OF2017-4

Quaternary stratigraphy and till composition along the Hayes, Gods, Nelson, Fox, Stupart, Yakaw, Angling and Pennycutaway rivers, northeast Manitoba (parts of NTS 53N, 54C, 54D, 54F)

By
T.J. Hodder, M.S. Gauthier
and E. Nielsen

OPEN FILE

Manitoba

Open File OF2017-4

Quaternary stratigraphy and till composition along the Hayes, Gods, Nelson, Fox, Stupart, Yakaw, Angling and Pennycutaway rivers, northeast Manitoba (parts of NTS 53N, 54C, 54D, 54F)

by T.J. Hodder, M.S. Gauthier and E. Nielsen

Winnipeg, 2017

When using information from this publication in other publications or presentations, due acknowledgment should be given to the Manitoba Geological Survey. The following reference format is recommended:

Hodder, T. J., Gauthier, M.S. and Nielsen, E. 2017: Quaternary stratigraphy and till composition along the Hayes, Gods, Nelson, Fox, Stupart, Yakaw, Angling and Pennycutaway rivers, northeast Manitoba (parts of NTS 53N, 54C, 54D, 54F); Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, Open File OF2017-4, 20 p.

NTS grid: 53N, 54C, 54D, 54F

Keywords: Angling River; clast lithology; Fox River; Gods River; Hayes River; Hudson Bay Lowland; KIM; kimberlite-indicator-minerals; Nelson River; northeast Manitoba; Pennycutaway River; Quaternary stratigraphy; Stupart River; till; till geochemistry; till provenance; Yakaw River

Published by:

Manitoba Growth, Enterprise and Trade
Manitoba Geological Survey
360–1395 Ellice Avenue
Winnipeg, Manitoba
R3G 3P2 Canada

Telephone: 1-800-223-5215 (General Enquiry)
204-945-6569 (Publication Sales)
Fax: 204-945-8427

E-mail: minesinfo@gov.mb.ca

Website: manitoba.ca/minerals

ISBN No.: 978-0-7711-1588-2

This publication is available to download free of charge at manitoba.ca/minerals

Cover illustration: Glacial and post-glacial sediments exposed along the Angling River, Hudson Bay Lowland, Manitoba. This site was visited in 2015 by T. Hodder and was sampled during the 2002 field season by E. Nielsen.

Abstract

The data enclosed within this report was collected by E. Nielsen while he was an employee of the Manitoba Geological Survey (MGS) during the 2001 and 2002 field seasons (Nielsen, 2001, 2002). The 2001 field data was published (Nielsen and Fedikow, 2002), but not the 2002 field data. Kimberlite-indicator-minerals results from 2002 field season were published within the Manitoba Geological Survey KIMs database (Keller et al., 2004), but are reproduced within this report to provide stratigraphic context.

Due the valuable nature of the unpublished data collected, and ongoing work in the Hudson Bay Lowland, the MGS has compiled both the published and unpublished data and released it within the this open file publication. E. Nielsen's original field notes and analytical data were compiled by T. Hodder, and utilized to construct stratigraphic columns and interpretations regarding the Quaternary sediments.

TABLE OF CONTENTS

Page

TABLES

FIGURES

APPENDICES

Introduction

The Manitoba Geological Survey (MGS) conducted multimedia surveys across the northern Superior Province during the 1990s as part of Operation Superior (e.g., Fedikow et al., 2000, 2001). At the time, kimberlite-indicator-mineral (KIM) anomalies attracted an interest within the exploration industry, but the source(s) remained elusive. To extend KIM data to the northeast, sediment exposures along river cuts were investigated by the MGS during the 2001 and 2002 field season (Nielsen, 2001, 2002; Nielsen and Fedikow, 2002). Results from the 2001 survey have been published (Nielsen and Fedikow, 2002), and additional data and interpretations are provided in this report (e.g., clast-fabric data and stratigraphic columns).

The purpose of this report is to release data from the 2002 field season and compile Quaternary stratigraphic data collected during fieldwork in the area. A total of 24 stratigraphic sections were logged and sampled during this study (Figure 1). Regional-scale insight into till composition, ice-flow history and dispersal patterns is provided using clast-lithology data and ice-flow indicators.

Regional Setting

The study area is located in northeastern Manitoba (Figure 1) and field sites were restricted to river bluffs that exposed Quaternary sediments. Elevation varies from 250 m above sea level at Brassey Hill near section HR6 to sea level at Hudson Bay. Drift cover is generally thick throughout the entire study area. Bedrock exposures are rare and often only observed at the base of river cuts. The area falls within the extensive discontinuous and continuous regions of permafrost (Sladen, 2011), and most of the area is covered by thick organic deposits (Klassen and Netterville, 1978; Klassen and Netterville, 1980; Dredge and Nixon, 1982; Clarke, 1989).

Bedrock Geology

The bedrock geology of the area consists of Precambrian (Proterozoic and Archean) rocks in the southwest and Paleozoic rocks in the northeast (Figure 2). Paleozoic rocks are predominantly Ordovician carbonate rocks of the Bad Cache Rapid Group, Churchill River Group and Red Head Rapids Formation (Nicolas and Young, 2014). Silurian carbonate rocks of the Severn River Formation and Ekwan River Formation are present in the northeast (Nicolas and Young, 2014).

The Proterozoic Fox River belt trends east–west across the study area (Figure 2) and is composed of mafic to ultramafic volcanic rocks, mafic to ultramafic intrusive rocks and sedimentary units comprising pelitic sandstone and siltstone with minor iron formation and calcareous beds (Rinne, 2016). A carbonate outlier has been identified in the Fox River belt from drillcores (Rinne, 2016). Proterozoic paragneiss and metagreywacke north of the Fox River belt, and Archean granitoid rocks are present south of the Fox River belt (Rinne, 2016; Figure 2).

Quaternary Geology

Northeast Manitoba has been repeatedly glaciated throughout the Quaternary period (Dredge and Nixon, 1992) and most recently during the Wisconsin glaciation by the Laurentide ice sheet (LIS). The Hudson Bay Lowland (HBL) was affected by ice flowing from the north trending to the south (from central mainland Nunavut) and from the east trending to the west (from central Quebec/Labrador). The waxing and waning of ice from these regions has resulted in a complex ice-flow history in northeast Manitoba, with a 270° spread in the orientation of ice flow over time (e.g., Trommelen, 2012; Trommelen, 2013a, 2014).

The study area contains thick sequences of glacial sediments that were transported, deposited and eroded during at least three glacial cycles. The stratigraphic framework for northeast Manitoba was compiled by Dredge and McMartin (2011) and consists of the pre-Wisconsinan Sundance (oldest) and Amery tills, followed by the Wisconsinan Long Spruce and Sky Pilot tills. The naming of till sheets originates from a time where surface tills (and hence buried tills) were assumed to be relatively homogeneous over long distances. Detailed work on the surface tills of northern Manitoba has shown that these tills are better understood as compositional mosaics, due to potentially complex spatiotemporal shifts between deposition, preservation and erosion (Trommelen et al., 2012; Trommelen and Ross, 2014; Trommelen, 2015, *in press*). It is likely that this interpretation applies to subsurface till sheets within the HBL as well (Trommelen, 2013b; Trommelen et al., 2014b; Hodder et al., 2015; Kelley et al., 2015; Gauthier et al., 2016).

Continental-scale erratics

The lithology of clasts within till can assist with the delineation of glacial transport directions and distances (glacial dispersal), as well as potentially identifying unmapped bedrock units. Glacial dispersal can be mapped at varying scales from continental (hundreds of kilometres) to regional (tens of kilometres) to local (<10 km). In northern Manitoba, two groups of distinctive erratics are the result of continental-scale glacial dispersal from northern and eastern source areas.

The Omarolluk Formation, of the Belcher Group in southeastern Hudson Bay (Figure 3), is a distinctive greywacke with hemispherical calcareous concretions (Gauthier, 2017). These erratics, commonly referred to as Omars (Prest et al., 2000), were transported westward ~800 km into the study area by the LIS. As such, the presence of Omars within glacial sediments has been used to infer an eastern provenance (Prest et al., 2000; Nielsen, 2002; Trommelen et al., 2013). Omars are easily identified in the large pebble to boulder size-fractions, but in smaller size-fractions these erratics become more difficult to confidently identify. Metavolcanic and metasedimentary rocks that comprise greenstone belts in the Canadian Shield can often resemble the matrix of Omar clasts. As such, Omar clasts without distinctive concretions and greenstone clasts are indistinguishable during clast-lithology counts.

Distinctive erratics derived from the Dubawnt Supergroup of central mainland Nunavut are also found throughout northern Manitoba (Dredge and McMartin, 2011). These include reddish to pinkish sandstone and conglomerates of the Thelon Formation, purple to mauve rhyolite with glassy quartz and chalky sanidine phenocrysts and volcaniclastics with phlogopite phenocrsyts of the Christopher Island Formation (Rainbird

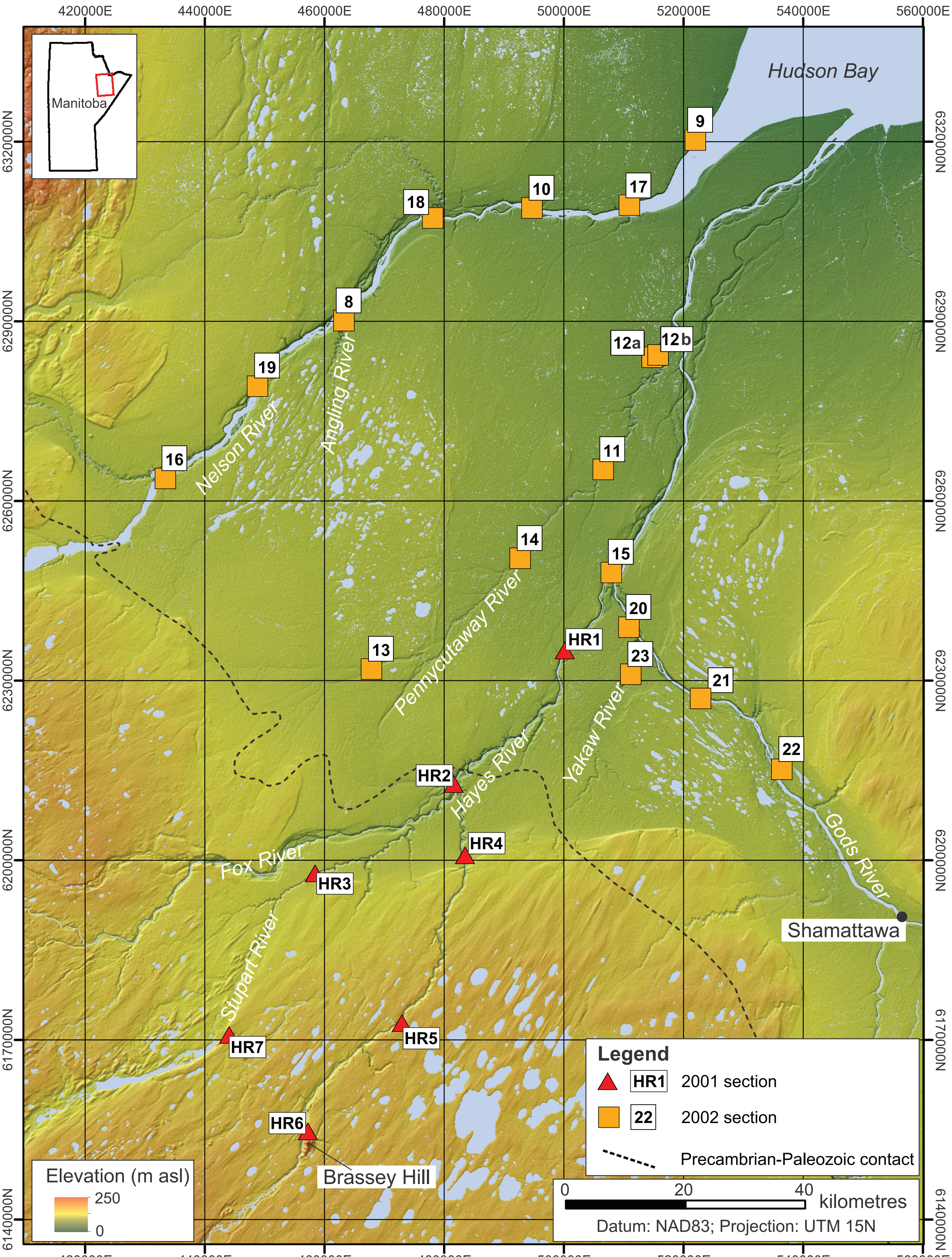

Figure 1: *Location of the 24 stratigraphic sites in northeast Manitoba that were visited during the 2001 and 2002 field seasons. The background image was generated using the the digital-elevation data from the Canadian digital surface model (Natural Resources Canada, 2015). A hill-shade model has been added with transparency effect to enhance relief.*

