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TILL COMPOSITION OF THE ARDEN AREA, SOUTHWEST MANITOBA (NTS 62J6)

Manitoba Geological Survey

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Till composition of the Arden area, southwest Manitoba (NTS 62J6)

by T.J. Hodder and M.S. Gauthier
Manitoba Geological Survey
Winnipeg, 2019

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Cover illustrations:

Left: MGS geologist M. Gauthier observing the characteristics of boulders derived from till in the Arden area.

Right: MGS geologist T. Hodder examining the surficial sediments exposed along a ditch cut in the Arden area.

Abstract

The Arden area (NTS 62J6) of southern Manitoba is draped by till. To aid drift exploration in this region, we analyzed regional till samples for kimberlite-indicator minerals (KIM) and to determine background composition and provenance. Univariate and multivariate statistics were used with both till-matrix geochemistry and till-clast lithology. This compositional analysis shows that the till can be subdivided along a continuum between two end-member populations: locally-derived till and more distally-derived till. The locally-derived component of the till consists of Cretaceous siliceous shale and/or black shales. *Inoceramus sp.*-bearing clasts, sourced from the Favel Formation, are an easily identifiable local marker–especially when the more friable black shales are no longer present as clasts in the till. The distally-derived component of the till consists of Paleozoic carbonate and Precambrian shield rocks. The proportion of local to distal detritus is related to accessibility of the local bedrock to erosion during glacial movement, in addition to englacial/subglacial transport distance and direction. The transport direction(s) are somewhat poorly constrained; ice flow interpreted from clast fabrics was to the east-southeast (122°), southeast (168°), south (184°, 195°, 206°) and southwest to west (224°, 245°, 266°). A 160°-trending dispersal train of Favel Formation clasts and molybdenum within the till matrix, was mapped at least 20 km down-ice from subcropping Favel Formation. A total of 44 kimberlite-indicator minerals were recovered during this till sampling program, and can now be placed into a regional till-compositional context. This study highlights a possible 160°-trending garnet-KIM dispersal train sourced from NTS 62J11.

Résumé

La région d'Arden (SNRC 62J6) du Sud du Manitoba est recouverte de till. Afin de faciliter l'exploration à flanc de colline dans cette région, nous avons analysé des échantillons de till provenant de celle-ci afin de trouver des minéraux indicateurs de kimberlite et d'en déterminer la composition et la provenance. Des statistiques à une variable et à plusieurs variables ont été utilisées à la fois avec la géochimie des matrices de till et la lithologie des clastes de till. Cette analyse de la composition démontre que le till peut se subdiviser le long d'un continuum compris entre deux populations de membres extrêmes : le till d'origine locale et le till d'origine distale. La partie du till d'origine locale se compose de schiste siliceux du crétacé et (ou) de schistes noirs. Les clastes contenant des inocérames, qui proviennent de la formation de Favel, constituent un marqueur local facilement identifiable, surtout lorsque les schistes noirs, qui sont plus friables, ne sont plus présents dans le till sous forme de clastes. La partie du till d'origine distale se compose de carbonate paléozoïque et de roches du bouclier précambrien. La proportion de roches détritiques d'origine locale et distale est liée à l'exposition du substratum rocheux local à l'érosion lors du mouvement glaciaire, ainsi qu'à la distance sur laquelle le transport intraglaciaire/sous-glaciaire s'est produit et à la direction de celui-ci. La ou les directions dans lesquelles le transport s'est effectué sont plutôt mal définies : selon l'interprétation de la fabrique des clastes, les glaces se sont déplacées vers l'est-sud-est (122°), le sud-est (168°), le sud (184°, 195°, 206°) et du sud-ouest vers l'ouest (224°, 245°, 266°). Une traînée de dispersion, de 160° d'orientation, des clastes provenant de la formation de Favel et du molybdène contenus dans la matrice de till, a été cartographiée à au moins 20 km en aval glaciaire de la formation de Favel subaffleurante. Au total, 44 minéraux indicateurs de kimberlite ont été récupérés au cours de ce programme d'échantillonnage de till; ils peuvent maintenant être placés dans un contexte régional de composition du till. Cette étude souligne la présence d'une éventuelle traînée de dispersion, de 160° d'orientation, de grenat indicateur de kimberlite provenant de la SNRC 62J11.

TABLE OF CONTENTS

Page

TABLES

FIGURES

APPENDICES

Introduction

Quaternary geology studies were undertaken in the Arden area (NTS 62J6; Figure 1), in 2015 (Hodder and Trommelen, 2015). This report provides the field site, stratigraphy and till-composition datasets to accompany the release of the kimberlite-indicator mineral sample results from the same area (Hodder and Gauthier, 2016). This work builds upon preliminary aggregate mapping (Mihychuk and Groom, 1979) and soil mapping (Ehrlich et al., 1958; Langman, 1984). A 1:50 000 scale surficial geology map is in preparation.

Southwest Manitoba kimberlite-indicator mineral (KIM) sampling

Five of the twelve G10 garnets recovered from an ultra-low density (1 sample per 800 km^2) prairie-wide survey were located in southern Manitoba (Thorleifson and Garrett, 1993). These initial results prompted a follow-up KIM survey (1 sample per 100 km^2) by the Manitoba Geological Survey (MGS) during the 1994 field season (Matile et al., 1996). While the prairie-wide survey collected 25L (mean moist weight of 28 kg) of till per sample, the Manitoba study collected 40L (~70 kg) of till per sample. Despite processing nearly twice the amount of sediment per sample, and a finer sample density, only one G10 garnet was recovered. The G10 garnet was from the Arden map area (NTS 62J6; Figure 1), prompting further KIM sampling as part of this study. Till-matrix geochemistry was also analyzed during the follow-up survey (Matile et al., 1996).

Regional setting

The study area is located in southwestern Manitoba (Figure 1). Elevation in the map area ranges from 270 m above sea level (asl) in the northeast, to 500 m asl in the west. Local

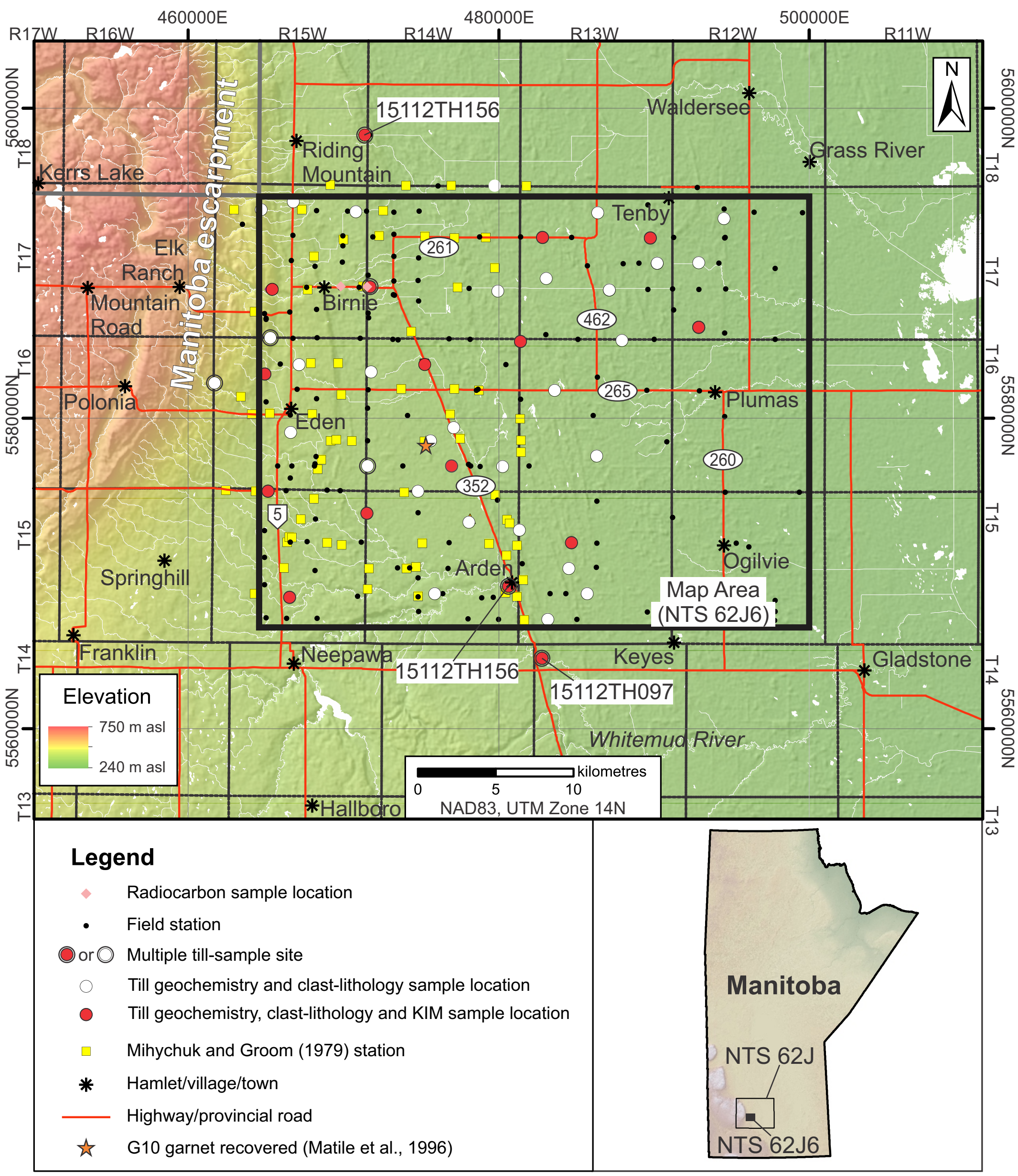

Figure 1: *Field sites and till samples within the Arden area (NTS 62J6), southwest Manitoba. MGS field sites from 1979 which were used as part of this study are also depicted. Sections where ice-flow data was obtained are labelled.*

relief is generally 5 to 10 m, except in the northwest part of the study area along the slopes of the Manitoba escarpment, where relief can be up to 60 m (Figure 1).

Bedrock geology

The study area is underlain in the east by the Jurassic upper member of the Amaranth Formation, which consists of gypsum and anhydrite (Nicolas, 2009; Nicolas et al., 2010). The Reston Formation is present in the central and east-central parts of the study area (Nicolas et al., 2010; Figure 2) and consists of shale and argillaceous limestone (Nicolas, 2009). The Melita Formation is present west of Arden and is composed primarily of shale, with some interbeds of sandstone (Nicolas, 2009; Nicolas et al., 2010). The Cretaceous Swan River Formation sandstone is present southwest and southeast of Arden (Nicolas et al., 2010; Figure 2). The west portion of the study area is underlain by the Cretaceous Ashville, Favel, Carlile and Pierre formations, which are shale dominated with minor siltstone, limestone and bentonite (Nicolas, 2009). The Keld Member of the Favel Formation (Favel) contains abundant *Inoceramus sp.* (McNeil and Caldwell, 1981). Fragments of *Inoceramus sp.* and clasts derived from the Favel Formation are easily identified in clast-lithology counts (Figure 3a, b). The Odanah Member (Odanah) is a hard, siliceous shale (Figure 3c), which is also identifiable in clast-lithology counts (Figure 3d).

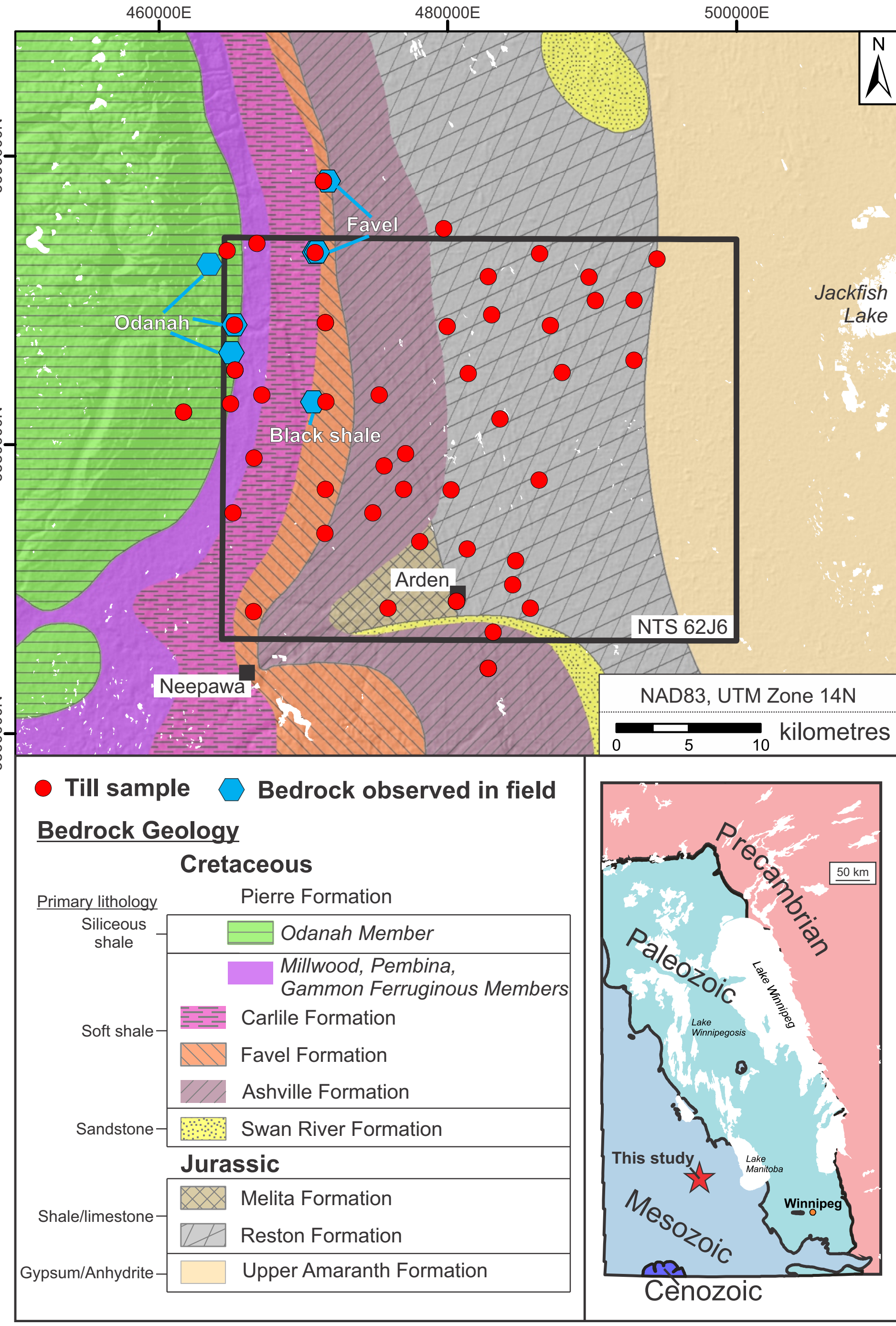

Figure 2: *Bedrock geology of the study area after Nicolas et al. (2010).*

Figure 3: *Examples of clasts recovered from till that are derived from the Favel* ***(a, b)*** *and Odanah* ***(c, d)*** *bedrock units.*

Quaternary geology

Alluvial and lacustrine sediments overlie till and/or bedrock across most of the study area (Figure 4). The region was repeatedly glaciated during the Quaternary, and most recently by the Laurentide Ice Sheet (LIS) during the Wisconsin glaciation (Klassen, 1979; Teller and Fenton, 1980; Clayton and Moran, 1982). Paleo-ice flow was towards the southwest, and then towards the south during the late Wisconsinan (Teller and Fenton, 1980). Following the initial retreat of the LIS, the area was inundated by glacial Lake Agassiz around 11.3 ^{14}C ka BP (Clayton and Moran, 1982). Retreat was not steady, as several oscillations (re-advances) of the LIS margin are evidenced by till overlying deltaic sediments south of Arden (Sinclair and Phimister, 1981) and buried forests in the northern United States (Clayton and Moran, 1982). Thick lacustrine sands were deposited in the eastern part of the study area, by underflow fans when major spillways drained towards the east into Lake Agassiz (Fenton et al., 1983). Prominent beach ridges formed at the shorelines of Lake Agassiz during retreat of lake waters from the area. Holocene alluvial sediments are thickest in the west (up to 10 m) and thin eastward. These sands, silts and gravels were deposited by water flowing towards the east off the escarpment.

