 km south of the Lloydminster Channel. It is generally thin, particularly within the Turtlelake Upland, where it is commonly between 4-15 m. The unit thickens in two areas, specifically within the North Battleford Valley (≤ 30 m) and towards its southern limit (≤ 46 m), the latter area being the location of large arcuate overridden ridges (TR-3). A gradational upper contact is recorded in the majority of boreholes between DU-4 and DU-5 but in some boreholes a thin ≤ 13 m layer of stratified sand and gravel (SU-D) separates DU-4 from DU-5.

Diamicton unit DU-5 covers the majority of the SWSS and comprises mainly sandy diamicton, the top of which is oxidised olive (5Y 4/3) to olive brown (2.5Y 4.5). Below this oxidised zone, the diamicton is dark grey (5Y 4/1 to 5Y 5/1). Like underlying DU-4, this unit is also rich in calcareous material, particularly dolostone. Iron oxide or manganese oxide staining is recorded. In several boreholes, boulders are recognised at the unconformable contact between DU-5 and the overlying DU-6. It is uncertain as to which unit the boulder concentrations should be associated. DU-5 is considerably thicker than underlying DU-4 and like DU-4, it shows a generalised thickening from 10-20 m in the northeast to 20-30 m in the southwest. It is also thick within the Battleford Valley system. In most boreholes, DU-5 has a distinctly higher resistivity than the base of overlying DU-6.

Stratified Unit E (SU-E) is dominated by sand and in two locations (eastern North Battleford Valley and north of the Western Hills Upland) also displays a basal layer of silt and clay. The sediments are

unoxidised and the sand is dark grey (5Y 4/1 to 5Y 5/1). It is also generally fine to medium-grained, well sorted and commonly free of clasts. It is mainly quartz, but may also contain small amounts of igneous, metamorphic and locally derived rock. SU-E forms a discontinuous layer across DU-4 and DU-5 in lowlands, increasing in thickness also in depressions on the surface of DU-4 and DU-5, especially in the Tyner and Battleford buried valley systems. Like many of the stratified units in this study, SU-E displays no distinct lithologic or compositional properties that differentiate it from other stratified units. Thus SU-E is differentiated and correlated mainly by stratigraphic position.

Diamicton unit DU-6 is a soft, massive and unstained sandy diamicton, which is oxidised olive brown (2.5Y 4/4 to 2.5Y 5/6) but becomes very dark grey with depth (5Y 5/1) and is light grey when unoxidised (5Y 7/1). Although clast-poor overall, boulder pavements are recorded at the base and within the unit. Glacially streamlined landforms on the surface of this unit have a characteristic N-S orientation. Where this unit is overlain by DU-7, a thin (0.5-4 m) layer of stratified sediment (Stratified unit F; SU-F) is recorded within numerous boreholes. DU-6 extends across the majority of the study area and averages 25 m thick (range 3-30 m), making it one of the thickest stratigraphic units. The unit thins along the central strip of the study area, thereby corresponding with many areas of streamlined glacial landforms. The unit also displays a generalised thickening towards the south of the study area, reaching thicknesses of 20-30 m at large terminal moraines. Additionally the unit also thickens within the Battleford and Tyner buried valley systems and thins immediately south of the North Battleford Valley.

Diamicton unit 7 (DU-7) is a clayey diamicton and in some cores contains glacially displaced older sediment. The unit is oxidised dark grey brown (2.5Y 4/2 to 2.5Y 5/2) in the upper part but becomes very dark grey (2.5Y 3/1) with depth. Well defined glacially streamlined landforms on the surface of the unit have a northwest-southeast orientation (Figure 3, Map Sheet 1). DU-7 is restricted in distribution to three W-E aligned corridors in the SWSS but the boundaries of this unit are not everywhere clear due to insufficient boreholes in the northwest and southeast. The surface topography is therefore most useful for establishing the boundaries and is defined by the extent of the streamlined landforms and in some areas lateral ridges. DU-7 is thickest within the North Battleford Valley (20 m) and the thinnest to discontinuous sediments (<1 m) are found along the northern margin of the central W-E corridor. DU-7 is differentiated from underlying DU-6 based on stratigraphic position, the less sandy nature and darker brown colour of DU-7, and the contrasting alignments of their glacially streamlined landforms.

Finally, the uppermost sediments in the SWSS are classified as surficial stratified deposits (SSD). These lie above the uppermost diamicton and occur in the majority of boreholes. They comprise sand, silt and clay and range in thickness from <1 m-100 m, with an average thickness of ~2-10 m. They commonly become finer grained with depth and display a gradational and conformable contact with DU-6/7.

5.2 Interpretations

The origins of the Empress Group deposits (EMP-1 to 3) have been elaborated by previous research and the interpretations proposed therein are accepted here. Situated within the floors of major preglacial valleys, EMP-1 is a fluvial sediment sourced from rivers flowing from the Cordillera (Stalker, 1968), an interpretation supported by the presence of chert and quartzite (Cummings et al., 2012).

The silts and clays of EMP-2 were deposited in lakes formed by the blockage of the preglacial valleys by the advancing Laurentide Ice Sheet, the influence of which is recorded by the appearance of Canadian Shield lithologies as dropstones (Stalker, 1968; Andriashek and Fenton, 1989; Evans & Campbell 1992, 1995). Locally sporadic appearances of EMP-2 are likely the result of glacial erosion prior to and during the deposition of DU-1 (e.g. Andriashek and Fenton, 1989; Evans and Campbell, 1995). EMP-3 is of glacial origin, as indicated by the presence of granitic clasts from the Canadian Shield.

Diamicton DU-1 is interpreted to be till deposited during the earliest recorded glaciation of the region. However, as noted by previous studies in the prairies (Andriashek and Fenton, 1989; Christiansen, 1968b), because this basal till unit is found at or near the base of major buried valleys, some of the unit may include diamicton derived from sediment slumping from the valley walls. Glacial erosion and incorporation/cannibalization and ingestion of the underlying Empress Group and bedrock is the likely cause of the local variance in grain size and the interbedded masses of clay, silt and sand (Christiansen 1968b; Andriashek and Fenton, 1989; Evans & Campbell 1992, 1995) as well as driller log descriptions of 'ice rafted shales' and 'claystone'.

Stratified unit SU-A varies in composition both spatially and temporally, resulting in distinct layers of clays, sands and gravels. The thick, often clayey deposits that lie at the base of multiple boreholes are interpreted as glacial lacustrine in origin, but where they are interbedded with sand and gravel are interpreted as having a glacial origin. A glacial origin is inferred for the thick deposits of sand and gravel within this unit. It is not known whether this unit was deposited in association with the underlying DU-1 or the overlying DU-2, or potentially in relation to the deposition of both diamictons.

Diamictons DU-2 and DU-3 are interpreted as tills deposited during the same early glaciation, due to their compositional similarity and the lack of a substantial thickness of stratified unit SU-B. The thickness of SU-A indicates that a significant ice-free period likely followed the deposition of DU-1, and it is thus reasonable to hypothesize that DU-2 and 3 were produced during a later glacial period. It is unknown if DU-2 and 3 were deposited by two separate ice advances or whether they are the product of slight compositional differences resulting from variation in sediment provenance during a single glacial advance/readvance cycle. The incorporation of the underlying bedrock is proposed as the source of the abundant silt and clay in DU-2, similar to the production of silty, clay rich tills proposed by Andriashek and Fenton (1989) in the Sand River area of Alberta. In contrast, the abundance of quartz and sand in DU-3 originates from either a distant source of quartz sandstone from the Athabasca Formation or more locally from the underlying SU-A. Andriashek and Fenton (1989) suggest that the latter is responsible for the quartz sand rich composition of lower tills (Bonnyville Formation) within the Sand River area. Along the Lloydminster Channel, Turtlelake Upland and small areas of the Tyner Valley system, sequences of sand and gravel (SU-B), interpreted as glacial origin, separate DU-2 from DU-3, indicating that these tills resulted from two separate advances. Additionally the sharp non-gradational contact between DU-2 and DU-3 in many boreholes may also represent a break in deposition. Importantly, the significant thickening ($\leq 64\text{m}$) of DU-3 within an arcuate band in the northwest of the SWSS potentially relates to glacier sub-marginal till thickening and hence ice-marginal stabilization during overall ice recession; if so DU-3 likely records a deglacial readvance.

Stratified unit SU-C, because it commonly occurs within areas that would have been low topography when DU-3 was the surficial material (Figure 3, Map Sheet 3), is tentatively related to deposition in proglacial lakes and streams (cf. Andriashek and Fenton, 1989) that formed during the advance of the ice sheet margin responsible for diamicton DU-4.

Diamicton units DU-4 and DU-5 are interpreted as tills deposited in quick succession during the same (third recorded) glaciation, as evidenced by the lack of substantial inter-till deposits. The arcuate wedge of DU-4 (as well as SU-C) in the centre and south of the study area indicates that an ice margin formed in this region of the SWSS. This proposal is supported by several pieces of evidence. Firstly, the thickening of the DU-4 in this area is consistent with models of glacial sub-marginal till thickening (Boulton, 1996a,b; Evans & Hiemstra 2005; Eyles et al. 2011). Secondly, a series of overridden ridges or moraines (Figure 10), coincide with the area of till thickening. Finally, the thick wedge-shaped sequences of stratified sediment in SU-C, which are present south of these overridden ridges and zones of thicker till, are similar to ice-contact fans and ramps reported from other ice sheet marginal locations (e.g. Johnson & Gillam 1995; Krzyszkowski 2002; Krzyszkowski & Zeilinski 2002). DU-5 also displays a thickening in a southwesterly direction, supporting the notion that these tills were deposited by ice flowing in the same direction during a single glacial period. The thin and discontinuous inter-till sand and gravel deposit SU-D and its association only with boreholes including DU-4 indicates that it is likely a glacialfluvial deposit formed in association with ice that deposited DU-4; its origins as either a series of subglacial canal fills versus discontinuous and/or partially eroded outwash deposits cannot be further refined based upon the data available.

The components of stratified unit SU-E are not all likely to have been deposited by the same process, nor at the same time and therefore its deposition, like SU-A, is inferred to have been spatially and temporally transgressive. The silty and clay rich, oxidised lower layer of SU-A within the eastern part of the Battleford buried valley system and north of the Western Hills Upland, was likely deposited in close succession to DU-5/4 in two large proglacial lakes. The more widespread unoxidised layer of sand that overlies both the oxidised silt and clay and the oxidised tills DU-5 and DU-4 is proposed here to have been deposited glacialfluvially in association with the ice advance that later emplaced DU-6.

Diamicton unit DU-6 is interpreted as a till deposited by ice flowing N-S through the SWSS, based on the orientation of the glacially streamlined features composed of this material. The thickening of this till from 11 m in the north to 30 m in the south at large terminal moraines (Figure 11) is indicative of rapid streaming ice (Piotrowski and Kraus, 1997; Engelhardt and Kamb, 1998), an interpretation supported by the convergent corridor of MSGs that are eroded into the top of the thinner zone of this unit. The thickening of DU-6 also within the Battleford and Tyner buried valleys (Figure 11) suggests that the pre-glacial topography and pre-existing valley fills were crucial to subglacial sediment generation. The stratified sediments (SU-F) that locally lies between DU-6 and 7, within the east of Corridor 2A and in the west of Corridor 2C, are interpreted as glacialfluvial or glaciallacustrine material deposited either during the deglaciation of DU-6 ice or during the early phase of the DU-7 ice advance. The boulder pavements that occur at the basal contact of, and within, DU-6, and at the contact between DU-6 and 7 have been previously reported from the area by Meneley (1964) and Christiansen (1968a), who noted the 'faceted and striated' nature of the boulders. They have been reported from similar stratigraphic positions also within western Manitoba (Klassen, 1979) and SE Alberta (Evans et al., 2012). A variety of mechanisms have been proposed to explain the formation of

boulder pavements (Clark 1991; see Evans 2018 for a review), but the appearance of the pavement between DU-5 and 6 and within DU-6 at the southernmost extent of the DU-6 till supports Boulton's (1996a) excavational deformation lag explanation, in which a pavement forms at the base of the subglacial deforming layer in association with advance and retreat phases of an ice sheet margin. This involves the downward migration of the base of a deforming layer into an older till unit, resulting in the preferential mobilisation of fine material and the localized concentration of the larger particles that resist entrainment. Hence the occurrence of a boulder pavement in the middle of DU-6 suggests minimal erosion and a large volume of advance phase till overlain by a thick retreat till sequence. Conversely the occurrence of a boulder pavement overlying stratified sediments and/or DU-5 is testament to a zone of strong erosion with retreat phase till deposition only.

Diamicton unit DU-7 is interpreted as a till deposited by three topographically confined ice streams that advanced from NE Alberta (Figure 12). This is particularly evident in the northernmost of the three corridors where DU-7 and NNW-SSE orientated glacial lineations are present. The ice that deposited this till unit was also strongly erosive and it glaciectonically displaced large parts of the underlying units, particularly evident as large ice thrust ridges within Corridor 2B (Ó Cofaigh et al., 2010). The lack of DU-6 in the easternmost part of Ice Stream 2B can be attributed to limited deposition during ice advance and retreat and strong erosion removing any contemporaneous till. Due to a lack of boreholes the extent of this unit in the west North Battleford Valley is unknown, however based on the clear geomorphological evidence (MSGL's and ice stream shear moraine ridges) of ice stream activity, it is highly likely that DU-7 is present in this region.

The surficial stratified deposits (SSD) are interpreted as a variety of deglacial lacustrine, outwash, and ice-contact sediments and postglacial alluvium, colluvium, aeolian and landslide deposits. The most significant of these deposits are glacial lacustrine, which in places reach ~100 m thick, especially in the south of the study area. These were likely deposited in glacial lakes impounded by the ice margin as it retreated downslope towards the northeast (Christiansen, 1979).

6. Discussion

Based upon the borehole-derived lithologic properties of the Quaternary sediments within the SWSS, it appears that ice advanced over the study area seven times, each time depositing a distinct till. The absence of chronological constraints from the borehole records makes it difficult to determine whether or not the tills record separate glacial advances or readvances during the same glacial period. Based on the thickness of stratified intertill units and the presence and/or absence of potential weathered and oxidised zones, there is a strong likelihood that some tills represent readvance/'retreat till' events (e.g. Boulton 1996a, b) or ice flow directional switches due to shifting ice stream locations within the LIS (e.g. Ross et al. 2009; Ó Cofaigh et al. 2010). Due to the lack of chronological control, we now review the glacial depositional history of the region in relation to the three broad periods of preglacial, Pre-Late Wisconsinan and Late Wisconsinan time.

