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Quaternary site, till composition and ice-flow indicator datasets in the Kaskattama highland area, northeastern Manitoba (parts of NTS 53N, O, 54B, C)

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Quaternary site, till composition and ice-flow indicator datasets in the Kaskattama highland area, northeastern Manitoba (parts of NTS 53N, O, 54B, C)

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Manitoba Geological Survey
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Front cover photos:

Section 112-16-416 (top photo) is a large natural exposure of Quaternary sediments near the First Nation community of Shamattawa. The Quaternary stratigraphy in the Kaskattama highland region includes multiple stacked tills (example in bottom left photo) and sediments deposited during previous interglacial periods (example in bottom right photo).

Abstract

The Kaskattama highland area in northeastern Manitoba preserves an exceptional stratigraphic record of multiple Quaternary glacial-interglacial cycles. Helicopter-supported fieldwork investigated the Quaternary stratigraphy at 27 sections and the surficial sediments at 54 stations. Released herein are the stratigraphic columns, clast fabric, till clast-lithology and till-matrix geochemical data.

Résumé

La région de hautes terres de Kaskattama, dans le nord-est du Manitoba, a préservé un profil stratigraphique exceptionnel de plusieurs cycles glaciaires-interglaciaires du Quaternaire. Du travail sur le terrain appuyé par hélicoptère a permis d'étudier la stratigraphie quaternaire de 27 coupes et les sédiments de surface de 54 stations. Publiées dans la présente sont les colonnes stratigraphiques, la fabrique des clastes, l'analyse pétrologique des clastes du till et les données géochimiques sur la matrice du till.

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Introduction

The Manitoba Geological Survey (MGS) conducted the first detailed study of Quaternary sediments in the Kaskattama highland area of northeastern Manitoba during the 2016, 2017 and 2019 field seasons. This area preserves a thick (~15–170 m) Quaternary stratigraphic record that encompasses sediments from multiple glacial-interglacial cycles. Natural exposures were visited at a reconnaissance scale over ~5 900 km^2 to document the stratigraphy and interpret the Quaternary geologic history. Numerous till units are present, samples of which enable us to begin evaluating the economic potential of the buried bedrock using samples analysed for kimberlite-indicator minerals (KIM), till-matrix geochemistry and till clast-lithology. Adding to samples and observations for assessing sediment composition, numerous paleo–ice-flow measurements were taken to assist reconstruction of the glacial dynamics of the area and guide drift exploration studies. This report publishes the field site, till composition and ice-flow indicator datasets, which have been used to provide an interpretation of the Quaternary stratigraphy (T.J. Hodder, M.S. Gauthier, M. Ross, S.E. Kelley, O.B. Lian, S.A. Dalton and S.A. Finkelstein, work in progress). It also provides context to the published KIM data (Hodder and Kelley, 2017; Hodder, 2018a).

Regional setting

The Kaskattama highland is a prominent topographic high that rises 130 m above the flat-lying Hudson Bay Lowland (HBL), reaching a maximum of 235 m asl (Figure 1). The study area lies within the zone of extensive discontinuous permafrost (Heginbottom et al., 1995; O'Neill et al., 2019), and evidence of active permafrost activity, such as mudboils and peat plateaus, were observed throughout the study area. The Gods River is the main drainage system in the study area, draining northwest to a confluence with the Hayes River, which then flows northeast into Hudson Bay. The headwaters of the Kaskattama River are located on the Kaskattama highland, and the river drains northeast from the highland into Hudson Bay. Access to the region is by air, or winter road from Gillam into the First Nation community of Shamattawa. The winter road into Shamattawa continues eastward, south of the Kaskattama highland, and services Fort Severn, Ontario (Figure 1).

Quaternary geology

The western HBL region of central Canada contains a stratigraphic record of Quaternary glacial and nonglacial sediments deposited across at least the past three glacial-interglacial cycles (Netterville, 1974; Shilts, 1984; Nielsen et al., 1986; Dredge et al., 1990; Dredge and McMartin, 2011). Interpreted ice-flow directions that deposited tills range from NW-trending to ESE-trending in the western HBL, spanning an azimuth of 205° (Gauthier et al., 2019). Many of these ice-flow directions were repeated over time, both within a single glaciation and in separate glaciations. Since all depositional ice-flow measurements are made using

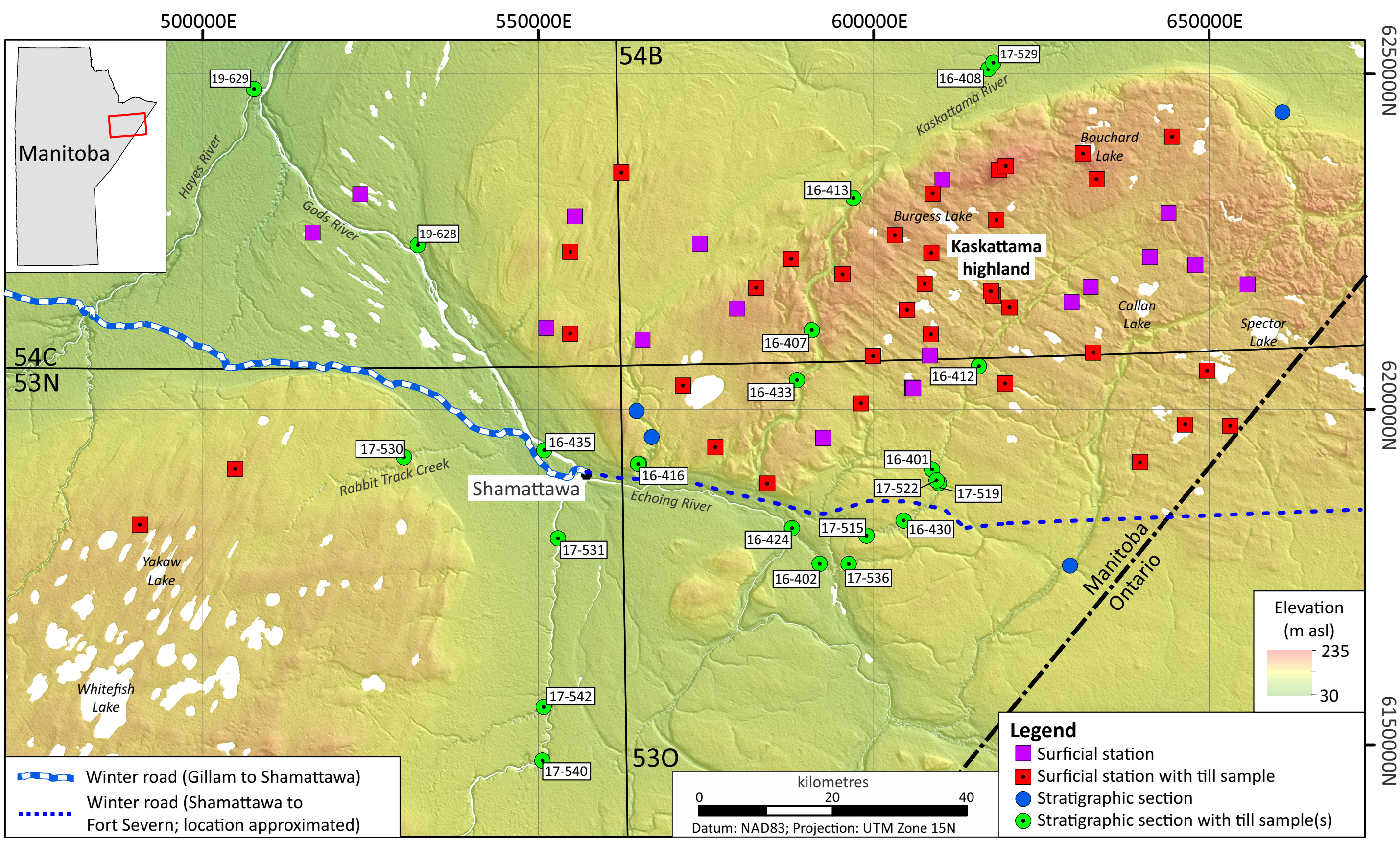

Figure 1: *Extent of the Kaskattama highland study area in northeastern Manitoba and stations visited as part of this study. Stratigraphic section labels are abbreviated from 112-1X-XXX to 1X-XXX for clarity. Background hillshade image was generated using Canadian Digital Surface Model (Natural Resources Canada, 2015).*

clasts within till ('clast fabric' or 'lodged clasts'), it is sometimes difficult to determine a specific direction (e.g., NW or SE ice flow; Gauthier et al., 2019).

Surficial geology

The surficial geology was mapped in the study area at 1:250 000 reconnaissance scale for NTS 53N, O and 54B by Clarke (1989a, 1989b, 1989c) and 54C by Klassen and Netterville (1979). The relative marine limit from the postglacial Tyrrell Sea is ~146 m asl (Dredge and Nixon, 1992). Below this limit the surficial materials are dominated by sorted sand, silt and clay that were deposited in a marine environment which masks the glacial geomorphology (Figure 2). Above the marine limit, till is the dominant surficial sediment on the Kaskattama highland, with organic and glaciolacustrine sediments occupying the low-lying, interdrumlin regions.

Stations visited during this study have been classified according to their surficial geology map unit and are plotted on Figure 2. In general, the existing 1:250 000 mapping is a reasonable depiction of the surficial sediments. The exception to this is in the far northeastern corner, where a blanket of silt to fine sand was observed in the field and the extent of this blanket was interpreted from satellite imagery (Figure 2). These sorted sediments are situated above marine limit and are interpreted to have been deposited in a subaqueous or subaerial fan as meltwater was released towards the northeast from subglacial corridors that crosscut the highland (Gauthier et al., 2020). The scale and frequency of these corridors across the region is unknown, since some corridors are completely or partially buried beneath postglacial sediments (Gauthier et al., 2020). For example, section 112-16-423 is located within a meltwater corridor and exposes 19.7+ m of marine sediments, providing a minimum thickness of marine sediments within this corridor (Figure 3).