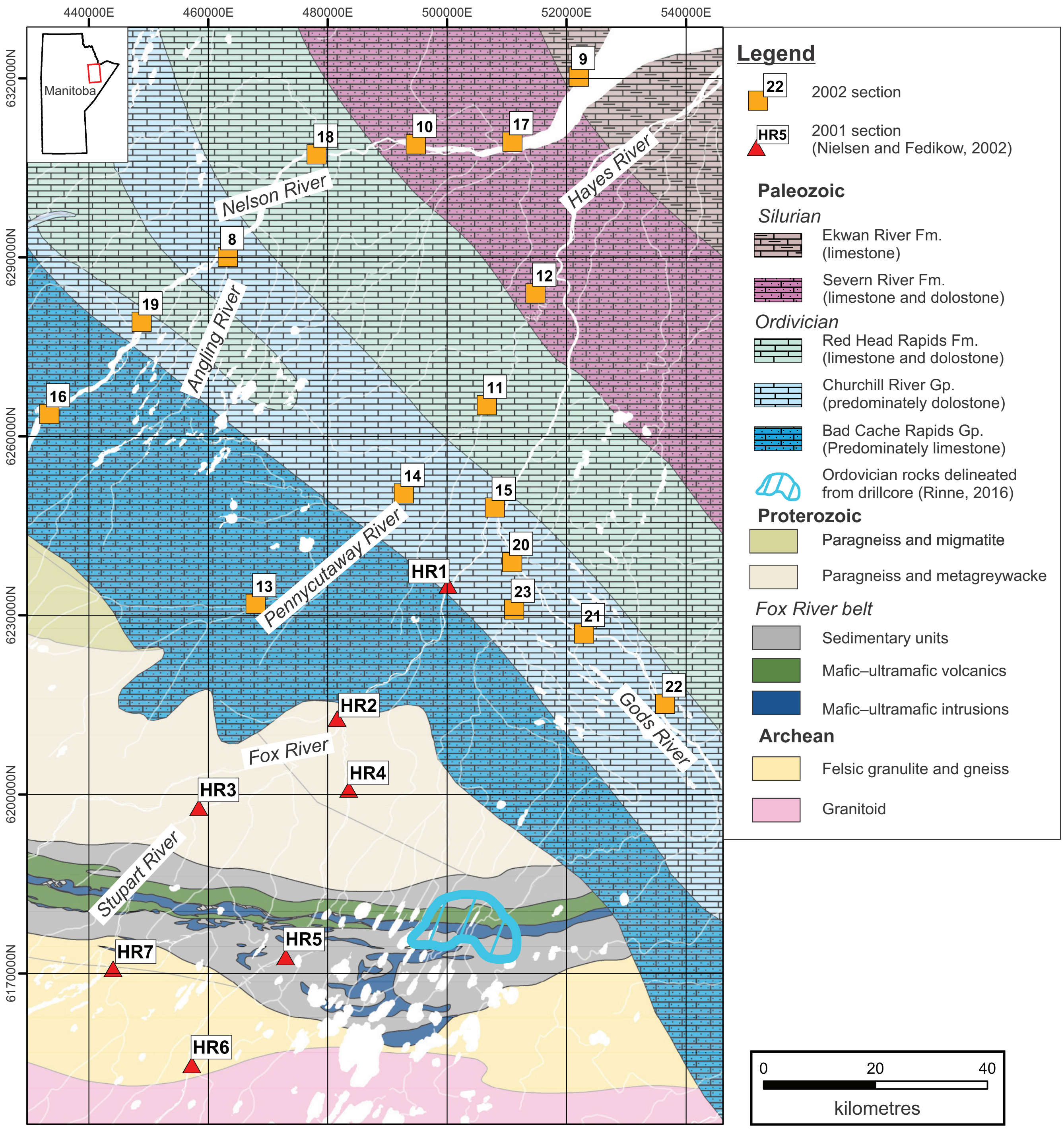

***Figure 2:** Regional bedrock geology of study area. Precambrian geology modified from Rinne (2016). Paleozoic geology modified from Nicolas and Young (2014). Abbreviations: Fm., formation; Gp., group.*

et al., 2003). These erratics were transported southwards over 800 km by the LIS into northeast Manitoba.

Drift thickness

Due to mineral exploration, the Fox River Belt area has a high concentration of depth-to-bedrock data. Data is sparser outside the belt, but some drillcores do exist. Bedrock outcrops have also been observed some along river cuts (e.g., Rinne, 2016). Depth-to-bedrock data was used to produce a drift thickness map for the study area (Figure 4). Drift thickness, interpolated from drillholes, ranges from 6–131 m below ground surface.

Thick drift overlies areas of both Precambrian and Paleozoic bedrock. Hence, thick till is not restricted to the HBL but extends onto what is typically considered the 'thinner' drift zone of the Precambrian Shield. Likewise, drillcores situated at, and north of, section 14 (Figure 4), delimit thinner drift areas within the HBL.

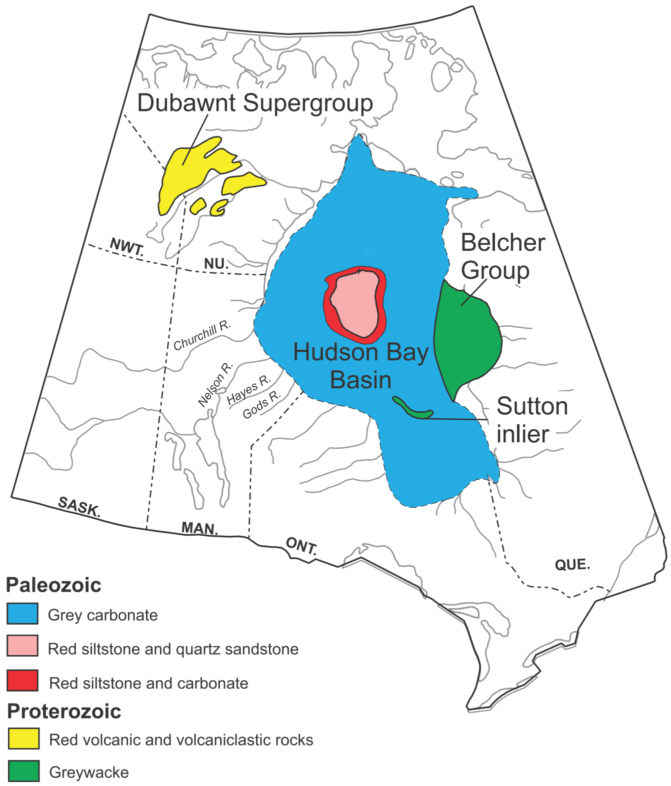

Figure 3: *Bedrock sources of distinctive continental-scale erratics observed in northern Manitoba. Figure is modified from Kaszycki et al. (2008).*

Methods

Field data collection

Till sampling and stratigraphic logging

Helicopter-supported fieldwork was conducted during the 2001 and 2002 field season in the HBL region of northeast Manitoba. Twenty-four sections along the Hayes, Stupart, Gods, Pennycutaway, Nelson, Angling, Fox and Yakaw rivers were investigated (Figure 1). At each section, the lithology and stratigraphy was logged and till samples were taken at 2 or 3 m intervals (Appendix 1). Stratigraphic logs for each section investigated and sampled during this study have been produced based on original field notes and are presented in Appendix 2. At each sample interval two samples were taken, an 11 L sample for KIM and clast lithology analysis and a 2 kg sample for geochemical analysis. A total of 143 till and 3 sand and gravel samples were collected in 2002 from 17 sections. An additional 69 till and 2 sand and gravel samples were collected from 7 sections during the 2001 field season (Nielsen and Fedikow, 2002).

Clast-fabric analysis and interpretation

To obtain ice-flow data for the thick-till stratigraphic sections, field investigations of boulder pavements, striated lodged boulders and the long-axes orientation, or fabric, of clasts within till are used as a proxy for ice-flow orientation. Certain shapes of clasts, defined as a particular arrangement of the a-axis (longest), b-axis (middle) and c-axis (shortest), are statistically proven to often deposit parallel to the direction of stress (Holmes, 1941).

A-axis clast-fabric measurements were conducted at 60 till-sample sites over the two field seasons. At each site, 30 elongate clasts were measured. To assist with ice-flow reconstructions, clast-fabric data was classified based on reliability as an ice-flow indicator, from very weak to very strong. Fabric modality was first assessed visually according to the method outlined by Hicock et al (1996). Eigenvectors and eigenvalues (Mark, 1973) were then calculated using Rockware Sterostat V1.6.1. Fabric indices ‘elongation’ and ‘isotropy’ (Benn, 1994) were calculated based on eigenvalues to assist with clast fabric interpretations. Table 6, Appendix 3 denotes the strength criteria used, with a higher weight placed on modality and S1. Fabrics considered to be of moderate to very strong strength were used to interpret ice-flow orientation; only 45 out of 60 clast fabrics fit these criteria. The remaining clast fabrics are valid measurements and can often provide an estimate of ice-flow orientation, but cannot be confidently used to interpret ice-flow orientation due to spread, bi-modality or multi-modality. Clast-fabric measurements, stereoplots, statistics and interpretations are presented in Appendix 3.

Laboratory and analytical procedures

Clast-lithology counts

The lithology of clasts within the till samples was determined to help identify major directions of glacial dispersal and hence till provenance. Clast-lithology counts were conducted on the 4–8 mm size fraction of till at the Midland Rock Preparation Laboratory in Winnipeg. Clasts were separated into to ten lithological classes: red carbonate, brown carbonate, sandstone, greywacke, oolitic jasper, red volcanic, volcanic, mafic crystalline, quartzite and granitoid. Clast counts are presented as weight percent and examples of sorted clast-lithology counts presented in Figure 5. The weight of the 4–8 mm size-fraction identified during clast counts was from 59–463 g, averaging 228 g per sample. Clast-lithology count results and summary statistics are presented in Appendix 4.

The classification used by E. Nielsen in 2001 and 2002 differs from the clast-count methodology currently used at the MGS in two ways. Firstly, the MGS uses the 2–4 mm, 4–8 mm and 8–30 mm size fractions, and presents the results as a summed count-percent of all size fractions. A comparison between weight percent and count percent was conducted on five samples during this study and found to have minimal (maximum of 4.2 % difference) influence on clast lithology interpretations (Appendix 4, Table 9). Secondly, the MGS includes a “greenstone-derived” lithological class, which was not included in original interpretations. Problematically, all greywacke clasts were interpreted to be from the Omarolluk Formation (Nielsen and Fedikow, 2002). This is an issue, because the Fox River greenstone belt and Proterozoic metagreywacke bedrock have been mapped in the study area and are known to outcrop or subcrop (Rinne, 2016). Since clasts derived from greenstone belts can be difficult to differentiate from greywacke clasts in the pebble fraction of till samples, and because greywacke occurs both locally and in the Belcher Island Group (Figure 3), clasts

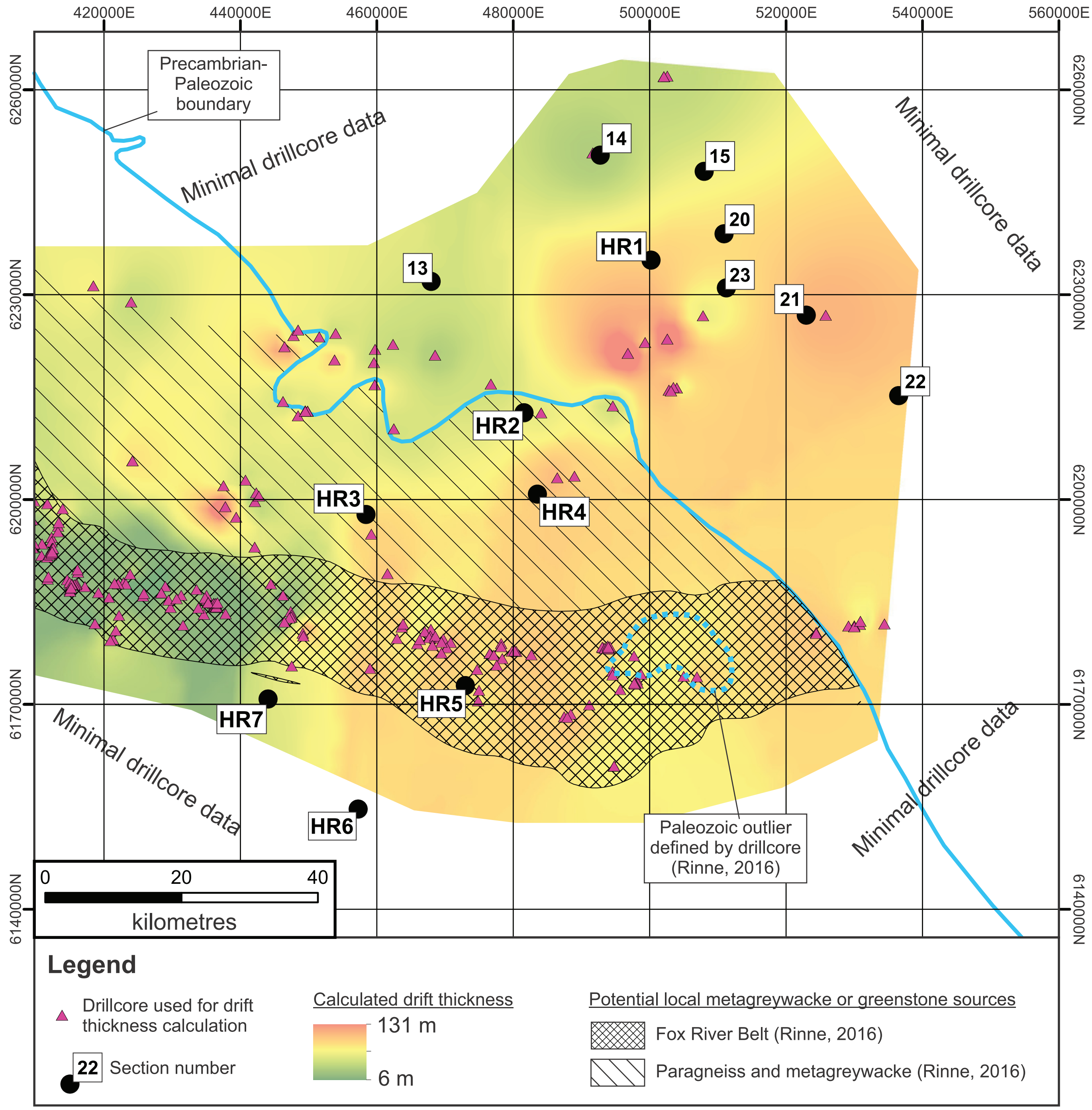

Figure 4: *Calculated drift thickness near the Fox River belt and Precambrian-Paleozoic boundary. An inverse distance weighted drift thickness surface was calculated using the drift thickness recorded at each of the drillcore locations displayed.*

originally identified as greywacke and interpreted to be sourced from eastern Hudson Bay (Nielsen and Fedikow, 2002) are herein reported as undifferentiated greenstone and greywacke (GG) clasts. These clasts can be either locally sourced from greenstone belts, such as the Fox River belt, or distally-derived, e.g., the Belcher Group in eastern Hudson Bay.

