GS-3 Far North Geomapping Initiative: Quaternary geology of the Great Island–Kellas Lake area, northern Manitoba (parts of NTS 54L, M, 64I, P)

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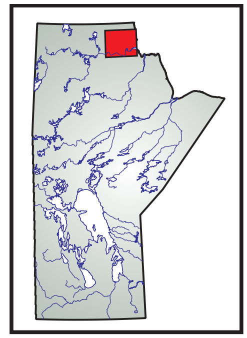

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Summary

This is the second of a multi-year collaboration between the Manitoba Geological Survey, the Geological Survey of Canada and the University of Waterloo to investigate the surficial geology in northern Manitoba, as part of the Manitoba Far North Geomapping Initiative. This surficial geology study aims to elucidate the glacial geology and geomorphology of Manitoba's far north (north of 58°) – an objective that, in conjunction with detailed bedrock mapping, will provide a modern geoscience knowledge base tailored towards current and future mineral exploration and development. This report presents a summary of fieldwork activities related to a month-long detailed survey in summer 2010. Geological observations, sampling of glacial sediments (till) and/or measurements of ice-flow indicators were recorded at 237 stations within an 8100 km^2 area in northeastern Manitoba, which extends from south of the Seal River in the Great Island area to Kellas Lake in the north. A series of 1:50 000 scale surficial geology maps is in progress for the Great Island–Kellas Lake area, which encompasses 5700 km^2. The preliminary findings of this mapping are presented herein.

The Quaternary geology survey focused on collection of ice-flow indicator data and till samples for dispersal train analysis. Samples were collected from till plains, till blankets, till veneers and from streamlined terrain and Rogen moraine terrain, in an effort to establish sediment–landform relationships in northeastern Manitoba. Once analysis and interpretations are completed, these relationships will be applied to update drift-prospecting methodologies for northern Manitoba. Additionally, Rogen moraine and streamlined terrain areas were mapped and sampled throughout the study area. To investigate the internal architecture of Rogen moraine ridges in the area, shallow shear-wave seismic reflection surveys were carried out on three Rogen moraine ridges in separate fields. Several ground-penetrating radar surveys were also attempted, but due to a combination of silty sand tills and permafrost, electromagnetic wave penetration was insufficient. New results are discussed to further the understanding of the Rogen moraine ridged landscape and to eventually postulate a formation model for Rogen moraines near the Keewatin Ice Divide in northern Manitoba.

New ice-flow indicators were found that delimit ice flow to the northeast, east and east-southeast, in addition to known ice-flow indicators trending towards the southeast, south, southwest and west-southwest. These new ice-flow indicators are usually rare and protected features, but also include fine striations on top of outcrops that signify the youngest regional flows. Not all striations and grooves developed and/or preserved directional indicators and it is hoped that dispersal train analysis, of pebbles and till matrix geochemistry, will provide additional constraints for relative chronology of the multiple ice-flow directions.

Introduction

As part of the Manitoba Far North Geomapping Initiative, an in-depth Quaternary geology study was conducted in northeastern Manitoba, from Great Island north to Kellas Lake, in July and August, 2010 (Figure GS-3-1). This report presents a summary of fieldwork activities that include surficial geology mapping at 1:50 000 scale, continued regional ice-flow indicator analysis and geophysical surveys on Rogen moraine ridges. This work builds on a reconnaissance field study undertaken in 2009 (Trommelen and Ross, 2009). The regional bedrock geological setting is provided by Anderson et al. (2009a) and Anderson et al. (GS-1, this volume).

Objectives

The main objectives of the surficial geology component of the Manitoba Far North Geomapping Initiative are to better understand the glacial geology and geomorphology of the study area and to generate geoscience data and maps that aid mineral exploration. The specific goals of the detailed surveys are to

- document micro- and meso-scale ice-flow indicators (e.g., glacial striae, roche moutonnées) in northeastern Manitoba,
- improve understanding of regional ice-flow phases,
- sample glacial sediments (till) to investigate compositional patterns (dispersal trains),

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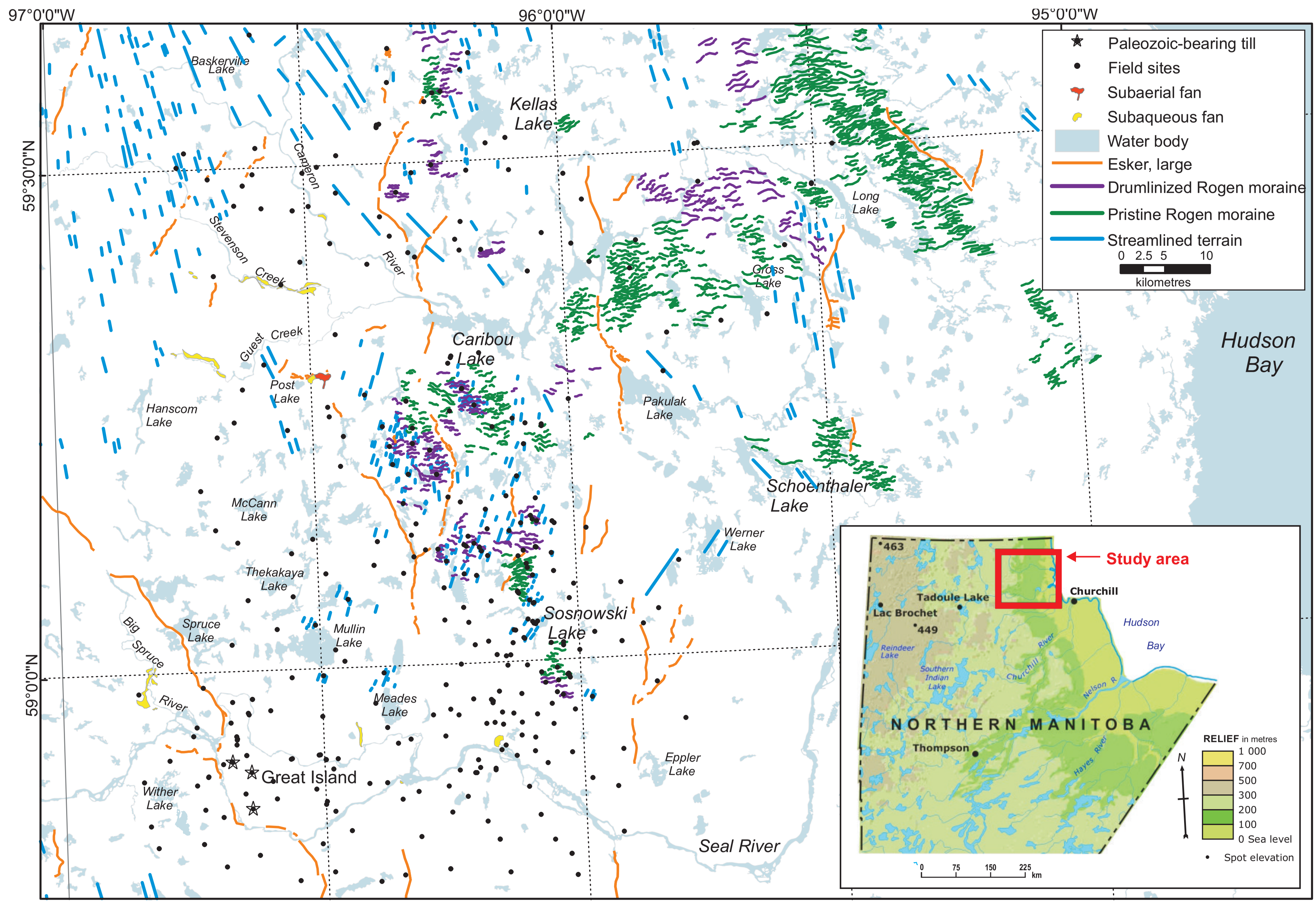

