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Glacial history and till composition, Knee Lake area, northeastern Manitoba (NTS 53L14, 15, 53M1, 2)

By
M.S. Trommelen

Manitoba

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(204) 945-6569 (Publication Sales)
Fax: (204) 945-8427

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Cover illustration: Mixed forest uplands and spruce forest lowland near the north end of Knee Lake. A meltwater channel meanders through the foreground, and follows alongside a low-lying drumlinoid ridge in the background.

Abstract

In 2012, the Manitoba Geological Survey (MGS) commenced Quaternary fieldwork in the Knee Lake area of northeastern Manitoba. The project builds on an already substantial amount of Quaternary data for this area, collected during the MGS Operation Superior project (1999–2001). The new research focuses on i) providing a better understanding of the glacial history of the region, ii) adding data to the till geochemistry and kimberlite-indicator-mineral sampling surveys, and iii) conducting lithology analyses of clasts within till to assist mineral exploration in this region, which is underlain by prospective bedrock but mantled by deposits of varying thicknesses.

Beige, calcareous, sparsely fossiliferous, silty till is widespread throughout the study area. The calcareous subglacial detritus within this till was sourced from either the east or northeast, and transported (~100 km) to the study area during the penultimate glaciation and/or southwesterly ice flow in the Late Wisconsinan. Sparse Omarolluk Formation erratics (Omars) and a lone Kipalu Formation clast were also transported west-southwest, presumably from the Belcher Group (~940 km) during these ice-flow phases.

More work needs to be completed in the surrounding regions, but it appears small areas of till contain elevated components of inherited shield-derived subglacial detritus (>95th percentile of granitoid clasts, exotic granitoid clasts and Dubawnt supergroup erratics), relative to the surrounding regions. These clasts were transported south and southeasterly to the study area, during early ice-flow phases in the Late Wisconsinan or the penultimate glaciation. This high-inheritance hybrid till is brown, red-brown, grey or beige, noncalcareous or weakly calcareous, and has a silty-sand matrix. These sites were protected (not diluted or reworked) from the ice-flow phases that transported substantial calcareous subglacial detritus to the area.

There are also noncalcareous tills that are enriched in greenstone-belt clasts (presumably locally derived) or consist of a mixture of greenstone-belt and granitoid clasts.

Within the regional calcareous till, till-matrix geochemistry does not depict any spatial patterns or obvious dispersal trains of metals from known mineralized source outcrops. Although regional variation of most element concentrations is masked, there are several sites with elevated gold concentrations (up to 560 ppm; background concentration is 2 ppm) and other multi-element highs (>99th percentile). Weakly calcareous (3.3% of sites) and noncalcareous (2.9% of sites) tills are 'more prospective' and may be 'truer' indications of local mineral potential. Ten sites exhibit multi-element highs (>99th percentile) of metals (As, Co, Cr, Fe, rare-earth elements). As such, detailed attention *must* be paid to calcium (instrumental neutron activation analysis), total carbonate (Chittick or calcium-magnesium method) and/or calcium oxide (near-total digestion and inductively coupled plasma–emission spectrometry) concentrations during drift exploration analyses. Consequently, calcareous till samples with moderate to elevated metal concentrations may be more prospective than noncalcareous till samples with high metal concentrations. The two populations should not be statistically treated as one dataset.

All three till types occur within streamlined landforms, as well as till blankets or veneers over bedrock. This diverse geomorphology indicates that the process of drumlinization within the deglacial Hayes lobe (300 by >400 km) was by subglacial erosion, modification or cannibalization of pre-existing inherited sediment. As such, in the Knee Lake area, the orientation of these widespread streamlined landforms should not be used as an indicator of ice-flow transport direction for drift exploration. The study area is also draped by a variable thickness of glaciolacustrine clay, which must be avoided during drift exploration programs.

TABLE OF CONTENTS

Page

TABLES

FIGURES

APPENDICES (on CD-ROM)

Introduction

Quaternary geology studies were conducted in northeastern Manitoba, encompassing Knee Lake and the easternmost portion of Oxford Lake (NTS 53L14, 15, 53M1, 2; Figure 1), in August 2012. The objectives of this project are to 1) compile and update surficial geology maps at 1:50 000 scale, suitable for property-scale exploration (Trommelen, 2014a–d); 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 till geochemistry (including instrumental neutron activation analysis [INAA], carbonate analysis, kimberlite-indicator-mineral [KIM] analysis) data collected at 1 km spacing during Manitoba Geological Survey's (MGS) Operation Superior project undertaken from 1999 to 2001 in the same area (Fedikow et al., 2001, 2002b, 2009).

This report provides the field site, till compositional and ice-flow indicator datasets to assist with the application of drift prospecting in the Knee Lake study area. 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. The results presented in this report show that till sampling, together with the new surficial-geological framework, should be an effective exploration tool in this region.

An interpretation of the report data that focuses on the paleoglaciological implications was published by Trommelen and Ross (2014).

Regional setting

The study area is located in northeastern Manitoba (Figure 1). Elevation varies primarily from 160 to 220 m above sea level (asl) with local relief of up to 10 m. The Hayes River is the major drainage channel in the study area; it flows northeast and eventually drains into Hudson Bay. Knee Lake and Oxford

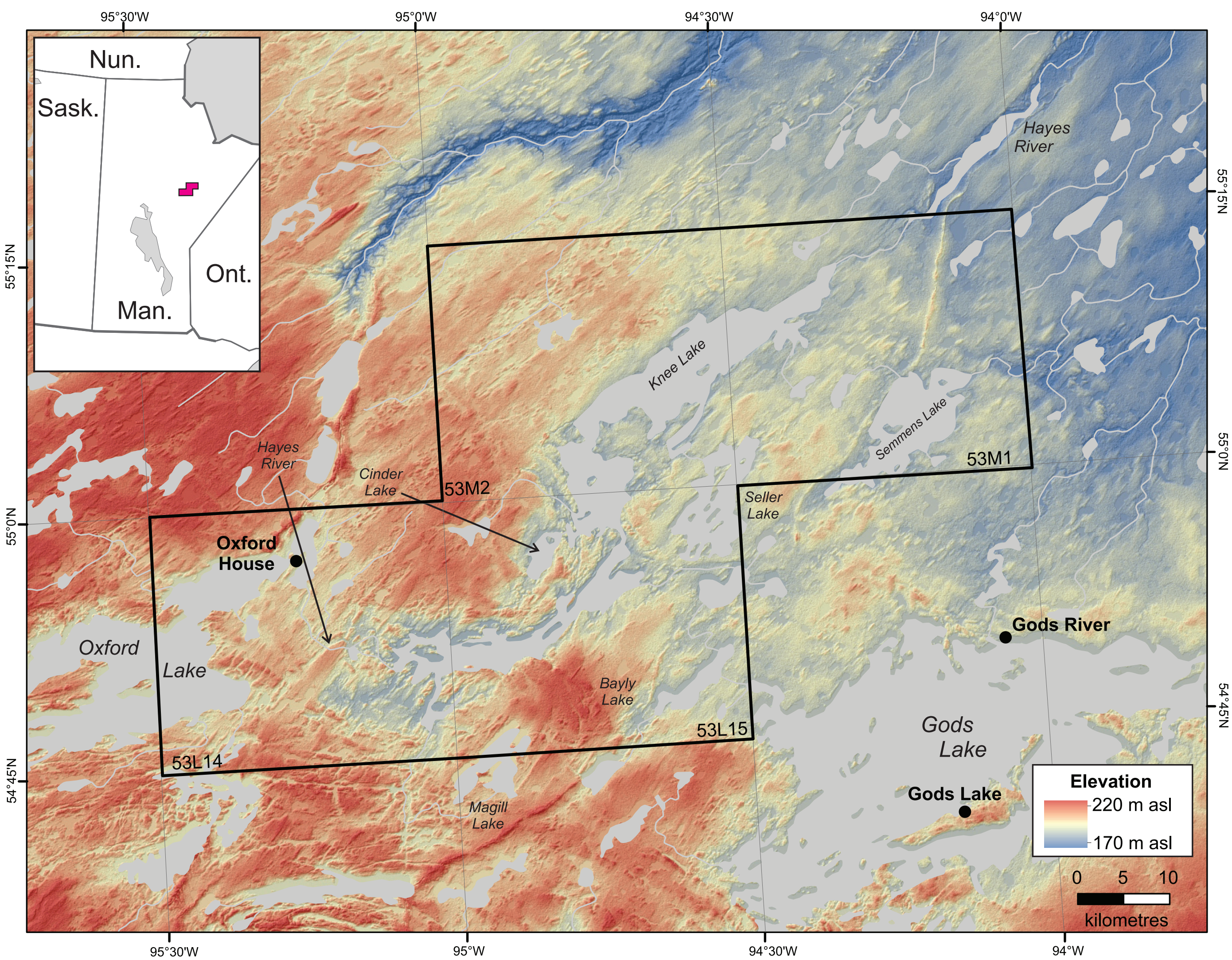

Figure 1: *Location of the Knee Lake study area (black rectangle) in northeastern Manitoba. The background image was generated using the radar-derived digital elevation data from the Shuttle Radar Topography Mission dataset (United States Geological Survey, 2002). A hill-shade model has been added with transparency effect to enhance relief.*

Lake are both widened expanses of the Hayes River. Numerous small streams flow across the drift plains from one lake to another in an immature drainage network, or flow through the muskeg. The northern part of the map area is characterized by poorly drained, closed coniferous forests (Mills et al., 1978), underlain by clay-rich till. Most drumlinoid ridges have a crest that sticks out above the thick cover. The remaining area is a mix of till blankets and till veneers over bedrock.

The region straddles the boundary between the zones of extensive and sporadic discontinuous permafrost (Sladen, 2011). Permafrost was encountered beneath most organic deposits. Periglacial features, such as mudboils, are rare and were only encountered in the northwesternmost portion of the study area.

Bedrock geology

The extensive Oxford Lake–Knee Lake greenstone belt (Figure 2) crosses the study area (Barry, 1959; Gilbert, 1985; Syme et al., 1998). The greenstone belt is composed of three distinct supracrustal sequences:

1) The older, ca. 2.83 Ga, Hayes River group is predominately a volcanic sequence dominated by pillowed basalt and related gabbro, minor intermediate to felsic volcanic rocks, and minor volcanogenic sedimentary rocks. The base of the group has been intruded by tonalitic to granitic plutons and related gneiss of the Bayly Lake complex (Syme et al., 1998).
2) At central Knee Lake, the metasedimentary Opischikona sequence is estimated to be ca. 2.78 Ga. These rocks consist of iron formation, argillite, greywacke, sandstone and conglomerate.
3) The younger, ca. 2.74–2.71 Ga, Oxford Lake group is a predominately sedimentary succession that lies unconformably on the Hayes River group volcanic rocks. The lower, dominantly volcaniclastic subgroup is overlain by more extensive sedimentary rocks, which include polymictic conglomerate, pebbly greywacke and greywacke.

All of the greenstone-belt rocks in the study area have been metamorphosed, and contain greenschist- to amphibolite-facies mineral assemblages.

These rocks are surrounded by intrusive rocks of several ages, which have not been subject to significant geological study except for the Cinder Lake nepheline syenite complex (Chakhmouradian, 2010).

Numerous mineral occurrences are scattered throughout the greenstone belt (Southard, 1977), including massive-sulphide (pyrite, pyrrhotite, chalcopyrite, sphalerite) and rare-earth-element occurrences within the Cinder Lake area (Chakhmouradian, 2010) and shear-hosted gold mineralization.

Quaternary geology

The study area was repeatedly glaciated by the Laurentide Ice Sheet (Klassen, 1986; Dredge and Cowan, 1989), as evidenced by stratigraphic sequences of two nonglacial units and up to four tills (Klassen, 1986; Nielsen et al., 1986; Nielsen, 2001, 2002; Dredge and McMartin, 2011) across the Hudson Bay Lowland (130 km to the northeast). The three uppermost tills were thought to have been deposited by ice flowing out of Hudson Bay in a southwesterly direction, whereas the lowest till was deposited by southeasterly flowing ice originating in the Nunavut region, north of Manitoba. In actuality, the stratigraphic dataset is more complex, and reflects a long history of major and minor shifts in ice-sheet behaviour throughout several advance and retreat cycles, as well as intervening interglacial stages. Nielsen (2002) conducted a study along the lower Nelson, Hayes, Gods and Pennycutaway rivers that incorporated an analysis of numerous upsection till fabrics and samples (composition, geochemistry). This study clearly documented 5–35 m of glacial sediments, including multiple till units with varying concentrations of north- and west-sourced indicator clasts (E. Nielsen, unpublished data, 2002) and a large range of till-fabric orientations (Nielsen, 2002).This indicates there were significant transitions in the source area of ice over time and the sediment record cannot be easily broken into four simple till units.

Regardless of this long glacial history, there is limited information on the extent and character of tills that overlie the Superior province of Manitoba. In the Knee Lake area, Fedikow et al. (2000, 2001, 2002a, b, 2009) assumed that the surface till sheet was relatively homogeneous and contained a large component of far-travelled subglacial detritus from the Hudson Bay area. This is because the till contains significant carbonate detritus derived from the carbonate platform in Hudson Bay, approximately 130 km to the northeast (Leslie and Pelletier, 1965; Grant and Sanford, 1988). This far-travelled till is correlated to a deglacial ice lobe (Hayes lobe, 300 by >400 km, Dredge and Cowan, 1989) that flowed southwest from the Hudson Bay area. Circa 8700 ^{14}C BP, a large portion of this lobe was thought to have stagnated over the study area, resulting in preservation of the streamlined landforms (Klassen, 1983). Klassen (1983) suggested the study area was inundated by glacial Lake Agassiz by 8200 ^{14}C BP (Ponton level, Thorleifson, 1996). Radiocarbon dates are rare in northeastern Manitoba, but it is thought that this inundation was short-lived and the lake had receded by ca. 7700 ^{14}C BP (Fidler level, Thorleifson, 1996; Teller and Leverington, 2004).

The distribution of the tills and other glacial and postglacial deposits is shown on Figure 3 and on the 1:50 000 scale surficial geology maps for this area (Trommelen, 2014a–d). Generally, the study area is mantled by organic and glaciolacustrine deposits of variable thickness, which overlie till and/or bedrock. Detailed descriptions of these sediments and the surficial geology of the Knee Lake area are provided in Trommelen (2012b). Regional Quaternary geology maps for this area are available in Klassen and Netterville (1979) and Clarke (1988), at a scale of 1:250 000, and Klassen and Netterville (1985), at a scale of 1:500 000.

Methods

Field-data collection

Boat- and helicopter-supported fieldwork was conducted in the summer of 2012, by two field crews. At each of the 198 sites visited (Figure 2), geomorphic and terrain characteristics,

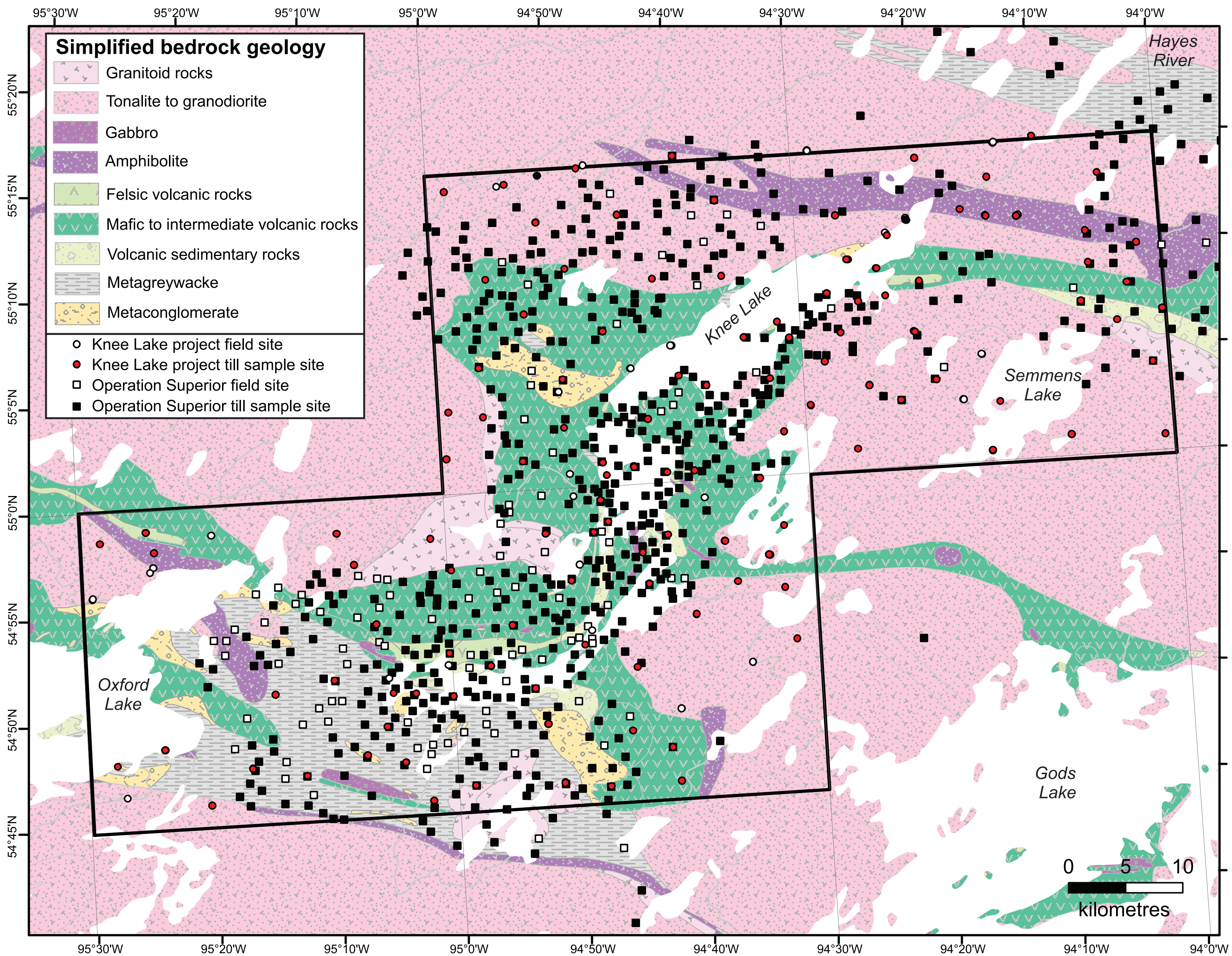

Figure 2: *Bedrock geology of the Knee Lake area, northeastern Manitoba, showing locations of field and sample sites. Bedrock geology is modified from an unpublished Manitoba Geological Survey bedrock compilation map (2013, scale 1:250 000).*