Till-type classification

To evaluate regional-scale till composition, clast lithology counts from 2001 (Nielsen and Fedikow, 2002) and 2002 (this study) were grouped into three simplified classes according to presumed provenance (Hudson Bay Basin, Shield–granitoid, Shield–greenstone/greywacke). The breakdown of clast lithologies included in the three classes is presented in Table 1.

These three simplified classes were then processed using statistical methods within ioGAS v. 6.0 software. The data was first transformed using a centered log ratio (CLR) transformation to avoid any effects of closure on the dataset (Grunsky, 2010). A K-means cluster analysis (Davis, 2002) was conducted on the transformed data and six clusters designated based on the sum of squares scree plot. The cluster results are classified by

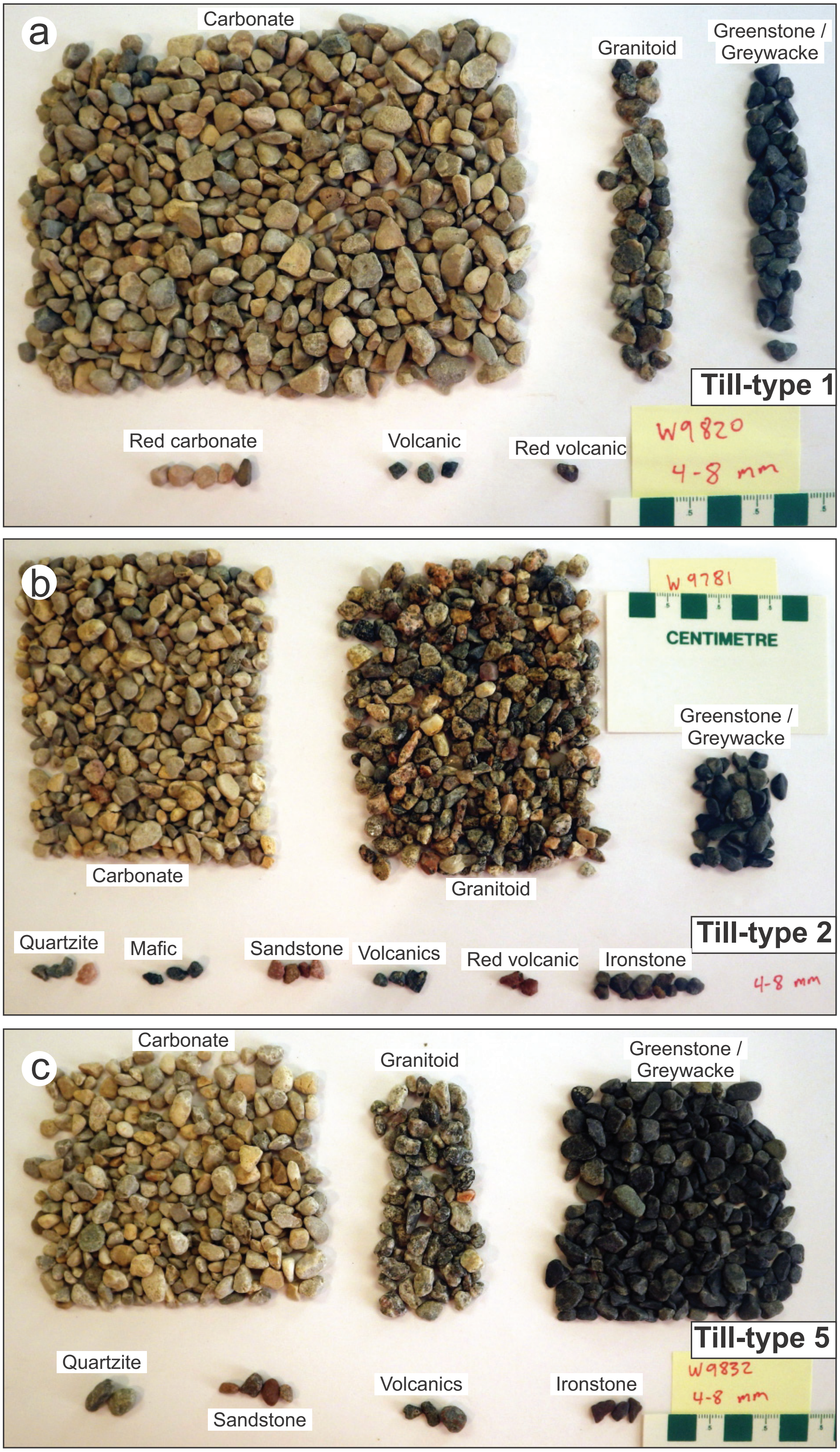

Figure 5: *Examples of sorted 4–8 mm size-fraction clast-lithology counts from till samples:* ***a)*** *Till-type 1 consisting of high carbonate content;* ***b)*** *Till-type 2 consisting of high granitoid content;* ***c)*** *Till-type 5 consisting of high undifferentiated greenstone and greywacke (GG) content.*

Table 1: Simplified and detailed lithological classes for till samples clasts.

<table>
<tr><th>Simplified class</th><th>Hudson Bay Basin</th><th>Granitoid</th><th>Greenstone and greywacke</th></tr>
<tr><td rowspan="4">Detailed classes</td><td>Brown carbonate</td><td>Granitoid</td><td rowspan="2">Undifferentiated greenstone and greywacke</td></tr>
<tr><td>Red carbonate</td><td>Red volcanic</td></tr>
<tr><td>Sandstone</td><td rowspan="2">Quartzite</td><td>Mafic crystalline</td></tr>
<tr><td>Oolitic Jasper</td><td>Volcanic</td></tr>
</table>

colour and displayed on both clast lithology ternary and scatter plot diagrams for visual purposes in Figure 6. Cluster results are referred to as till-types within this report.

Carbonate content

Till-matrix (<63 µm size-fraction) carbonate content was determined using the Chittick method. Analysis was conducted at the Terrain Sciences Division Sedimentology lab at the Geological Survey of Canada. Analytical results are provided in Appendix 5. Carbonate content of samples from the 2001 samples was not determined.

Geochemistry

Geochemical analysis was conducted on the <63 µm (silt and clay) size-fraction and the <2 µm (clay) size-fraction. The <63 µm size-fraction was analyzed for 35 elements by instrument neutron activation analysis (INAA) and the <2 µm was analyzed for 36 elements by inductively coupled plasma-atomic emission spectroscopy (ICP-AES). Analytical results are provided in Appendix 6. Results from the 2001 field season were previously released (Nielsen and Fedikow, 2002), and have also been included herein.

Kimberlite-indicator-mineral analysis

KIMs were concentrated, picked and analyzed by electron microprobe through in-kind support by De Beers Group of Companies (De Beers). Results from the 2001 field season have previously been released (Nielsen and Fedikow, 2002), while results from 2002 were included within the Manitoba KIM database (Keller et al., 2004) without stratigraphic context

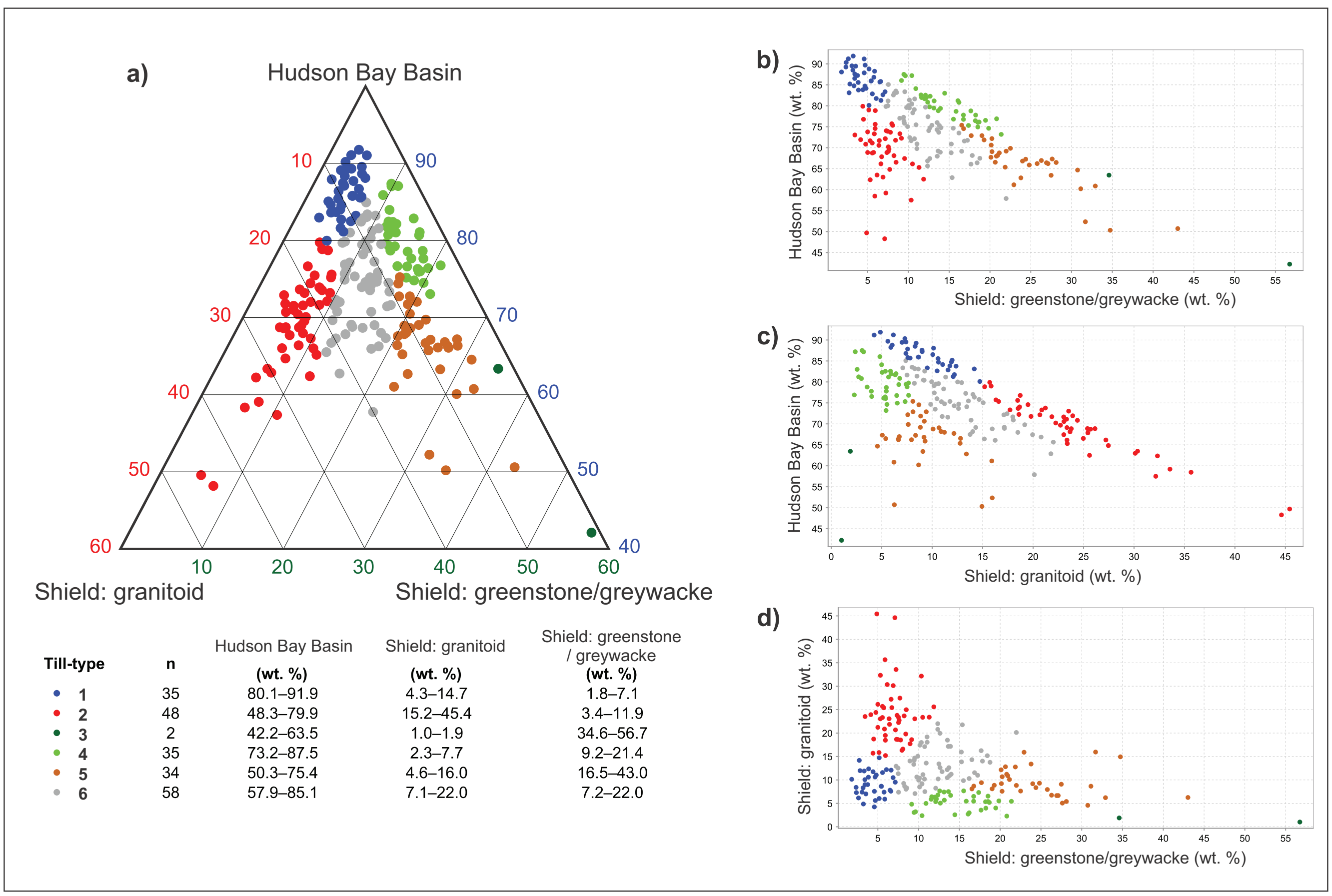

Figure 6: Clast-lithology till-types classified by K-means cluster analysis: a) Hudson Bay Basin-Granitoid-Greenstone/Greywacke ternary diagram showing the designated till-types and clast-lithology ranges for each till-type; b) Hudson Bay Basin vs. Shield-Granitoid scatter plot color-coded by till-type; c) Hudson Bay Basin vs. Shield-Greenstone scatter plot color-coded by till-type; d) Shield-granitoid vs. Shield-greenstone/greywacke scatter plot color-coded by till-type.

and are reproduced as part of this report. Analytical microprobe results and KIM counts for the 0.3–0.5 and 0.5–2.0 mm size-fractions are provided in Appendix 7.

Grains were first classified based on the method outlined in Thorleifson et al. (1994) to distinguish erroneous visually identified KIMs, e.g., differentiating magnetite from visually identified ilmenite. Garnets were additionally classified according the method of Grütter et al. (2004) and the Cr_2O_3 vs. CaO discriminate diagram is provided in Figure 7a. Mg-ilmenite was distinguished from the ilmenite population based on the TiO_2 vs. MgO discriminate diagram curve proposed by Wyatt et al. (2004; Figure 7b). Chromites were plotted on a Cr_2O_3 vs. TiO_2 discriminate diagram modified from Fipke (1995; Figure 7c) to assess if any were considered diamond-inclusion Cr-spinel.

Results

A total of 24 stratigraphic sections were logged and sampled during this study (Figure 1). These sections expose multiple tills, in addition to interglacial and postglacial sediments.