Unconsolidated sediment thickness

Drillcore to bedrock and observations of outcropping bedrock are rare in the western HBL (Hodder and Gauthier, 2021). Depth to bedrock on and around the Kaskattama highland is constrained by just four sites (Figure 4). Paleozoic carbonate bedrock outcrops along the base of the Gods River at two known sites, constraining Quaternary sediment thickness to 15 and 30 m (Figure 4). To the northwest of one of those sites though, the Trout-1

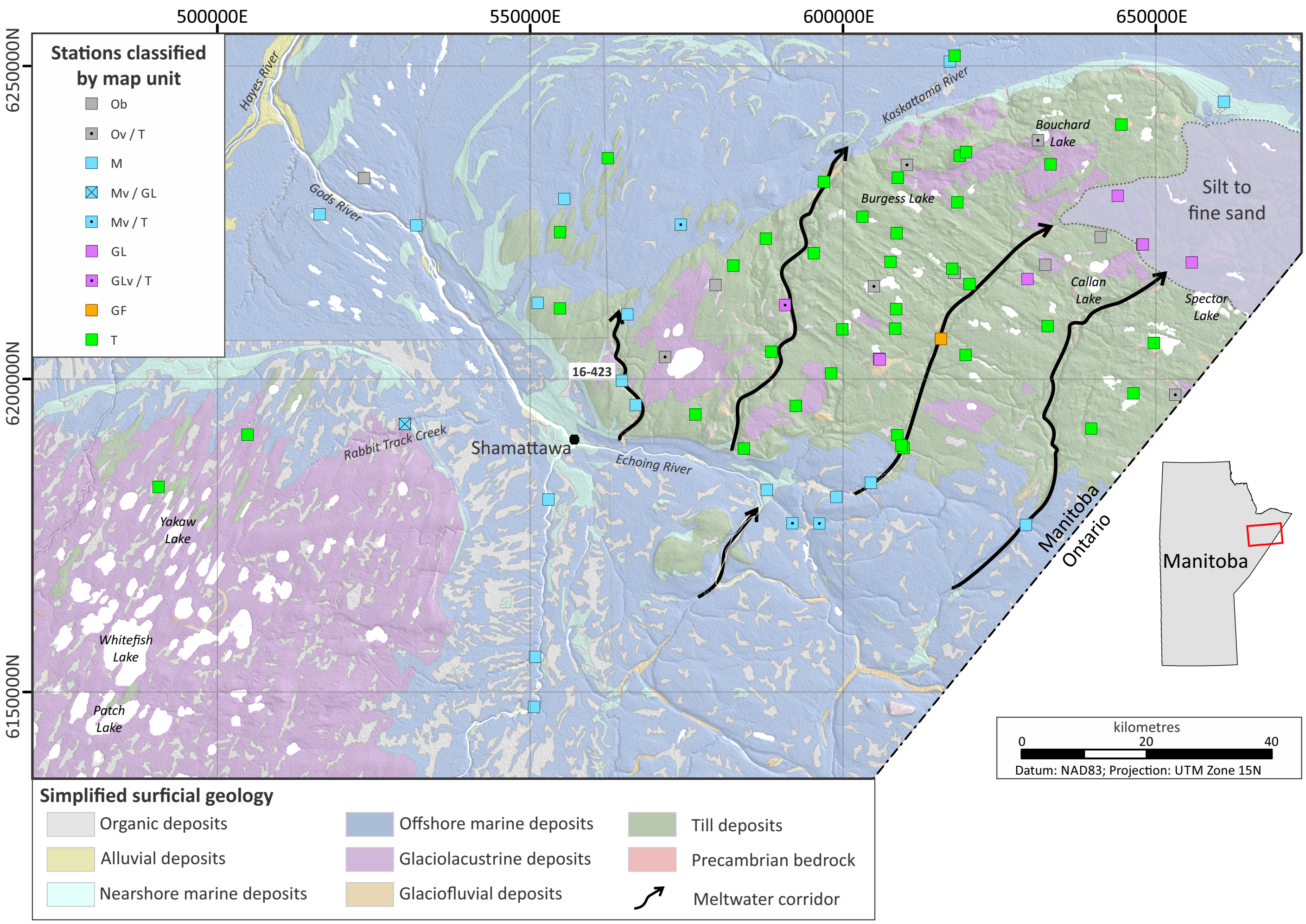

Figure 2: *Simplified surficial geology in the Kaskattama highland area (modified after Clarke, 1989a–c and Klassen and Netterville, 1979). Meltwater corridors with routing direction shown are from Gauthier et al. (2020). Stations from this study have been classified according to their map unit. Abbreviations: GF, glaciofluvial; GL, glaciolacustrine; GLv, glaciolacustrine veneer; M, marine; Mv, marine veneer; Ob, organic blanket; Ov, organic veneer; T, till.*

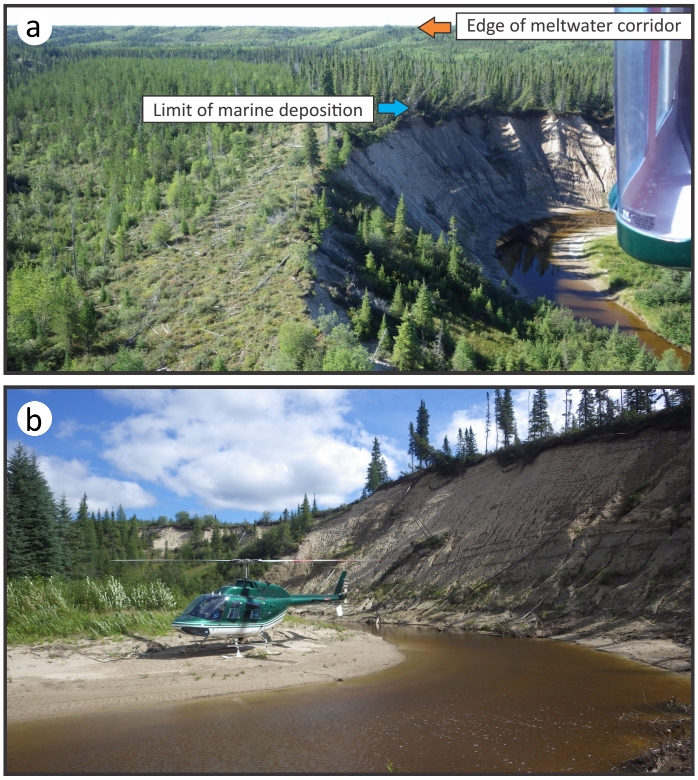

Figure 3: *Marine sediments observed at section 112-16-423 within a northeast-southwest-oriented meltwater corridor (location in Figure 2):* ***a)*** *oblique aerial photo showing the limit of marine deposition in relation to the edge of the meltwater corridor;* ***b)*** *ground photo of the 19.7 m of bedded marine sediments exposed at section 112-16-423.*

drillcore (Figure 4) indicates that local sediment thickness is 89.2 m (Figure 4; Assessment File 74249, Manitoba Economic Development, Investment, Trade and Natural Resources, Winnipeg). A single drillcore (KK1) near Bouchard Lake, provides the only subsurface bedrock observation of Kaskattama highland (Hodder, 2018b). It was drilled to test a circular magnetic anomaly, to a true vertical depth of 332 m (Hodder, 2018b; Assessment File 74223). This drillcore intersected 223 m of unconsolidated sediments, of which at least 170 m were interpreted to have been deposited during the Quaternary period as evidenced by glacial deposits (till) at this depth (Hodder, 2018b). Hence, the known thickness of Quaternary sediments on and near the Kaskattama highland range from 15–170 m.

Bedrock geology

The study area is primarily underlain by limestone and dolomite (carbonate) Paleozoic rocks of the Hudson Bay Basin (Nicolas and Armstrong, 2017), which unconformably overlie Precambrian rocks (Figure 4). Of particular interest to till-provenance studies, the middle member of the Kenogami River Formation contains noncalcareous fine-grained red siltstone to sandstone. However, the exact mapped distribution of this bedrock is poorly constrained, since the KK1 drillcore intersected an older bedrock unit than what was anticipated and required a reinterpretation of the bedrock map in the study area (Nicolas and Armstrong, 2017). The Proterozoic Fox River belt is mapped in the southwestern region of the study area (Figure 4). The mafic to ultramafic rocks within this belt contain local Cr, Ni, Cu and platinum-group element mineralization (Rinne, 2020). The northeastern extension of this belt has been delineated using geophysical datasets and is presumed to be covered by Paleozoic rocks in the Kaskattama highland area based on current bedrock geology mapping of the region (Nicolas and Armstong, 2017).

Methods

Field data collection

Helicopter-supported fieldwork was conducted over 8–10 days in both July of 2016 and 2017 and two days in 2019. A large wildfire in the mid-2000s significantly increased the accessibility for helicopter landing over the highland; tree growth by 2019 already made landing more complicated.

A total of 81 stations (27 sections, 54 surficial) were visited to document the surface and subsurface sediments (Figure 1), as well as collect till samples and ice-flow data. Station information is included in Appendix 1. The majority of section exposures visited were situated along active waterways or at the edge of meltwater corridors in the study area. Descriptions of the Quaternary sediments and stratigraphy observed at each section are provided in Appendix 2.

A total of 124 till samples were collected from surface and section exposures (34 surficial and 90 stratigraphic section samples; Figure 5). At 64 till sample sites, an additional 11.4 L of till was collected for KIM analyses. The weight of the KIM samples ranged from 11.7 to 25.2 kg, averaging 18.5 kg (Hodder, 2018a) and results are discussed in Hodder and Kelley (2018). Surface till samples were collected from C-horizon material that was obtained from either mudboils (Figure 6a–d), hand-dug pits (e.g., Figure 6e) or using a dutch auger (Figure 6f). Mudboils were the preferred sampling sites, as these permafrost features bring unweathered till to the surface (McClenaghan et al., 2023). Sediments exposed at stratigraphic sections were first cleared to remove any slump material and till samples were collected every 1–4 m depth, depending on the stratigraphy observed at the section.

Ice-flow indicators

Ice-flow indicators in the study area include clast fabrics measured within till, and in situ lodged cobble- to boulder-sized clasts that had parallel striations on their upper surfaces, which are considered a good indicator of paleo–ice-flow direction (McMartin and Paulen, 2009). Clast-fabric measurements were conducted on three vertical faces of a 'box' carved into the till, after the section was cleared of slumped material, at 13 sections. At each site, the trend and plunge of the a-axis was measured from at least 30 clasts with a:b axis ratio >1.5. At one site, only 20 clasts were measured due to a time constraint during fieldwork. A non-magnetic knitting needle was used to extrapolate the plunge of the a-axis out of the till face, allowing for increased