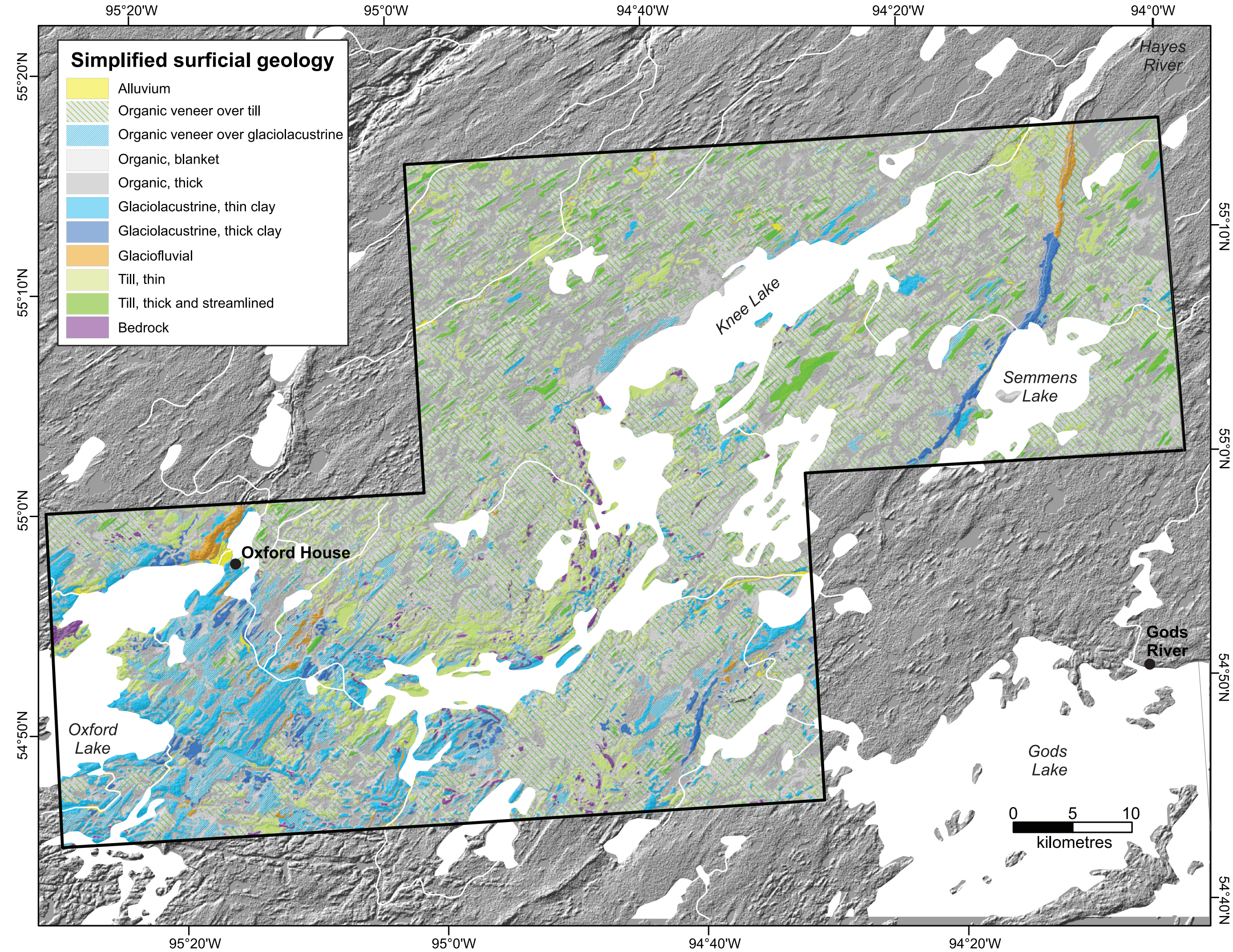

Figure 3: *Simplified surficial geology of the Knee Lake area (modified from Trommelen, 2014a–d).*

map unit and geological interpretation were recorded in addition to location co-ordinates. This site information is included in Appendix 1, together with previously unpublished site information from 695 Operation Superior field sites in the same area.

Ice-flow indicator mapping

Erosional ice-flow indicators (Figure 4), the orientations and relative ages of which were documented at 27 sites in the study area, 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 the recording of rare and protected ice-flow indicators, in addition to the dominant indicators. Where crosscutting patterns were found, the relative ages of flows were determined when possible. Detailed ice-flow indicator measurements for the 27 sites, plus 49 additional sites from unpublished Operation Superior data, are found in Appendix 2, originally released as Trommelen (2012a). Photos related to ice flow in the Knee Lake area can be found in Trommelen (2012b, Figure GS-17-6).

The Knee Lake area contains evidence of at least five different ice-flow phases (Figure 5). The old, rare, ice-flow phase trending to the southeast (between 150 and 160° azimuth, phase I), and the more widespread old phase trending to the west (between 255 and 280°, phase II) are likely correlative to the Sundance (pre-Illinoian, Nielsen et al., 1986; Dredge et al., 1990; Dredge and McMartin, 2011) and Amery (Illinoian, Nielsen et al., 1986; Dredge et al., 1990; Dredge and McMartin, 2011) glaciations. Late Wisconsinan ice-flow phases include a rare but widespread southward-trending ice-flow phase (between 180 and 194°, and toward 200°, phase III), followed by a major southwest-trending phase (between 230 and 248°, phase IV). There is also a young, presumably late deglacial, south-southwest-trending phase (between 212 and 220°, phase V). At one site, a rare young westward-trending ice-flow phase may correlate to the possibly young westward-trending drumlinoid ridges situated between the town of Gillam and city of Thompson, approximately 130 km northwest of the study area.

The dominant Late Wisconsinan southwest-trending phase, associated with the deglacial Hayes lobe, is recorded in the streamlined landform record (Figure 5).

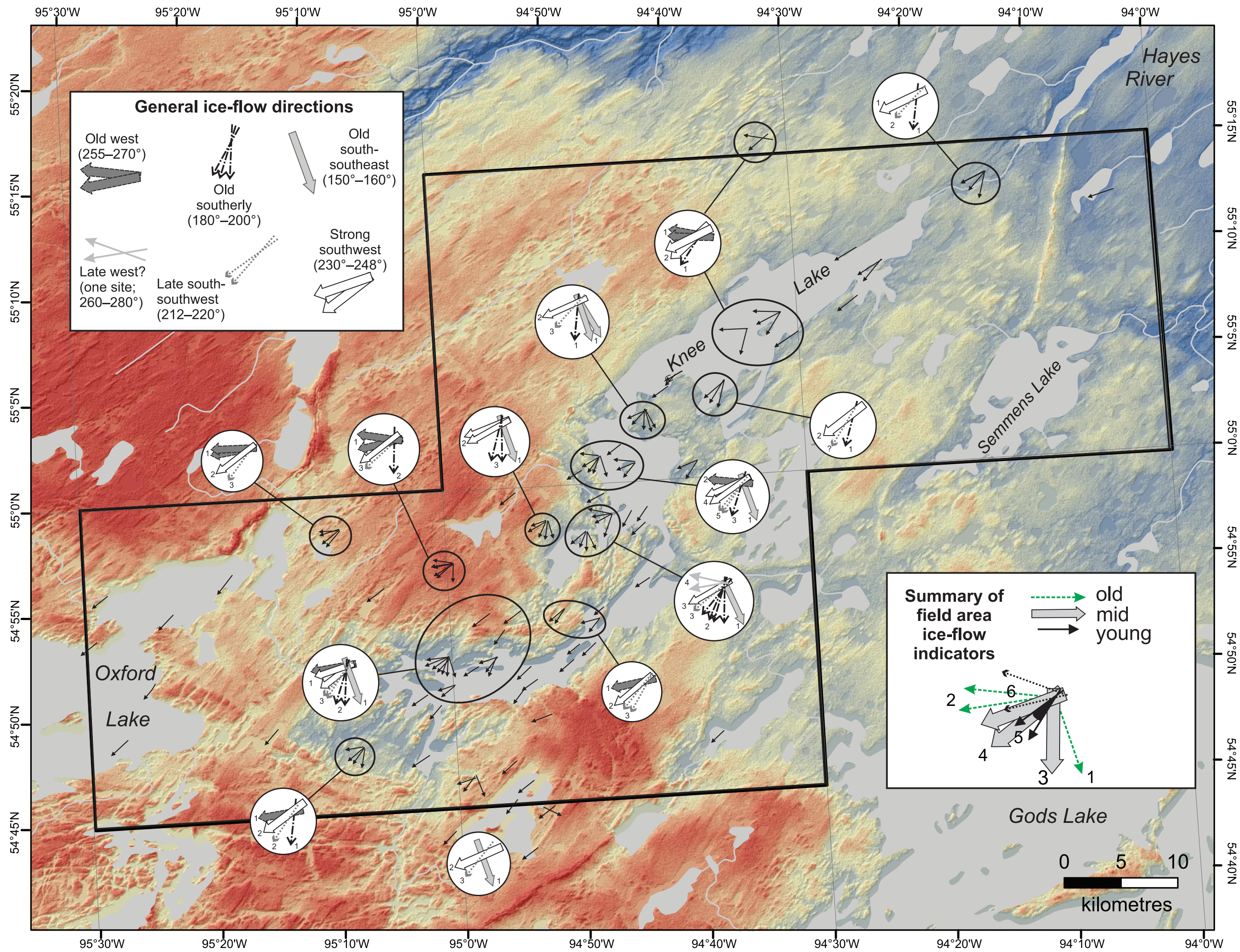

***Figure 4:** Relative-age ice-flow indicator map, based on striations, grooves, chattermarks, crescentic scours and roche moutonnées in the Knee Lake area, northeastern Manitoba. Direction was not known at every site, but enough sites in the area provided information to consistently assign the directions as shown here. The general ice-flow directions (left-upper inset) provide a key for differentiating between old and young ice flows in the same orientation. 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 interpretations regarding ice-flow phases are made on this figure, to allow for new unbiased interpretations when further data is collected in the region. Background image was generated using a Shuttle Radar Topography Mission digital elevation model (United States Geological Survey, 2002).*

Till sampling

A surface-till sampling survey was conducted on a regional scale in the map area. Helicopter landings were largely restricted to areas of open untreed fens, which heavily influenced the location of field and sampling sites. In total, 68 till samples of ~2 kg each were collected (Figure 2) for matrix major-and trace-element geochemical, grain size, carbonate and organic carbon content, and lithological analyses. An additional 57 till samples were collected for lithological analysis, from areas where till was sampled for geochemical analysis during Operation Superior (Figure 2). The surface-till samples (between 25 and 130 cm depth) were collected with a shovel, Dutch auger and/or trowel from the B, B/C or C soil horizon in hand-dug pits. 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.

A field duplicate was collected at five sites, to test sediment heterogeneity and field variability. Each field duplicate was taken from the same sample pit approximately 10–20 cm lower than the original sample. The duplicate sample was bagged separately and given a unique sample number.

Laboratory and analytical procedures

The samples were prepared at the Saskatchewan Research Council (SRC) Geoanalytical Laboratories. Approximately 1 kg of each till sample was air dried and dry sieved, using stainless steel mesh screens to obtain the <2 mm fraction for texture and carbonate-content determinations and the <63 µm fraction for geochemical analyses. The remainders of the original samples were archived at MGS storage facilities.

During Operation Superior, approximately 1 kg of each till sample was air-dried and dry-sieved, using stainless steel mesh

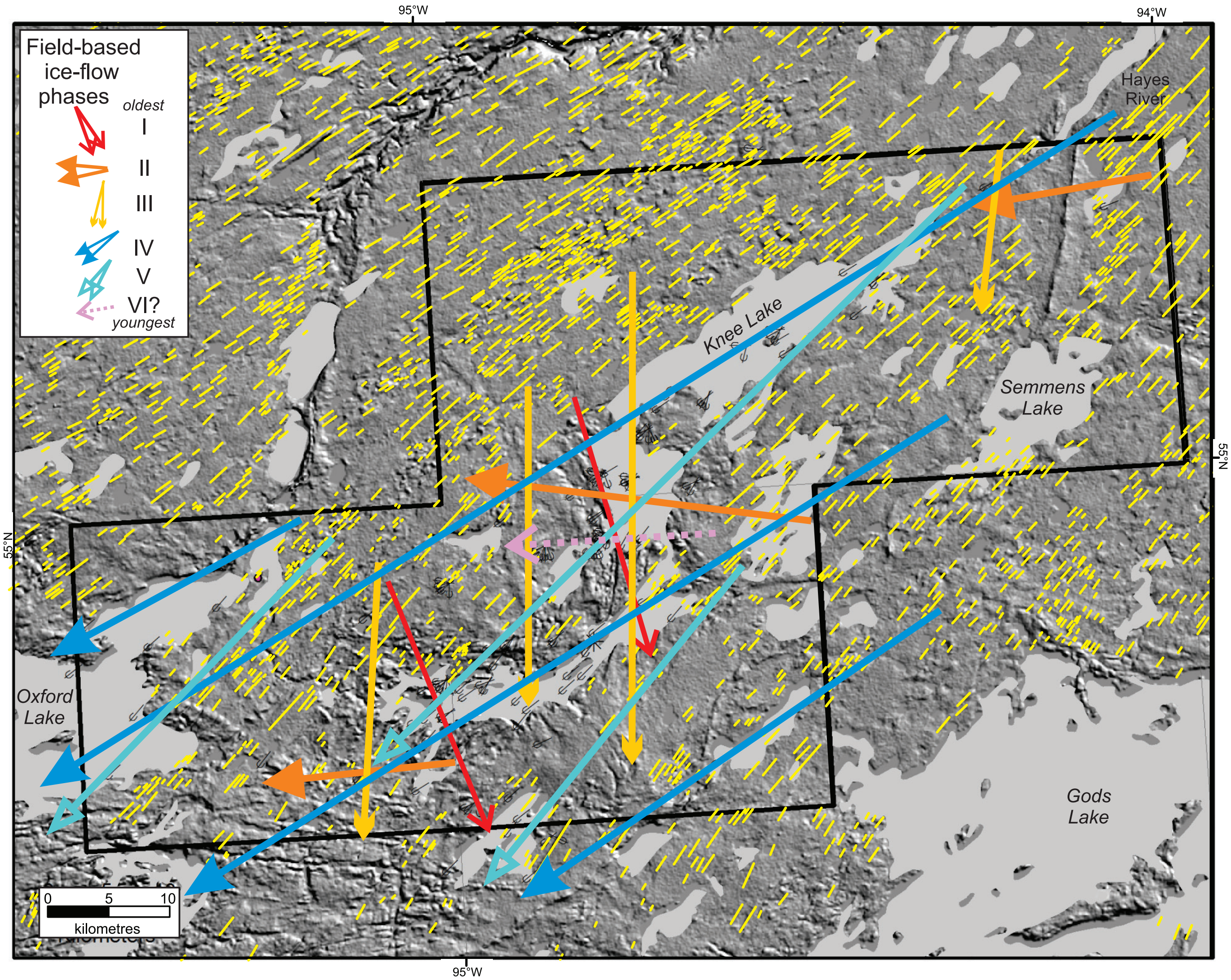

***Figure 5:** Six ice-flow phases in the Knee Lake area, northeastern Manitoba, assigned based on consistent repetition of relative ages for similarly oriented ice-flow indicators. The location of streamlined landforms (drumlins and drumlinoid ridges) is also depicted (yellow lines). Background image was generated using a Shuttle Radar Topography Mission digital elevation model (United States Geological Survey, 2002).*

screens to obtain the <63 µm (silt+clay) and <2 µm (clay) till-matrix fractions, at MGS's Midland Sample and Core Library (Fedikow et al., 2002b). The remainder of the prepared <63 µm and <2 µm fractions are stored at MGS storage facilities, but separated clasts and/or archived till samples could not be found.

Kimberlite-indicator-mineral (KIM) analysis

As with the Operation Superior project (Fedikow et al., 2002a), an opportunity to further assess the diamond potential of the Knee Lake region has been provided by co-operative efforts with De Beers Canada Exploration Inc. (De Beers). Samples of till (11.4 L pails), from 23 new target sites, were concentrated, picked and analyzed by electron microprobe by De Beers. The <0.5 mm size fraction was passed over a 0.3 mm aperture sieve and the <0.3 mm size fraction was discarded. Guidelines for the KIM classification used are outlined in Thorleifson and Matile (1993). Sample locations were withheld from De Beers to ensure security and allow equal opportunity for follow-up by all interested exploration parties after release of the results. The results of the new KIM analyses, including an updated Manitoba classification (Syme et al., 2004) of Operation Superior samples (1999–2001), are included in Appendix 3.