Figure GS-3-1: *Study area in northern Manitoba. Field sites include both 2009 and 2010 sites. Inset map was generated using a Shuttle Radar Topography Mission (SRTM) digital elevation model.*

- contribute empirical data from Rogen moraine ridges, as well as provide characterization of the ridges to test the various existing models of formation based on the glacial theory, and
- examine field evidence (sedimentology, geochemistry, pebble lithology) to determine if there is differentiation in internal composition between different subglacial landforms (sediment–landform relationships), with particular emphasis on establishing potential links between subglacial processes and the unusual landscape areas characterized by extensive swaths of Rogen moraine ridges alternating with streamlined terrain.

Physiography

The study area is located in the northeastern part of Manitoba (Figure GS-3-1). Elevation varies mainly from sea level to 270 m asl. Local relief is up to 30 m high.

The Seal River is the major drainage channel in the southern portion of the study area, flowing east from Tadoule Lake into Hudson Bay. Great Island refers to the area where the Seal River splits into north and south channels, before connecting into one river again. Caribou River is the major drainage channel in the northern portion of the study area, flowing east into Hudson Bay. Numerous small streams flow across the drift plains from one lake to another in an immature drainage network, or flow through the muskeg. The northern part of the map area is characterized by extensive swaths of bouldery drumlinized and pristine (nondrumlinized) Rogen moraine ridges alternating with swaths of streamlined terrain (Trommelen and Ross, in press) and areas of bedrock outcrops. The remaining area is a mix of till blankets and till veneers over bedrock. Long, large eskers are present throughout the area, at roughly 18 km intervals. Where the eskers are located below approximately 200 m asl, they have been partially eroded by lacustrine and/or marine waters. Below 150 m asl, the eskers exist as washed, low-lying sand and gravel blankets rather than ridges.

Regional glacial history

The study area was repeatedly glaciated by the Laurentide Ice Sheet (LIS) during the Quaternary, predominately from central Nunavut (Dyke and Prest, 1987; McMartin and Henderson, 2004) but also from an ice divide to the east-southeast in Quebec-Labrador (Dyke et al., 1982; Dredge, 1988; Clark et al., 2000; McMartin et al., 2009).

The central and northeastern parts of the study area are dominated by fields of Rogen moraine ridges, alternating with streamlined terrain (Aylsworth and Shilts, 1989; Dredge et al., 2007; Trommelen and Ross, in press). There is currently insufficient knowledge of the glaciological conditions and processes involved in Canadian Rogen moraine formation (Aylsworth and Shilts, 1989; Bouchard, 1989; Fisher and Shaw, 1992; Stokes et al., 2006, 2008), owing to the paucity of fieldwork in northern Canada. Several models to explain the formation of Rogen and/or ribbed moraine ridges suggest that the ridges may be draped by local detritus and that sediment at depth is farther travelled, and this has implications for drift prospecting in northern Manitoba.

The interpretation of Rogen (ribbed) moraine is contentious and some authors suggest that all ribbed moraine is formed by a similar mechanism (Hattestrand, 1997; Hattestrand and Kleman, 1999; Dunlop et al., 2008), while others suggest that various ridge types may have been formed by somewhat different processes or driving forces (cf. Moller, 2006; Linden et al., 2008; Moller, in press). Hypotheses to explain the formation of Rogen moraine ridges, based mainly on work in Scandinavia, vary in terms of subglacial process (subglacial deformation, natural instability, sliding, melt-out; Aario, 1977; Shaw, 1979; Boulton, 1987; Bouchard, 1989; Lundqvist, 1989; Hattestrand, 1997; Hattestrand and Kleman, 1999; Moller, 2006; Sarala, 2006; Schoof, 2007; Dunlop et al., 2008; Linden et al., 2008; Stokes et al., 2008; Moller, in press), ice-flow dynamics (extensional or compressional; Shaw, 1979; Bouchard and Marcotte, 1986; Boulton, 1987; Hattestrand, 1997; Hattestrand and Kleman, 1999; Sarala, 2006; Dunlop et al., 2008; Fowler, 2009), basal thermal regime (cold/warm interface or warm-based; Sollid and Sorbel, 1984; Boulton, 1987; Dyke and Morris, 1988; Bouchard, 1989; Hattestrand, 1997; Hattestrand and Kleman, 1999), water availability (sliding ice to sticky ice, subglacial meltwater; Stokes et al., 2008), and theorized obstacles at the base of the ice sheet (megaflutes, rough bedrock topography; Boulton, 1987; Bouchard, 1989; Lundqvist, 1989, 1997; Moller, 2006; Stokes et al., 2008). Most authors suggest that Rogen moraine ridges were formed subglacially under a slow or sluggish ice-flow regime, rather than a steady or fast ice-flow regime (Aario, 1977; Boulton, 1987; Dyke et al., 1992; Hattestrand and Kleman, 1999; Linden et al., 2008; Stokes et al., 2008; Fowler, 2009).

The study area has, in part, been wave washed by both the postglacial Tyrrell Sea and Glacial Lake Agassiz and other smaller disconnected glacial lakes (Dredge, 1983; Dredge and Cowan, 1989). The marine limit in the study area was previously cited as occurring between 165 and 180 m asl (Dredge and Nixon, 1992). A radiocarbon date of 7750 ±140 BP (sample GSC-3070) for emergence from the LIS was obtained from paired valves just south of the study area along the North Knife River at 110 m elevation (Dredge and Nixon, 1992).