Methods

Field data collection

Field work was undertaken during a three-week period in the summer of 2015 and two days in 2018. A total of 237 field sites were visited to ground truth the surficial geology mapping, collect till samples, and establish the ice-flow history. At each site, the sediments were described and geomorphic and terrain characteristics were noted. Site location, sample descriptions and additional comments are provided in Appendix 1. Seven exposures of Quaternary sediments were investigated in detail during this study. Stratigraphic columns and photos of studied sections are presented in Appendix 2.

Till sampling

A till-sampling survey was conducted in the map area at roughly 1 sample per 4 km^2. Grid-based sampling was not possible, and instead till was opportunistically sampled at surface, beneath a veneer of overlying sediments or at exposures that allowed sampling of till at depth (Figure 1). A total of 61 till samples, of ~2 kg each, were collected from exposures of Quaternary sediments (19 samples) and from surficial stations (42 samples). An additional 22.7 L of till was collected at 20 sites

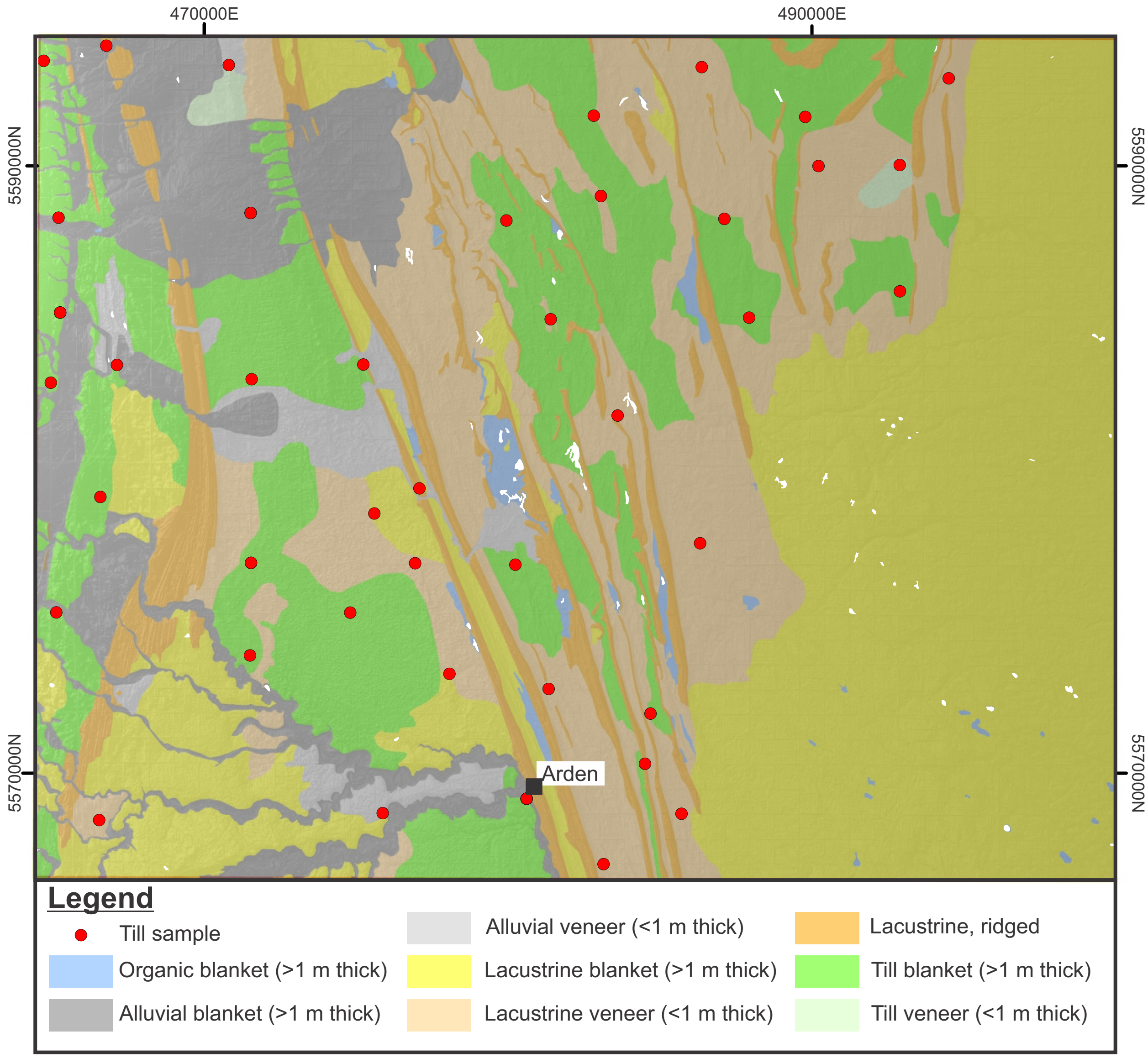

Figure 4: *Simplified surficial materials of the Arden (NTS 62J6) area, modified from ongoing mapping. Background is a hillshaded LiDAR (light detection and ranging) image (Manitoba Land Initiative, 2018).*

for KIM analysis (Figure 1). The surface-till samples (between 25 and 130 cm depth) were collected with a shovel or extendable Dutch auger from the B/C or C soil horizon in hand-dug pits/auger holes. Field duplicates were collected approximately every 10 samples (5 total), to test field variability.

Till-clast fabric

To obtain ice-flow data, field measurements of the long-axes orientation, or fabric, of clasts and particles within till are used as a proxy. This is because certain shapes of clasts, defined as a particular arrangement of the a-axis (longest), b-axis (middle) and c-axis (shortest), are statistically proven to often align parallel to the direction of stress (Holmes, 1941). Till fabrics were conducted at nine sample sites across three sections. Sites were chosen based on uniformity of till, where no sand lenses or discontinuous bedding was present. At each site, a horizontal step was excavated at least 20 cm into the section face. Clasts were then carefully excavated and measured from within a 'box' consisting of three vertical faces of different orientations, over a max distance of 30x30x30 cm. Measurements consisted of the length of all axes and the a-axis orientation and the dip. Till-fabric measurements, stereoplots and statistics are provided in Appendix 3.

Accepted clasts included in these analyses met the following criteria:

- clast was free to rotate in the matrix (not clast-supported or close to much larger clasts),
- rod, tabular-rectangle or wedge-shaped,
- ratio of the a:b axis was 1.5 or greater, and
- dip of the a-axis was less than 80° (average=25° and standard deviation=18°).

At two sample sites, measurement of the a-b plane was conducted in addition to the a-axis. This method includes measurement of the length of all axes, and the orientation and dip of the a-b plane. Accepted clasts included in these analyses met the following criteria:

- shape: tabular-rectangular, tabular-square, wedge-shaped or ovoid with one flat side,
- ratio of the b:c axis was 1.5 or greater,
- dip of the a-b plane was less than 80° (average=40° and standard deviation=18°).

Fabric data is represented graphically on rose diagrams and Schmidt equal-area stereonets. Assuming a unimodal distribution, fabric data can be analyzed statistically using three mutually orthogonal eigenvectors (V_1, V_2, V_3), and their normalized vector magnitudes (eigenvalues S_1, S_2, S_3) (Mark, 1973, 1974; Benn, 1994). Bimodal or multimodal fabric patterns cannot be described using these procedures and must be interpreted qualitatively using stereonet and rose diagrams (Ramsden, 1970; Mark, 1973). V_1 parallels the axis of maximum clustering of the a-axes while V_3 represents the axis of minimum clustering and is orthogonal to the preferred plane of the fabric. Elongation ($E=1-(S_2/S_1)$) and isotropy ($I=S_3/S_1$) are also used to statistically define the clast-fabric shape (Benn, 1994). The elongation index indicates the preferred orientation in the V_1/V_2 plane, where E=1 is defined as a very strong fabric in perfect alignment. The isotropy index measures the similarity to a uniform distribution, where I approaching 0 is defined as a very strong fabric in perfect alignment.

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 sieved, using stainless-steel mesh screens, to obtain the <2 mm size-fraction for texture and <63 µm size-fraction for geochemical analyses and carbonate-content determination. The remainders of the original samples were archived at MGS storage facilities.

KIM sample processing, visual KIM counts and microprobe analysis was provided through in-kind support provided by De Beers Group of Companies (De Beers). Sample locations were withheld from De Beers to ensure security and allow equal-opportunity for follow-up by all interested exploration parties upon release of the data (Hodder and Gauthier, 2016). This data is reproduced in Appendix 4.

Clast-lithology counts

Clast lithology of the till samples was determined to help identify the dominant direction of glacial dispersal, and hence 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 (e.g., Figure 5), 4–8 and 8+ mm. The granules or pebbles within each clast-size fraction were separated according to lithology by the author, using a 10x optical microscope. B horizon till samples (n=2) were counted, but not included in the analysis stage, due to adverse effects of post-depositional soil weathering processes. The results of the clast counts are expressed as count percent (ct. %) for each size-fraction analyzed and presented in Appendix 5. Photos of sorted 2–4 mm size-fractions are presented in Appendix 6.

For interpretation of till composition and dispersal patterns, the clasts were grouped into six simplified classes (Table 1). Locally-derived clasts are included within the Cretaceous black shale (Pierre, Carlile, Favel and Ashville formations), Odanah (Odanah Member) and Favel (resistant *Inoceramus sp.* fossils from the Favel Formation, Figure 3) classes (Figure 2). Clasts that could not be assigned a lithology were classified as unknown and comments are provided in Appendix 5; the majority of these clasts are suspected to be from local sedimentary sources. Far-travelled clasts are included within the carbonate and shield classes. The carbonate clasts are likely sourced primarily from Paleozoic rocks in central Manitoba, which are situated a minimum of 50 to 90 km northeast of the study area (Figure 2). The shield clasts are primarily granitoids and greenstones derived from the Precambrian shield, which is situated a minimum of 160 km east of the study area (Figure 2).

Comminution and fractionation

When comparing the relative percentages of different clast lithologies within till, the user must be aware of the concept of comminution. Comminution is the reduction of solid material particle size (e.g., clasts) by crushing and abrasion beneath the glacier during transport of detritus. Interestingly, some rock types will break down into smaller clasts than other rock types (Dreimanis and Vagners, 1971). Also, clasts that have experienced prolonged subglacial transport have been exposed to a greater degree of comminution over time. Therefore, the effects of comminution are related to transport distance and rock type. In this study, the fractionation of clasts can be seen in Figure 6, where the three different clast-size fractions are displayed for one sample. This till sample overlies Cretaceous bedrock so the fractionation is not due to the dilution effects of local bedrock input. The 8+ mm size fraction is predominately carbonate, and the sample only contains 4.7 ct. % granitoid clasts. The proportion of granitoid clasts increases in the 4–8 mm size fraction to 14.2 ct. %, and further increases in the 2–4 mm size fraction to 24.6 ct. %. The observation that there is an increase in granitoid clasts (and decrease in carbonate clasts) within the smallest size fraction holds true for the entire dataset (Table 2). To avoid the effects of fractionation on clast-lithology count interpretations we have chosen to use only the 2–4 mm size-fraction and not the 2–30 mm size-fraction, which is more commonly used during recent MGS studies. Second, the 2–4 mm size-fraction was also chosen because this size-fraction had the highest number of clasts counted (average of 316 per sample). Thirdly, the smaller clast-size fraction is more easily relatable to the fine-grained till matrix fraction, as it contains more distally-derived (far-travelled) material.

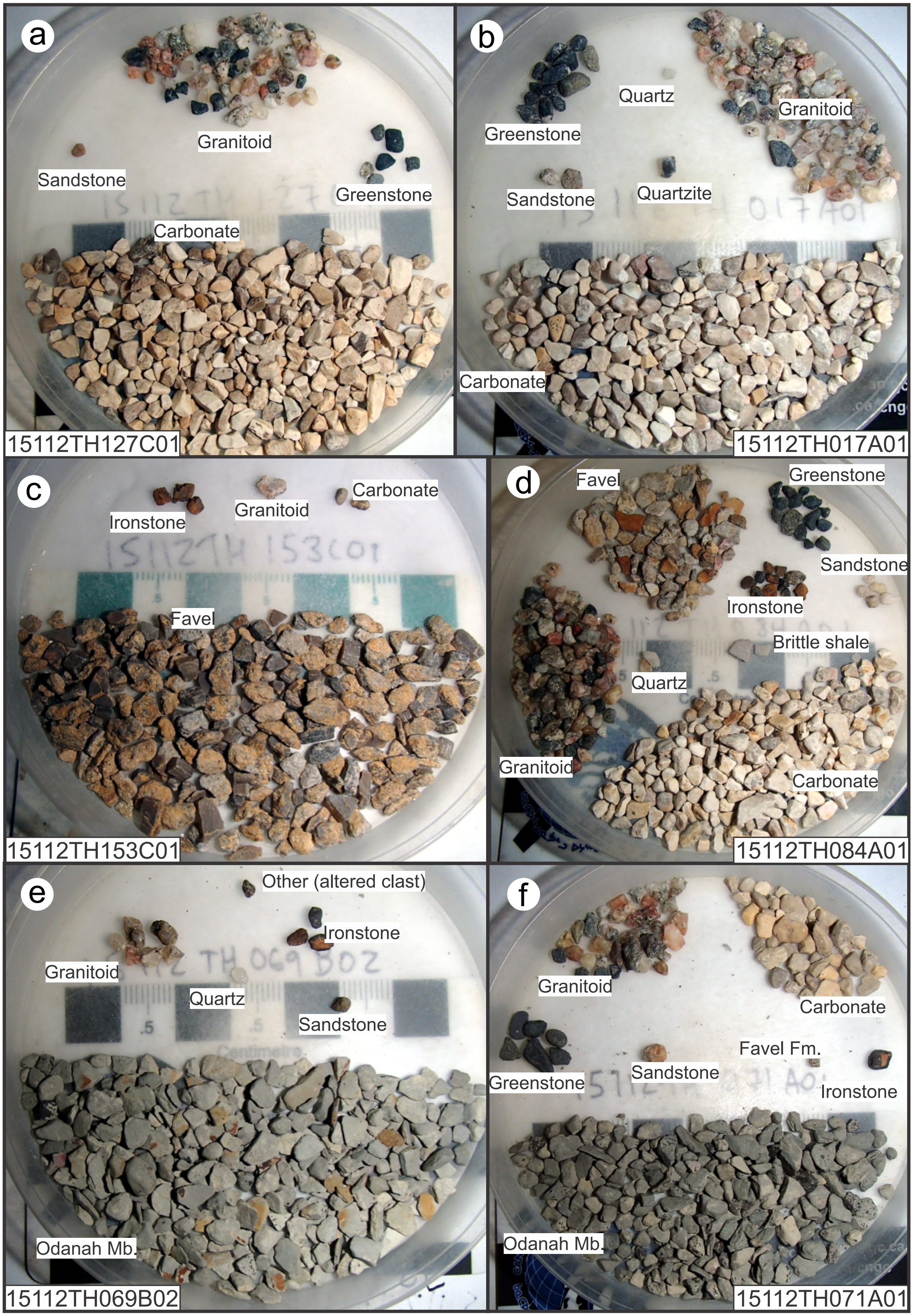

Figure 5: *Examples of sorted 2–4 mm clast-lithologies* ***(a–f)****.*

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

Simplified classes	Shield	Carbonate	Cretaceous black shale	Odanah	Favel	Unknown provenance
Detailed classes	Granitoid; Greenstone; Quartz; Quartzite	Grey, white, tan, pink or white limestone and dolostone	Black, grey or brown, soft speckled shale; black to brown, brittle shale	Grey or light grey, hard competent shale	*Inoceramus* bearing clasts	Undifferentiated sedimentary; ironstones; iron-rich sandstones; chert; other (explained in Appendix 5)