Eleven litre samples of till were collected for KIM analysis during the Operation Superior project (Fedikow et al., 2002a) and from stratigraphic sections along the lower Hayes and Stupart rivers (Nielsen and Fedikow, 2002). The samples were concentrated, picked and analyzed by electron microprobe by De Beers. Sampling and analytical procedures are, therefore, the same for the Knee Lake and Operation Superior (Fedikow et al., 2002a) projects. It should be noted that KIM results herein (Appendix 3) are reported for the 0.3–0.5 mm size fraction for both projects, while the previously published Operation Superior data (Fedikow et al., 2002a) includes the compiled 0.3–2 mm size fractions.

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 then separated according to lithology by the author, using an optical microscope. An average of 620 clasts was counted for each till sample (averages of 395, 193 and 31 for 2–4 mm, 4–8 mm and 8–30 mm 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-percentage (ct. %) of the total number in a separate table (Appendix 4, Table 14). Photos of the 2–4 mm size-fraction for each sample are presented in Appendix 5.

Clasts were classified as 16 initial rock types (Appendix 4), and grouped into six simplified classes for interpretation purposes.

Regional to local clasts (Figure 6) are classified as follows:

- ***Greenstone belt***: grey fine-grained metasedimentary and metavolcanic clasts, schistose or psammitic clasts, gabbro or amphibolite clasts
- ***Granitoid:*** granitic or gneissic clasts, quartz

Exotic (continental-scale dispersal) clasts (Figure 7) are classified as follows:

- ***Calcareous:*** beige limestone, pink limestone, Paleozoic fossils, Quaternary shell fragments, calcrete
- ***Shield exotic***: exotic red granitoid clasts, red/purple volcanic clasts
- ***Eastern exotic***: oolitic red jasper, greywacke with eroded recessive calcareous concretions
- ***Unknown:*** chert, unmetamorphosed conglomerate or sandstone

Greenstone-belt clasts are resistant, black or grey or rarely green, and generally fine grained (Figure 6a–d). Greenstone clasts range in shape from angular to subrounded. Granitoid clasts are pink to white, with common quartz, potassium feldspar and rare mica (Figure 6e, f). Granitoid clasts are commonly angular to subangular. Shield exotic red granitoid clasts are faceted and bullet shaped, often with different mineralization and/or colour alteration. They have been derived from unknown Canadian Shield source rocks.

Chert and unmetamorphosed conglomerate or sandstone clasts were noted, but it is difficult to attribute a source area to these rocks. As such, they are not included within the interpretations.

Clast lithologies that indicate continental-scale transportation of subglacial detritus include both eastern-sourced and northern-sourced clasts (Figure 8). Eastern-sourced clasts include Palaeozoic calcareous clasts (Figure 7a, b) derived from the Hudson carbonate platform (Manitoba Department of Energy and Mines, 1980), at least 100 km northeast of the study area, and Proterozoic red oolitic jasper (Kipalu Formation clast [Kipalu]) and greywacke with recessive weathering of calcareous concretions (Omarolluk Formation erratic [Omar], Figure 7c, d) derived from the Belcher Group, ~940 km east-northeast of the study area (Prest et al., 2000). Northern-sourced clasts include red/purple volcanic clasts (Figure 7e, f) sourced from the Dubawnt supergroup, ~700 to 1000 km north-northwest of the study area (Peterson, 2006; Tella et al., 2007).

Texture

The matrix textural results for 2012 samples were calculated as sand, silt and clay weight percent of the <2 mm fraction and are presented in Appendix 6. Texture was not analyzed during Operation Superior.

At SRC, an aliquot of <2 mm sample material was transferred to a flask and 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 was dependent on the ambient room temperature). The sieved sand and aliquots of sample material were dried and reweighed. 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. In 2012, an aliquot of the till matrix (<2 mm, agate ground) was digested at SRC using HCl, then analyzed using a PerkinElmer Optima 5300DV inductively coupled plasma–emission spectrometer (ICP-ES). The samples were analyzed for Ca and Mg (in percent), and then calcite, dolomite and total carbonate (CO_3) were calculated (all in weight percent). Quality-control samples were prepared and analyzed with each batch of samples. One in every 40 samples was analyzed in duplicate. The <63 µm fraction of an additional 10 samples was analyzed to provide a 'translation factor' between the <2 mm results and the Operation Superior <63 µm dataset.

During Operation Superior, a separate 4 g split of the till matrix (<63 µm fraction) was submitted to the Geological Survey of Canada (GSC) Sedimentology Laboratory for carbonate analysis, using the Chittick apparatus (Appendix 7). Operation Superior data from 2000 can also be found in Fedikow et al. (2002b), the 1999 data was previously unpublished and the 2001 samples were not submitted for Chittick analysis.

Loss-on-ignition

Loss-on-ignition (LOI) provides an estimate of the degree to which the sample composition has been modified by post-depositional weathering. The results for LOI at 1000°C are included in Appendix 8. The LOI content was not analyzed during Operation Superior.

At SRC, an aliquot of <63 µm matrix fraction was weighed into the crucible and the total initial weight was recorded. The sample was placed in an oven to dry. It was then removed from

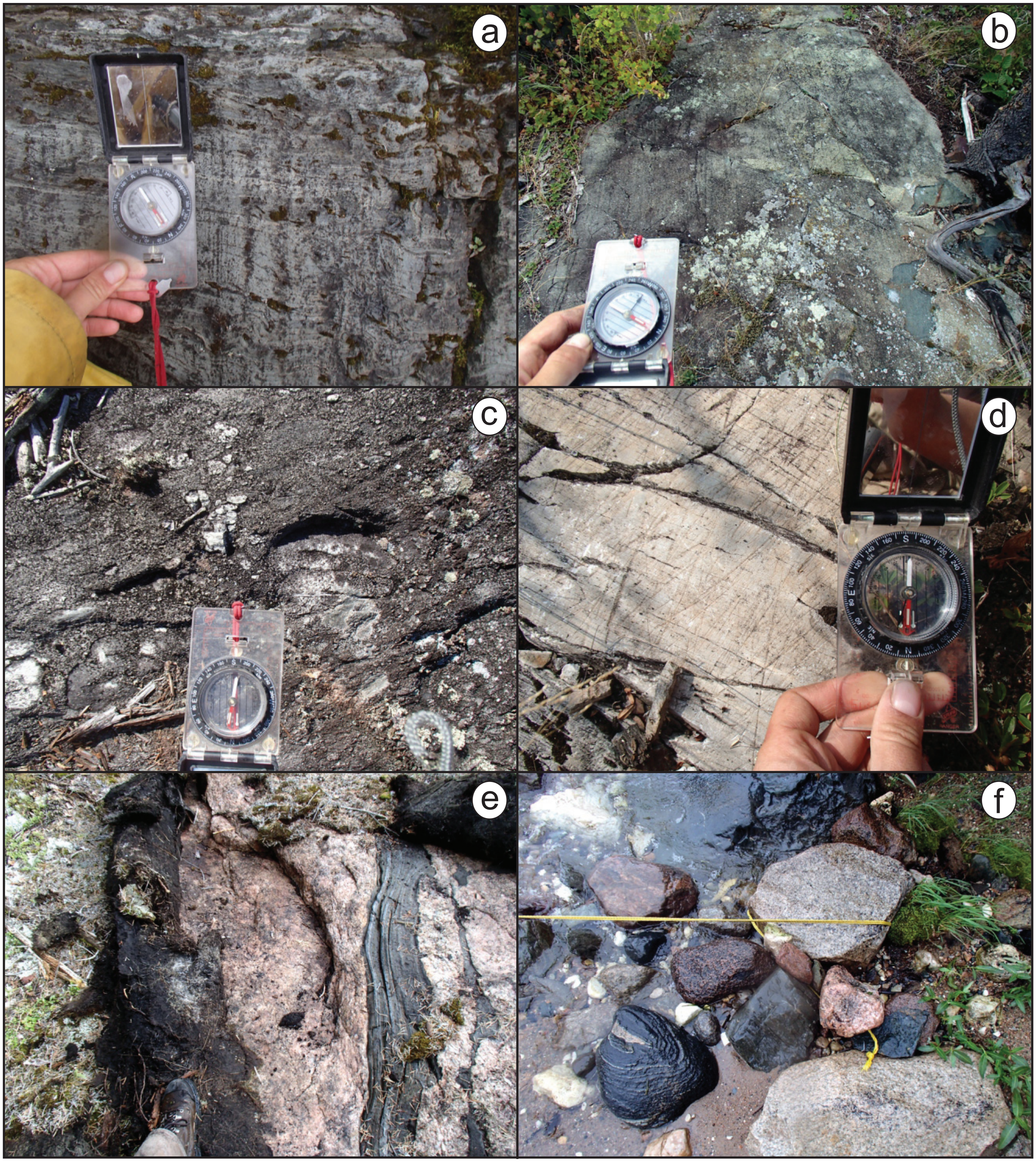

Figure 6: *Examples of greenstone-belt and granitoid rocks that outcrop and occur in the Knee Lake study area, northeastern Manitoba:* ***a)*** *intermediate volcanic flows;* ***b)*** *mafic volcanic rocks;* ***c)*** *volcaniclastic rocks;* ***d)*** *felsic volcanic rocks;* ***e)*** *granite with interbedded gabbro layers;* ***f)*** *small boulders eroded out from till at a lakeshore; there are several types of granite as well as mixed greenstone-belt rock types.*

Figure 7: *Examples of exotic, far-travelled clasts encountered during fieldwork, Knee Lake area, northeastern Manitoba:* ***a)*** *limestone;* ***b)*** *fossiliferous limestone;* ***c)*** *Omarolluk Formation cobble (greywacke with calcareous concretions that are often eroded out) near Magill Lake;* ***d)*** *Omarolluk Formation pebbles from two different sites;* ***e)*** *Dubawnt supergroup red volcanic cobble with white phenocrysts;* ***f)*** *darker red Dubawnt supergroup pebble.*

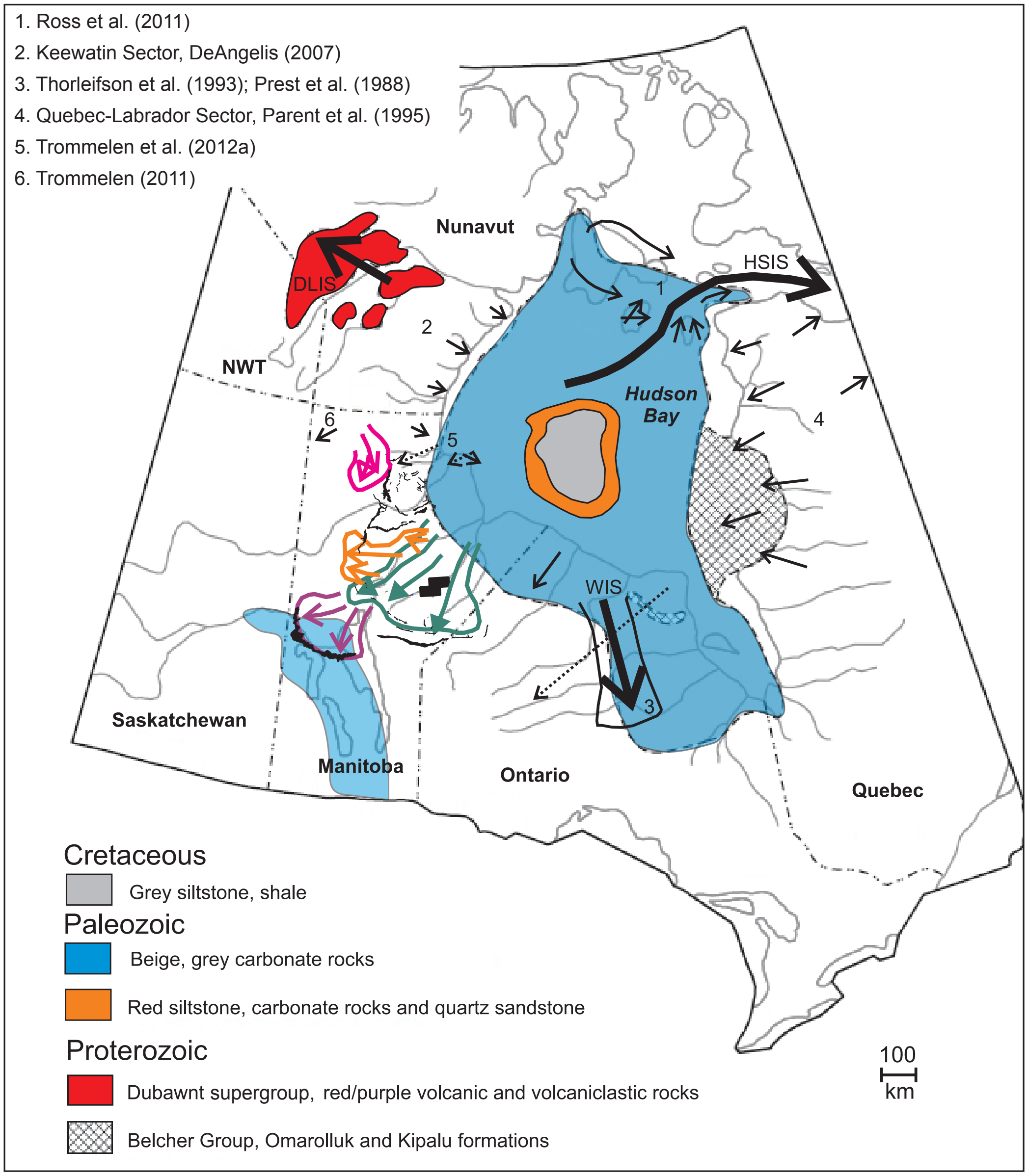

Figure 8: *Known outcrops of red/purple volcanic rocks (Dubawnt supergroup), carbonate, Belcher Group rocks (Omarolluk Formation greywacke and Kipalu Formation oolitic red jasper) in central Canada. The Knee Lake study area is shown as black rectangles. Coloured arrows represent flowsets summarized from glacial landform mapping, and the black arrows represent major late deglacial ice-flow orientations sourced from the numbered citations. Major moraines (black lines) are also depicted. Abbreviations: DLIS, Dubawnt Lake Ice Stream; HSIS, Hudson Strait Ice Stream; NWT, Northwest Territories; WIS, Winisk Ice Stream.*

the oven, allowed to cool and then reweighed. One in every 40 samples was analyzed in duplicate. The detection limit for the LOI method is 0.1%.

Geochemistry

Partial digestion (HNO_3:HCl) ICP-MS

For the determination of 41 elements, a portion of the <63 µm size fraction of each sample was analyzed at SRC. An aliquot of the fraction 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 9, together with analytical data for control reference standards, analytical and field duplicates, and blanks. The acid leach used for this method is weaker than what is used for aqua regia ICP-MS (1:3 HNO_3:HCl) and, as such, the concentrations reported herein cannot be directly compared to till-geochemistry values commonly reported by the GSC (Spirito et al., 2011).

Near-total digestion (HF:HNO_3:$HClO_4$) ICP-MS and -ES

For the determination of 49 elements and oxides, a portion of the <63 µm size-fraction of 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 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 10, together with analytical data for control reference standards, analytical and field duplicates, and blanks. 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 INAA

For the determination of Au plus a 34-element suite, a 30 g aliquot of the <63 µm size-fraction for each sample was sent to Activation Laboratories Ltd. (ActLabs). The aliquots underwent INAA, which measures gamma radiation induced in the sample by irradiation with neutrons. The analytical results are presented in Appendix 11, together with analytical data for control reference standards, analytical and field duplicates, and blanks.

During Operation Superior, a portion of the <63 µm till-matrix fraction underwent INAA for Au plus a 34-element suite (Fedikow et al., 2000, 2002b, 2009). The exact method, laboratory and detection limits are unknown. These analytical results are also presented in Appendix 11. This data was originally released within Fedikow et al. (2000, 2002b, 2009).