Methods

This summer's work builds on the previous work initiated in 2009 (Trommelen and Ross, 2009). One goal for this season was to map the surficial geology, in order to provide a better delineation of the complex geomorphology and surficial geology in the area. Surficial geology in the Great Island–Kellas Lake area was first mapped in the early 1980s at a 1:250 000 scale (Dredge and Nixon, 1981a, b, 1982a, b), and later recompiled as two 1:500 000 scale maps (Dredge et al., 1985; Dredge and Nixon, 1986) along with comprehensive reports (Dredge et al., 1986; Dredge and Nixon, 1992). This extensive body of research has allowed the authors to expand upon the surficial geology and glacial dynamics at a detailed 1:50 000 scale for the study area. Prior to fieldwork, 1:50 000 scale black and white aerial photographs were pre-mapped using a stereoscope. Mapping of the 2010 project area was finalized during August and September, and submitted for digitization.

Helicopter-supported fieldwork was undertaken during a four-week period in July and August 2010, based out of a camp at Sosnowski Lake (Figure GS-3-1). A total of 237 field sites was visited to ground truth the surficial geology mapping, collect till samples, run geophysical surveys and identify ice-flow indicators. Field sites were pre-selected from Landsat and SPOT imagery, and based on potential pebble and/or geochemical tracers identified during bedrock mapping (Anderson et al., 2009a). Rogen moraine ridges and streamlined landforms were targeted for sampling to characterize the sediment–landform relationship. A total of 118 samples, each weighing approximately 2 kg, was collected from till plains, blankets, veneers, Rogen moraine ridge crests and streamlined landforms throughout the area for geochemical analysis. An additional 13 samples were collected from crests and lee-slopes of Rogen moraines to assess variability within the ridges and assist in delimiting a formation model. Striations and other ice-flow indicators were measured at 63 sites, in addition to 11 sites from 2009.

Geophysics

To better understand the internal architecture of Rogen moraine ridges in the area, two geophysical survey techniques were used – shallow shear-wave seismic reflection and ground penetrating radar (GPR). The aim of this study was to test if it was possible to identify any features of extension (cracks, wedges, normal faults) or compression (thrust planes, reverse faults, stacking, folds) within the ridges, which would aid in determining a correct model to explain Rogen moraine formation in northern Manitoba.

In the field, near-surface shear-wave seismic survey lines were run perpendicular to three Rogen moraine ridge axes, using a 24-geophone array, with a geophone spacing of 1.5 m. One additional survey was run parallel to a Rogen moraine ridge axis. This array was chosen to optimize near-surface vertical and horizontal resolution. Topography was measured along-profile using a metrestick.

Several GPR surveys were run on Rogen moraine ridges using a pulseEKKO 100 with 100 Mh antennas with 1 m separation and a step size of 0.25 m. GPR reflections are a function of the electrical properties of the dielectric permittivity (measure of a material's ability to store charge), as such the electromagnetic (EM) wave attenuates in conductive clays and silts (Schrott and Sass, 2008). Both GPR and shallow seismic surveys were chosen to increase the chance of a successful geophysical field survey in the remote north.

Results

Surficial geology

Keewatin till

The subglacial till in the Great Island–Kellas Lake area typically has a massive sandy silt to silty sand matrix with 5–30% angular to subrounded clasts. In granitic areas (Anderson et al., 2009a), the till is clast rich and boulders (40–300 cm) are often found scattered on the surface (Figure GS-3-2a).

The percentage of surface boulders varies by glacial landform, though in all cases the boulders are usually partially buried and only rarely perched or stacked. The surface of Rogen moraine ridges consists of 40–60% boulders, while the surface of streamlined terrain and till blankets/veneers consists of 10–20% boulders. In supracrustal areas (Anderson et al., 2009a), the percentage of clasts in the till depends on the lithology of the local bedrock. Generally, 5–10% boulders (26–150 cm) are present at the surface, representative of the clast-content of the till itself (Figure GS-3-2b). Where the till is thin and overlies quartz arenite or psammite, these locally derived tills appear similar to colluvium, in that the diamict contains 30–40% platy clasts – an effect of frost shattering. In depressions or in areas of previously running water, where peat is not present, the till is typically modified by frost heave, leading to the development of extensive boulder fields consisting of subrounded to rounded clasts and mixed rock types.

In general, the lithology of the till is correlative to the underlying/nearby bedrock, and exotic clasts only make up <1% (n=70) of a typical till sample. Exotic clasts include red arkose and sandstone (Thelon Formation), reddish pebble conglomerate (South Channel Formation) and red-brown feldspar rhyolite porphyry with white phenocrysts (Pitz Formation) of the Dubawnt region in Nunavut, situated approximately 300 km north of Caribou Lake (Shilts et al., 1979; Shilts, 1980; Peterson, 2006; Kaszycki et al., 2008).

Below 180–200 m asl, the tills are typically wave washed and winnowed. The intensity of washing and removal of fines varies greatly. Generally, between 140 and 200 m asl, the upper 0.5–1 m of surface tills are

***Figure GS-3-2:** Examples of till in the study area, northern Manitoba: **a)** granitoid-dominated till with abundant boulders at surface; **b)** till derived primarily from supracrustal bedrock with few boulders at surface and a finer grained matrix; **c)** hummocky ablation till near Wither Lake; **d)** Hudsonian/Labradorean till encountered in a hand-dug hole; note the silty matrix, the whitish yellow specks of weathered carbonate granules and the reddish brown specks of weathered mudstone granules.*

washed, and the resultant material is a sand-rich diamict with subangular to subrounded clasts. Fines are usually present as clay skins on clasts, but may otherwise be absent. Where sand, silt and clay have been extensively removed from thick till, boulder fields are the dominant landform. Below 140 m asl, till has often been entirely removed from the area, leaving behind bedrock draped by 10–20% boulders, and/or pebbly sand veneers and blankets.

Ablation till is present primarily in the southwestern portion of the study area (Figure GS-3-2c). The geomorphology in this area consists of hummocks, undulations and ridges, with no bedrock outcrops. The ablation till has a sandy matrix, with small (2–10 cm) lenses of well-sorted sand and clasts that are dominantly angular. Glaciofluvial ice-contact sediments/landforms in the same area suggest that abundant meltwater was present in the subglacial environment during deposition.

