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TILL COMPOSITION, STRATIGRAPHY, ICE-FLOW INDICATOR DATA AND GLACIAL HISTORY OF THE NORTH KNIFE RIVER–CHURCHILL RIVER REGION, MANITOBA (PARTS OF NTS 54L, 64I)

Manitoba Geological Survey

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Geoscientific Paper GP2019-1

Till composition, stratigraphy, ice-flow indicator data and glacial history of the North Knife River–Churchill River region, Manitoba (parts of NTS 54L, 64I)

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Manitoba Geological Survey
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Cover photo:

A small river exposes boulders eroded from the till banks. The helicopter is sitting on metasedimentary bedrock.

Abstract

Quaternary geology investigations, including mapping of surficial materials and ice-flow indicators, and regional till-sampling surveys, were undertaken in the North Knife River–Churchill River region (parts of NTS 54L, 64I) in September of 2013, in partnership with the De Beers Group of Companies. An additional week of fieldwork was completed by the Manitoba Geological Survey along the Churchill River in August of 2014. Geological observations, and/or measurements of ice-flow indicators were recorded at 276 field sites within a 7500 km^2 area in this far northeastern part of Manitoba. To determine the composition and regional heterogeneity of the till, the <63 µm fraction of the till matrix, from 235 samples, was analyzed for total-carbonate (Ca-Mg), inorganic carbon, organic carbon and sulphur (LECO, LOI), and trace-element and major-element geochemistry (ICP-ES and MS; INAA) at the Saskatchewan Research Council Geoanalytical Laboratory, and at Activation Laboratories. Additionally, clasts (2–30 mm fraction) were separated from the till matrix and classified according to lithology. This report releases that data, as well as provides context for its use.

Résumé

En septembre 2013, des études géologiques quaternaires, y compris la cartographie des matériaux de surface et des marques d'écoulement glaciaire, ainsi que des levés régionaux d'échantillonnage de tills, ont été entrepris dans la région de la rivière North Knife et de la rivière Churchill (parties du SNRC 54L, 64I), en partenariat avec le De Beers Group of Companies. En août 2014, la Direction des services géologiques du Manitoba a terminé une semaine supplémentaire de travaux sur le terrain le long de la rivière Churchill. Des observations géologiques et des mesures de marques d'écoulement glaciaire ont été enregistrées à 276 sites dans un secteur de 7 500 km^2 dans cette partie de l'extrême nord-est du Manitoba. Pour déterminer la composition et l'hétérogénéité régionale du till, la fraction <63 µm de la matrice du till, provenant de 235 échantillons, a été analysée pour la teneur en carbonates totaux (Ca-Mg), le carbone inorganique, le carbone organique et le soufre (LECO, LOI) et la géochimie des éléments traces et majeurs (ICP-ES et MS; INAA) au Saskatchewan Research Council Geoanalytical Laboratory et aux laboratoires Activation. De plus, des clastes (fraction de 2 à 30 mm) ont été séparés de la matrice du till et classés selon la lithologie. Le présent rapport publie ces données et fournit le contexte de leur utilisation.

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Introduction

Quaternary geology studies were conducted in 2013 and 2014 within an area of about 11,370 km^2 (Figure 1) between the North Knife River and the Churchill River. The objectives of this project are to 1) investigate the surficial geology; 2) interpret the glacial history; and 3) conduct a till-sampling program to examine variability within the regional till compositional data as a means to determine background and threshold element concentrations, sediment-landform relationships, and glacial dispersal distances and directions. This work builds on detailed paleoglaciologic studies conducted in the same area (Trommelen and Ross, 2009; Trommelen et al., 2010; Trommelen and Ross, 2011; Campbell et al., 2012; Trommelen et al., 2012; Trommelen et al., 2013; Trommelen et al., 2014a; Trommelen, 2015a).

As in 2012, De Beers Group of Companies graciously allowed the Manitoba Geological Survey (MGS) to jointly conduct Quaternary geology studies in far northeast Manitoba during their exploration program in 2013. Additional fieldwork was completed by the MGS in August of 2014, along the Churchill River. The initial MGS Far North Geomapping Initiative in Quaternary geology studies occurred between 2009 and 2011, with support from the Geological Survey of Canada's (GSC) Geo-mapping for Energy and Minerals (GEM) Multiple Metals–Northeast Manitoba Project.

This report releases the field site, till compositional and ice-flow indicator data sets collected to assist with the application of drift prospecting in the North Knife River–Churchill River region. The report also includes the regional physiographic and geological setting, regional interpretation of ice-flow chronology and subglacial dispersal, and detailed descriptions of the till sampling methods, laboratory procedures and quality assurance–quality control for the analytical data. Till sampling, together with the new surficial geological framework, should be an effective exploration tool in this region.

Regional setting

The study area is located in northeastern Manitoba (Figure 1). Elevation varies mainly from 50 to 340 m above sea level

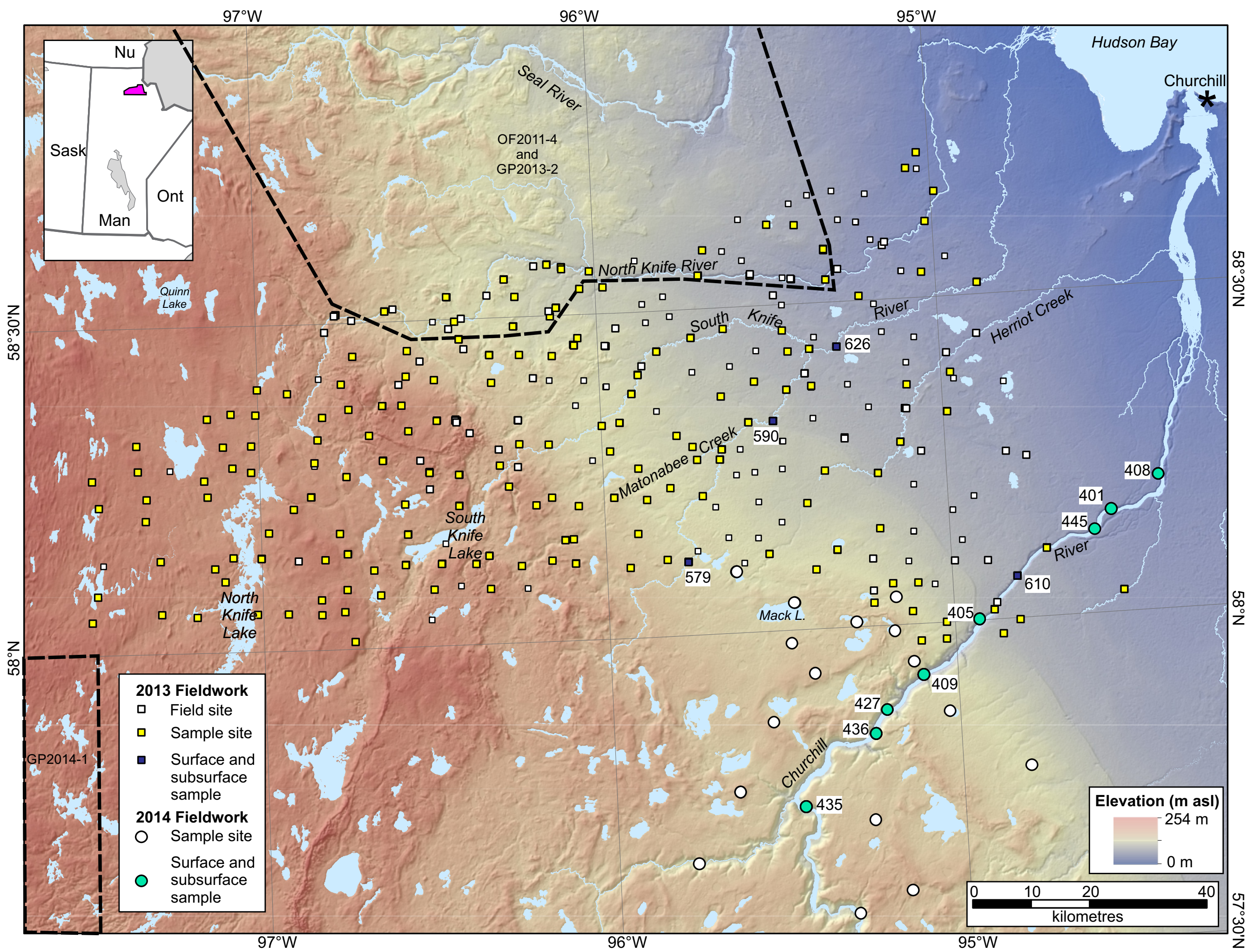

Figure 1: Location of the North Knife River–Churchill River region field sites in northeast Manitoba. The upper dashed area depicts part of the 2009–2012 field area (Campbell et al., 2012; Trommelen, 2015a), while the lower-left depicts the northern extent of the 2013 Gauer Lake–Wishart Lake field area (Trommelen, 2015g). Labelled sites are the locations of stratigraphic sections where multiple samples were taken. The background image was generated using the radar-derived digital elevation data from the Shuttle Radar Topography Mission data set (United States Geological Survey, 2002). A hill-shade model has been added with transparency effect to enhance relief.

(asl). Local relief is up to 30 metres. The North Knife and South Knife rivers are the major drainage channels in the study area, flowing east from North Knife and South Knife lakes 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 area is predominantly mantled by till with expansive regions of organic deposits (muskeg). Bedrock outcrops are scarce, and generally limited to exposures along creeks and rivers. The study area has been partially wave-washed by both the postglacial Tyrrell Sea and glacial Lake Agassiz (Dredge, 1983; Dredge and Cowan, 1989).

The region falls within the zone of discontinuous permafrost (Sladen, 2011). Bogs are commonly frozen and ice-rich below one metre. Periglacial features such as mudboils, peat plateaus, ice-wedge polygons and frost-shattered rock are common.

Bedrock geology

Precambrian bedrock mapping in Manitoba's far northeast, an area that is largely devoid of outcrop, is supported by an aeromagnetic and gamma-ray spectrometric geophysical survey of the Great Island–Seal River area (Fortin et al., 2009).

Manitoba's far northeast forms part of the southeast margin of the Hearne craton, which comprises a heterogeneous basement of Archean orthogneiss, granitoid intrusions and rare supracrustal rocks overlain by scattered erosional remnants of latest Archean and Paleoproterozoic siliciclastic cover sequences (Figure 2), all of which have been variably overprinted by tectonothermal and magmatic activity associated

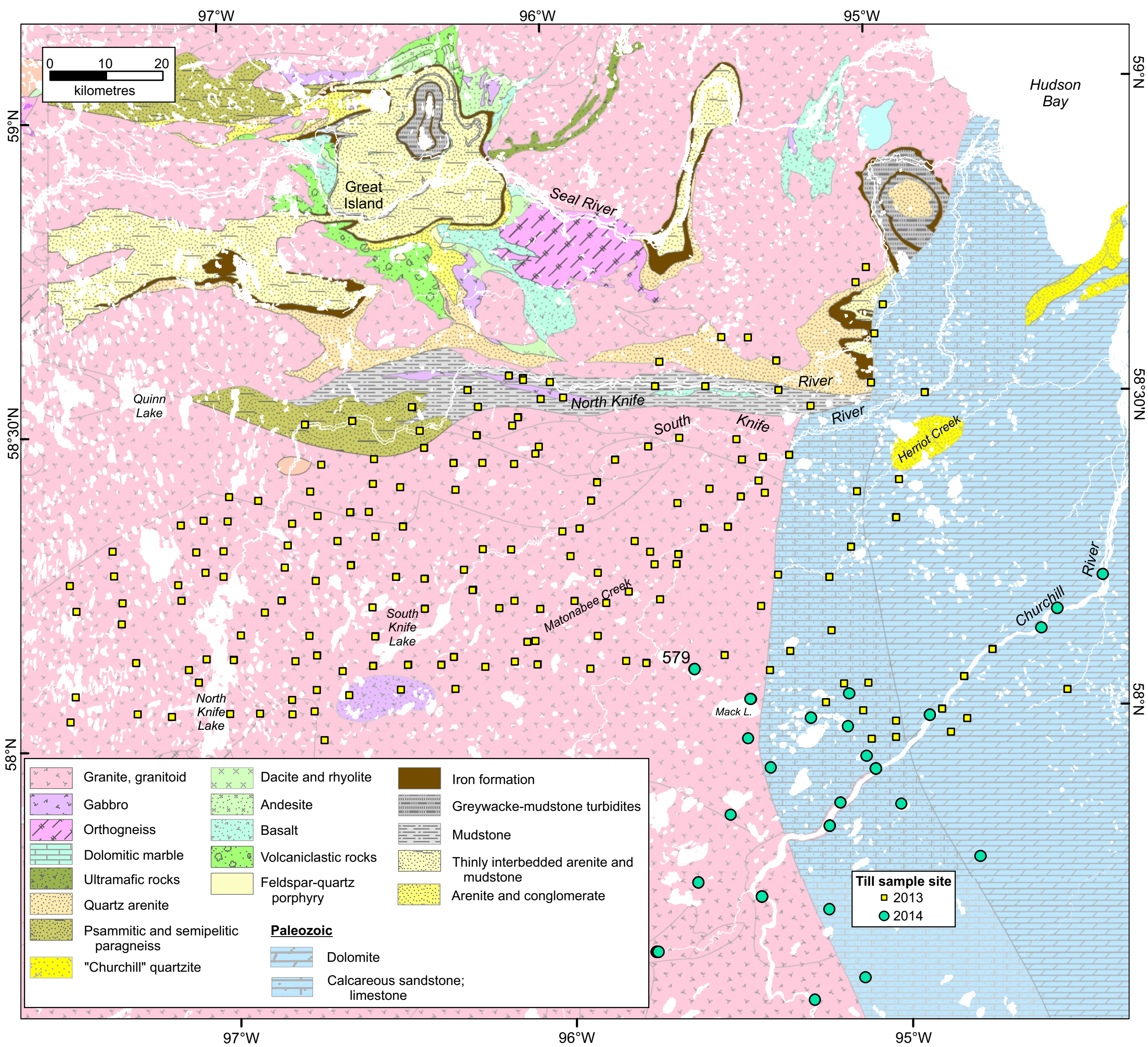

Figure 2: Bedrock geology map of the Seal River to Churchill River area, northeastern Manitoba, showing locations of till-sample sites. Bedrock geology is modified after Anderson et al. (2009; 2010b) in the north, and an unpublished MGS compilation in the south.

with the Paleoproterozoic Trans-Hudson orogeny (Anderson et al., 2010a). The Seal River domain, which defines the southeast margin of the Archean Hearne craton in Manitoba, is characterized by a dome-and-basin structural geometry, with the 'domes' defined by Meso- to Neoarchean metaplutonic and metavolcanic rocks, and the 'basins' defined by synforms of latest Archean and Paleoproterozoic continental and marine siliciclastic rocks. The siliciclastic cover rocks have been subdivided into four distinct sequences that provide a discontinuous ca. 2.7 to 1.9 Ga record of intracratonic sedimentation and basin evolution at the south margin of the Hearne craton (Anderson et al., 2010a). Metamorphic grade in the North Knife River–Churchill River region ranges from upper greenschist to middle amphibolite facies.

In the easternmost North Knife River–Churchill River region, the Precambrian shield rocks are unconformably overlain by gently dipping Paleozoic platform calcareous sandstone, limestone and dolomite that form the western margin of the Hudson Bay Basin (Nicolas and Armstrong, 2017).

Quaternary geology

The study area was situated 250 to 550 km from the Late Wisconsinan Keewatin Ice Divide (KID) and ~1 500 km from the Quebec–Labrador sector of the Laurentide Ice Sheet. At multiple periods in time, ice transported and deposited carbonate-bearing detritus ~100 km inland (Dredge, 1988) from the Paleozoic carbonate platform in Hudson Bay (Nicolas and Armstrong, 2017). The nature of interaction between ice from Keewatin and from Hudson Bay is uncertain, but a thick ice saddle was likely present over southern Hudson Bay during late deglaciation (Dyke and Prest, 1987; Thorleifson et al., 1993; Trommelen et al., 2012). The field area is within the expected zone of confluence between the Keewatin and Quebec–Labrador ice, and the nature of till composition mixing is examined herein. The post-glacial history of this area can be found in Gauthier (2016a).

The surficial geology (Figure 3) for most of the 2013 field area is available at 1:100 000 scale (Gauthier, 2016b, c). Geologic materials encountered at field sites in 2013 are displayed

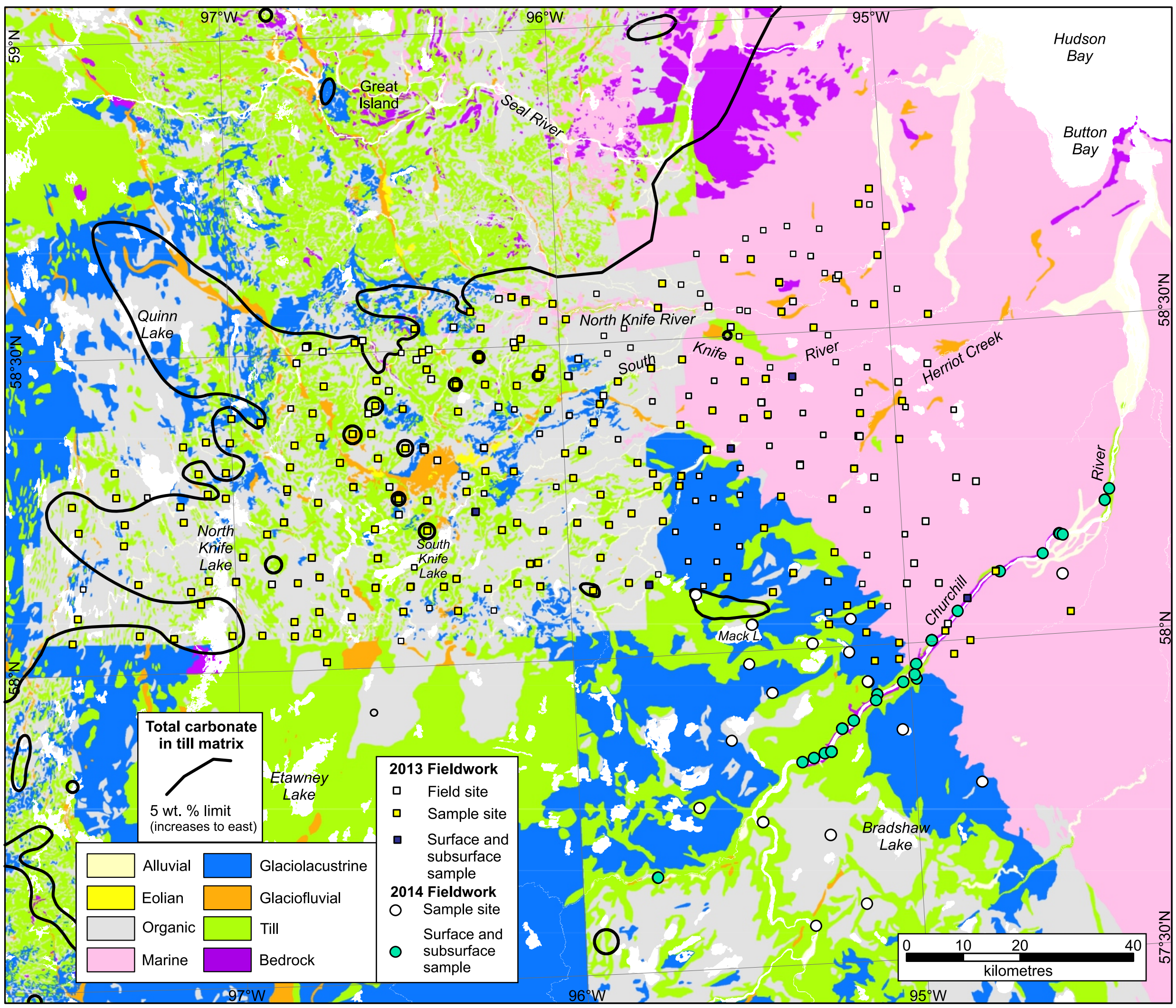

***Figure 3:** Simplified surficial geology map of the North Knife River–Churchill River region, showing locations of field and till-sample sites. Geology is modified from Klassen and Netterville (1980), Dredge et al. (2007), Trommelen and Campbell (2012a, b, c, d), Trommelen (2014a, b, c, d, e) and Gauthier (2016b, c). Till was sampled wherever possible, so the reader can infer that till was not encountered at 'field sites'. The black line denotes the western and northwestern limits of carbonate dispersal within till matrix (sourced from ongoing compliation at the MGS [Trommelen and McMartin, 2019] and includes the data from this project).*

on Figure 4. Regionally, the surficial geology is available as a mix of updated 1:50 000 scale mapping (Trommelen and Campbell, 2012a, b, c, d; Trommelen, 2014a, b, c, d, e) and older 1:250 000 scale (Dredge and Nixon, 1981, 1982) and 1:500 000 scale mapping (Dredge et al., 1986; Dredge and Nixon, 1992; Dredge et al., 2007).

Stratigraphy

The stratigraphy in the Hudson Bay Lowland (HBL) reflects a long history of major and minor shifts in ice-sheet behaviour throughout several advance and retreat cycles, as well as intervening interglacial and interstadial stages (Dredge and McMartin, 2011). There are four named till sheets in the Manitoba portion of the HBL (Klassen, 1986; Nielsen et al., 1986; Dredge et al., 1990; Dredge, 1992; Roy et al., 1995; Roy, 1998; Nielsen, 2001, 2002), which are interpreted to be correlative to three or four named till sheets in the Ontario portion of the HBL (Skinner, 1973; Thorleifson et al., 1993). These include the pre-Illinoian Sundance, the Illinoian Amery, and the Wisconsinan Long Spruce/Wigwam Creek and Sky Pilot tills. Along many rivers, these units are capped by glaciolacustrine and/or Tyrrell Sea sediments (Dredge and Nixon, 1992).