Results

Till-matrix colour

A colour was assigned to samples in the field in 2012 and during Operation Superior (Appendix 1). Baring differences due to soil processes (i.e., grey due to gleying), the till is predominately a light beige colour (82% of sites where colour was noted, 270 sites; Figure 9a). The till is brown (Figure 9b) at 9.4% of sites (31 sites), greyish-brown (Figure 9c) at 5.2% of sites (17 sites) and grey at 2.4% of sites (8 sites). Reddish-brown

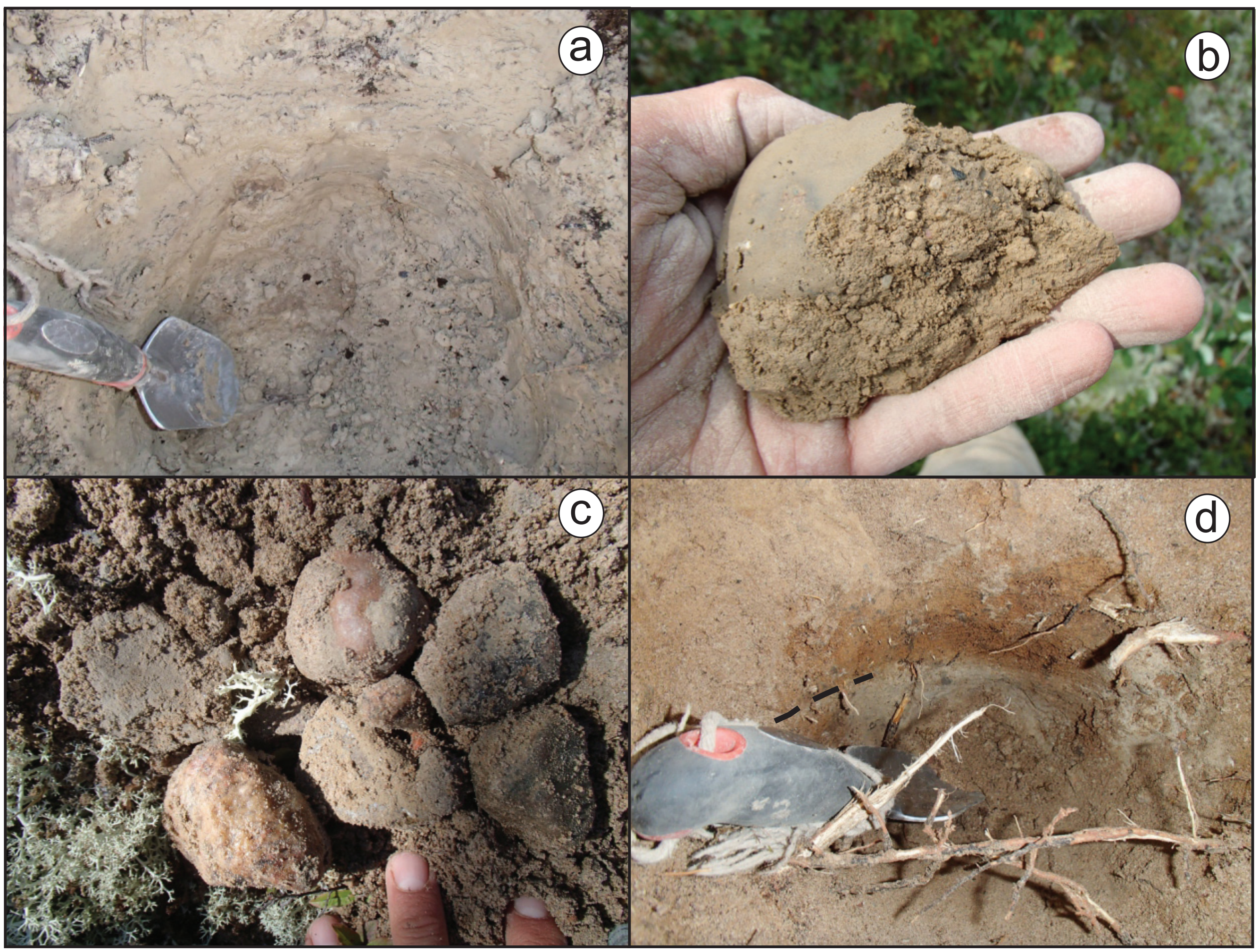

Figure 9: *Examples of till encountered during the 2012 field season, Knee Lake area, northeastern Manitoba:* ***a)*** *beige, clast-poor, calcareous (40.9% carbonate matrix), silty (21% sand, 54% silt, 24% clay) till sampled from the nose of a drumlinoid ridge;* ***b)*** *light brown, clast-rich, calcareous (35.3% carbonate matrix), sandy-silt (37.2% sand, 51.5% silt, 11.3% clay) till sampled from a narrow drumlinoid ridge;* ***c)*** *greyish-brown, clast-rich, noncalcareous (1.7% carbonate matrix), silty-sand (60% sand, 33% silt,7% clay) till;* ***d)*** *25 cm of reddish-brown, noncalcareous (1.3% carbonate matrix), silty-sand (45% sand, 37.9% silt, 17% clay) till overlies 15 cm beige, calcareous (28.1% carbonate matrix), sandy-silt (45.7% sand, 48.5% silt, 5.8% clay) till, over bedrock at site 12115MT295.*

till was noted at three sites. At site 12115MT295 (Figure 10), 25 cm of noncalcareous reddish-brown till overlies 15 cm of calcareous beige till (Figure 9d). The spatial distribution of till colour seems random (Figure 10).

Till texture

There is a large spread in the textural composition of tills in the study area (Table 1; Appendix 6). The samples contain 8–75% sand (2 standard deviation [σ]; mean of 40%), 25–67% silt (2σ; mean of 45%), and 0–42% clay (2σ; mean of 15%).

Sand and silt distribution are linear and random throughout the area (Figure 11), but the data indicate a separate population of clay-enriched till (>22% clay). Five samples enriched in clay (>39%) were taken from the northeasternmost corner of the study area and one from north of Knee Lake.

Till composition

Till-matrix total carbonate

The results for carbonate analyses on the till matrix for 2012 samples and the Operation Superior 1999 (Fedikow et al., 2000) and 2000 (Fedikow et al., 2002b) samples are in Appendix 7. Results from the comparison between the <2 mm and <63 µm size fractions indicate that the percent difference can be up to 50% for very low concentrations (<3%), and averages around 25%. In all cases, the carbonate concentration is higher for the <63 µm size fraction. Thus for purposes of regional comparison, for this particular sample set the <2 mm carbonate concentration is considered to be equivalent to 75% of the carbonate concentration of the <63 µm fraction.

Analysis procedures are different for the two sample sets (<2 mm, ICP-ES this project, <63 µm, Chittick method for Operation Superior), which may lead to difficulty in comparison. Two 2012 sites are within 40 m of Operation Superior sample sites, and the <2 mm fraction results are 90–93% of the <63 µm results. Three additional 2012 sites, 100–150 m from Operation Superior sites, are 100–117% of the 1999–2000 site values. Thus while the results from both methods appear similar, because of the difference in grain-size fraction analyzed, the two datasets are kept separate but considered equivalent for regional-scale interpretation purposes.

Till sampled in 2012 contains 9–55% carbonate (<2 mm, 2σ; mean of 32%), whereas till sampled in 1999 to 2000 contains

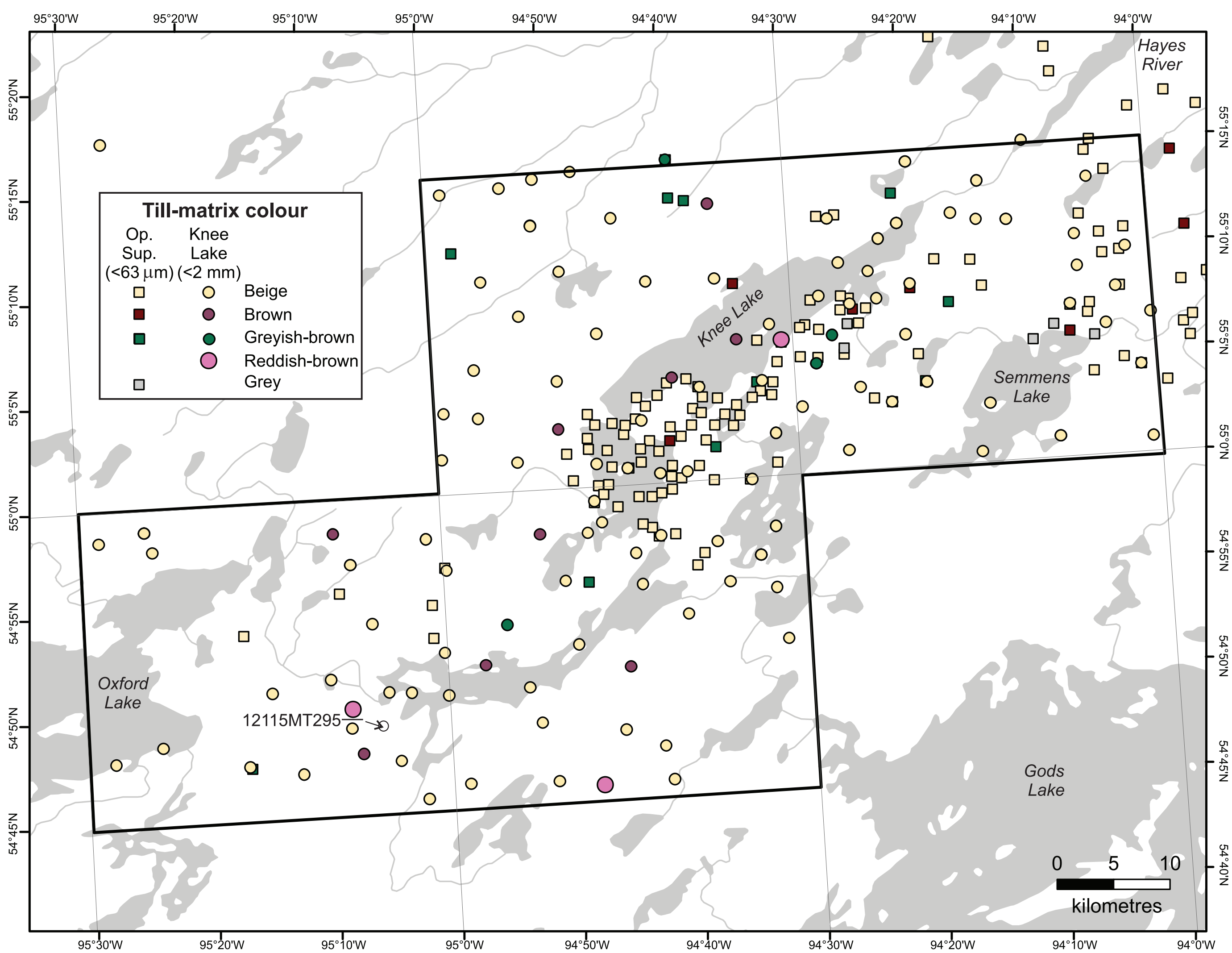

Figure 10: *Spatial distribution of sampled-till matrix colour in the Knee Lake study area, northeastern Manitoba. Abbreviation: Op. Sup., Operation Superior.*

Table 1: Characteristics of noncalcareous and weakly calcareous tills (2012 samples) in the Knee Lake study area, northeastern Manitoba.

	Sample site	Depth (m)	Colour	Map unit	Total carbonate (wt. %, <2 mm)	CaO (wt. %; near-total digestion, ICP-ES)	Ca (%; INAA)	Sand (%)	Silt (%)	Clay (%)	Green-stone belt (ct. %)	Granitoid (ct. %)	Exotic: Calcareous (ct. %)	Exotic: Shield (ct. %)	Exotic: Dubawnt Super-group (ct. %)	Unknown (ct. %)
Non-calcareous till sites	12115MT213	0.1	beige	Tv, R at 15 cm	-	-	-	-	-	-	32.5	55.2	2.84	1.5	0.4	7.4
	12115MT230	1	brown and red-brown	end of drumlinoid ridge	-	-	-	-	-	-	6.9	85.5	4.62	2.0	0.8	0.2
	12115MT234	0.7	brown	Tv, R nearby	1.57	2.34	4.0	56.6	38.8	4.7	28.4	64.6	2.90	1.9	0	2.3
	12115MT245	0.8	brown	Tv, R at 95 cm	-	-	-	-	-	-	69.2	27.6	2.73	0.2	0.2	0
	12115MT278	0.9	grey	GFv over Tb	1.73	2.08	bd	59.8	33.1	7.1	5.1	89.9	0.0	3.7	1.4	0
	12115MT284	2.1	gleyed*	low in drumlinoid area	-	-	-	-	-	-	14.4	77.1	6.61	1.5	0	0.3
	12115MT295B (upper)	0.3	red-brown	Tv, R at 55 cm	1.3	1.68	bd	45	37.9	17	43.4	50.8	2.52	0.7	0	2.7
	12115MT296	0.1	brown	Tv, R at 15 cm	-	-	-	-	-	-	80.5	8.7	0.53	0	0	10.3
	12115MT299	0.2	brown	Tv, R at 25 cm	-	-	-	-	-	-	61.7	32.8	1.41	0.2	0.4	3.5
	12115MT332	1.1	gleyed*	Tb	1.4	2.18	bd	50.7	35.6	13.6	6.3	88.5	0.13	3.3	1.7	0
	12115MT355	0.3	light brown	Tvx, R at 20–50 cm	0.98	1.61	bd	64.7	30.7	4.6	30.9	64.0	2.52	1.3	0	1.3
	12097CB019	0.4–1.2	beige	Tb	23.78	10.80	8.0	2.1	37.3	60.6	13.6	17	68.68	0.2	-	0.4
	12097CB034	0.6–0.8	grey	Tb or Tv	-	-	-	-	-	-	13.6	74.4	10.91	1.1	0	0
Weakly calcareous till sites	12097CB036	0.6–1.3	beige	side of drumlinoid ridge	-	-	-	-	-	-	30.0	33.3	35.22	1.0	0.2	0.2
	12115MT229	0.80	beige	Tv over GL	-	-	-	-	-	-	18.1	64.1	14.69	1.0	0.6	1.5
	12115MT231	1	beige-grey	Tb	15.37	10.10	8.0	49.1	37.5	13.4	12.2	55.7	29.48	1.9	0.5	0.3
	12115MT275	0.9–1.1	beige	T mixed with GL	-	-	-	-	-	-	4.7	81.6	12.81	0.0	0.2	0.8
	12115MT314	0.35	beige	Tv, R at 40 cm	26.4	14.10	12.0	40.4	52.5	7.1	4.7	59.5	35.28	0.2	0	0.3
	12115MT318	1.2	gleyed*	T mixed with GL	19.8	6.73	bd	15.4	32.1	52.6	11.5	44.8	40.75	2.0	1.0	0
	12115MT322	0.9–1.3	beige	Tb	12.2	6.06	3.0	38.5	39.7	21.8	7.1	74.2	16.58	1.1	1.0	0
	calcareous till sites median	-	*beige*	-	*35.64*	*18.1*	*12.0*	*41.1*	*46.0*	*9.2*	*14.41*	*23.77*	*59.62*	*0.66*	*0*	*0*

*gleyed soil horizon masks the original parent material colour

Abbreviations: GFv, glaciofluvial veneer; GL, glaciolacustrine; R, Precambrian bedrock; T, till; Tb, till blanket; Tv, till veneer; Tvx, washed till veneer.

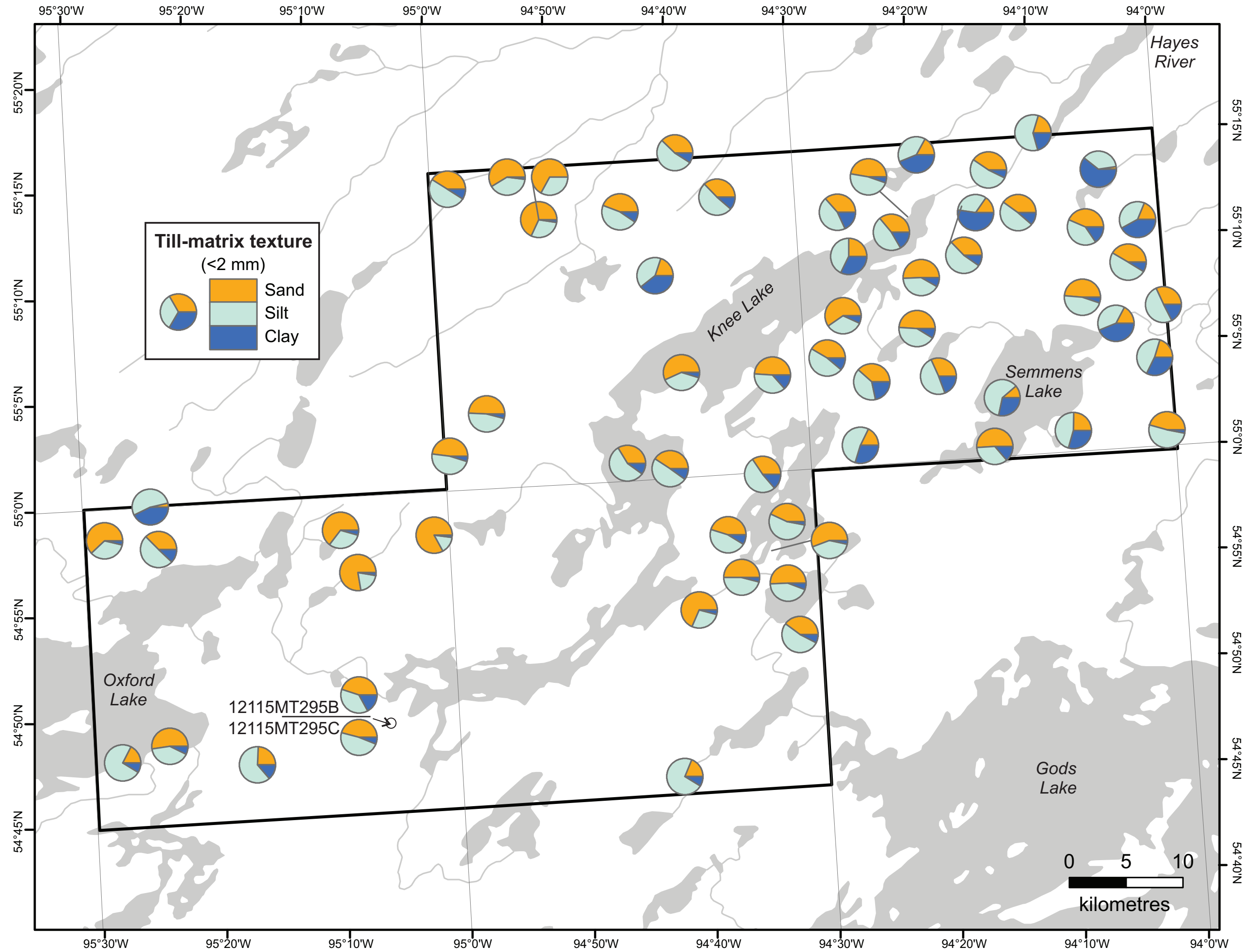

Figure 11: *Spatial distribution of sampled-till matrix texture in the Knee Lake study area, northeastern Manitoba.*

26–52% carbonate (<63 µm, 2σ; mean of 39%). In both datasets, carbonate content distribution is linear, but the data indicate separate populations of high-carbonate (>46%, Operation Superior), low-carbonate (<23%, this project and <31%, Operation Superior) and very low carbonate (<1.57%, this project) are present. Spatially, the high- and the very low-carbonate populations appear to have a random distribution through the study area (Figure 12). The low-carbonate population distribution is somewhat random throughout the area, but also clusters just south of upper Knee Lake.