The above tills are considered to be of Keewatin origin, deposited by ice flowing southeast, south and southwest from the Keewatin Ice Divide (Dredge et al., 1986; Dredge and Nixon, 1992) north of the study area.

Hudsonian/Labradorean till

Till with a silty matrix was encountered in western Great Island (Figure GS-3-2d). At several sites, hand-dug holes exposed the till (Paleozoic-bearing till; Figure GS-3-1) beneath a gradational contact with 15–50 cm of glaciolacustrine silt and clay and/or Keewatin till. At one site, a field count of pebbles in the till revealed 41% granitic clasts derived from the Canadian Shield, 38% local supracrustal clasts and 22% Paleozoic (carbonate) clasts. This till is differentiated from Paleozoic clast-bearing glaciolacustrine silt and clayey silt by its massive structure, lower density and the presence of sand in the matrix.

Paleozoic bedrock is located approximately 90 km southeast of the area, near Churchill, and 110–120 km east-northeast of the area in Hudson Bay (Manitoba Department of Energy and Mines, 1980). Hence the deposition of Paleozoic clasts in the study area required transportation by ice flowing to the southwest from an ice centre in Hudson Bay, or from ice flowing west or northwest from southern Hudson Bay (Hudsonian till) or the Quebec/Labrador Ice Divide (Labradorean till; Dredge et al., 1986; Dredge and Nixon, 1992; Kaszycki et al., 2008), farther to the east-southeast.

Glaciofluvial sediments

Glaciofluvial sediments in the Great Island–Kellas Lake area predominately consist of light orange pebbly sand with occasional (2%) boulders at surface. The sand is often well sorted and massive, though occasional bedding is present in some esker ridges.

Esker ridges are the dominant glaciofluvial landform in the area. The four main esker systems consist of large (3–10 m high), long (10–25 km) and regularly spaced (10–18 km) esker segments, with smaller (1–5 m high) and shorter (0.5–10 km) esker ridges found between the large ridges. Occasional esker segments consist of kame and kettle topography up to 20 m high (Figure GS-3-3a).

Eskers below 170 m asl have been extensively wave washed, which has created resultant 'ridges' 0.25–2 m high, and a blanket of pebbly sand near the 'ridge' location. Below 155 m asl, portions of the eskers have been modified into beach ridges.

Rectilinear crosscutting pebbly sand ridges, interpreted as crevasse ridges, occur along the eastern part of the study area (Figure GS-3-3b). As these ridges occur below marine limit, wave washing has reduced the ridges down to a common height of 0.25–1 m through redistribution of sand. The distinct patterning remains and separates these landforms from true beach ridges.

Ice-contact glaciofluvial sediments occur as hummocky, undulating and ridged terrain that creates a chaotic landscape (Figure GS-3-3c). Commonly, these landforms consist of fine to medium sand, massive to horizontally bedded, with few clasts.

Glaciofluvial subaqueous fan sediments are situated at the mouth of Big Spruce River (~185 m asl), Guest Creek (~175 m asl), Stevenson Creek (~165–150 m asl) and a few other sites (Figure GS-3-1). At each site, the fans are flat topped, with no kettles or fluvial channels visible. Fan sediments were exposed at a 10 m high section along the Stevenson Creek valley (Figure GS-3-3d). The fine to medium, well-sorted sands are predominately crossbedded, with a paleocurrent direction