The Preglacial depositional period is recorded in the sedimentary infills of the two major drainage systems, the Battleford and Tyner Valleys, which contain Cordillera-sourced quartzitic and chert gravel and sand mixed with locally-derived quartzitic sand and dark chert (EMP-1). Previously related to preglacial valley sedimentation and classified as 'Saskatchewan Gravels and Sands' (Stalker, 1968) and the 'Empress Group' (Whitaker & Christiansen, 1972; Evans & Campbell 1995), these deposits

represent a drainage system that developed during the latter part of the Tertiary and likely the preglacial early Quaternary.

The onset of the pre-Late Wisconsinan depositional period is represented by the evidence for the first advance of the LIS and the concomitant termination of EMP-1 sedimentation (Figure 13). The Battleford and Tyner valley drainage was progressively blocked by advancing ice, forming a series of elongate ice-dammed lakes, and diverted southwards. Suspension sedimentation in the lakes is manifest in EMP-2. Glacifluvial sand and gravel of EMP-3 was then deposited either on top of EMP-2 or in some areas on the underlying bedrock (Figure 13). Where mudstone and siltstone bedrock was not protected by the deposits of EMP-1 – EMP-3, early ice advances eroded or cannibalized it to create the earliest clay-rich till (DU-1). This till is confined to preglacial valleys but was likely originally more extensive and later reworked on upland surfaces by subsequent ice advances. The origin of SU-A overlying DU-1 is in some areas, where it comprises minor layers of clay, related to proglacial lakes formed against the retreating ice margin, but mostly is related to glacifluvial sedimentation fed either by deglacial meltwater or proglacial outwash streams associated with the ice advance that deposited till DU-2.

The thick DU-2 till displays an abundance of quartz and hence its likely provenance is the Athabasca Formation to the northeast of the SWSS, as well as underlying SU-A (Andriashek and Fenton, 1989). Additionally, the clay-rich nature of DU-2 is likely the result of erosion and incorporation of the underlying claystone and siltstone bedrock. The separation of DU-2 and overlying DU-3 by only a thin and sporadic layer of stratified sediment (SU-B) indicates either a very short period of deglaciation or the production of subglacial meltwater deposits in canals due to a phase of elevated till porewater pressures (Clark & Walder 1994; Evans et al. 1995; Boyce & Eyles 2000; Meriano & Eyles 2009). The thickening of DU-3 in the North Battleford Valley potentially represents the location of former glacier margin stabilization where sub-marginal till thickening operated (cf. Boulton 1996a, b; Johnson & Hansel 1999; Eyles et al. 2011; Evans et al. 2012); the orientation and arcuate form of this area of thickened till indicates that net advection was from the northeast. The surface of DU-3, were it was not later eroded, for example in the North Battleford Valley, is classified in log records as weathered but the occurrence of sand and gravel (SU-C) above this makes it highly likely that the till aquitard was merely stained by groundwater moving through the overlying SU-C aquifer.

The silt and clay of SU-C records the return of proglacial lake sedimentation in the eastern parts of the North Battleford Valley and Lloydminster Channels when the advancing LIS again blocked the regional northeasterly drainage. The arcuate distribution of SU-C most likely demarcates the lobate marginal zone of the ice sheet for two reasons. Firstly, in addition to SU-C being absent in the southwest of the study area, DU-4 is also absent and displays a similar lobate distribution confined to the northeast of the study area. Secondly, DU-4 and SU-C both thicken considerably towards this lobate margin and hence can be interpreted as the product of sub-marginal till thickening (cf. Boulton 1996a, b; Evans et al. 2012), especially as the area of thickening coincides with an overridden ridge complex (Figure 10). The thin and localised appearance of SU-D indicates that DU-5 was likely deposited only a short time after DU-4 and during the same glacial event, suggestive of a subglacial canal fill origin similar to SU-B. Interestingly, within the bordering Sand River area of Alberta, a similar lobate distribution of clay rich till is recorded (Andriashek and Fenton, 1989), which could represent an extension of the ice

marginal position of DU-4, although a lack of chronological constraints make correlation across regions tentative.

The widespread distribution of DU-5 across the entire study area indicates that the ice responsible for its deposition extended across the entirety of the SWSS. During DU-5 deglaciation, meltwater eroded a number of channels on the till surface, into which was deposited stratified sediment SU-E, relating to either proglacial lakes or streams. The extensive weathering zone reported in the borehole log records for the surface of DU-5 is again highly likely to be the product of groundwater staining beneath the SU-E aquifer, rather than an indication of an extended period of non-glacial conditions.

The Late Wisconsinan depositional period, because it is the last glacial event to have impacted on the region, is recorded not just by the borehole stratigraphy but also the glacial geomorphology, thereby allowing a more detailed reconstruction of the palaeoglaciology. The chronological control on this period is poorly constrained but what is available has been defined by Ross et al. (2009) and Ó Cofaigh et al. (2010) based on the reconstruction of LGM deglaciation by Dyke et al. (2003) and is developed below using ice stream events in Western Manitoba (Patterson, 1997; Jennings, 2006) and Western Alberta (Andriashek and Fenton, 1989; Evans et al., 2008).

Well preserved ice stream flow sets (Figure 3, Map Sheet 1,2) record the dynamic behaviour of the southwest LIS over the SWSS. Based on the relationship of cross cutting Ice Streams 2A, B and C in relation to the flow path of Ice Stream 1, it is clear they record progressive changes in ice sheet behaviour through the Late Wisconsinan deglaciation from an unconfined 'pure' ice stream to a series of topographically confined flow lobes (Figure 3, Map Sheet 2). It appears that this dynamic flow shift is also recorded within the stratigraphic record. Based on sediment-landform relationships it is proposed that DU-6 was deposited by Ice Stream 1 and DU-7 relates to the activity of Ice Streams 2A, B and C. This interpretation is based on several lines of evidence: 1) the corresponding narrow distribution of DU-7 within three strips all within the smoothed corridors 2A, B and C; 2) the stratigraphic position of DU-7, which overlays DU-6 in areas where the flow paths of Ice Streams 2A, B and C and Ice Stream 1 are present; and 3) thickening of DU-6 in relation to the terminus of Ice Stream 1. Two main phases of ice stream activity can be recognized, each of which is now discussed in turn.

Phase 1 dates to the regional LGM of $\sim 18^{14}\text{C}$ ka BP and is characterized by the Ice Stream 1 active flow phase. The corridor of MSGs that document this palaeo-ice stream can be traced throughout the SWSS down to the Great Sand Hills Lowland, indicating that it terminated at a series of moraines on the northern slope of the Cypress Hills (Figure 3, Map Sheet 1). These moraines are interpreted as ice thrust terrain by Kupsch (1962) and hence are here related to ice stream marginal construction (Figure 14); the extension of MSGs beyond the moraines indicates that Ice Stream 1 did at some earlier time feed ice lobes located further south, between the Cypress Hills and Wood Mountain Uplands (Klassen, 1991, 1992, 1994; Ross et al., 2009). At the same time similar fast ice flow was active within the bordering provinces of Manitoba and Alberta; the James Lobe to the east was fed by a system in Manitoba and eastern Saskatchewan (Patterson, 1997; Jennings, 2006), and within Alberta the CAIS (Central Alberta Ice Stream) and HPIS (High Plains Ice Stream) were flowing N-S (Figure 15). The HPIS, CAIS, James Lobe and Ice Stream 1 all display a general N-S flow against the regional slope and crossed preglacial valleys without significant deflection. This flow pattern indicates that ice was thick over the

Interior Plains while these ice streams were active and likely resulted from coalescence with Cordilleran ice in the west (Dyke and Prest, 1987; Klassen, 1989; Rains et al., 1999; Figure 15).

Phase 2 dates to the period ~14,500 - 12,500 yrs ¹⁴C BP and is characterized by regional flow reorganisation in the SW LIS, which had begun to thin and its marginal regime transitioned from steady state flow to dynamic temperate ice-marginal conditions (Ross et al., 2009; Evans et al., 2014). Ice-marginal recession also led to the ponding of meltwater in proglacial lakes (Mathews, 1974; Figure 14), within which Ice Stream 1 terminated, potentially initiating the early stages of snout instability (e.g. Stokes & Clark 2003, 2004). A major change in flow direction, first proposed by Clayton and Moran (1982), then occurred, with Ice Streams 2A, B and C from farther west dissecting Ice Stream 1 after it had shut down and depositing till DU-7 as their subglacial footprint (Figure 14). These ice streams relate to Patterson's (1997) proposal that the ice stream system feeding the James Lobe (Figure 15) started to expand northwestward subsequent to 14 ¹⁴C ka BP, due to ice sheet thinning and increasing meltwater lubrication. The stagnation of Ice Stream 1 followed by the progressive migration of the James Lobe onset zone (Patterson, 1997) and associated tributaries explains well the sharp contact between Ice Stream corridors 2A, B and C and Ice Stream 1. Stagnation of Ice Stream 1 is suggested by both the excellent preservation of MSGs in its footprint as well as the widespread occurrence of crevasse-squeeze ridges indicative of subglacial till injection into late stage crevasses (Evans et al. 2016; Figure 14). Nevertheless, some spatially restricted areas of the margins of the Ice Stream 1 footprint record overprinting by younger ice recessional or ice readvance activity; for example, Evans et al. (2016) report an assemblage of features comprising a fluted hill-hole pair and esker complex and small lobate moraine ridges (Handel Moraine) that demarcates the incursion of a small glacial lobe flowing from the NNW-SSE after Ice Stream 1 stagnation (Figure 14).

In contrast to the pure nature of Ice Stream 1, Ice Streams 2A, B and C are constrained by the lower topography of the Battleford and Tyner buried valley systems but the location of the onset zone of these ice streams is unknown. Reconciliation of the SWSS palaeo-ice stream features with those of Andriashek and Fenton (1989) in the Sand River area indicates that Corridors 2A and B are a clear continuation of the formerly NNE-SSW flowing Lac La Biche Ice Stream that flowed through the Sand River area and split into multiple lobes within Saskatchewan (cf. Evans et al. 2008; Ross et al. 2009; Ó Cofaigh et al. 2010). A source within central Alberta is indicated by the low carbonate concentrations of the surficial (DU-7) till that demarcates the footprints of Ice Streams 2A, B and C and contrasts with the tills of Ice Stream 1 (Ross et al., 2009). The fields of attenuated bedforms and their large (>10:1) length to width ratios suggest rapid flow speeds occurred along the Ice Streams 2A, B and C (cf. Dyke and Morris, 1988; Clark 1993; Wellner et al., 2001; Ó Cofaigh et al., 2002; Stokes & Clark 2002a; Briner, 2007), especially clear within the Ice Stream 2A footprint. Although Ice Stream 2 corridors were bound by relatively higher topography, dynamic shifts of their lateral margins are manifest in overprinted landforms. Ice stream dynamism is evident also in landform-sediment assemblages diagnostic of the surging glacier landsystem (Evans et al. 2008). Such dynamism has been proposed also by Evans et al. (2008, 2012, 2014) based upon spatial and temporal changes in landsystem imprints (surging, active temperate and warm polythermal) that document ice stream lobe recession in southern Alberta.

Integration of observations from this study with existing reconstructions from Alberta and Manitoba (Figure 15) allows a regional reconstruction of palaeo-ice stream flow paths for the Western Canadian Prairies, which indicates that this sector of the LIS was characterised by a complex series of flow events

during deglaciation from the LGM limit. Such marked spatial and temporal shifts in flow trajectory suggest that streaming may have been transitory in many cases and did not reach steady state. This is consistent with both reconstructions from the other sectors of the LIS (e.g. Boulton and Clark, 1990; De Angelis and Kleman, 2005; Jennings, 2006) and with observations of modern ice streams (Alley and Bindshadler, 2001; Conway et al. 2002; Vaughan et al. 2008; Winter et al. 2015).

In addition to facilitating the identification of the extent of palaeo-ice streams through time, the distribution and thickness of tills in the SWSS can be employed in the assessment of till architecture and the testing of models of sub-marginal till thickening predicted by Boulton (1996a, b) using glaciological theory and proposed by Evans et al. (2012, 2014) using stratigraphic outcrops. Evidence of sub-marginal thickening is manifest by DU-6 and its association with the southern limits of Ice Stream 1. Within this marginal zone this till unit ranges in thickness from 9-30m. Such thicknesses are not consistent with those recorded in modern subglacial traction tills (Evans et al., 2006a; Evans 2018) but have been reconciled with the sub-marginal accretion of deforming sediment units (Boulton 1996a, b; Evans & Hiemstra 2005; Eyles et al., 2011; Evans et al., 2008). Furthermore within the northernmost limits of the study area till is considerably thinner and in some areas of the Turtlelake Upland bedrock is exposed. It is proposed, due the presence of a boulder pavement at the base of this unit, that the unit is analogous to a retreat phase till (where no advance phase till is preserved), consistent with the erosional zone of Boulton's (1996a, b) model. This boulder pavement can be traced to the southern margin of the SWSS and in this area is recorded within rather than at the contact of DU-6.

The characteristics of DU-6 thus lend support to Boulton's (1996a, b) model of regional till deposition patterns beneath former ice sheets. The thickening of DU-6 in association with terminal moraine ridges in the south of the study area suggests that: 1) the snout was stable over a period of time during the Late Wisconsinan that was sufficiently long for till incremental stacking to occur; and 2) till deformation was, at least within the marginal zone of this ice stream, significant in the net down glacier transfer of subglacial sediment. The characteristics of DU-6 thus provides the first evidence within southwestern Saskatchewan of large scale patterns of marginal till thickening. This is consistent with site specific evidence of ice stream downflow to sub-marginal thickening of glaciogenic sediments in Alberta (Evans et al., 2008), there associated with the HPIS and CAIS. Distinct from both of these ice streams, till associated with Ice Streams 2A, B and C (DU-7) displays limited thickening in the SWSS but its extent is limited and therefore regional architecture is difficult to reconcile. Nevertheless, the surface till equivalent to DU-7 does thicken considerably in a southeast direction towards the James Lobe, attaining a thickness of up to 15 m in eastern North Dakota (Hallberg and Kemmis, 1986), and thereby does exhibit gross scale ice stream downflow to sub-marginal thickening. The occurrence of thin tills at the centres of the fast-flow corridors, in many places unconformably overlying stratified sediments, may indicate that widespread till deformation in some locations within the SWSS was secondary to basal sliding in driving palaeo-ice streams (e.g. Piotrowski et al., 2004) but the general thickening of tills towards the ice stream/lobe margins is consistent with the theory of deformation-controlled regional till architecture proposed by Boulton (1996a, b), which in itself is not necessarily incompatible with localized basal sliding.

In addition to the surface tills DU-6 and DU-7, the older till units DU-4 and DU-5 also display a generalised pattern of thickening towards the south/southwest beneath the Ice Stream 1 footprint.