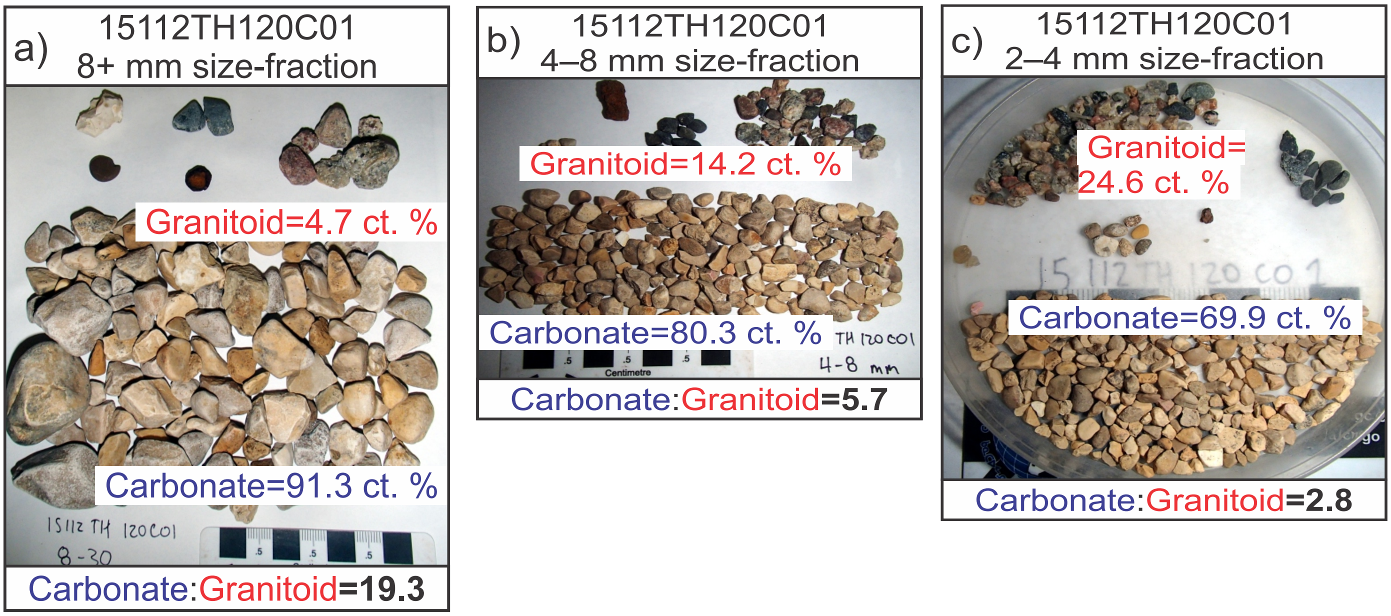

Figure 6: *Fractionation of granitoid and carbonate clasts within clast-size fractions of sample 15112TH120C01:* ***a)*** *8+ mm size-fraction;* ***b)*** *4–8 mm size-fraction; and* ***c)*** *2–4 mm size fraction.*

Table 2: Proportion of granitoid and carbonate clasts for each size-fraction analyzed.

Size-fraction		Carbonate clasts	Granitoid clasts	Carbonate:Granitoid
2–4 mm	n	11068	3682	3.0
	ct. %	57.0	18.9	
4–8 mm	n	6932	1392	5.0
	ct. %	62.2	12.5	
8+ mm	n	1792	220	8.1
	ct.%	64.1	7.9	

Effects of chemically-weathered clasts

Evidence of chemical weathering was observed in the field where granite cobbles would disintegrate into sandy granule fragments when dislodged (e.g., Figure 7a). This is problematic when interpreting the clast-lithology composition of till where one rock type is artificially inflated by chemical weathering. Sample 15112TH111A01 contained 127 (out of a total of 168 granitoid clasts; 76%) micaceous tonalite clasts (Figure 7b), and sample 1511TH079B01 contained 73 (out of a total 95 granitoid clasts; 77%) quartz syenite clasts (Figure 7c). The monolithic nature, and angular edges, of some granitoid clasts in these samples is unusual within a till sample. This observed elevated granitoid ct. % in these two samples is interpreted to be a result of the incorporation of a chemically weathered clast. These observations were kept in the clast-count table (Tables 11–13, Appendix 5), but removed from the sample population prior to calculating the clast-count percentage tables (Tables 14–16, Appendix 5).

Grain size distribution

At SRC, an aliquot of <2 mm sample material was transferred to a flask and an aliquot of Calgon® was added. Deionized water was then added to the flask and the flask was shaken until the contents were thoroughly mixed. The contents of the flask were sieved through a screen into a graduated cylinder. An aliquot of sample was immediately removed. A second aliquot of clay was removed from the cylinder after a certain period of time; the time period is dependent on the ambient room temperature. The sieved sand and aliquots of sample material were dried and 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 15 samples. Replicate samples were inserted after every 40 samples or at the end of smaller groups. Till-matrix textural results were calculated as weight percent (wt. %) of sand, silt and clay in the <2 mm size-fraction and are presented in Appendix 7.

Geochemistry

Carbonate content

At SRC, an aliquot of the till matrix (<63 µm size-fraction, agate ground) was digested using HCl, then analyzed using a PerkinElmer Optima 5300DV inductively coupled plasma–optical emission spectrometer (ICP-OES). The samples were analyzed for Ca and Mg (wt. %), and then calcite, dolomite and total carbonate were calculated. Quality-control samples were prepared and analyzed with each batch of samples. The results for carbonate content are provided in Appendix 8.

Carbon, organic carbon and sulphur

To determine carbon and sulphur, an aliquot of the till-matrix (<63 µm size-fraction) was combusted at SRC in a LECO induction furnace with an oxygen supply. The results for total carbon, organic carbon and sulphur (all in wt. %) are included in Appendix 9. The percentage of organic carbon is determined from the percentage of inorganic carbon (in an aliquot of sample) using the LECO induction furnace with an argon supply. At least one standard was analyzed in every 15 samples, as well as after all the samples. One sample duplicate was analyzed in every 40 samples. The detection limit for carbon, sulphur and organic carbon is 0.01%.

Loss-on-ignition

Loss-on-ignition (LOI) gives an estimate of the total organic content, and can help to give a measure of the degree to which the sample geochemistry has been modified by post-depositional weathering.

At SRC, an aliquot of till-matrix (<63 µm size-fraction) was weighed into the crucible and the total initial weight was recorded. The sample was placed in a muffle oven to dry. It was then removed from the oven, allowed to cool and reweighed. One in every 40 samples was analyzed in duplicate. The detection limit for the LOI method is 0.1%. The results for LOI at 1000°C are included in Appendix 10.

Partial digestion (HNO_3:HCl) ICP-MS

For the determination of 41 elements, a portion of the <63 µm size-fraction for each sample was analyzed at SRC.

Figure 7: *Evidence of chemical weathering observed in till-clast counts and within till exposures observed in the field:* ***a)*** *chemically weathered granite cobble in till at station 15112TH156 which disintegrates into sand-size fragments when moved;* ***b)*** *micaceous tonalite clasts highlighted by the red ellipse in sample 15112TH111A01; and* ***c)*** *quartz syenite clasts highlighted by the red ellipse in sample 15112TH079B01.*

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 11, 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).

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

For the determination of 49 elements and oxides, a portion of the <63 µm size-fraction for each sample was analyzed at SRC. An aliquot of the fraction was digested to dryness in a hot-block digesting system using a mixture of ultra-pure concentrated acids (HF:HNO_3:$HClO_4$). The residue was dissolved and made up to volume using de-ionized water prior to analysis. The sample solution was analyzed by ICP-OES to measure Al, Ba, Ca, Cr, Fe, La, Li, Mg, Mn, P, K, N, Sr and T, and by ICP-MS for the remaining elements. The analytical results are presented in Appendix 12, together with analytical data for control reference standards, analytical and field duplicates, and blanks.

'Total' digestion, instrumental neutron activation analysis (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 13, together with analytical data for control reference standards, analytical and field duplicates, and blanks.

Radiocarbon analyses

A piece of buried wood, and some snail shells, were collected and submitted for radiocarbon dating as part of this project. These samples were first cleaned and identified by A. Telka (Paleotec Services), and then submitted to the W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory (Irvine, California) for accelerator mass spectrometry radiocarbon dating. Sample photos and radiocarbon results are presented in Appendix 14.

Statistical interpretation procedures

K-means cluster and principal component analysis

Multivariate statistical methods allow large datasets to be explored statistically, while still incorporating as much information (variables) as possible. To assist with till-provenance interpretations, we use K-means cluster analysis (K-means cluster) and principal component analysis (PCA) on the till matrix near total-digestion ICP-MS data within ioGAS software. The near-total digestion was chosen for provenance analysis because it dissolves more minerals than the partial digestion, and thus allows a more complete profile of the <63 µm size-fraction composition. Arsenic values from the partial-digestion dataset were also included, because there is a known association to shale, and arsenic is not measured by near total-digestion. Rare-earth elements (Ce, Dy, Er, Eu, Gd, Ho, La, Nd, Pr, Sm, Tb, Y, Yb) were grouped into total rare-earth elements (TREE) to reduce the total number of variables. Sample 151112TH153C01 has elevated (>95th percentile) concentrations of Ca, Na, P, Sr, Cd, Mo, Ni, U and Zn and is depleted (<5th percentile) in Na, Zr and Hf. Sample 15112TH153C01 is an outlier within the data and was removed prior to analysis.

The dataset was transformed using a centered-log ratio transformation, to avoid the effects of closure on the dataset (Grunsky, 2010). Following transformation, samples were classified by colour according to their by K-means cluster results and displayed on biplots depicting PCA results. These elemental vector plots are used to help understand the significance of identified clusters.

Results

Ice-flow

Streamlined landforms

No streamlined landforms were identified within the map area (NTS62J6), possibly because the map area is overprinted by post-glacial erosion and deposition. Outside of the study area, three sets of streamlined landforms were identified using LiDAR elevation models (Figure 8). The largest landforms are situated 45 km to the north-northeast of this study area. Here, large streamlined landforms whose morphology has been modified by post-glacial processes trend 185–190°. To the northwest of these landforms, smaller streamlined landforms trend 175°. East of the study area, in the Jackfish Lake area (Figure 8), streamlined landforms trend 160°.

Stratigraphic ice-flow data

Till-clast fabrics were measured at three sections (Figure 9) within the study area, to interpret the ice-flow direction during till deposition. At section 15112TH156 (Figure 9a), a lower till was observed underlying an upper till and an inter-till massive to cross-bedded sand unit. A clast-fabric conducted in the lower till indicates deposition by SSE-trending (168°) ice-flow. No organics were observed within the inter-till sand and the age of these sediments is unknown. Within the upper till at section 15112TH156, W-trending (266°) ice-flow was measured. Up-unit, the ice-flow direction measured changes to SE-trending (122°) at 2 m depth and SSW-trending (206°) at 1.0 m depth. At sections 15112TH118 (Figure 9b), SSW-trending (193°) and WSW-trending (245°) ice-flow directions were

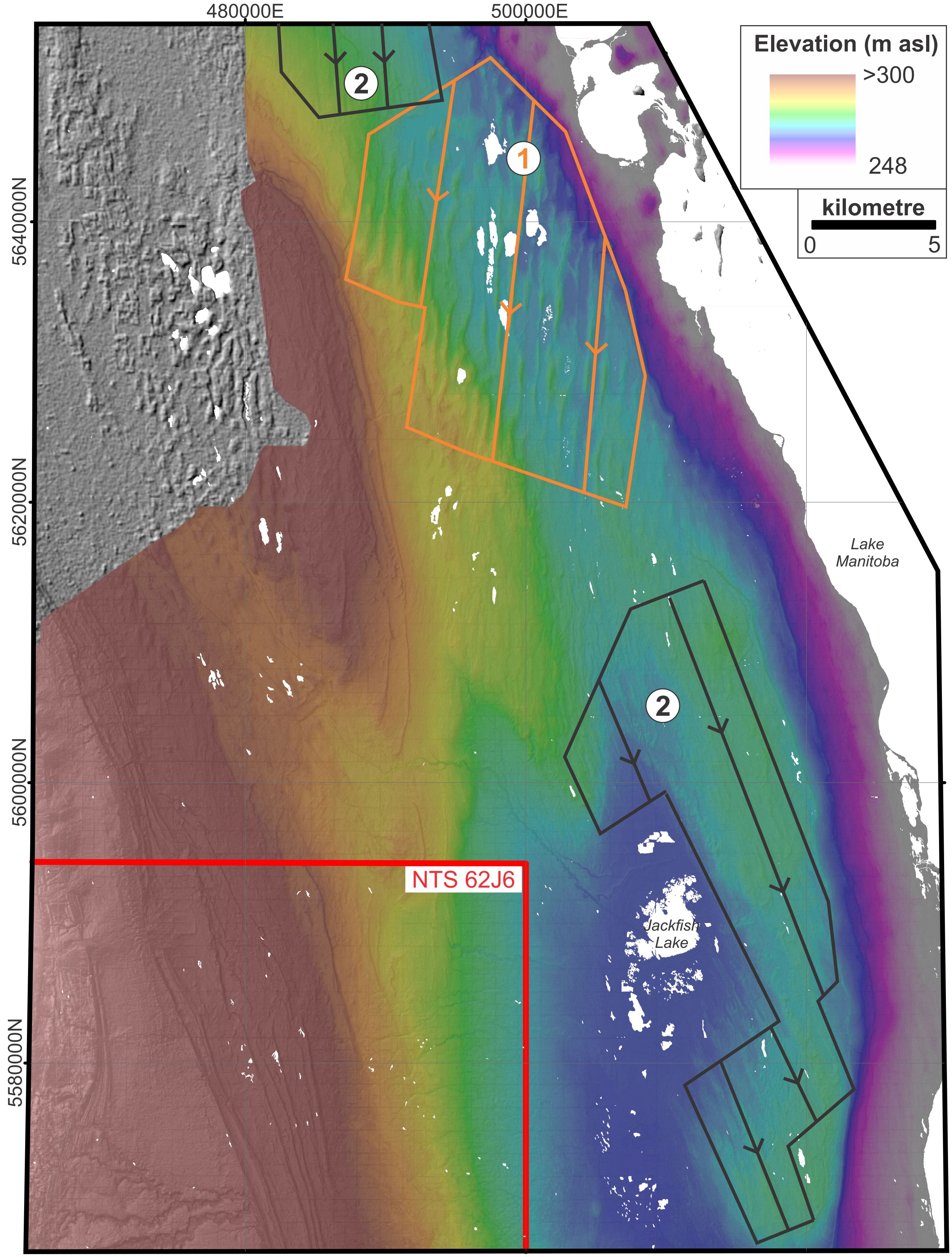

***Figure 8:** Streamlined landforms in the regional record between Lake Manitoba and Riding Mountain. Background elevation is hillshaded LiDAR data (Manitoba Land Initiative, 2018) where available and hillshaded SRTM data in the northwest (Natural Resources Canada, 2012).*