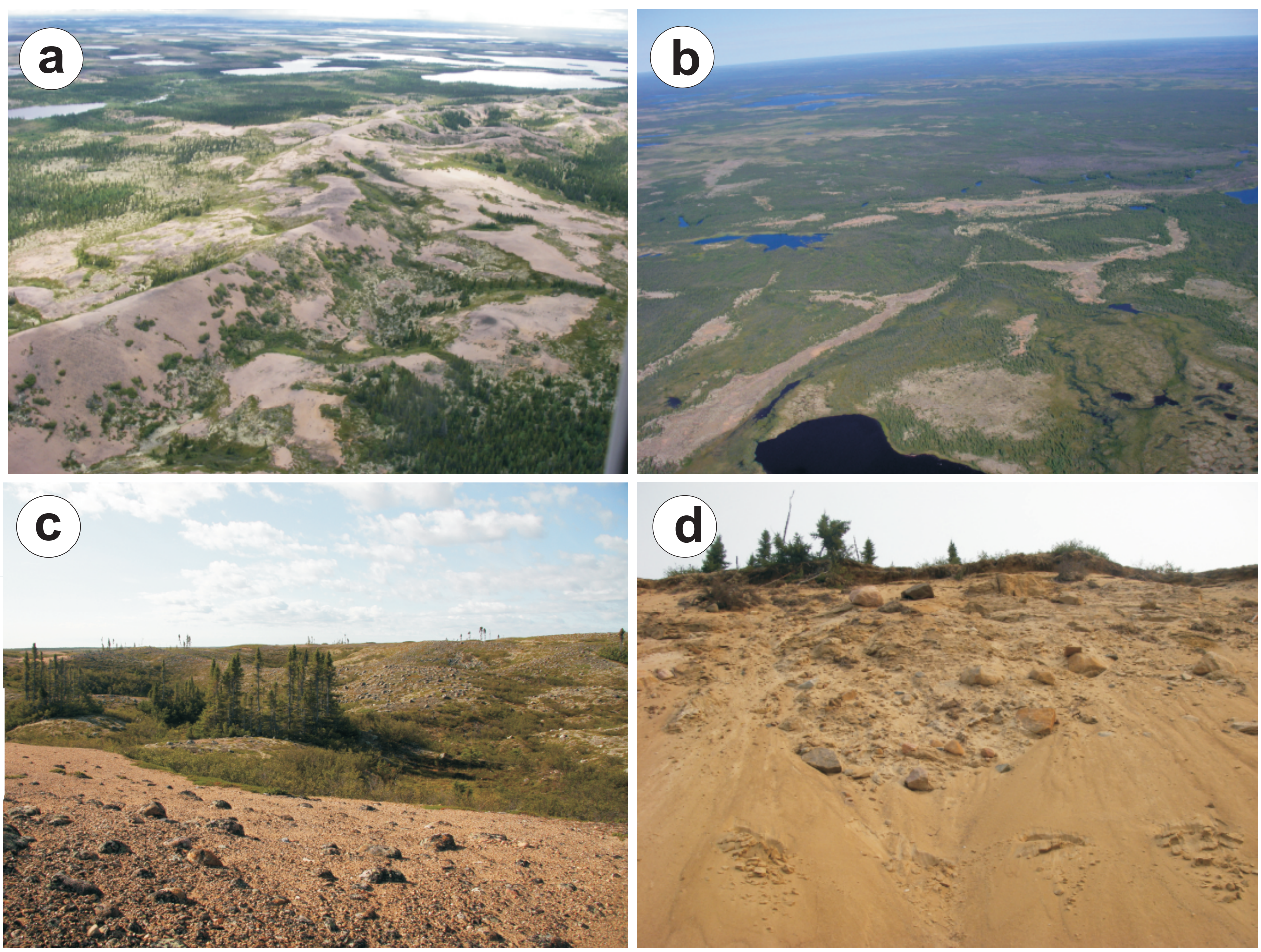

Figure GS-3-3: *Examples of glaciofluvial sediments in the Great Island–Kellas Lake area:* ***a)*** *kame and kettle segment of an esker near Sosnowski Lake;* ***b)*** *rectilinear pebbly sand ridges – crevasse ridges – in the eastern part of the study area, washed by the Tyrrell Sea;* ***c)*** *hummocky, undulating sandy glaciofluvial terrain near Kellas Lake;* ***d)*** *subaqueous fan section along Stevenson Creek; note the presence of large boulders within a fine-grained low-energy matrix.*

of east-southeast, parallel to the valley. Occasional silt drapes on ripples attest to the subaqueous nature of the deposit. In contrast to the fine-grained low-energy sands, there are a few massive to stratified diamict beds that contain facetted and striated clasts up to 1.2 m in diameter. Organic matter was not found at any of the sites. Additionally, a subaerial fan (~185 m asl) is situated just east of Post Lake (Figure GS-3-1).

The northwestern portion of the map area has been heavily inundated by subglacial meltwater, evidenced by numerous eskers (Figure GS-3-1) and minor meltwater channels but also extensive areas of washed (possibly proglacial) weathered bedrock with no till at surface and scattered glaciofluvial sandy veneers. These washed areas typically occur as corridors 250–700 m wide, which often contain an esker ridge in the middle of the corridor and 'clean' bedrock sides.

Glaciolacustrine and glaciomarine sediments

Description

Silt, clay and fine to very-fine sand, massive to weakly stratified, were encountered at 10 sites in the southwestern portion of the map area at elevations that range between 128 and 140, and between 182 and 217 m asl. Massive silts and dense/compact massive clayey silts, containing carbonate in the matrix and/or carbonate pebbles or granules, were encountered at an additional seven sites (202–262 m asl; Figure GS-3-4a).

Massive, poorly to well-sorted pebbly sand was encountered at 51 sites below elevations of 202 m asl (Figure GS-3-4b). Below 160 m asl, till has been extensively washed/winnowed. All sediments were devoid of organics with the exception of shell fragments found in a water-laid grey clay at 71 m asl.

Near esker and crevasse ridges, wave washing has redistributed the sand from these landforms, creating veneers and blankets of light orange, pebbly sand with variable percentages of more exotic rock types. East of Sosnowski Lake, bedrock draped by scattered clasts and/or sand and gravel patches is often present below elevations of 170 m asl and dominant below 130 m asl (Figure GS-3-4c).

Beach ridges are present in the study area, at elevations of 155–165 m asl (Figure GS-3-4d). Large eskers throughout the study area have been partially wave

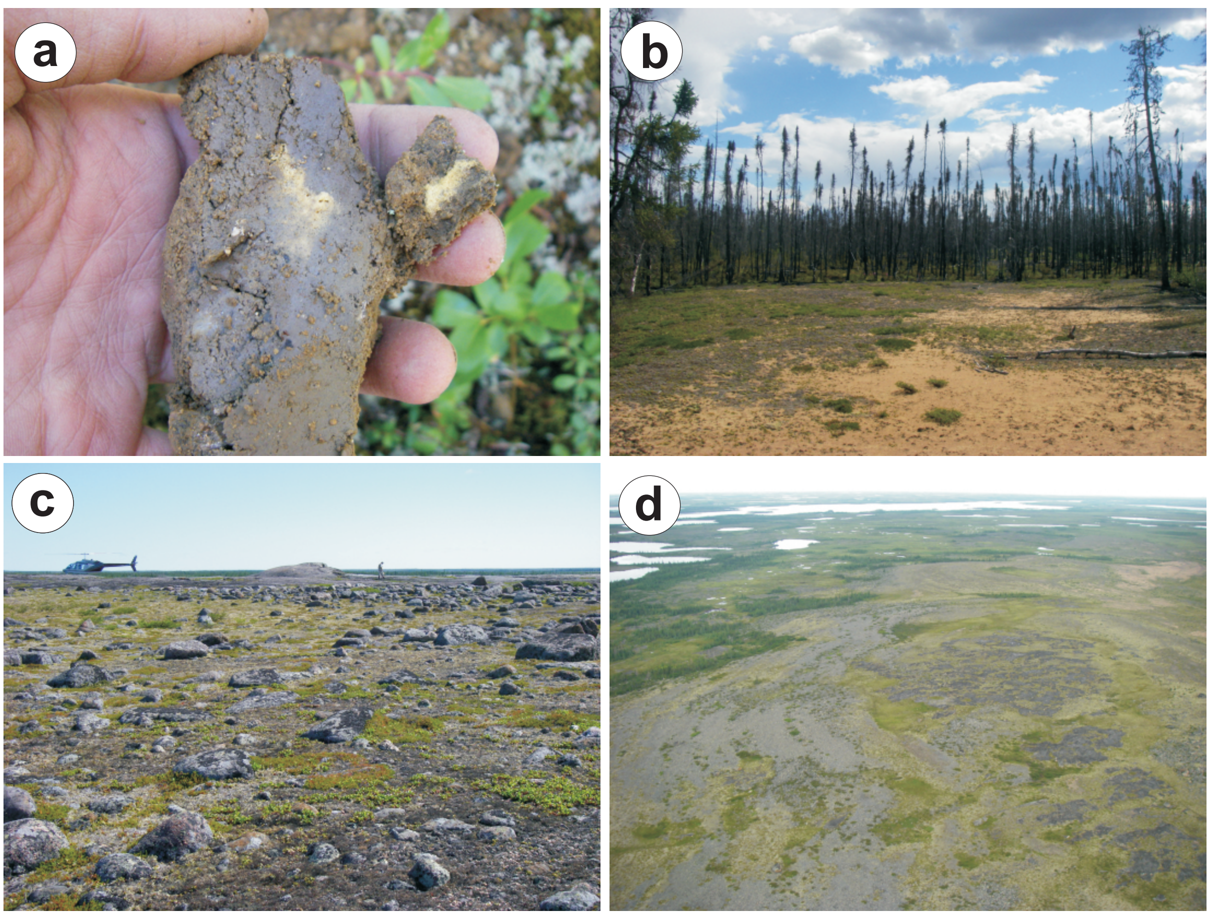

Figure GS-3-4: *Glaciolacustrine and glaciomarine sediments in the Great Island–Kellas Lake area:* ***a)*** *dense clayey silt with carbonate pebbles;* ***b)*** *massive pebbly sand blanket;* ***c)*** *typical low-lying partially wave-washed bedrock outcrop with scattered cobbles and boulders;* ***d)*** *bedrock-cored rise southeast of Kellas Lake; numerous beaches have formed on all sides and till has been removed from the top leaving bedrock with patches of sand and boulders.*

washed up to elevations of 210 m asl. Multiple subaqueous fans are documented in the area (see 'Glaciofluvial sediments' above), and water bodies at 150–185 m asl are required for the deposition of these fans.