This characteristic of stratigraphically older tills is pertinent for two reasons. Firstly, if DU-6 can be regarded as an exemplar for wedge-like till thickening due to subglacial deformation, then the earlier till wedges suggest that during several phases of ice sheet coverage, ice streams reached the southern border of Saskatchewan and may have occupied a similar flow path as that recorded by the surficial geology. Secondly, recognition of these regional architectural characteristics in multiple units of different ages suggests that they may be invaluable diagnostic criteria for the recognition of palaeo-ice streams using only borehole stratigraphic records.

In addition to this generalised thickening of till towards ice stream margins, more localised thickening, not predicted within Boulton's (1996a, b) model, is recognised in the SWSS. This variation in sediment thickness is attributed to two processes: 1) down-ice thickening associated with buried valley margins; and 2) thickening as a result of overridden glacial-marginal landforms.

Substantial thickening of tills and plucked bedrock immediately down-ice of buried valleys indicates that pre-existing sediment sequences (valley fills) are crucial to the subglacial generation of sediment (Evans et al. 2012). This is partially applicable to DU-6 and 5, which display thickness increases typically of 12 m and 9 m respectively in such situations. Pre-advance sediment was created in these locations due to ice-marginal flow against the regional slope and the concomitant creation of proglacial lakes and their infilling with thick glacial-lacustrine deposits (Proudfoot, 1985; Evans and Campbell, 1995; Evans 2000; Evans et al. 2006b, 2008, 2012) and mass flow diamictons associated with the advection of sub-marginal till (Evans et al. 2012). It is also likely that the preglacial (Empress Group) sands and gravels in the buried valleys acted as aquifers once overridden by ice, locally evacuating subglacial meltwater, increasing the basal shear stress and thereby causing till thickening either by tectonic stacking or by freeze-on and later melt-out (e.g. Christofferson and Tulaczyk, 2003). In addition this also explains how the leakage of subglacial meltwater through preglacial valley aquifers could conceivably have caused periodic ice stream deceleration.

Unrelated to buried pre-glacial valleys, stratigraphically older tills also thicken. Based on the similarities of these cases of abnormally thick till to those recorded by Evans et al. (2008) in southern Alberta which occur in association with overridden ridges, it is proposed that these localised thickenings mark former overridden ice-marginal landforms. These thick till sequences likely record ice-marginal moraine construction and subglacial till thickening during ice sheet advance. One example of this occurs within DU-3 on the southern side of the North Battleford Valley. However the proposal that this type of thickening is related to overridden ice margins is made especially clear where till thickening coincides with overridden ridge complexes. This is illustrated in relation to the large lobate complex of overridden transverse ridges interpreted as terminal moraines. This ridge complex is associated with glaciotectionised bedrock and tills (specifically DU-4, which is present only within the margins of this lobate ridge complex), which are stacked at the centre of large transverse ridges.

This case study and synthesis of 3D till architecture associated with regional palaeo-ice stream activity is now summarized in a conceptual model of ice stream till deposition (Figure 16). This is a synthesis of observations from the SWSS presented above and the findings of previous studies of palaeo-ice streams in adjacent areas (e.g. Patterson, 1997, 1998; Evans et al., 2008, 2012). It provides a generalised view of the pattern of deposition resulting from fast flow over an unlithified sediment bed and thus, much like geomorphic landsystem models of palaeo-ice stream imprints (Hart, 1999; Stokes

and Clark, 1999, 2001), can be used to infer the dynamic behaviour of former ice sheet fast flow corridors from their sedimentary imprint. The model can be visualised as the evolution of 5 zones (Figure 16). Zone 1 encompasses the marginal area of an ice stream; in this location the model depicts a generalised sub-marginal till thickening. Zone 2 depicts a region in which erosion/sliding are dominant and associated with the ice stream's fast flowing trunk region. It should be noted that while in this zone deformation may have been subordinate to sliding of the glacier bed, this does not mean that deformation was absent; indeed it is likely that locally this process would also have been an important process within these trunk zones. Zones 3, 4 and 5 illustrate localised processes and are thus spatially variable within a single ice sheet. Thickening as a result of overridden glacial-marginal landforms is displayed as Zone 3. Zone 4 depicts down-ice side valley thickening; in such locations till is expected to thicken significantly as a result of ice stream deceleration. Linked to Zone 4, Zone 5 encompasses areas of upland thinning resulting from fast flow.

7. Conclusions

Detailed mapping over a 57,400 km² area of southwestern Saskatchewan reaffirms the former existence of a south-southwest flowing ice stream (Ice Stream 1) in the LIS, demarcated by a corridor of megaflutes and MSGs, extending from the Canadian Shield to southwestern Saskatchewan. This corridor is cross cut by three (one previously unrecognised) south to southeast trending ice stream footprints (Ice Streams 2A, B and C). The superimposition of these corridors suggests that a dynamic switch in flow direction occurred in this region, when the persistent fast flow of Ice Stream 1 gave way to the more transitory surging system of Ice Streams 2A, B and C. This reinforces previous proposals for periodic instability within this region of the LIS during the Late Wisconsinan. Thin tills at the centre of the trunk zone of Ice Stream 1 in many places lie unconformably over stratified sediments, suggesting widespread basal sliding may have been subordinate to deformation, but the general thickening of tills towards the lobate terminal margins is consistent with subglacial deformation theory (Boulton 1996a, b). Variation in till thickness is also recognised on a more localised scale with the variations attributed to the processes of down-ice thickening associated with buried valley margins and the overriding of ice-marginal landforms. Additionally, the lithological characteristics of 197 boreholes within the palaeo-ice stream footprints reveals a superimposed glaciogenic sequence comprising 17 stratigraphic units, allowing the spatial and temporal reconstruction of multiple fast flow events pre-dating the Late Wisconsinan. This regional till architecture reveals that the dynamic behaviour of palaeo-ice streams can be recognised from their sediment imprint, which can be used to augment Stokes and Clark's (1999) diagnostic geomorphological criteria or, in the absence of landform expressions of till sheets, be used to identify ice streams in the older stratigraphic record.

Acknowledgements

Borehole records used in this study were kindly made available by the Saskatchewan Research Council in Saskatoon. Constructive reviews of this paper were provided by Rod Smith (GSC) and John Hiemstra (Swansea University).

References

- Aber, J.S., 1993. Geomorphic and structural genesis of the Dirt Hills and Cactus Hills, southern Saskatchewan, in: Aber, J.S. (ed.) *Glacio-tectonics and Mapping Glacial Deposits*. Canadian Plains Research Centre, Regina.
- Alley, R.B., 1991. Deforming bed origin for southern Laurentide till sheets? *J. Glaciol.* 37, 67-76.

Alley, R.B., Bindschadler, R.A., 2001. The West Antarctic ice sheet and sea-level change, in: Alley, R. B., Bindschadler, R.A. (eds.) *The West Antarctic Ice Sheet: Behaviour and Environment*. American Geophysical Union, Antarctic Research Series. 7.

Andriashek, L.D., Fenton, M.M., 1989. Quaternary stratigraphy and surficial geology of the Sand River area 73L. Alberta Research Council, Edmonton.

Barendregt, R.W., Irving, E., Christiansen, E.A., Sauer, E.K., Schreiner, B.T., 1998. Stratigraphy and paleomagnetism of Late Pliocene and Pleistocene sediments in the Wellsch Valley and Swift Current Creek areas, southwestern Saskatchewan, Canada. *Can. J. Earth Sci.* 35, 1347–1361.

Bik, M.J.J., 1969. The origin and age of prairie mounds of southern Alberta. *Biul. Peryglac.* 19, 85-130.

Boulton, G.S., 1972. Modern arctic glaciers as depositional models for former ice sheets. *J. Geol. Soc. London* 128, 361-93.

Boulton, G.S., 1996a. Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation. *J. Glaciol.* 42, 43-62.

Boulton, G.S., 1996b. The origin of till sequences by subglacial sediment deformation beneath mid-latitude ice sheets. *Ann. Glaciol.* 22, 75-84

Boulton, G.S., Clark, C.D., 1990. A highly mobile Laurentide Ice Sheet revealed by satellite images of glacial lineations. *Nature* 346, 813–817.

Boulton, G.S., Smith G.D., Jones, A.S., Newsome, J., 1985. Glacial geology and glaciology of the last mid-latitude ice sheets. *J. Geol. Soc. London* 142, 447-474.

Boyce, J.I., Eyles, N., 2000. Architectural element analysis applied to glacial deposits: internal geometry of a late Pleistocene till sheet, Ontario, Canada. *Bull. Geol. Soc. Amer.* 112, 98–118.

Briner, J.P., 2007. Supporting evidence for the New York drumlin field that elongate subglacial bedforms indicate fast ice flow. *Boreas* 36, 143-147.

Campbell, J.C., 1986a. *Surficial Geology of the Kindersley Area (72N)*. Saskatchewan: Saskatchewan Research Council, Sedimentary Resources. Map 1:250,000 scale.

Campbell, J.C., 1986b. *Surficial Geology of the Melville Area (72K)*. Saskatchewan: Saskatchewan Research Council, Sedimentary Resources. Map 1:250,000 scale.

Campbell, J.C., 1987a. *Surficial Geology of the St. Walburg Area (73F)*. Saskatchewan: Saskatchewan Research Council, Sedimentary Resources. Map 1:250,000 scale.

Campbell, J.C., 1987b. *Surficial Geology of the North Battleford Area (73C)*. Saskatchewan: Saskatchewan Research Council, Sedimentary Resources. Map 1:250,000 scale.

Christiansen, E.A., 1968a. A thin till in west-central Saskatchewan, Canada. *Can. J. Earth Sci.* 5, 329–336.

- Christiansen, E.A., 1968b. Pleistocene stratigraphy of the Saskatoon area, Saskatchewan, Canada. *Can. J. Earth Sci.* 5, 1167–1173.
- Christiansen, E.A., 1971. Tills in Southern Saskatchewan, Canada, in: Goldthwait, R. P. (ed.) 2004. *Till: A Symposium*. Ohio State University Press, Columbus.
- Christiansen, E.A., 1979. The Wisconsinan deglaciation of southern Saskatchewan and adjacent areas. *Can. J. Earth Sci.* 16, 913-938.
- Christiansen, E.A., 1987. Verendrye valley and the Glidden esker, Saskatchewan: subglacial and ice walled features in southwestern Saskatchewan, Canada. *Can. J. Earth Sci.* 24, 170-176.
- Christiansen, E.A., 1992. Pleistocene stratigraphy of the Saskatoon area, Saskatchewan, Canada – an update. *Can. J. Earth Sci.* 29, 1767–1778.
- Christoffersen, P., Tulaczyk, S., 2003. Thermodynamics of basal freeze-on: predicting basal and subglacial signatures of stopped ice streams and interstream ridges. *Ann. Glaciol.* 36, 233-243.
- Clark, C.D., 1993. Mega-scale glacial lineations and cross-cutting ice-flow landforms. *Earth Surf. Proc. Landf.* 18, 1-29.
- Clark, C.D., 1994. Large-scale ice-moulding: a discussion of genesis and glaciological significance. *Sed. Geol.* 91, 253-268.
- Clark, C.D., Stokes, C.R., 2003. Palaeo-ice stream landsystem, in: Evans, D.J.A. (ed.) *Glacial Landsystems*. Arnold, London.
- Clark, P.U., 1991. Striated clast pavements: products of deforming subglacial sediment? *Geology* 19, 530-533.
- Clark, P.U., 1992. Surface form of the southern Laurentide Ice Sheet and its implications to ice-sheet dynamics. *Bull. Geol. Soc. Amer.* 104, 595-605.
- Clark, P.U., Walder, J.S., 1994. Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. *Bull. Geol. Soc. Amer.* 106, 304–314.
- Clayton, L., 1967. Stagnant glacier features of the Missouri Coteau in North Dakota. *North Dakota Geological Survey. Miscellaneous Series.* 30: 25-46.
- Clayton, L., Moran, S.R., 1982. Chronology of Late Wisconsinan glaciation in middle North America. *Quat. Sci. Rev.* 1, 55–82.
- Clayton, L., Teller, J.T., Attig, J.W., 1985. Surging of the south- western part of the Laurentide Ice Sheet. *Boreas* 14, 235–241.
- Conway, H., Catannia, G., Raymond, C.F., Gades, A.M., Scambos, T.A., Engelhardt, H., 2002. Switch of flow direction in an Antarctic ice stream. *Nature* 419, 465-467.
- Cummings, D.I., Russell, H.A.J., Sharpe, D.R., 2012. Buried valley aquifers in the Canadian Prairies: geology, hydrogeology, and origin. *Can. J. Earth Sci.* 49, 987-1004.

- De Angelis, H., Kleman, J., 2005. Palaeo-ice streams in the northern Keewatin sector of the Laurentide ice sheet. *Ann. Glaciol.* 42, 135-144.
- Dowdeswell, J.A., Ottesen, D., Rise, L., 2006. Flow switching and large-scale deposition by ice streams draining former ice sheets. *Geology* 34, 313-316.
- Dyke, A.S., Prest, V.K., 1987. Late Wisconsinan and Holocene history of the Laurentide Ice Sheet. *Geogr. Phys. Quat.* 41, 237–263.
- Dyke, A.S., Morris, T.F., 1988. Drumlin fields, dispersal trains, and ice streams in Arctic Canada. *Can. Geogr.* 32, 86-90.
- Dyke, A.S., Morris, T.F., Green, D.E.C., England, J.H., 1992. Quaternary geology of Prince of Wales Island, central Canadian Arctic. *Geological Survey. Canada.* 2, 433-438.
- Dyke, A.S., Moore, A., Robertson, L., 2003. Deglaciation of North America. Geological Survey of Canada Open File 1574. Available at: <http://geopub.nrcan.gc.ca>.
- Englehardt, H., Kamb, B., 1998. Basal sliding of Ice Stream B, West Antarctica. *J. Glaciol.* 44, 223-230.
- Evans, D.J.A., 2000. Quaternary geology and geomorphology of the Dinosaur Provincial Park area and surrounding plains, Alberta, Canada: the identification of former glacial lobes, drainage diversions and meltwater flood tracks. *Quat. Sci. Rev.* 19, 931–958.
- Evans, D.J.A., 2018. *Till – A Glacial Process Sedimentology*. Routledge, London.
- Evans, D.J.A., 2003. Ice-marginal terrestrial landsystems: active temperate glacier margins. in: Evans, D.J.A. (ed.) *Glacial Landsystems*. Arnold, London.
- Evans, D.J.A., Campbell, I.A., 1992. Glacial and postglacial stratigraphy of Dinosaur Provincial Park and surrounding plains, southern Alberta, Canada. *Quat. Sci. Rev.* 11, 535-555.
- Evans, D.J.A., Campbell, I.A., 1995. Quaternary stratigraphy of the buried valleys of the lower Red Deer River, Alberta, Canada. *J. Quat. Sci.* 10, 123-148.
- Evans, D.J.A., Hiemstra, J.F., 2005. Till deposition by glacier submarginal, incremental thickening. *Earth Surf. Proc. Landf.* 30, 1633–1662.
- Evans, D.J.A., Rea, B.R., 1999. Geomorphology and sedimentology of surging glaciers: a landsystems approach. *Ann. Glaciol.* 28, 75-82.
- Evans, D.J.A., Rea, B.R., 2003. Surging glacier landsystem. in: Evans, D.J.A. (ed.) *Glacial Landsystems*. Arnold, London.
- Evans, D.J.A., Twigg, D.R., 2002. The active temperate glacial landsystem: a model based on Breidamerkurjökull and Fjallsjökull, Iceland. *Quat. Sci. Rev.* 21, 2143-2177.
- Evans, D.J.A., Lemmen, D.S., Rea, B.R., 1999. Glacial landsystems of the southwest Laurentide Ice Sheet: modern Icelandic analogues. *J. Quat. Sci.* 14, 673-679.