Interglacial sediments

Interglacial sediments are not the focus of this report, but they do provide an indicator of the relative age of the till sheets. No new interglacial deposits were confirmed during this study, though four classes of sites are found in the study area (Figure 8). Firstly, 'confirmed' interglacial sites are accompanied by paleo-environmental analysis (Netterville, 1974; Nielsen et al., 1986; Dredge et al., 1990; Roy, 1998). Secondly, 'likely' interglacial sites are sites where sub-till organic-bearing sediments have been described, but lack detailed paleo-environmental analysis. Thirdly, 'suspected' interglacial sites are sites with sub-till silt and/or clay. Fourthly, 'sub-till sediments of unknown rank' are sites with sub-till sand and/or gravel. This 4th class of sites is unknown, because a distinction between interglacial, interstadial and subglacial depositional environments has not been made.

Nelson River area

Along the Nelson River, several researchers noted the presence of a sub-till non-glacial unit that includes facies from fluvial, lacustrine, terrestrial and glaciolacustrine environments. The unit is discontinuous, occurs at 18–25 m depth (65 to 77 m asl and 45 to 50 m asl), and contains paleoecological evidence for both black spruce bog and tundra environments (Nielsen et al., 1986; Dredge et al., 1990; Roy, 1998). Nonetheless, these sediments have been correlated as one unit, and termed the "Nelson River Sediments" (NRS; Nielsen et al., 1986). NRS have previously described in detail at section 16 (Roy, 1998). Section 9 is located between the undated Flamborough and Port Nelson interglacial sites (Dredge et al., 1990) and is a suspected interglacial unit based on the presence of sub-till silt and sandy-gravel devoid of organics. The sub-till gravel at section 19 is of unknown rank.

Gods River area

Along the Gods River, Netterville (1974) studied exposures of sub-till organic-bearing sediments that include lacustrine, fluvial and terrestrial environments. The unit is discontinuous and in many cases is represented by sub-till sand and gravel devoid of organics (Netterville, 1974). The pollen assemblage from the Gods River sediments (GRS) indicates a progression from tundra to forest-tundra environments before returning to a tundra environment (Netterville, 1974). Radiocarbon dated wood returned an infinite age (>41 000 y ^{14}C BP, GSC-1736). Section 21, in close proximity to confirmed interglacial sites, contains sub-till organic-bearing sand that contains wood, and is a likely interglacial unit. Section 22 is a suspected interglacial unit based on the presence of a thick (16 m) sand and gravel unit and supporting observations by previous work. Craig et al. (1967) observed silt and clay pinching out towards the south into the sand and gravel at a station 400 m to the north of section 22. Section 15 exposes 2 m of sub-till silt and sand, which is corroborated by Craig et al. (1967) at a section 280 m to the east where the presence of fairly abundant tiny shell fragments within a lower sandy-gravel at this interval was noted. Future sampling and dating of the shell fragments would help to confirm whether the sub-till sediments at section 15 are interglacial.

Fox, Stupart and Hayes rivers area

Relatively little work has been conducted on sub-till sediments exposed along the Fox, Stupart and Hayes rivers, except where sub-till lacustrine clay to glaciolacustrine clay and silt rhythmites were noted at the confluence of the Stupart and Fox rivers (Dredge et al., 1990). Dredge et al. (1990) radiocarbon-dated wood from till above the sediments that returned an infinite age (>37 000 ^{14}C BP; GSC-2481) and hence these sub-till units were tentatively correlated to the GRS and NRS. Section HR1 has poorly exposed sub-till silt which is a suspected interglacial unit. Section HR4 exposes two inter-till units of fine-sand and silt of unknown rank. Interestingly, Craig et al. (1967) indicated at multiple exposures along this stretch of the Hayes River, including at HR4, the presence of a sub-till clay, silt and gravel unit interpreted to be interglacial near river level. Section HR5 exposes 1 m of inter-till sand of unknown rank. Section HR6 exposes 0.6 m of organic-bearing silt and fine-sand and is classified as a likely interglacial unit.

Age of interglacial deposits

The age of confirmed interglacial deposits ranges from Sangamon to Mid-Wisconisin (Netterville, 1974; Berger and Nielsen, 1990; Roy, 1998). Attempts to refine the age of the NRS, GRS, and other sub-till 'nonglacial' units have met with uncertainty. For example, Netterville (1974) observed thin sand and gravel units higher in the stratigraphy than the GRS, which he interpreted to be interstadial and named the "Twin Creek Sediments". These organically-barren sediments have since been proposed to be of subglacial in origin (Dredge et al., 1990). A lack of consistent age dating has created issues resolving HBL stratigraphy. For example, the age-relationship between the Gods River Sediments and Nelson River Sediments

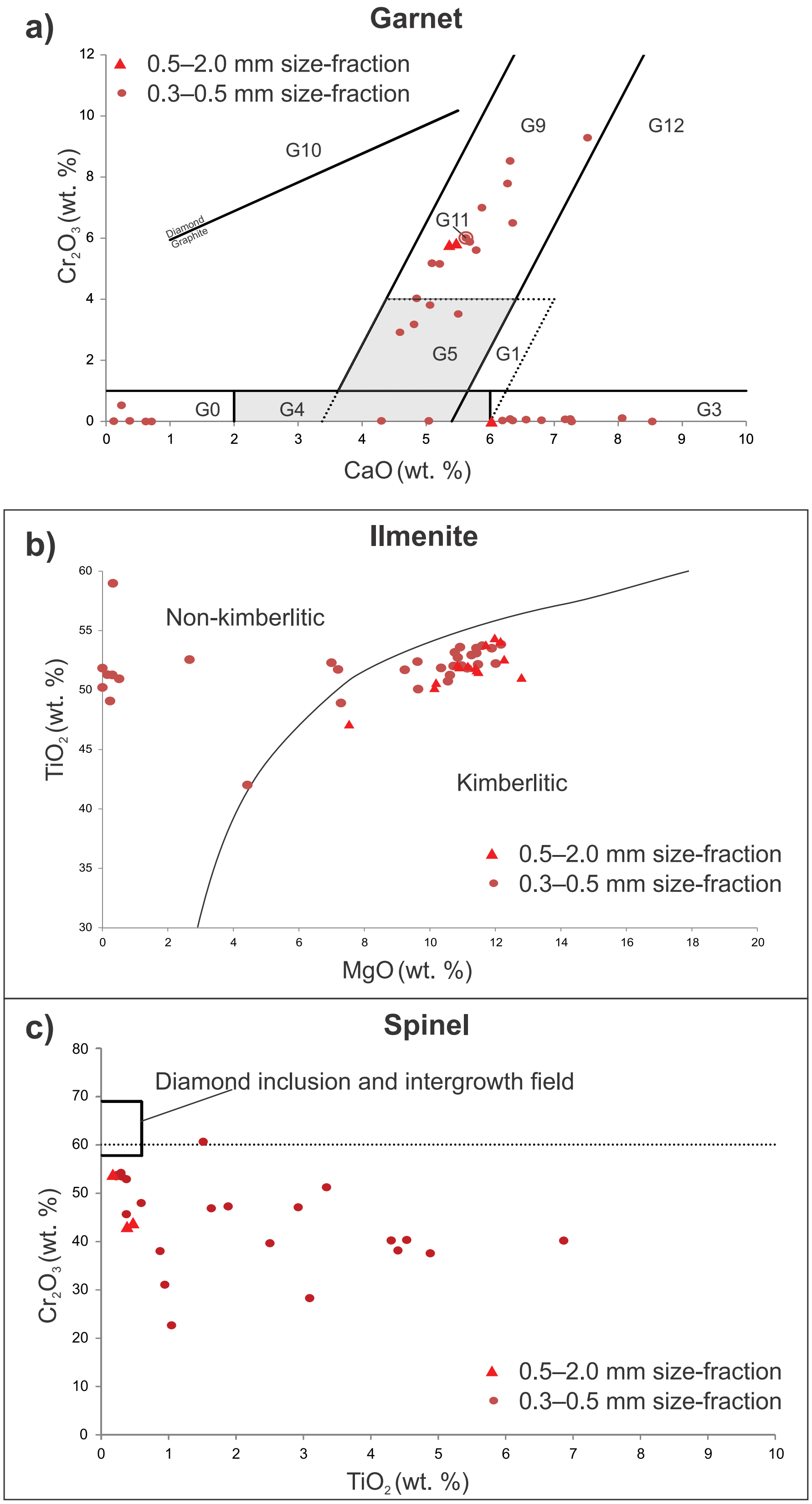

Figure 7: *Discriminate diagrams for kimberlite-indicator-minerals recovered from 2002 samples:* ***a)*** *Cr_2O_3 versus CaO discriminate diagram for garnet grains after Grütter et al. (2004). The G5 and G4 classifications indicated by the light grey fill pattern are distinguished by Mg-number. The stippled G1 group does not overlap G4, G5, G9 or G12 categories as G1 garnet grains are distinguished by a higher TiO_2 content. G11 garnets are classified based on a higher TiO_2 content and are differentiated from G1 garnets by a higher Cr_2O_3 content. A G11 garnet classified from this study is highlighted;* ***b)*** *TiO_2 versus MgO discriminate for ilmenite grains after Wyatt et al. (2004);* ***c)*** *Cr_2O_3 versus TiO_2 for chromite grains modified after Fipke (1995). A dashed line representing 60 wt. % Cr_2O_3 is shown for visual reference.*

is only inferred based on stratigraphic position. The simple case scenario is to consider them correlative and deposited during the Sangamon interglacial period, but the presence of multiple interglacial records present in the study area (e.g., Dredge and McMartin, 2011) and interpreted interstadial deposits just outside of the study area (Dalton et al., 2016) indicates caution must be exercised when correlating sub-till organic bearing units across the region.

Till composition

Thick till packages are exposed within the 24 sections examined in this report (Appendix 2) and clast counts were conducted to assist with establishing till provenance. The tills contain 1.0–45.4 wt. % granitoid, 42.2–91.9 wt. % Hudson Bay Basin (HBB) and 1.8–56.7 wt. % GG (greenstone-greywacke) content in the 4–8 mm size-fraction analyzed.

Clast-lithology till-types

In an attempt to identify regional-scale trends in till composition across the study area, we have conducted K-means cluster analyses of the clast-lithology composition in order to produce 'till-types' (Figure 6). Figure 9 displays the spatial distribution of the statistical till-types.

Till-type 1

Till-type 1 has a high HBB (80.1–91.8 wt. %), low granitoid (4.3–14.7 wt. %) and low GG (1.8–7.1 wt. %) content (Figure 6). Till-type 1 is situated mainly overlying Paleozoic bedrock (Figure 9), which is expected. At section HR6, four samples from 12–18 m depth are classified as till-type 1. This site is interesting, because it is situated 65 km southwest of the Paleozoic-Shield contact and 37 km southwest of a mapped carbonate bedrock inlier (Figure 2); where more entrainment

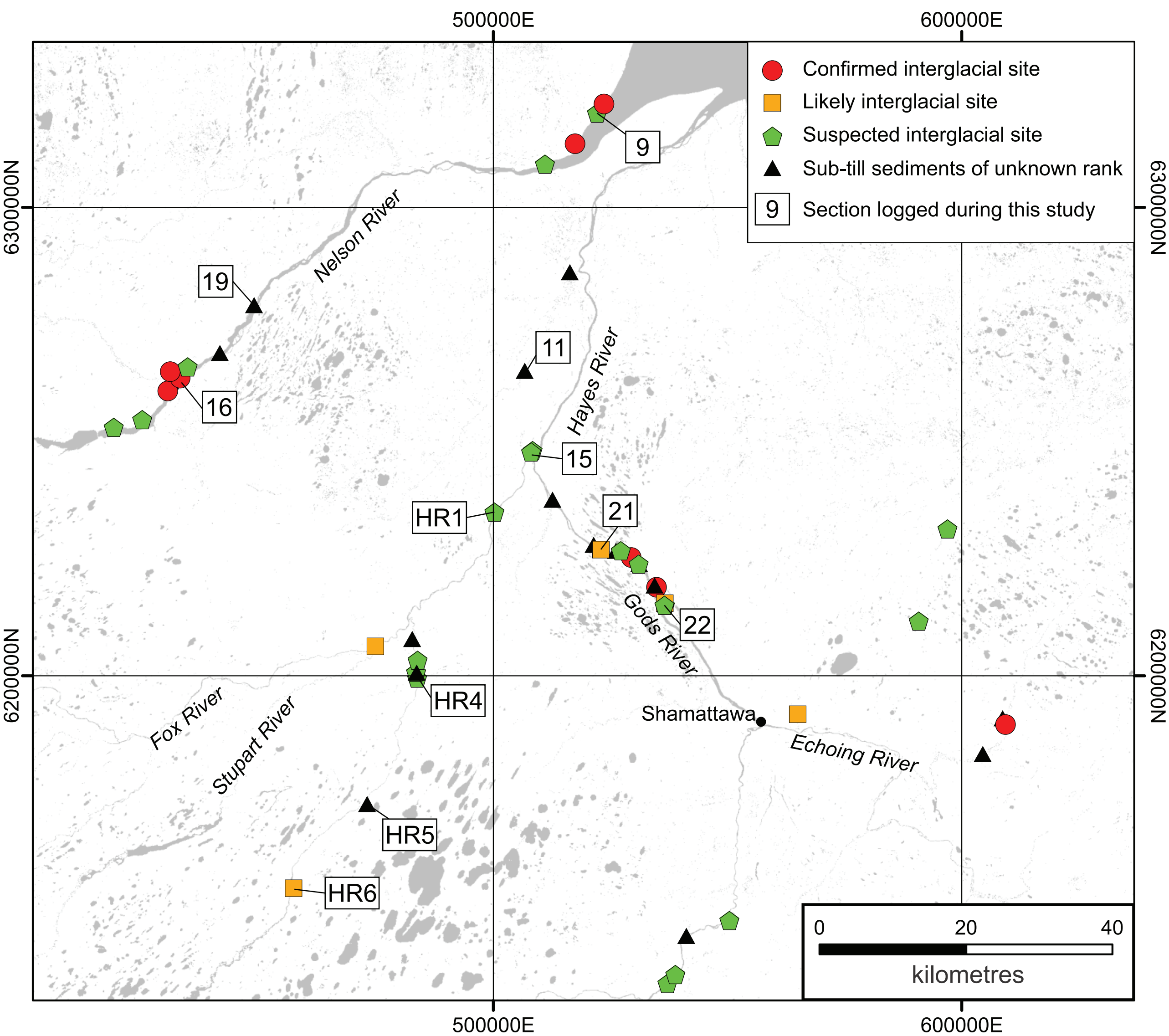

Figure 8: Buried non-till sediment sites in northeastern Manitoba. Confirmed interglacial sites area are accompanied by paleoenvironmental analyses. Likely interglacial sites contain sub-till organic-bearing sediments without further analyses. Suspected interglacial sites contain sub-till silt and/or clay. Unknown-rank sites contain sub-till sand and/or gravel. Data sources: (Craig et al., 1967; Nielsen and Dredge, 1982; Dredge and Nielsen, 1985; Nielsen et al., 1986; Dredge et al., 1990; Roy, 1998; Hodder and Kelley, 2017; Gauthier, unpublished).