Interpretation

The depositional environment of these water-laid sediments is difficult to interpret. The northernmost limit of Glacial Lake Agassiz is thought to occur in this area and other ice-marginal glacial lakes existed wherever drainage was blocked by topography or ice (Dredge et al., 1986). Dense glaciolacustrine clays and silts, containing carbonate granules and pebbles, found at 202–262 m asl in the Great Island area have similar characteristics to Glacial Lake Agassiz sediments situated 55 km south of the area (Dredge and Nixon, 1992). The postglacial Tyrrell Sea, however, also extended to its maximum marine limit in this area, making differentiation between marine limit and glacial lake limit difficult in some places.

Rogen moraine ridges and streamlined terrain

In northeastern Manitoba, transverse, anastomosing ridges are mapped as Rogen moraines, according to the classic definition by Lundqvist (1969, 1989, 1997), and are considered part of a landform assemblage where the ridges transition up-ice, down-ice and/or laterally to streamlined landforms. As in other Rogen moraine studies (Aylsworth and Shilts, 1989; Bouchard, 1989; Lundqvist, 1989; Hattestrand and Kleman, 1999; Dunlop and Clark, 2006), the ridges

- can occur in fields that cover extensive and continuous areas, as elongated ribbons or as narrow tracks;
- can be densely packed or dispersed or occur as isolated ridges;
- are not associated with any particular topographic expression;
- are nearly always asymmetric (cross-section) with gentle proximal slopes (10–20°) and steep distal sides (30–40°);
- exhibit undulating longitudinal crest profiles with multiple subcrests;
- have tops that are commonly drumlinized and/or exhibit close spatial associations with drumlins; and
- have tops that are often draped by angular blocks to boulders at the surface – these blocks and boulders only occur at depth in some ridges.

Five fields of Rogen moraine ridges and streamlined terrain were visited during the 2010 field season (Figure GS-3-1). Individual Rogan moraine ridges in the study area can be classified as jagged, anastomosing, broad arcuate, down-ice curving, and barchan shaped (Dunlop and Clark, 2006; Trommelen and Ross, in press). While it was originally thought that Rogen moraine ridges situated near the Keewatin Ice Divide radiated around the migratory divide (Aylsworth and Shilts, 1989; Hattestrand and Kleman, 1999; Kleman and Hattestrand, 1999; Kleman et al., in press), new detailed mapping shows that Rogen moraine ridges in northeastern Manitoba distinctly trend approximately 105, 90 or 40° in a non-radial pattern (Figure GS-3-1). Whether these orientations relate to different positions of the Keewatin Ice Divide or were caused by some other factor is unknown at this time.

Streamlined landforms (drumlins and megaflutes) range from one half to a few metres in height and 0.3–2 km in length. In the Great Island–Kellas Lake area, the streamlined landforms generally trend towards 140, 170, 180, 200 and 215° (Figure GS-3-1).

Four near-surface shear-wave seismic reflection surveys (150–200 m long) were successfully run on drumlinized Rogen moraine ridges and the data will be processed in the coming months. While conducting the GPR surveys, several field tests showed that EM wave penetration was severely limited, which was attributed to the silty sand till matrix and the presence of permafrost. As such, GPR surveys were abandoned in favour of the seismic surveys.

Ice flow

Evidence from small-scale erosional indicators

New ice-flow measurements were obtained from striations, grooves, chattermarks, crescentic scours and roche moutonnées, at 63 field sites in the Great Island–Kellas Lake area, in addition to 11 field sites from 2009. Where crosscutting striae patterns were found, the relative ages of flows were determined when possible. Directional indicators (stoss-lee relationships, crescentic scours, chattermarks) were usually present. Particularly well-preserved crosscutting relationships were obtained from well-preserved ice-flow indicators on the basalt and andesite bedrock outcrops surrounding the Meades Lake basin and in the north on granulite-grade granitoid facies. Ice-flow indicators in the study area are summarized in Figure GS-3-5.

In Figure GS-3-5a, ice-flow indicators document an early, rarely preserved, flow direction that trends 235°, and a widespread early flow direction that trends 140–160°. Isolated between Hanscom Lake, Great Island and Sosnowski Lake, some early ice-flow indicators trend 090–125°. Roche moutonnée and/or whalebacks trend to both of the above directions. Figure GS-3-5b delimits the main ice-flow direction in the study area. At almost all sites, ice-flow indicators trend between170 and 230°. Generally, most field sites indicated a shift in ice flow over time, from southeast to southwest. Several sites in the area exhibit macroforms (roche moutonnées, rock drumlins) that trend approximately 180–210°. Just north of Baskerville Lake, striations trend 045–065°. These