Till-matrix (<63 µm) geochemistry

INAA

Proportional-symbol plots of the concentrations of most elements analyzed are presented in Appendix 12, which includes the data from this project (63 sites) as well as the Operation Superior project (713 sites). The results for Ag, Hg, Ir, Se, Sn, Sr and W are mainly below detection limit and are not depicted. Individuals and companies are encouraged to undertake their own interpretation of the data, the discussion within being a preliminary guide.

Several low-Ca (<25th percentile) sites (Figure 13) are elevated in certain elements, including

- Site 12097CB001 (16% Ca) has high concentrations (>99th percentile) of Au, Sb and U and elevated concentrations (>97th percentile) of Fe and Nd.
- Site 12097CB019 (8% Ca) has high concentrations (>99th percentile) of Ce, Co, Fe, Sb and Sc and elevated concentrations (>97th percentile) of Cr, Cs, La, Rb, Th and U.
- Site 12097CB025 (11% Ca) has high concentrations (>99th percentile) of As, Cr and Fe and elevated concentrations (>97th percentile) of La, Nd, Rb, Sc, Th and U.
- Site 12115MT221 (12% Ca) has high concentrations (>99th percentile) of Au, Rb and Sb and elevated concentrations (>97th percentile) of Fe, Sc and U.
- Site 12115MT307 (10% Ca) has high concentrations (>99th percentile) of Au, Co, Fe, Nd and U and elevated concentrations (>97th percentile) of Ba, Ce, Cr, Rb, Sc and Th.

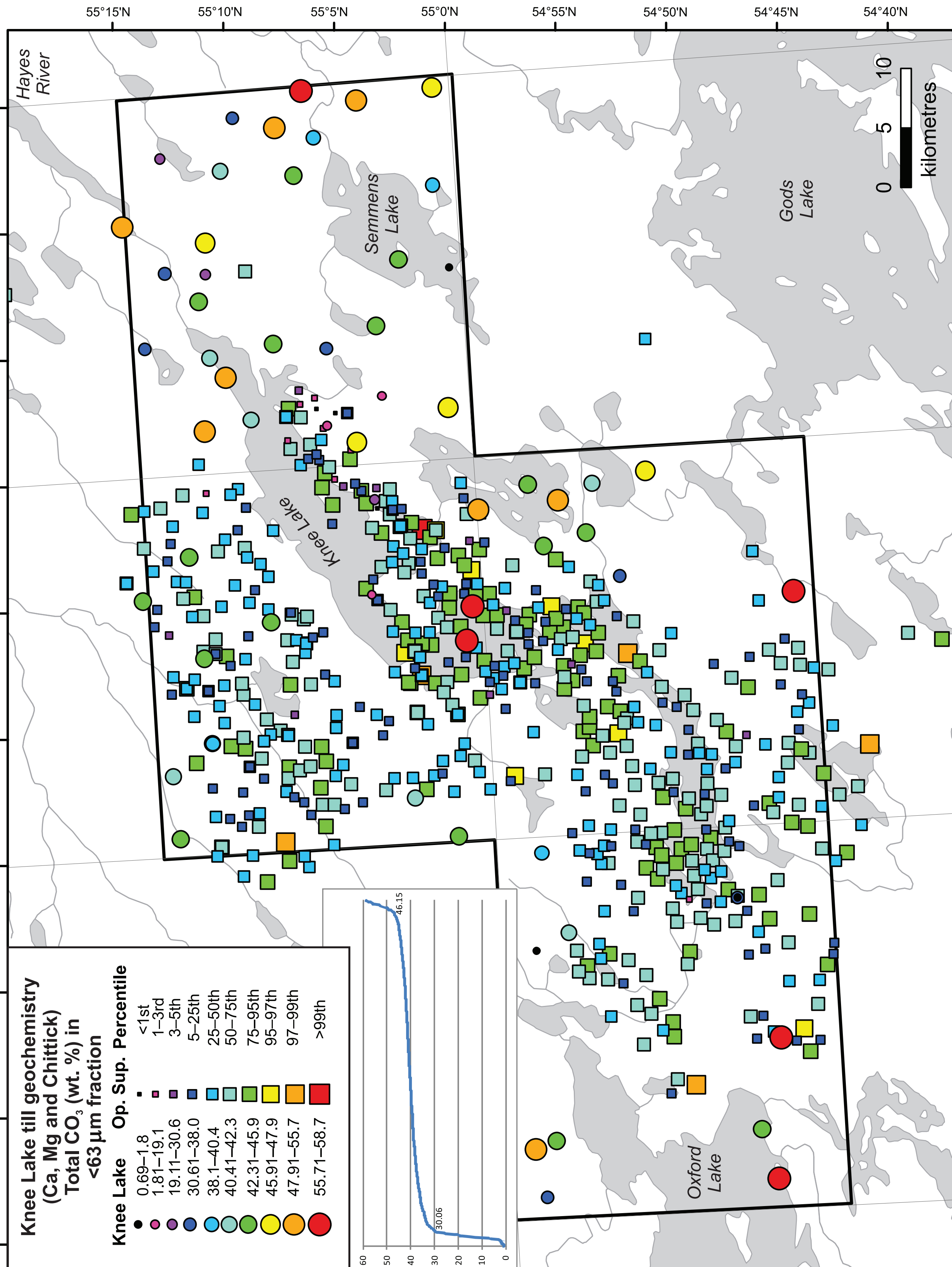

Figure 12: *Spatial distribution of sampled-till matrix total-carbonate concentration in the Knee Lake study area, northeastern Manitoba. Abbreviation: Op. Sup., Operation Superior.*

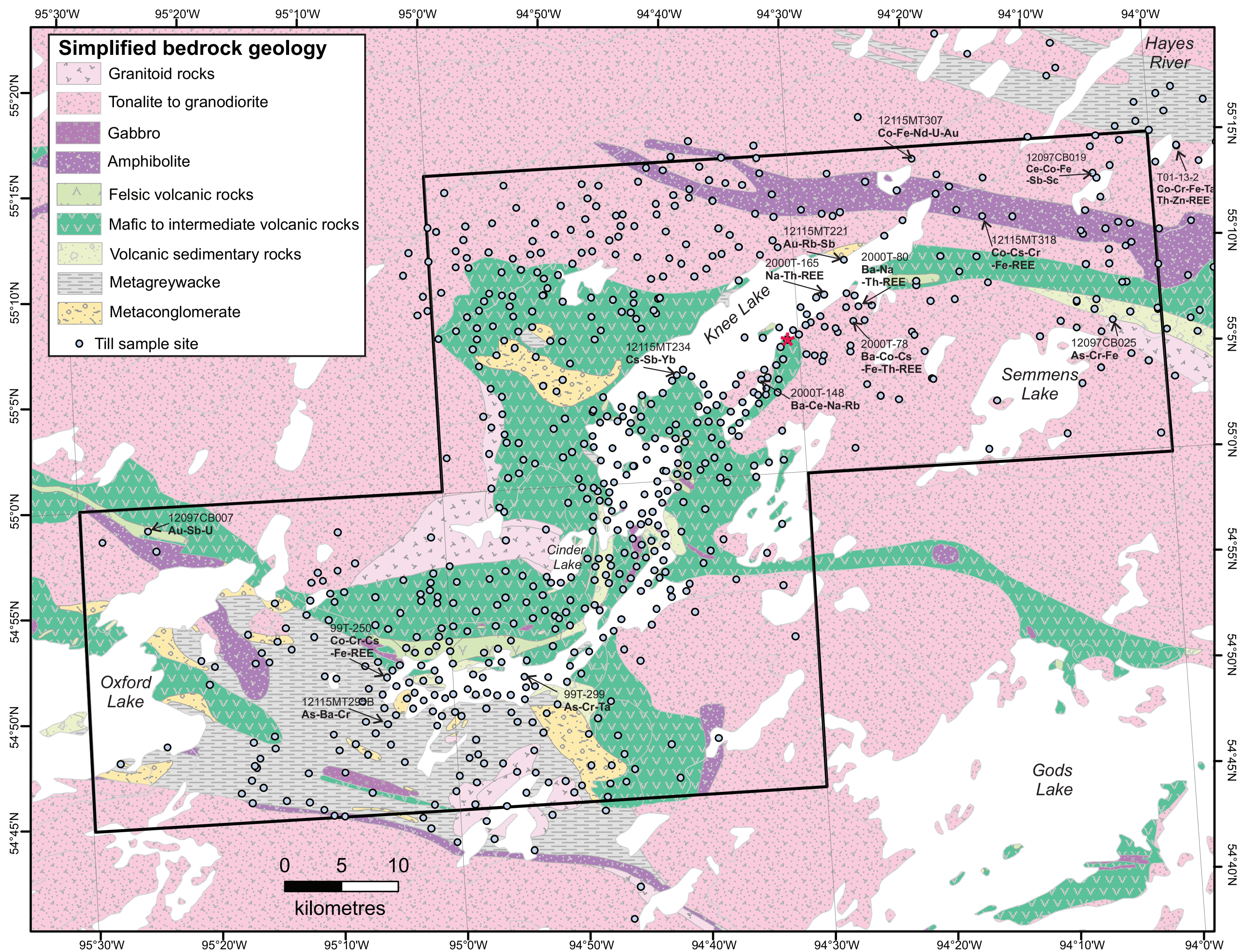

Figure 13: *Numbered sites identify where the till-matrix geochemistry (determined by instrumental neutron activation analysis) is elevated (>99th percentile) in multiple element concentrations. The red star on the northern portion of Knee Lake highlights the location of the old Knee Lake Gold mine and Johnson Knee Lake mine. Gold was not found in the till sampled from this site. Abbreviation: REE, rare-earth elements.*

- Site 99T-250 (9% Ca) has high concentrations (>99th percentile) of Ce, Co, Cr, Cs, Eu, Fe, La, Lu, Sc and Sm and elevated concentrations (>97th percentile) of Mo, Nd, Rb, Sm, Th, U, Yb and Zn.
- Site 99T-299 (13% Ca) has high concentrations (>99th percentile) of As, Cr and Ta and elevated concentrations (>97th percentile) of Au.
- Sample T01-13-2 (7% Ca) has the highest concentrations of Ce, Co, Cr, Eu, Fe, Lu, Nd, Sc, Sm, Ta, Th and Zn in the study area and has high concentrations (>99th percentile) of La, Ni and U. It should be noted that sample T01-13-1 has concentrations of these elements that are roughly halved (though still >95th percentile). These two samples are field duplicates, and provide a measure of variability within the field. Sample T01-13-2 has 35% less Ca than sample T01-13-1.

Several very low Ca (<2.5th percentile) sites (Figure 13) are elevated in certain elements, including

- Site 12115MT234 has high concentrations (>99th percentile) of Cs, Sb and Yb and elevated concentrations (>97th percentile) of Co, Cr, Eu, Fe, Na, Nd, Sc and U.
- Sample 12115MT295B has high concentrations (>99th percentile) of As, Ba and Cr and elevated concentrations (>97th percentile) of Fe, Na, Sc, U and Yb.
- Site 12115MT318 has high concentrations (>99th percentile) of Co, Cs, Cr, Eu, Fe, La, Rb, Sb and Sc and elevated concentrations (>97th percentile) of Ba, Ce, Nd and Th.
- Site 2000T-78 has high concentrations (>99th percentile) of Ba, Ce, Co, Cs, Eu, Fe, La, Lu, Rb, Sc, Sm, Th and Yb and elevated concentrations (>97th percentile) of Cr, Na and Nd.
- Site 2000T-80 has high concentrations (>99th percentile) of Ba, Ce, Eu, La, Na, Nd, Sm, Tb and Th and elevated concentrations (>97th percentile) of Sc, Yb and Zn.
- Site 2000T-148 has high concentrations (>99th percentile) of Ba, Ce, Na and Rb and elevated concentrations (>97th percentile) of Eu, La, Lu, Na, Sm, Th and Yb.
- Site 2000T-165 has high concentrations (>99th percentile) of Ce, Eu, Na, Nd, Sm, Ta, Th and Yb and elevated concentrations (>97th percentile) of La, Lu and Sc.

Several sites from both projects have elevated Au concentrations, including an anomalously high value (560 ppm; background is 2 ppm) at site 12097CB001. For each of the Knee Lake sites that had elevated Au concentrations, there was also a laboratory- or field-duplicate sample but the duplicates all returned Au results below detection limits. This poor reproducibility (analytical precision) of Au concentrations in till matrix is a well known problem, attributed to the small number and the heterogeneous distribution of Au particles in the sediment known as the nugget effect (Harris, 1982). Consequently, any detailed follow-up survey on any of the high Au concentrations reported here should not be undertaken prior to testing the reproducibility of the values. This should be done by resampling till in the region of interest and conducting geochemical analyses on the same grain-size fraction. However, it can be presumed that an anomalous Au concentration reflects the presence of some gold in till at a site, even if the second analysis returns a low value. This is especially true if a site is elevated in associated elements as well (such as As, Cu, Ni, Zn).

Partial digestion ICP-MS

These results for Ag, Hg, Ta, Te and W are mainly below detection limit. Further, the results for Bi, Cd, Ge, Ho, Sb and Se are fairly homogeneous and do not show any variety across the study area. Individuals and companies are encouraged to undertake their own interpretation of the data, the discussion within being a preliminary guide.

Several sites (see Figure 13 for locations) are elevated in certain elements, including

- Site 12115MT234 has elevated concentrations of Cs (<5σ), Cu (<5σ) and Mo (<6σ).
- Site 12097CB001 has somewhat elevated concentrations (between 2 and 3σ) of Cu, Ni and Zn.
- Site 12115MT307 has somewhat elevated concentrations (between 2 and 3σ) of Eu, Pb and Sc.

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 (<10 km).

To determine clast dispersal patterns within the study area, the 16 lithological classes (Appendix 4) were first grouped into five simplified classes. 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. These classes are depicted spatially (ArcGIS) using count-percentage proportional-symbol plots by percentiles (Appendix 13).

Greenstone-belt clasts

Metamorphosed greenstone-belt clasts are present at all sampled till sites (Appendix 13), and exhibit a large range in concentration from 2.4 to 80.5 ct. %. Concentrations are highest overlying mapped greenstone-belt bedrock, and all elevated values (>95th percentile, 29.9 ct. %) are associated with noncalcareous or weakly calcareous till sites (Figure 14, Table 1). The exact source of these clasts is unknown, as greenstone-belt rocks are situated throughout the study area and also throughout the surrounding area. The suspected dispersal distances are local to regional (0.1 to 10s of km), but no distinctive dispersal patterns were observed.