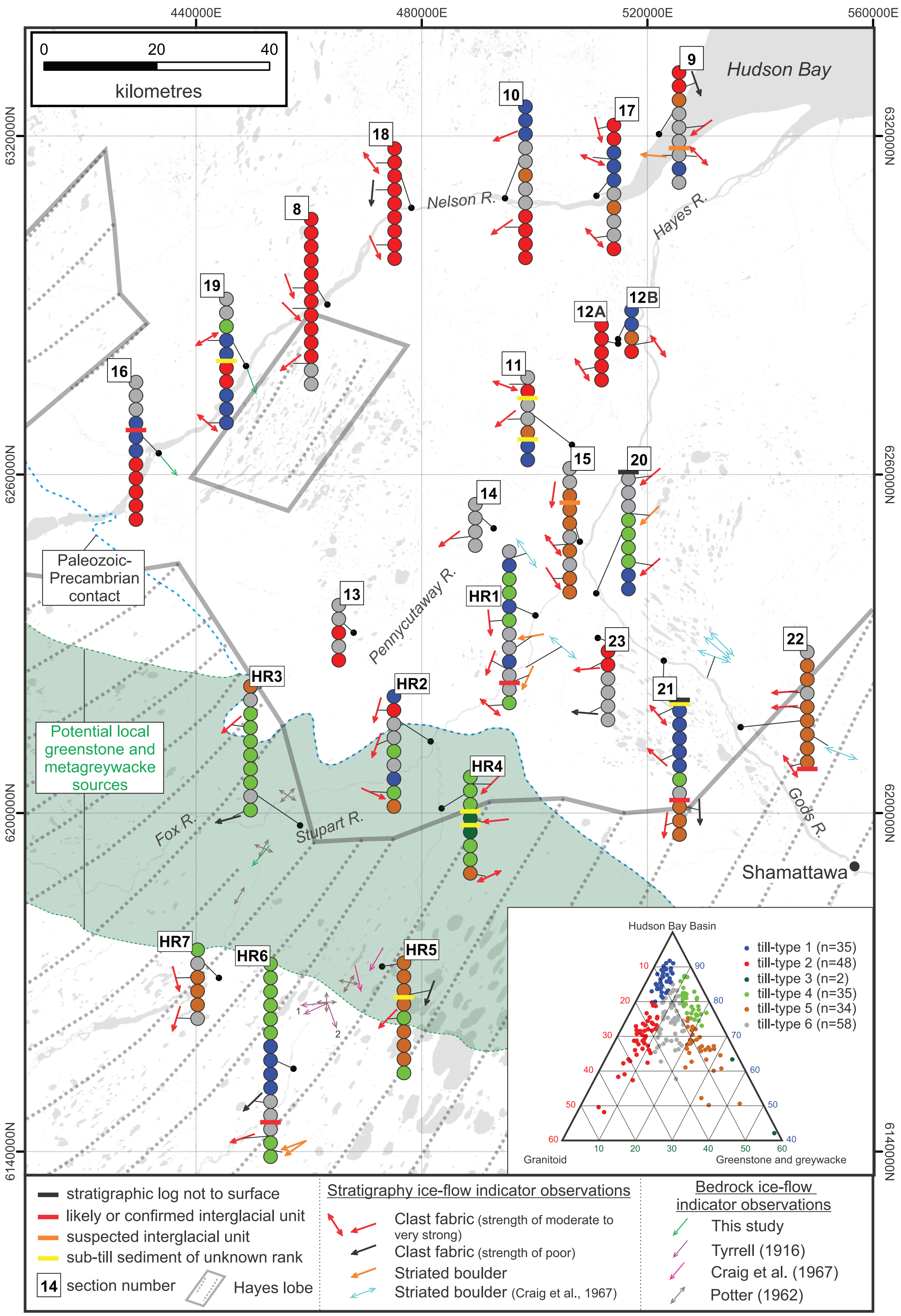

***Figure 9**: Spatial distribution of interpreted till-types, based on multivariate analyses of till-clast lithologies. Till samples from stratigraphic sections are shown as stacked circles and referenced to section location. Till samples are coloured according to designated till-type. Clast-fabric interpretations are classified according to strength and shown at depth where conducted in section. Bedrock geology contacts are reproduced from Figure 2. The ternary diagram showing clast lithology counts is reproduced from Figure 6 for reference. Bedrock ice-flow indicators from this study and others are included for reference. Striated boulder observations from this study and others are included for reference.*

of shield-derived clasts is expected. Till-type 1 outcrops at the base, middle and upper portion of exposed sections, both above and below interglacial units.

Till-type 2

Till-type 2 has a high granitoid content (15.2–45.4 wt. %), low GG content (3.4–11.9 wt. %) and medium to low HBB (48.3–79.9 wt. %) content (Figure 6). Till-type 2 is situated mainly overlying Paleozoic bedrock, and is concentrated along the Nelson River and north region of the Hayes River (Figure 9).Till-type 2 outcrops at the base, middle and upper portion of exposed sections, both above and below interglacial units.

Till-type 3

Till-type 3 has a high GG content (34.6–56.7 wt. %), very low granitoid content (1.0–1.9 wt. %) and low HBB (42.2–63.5 wt. %) content (Figure 6). Till-type 3 only outcrops at the middle of section HR4 (Figure 9).

Till-type 4

Till-type 4 has a medium GG content (9.2–21.4 wt. %), moderate to high HBB content (73.2–87.5 wt. %) and a low granitoid content (2.3–7.7 wt. %). Till-type 4 is predominantly present in the south region of the study area (Figure 9), where it outcrops along the Hayes, Fox, Gods and Stupart rivers. Till-type 4 is present at only one till sample site along the Nelson River (Section 19; Figure 9) and not present along the north region of the Hayes or Pennycutaway rivers. Till-type 4 outcrops at the base, middle and upper portion of exposed sections, both above and below interglacial units.

Till-type 5

Till-type 5 has a high GG content (16.5–43.0 wt. %), low granitoid content (4.6–16.0 wt. %) and moderate to low HBB (50.3–75.4 wt. %) content (Figure 6). Till-type 5 commonly outcrops along stretches of the Gods River, Stupart and Hayes rivers in the south half of the study area (Figure 9). In contrast, till-type 5 is only present as single sample intervals at sections 10, 17 and 9 along the Nelson River. Till-type 5 outcrops at the base, middle and upper portion of exposed sections, both above and below interglacial units.

Till-type 6

Till-type 6 has a moderate GG (7.2–22.0 wt. %), HBB (57.9–85.1 wt. %) and granitoid (7.1–22.0 wt. %) content (Figure 6). Till-type 6 outcrops throughout the study area, at the base, middle and upper portion of exposed sections, both above and below interglacial units (Figure 9).

Ice-flow history

Bedrock exposures are rare in the study area due to widespread thick drift cover. Outcrop-scale ice-flow indicators are observed exclusively along river cuts within the study area and have been noted by Bell (1879), Tyrrell (1916), Potter (1962), Operation Winisk (Craig et al., 1967) and during this study (Figure 9). The paucity of outcrop ice-flow indicators in the study area increases the importance of stratigraphic clast-fabric measurements within till, to decipher the paleo–ice-flow record.

Surface streamlined-landform orientation can also be used as a proxy for ice-flow (Figure 9). Surface streamlined landforms were not mapped as a part of this study, but were obtained from ongoing mapping at the MGS (Trommelen et al., 2014a). The largest is the Hayes Lobe (Dredge and Cowan, 1989), which is 300 by >400 km. Across the Hayes area, these streamlined landforms trend 220 to 245°. In the Knee Lake area, 80 km to the southwest of HR6, the Hayes Lobe was interpreted as a late-stage erosional event, that did not affect the composition of the underlying till(s) (Trommelen and Ross, 2014; Trommelen, 2015).

Clast-fabric analyses were conducted at 60 sites within 24 sections (Appendix 3) in the study area. The result of this work is presented in Figure 9. Using clast-fabric data to interpret ice flow direction is often uncertain. To quantify uncertainty, we have classified clast-fabric results from very poor to very strong in terms of their indication of ice-flow (Table 6, Appendix 3; Figure 9). However, a number of clast fabrics returned bi-directional, unimodal data (Appendix 3), which does not give a preferred indication of ice-flow direction. Also, even when fabric data is uni-directional, clasts sometimes dip down-ice instead of the presumed up-ice direction. This has been exhibited in eastern Finland, where a study of over 100 clast fabrics observed that approximately 60% of the clasts in the till were inclined in the up-ice direction and 40% were inclined in the down-ice direction (Saarnisto and Peltoniemi, 1984). Similarly, Larsen and Piotrowski (2003) observed that 40% of the clast fabrics dipped up-ice while 60% dipped down-ice at a study between two end moraines in Poland. This means that while the orientation can be used, the direction (up-ice or down-ice) is uncertain. Directional uncertainty is a problem in the study area, given the widespread variation within the ice-flow record in northeast Manitoba; from north to west trending ice-flow (Trommelen and Ross, 2011; Trommelen et al., 2012; Trommelen, 2013a, 2014; Trommelen, *in press*). This is a particular problem for interpreting between NW- and SE-trending ice-flow, as the regional history suggests that both directions are possible. As such, most of these fabrics have been shown as bi-directional on Figure 9.

It is difficult to correlate ice-flow data between sections, as adjacent sections (i.e., sections 15 and 20, Figure 9) commonly provide contrasting information. The lack of chronological control, and difficulty correlating between interglacial units in the HBL, can introduce error into ice-flow reconstructions.

Kimberlite-indicator-mineral stratigraphy

A total of 90 KIM grains were recovered from the 2002 survey. KIM anomalies were concentrated at Section 15 where nearly half (43 of 90) of these indicator-minerals were recovered from 2002 samples (Figure 10). A total of 15 KIM grains were recovered from till and 5 KIM grains from sand and gravel samples during the 2001 survey (Nielsen and Fedikow, 2002; Appendix 7). Elevated KIMs were also sampled at sections 13 and 19, where seven and five KIM grains were recovered from till samples, respectively (Figure 10).