As the study of till stratigraphy in Manitoba increases in detail, the interpretation appears to become more complex. For instance, a study conducted along four rivers that incorporated analysis of numerous up-section till fabrics and sample analyses documented 5 to 35 m of glacial sediments that included multiple till units with varying concentrations of north- and east-sourced indicator clasts and a large range of till-fabric orientations (Nielsen, 2002; Hodder et al., 2017). This study indicated significant transitions in the source area of ice over time, which is not easily broken into four till units. Ongoing field studies in the Gillam area of northern Manitoba (Trommelen, 2013; Trommelen et al., 2014b; Kelley et al., 2015), ~200 km southeast of the North Knife River–Churchill River region, have also identified thick (1–40 m) sections of till with up-section fluctuations in texture, matrix carbonate concentration and clast lithologies. Some till units are separated by sand and/or gravel beds, but obvious indicators of interglacial or interstadial conditions are rare.

Methods

Field data collection

Helicopter-supported fieldwork was conducted in the first two weeks of September 2013, alongside the De Beers Group of Companies field crews. At each of the 211 sites visited (Figure 1), geomorphic and terrain characteristics, map unit and geological interpretation were recorded in addition to location coordinates.

In late August of 2014, the MGS surficial geologists conducted fieldwork along the Churchill River, in conjunction with MGS bedrock geologists (Nicolas and Young, 2014). 45 field sites were visited; 12 of which were stratigraphic sections (Figure 1).

The site information for both years is included in Appendix 1.

Till sampling

A surface till sampling survey was conducted at regional-scale in the map area (Figure 1). Site location and description, sample information (e.g., sample material, sample depth and soil horizon) and additional comments related to the sample and/or site are provided in Appendix 1. In total, 235 till samples *(*Appendix 1) of ~2 kg each were collected (Figure 1) for till-matrix major- and trace-element geochemistry, grain size, carbonate and organic carbon content, and lithological analyses. The surface-till samples were collected between 20 and 70 cm depth, with a shovel, and/or trowel from the B-, B/C- or C-soil horizon in hand-dug pits. Where present, samples were collected from mudboils in an attempt to sample the least oxidized and most representative material. At stratigraphic sections, samples were taken where opportunity permitted (Figure 1).

Stratigraphic sections

Fourteen stratigraphic sections were documented during this project, situated mainly along the Churchill River (Figure 5). Stratigraphic columns and a photo of each section are included in Appendix 2. Additional stratigraphic data involving Holocene sediments was released in Gauthier (2016a). Stratigraphic research has a long history in northeast Manitoba (B.G. Craig, H. Gwyn and B.C. McDonald, unpublished notes, 1967; Craig, 1968; McDonald, 1968; Nielsen and Young, 1981; Dredge and Nixon, 1992; Trommelen, 2015a). Unpublished data from Operation Winisk is available for viewing at the MGS.

Ice-flow indicator mapping

Erosional ice-flow indicators, the orientations and relative ages of which were documented at 10 sites in 2013 and 2 sites in 2014, include micro-scale nondirectional indicators (striations and grooves) and directional indicators (chattermarks, crescentic gouges and stoss-lee relationships). Macroform features encountered in the study area include roches moutonnées. Detailed attention was paid at all outcrops to record rare and protected ice-flow indicators, in addition to the dominant indicators. Where crosscutting patterns were found, the relative ages of ice-flow orientations observed were determined where possible. Detailed ice-flow indicator measurements are found in Appendix 3. Observations collected supplement data from the work undertaken in 2012 to the north (Trommelen, 2015a).

Remotely-sensed mapping

Mapping of remotely-sensed glacial geomorphology, including ice-flow parallel streamlined landforms (drumlins,

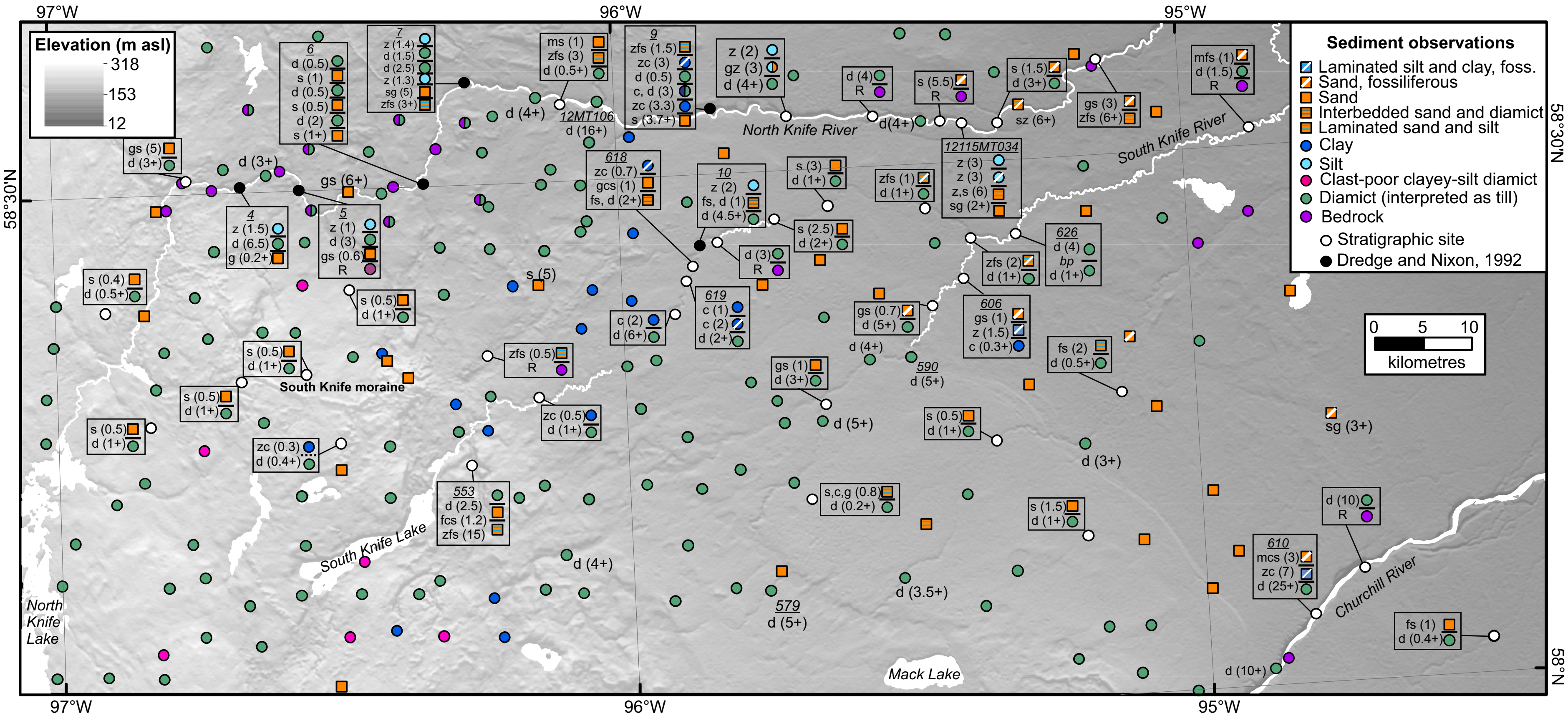

***Figure 4**: Depth (m; in brackets) and type of sediment encountered in the North Knife River to Churchill River area. Important stratigraphic sites are labelled; 533 and 6xx refer to the label 13115MT6xx. This data is also included within Appendix 1. Abbreviations: bp, boulder pavement; c, clay; d, diamict; fcs, fine to coarse sand; foss., fossiliferous; fs, fine sand; g, gravel; gcs, gravelley coarse sand; gs, gravelly sand; gz, gravelley silt; mcs, medium to coarse sand; mfs, medium to fine sand; ms, medium sand; R, bedrock; s, sand; z, silt; zc, silty clay; zfs, silty fine sand.*

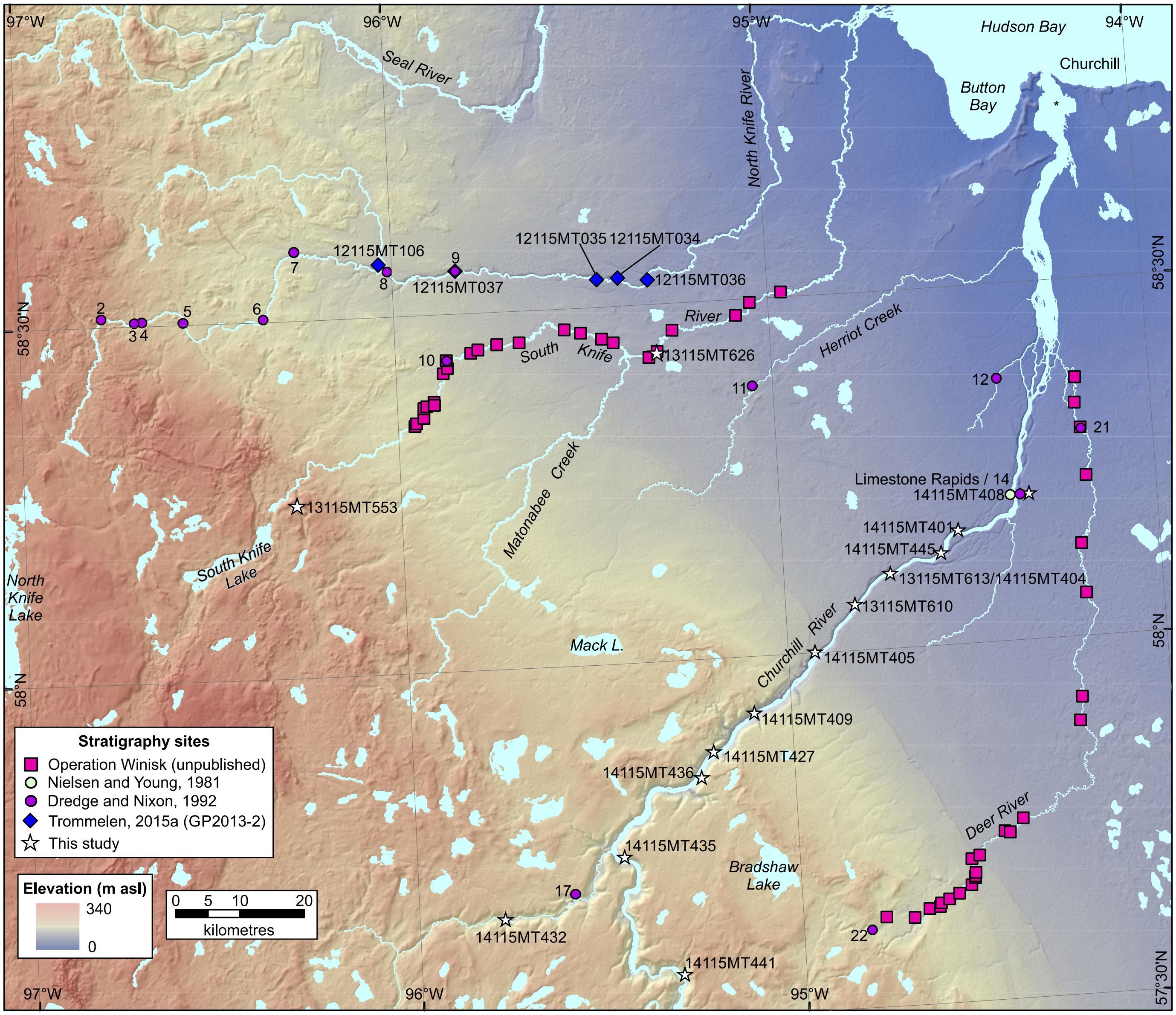

***Figure 5:** Stratigraphic sites in northeast Manitoba, from this study as well as previous work. The background image was generated using the radar-derived digital elevation data from the Shuttle Radar Topography Mission data set (United States Geological Survey, 2002). A hill-shade model has been added with transparency effect to enhance relief.*

megaflutes, crag-and-tails, streamlined bedrock), esker ridges and moraine ridges, was performed as part of ongoing mapping efforts (Manitoba Growth, Enterprise and Trade, 2018a). Landform mapping used imagery from SPOT4/5 satellite imagery (10 m resolution, Geobase®, 2005–2010), in combination with a Shuttle Radar Topography Mission (SRTM) digital elevation model (30 and 90 m resolution, United States Geological Survey, 2002). Within the field areas, mapping was performed on 1:60 000 scale black and white aerial photographs.

Laboratory and analytical procedures

Till-sample splits were sent to the Saskatchewan Research Council (SRC) Geoanalytical Laboratory. Approximately 1 kg of each till sample was air dried and dry sieved, using stainless steel mesh screens to obtain the <2 mm size-fraction for texture and <63 µm size-fraction for geochemical analyses and carbonate content determination. The remainder of the original samples was archived at the MGS.

Clast lithology

Clast lithology of the till samples was determined to help identify major directions of dispersal and till provenance. Clasts larger than 2 mm were sieved from a portion of each till sample collected and further separated into clast-size fractions of 2–4 mm, 4–8 mm and 8–30 mm. The granules or pebbles within each clast-size fraction were separated according to lithology by the author, using an optical microscope. An average of 196 clasts was counted for each till sample, with averages of 91, 27 and 79 clasts for the 2–4 mm, 4–8 mm and 8–30 mm size fractions, respectively. In Appendix 4, the lithological class results are expressed as numbers of clasts in a separate table for each size fraction. The fractions were then summed (2–30 mm) and expressed as a count percent (ct. %) of the total number in another table. Photos of each sorted 2–4 mm size fraction are presented in Appendix 5.

Clasts were separated into 22 rock types (Appendix 4). The greenstone belt (sedimentary, volcanic) rock types are at low to medium metamorphic grade, and may contain garnet, andalusite and sillimanite. These greenstone clasts are typically angular to subrounded and grey, dark green or black; with rare burnt-umber red. Sedimentary and volcanic rock types in bedrock exposures are quite varied (Anderson et al., 2009; Anderson et al., 2010b), and include mudstone, phyllite, arenite, psammite, schist, quartz arenite, conglomerate, paragneiss, marble, iron formation, gabbro, amphibolites, basalt, andesite, dacite, rhyolite, and volcaniclastic rocks. Granitoid and gneissic rocks types, angular to subangular in shape, include granite, porphyritic granite, granodiorite, biotite-granite, syenogranite, quartz syenite, quartz diorite and tonalite.

Exotic granitoid clasts are subrounded and/or faceted in shape, and consist of darker red or purple lithologies foreign to the Hearne craton. Exotic red or purple metavolcanic clasts (Figure 6 a–c, g) are typically resistant, rounded to subrounded in shape, and include porphyries with white phenocrysts (Pitz

Figure 6: *Transported foreign clasts encountered in the North Knife River–Churchill River region include red/purple metavolcanic porphyries* ***(a–c, g)*** *and greywackes with recessive circular calcareous concretions* ***(d–g)****. Soft, unmetamorphosed Paleozoic carbonates* ***(h)*** *have also been transported west across the Precambrian shield.*

Formation of the Dubawnt Supergroup) and/or with phlogopite phenocrysts (Christopher Island Formation of the Dubawnt Supergroup; Peterson, 2006).

Exotic 'eastern' Proterozoic clasts include unmetamorphosed red siltstones and sandstones and resistant greywacke. Greywacke erratics with tan to light grey calcareous concretions are derived from the Omarolluk Formation of the Belcher group in eastern Hudson Bay (Ricketts and Donaldson, 1981; Prest et al., 2000; Johnston and Schreiner, 2011). These distinctive erratics are easily diagnosed as larger clasts and commonly referred to as 'Omars' (Prest et al., 2000; Figure 6 d–g). These clasts are difficult to distinguish as pebbles, and can be confused with the greenstone belt clasts, as the rock matrix properties are variable and concretions may be absent. Proterozoic greywackes are probably under-mapped in concentration, as dark fine-grained clasts of uncertain lithology were placed in the greenstone category. Paleozoic carbonate (limestone, dolostone, carbonate-rich sedimentary) clasts (Figure 6h) are unmetamorphosed tan, off-white, light grey or pink, rounded to subrounded, and react with diluted hydrochloric acid when crushed. Chert and rare, abraded, shell fragments were also found within the smallest size fractions.

For interpretation of till composition and dispersal patterns, the clasts were grouped into six simplified classes (granitoid; greenstone; Paleozoic carbonate; exotic northern; exotic eastern; quartz) to reduce lithological identification errors. The breakdown of clast-types included in the six classes is presented in Table 1.

Grain size distribution

The matrix textural results were calculated as weight percent (wt. %) sand, silt and clay of the <2 mm fraction and are presented in Appendix 6.

At SRC, an aliquot of <2 mm sample material was transferred to a flask. An aliquot of Calgon® was added. De-ionized water was added to the flask and the flask was shaken until the contents were thoroughly mixed. The contents of the flask were sieved through a screen into a graduated cylinder. An aliquot of sample was immediately removed. A second aliquot (of clay) was removed from the cylinder, after a certain period of time (the time period is dependent on the ambient room temperature). The sieved sand and aliquots of sample material were dried and re-weighed. Calculations were performed to determine the percentage of sand, silt, and clay in the sample based on the total weight. An SRC standard was prepared and inserted into the group every 12 samples. Replicate samples were inserted after every 40 samples or at the end of smaller groups.

Carbonate content

The results for carbonate content are provided in Appendix 7. At SRC, an aliquot of the till matrix (<63 µm, agate ground) was digested using HCl, and then analyzed using a PerkinElmer Optima 5300DV. The samples were analyzed for Ca and Mg (in wt. %), and then calcite, dolomite and total carbonate (CO_3) were calculated (in wt. %). Quality-control samples were prepared and analyzed with each batch of samples.

Carbon, organic carbon and sulphur

To determine carbon and sulphur, an aliquot of the <63 µm till-matrix size-fraction was combusted at SRC in a LECO induction furnace with an oxygen supply. The results for total carbon, organic carbon and sulphur (all in wt. %) are included in Appendix 8. The percentage of organic carbon is determined from the percentage of inorganic carbon (of an aliquot of sample) using the LECO induction furnace with an argon supply. At least one standard was analyzed in every 20 samples as well as after all the samples. One sample duplicate was analyzed in every 40 samples. The detection limit for carbon, sulphur and organic carbon is 0.01%.

Loss-on-ignition

Loss-on-ignition (LOI) gives an estimate of the total organic content, and can help to give a measure of the degree to which the sample geochemistry has been modified by post-depositional weathering. The results for LOI at 1000°C are included in Appendix 9.

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

Simplified class	Granitoid	Greenstone	UGG	Carbonate	Hudson Bay Basin	Exotic northern	Exotic eastern	Unknown
Detailed classes	Granitoid	Phyllite/ Psammite	Undifferentiated greenstone and greywacke	Grey, tan, black, limestone/ dolostone	Kenogami Formation	Exotic, faceted granitoids and gneiss	Omar	Quartz
		Dark green volcanic			Lower Portage Chute Formation		Shell fragment	Quartzite
		Quartz arenite		Pink limestone			Unmetamorphosed sediment	Chert
		Paragneiss				Exotic, red metasediment and metavolcanics		Iron formation
		Sulphide						
		Amphibolite						
		Gabbro						
		Diorite						

At SRC, an aliquot of <63 µm till-matrix size-fraction was placed into a crucible and the total initial weight was recorded. The sample was then placed in a muffle oven for a suitable period of time. The samples were then removed from the oven, allowed to cool and reweighed. One in every 40 samples was analyzed in duplicate. The detection limit for the determination of LOI is 0.1 wt. %.

Geochemistry

ICP-MS partial (HNO_3:HCl) digestion

For the determination of 41 elements, an aliquot of the <63 µm size-fraction of each sample was analyzed at SRC. The sample aliquot was digested in a mixture of ultra-pure, concentrated nitric and hydrochloric acids (HNO_3:HCl) in a hot-water bath and then diluted using de-ionized water prior to analysis. The sample solution was analyzed by inductively coupled plasma–mass spectrometry (ICP-MS). The analytical results are presented in Appendix 10. Analytical data for control reference standards, analytical and field duplicates, and blanks are also included. The acid digestion is weaker than an aqua regia (1:3, HNO_3:HCl) digestion, as such, the concentrations reported herein cannot be directly compared to till-geochemistry values commonly reported by the GSC (Spirito et al., 2011).

ICP-MS near-total (HF:HNO_3:$HClO_4$) digestion

For the determination of 49 elements, a portion of the <63 µm size fraction for each sample was analyzed at SRC. An aliquot of the fraction was digested to dryness in a hot-block digesting system using a mixture of ultra-pure concentrated acids (HF:HNO_3:$HClO_4$). The residue was dissolved and made up to volume using de-ionized water prior to analysis. The sample solution was analyzed by inductively coupled plasma–emission spectrometry (ICP-ES; Al_2O_3, Ba, CaO, Cr, Fe_2O_3, La, Li, MgO, MnO, P_2O_5, K_2O, Na_2O, Sr, TiO_2) and ICP-MS (remaining elements). The analytical results are presented in Appendix 11. Analytical data for control reference standards, analytical and field duplicates, and blanks are also included. The three-acid leach used for this method is weaker than what is used for 'total' digestion (four-acid) till geochemistry and, as such, the concentrations reported herein cannot be directly compared to till geochemistry values commonly reported by the GSC (Spirito et al., 2011).

'Total' digestion, instrument neutron activation analysis

For the determination of Au plus a 34 element- or oxide-suite, a 30 g aliquot of the <63 µm size fraction for each sample was sent to Activation Laboratories Ltd. (ActLabs). There, the aliquots were analyzed by instrumental neutron activation analysis (INAA), which measures gamma radiation induced in the sample by irradiation with neutrons. The analytical results are presented in Appendix 12, together with analytical data for control reference standards, analytical and field duplicates, and blanks.

Till samples were also sent to ActLabs for INAA during the re-analyses completed in the adjacent area of northwestern Manitoba (Lenton and Kaszycki, 2005), and the results are directly comparable.

Statistical interpretation

Principal component analysis

Multivariate statistical methods allow large datasets to be explored, while still incorporating as much information (variables) as possible (Grunksy, 2010). To analyse the till-matrix geochemistry for provenance information, we examined the near total-digestion ICP-MS data. The dataset includes samples from the 2012 study to the north (Trommelen, 2015a), as well as from this study. Data from the 2009 and 2010 area was analyzed using a different laboratory method (Campbell et al., 2012) and cannot be directly compared. After dataset preparation (removal of elements that were consistently near or at detection limits, substitution of other near/at detection limit values and removal of oxides), the dataset was transformed using a centered-log ratio transformation to avoid the effects of closure on the dataset (Grunksy, 2010). For a more thorough examination of the geochemistry data for mineral exploration purposes, the reader is referred to methods in Chen et al. (2019) and others (e.g., Barnett and Williams, 2009; Grunksy, 2010; Grunksy and McClenaghan, 2013; Sacco et al., 2018).