- Evans, D.J.A., Philips, E.R., Hiemstra, J.F., Auton, C.A., 2006a. Subglacial till: formation, sedimentary characteristics and classification. *Earth Sci. Rev.* 78, 115-176.
- Evans, D.J.A., Rea, B.R., Hiemstra, J.F., Ó Cofaigh, C., 2006b. A critical assessment of subglacial megafloods: a case study of glacial sediments and landforms in south-central Alberta, Canada. *Quat. Sci. Rev.* 25, 1638–1667.
- Evans, D.J.A., Twigg, D.R., Rea, B.R., Shand, M., 2007. Surficial geology and geomorphology of the Bruarjokull surging glacier landsystem. *J. Maps.* 349-367.
- Evans, D.J.A., Clark, C.D., Rea, B.R., 2008. Landform and sediment imprints of fast glacier flow in the southwest Laurentide Ice Sheet. *J. Quat. Sci.* 23, 249–272.
- Evans, D.J.A., Hiemstra, J.F., Boston, C.M., Leighton, I., Ó Cofaigh, C., Rea, B.R., 2012. Till stratigraphy and sedimentology at the margins of terrestrially terminating ice streams: case study of the western Canadian prairies and high plains. *Quat. Sci. Rev.* 46, 80–125.
- Evans, D.J.A., Owen, L.A., Roberts, D., 1995. Stratigraphy and sedimentology of Devensian (Dimlington Stadial) glacial deposits, east Yorkshire, England. *J. Quat. Sci.* 10, 241–265.
- Evans, D.J.A., Young, N.J.P., Ó Cofaigh, C., 2014. Glacial geomorphology of terrestrial-terminating fast flow lobes/ice stream margins in the southwest Laurentide Ice Sheet. *Geomorph.* 204, 86-113.
- Evans, D.J.A. Storrar, R.D., Rea, B., 2016. Crevasse-squeeze ridge corridors: diagnostic features of late-stage palaeo-ice stream activity. *Geomorph.* 258, 40-50.
- Eyles, N., Boyce, J.I., Barendregt, R. W., 1999. Hummocky moraine: sedimentary record of stagnant Laurentide Ice Sheet lobes resting on soft beds. *Sediment. Geology* 123, 163-174.
- Eyles, N., Eyles, C., Menzies, J., Boyce, J., 2011. End moraine construction by incremental till deposition below the Laurentide Ice Sheet: Southern Ontario, Canada. *Boreas* 40, 92-104.
- Fenton, M.M., 1984. Quaternary stratigraphy of the Canadian Prairies. in: R.J. Fulton (ed.) *Quaternary Stratigraphy of Canada - A Canadian Contribution to IGCP Project 24*. Geological Survey Canada 2, 57-68.
- Fisher, D.A., Reeh, N., Langley, K., 1985. Objective reconstructions of the Late Wisconsinan Laurentide Ice Sheet and the significance of deformable beds. *Geogr. Phys. Quat.* 39, 229–238.
- Foster, J.H., Stalker, A. Mac, S., 1976. Paleomagnetic stratigraphy of the Wellsch Valley site, Saskatchewan. *Geological Survey Canada* 1, 98-107.
- Fulton, R.J., Fenton, M.M., Rutter, N.W. 1986. Summary of Quaternary Stratigraphy and History, Western Canada. *Quaternary Science Reviews*, 5, 229-241.
- Grant, N.M., 1997. Genesis of the North Battleford Fluting Field, West-Central Saskatchewan. Department of Earth and Atmospheric Sciences. Masters Thesis. University of Alberta.
- Gravenor, C.P., Meneley, W.A., 1958. Glacial flutings in central and northern Alberta. *Amer. J. Sci.* 256, 715–728.

- Gravenor, C.P., Kupsch, W.O., 1959. Ice-disintegration features in western Canada. *J. Geol.* 67, 48-64.
- Hallberg, G.R., Kemmis, T.J., 1986. Stratigraphy and correlation of the glacial deposits of the Des Moines and James lobes and adjacent areas in North Dakota, South Dakota, Minnesota, and Iowa. *Quat. Sci. Rev.* 5, 65–68.
- Hart, J.K., 1999. Identifying fast ice flow from landform assemblages in the geological record: a discussion. *Ann. Glaciol.* 28, 59-66.
- Hindmarsh, R.C.A., Stokes, C.R., 2008. Formation mechanisms for ice-stream lateral shear margin moraines. *Earth Surf. Proc. Landf.* 33, 610- 626.
- Hulbe, C.L., Fahnestock, M.A., 2004. West Antarctic ice stream discharge variability: Mechanism, controls and pattern of grounding line retreat. *J. Glaciol.* 50, 471-484.
- Jacobel, R.W., Scambos, T., Raymond, C.F., Gades, A.M., 1996. Changes in the configuration of ice stream flow from the West Antarctic Ice Sheet. *J. Geophys. Res.* 101, 5499-5504.
- Jennings, C.E., 2006. Terrestrial ice stream – a view from the lobe. *Geomorph.* 75, 100-124.
- Johnson, M.D., Gillam, M.L., 1995. Composition and construction of Late Pleistocene end moraines, Durango, Colorado. *Geol. Soc. Amer. Bull.* 107, 1241-1253.
- Johnson, W.H., Hansel, A.K., 1990. Multiple Wisconsinan glacial sequences at Wedron, Illinois. *J. Sediment. Petrol.* 60, 26–41.
- Joughin, I., Fahnestock, M., MacAyeal, D., Bamber, J., Gogineni, P., 2001. Observation and analysis of ice flow in the largest Greenland ice stream. *J. Geophys. Res.* 106, 34021-34034.
- Klassen, R.W., 1979. Pleistocene geology and geomorphology of the Riding Mountain and Duck Mountain areas, Manitoba-Saskatchewan. Geological Survey Canada. Memoir 396.
- Klassen, R.W., 1989. Quaternary geology of the southern Canadian interior plains, in: Fulton, R.J. (ed.) *Quaternary Geology of Canada and Greenland*. Geological Society America, Colorado.
- Klassen, R.W., 1991. Surficial geology and drift thickness, Cypress Lake (72F). Saskatchewan: Geological Survey Canada. Map 1:250,000 scale.
- Klassen, R.W., 1992. Nature, origin and age relationships of landscape complexes in southwestern Saskatchewan. *Geogr. Phys. Quat.* 46, 361-388.
- Klassen, R.W., 1994. Late Wisconsinan and Holocene History of southwestern Saskatchewan. *Can. J. Earth Sci.* 31, 1822-1837.
- Krzyszkowski, D., 2002. Sedimentary successions in ice marginal fans of the Late Saalian glaciation, southwestern Poland. *Sediment. Geol.* 149, 93-109.
- Krzyszkowski, D., Zeilinski, T., 2002. The Pleistocene end moraine fans: controls on their sedimentation and location. *Sediment. Geol.* 149, 73-92.

Kulig, J.J., 1996. The glaciations of the Cypress Hills of Alberta and Saskatchewan and its regional implications. *Quat. Int.* 32, 53–77.

Kupsch, W.O., 1962. Ice thrust ridges in western Can. *J. Geol.* 70, 582-588.

Lowe, A.L., Anderson, J.B., 2002. Reconstruction of the West Antarctic Ice Sheet in Pine Island Bay during the last Glacial Maximum and its subsequent retreat history. *Quat. Sci. Rev.* 21, 1879-1897.

Marshall, S.J., Clarke, G.K.C., Dyke, A.S., Fisher, D.A., 1996. Geologic and topographic controls on fast flow in the Laurentide and Cordilleran Ice Sheets. *J. Geophys. Res.* 101, 17827–17839.

Mathews, W.H., 1974. Surface Profiles of the Laurentide Ice Sheet in its Marginal Areas. *J. Glaciol.* 13, 37-43.

Matthews, J.A., Cornish, R., Shakesby, R.A., 1979. 'Saw-tooth' moraines in front of Bodalsbreen, southern Norway. *J. Glaciol.* 22, 535-546.

Maathuis, H. and Thorleifson, L. H., 2000. Potential impact of climate change on Prairie groundwater supplies: review of current knowledge, Saskatchewan Research Council. Publication No. 11304-2E00.

Meneley, W.A., 1964. Geology of the Melford area (73A) Saskatchewan. Unpublished PhD thesis. University of Illinois.

Meriano, M., Eyles, N., 2009. Quantitative assessment of the hydraulic role of subglaciofluvial interbeds in promoting deposition of deformation till (Northern Till, Ontario). *Quat. Sci. Rev.* 28, 608–620.

Mossop, G.D., Shetsen, I., 1994. Geological Atlas of the Western Canada Sedimentary Basin. Available at: http://ags.gov.ab/publications/wcsb_atlas/atlas.ca.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J.A., Morris, P., 2002. Evolution of subglacial bedforms along a palaeo-ice stream, Antarctic Peninsula continental shelf. *Geophys. Res. Lett.* 29, 29-36.

Ó Cofaigh, C., Evans, D.J.A., Smith, R., 2010. Large-scale reorganization and sedimentation of terrestrial ice streams during late Wisconsinan Laurentide Ice Sheet deglaciation. *Geol. Soc. Amer.* 122, 743-756.

Oldenborger, G.A., Pugin, A.J.M., Hilton, M. J., Pullan, S.E., Russel, H.A.J., Sharpe, D.R., 2010. Airborne time-domain electromagnetic data for mapping and characterization of Spiritwood Valley aquifer, Manitoba, Canada. Geological Survey of Canada. Current Research 2010-11.

Patterson, C.J., 1997. Southern Laurentide ice lobes were created by ice streams: Des Moines Lobe in Minnesota, USA. *Sediment. Geol.* 111, 249-261.

Patterson, C. J., 1998. Laurentide glacial landscapes: The role of ice streams. *Geol.* 26, 643-646.

Piotrowski, J.A., Kraus, A.M., 1997. Response of sediment to ice sheet loading in northwestern Germany: effective stresses and glacier bed stability. *J. Glaciol.* 43, 495–502.

Piotrowski, J.A., Larsen, N.J., Junge, F.W., 2004. Reflections on soft subglacial beds as a mosaic of deforming and stable spots. *Quat. Sci. Rev.* 23. 993-1000.

- Price, R.J., 1970. Moraines of Fjallsjökull, Iceland. *Arct. Alp. Res.* 2, 27-42.
- Price, S.F., Whillans, I.M., 2001. Crevasse patterns at the onset to Ice Stream B, West Antarctica. *J. Glaciol.* 47, 29-36.
- Proudfoot, D.N., 1985. A lithostratigraphic and genetic study of Quaternary sediments in the vicinity of Medicine Hat, Alberta. Unpublished PhD thesis. University of Alberta.
- Rains, R.B., Kvill, D., Shaw, J., 1999. Evidence and some implications of coalescent Cordilleran and Laurentide glacier systems in western Alberta. In *A World of Real Places: Essays in Honour of William C. Wonders*. University of Alberta.
- Raymond, C.F., Echelmeyer, K.A., Whillans, I.M., Doake, C.S.M. (2001) Ice stream shear margins. in: Alley, R.B., Bindschadler, R.A. (eds) *The West Antarctic Ice Sheet: Behaviour and Environment*. American Geophysical Union, Washington.
- Rignot, E., 2006. Changes in ice dynamics and mass balance of the Antarctic ice sheet. *Philosoph. Trans. R. Soc.* 364, 1637-1655.
- Rockware Inc. 2013. 3.23 User Manual. Available at: <http://rockware.com/usermanual9.88.73>
- Ross, M., Campbell, J., Parent, M., Ross, R., 2009. Palaeo-ice streams and the subglacial landscape mosaic of the North American mid-continental prairies. *Boreas* 38, 421-439.
- Sauer, E.K., Christiansen, E.A., 1991. Preconsolidation pressures in the Battleford Formation, Southern Saskatchewan, Canada. *Can. J. Earth Sci.* 28, 1613–1623.
- Sauer, E.K., Egeland, A.K., Christiansen, E.A., 1993. Pre-consolidation of tills and intertill clays by glacial loading in southern Saskatchewan, Canada. *Can. J. Earth Sci.* 30, 420–433.
- Scott, J.S., 1976. Geology of Canadian tills, in: Leggett, R.F. (ed.) *Glacial Till*. Royal Society of Canada, Ottawa.
- Sharp, M. J., 1985. 'Crevasse-fill' ridges: a landform type characteristic of surging glaciers? *Geogr. Ann.* 67, 213-220.
- Smith, M.J., Clark, C.D., 2005. Methods for the visualization of digital elevation models for landform mapping. *Earth Surf. Proc. Landf.* 30, 885-900.
- Stalker, A.M., 1960. Ice-pressed drift forms and associated deposits in Alberta. *Geol. Surv. Can. Bull.* 57, 30-38.
- Stalker, A.M., 1961. Buried valleys in central and southern Alberta. *Geol. Surv. Can. Bull.* 15, 60-32.
- Stalker, A.M., 1968. Identification of Saskatchewan Gravels and Sands. *Can. J. Earth Sci.* 5, 155-163.
- Stokes, C.R., Clark, C.D., 1999. Geomorphological criteria for identifying Pleistocene ice streams. *Ann. Glaciol.* 28, 67-74.
- Stokes, C.R., Clark, C.D., 2001. Palaeo-ice streams. *Quat. Sci. Rev.* 20, 1437–1457.