Granitoid clasts

Granitoid clasts are present at all sampled till sites (Appendix 13), and exhibit a large range in concentration from 2.7 to 89.87 ct. %. Concentrations are highest overlying mapped granitoid bedrock, and all elevated values (>95th percentile, 71.15 ct. %) are associated with noncalcareous or weakly calcareous till sites (Figure 15). Spatially, elevated granitoid-clast

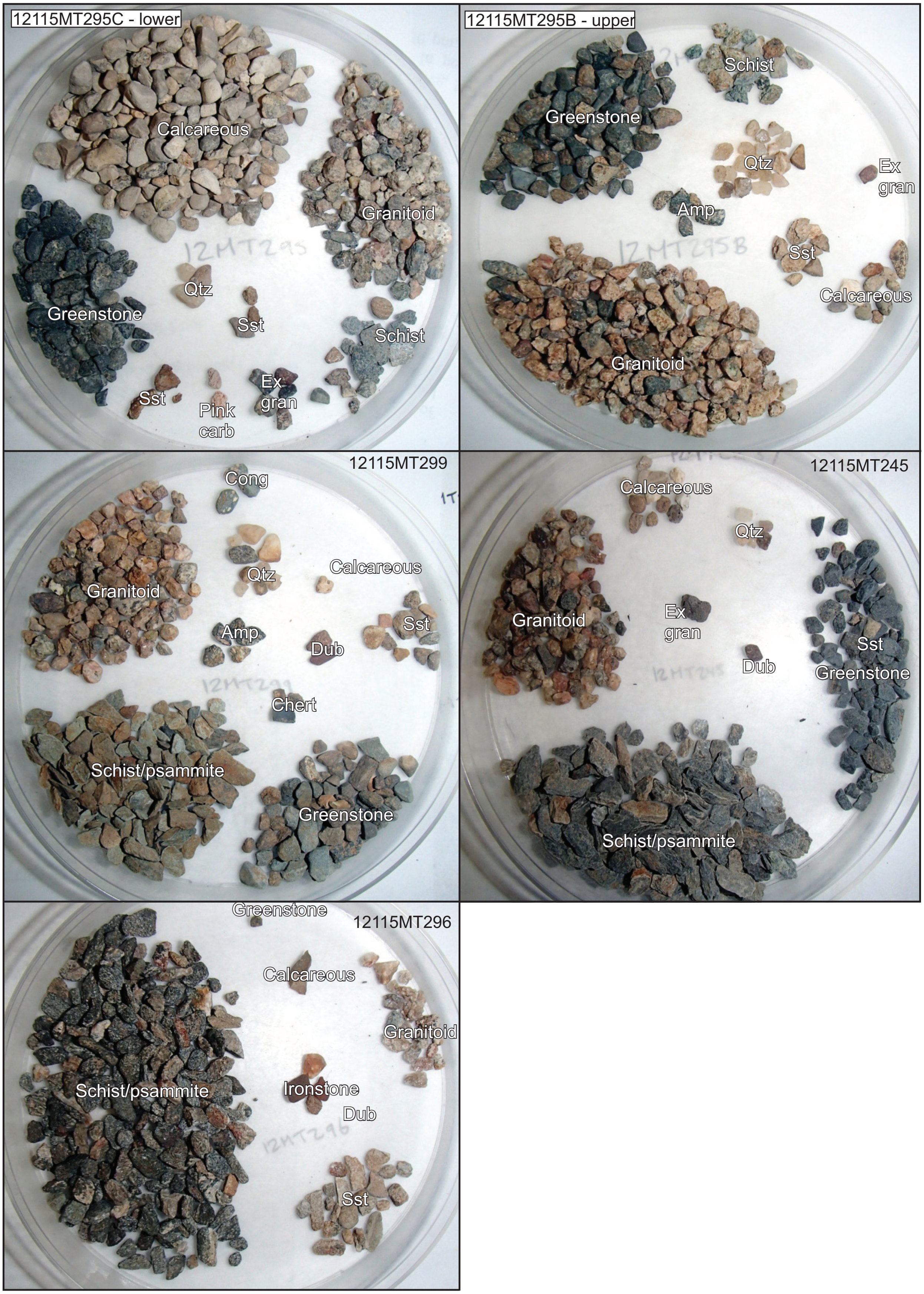

Figure 14: *Examples of till-clast lithologies of the 2–4 mm size fraction from samples that contain elevated (>95th percentile) concentrations of greenstone-belt (includes schist/psammite and amphibolite/gabbro) clasts. The exception is sample 12115MT295C-lower (upper left), which is provided as a comparison for sample 12115MT295B-upper (upper right). Abbreviations: Amp, amphibolite/gabbro; Carb, carbonate; Cong, conglomerate; Dub, Dubawnt supergroup; Ex gran, exotic granitoid; Qtz, quartz; Sst, sandstone.*

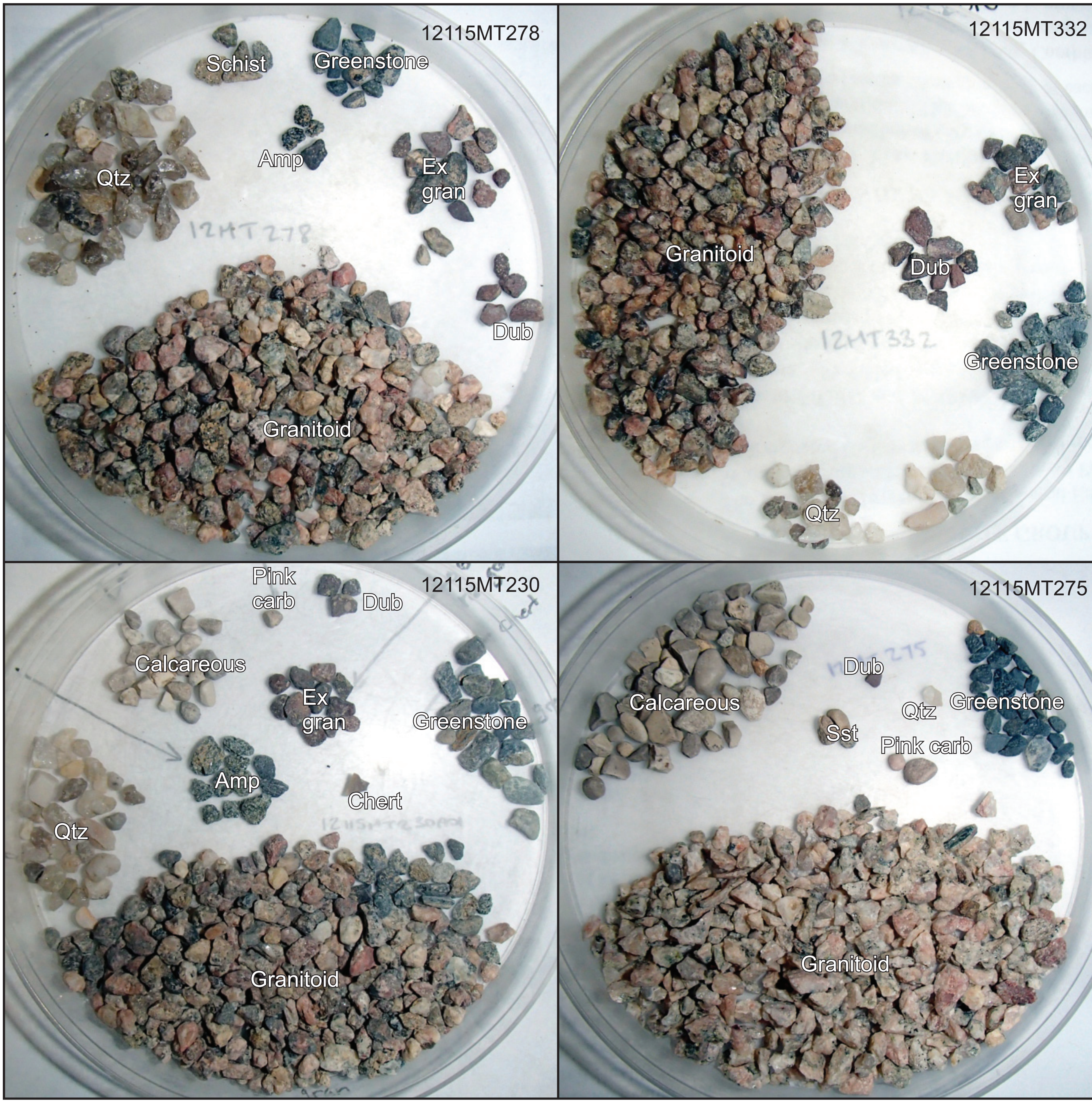

Figure 15: *Examples of till-clast lithologies of the 2–4 mm size fraction from samples that contain elevated (>95th percentile) concentrations of granitoid (includes quartz) clasts. Abbreviations: Amp, amphibolite/gabbro; Carb, carbonate; Dub, Dubawnt supergroup; Ex gran, exotic granitoid; Qtz, quartz; Sst, sandstone.*

concentrations are situated within the eastern half of the study area. The source of these clasts is unknown, as granitoid rocks are situated throughout the study area but also throughout the surrounding area.

Granitoid-clast concentrations have also been documented within regional surface tills in the area (maximum of 34 wt. % for a 100 km radius, Thorleifson and Matile, 1993) and from tills within stratigraphic sections (Sky Pilot, Long Spruce, Amery and Sundance tills) in the Hudson Bay Lowland of Manitoba (maximum of 45 wt. % within Sundance till, Nielsen, 2001; Nielsen, 2002; E. Nielsen, unpublished data, 2002). Regional granitoid-clast concentrations between 34 and 100 wt. % (M.S. Trommelen, unpublished data, 2014) are documented outside, and near the margins, of the Hayes lobe. Inside this large lobe, granitoid clast concentrations are typically diluted by the large concentrations of exotic calcareous clasts.

Exotic granitoid clasts, which have travelled farther distances, are present at 92% of sampled till sites (Appendix 13), in concentrations up to 3.67 ct. % (e.g., sample 12115MT278, Figure 15). Spatially, elevated exotic granitoid–clast concentrations (>95th percentile, 1.89 ct. %) are also situated within the eastern half of the study area.

The granitoid-clast data indicates that the elevated concentrations within the eastern half of the study area are elevated above the regional expected values. As such, the author suggests that the till in this area has a somewhat different glacial history than the till in the western half of the study area. More work needs to be completed in the surrounding regions, but it appears that the eastern till generally contains a higher component of inherited (cf. Trommelen et al., 2013b) shield-derived subglacial detritus (deposited during earlier southerly ice-flow phases) that was not diluted by the southwesterly ice-flow phases that transported substantial calcareous subglacial detritus to the area (Trommelen and Ross, 2014).

Shield exotic (red/purple volcanic) clasts

Red/purple volcanic clasts are present at 40% of sampled till sites (Figure 16), at up to 1.71 ct. %. Concentrations greater than the 95th percentile (0.79 ct. %) are associated with noncalcareous or weakly calcareous till sites. Similar clasts, attributed to the Dubawnt supergroup, have also been documented within tills from stratigraphic sections (Sky Pilot, Long Spruce and Amery tills) in the Hudson Bay Lowland of Manitoba (maximum of 1.38 wt. %; Nielsen, 2001; Nielsen, 2002; E. Nielsen, unpublished data, 2002). Although these concentrations are not high, they are indicative of the tail-end of a continental-scale dispersal fan. More clasts attributed to the Dubawnt supergroup have been documented in northeastern Manitoba (maximum of 5.6 ct. %, Campbell et al., 2012), 475 km north-northwest of the study area. The maximum ice-transport distance of this subglacial detritus has now been extended to between 800 and 1000 km south and south-southeast.

Calcareous and eastern exotic clasts

The spatial distribution of calcareous clasts (Figure 17) from sampled tills is surprisingly complex. Whereas older data (Thorleifson and Matile, 1993) indicated that surface tills within the study area should contain 50–70% calcareous pebbles, this study documents a large range of calcareous pebbles (0–91 ct. %). This large range of calcareous clast concentration does not exhibit an obvious spatial pattern, but is heterogeneous throughout the study area.

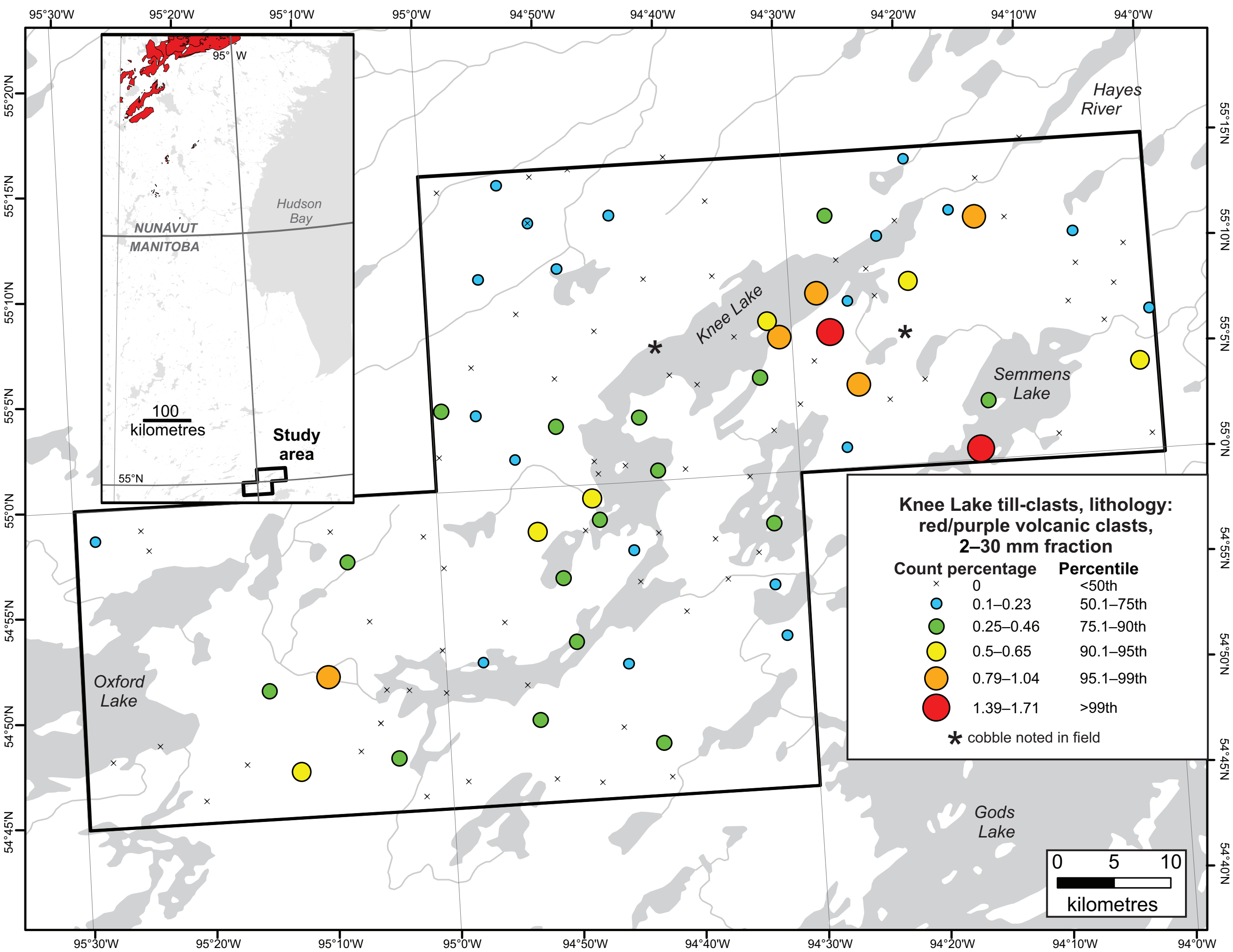

Figure 16: Spatial distribution of red/purple volcanic clasts (2–30 mm) within till samples in the Knee Lake area, interpreted as derived from the Dubawnt supergroup rocks in Nunavut (area shown in red in the inset map). The pattern of elevated concentrations (>95th percentile) in the eastern portion of the study area is similar to the distribution of elevated concentrations of both granitoid and exotic granitoid clasts (Appendix 13).

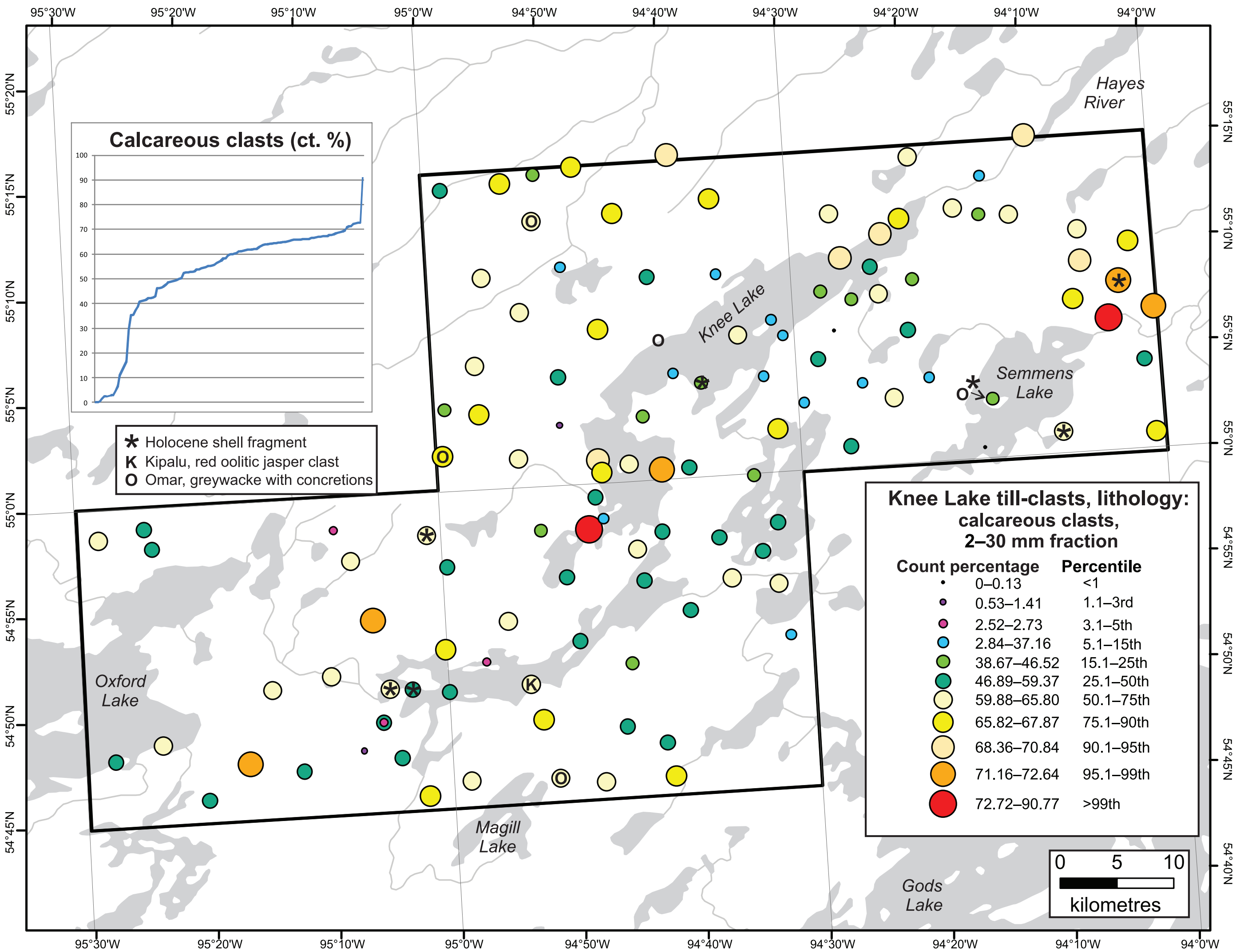

***Figure 17:** Spatial distribution of calcareous clasts (2–30 mm) within till samples in the Knee Lake study area, interpreted as derived from the Paleozoic Hudson carbonate platform to the northeast. These calcareous tills are variable in composition, but typically contain 45–65 ct. % calcareous clasts (beige, grey, white, pink carbonate). They also include eastern- or northeastern-sourced Holocene shell fragments, Paleozoic fossils (crinoid ossicles, pelecypods, corals), greywacke with concretions (Omarolluk Formation, Belcher Group) and, at one site, a red oolitic jasper clast derived from the Kipalu Formation of the Belcher Group (outcrops in southeastern Hudson Bay). Lower concentrations of calcareous clasts (<5^{th} percentile) are documented at 15.6% of sites.*

A shell fragment was encountered within the sieved clasts at seven 2012 field sites (Figure 17). These resistant, weathered shell fragments (2–4 mm) are most likely from marine shells. The regional glacial history suggests these shell fragments are likely sourced from shells that grew during the Sangamonian (Bell Sea, 130 ka, Andrews et al., 1983) or during late oxygen isotope stage 5 (80–75 ka, Wyatt, 1990). The Holocene marine limit for the Tyrrell Sea is around 120 m asl, which occurred 80–125 km northeast of the study area. While the configurations of these older water bodies are unknown (Dredge and Thorleifson, 1987; Vincent and Prest, 1987; Kleman et al., 2010), the shell fragments found within till in the study area were presumably transported a similar distance and direction from Hudson Bay.