Results

Ice-flow history

For most of the study area, thick sediment cover precludes detailed interpretation (Figure 3). Where encountered, the bedrock surfaces were commonly rough, weathered and/or lichen-covered, which further inhibits data collection. Erosional ice-flow indicators in the northern portion of the study area are oriented between 110 and 290° (Figure 7, Appendix 3).

Rare and protected erosional ice-flow indicators trend to the W–NW and SE. First, W–NW-trending (270 and 290°) chattermarks were mapped at two new sites, where they are the oldest mapped erosional indicators (Figure 7, Figure 8a, b). At site 13115MT626, 4 m of clast-poor till overlies lodged boulders striated to 270°, which overlies 1+ m of a different, bouldery till (Figure 8c). Second, 1 m wide gouges that trend to 160° were mapped at two new sites along Calder Creek, where they are the oldest mapped erosional indicators (Figure 7, Figure 8d).

Widespread and abundant erosional ice-flow indicators trend to the SSW and SW. First, SSW-trending (185 to 220°) striations, grooves and chattermarks were mapped at seven new

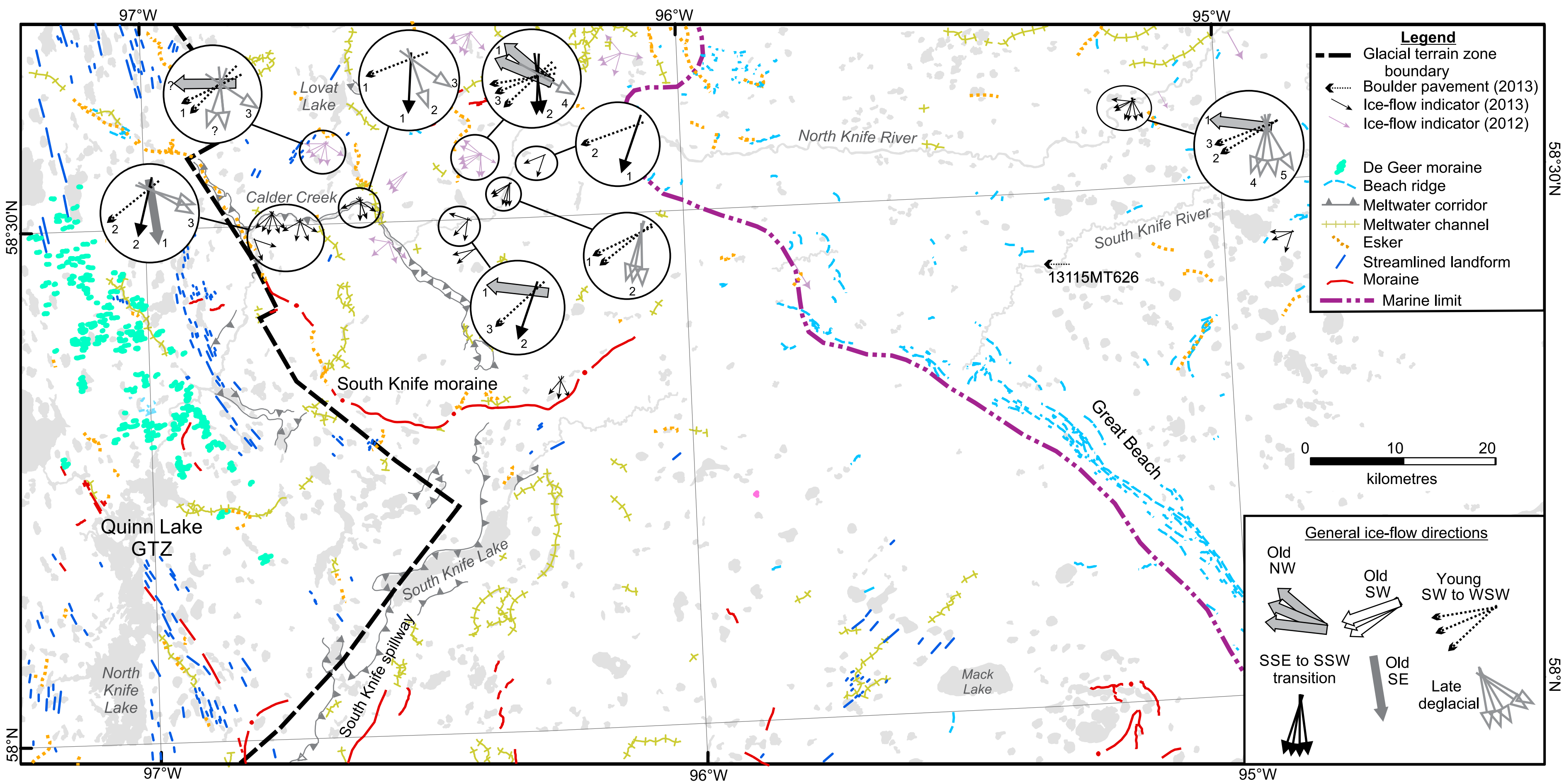

Figure 7: *Erosional ice-flow indicators (striae, chattermarks, gouges, grooves, roches moutonnées) collected in the summer of 2013 from the North Knife River–Churchill River region. Direction was not known at every site, but enough sites in the area provided information to consistently assign the directions, as shown here. Larger circles are a compiled summary of the relative ages (1=oldest) and trends of ice-flow indicators for a single site or sites in close proximity to each other. No age relationships were documented at sites where small black arrows are not accompanied by a large circle. At site 13115MT626 (labelled) 4 m of till overlies a striated boulder pavement, which overlies 1+ m of a different bouldery till. Geomorphic features are available online as both a PDF and a digital data download (Manitoba Growth, Enterprise and Trade, 2018a). Abbreviation: GTZ, glacial terrain zone.*

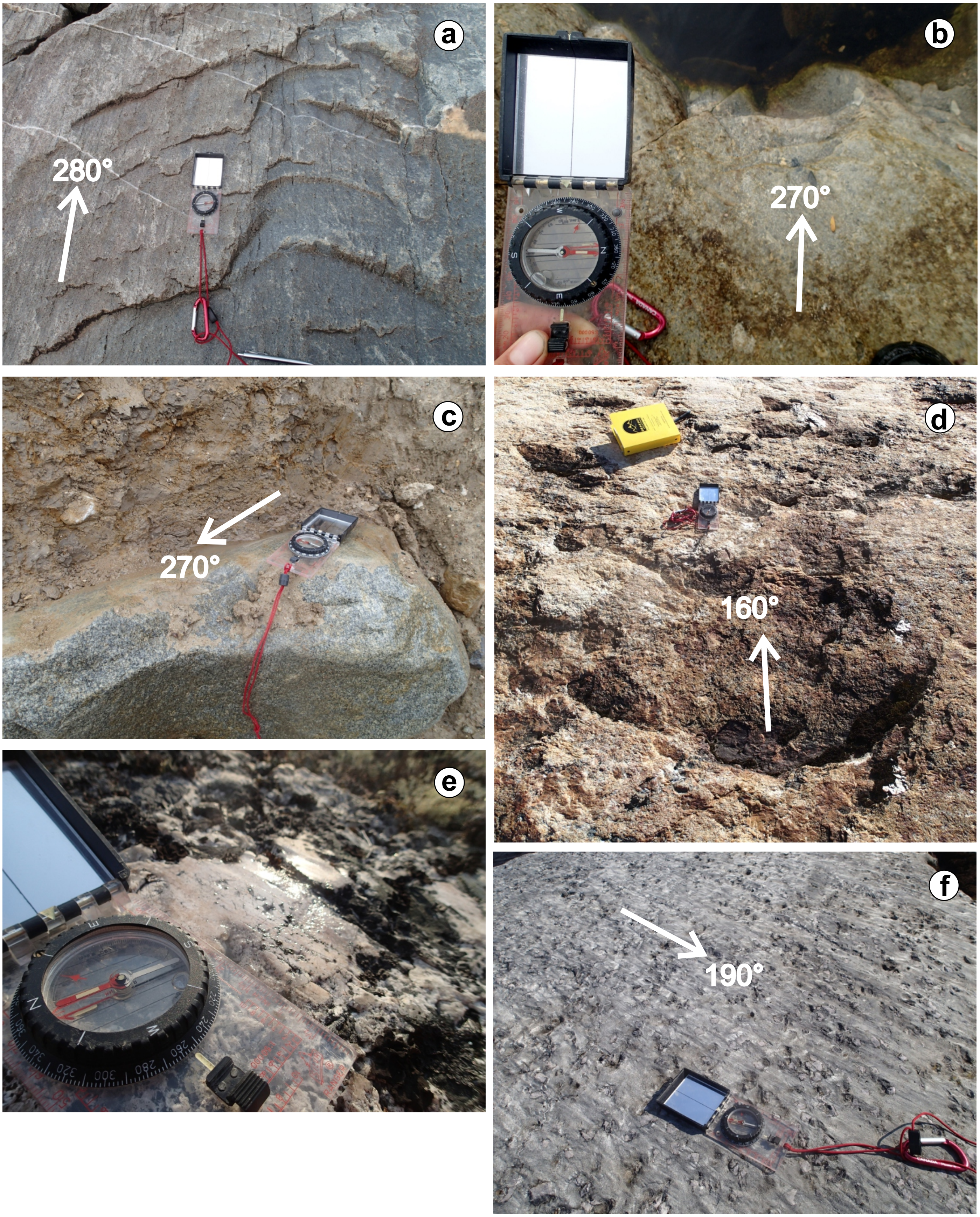

Figure 8: *Various ice-flow indicators collected in the summer of 2013 from the North Knife River–Churchill River region:* ***a)*** *chattermark set that trends 280° at site 13115MT500;* ***b)*** *chattermark set trending 270°, on the edge of an outcrop at site 13115MT549;* ***c)*** *striations that trend 270° at the top of a dipping boulder embedded in the contact between two different till units at site 13115MT626;* ***d)*** *a large chattermark that trends 160° at site 13115MT602;* ***e)*** *very fine striations that trend 245° at the top of an outcrop at site 13115MT598;* ***f)*** *striations and grooves that trend 190° on psammitic outcrop at site 13115MT599.*

sites, where they are either the oldest mapped erosional indicators, or are of unknown age (Figure 7). Second, SW-trending (230 to 250°) striations (Figure 8e), grooves and chattermarks were mapped at eight new sites, and are of variable cross-cutting age (Figure 7). Lastly, fine striations, chattermarks and grooves trend to the ESE (110 to 150°; 4 new sites) and S (170 to 200°; 2 new sites; Figure 8f) at the top of outcrops (Figure 7).

S–SE-trending streamlined landforms overlie most of the western side of the study area. These ice-parallel landforms are part of a larger lobate flowset that is approximately 70 km wide and 200 km long. This flowset—termed the Quinn Lake re-advance or the Quinn Lake Ice Stream—advanced into Lake Agassiz (Dredge et al., 1986; Dredge and Nixon, 1992; Trommelen, 2015g; Gauthier, 2016a). Small patches of SW-trending streamlined landforms are also present near Lovat Lake and Mack Lake (Figure 7, Figure 8).

Ice-flow data is also sparse in the Churchill River area (Figure 9). Striations toward the SSW were mapped at just two sites (Appendix 3), and a SSW-trending boulder pavement was noted at one site during Operation Winisk in 1967. Till fabrics interpreted to have been formed by SE-, SW-, and S-trending ice flow were measured at the Limestone Rapids section (14115MT408, Figure 5; Nielsen and Young, 1981).

Summary

The glacial ice-flow record in northeastern Manitoba is complex. While erosional ice-flow indicators were only documented within a small portion of the study area, there is better erosional ice-flow indicator data to the north in the Seal River area (Campbell et al., 2012; Trommelen, 2015a) and to the northeast in the Churchill area (Trommelen and Ross, 2011). All regional data have been integrated, leading to reconstruction of 10 ice-flow phases in northeastern Manitoba (Trommelen et al., 2012; Gauthier et al., 2019). Regionally, there are two W- to NW-, two S- to SE-, and two SW-trending ice-flow phases. In this study area, W-trending striated boulders overlie an older till (section 13115MT626, Appendix 2), indicating that the boulders were striated during the regional ice-flow Phase 5 (Figure 10e). The rare and protected W–NW- and SE-trending erosional ice-flow indicators in the study area (Figure 7, Figure 9) may correlate to either regional ice-flow phases 1 and 2, or 5 and 6 (Figure 10). Widespread SSW- and SW-trending erosional ice-flow indicators likely correlate to regional ice-flow phases 7 and 8 (Figure 10g and h), as do the SW-trending streamlined landforms near Mack Lake and Calder Creek (Figure 7). The delicate erosional ice-flow indicators that trend towards the S and ESE are likely deglacial, and correlate to regional ice-flow phases 9 and 10 (Figure 10). S-trending ice flow was likely necessary during emplacement of the South Knife moraine, which was also formed at the same time as the S- to SE-trending streamlined landforms belonging to the Quinn Lake ice stream (Gauthier, 2016a).

Glacial terrain zones (GTZ)

In glaciated areas with complex histories, the landscape can be partitioned into glacial terrain zones (GTZ, Trommelen et al., 2012). Each GTZ is a coherent "puzzle piece" that records a unique glacial history (i.e., a record that is distinct than the one found in adjacent zones). The field area (Figure 7) contains a portion of the deglacial-type Quinn Lake GTZ (Trommelen et al., 2012; Trommelen, 2015g). This GTZ formed during a deglacial surge of an ice stream into glacial Lake Agassiz (Dredge et al., 1986; Dyke and Dredge, 1989). The boundaries are closely tied to the edge of the internally-consistent, curvilinear Quinn Lake streamlined-landform flowset, as well as the pattern of divergent eskers (Figure 7).

Stratigraphy

Fourteen stratigraphic sections were documented in 2013 and 2014 (Figure 5, Appendix 2), twelve of which are along (or close to) the Churchill River (Figure 11). Most of these sections were visited briefly, and the descriptions that follow are simplified. Detailed sampling and till fabrics were not completed due to time constraints, and the sections were not fully cleared of colluvium prior to study. The 14 sections described here expose clay, sand, gravel and diamict. Two chronostratigraphic units (pre-Holocene and Holocene) and three lithostratigraphic units were recognized based on lithology, texture, sedimentary structures, stratigraphic position and fossil content. Granitic and/or calcareous bedrock outcrops were found at the base of seven sections (Figure 11). Bedrock outcrops are not consistent, and may be present on one side of the river and not the other.

Pre-Holocene sediments

Unit A: Diamicton

Unit A is a blocky and dense, massive, matrix-supported diamict that ranges from 2 to 8 m thick and is situated near the base of four sections (Figure 11). This diamict either overlies bedrock, or has a colluviated and obscured lower contact. Clast content is typically 5–10%, though can be as high as 15%; clasts are subangular to subrounded, granule- to cobble-sized with rare boulder-sized clasts. Some clasts are bullet-shaped and striated. The till-matrix consists of a dark grey to grey-brown to black, clayey-silty sand, though the proportion of each texture-class can vary (Figure 12a–d, Appendix 2).

Unit B: Clay, sand and gravel

Unit B consists of three subunits, stratigraphically situated below and/or between diamict units (Figure 11). The first subunit (B-1) is a 1 to 12 m thick, poorly sorted, massive to weakly-stratified, sand and pebble- to boulder-sized gravel (Figure 13a, b). This unit was too steep to access at section 14115MT405 (Figure 13c) and only briefly examined at sections 14115MT408 and 141115MT409 (Appendix 2). Though

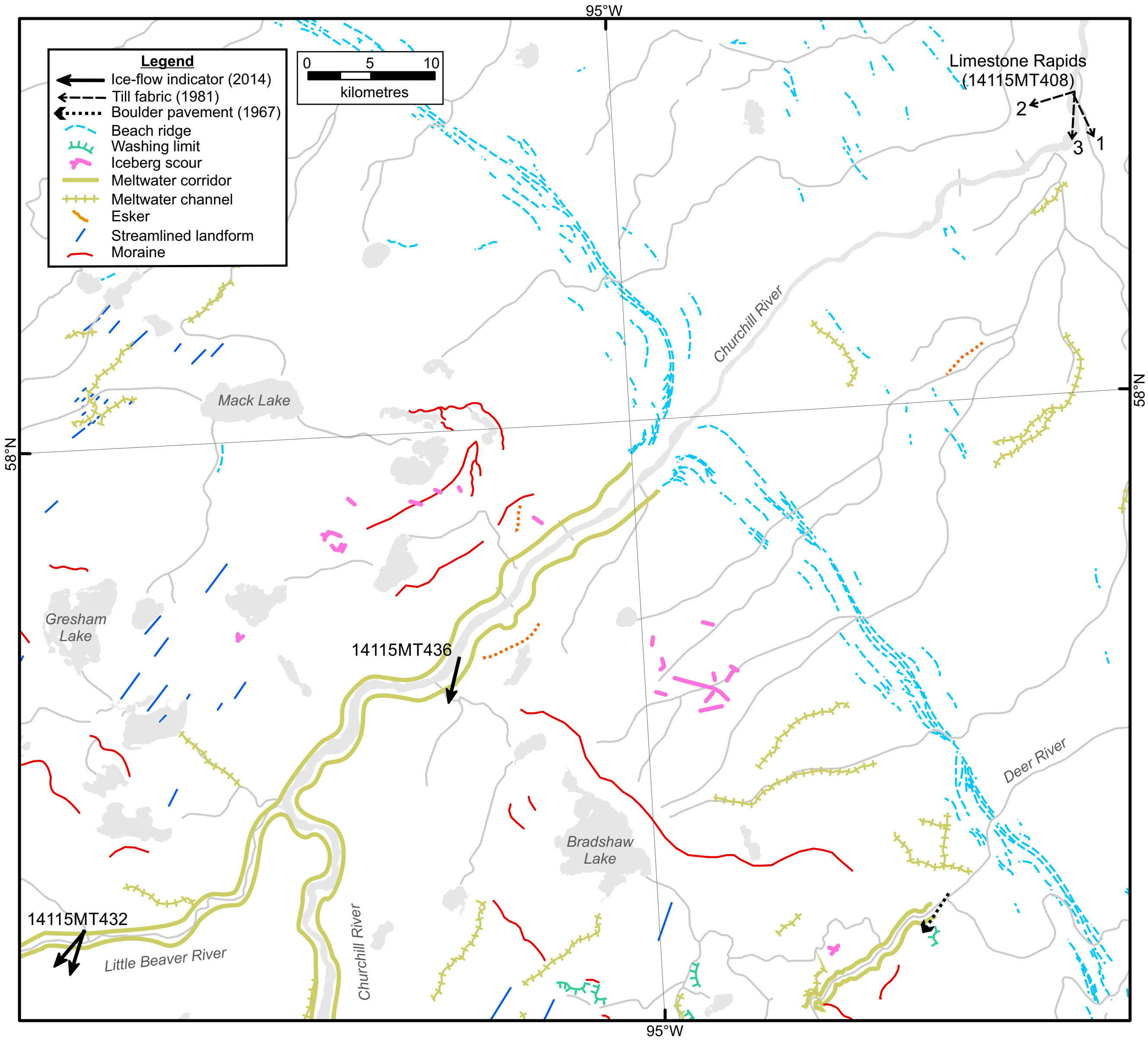

***Figure 9**: Ice-flow indicators (striae, till fabrics) and geomorphology for the Churchill River region. Stratigraphic sections are labelled by site number. The relative ages (1=oldest) for a single site are shown where applicable. Geomorphic features are available online as both a PDF and a digital data download (Manitoba Growth, Enterprise and Trade, 2018a).*

not observed in 2014, Dredge and Nixon (1992) sampled a layer of detrital organics from within this unit at section 14115MT408 (Limestone Rapids), that contained beetles, tadpole shrimp, small mammal bones, birch fragments and various plant seeds (Dredge et al., 1990). Unit B-1 also includes a 0.3 m thick unit of interbedded clayey silt, silt and fine sand at section 14115MT409 (Figure 12 and Figure 13d). The second subunit (B-2) is a 4 m thick, massive to weakly-stratified (beds 0.3 to 1.0 m thick), sand and granule- to cobble-sized gravel that outcrops at section 14115MT436 (Figure 12, Figure 13e, and Appendix 2). The upper contact with Unit C is sharp and horizontal, and the lower contact with Unit A is sharp and undulatory. Clast content is 25% and contains clasts that are commonly derived from the Precambrian Shield, and rare diamict rip-up clasts (Figure 13f). The third subunit (B-3) is a 2 to 16+ m thick, well-sorted, massive to horizontally-laminated, beige to orange-brown, medium- to coarse-grained sand, that contains minor pea gravel (Figure 13g). Unit B-3 is situated at 149 m asl at section 14115MT441 and 168 m asl at section 14115MT432 (Appendix 2). Rare, small, abraded shell fragments were noted within the sand at section 14115MT441, but were not photographed or sampled. The upper contact with Unit C is sharp and horizontal to undulatory, with some diamict injected down into the sands at section 14115MT432 (Figure 13h).