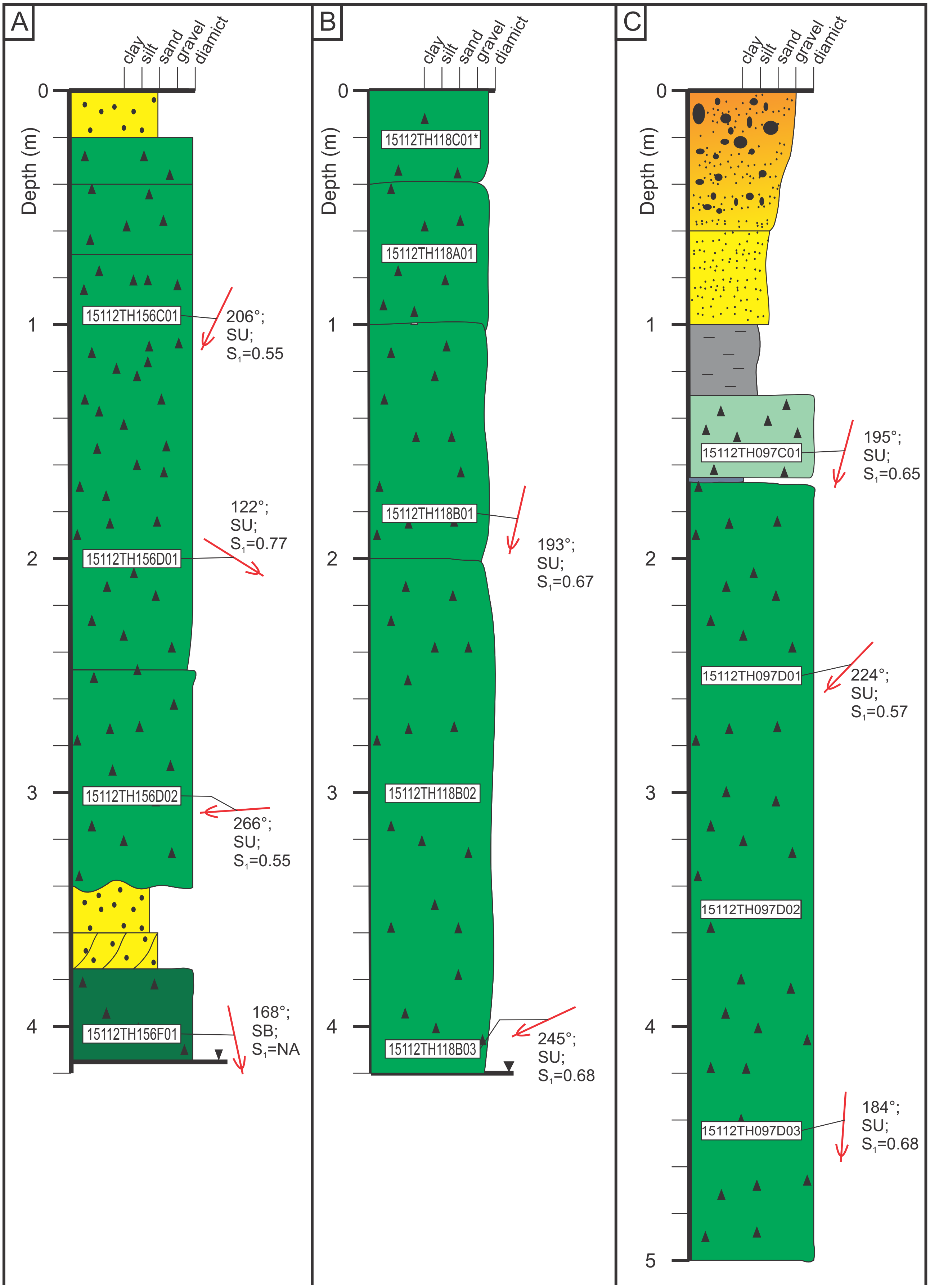

Figure 9: *Simplified stratigraphic columns depicting an interpretation of paleo ice-flow based on clast-fabric data at sections 115112TH097* ***(a)****, 15112TH118* ***(b)*** *and 15112TH156* ***(c)****. Abbreviations: NA, not applicable due to fabric modality;* S_1*, principal eigenvector; SB, spread bimodal; SU, spread unimodal. Section locations are on Figure 1.*

measured. At section 15112TH097 (Figure 9c), S-trending (184°) and SW-trending (224°) ice-flow directions were measured within a lower till unit. Within the upper till, which is separated from the lower till by 0.1 m of clay, a SSW-trending (195°) ice-flow direction was measured. The collection of additional till clast-fabric measurements from exposed sections is necessary to fully reconcile the ice-flow history recorded in the stratigraphic record from this area of southwest Manitoba.

Drift thickness

Till composition is related not only to ice-flow direction from a specific bedrock source, but also the accessibility of the local bedrock to erosion during glacial movement. Bedrock accessibility is related to the underlying bedrock topography and drift thickness. Drift thickness refers to the depth of Quaternary sediments that overlie bedrock. In the study area (NTS 62J6; Figure 10), modelled sediment thickness varies from 0.0 to 95.9 m. Bedrock outcrops (thickness = 0) occur along and above the Manitoba escarpment in the northwest region of the study area, as confirmed during field investigations. The modelled sediment is thickest in the southeast and north-central regions of the map area.

Sediment thickness is determined herein by modelling the current MGS bedrock surface model with the Canadian digital surface model (Natural Resources Canada, 2015). Considering the coarse resolution (500 m) and lack of quality drillholes in the map area, these drift thickness maps should be verified in the field and are only intended to provide an estimate of drift thickness patterns. For example, bedrock was observed at a depth of 1.5 m below Quaternary sediments at station 15112TH153; however, the model predicts ~60 m of sediment in this area. Due to the coarse resolution of this model (500 m horizontal resolution), these figures are meant to provide a broad overview of drift thickness and are not accurate for property-scale work. Future versions of the 3D bedrock surface model will better-reflect this new data.

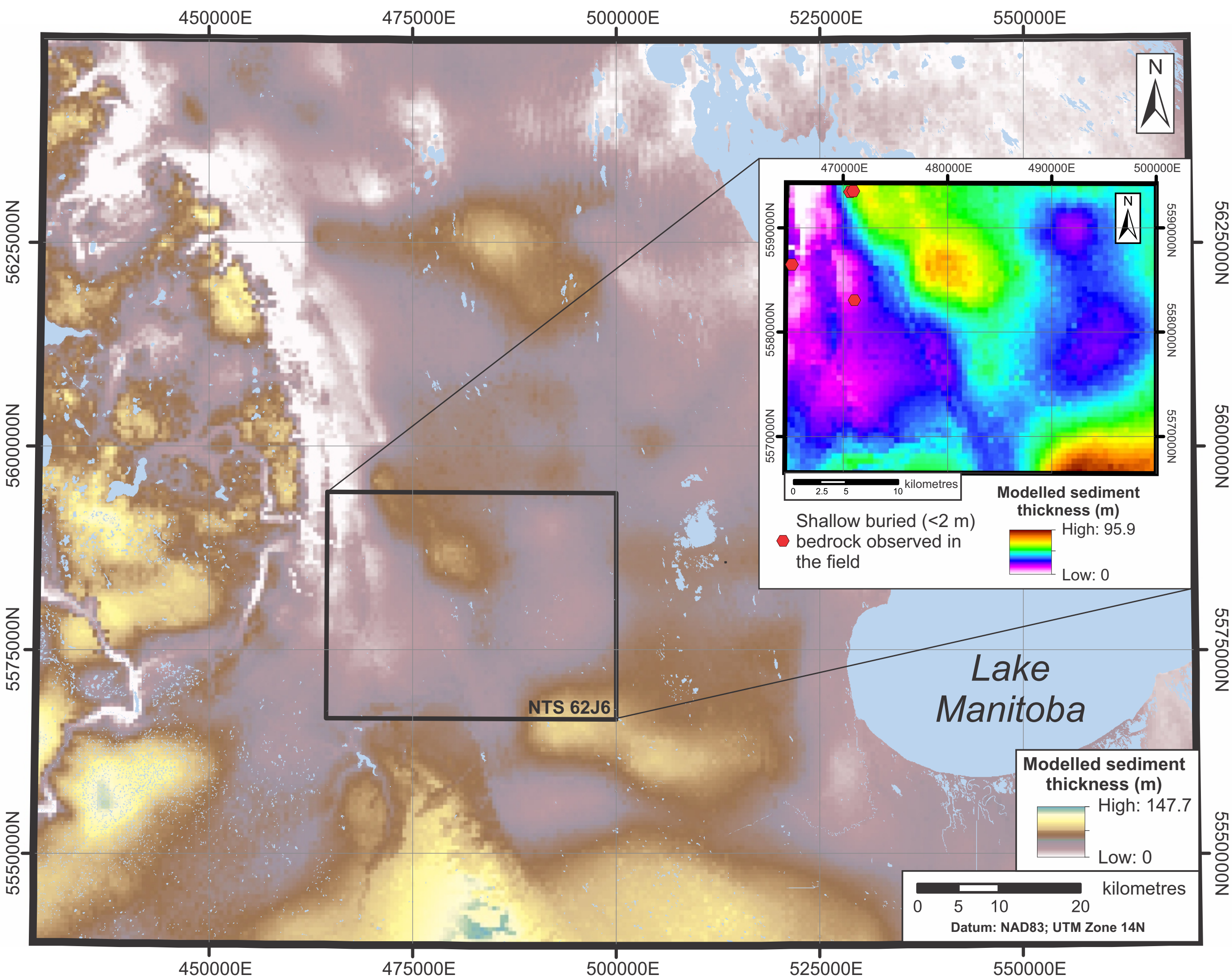

Figure 10: *Modelled drift thickness in the study area (NTS 62J6) and surrounding area for context (NTS 62J). Drift thickness was calculated using the Canadian digital surface model (Natural Resources Canada, 2015) and the current MGS modelled bedrock surface (Manitoba Mineral Resources, unpublished data, 2015). Due to the coarse resolution of this model (500 m horizontal resolution), these figures are meant to provide a broad overview of drift thickness and are not accurate for property-scale work.*

Till grain size

Tills within the study area exhibit a wide range in textural composition (Figure 11). Till-matrix (<2 mm size-fraction) ranges from 7.9–64.6 wt. % sand, 27.4–74.7 wt. % silt and 6.5–48.6 wt. % clay.

Arden map area till composition

Understanding the clast composition of till aids interpretations of the till-matrix geochemical profile and vice-versa. The two data types together provide an understanding of till composition and how it relates to provenance.

Till-clast lithology

Granitoid clasts are present at all sampled till sites (Appendices 5, 6), and exhibit a large range in concentration from 0.4 to 38.4 count percent (ct. %). In an attempt to identify regional-scale trends in till composition across the study area, we have grouped the clasts into simplified classes according to lithology and presumed provenance (Table 1). Then, we divided the till in the study area into three till-clast groups, based on the proportions of local- (Favel (5–19 ct. %) and Odanah (51–97 ct. %) clasts) and distal-derived (shield and carbonate clasts) detritus (Figure 12). Soft black shale clasts are also locally-derived, and were found within 26% of till samples, at concentrations between 0.3 and 18.0 ct. % (Appendix 5, Table 14). Biplots of carbonate vs. shield clast concentration (Figure 13a) and Favel vs. Odanah clast concentration (Figure 13b) confirm that there is a Cretaceous-bearing till with >5 ct. % Favel or >50 ct. % Odanah. The Cretaceous-poor till also has some trends, whereby some samples have elevated shield clasts (red dots on Figure 13a) or elevated carbonate clasts (blue dots on Figure 13a).

Till type 1 (carbonate-shield till)

The first till type is distally-derived, and contains 52–83 ct. % carbonate clasts, 16–38 ct. % shield clasts and only 0–7 ct. % local Cretaceous clasts (Figure 12). Four samples are elevated in shield-clast concentration (31–38 ct. %) relative to carbonate clasts (Figure 13a), resulting in separation into till types 1a (carbonate-rich) and 1b (shield-rich).

Till type 1a is situated in the northeast, south and southwest parts of the study area and till type 1b samples are situated in the central part of the study area (Figure 14).