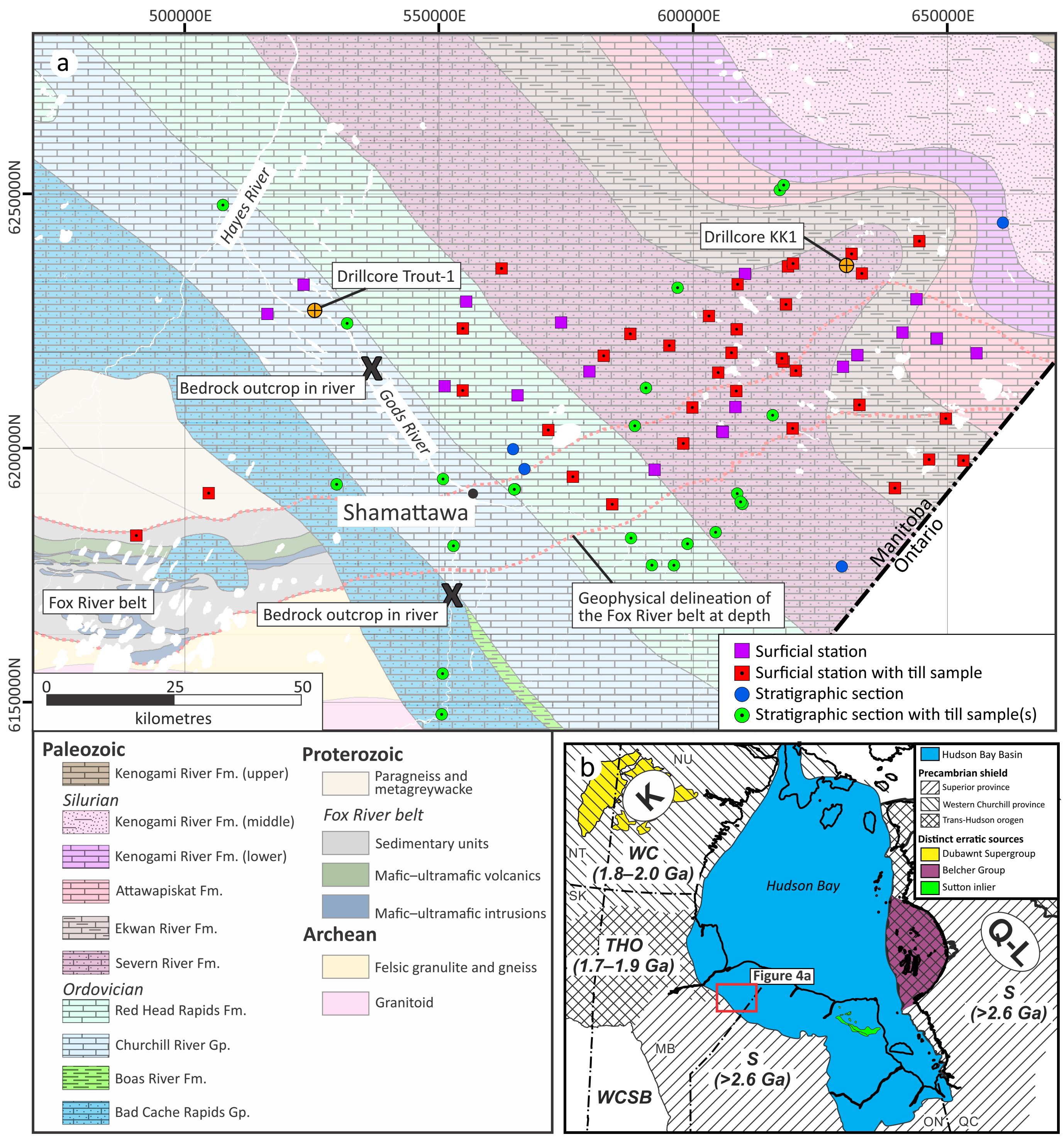

***Figure 4:** Bedrock geology: **a)** regional-scale bedrock geology in the Kaskattama highland area and surrounding region. Paleozoic geology from Nicolas and Armstrong (2017). Precambrian geology from Rinne (2020); **b)** bedrock geology of central Canada (modified from Wheeler et al., 1996) and tectonic age of geological provinces, which is derived from Roy et al. (2007). The location of the Keewatin (K) and Quebec-Labrador (Q-L) domes of the Laurentide Ice Sheet is their position during deglaciation from Dalton et al. (2020). Abbreviations: HBB, Hudson Bay Basin; MB, Manitoba; NT, Northwest Territories; NU, Nunavut; ON, Ontario; QC, Quebec; S, Superior; SK, Saskatchewan; THO, Trans-Hudson orogen; WC, Western Churchill; WCSB, Western Canada Sedimentary Basin.*

accuracy of measurements. We did not measure clasts in contact with other clasts or clasts that were adjacent to large boulders, which could restrict rotation of clasts (Andrews and Smith, 1969). Data was plotted on equal-area stereonets and the modality of each fabric was assessed visually (Hicock et al., 1996). Eigenvectors and eigenvalues were calculated to get insights into the preferred orientation and strengths of the fabrics (Mark, 1973; Benn, 1994). All ice-flow-directional interpretations based on clast fabrics were initially considered bidirectional, since the imbrication of clasts up-ice is not consistent (Andrews and Smith,

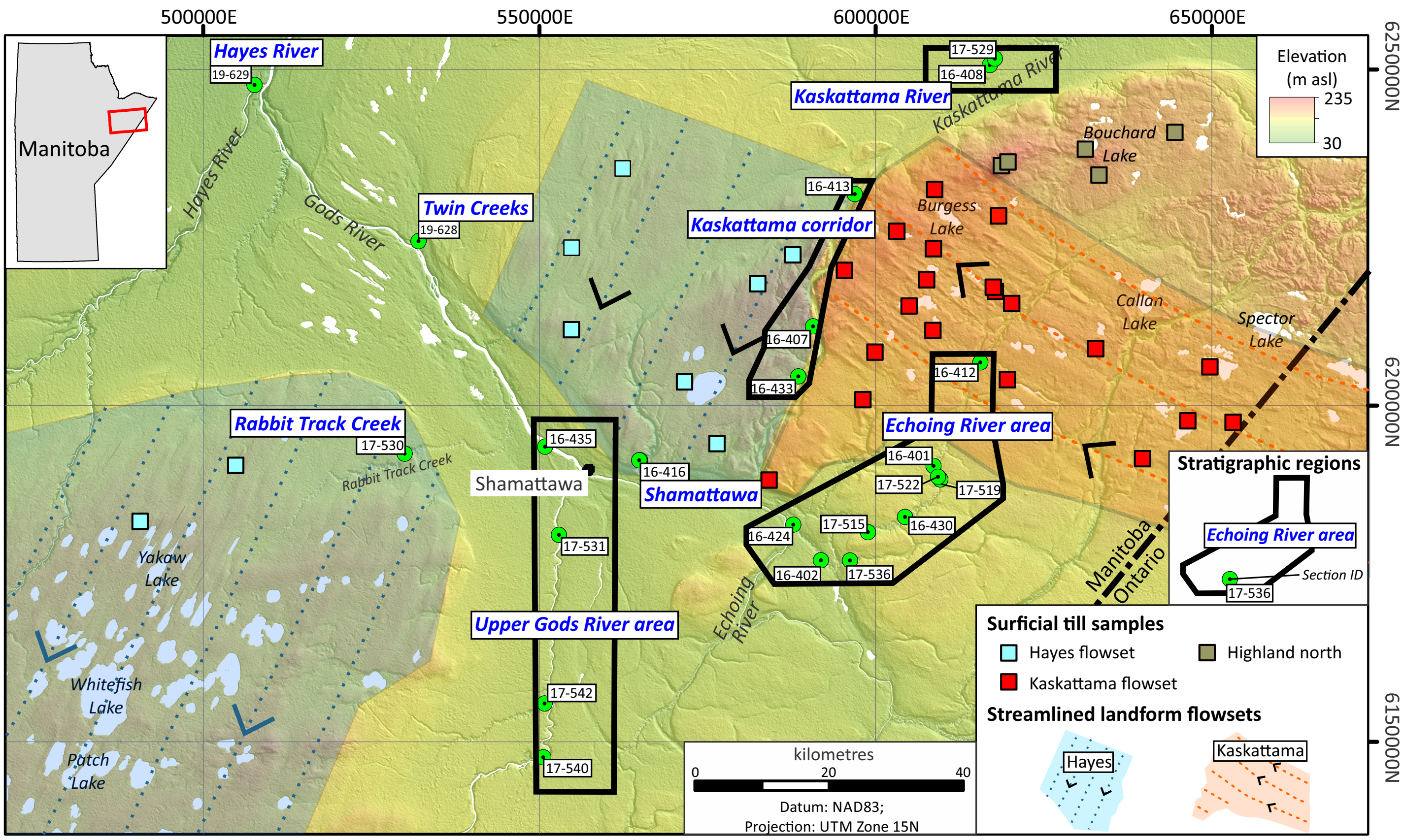

***Figure 5**: Surficial till samples and sections with till sampled that are grouped according to their stratigraphic region investigated.*

1969; Saarnisto and Peltoniemi, 1984; Larsen and Piotrowski, 2003; Gauthier et al., 2019). Clast-fabric measurements, statistics and interpretations, along with lodged clast observations, are provided in Appendix 3.

Till clast-lithology

Clast-lithology counts were conducted for each till sample to help identify till provenance and hence major directions of dispersal. Clast-lithology counts initially sorted the 2–4 and 4–8 mm size fraction of till samples into 16 detailed classes (Table 1; e.g., Figure 7a–d). These two size fractions were then summed and expressed as a count percentage of the 2–8 mm size fraction. An average of 437 clasts were counted for each till sample, ranging from 227–808 clasts per sample, and totaling 54 194 observations. For 2016 and 2017 till samples, the entire 8–30 mm size fraction was counted which resulted in an average of 62 clasts counted but a standard deviation of 81. This high standard deviation is due to large variation in the amount of material available to count between till samples, since samples processed for heavy minerals had a higher amount of clasts available to count in the 8–30 mm size fraction. For this reason, the 8–30 mm size fraction was not incorporated at the analysis stage and 2–8 mm size-fraction data was used instead. No clasts in the 8–30 mm size fraction were counted for 2019 till samples. All clast-lithology count data is provided in Appendix 4 and photos of sorted clasts for each sample are provided in Appendix 5.

Glacial detritus sources

For interpretation of till composition and dispersal patterns, the clasts were grouped into five simplified classes to reduce lithological identification errors (Table 1; Hudson Bay Basin [HBB], Granitoid, Undifferentiated greenstone and greywacke [UGG], Distinctive erratics, and Other). Most lithologies within the HBB class can not be confidently tied to any specific source. Shell fragments observed in till have been eroded from previously deposited marine sediment during the Quaternary period. The original source of these fragments is unknown but is constrained by limit of marine inundation following deglaciation episodes. Pink to red carbonate clasts are easily identified in clast counts and are interpreted to be sourced from the Kenogami River Formation, middle member (Gao et al., 2020). Similarly, fine-grained red sandstone to siltstone clasts are sourced from the Kenogami River Formation, middle member. Next, granitoid rock fragments in till are sourced from the Precambrian shield surrounding the Hudson Bay Basin (Figure 4b) and can be transported into the study area by ice flowing from both the Keewatin or Quebec-Labrador domes; therefore, they offer limited assistance in discriminating ice-flow directions.

Significant greywacke clast concentrations have been documented in tills of the central HBL and the provenance of these clasts has been interpreted to be the Belcher Group to the east (Figure 4b; Shilts, 1980; Thorleifson et al., 1993). These distinctive erratics are easily diagnosed as larger clasts and commonly

Figure 6: *Example of surface till sampling sites in the Kaskattama highland area:* ***a–d)*** *example of mudboils that were used to sample unweathered till;* ***e)*** *example of a hand-dug pit in a region with no mudboils that was used to sample C-horizon till at depth;* ***f)*** *example of C-horizon till sample that was sampled at depth underlying organic material using the assistance of a dutch auger.*

referred to as 'Omars' (Prest et al., 2000). 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. The Belcher Group and Sutton inlier also contain metavolanic rocks (Jackson, 2013), similar to greenstone belts on the Precambrian shield. Hence the provenance of these dark grey rocks needs to be carefully considered (Hodder et al., 2017), leading us to lump these within an UGG class.

Continental-scale erratics

In northern Manitoba, distinctive erratics indicative of continental-scale dispersal include both northwestern- and eastern-sourced clasts. Northwestern erratics have been transported southeastward over 800 km from the Dubawnt Supergroup (Figure 4b; Rainbird, 2003). Examples include Pitz Formation clasts (purple to mauve-coloured volcanic rocks with distinctive chalky sanidine phenocrysts; e.g., Figure 7e) and Christopher Island Formation clasts (red volcanic rocks with phlogopite phenocrysts). Eastern erratics have been transported west to southwestward a minimum of 650 km from the Belcher Group (Figure 4b; Jackson, 2013). In addition to the Omars above, greenish to grey porphyritic rocks with distinctive cm-scale plagioclase crystals ('Belcher porphyries') are sourced from the Flaherty or Eskimo formations, and oolitic jasper is derived from the Kipalu Formation. Problematically, oolitic jasper have multiple source areas and can also be from iron formations within the Sutton inlier (Figure 4b), 400 km to the southeast (Stott et al., 2010).

Table 1: Simplified and detailed lithological classes for till clast-lithology counts.