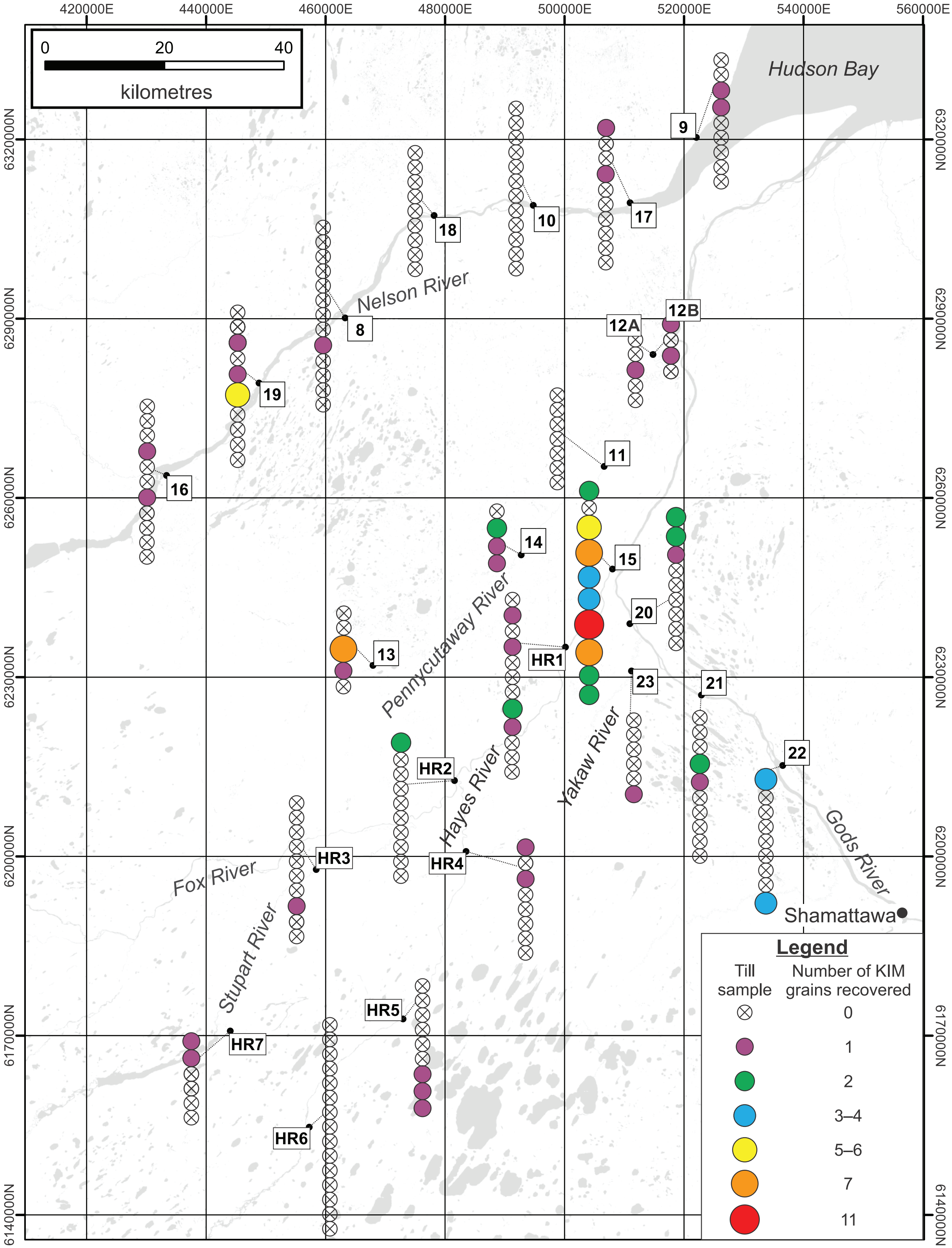

Figure 10: *KIM results displayed as proportional-sized symbols. Results for sections HR1–7 are from Nielsen and Fedikow (2002) and reproduced in Appendix 7.*

KIM grains recovered at section 15 are presented alongside the Quaternary stratigraphy in Figure 11. At this site, the till composition repeatedly cycles from till-type 5 (six samples) to till-type 6 (five samples). A two meter thick silt and sand unit is present from 14–16 m depth and is a suspected interglacial unit based on the presence of fairly abundant tiny shell fragments observed within this unit (Craig et al., 1967). A clast fabric conducted above the silt and sand indicates till deposition by south-trending (188°) ice. Two clast-fabrics were conducted below the silt and sand at 21 and 26 m depth. At 21 m depth, the clast-fabric indicates a NW–SE (142-322°) oriented ice-flow. At 26 m depth, the clast-fabric indicates deposition by SE (147°) trending ice-flow. Importantly, clast-fabrics were not completed at till-sample sites with the highest KIM counts. Given the inconclusive NW–SE ice-flow interpretation, the uncertainty about which till-type the middle clast-fabric was conducted in, and the lack of correlation with surrounding sections (Figure 9), until more work is done both directions should be considered as potential source areas. Drift thickness is poorly constrained near section 15, but three drillcore along the Pennycutaway River ~15 km to the northwest indicate 35–41 m of drift and four drillcore along the Hayes River (20–30 km to the south) indicate thicker (55–124 m) drift (Figure 4).

Discussion

Unexpected greywacke and greenstone dispersal patterns

The spatial patterns of till-types that contain elevated GG concentrations are interesting (Figure 9). Till-types 3 and 5 were sampled mainly along the Gods and Hayes rivers, with only a few isolated samples near the terminus of the Nelson River. Tills associated with moderate GG concentrations (till-types 4 and 6) were sampled everywhere, but are more predominant south of the Hayes and Pennycutaway rivers.

Distribution of GG concentration in the till is shown in Figure 12, to further examine these patterns. The highest GG content occurs within section HR4 (56.7 wt. %, 21 m depth in a 33+ m section), while the second-highest GG content occurs within section HR7 (40.2 wt. %, 12 m depth in a 18+ m section). Looking to the cumulative GG plot, elevated samples are above the 90th percentile. Figure 12 confirms that these GG-elevated till samples are generally situated in the southern half of the study area—with two exceptions near the terminus of the Nelson River.

Input from ice-flow history

Tills containing elevated GG concentrations are associated with clast-fabric measurements suggestive of ice flow to the west, west-southwest, southwest, south-southwest, south-southeast and northwest-southeast (Figure 12). This information alone seems to suggest that there is not just one source of GG clasts.

Potential sources

GG clasts can be sourced from the local Proterozoic bedrock (Figure 2), unmapped Precambrian inliers, or from the Belcher Group in eastern Hudson Bay (Figure 3). The local Fox River greenstone belt and metagreywacke rock are shown on Figure 12 and they often outcrop at the base of river cuts in this region as well (Rinne, 2016). The multiple ice-flow orientations interpreted from tills with elevated GG concentration support the idea that there is more than one source area. Some of the tills with elevated GG concentrations overlie the greenstone and metagreywacke rocks, and could be comprised of locally-derived clasts. Clast-fabric measurements from these tills, at sections HR4, HR5 and HR7, support this interpretation.

Interestingly, elevated tills are also situated to the northeast of the potential local sources within the Hudson Bay Basin. Clast-fabric measurements from these tills, at sections 21 and 22, trend to the west, south-southwest and northwest-southeast—all of which preclude the Fox River greenstone belt and metagreywacke as a source. The possibility of these clasts being entirely derived from the Belcher Group (Nielsen and Fedikow, 2002) is uncertain based on the difficulty separating Omars vs. other rock types using small clast sizes. A second possibility is that the presence of GG clasts in any till sheet could have been derived from materials that have been reincorporated from underlying till sheets and previous ice flows. However, the elevated concentration of GG clasts at sections 21 and 22—up to 34.7 wt. %—suggests that some of these clasts must have a more local source, in addition to the Belcher group which is ~800 km from the study area. The local bedrock underlying sections 21 and 22 is presumed to be carbonate. However, the carbonate bedrock and presumed thick drift (223 m) to the east in the Kaskattama highlands (Assessment File 74223, Manitoba Growth, Enterprise and Trade, Winnipeg) has precluded drilling in this area and depth to bedrock data is sparse. Hence, the potential for additional unknown greenstone and/or greywacke bedrock inliers to the northeast and east cannot be disregarded (Hodder et al., 2017).

Effect of drift thickness on till-composition

The variability of drift thickness in the vicinity of the Fox River Belt influenced the clast-lithology content within till and this is exemplified at section HR7 (Figure 13). Section HR7 is located 6 km south of the Fox River belt and has a GG clast-content ranging from 10.4–40.2 wt. % (Figure 13b). The deepest sample, H7-01-12, contains 10.4 wt. % GG clasts and a clast-fabric that indicates deposition by 197° trending ice flow. GG content increases up-section and reaches 40.2 wt. % at sample HR-01-06. A clast-fabric conducted from this sampling interval indicates deposition by 165° trending ice flow. The upper two samples (HR-01-02 and HR-01-04) have decreased GG content of 11.0–16.8 wt. %. No clast fabric was conducted in the upper till unit, but the surface till in this region is streamlined to the southwest (~226°).

The drift thickness changes considerately in the area surrounding HR7. To the northeast, the drift is very thick, while drift is thinner to northwest (Figure 13c). Therefore, ice flowing to the southwest would most likely slide over, or rework pre-existing sediment, and incorporate minimal local greenstone bedrock. Alternatively, ice flowing to the southeast, in the area of thin drift, would be more likely to incorporate the local greenstone bedrock. These differences can be seen in