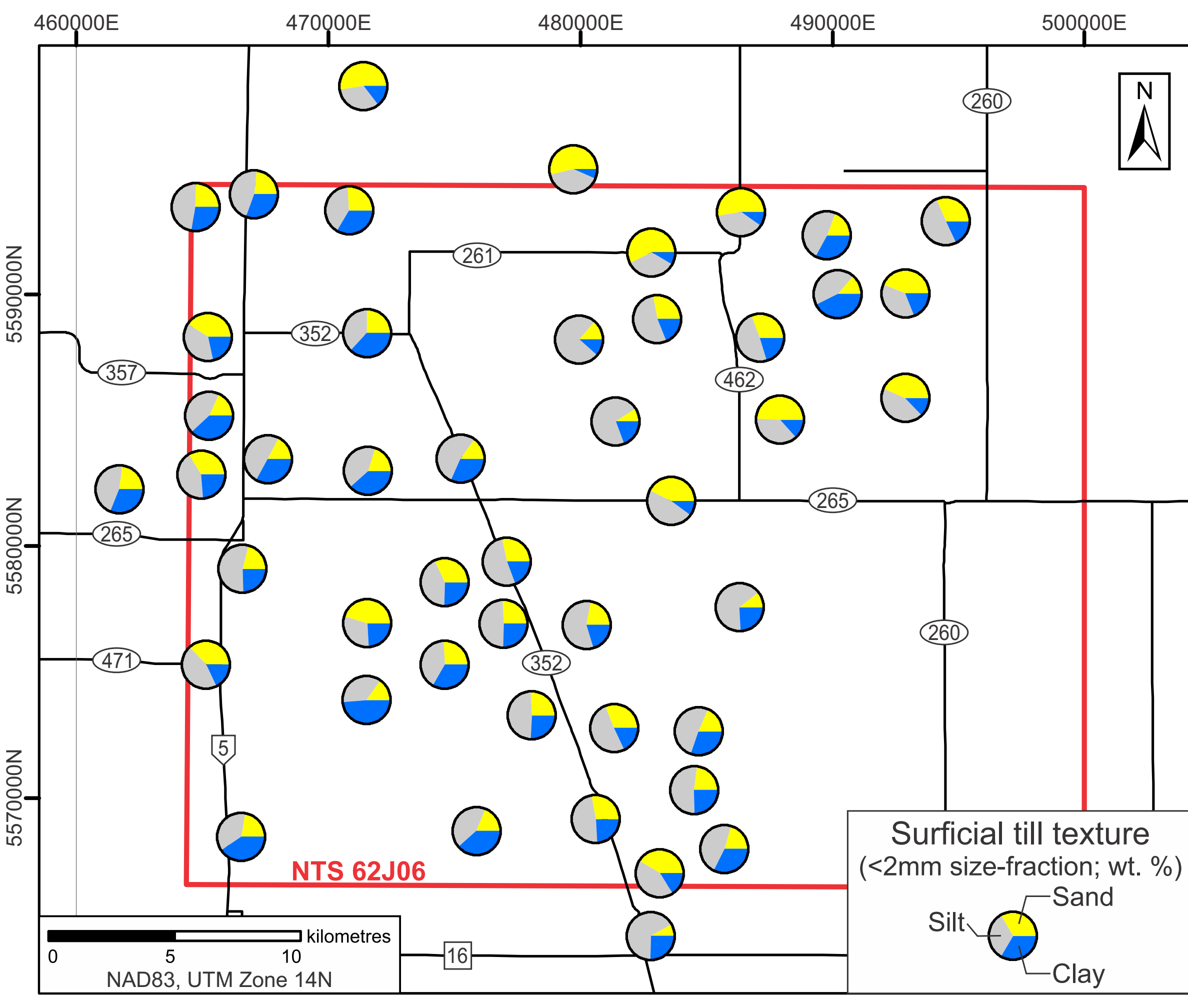

***Figure 11:** Surficial till-matrix (<2 mm) textural results.*

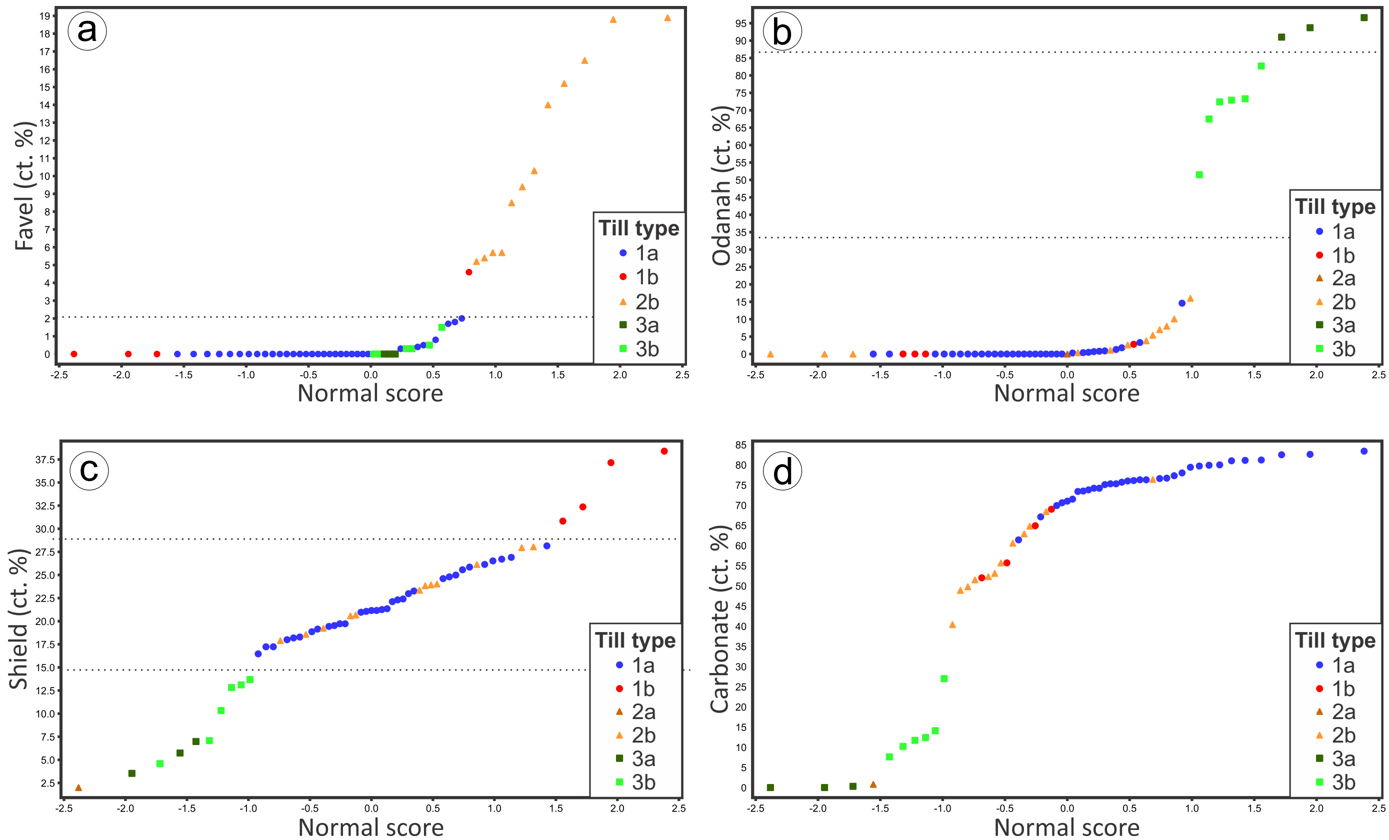

***Figure 12:** Probability plots displaying the distribution of four different clast lithologies **(a–d)** within the till samples. The data is symbolized according to assigned till type to highlight the differences between sample populations.*

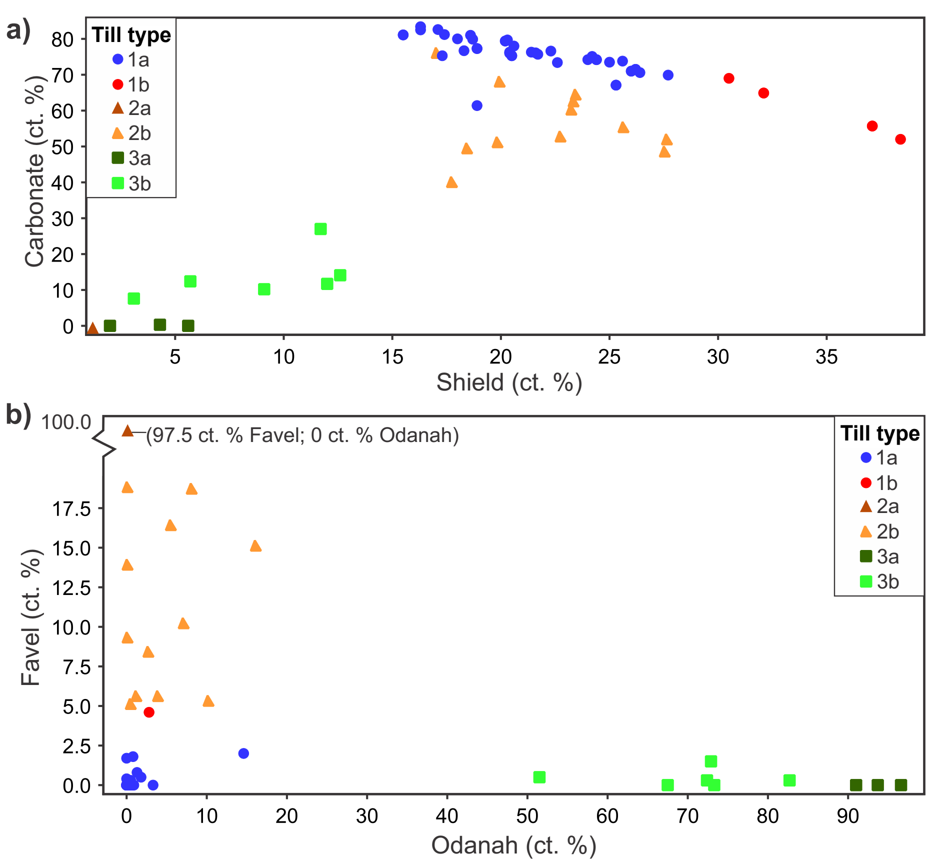

***Figure 13:** Biplots showing the distribution of distally-derived carbonate vs. shield clasts **(a)** and locally-derived Favel vs. Odanah clasts **(b)**. The data is symbolized according to assigned till type to highlight the differences between sample populations.*

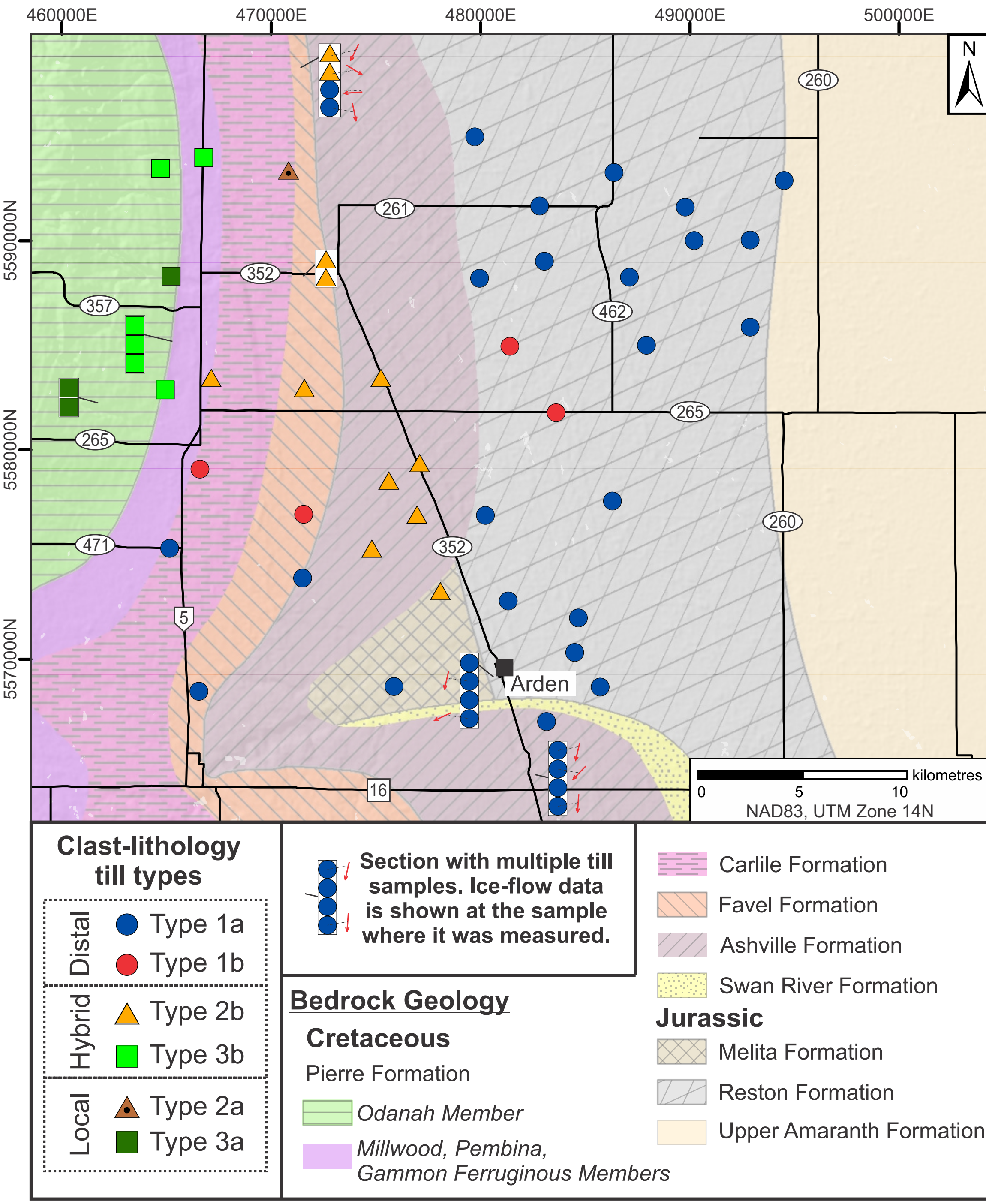

Figure 14: *Spatial distribution of clast till types in the Arden study area. Stations with multiple till samples are shown as stacked symbols.*

Till type 2 (Favel till)

The concentration of Favel clasts within till shows two separate populations, with a natural break in the dataset at 2 ct. % (Figure 12a). We have separated these into a second till type, which is more locally-derived and contains 2–98 ct. % Favel clasts, 0–16 ct. % Odanah clasts, 0–76 ct. % carbonate clasts, and 0–28 ct. % shield clasts (Figure 12). One till sample (15112TH153C01) is not shown on Figure 12a, as it contains 98 ct. % Favel clasts and is an outlier within the dataset (Figure 13). This till sample was collected in an area of thin drift where the local bedrock (Favel Formation) was subcropping, and is separated into local till type 2a (Figure 14). The remaining Favel-bearing sample with >2 ct. % Favel clasts are classified as till type 2b and interpreted as a hybrid till composed of both local- and distal-derived detritus. Till type 2b is situated in the central part of the study area, within 0 to 21 km from mapped Favel bedrock (Figure 14).

Till type 3 (Odanah till)

The concentration of Odanah clasts within till also shows two distinct populations, and there is a natural break in the dataset at 50 ct. % (Figure 12b). We have separated these into a third till type, which is more locally-derived and contains 52–97 ct. % Odanah clasts, 0–2 ct. % Favel clasts, 0–27 ct. % carbonate clasts, and 2–13 ct. % shield clasts (Figure 12). Three till samples contain elevated concentrations of Odanah clasts (90–97 ct. %), overlie mapped Odanah bedrock (Figure 12; Figure 26, Appendix 2), and are separated into a local till type 3a. The remaining Odanah-rich samples are classified as till type 3b and interpreted as a hybrid till composed of both local- and distal-derived detritus. Till type 3b is situated in the northwestern part of the study area, overlying Odanah bedrock or within 2 km from mapped Odanah bedrock, and spatially restricted to the Manitoba escarpment (Figure 2).

Till-matrix geochemistry

Till-matrix carbonate content

Carbonate content in the till matrix is derived from the comminution of calcareous bedrock within the till, which has been transported to the Arden area from the Paleozoic bedrock sources (Figure 2). Thus, the concentration of carbonate can be used as a proxy to determine the percentage of far-travelled detritus that the Arden tills contain. Till-matrix (<63 µm size-fraction) total carbonate concentration ranges from 2.2–79.3 wt. %. Statistically, the dataset exhibits three natural breaks within the probability plot; these three populations are also spatially distinct (Figure 15). Non-calcareous till (<5.0 wt. %) occurs along the Manitoba escarpment and was sampled at the three sites interpreted as Odanah till type 3a (Figure 14). Weakly to moderately calcareous till (5.0–45.9 wt. %) was sampled along the escarpment and confined to beneath or west of the Campbell beaches (northwest trajectory of Highway 352 on Figure 15). These samples are classified as till types 1b, 2b, or 3b (Figure 14). Moderately to highly calcareous till (45.9–79.3 wt. %) is present throughout the remainder of the study area (Figure 15). These samples are classified mainly as the carbonate-shield till type 1 (Figure 14). The total carbonate concentration is somewhat correlative to carbonate-clast concentrations (R^2=0.627), but, there is clearly perturbations within the relationship which are largely controlled by the incorporation of local Cretaceous detritus (till type 2 samples; Figure 16).