Simplified	Detailed class
Hudson Bay Basin	Grey, tan, white carbonate
	Pink carbonate
	Undifferentiated sandstone and siltstone
	Fine-grained red sandstone (Kenogami Formation)
	Chert
	Ironstone
	Paleozoic fossil
	Shale
Granitoid	Granitoid
UGG	Undifferentiated greenstone and greywacke
Distinctive erratics	Shell fragment
	Oolitic Jasper
	Red or purple volcanic (Dubawnt Supergroup)
Other	Quartz
	Quartzite
	Sulphides

Till-matrix geochemistry

Till-sample splits were sent to Activation Laboratories Ltd. (Actlabs; Ancaster, Ontario). Approximately 1 kg of each till sample was air dried and dry sieved, using stainless steel mesh screens to obtain the <63 µm size fraction for geochemical analyses and carbonate content determination. The remainder of the original samples was archived at the MGS. The geochemical dataset published in Appendices 6–8 herein is exclusive to till samples collected during the 2016 and 2017 field seasons. The 2019 till-geochemical data from sections 112-19-628 and 112-19-629 is published in DRI2022006 (Hodder and Gauthier, 2022).

Ca/Mg method for carbonate content

An aliquot of the till matrix (<63 µm size fraction) was digested using HCl and analyzed for Ca and Mg by inductively coupled plasma–optical emission spectrometry (ICP-OES) at Actlabs. The proportion of calcite and dolomite were then calculated (wt. %). The results for till-matrix carbonate content are provided in Appendix 6.

Partial digestion till-matrix geochemistry

An aliquot of the <63 µm size fraction was digested in an aqua-regia (1:3 HNO_3:HCl) mixture at Actlabs. Following digestion, samples were analyzed by inductively coupled plasma–mass spectrometry (ICP-MS) and by inductively coupled plasma-optical emission spectrometry (ICP-OES) techniques for 63 elements. The analytical results are presented in Appendix 7, together with summary statistics and analytical data for control reference standards, analytical and field duplicates, and blanks.

Near-total digestion till-matrix geochemistry

An aliquot of the <63 µm size fraction was digested in a four-acid (HF:HNO_3:$HClO_4$:HCl) mixture at Actlabs. Following digestion, samples were analyzed by ICP-MS techniques for 58 elements. The analytical results are presented in Appendix 8, together with summary statistics and analytical data for control reference standards, analytical and field duplicates, and blanks.

Till-matrix geochemistry quality assurance and quality control

Copper contamination

The partial and near-total digestion results for 2016 samples indicated a significant Cu anomaly from a section sampled on the Kaskattama River (sample 112-16-408-B2), which is summarized in Table 2. During clast-lithology counts, a malachite-bearing rock fragment was observed within the 2–4 mm size fraction. This was unexpected since this locality is situated within the Hudson Bay Basin and located far from known Precambrian bedrock sources, but it did explain the elevated Cu concentrations in the sample. To verify these results, first the pulp of the original analysis was re-analyzed. This indicated an even larger Cu anomaly within the partial digestion results, but similar near-total digestion results (Table 2). Second, the archive field-split for sample 112-16-408-B2 was pulled from storage and processed at the Saskatchewan Research Council Geoanalytical Laboratories (Saskatoon, Saskatchewan) to obtain the <63 µm size fraction. The <63 µm size fraction was then submitted to Actlabs for geochemical analysis and returned a value that is similar to background concentrations for the region (Table 2). These findings suggest that during the initial grain-size separation at Actlabs, Cu contamination was introduced into the 2+ mm and <63 µm size fraction of the till sample. Sample 112-16-408-B2 was sampled from a compact till, and Actlabs later stated that this sample had to undergo additional processing with a jaw crusher. It is suspected that the contamination was introduced at this stage of grain-size processing. Since this is the only known sample that was processed using a jaw crusher, we expect this issue of Cu contamination to be an isolated incident associated with a single sample. As evidenced herein, thorough verification of geochemical anomalies is always necessary, especially data of economic interest.

Near-total digestion dataset

Exploratory data analysis of the near-total digestion dataset indicated significant variation between the 2016 and 2017 dataset. The observations herein cannot be explained by geological field variability, as the 2017 survey increased the density of sampling, but did not expand the spatial bounds of the 2016 survey. Normal probability plots for four elements comprising both major

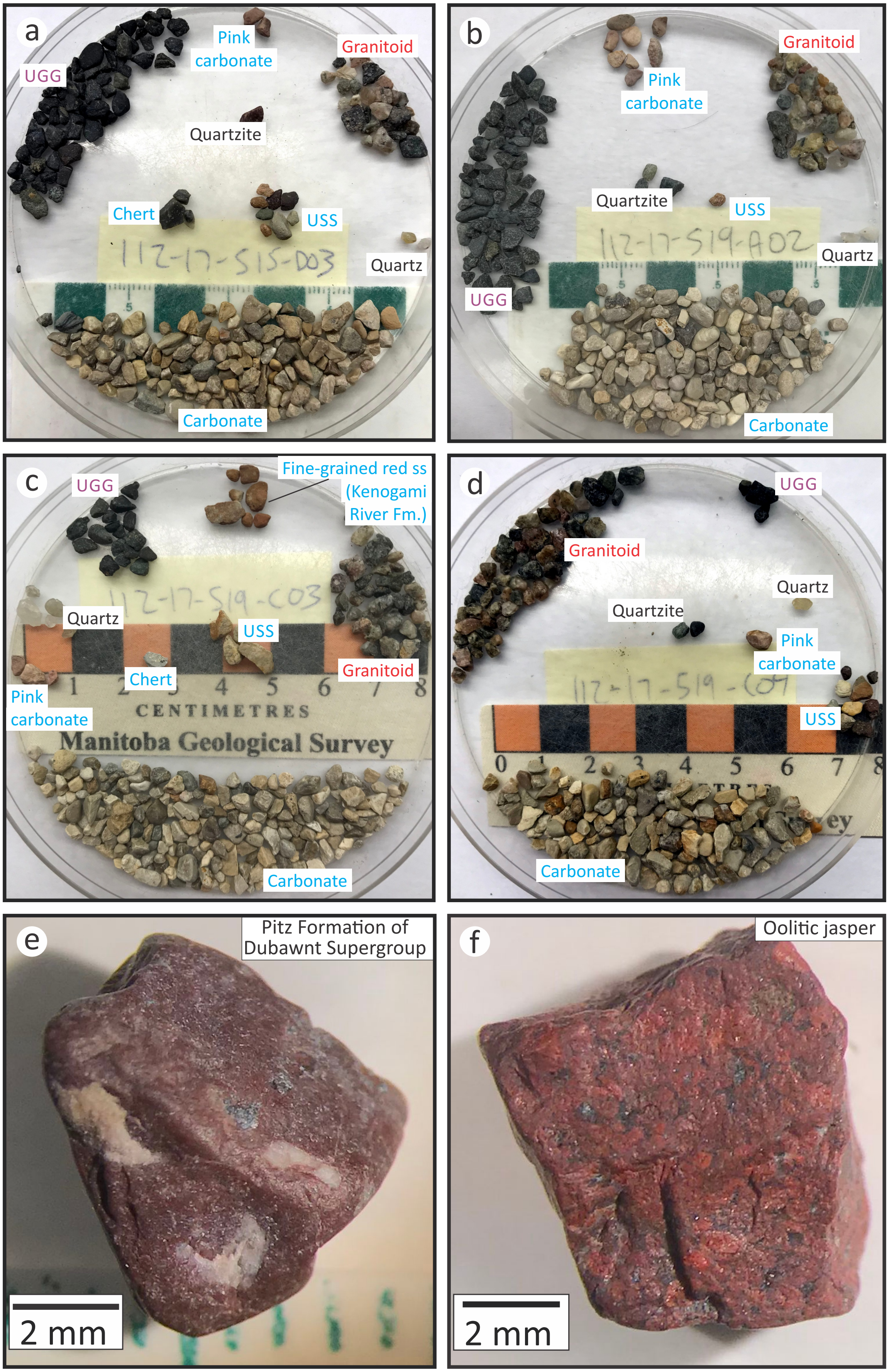

Figure 7: *Example of sorted till clast-lithology counts:* ***a–d)*** *sorted 2–4 mm size fraction;* ***e)*** *example of a Pitz Formation clast recovered in the 4–8 mm size fraction;* ***f)*** *example of an oolitic jasper clast recovered in the 4–8 mm size fraction. Abbreviations: ss, sandstone and siltstone; UGG, undifferentiated greenstone and greywacke; USS, undifferentiated sandstone and siltstone.*

Table 2: Cu analytical results for sample 112-16-408-B2.

Sample_ID	Year [Report]	Cu_ppm [Ar-MS]	Cu_ppm [TD-MS]	Cu_ppm [FUS-MS]	Comments
112-16-408-B2	2016 [A16-10238]	80.4	95.7	--	<63 µm size fraction separated at Actlabs
112-16-408-B2	2017 [A17-13888]	192	91.9	--	<63 µm size-fraction pulp re-analysis
112-16-408-B2	2019 [A19-16748]	20.8	--	20	Archive split with <63 µm size fraction separated at another lab

Abbreviations: Ar, aqua regia; FUS, fusion; ID, identification; MS, mass spectrometry; TD, total digestion.

and trace elements (K, Al, Ga, Zn; near-total digestion [Ultratrace 4 package]) are displayed in Figure 8. These elements demonstrate the variability between analyses in 2016 and 2017. In some cases (e.g., Ga, Figure 8g), the range in the datasets between the two years barely overlap. The quality assurance–quality control provided by the lab (Appendix 8) also points to poor precision and accuracy between the two years. For example, the Al concentration of reference standard GXR-1 in 2016 was 4.32 wt. % and in 2017 was 2.28 wt. % (certified standard value of 3.52 wt. %). The data quality issue is suspected to be due to inconsistencies in the strength of the digestion used between analysis years, but this is not known for sure.

Dataset levelling

Exploratory data analysis of the near-total digestion geochemistry data revealed there were issues with the quality of the 2017 near-total digestions ICP-MS dataset. To perform statistical analysis of the dataset for both years together, the 2017 dataset was levelled to 2016 data. A linear regression-based levelling approach as described in Grunsky (2010), corrected the 2017 data with respect to the 2016 data following our assumption about incomplete digestion.

Results

Quaternary stratigraphy

The Quaternary sediments at 27 sections were described in detail, and complete stratigraphic columns with photos for each section are provided in Appendix 2**.** A hybrid lithostratigraphy-allostratigraphy approach was used to decipher the palimpsest depositional record and create a Quaternary stratigraphic framework for the Kaskattama highland region (Figure 9; T.J. Hodder, M.S. Gauthier, M. Ross, S.E. Kelley, O.B. Lian, S.A. Dalton and S.A. Finkelstein, work in progress). This framework consists of five glacial (till) units and three nonglacial (sorted sediment) units that were deposited across at least three glacial-interglacial cycles; constrained by radiocarbon (^{14}C) and optically stimulated luminescence (OSL) age datasets (Figure 9). Representative sediment photos of each unit are provided in Figure 10 and the Quaternary stratigraphy is summarized as follows. Unit 1 is the oldest recognized till and was deposited by SW-trending ice flow (Figures 9, 10a). Next, Unit 2 (heterogeneous non-glacial sediments; Figure 10b) suggests ice-free conditions where paleoenvironmental indicators (pollen) suggest conditions indistinguishable from present-day, within a local boreal peatland. Optical dating from one section suggests that these sediments were deposited at 191 ±29 ka (1σ, 112-19-630-OSL025), which indicates deposition during the Marine Isotope Stage 7 interglacial period (T.J. Hodder, M.S. Gauthier, M. Ross, S.E. Kelley, O.B. Lian, S.A. Dalton and S.A. Finkelstein, work in progress). Overlying Unit 2 sorted sediments are tills that were deposited by NW-trending ice flow (Unit 3; Figure 10c) followed by S- to SW- to W- trending (Unit 4; Figure 10f) ice flows (Figure 9). Next, Unit 5 (heterogeneous non-glacial sediments; Figure 10d) contains bedded sands that were dated via optical dating to 146 ±20 and 166 ±12 ka, and 150 ±22 ka (1σ, 112-19-629-024; 112-16-407-019; 112-19-605-004; Hodder et al., 2023), which supports deposition during Marine Isotope Stage 5 to 6. Overlying Unit 5 sorted sediments are tills that were deposited by NW-trending (Unit 6; Figure 10e) followed by S- to SW-trending (Unit 7) ice flows (Figures 9, 10f). Unit 6 and Unit 7 are expressed in the geomorphic record as NW- and SSW-trending streamlined landforms, respectively (Figure 9). The stratigraphic record is capped by postglacial sediments that were deposited in glaciolacustrine, marine or fluvial environments during the Holocene (Unit 8) and radiocarbon ages obtained with this study are presented in Appendix 9.