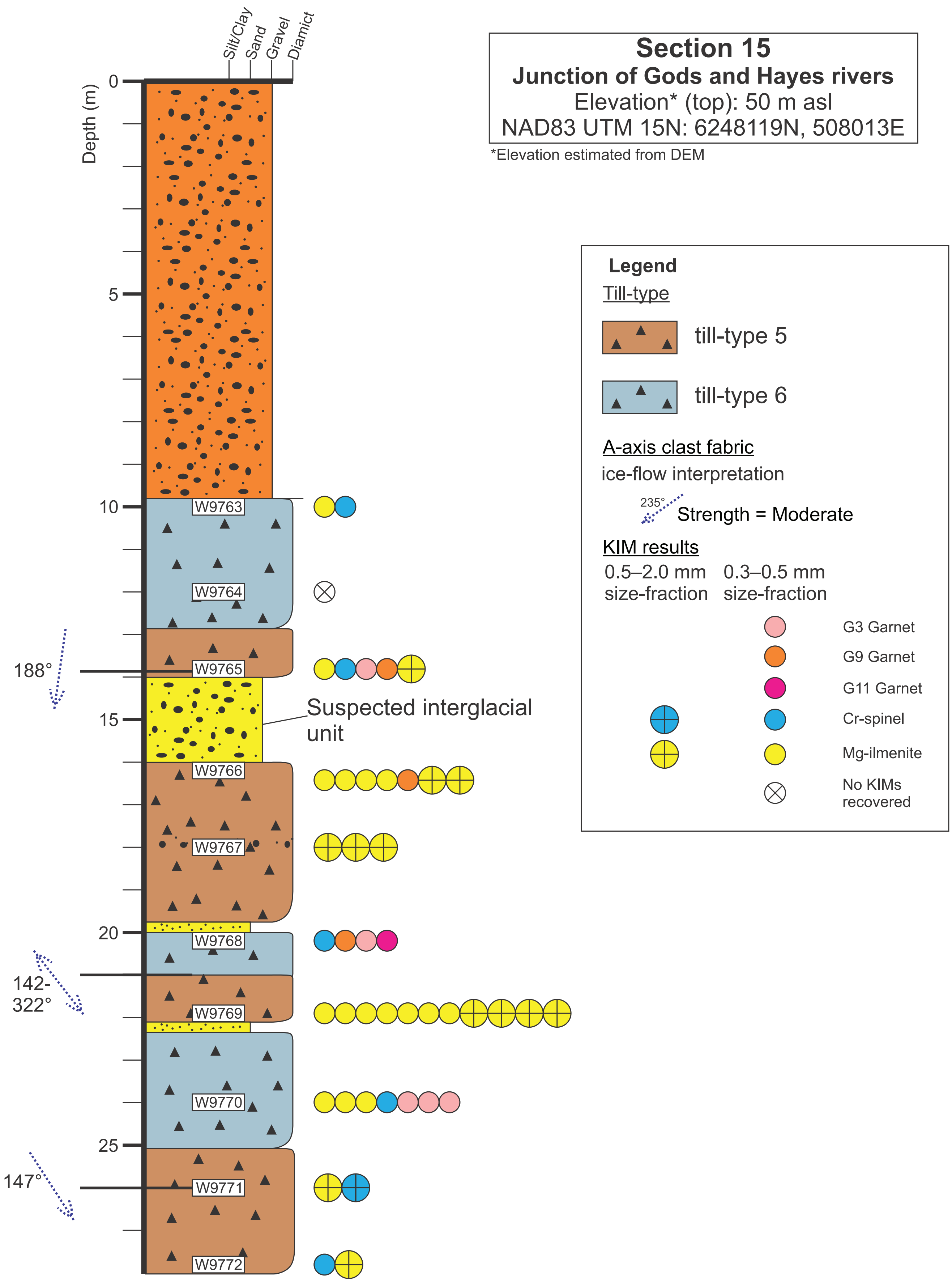

***Figure 11:** Quaternary stratigraphic log section 15 showing KIM results.*

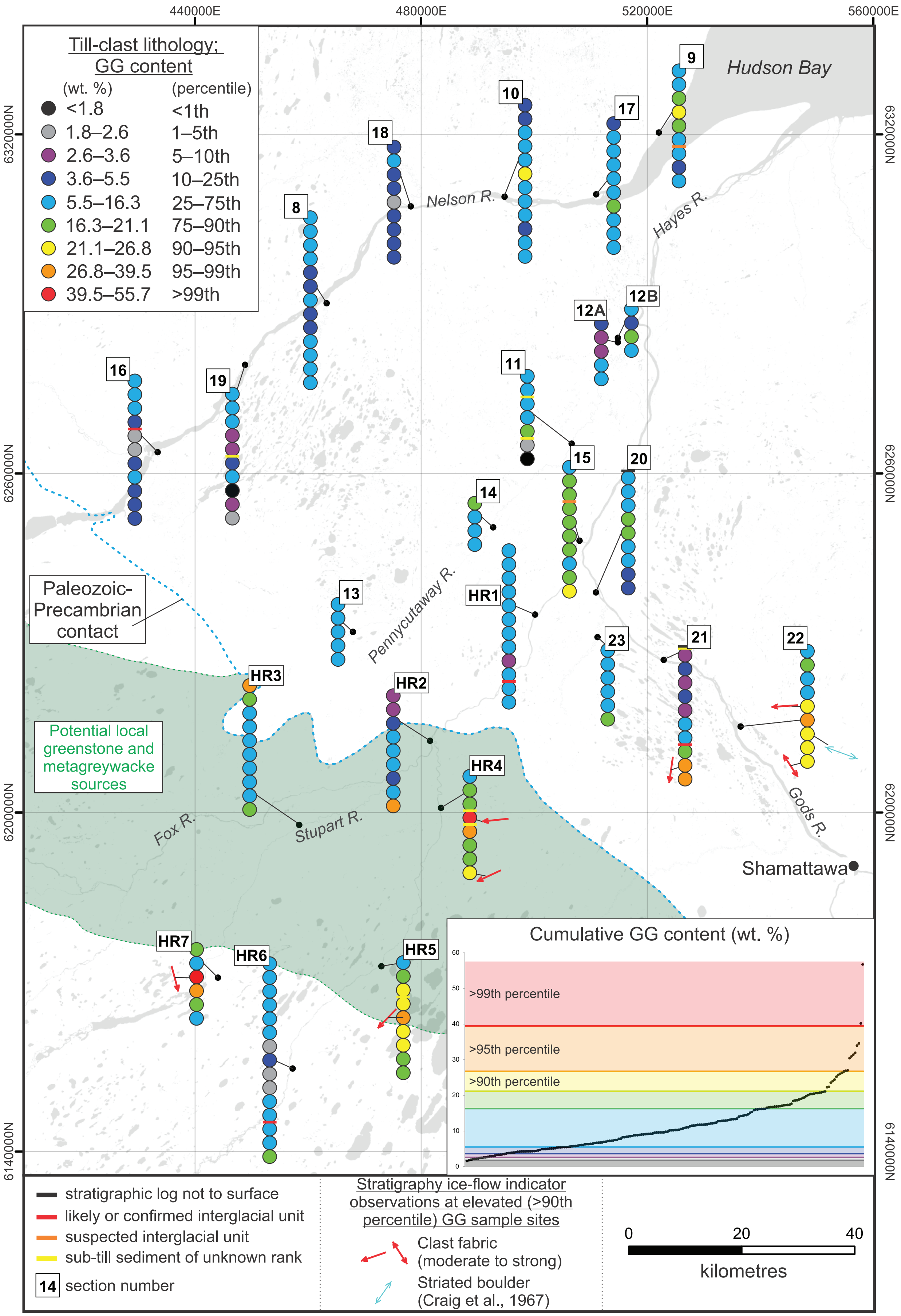

Figure 12: *Undifferentiated greenstone and greywacke (GG) content of till samples. Ice-flow indicators are displayed where GG content is >90th percentile.*

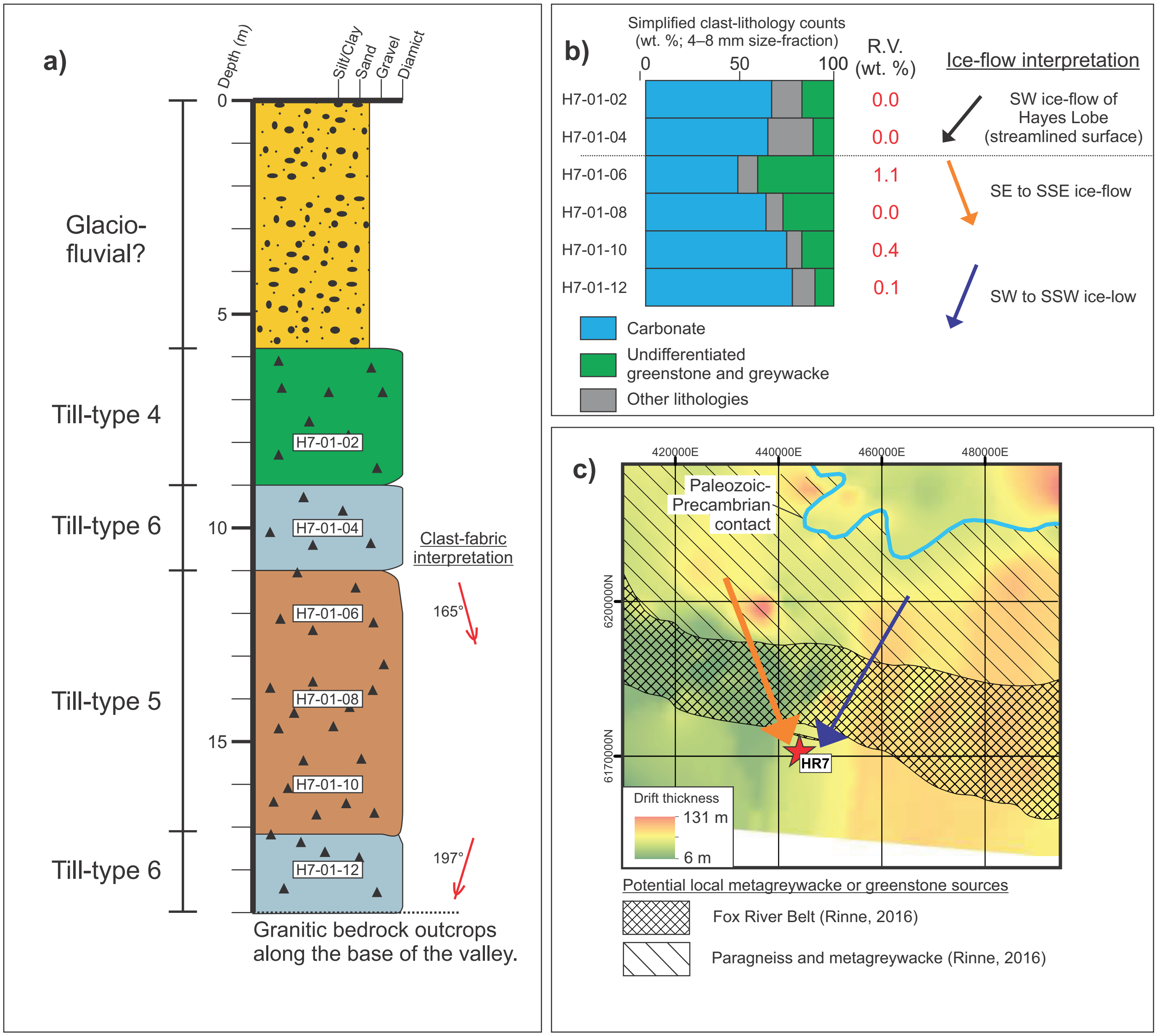

***Figure 13:** Simplified stratigraphy and till composition at section HR7: **a)** Simplified stratigraphic column and ice-flow indicator data; **b)** Simplified clast-lithology counts with interpreted ice-flow trajectory during deposition; **c)** Drift thickness map generated from Figure 4 for the area surrounding section HR7. Abbreviation: R.V., red volcanics.*

GG content of the tills at HR7, whereby the basal and upper tills–with inferred southwest-trending ice flow–contain fewer GG clasts than the middle tills with inferred southeast-trending ice flow. An inferred northwest provenance for the middle tills with increased greenstone content is further supported by the presence of elevated red volcanic clasts in this interval (Figure 13b). Sample HR7-01-06 has >99th percentile (1.1 wt. %) red volcanic clasts, which have a northwest provenance (Figure 3). Section HR7 was initially interpreted to consist of the Amery (lower) and Long Spruce (upper) tills with the contact placed at 13 m bgs (Nielsen and Fedikow, 2002). This was based on field observations and reinforced by the proportion of interpreted Omarolluk Formation 'greywacke pebbles' in the Amery formation (Nielsen and Fedikow, 2002). Re-interpretation suggests that these 'greywacke pebbles' are at least in part locally-derived greenstone clasts, and that the section cannot easily be split into just two tills based on provenance.

Though just one example is provided above, the effect of drift thickness on till composition cannot be ignored. More drillcores, and/or geophysical methods, are required to help elucidate the drift thickness in the HBL. This work is necessary to help understand the nuances between till provenance and spatio-temporal trends in till composition.

Elevated carbonate content on the shield

The majority of elevated-carbonate till samples (till-type 1, Appendix 4) are situated overlying the Paleozoic carbonate bedrock (Figure 9), with the exception of section HR6. At section HR6, till from the middle of the section (8–16 m depth) has an elevated-carbonate clast-content (86.3–91.2 wt. %, >90th to >99th percentile, Appendix 4). The closest possible source for this elevated-carbonate content is an outlier of Paleozoic bedrock that has been mapped by drillcore (Figure 2), situated 37 km to northeast. This carbonate outlier was only recently recognized (Rinne, 2016), and it is possible that additional bedrock mapping may identify other carbonate outliers within the HBL thick drift region.

Summary

- This report releases stratigraphic data on till composition, including ice-flow indicators, from 24 sections in the HBL, based on fieldwork conducted in 2001 and 2002.
- Sub-till non-glacial sediments are not laterally extensive, and can be correlated to either one of two interglacial deposits, or a potential interstadial event recorded in the stratigraphy. More detailed chronology studies are necessary to facilitate regional correlations of these units.
- Till in the Hayes River area can be separated by till-clast lithologies into 6 types that do not exhibit significant vertical or horizontal trends. We note that spatial-temporal variability of deposition, erosion and preservation of sediment in the stratigraphic record will continue to complicate regional correlation of till units.
- The differentiation of distally-sourced greywacke clasts derived from the Omaralluk Formation in eastern Hudson Bay and locally-sourced metagreywacke and greenstone derived clasts is imperative and should be approached cautiously with consideration for the implications on till provenance interpretation. This study demonstrated that the input of local greenstone and metagreywacke sources has a significant influence on the till-composition of the region and dismisses the notion that 'greywacke' clasts are entirely sourced from the Belcher Group.
- Depth to bedrock is spatially variable, and poorly mapped throughout the Manitoba HBL. It is an important parameter to consider when interpreting till composition in areas of thick drift, as variations in drift thickness mean that the local bedrock wasn't always accessible for erosion and incorporation into till. Instead, glaciers may have slid over, or reworked, pre-existing glacial and nonglacial sediment—leading to palimpsest till compositions that are not reflective of bedrock directly up-ice.
- The mapping of outliers of Paleozoic bedrock on the Precambrian Shield and inliers of Precambrian bedrock in the Hudson Bay Basin is poorly constrained, due to thick drift, organic cover and remoteness. These uncertainties present significant challenges to interpreting glacial-dispersal trends.

Recommendations for future exploration

A total of 105 kimberlite-indicator-mineral grains were recovered from till during this study. Nearly half (43 of 105) of these indicator-minerals were recovered from section 15 at the junction of the Hayes and Gods rivers. Clast fabrics conducted here indicate deposition by southeast (142°), a northwest-southeast bimodal fabric (147-327°) of uncertain trend and a south trending fabric (188°) above a suspected interglacial unit. Given the surrounding ice-flow history though, ice-flow toward the southwest (200 to 230°) should not be ignored—especially since clast-fabric analyses were not completed at till-sample sites with the highest KIM counts. Till-clast lithologies at section 15 include elevated-greenstone and greywacke content from unknown source(s), though there is no obvious relationship between increased KIMs and greenstone and greywacke content. Follow-up studies should focus on conducting additional sampling and ice-flow measurements in the area around the junction of the Hayes and Gods rivers, to delineate the source of these indicator-minerals.

Due to the complex ice-flow history, drift prospecting practises should focus on detailed clast-fabrics associated with individual till samples, to follow-up on any anomalies.

Economic considerations

The HBL region of northeastern Manitoba is a remote, largely unexplored region of Manitoba. Results from this study have provided the first reconnaissance-scale insight into the diamond potential of the region. This open file provides the necessary Quaternary stratigraphy, ice-flow and till-composition data to assist with interpreting indicator-mineral and till-matrix geochemistry results from the region.

Acknowledgments

Thanks to H. Thorleifson of the Minnesota Geological Survey for countless discussions regarding the Quaternary geology of the Hudson Bay Lowland region and providing the original field notes from Operation Winisk. P. Lenton is thanked for providing the data necessary for this report and historical knowledge of the field program. C. Epp is thanked for providing assistance locating sample material. De Beers Group of Companies is thanked for their analytical support for processing kimberlite-indicator-mineral samples. The authors thank M. Nicolas and C. Beaumont-Smith for providing reviews of this Open File.

References

Bell, R. 1879: Report on the country between Lake Winnipeg and Hudson Bay; Geological Survey of Canada, Report of Progress for 1877-78, p. 1CC-31CC.

Benn, D.I. 1994: Fabric shape and the interpretation of sedimentary fabric data; Journal of Sedimentary Research, v. A64, no. 4, p. 910–915.

Benn, D.I. 2004: Macrofabric; *in* A practical guide to the study of glacial sediments, D.J.A. Evans and D.I. Benn (eds.), Hodder Education, p. 93–114.

Berger, G.W. and Nielsen, E. 1990: Evidence from thermoluminescence dating for Middle Wisconsinan deglaciation in the Hudson Bay Lowland of Manitoba; Canadian Journal of Earth Sciences, v. 28, p. 240–249.

Clarke, M.D. 1989: Surficial geology, Gods River, Manitoba; Geological Survey of Canada, Map 1684A, scale 1:250 000.

Craig, B.G., Gwyn, H. and McDonald, B.C. 1967: Quaternary observations from Operation Winisk; unpublished field notes, Geological Survey of Canada.

Dalton, A.S., Finkelstein, S.A., Barnett, P.J. and Forman, S.L. 2016: Constraining the Late Pleistocene history of the Laurentide Ice Sheet by dating the Missinaibi Formation, Hudson Bay Lowlands, Canada; Quaternary Science Reviews, v. 146, p. 288–299.