Unit C: Diamicton

Unit C is a massive, matrix-supported diamict that ranges from 5 to 24+ m thick and is laterally exposed for tens to hundreds of metres at all sections (Figure 11). This diamict either overlies bedrock, sand, sand and gravel, or extends to the base

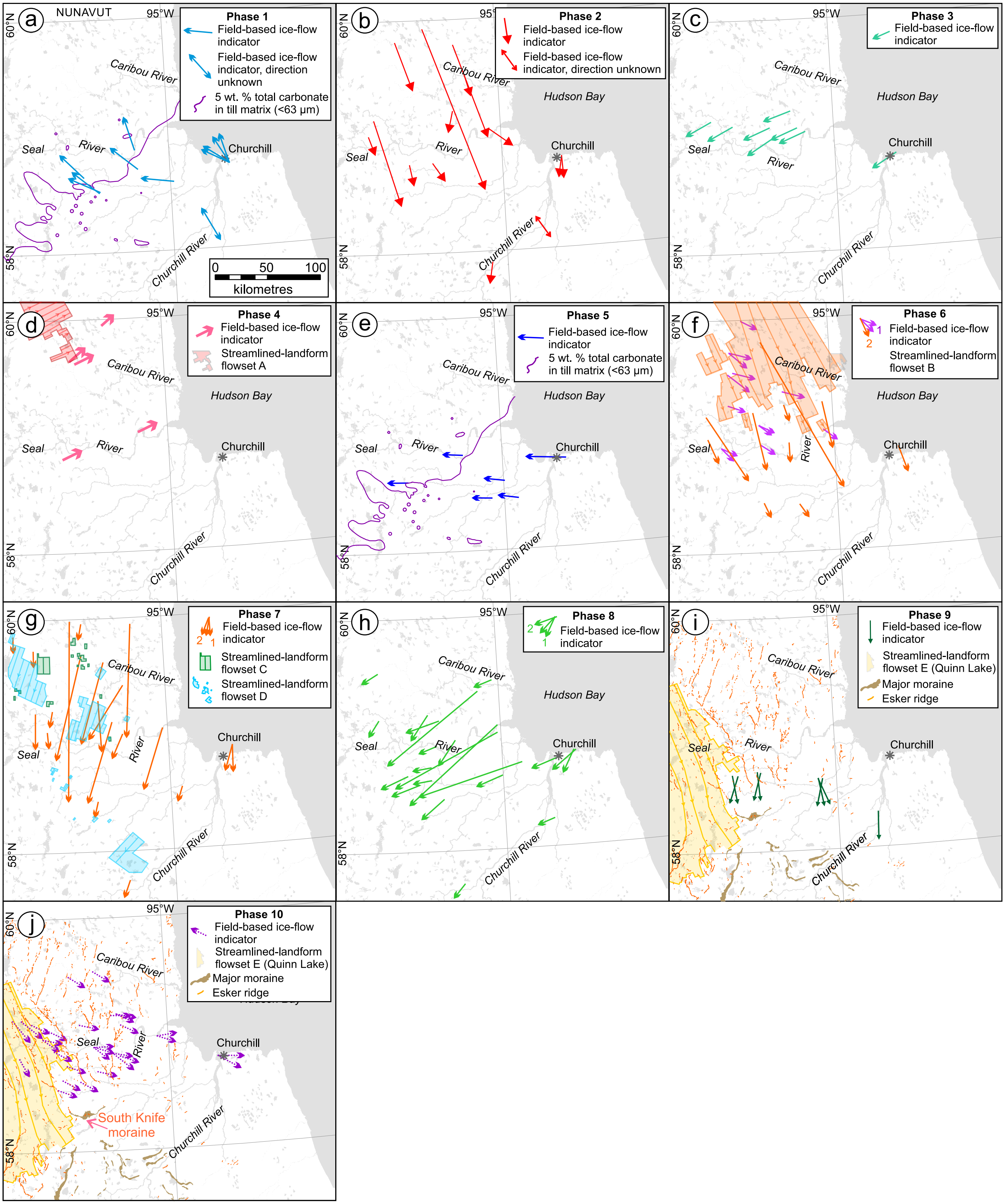

Figure 10: *Regional ice-flow phases in northeastern Manitoba, reconstructed from field-based erosional ice-flow indicators, till fabrics, streamlined-landform orientation and geomorphology. The reader is referred to Gauthier et al. (2019) for more information. The arrows outline the minimum spatial extent of each phase, where mapped in the field.*

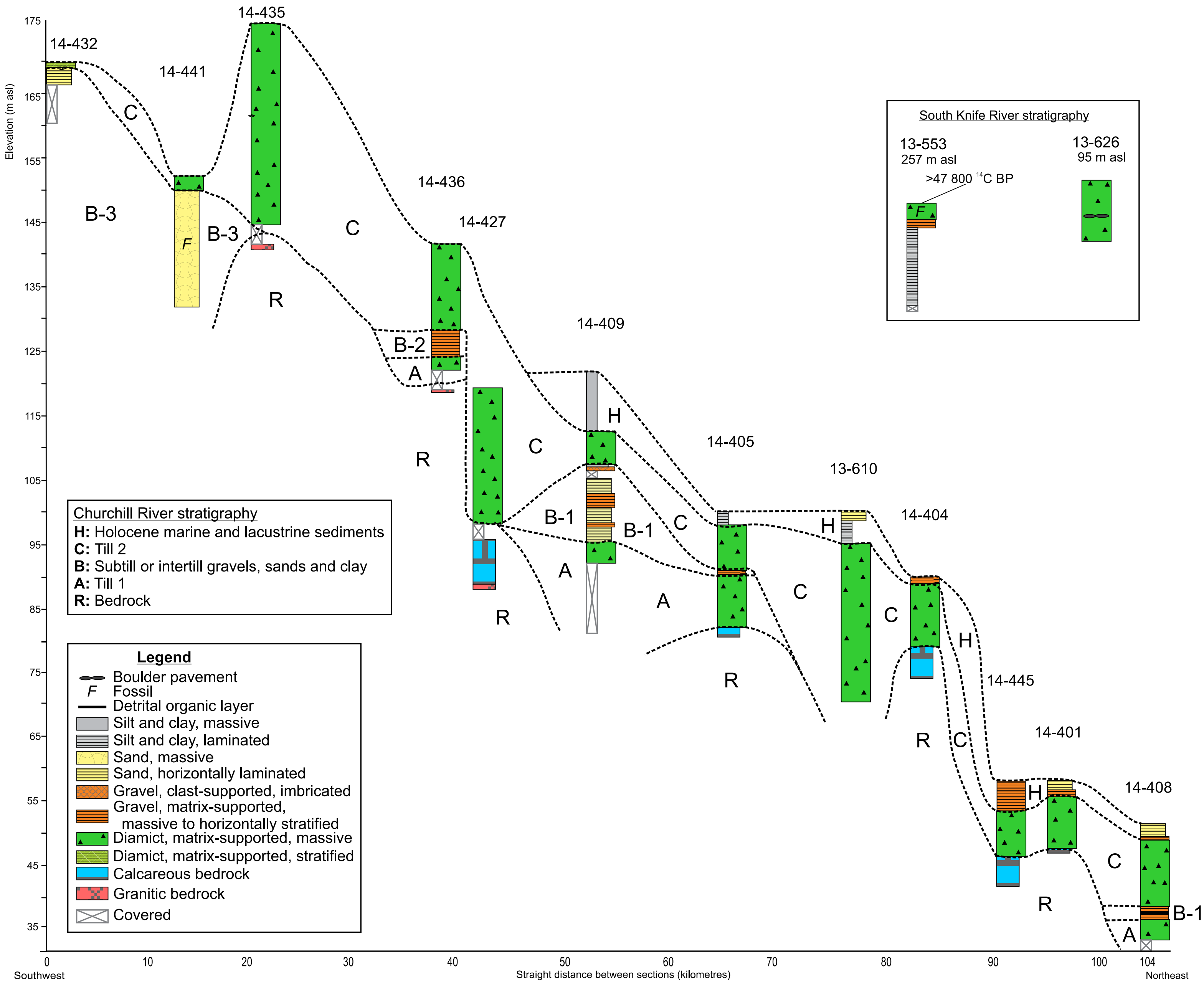

Figure 11; *Interpreted correlation of chronostratigraphic/lithostratigraphic sections along the Churchill River. 14-xxx and 13-xxx refer to the site locations, simplified from the full label (14115MT- and 13115MT-, see Figure 5).*

Figure 12*: Photographic examples of lower Unit A* ***(a–d)*** *and upper Unit C* ***(e–h)*** *diamictons from the same four sections along the Churchill River. The label refers to the site number and sample number.*

***Figure 13**: Photographic examples of Unit B clay, sand and gravel; including lithofacies B-1 **(a–d)**, B-2 **(e, f)** and B-3 **(g, h)** from six different sections along the Churchill River. The label refers to the site number.*

of the river level. Clast content is typically 10–15%, though can be as low as 5%; clasts are subangular to subrounded, granule- to cobble-sized with rare boulders. Some clasts are bullet-shaped and striated. The matrix consists of a grey to grey-brown to beige clayey-sandy silt, though the proportion of each texture-class can vary (Figure 12e–h, Appendix 2). The density and blocky structure of the diamict increase with depth. Similar diamict was documented in two sections along the South Knife River (Figure 11), including within the upper portion of section 13115MT626. At that site, the upper clayey-sandy-silt diamict contains 10% clasts that are granule- to pebble-sized, and is separated from a lower till by a striated boulder pavement (Figure 8c). The lower silty sand diamicton contains 10–15% clasts that are granule- to boulder-sized.

At section 14115MT432 (Figure 11, Appendix 2), a thin (0.7 m), weakly-stratified, matrix-supported diamict overlies >2.0 m of horizontally laminated, well-sorted sand (Figure 13h). The clayey-sandy-silt diamict contains 10–15% clasts, and was injected into the underlying sand. This diamict is included within Unit C, because it is situated at surface. The top of this section is at 170 m asl, which is ~30 m above marine limit (Gauthier, 2016a).

Holocene sediments

Holocene sediments consist of massive to horizontally-bedded silt and clay, silt and sand, gravelly sand, and gravel (Figure 11). The Holocene portion of sections, including radiocarbon ages obtained on marine molluscs, is discussed in Gauthier (2016a).

Till composition

Texture

There is a large spread in the textural composition of tills in the field area (Appendix 6). The samples contain 3 to 76% sand (median=48%), 20 to 78% silt (median=36%), and 1 to 50% clay (median=13%).

Clay, sand and silt distribution are spatially variable throughout the southern part of the field area (Figure 14), while clay is only rarely present north of the Seal River. Sandy till (>60% sand) is situated throughout the field area, and dominant north of the Seal River. Silty till (>60% silt+clay) is also present throughout the field area. The majority of tills in the field area are composed of sand and silt in equal proportions.

Carbonate

The concentration of carbonate in local tills is important, because the carbonate is sourced from Paleozoic calcareous bedrock on the shores of, and beneath, Hudson Bay. Over the Precambrian shield, the concentration of carbonate can be used as a proxy to determine the percentage of far-travelled detritus that the local tills contain. This is important information, because the calcareous, far-travelled detritus can mask and/or dilute the geochemical component of the local shield bedrock, which is problematic for drift exploration. There are several methods to determine the calcareous concentration of the tills (total carbonate wt. %, inorganic carbon wt. %, CaO wt. %), and each will be discussed in turn.

Matrix total carbonate

The results for carbonate analyses of the till matrix (<63 µm size-fraction) are in Appendix 7. Till sampled in 2013 and 2014 contains 0.93 to 70.06% total carbonate (<63 µm size-fraction). The surface till is calcareous throughout most of the region (Figure 15), and becomes noncalcareous (<5 wt. % total carbonate) between South Knife Lake and Quinn Lake. This data has been added to an online hand-contoured map of carbonate content in the surface till of Manitoba (Trommelen and McMartin, 2019).

Matrix inorganic carbon

Inorganic carbon may be a useful provenance indicator for tills, and can be used to identify the presence of a buffering agent which could affect the sample geochemistry. The results for inorganic carbon analyses on the till matrix (<63 µm fraction) are in Appendix 8. Inorganic carbon concentrations are not correlative to the total-carbonate concentration (R^2=0.4837, Figure 16).

Matrix calcium oxide (CaO)

Calcium oxide, analysed by near-total digestion ICP-MS (Appendix 11), is another useful provenance indicator for tills, and is a buffering agent that could affect the sample geochemistry. Till sampled in 2013 and 2014 contains 1.5 to 28.7 wt. % CaO (<63 µm size-fraction) (Figure 17). Figure 16b shows that CaO concentrations are strongly correlative to the total-carbonate concentration (R^2=0.9567).

Oxide ratio

Analyses in other areas of Manitoba have defined carbonate till using a ratio between CaO+MgO, normalized to Na_2O values (McMartin et al., 2016). This is because some calcium and magnesium can be sourced from the dissolution of feldspars, and dividing by sodium removes this non-carbonate presence. Figure 16c shows that there is a logarithmic correlation between this ratio and the total carbonate concentration (R^2=0.8615).

Matrix calcium (Ca)

Calcium analysed by INAA (Appendix 12) may be another useful provenance indicator for tills, as well as the presence of a buffering agent which could affect the sample geochemistry. However, Figure 16d shows that Ca concentrations are only weakly correlative to the total carbonate concentrations (R^2=0.5883).

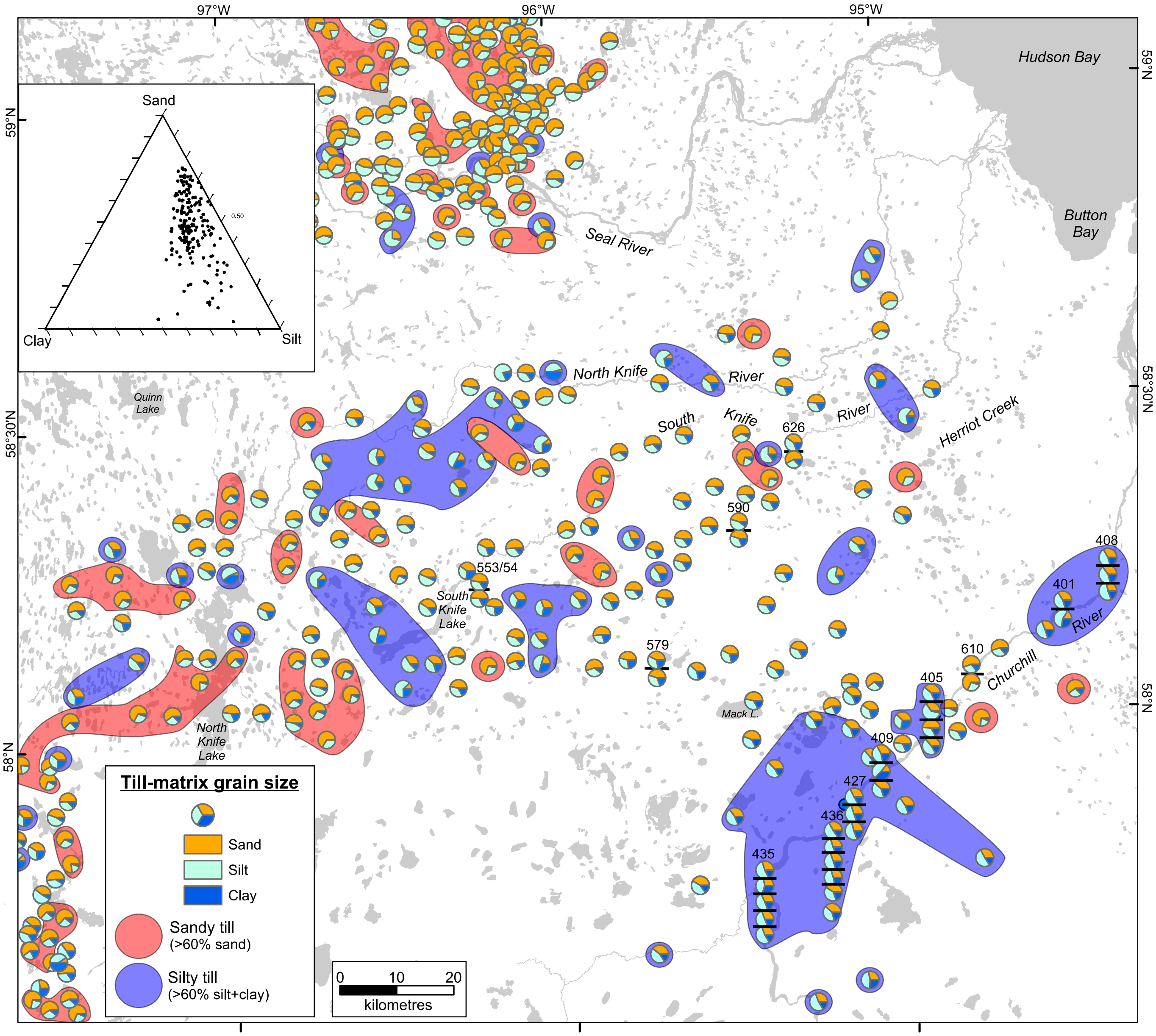

Figure 14: *The spatial distribution of sampled till-matrix texture in the North Knife River–Churchill River region. The inset triangle diagram depicts the grain size distribution for the sampled till matrices.*

Summary

The best method to determine till-matrix carbonate concentration is by the Ca, Mg method. This is correlative with measurement of CaO by near-total digestion ICP-MS, and has a logarithmic correlation with the oxide ratio ($CaO+MgO/Na_2O$). Total carbonate in the till matrix is also correlative to the concentration of carbonate clasts in the till (Figure 16e).

Till-matrix (<63 µm) geochemistry

Proportional-symbol plots of the concentrations of some major elements analyzed are presented in Appendix 13. The data from this project (n=231 sites) is depicted along with data from 2013 (Trommelen, 2015g), 2012 (Trommelen, 2015a) and 2009–2010 fieldwork in the same region (Campbell et al., 2012). The acid leach used at SRC is weaker than what was used in 2009–2010 (LiBO at ActLabs), and thus the datasets are not treated as equivalent. Instead, the natural breaks (jenks) are calculated for the SRC dataset, and the older sites are shown for interpretation purposes with the same classification. Readers are encouraged to undertake their own interpretation of the data.

Till-matrix geochemistry data shows that noncalcareous till is elevated in elemental concentrations, while calcareous till masks and/or dilutes the signature of the underlying bedrock. It is not that simple, however, as the majority of the 2013 field area is underlain by granitoid and carbonate rocks, all of which tend to be naturally lower in base metals than the metasedimentary and metavolcanic rocks to the north. Additionally, while near-total digestion data is displayed in Appendix 13, partial-digestion data is preferable for drift exploration purposes.

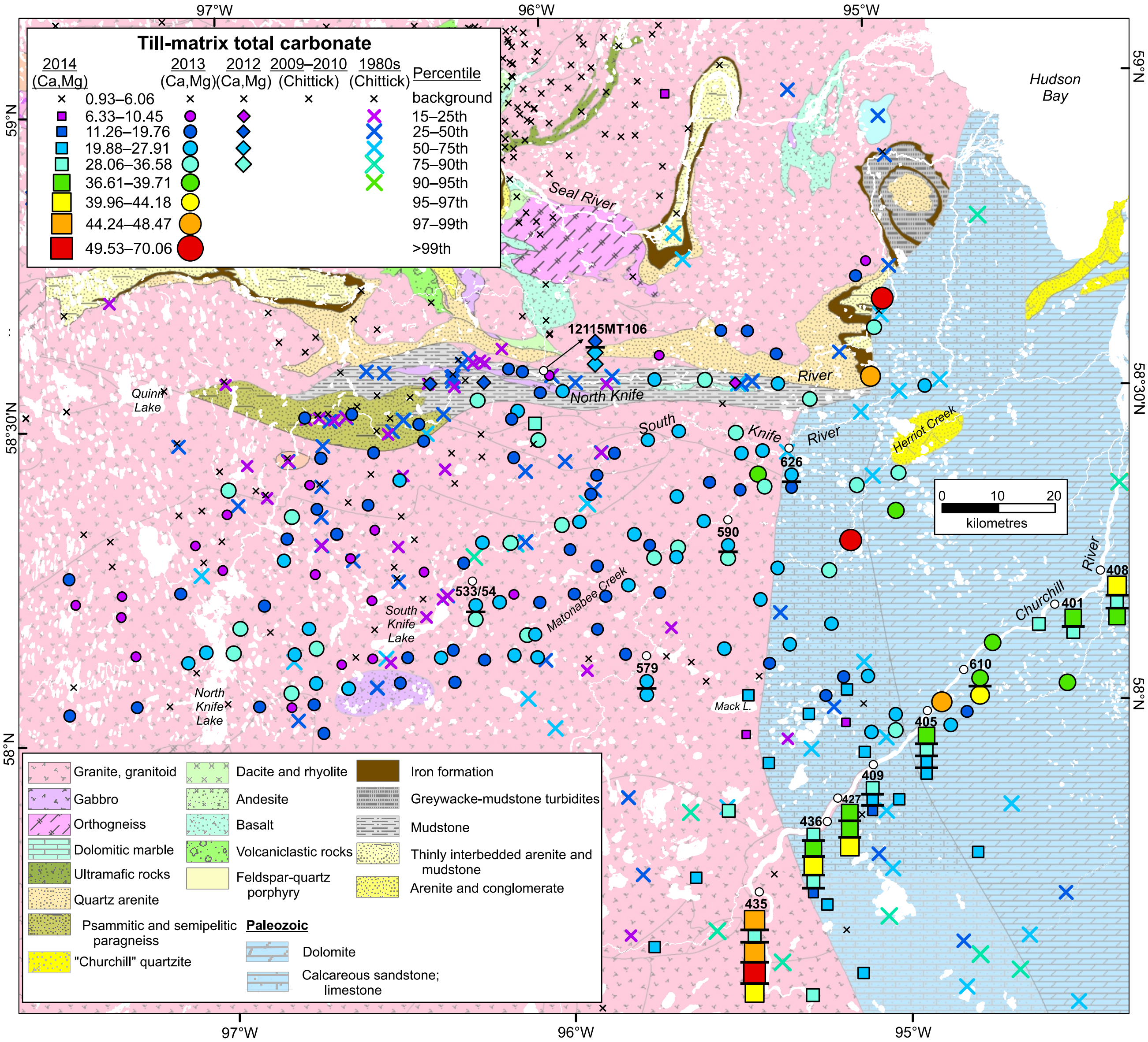

Figure 15: *The distribution of till-matrix total carbonate (CO_3; weight percentage) in the North Knife River–Churchill River region. The 2012–14 samples were analyzed at the SRC laboratory using the Ca, Mg method (Trommelen, 2015a) while the 2009–10 and 1980s samples were analyzed at the GSC laboratory using Chittick method (Dredge and Pehrsson, 2006; Campbell et al., 2012). At low percentages, the Chittick method is more precise than the Ca, Mg method, which is why we have classified concentrations <5% as background (~null) values. The 1980's Chittick was run on the <2 mm sized fraction, where concentrations are somewhat lowered. As such, the <7% concentrations from these sites have been denoted as background. Bedrock geology is modified from Anderson et al. (2009) and an ongoing unpublished regional compilation.*

Gold

Gold was analyzed by INAA in this, and in the 2009 and 2010 studies (Campbell et al., 2012). The majority of the till samples in this study do not have gold (96%). However, three sites yielded gold concentrations that are comparable to the 95th percentile for till in the area to the north that overlies the Seal River greenstone belt (Campbell et al., 2012). These sites are AN344213 (<63µm, 50 ppb), AN360213 (<63µm, 46 ppb) and AN352413 (<63µm, 32 ppb).