- Stokes, C. R., Clark, C.D., 2002a. Are long subglacial bedforms indicative of fast ice flow? *Boreas* 31, 239-249
- Stokes, C.R., Clark, C.D., 2002b. Ice Stream Shear Margin Moraines. *Earth Surf. Proc. Landf.* 27, 547-558.
- Stokes, C.R., Clark, C.D., 2003. The Dubawnt Lake palaeo-ice stream: evidence for dynamic ice sheet behaviour on the Canadian Shield and insights regarding the controls on ice-stream location and vigour. *Boreas* 32, 263-279.
- Stokes, C.R., Clark, C.D., 2004. Evolution of late glacial ice-marginal lakes on the northwestern Canadian Shield and their influence on the location of the Dubawnt Lake palaeo-ice stream. *Palaeogeogr. Palaeoclim. Palaeoecol.* 215, 155-171.
- Stokes, C.R., Lian, O.B., Tulaczyk, S., Clark, C.D., 2008. Superimposition of ribbed moraines on a palaeo-ice-stream bed: implications for ice stream dynamics and shutdown. *Earth Surf. Proc. Landf.* 33, 593-609.
- Thomas, R., 1979. The Dynamics of marine ice sheets. *J. Glaciol.* 24, 167-177.
- Van der Kamp, G., 2001. Methods for determining the in situ hydraulic conductivity of shallow aquitards – an overview. *Hydrogeol. J.* 9, 5–16.
- Vaughan, D.G., Corr, H.F.J., Smith, A.M., Pritchard, H.D., Shepherd, A., 2008. Flow-switching and water piracy between Rutford ice Stream and Carlson Inlet, West Antarctica. *J. Glaciol.* 54, 41-48.
- Vaughan, D.G., Smith, A.M., Corr, H.F.J., Jenkins, A., Bentley, C.R., Stenoienm, M.D., Jacobs, S.S., Kellog, T.B., Rignot, E., Lucchitta, B.L., 2001. A review of Pine Island Glacier, West Antarctica: Hypotheses of instability vs. observations of change, in: Alley, R. B., Bindshadler, R. A. (eds.) *The West Antarctic Ice Sheet: Behaviour and Environment*. American Geophysical Union, Antarctic Research Series. 77, 257-281.
- Wellner, J.S., Lowe, A.L., Shipp, S.S., Anderson, J.B., 2001. Distribution of glacial geomorphic features on the Antarctic continental shelf and correlation with substrate. *J. Glaciol.* 47, 397-411.
- Whitaker, S.H., Christiansen, E.A., 1972. The Empress Group in Saskatchewan. *Can. J. Earth Sci.* 9, 353-360.
- Winter, K.J., Woodward, J., Ross, N., Dunning, S. A., Bingham, R.G., Corr, H.F.J., Siegert, M.J., 2015. Airborne radar evidence for tributary flow switching in Institute Ice Stream, West Antarctica: Implications for ice sheet configuration and dynamics. *J. Geophys. Res. Earth Surf.* 120, 1611–1625.

Figure captions

Figure 1: Provincial map of Saskatchewan showing the study area outlined in black.

Figure 2: Workflow model displaying the various stages of data compilation and processing employed in the analysis of the glacial geomorphology and stratigraphy of the SWSS.

Figure 3: Maps and regional stratigraphic compilations of the glacial geomorphology and surficial geology of the SWSS: Map Sheet 1 shows glacial geomorphology and surficial geology; Map Sheet 2 shows sediment thickness, palaeo-ice stream locations and bedrock topography; Map Sheet 3 shows stratigraphic cross sections compiled from borehole records.

Figure 4: Example of a composite borehole log from the SWSS: a) log created using both DIGIDATA and LOGPLOT extension in Rockworks 16™ and has been manipulated and finalised in Adobe Illustrator CS4; b) original drillers' descriptive log.

Figure 5: Buried valleys on the Canadian Prairies and North Dakota (WCSB stands for Western Canadian Sedimentary Basin). Buried valley extents are approximately denoted by double grey lines, whereas buried valley thalwegs are indicated by black lines. Red/orange colours indicate Precambrian Shield rocks; blue and purple are Palaeozoic carbonate rocks; green is Mesozoic sedimentary rock (primarily shale); and yellow is Tertiary sedimentary rock. From Cummings et al. (2012), compiled from Stalker (1961), Whitaker and Christiansen (1972), Maathuis and Thorleifson (2000) and Oldenborger et al. (2010).

Figure 6: Proposed regional correlations and estimated ages (Christiansen, 1972) of lithostratigraphic units compiled. This includes the stratigraphic framework constructed for southern Saskatchewan after Christiansen (1992) and Barendregt et al. (1998). Compiled from: Klassen (1979, 1989), Fulton et al. (1986), Andriashek and Fenton (1989), Christiansen (1992) and Barendregt et al. (1998).

Figure 7: Examples of transverse ridge types 1-4 a) SRTM imagery of TR-1 showing dense spacing and arcuate planform, (b) & (c) SRTM image and map of TR-2 depicted as green lines, d) SRTM imagery of a TR-3 complex is southern part of ice stream 1, and e) SRTM image of TR-4 (outlined by dashed line) on the ice stream 2A, interpreted as an overridden (fluted) moraine. General summit ridge is marked by line X-X'.

Figure 8: Map of the geomorphic surge signature on the footprint of Ice Stream 2B.

Figure 9: Exploded stratigraphic model of all 17 stratigraphic units recorded within the SWSS. Model is overlain with a SRTM DEM of the study area, and underlain with a bedrock topography map.

Figure 10: The pattern of distribution and thickness of DU-4 and its coincidence with faint overridden moraines (depicted in orange on Figure 3, Map Sheet 1) demarcated here by dashed black line.

Figure 11: A 2D isopach map and N-S transect through the SWSS showing the thickness of DU-6 in relation to underlying topography and the locations of the palaeo-ice stream footprints. Notable is the downflow/ice-marginal thickening towards the south along the ice stream bed. Contour intervals are in meters.

Figure 12: A 2D isopach map through the SWSS showing the thickness of DU-7 in relation to underlying topography and the locations of the palaeo-ice stream footprints. Notable is the coincidence of thickest sediment and the locations of Ice Streams 2A, B and C. Contour intervals are in meters.

Figure 13: Diagrammatic reconstructions of the Preglacial and Pre-Late Wisconsinan depositional history within the SWSS: A) Preglacial development of the Tyner and Battleford Valley systems and deposition of EMP-1 as a preglacial fluvial deposit; B) Glacial Event 1, including the advance of the first LIS ending deposition of EMP-1, deposition of EMP-2 as a lacustrine/ fluvial deposit, deposition of EMP-3 as a glacifluvial deposit, deposition of till (DU-1) and erosion of the underlying bedrock; C)

Retreat of the first LIS and deposition of glacialfluvial deposit SU-A; D) Glacial Event 2, including the advance of the second LIS and deposition of till (DU-2) and the erosion and incorporation of underlying glacialfluvial deposit SU-A; E) Readvance of ice during glacial event 2 and deposition of till (DU-3) and glacialfluvial deposit SU-B; F) Glacial Event 3, including the development of proglacial lakes and deposition of SU-C, the advance of the LIS and deposition of till (DU-4); G) Readvance of ice during glacial event 3 and deposition of till (DU-5); H) Retreat of ice and deposition of glaciallacustrine/glacialfluvial deposit SU-E.

Figure 14: Late-Wisconsinan depositional history within the SWSS: Phase A) Ice Stream 1 active flow phase resulting in the deposition of DU-6. Thick till sequences and a series of moraine ridges developed at the ice stream terminus are indicative of glacial tectonic thrusting against the regional slope; Phase B) Regional flow reorganisation after ice had reached its maximum extent during the Late Wisconsinan, including a major change in ice flow direction whereby Ice Streams 2A, B and C flow from the west and dissect Ice Stream 1. This new ice stream system expanded and captured subglacial water associated with Ice Stream 1, resulting in its eventual shutdown and stagnation. Flowing through the Battleford and Tyner buried valley systems, the active flow phase of Ice Stream 2A, B, C was topographically confined. These much thinner ice streams exhibit a surge signature, including dense CSR networks indicative of heavily crevassed termini; Phase C) Ice Stream 2A, B, C active flow phase and Ice Stream 1 stagnation, whereby moraine ridges, CSRs and lineations are preserved at the former glacier bed. Prior to complete shutdown within the trunk zone of Ice Stream 1, a linear zone of ice CSRs and hence fracturing developed in response to extension of the last active flow lobes. The incursion of small glacier lobes flowing from the NNW-SSE into the trunk zone of Ice Stream 1 also occurred leaving minor morainic arcs.

Figure 15: Regional reconstruction of ice stream flow paths during the Late Wisconsinan within eastern Alberta and western Saskatchewan. Ice stream flow paths have been drawn based on mapping undertaken in previous studies, including Atkinson et al. (2014) and Evans et al. (2014) in Area 1, Andriashek and Fenton (1989) in Area 2 and Ross et al. (2009) in Area 3. Late Wisconsinan Maximum extent drawn based on the reconstruction of Dyke et al. (2003). Ice streams are separated into flow phases 1 (white ice stream flow paths) and 2 (black ice stream flow path). It should be noted that all ice streams in each phase may not have been active simultaneously and there may have been some temporal separation in the exact timing of advance and retreat.

Figure 16: Model of till deposition associated with fast ice flow, shown by 3D and long profile depictions of variable sediment thickness across the SWSS (numbers on long profile correspond to processes in numbered panels on the left and transverse profiles in the 3D diagram labelled A-D are represented as down-ice flow till thickness changes in the panels on the right): 1. marginal thickening; 2. ice stream trunk thinning; 3. thickening as a result of overridden glacial-marginal landforms; 4. down-ice thickening associated with buried valley margins; 5. upland thinning; A. Thin till accumulation associated with the onset zone of an ice stream (Ice Stream 1) due to low sediment flux and high erosion; B. Increased till deposition associated with marginal thickening of Ice Stream 1 and also including till thickening due to overridden glacier margins; C. Increased till deposition associated with thickening down-ice of preglacial valley; D. High net till deposition associated with the terminus of an ice stream.

Table 1: Data types used in the identification and differentiation of stratigraphic units

Data type/properties	Details
Lithologic - colour	Munsell colour recorded moist for both weathered/oxidised and unweathered/unoxidised sediments. Oxidation of whole units interpreted to indicate exposure to post-depositional surface weathering (unoxidised till overlain by oxidised till is considered to represent a weathered till surface).
Lithologic – grain size	Field estimates of the dominant grain size in the <2 mm fraction. Moisture content related to grain size and expressed as dry, moist or wet.
Lithologic – pebble lithology	Only easily recognised differences in pebble lithology recorded. Many logs did not contain sufficient pebbles for meaningful counts.
Lithologic – Stratification, partings and laminations	Bedding and partings were recorded but were often distorted by drilling process.
Lithologic – Inclusions of glacially displaced sediments	Intraclasts or incorporated masses of older sediment are recorded where they are lithologically distinct from host material.
Lithologic – Nature of contact	Contact type recorded on majority of borehole logs.
Geophysical – self potential and electrical resistance	<p>Electric logs with self potential and electrical resistance available at all borehole locations. Electric logs appear to be affected by a number of factors:</p> <ul style="list-style-type: none"> - coarse-grained sediment = high resistance, only if dry. Presence of water and dissolved salts reduces resistance. - fine-grained sediment = low resistance. - lithified silt and clay (e.g. claystone & siltstone bedrock = lowest electrical resistance and higher self-potential). <p>Electric logs sensitive enough to detect differences in the properties of different tills (i.e. grain size – but also fracturing or abundant carbonate create higher electrical resistance).</p>

Table 2: Summary of subsurface-stratigraphy of the SWSS.

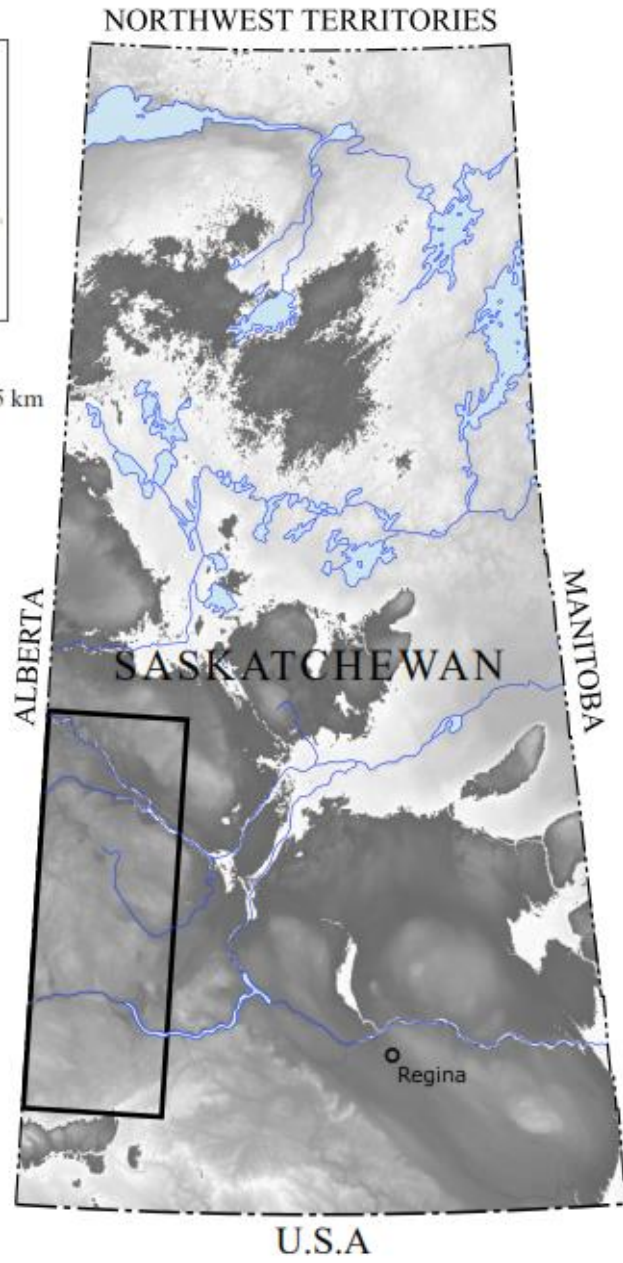
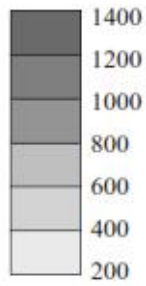
Unit	No. of samples	Unit description	Maximum Thickness (m)	Elevation Range (m a.s.l.)	Origin
Surficial Stratified Deposits (SSD)	104/197	<i>Stratified gravel, sand, silt and clay</i>	76	469-799	<i>Fluvial, lacustrine or aeolian origin</i>
Diamicton Unit 7 (DU-7)	59/197	<i>Diamicton; silty-sand</i>	20	782-467	<i>Till</i>
Stratified Unit F (SU-F)	20/197	<i>Stratified sand, gravel and silt</i>	4	707-511	<i>Glacifluvial or glacialacustrine origin</i>
Diamicton Unit 6 (DU-6)	163/197	<i>Clayey and sandy diamicton, commonly containing incorporated masses of glacially displaced sediment</i>	30	796-504	<i>Till</i>
Stratified Unit E (SU-E)	79/197	<i>Stratified sand and gravel and small amounts of silt and clay</i>	37	779-494	<i>Glacialacustrine or glacifluvial origin</i>
Diamicton Unit 5 (DU-5)	136/197	<i>Silty-sand rich diamicton; very coarse sand rich in carbonate fragments</i>	41	799-468	<i>Till</i>
Stratified Unit D (SU-D)	35/197	<i>Stratified sand and gravel</i>	13	737-490	<i>Glacifluvial origin</i>
Diamicton Unit 4 (DU-4)	47/197	<i>Clayey glacial diamicton</i>	46	730-476	<i>Till</i>
Stratified Unit C (SU-C)	62/197	<i>Stratified silt and clay in many locations also contains small amounts of sand and gravel</i>	38	745-467	<i>Glacialacustrine origin</i>
Diamicton Unit 3 (DU-3)	117/197	<i>Sand rich glacial diamicton</i>	66	743-456	<i>Till</i>
Stratified Unit B (SU-B)	16/197	<i>Stratified clay, sand and gravel</i>	24	683-559	<i>Glacifluvial origin</i>
Diamicton Unit 2 (DU-2)	61/197	<i>Clay rich glacial diamicton</i>	52	745-451	<i>Till</i>
Stratified Unit A (SU-A)	51/197	<i>Silt, sand and gravel</i>	97	735-473	<i>Glacifluvial origin</i>
Diamicton Unit 1 (DU-1)	56/197	<i>Clayey glacial diamicton interbedded with well sorted clays, silts and sands, overlain by stratified sediment in some places</i>	58	726-422	<i>Till</i>
Empress (Unit 3) (EMP-3)	16/197	<i>Stratified sand and gravel; contains clasts derived from Canadian Shield</i>	35	706-453	<i>Glacifluvial origin</i>
Empress (Unit 2) (EMP-2)	47/197	<i>Stratified clay and silt</i>	49	699-451	<i>Lacustrine or fluvial origin</i>
Empress (Unit 1) (EMP-1)	42/197	<i>Stratified sand and gravel, mainly chert and quartzite derived from the Cordilleran</i>	70	680-415	<i>Preglacial fluvial origin</i>
Bedrock	164/197	<i>Defined as all lithified clastic sediment that underlies the early Tertiary erosional surface commonly of crystalline Precambrian rock overlain by sedimentary rock cover</i>	N/A	N/A	N/A