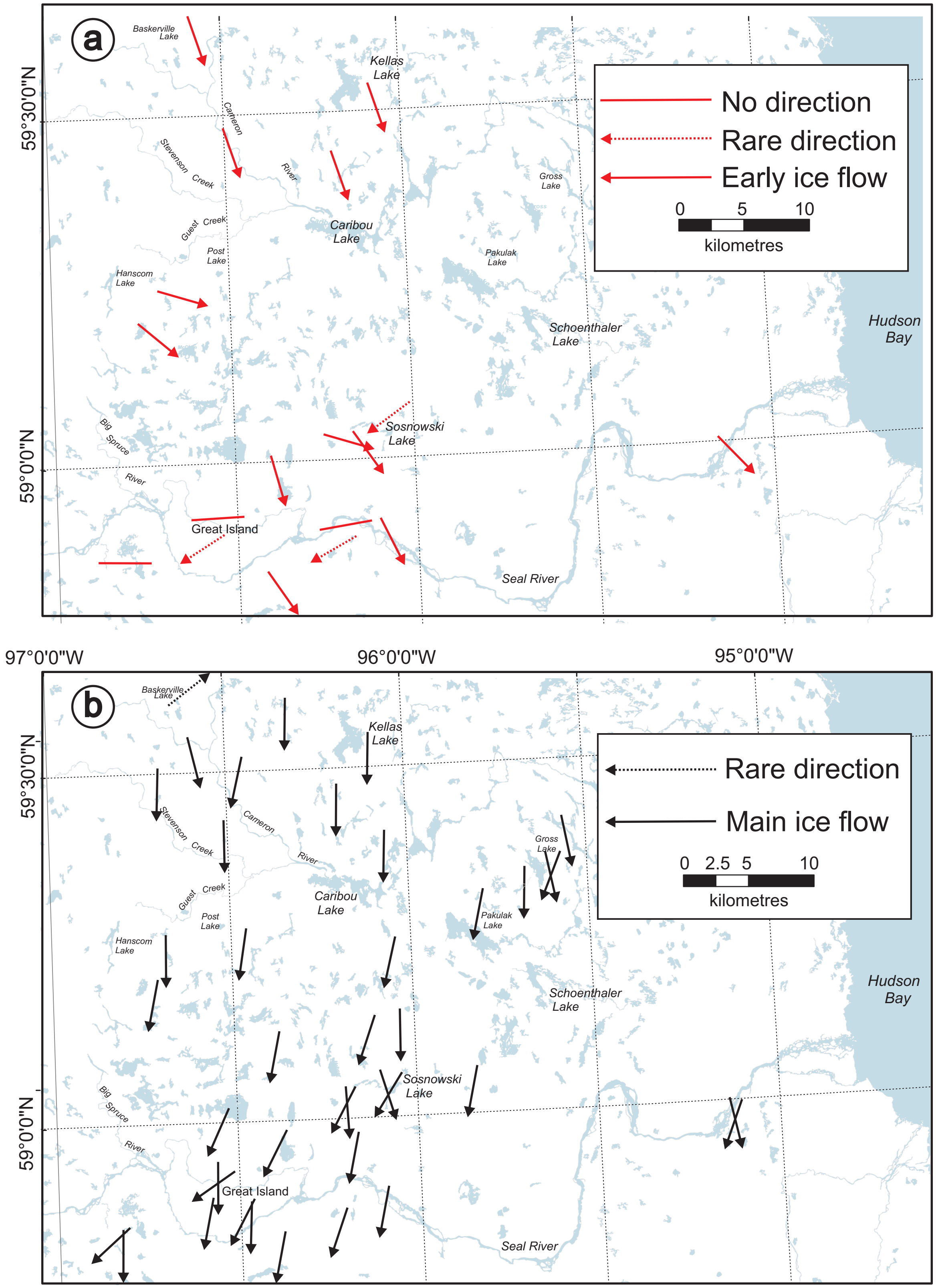

Figure GS-3-5a), b): *Simplified ice-flow indicator map (striations, grooves, chattermarks, crescentic scours, roche moutonnées, whalebacks) in the Great Island–Kellas Lake area. Direction was not known at each site, but enough sites in the area provided information to consistently assign the directions as seen on this figure:* ***a)*** *early, old ice-flow indicators are rare and/or protected in hollows or lee-slopes relative to younger ice-flow indicators;* ***b)*** *main ice-flow indicators, common throughout the area and dominant at almost any one site.*