A Kipalu (red oolitic jasper, sample 12115MT252, Figure 18) clast was found within the 2–4 mm size-fraction at site 12115MT252. The dispersal of these clasts is known to extend at least as far west-southwest as the Manitoba-Saskatchewan border (Prest et al., 2000).

Omar clasts (greywacke with concretions, sample 12097CB026, Figure 18) were found within the 2–4 and 4–8 mm size-fractions at three sites (12115MT345, 12097CB014, 12097CB026, Figure 17). These clasts were also noted in the field at site 12115MT345 and on the shores of Magill Lake. Because of the small size-fractions classified and the larger size of the obvious characteristic calcareous concretions (Figure 7c, d), the percentage of these clasts may be underestimated. The dispersal of these clasts is known to extend at least as far west-southwest as the Missouri River (Prest et al., 2000).

Kimberlite-indicator-mineral analysis

Field boundaries for garnets, chrome spinel and ilmenite discriminant diagrams (Figure 19) are used to determine the

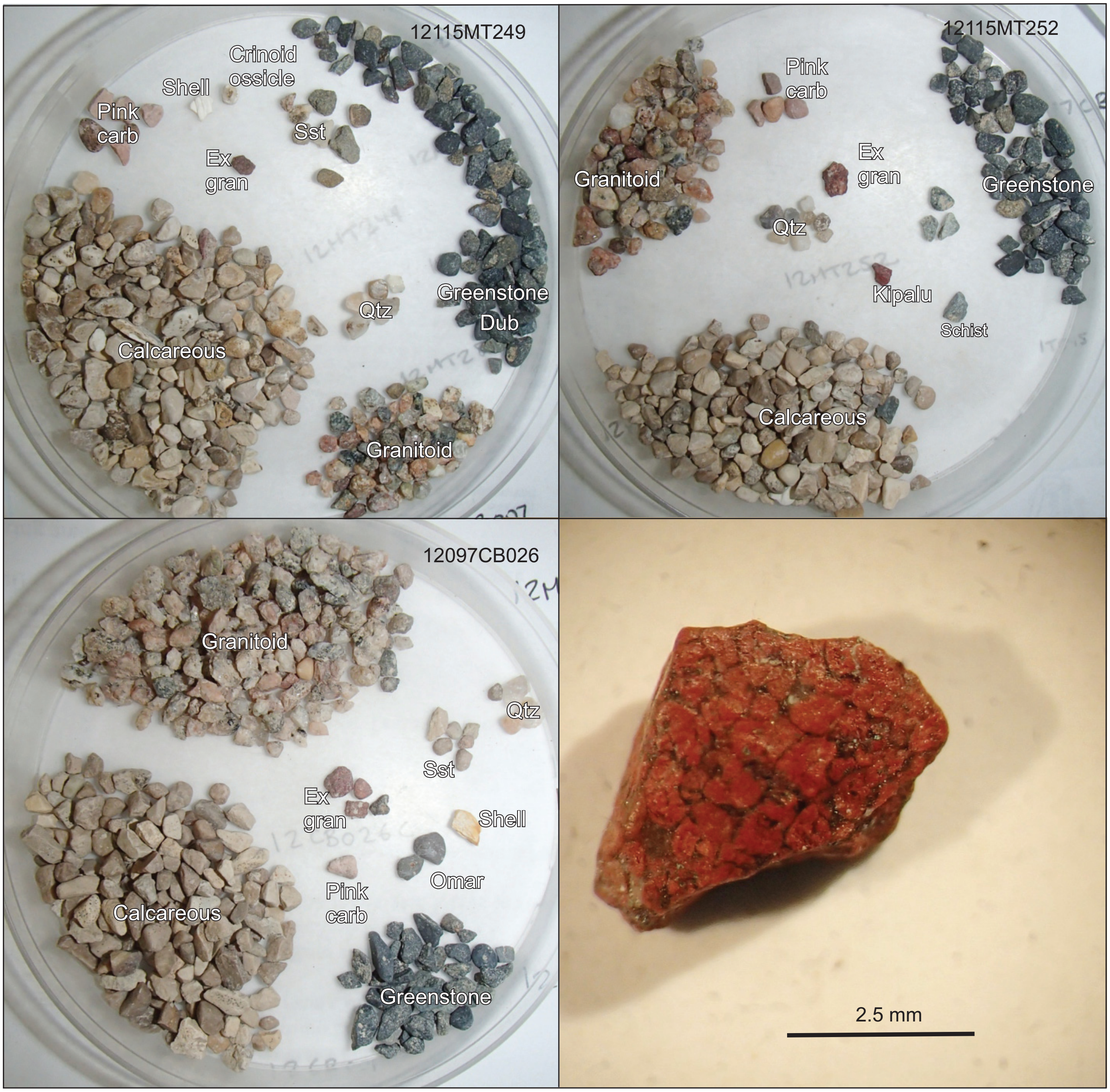

***Figure 18:** Examples of till-clast lithologies of the 2–4 mm size fraction from samples that contain typical concentrations of calcareous (includes pink carbonate and fossils) clasts. The Kipalu Formation clast from sample 12115MT252 is enlarged beneath a microscope to show details (bottom right). Abbreviations: Carb, carbonate; Ex gran, exotic granitoid; Qtz, quartz; Sst, sandstone.*

potential kimberlite origin of probed indicator-mineral grains (Syme et al., 2004). Mantle-derived garnets that are commonly recovered in diamond exploration surveys show variations in major-element composition that reflect the chemical, physical and lithological environments in which they formed, occasionally together with diamonds (Gurney et al., 1993). The majority of kimberlitic garnets in till samples from the study area plot in the fields of lherzolitic (G9) and pyroxenitic (G5) compositions. The G5s are similar to G9s, but are richer in Fe and are separated from G9s by a magnesium number (Mg#) less than 0.7 (Grütter et al., 2004). Ilmenite, another common KIM recovered during diamond exploration surveys, can be derived from kimberlitic rocks (e.g., kimberlite, lamproite, ultramafic lamprophyre) as well as other rock types (e.g., gabbro, norite, granite, anorthosite). Based on compositional fields and bounding reference lines for ilmenite derived from kimberlitic rocks worldwide (Gurney et al., 1993), the Mg-ilmenites from the study area plot as kimberlitic (Figure 19).

A total of 33 KIMs was recovered from 23 samples during the Knee Lake project and 431 KIMs from 336 till samples during the Operation Superior project (1999–2001). Most probed grains for the study area are spinels, of which only chromites are

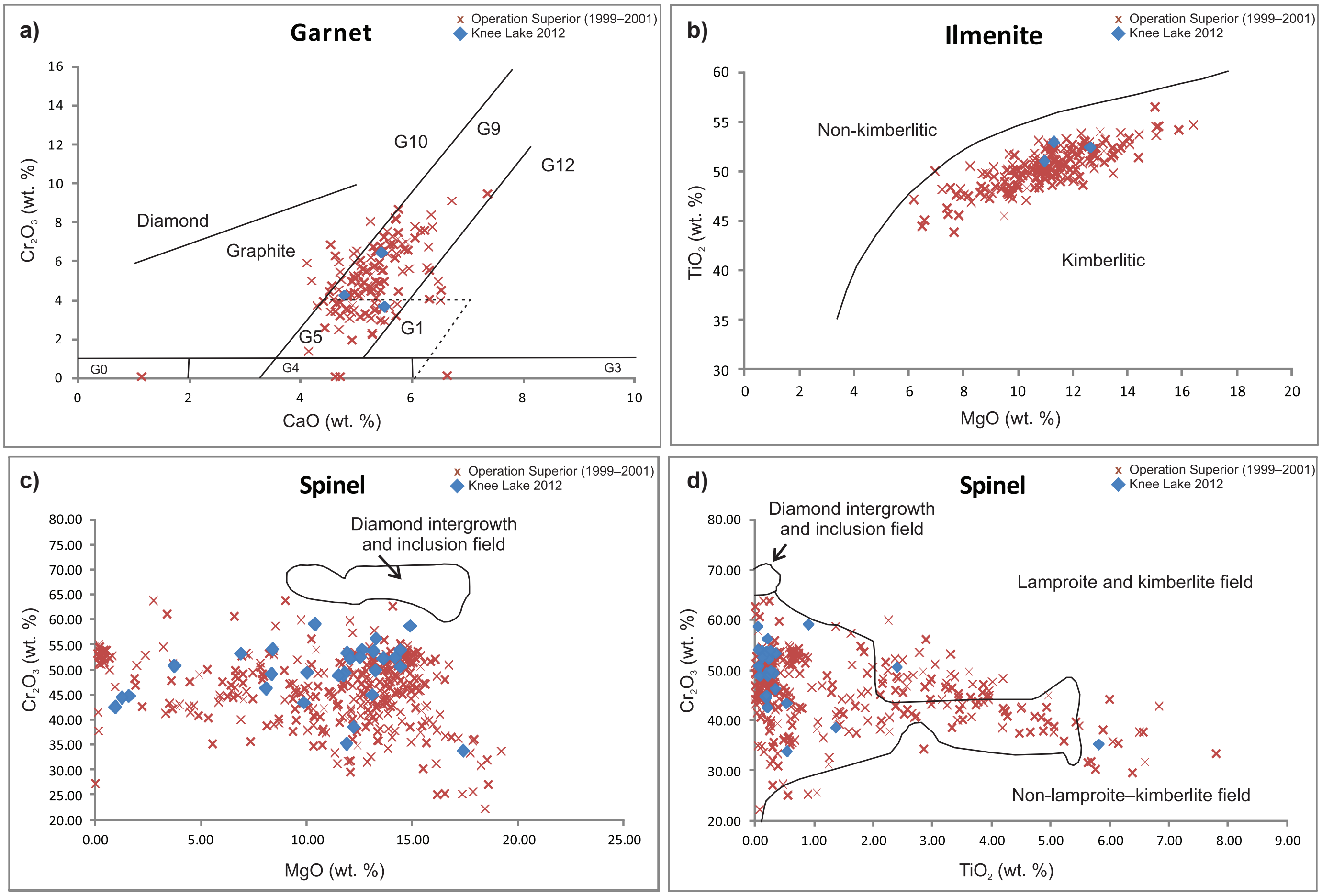

***Figure 19:** Discriminant diagrams for kimberlite indicator minerals: **a)** Cr_2O_3 versus CaO discriminant diagram for garnets, after Grütter et al. (2004) and Grütter and Sweeney (2000); **b)** TiO_2 versus MgO discriminant diagram for ilmenites, after Wyatt et al. (2004); **c)** Cr_2O_3 versus MgO discriminant diagram for chromites (>20 wt. % Cr_2O_3 and >5 wt. % MgO), after Fipke et al. (1995); **d)** Cr_2O_3 versus TiO_2 discriminant diagram for chromites (>20 wt. % Cr_2O_3 and >5 wt. % MgO), after Fipke et al. (1995).*

reported herein as kimberlitic (>20 wt. % Cr_2O_3 and >5 wt. % MgO). Two of the chromite grains from site 12115MT353 are Ti-chromites (>2 wt. % TiO_2 and >40 wt. % Cr_2O_3). The total KIM abundance for till samples in the study area is plotted in Figure 20.

Implications for kimberlite exploration

A principal goal of KIM surveys is to determine where the minerals came from. In glaciated terrains, knowledge of the direction in which the indicator minerals have been displaced by ice provides important guidance on where to search for the source of these minerals. In complexly glaciated terrain, such as the Knee Lake study area, which has been affected by multiple ice-flow directions, it is exceedingly difficult to reconstruct the transport history of indicator minerals. One needs to know not only the directions but also the distances that minerals have been moved by the motion of various lobes of ice in order to provide even vague speculation as to the place from where they came.

The highest number of KIMs analyzed during the Operation Superior project was in the Knee Lake area. Though a number of caveats were mentioned, Fedikow et al. (2002a) suggested that "preliminary inspection indicate a KIM dispersal train aligned parallel to the direction of the last ice advance at approximately 235°." Based on the updated regional geochemistry results presented in this report, and the discussion below, this interpretation is problematic as KIM results from beach and till samples were combined in the Operation Superior project. Beach sand is a secondary material, derived from unknown parent materials (probably till in this case) from an unknown catchment area, and hence are high-graded and transported differently than in till. Additionally, because the Knee Lake shoreline trends to 235°, this may create a false dispersal train. By examining the spatial pattern of KIM abundance in till samples, no clear dispersal train can be delineated (Figure 20). The new 2012 results have identified two clast-rich till sites that each yielded nine KIMs. Both sites are located east of Oxford Lake and out of the dispersal train. This new discovery suggests that the dispersal pattern of KIMs (and hence a source area) in the Knee Lake area is not yet constrained. New ice-flow indicator data (Figure 4), which can be used to guide further sampling, suggests that dispersal patterns could form widespread fans that trend between 150 and 270°.

All but one of the 17 sites with elevated total KIMs (4–19) are classified as calcareous silty till (see below). This regional

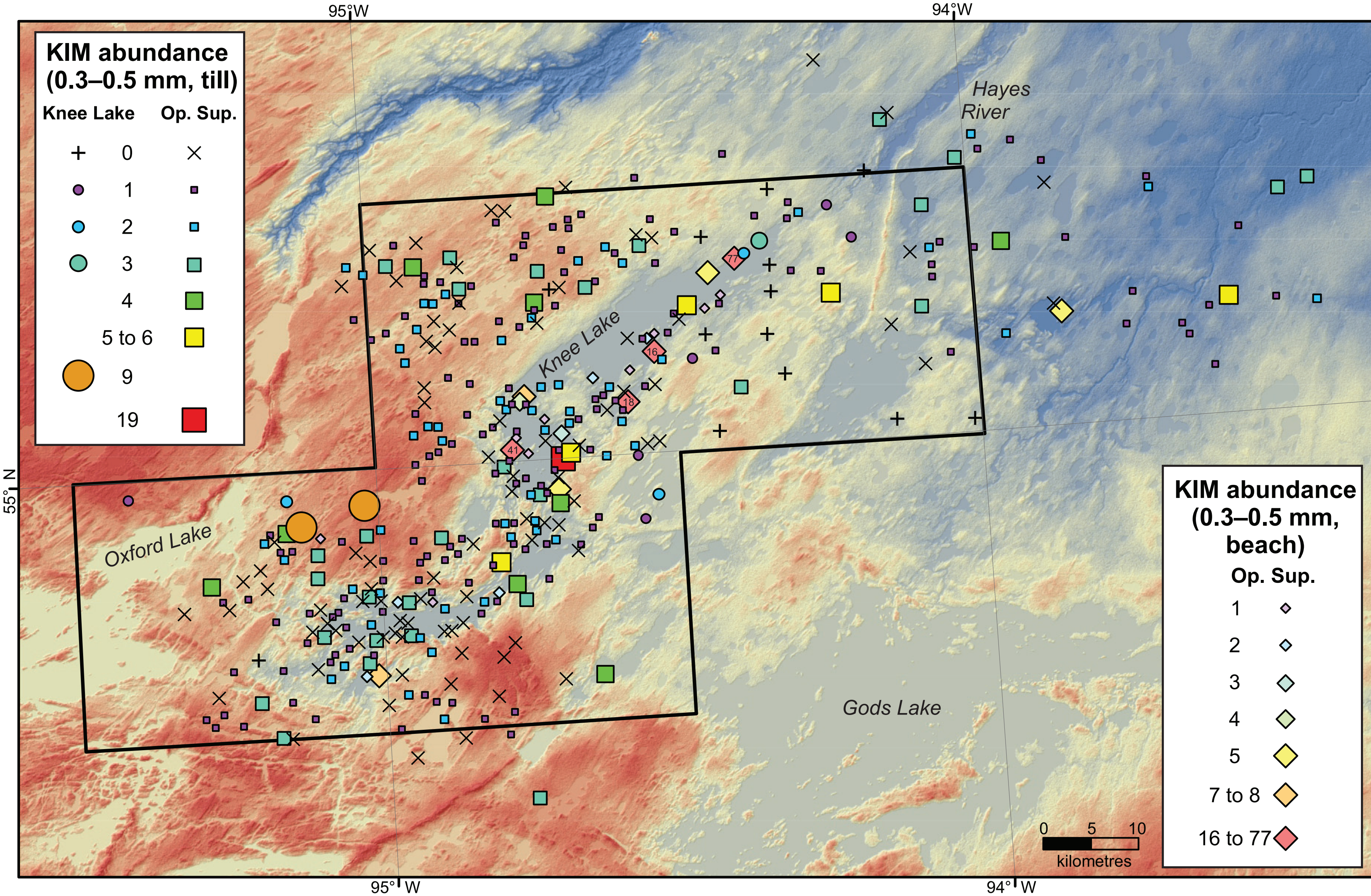

Figure 20: *Total kimberlite-indicator-mineral (KIM) abundance (0.3–0.5 mm size-fraction) for till samples in the Knee Lake study area, northeastern Manitoba. Total KIM abundance for beach samples taken during Operation Superior (Op. Sup.; 1999–2001) are also shown; sites with highest KIM counts include number of KIMs. Background image was generated using a Shuttle Radar Topography Mission digital elevation model (United States Geological Survey, 2002). A hill-shade model has been added with transparency effect to enhance relief.*

calcareous till is a hybrid till that contains material inherited from the underlying bedrock/pre-existing sediments that has been overprinted by calcareous detritus transported west or southwest from the carbonate platform in Hudson Bay.