Multivariate till-matrix geochemistry analysis

Till in the study area has six different till-geochemistry clusters (till classes A–F), separated using K-means cluster analysis, and the compositional characteristics of each class are discussed using the PCA results (Figure 17). Positive principal component (PC) 1 values reflect an increased influence of carbonate detritus, as evidenced by the elemental assemblage Ca-Mg-Sr. As such, till-class E has the strongest carbonate influence (Figure 17a). Positive PC2 values indicate an increased influence of black shale detritus, as evidenced by the elemental assemblage As-Cd-Mo, and to a lesser extent Cu (Figure 17a, b). Class A has the strongest black shale signature (Figure 17a, b). Negative PC3 and PC2 values reflect samples with a higher granitoid concentration, as indicated by the elemental assemblage K-Al-Co-Na-Rb-Cr-Ga-Sc (Figure 17b). Class C has the highest granitoid signature followed by class E (Figure 17b). Strongly negative PC1 and PC2 values, and positive PC3 values, point to low carbonate contribution and a TREE-Th-Ti-Ba elemental assemblage (class F). The signature of remaining class B and D tills is harder to interpret. Class B also falls within negative PC1 (low carbonate) and positive PC2 (black shale) values, though not as strongly as class A. Class D has positive PC1 (carbonate) and PC2 (black shale) values, though not as strongly as class E or class A.

The six till classes are displayed spatially in Figure 18. Class A overlies the soft black shale Favel, Ashville and Carlile formations, as expected from the PCA analysis. Similarly, class E is situated in the east, furthest from the black shales. Class F, with its elevated TREE-Th-Ti-Ba signature, overlies the Manitoba escarpment, which shows that it may be related to the composition of the Odanah Member of the Pierre Formation. Class B, with its negative-carbonate and positive black-shale signature, is situated on the edge of the Manitoba escarpment, and hence may also be sourced from the Pierre Formation. Spatially, classes C and D are intermixed with, or intermediate between, the other classes.

Kimberlite-indicator minerals (KIMs)

A total of 44 KIMs were recovered during this study (Figure 19; Appendix 4). The majority of KIMs recovered are Cr-spinel (35/44; 80%). Cr-diopside (6), Mg-ilmenite (2), G9 garnet (1) and DI-Cr-spinel (1) were also recovered.

Discussion

Till composition

Using both till-clast lithology and till-matrix geochemistry, till samples in the Arden area were separated by composition into locally-derived Odanah/escarpment and Favel/black shale tills, and a hybrid, farther-travelled carbonate-shield till (Figure 14; Figure 18). Similar, but not identical, till provenance conclusions can be drawn from the spatial pattern of clast-lithology and till-matrix geochemistry proxies. The reader is encouraged to compare each of the provenance proxies and assess which proxy is most suitable to address their needs.

Black shale till and Favel dispersal train

A population of till samples east of the escarpment is associated with elevated Favel clast concentrations (Type 2, Figure 14), and classified as moderate-carbonate (<49^{th} percentile, Figure 15) till classes A (62%) and D (38%) (Figure 18). These geochemical signatures are distinguished by elevated concentrations of As, Cd, Mo and Cu (class A, Figure 17b), as well as U and P (class D, Figure 17b). In the till matrix, Mo has a strong

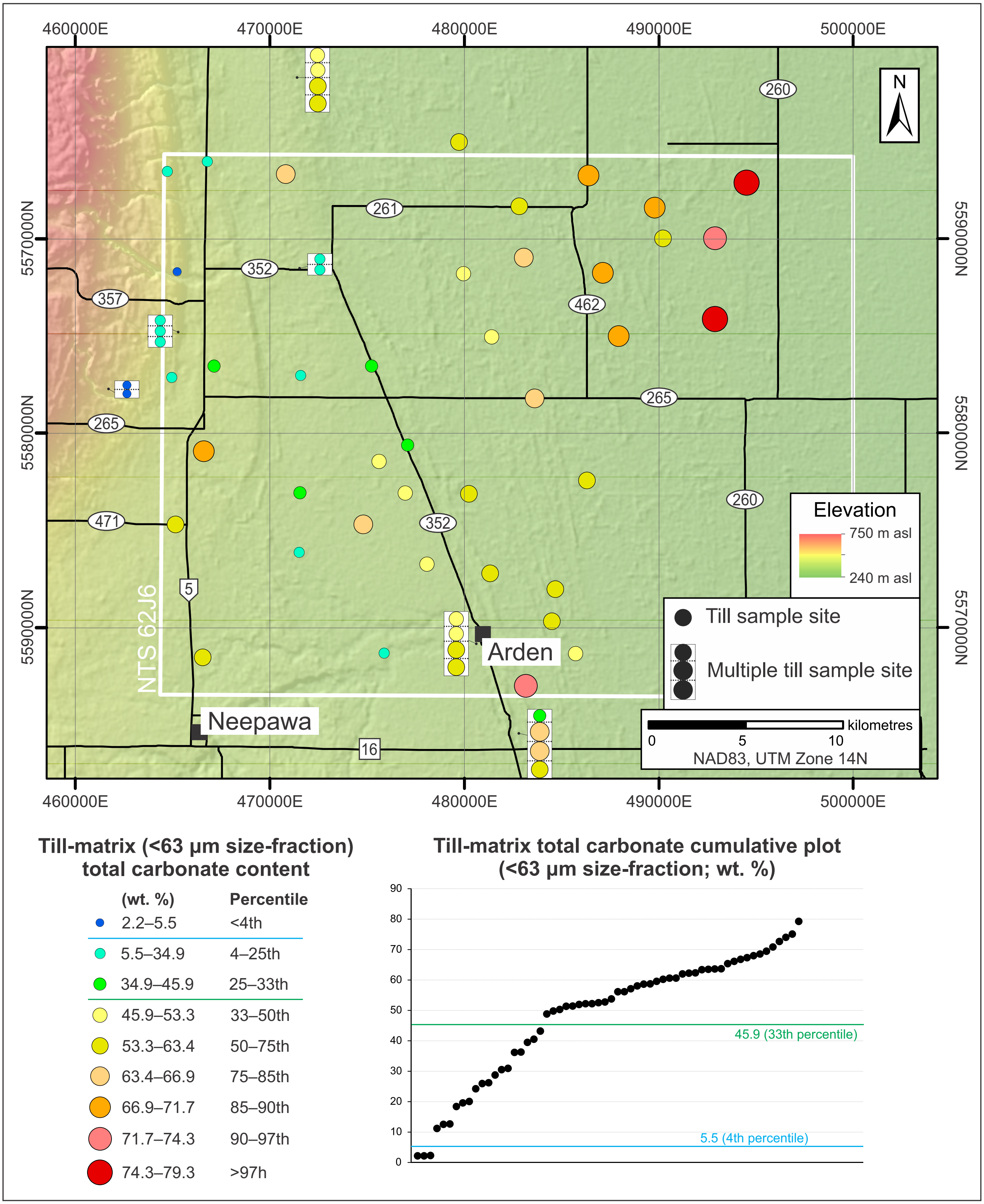

Figure 15: *Till-matrix (<63 µm size-fraction) total carbonate content across the study area. Samples are classified based on natural breaks in the probability plot and displayed by percentile.*

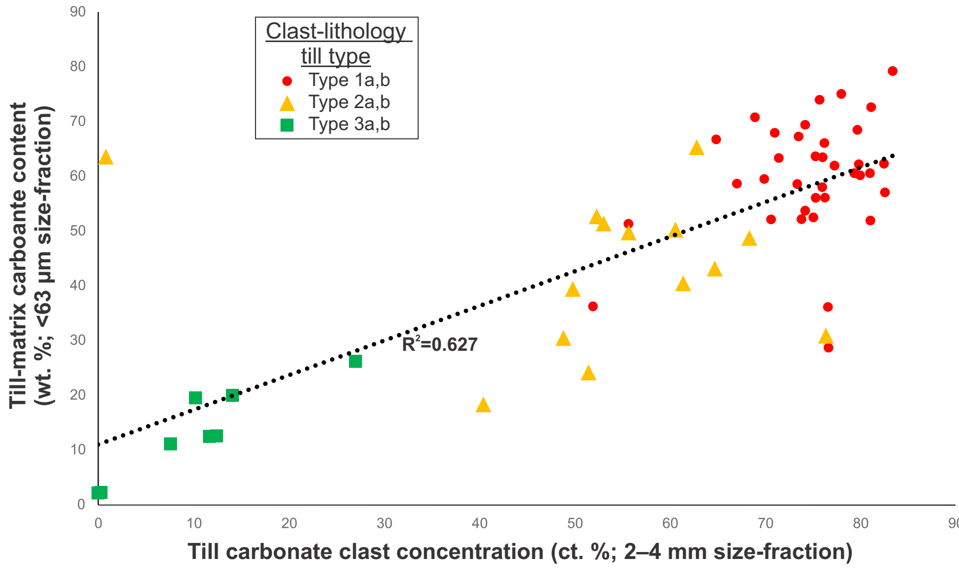

Figure 16: *Till-matrix (<63 µm size-fraction) total carbonate content vs. till carbonate clast concentration (2–4 mm size-fraction) symbolized according to clast-lithology till type.*

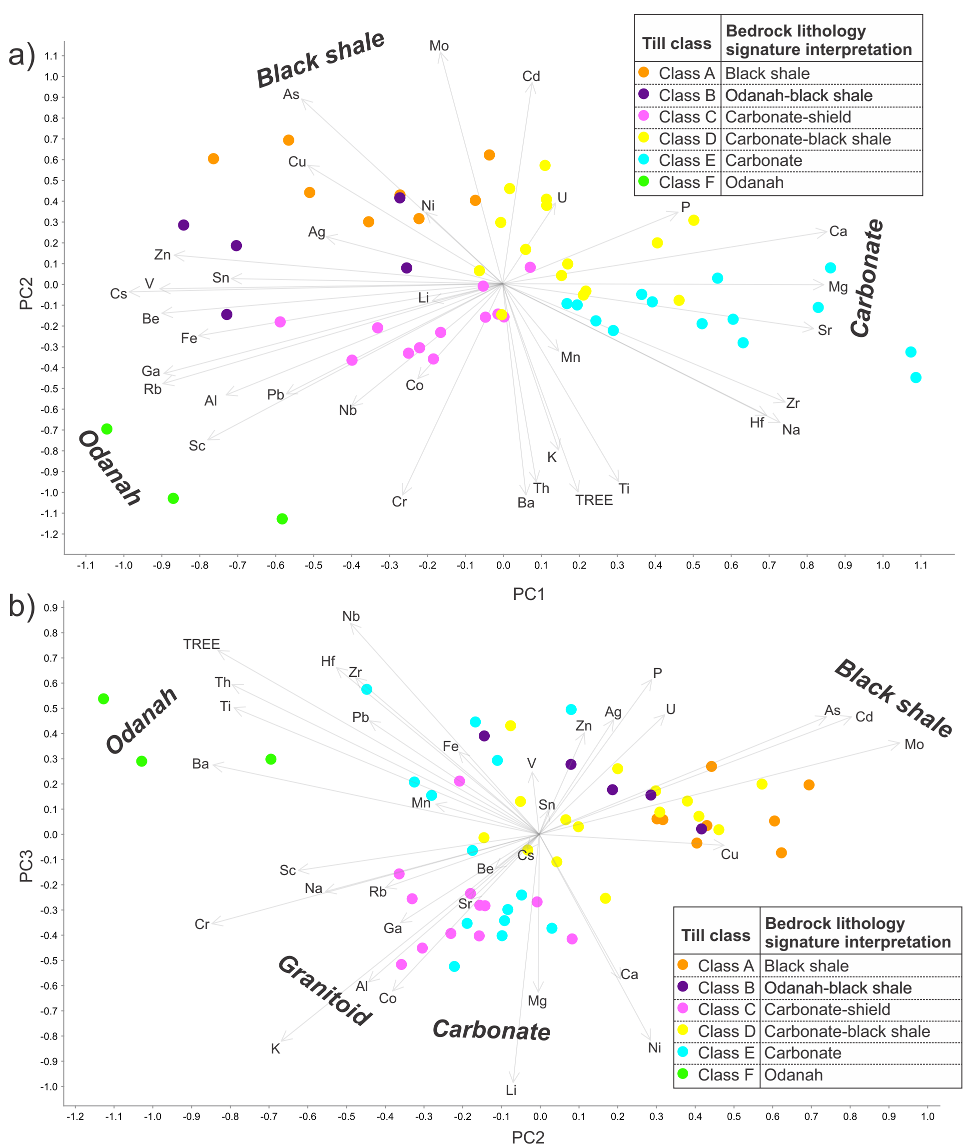

Figure 17: *Multivariate classification of till-matrix geochemistry data and interpreted lithologic controls on cluster results:* ***a)*** *PC2 vs. PC1;* ***b)*** *PC3 vs. PC2. Plots display the scaled elemental vectors and samples as points.*

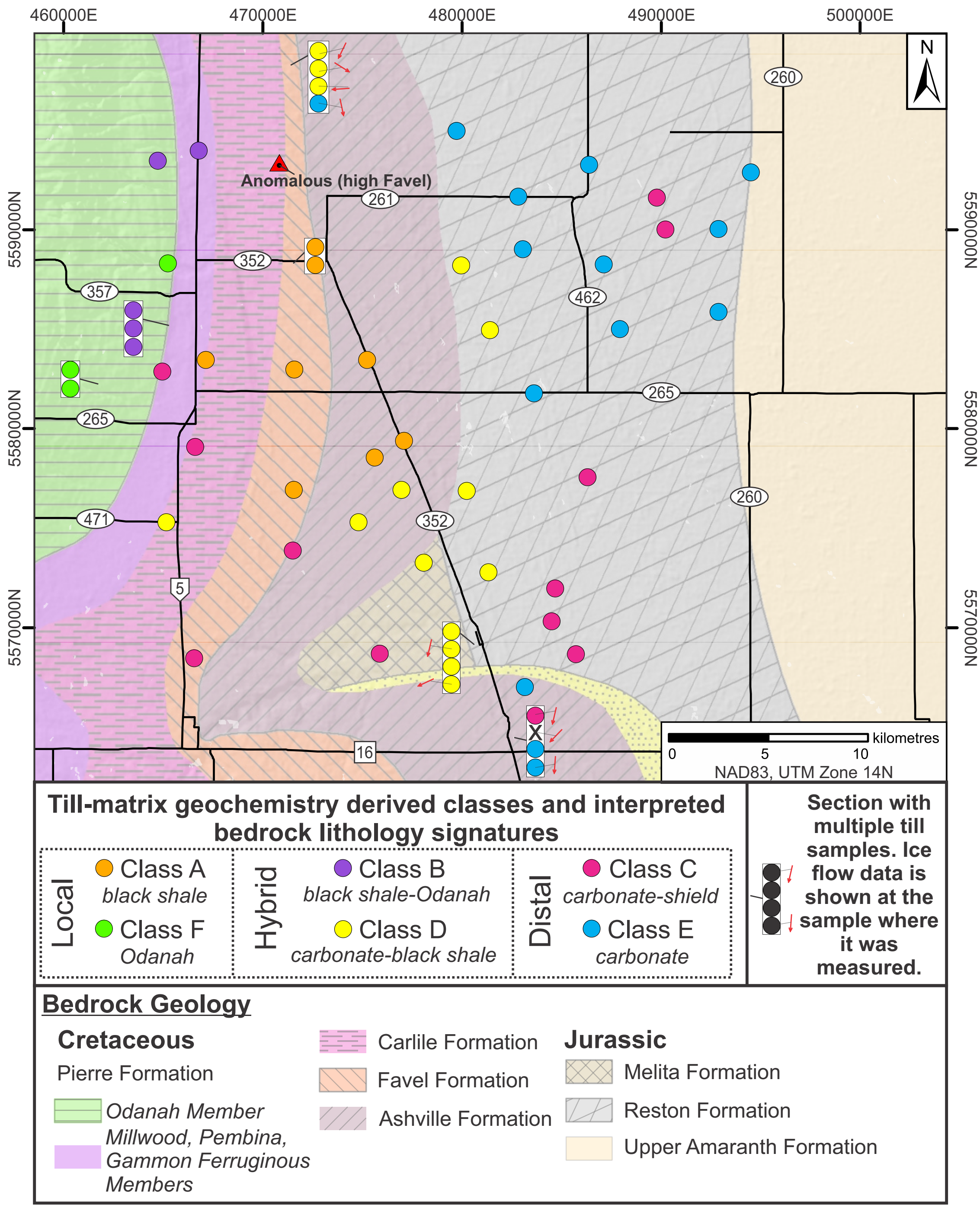

Figure 18: *Distribution of till-matrix geochemistry derived till classes.*

correlation (correlation coefficient of 0.94) with the proportion of Favel clasts observed in till samples. Till type 2 samples also include 0–28 ct. % shield and 0–76 ct. % carbonate clasts, which indicates that a variable portion of these tills is distally-derived.