Nickel and copper

The regional distribution of nickel concentration in till (near-total ICP-MS data) delimits high values (>99th percentile, 113–231 ppm, 3 sites) near the ultramafic rocks north of the Seal River, where mineralization occurrences are known in exposed bedrock and drillcore (Figure 18). Similarly, the regional distribution of copper concentration in till (near-total ICP-MS data) delimits high values (>99th percentile, 33.7–85.4 ppm, 14 sites) near the metasedimentary rocks of the Seal River greenstone belt (Figure 19). For both metals, elevated values (90–99th percentile) in tills nearby were likely dispersed southeast and/or southward from those rocks. Interestingly, there are also elevated values (90–99th percentile) for both metals within till from scattered surface-sample sites near North Knife Lake, South Knife Lake, between Mack Lake and Wood Lake (5 sites nickel, 10 sites copper), and from buried, shale-rich (site 14115MT405) and shield-rich (14115MT436)

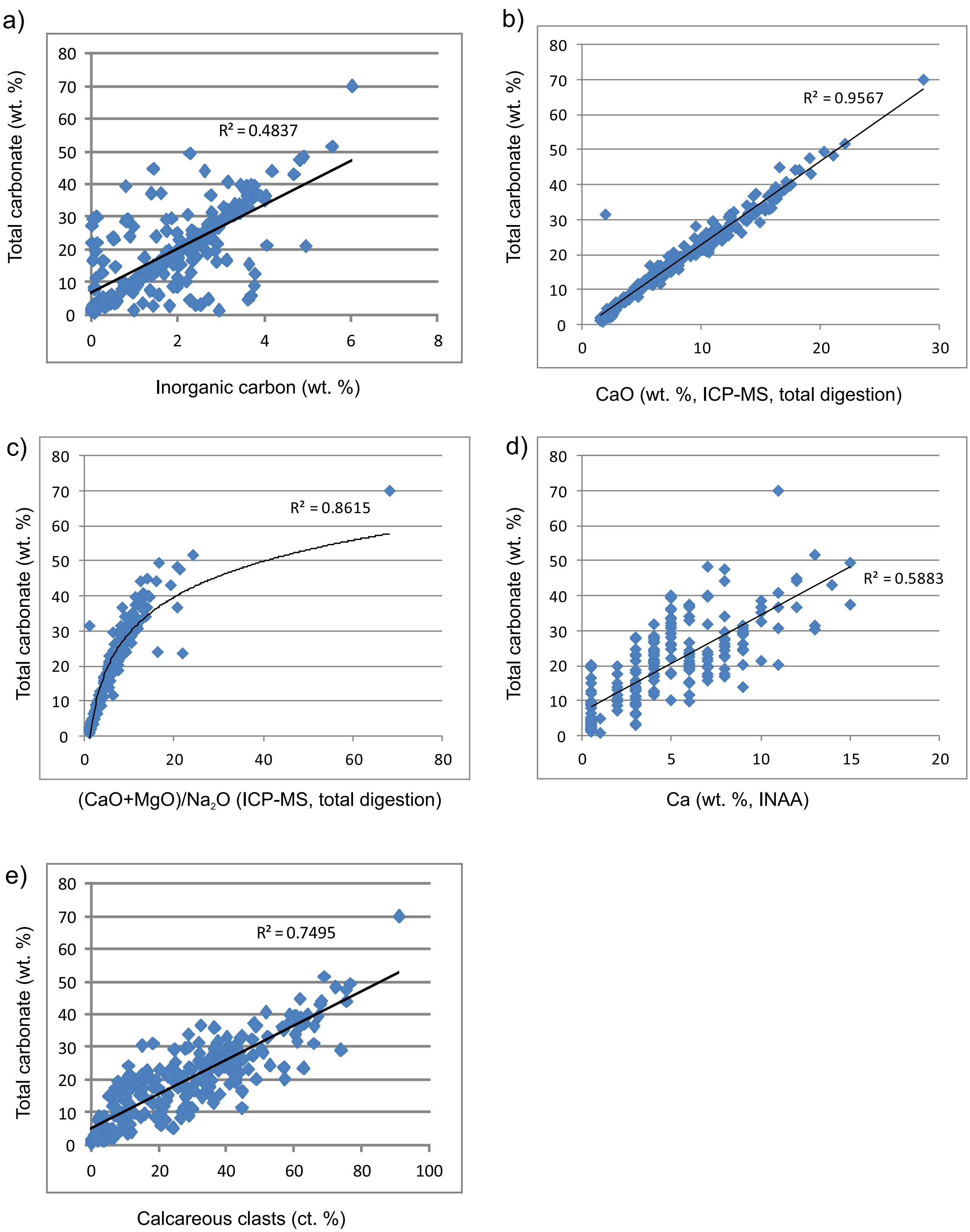

***Figure 16:** Scatter plots of total carbonate concentrations vs. **a)** inorganic carbon, **b)** calcium oxide, **c)** the ratio between calcium oxide+magnesium oxide divided by sodium oxide, **d)** calcium, and **e)** calcareous-clast percentage.*

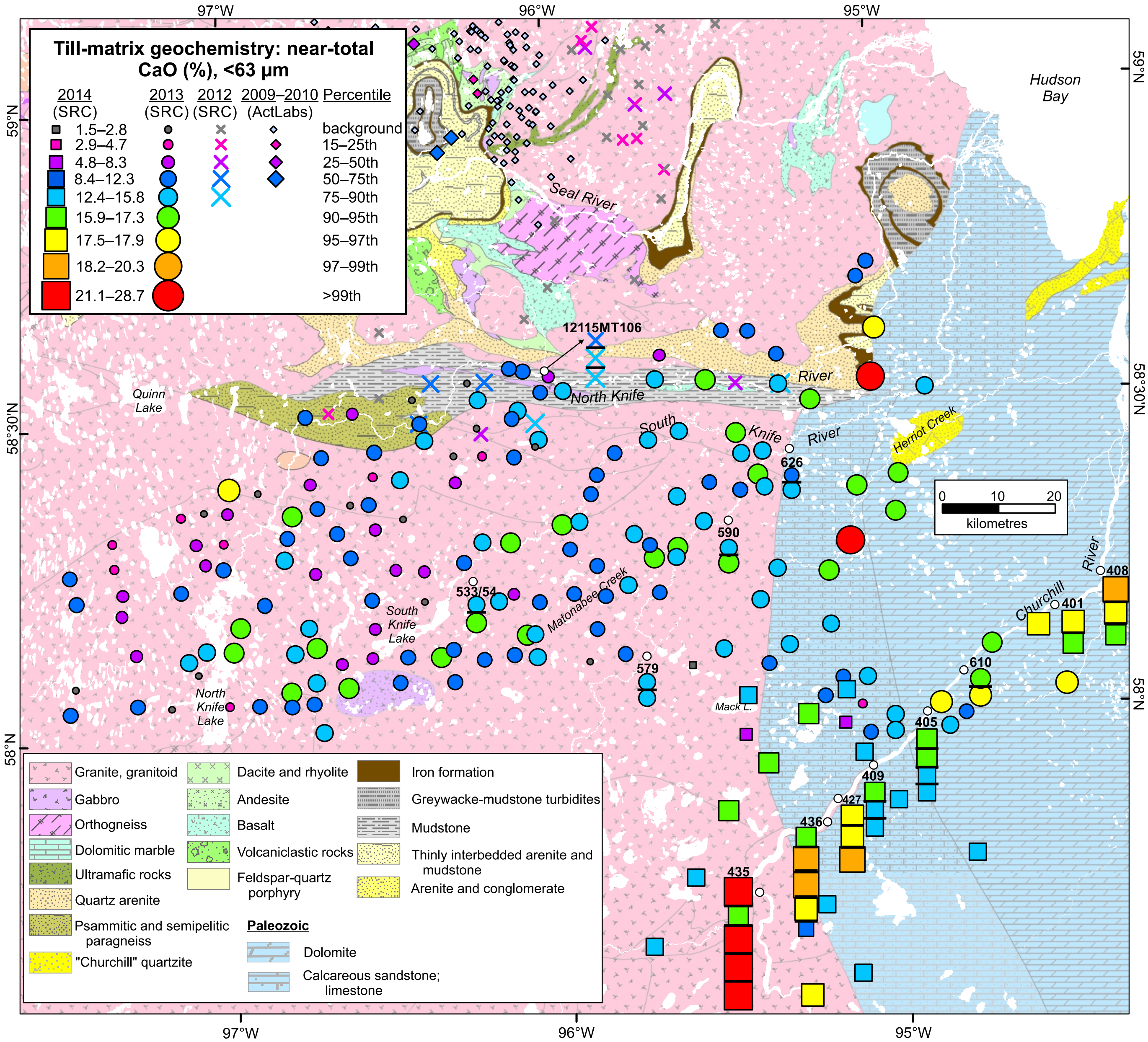

***Figure 17:** CaO dispersal in till in the North Knife River–Churchill River region. The 2012–14 samples were analyzed at the SRC laboratory using ICP-ES near-total ($HF:HNO_3:HClO_4$) digestion (Trommelen, 2015a) while the 2009–10 samples were analyzed at ActLabs using ICP-ES and -MS total ($LiBO_2$) digestion (Campbell et al., 2012). Bedrock geology is modified from Anderson et al. (2009) and an ongoing unpublished regional compilation.*

tills along the Churchill River. The source of elevated copper and nickel within these tills is unknown.

Clast composition

Clasts within till can assist with the delineation of glacial transport directions and distances as well as identifying unmapped bedrock units, including outliers. Glacial dispersal can be mapped at varying scales from continental (hundreds of kilometres) to regional (tens of kilometres) to local (less than 10 km).

To determine clast-dispersal patterns within the field area, the 19 lithological classes (Appendix 4) were first grouped into six simplified classes (Table 1). Because the effects of comminution on each rock type are unknown, or may not be comparable over all classes, the clast-size fractions were grouped together for spatial analysis. Table 2 demonstrates the validity of this grouping, as the percentage of each simplified class is similar for each size fraction. The simplified classes are plotted spatially in ArcGIS using count percentage bubble plots by percentiles (Appendix 14).

Granitoid clasts

Granitoid clasts are present at all sampled till sites (Appendices 4, 14), and exhibit a large range in concentration from 6.1 to 99.5 ct. %. Concentrations are highest in tills overlying mapped granitoid bedrock. All elevated values (>90th percen-

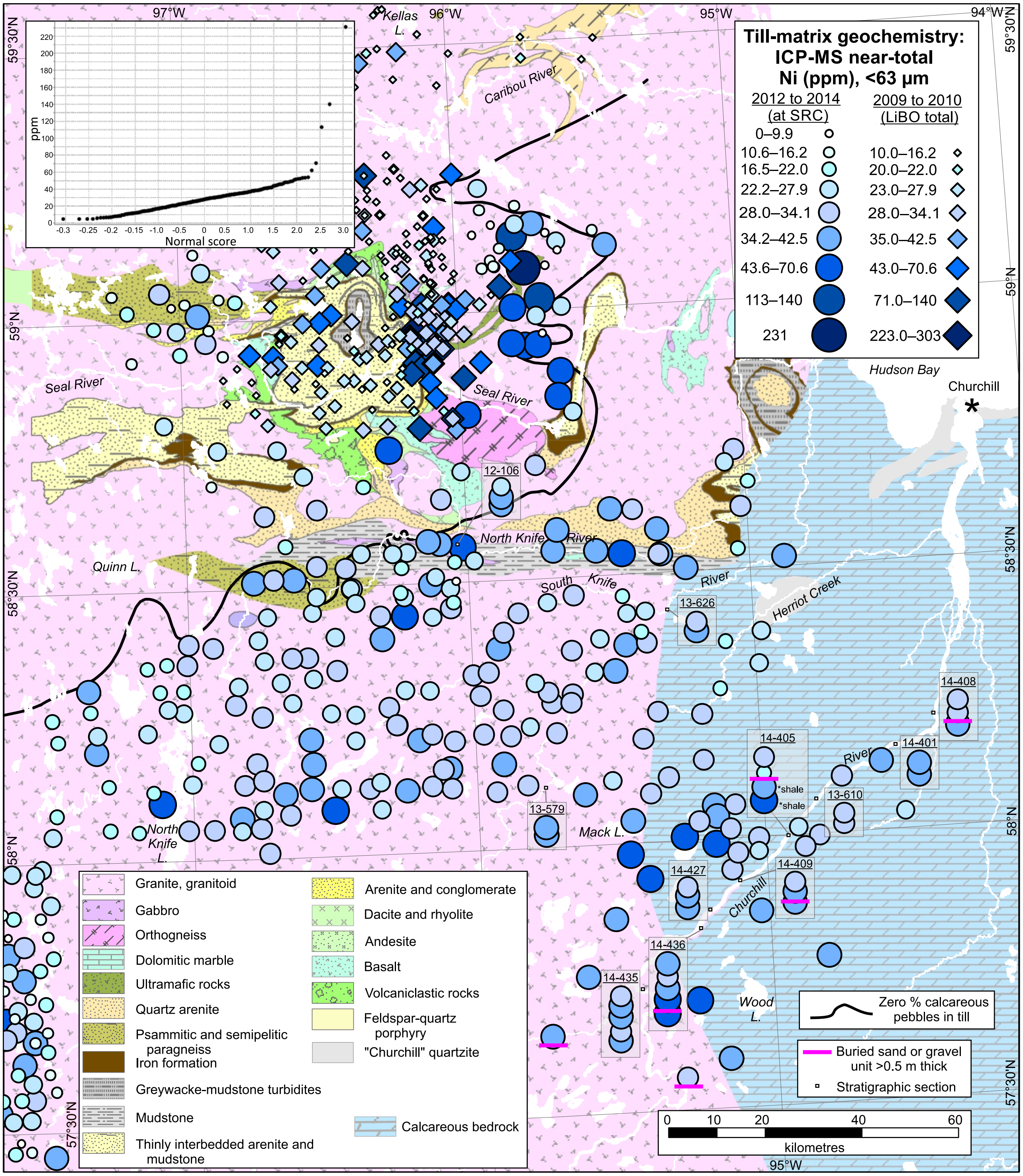

Figure 18: Regional concentration of nickel in till-matrix samples, analyzed using ICP-MS after near-total digestion at SRC analytical laboratory. Includes data from this project as well as the Seal River project in the north (Trommelen, 2015a) and the Gauer Lake project in the southwest (Trommelen, 2015g).

tile) are spatially situated north or west of the North Knife River (Figure 20), which is within 11 km of the maximum limit of carbonate dispersal. The provenance of these clasts is unknown, as granitoid rocks are situated throughout the north (Manitoba Department of Mines, Natural Resources and Environment, 1979).

Exotic, further-travelled granitoid clasts are present at 71.7% of sampled till sites (Appendix 4), at up to 4.6 ct. % and throughout the entire field area.

Greenstone belt clasts

Metamorphosed greenstone clasts are present at 97.8% of sampled till site (Appendices 4, 13), and exhibit a range in concentration from 0.0 to 36.1 ct. %. The spatial distribution of greenstone clasts (Figure 21) from sampled tills is complex, producing an amoeboid pattern. Local patterns of greenstone-clast dispersal in the Great Island–Seal River area are discussed in Trommelen et al. (2013). Regional dispersal patterns are

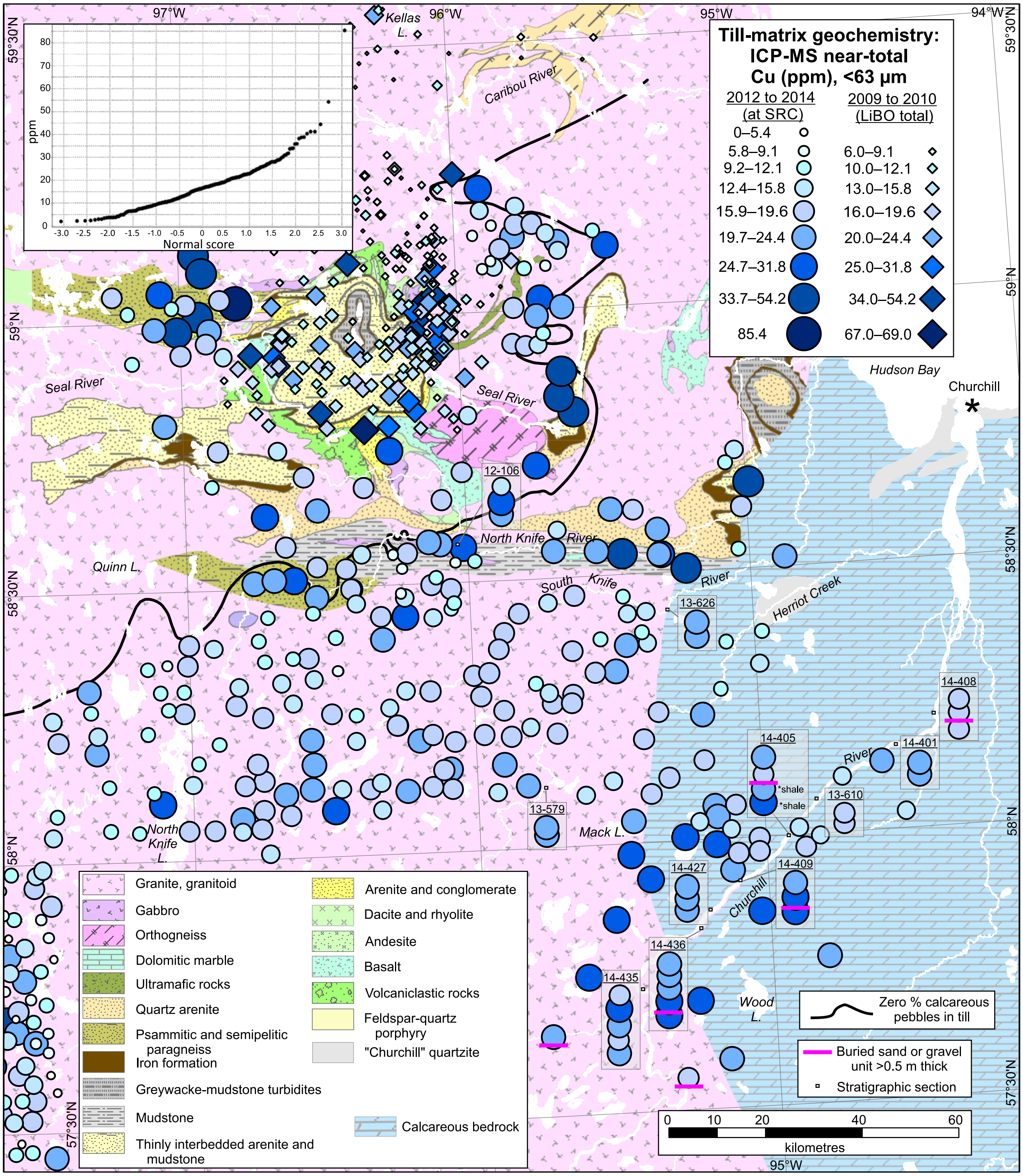

Figure 19: Regional concentration of copper in till-matrix samples, analyzed using ICP-MS after near-total digestion at SRC analytical laboratory. Includes data from this project as well as the Seal River project in the north (Trommelen, 2015a) and the Gauer Lake project in the southwest (Trommelen, 2015g).

difficult to define, given the lack of point-source distribution, the mix of lithologies and the variability in paleo–ice-flow orientation. The stratigraphy at section 13115MT626 (Appendix 2) indicates that greenstone dispersal to the southeast occurred before carbonate dispersal to the west (Figure 8c). The lack of till-fabric studies along the Churchill River precludes other interpretations.

Phyllite/psammite clasts (Appendix 4) are likely sourced from the Seal River greenstone belt rocks, as these soft clasts are recessive and comminute easily. The regional pattern of phyllitic and psammitic clasts in till (Figure 22) delimits spatially variable dispersal distances. The dominant dispersal (>80th percentile, >6 ct. %) ends roughly 20 to 30 km down-ice, while the tail end of southwesterly dispersal is cf. 100 km (65–80th

Table 2: The average percentage of each simplified clast-lithology class in comparision to the three clast size fractions.