Discussion

Deciphering the fragmented depositional record from the Kaskattama highland, and especially identifying till units, is challenging because the stratigraphic framework relies on observations across all sections investigated and is not complete at any one location in the study area (Figure 9a). This highly fragmented record highlights either patchy deposition of till, patchy erosion of tills, or likely a combination of both processes over time. Furthermore, the stratigraphic framework constructed for the Kaskattama highland was restricted to sediments exposed near surface in sections (≤32 m bgs) and the full breadth of the record down to bedrock is largely unknown. Additional drilling of the Quaternary record of the Kaskattama highland and/or field-based investigations in the region would further advance our understanding of the stratigraphic record, which is evident based on preliminary stratigraphic work on sections situated along Gods River (Mesich et al., 2023).

Red till: Kenogami River Formation dispersal

In the HBL, there is till that has a distinctive red matrix colour (e.g., Nielsen et al., 1986; Gao et al., 2020; Gauthier et al., 2022).

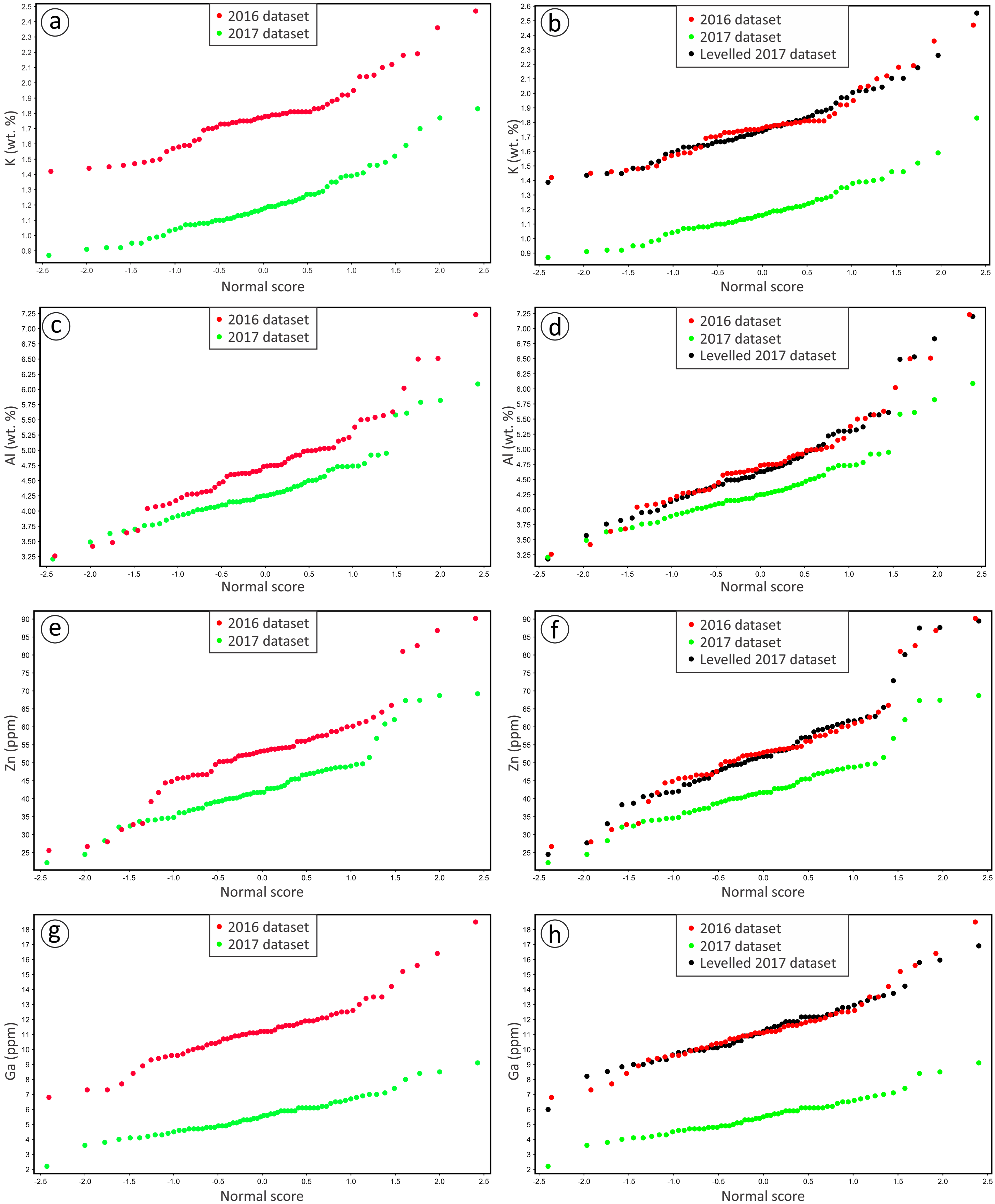

Figure 8: *Comparison of the near-total digestion dataset from 2016, 2017 and the levelled 2017 data for elements **a, b)** K, **c, d)** Al, **e, f)** Zn, and **g, h)** Ga.*

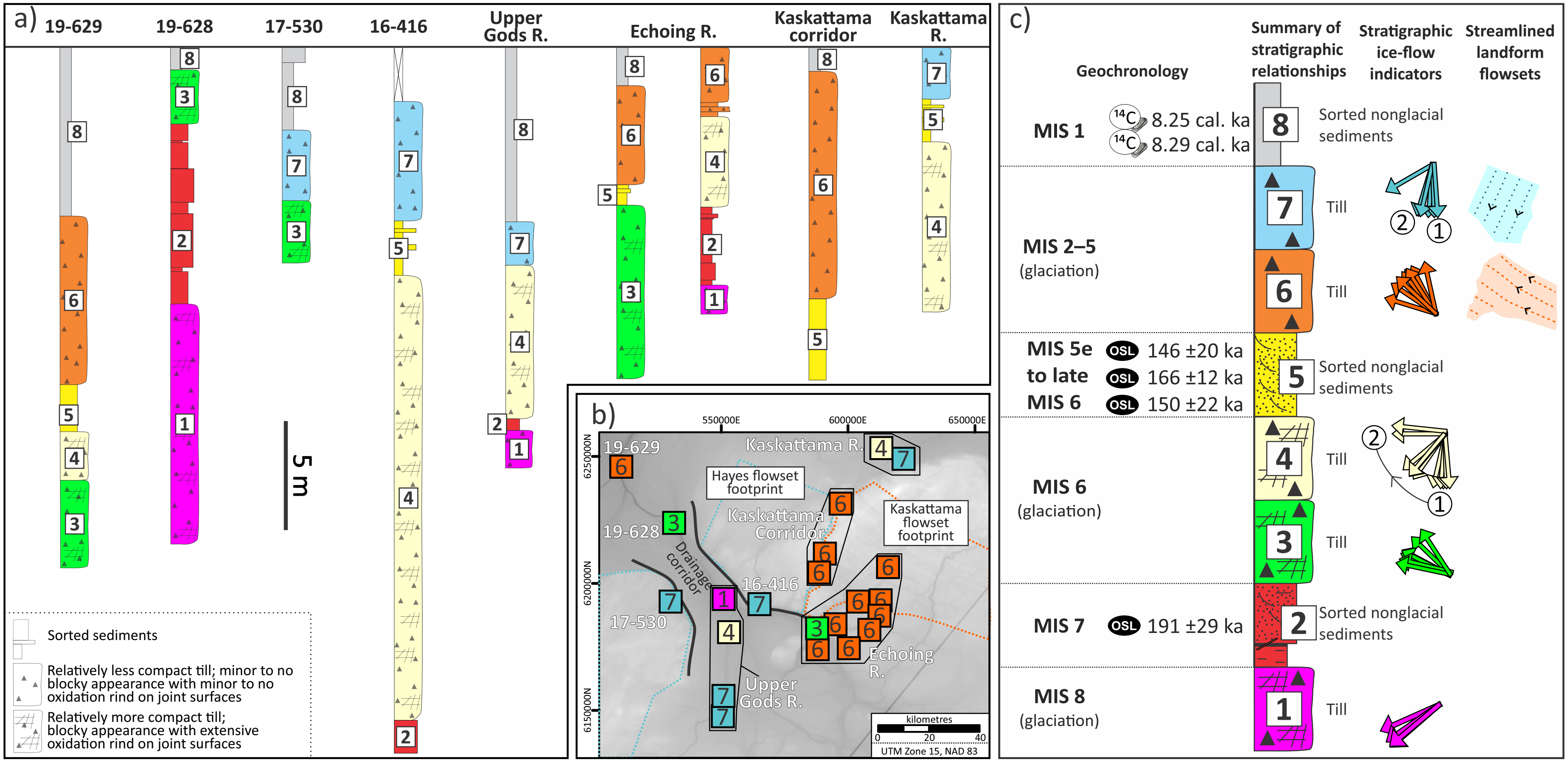

***Figure 9**: Quaternary stratigraphic framework of the Kaskattama highland region (modified from T.J. Hodder, M.S. Gauthier, M. Ross, S.E. Kelley, O.B. Lian, S.A. Dalton and S.A. Finkelstein, work in progress): **a)** the stratigraphy for each stratigraphic region (Figure 5) is shown highlighting the fragmented nature of the stratigraphic record. Note, some locations are a stratigraphic composite of multiple sections (e.g., Echoing River) and additional cross-sections are provided in Appendix 2; **b)** the uppermost till unit exposed either at surface or underlying postglacial sediments (Unit 8) at each section investigated is shown. Note the location of a drainage corridor which has eroded up to 60 m of sediments from the stratigraphic record exposing relatively old till units overlain by postglacial sediments; **c)** Quaternary stratigraphic column with dated intertill sorted sediment units providing age constraints (modified from T.J. Hodder, M.S. Gauthier, M. Ross, S.E. Kelley, O.B. Lian, S.A. Dalton and S.A. Finkelstein, work in progress). Abbreviations: MIS, marine isotope stage; OSL, optically stimulated luminescence.*