The Favel clasts, and associated Mo concentrations within till, outline a SSE-trending dispersal train (Figure 20). The head of this dispersal train is at site 15112TH153C01, where Favel Formation subcrops and the till contains 97.5% Favel clasts. Favel detritus within the dispersal train (1.9–18.9 ct. %, 2–4 mm size-fraction; 75th–99th percentile) extends approximately 20 km and exhibits an exponential decay trend down-ice towards the SSE (Figure 20b). The orientation of the dispersal train is roughly 160°. Streamlined landforms with a similar orientation are situated 25 km to the east of the dispersal train (Figure 8).

Odanah escarpment till

Till samples that overlie the Manitoba escarpment edge are locally-derived tills associated with elevated Odanah clast concentrations (Type 3, Figure 14), and classified as low-carbonate (Figure 15) till classes F and B (Figure 18). The three till

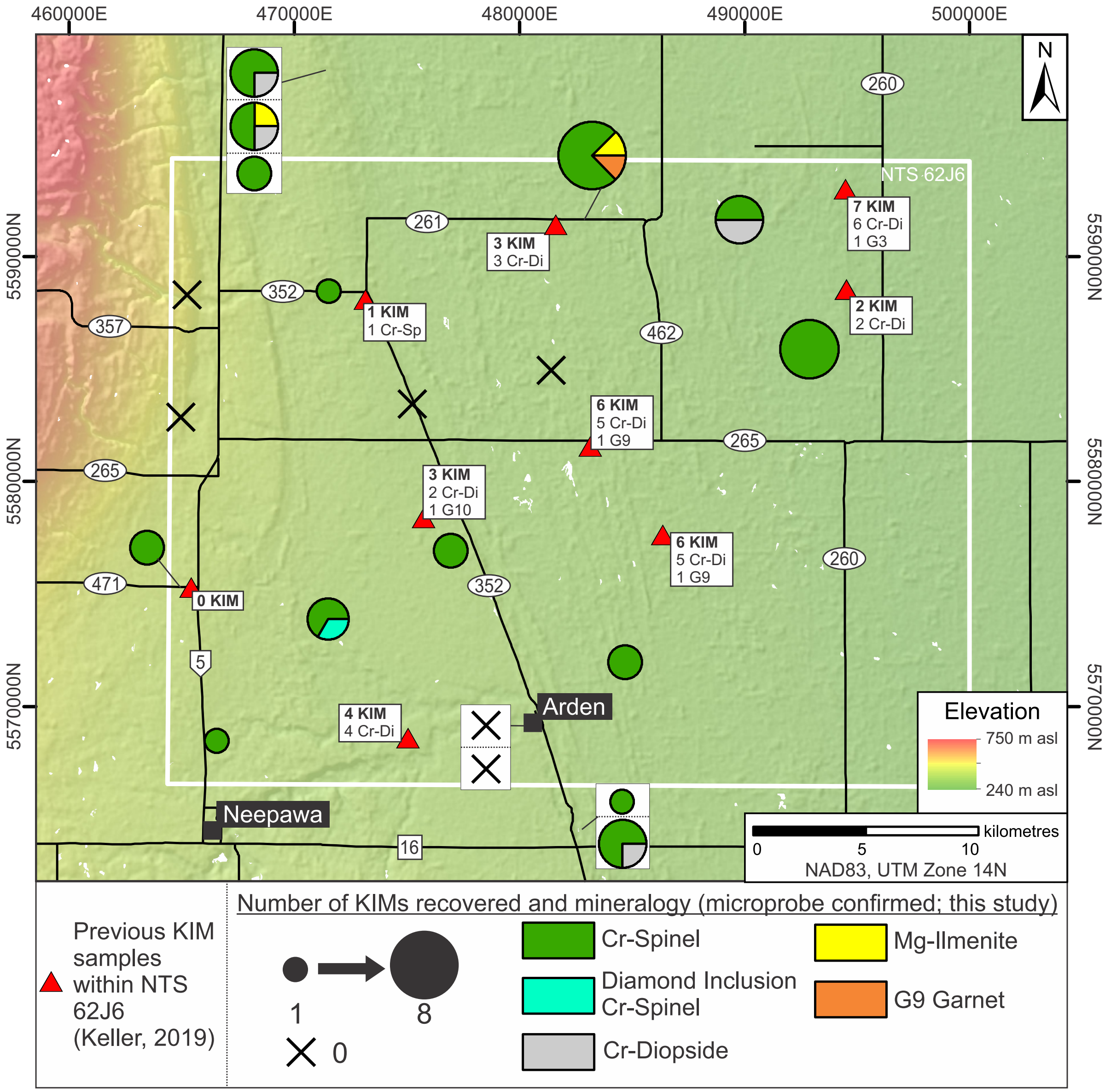

***Figure 19:** Distribution of kimberlite-indicator mineral results from this study. The circles are sized proportionally relative to the amount of KIMs recovered, and as pie charts depicting KIM type. Previous results within NTS62J6 are plotted. Abbreviations: Cr-Di, chrome diopside; Cr-Sp, chrome spinel; G3, eclogitic garnet; G9, lherzolitic pyrope garnet; G10, harzburgitic pyrope garnet; KIM, kimberlite-indicator mineral.*

type 3a (>90 ct. % Odanah clasts) samples correlate to the three class F samples. Based on this correlation, till enriched in Odanah detritus has a TREE-Th-Ti-Ba geochemical signature within the dataset. The six till type 3b (51–83 ct. % Odanah clasts) samples are class B (5 samples), except one that is a class C. Class B has partial black shale signature (As-P-Ag-Zn), which is likely sourced from the local Pierre Formation shales. Till type 3a samples also include 2–6 ct. % shield clasts but have no carbonate clasts, whereas till type 3b samples have 3–13 ct. % shield clasts and 8–27 ct. % carbonate clasts. As such, a small but variable portion of these tills is distally-derived.

Hybrid carbonate-shield till

The remainder of till samples overlying the plains are a hybrid mix of locally-derived and distally-derived (Type 1 on Figure 14, and classes C (30%), D (28%) and E (42%) on Figure 18). The matrix is enriched in K-Al-Co-Na-Rb-Cr-Ga-Sc (elevated shield detritus) or Ca-Mg-Sr (elevated calcareous detritus). The carbonate portion of these tills, and the Cretaceous-rich tills above, are derived from the local to regional Mesozoic and Paleozoic bedrock sources (Figure 2). The shield portion of these tills is derived from the Precambrian shield situated 390 km northeast and 160 km east of the Arden map area.

Regional till composition

Given that both local and far-travelled tills are present in the Arden area, we investigated if other local Cretaceous tills could be identified in southwestern Manitoba. To do this, we applied multivariate statistical methods to the total INAA till-matrix geochemistry data from Matile et al. (1996). This is a first-pass attempt, given that: 1) INAA is not as good at capturing the 'whole rock' geochemistry as near-total digestion ICP

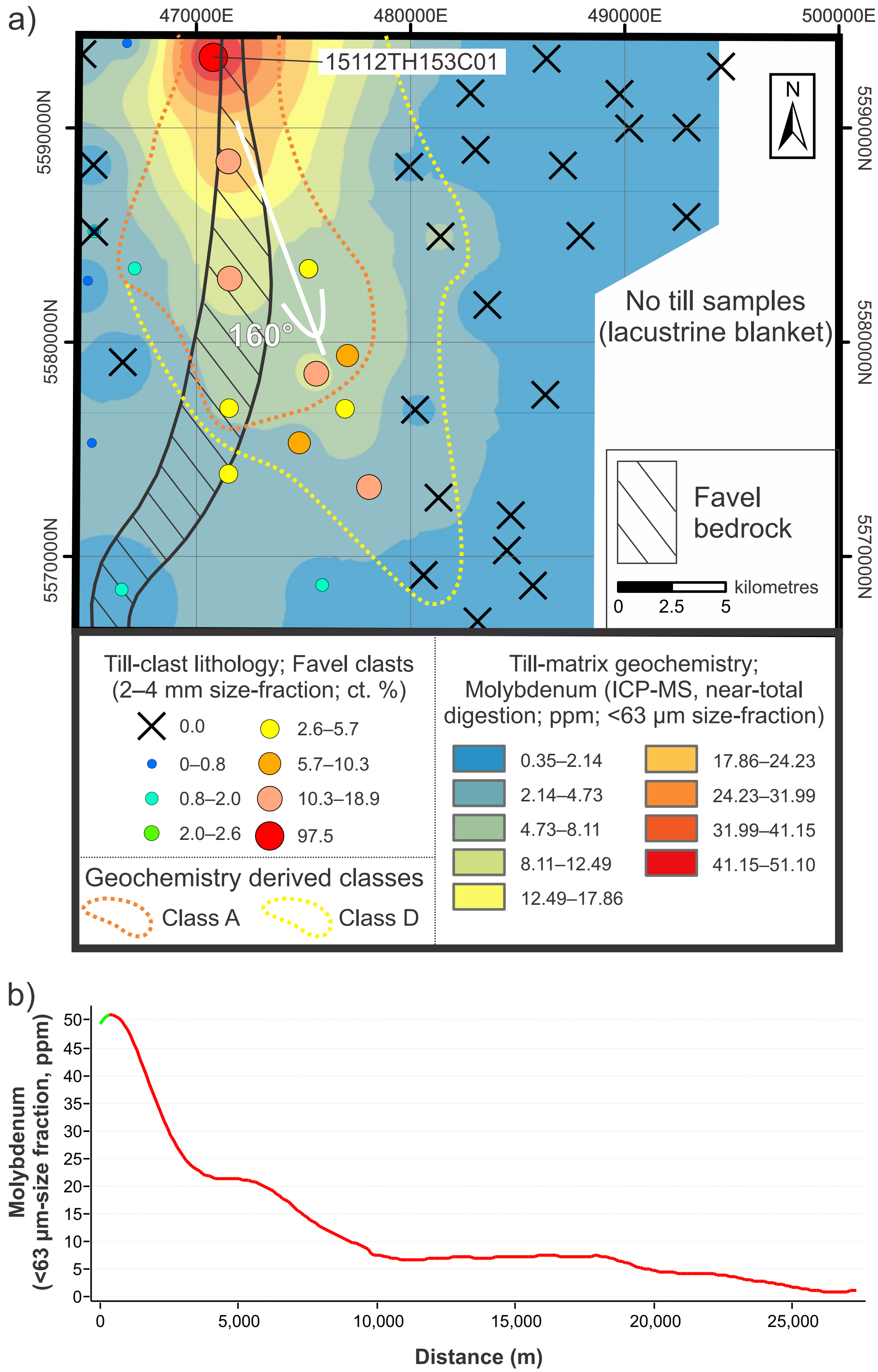

Figure 20: *Local shale dispersal train identified east of the Manitoba escarpment:* ***a)*** *dispersal of Favel Formation clasts and molybdenum concentrations (contoured inverse-distance weighted raster using near-total digestion ICP-MS data) within till. Favel Formation subcrops at site 15112TH153C01. This figure also shows outlines of the till classes A and D, which are interpreted as locally-derived black shale tills, and an outline of the mapped Favel Formation;* ***b)*** *exponential decay of molybdenum concentrations in till sampled down-ice from the subcropping Favel bedrock source.*

and, 2) while Ca and Mg are important elements in the Arden area, these were not part of the INAA dataset. Despite the difference in elemental inputs of the Matile et al. (1996) dataset compared to our study, there are some similar patterns. Positive PC1 values are controlled by As, Sb and U, grouped as cluster 7, and to a lesser extent 1 and 4. Negative PC1 values form an elemental assemblage of Sc-Na-Cr-Rb-Th-La-Ce, which is less distinct but consists of clusters 2, 3 and 5. Using the interpretations from our study, As and U are most likely sourced from Cretaceous black shales, while Sc-Na-Cr-Rb-Th-La-Ce is a granitoid assemblage. To see if the multivariate statistics yield spatial patterns, we plotted both the K-means clusters and interpolated/contoured PC1 values (Figure 21a). Indeed, the interpreted black shale cluster 7 is restricted to till-sample sites near or on top of the Manitoba escarpment. Additionally, clusters 1 and 4, which also have a black shale signature, are situated closer to the escarpment than clusters 2, 3 and 5–which do not. Importantly, the PCA and K-means analysis of the INAA data replicates our findings herein that there is a shale till in the western half of the study area. Hence, this regional-scale till-composition map can be used as a proxy for drift prospecting to assess the degree of local shale till vs. mixed, non-shale bedrock detritus in till samples. As always, local-scale till sampling and analyses should be used to solve property-scale prospecting questions.

Southwest Manitoba garnet KIMs

KIMs of unknown source(s) have been recovered from a number of different till samples in southern Manitoba, both in this study area (Figure 19) and at other localities (Thorleifson and Garrett, 1993; Matile et al., 1996; Garrett et al., 2008). To test whether there is a relationship between Cretaceous-rich till and KIMs recovered, we overlaid the occurrence of G3, G9 and G10 garnet KIMs on a first-pass map that highlights regions with a high concentration of local Cretaceous detritus (Figure 22, derived from the till-matrix geochemistry trends on Figure 21). These garnet KIMs were chosen based on their importance for diamond exploration and overall abundance within the dataset; for a more thorough analysis of the till KIM signature in southwest Manitoba, the reader is encouraged to explore the entire datasets within the Manitoba KIM database (Keller, 2019). In Figure 22, there appears to be little definitive correlation between garnet recovery and Cretaceous-rich till. G10 garnets were found in both local shale till near the Manitoba escarpment (Arden area), and in distally derived till northeast of Dauphin Lake and near the southern end of Lake Manitoba. Outside of the 1996 study area, two G10 garnets were recovered east of the Manitoba escarpment near Morden, and one G10 garnet was sampled in drillhole CC south of Riding Mountain (Figure 22).