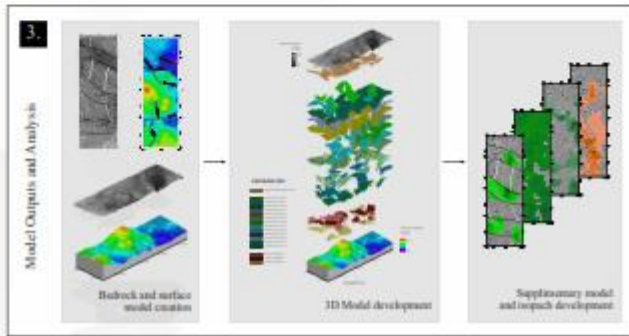
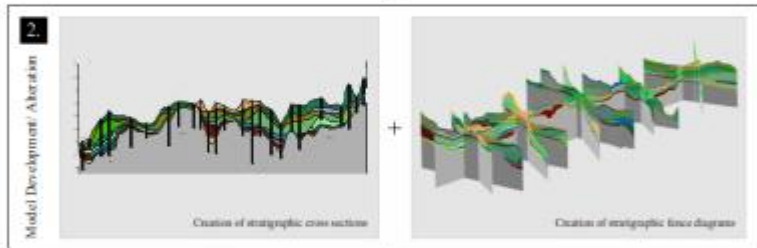
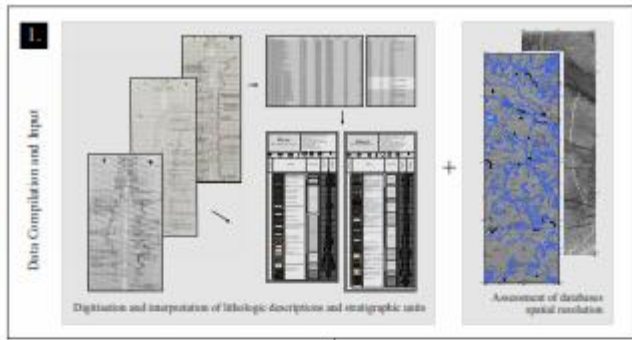


75 0 75 150 225 km

A horizontal scale bar with tick marks at 75, 0, 75, 150, and 225 km.

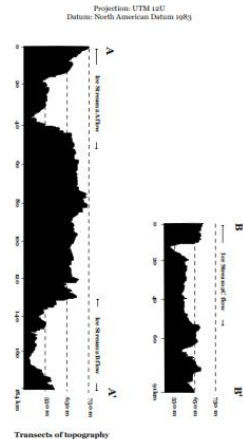
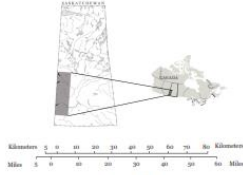
Elevation
(m a.s.l.)



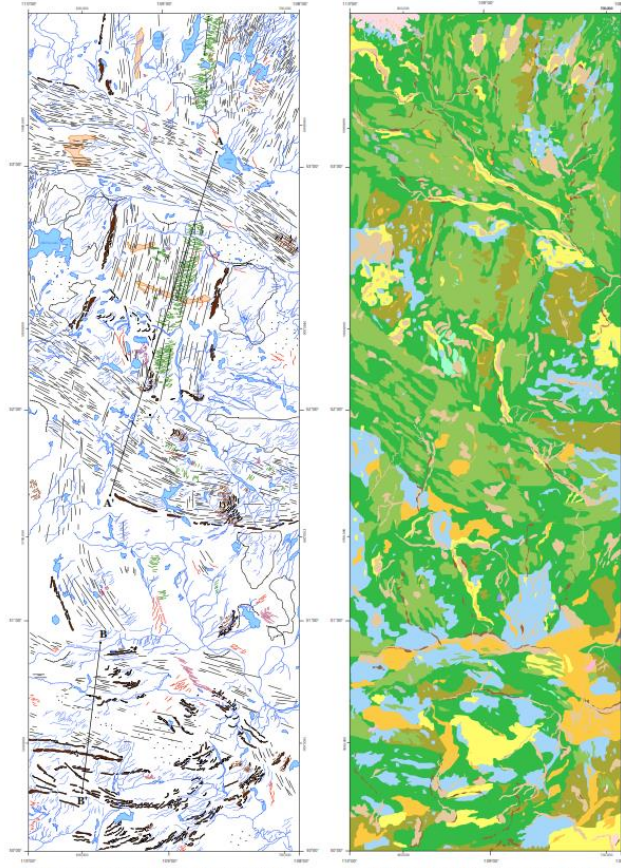


GLACIAL
GEOMORPHOLOGY and
SURFICIAL GEOLOGY
of the
SOUTHWESTERN
SASKATCHEWAN
SWATH

Map Sheet 1
(NTS 73F, 73C 72N, 72K)



Transects of topography



Glacial geomorphology of the southwestern Saskatchewan swath.

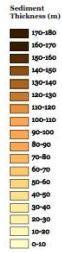
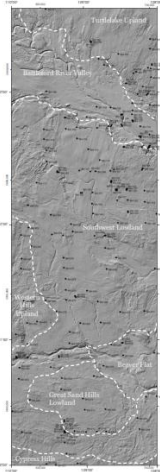
Surficial geology of the southwestern Saskatchewan swath. Adapted from: Campbell (1986a, b, 1987a, b).

LEGEND

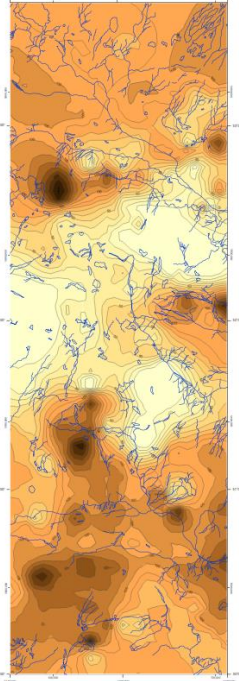
- Rivers** - Active channels
- Ponds and lakes**
- Dunes** - Small stabilized sand dunes and blowouts
- Midwater channels** - Channels cut by former glacial outflow
- Hemlocky terrane** - Heterolithic, silty ice and clastic-proximal moraine; includes glacial sands and some non-glacially derived moraine and local glacial lacustrine deposits
- Moraine crest (major)** - Ridges greater than 20 m in crest to saddle, sometimes, an entire lateral and marginal moraine
- Moraine crest (minor)** - Ridges less than 20 m in crest and usually less than 2 m high, includes interlobes, ice flow parallel ridges and marginal moraine
- Overthrust moraine crest** - Moraine ridges exhibiting geomorphological evidence for an overthrust
- Ice flow parallel lineations** - Includes glacial fluting, subterminal ridges, drumlins and mega-scale glacial lineations
- Lobes, hums, hums complex**
- Encouragement** - Bedrock, ice contact
- Geometric ridge networks** - Comprising fill areas, straight or slightly arcuate, and intersecting ridges
- Ice thrust ridges** - 20-100 m parallel sharply-crested ridges
- Organic deposits** - Silt, organic rich peat, commonly occurs as blankets found in bays occurring in low lying, poorly drained areas
- Sand deposits** - Finely sorted, sandy to gravelly material, found along slopes and at the base of steep bedrock cliffs
- Fluvial deposits** - Sand and gravel deposited by a modern stream, commonly occur on terraces and floodplains in river valleys, occasionally in well-arranged sand and gravel
- Lacustrine deposits** - Siltstone deposited in and adjacent to lakes, includes beach deposits. Predominantly sand and gravel, stratified to massive, generally moderately to well sorted
- Bedrock deposits** - Well-sorted siltstone, medium to fine grained sand, well sorted, generally massive; local sand bedding or ripple lamination
- Clastic-lacustrine deposits** - Siltstone deposited in glacial meltwater lakes, sand, silt and minor silt and gravel, generally well stratified and sorted
- Clastic-fluvial deposits** - Fine to coarse sand and pebbles to rubble-sized gravels, deposits are typically found in terraces and channel plains and in association with meltwater channels
- Moraine deposits** - Terraces consisting of unstratified, unsorted sediment deposited by a glacier; usually all the material of sand, silt and clay; locally may be composed of one or more of silt, silty sand, silty clay or siltstone and includes discontinuous layers of stratified sediment generally sand
- Fluvial moraine deposits** - All glacially originated terraces, occur from alternating furrows and ridges to nearly continuous crested hills, all sandstone flutes, drumlins and mega-scale glacial lineations, all with local sand and gravel
- Non-sand ice moraine deposits** - Terraces resulting from the collapse and lateral movement of supraglacial sediments in response to the melting of thermal dependent ice
- Ice-thrust moraine deposits** - Masses of originally subglacial sediment incorporated, transported and deposited by a glacier surge or ice mass; deposits may include supraglacial fill and masses of pre-existing till, stratified drift and/or bedrock
- Bedrock deposits**

**SEDIMENT THICKNESS,
ICE STREAM LOCATIONS and
BEDROCK TOPOGRAPHY
of the
SOUTHWESTERN
SASKATCHEWAN SWATH**

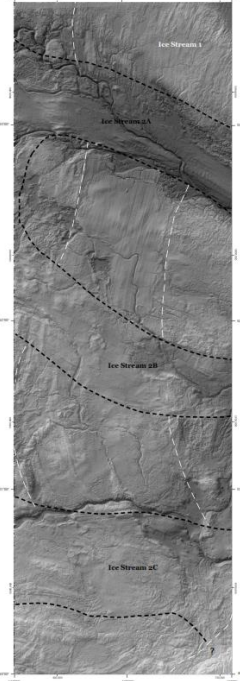
Map Sheet 2
(NTS 73F, 73C 72N, 72K)



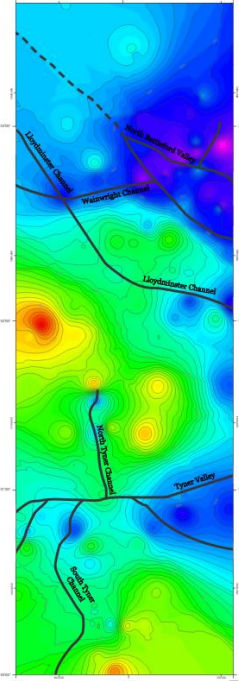
Distribution of thickness and lithographic regions referred to in this study. Each point refers to a depth interval. Location of each interval is indicated by the color. Data for this map were derived from drill cutting and core-log computer outputs.



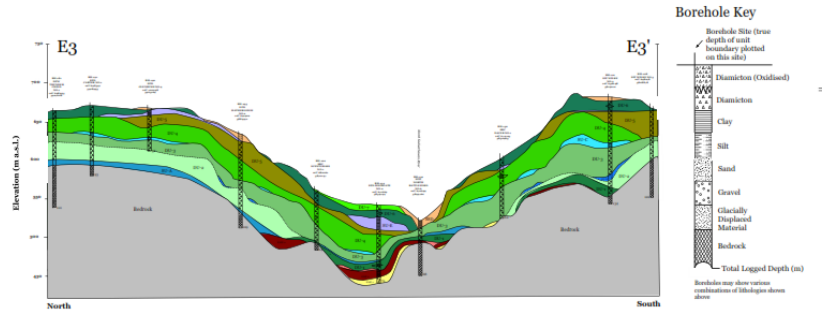
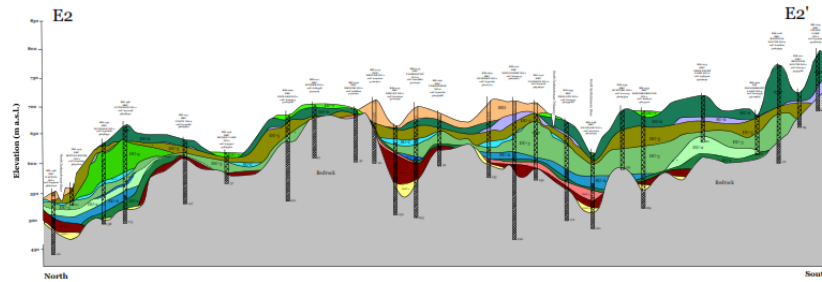
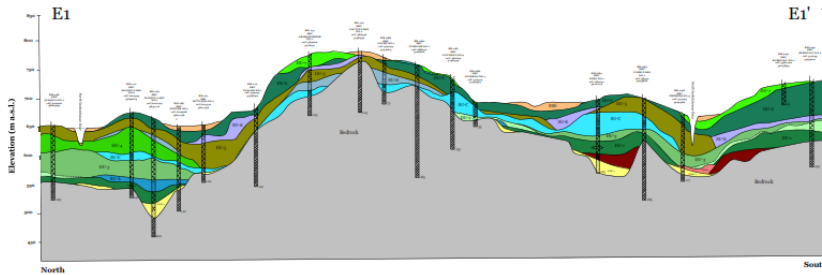
Sediment thickness of the southwestern Saskatchewan swath (this study).