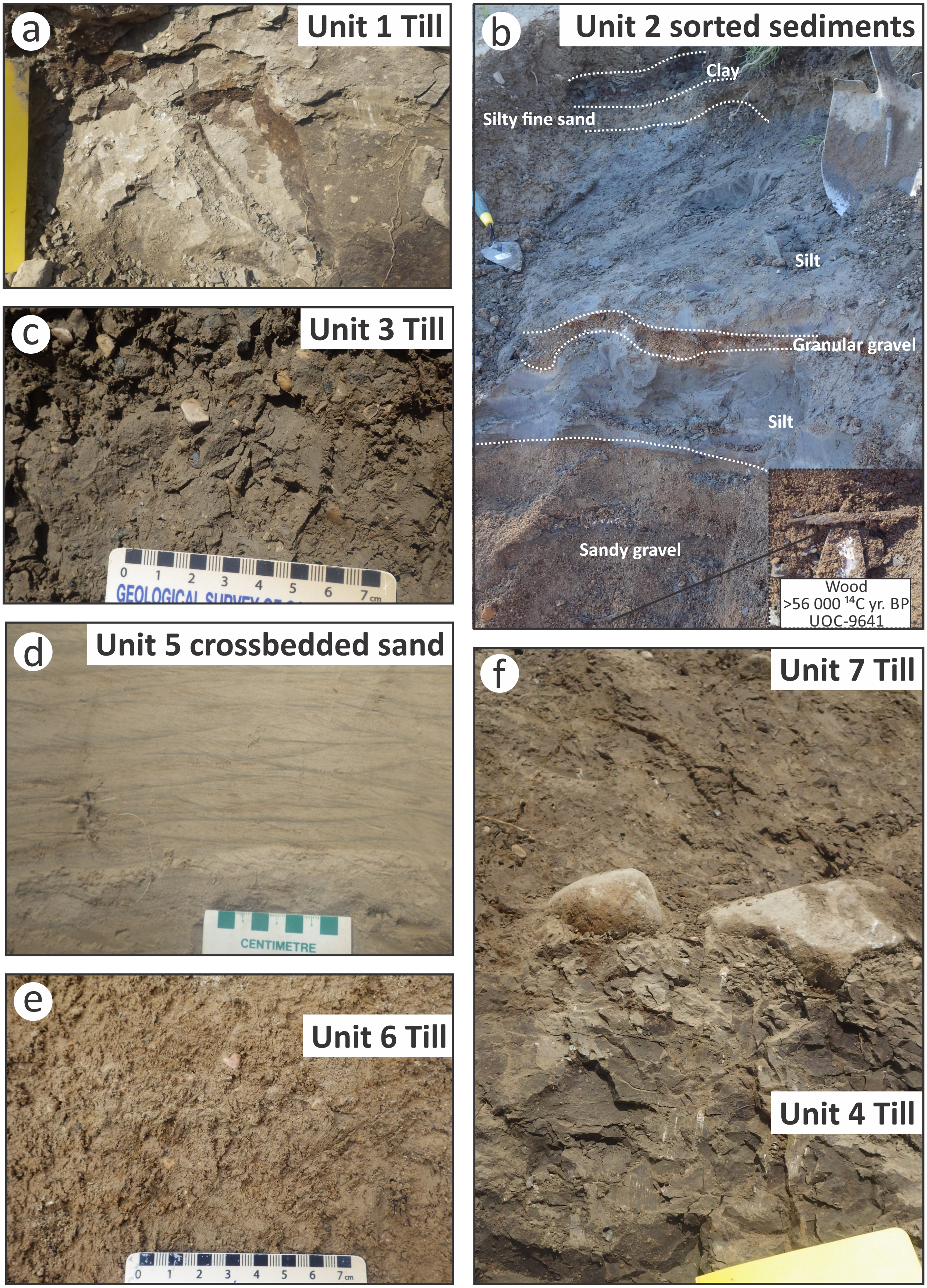

Figure 10*: Photo examples of sediment for each identified stratigraphic unit:* ***a)*** *Unit 1 till at section 17-542;* ***b)*** *Unit 2 sorted sediments at section 16-416 that contains wood with a non-finite radiocarbon age;* ***c)*** *Unit 3 till at section 17-536;* ***d)*** *Unit 5 fine sand with ripple cross-laminations at section 16-407;* ***e)*** *Unit 6 till at section 17-519;* ***f)*** *sharp contact with a boulder pavement that separates Unit 7 till and Unit 4 till at section 17-542. Please note, additional sediment photos are provided for each section alongside the stratigraphic column in Appendix 2.*

This red matrix colour has previously been attributed to the till containing elevated proportions of pink or red carbonate detritus within the till (Thorleifson et al., 1993; Gao et al., 2020). The source of pink to red carbonate has been thought to be either Devonian rocks in the centre of the Hudson Bay Basin (Dredge and Nixon, 1992; Thorleifson et al., 1993; Dredge and McMartin, 2011) or from the Silurian-aged Kenogami River Formation (Gao et al., 2020).

This study encountered two occurrences of relatively old (Unit 1) compact red till that is a 0.2–0.3 m thick bed within an otherwise dense dark greyish brown to brown till (Figure 11a, b). In both cases, the sediment has elevated fine-grained red siltstone to sandstone clast concentrations (>98th percentile [8.6 and 17.5 ct. %]; e.g., Figure 11c). These red siltstone and sandstone clasts are interpreted to be sourced from the Kenogami River Formation (middle member). Hence, we suggest that the distinctive red colour of these tills is attributed to comminution of the recessive fine-grained red sandstone and siltstone clasts into the till matrix and not from the incorporation of pink to red carbonate clasts. Indeed, in the Gillam area the highest proportion of pink carbonate clasts are found within a brown till (M.S. Gauthier, unpublished data, 2013–2023).

To investigate the dispersal patterns from this bedrock source, the concentration of fine-grained red siltstone to sandstone and pink to red carbonate (both classes interpreted to be sourced from the Kenogami River Formation, middle member) is summed for each sample and plotted in Figure 12. The distribution of till with elevated proportions (>98th percentile [>6.3 ct. %]) of Kenogami River Formation, middle member clasts is not related to any specific stratigraphic unit (Figure 12). Interestingly, other than the two occurrences of red till, there are elevated proportions of Kenogami River Formation, middle member clasts documented at four sites (two surface samples and two sections) that are spatially coincident. The two surface sites were sampled from streamlined landforms situated within the SSW-trending Hayes flowset. The till at the two sections (n = 6 samples) has a yellowish-brown matrix and is correlated to Unit 6 based NW-trending ice-flow data at section 16-407 (Appendix 2, Figure 18). Thus, elevated proportions of Kenogami River Formation, middle member detritus is documented at locations that were deposited by near perpendicular trending ice flow, but are spatially coincident. The KK1 drillcore also contains elevated fine-grained red sandstone clasts (Kenogami River Formation, middle member) in till from 97–146 m bgs (Hodder, 2018b). The exact location of Kenogami River Formation, middle member bedrock is poorly constrained in the study area (Figure 3), but there is no mapped source in the up-ice direction (SE) of these two sections. This could indicate an unknown occurrence to the SE or provide evidence of a complex palimpsest dispersal from known bedrock sources to the northeast. The elevated concentrations in the Hayes flowset could be related to SSW-trending dispersal from bedrock occurrences to the northeast, similar to the red till in Unit 1 that was deposited by SW-trending ice flow, or these elevated concentrations could be an inherited compositional signature from previous NW-trending dispersal. Nonetheless, the simplest explanation here is multiple sources of Kenogami River Formation, middle member detritus or that our current understanding of the extent of this bedrock unit in the Kaskattama highland region is poorly constrained.

Till-matrix geochemistry signatures of economic interest

Till-matrix geochemistry datasets are published in Appendices 6–8 and all interested parties are encouraged to explore these datasets further. This report highlights several till-matrix signatures of interest that were identified through exploratory data analysis. This includes eight samples with elevated Zn, Ni, Co and Fe; plotted on probability plots and spatially in Figure 13. The highest till-matrix (<63 µm size fraction) concentrations of Fe, Zn and Ni are from till sampled on a NW-trending streamlined landform (sample 112-16-411-C01 on Figure 15). Four till samples with elevated Fe-Ni-Zn±Co signatures were sampled at section 17-530, which is situated near the boundary between the Hudson Bay Basin and Precambrian shield (Figure 13). The two till samples from the lowermost till unit exposed at section 17-530 (Unit 3, interpreted NW-trending ice flow) have elevated granitoid concentrations relative to till sampled from the same stratigraphic unit (Appendix 4, Figure 44). This indicates that there is a possible local granitoid source. The proximity of section 17-530 to the mapped contact with the Precambrian shield suggests that this is a reasonable possibility. Three till samples from section 16-407 and 16-416 have elevated a Fe-Ni-Zn geochemical signature, and are also elevated in Kenogami River Formation clasts (16-407 and 16-416; compare with Figure 12). Interestingly, not all samples elevated in Kenogami River Formation clasts have a similar geochemical signature, which would suggest additional factors are influencing the matrix geochemical signature.

The case for the occurrence of shallow buried Precambrian bedrock

The Kaskattama highland is one of several distinct patches of elevated terrain in the flat-lying Hudson Bay Lowland region of Ontario and Manitoba, which are commonly referred to as the Sutton Ridge and Kaskattama highland, respectively (Figure 14a). The Sutton Ridge contains a series of Precambrian inliers that are cuestas with steep-facing south faces that rise up to 90 m above the surrounding peatland with gentle sloping north faces that have been sculpted by glaciers – similar to roches moutonées (Stott et al., 2010). These rocks are part of the Proterozoic Circum Ungava belt and were formed during the Trans-Hudson Orogen, which is the same tectonic event that formed the Fox River belt in Manitoba (Stott et al., 2010). Despite the occurrence of bedrock ridges that rise dramatically 90 m above the surrounding peatlands, there is thick Quaternary sediment (92–134 m) within 15 km of these bedrock ridges (Figure 14c), which indicates that the bedrock topography and Quaternary sediment thickness is highly variable in the region. Furthermore, it's likely that the Sutton Ridge—a local topographic bedrock high—has facilitated the