Interestingly, there is a line of five till samples that contain garnet KIMs, in the area between Lake Manitoba and the Arden map sheet (pink box on Figure 22). This line is oriented to 160°, which is parallel to both the surface Favel Formation dispersal train in the Arden area (Figure 20) and the streamlined landforms in the Jackfish Lake area (Figure 8). At these five sample stations, the modelled drift is thick (>40 m; Figure 23), which shows that these surface-sampled garnet KIMs are likely not sourced directly from the underlying bedrock at those sample stations. However, if this is a dispersal train, the modelled drift thickness shows region(s) of thinner drift in the presumed 'up-ice' direction (to the northwest). This area (within NTS 62J11) should be a target of future exploration.

Recommendations for drift prospecting

The following statements pertain to the Arden map area:

- The source of KIM grains recovered from till in southwest Manitoba remains elusive. Future studies should include analyses of the till composition, drift thickness, and local ice-flow history, in addition to till sampling for KIMs.
- Parts of the study area are draped by a variable thickness of alluvial or glaciolacustrine clay, silt, sand, and gravel, which must be avoided during till sampling programs.
- Till samples should be collected from the C horizon whenever possible, to avoid the effects of chemical weathering. Even so, secondary dilution from the breakdown of post-glacial, chemically-weathered clasts (in the field) and physically-weathered clasts (in the lab during sample preparation) is still a concern. Both factors will adversely alter the clast and matrix composition.
- Till-composition data should include both clast-lithology and till-matrix geochemistry. Clast-lithology counts are used to guide geochemical interpretations, and can identify trends not readily apparent in till-matrix geochemistry. Similarly, till-matrix geochemistry trends can be used to highlight bedrock contributions that have been largely comminuted (e.g., black shale). These methods should be used together whenever possible.
- Our till-compositional analyses shows that the till can be subdivided along a continuum between two end-member populations: locally-derived till and more distally-derived till. The user needs to know where a particular till sample falls on that continuum, in order to help determine the transport distance of any particular mineralized detritus.
- The ice-flow history of the study area is somewhat poorly constrained. During one or more time periods, ice-flow orientation interpreted from till-clast fabrics and streamlined-landform orientations suggests that ice flowed to the south (175°, 184–196°, 206°), southwest (225°, 245°, 266°) and southeast (122°, 160°). A 160°-trending glacial dispersal train composed of *Inoceramus sp.*-bearing clasts and increased levels of molybdenum in till was delineated in the study area, is 20 km long, and originated at a site where the Favel Formation subcrops beneath 1.5 m of till. The user should use these ice-flow directions to guide regional drift exploration, but must conduct additional clast-fabric analyses where specific information is needed.
- Depth to bedrock also needs to be considered when interpreting till composition. The modelled drift-thickness

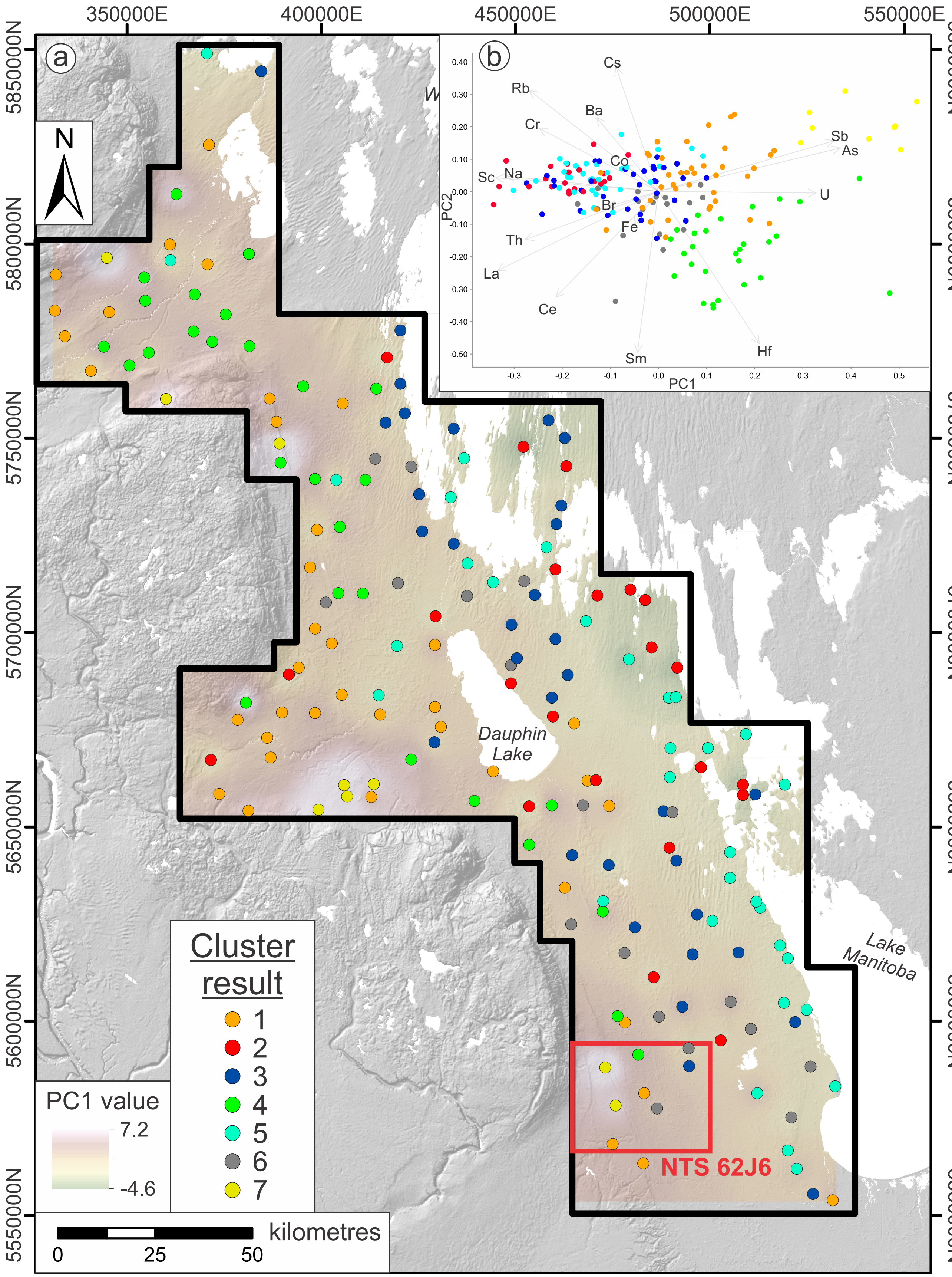

Figure 21: *PCA results from analysis of the Matile et al. (1996) regional geochemical survey:* ***a)*** *interpolated raster of PC1 results for the Westlake Plain;* ***b)*** *PC2 vs. PC1 with samples classified according to their cluster analysis result.*

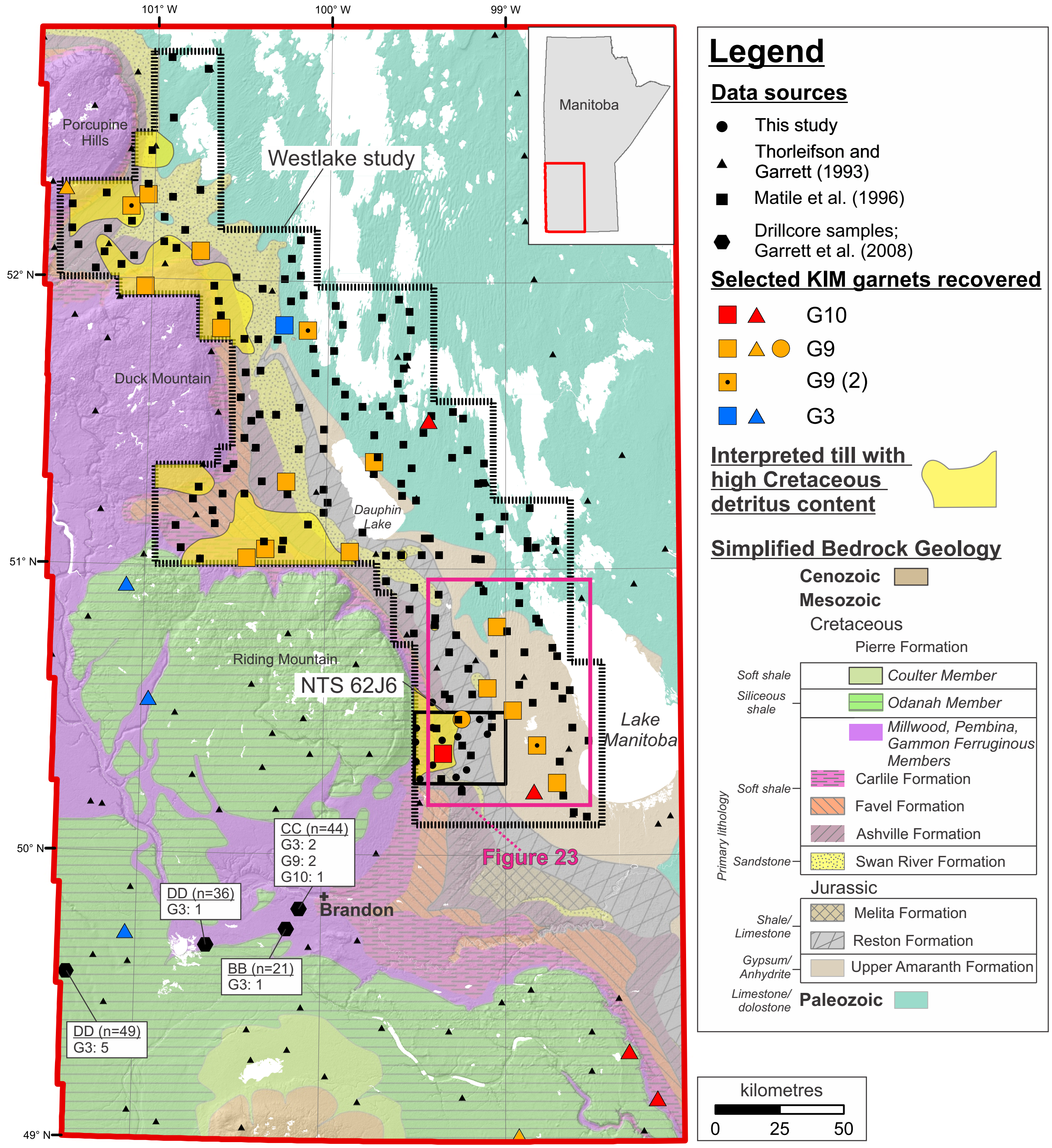

Figure 22: *Selected KIM garnets within till samples in southwest Manitoba. Bedrock map is simplified from Nicolas et al. (2010), and overlies a hill-shaded DEM that shows the topography of the Manitoba Escarpment along the Porcupine Hills, Duck Mountain and Riding Mountain. Regional KIM data can be found in Keller (2019), Thorleifson and Garrett (1993), Matile et al. (1996), and Garrett et al. (2008).*

in the study area indicates a spatially variable cover of 0.0 to 95.9 m of sediment. While the sediment thickness during till formation is unknown, there is a high likelihood that in some areas pre-existing sediment cover may have inhibited erosion of the local bedrock.

Acknowledgments

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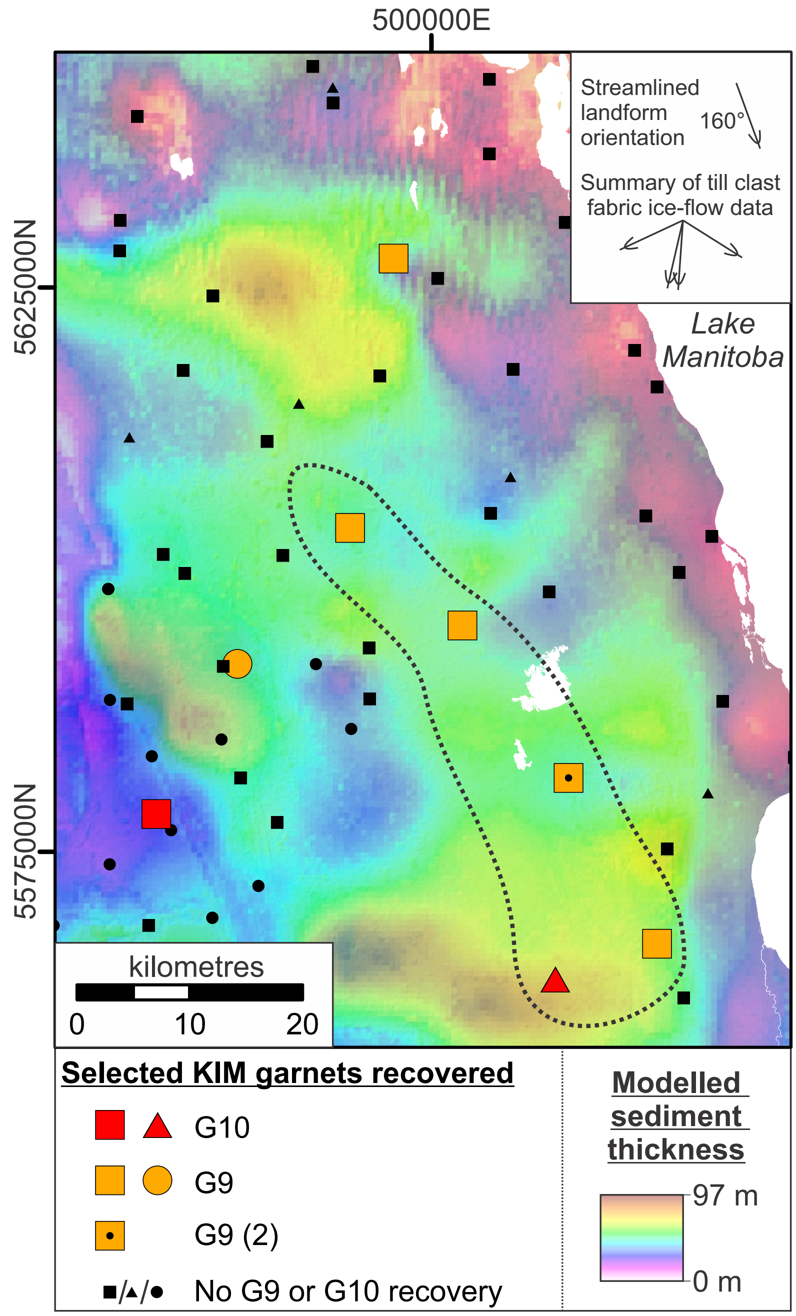

Figure 23: *Drift thickness and garnet KIM recovery west of Lake Manitoba. See Figure 22 for location.*

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