Davis, J.C. 2002: Statistics and data analysis in geology; John Wiley and Sons, New York.

Dredge, L.A. and Cowan, W.R. 1989: Quaternary geology of the southwestern Canadian Shield; *in* Quaternary Geology of Canada and Greenland, R.J. Fulton (ed.), Geological Survey of Canada, Geology of Canada Series, no 1, p. 214–248.

Dredge, L.A., Morgan, A.V. and Nielsen, E. 1990: Sangamon and pre-Sangamon interglaciations in the Hudson Bay Lowlands of Manitoba; Geographie Physique et Quaternaire, v. 44, no. 3, p. 319–336.

Dredge, L.A. and McMartin, I. 2011: Glacial stratigraphy of northern and central Manitoba; Geological Survey of Canada, Bulletin 600, 27 p.

Dredge, L.A. and Nielsen, E. 1985: Glacial and interglacial deposits in the Hudson Bay lowlands: a summary of sites in Manitoba; *in* Current Research, Paper 85-1A, Geological Survey of Canada (ed.), p. 247–257.

Dredge, L.A. and Nixon, F.M. 1982: Surficial Geology, York Factory, East of Second Meridian-east, Manitoba; Geological Survey of Canada, Preliminary Map 2-1980, scale 1:250 000.

Dredge, L.A. and Nixon, F.M. 1992: Glacial and environmental geology of northeastern Manitoba; Geological Survey of Canada, Memoir 432, 80 p.

Fipke, C.E., Gurney, J.J. and Moore, R.O. 1995: Diamond exploration techniques emphasising indicator mineral geochemistry and Canadian examples; Geological Survey of Canada, Bulletin 423, 96 p.

Fedikow, M.A.F., Nielsen, E., Conley, G.G. and Lenton, P.G. 2000: Operation Superior: multimedia geochemical and mineralogical survey results from the southern portion of the Knee Lake greenstone belt, northern Superior Province, Manitoba (NTS 53L); Manitoba Industry, Trade and Mines, Manitoba Geological Survey, Open File Report OF2000-2.

Fedikow, M.A.F., Nielsen, E., Conley, G.G. and Lenton, P.G. 2001: Operation Superior: kimberlite indicator mineral survey results (2000) for the northern half of the Knee Lake greenstone belt, northern Superior Province, Manitoba (NTS 53M/1, 2, 3, 7 and 53L/15); Manitoba Industry, Trade and Mines, Manitoba Geological Survey, Open File Report OF2001-5.

Gauthier, M.S. 2017: Have you seen an Omar (Omarolluk erratic)?; Manitoba Geological Survey, URL <http://www.gov.mb.ca/iem/geo/surficial/omar_erratics.html> [September 2017].

Gauthier, M.S., Hodder, T.J., Kelley, S.E., Wang, Y. and Ross, M. 2016: Drift Exploration Techniques in the Gillam Area – Year 4 (NTS 54D, 54C); Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, Manitoba Mining and Minerals Convention 2016, Winnipeg, Manitoba, November 16–18, 2016, poster presentation.

Grunsky, E. 2010: The interpretation of geochemical survey data; Geochemistry, Exploration, Environment, Analysis, v. 10, p. 27–74.

Grütter, H.S., Gurney, J.J., Menzies, A.H. and Winter, F. 2004: An updated classification scheme for mantle-derived garnet, for use by diamond explorers; Lithos, v. 77, p. 841–857.

Hicock, S.R., Goff, J.R., Lian, O.B. and Little, E.C. 1996: On the interpretation of subglacial till fabric; Journal of Sedimentary Research, v. 66, no. 5, p. 928–934.

Hodder, T.J. and Kelley, S.E. 2017: Kimberlite-indicator-mineral results derived from glacial sediments (till) in the Kaskattama highland area of northeast Manitoba (parts of NTS 53N, O, 54B, C); Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, Open File OF2017-1, 6 p.

Hodder, T.J., Kelley, S.E., Trommelen, M.S., Ross, M. and Rinne, M.L. 2017: The Kaskattama highland: till composition and indications of a new Precambrian inlier in the Hudson Bay Lowland?; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Kingston, Ontario, May 14–17, 2017, poster presentation.

Hodder, T.J., Trommelen, M.S., Kelley, S.R., Wang, Y. and Ross, M. 2015: Revisiting the till stratigraphy in the Hudson Bay lowland region of Manitoba; CANQUA, St. John's, Newfoundland, August 17–20, 2015, poster presentation.

Holmes, C.D. 1941: Till fabric; Bulletin of the Geological Society of America, v. 52, p. 1299–1354.

Kaszycki, C.A., Dredge, L.A. and Groom, H. 2008: Surficial geology and glacial history, Lynn Lake–Leaf Rapids area, Manitoba; Geological Survey of Canada, Open File 5873, 105 p.

Keller, G.R., Bogdan, D.J. and Matile, G.L.D. 2004: Manitoba Kimberlite Indicator Mineral Database (Version 3.0); Manitoba Industry, Economic Development and Mines, Manitoba Geological Survey, Open File Report OF2004-25, zipped Microsoft Access2000 database.

Kelley, S.E., Hodder, T.J., Wang, Y., Trommelen, M.S. and Ross, M. 2015: Preliminary Quaternary geology in the Gillam area, northeastern Manitoba – year 3 (parts of NTS 54D5–9, 11, 54C12); *in* Report of Activities 2015, Manitoba Mineral Resources, Manitoba Geological Survey, p. 131–139.

Klassen, R.W. and Netterville, J.A. 1978: Surficial geology, Hayes River, Manitoba; Geological Survey of Canada, Map 2-1978, scale 1:250 000.

Klassen, R.W. and Netterville, J.A. 1980: Surficial geology, Kettle Rapids, East of Principal Meridian, Manitoba (54D); Geological Survey of Canada, "A" Series Map 1481A, scale 1:250 000.

Larsen, N.K. and Piotrowski, J.A. 2003: Fabric pattern in a basal till succession and its significance for reconstructing subglacial processes; Journal of Sedimentary Research, v. 73, no. 5, p. 727–734.

Mark, D.M. 1973: Analysis of axial orientation data, including till fabrics; Geological Society of America Bulletin, v. 84, p. 1369–1374.

Munsell Color–X-Rite, Incorporated 2015: Munsell Soil Color Book; Pantone LLC, Carlstadt, New Jersey, 42 p.

Natural Resources Canada 2015: Canadian digital surface model; Natural Resources Canada, URL <http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/34f13db8-434b-4a37-ae38-03643433fbbb.html> [September 2015].

Netterville, J.A. 1974: Quaternary stratigraphy of the lower Gods River region, Hudson Bay lowlands, Manitoba; Master of Science thesis, The University of Calgary, Calgary, Alberta, Canada, 79 p.

Nicolas, M.P.B. and Young, G. A. 2014: Reconnaissance field mapping of Paleozoic rocks along the Churchill River and Churchill coastal area, northeastern Manitoba (parts of NTS 54E, L, K); *in* Report of Activities 2014, Manitoba Mineral Resources, Manitoba Geological Survey, p. 148–160.

Nielsen, E. 2001: Quaternary stratigraphy, till provenance and kimberlite indicator mineral surveys along the lower Hayes River; *in* Report of Activities 2001, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 121–125.

Nielsen, E. 2002: Quaternary stratigraphy and ice-flow history along the lower Nelson, Hayes, Gods and Pennycutaway rivers and implications for diamond exploration in northeastern Manitoba; *in* Report of Activities 2002, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 209–215.

Nielsen, E. and Dredge, L.A. 1982: Quaternary stratigraphy and geomorphology of a part of the lower Nelson River; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Winnipeg, Manitoba, May 17–19, 1982, Field Trip Guidebook 5, 56 p.

Nielsen, E. and Fedikow, M.A.F. 2002: Kimberlite indicatormineral surveys, lower Hayes River; Manitoba Industry, Trade and Mines, Manitoba Geological Survey, Geological Paper GP2002-1, 39 p.

Nielsen, E., Morgan, A.V., Morgan, A., Mott, R.J., Rutter, N.W. and Causse, C. 1986: Stratigraphy, paleoecology and glacial history of the Gillam area, Manitoba; Canadian Journal of Earth Sciences, v. 23, p. 1641–1661.

Potter, R.R. 1962: Gods River map-area, Manitoba, Geological Survey of Canada, Paper 62-8, 12 p.

Prest, V.K., Donaldson, J.A. and Mooers, H.D. 2000: The Omar story: the role of Omars in assessing glacial history of west-central North America; Géographie physique et Quaternaire, v. 54, no. 3, p. 257–270.

Rainbird, R.H., Hadlari, T., Aspler, L.B., Donaldson, J.A., LeCheminant, A.N. and Peterson, T.D. 2003. Sequence stratigraphy and evolution of the Paleoproterozoic intracontinental Baker Lake and Thelon basins, western Churchill Province, Nunavut, Canada; Precambrian Research v. 125, p. 21–53.

Rinne, M.L. 2016: Geological compilation of the Fox River belt, Manitoba; Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, Manitoba Mining and Minerals Convention 2016, Winnipeg, Manitoba, November 16–18, 2016, poster presentation.

Roy, M. 1998: Pleistocene stratigraphy of the lower Nelson River area – implications for the evolution of the Hudson Bay Lowland of Manitoba, Canada; M.Sc. thesis, Université du Québec à Montréal, Montréal, Quebec, 220 p.

Saarnisto, M. and Peltoniemi, H. 1984: Glacial stratigraphy and compositional properties of till in Kainuu, eastern Finland; Fennia, v. 162, p. 163–199.

Sladen, W.E. 2011: Permafrost; Geological Survey of Canada, Open File 6724.

Thorleifson, L.H., Garrett, R.G. and Matile, G. 1994: Prairie Kimberlite study - indicator mineral geochemistry; Geological Survey of Canada, Open File 2875, 15 p.

Trommelen, M.S. 2012: Field-based ice-flow indicator data, Oxford House–Knee Lake area, northeastern Manitoba (NTS 53L14, 15, 53M1, 2); Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Data Repository Item DRI2012004, Microsoft® Excel® file

Trommelen, M.S. 2013a: Field-based ice-flow indicator data, Gillam to Split Lake, north-central Manitoba (NTS 54D, 64A); Manitoba Mineral Resources, Manitoba Geological Survey, Data Repository Item DRI2013005, Microsoft® Excel® file

Trommelen, M.S. 2013b: Preliminary Quaternary geology in the Gillam area, northeastern Manitoba (parts of NTS 54D5-9, 11, 54C12); in Report of Activities 2013, Manitoba Mineral Resources, Manitoba Geological Survey, p. 169–182.

Trommelen, M.S. 2014: Field-based ice-flow indicator data, Gillam to Gull Lake, north-central Manitoba (NTS 54D5, 6, 7); Manitoba Mineral Resources, Manitoba Geological Survey, Data Repository Item DRI2014003, Microsoft® Excel® file.

Trommelen, M.S. 2015: Glacial history and till composition, Knee Lake area, northeastern Manitoba (NTS 53L14, 15, 53M1, 2); Manitoba Mineral Resources, Manitoba Geological Survey, Geoscientific Paper GP2013-3, 30 p. plus 13 appendices.

Trommelen, M.S. in press: Surficial geology, till composition, stratigraphy and ice-flow indicator data, Seal River–North Knife River area, Manitoba (parts of NTS 54L, M, 64I, P); Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, Geoscientific Paper 2014-2.

Trommelen, M.S., Keller, G.R. and Lenton, B.K. 2014a: Digital compilation of surficial point and line features for Manitoba north of 54°: datasets; Manitoba Mineral Resources, Manitoba Geological Survey, Open File OF2013-10, 7 p.

Trommelen, M.S. 2011: Field-based ice-flow indicator data, Churchill area, northeastern Manitoba (part of NTS 54L16); Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Data Repository Item DRI2011001, Microsoft® Excel® file.

Trommelen, M.S. and Ross, M. 2014: Distribution and type of sticky spots at the centre of a deglacial streamlined lobe in northeastern Manitoba, Canada; Boreas, v. 43, p. 557–576.

Trommelen, M.S., Ross, M. and Campbell, J.E. 2012: Glacial terrain zone analysis of a fragmented paleoglaciological record, southeast Keewatin sector of the Laurentide Ice Sheet; Quaternary Science Reviews, v. 40, p. 1–20.

Trommelen, M.S., Ross, M. and Campbell, J.E. 2013: Inherited clast dispersal patterns: implications for paleoglaciology of the southeast Keewatin Sector of the Laurentide Ice Sheet; Boreas, v. 42, no. 3, p. 693–713.

Trommelen, M.S., Wang, Y. and Ross, M. 2014b: Preliminary Quaternary geology in the Gillam area, northeastern Manitoba (parts of NTS 54D5–11, 54C12) – year two; *in* Report of Activities 2014, Manitoba Mineral Resources, Manitoba Geological Survey, p. 187–195.

Tyrrell, J.B. 1916: Notes on the Geology of Nelson and Hayes rivers; Transactions of the Royal Society of Canada, v. 10, p. 1–29.

Wyatt, B.A., Baumgartner, M., Anckar, E. and Grütter, H.S. 2004: Compositional classification of ‘kimberlitic’ and ‘non-kimberlitic’ ilmenite; Lithos, v. 77, p. 841–857.