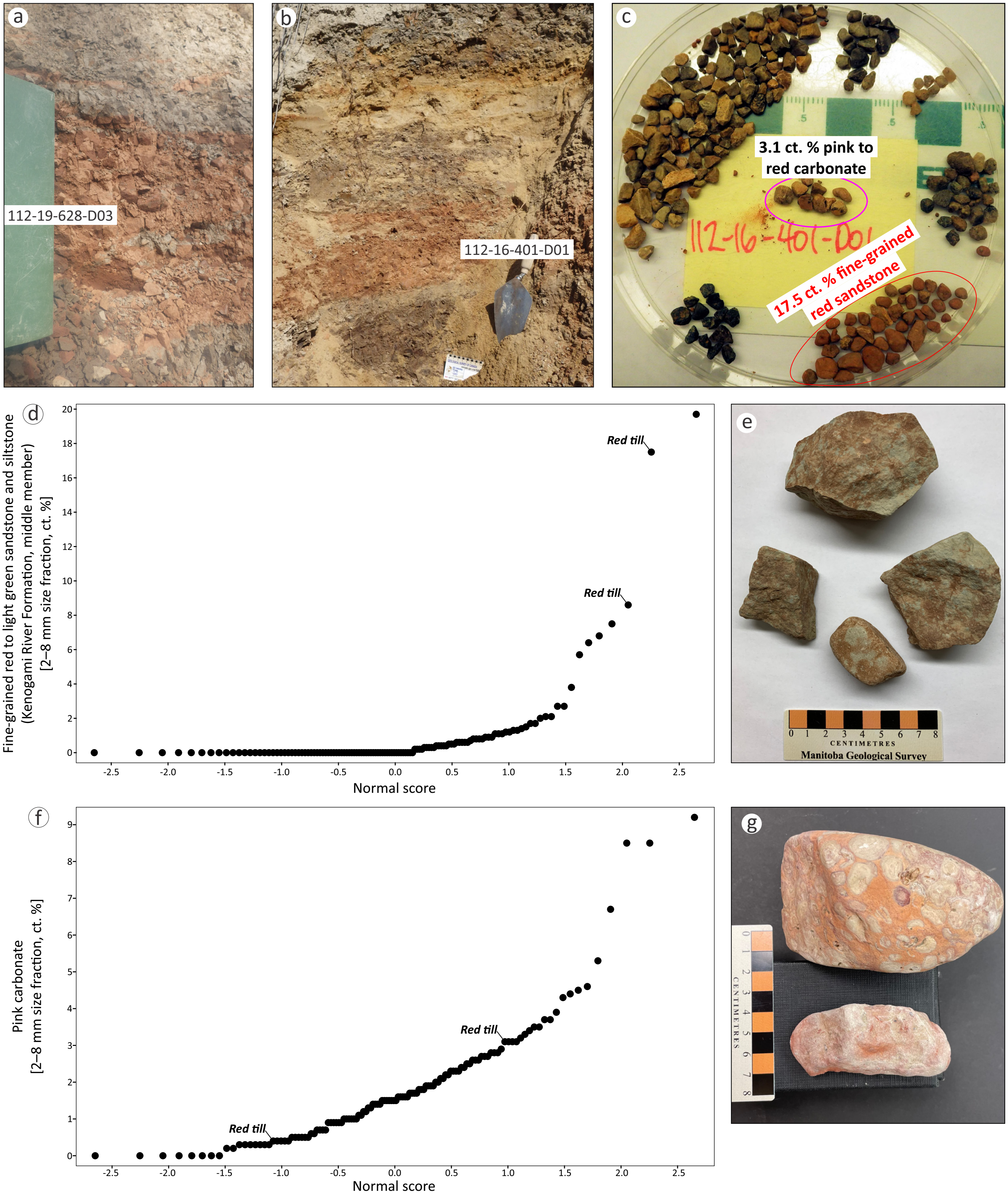

Figure 11: *Examples of red till and normal probability plots for selected classes:* ***a)*** *red till observed in Unit 1 at section 112-19-628;* ***b)*** *red till observed in Unit 1 at section 112-16-401;* ***c)*** *clasts in the 2–4 mm size fraction of sample 112-16-401-D01 sorted by rock type with the proportions of fine-grained red sandstone and pink to red carbonate clasts highlighted;* ***d)*** *probability plot of fine-grained red siltstone and sandstone clasts with red till samples highlighted;* ***e)*** *hand specimen examples of Kenogami Formation, middle member rocks;* ***f)*** *probability plot of pink carbonate clasts with red till samples highlighted;* ***g)*** *hand specimen examples of pink carbonate rocks with the top cobble containing a high proportion of fossils.*

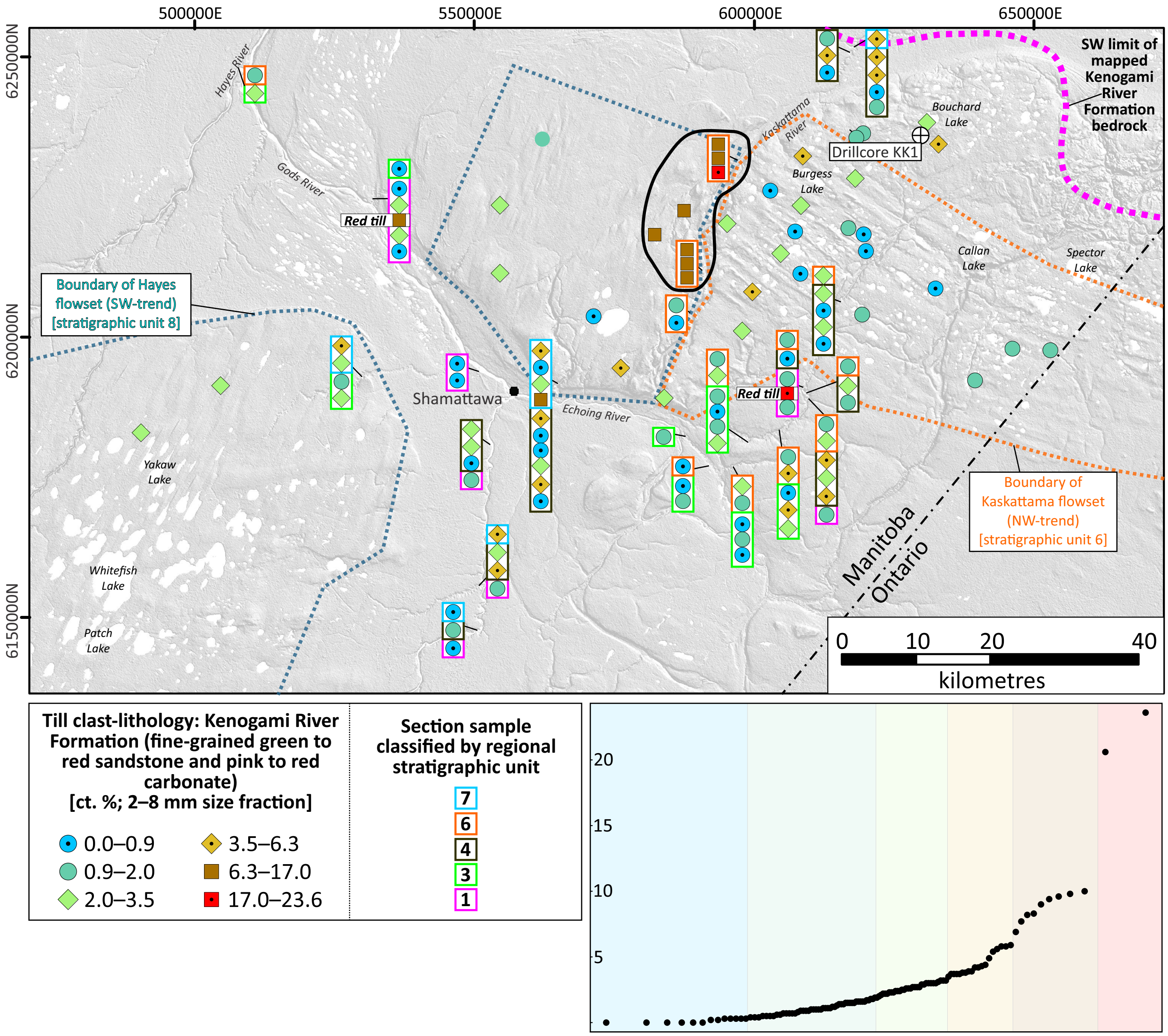

Figure 12: *Distribution of interpreted Kenogami River Formation, middle member clasts (fine-grained red sandstone and pink to red carbonate summed) in till samples. An area with relatively elevated Kenogami River Formation clasts is highlight by the black polygon.*

deposition of sediment, similar to how crag-and-tail landforms form but at a much larger scale. Considering that the Kaskattama highland is the only other significant highland in the southwestern HBL (Figure 14a), it is not unreasonable to expect a similar shallow-buried bedrock topographic high or Precambrian inlier buttressing the Kaskattama highland, with the Sutton Ridge being an analogous geological setting in this model.

Unconsolidated sediment thickness is largely unknown for vast regions of northeastern Manitoba (Hodder and Gauthier, 2021), and this is exacerbated in the Kaskattama highland where there is only a single drillcore. The drillcore targeted a circular airborne magnetics anomaly and intersected sorted sediments of an unknown age between 223 and 257 m depth, which could be Paleogene or Cretaceous (Nicolas and Armstrong, 2017), but are currently not mapped as a bedrock unit in the region. These lowermost sorted sediments have been described to contain “layers rich in coarse (1–3 mm) magnesium-rich phlogopite mica which can only be derived from an igneous, ultramafic, or metamorphic source” (Assessment File 74223). The spatial extent of these sorted sediments was delineated further by a magnetotelluric survey over the northern edge of the Kaskattama highland (Craven et al., 2017; Ferguson et al., 2023), which suggest that there is possibly a basin in the area that is unmapped.

The possibility of a bedrock inlier buttressing the Kaskattama highland is supported by the recovery of elevated Precambrian clasts in surficial till at two sites (Figure 14b). In both cases, there is no known local bedrock source that could easily explain the elevated Precambrian clast composition of these surficial till samples. Sample 112-16-411-C01 contains 79.4 ct. % and sample 112-16-425-A01 contains 62.7 ct. % Precambrian clasts (Figure 14). Till sample 411-C01 has the highest concentration of UGG clasts in the dataset (Figure 15; 55.2 ct. % [2–8 mm size fraction])

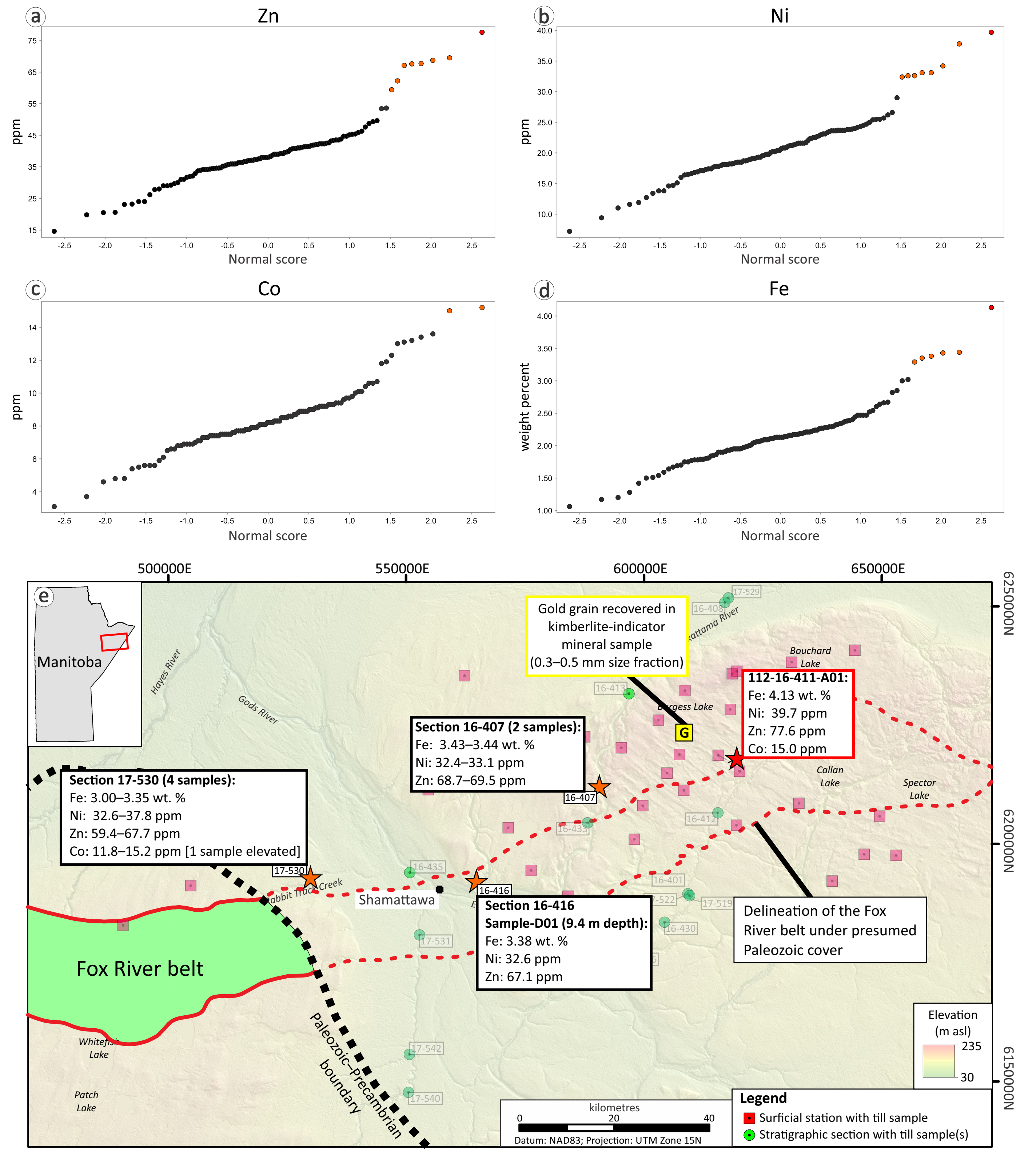

Figure 13: *Normal probability plots displaying the distribution of* ***a)*** *Zn,* ***b)*** *Ni,* ***c)*** *Co,* ***d)*** *Fe and* ***e)*** *the location of till samples with the highest concentrations that are highlighted by the orange or red points in a–d, which correspond to the star colour in (a).*

and the highest proportion of base metals Fe, Zn, Ni and Co (Figure 13). Notably, these values are also elevated when compared to till samples in the province-wide dataset (Fe >99th percentile; Zn >97th percentile; Ni >94th percentile and Co >97th percentile; Gauthier, 2020). This till sample is from a streamlined landform that was formed by NW-trending ice flow and is part of the Kaskattama flowset (Figures 5, 9c). The high base metal values suggest that the UGG clasts that comprise 55.2 ct. % of the till sample contain more rock types than just greywacke clasts. Till sample 112-16-425-A01 is from a streamlined landform formed by SSW-