Shuttle Radar Topographic Mission (SRTM) image of ice stream flow paths in the southwestern Saskatchewan swath.

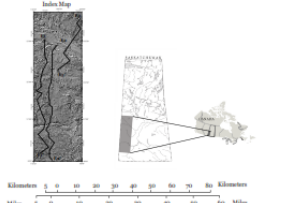


Bedrock topography of the southwestern Saskatchewan swath (this study). Solid black lines denote buried valleys (adapted from: Staffer (1981)). Dashed line represents potential buried valleys.



STRATIGRAPHIC UNITS

Artificially Modified Deposits (AMD)	Bedrock ground level and top of bedrock basement or water table
Diamictic Unit 1 (DU-1)	Thin of diamictic, clay sandy
Identified Unit 1 (IU-1)	Identified sand and gravel with clay (glaciolacustrine or glaciolacustrine origin)
Diamictic Unit 2 (DU-2)	Thin and sandy glacial diamictic, commonly interstratified with glaciolacustrine sediment
Identified Unit 2 (IU-2)	Identified sand and gravel and small amounts of silt and clay of glaciolacustrine or glaciolacustrine origin
Diamictic Unit 3 (DU-3)	Thin sand and clay diamictic, very coarse sand and silt
Identified Unit 3 (IU-3)	Identified sand and gravel of glaciolacustrine origin
Diamictic Unit 4 (DU-4)	Thin glacial diamictic
Identified Unit 4 (IU-4)	Identified silt and clay in some locations also glaciolacustrine sediment of sand and gravel of glaciolacustrine origin
Diamictic Unit 5 (DU-5)	Thin and sandy glacial diamictic
Identified Unit 5 (IU-5)	Identified silt and gravel of glaciolacustrine origin
Diamictic Unit 6 (DU-6)	Thin and sandy glacial diamictic
Identified Unit 6 (IU-6)	Thin and sandy glacial diamictic
Diamictic Unit 7 (DU-7)	Thin and sandy glacial diamictic
Identified Unit 7 (IU-7)	Thin glacial diamictic interbedded with well sorted clay with sand, commonly by irregular sandstone in some places
Diamictic Unit 8 (DU-8)	Thin and sandy glacial diamictic
Identified Unit 8 (IU-8)	Identified sand and gravel of glaciolacustrine origin
Impure Group (IGMP-1)	Identified silt and clay of glaciolacustrine or fluvial origin
Impure Group (IGMP-2)	Identified sand and gravel, mainly short and particles derived from the Canadian Shield
Impure Group (IGMP-3)	Identified sand and gravel, mainly short and particles derived from the Canadian Shield
Bedrock	Defined as all bedrock units, whether they are the early Precambrian or later Precambrian or Quaternary. Present on rock surface in unconsolidated form.



Borehole Key

Borehole Site (true depth of each boundary plotted on this site)

Symbol	Description
Symbol	Diamiction (Outlined)
Symbol	Diamiction
Symbol	Clay
Symbol	Silt
Symbol	Sand
Symbol	Gravel
Symbol	Glacially Displaced Material
Symbol	Bedrock

— Total Logged Depth (m)

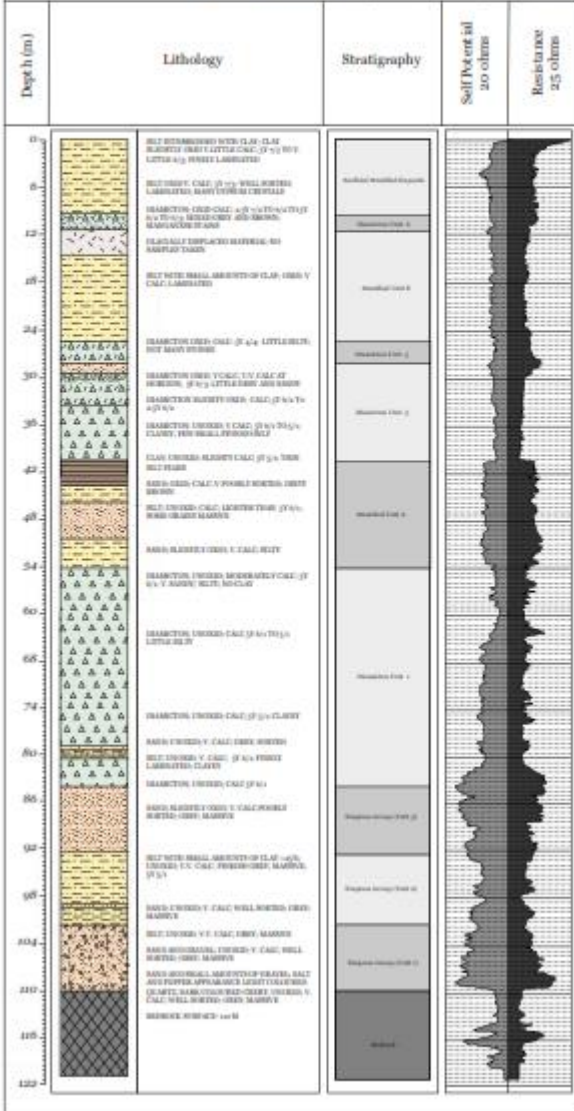
Boreholes may show various combinations of lithologies shown above

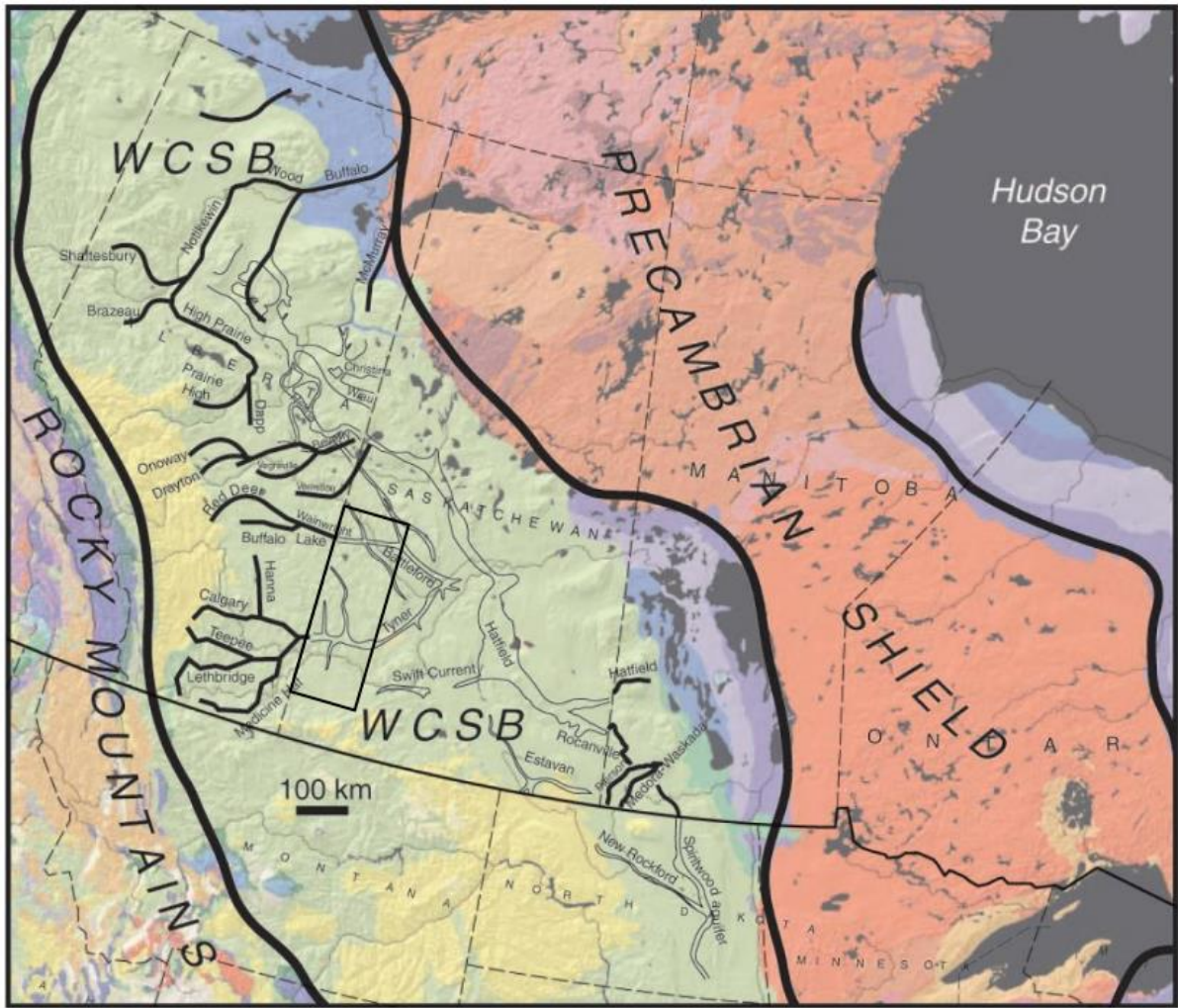
QUATERNARY STRATIGRAPHY of the SOUTHWESTERN SASKATCHEWAN SWATH

Map Sheet 3
(NTS 73F, 73C 72N, 72K)

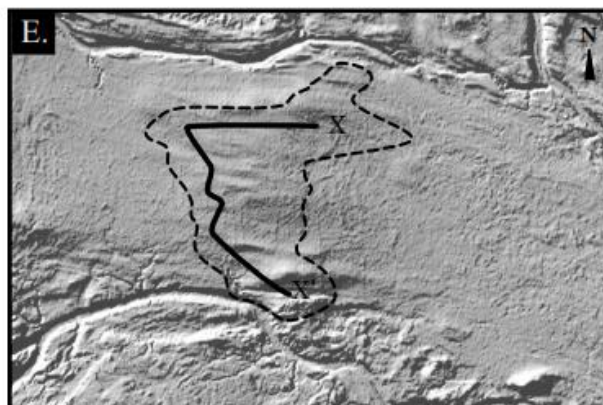
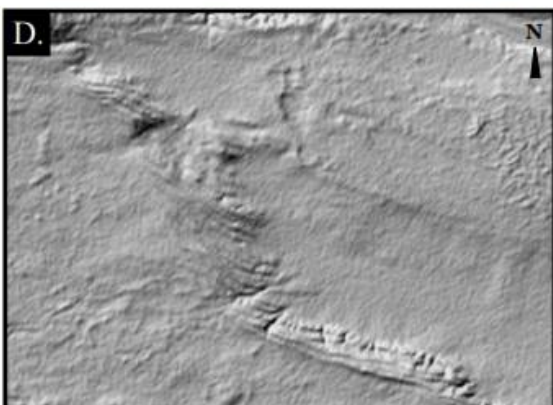
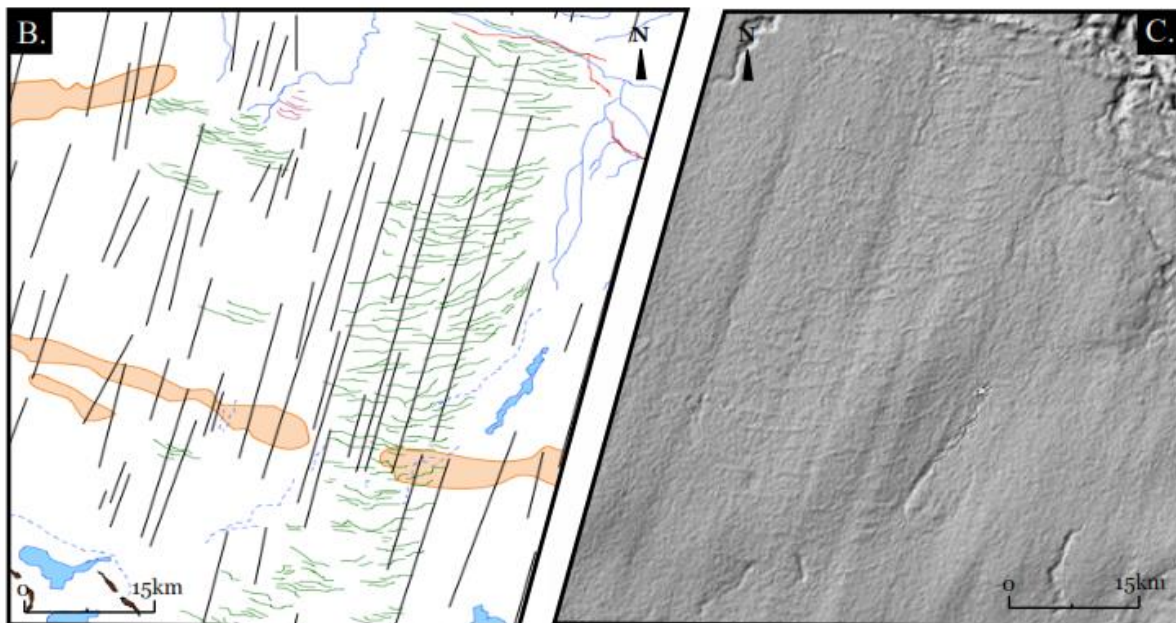
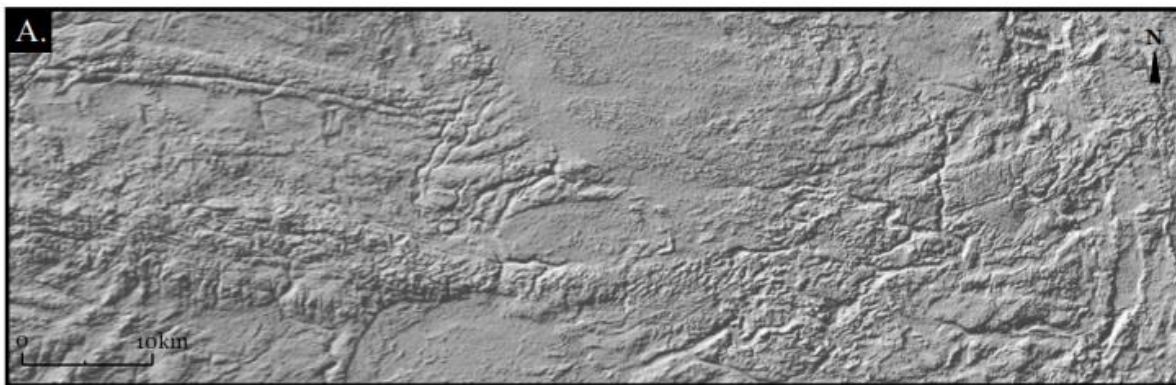
BH-038 SRC LEADER NO.1