Clast fraction	Granitoid	Greenstone	Unknown	Exotic northern	Exotic eastern	Calcareous	Sum
2–4 mm	67.63	0.69	3.66	1.05	0.06	21.36	17304
4–8 mm	58.51	1.20	3.71	1.36	0.13	25.40	5036
8–30 mm	59.65	1.14	3.42	1.17	0.21	25.22	14972

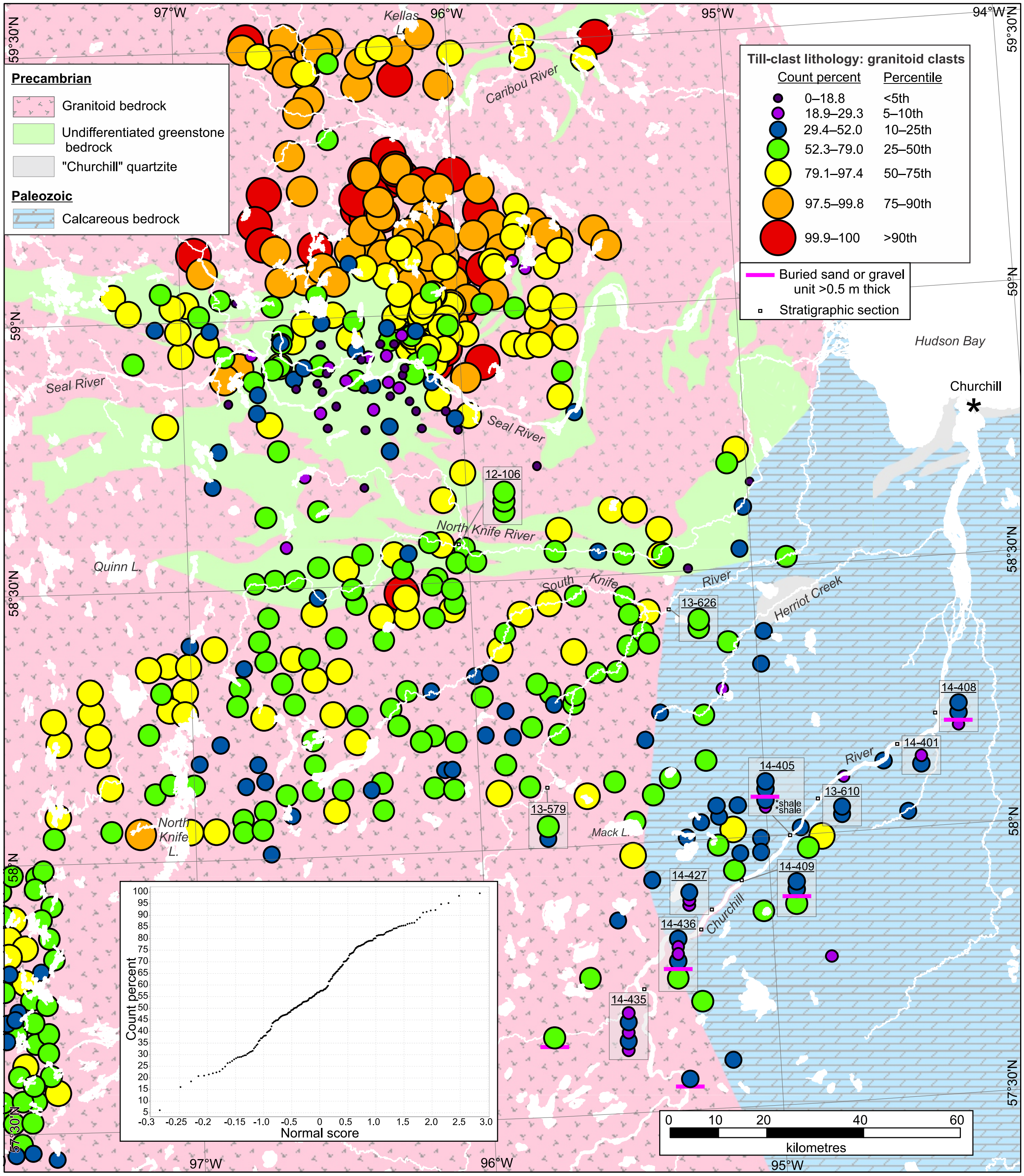

Figure 20: The spatial distribution of granitoid clasts (2–30 mm) within till samples in northeast Manitoba. This figure includes data from surrounding studies (Campbell et al., 2012; Trommelen, 2015a, b). Bedrock geology is simplified from Anderson et al. (2009) and an ongoing unpublished regional compilation.

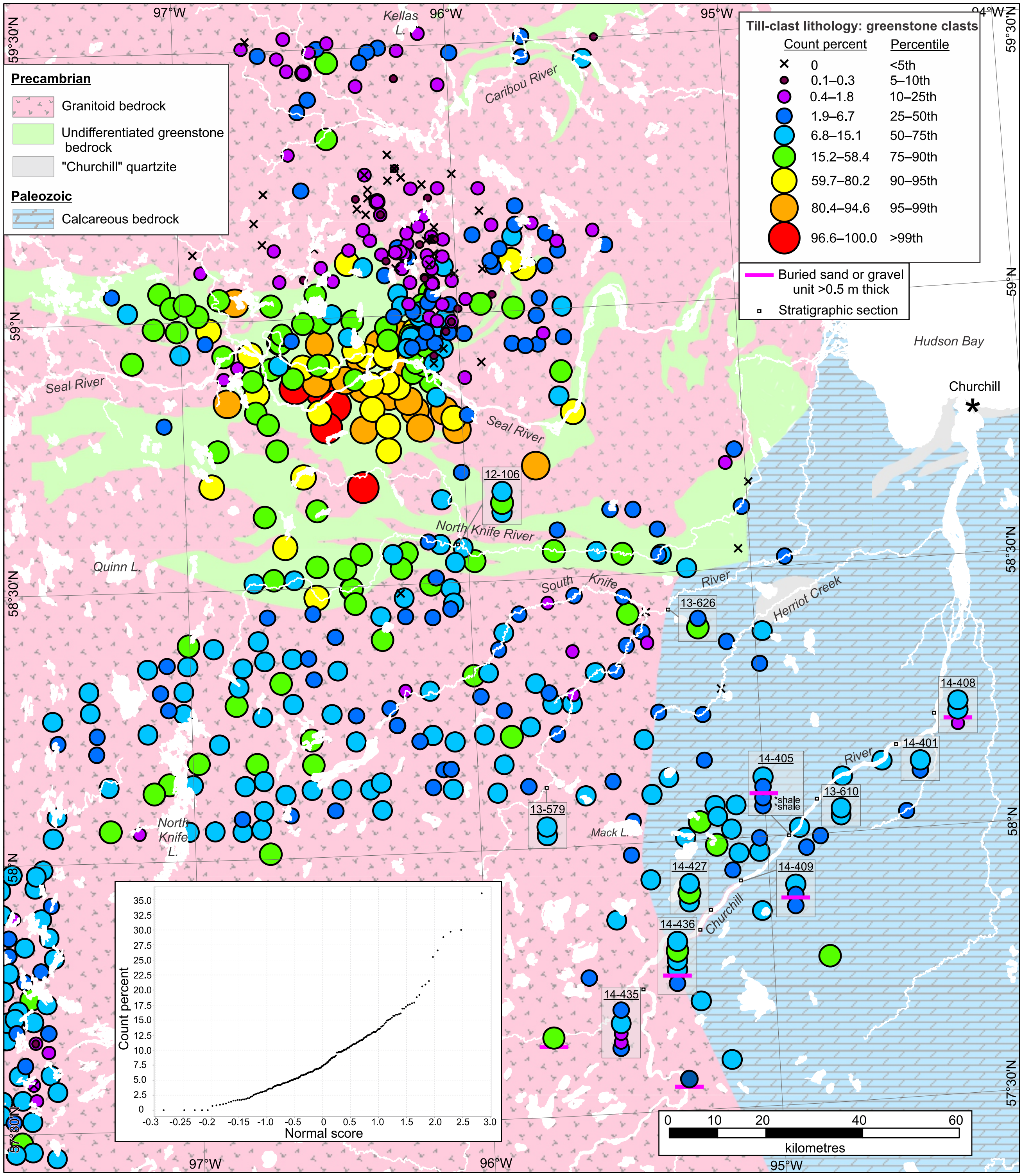

Figure 21: The spatial distribution of undifferentiated greenstone and greywacke clasts (2–30 mm) within till samples in northeast Manitoba. This figure includes data from surrounding studies (Campbell et al., 2012; Trommelen, 2015, b). Bedrock geology is simplified from Anderson et al. (2009) and an ongoing unpublished regional compilation.

percentile, 2–5 ct. %), in the Gauer Lake–Wishart Lake area (Trommelen, 2015g).

Calcareous clasts

Calcareous clasts are present at 96.8% of sampled till sites (Appendices 4, 14), and exhibit a range in concentration from 0.0 to 90.9 ct. % (Figure 23). Concentrations are highest overlying calcareous bedrock. The spatial distribution of calcareous clasts within till shows that carbonate detritus was dispersed at least 130 km to the west. Dispersal drops off sharply to the north, along the North Knife River, though calcareous clasts can be found at a few isolated sites in the north (Trommelen

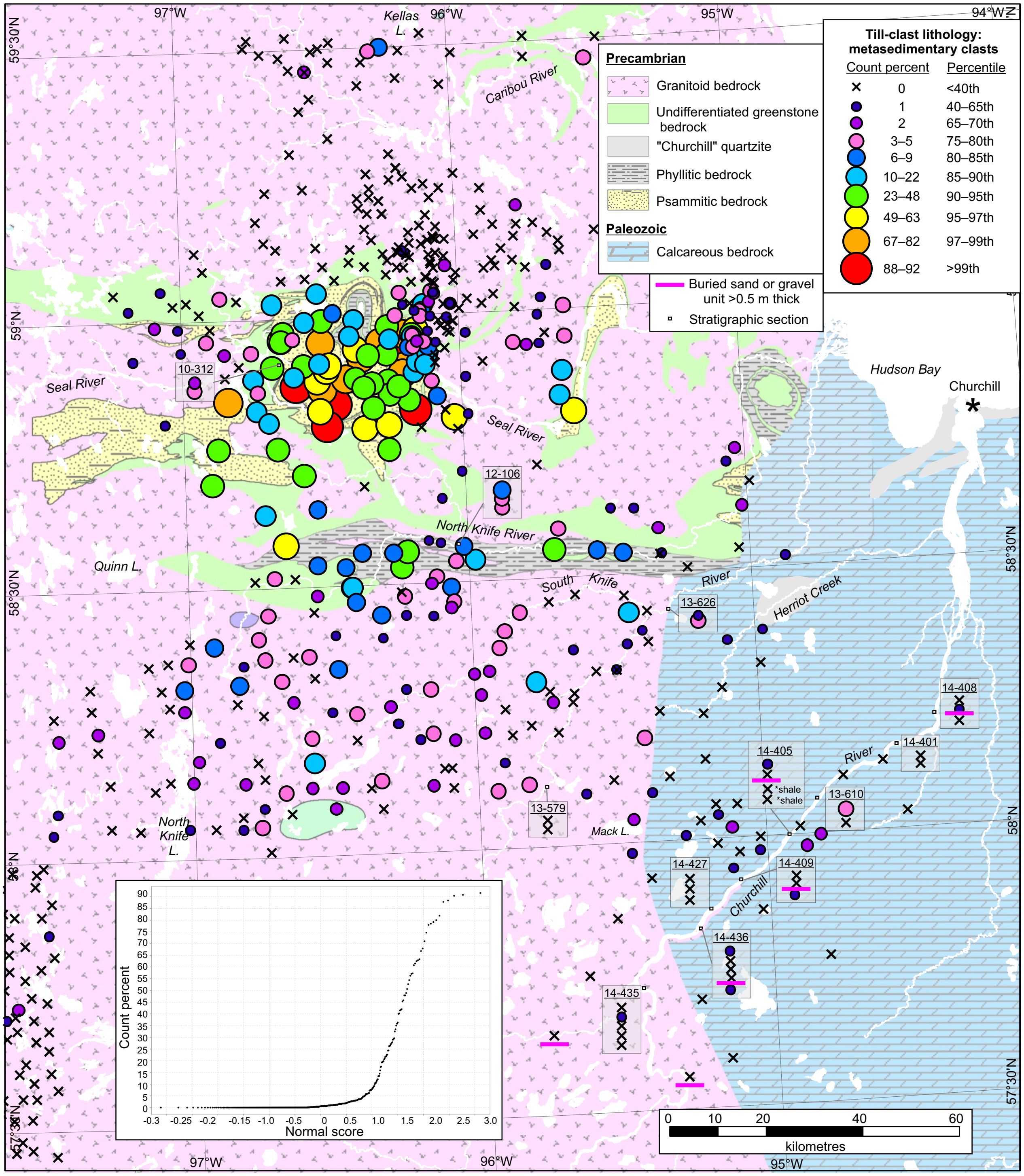

__Figure 22:__ The spatial distribution of phyllitic and psammitic clasts (2–30 mm) within till samples in northeast Manitoba. Bedrock geology is simplified from Anderson et al. (2009) and an ongoing unpublished regional compilation.

et al., 2013). Generally, calcareous-clast concentrations are correlative with the total carbonate concentration (R^2=0.7495, Figure 16e).

Shell fragments

Shell fragments were encountered within the sieved clasts at four field sites (Figure 23). These resistant, weathered shell fragments (2–4 mm size fraction) are most likely from marine shells. An additional shell fragment (10x20 mm) was found during fieldwork within the till at site 13115MT553 (Appendix 3). This sample returned a radiocarbon age of 47800±1900 ^{14}C yr. BP (UCIAMS-135234, Gauthier, 2016a). At all five sites, the shell fragments are associated with calcareous till.

Black shale clasts

A unique grey-black till was sampled from the lower-half of section 14115MT405 (Figure 24), at the mouth of Chasm Creek just before it enters the Churchill River (Figure 1). This

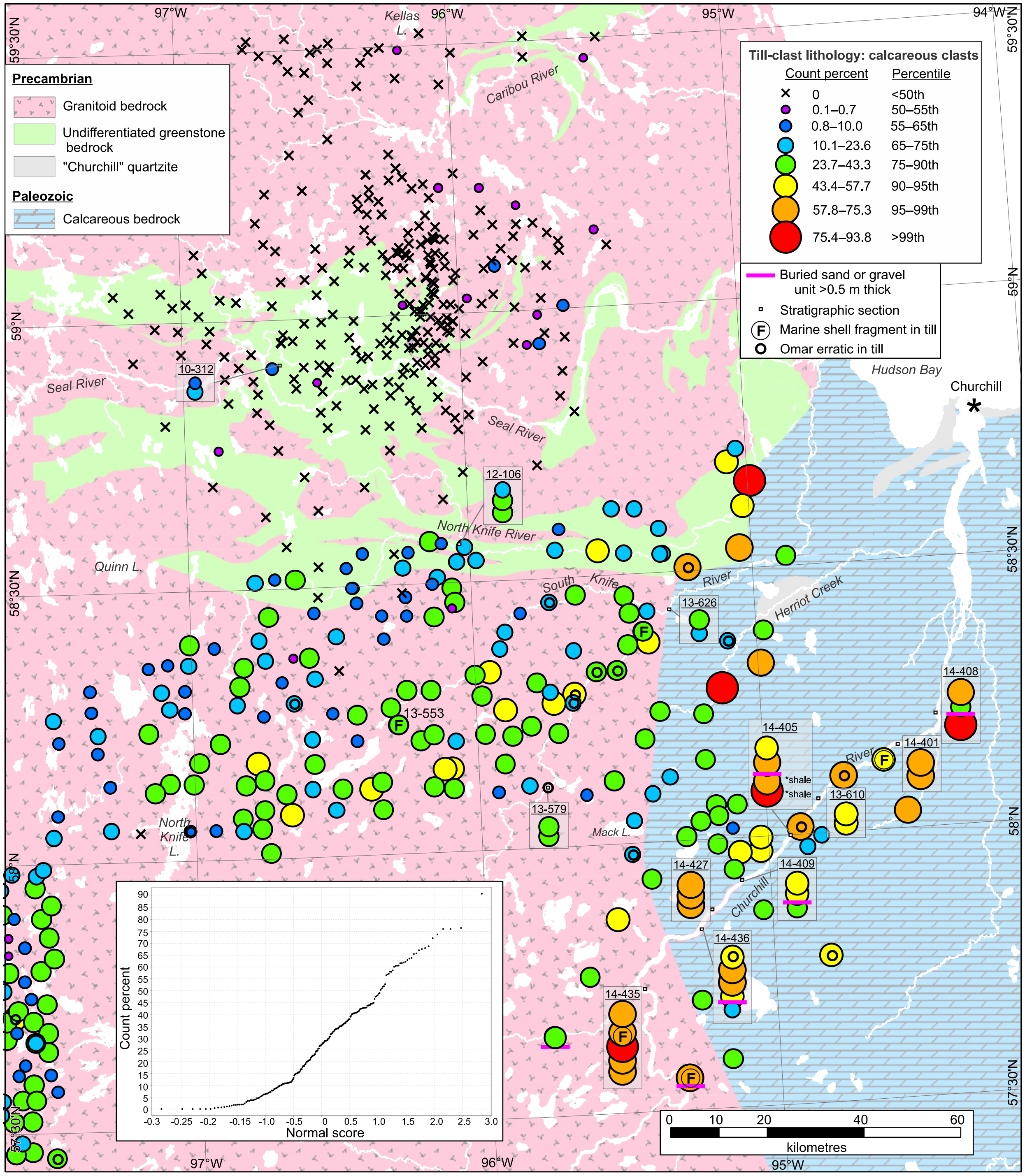

***Figure 23:** The spatial distribution of calcareous clasts (2–30 mm) within till samples from northeast Manitoba. This figure includes data from surrounding studies (Campbell et al., 2012; Trommelen, 2015, b). Sampled till sites with Omar erratics (n=14; greywacke with concretions from the Omallaruk Fm, Belcher Group), and five sites with transported marine shell fragments, are also delimited. Site 13-553 is 13115MT553, where a shell fragment returned a near-finite radiocarbon age. Bedrock geology is simplified from Anderson et al. (2009) and an ongoing unpublished regional compilation.*

section is ~17 m high, and consists of 2 m of marine clay and silt that overlies 7 m of grey-brown till, ~1 m of sand and gravel (too steep to access in field), and ~8 m of dark grey-black till (Appendix 2). The upper till is a massive, loose, grey-brown diamict with 15% clasts and a clayey-sandy-silt to sandy-silt, calcareous matrix. The lower till is a massive, dense and blocky, dark grey-black to black diamict with 10–15% clasts and a clayey-sandy-silt to clayey-silty-sand, calcareous matrix. The upper till consists of calcareous (55.0 ct. %) and granitoid (39.4 ct. %) clasts, with rarer undifferentiated greenstones (4.9 ct. %, Figure 24b). The lower till consists of calcareous (61.7 ct. %) and granitoid (23.5 ct. %) clasts, with rarer black to grey fragile shale clasts (4.0–7.0 ct. %, Figure 24h), undifferentiated greenstones (3.1 ct. %, Figure 24d), ironstone (1.0–4.0 ct. %, Figure 24f) and sulphides (0.0–1.0 ct. %, Figure 24g).

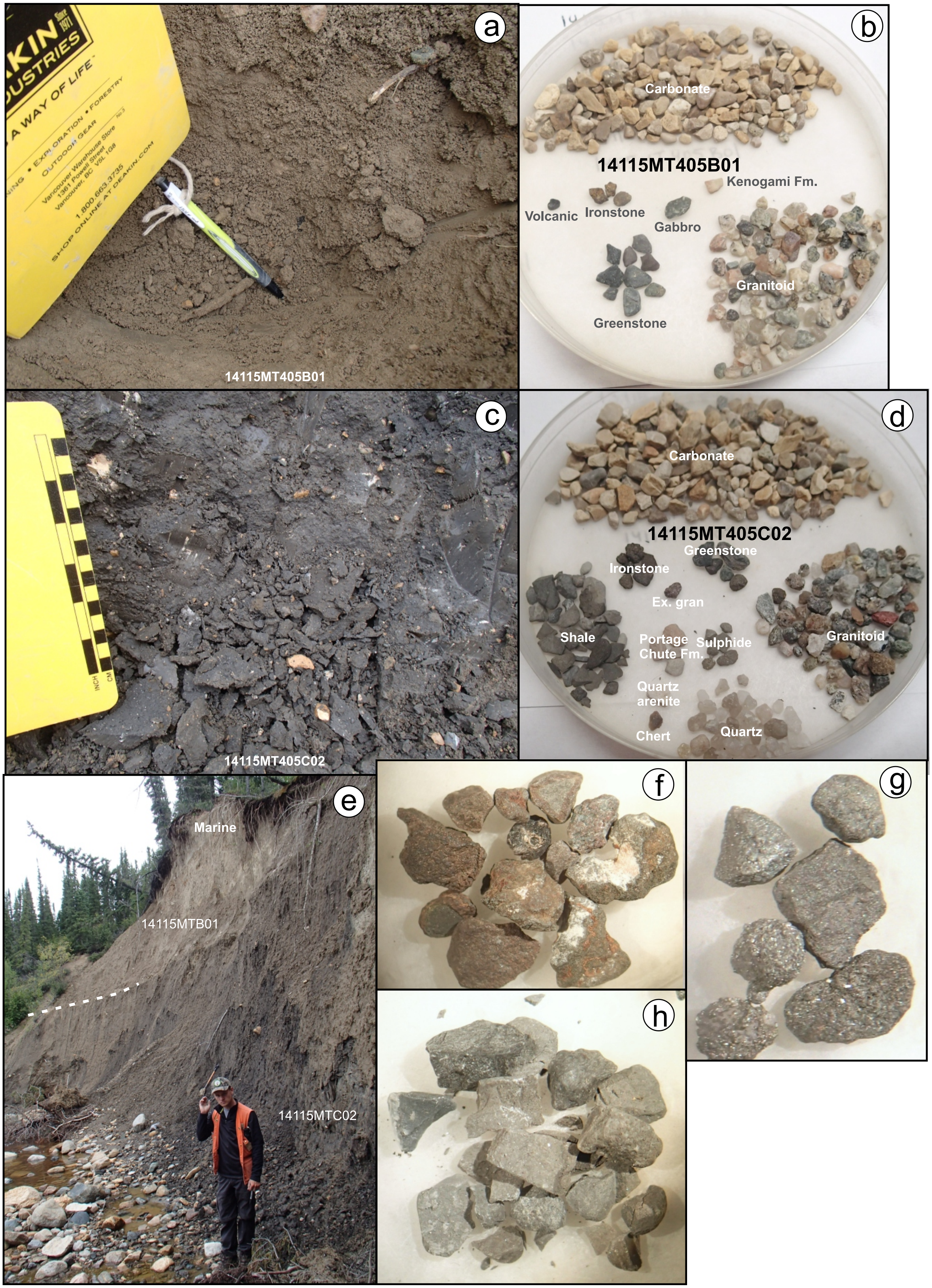

Figure 24: *Brown till* ***(a, b)*** *overlies a black till* ***(c, d)*** *at section 14115MT405* ***(e)****, at the mouth of the Chasm Creek just before it enters the Churchill River. Clast pictures are from the 2-4 mm size fraction;* ***f–h*** *are from sample 14115MT405C02 as viewed through the optical microscope.*

Dubawnt erratics

Red/purple unmetamorphosed volcanic clasts are present at 16.4% of sampled till sites (Appendix 4), from trace amounts up to 1.6 ct. %. Similar clast lithologies, thought to be sourced from the Dubawnt Supergroup in Nunavut (Peterson, 2006), have also been documented in the Great Island area (up to 5.6 ct. %, Campbell et al., 2012; Trommelen, 2015a). While these concentrations are not high, they are indicative of the tail-end of a continental-scale dispersal fan (Shilts et al., 1979). Dubawnt erratics are found in tills with and without carbonate detritus, which provides evidence of re-entrainment during multiple glacial cycles.

Omar erratics

Omar erratics (Figure 6d–g) were noted in the field, or in the sieved clasts (Appendix 4), at fourteen sites south of the North Knife River (Figure 23). These clasts have been transported at least 1000 km west from the Belcher Islands. The dispersal of these clasts is known to extend at least as far west-southwest as the Missouri River (Prest et al., 2000).