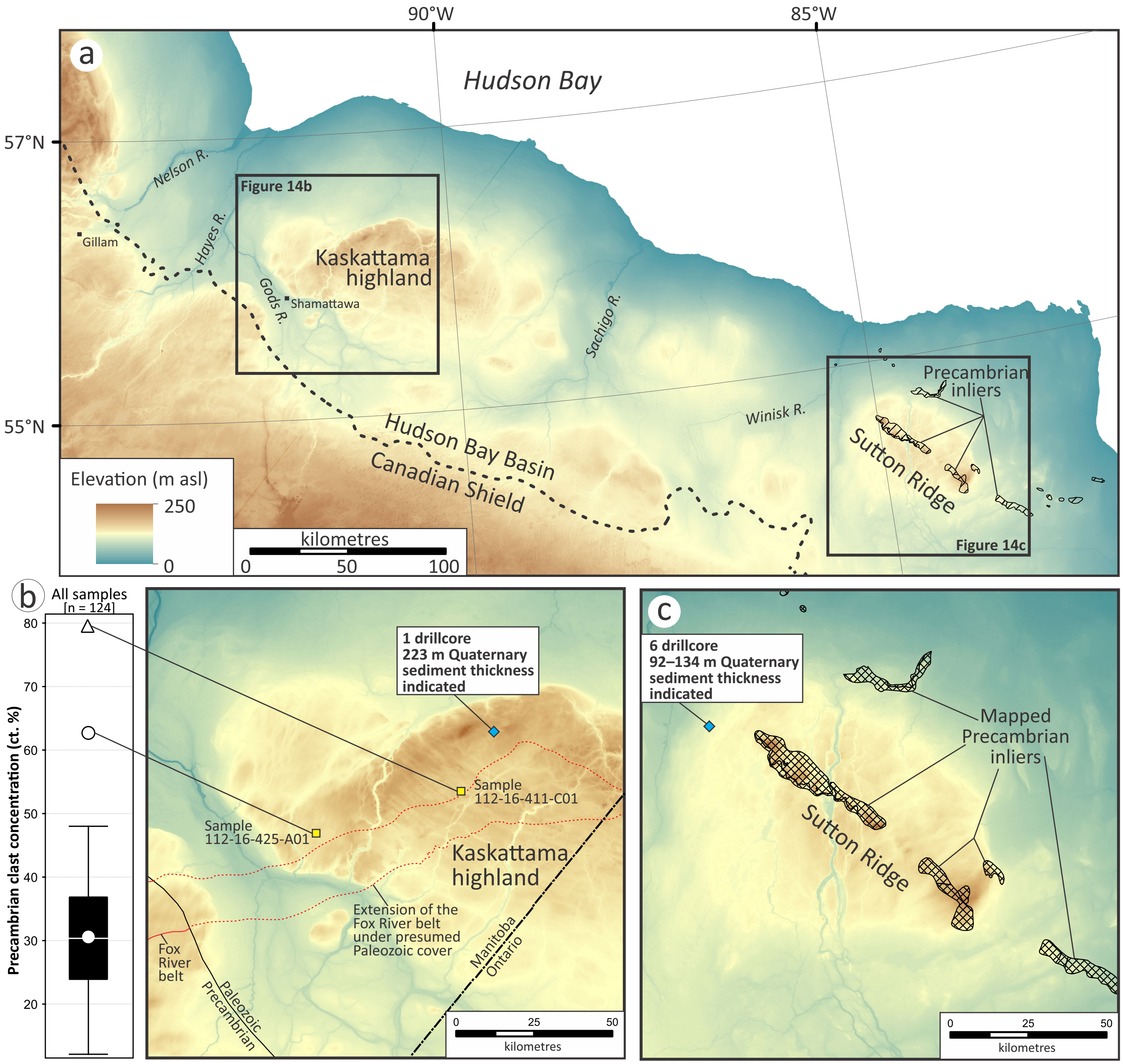

Figure 14: *Elevation of northeastern Manitoba and northwestern Ontario and comparison between the Kaskattama highland and Sutton Ridge:* ***a)*** *elevation model of the region highlighting the two highlands in the region that rise above the flat-lying Hudson Bay Lowland terrain;* ***b)*** *proportion of Precambrian clasts in till samples from this study area and spatial location of elevated surficial samples in the Kaskattama highland area;* ***c)*** *Sutton Ridge area where Precambrian inliers have been mapped in the region.*

trending ice flow and is part of the Hayes flowset (Figures 5, 9c). Indeed, these two till samples have the highest count percent of Precambrian shield clasts for tills that overlie Paleozoic bedrock (n = 593; internal MGS database), between the Nelson River and the Ontario border. The morphological similarities of the Kaskattama highland to the Sutton inlier coupled with elevated Precambrian clasts in surface till are intriguing and could indicate that the underlying bedrock topography is much more complex than currently understood. It is worth noting that any Precambrian ridge (or crag) would have affected the depositional and erosional patterns during the Paleozoic era, which could result in not only the formation of a sub-basin, but also in the preferential preservation certain sediments (e.g., Kenogami Formation).

Conclusions

This study provides the first investigation of the Quaternary geology in the remote Kaskattama highland region and releases the datasets to support interpretations (T.J. Hodder, M.S. Gauthier, M. Ross, S.E. Kelley, O.B. Lian, S.A. Dalton and S.A. Finkelstein, work in progress). The region contains a thick depositional record and at least five distinct till units and at least two intertill nonglacial units were identified. The subsurface bedrock geology

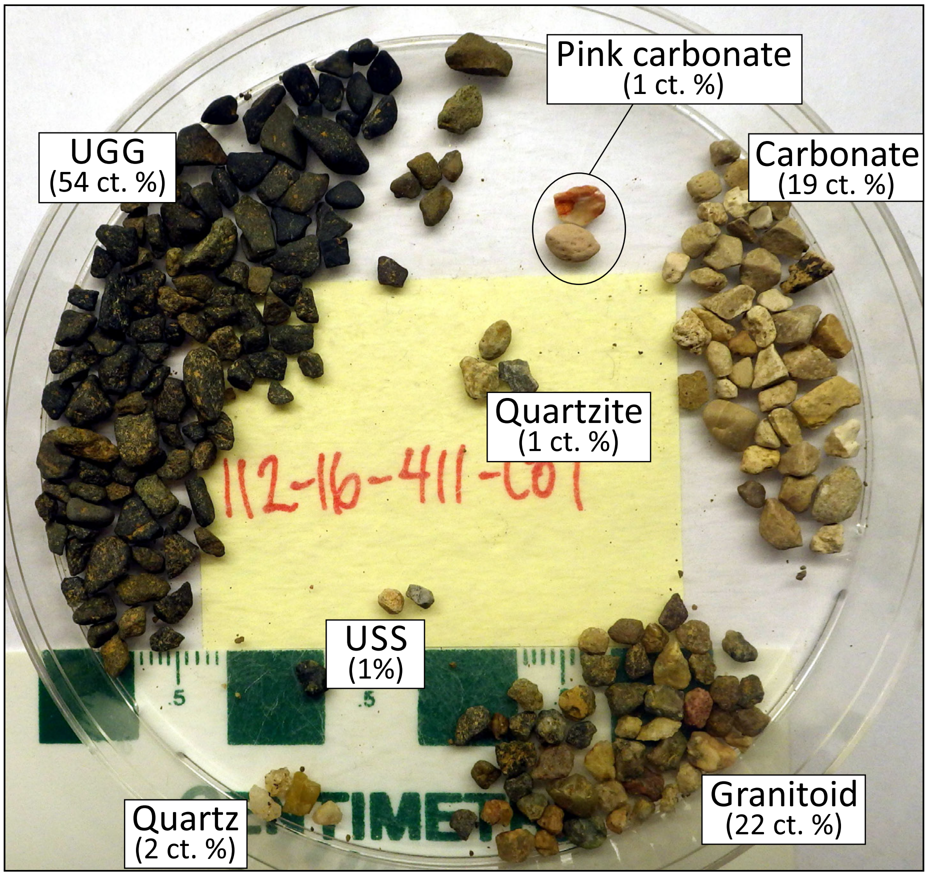

Figure 15: *Sorted till clast-lithology counts (2–4 mm size fraction) of surficial till sample 112-16-411-C01. Count percentages shown are for the 2–4 mm size fraction. Abbreviations: UGG, undifferentiated greywacke and greenstone; USS, undifferentiated sandstone and siltstone.*

and topography of the region is largely unknown and a theory is presented herein, supported by till-composition data, that the highland be buttressed by a bedrock topographic high, such as a Precambrian inlier. Therefore, it is unlikely that the highland is composed entirely of thick Quaternary-aged sediment. In this scenario, this bedrock topographic high has acted as a mega-scale crag-and-tail feature that has facilitated the deposition of sediment throughout the Quaternary period forming the Kaskattama highland.

Mineral exploration considerations

Surface access to the Kaskattama highland is hindered by extensive Boreal Forest cover over much of the region. During this study, helicopter landing at surficial stations was restricted to recently burned areas where the machine could be shut down, or bogs where the machine needed to be kept running. The use of a helicopter with floats would greatly increase access and the ability to shut down in bogs, fens and lakeshores throughout the region. River sections can largely be accessed by helicopter and provide insight into the near-surface (≤32 m bgs) Quaternary record. Note, due to variable source and age of surficial sediments, soil sampling would not be effective and is not recommended. Till is the recommended sample medium. To properly document this record and collect till samples, the sections must first be cleared of colluvium to expose in-situ sediments. It is recommended to completely describe the sediments exposed at any section to try and understand where you may be within the stratigraphic framework. Next, if sampling till, then you must collect accompanying ice-flow data from these beds through the measurement of clast fabrics.

The greatest unknown factor for drift prospecting in the region is that the Kaskattama highland is covered by a largely unknown thickness of Quaternary sediments. For example, if the highland is composed entirely of thick (>50 m) Quaternary sediments, then drift prospecting will require drilling to access and analyze the Quaternary sediments closest to bedrock. However, if bedrock is closer to surface in some areas, as suggested by the two sites herein with elevated proportions of Precambrian clasts and till-matrix base metal values, then a shallower till sampling program could help elucidate exploration targets. Further understanding the thickness of these sediments and bedrock topography will help guide drift exploration efforts.

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