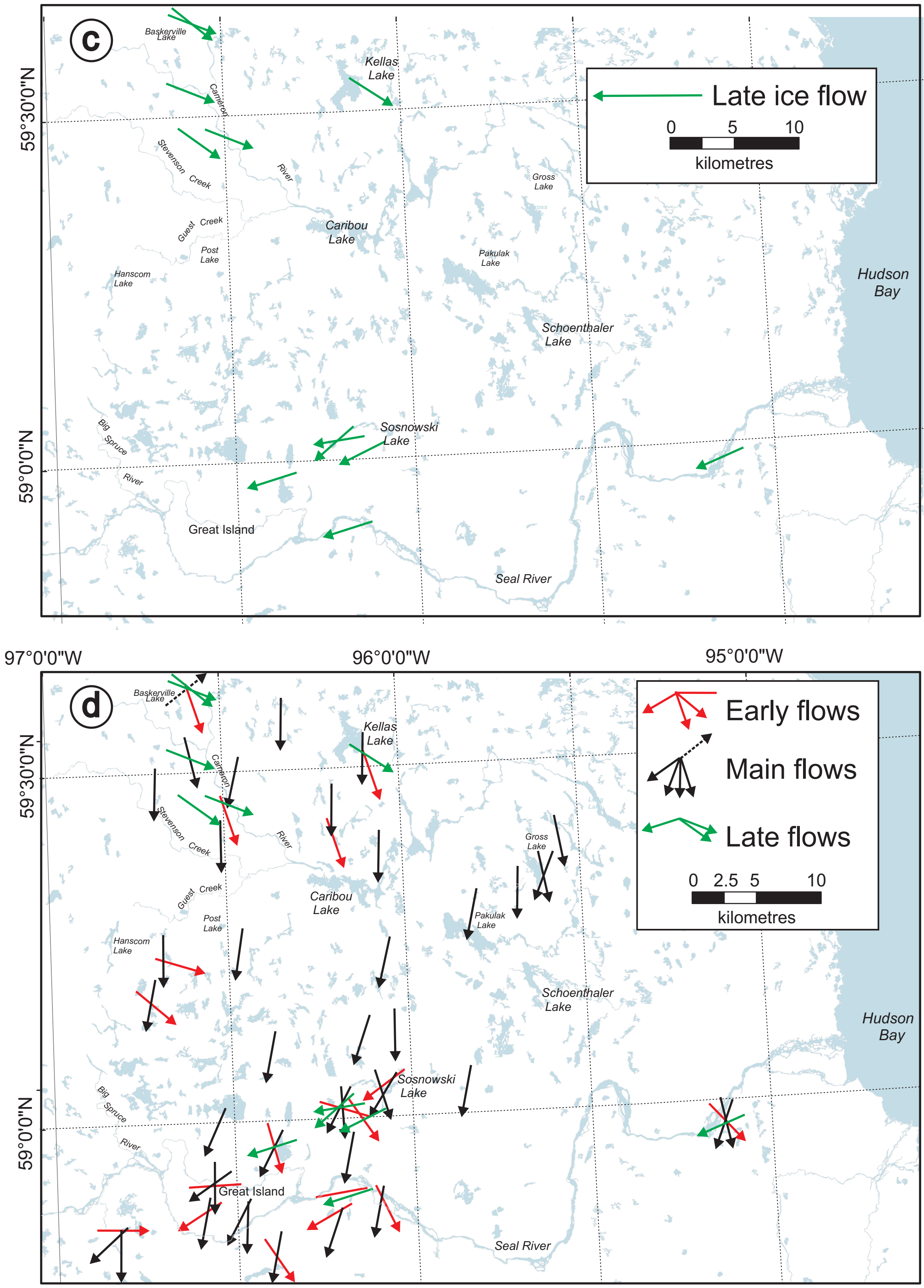

***Figure GS-3-5c), d):** Simplified ice-flow indicator map (striations, grooves, chattermarks, crescentic scours, roche moutonnées, whalebacks) in the Great Island–Kellas Lake area. Direction was not known at each site, but enough sites in the area provided information to consistently assign the directions as seen on this figure: **c)** late, youngest ice-flow indicators, rare or not present on coarser grained rocks – these are all fine, short striations, commonly situated on the top of outcrops; **d)** simplified map of all ice-flow indicators in the study area.*

striations were first identified by Dredge and Nixon (1981b) and their presence and direction was confirmed during fieldwork in 2010. Lastly, Figure GS-3-5c documents the younger ice-flow indicators in the area, as determined by crosscutting relationships. These ice-flow indicators are almost all fine striations that occur on the top of outcrops. In the north, from Baskerville Lake south to the Stevenson Creek, and east to Kellas Lake, striations were found that trend 110–120°. In the south, from Sosnowski Lake to Meades Lake and along the Seal River to a site 20 km west of Hudson Bay, young striations trend 250–260°. Figure GS-3-5d is a simplified summary of ice-flow indicators in the study area.

Evidence from large-scale indicators

The orientation of streamlined landforms in the study area can be seen in Figure GS-3-1. Between Sosnowski Lake and Caribou Lake, the majority of these drumlins and megaflutes trend south to southwest (180–205°). From Caribou Lake to the northern limit of the study area, most streamlined landforms trend southeast to south-southeast (160–170°). In the northwest, at Baskerville Lake, a few streamlined landforms also trend approximately 050–230°. The abundance of these northeast-trending streamlined landforms increases north of the study area (Trommelen and Ross, in press) to Commonwealth Lake and into Nunavut (Aylsworth et al., 1990).

Preliminary interpretations

Both small- and large-scale ice-flow indicators suggest the position of the Keewatin Ice Divide shifted over time, generally resulting in ice-flow directions first to the southwest, then to the southeast, and followed by a clockwise shift to south and southwest. These observations are consistent with a published reconstruction suggesting major shifts of the Wisconsinan Keewatin Ice Divide north of the study area (e.g., McMartin and Henderson, 2004). Newly discovered early ice-flow indicators in the Great Island area suggest ice flowed to the east-southeast, and to the east or west, at some point in time. Dredge et al. (1986, Chekask hills), Campbell (2002, part of 64M) and Smith (2006, part of 64L) have also recorded rare striae that trend 115–295° in northwestern Manitoba and northeastern Saskatchewan. It is possible that these striations indicate ice flow from an ice divide centred farther west in the south-central part of the District of Mackenzie (Dredge et al., 1986).

Both striations and streamlined landforms in the northwestern corner of the study area indicate flow to the northeast. It is possible that these drumlins and striations were formed by ice flowing northeast into a tributary of the Hudson Strait ice stream (Ross et al., in press) or into an open Hudson Bay.

The youngest striations discovered during the 2010 mapping are particularly interesting. The northern set of east-southeast-trending striations is not parallel to esker ridges, but is parallel to a few minor meltwater channels that crosscut the main eskers, as well as the subaqueous fans in Stevenson Creek and Guest Creek. Thus, the east-southeast-trending striations likely record local ice flow, near the margin, during late deglacial retreat in the northwestern part of the study area. The southern west-southwest-trending striation set is more problematic to interpret. These striations suggest ice flowed from the east-northeast, which is the centre of Hudson Bay, north of the deglacial position the Quebec/Labradorean Ice Divide (Kleman et al., 1994; Clark et al., 2000; Jansson et al., 2002). Hence, the orientation of these striations lends credence to the concept of a 'Hudsonian' ice centre or 'saddle' (Dredge and Cowan, 1989) located in central Hudson Bay during Late Wisconsinan deglaciation. Contrastingly, these striations may have been formed by a very late-stage deglacial ice remnant in northeastern Manitoba, though there are no esker ridges of this orientation.

Future work

Ongoing surficial geological analysis focuses on tracing lithological indicators from known bedrock source areas, using pebble counts and analysis of the major- and trace-element geochemical composition of the till samples collected. Results of these analyses will

- establish the compositional till characteristics of Rogen moraine fields and streamlined terrains and aid in the investigation of subglacial transport processes and distances;
- confirm the known fuchsite-rich (Cr-rich mica), silicified and brecciated metavolcanic outcrops just northeast of Great Island (Anderson et al., 2009b) as the source for reported arsenic till geochemistry anomalies (Dredge and Nielson, 1986; Dredge and Pehrsson, 2006; Dredge and McMartin, 2007), and to map its glacial dispersal train; and
- delimit how the complex ice-flow record affected the strength of sediment erosion/transportation/deposition in the area, knowledge of which is required for mineral exploration using tills.

Economic considerations

As bedrock outcrops are rare, a thorough understanding of surficial geology is essential for drift prospecting in Manitoba's northern region. Till geochemistry is commonly used in drift-covered regions, but is more difficult to interpret in palimpsest terrains that have been modified by more than one ice advance and transport direction. Forthcoming results will provide new constraints to drift exploration in this area, applicable to exploration for a variety of commodity types including diamonds, precious and rare metals and uranium (Dredge and Nielson, 1986; Dredge et al., 1986; Syme et al., 2004; Dredge and

Pehrsson, 2006; McCurdy et al., 2010). Ongoing surficial geological studies aim to provide

- a detailed framework for the directions, timing and nature (e.g., erosional or depositional) of major and minor ice-flow events in the area;
- dispersal train patterns as measures for ice transport distances and directions; and
- guidelines for the preferred sampling media for geochemical analysis, as a large portion of the area has been wave washed and may not have retained its local geochemical signature indicative of the underlying bedrock.

The outcomes of these studies are geared toward providing mineral exploration geologists with an up-to-date surficial geology knowledge base and the adequate tools to more accurately locate exploration targets in Manitoba's far north.

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