These clasts may be more prevalent in the field area, but because of the small size-fractions classified during clast-lithology counts, and the variable matrix textures observed within Omar erratics, they are difficult to identify if an ‘obvious’ calcareous concretion is not present. As such, Proterozoic greywackes are probably under-mapped in concentration, as dark fine-grained clasts of uncertain lithology were placed in the greenstone category. Hence, Figure 21 most likely includes an unknown proportion of Omar clasts, wherever the calcareous-clast concentration is greater than 5%.

Multi-variate analyses

Till-clast lithology

In an attempt to identify regional-scale trends in till composition across the study area, clasts were grouped into regional classes according to lithology and presumed provenance (Hudson Bay Basin, HBB; granitoid, GR; undifferentiated greywacke/greenstone, UGG; and unknown; Table 3). For the regional-scale study, the till-clast lithology counts from this study were combined with till-clast lithology counts from the surrounding area (Campbell et al., 2012; Trommelen, 2015a). The data was then normalized to remove the ‘unknown’ class. Ten till-clast groups were designated, based first on the HBB concentration, and second on the UGG concentration. The statistics for each group are in Table 4, and depicted visually in Figure 25. Divisions between the different groups were made manually using percentiles, probability distributions and natural breaks in the data as a guide. There appears to be two main categories of samples: no carbonate (till-clast groups 1b, 4b, 5b, 6b) and calcareous (till-clast groups 2, 3, 1). Till-clast group 6 looks like a hybrid between these two main categories.

Geology has spatial patterns, and hence for statistics to be considered useful, there must be spatial patterns in the landscape. In other words, if there were no spatial patterning to the different groups, the groupings would be considered random and not useful. As expected from Figure 23, the till-clast groups with no carbonate (5b, 1b, 4b and 6b) are clustered in the northwest corner of the study area (Figure 26). There are a few exceptions—e.g., till-clast group 5b samples were collected near North Knife Lake and Nares Lake. Similarly, the greenstone-rich till-clast group (4, 4b) samples overlie—or are within 5 km of—greenstone rocks. An exception is sample AN351813 near Nares Lake, which contains 33% quartz arenite (Appendix 4) that is probably from a nearby unmapped bedrock outcrop. Likewise, granitoid and granitoid-rich till-clast group (1, 1b, 5, 5b) samples overlie—or are within 5 km of—granitoid rocks. Exceptions here include four surface samples and one sub-surface sample that overlie Paleozoic carbonate rocks between Herriot Creek and the Churchill River.

Group 2 is interesting as it is a calcareous group that contains 15.1–22.1 count percent UGG clasts (75–80th percentile), and is situated 10 to 85 km south of the closest known greenstone belt. Contrastingly, group 6, which also has elevated UGG concentrations (17.8–48.0 ct. %), contains less carbonate and is limited to <27 km south of the greenstone belt. Given that the transport of metasedimentary rocks exposed in

Table 3: Regional and detailed lithological classes for till-sample clasts.

Regional class	Granitoid	Undifferentiated greenstone and greywacke	Hudson Bay Basin	Unknown
Detailed classes	Granitoid	Quartz arenite	Grey, tan, black, limestone/ dolostone	Quartz
		Quartz pebble conglomerate		Quartzite
	Amphibolite	Paragneiss	Pink limestone	Unmetamorphosed shale
	Gabbro	Phyllite/Psammite	Kenogami Formation	
	Exotic, faceted granitoids and gneiss	Ultramafic	Lower Portage Chute Formation	Chert
		Undifferentiated greenstone		Iron formation
		Sulphide	Omar	
	Exotic, red metasediment and metavolcanics	Volcanic	Shell fragment	
		Volcaniclastic		
			Unmetamorphosed sediment	

Table 4: Clast-type concentration ranges for each till-clast group.

Till-clast group	Color	Number of samples	HBB	GR	UGG	Summary
1	dark orange	63	4.9–22.3	63.0–91.7	0–14.8	Granitoid (40–65th percentile), low carb (60–75th percentile)
1b	light orange	47	0.0	85.1–97.3	2.7–14.9	Granitoid (55–75th percentile), no carb
2	light blue	17	26.3–61.1	16.5–59.4	15.1–22.1	Carbonate-rich (>75th percentile), greenstone-rich (75–80th percentile)
3	dark blue	116	23.0–93.8	6.3–71.4	0–14.8	Carbonate-rich (>75th percentile), low greenstone (<75th percentile)
4	light green	5	0.2–4.2	13.3–76.4	22.8–86.2	Greenstone-rich (>75th percentile), very low carb (<60th percentile)
4b	dark green	52	0.0	0–41.6	58.4–100.0	Greenstone-rich (>90th percentile), no carb
5	pink	35	0.1–4.3	81.2–99.5	0.4–15.4	Granitoid-rich (>50th percentile), very low carb (<60th percentile)
5b	dark red	127	0.0	97.4–100	0–2.6	Granitoid-rich (>75th percentile), no carb
6	purple	15	5.6–20.4	46.4–75.0	17.1–48.0	Greenstone-granitoid, low carb (60–75th percentile)
6b	aqua	42	0.0	42.9–84.5	15.5–57.6	Greenstone-granitoid, no carb

Abbreviations: GR, granitoids; HBB, Hudson Bay Basin; UGG, undifferentiated greenstones and greywackes.

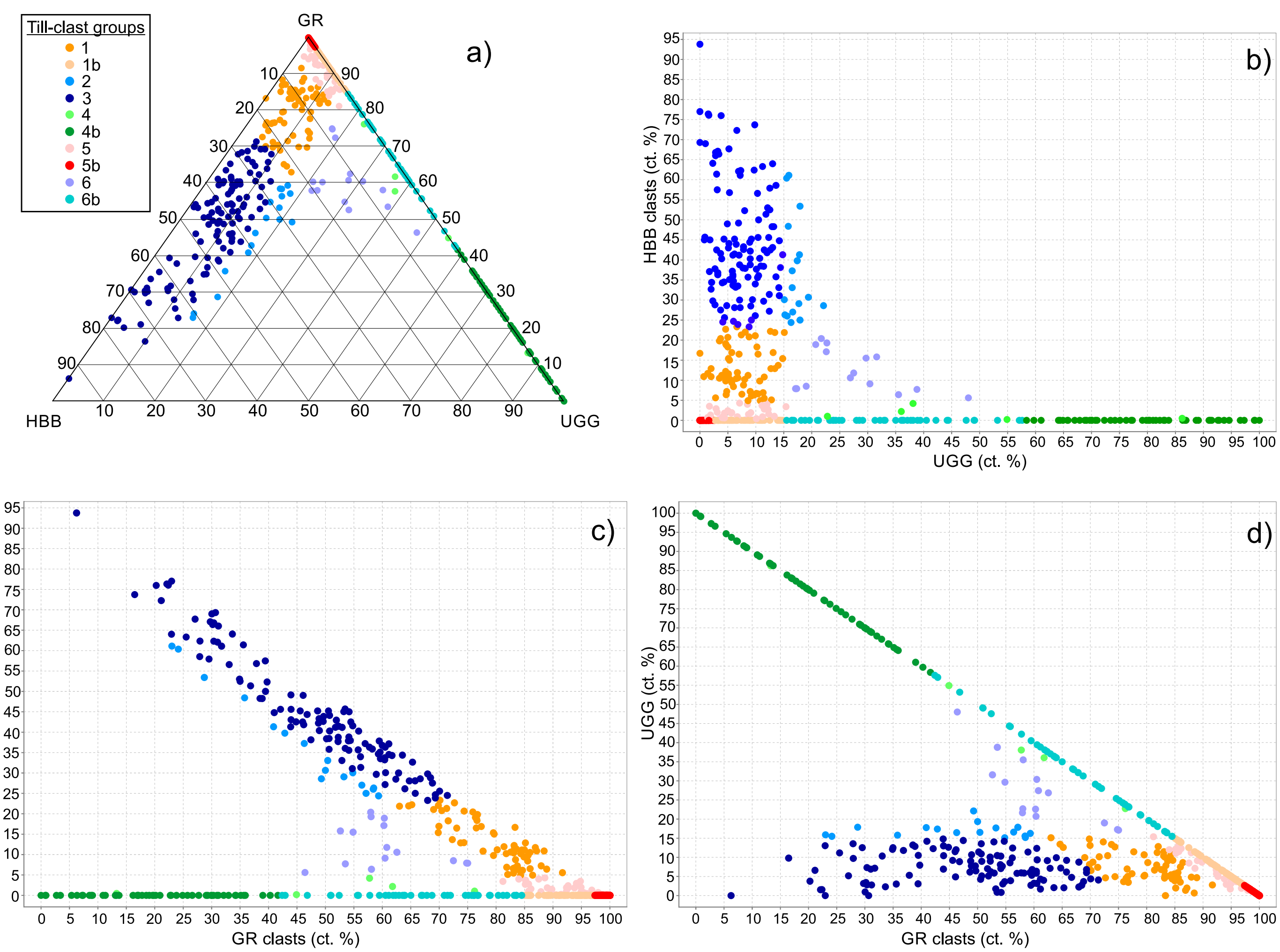

Figure 25: *Ternary diagram **(a)** and biplots **(b–d)** of the regional till-lithology data, coloured by till-clast group.*

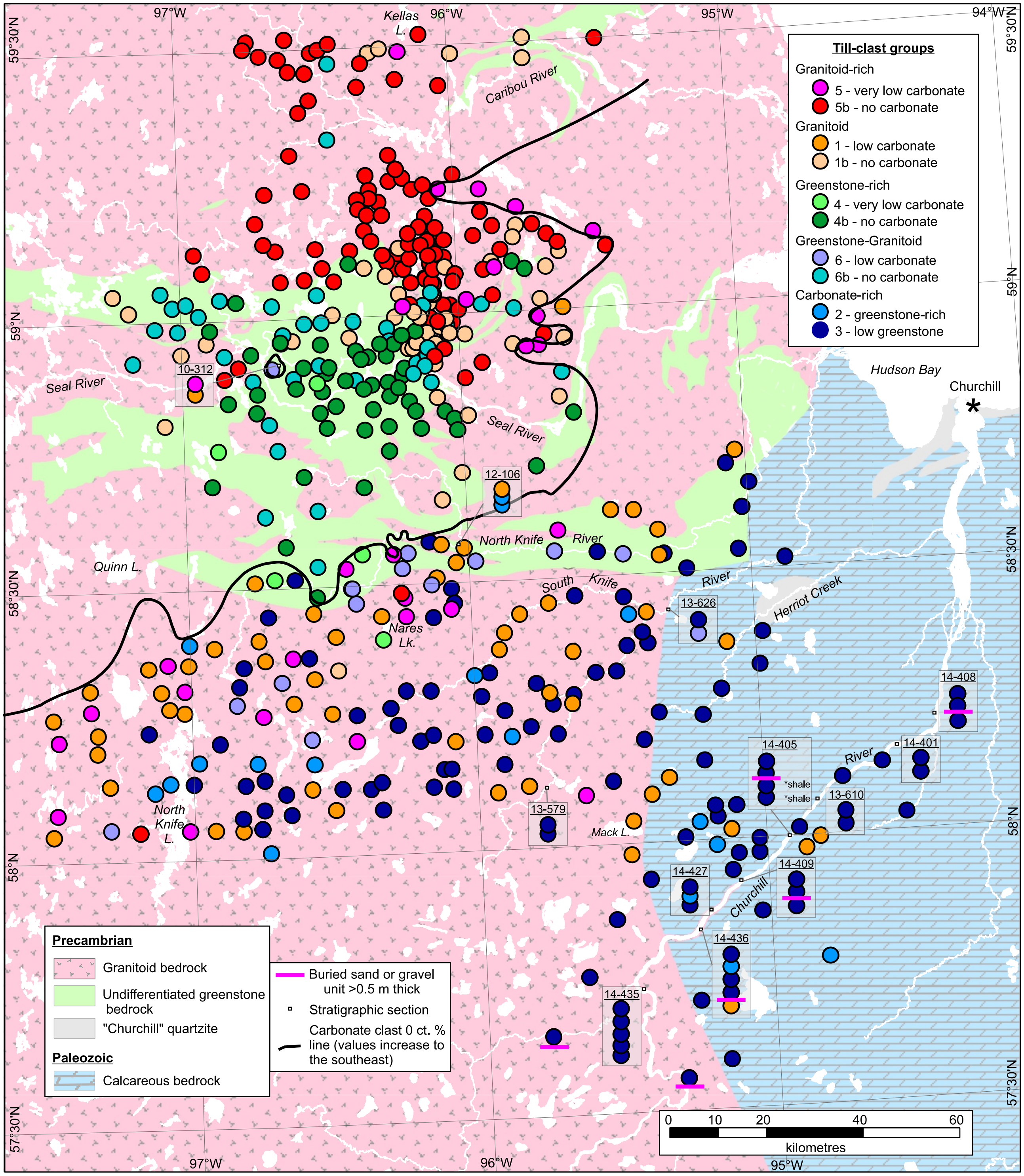

__Figure 26:__ The spatial distribution of till-clast groups between the Churchill River and the Caribou River, based on the varying concentrations of three regional till-clast lithology classes depicted in Figure 25. Bedrock geology is modified after Anderson et al. (2009; 2010b) in the north, and an unpublished MGS compilation in the south. The carbonate-clast contour line is from an ongoing MGS compilation project (Trommelen and McMartin, 2019).

the study area is generally <30 km (Figure 22), it is possible that these UGG clasts within group 2 are actually greywackes sourced from the east.

Stratigraphic till-composition relationships are difficult to discern on this figure, as most of the stratigraphic sites are situated over Paleozoic rocks and fall under group 3 (Figure 26). An exception is the lowermost till at section 14115MT436, which contains less calcareous detritus and is classified as group 1. The stratigraphy at section 13115MT626 is similar (Figure 27), as an upper calcareous till (group 3) overlies a less-calcareous till (group 6). Lodged boulders at the contact between the two tills were striated towards the west. The opposite relationship is present at section 12115MT106 (Trommelen, 2015a), which overlies greenstone-belt rocks that outcrop at site, and

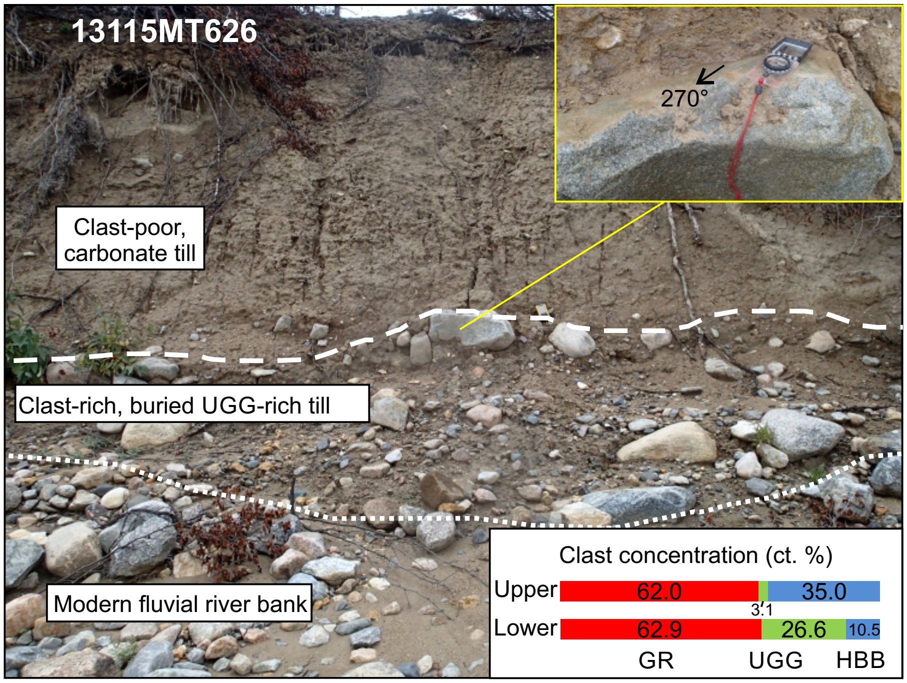

Figure 27*: Till stratigraphy and lithology at section 13115MT626, along the South Knife River. The upper till is ~4 m thick and the lower is ~4.5 m. A detailed stratigraphic log for this site can be found within Appendix 2. Abbreviations: GR, granitoid; HBB, Hudson Bay basin; UGG, undifferentiated greywacke and greenstones.*

is situated ~46 km west of the Paleozoic boundary. There, the uppermost till (group 1) contains less calcareous detritus than the underlying tills (group 2), owing to an increase in granitic detritus (Figure 27, Figure 28).

Till-matrix geochemistry

To see if tills could be differentiated based on the matrix geochemistry, principal component analyses (PCA) was applied. The objective of PCA is to reduce the number of variables necessary to describe the observed variation within a set of data. The results of PCA are presented herein as bi-plots (Figure 29) to show elemental influence on classifications. Generally, PC1 accounts for 38.6% of the variance, PC2 for 15.8%, and PC3 for 9.2%. There is good separation between Ca and Mg (negative PC1), which is a proxy for carbonate, and the rare earth elements (REE) such as La, Nd, Ce, Pr, Tb, Gd, Sm, Dy, Er, Ho, and Yb (positive PC1). This is confirmed on bi-plots of Ca vs. Mg, and Ca vs. ΣREE (Figure 30).

In order to assess whether the multivariate statistics are a representation of geologic differences, PC1 is mapped spatially (Figure 31). There is a definite spatial difference between the negative loadings in the southeast and the positive loadings in the west and northwest. This difference roughly follows the zero percent calcareous pebble contour, but largely reflects the increased ΣREE concentration in the northwest, where granitoid rocks dominate.

Discussion

Till composition in the study area can be examined in a number of different ways, depending on what the end goal is. For the discussion herein, we choose to examine the variability within the regional till composition, as a means to determine background and threshold element concentrations. In addition, we then use this data, along with ice-flow information, to determine glacial dispersal distances and directions.

Calcareous vs. noncalcareous till

Till composition in the study area is broadly subdivided into noncalcareous till in the northwest and calcareous till in the southeast (Figure 32). A number of different proxies for carbonate were examined, including univariate measures like total carbonate wt. % (PerkinElmer Optima 5300DV, Figure 15), CaO wt. % (near-total ICP-MS, Figure 17), oxide ratios (near-total ICP-MS, {CaO+MgO}/Na_2O, Figure 16c), and calcareous clasts (Figure 23); and multivariate statistics on the near-total digestion ICP-MS data. Calcareous tills contain lower REE concentrations (Figure 30b). The spatial boundary that marks the ‘zero percent’ carbonate clasts (Figure 32) is not definitive, but rather an artifact of sample location, till processes and the proxy used. The equivalent ‘five percent’ till-matrix, total-carbonate, hand-contoured, spatial boundary is also shown. This is an update on work presented in Dredge (1988). As discussed in Gauthier et al. (2019), calcareous detritus was likely transported northwest and west during pre-MIS 2 ice growth phases 1 and 5 (Figure 10).