Discussion

Tale of multiple tills

Widespread calcareous silty till

The dominant till in the Knee Lake area (Figure 21) is beige, has a silty-sand matrix and is calcareous (till matrix 24–53 wt. % total carbonate, 10.8–22.5 wt. % CaO [ICP-ES], 11–17% Ca [INAA]; with 30–70 ct. % calcareous clasts). The Knee Lake till samples are composed of 8–75% sand, 25–67% silt and 1–42% clay. These samples are less sandy than the shield-derived till in northeastern Manitoba (64% sand, 31% silt, 4.7% clay, 222 samples, Campbell et al., 2012) or northwestern Manitoba (70% sand, 23% silt, 7% clay, Kaszycki et al., 2008; 60% sand, 39% silt, 1% clay, 41 samples, Trommelen et al., 2013a). However, the Knee Lake samples have a similar texture to the 'silty till' identified by Dredge and Nixon (1992, 33% sand, 43% silt, 22% clay) in northeastern Manitoba river sections (and underlying glaciolacustrine/glaciomarine sediments close to Hudson Bay) and by Kaszycki et al. (2008) in northwest-central Manitoba (49% sand, 36% silt, 15% clay). This sandy silty till is described as clast-poor, calcareous and sparsely fossiliferous. The Knee Lake beige till is also sparsely fossiliferous, and as such this till likely has a similar provenance to the northern Manitoba 'silty till'.

Interestingly, the composition of the 'regional' till is bracketed by large standard deviations in matrix carbonate content, texture and geochemistry. Thus while the orientation of overlying streamlined landforms indicates the position of a major ice lobe in the study area (Figure 5), the till is not as homogeneous as expected.

The wide range in eastern- and/or northeastern-sourced calcareous and locally-sourced greenstone clast concentrations, combined with the occurrence of northern-sourced clasts (attributed to the Dubawnt supergroup) within 40% of till sites sampled in 2012, suggests that the regional calcareous till is a hybrid till that contains a mix of inherited and overprinted detritus (till type B, C or D, Figure 12, Trommelen et al., 2013b).

All three till types occur within streamlined landforms, as well as in till blankets or veneers over bedrock. This diverse geomorphology indicates that the process of drumlinization within the deglacial Hayes lobe was by subglacial modification/cannibalization of pre-existing inherited sediment, rather than formed by sediment transported over long distances within the Hayes lobe itself. This agrees with previous findings of Fedikow et al. (2000) regarding the streamlined sand and gravel deposits southeast of Oxford House. As such, the formation of the Hayes lobe is not directly (or not at all) responsible for regional- to continental-scale transport of subglacial detritus. Consequently, in this area, the orientation of streamlined landforms should not be used as an indicator of ice-flow transport direction during drift exploration.

Weakly calcareous till

Weakly calcareous till was sampled at 3.3% of field sites (Figure 21; sample 12115MT275, Figure 15). This till is defined by lower till-matrix concentrations of calcium (<10%, INAA), calcium oxide (<10 wt. %, ICP-ES), total carbonate (<30 wt. %) and/or calcareous clast concentrations (<35 ct. %). The concentration of calcium oxide (weight percent, near-total digestion and ICP-ES) is correlative (R^2=0.8) to the total carbonate content in the till matrix. For the Operation Superior project dataset, the concentration of calcium (percent, INAA) is also correlative (R^2=0.6) to the total carbonate content of the till matrix. The concentration of calcareous clasts (count percentage, 2–30 mm) also generally mimics the spatial pattern of total carbonate within the till matrix. Any of these methods can be used to identify weakly calcareous or noncalcareous tills in the region, though the classification is strengthened by the use of multiple proxies. Weakly calcareous tills contain a range of rock types (Table 1), which may be dominated by Shield detritus, or may be a mixture of all identified rock types.

Noncalcareous till

Noncalcareous till was sampled at 2.9% of field sites (Figure 21). This till is defined by low till-matrix concentrations of calcium (<4%, INAA), calcium oxide (<5.4 wt %, ICP-ES), total carbonate (<5 wt. %) and/or calcareous clast concentrations (<7 ct. %). Noncalcareous tills contain a range of rock types (Table 1), which may be dominated by greenstone-belt (Figure 14) or granitoid clasts (Figure 15), or may be a mixture of both rock types.

Sky Pilot till?

During the Operation Superior project, a fine-textured, reddish, silty till was encountered at several sites. This till was interpreted (Fedikow et al., 2009) to be the southernmost occurrence of the Sky Pilot till– the uppermost reddish or red-brown (colour 10YR6/2) till situated along the Nelson River, below glaciolacustrine and glaciomarine sediments (Nielsen et al., 1986). Regionally, the Sky Pilot till has been correlated to the Severn till of northern Ontario (Thorleifson et al., 1993) and the Kipling till from the James Bay area of Ontario (Skinner, 1973). This correlation was made on the basis of stratigraphic position, southwestern (~220°) ice-flow direction determined from till fabrics, and red carbonate clast content (between 0 and 5.5 ct. %, Thorleifson et al., 1992; Thorleifson et al., 1993; Nielsen, 2001, 2002; E. Nielsen, unpublished data, 2002). The source for these red-pink carbonate clasts, and the resulting reddish-brown colour of the till, is thought to be Devonian bedrock formations (such as the Williams Island and Kenogami River formations, Henderson, 1989) of a similar colour that subcrop in Hudson Bay. Reddish-brown till was noted at three field sites in 2012 (Figure 10), most notably at site 12115MT295 where it overlies a thin unit of beige (Figure 9d) calcareous till (bedrock at 55 cm depth). While the colour of this till was notable, the upper reddish-brown till is actually a noncalcareous clay-rich (17%) till dominated by granitoid (51 ct. %) and greenstone-belt (43 ct. %) clasts. While this till does contain 0.1 ct. % pink carbonate clasts and 2.7 ct. % unmetamorphosed sandstone clasts,

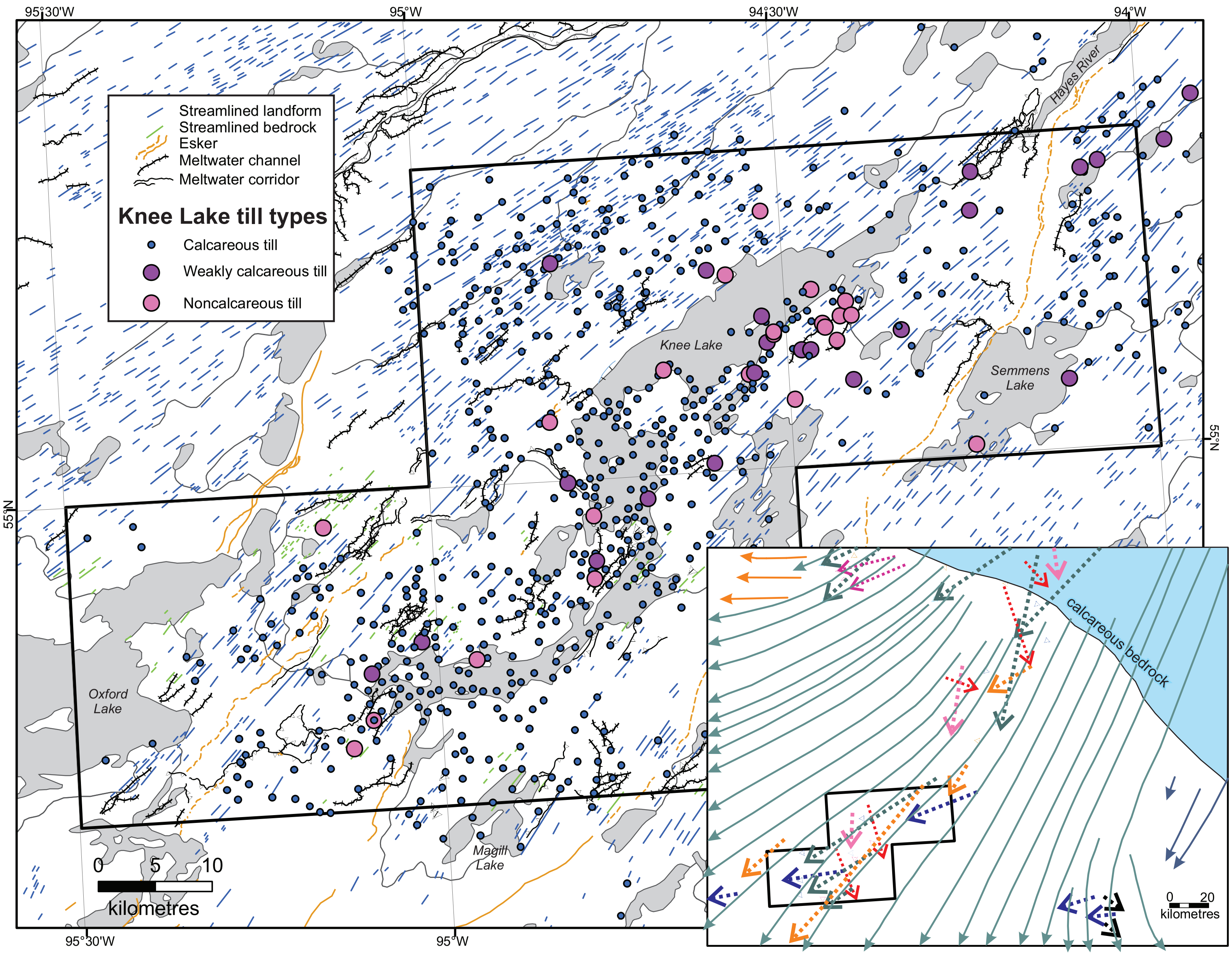

Figure 21: *Spatial map of calcareous silty-sand till, weakly calcareous and noncalcareous tills in the Knee Lake study area, northeastern Manitoba. All three till types occur within streamlined landforms, as well as till blankets or veneers over bedrock. The inset figure depicts a portion of the deglacial Hayes lobe, as defined by streamlined ridge orientation. The calcareous detritus within the widespread regional till is assumed to be sourced from the calcareous bedrock to the northeast (at the head of the lobe), which may have been transported or deposited during the west ice-flow phase II and/or the southwest ice-flow phases IV and V (see legend in Figure 5). Solid arrows on the inset figure summarize landform flowsets, while dashed arrows summarize field-based ice-flow indicator orientations.*

it is difficult to understand how this till could have been derived from central Hudson Bay without incorporating a higher concentration of calcareous detritus. The mixed red and brown till noted at site 12115MT230 is also a noncalcareous till, while the mixed beige and red till at site 12097CB09 contains 63 ct. % calcareous clasts. The provenance of these noncalcareous tills is problematic and uncertain.

The last regionally widespread ice-flow phase in the Knee Lake area was to the south-southwest (between 212 and 220°, Phase V, Figure 5), which is a similar orientation to the transport directions of the Sky Pilot and Severn tills. Additionally, 92% of till sites sampled in 2012 contain between 0.1 and 4.1 ct. % pink carbonate. Thus according to these characteristics, if till colour is discounted, it may be possible to suggest that the till within the Knee Lake area is correlative to the Sky Pilot till. However, it should be noted that red carbonate clast content is also similar near the top of the underlying Long Spruce (Manitoba; Nielsen, 2001; Nielsen, 2002; E. Nielsen, unpublished data, 2002) and Sachigo (northern Ontario, 250–260° ice-flow; Thorleifson et al., 1993) river-section tills. Furthermore, it is difficult to correlate directly between a thin till sheet, such as in the Knee Lake area, and river sections with thick till layers. Unlike paleoriver channels, where deposition is dominant within topographic lows over a very long time period with multiple ice-flow orientations (Nielsen and Dredge, 1982; Klassen, 1986; Nielsen, 2001, 2002), a thin surface till is most likely a hybrid that contains a mixture of inherited and overprinted detritus (Trommelen et al., 2013b) formed over multiple ice-flow phases. As such, until further detailed work is completed to thoroughly characterize the surface till throughout north-central Manitoba, direct correlation to any named river-section tills is avoided.

Summary

There are at least three different populations of sandy-silt till in the study area. The first is a widespread blanket of beige, calcareous, sparsely fossiliferous till that contains 40–72 ct. % calcareous clasts, 9–55 ct. % granitoid clasts, 6–25 ct. % greenstone-belt clasts (metasedimentary and metavolcanic rocks), and low concentrations of other clasts (Dubawnt supergroup, exotic granitoid, unmetamorphosed sandstone/conglomerate, chert, Omars, Kipalu). This heterogeneous till sheet was likely formed during ice-flow phases II and/or IV and V, when the large component of allochthonous calcareous detritus (carbonate-bearing clasts, carbonate fossils, shell fragments) was transported at least 125 km west or southwest from the carbonate platform in Hudson Bay.

Patchy weakly calcareous till was encountered at 3.3% of field sites. This sandy-silt till is defined by lower till-matrix concentrations of calcium (<10%, INAA), calcium oxide (<10 wt. %, ICP-ES), and/or total carbonate (<30 wt. %). This grey or beige till contains 10–40 ct. % calcareous clasts, 33–82 ct. % granitoid clasts, 5–30 ct. % greenstone-belt clasts (metasedimentary and metavolcanic rocks), and low concentrations of other clasts (Dubawnt supergroup, exotic granitoid, unmetamorphosed sandstone/conglomerate, chert).

Patchy noncalcareous till was encountered at 2.9% of field sites. This silty-sand till is defined by low till-matrix concentrations of calcium (<4%, INAA), calcium oxide (<5.4 wt. %, ICP-ES) and/or total carbonate (<5 wt. %,). This brown, red-brown, grey or beige till contains 0–7 ct. % calcareous clasts, 9–90 ct. % granitoid clasts, 5–80.5 ct. % greenstone-belt clasts (metasedimentary and metavolcanic rocks), and low concentrations of other clasts (Dubawnt supergroup, exotic granitoid, unmetamorphosed sandstone/conglomerate, chert).

These heterogeneous weakly calcareous to noncalcareous till samples were likely deposited during southerly ice-flow phase III, and protected from dilution/reworking during the later southwesterly and/or westerly ice-flow phases.

All three till types occur within streamlined landforms, as well as till blankets or veneers over bedrock. This diverse geomorphology indicates that the process of southwesterly drumlinization within the deglacial Hayes lobe was by subglacial modification/cannibalization of pre-existing inherited sediment. As such, in the Knee Lake area, the formation of these widespread streamlined landforms may have occurred between or after ice-flow phases IV and V, but is not directly related to sediment transport.

Economic considerations

There are no obvious glacial dispersal patterns from any of the field sites with elevated till-matrix concentrations of multiple metals (Figure 13; Appendix 12). In large part, this is likely because the widespread regional calcareous till is partially masking the local bedrock signature. The detailed data clearly show that elevated metal concentrations within till matrix, presumably derived from the underlying greenstone belt, are predominately detectable within the noncalcareous or weakly calcareous tills (<10 wt. % CaO, ICP-ES, or <10% Ca, INAA, or <30 wt. % total CO_3). Thus for most greenstone-belt derived elements, low concentrations within the till matrix should *not* be taken as indicative of a lack of local mineralization. Even a small difference in carbonate content (7 versus 10% Ca) may lead to drastically different element concentrations (roughly halved at site T01-13). As such, detailed attention *must* be paid to calcium (INAA), total carbonate (Chittick apparatus or calcium-magnesium method) and/or calcium oxide (near-total digestion and ICP-ES) concentrations during drift exploration analyses. Calcareous till samples with moderate to elevated metal concentrations may be more prospective than noncalcareous till samples with high metal concentrations. The two populations should not be statistically treated as one dataset. The study area is also draped by a variable thickness of glaciolacustrine clay, which must be avoided during drift exploration programs.

Despite a lack of glacial dispersal patterns, there is mineralization potential within the Knee Lake area. Gold potential occurs throughout, especially at the historic Knee Lake Gold mine and Johnson Knee Lake mine gold-silver occurrences (Southard, 1977). Massive sulphide–type mineralization was investigated near upper Knee Lake and at Cinder Lake (Gale et al., 1980). Rare-earth-element–bearing minerals have been observed in the fine-grained silica-undersaturated syenite, the metasomatized pegmatite and within calcite veining at Cinder Lake (Kressall et al., 2010).

In contrast to previous work completed during the Operation Superior project (i.e., Fedikow et al., 2009), it is suggested that the orientation of the overlying streamlined landforms is not directly related to the transport directions of the subglacial detritus. The orientation of field-based ice-flow indicators, such as striae, grooves, chattermarks and roches moutonnées, may better guide up-ice drift exploration work. Till-fabric measurements may also prove valuable, as till is a product of deposition, and most field-based ice-flow indicators only provide a record of the erosional glacial history. The till within the Knee Lake area contains a mixture of inherited and overprinted detritus, and thus the transport directions of older ice-flow phases should not be ignored.

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