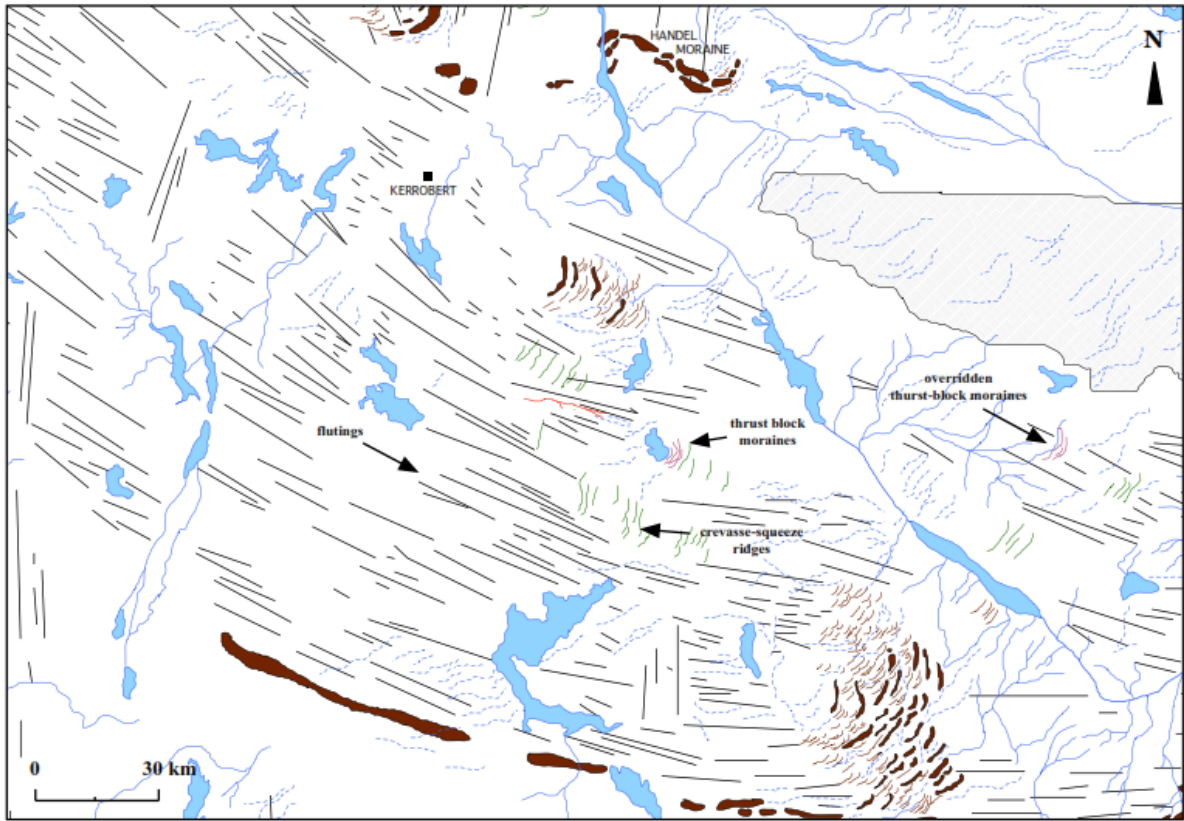
Date of Drilling (mm/dd/yyyy): --/--/1966
 Location (UTM): 12U 607022 563334
 Total Depth: 120 m
 Elevation (Ground Surface): 606 m
 Drilled by: ELK POINT DRILLING LTD.
 Drillers: Peter Malik, John Solominko
 SP COND MUD 250 0000000
 SP COND WATER 995 0000000





TIME UNITS		ENVIRONMENT	STRATIGRAPHIC UNITS							
			Saskatoon Area, Saskatchewan (Christiansen, 1992; and Barendregt et al., 1998)	Sand River Area, Alberta (Andriashek and Fenton, 1989)	Southern Alberta (Fulton et al., 1985; Klassen 1989)	Southern Manitoba (Klassen 1979, 1989)				
Quaternary	Holocene	Postglacial	Saskatoon Group	Stratified Drift	Deglacial and Postglacial Deposits	Surficial Deposits	Surficial Deposits			
		Deglacial								
	Late Pleistocene	Late Wisconsinan		Glacial	Battleford Fm.	Battleford Till (Upper)	Grand Central Fm.	Buffalo Lake Till	Arran Fm, Zelena Fm., Lennard Fm.	
				Proglacial		Battleford Till (Lower)				
		Middle Wisconsinan		Nonglacial	Floral Fm.	Weathered Zone	Sand River Fm.	Evil-smelling Band	Unnamed Deposits	
				Proglacial						
		Early Wisconsinan		Glacial		Floral Upper Till	Marie Creek Fm. (Unit 2)	Cameron Ranch Fm.	Minnedosa Fm.	
				Proglacial		Riddel Member		Mitchell Bluff Fm.	Roaring River Clay	
		Sangamon		Nonglacial		Floral Lower Till	Marie Creek Fm. (Unit 1)	? ↑ Brocket Till Maunsell Till Labuma Till ↓ ?	? ↑ Shell Fm. Tee Lakes Fm. Larg Fm. ↓ ?	
		Illinoian		Proglacial		Weathered Zone	Ethel Lake Fm.			
				Glacial						Warman Fm.
		Early and Middle Pleistocene		Pre-Illinoian		Proglacial	Dunburn Fm.			Weathered Zone
	Nonglacial					Dunburn Till				
	Proglacial					Mennon Fm.	Weathered Zone			Bronson Lake Fm.
	Glacial				Mennon Till					
	Proglacial				Empress Group	Empress Unit 3				
	Nonglacial						Empress Unit 2			
	Proglacial				Empress Unit 1					
	Glacial									
	Proglacial									
Tertiary	Pliocene		Preglacial							

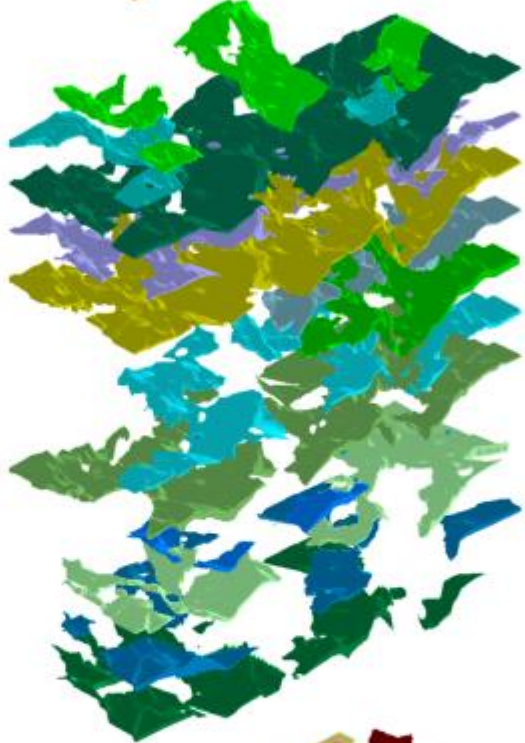
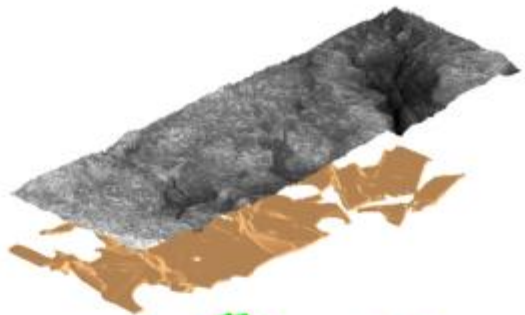




Surface Topography
Elevation
(m a.s.l.)

High
942

Low
460

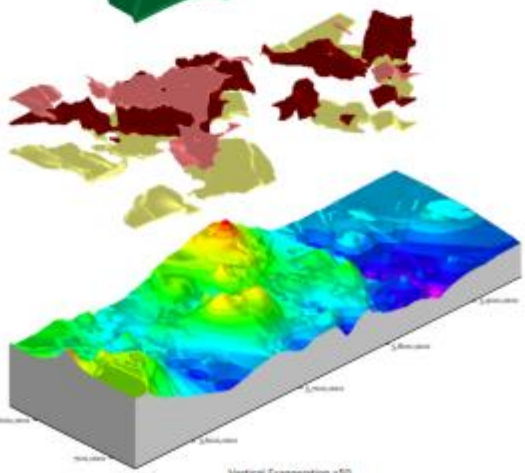


STRATIGRAPHIC UNITS

- Surficial Stratified Deposits (SSD)

- Diamicton Unit 7 (DU-7)
- Stratified Unit F (SU-F)
- Diamicton Unit 6 (DU-6)
- Stratified Unit E (SU-E)
- Diamicton Unit 5 (DU-5)
- Stratified Unit D (SU-D)
- Diamicton Unit 4 (DU-4)
- Stratified Unit C (SU-C)
- Diamicton Unit 3 (DU-3)
- Stratified Unit B (SU-B)
- Diamicton Unit 2 (DU-2)
- Stratified Unit A (SU-A)
- Diamicton Unit 1 (DU-1)

- Empress Group (EMP-3)
- Empress Group (EMP-2)
- Empress Group (EMP-1)

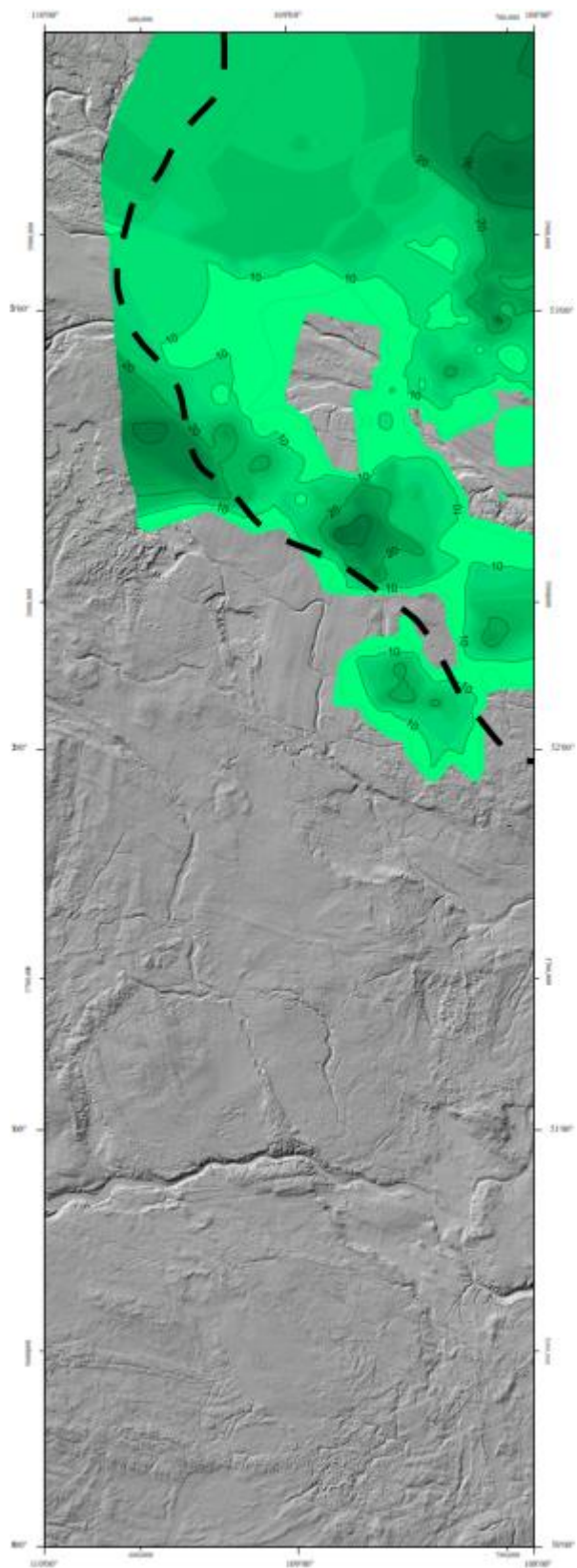


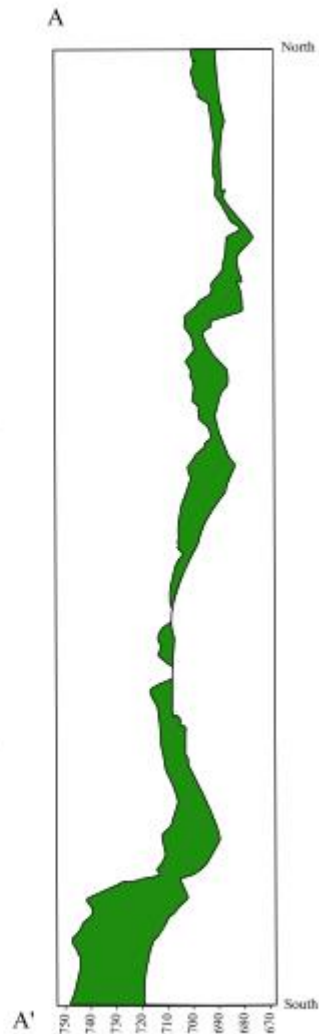
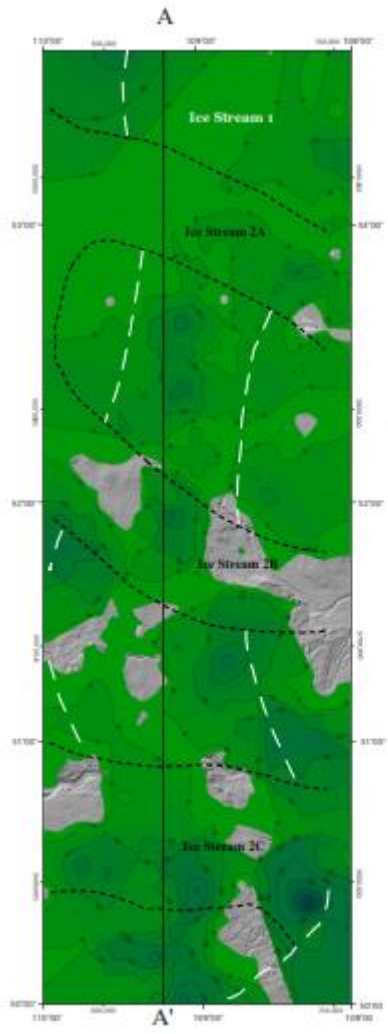
Bedrock Topography
Elevation
(m a.s.l.)

High
750

Low
490

Vertical Exaggeration x50
Vertical Offset 50 m-100 m





Elevation (m a.s.l.)