Calcareous till variability

It should be noted that the ‘calcareous’ till is not a single till sheet, but rather a definition that simply means the till

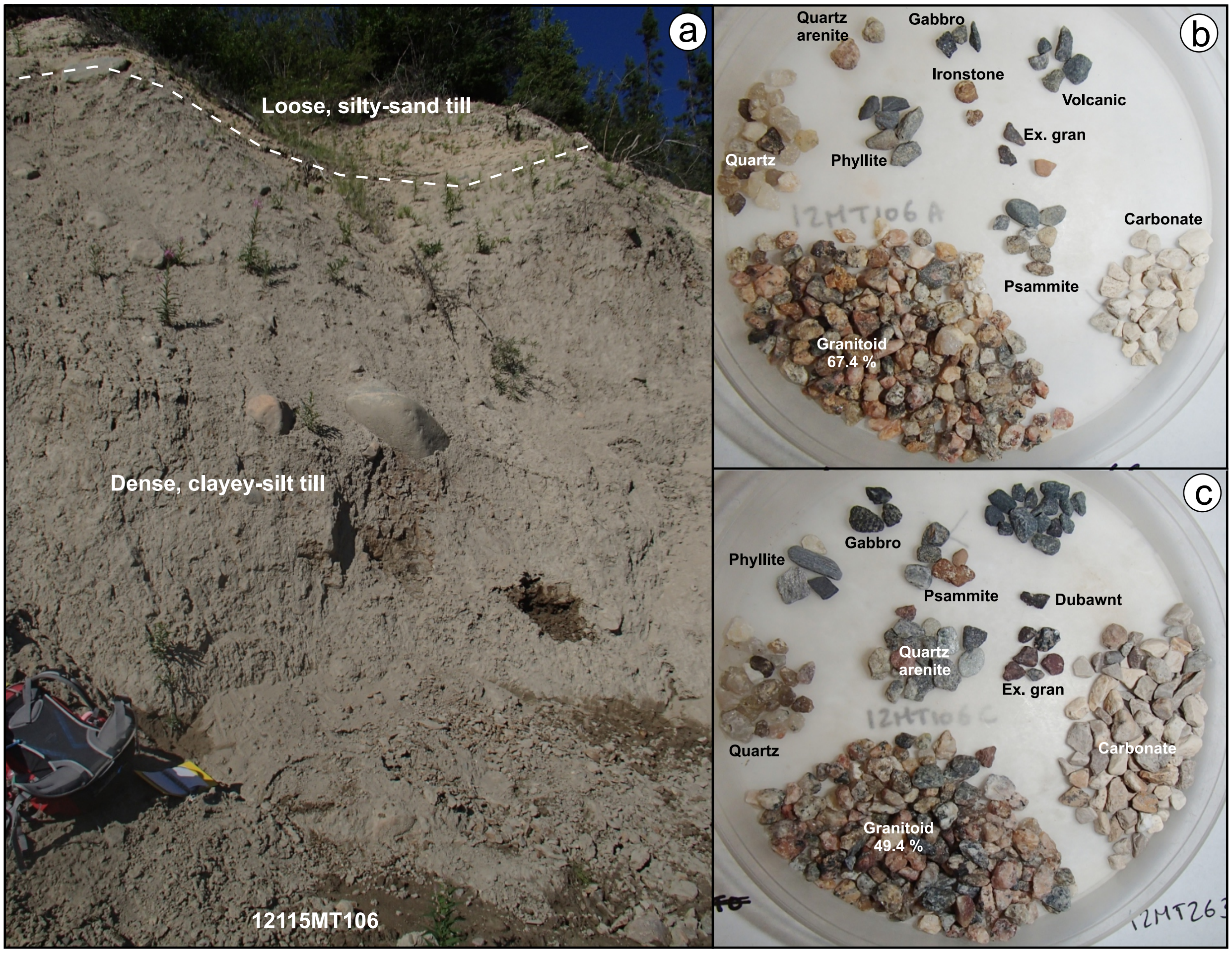

***Figure 28**: Till stratigraphy and lithology at section 12115MT106, along the North Knife River. More details about this section can be found in Trommelen (2015a). Abbreviation: Ex. gran, exotic granitoid.*

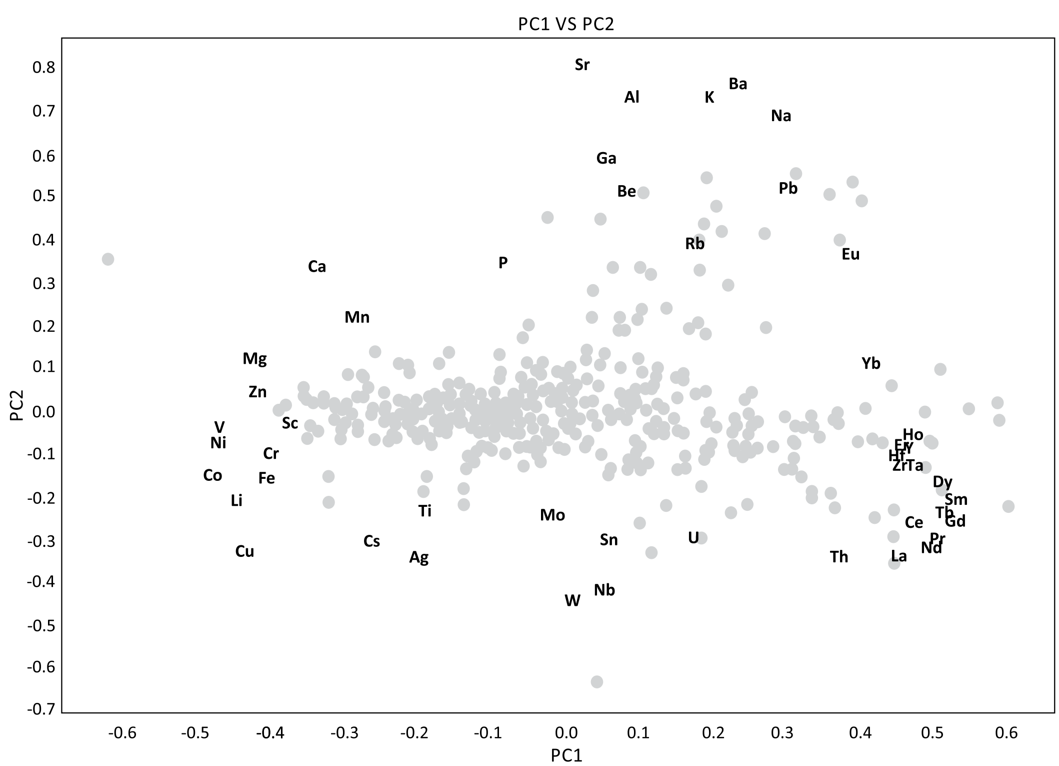

***Figure 29:** Multivariate classification of till-matrix geochemistry data, PC2 vs. PC1. This figure includes data from the 2012 study, since samples were analyzed by the same methods at SRC (Trommelen, 2015a).*

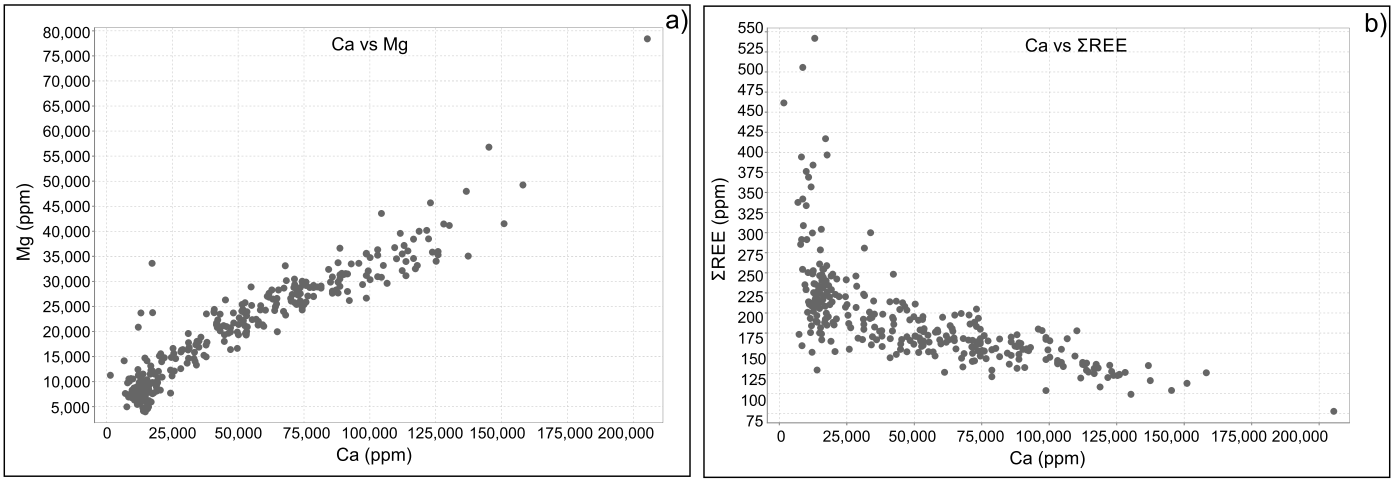

***Figure 30:** Biplots of a) Ca vs. Mg (near-total ICP-MS) and b) Ca vs. total rare earth elements (ΣREE) of the till matrix. This figure includes data from the 2012 study, since samples were analyzed by the same methods at SRC (Trommelen, 2015a).*

contains greater than zero percent carbonate. As depicted in Figure 32, the concentration of carbonate clasts within till increases closer to the Paleozoic platform (the source). The hand-contoured dispersal pattern is not simple, however, but instead reflects complex spatial variabilities. The 'calcareous' till is a hybrid till that contains a wide range of eastern- and/or northeastern-sourced (Paleozoic/Proterozoic sedimentary) detritus, as well as 'locally'- and northern-sourced (Precambrian shield) detritus. The palimpsest till composition is a result of the characteristics of the underlying bedrock or pre-existing sediment (Klassen, 1997), spatio-temporally variable inheritance and overprinting generated by multiple ice-flow transport directions over a long time period (Stea and Finck, 2001; Trommelen et al., 2013; Gauthier et al., 2019), and the subglacial conditions at the base of the paleo ice sheet (Trommelen et al., 2013; Trommelen and Ross, 2014).

Noncalcareous till source

Noncalcareous till is derived primarily, but not exclusively, from Precambrian shield rocks of northern Manitoba and Nunavut. These tills may be granitoid-derived (till-clast group 5b), mainly greenstone-derived (till-clast group 4b), or mixed (till-clast groups 1b and 6b; Figure 25d). These tills contain elevated ΣREE concentrations (Figure 30b), as well as locally-elevated concentrations of various metals.

Buried granitoid-rich till

While calcareous till covers most of the study area (Figure 32), buried till enriched in Precambrian granitoid clasts, relative to the overlying calcareous till, has been found at sites 14115MT409 and 14115MT436 along the Churchill River (Figure 20). At both sites, the lower granitoid-rich till is separated from upper calcareous till by nonglacial units (Figure 11, Appendix 2). The composition of both buried granitoid tills is similar, though the lower till at site 14115MT409 contains 12% more carbonate clasts (Appendix 4). Site 14115MT409 overlies the Paleozoic platform, while site 14115MT436 is situated near the Precambrian boundary and actually overlies granitoid bedrock striated towards 192°.

Buried shale-rich till

Till containing shale is rare in northeast Manitoba. A grey-black till was sampled from the lower-half of section 14115MT405 (Figure 24), at the mouth of Chasm Creek just before it enters the Churchill River (Figure 1). The till contains 4–7 ct. % shale clasts, and the till colour is likely derived from the comminution of these clasts. Dense, black till containing shale particles was also mapped below brown and grey tills at two sites along the Little Churchill River, 78 and 97 km south-southwest of section 14115MT405, respectively (sections 18 and 20, Dredge and Nixon, 1992). Shale clasts have also been documented at four sections in the Kaskattama highland (0.2–1.1 ct. % shale, 2 to 12 m depth, T. Hodder, work in progress) and within drillcore KK1 (Hodder, 2018). Black shale and siltstone clasts are present throughout the grey-black till drilled at KK1 (83 to 161 m depth), and are elevated in concentration (8.5 to 16.3 ct. %) between 83 and 102 m depth. The thickness of this black till within KK1 (78 m) is intriguing, given that it is 8 m thick at Chasm Creek, and ~3 m thick along the Little Churchill River.

Black shale bedrock, of unknown age, was encountered within the drillcore KK1 at 223 m depth overlying the Paleozoic carbonate Severn Formation (Nicolas and Armstrong, 2017). Preliminary results from a magnetotelluric geophysical survey in the region indicate that this shale is more extensive in the subsurface than previously suspected (Craven et al., 2017).

Elevated metals

Elevated Cu and Ni concentrations in the area between Mack Lake and Wood Lake (Figure 18, Figure 19) were sampled

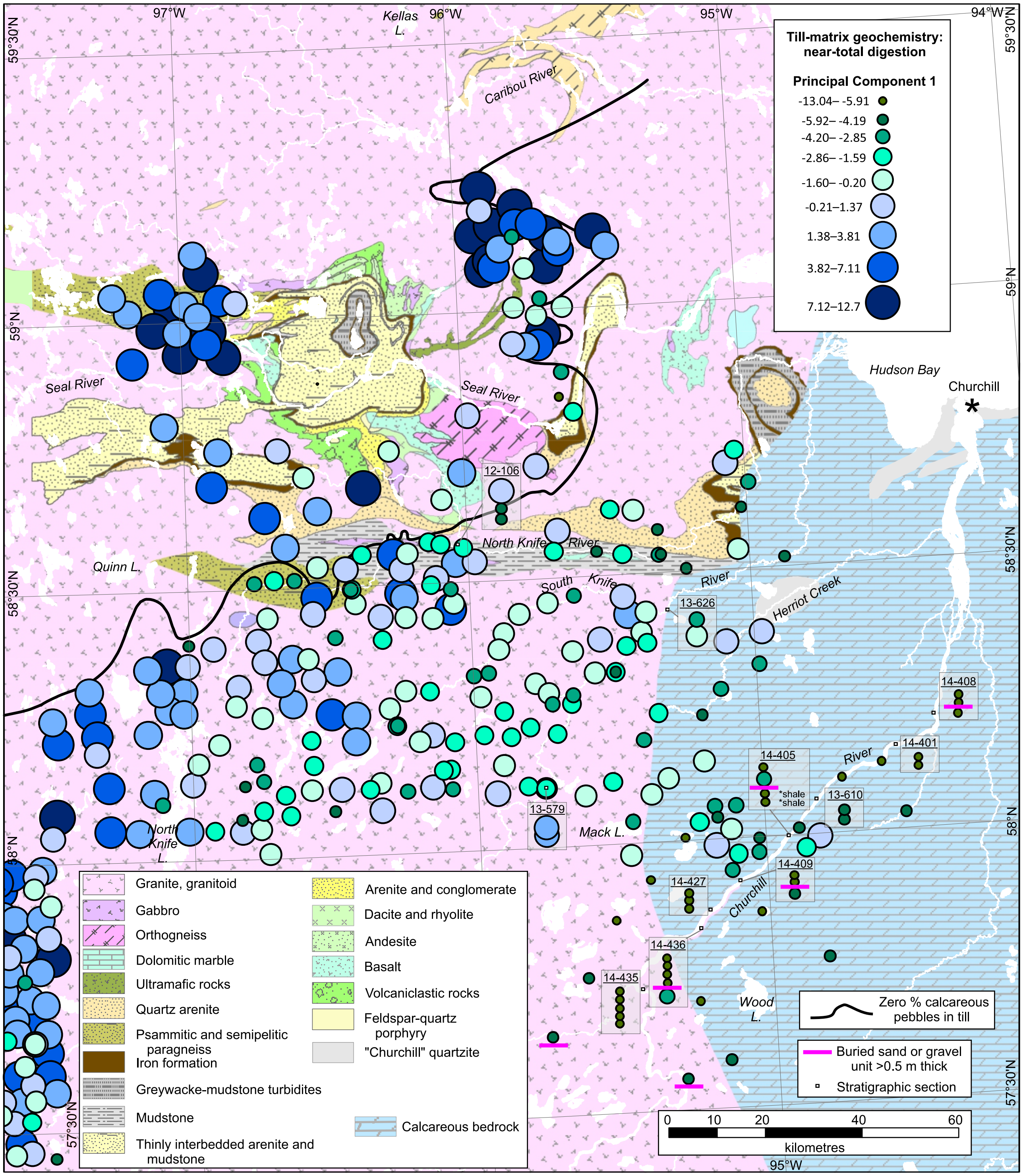

***Figure 31**: Spatial distribution of PC1, based on analyses of the till-matrix near-total geochemistry. PC1 has positive eigenvalues for REE, and negative eigenvalues for metals and Ca-Mg. Till samples from stratigraphic sections are shown as stacked circles and referenced to section location. This figure includes data from the 2012 study, since samples were analyzed by the same methods at SRC (Trommelen, 2015a).*

from both calcareous (till-clast group 3) and noncalcareous tills (till-clast group 1). The reason for this patch of 'elevated metals' within till is unknown.

Transport distance and direction

Regional dispersal patterns are difficult to define, given the lack of point-source distribution, the range and abundance of lithologies (Table 1), and the variability in paleo–ice-flow orientation. Glacial transport distance of detritus can vary greatly, depending on the specific site. Below are some general observations.

- **Carbonate**: The isolated patch of calcareous till in the Great Island area (Seal River) represents the furthest known northwest to west dispersal, with a transport distance of ~100 km (Trommelen et al., 2013).

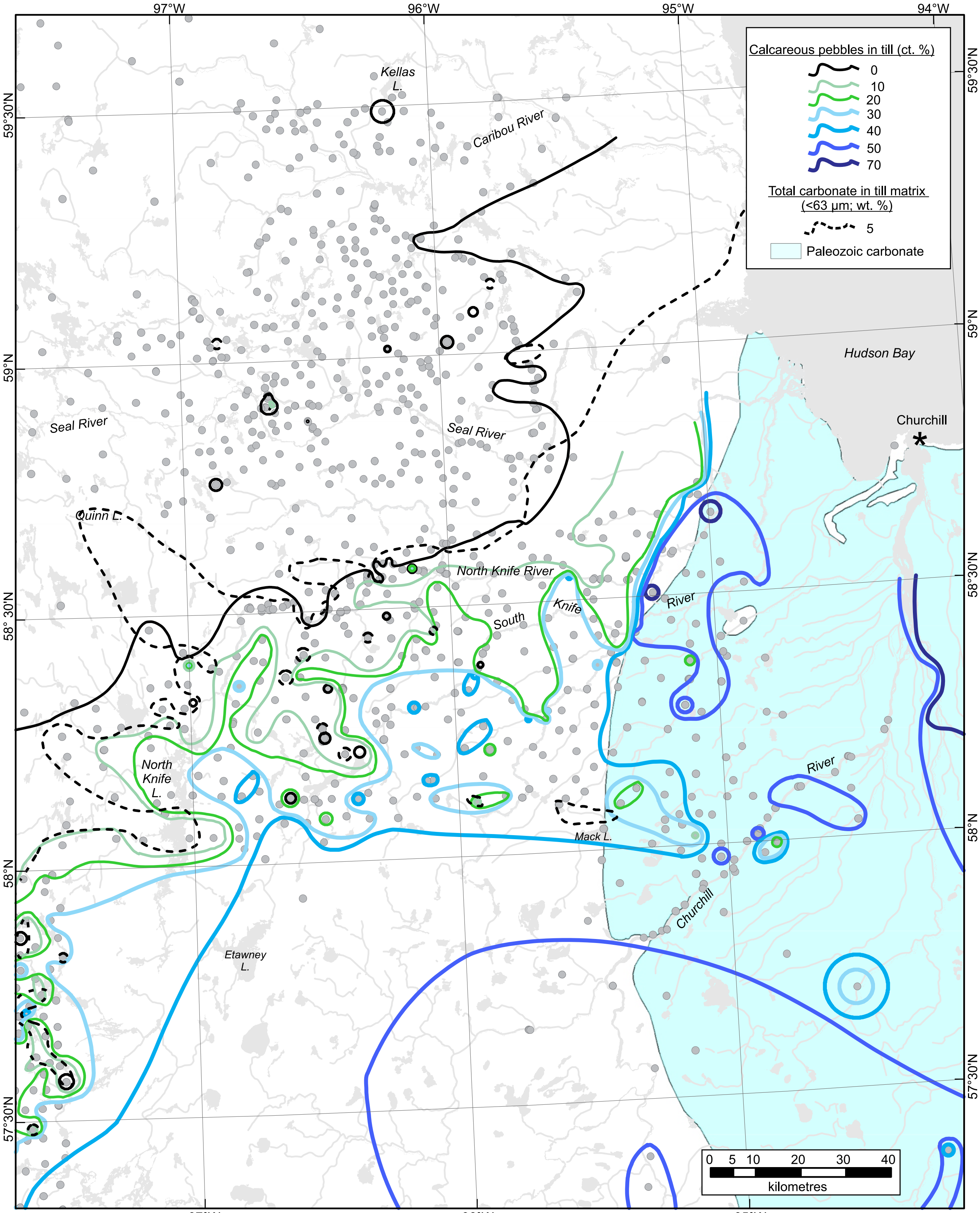

Figure 32*: Regional carbonate dispersal patterns in surface till. This till-clast pebble (2–30 mm) compilation represents ongoing work in the area and is sourced from a number of different studies with slightly different methods (Trommelen and McMartin, 2019). Owing to the limited number of data points in most areas, the hand-contoured data are not accurate at a detailed scale but provide a general overview of the carbonate dispersal pattern. Similarly, the contours are more detailed where local-scale fieldwork has been conducted. The area in white is underlain by Precambrian shield rocks (Manitoba Department of Mines, Natural Resources and Environment, 1979).*

- **Metasedimentary:** Clasts were transported 20 to 30 km towards the south (Figure 22), though the tail end of southwestward dispersal is 100 km in the Gauer Lake–Wishart Lake area (Trommelen, 2015g).
- **Shell fragments**: Marine shell fragments sourced from pre-MIS 2 marine sediments have been transported at least 40 km southwestward; assuming the marine sediment distribution at pre-MIS 2 times was similar to present (site 13115MT553, Figure 23).
- **Granitoids**: Generally, granitoid-rich tills (till-clast groups 5b) overlie granitoid bedrock (Figure 26). Granitoid clasts have been transported at least 50 km southeastward onto the Paleozoic platform (Figure 20).
- **Greenstones**: Generally, greenstone-rich tills (till-clast group 4b) overlie greenstone bedrock (Figure 26). The spatial distribution of greenstone clasts (Figure 21) from sampled tills is complex, producing an amoeboid pattern. Local patterns of greenstone-clast dispersal in the Great Island–Seal River area are discussed in Trommelen et al. (2013). Because this group includes undifferentiated greenstone clasts, it is difficult to determine a single transport distance.
- **Seal River ultramafic rocks**: dispersal from these rocks have transport distances of 3.5 to 10 km, as discussed in Trommelen (2015a).

Longer-distance transport of some clasts has also occurred, evidenced by the presence of faceted 'exotic' granitoids (sources unknown), Dubawnt erratics from Nunavut, and Omar erratics from the Belcher Islands. Dubawnt erratics have been transported at least 680 km into the study area (Shilts et al., 1979; Trommelen et al., 2013). Omar erratics have been transported at least 1000 km into the study area.

The direction of glacial transport is complex, and the 'rare' and/or 'old' directions can not be discounted. There is an isolated remnant patch of calcareous till in the Great Island area (Figure 32) that was formed by very old, west or northwest-trending glacial transport, in addition to another relict northeastward dispersal in the Great Island area (Trommelen et al., 2013).

Recommendations for future exploration

Parts of the field area are draped by a variable thickness of glaciolacustrine and/or marine clay, silt or sand, which must be avoided during drift exploration programs. The reader is encouraged to make use of existing surficial geology maps (Manitoba Growth, Enterprise and Trade, 2018b), and conduct further mapping as needed.

Far-travelled carbonate detritus can dilute and/or mask the geochemical contribution of the local bedrock to till, which is problematic for drift exploration. Overlying the Precambrian Shield, the larger the calcareous component of the till, the more tenuous is the correlation between the till composition and the composition of the local bedrock. Similarly, overlying the Paleozoic platform, the larger the granitoid and/or greenstone component of the till, the more tenuous is the correlation between the till composition and the composition of the local bedrock. Total carbonate (wt. % CO_3) and/or CaO (wt. %, near-total digestion ICP-ES) concentrations within the till matrix are positively correlative and should be used together with carbonate-clast concentration to quantify this calcareous component. Statistically, an increased concentration of total rare earth elements may provide a good proxy for the increased concentration of Precambrian detritus, and hence less carbonate masking, in till.

Important notes related to drift exploration in this area are as follows:

- This report has not examined the mineral potential of the area. The reader is encouraged to examine the data herein for any particular commodities of interest.
- The ice-flow history in this area is complex, and older ice-flow directions should not be ignored by exploration projects.
- Bedrock outcrops are rare and limited to areas where bedrock was exposed along rivers/creeks or by paleo-meltwater channels. Till clast-fabric analyses are recommended to better document the associated ice-flow orientations of till in areas where bedrock is absent, outcrops surfaces are rough, weathered and/or lichen-covered, or where till is thick and possibly multi-layered.
- The intensity of overprinting of an old, pre-existing, calcareous till sheet, during younger ice-flow phases, is not homogeneous but was spatially variable within the North Knife River–Churchill River region. Interpretation of till composition for drift exploration purposes should be understood within this context.

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